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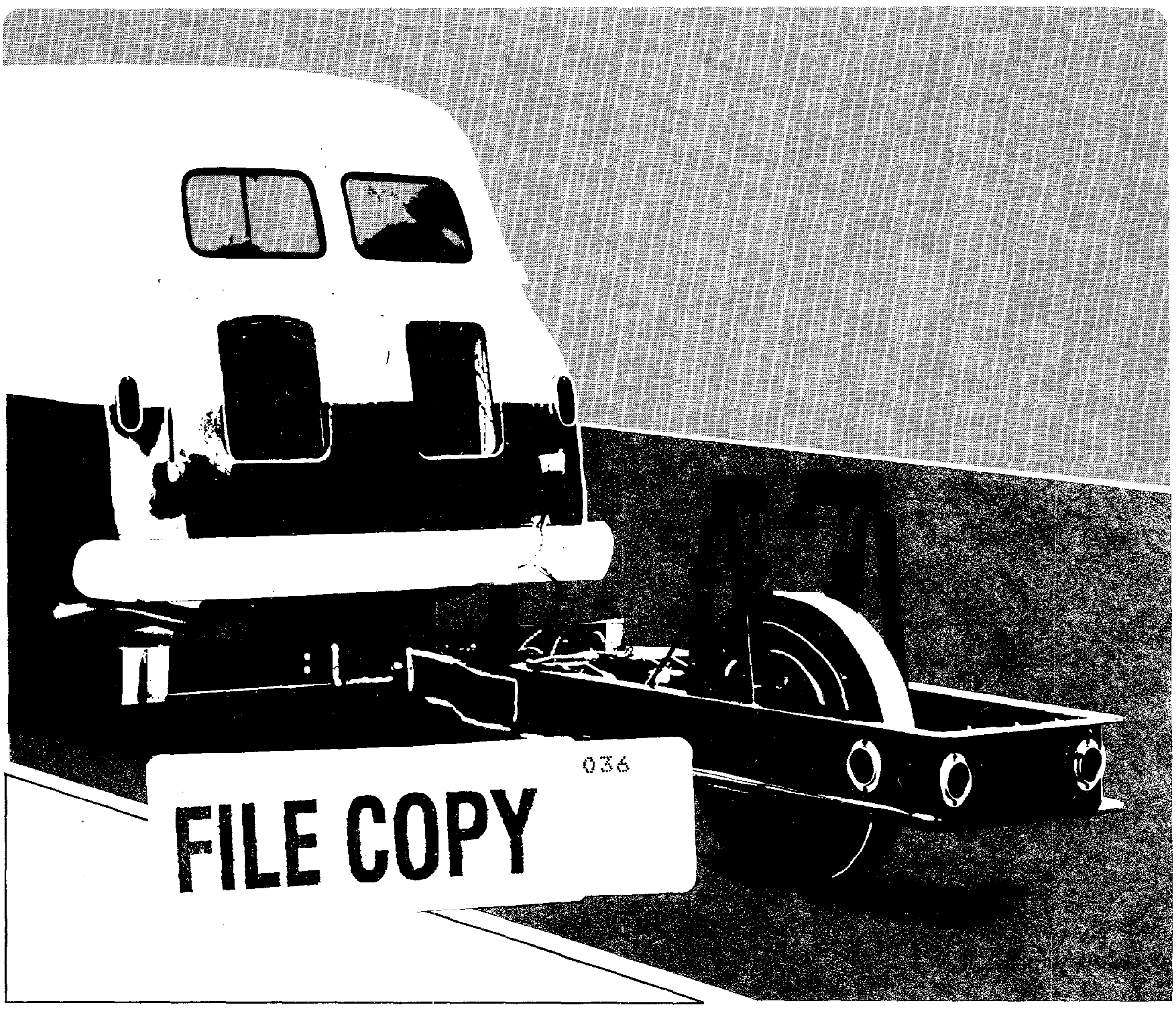
The International Road Roughness Experiment

Establishing Correlation and a Calibration Standard for Measurements

Michael W. Sayers, Thomas D. Gillespie, and Cesar A. V. Queiroz



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Michael W. Sayers, Thomas D. Gillespie, and Cesar A. V. Queiroz

A collaborative study undertaken by

The University of Michigan Transportation Research Institute
GEIPOT-Empresa Brasileira de Planejamento de Transportes, Brazil
IPR/DNER-Instituto de Pesquisas Rodoviárias, Brazil
Laboratoire Central des Ponts et Chaussees, France
Centre de Recherches Routières, Belgium
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ABSTRACT

Road roughness is gaining increasing importance as an indicator of road condition, both in terms of road pavement performance, and as a major determinant of road user costs. This need to measure roughness has brough a plethora of instruments on the market, covering the range from rather simple devices to quite complicated systems. The difficulty is the correlation and transferability of measures from various instruments and the calibration to a common scale, a situation that is exacerbated through a large number of factors that cause variations between readings of similar instruments, and even for the same instrument at different times and under different conditions. This need to correlate and calibrate led to the International Road Roughness Experiment (IRRE) in Brazil in 1982.

The IRRE covered two categories of instruments - profilometers, which measure the logitudinal elevation profile of the road and converts this into a roughness index - and response-type road roughness measuring systems (RTRRMS's), which integrate readings of the device into an instrument-specific numeric. The analyses demonstrated a good correlation between the RTRRMS' and between the RTRMM's and profilometer records, and showed that they could all be calibrated to a single roughness scale without compromising their accuracy. Thus, all the instruments tested will give outputs which are sufficiently accurate and reproducible for comparative evaluation, but will need to be correlated to some given standard to ensure transferability and consistency over time.

A large array of possible Standard Indices were evaluated, some based purely on the geometric charateristics of the road profile, some based on simulation of the road profile - vehicle interaction, and some based on spectral analysis of the roughness recorder output. These analyses, which also include measurement travelling speed, are described in the text, and elaborated in the Appendices, with ample tabulations and diagrams to illustrate the correlations. A practical manual emanating from the IRRE is contained in a companion volume in this Series, entitled Guidelines for Conducting and Calibrating Road Roughness Measurements (World Bank Technical Paper Number 46).

Appendices contain full documentation of the data collected and the analyses performed.

ACKNOWLEDGEMENTS

The International Road Roughness Experiment (IRRE) reported here was sponsored by a number of institutions: the Brazilian Transportation Planning Agency (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.

Appendix H, included in this volume, was prepared by S. W. Abaynayaka and L. Parsley of TRRL. Appendices E and G were prepared jointly by UMTRI, IPR/DNER, CRR, and LCPC. Appendix K was prepared by W. D. O. Paterson of 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 reesearch team from LCPC; J. Reichert and M. B. Gorski formed the research team from CRR; M. I. Machado (GEIPOT) supervised the subjective rating study and aided in the data entry; I. L. Martins (GEIPOT), Z. M. S. Mello (IRP/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.

Finally, grateful acknowledgement is extended to C. G. Harral (World Bank), who conceived the idea of the IRRE and arranged for the participation of the different agencies worldwide; to P. E. Fossberg, who supervised subsequent phases of the work by the World Bank; and to W. D. O. Paterson, who participated during the planning and execution of the field work and had an active role in the subsequent evaluation.

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LIST OF ABBREVIATIONS AND ACRONYMS

Note: English equivalents are given when abbreviations refer to non-English expressions.

ARRB - Australian Road Research Board
APL - Longitudinal Profile Analyzer
ARS - Average Rectified Slope
ARV - Average Rectified Velocity
BI - Bump Integrator
BPR - Bureau of Public Roads
CA - Asphaltic Concrete
$CAPL_{25}$ - APL Coefficient (of roughness over 25 m)
COPPE/UFRJ - Federal University of Rio de Janeiro
CP - Coefficient of Smoothness
CRR - Road Research Center, Belgium
GEIPOT - Brazilian Transportation Planning Agency
GMR - General Motors Research
GR - Gravel
HCS - Half-car Simulation
BRD - The World Bank
IPR/DNER - Road Research Institute, Brazil
IRRE - International Road Roughness Experiment
IRI - International Roughness Index
LCPC - Central Bridge and Pavement Laboratory, France
NCHRP - National Cooperative Highway Research Program, United States
PSD - Power Spectral Density
QCS - Quarter-car Simulation
QI - Quarter-car Index (originally)
RARS - Reference Average Rectified Slope
RARV - Reference Average Rectified Velocity
RBI - Reference BI Trailer Index
ROCS - Reference Quarter-car Simulation
RMS - Root-mean-square
RMSD - RMS Deviation (from a linear regression line)
RMSE - RMS Elevation
RMSVA - RMS Vertical Acceleration
RTRRMS - Response-type Road Roughness Measuring System
SR - Subjective Rating
TE - Earth Surface
TRRL - Transport and Road Research Laboratory, Great Britain
TS - Surface Treatment
UMTRI - University of Michigan Transportation Research Institute

SUMMARY

The International Road Roughness Experiment (IRRE) was proposed to find the best practices appropriate for the many types of roughness measuring equipment now in use. At the same time, the IRRE was planned to provide a means for comparing roughness data obtained by different procedures and instruments. This research was needed because different methods used for characterizing road roughness are generally not equivalent. In some cases, the measures are neither consistent nor stable with time. Thus, utilization of roughness data can be difficult, particularly when considering roughness data obtained by more than one method. Ideally, a standard roughness index could be used to eliminate most of these problems.

The IRRE was held in Brasilia, Brazil in 1982, and was conducted by research teams from Brazil, England, France, the United States, and Belgium. Forty-nine (49) test sites were measured using a variety of test equipment and measurement conditions. The sites included a full roughness range of asphaltic concrete, surface treatment, gravel, and earth roads.

The equipment included two categories. In the first--profilometric methods--the longitudinal elevation profile of the road is measured and then analyzed to obtain one or more roughness indices. Both manual quasi-static methods and high-speed profilometers were used in the IRRE. In the second category--Response-Type Road Roughness Measuring Systems (RTRRMSs)--a vehicle is instrumented with a roadmeter device. The roadmeter produces a roughness reading as the result of the vehicle motions that occur while traversing the road. Seven RTRRMSs participated in the experiment, including five that consisted of roadmeters installed in ordinary passenger cars, and two that are self-contained roadmeter/trailer units. Each RTRRMS made repeated measures on all of the sites at several speeds.

Analyses of the collected data showed that all of the RTRRMSs give highly correlated measures when they are operated at the same test speed, and that all could be calibrated to a single roughness scale without compromising their accuracy. Analyses of the profile data demonstrated that the different profilometric methods can yield some--but not all--of the common roughness indices when the appropriate analysis is applied to the measured profile. Several of the profile-based roughness indices showed excellent correlation with the measures from the RTRRMSs. Thus, a single index is proposed, called the International Roughness Index (IRI). The IRI is measurable by all of the roughness measuring equipment included in the IRRE, and is also compatible with nearly all equipment used worldwide.

The IRI is based on the roadmeter measure, called by its technical name of average rectified slope (ARS), or more typically by the units used (m/km, in/mi, etc.). For technical and practical reasons, a standard speed of 80 km/h (50 mph) is proposed. The calibration reference is a mathematical model of a RTRRMS, that provides a reference ARS (RARS) index computed from a measured profile. This index, designated $RARS_{80}$, is identical to the calibration reference described earlier in NCHRP Report No. 228. It was selected over several other profile based numerics that were also considered because: 1) it most closely matches the concept of a reference RTRRMS, 2) it results in the best RTRRMS accuracy, and 3) it is compatible with more profilometric methods than any of the other indices. A separate document contains practical guidelines for measuring the IRI with various instruments (see reference 35).

CHAPTER 1

INTRODUCTION

Background

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

As a consequence, the characterization and measurement of road roughness is a major concern of highway engineers 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. Analysis of roughness can aid in the diagnosis of roadway deterioration and the design of appropriate maintenance. 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 user costs and road costs. User costs are strongly related to road roughness and are typically many times greater than road construction and maintenance costs. Hence, studies of the important relationship between roughness and vehicle operating costs (fuel, oil, tires, maintenance parts and labor, vehicle depreciation) have been or are being undertaken in Kenya [2], India [6], Brazil [7, 8], and other locations. Other user costs are less direct but are also a consequence of roughness. These include 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. (Note that wavelength limitations of profilometers usually do not limit their utility, since long wavelengths are of no consequence for most applications, including measurement of all of the roughness indices described in this report.)

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 relevance 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 they can be expected to play a large role in measurement methodology in the near future.

Early high-speed profilometers were costly, complex, difficult to maintain, and required knowledgeable users to operate them and make good use of the measurements. This is one of the reasons why the more simple RTRRMSs have been so popular. More recent designs have resulted in profilometers that are less complicated, less expensive, and can be used over a wider range of conditions. Future trends in profilometry are likely to yield lower costs and greater operating simplicity, making these instruments more comparable with RTRRMSs for routine use. Already they have advantages in terms of improved accuracy and relatively simple calibration procedures that make them more cost-effective overall than RTRRMSs for some uses. 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, purchasing roadmeter instruments for mounting in vehicles for use as "entry-level" roughness measurement systems.

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.

One method for calibrating a RTRRMS is by the use of control sections to perform a "calibration by correlation." The calibration is performed by running the RTRRMS over a number of "control" road sections that have known values of 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. Variations of this approach has been developed since 1970 by several agencies [7, 27, 40]. More recently, comprehensive research on the topic, funded by the National Cooperative Highway Research Program (NCHRP), has indicated that the "calibration by correlation" approach is in fact the only calibration approach that will be valid for any roughness level or surface type [9].

The key to this approach is the ability to assign reference roughness levels to the control sections. This requires the ability to accurately measure the longitudinal profiles of the control sections in the wheeltracks traversed by the RTRRMS. It also requires a method for reducing 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). The purpose was 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 Agency (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 subjectively evaluated for roughness 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 imprecise and often valid only under limited conditions. By selecting a single standard roughness measurement to which all measurements are scaled, information can be compared directly.

In order for the IRI to eliminate these problems, it must be:

* Stable with time

* Transportable (measurable with equipment available in most countries, including developing countries with less technical support)

* Valid (reproducible 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 also be:

* Simple and convenient

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

In order to qualify for these criteria, the IRI must be compatible with the RTRRMSs now in use, 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 valid calibration procedures for popular measurement practices. Obtaining a roughness measure that is stable with time has often proven difficult. The IRRE allows the evaluation of alternate calibration methods for many of the combinations of equipment and procedure that were included. Thus, the reproducibility of the measures obtained using specific methods can be determined, and practitioners can rationally select a method that is best for local conditions.

Sub-Objective #2: Establish the correlation between different RTRRMSs. Measures from two different RTRRMSs can be made somewhat "equivalent" (and therefore reproducible) through calibration. 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 #3: 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 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 #4: 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 both an appropriate reference numeric **and** the appropriate operation of the RTRRMS to best match that reference.

Sub-Objective #5: 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 Appendices A - K, contained in Volume II.

CHAPTER 2

EXPERIMENT

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 eleven pieces of equipment, which are separated into three categories in this report: response-type road roughness measurement 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 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. Four types of RTRRMSs (seven total) participated in the IRRE:

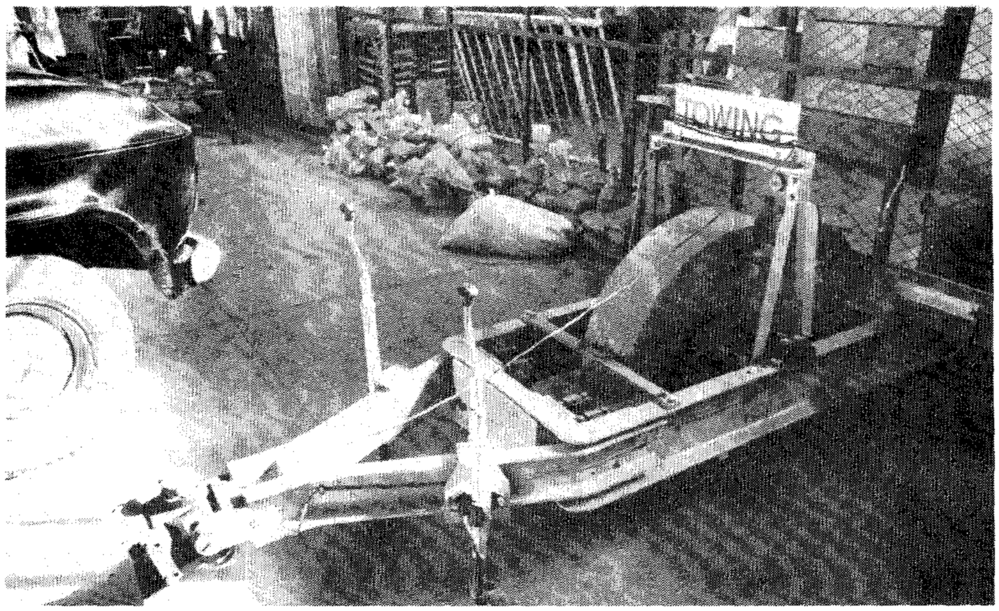
1. **Opala-Maysmeter Systems.** Three RTRRMSs were provided and operated by the Brazilian Transportation and Planning Agency

(GEIPOT). These consisted of Chevrolet Opala passenger cars equipped with Maysmeters, manufactured by the Rainhart Co. of Austin, Texas [10] as modified by the researchers of the international project, "Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization" (PICR). 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 [7]. 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.

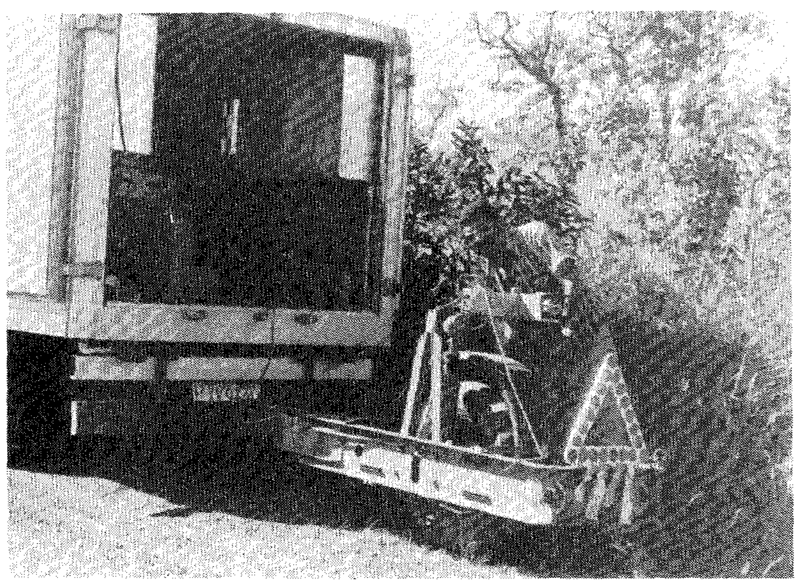
2. **A Caravan station wagon with two roadmeters.** A Bump Integrator (BI) unit, produced and operated by the British Transport and Road Research Laboratory (TRRL) [11], and a NAASRA Roughness Meter, provided by the Australian Road Research Board (ARRB) [12], were both installed in a single Chevrolet 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) [11]. It is based on the old BPR Roughometer design [13], 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 is owned by the Federal University of Rio de Janeiro (COPPE/UFRJ) and was operated by personnel from the Brazilian Road Research



a. Bump Integrator Trailer



b. BPR Roughometer made by Soiltest, Inc.

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

Institute (IPR/DNER). The trailer is built to the specifications of the BPR Roughometer (see Figure 1.b) [13].

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 PICR project were 80 (96% of the paved roads), 50 (94% of the unpaved roads), and 20 km/h [14]. Standard test speeds for the NAASRA Meter as used in Australia with a different vehicle are 50 and 80 km/h.

Static Profile Measurement. Two static methods were used to obtain the longitudinal elevation profile of each wheeltrack 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. Using a measurement interval of 500 mm, a trained crew of three can survey both wheeltracks of two 320 m test sections in an eight-hour working day (about 2500 elevation points for three man-days). The rod and level survey method was included in the IRRE because previous study in Brazil demonstrated that a relevant roughness index can be determined from analysis of rod and level profile [8].

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 the 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

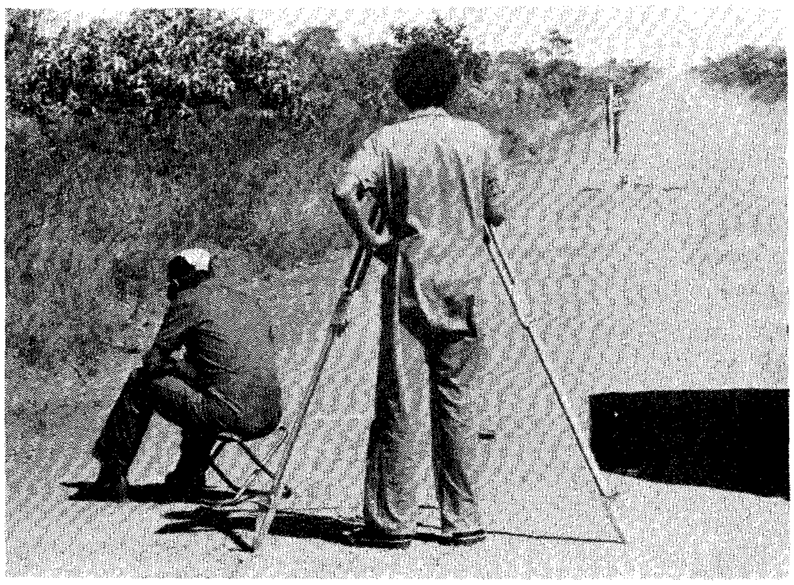


Figure 2. Measurement of longitudinal profile by the rod and level method.

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

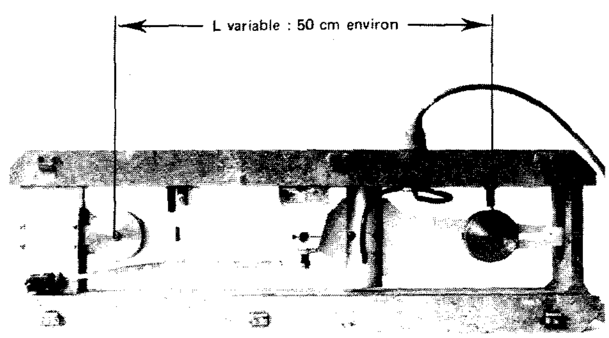
intervals of 100 mm and prints them on paper tape. A trained crew of two or more was able to survey two wheeltracks of a 320 m test section in one day (about 6400 elevation points for two man-days). Subsequent development of the TRRL Beam has included automatic processing of the profile, including the computation and printing of a roughness numeric. With the improved version, a 320 m wheelpath can be surveyed in one hour, resulting in more than 25000 elevation measures for two man-days of effort.

Dynamic Profile Measurement (Profilometers). The two vehicle-based profilometer systems that participated are each designed to measure longitudinal profile over a selected wavenumber range (wavenumber = 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.

The name "profilometer" is sometimes controversial, as opinions differ as to what qualifies an instrument as a profilometer. In this report, a system is considered to be a profilometer if it produces a signal that can be processed directly to yield the correct value of a profile-based roughness numeric. "Processed directly" means that the numeric is computed directly from the profilometer signal based on the mathematical definition of the numeric, as opposed to a "calibration by correlaton" that must be derived empirically using regression methods. It is expected that most profilometric instruments qualify as "profilometers" for some applications but not others.

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

a. APL Trailer



b. Inertial reference of the APL Trailer.

Figure 4. The APL Profilometer.

for frequencies up to 20 Hz [15, 16, 17]. 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 [15, 17, 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). 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 [19, 20]. 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 analyzed. 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 [21, 22].

This particular GMR-type Profilometer was used in the early portion of the PICR project [7, 8], 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 half of the sections. Due to a number of factors discovered by the Brazilian engineers in preparation for the IRRE, the on-board data analysis equipment was not valid for the conditions covered in the IRRE [23]. It was also found that the measures made during the PICR 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.

As other sources of profile data became available from the TRRL Beam and the APL Trailer, the measures from this profilometer assumed less importance, and the signal processing was never completed. Most of the GMR-type profilometers now in operation do not employ mechanical follower wheels, but instead use non-contacting displacement sensors. Thus, the data from this particular instrument (with a mechanical follower wheel) are not nearly as relevant to present-day practice as they were during the planning of the IRRE.

Subjective Rating Studies

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 second study, of a much more limited scope, was also conducted to determine whether descriptions and photographs of representative roads could be used to "calibrate" raters so that ratings assigned are comparable to an objective roughness scale. Results are presented in Appendix K.

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.

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

* 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 (0.1 mile) to over 3 km.

* The Maysmeters used in Brazil can only be used on sections with lengths that are integer multiples of 80 m (0.05 mile): the readout frequency.

* 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.

* 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.

* 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 with the available 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. The test sites were generally homogeneous over their length, yet it should be understood when comparing results that some of the APL numerics presented later were not computed over the entire site length.

Test speed. 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 PICR 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.

Initially, all of the RTRRMSs were operated at all four speeds. After the first week of testing, the operators of the BPR roughometer limited testing to 50 km/h and less, because the equipment kept breaking at the highest speed. The BI Trailer and Caravan system (with two installed roadmeters) were both able to operate at 80 km/h without damage, but the operators (the research team from TRRL) declined to make measurements with these systems at 80 km/h after the first week on the grounds that the speed was unsafe for some of the sites, and also that they felt the speed was not relevant to developing country environments. As a result, only the three Opala-Maysmeter systems were run at 80 km/h on all of the surface types.

Repeatability. 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 wheeltrack (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.

Sequence. 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 schedul[illegible] 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 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 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 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 the full range of surface types and roughness conditions. Ten sites were completely profiled by the Beam. An additional eight wheeltracks were profiled on sections that displayed nearly identical roughness levels on the right and left wheeltracks (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 wheeltrack 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 641 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, and also by four persons rating the surfaces by a "calibrated description" method.

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. (Results of the "calibration by description" experiment were analyzed even more recently and are reported in Appendix K.)

Spectral Analyses of the Road Profile

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 can all be considered valid methods for measuring profile amplitude 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 profile 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 some of the analyses considered.

* The APL Trailer bandwidth, measured in the laboratory to cover the temporal frequency range of 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.

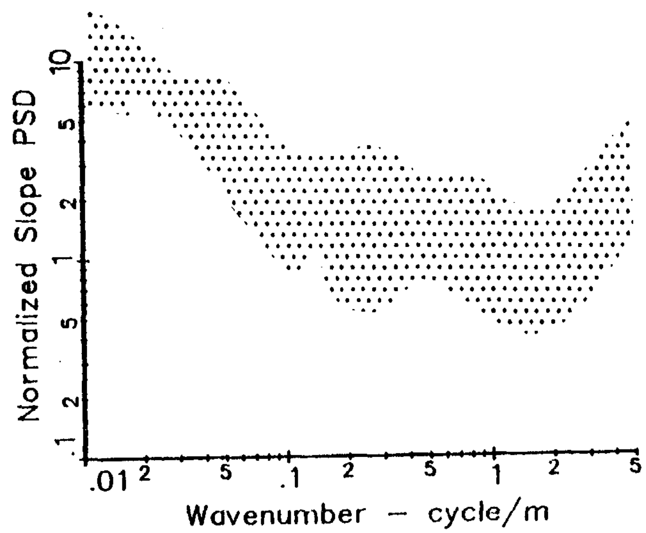
The PSD functions alone (shown in Appendix I) are not adequate to determine the accuracy of each profilometric method for the measurement of specific roughness indices. The more direct validation for a particular application is made by applying the actual analysis to the different profiles, and determining 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:

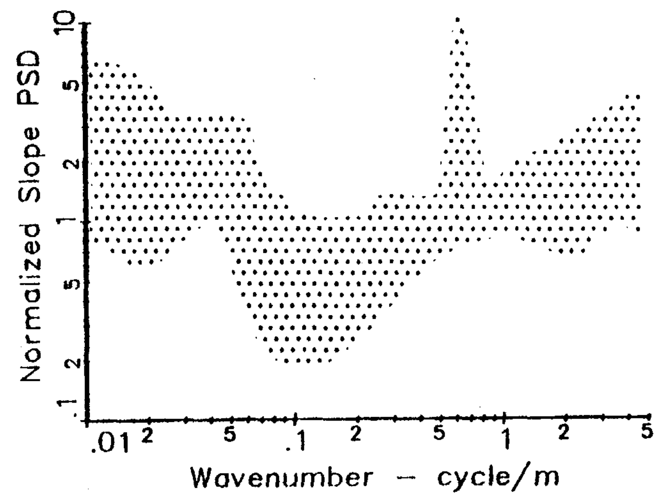
* The asphaltic concrete (CA) sites have proportionately the least roughness at high wavenumbers.

* 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.

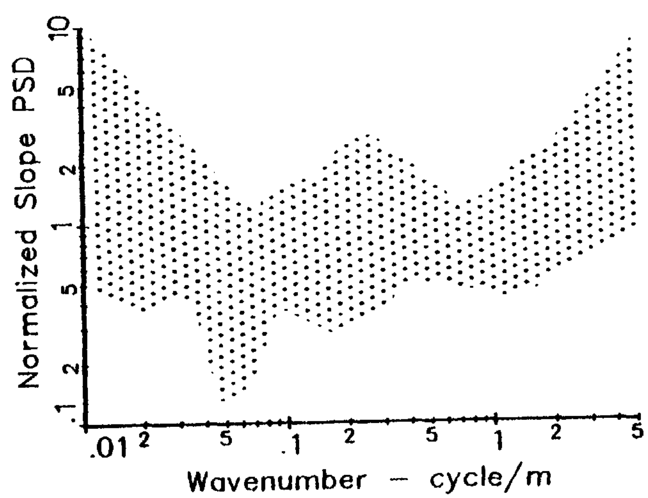
* The earth sites generally show the highest concentration at high wavenumbers.



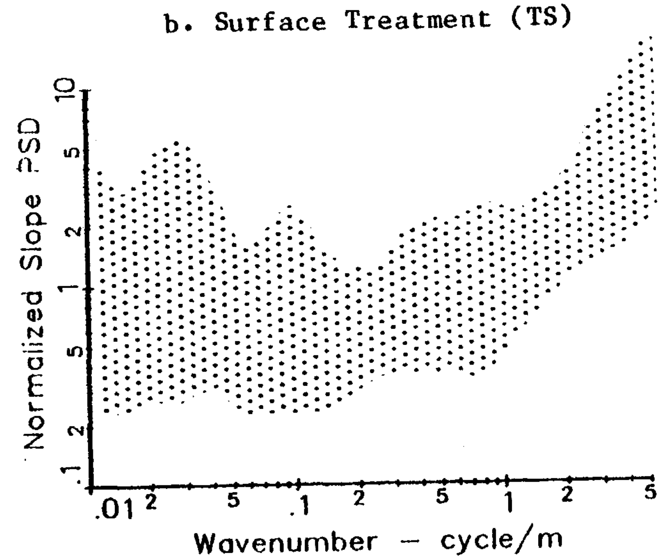
a. Asphaltic Concrete (CA)



b. Surface Treatment (TS)



c. Gravel (GR)



d. Earth (TE)

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

* Several of the sites include corrugations, and these sites also appear as "outliers" in correlation plots ("outliers" are data points that do not fall within the scatter range exhibited by the rest of the data). This is because the site has a corrugation that causes one measuring system (or analysis method) to "tune in" and respond highly, while other systems respond more conventionally. Several of the surface treatment had 2.0 m corrugations (wavenumber = 0.5), as shown in Figure 5b.

These "signatures" are also evident from the waveband analyses used in 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. Note that most of the names of roughness numerics used in this report are more explicit than is common in other reports. This is necessary to clearly distinguish the many measures under discussion. (Most of the following numerics are called "roughness" by users.) Whenever possible, simple metric units are used to facilitate comparisons. (For example, all slope measures are reported as "m/km," and can be readily converted to other units used, such as mm/km and inches/mi.)

1. Reference Quarter-Car Simulation (RQCS). The concept of using a reference RTRRMS has shortcomings when applied to a mechanical vehicle-based system, which 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:

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

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 interpretations, with the most direct being that RARS is the average slope of the profile, seen through the RQCS "filter." Hence, it can be visualized as a profile attribute. A perfectly smooth profile (no variation in slope) has an RARS value of zero. RARS is linearly proportional to the profile amplitude, such that the units of RARS are determined by the scaling of the profile elevation. A second interpretation is that of a reference RTRRMS, where RARS is similar to the ARS measure obtained with a mechanical RTRRMS. When the same units are used for RARS and the ARS measure from a RTRRMS, the practitioner can see whether the 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 replicates 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 PICR project as a means for using rod and level profiles to calibrate RTRRMSs [8]. It replaces a numeric obtained from a particular piece of hardware (that numeric, QI, was an abbreviation of Quarter Car Index). In concept, QI is identical to the RARS statistic. However, due to hardware problems described in Appendix E, the original QCS definition cannot be used to reproduce the QI roughness scale, and QI is therefore effectively defined by the more recent QI_r numeric.

The QI_r numeric that replaced the electronic QCS is independently defined strictly by profile geometry, and has been suggested as a standard roughness scale for calibrating RTRRMSs. QI_r is based on the RMSVA summary statistic (hence the subscript "r"). RMSVA is an abbreviation for root-mean-square (RMS) vertical acceleration [25], even though 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 of length 2*b, as shown in Appendix E (RMS mid-chord deviation). (Since RMSVA varies with b, the baselength should be subscripted.) Mathematically, $RMSVA_b$ is the RMS value of the variable VA_b, which is defined as:

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

where Y(x) is the profile elevation at position x.

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:

$$QI_r = -8.54 + 6.17 * RMSVA_{1.0} + 19.38 * RMSVA_{2.5} \tag{3}$$

The above equation assumes that elevation is measured in mm and that b (1.0, 2.5) is measured in m, resulting in RMSVA numerics with the units: $1/m * 10^{-3}$.

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

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 linearly with profile amplitude.

Due to the simple nature of the computation, the CAPL 25 is defined in part by the response properties of the APL Trailer, and it is shown in Appendix G that suitable filtering of the APL 72 signal can produce a "simulated" APL 25 signal. However, given the objectives of this report (which emphasize compatibility with RTRRMSs), further 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).

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 often had a value of 1 (the worst), 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 to input amplitude.

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. CP (Moving Average). 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 called CP, and is obtained by evaluating the variation of the surface profile relative to a reference line obtained by smoothing the same profile using a moving average. The CP analysis acts as a filter, attenuating long 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 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. 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 1.0 m, 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 b 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. TRRL considered various combinations of baselength and sample interval, which both affect the RMSD numeric, and found that a baselength of 1.8 m together with a sample interval of 300 mm gave the best correlation with several of the RTRRMSs when they were operated at 32 km/h. Unlike the other numerics, sample interval is standardized for the RMSD numeric, therefore both baselength and sample interval are subscripted, e.g. $RMSD_{1.8,300}$.

The $RMSD_{1.8,300}$ 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 $RMSD_{1.8,300}$ 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 $RMSD_{1.8,300}$ numeric in the ARS units familiar to users of RTRRMSs, the displacement $RMSD_{1.8,300}$ 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 $RMSD_{1.8,300}$. The regression equation is:

$$RBI_{32r} = 472 + 1437 * RMSD_{1.8,300} + 225 * (RMSD_{1.8,300})^2 \qquad (4)$$

The name RBI_{32r} indicates that the numeric represents the measure of a Reference Bump Integrator, at a speed of 32 km/h, as defined by RMSD (the small "r" in the subscript.) The units recommended by TRRL are "mm/km," which correspond to ARS/2. (When ARS has units of m/km as used in this report, then "mm/km" = ARS m/km x 500.) The $RMSD_{1.8,300}$ 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 $RMSD_{b,dx}$ analyses applied, the $RMSD_{b,dx}$ 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 CP (moving average) analyses 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), specific standard values have been determined for each type of analysis.

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

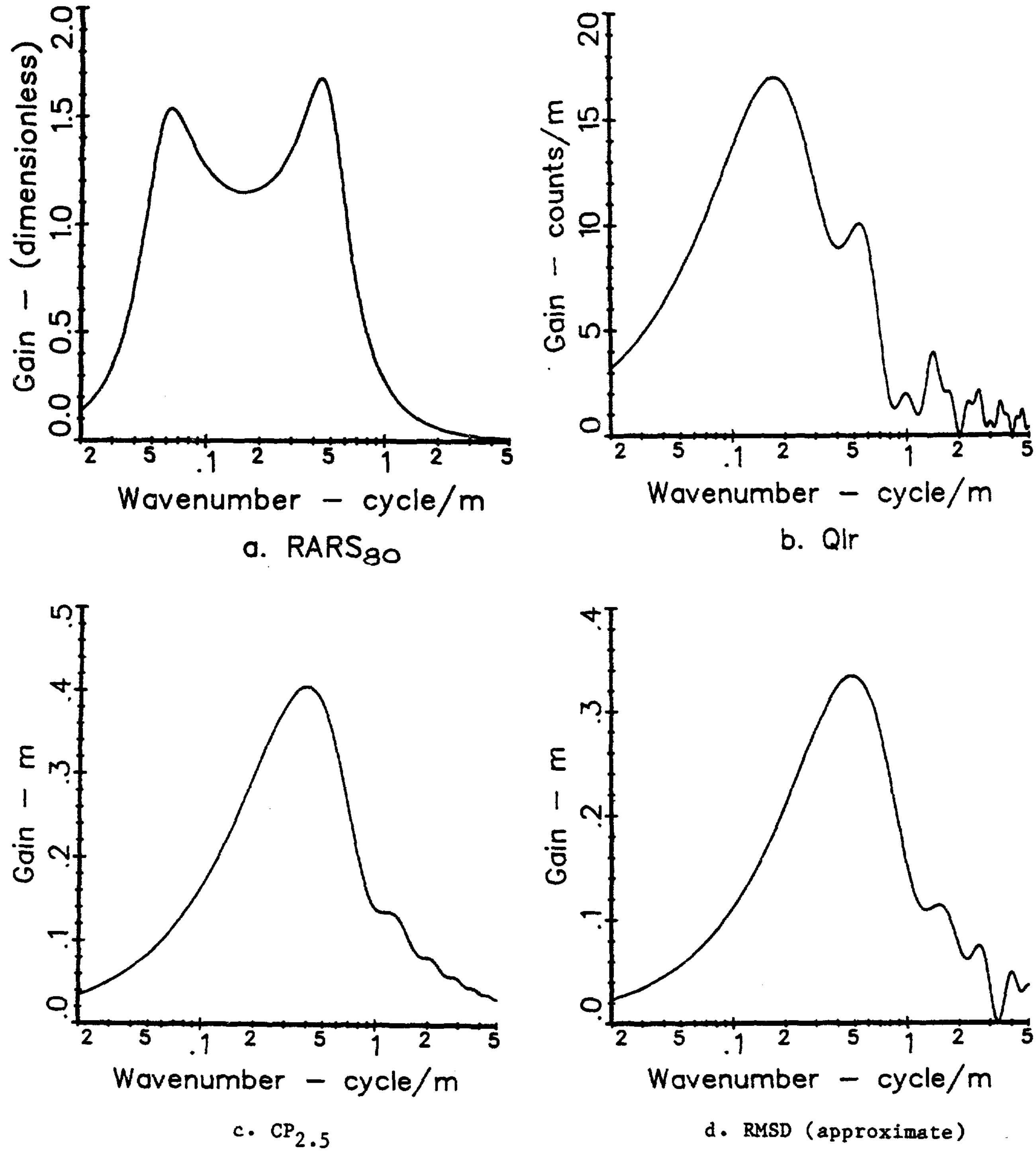


Figure 6. Sensitivity to wavenumber of four profile analyses.

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. (Due to the fact that different units are used for each roughness index, the "weightings" shown also have different units, meaning that comparisons between analyses must be relative rather than absolute.)

All of the above analyses can be affected by the choice of sample interval. In each case, the analysis will converge when sufficiently small sample intervals are used to the limit reached when dx--> 0. Most of the analyses are intended to be used for sample intervals that are sufficiently small to eliminate the effect of variations in sample interval. For example, nearly the same values of $RARS_{80}$ are obtained for any value of dx less than 700 mm.

In contrast, the RMSD analysis is recommended by TRRL along with the "standard" sample interval of dx = 300 mm. For this interval, the $RMSD_{1.8}$ analysis has not yet converged, with the result that use of a different sample interval will result in a different $RMSD_{1.8}$ value (e.g., $RMSD_{1.8,300} \neq RMSD_{1.8,200}$). Standardizing dx has two implications: first, error due to a poor choice of dx is eliminated; second, the options available for measuring profile become limited. (In the IRRE, the $RMSD_{1.8,300}$ analysis could not be applied to the rod and level data, nor to the APL 25 data because of incompatibility in the sample interval.)

Comparison of Profile Measurement and Analysis Methods

For a roughness measure to be transportable, it must be measurable 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 computed from different profile measures are not always of interest here. Rather, the level of agreement is quantified simply by the absolute differences in the numerics obtained from the different profilometric methods. In some cases, the effects of other variables were also studied. These include:

* Sample interval. What is the maximum sample interval allowed before the measures are biased or have unacceptable random error?

* Waveband requirements. What range of wavelengths must be included in the profile measurement to accurately obtain the numeric?

* Precision. How precisely must profile elevation be measured to obtain an acceptable reading for each numeric?

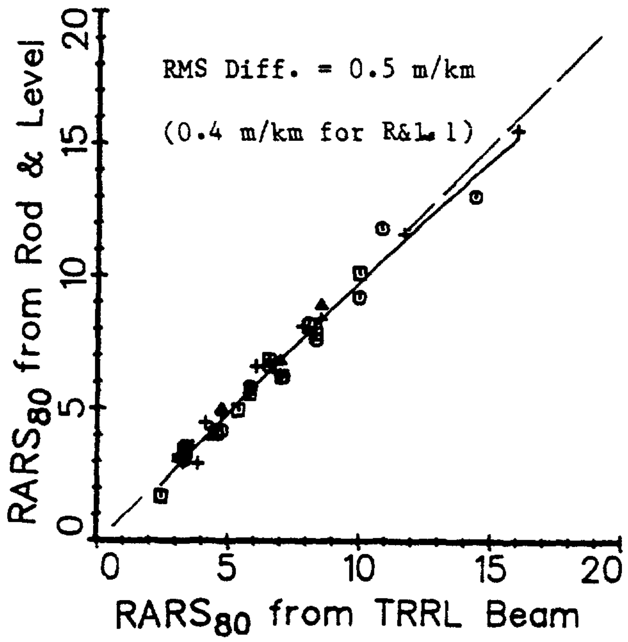
The RARS (RQCS), QI_r (RMSVA), and CP (moving average) analyses were applied to profiles obtained by different methods, and the results are summarized here.

RARS. This method of profile analysis had been used mainly with GMR-type profilometers in the United States, Brazil, and elsewhere prior to the IRRE. (The name RARS implies a specific set of vehicle parameter values, defined in an NCHRP project [9]. Similar analyses, using different vehicle parameter values, have a long history of use in the United States and elsewhere, and involve other profilometric methods.) 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 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:

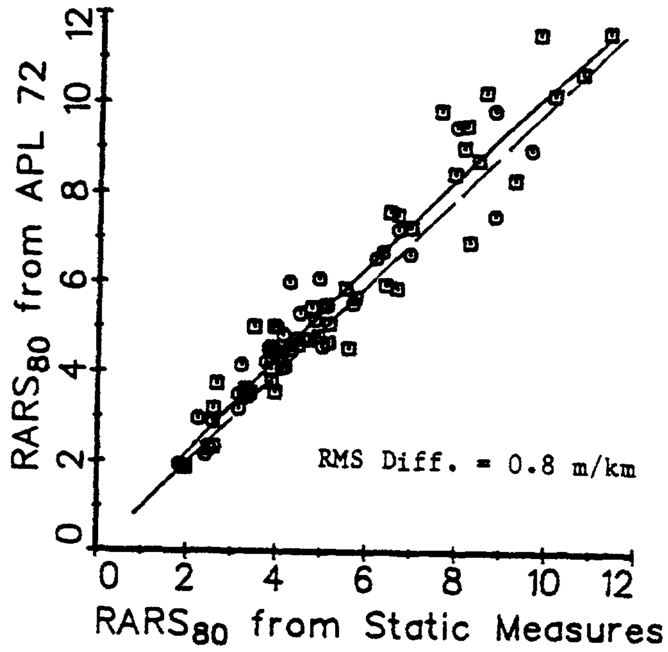
* **Sample interval.** For simulation speeds of 50 km/h and higher, the sample interval can be as large as 500 mm without introducing bias. As sample interval decreases, slightly better accuracy is obtained, and the chances of error due to missing significant profile features in the measurement are reduced. For sample intervals less than 250 mm, little effect is observed. 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). The effect of sample interval decreases with simulation speed, with $RARS_{80}$ being the least sensitive to sample interval for the speeds considered.

* **Waveband of measurement.** The waveband required for the $RARS_{80}$ 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 Trailers 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 measures of $RARS_{80}$ 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, bias error is negligible.

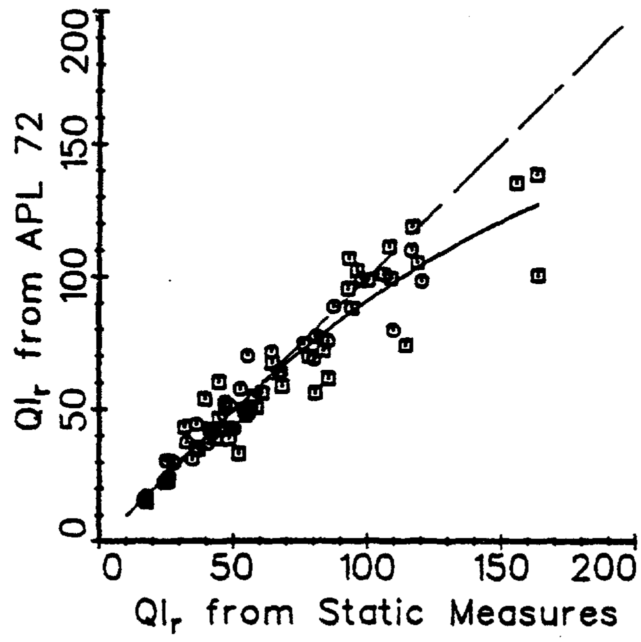
* **Precision of measurement.** A study was performed using the profiles measured with the TRRL Beam. The profiles, measured with a precision of 1.0 mm, were rounded off on the computer to determine the effect of less precise measurement. It was found that the precision needed was directly proportional to $RARS_{80}$, with less precision needed on rougher roads. For negligible



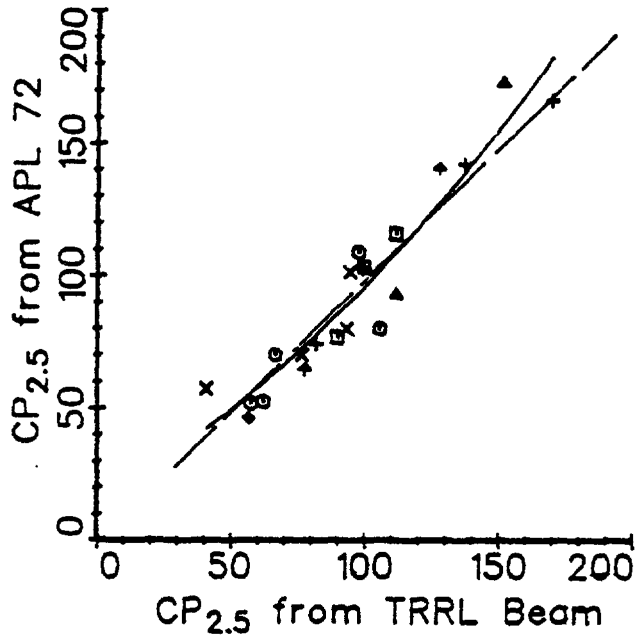
a. Two static measures of $RARS_{80}$



b. Static and dynamic measures of $RARS_{80}$



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.

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 the roughest paved roads and 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, QI_r 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, these 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). The plot shows that the QI_r response resembles that of a quarter-car, as was intended in its derivation. 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.

Although the QI_r numerics computed directly from APL profiles are biased, there is excellent correlation. 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 demonstrate the methods that may be needed in adopting the QI_r analysis to new types of profile measuring equipment and/or road types. (Because the wavenumber content of the APL profile signal is the result of both the APL and the road surface type, the relations developed are not necessarily valid for road types not included in the IRRE.)

* **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 magnitude of QI_r, and is almost exactly the same as the precision needed for the RARS computation.

CP (Moving Average). The CP numerics used by CRR are obtained with a moving average. All of the analyses applied by TRRL (moving average, RMSVE, and RMSD) are also related to a moving average. 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. But when 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 CP_{10} numeric can be obtained without bias using intervals up to at least 500 mm, although it was found that $CP_{2.5}$ 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 biased low.) 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. 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 m 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 better match between the $CP_{2.5}$ numerics obtained for APL and rod and level, the analysis for rod and level would need to account for the long wavelength response attenuation 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.

Although the data presented in the appendices could be used to derive empirical relationships between all of the profile-based numerics, this was not done as part of the IRRE analyses. The rationale is that anyone making profile measurements in the future can usually compute these numerics directly, and should be encouraged to do so because direct computation is more accurate than indirect estimation. Should an approximate "conversion" between two of the profile-based roughness scales be needed to consider existing data bases, the data in the appendices can of course be used to derive regression equations for the surface types of interest.

Nonetheless, there are several cases in which correlations between different profile-based numerics are relevant to the objectives of the IRRE, because most of the profile-based numerics could not be measured by every profile measurement method represented in the IRRE. Consider some of the profile-based numerics proposed as calibration references for RTRRMSs: QI_r cannot be measured directly with the APL trailer; RBI_{32r} (based on the $RMSD_{1.8,300}$ statistic) requires a sample interval of exactly 300 mm; and the half-car simulation requires the measurement of both profiles, and further requires that the two profiles be properly synchronized. On the other hand, the RARS numerics can be measured by all of the methods. Therefore, it is helpful to know how the above numerics are related to RARS.

Half-car Simulation (HCS). The closest agreement between any two profile-based numerics was between the ARS as computed with a Half-Car Simulation (HCS) and the RARS numeric, computed with the RQCS. These two 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 RQCS, 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 RQCS numerics. This relationship should not be assumed to be universally valid for arbitrary road inputs, however. For example, if one wheeltrack is perfectly smooth (RARS=0), 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 in the more realistic conditions of the IRRE, differing by a scale factor of 0.76, only the the RQCS numerics are shown in this report. (HCS numerics are presented in Appendix F.)

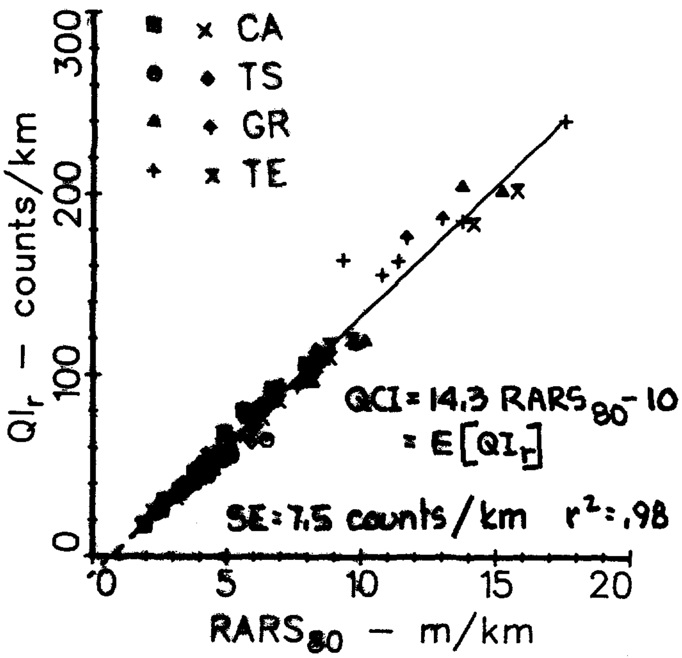
QI_r. CRR and LCPC have shown that the QI_r numeric is strongly correlated with the $CP_{2.5}$ numeric routinely used by CRR. An even stronger correlation was noted between QI_r and $RARS_{80}$. These relations are shown in Figure 8. Note that the relationship between QI_r and $RARS_{80}$ is very good, differing only for one of the earth sites. (When only the paved road data are plotted on a more detailed scale, differences can also seen for a few of the surface treatment sites.)

For all practical purposes, $RARS_{80}$ can be viewed as an improved computation method for obtaining QI, since it is in fact a true Quarter-car Index rather than an estimate of one. The main functional differences between QI_r and $RARS_{80}$ are: 1) $RARS_{80}$ agrees better with measures from RTRRMSs on surface treatment sites, and 2) $RARS_{80}$ can be measured with a wider range of instruments.

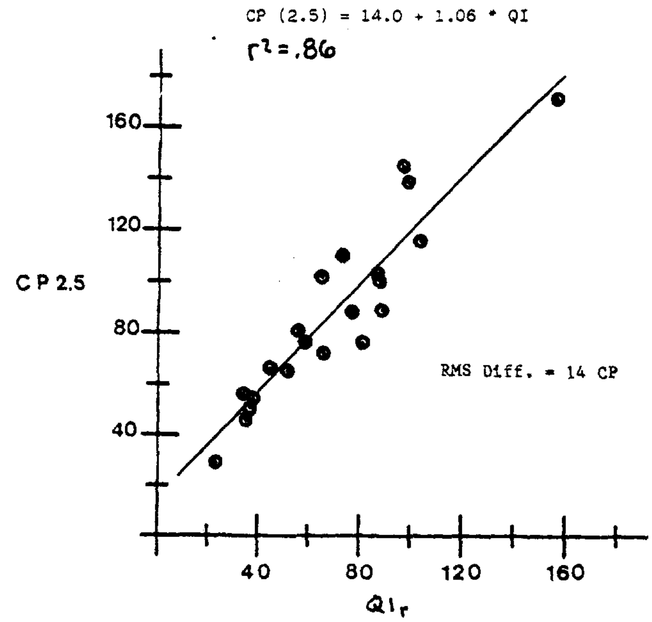
Since the QI^* roughness scale used in the PICR project rescaled RTRRMS measures made at 80 km/h, the close relationship to $RARS_{80}$ indicates that RTRRMS measures calibrated against $RARS_{80}$ should be compatible with QI^*.

An approximate "conversion" equation between QI_r and $RARS_{80}$ is provided in the next chapter.

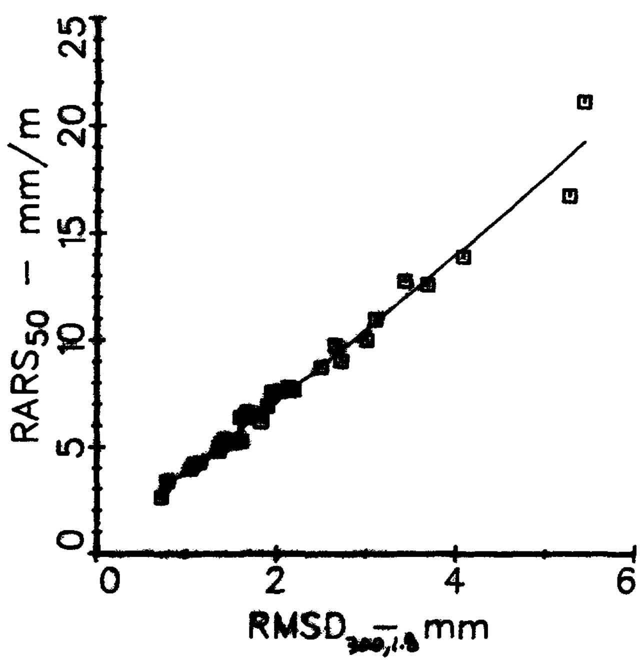
$RMSD_{1.8,300}$ and RBI_{32r}. The $RMSD_{1.8,300}$ numeric is very well suited to the TRRL Beam because the numeric can be computed independently from each consecutive set-up. However, this is not an advantage for continuous profilometric methods, and many methods will not be convenient for the 300 mm sample interval required by $RMSD_{1.8,300}$. For example, the rod and level profiles measured in the IRRE cannot be processed to yield the $RMSD_{1.8,300}$ numeric because a different sample interval was used. Other $RMSD_{b,dx}$ numerics might also be evaluated that might be more universally applicable (for example, using RMSD for a sample interval sufficiently short that the analysis has converged and is no longer influenced by variations in sample interval); however, this was not done during the study.



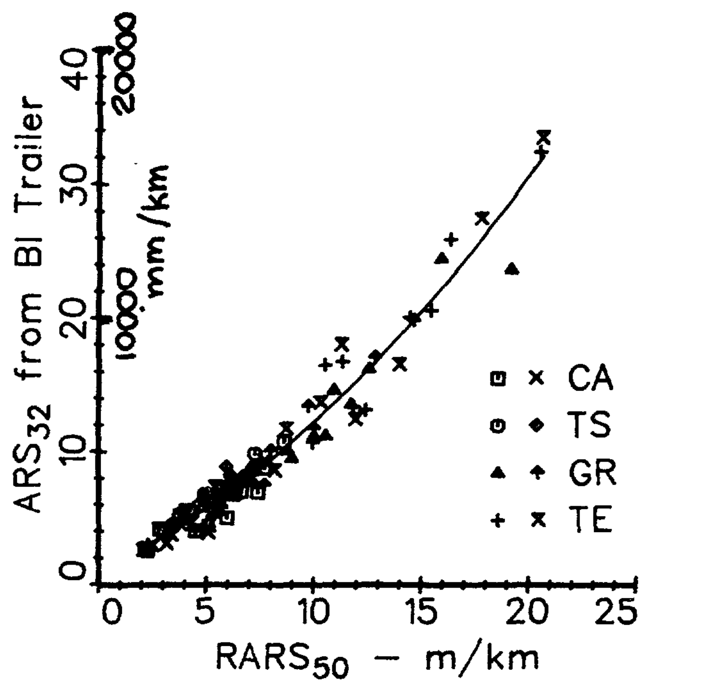
a. QI_r and $RARS_{80}$



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

Figure 8c shows that the $RMSD_{1.8,300}$ and $RARS_{50}$ numerics are highly correlated. The $CP_{2.5}$, $RARS_{32}$, and $RARS_{80}$ numerics are also highly correlated. Given that the $RMSD_{1.8,300}$ numerics are converted to RBI_{32r} according to Eq. 4, the correlation between $RARS_{50}$ and $RMSD_{1.8,300}$ is of less interest than the correlation between $RARS_{50}$ and the measures obtained from the BI Trailer (RBI_{32}), which defined the reference roughness measure in the derivation of Eq. 4 in Appendix H. Figure 8d shows that indeed, the $RARS_{50}$ and RBI_{32} numerics are also highly correlated. The correlation between the BI trailer measures (at 32 km/h) and $RARS_{50}$ (as calculated using all 98 wheeltracks from the IRRE) is actually better than the correlation with $RMSD_{1.8,300}$ (calculated using the 28 wheeltracks measured with the TRRL Beam). The correlation is also better with $RARS_{32}$ (using the 28 wheeltracks measured with the TRRL Beam) than with $RMSD_{1.8,300}$.

Other correlation plots between RBI_{32} and profile-based numerics are shown in the appendices. A plot for the BI Trailer and $CP_{2.5}$ is shown in Appendix G, and plots of RBI_{32} vs. the quarter-car numerics $RARS_{32}$ and $RARS_{80}$ are shown in Appendix F. An approximate "conversion" equation between RBI_{32} and $RARS_{80}$ is provided in the next chapter.

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 PICR project [7].

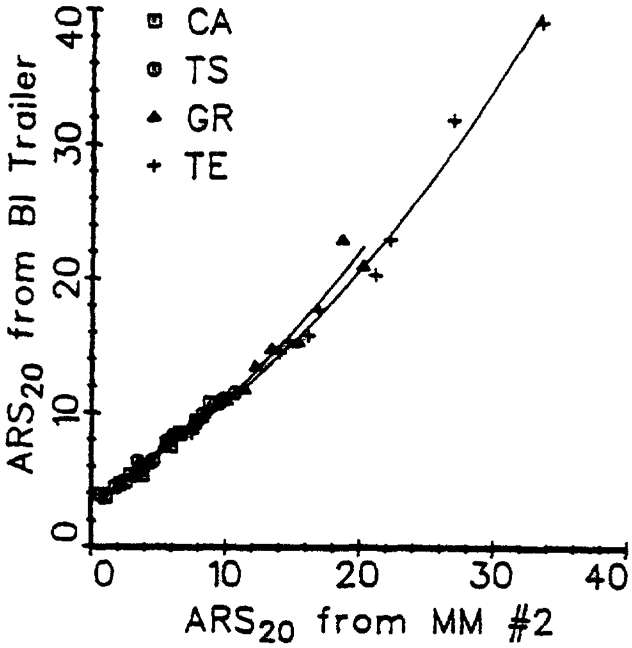
Assuming that good practices are used to ensure that day-to-day measures made with a RTRRMS are repeatable, the final "calibrated" RTRRMS measures may still have only limited equivalence if the different RTRRMSs are producing raw measures that are largely unrelated. No transformation will make the measures 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.

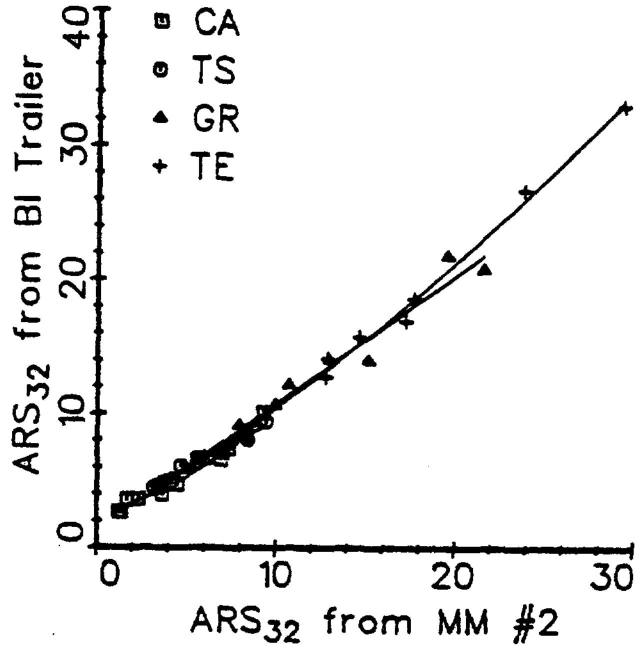
Repeatability. The repeatability error is neither constant for all roughness levels, nor proportional to roughness, but something in between. By and large, the repeatability of the instruments in the IRRE was better than 5% (standard deviation of repeated ARS measurements divided by the mean value), 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 can be considered 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: a BI unit and 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 experimental 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].

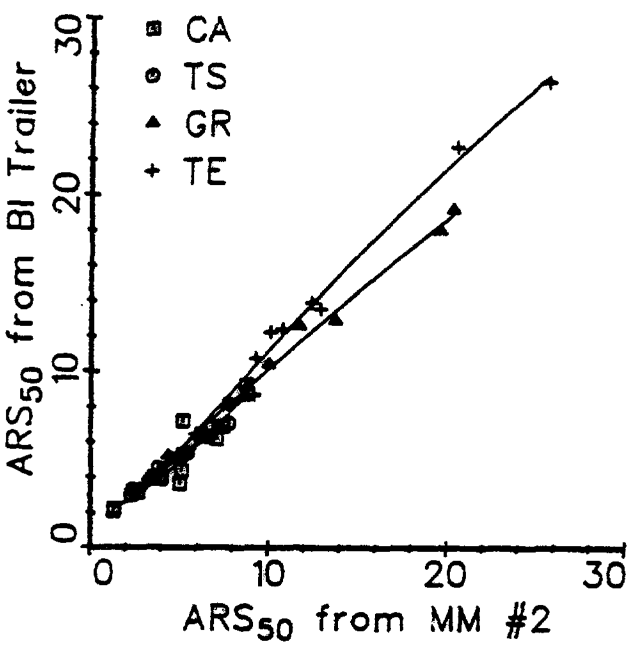
Correlation for different RTRRMS speeds. In every case, the best correlations between two RTRRMSs are obtained when the instruments are operated at the same test speed, even when the test speed is not "standard" for one of the instruments. For example, the BI trailer is normally operated at 32 km/h, 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 more scatter when different test speeds are used by the different devices (Fig. 9d), and separate underlying relationships appear (as shown by the regression lines) for the individual 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.



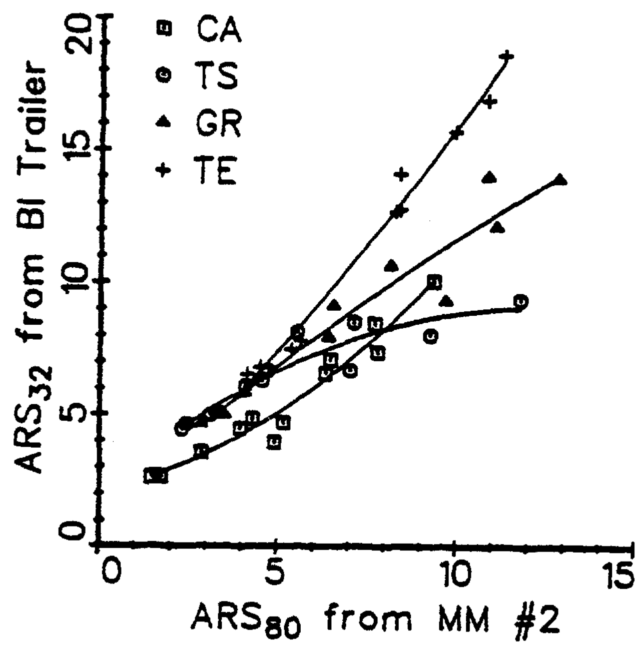
a. Both speeds = 20 km/h



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.

Correlation across surface type. When the same speed is used for two RTRRMSs, the regression lines obtained for the different surface types usually 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 correlation plots, the variation about the regression line (scatter) is fairly constant for all roughness levels; the "error" that would be left after a calibration by correlation does 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. 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, relative to the ARS_{80} measures.

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:

$$ARV = ARS * speed.$$

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 the more 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 usually introduces an artificial bias with speed, and is therefore 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. Therefore, a 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 reproducibility of a calibrated RTRRMS measurement is improved with better correlation between the RTRRMS and the reference. Note that for the case of a RTRRMS that accuracy is the same as reproducibility.

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, at the same roughness level, that bias the regression in the other direction.

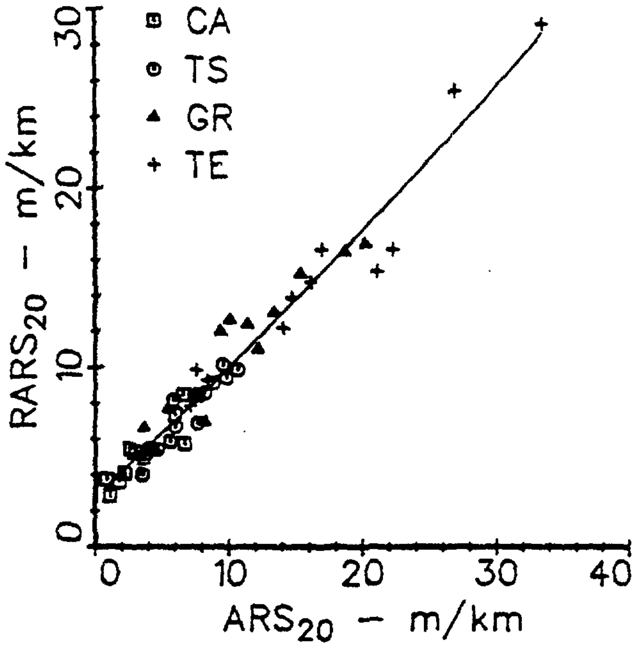
RARS. When the RQCS speed is set equal to the RTRRMS measurement speed, correlations between RARS and the ARS measures obtained from the RTRRMSs are very good at all speeds and surface types, with the one exception of the 80 km/h data from the surface treatment sections. Figure 10 shows calibration plots 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 2 m corrugation. At 80 km/h, this corrugation 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 roughness numerics, nor in the subjective ratings (discussed later). (These four sites appear as outlier data points when comparing the ARS80 measures to any of the profile-based numerics, with the problem being smallest for RARS80.) 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 "tuning."

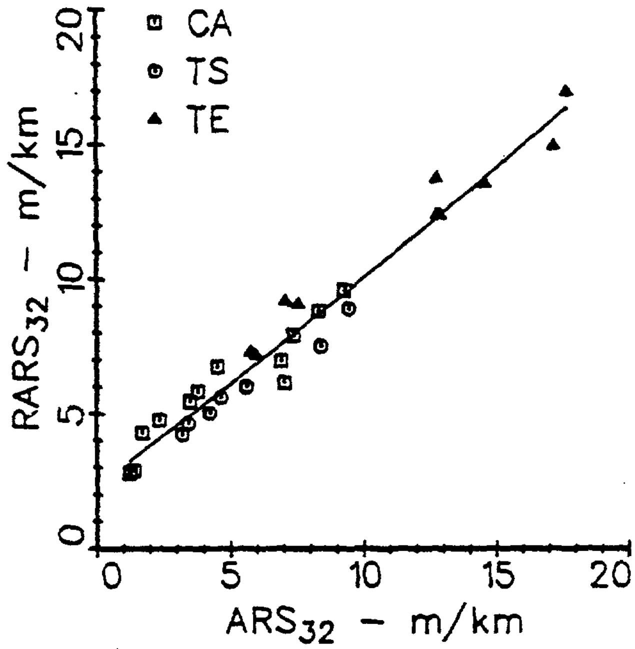
Not all RTRRMS vehicles will have the same tuning characteristics as the Opala passenger car. Unfortunately, however, only the Opalas were operated at the speed of 80 km/h, so comparisons with the Caravan and BI trailer vehicles are not possible.

The difficulties presented by these "outliers" demonstrate that sites with corrugations should be avoided as calibration sites, due to tuning of RTRRMSs.

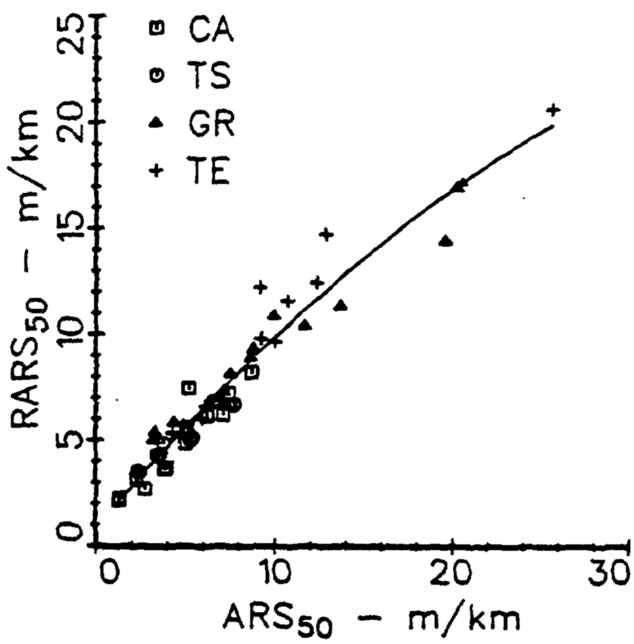
A small bias also exists for some, but not all, of the RTRRMSs between paved and unpaved roads. When a bias exists, the RARS numerics tend to be



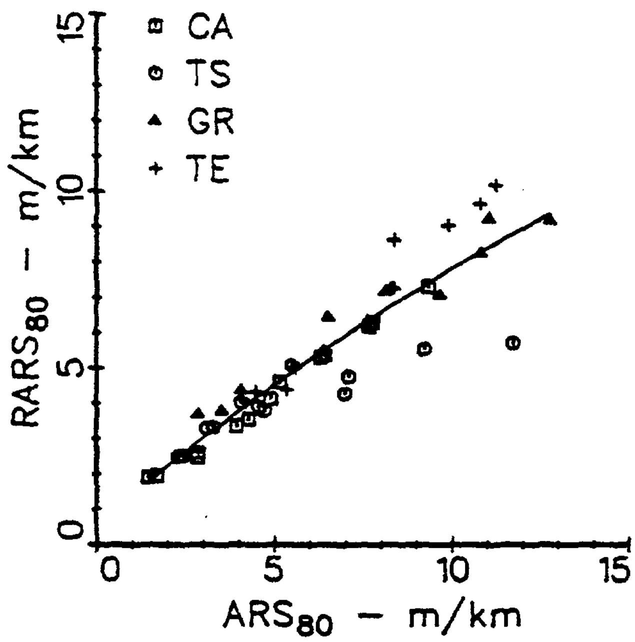
a. 20 km/h. $RARS_{20}$ from APL 25.



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.

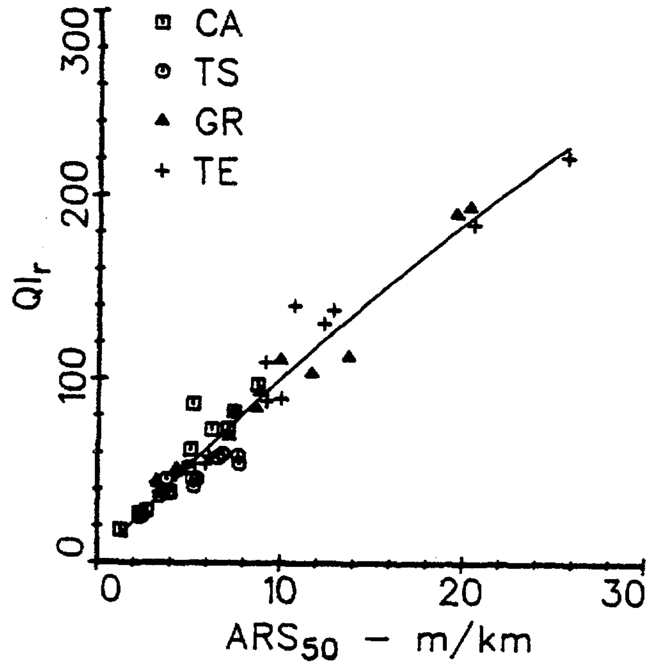
high on the unpaved roads and low on the paved roads. This effect can occur when: 1) roadmeters have hysteresis and 2) the different road types have different spectral compositions [9]. On the unpaved roads, where there is less low-frequency content in the vehicle vibrations, the hysteresis results in a greater loss of counts for the RTRRMS. This effect was also seen to a lesser degree in the correlation plots 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 some of the correlations obtained with the $RMSD_{1.8,300}$ numeric (based on only ten of the sites). 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.)

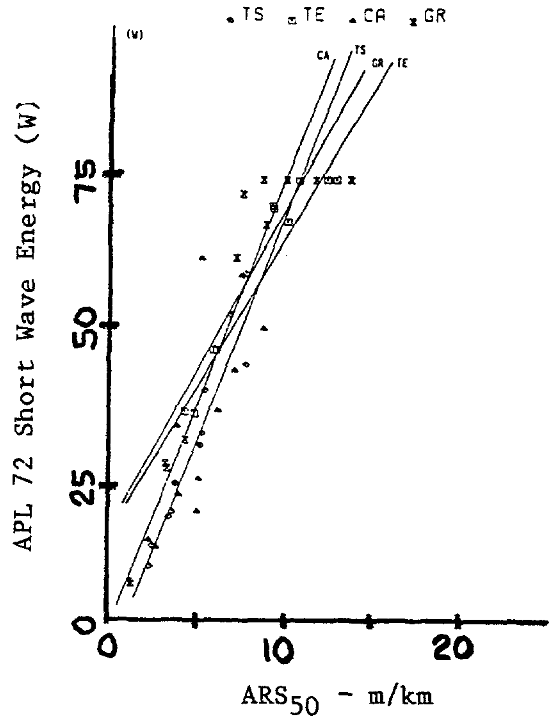
Further correlation information for the RARS standard is included in Appendix F, including example calibration plots for three of the other RTRRMSs.

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.

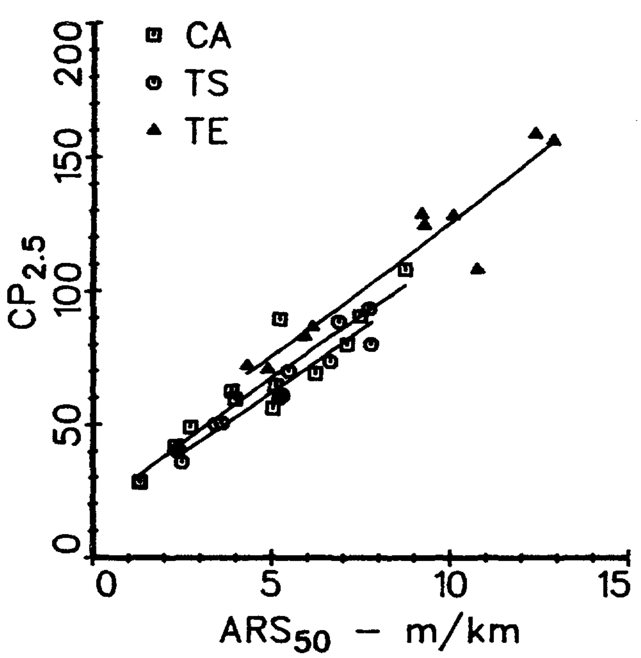
Given that QI was originally based on a QCS with a simulation speed of 55 km/h (see Appendix E for details), it is not completely unexpected that 50 km/h is the best RTRRMS speed for estimating QI_r. Yet, in light of the



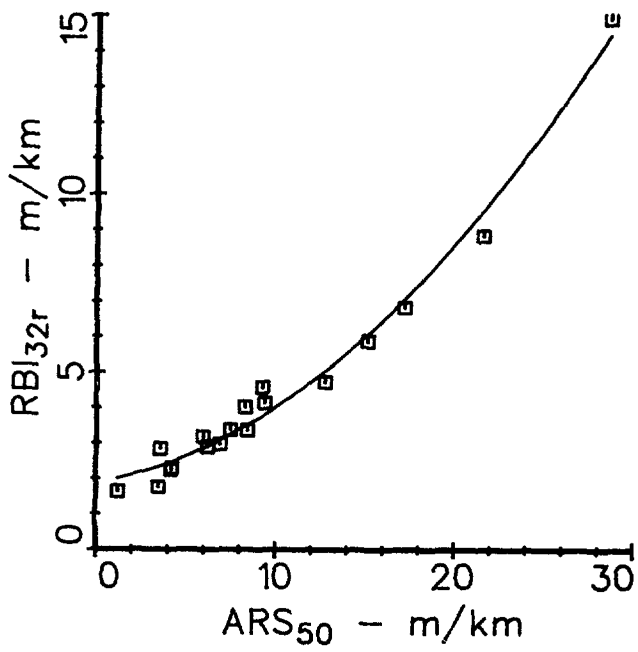
a. QI_r



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



c. APL 72 $CP_{2.5}$



d. RBI_{32r}

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

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 corrugation. 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. (This effect is obscured in most of the plots included in the report, because they are scaled to include the entire roughness range.) 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 when the plotting scale is selected to show mainly the data from the paved roads. The reason is that the QI_r analysis has its maximum sensitivity at wavenumbers near 0.2 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 be just as good at 80 km/h if the "outliers" were eliminated either by using vehicles with higher damping or by avoiding sites with corrugations. More example calibration plots and correlation data are included in Appendix E.

Appendix E also describes the calibration procedures used in the PICR 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 PICR 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 exactly equivalent, largely because of the form of the speed conversion applied to the measurements on the unpaved roads, and also because of the presence of the four outliers.

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 the CA surfaces have the greatest significant content.

LCPC APL 72 Wave Band Numerics. Among the three wavebands used in these analyses, the best correlations with the RTRRMSs 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 (worst) 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 $RMSD_{1.8,300}$ numeric. Further development of the use of

CP numerics to calibrate RTRRMSs may not be justified, however, since the RARS numerics can already be computed directly from the APL signal.

RBI_{32r} and $RMSD_{1.8,300}$. The $RMSD_{1.8,300}$ 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 $RARS_{32}$ (see Appendices F and H). As Figure 11d shows, excellent correlation is also obtained for the RTRRMS test speed of 50 km/h. The $RMSD_{1.8,300}$ analysis uses short segments of profile that are processed independently. Thus, the analysis is ideally suited to the TRRL Beam, and might be 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 part of the IRRE data, care must be taken not to assume equivalent relations involving $RMSD_{1.8,300}$ 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. Note, however, that the testing of the RMSD analysis was not as comprehensive as for the other numerics: three of the RTRRMSs were not included at all; only 28 of the 98 wheeltracks could be used with the BI Trailer correlations; and only ten of the 49 sites could be used with the correlations computed for the Maysmeter-Opala RTRRMS and the Caravan-BI-NAASRA RTRRMS. Appendix H includes more correlation data, as well as the results from a second experiment conducted by TRRL in St. Lucia to validate the RBI_{32r}-$RMSD_{1.8,300}$ calibration method.

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 when the objective is to achieve the best engineering accuracy possible over all road conditions. The following conclusions are based both on theoretical considerations [9] and the experimental verification provided by the IRRE. (The basis for each conclusion is included in parentheses.)

1) Measurement speed must be standardized, and matched to the profile-based numeric to maximize correlation. (Standardizing speed approximately standardizes the waveband seen by a RTRRMS.)

2) The calibration sites should be selected to cover the total range of roughness that will be measured with the RTRRMS. (Both the vehicle and roadmeter components of an RTRRMS have inherent and significant nonlinearities. Extrapolation of a calibration equation can lead to errors of 100% and more.)

3) Each approximate roughness level should be equally represented. The roughness levels should be spaced at approximately uniform intervals on a roughness scale that is linear with profile amplitude. (This insures that the calibration equation minimizes error over the entire roughness range covered.)

4) All calibration sites should have the same length, and the length selected should be sufficiently long to obtain a reasonable measure with a RTRRMS. (This makes all of the sites equally significant, and allows meaningful estimates of error to be computed as part of the calibration.) The minimal length that can be used is proportional to test speed. (Many of the random errors involved in RTRRMS use are time-based, rather than distance based.)

5) The total length of the calibration sites should be specified to exceed some minimal length. (A large number of short sites will give the same calibration equation as a smaller number of long sites.)

6a) Separate calibrations should be provided for each surface type. (Different surface types have different characteristic PSD signatures, which can combine with differences between the RTRRMS and the calibration reference to introduce a bias according to surface type. Separate calibrations for each surface type eliminate such biases.)

6b) If separate calibrations for different surfaces (per 6a) are unacceptable due to the extra effort involved, and the possibility of less accuracy is accepted, then the different surface types should be equally represented at each level of roughness. (Biases related to surface type will not be included in the calibration equation, although they will be present in the individual calibrated RTRRMS measurements.)

7) Calibration equations 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. The data from the IRRE showed an error distribution (scatter) that was already fairly constant with roughness for all but the roughest unpaved roads. Therefore, changes in the error weighting are undesirable for the objective of minimizing error over the entire range.)

8) The calibration equation should be obtained using a quadratic regression model of the form:

$$E[\text{reference}] = A + B * ARS + C * ARS^2$$

Where A, B, and C are determined to minimize the mean-square error. If the curvature is small, than a linear regression model (C = 0) can be used for simplicity. (Due to nonlinearities of vehicles and roadmeters, a linear regression model may not be adequate when wide ranges of roughness are covered. As mentioned in item (7), non-linear transformations will also influence the error weighting, and should be avoided.)

Comparison of Subjective Ratings with Roughness Measures

In addition to its importance in economic matters, road roughness is also the primary factor influencing the public opinion of road quality. The Pavement Serviceability Rating (PSR) developed by 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]. Because of this historical association, a subjective rating (SR) survey was performed during the IRRE to assign a SR value to each of the 49 test sites, as 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.)

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 the short-wave $CP_{2.5}$ is a better predictor of SR than the medium-wave CP_{10}. The surface treatment (TS) sites which had periodicities (corrugations) that influenced the ARS_{80} measures appear as outliers when ARS_{80} measures are compared to any other roughness numeric, but

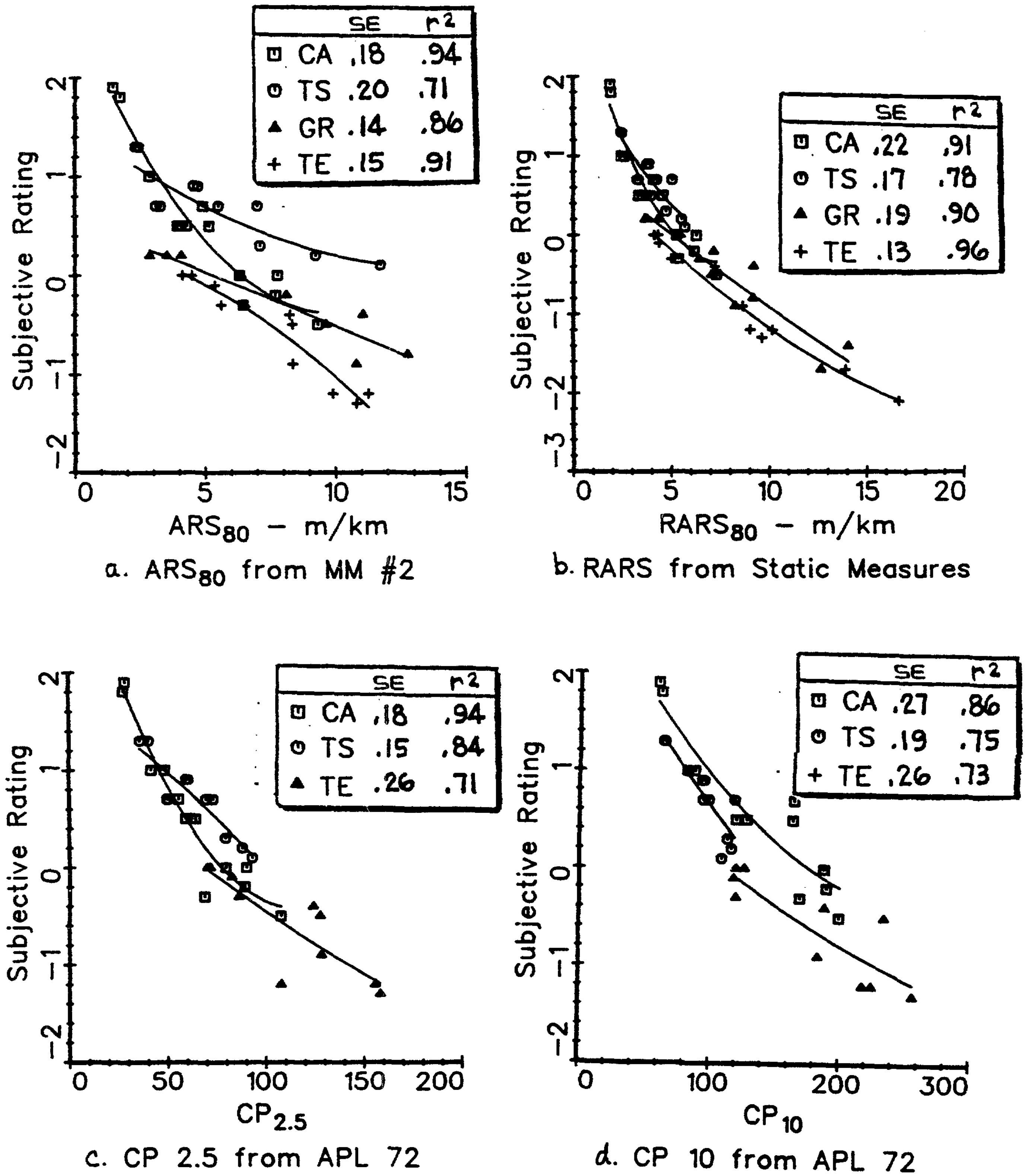


Figure 12. Comparison of subjective panel ratings with profile-based numerics.

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.)

A second subjective rating experiment is described in Appendix K. In this case, the intent was to try to estimate an ARS-type of roughness index subjectively, using detailed descriptions of roads and example roughness levels. Conceptually, this is a "calibration (of the rater) by description." The results show that the method is viable, and can be used with a very small number of raters. The accuracy is not as good as can be obtained with a calibrated RTRRMS, but would be adequate for some applications.

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 definition of the important variables in its measurement.

Criteria for the 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 both practitioners and researchers that the IRI must be defined by a mathematical function of the longitudinal profile of the road, rather than by a standardized piece of hardware. 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 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. (Even though vehicles appear outwardly much different, or are disparate in size, the dynamic properties are only slightly affected [32].) The poor correlations between different RTRRMSs that have often been reported are seen to be caused more by differences in procedure, rather than the equipment. Thus, it is essential that the IRI be defined in consonance with specification of RTRRMS operating procedure.

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 used to measure the IRI must ensure that methods used with different pieces of hardware will result in 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. Conversely, the analysis must fit common measurement methods directly (as opposed to a correlation). It is therefore desirable that the IRI be measurable by a wide variety of profilometric methods. 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. Thus, it is desirable for the IRI to closely reflect roughness as "seen" by an RTRRMS.

Definition of the IRI

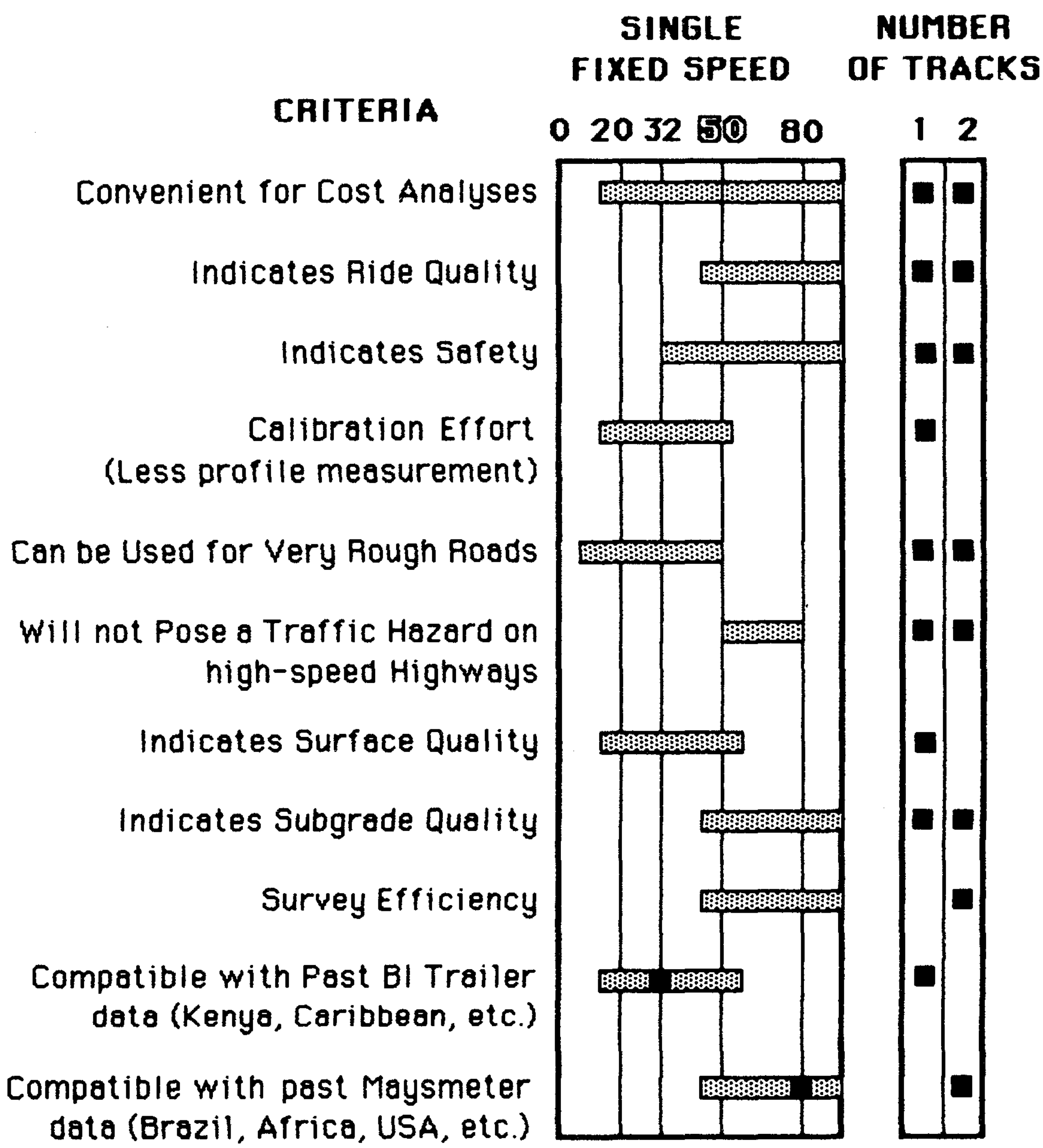
Choice of RTRRMS speed. On any particular road, the roughness level measured by a RTRRMS will depend on its test speed. The "best" speed for testing depends on local circumstances and the end use of the data. The fact that roughness varies with speed implies that a standard speed must be selected as 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. The testing in the IRRE covered the four listed speeds of 20, 32, 50, and 80 km/h. Before discussing the factors shown in the table, it is helpful to review the major implications of a standard test speed.

Low Standard Speed:

* Testing at the specified speed is possible even on roads with restrictive geometries and roads that are extremely rough.

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



* Testing at a the standard speed on high-speed roads can pose a traffic hazard unless traffic control is provided.

* Testing at a low speed takes longer, so less data can be acquired in a given time than would be the case for a higher standard speed.

* Measures from a RTRRMS will mainly reflect short wavelengths, with little influence of the longer wavelengths.

High Standard Speed:

* Testing at the standard speed is possible on high-speed roads without special traffic controls.

* Some roads will require reduced speed, and testing at the standard speed will not be possible.

* Data takes less time to acquire at high speeds, and thus greater efficiency is achieved.

* Measures from a RTRRMS will include the effects of longer wavelengths, and be less influenced by very short wavelengths.

The relevance of the roughness measures obtained at a given speed is largely determined by the range of wavelengths included in the measurement. If only short wavelengths are of interest, then a low test speed is most relevant. However, if longer wavelengths are relevant, then a higher speed is more appropriate.

From the standpoint of road-user cost studies, the value chosen for a standard measurement speed is actually not critical because traffic speed is included as a separate variable in most of the cost analyses. The possible error introduced by covering an inappropriate range of wavelengths must be viewed in comparison with the errors introduced in other aspects of a cost study. (User cost data is generally much less precise than roughness data.)

When viewing roughness data in ways other than vehicle operating cost, specifically the vibrations affecting rideability and safety, the choice of measurement speed becomes more critical. The most appropriate measure of roughness is generally observed at the prevailing traffic speed, because the measure then includes the same band of wavelengths that affect highway vehicles using the road [4, 9]. This is most acutely evident, for example, when examining the road damaging dynamic loads under a vehicle's tires [34].

Table 1 visually indicates that a standard measurement speed in the range of 50 - 80 km/h would satisfy the broadest range of factors when considering the majority of roads. However, given that most of the road-related resources of a country are often spent building and maintaining the primary roads, a measurement geared towards those high-speed, high-volume roads can be more relevant than a measure geared for both high-speed and low-speed roads. If the high-volume roads are of greater interest, than a higher test speed such as 80 km/h is the best choice.

Although a speed of 80 km/h appears to be the most relevant and the most convenient, evaluation of measurement accuracy at 80 km/h was hampered in the IRRE because only the three Opala-Maysmeter RTRRMSs were routinely operated at this speed. The accuracy possible using these Opala vehicles was significantly degraded because they exhibited a "tuning effect," over-responding to corrugations on four of the surface treatment sites. The measures obtained on these sites appeared as "outlier" data points in comparisons with the various profile-based numerics. ("Outlier" data points were never omitted in any of the analyses performed with the IRRE data. However, simple inspection of the scatter plots involving the 80 km/h measurements (Figure 10d and numerous plots in the appendices in Volume II) shows that the accuracy obtained by calibrating RTRRMS measures made at 80 km/h is comparable to the accuracy for other speeds if the four surface treatment "outliers" are not considered.)

Another source for comparisons is available from one of the profile analyses, namely the reference quarter-car simulation (RQCS). This profile analysis closely matches the sensitivities of a mechanical RTRRMS that does not have the specific "tuning" problem of the Opala. Comparisons of RARS with other common roughness indices showed that a simulation speed of 80 km/h resulted in measures with the highest correlations with the QI_r, $CP_{2.5}$, and APL 72 short wave (energy) indices. Also, the best agreement between RARS and the panel ratings occurred with a simulation speed of 80 km/h. Thus, a speed of 80 km/h would be good for a RTRRMS whose dynamic properties were similar to the RQCS, in order to best match the QI_r, $CP_{2.5}$, and the APL 72 Short wave index (energy) roughness scales. A speed of 80 km/h also appears to be best for matching public opinion.

When considering only the experimental data gathered in the IRRE, the 80 km/h speed is not supported well, because 1) the two RTRRMS trailers and the Caravan were not operated at 80 km/h, and 2) the "outlier" data points degraded the accuracy associated with the Opalas at 80 km/h. The 50 km/h test speed showed some strong advantages:

* Correlations involving the different RTRRMSs and the profile-based numerics were highest at 50 km/h, such that the best accuracy was obtained for calibrated RTRRMSs.

* More profile points are needed (and greater effort if manual profile measurement is undertaken) to calibrate the RTRRMS if it is operated at a higher speed. (Due to the mechanical properties of the vehicle in a RTRRMS, shorter sample intervals are needed at lower speeds to capture the relevant frequencies. A second factor is that longer sites are needed for higher speeds, in order to obtain measures from the RTRRMS with equivalent reliability. A third factor is that a minimum sample interval of about 500 mm is needed for most types of road surface in order to capture localized surface defects. When all three factors are considered, the number of profile elevation measurements increases with speed for speeds above 50 km/h.

* The speed of 50 km/h was the highest speed that could be used over the full range of roughness in the IRRE with all of the RTRRMSs (other than the fragile BPR Roughometer). The four roughest unpaved sites could not be measured at 80 km/h.

* Measurements at this speed are correlated well to earlier measures obtained with the BI Trailer used at 32 km/h in many past road-user cost studies, as well as measures obtained by other RTRRMSs at the 50 and 80 km/h test speeds used in the Brazil PICR project. In effect, 50 km/h is a compromise between the speeds of 32 and 80 km/h.

When all factors were considered, the consensus of the participants in the IRRE was that a speed of 50 km/h was a good choice for defining an IRI, which was well supported by the IRRE data. Thus, the speed of 50 km/h was recommended in an earlier draft of this report (dated May 1984). (A dissenting opinion was held by the Overseas unit of TRRL, maintaining the view that 32 km/h is a more suitable speed for use in all developing country environments.) Copies of that draft were then reviewed by a number of agencies.

The overwhelming response from users of RTRRMSs was that they would be making nearly all measurements at a speed of 80 km/h, due to requirements of survey efficiency, even if they were calibrating the measures to a reference optimized for greatest accuracy with a RTRRMS speed of 50 km/h.

Thus, there are several conflicting factors to consider in selecting a standard speed for use in defining an IRI:

1) The best demonstrated accuracy is obtained when the RTRRMS is operated at 50 km/h, and this speed also offers the best compatibility with past measures made at the other speeds.

2) Most practitioners are using a speed of 80 km/h, and will continue to do so in the near future. For these practitioners, an IRI based on the speed of 80 km/h would result in the best accuracy.

3) The Overseas Unit of TRRL has acquired a great deal of data using a speed of 32 km/h, and has indicated it will continue to use that speed (together with the RMSD calibration reference) for future work regardless of what is adopted by other agencies.

4) A speed of 80 km/h results in the most relevant measures by covering the same wavelengths that affect road-using vehicles. It is most compatible with the roughness scales QI_r, $CP_{2.5}$, and APL 72 Short wave energy. It is also the most closely related to the subjective ratings, associated with public opinion and the PSI/PSR concept.

Overall, a choice of 80 km/h appears to be best for the majority of RTRRMS users. In the long run, the rapidly growing use of profilometers means that slightly higher accuracy for RTRRMS users (at 50 km/h) may never outweigh the practical advantages associated with the speed of 80 km/h. For profilometer users, the choice of 80 km/h means that a slightly more relevant roughness index is obtained.

80 km/h is the standard RTRRMS speed recommended for the IRI.

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 criteria indicated in Table 1 do not support one choice over the other.

A two-track RTRRMS is preferable when summary roughness measures are desired for the travelled lanes in a road network. This is because a two-track RTRRMS obtains the information in a single pass, whereas a single-track RTRRMS must make either one pass for each wheeltrack, or else cover only one of the two travelled wheeltracks in a lane. However, a standard based on the concept of a single-track RTRRMS has several advantages that are quite appealing: A single-track RTRRMS requires less profile measurement for calibration (since two-track RTRRMSs require the measurement of both wheeltrack profiles for any site). Also, it is compatible with single-wheeltrack profilometers (such as the APL) which cannot be used for profile analyses that require accurately synchronized measures of both wheeltrack profiles. And finally, a roughness scale based on a single-track RTRRMS can be used to provide more detailed information about pavement condition, since each individual wheeltrack can have a separate roughness level.

The proposed IRI is based on the single-track RTRRMS concept.

Selection of a Calibration Reference.

The choice for an IRI calibration reference that has the broadest application is the $RARS_{80}$ 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 the most closely related to the ARS_{80} measure obtained with a RTRRMS. It showed the highest correlation with ARS_{80} measures of any of the profile-based numerics, and the least bias due to surface type. It also has the advantage of being an easy numeric to understand because: 1), it describes a simple profile characteristic (slope), and 2), it is a standardized RTRRMS.

$RARS_{80}$ is the IRI recommended by this report.

Although it is selected on its technical merits, the $RARS_{80}$ numeric might also be the first choice based on present and past usage. Beginning with the Bureau of Public Roads (BPR) Roughometer in the 1930's, the arbitrary measure of "inches/mile" has been widely used as a measure of road roughness.

QCS versions of the inches/mile (ARS) numeric have been available on profilometers since the late 1960's. (For example, the GMR-type profilometers made by K.J. Law, Inc. have been equipped with either the QCS or HCS implementation of the $RARS_{80}$ computation since 1979.) The RARS statistic, defined in the NCHRP study [9], is simply a precise mathematical description for this common measure.

Among the other established roughness statistics used for calibrating RTRRMSs that have been developed, the most common goal has been to relate as closely as possible to the RTRRMS measure of road roughness, usually by establishing correlations and using regression equations to accomplish what the RARS does directly. For example, $RARS_{80}$ is closely related to the QI scale used in the Brazil PICR study, improving on the RMSVA-based QI_r analysis used most recently.

However, the Overseas Unit of TRRL holds the view that the RBI_{32r} statistic is a more suitable statistic selection as an IRI, and therefore do not accept that the IRI should be based on $RARS_{80}$.

Table 2 summarizes the qualifications of $RARS_{80}$ and some of the other profile-based roughness numerics that have been considered as standard calibration references for RTRRMSs. Note that only those profile-based numerics that are well-known **and** highly correlated with RTRRMS measures are shown. (For example, the CHLOE profilometer is omitted because it has been repeatably shown to be poorly correlated with RTRRMS measures.) 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 because they are not stable with time. In the IRRE, $RARS_{80}$ was shown to have excellent correlation with subjective ratings; thus $RARS_{80}$ can be viewed as a time-stable measure indicative of public opinion.

Standard Hardware. Although standardization of hardware has been attempted many times, this approach has yet to be demonstrated in practice.

Table 2. Comparison of profile-based roughness indices that show excellent correlation with RTRRMS measures.

DEFINITION OF THE IRI*

*** INTERNATIONAL ROUGHNESS INDEX**

	Subj. Rating (PSR)	Std. Hardware	PROFILE-BASED NUMERICS				
			$RARS_{80}$	QI_R	RBI_{32}	APL 72 SW (W)	$CP_{2.5}$
TIME-STABLE			✓	✓	✓	✓	✓
TRANSPORTABLE			✓	✓	✓	✓	✓
VALID FOR: ROD & LEVEL (500 mm)			✓	✓			
TRRL BEAM			✓	✓	✓		✓
APL TRAILER			✓			✓	✓
PHYSICAL MEANING	PUBLIC OPINION	INSTRUMENT RESPONSE	1. REF. RTRRMS 2. PROFILE SLOPE*	1979 QUARTER CAR INDEX	1982 BI TRAILER	MEAN SQUARE DISP.*	AVERAGE RECTIFIED DISP.*
PRESENT AND PAST USAGE	AASHO ROAD TEST, NEW YORK	BPR ROUGH., NAASRA, BI TRL.	NCHRP 228, MOST PROFILOMETERS IN USA	PICR, BRAZIL, BOLIVIA, S.AFRICA	TRRL OVERSEAS UNIT	FRANCE, LCPC	BELGIUM, ENGLAND

*Indicates filtered profile

It also has a conceptual ambiguity: in order to be assured that the properties of the hardware do not change (is it 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. These problems are eliminated by choosing a mathematical model ($RARS_{80}$) to be the standardized RTRRMS.

QI_r. The QI scale was intended to be the equivalent of the $RARS_{80}$ scale. (It is an estimate of an earlier quarter-car ARS measure.) The reasons for any differences in performance between QI_r and $RARS_{80}$ lie in the fact that the QI_r analysis (a weighted sum of two RMSVA numerics) does not approximate a vehicle response as closely as a true quarter-car simulation. One problem that results from the nature of the QI response properties is a degraded correlation with RTRRMSs on some surface types, such as the surface treatment sites. (This is because the surface treatment roads show a markedly different PSD signature than the asphaltic concrete roads used in the derivation of QI_r.)

A second problem that occurred in the IRRE is that QI_r cannot be computed from the defining equations when using the profile signals measured directly by the APL Trailer. (This is because deviations in the response of the RMSVA analysis interact with the response of the APL Trailer, resulting in bias.) However, QI_r has been estimated using an alternative computation method devised by LCPC. This illustrates an undesirable conceptual characteristic of the QI scale: it is possible for the scale to continue to develop and evolve in the future when measurement problems are encountered. The possibility exists because QI_r does not define a unique physical profile attribute that can be used as a definition of "truth" that can be used in evaluating measurement error.

For all practical purposes, $RARS_{80}$ can be considered to be an improvement of the original QI concept. It is in fact the <u>Q</u>uarter-car <u>I</u>ndex of the sort estimated by QI_r. All of the problems with the QI_r scale (as defined with the RMSVA statistic) are either reduced or eliminated when QI is redefined as the $RARS_{80}$ numeric using the arbitrary QI units of "counts/km," where one "count" is defined in Table 3 at the end of this chapter.

$RMSD_{1.8,300}$ and RBI_{32r}. The Overseas unit of TRRL holds the view that RBI_{32r}, based on the $RMSD_{1.8,300}$ profile numeric as developed in the course of the IRRE, is the most suitable statistic selection for an IRI. This view is linked to their position that a speed of 32 km/h is the most suitable standard speed. Since the IRRE, the RBI_{32r} statistic has been used to calibrate RTRRMSs in several developing countries.

The RBI_{32r} numeric is optimized for the speed of 32 km/h, and is therefore not the best for use as a calibration reference for RTRRMSs operating at 80 km/h. Even for a RTRRMS speed of 32 km/h, however, the numeric has some undesirable characteristics that should be considered.

The RBI_{32r} numeric is similar to the QI_r numeric in that it does not describe a simple profile characteristic. It is instead a numeric that correlates well with other measures and has been scaled to yield the ARS-type of measure. Because the $RMSD_{1.8,300}$ numeric is rescaled to a mechanical reference (the BI Trailer as it existed in 1982), there is a potential for further evolution of this scale since the mechanical reference is not stable with time. The validation work used only a small portion of the IRRE data (10 sites for a Maysmeter-Opala RTRRMS, 10 sites for the Caravan-BI-NAASRA RTRRMS, and 28 wheeltracks for the BI Trailer); thus, the accuracy of the method is not as well established as for all of the other candidate profile-based numerics.

The requirement of a single sample interval of 300 mm could be an inconvenience for many profile measurement methods, in contrast to the other numerics that can be used with a range of permissible sample intervals.

Finally, it should be noted that the BI Trailer ARS measures, the $RMSD_{1.8,300}$ numerics, and the $RARS_{80}$ numeric were all highly correlated for the data collected in the IRRE. The reference defined by the BI Trailer (RBI_{32}) can be estimated from $RARS_{80}$, $RARS_{50}$, and $RARS_{32}$ with accuraccy comparable with that obtained using $RMSD_{1.8,300}$.

APL Short-Wave "Energy" (W). The measurement requirements for this numeric have not been determined for rod and level measurement, as it was designed for use with analog profile signals. Thus, it is not as transportable as the other numerics. The correlations with ARS_{80} are very good, but not as high as those obtained with $RARS_{80}$. Thus, estimates of (W) based on RTRRMS measures would be less accurate then estimates of $RARS_{80}$. Although not developed with any regard for RTRRMSs, the high correlation between APL short-wave energy and $RARS_{80}$ does allow empirical "conversions" to be made with reasonable accuracy.

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_{80} measures obtained from RTRRMSs, and the relationships appear to be unaffected by surface type. Three differences between $RARS_{80}$ and $CP_{2.5}$ are: 1) $RARS_{80}$ is more closely linked to the RTRRMS concept, 2) the correlations with ARS from the RTRRMSs are better with RARS, and 3) the $CP_{2.5}$ analysis requires a smaller profile measurement interval (and thus more effort when manual profile measurement is involved). The details concerning measurement requirements were not investigated as thoroughly as for $RARS_{80}$, but it was determined that a 500 mm interval is not adequate. The good correlation between $RARS_{80}$ and $CP_{2.5}$ indicates that when necessary, empirical conversions can be made with reasonable accuracy.

Classification of Measurement Methods

Having defined the IRI as $RARS_{80}$, it is appropriate at this point to classify the various methods that can be used for its measurement. The many potential methods, including those demonstrated in the IRRE, are divided into four classifications, on the basis of how directly their measures pertain to the IRI, which in turn affects the calibration requirements and the accuracy associated with their use. A wide range of instrumentation can be used within each class, with better accuracy being obtainable with better instrumentation. Note that because the classification is based partly on procedures, the same piece of equipment can fall into one of several classes, depending on how it is used.

Class 1: Precision profiles. This class represents the highest standards of accuracy for measurement of IRI. A Class 1 method requires that the longitudinal profile of a wheeltrack be measured (as a series of accurate elevation points closely-spaced along the travelled wheelpath) as a basis for calculating the IRI value. For static profilometric methods, the distance between samples should be no greater than 250 mm (4 measures/meter) and the precision in the elevation measures must be 0.5 mm for very smooth pavements [35]. Less precise elevation measurements are acceptable for rougher surfaces.

It is of course not possible to produce a profile measurement with zero error. But even if this were possible, there would still be a certain amount of variation in repeated field measurements that is associated with locating the wheeltrack to be profiled. The replicate measures made in the IRRE indicate that uncertainty (repeatability) in a IRI measure cannot be reduced beyond several percent for the 320 m section lengths used. A procedure for measuring IRI that falls within this level therefore qualifies as a Class 1 method, because improvements in accuracy cannot affect the quality of the IRI index obtained. (Experience outside of the IRRE indicates that less variation is obtainable with longer sections, while more uncertainty is expected for shorter sections; however the specific influence of site length on repeatability has not been investigated.)

Static profilometric methods, such as the TRRL Beam or the rod and level, can qualify as Class 1 methods when sufficiently short sample intervals are used together with sufficient precision in the individual elevation measures. For most surface types, an interval of 250 mm is acceptable for Class 1. 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 must be used. (None of the sites in the IRRE had this type of feature.) The 500 mm interval used in the IRRE for rod and level measures introduces a small amount of random error, which was reduced by going to a shorter interval. Thus, measures made using this interval do not qualify as "Class 1."

The required precision of the individual elevation measures depends on the roughness level, and is approximately equal to IRI / 4, where IRI has units "m/km" and the precision has units of mm. This level of precision forces the measurement round-off to be negligible in comparison to the true deviations in the road profile. For most paved roads, a precision of 1 mm is adequate for a Class 1 method; on very high quality roads, however, some error can be introduced unless greater precision is used. The IRRE data indicate that on the three smoothest sites, a precision of about 0.8 mm was needed to obtain a Class 1 profile measurement.

High-speed profilometers offer a potential means for measuring IRI quickly; however, the profilometer must be validated at some time against an established procedure such as rod and level to prove its accuracy. Determining the accuracy of a profilometer is not as simple as for the static profilometric methods, because profilometers usually respond only to a band of wavelengths. While this is not a disadvantage in use, it does make it difficult to determine how accurately a profilometer can measure IRI. To qualify as a Class 1 instrument, the frequency response of the profilometer should be adequate to cover the wavelength range from 0.5 - 20 m, within an amplitude accuracy of several percent. In addition, the criteria regarding sample interval and precision that were described above also apply. One issue that has not been addressed yet is the level of repeatability that can be obtained using a high-speed instrument. Given that repeatability is several percent using quasi-static profilometric methods, the repeatability associated with a "perfect" profilometer instrument can be expected to be more of a problem because of the greater difficulty in locating a wheeltrack precisely at a highway speed.

Although the APL Trailer has specifications that indicate it could be used as a Class 1 instrument, the measures obtained in the IRRE showed more random error than is allowed. Thus, the APL Trailer does not qualify at this time as a Class 1 measurement. Perhaps by refining measurement procedures, the APL Trailer (or other high-speed profilometers) could qualify as Class 1 methods in the future. The accuracy of a profilometer should be demonstrated by selecting several sites covering the range of conditions (roughness, surface type), and then measuring them using the profilometer and also a Class 1 static method.

Note that the results of the IRRE have been used to specify a quality for profile measurement 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 qualify as Class 1, and even these exclude the smoothest three sites, where better precision is now known to influence the IRI measure. These rigorous requirements are to ensure that procedures exist to obtain "true IRI roughness" with the accuracy that should be associated with a standard. For nearly all applications of roughness data, this precision is not needed and procedures in the other classes are probably preferable because they require less effort. The main utility of a Class 1 measure is probably for the calibration and/or validation of other measures.

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

Appendix F provides a more technical background of the measurement requirements for IRI, including the effects of variables in a profile measurement.

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

The rod and level profiles measured at 500 mm intervals in the IRRE, when processed to yield IRI, are Class 2 methods.

At the present time, the APL Trailer is the only dynamic profilometer that has been experimentally validated over the range of roughness covered in the IRRE. The GMR-type Inertial Profilometer with follower wheels has been validated for roads with roughness levels less than an IRI value of about 3 m/km [9], above which errors are introduced due to bounce of the follower wheels. This type of design is no longer commercially available in the United States, however, as the follower wheels have been replaced with non-contacting sensors to eliminate the bounce problem. Two high-speed profilometers are presently sold by K.J. Law, Inc., and both are designed to provide the IRI roughness during measurement. Both are expected to be Class 2 systems, although their accuracy and range of operation have not yet been verified.

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

Class 3: IRI estimates from correlation equations. This class includes all roughness measuring instruments capable of generating a roughness numeric reasonably correlated to the IRI (e.g., a rolling straightedge). The measures obtained can be used to estimate IRI through regression equations if a correlation experiment is performed. In order to estimate IRI, a calibration is needed which is performed on actual road surfaces, following the normal operating procedures used to measure roughness. The IRI values of the calibration sites are obtained using a Class 1 or Class 2 method.

By far, the majority of road roughness data that is collected throughout the world today is obtained with RTRRMSs, which are Class 3 measures. The RTRRMS measure is dependent on the dynamic properties of a vehicle. These properties are unique for each vehicle and may change with time, Thus, the "raw" measures of ARS obtained from the RTRRMS must be corrected to the IRI scale using a calibration equation derived from an experimental correlation between the IRI and the ARS meassures for that specific RTRRMS. Because the dynamics of a vehicle change easily, very rigorous maintenance and operating procedures must be employed for the vehicles used, and control testing must be made a routine part of normal operations. When changes occur, there is no simple correction that can be applied; instead, the entire roadmeter-vehicle system must be re-calibrated. Unless a RTRRMS is calibrated by correlation it does **not** qualify as a Class 3 method, because without the calibration there is no verifiable link between the measures obtained with any two RTRRMSs, nor to the IRI scale.

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]. At the present time, very little data from RTRRMSs qualify as Class 3, because calibration was not complete. Even in the PICR project, the QI^* data for unpaved roads would not qualify completely as Class 3 because the calibration against rod and level did not correctly cover the speeds, roughness levels, and surface types. (The QI^* data for the asphaltic concrete roads qualify in concept, except that the reference was QIr rather than IRI.)

The reproducibility associated with a calibrated RTRRMS is about 0.5 m/km for paved roads for sections 320 m long, and about 1.0 m/km for unpaved surfaces of that length. Better accuracy is possible by using longer test sections.

A method for measuring roughness qualifies as Class 3 if it uses the "calibration by correlation" approach, regardless of what type of instrumentation or vehicle is used to obtain the uncorrected roughness measure. While most Class 3 methods will employ a roadmeter that accumulates suspension motion to measure

ARS, other systems are in use that employ accelerometers or other types of instrumentation. However, the roadmeter-based RTRRMS that measures ARS most closely matches the IRI concept.

The practice of measuring other profile-based statistics to estimate IRI via correlation also falls within this class, including measurements of $CP_{2.5}$, APL 72 short-wave energy (W), $RMSD_{1.8,300}$, and QI_r. In most cases, there is more error in using one of these statistics to estimate IRI than when IRI is calculated directly from the profile signal. Therefore, this approach is not recommended. It might be required, however, when the actual profiles used to compute summary statistics are no longer available. The IRI may then be estimated using these correlated statistics. (If the IRI is estimated from another profile-based numeric, the equation should be derived for a particular type of road and roughness range through regression with IRI as measured with a Class 1 method or "validated" Class 2 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.)

The accuracy associated with a class 3 roughness measure covers a wide range, which overlaps the accuracy ranges covered in Classes 2 and 4. Unless the test sites are very long (several miles or longer), the accuracy of a RTRRMS cannot approach that of a Class 1 method or a relatively accurate Class 2 method, although it can be better than some Class 2 methods. Ultimately, after problems with operational procedures and with time stability are solved, the accuracy of a RTRRMS is limited by inherent mechanical properties of the vehicle and roadmeter, which include several notable nonlinearities. The best accuracy is obtained when the RTRRMS matches the reference as closely as possible [9, 35].

Class 4: Subjective ratings and uncalibrated measures. This class includes roughness measures that have no verifiable link to the IRI scale. The only recourse in these cases is to match field measurements to the reference scale, based on descriptions of benchmark roughness levels. This class also covers a wide range of accuracy and methodologies, although it is not possible to obtain accuracies nearly as good as with the other three classes. This is because the overall accuracy of a IRI value is limited by the weakest link in a chain of calibrations, conversions, and actual measurement. Thus, a Class 4 measure cannot be any more accurate than the accuracy of the final conversion, which is at best based only on descriptions of benchmark roughness levels. For example, there could be roughness data measured with an accurate instrument that no longer exists (or has changed with time). Even if the data are internally consistent and were obtained with an accuracy of a few percent, it is impossible to replicate the measurements to link them to IRI. Thus, there will be an uncertainty about the "converted" data caused by the conversion to the standard scale.

There may also be situations in which a roughness data base is needed, but high accuracy is not essential, or cannot be afforded. Still, it is desirable to relate the measures to the IRI scale. In those cases, a subjective evaluation involving either a ride experience on the road or a visual inspection could be used. Another possibility is to use the measurements from an uncalibrated instrument. Conversion of these observations to the IRI scale is limited to an approximate equivalence, which can best be established by comparison to verbal and/or pictorial descriptions of roads identified with their associated IRI values [35]. Essentially, the estimates of equivalence are the calibration, however approximate, and they may be considered to be "calibration by description."

When these subjective estimates of roughness are converted to the IRI scale, the resolution is limited to about six levels of roughness, with accuracy no better than 2 m/km on the IRI scale.

Most measurements made in the past with RTRRMSs fall within Class 4, either because they weren't calibrated to a reference that can be replicated, or because the calibration wasn't completely valid. (A valid calibration of a RTRRMS is a calibration by correlation, as described in Chapter 3.) Note that unless a valid calibration by correlation is used with a RTRRMS, there is no way to link the measure to the standard scale. Thus, an uncalibrated RTRRMS falls within Class 4.

Given that methods and the associated data that fall within this class have inherent accuracy limitations, it may not be worthwhile to obtain highly repeatable roughness measures if a valid calibration is not also planned.

When only approximate roughness levels are needed, simpler methods may prove useful. Appendix K describes a subjective rating method, in which descriptions of road roughness are used to help assign roughness ratings on the $RARS_{50}$ scale. It was tested during the IRRE, and showed that Class 4 subjective ratings are viable and would be useful for some applications where the accuracy possible in the other classes of measurement is not needed.

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 using measurements from the TRRL Beam. That is, the 28 profiles measured by the Beam were used to calculate the IRI values for the sites, which were then regressed against the corresponding 28 measures from the Trailer to determine a calibration equation. Then all 98 of the measures from the BI Trailer were corrected to the IRI scale using the calibration equation. The BI Trailer was never operated at 80 km/h; the examples shown are based on measures made at 50 km/h (Fig. 13b) and 32 km/h (Fig 13d).

2) One of the Opala-Maysmeter systems (MM #2) was calibrated against IRI determined from the rod and level profiles. Then the 49 measures from MM #2 were rescaled to the IRI scale. ARS_{50} measures were transformed for Fig. 13a, while ARS_{80} measures were used in preparing Fig. 13c.

3) The APL 72 signals were processed to yield IRI directly.

4) The Caravan-NAASRA system was calibrated against IRI determined from the APL 72 system. The APL measures of IRI on 31 of the

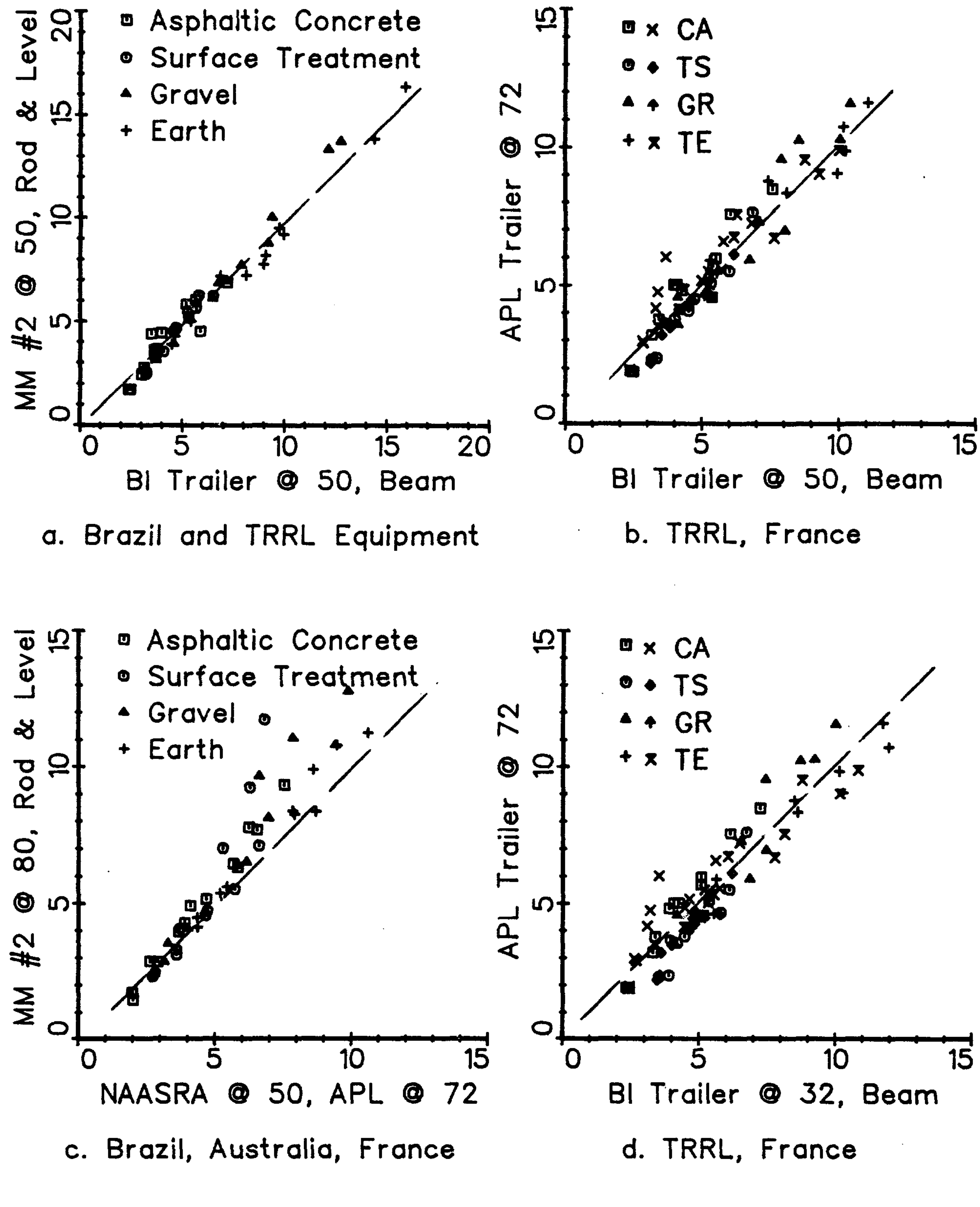


Figure 13. Examples of the agreement that is obtained using alternate measures of the IRI.

sites were regressed against the ARS_{50} measures of the NAASRA meter, and the resulting equation was used to re-scale all 49 measures. This calibration does not include any gravel test sites.

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 four of the plots, the agreement is sufficient to exchange roughness information in general terms: over a range of 2 to 20 m/km, reproducibility within 1 m/km is typical.

Figure 13a illustrates the good agreement obtained when RTRRMS calibrations include all four surface types, and similar speeds are used by the different RTRRMSs.

In comparing Figures 13b and 13d, the effect of the RTRRMS speed can be seen. Note that the data points for the surface treatment and some of the earth sites (TS and TE) tend to lie under the line of equality, whereas the points for the other two surface types tend to lie above the line. This bias due to surface type can be expected when the RTRRMS speed differs from the 80 km/h speed selected as standard. The biases increase with the difference in speed: greater bias is seen in Figure 13d for the lower RTRRMS speed of 32 km/h.

The greatest errors in the four examples are seen in Figure 13c, for two reasons. First, the Opala-Maysmeter measures include the "outlier" surface treatment sites that had corrugations. (The calibrated MM #2 measure for one of those sites is 80% higher than the calibrated measure from the NAASRA.) This illustrates once again that the "tuning effect" of a RTRRMS cannot be compensated using an aggregate calibration equation. Instead, it should be reduced mechanically, by installing stiffer shock absorbers. Figure 13c also shows measures based on an incomplete calibration. The gravel roads were not measured in both wheeltracks with the APL 72, and are therefore not included in the calibration of the NAASRA. When the calibration equation is applied to the NAASRA measures on the gravel roads, the estimates of IRI are too low.

Even with these sources of error, the agreement is sufficient for most applications involving roughness data from different sources. Note that the agreement is quite good for the majority of the sites, which were represented in the calibrations.

Conversion to the IRI from QI and BI

Hopefully, future problems in comparing roughness measures from different sources will be reduced by the application of the findings of the IRRE. In the simplest of cases, roughness measures will be made using the IRI directly. Even if a different index is used, comparisons are simplified when higher quality data are obtained through the use of improved practices. Yet there is still the problem of relating to past measurements of road roughness. Specifically, relationships between road roughness and user-cost have been developed using roughness measures from BI Trailers, operated at 32 km/h, and also from other RTRRMS measures calibrated to the QI_r scale. The IRI is proposed, in part, because there have been problems associated with the QI and BI Trailer measures, which limit their accuracy and transportability. Nonetheless, the IRRE provides a unique opportunity to compare these roughness scales, and to derive approximate conversions between them.

Table 3 presents four equations that are suggested to convert back and forth between IRI, the BI Trailer "mm/km," and QI_r. They are derived from the IRRE data, and thus reflect the surface types and roughness amplitudes covered. Therefore, they may or may not be appropriate to other conditions. Note that the two equations in each pair are reversible. That is, they are algebraically equivalent. They were obtained by simplifying more complex least-square regression equations, and thus reflect a trade-off of accuracy to obtain the convenience of reversible conversions between the roughness scales.

Table 3. Approximate Conversions between IRI, BI, and QI

Conversion Equation	RMS Error		Percent Error	
	1-track	(2-track)	1-track	(2-track)
$QI_r \simeq 14 * IRI - 10$	7.7	(6.4)	10%	(8%)
$IRI \simeq (QI_r + 10) / 14$	0.55	(.46)	9%	(8%)
$RBI_{32} \simeq 630 * (IRI)^{1.12}$	804	(680)	17%	(14%)
$IRI \simeq 0.0032 * (RBI_{32})^{0.89}$	0.88	(.75)	15%	(12%)

Units: IRI: m/km

RBI_{32}: mm/km

QI_r: counts/km

Errors for 1-track are based on measures for 98 wheeltracks; errors for 2-tracks are based on 49 lanes.

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 that includes 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 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 compared graphically with the statically measured profiles, spectral analyses and some of the roughness numerics validate the APL Trailer as a profilometer 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 PICR 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 conclusion 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). Based on both technical and practical considerations, it is clear that a choice of 80 km/h would be most appropriate for the greatest number of RTRRMS users. For profilometer users, the choice is not at all critical, since the only implication is that different data reduction methods should be used in conjunction with different RTRRMS speeds. Therefore, the speed selected for the IRI is 80 km/h. (This differs from the 50 km/h speed recommended in an earlier draft of this report, and in several related technical papers that have recently been published.)

A number of profile-based numerics were considered to provide a time-stable definition of the IRI. Of these, the $RARS_{80}$ numeric, developed earlier in an NCHRP project as a reference quarter-car simulation, was the most closely linked to the concept of a RTRRMS operated at 80 km/h. This numeric was also the most highly correlated with the RTRRMs measures, and thus offers the greatest accuracy for users of RTRRMSs. The $RARS_{80}$ numeric was one of only two profile-based numerics that could be measured with all of the profile measurement methods represented in the IRRE. (The other was $RARS_{50}$, computed from the same reference quarter-car simulation but using a different simulation speed.) Thus, the IRI is defined as $RARS_{80}$: the numeric obtained from the reference RTRRMS simulation for a speed of 80 km/h.

Guidelines for measuring $RARS_{80}$, the proposed IRI, are available [35]. They describe the procedures for planning and operating programs for monitoring road roughness using the $RARS_{80}$ scale with several types of equipment, including RTRRMSs calibrated against 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) $RMSD_{1.8,300}$, 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.

Conversion equations were derived for converting old data based on the Brazil QI scale and the TRRL BI Trailer. They are suggested for use when derivation of more accurate relationships (reflecting local road characteristics) is not possible.

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 of equipment was by no means complete, equipment and methods that were not included should also be validated for use in measuring the IRI and other roughness indices.

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 RTRRMSs, the acquisition of a profilometer or other instrument that is stable with time may at first appear 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 IRI) by direct comparison with rod and level.

The influence of site length on accuracy was not investigated in the IRRE. Generally, variations due to random effects (e.g., the lateral positioning of the instrument in the travelled lane) can be reduced by selecting longer standard lengths. Test lengths other than 320 m, of course, can be used when measuring IRI (or any of the roughness numerics described in this report), although lengths shorter than 160 m should be avoided due to repeatability problems with RTRRMSs. When site lengths other than 320 m are used, the accuracy of the measurements (as characterized by reproducibility) should be determined when possible.

In addition to the four surface types included in the IRRE, the $RARS_{80}$ numeric has also been demonstrated to be valid for PCC roads [9]. Care should be taken when performing calibrations to avoid surfaces with corrugations that could result in vehicle tuning. If measures are to be made on roads with unusual properties (corrugations, brick, etc.) then extra care should be taken to ensure valid measurements. If a profilometer is used, the measured profile should include all of the relevant pavement irregularities. If a RTRRMS is used, the vehicle should be de-tuned by installing stiff shock absorbers. Naturally, the procedures developed as a result of the IRRE [35] should be refined as necessary.

It is recognized that the proposed IRI is a numeric that summarizes the roughness spectrum in a single number which is appropriate to vehicle calibration, but which is not the most appropriate for other applications, especially when profile measurement is performed. Other measures may serve as better indices of various qualities of pavement condition, or specific components of vehicle cost. As profilometric methods become more common, specialized analyses tailored to those applications may be considered candidates for future standardization. The various numerics used by CRR and LCPC from the APL dynamic profilometer already show this philosophy.

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APPENDIX A

DESCRIPTION OF THE EQUIPMENT

This appendix describes the various instruments that were used in the International Road Roughness Experiment (IRRE) to obtain measures of road roughness. In addition to detailing their design and normal usage, operational problems that occurred in the IRRE are noted.

In all, there were seven Response-Type Road Roughness Measuring Systems (RTRRMSs), one APL dynamic profilometer (operated in two different modes), and two methods for statically measuring longitudinal profile.

A GMR-type profilometer was also used, but it experienced a number of problems that prevented immediate data processing. (Rather than the instrumentation, the problems were mainly related to the age of the USA-made vehicle and the fact that it is not normally sold or serviced in Brazil.) The availability of other profile measurements reduced the importance of this data with respect to the objectives of the IRRE, and the signals were not processed.

Texture depth measurements were made on the paved road sections by the sand patch method. The texture measures were found to be uncorrelated to any of the roughness measures, and are not included in this report.

RESPONSE-TYPE ROAD ROUGHNESS MEASURING SYSTEMS (RTRRMSs)

A RTRRMS consists of a vehicle instrumented with a roadmeter, which transduces and accumulates the suspension motion of the vehicle. The measure obtained from the roadmeter is generally a number of counts, where each count corresponds to a certain amount of suspension displacement. When the measure is normalized by the distance travelled during a test, the resulting measure has units of slope. Since the accumulation performed by the roadmeter is equivalent to a rectification of the suspension stroking speed, the measure obtained is proportional to the Average Rectified Velocity (ARV) of the axle-body motion. When reported as a slope, it is called Average Rectified Slope (ARS). The ARV and ARS measures are influenced by the speed of the vehicle, and therefore the RTRRMS speed is included in this report as a subscript, e.g., ARS_{50} would be the measure obtained at 50 km/h.

Four types of RTRRMSs participated in the IRRE, and are described below. The descriptions focus on the distinguishing features of each system; a more complete technical description of RTRRMS operation can be found in Reference [9]. (Note--numbers in brackets indicate references in the main text.)

Opala-Maysmeter Systems

Three of the RTRRMSs consisted of Chevrolet Opala passenger cars, made in Brazil, equipped with Maysmeters that are manufactured by the Rainhart Company in the USA [10]. The Opala-Maysmeter systems, owned and operated by GEIPOT, had been used in the ICR project (Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization) [7].

As delivered by Rainhart, the Maysmeter consists of two units: a transducer that is mounted in the rear of the vehicle; and a strip-chart recorder, normally placed in the front seat of the vehicle, which produces a paper plot whose length at the end of a test is the raw roughness numeric for that test. The units of the roughness measure are, therefore, those of length. The recorder employs two stepper motors, and is designed to advance the paper in proportion to accumulated axle deflection. For low roughness levels, the stepper motors perform as intended. However, the motors are not capable of responding accurately for high roughness levels that were covered in the ICR. Accordingly, the strip-chart units were replaced with electronic counters and digital displays [7]. Each electronic pulse that would normally be sent to the stepper motor instead increments an electronic counter. The Brazilian units are therefore capable of accurately measuring deflection for roughness levels much higher than would be possible with unmodified units. (Laboratory measurements made at The University of Michigan showed that the the stepper motors cannot track stroking speeds in excess of 800 mm/sec [7].)

The transducer is based on an optical system, and produces counts when the deflection crosses thresholds, in effect, quantizing the suspension deflection. In addition to the quantization, the units are affected by hysteresis, caused by spaces between windows in the film used by the optical sensor. Measurements of similar units have shown quantization levels of 2.54 mm and hysteresis levels of 0.75 mm [9].

In normal operation, the roughness measures are reported as "counts/km," and calibration equations are used to convert to the QI* roughness scale used in Brazil and described in Appendix E. The Brazilian meters were designed to produce one count for deflection quantities of 5.08 mm; however, it was found that one of the units (designated MM #3) required 10.16 mm of deflection to produce a count. The reason for this discrepancy was not found.

Normal operating speeds used by GEIPOT since the ICR project are 80, 50, and 20 km/h.

During the IRRE, the results of MM #3 were suspected of being invalid because they were much lower than the readings from the other two systems. Also, near the end of the IRRE, one of the mechanical connections loosened, causing a part of the transducer to fall off. The low readings were later explained by the different deflection/count calibration, and even though the failure of the roadmeter led to early speculation that the data would not be usable, the measures collected with MM #3 compare closely with measures obtained from the other two Opala-Maysmeter systems.

The readings from MM #1 were also suspect. Calibrations were performed by the Brazilian team for all three Opala-Maysmeter Systems, before and after the experiment, over a series of control sections of road. The measures obtained with Maysmeter #1 differed by about 10% before and after the experiment, indicating that something was wrong. A quick examination of the instrument after the discrepancy was found did not reveal the cause. Since this type of variation is a normal characteristic of RTRRMSs, the results are considered representative and valid.

The Opala-Maysmeter system designated MM #2 operated without any failures during the IRRE, and is usually used as the example Opala-Maysmeter system in plots and limited analyses.

Caravan Car-Based Systems

A Caravan station wagon, made in Brazil, was instrumented with two independent roadmeters: a BI unit and a NAASRA meter. All measures taken by the two roadmeters were made simultaneously, and were operated by the TRRL research team. Although neither the BI nor the NAASRA meters are normally used with this particular passenger car, the data obtained allow comparison of the meters, and provide what should be redundant measures.

BI Roadmeter. The Bump Integrator (BI) is an instrument manufactured by TRRL that mounts between the axle and body of a vehicle and produces counts that are proportional to suspension motion [11]. The unit consists of a body-mounted transducer containing a pulley on a shaft, which is spring-loaded to maintain a cable in tension that connects the body and axle of the vehicle. Hence, the pulley rotates proportionately to the suspension motion. A mechanical clutch is used to transmit rotation in one direction only to a pulse generator component. The overall effect is that the instrument follows the suspension deflection in one direction, while remaining unresponsive to movement in the other direction, thereby accumulating the displacement. When the accumulated movement reaches 25.4 mm (1.0 inch), a pulse is sent to an electronic counter. Therefore, each count corresponds to one inch of deflection in one direction, or 50.8 mm when considering both directions. ARS numerics reported for the BI roadmeter in this report are based on the scale factor of 50.8 mm/count. Normally, TRRL reports the measures using a scale factor of 25.4 mm/count, resulting in numerics that would have 1/2 the amplitude of the ARS measures repored here.

Unlike the Maysmeter, the BI transducer has no design hysteresis or quantization. (The quantization involved in producing the discrete counts occurs in the display, rather than the transducer.) In practice, however, the transducer has limitations due to its mechanical properties. Very small vibrations were seen to produce no response, due to small amounts of free play (hysteresis) in various parts of the system (bearings, linkages, etc.).

During the experiment, the BI suffered a broken spring, which was replaced. As soon as the measurements were finished, this particular BI was installed in the BI trailer, to replace a more troublesome BI roadmeter.

NAASRA Roadmeter. The NAASRA meter is a mechanical instrument that operates on the same principles as the BI. One count produced by the NAASRA meter corresponds to an accumulated deflection in one direction of 15.2 mm, or a total accumulated deflection in both directions of 30.4 mm. ARS numerics presented in this report are based on the scale factor of 30.4 mm/count.

This meter also demonstrated a small amount of mechanical hysteresis (free play), which was not measured.

The NAASRA meter was operated by members of the the TRRL research team. Although they had little experience with the device, it was simple to use, and only suffered one problem with a broken wire that was easily repaired.

The Bump Integrator Trailer

The BI Trailer, also called the towed fifth wheel, is basically a BPR Roughometer that has undergone a great deal of development by TRRL. It consists of a single-wheeled trailer with a leaf spring suspension and special shock absorbers and is shown in Figure 1 in the main report. The shock absorbers are claimed to have damping properties that are fairly insensitive to time and operating conditions. All BI Trailers are constructed to be nearly identical. Because most of the vehicle properties that influence the roughness measure are controlled, measures from a BI Trailer have been reported without any further corrections or calibration, usually in units of mm/km, corresponding to the accumulated suspension movement in one direction. The ARS measures reported in this document assume a scaling of 50.8 mm/count, and are twice the value of the "mm/km" numeric normally reported by TRRL, since ARS is based on the accumulated motion in both directions.

The BI trailer is designed to be unresponsive to movements of the towing hitch induced by the towing vehicle through the careful placement of the percussion center of the trailer frame. Nevertheless, the trailer used in the IRRE did produce measurements in the garage when the towing vehicle was bounced, indicating that dynamic properties of the towing vehicle can influence the roughness measures. The mechanical properties of the trailer are checked periodically using simple bounce tests [11], although even when the bounce tests are within tolerances, changes in the response properties have been observed [7].

A BI roadmeter is attached on one side of the trailer to measure the movement of the axle relative to the trailer frame.

The normal towing speed of the trailer is 32 km/h.

The tow hitch for the trailer was fabricated in Brasilia for the experiment, and a number of problems were experienced until the hitch attachment was properly strengthened and aligned. Other problems existed in the BI unit attached to the trailer. A spring broke and was repaired; the clutch failed and needed to be stripped, cleaned, and reassembled; and the unit produced extraneous counts on occasions. As a result, all of the tests on the paved sections were repeated after the other instruments had finished. During the entire experiment, many of the measurements made by the BI Trailer were "make-ups," made on week-ends, during lunch, etc. The measurements made last were accomplished with the use of the BI Transducer that had been in the Caravan.

BPR Roughometer

The BPR Roughometer that participated in the IRRE, shown in Figure 1 in the main report, is a single-wheeled trailer built to the specifications published in 1940 by the Bureau of Public Roads [13] by Soiltest, Inc., as the Road Roughness Indicator Model CT444. This trailer is equipped with a magnetic sensor that produces a pulse for a deflection of 0.002 inch in either direction. Because the original BPR mechanical transducer measured deflection in only one direction, the display is scaled to show one half of the accumulated deflection, in inches. Although the actual transducer is not mechanical, a cable connection with a tension spring is employed, with the potential for vibration problems at high roughness levels. One gear involved in the linkage often slipped on its shaft, resulting in a loss of counts.

The normal measurement speed for a BPR Roughometer is 32 km/h (20 mph).

During the experiment, the BPR trailer experienced breakdowns and failures almost on a daily basis. Support pins for the shock absorbers were broken frequently. On two occasions, studs for universal joints in the shock absorber connections were lost and replacements had to be fabricated in a local machine shop. All too frequently, screws that held a critical gear to the main shaft in the transducer loosened, allowing slippage and therefore reduced roughness measures. At the beginning of the experiment, the trailer was towed to and from the test sites. After the first two weeks, it was carried in the truck that served as the towing vehicle, and unloaded at the test sites to minimize its exposure to road vibrations and damage. Also, the operators learned the limits of the instrument, and declined to subject it to the more demanding conditions near the end of the experiment.

THE APL DYNAMIC PROFILOMETER

The APL Trailer

The Longitudinal Profile Analyser (APL) Trailer, shown in Figure 2 in the report, is an instrument developed by the French Bridge and Pavement Laboratory (LCPC) to obtain a signal proportional to profile over the frequency range 0.5 - 20 Hz [15, 17, 18]. The trailer consists of three mechanical elements: a frame that acts as a sprung mass, a follower wheel, and a horizontal pendulum. The trailer frame and the suspension serve only to keep the follower wheel on the road by reducing bouncing and oscillations. Compared to a passenger car, the suspension is soft and exhibits high damping. The observed resonance of the sprung mass is well below 1 Hz, and the damping is close to critical.

Unlike the BI Trailer and BPR Roughometer, the APL Trailer does not include a roadmeter, and does not measure the deflection between the axle and frame. Instead, a LVDT displacement transducer is located between the trailing arm that supports the follower wheel and the horizontal pendulum. The horizontal pendulum consists of an arm with weights at each end, supported in the center by a Bendix-type pivot with crossed blades. One of the weights can be repositioned, allowing adjustment of the rotational moment of inertia. The pendulum is centered by a coil spring, while damping is provided magnetically. Together, the pendulum, spring, and damper constitute a mechanical system that is tuned in the laboratory to provide a unity gain for input frequencies over 0.5 Hz. (Lower input frequencies result in an attenuated response.)

The displacement that is measured is designed to replicate the wavenumber content of the longitudinal road profile over the wave number range that corresponds to the frequency range of 0.5 - 20 Hz at the measurement speed. The upper limit is imposed by the dynamic response of the follower-wheel assembly, which will attenuate any inputs at frequencies above 20 Hz. Rather than following changes in road elevation at high frequencies, the follower wheel will absorb the changes through deflections of the compliant tire. This device contrasts with a conventional passenger car design, in which the unsprung mass (axle and wheels) will over-respond at the resonance frequency of the unsprung mass. This behavior is avoided with the APL Trailer because the suspension is designed to provide much more damping. The lower limit of the trailer response at 0.5 Hz is imposed by the dynamic properties of the horizontal pendulum.

The trailer is certified at manufacture by placing a dynamic shaker under the follower wheel and measuring the ratio of the output signal amplitude to the input amplitude for sinusoidal inputs. The locations of the shock absorber and coil spring in the suspension are adjusted to optimize the response. The shaker is also placed under the towing hitch, to assure that the trailer is acceptably unresponsive to these movements. The trailer used in the IRRE was demonstrated to be completely unaffected by movements of the towing vehicle. With the vehicle stationary in the garage and the instrumentation functioning, bouncing motions of the towing vehicle did not cause any signal to appear. This contrasts with similar checks of the other two trailers (BPR and BI), which showed that these two systems were not decoupled, but did in fact respond to movements of the hitch.

The distance travelled and the towing speed are measured from a signal generated with the use of a toothed disk attached to the follower wheel.

The instrumentation that is used to record data varies with the configuration of the APL trailer (APL 25 and APL 72), described below.

APL 25 System

When operated for the APL 25 analysis, the trailer was towed at 21.6 km/h (6.0 m/s), and the transducer signal was digitized with a resolution of 1.0 mm at 250 mm intervals (as detected by the distance pulse signal). The samples were summed over an interval of 25 m to yield the CAPL 25 roughness statistic during measurement. (The CAPL 25 analysis is discussed in more detail in Appendix G.) The digitized signal, and also the CAPL 25 numerics, were stored in digital form on a tape cassette. Later, in the laboratory, the cassette was played back into a microcomputer (a European version of the Apple II+, made by ITT) for plotting of either the raw signal, or the CAPL 25 coefficients as functions of the distance travelled, using a digital X-Y recorder (examples are presented in Appendix G). The computer also created copies of the cassette data files on flexible diskettes, to facilitate further analyses. Copies of these diskettes were used for the alternate analyses described in Appendix E and F, performed after the completion of the experiment.

APL 72 System

During testing in the APL 72 configuration, the signals were recorded on an analog FM tape recorder. Back in the laboratory, the tapes were played back, with the profile signal going into a bank of three electonic processors. (Six processors are used when two APL Trailers are towed together over both travelled wheeltracks.) Each processor passes the signal through an electronic bandpass filter, then squares and integrates the signal over a travelled distance of 200 m. The resulting three numerics (per wheeltrack) are the APL 72 coefficients, described in more detail in Appendix G.

The tapes were also played into a microcomputer (a European equivalent to the Apple II+ made by ITT) through an 8-bit (resolution = 0.35 mm) digitizer, sampling at 50 mm intervals for plotting purposes. Normally, the digitized data were plotted but not stored in digital form, since the routine analyses performed in Europe by LCPC use the analog signal. During the IRRE, a program was written on the microcomputer to edit and store these data on diskette, for the alternate processing of APL 72 signals described in Appendices E, F, and J.

After returning to France, the tapes were re-processed by LCPC to obtain complementary numerics and to validate the results provided by the LCPC team in Brazil. The analog tapes were loaned to the Belgian Road Research Center (CRR) for analyses there. At CRR, the analog signals were digitized at 1/3 m intervals, using equipment that processed 100 m sections. These digitized signals were used to prepare the CP numeric reported in Appendix G.

STATIC PROFILE MEASUREMENTS

Rod and Level Survey

The longitudinal profile of each wheeltrack was measured directly with the conventional rod and level method. In this measurement, a crew of three persons was used, as shown in Figure 3 in the report. A surveying level is used to establish a horizontal reference, and is operated by one of the crew members. One of the wheelpaths of the test site is marked and a surveyor's tape is placed on it to provide a simple distance reference. A second crew member holds the rod, marked in mm, on the tape at the appropriate distance. Sighting through the level, the first crew member calls out the reading from the rod (which is the difference in elevation between the level and the road surface where the rod is placed) to the third crew member, who writes the figure on a special coding. When possible, a fourth crew member was included. The members would rotate positions to reduce fatigue. In this experiment, elevations were measured at 500 mm intervals. It normally took about 3 - 1/2 hours for a trained crew to complete both wheeltracks of one of the 320 m long test sections.

All of the paved test sections were surveyed before the start of the experiment. During the experiment, many of the sections were re-surveyed. The second half of the experiment, covering unpaved sections, was scheduled such that all of the sections were surveyed before being measured by the other equipment. In all cases, the survey was performed no more that two days before the other equipment was run. At the end of the experiment, six wheelpaths were surveyed with a 100 mm interval. At various times throughout the project, there were from one to three crews operating simultaneously.

The field forms were checked back in the offices at GEIPOT, and submitted to keypunchers who entered the data into the GEIPOT computer system. There, the profile was computed, and checked for obvious errors. Further details about the procedures used are given in Reference [8].

All of the rod and level profiles were put on an IBM 9-track tape, and taken to UMTRI, where they were copied onto floppy diskettes for distribution to the other participants.

The TRRL Beam

The TRRL Beam is an experimental device developed by TRRL to measure longitudinal profile, with less effort than is needed with the rod and level surveying approach. A beam, 3 meters long, is supported at each end by a tripod with adjustable height, as shown in Figure 4 in the report. The beam acts as a track and guide for an instrumented sliding fixture, that contacts the ground via a 250 mm follower wheel. The sliding fixture contains a transducer that detects its position along the length of the beam, and a second transducer that detects the vertical position of the follower relative to the beam. The signals from these two transducers are fed to a microcomputer that digitizes the vertical position signal (resolution = 1.0 mm) at constant intervals.

The Beam is operated by placing each tripod on the endpoints of the three-meter section of track to be measured. One or both of the tripods are adjusted to level the beam. The sliding unit is moved to the "begin" end of the beam, and the instrumentation is activated. Then the sliding unit is moved to the "finish" end of the beam, at a normal walking pace, such that no bouncing of the follower wheel occurs. Then, the entire Beam assembly is picked up and relocated, such that the new "start" position of the first tripod coincides with the old "finish" position of the second tripod. The Beam is again levelled, and the process is repeated.

At the time that the experiment began, the Beam was still being tested and programmed in the UK. The Beam did not arrive in Brasilia until the experiment was nearly finished for the other equipment; therefore, the profile measures made with the Beam were not within the same 1 - 2 day time frame as the other measures. In all, 28 wheeltracks were profiled with the Beam, at the rate of about two per day.

The microcomputer used in the Beam was programmed to calculate two roughness measures and to store the profile at 100 mm intervals. Only the profile measures (relative to the Beam reference for each set-up) were validated by the TRRL team, and submitted as valid data. These measures were available only as paper printouts, and had to be typed into a computer system by hand for analysis. A program was written in Brasilia to allow rapid entry of the data into an Apple II+ computer, and the data for all 28 sections were entered in Brasilia by members of the GEIPOT staff. (Due to time limitations, some of the profiles were entered by the TRRL team in the UK using the same computer program, so that they could begin their analyses immediately.) With practice, it took slightly under two hours to enter all 3,200 data points for one wheeltrack. Once in the computer, another program was used to convert each set of 30 relative measurements corresponding to one Beam set-up to a continuous profile and check for errors.

APPENDIX B

DATA FROM THE RTRRMSs

This appendix presents all of the average rectified slope (ARS) measures that were gathered by response-type road roughness measuring systems (RTRRMSs) during the International Road Roughness Experiment (IRRE).

Summary of Measurements

All of the roadmeters used in the IRRE produce measurements that are equivalent, being the accumulation of suspension deflection of the host vehicle. Each instrument reports the measure in "counts," however, rather than a standard unit. To facilitate simple comparisons, all of the results have been converted to the same units, namely, "slope x 1000." The "slope" represents the accumulated suspension deflection (in both directions) divided by the distance travelled. This measure is dimensionally equivalent to the "Inches/Mile," "mm/km," and "counts/km" that are used by different agencies throughout the world, with the scaling differences clearly defined by the units. The factor of 1000 corresponds to the metric ratios: "m/km" and "mm/m." This particular scaling was selected for convenience in preparing tables and figures for this report: slope (m/m) values were too small, and slope x 1,000,000 (mm/km) figures were too large for fitting onto the tables and plot axes.

Tables B.1 - B.28 present the results for the RTRRMSs. The paved sections were divided into categories of asphaltic concrete and surface treatment types. The unpaved sections were split into groups with gravel and earth surfaces. These four surface types are abbreviated (based on their spelling in Portuguese) as CA, TS, GR, and TE, respectively. During testing, the car-based systems generally made five consecutive measurements for each section. These measures are listed as "RUN 1," "RUN 2," etc. The "B" listed under TRACK indicates that the vehicle travelled both the right- and left-hand tracks simultaneously during each run, and that the RTRRMS was a "two-track" type. The two single-track trailer instruments usually made three repeats in each of the two wheel-tracks. The track is indicated by an "R" or "L," for right or left.

The mean and standard deviation of the test results are listed under MEAN and SIGMA, while the relative error, defined by SIGMA/MEAN is listed under S/M. Although the testing procedure was intended to allow each vehicle to "warm up" prior to testing, the possibility exists that the shock absorbers or pneumatic tires had not reached steady-state temperature, and were changing during testing. To examine this possibility, a regression was performed between the measures and the run number for each test condition (site and speed). The slope of the regression equation, with units "slope x 1000/run," is reported under TREND, while the correlation coefficient is reported under R. These two columns allow one to determine, at a glance, whether or not the measures were consistently increasing or decreasing during testing for any condition.

Tables B.29 - B.32 summarize the results of all seven instruments, by presenting only the mean values. The data from the trailers are combined to yield the average of the two wheeltrack measures for each site, for comparison with the two-track RTRRMS measurements.

Discussion

Tables B.1 - B.28 indicate that, by and large, the repeatability of the instruments is better than 5% (S/M), with a repeatability of around 3% being typical for this test length of 320 m. Relative measurement error is larger on the smoothest sections, although in absolute units, the errors are still smaller than the errors on the rougher sections. In most cases, trends were very small, leading to the conclusion that the warm-up procedures used in the testing were adequate. However, there was concern that the warm-up was insufficient for the roughest surfaces, which show high R values. Some repeat tests were made with one of the Maysmeter systems on the roughest sections (GR11, GR12, TE05, and TE06) after the IRRE was complete, to ensure that steady-state conditions had been achieved. In each case, 12 or more consecutive measures were made. These results indicated that an absolute steady state was difficult to obtain, but that the results obtained earlier were representative. In practice, a true steady state may not exist for the extremely rough sections because the rough sections of the road are quite short. The best practice here is to use heavy-duty shock absorbers, selected for maximum damping and minimum sensitivity to temperature.

Tables B.29 - B.36 offer a direct comparison of the different RTRRMSs. A larger number for one system in comparison with another means that there was more response, either by the vehicle or by the meter. In most cases, the results of all five of the car-based systems are similar. As should be expected, the measures from the BI and the NAASRA meter, which were both mounted in the same vehicle, were usually redundant. These data are analyzed in Appendix C, in terms of correlation.

Table B.1. Summary of Results from Mays Meter #1 on the Asphaltic Concrete Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

MAYS METER #1

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
CA01	20	B	2.54	2.57	2.4	2.54	2.6	2.6	.09	.034	.027	.497
	32	B	3.13	3.33	3.17	3.13	3.16	2.84	.18	.057	-.1	-.886
	50	B	3.92	3.83	3.75	3.97	3.98	4.1	.14	.035	.078	.89
	80	B	4.29	4.19	4.25	4.29	4.25	4.44	.1	.022	.051	.843
CA02	20	B	3.26	3.19	3.27	3.33	3.17	3.32	.07	.022	.016	.348
	32	B	3.78	3.86	3.73	3.73	3.76	3.83	.06	.015	-3E-03	-.087
	50	B	4.32	4.16	4.35	4.3	4.37	4.41	.1	.023	.052	.852
	80	B	4.5	4.35	4.43	4.57	4.48	4.67	.12	.028	.068	.872
CA03	20	B	6.01	5.97	6.03	6	6.1	5.97	.05	9E-03	6E-03	.189
	32	B	6.12	6.05	6.19	6.08	6.13	6.18	.06	.01	.019	.495
	50	B	5.7	5.62	5.76	5.84	5.72	5.56	.11	.02	-.017	-.244
	80	B	6.18	6.16	6.18	6.08	6.27	6.19	.07	.011	.016	.368
CA04	20	B	5.34	5.21	5.29	5.37	5.45	5.4	.09	.018	.054	.905
	32	B	5.86	5.84	5.86	5.86	5.87	5.89	.02	3E-03	.011	.971
	50	B	5.98	5.78	5.91	6.03	6.13	6.05	.14	.023	.076	.878
	80	B	5.55	5.37	5.51	5.62	5.68	5.56	.12	.022	.056	.728
CA05	20	B	7.47	7.38	7.48	7.490	7.46	7.56	.06	8E-03	.033	.838
	32	B	7.27	7.25	7.19	7.41	7.33	7.16	.1	.014	-5E-03	-.072
	50	B	6.98	6.91	7.06	6.95	7.05	6.92	.07	.01	2E-03	.034
	80	B	6.5	6.29	6.51	6.59	6.48	6.64	.13	.021	.067	.784
CA06	20	B	7.77	7.7	7.78	7.84	7.72	7.79	.06	8E-03	.013	.342
	32	B	7.5	7.4	7.46	7.59	7.45	7.6	.09	.012	.04	.685
	50	B	7.43	7.33	7.35	7.46	7.48	7.52	.08	.011	.051	.965
	80	B	7.53	7.43	7.48	7.59	7.68	7.46	.11	.014	.027	.404
CA07	20	B	2.1	2.17	2.08	2.1	2.05		.05	.026	-.037	-.872
	32	B	2.11	2.17	2.08	2.1	2.03	2.16	.06	.028	-8E-03	-.214
	50	B	2.62	2.71	2.6	2.62	2.57	2.57	.06	.022	-.032	-.854
	80	B	3	3.1	3.03	2.98	2.97	2.92	.07	.022	-.041	-.983
CA08	20	B	2	1.94	2.02	2	2.06		.05	.026	.037	.899
	32	B	1.75	1.73	1.67	1.75	1.78	1.84	.06	.037	.033	.822
	50	B	2.31	2.3	2.4	2.25	2.27	2.3	.06	.024	-.013	-.362
	80	B	2.89	3.06	2.86	2.79	2.83	2.89	.11	.037	-.038	-.571
CA09	20	B	3.6	3.62	3.49	3.65	3.56	3.67	.07	.02	.016	.347
	32	B	3.47	3.35	3.49	3.46	3.51	3.52	.07	.02	.037	.828
	50	B	3.79	3.86	3.79	3.76	3.84	3.68	.07	.018	-.03	-.684
	80	B	4.25	4.35	4.27	4.18	4.21	4.24	.07	.016	-.029	-.675
CA10	20	B	2.81	2.71	2.81	2.86	2.87		.07	.025	.052	.947
	32	B	2.98	2.89	2.94	3	3.05	3.03	.07	.022	.04	.94
	50	B	3.44	3.4	3.4	3.49	3.44	3.44	.04	.012	.014	.567
	80	B	3.72	3.59	3.73	3.64	3.75	3.92	.13	.034	.068	.841
CA11	20	B	6.43	6.37	6.4	6.51	6.4	6.48	.06	9E-03	.022	.581
	32	B	6.72	6.78	6.73	6.65	6.76	6.7	.05	8E-03	-.013	-.394
	50	B	5.7	5.72	5.59	5.73	5.65	5.81	.08	.015	.025	.478
	80	B	5.95	5.84	5.95	6.03	5.91	6	.08	.013	.027	.563
CA12	20	B	1.23	1.32	1.24	1.16	1.25	1.16	.07	.055	-.03	-.704
	32	B	1.32	1.29	1.48	1.37	1.19	1.27	.11	.082	-.032	-.464
	50	B	1.26	1.17	1.37	1.35	1.29	1.13	.11	.084	-.017	-.261
	80	B	1.96	2	1.87	2.06	1.9	1.97	.08	.039	-3E-03	-.066
CA13	20	B	1.16	1.19	1.14	1.19	1.08	1.19	.05	.042	-6E-03	-.205
	32	B	1.14	1.1	1.24	1.17	1.08	1.13	.06	.056	-.01	-.234
	50	B	1.36	1.44	1.33	1.33	1.4	1.29	.06	.046	-.025	-.647
	80	B	2.09	1.92	2.21	2.06	2.22	2.03	.13	.06	.024	.298

Table B.2. Summary of Results from Mays Meter #1 on the Surface Treatment Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

MAYS METER #1

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
TS01	20	B	7.47	7.56	7.51	7.46	7.38	7.43	.07	9E-03	-.038	-.887
	32	B	5.72	5.72	5.65	5.64	5.75	5.86	.09	.016	.038	.678
	50	B	5.21	5.25	5.19	5.14	5.29	5.18	.06	.011	-6E-03	-.171
	80	B	6.14	6.18	6.21	6.1	6.08	6.16	.05	9E-03	-.016	-.466
TS02	20	B	9.39	9.45	9.35	9.38	9.48	9.29	.08	8E-03	-.019	-.397
	32	B	7.44	7.46	7.6	7.43	7.38	7.33	.1	.014	-.048	-.735
	50	B	5.62	5.57	5.64	5.43	5.7	5.75	.12	.022	.041	.528
	80	B	4.92	4.92	5.02	4.84	4.89	4.92	.06	.013	-.013	-.314
TS03	20	B	8.73	8.79	8.72	8.72	8.64	8.79	.07	8E-03	-8E-03	-.189
	32	B	7.68	7.6	7.68	7.72	7.640	7.75	.06	8E-03	.024	.65
	50	B	6.9	6.89	6.89	6.95	6.89	6.86	.03	5E-03	-6E-03	-.289
	80	B	5.9	5.84	5.89	5.86	5.97	5.92	.05	9E-03	.024	.739
TS04	20	B	8.17	8.22	8.1	8.25	8.19	8.1	.07	9E-03	-.016	-.343
	32	B	7.85	8.08	7.91	7.79	7.640	7.84	.16	.021	-.075	-.728
	50	B	6.33	6.16	6.21	6.35	6.48	6.48	.15	.023	.09	.966
	80	B	7.890	7.79	7.94	7.87	7.95	7.91	.06	8E-03	.024	.599
TS05	20	B	9.47	9.37	9.41	9.51	9.49	9.59	.09	9E-03	.052	.957
	32	B	8.53	8.43	8.56	8.59	8.57	8.49	.07	8E-03	.014	.343
	50	B	7.05	6.92	7.05	6.98	7	7.3	.15	.021	.071	.766
	80	B	9.58	9.4	9.54	9.68	9.6	9.65	.11	.012	.057	.799
TS06	20	B	4.69	4.81	4.67	4.71	4.64	4.6	.08	.017	-.044	-.873
	32	B	3.84	3.84	3.84	3.84	3.83	3.84	.01	2E-03	-2E-03	-.354
	50	B	3.48	3.54	3.57	3.4	3.48	3.4	.08	.023	-.038	-.751
	80	B	3.22	3.41	3.32	3.03	3.22	3.11	.15	.048	-.07	-.721
TS07	20	B	3.9	4.05	3.89	3.83	3.89	3.86	.09	.022	-.038	-.702
	32	B	3.72	3.75	3.91	3.73	3.64	3.59	.12	.033	-.059	-.76
	50	B	3.41	3.44	3.4	3.4	3.32	3.48	.06	.018	-2E-03	-.042
	80	B	3.14	3.17	3	3.17	3.1	3.25	.1	.031	.025	.418
TS08	20	B	5.36	5.51	5.32	5.4	5.24	5.35	.1	.019	-.04	-.627
	32	B	4.51	4.81	4.48	4.44	4.51	4.32	.18	.04	-.095	-.828
	50	B	3.38	3.4	3.25	3.37	3.38	3.51	.09	.027	.035	.61
	80	B	3.74	3.62	3.81	3.78	3.67	3.81	.09	.024	.024	.427
TS09	20	B	5.6	5.65	5.72	5.62	5.48	5.56	.09	.016	-.043	-.743
	32	B	5.25	5.41	5.3	5.11	5.19	5.21	.12	.022	-.052	-.715
	50	B	5.05	4.92	4.92	4.71	4.78	5.92	.49	.098	.186	.594
	80	B	3.93	3.91	4.03	3.89	3.94	3.87	.06	.016	-.016	-.398
TS10	20	B	5.85	5.79	5.89	5.79	6	5.75	.1	.017	2E-03	.025
	32	B	5.15	4.94	5.24	5.19	5.24	5.14	.13	.024	.041	.521
	50	B	4.66	4.7	4.76	4.62	4.57	4.65	.07	.016	-.029	-.617
	80	B	4	3.95	3.98	4.13	3.91	4.03	.08	.021	8E-03	.148
TS11	20	B	3.71	3.76	3.71	3.79	3.68	3.6	.07	.02	-.035	-.747
	32	B	3.11	2.89	3.1	3.22	3.11	3.25	.14	.046	.075	.822
	50	B	2.34	2.32	2.41	2.29	2.3	2.37	.05	.022	-2E-03	-.048
	80	B	2.82	2.78	2.86	2.75	2.79	2.92	.07	.025	.022	.504
TS12	20	B	3.67	3.65	3.59	3.67	3.71	3.75	.06	.017	.032	.822
	32	B	3.15	3.1	3.17	3.24	3.14	3.11	.06	.018	0	0
	50	B	2.43	2.44	2.37	2.37	2.35	2.64	.12	.049	.037	.483
	80	B	2.79	2.7	2.83	2.76	2.79	2.87	.07	.024	.032	.762

Table B.3. Summary of Results from Mays Meter #1 on the Gravel Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

MAYS METER#1

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/N	TREND	R
GR01	20	B	3.81	3.95	3.75	3.86	3.78	3.73	.09	.024	-.041	-.708
	32	B	3.68	3.7	3.67	3.68	3.75	3.62	.05	.013	-8E-03	-.271
	50	B	2.8	2.76	2.91	2.87	2.83	2.64	.11	.038	-.033	-.493
	80	B	3.28	3.41	3.33	3.16	3.19	3.3	.1	.032	-.037	-.553
GR02	20	B	4.12	4.08	4.14	4.05	4.19	4.14	.06	.014	.017	.486
	32	B	3.9	3.89	3.95	3.84	3.78	4.03	.1	.025	.011	.179
	50	B	3.25	3.24	3.32	3.35	3.21	3.16	.08	.024	-.027	-.543
	80	B	3.17	3.16	3.27	3.21	3.14	3.1	.07	.021	-.025	-.605
GR03	20	B	10.23	10.29	10.21	10.18	10.26	10.22	.04	4E-03	-8E-03	-.293
	32	B	8.7	8.65	8.81	8.64	8.73	8.68	.07	8E-03	-2E-03	-.036
	50	B	7.490	7.48	7.51	7.45	7.54	7.490	.04	5E-03	6E-03	.283
	80	B	6.58	6.48	6.62	6.490	6.54	6.75	.11	.017	.046	.657
GR04	20	B	8.14	8.11	8.19	8.25	8.08	8.08	.08	9E-03	-.017	-.359
	32	B	7.25	7.27	7.16	7.3	7.32	7.21	.07	9E-03	3E-03	.075
	50	B	6.45	6.41	6.54	6.52	6.43	6.32	.09	.014	-.03	-.527
	80	B	5.73	5.76	5.68	5.75	5.79	5.65	.06	.01	-.011	-.299
GR05	20	B	13.4	12.64	13.51	13.64	13.49	13.73	.44	.033	.217	.784
	32	B	12.71	12.73	12.62	12.54	12.7	12.95	.16	.012	.052	.533
	50	B	11.15	11.53	11.06	10.94	11.26	10.95	.25	.022	-.095	-.611
	80	B	10.79	10.65	10.94	10.76	10.78	10.83	.1	.01	.019	.29
GR06	20	B	12.34	12.45	12.32	12.41	12.37	12.18	.11	9E-03	-.049	-.736
	32	B	11.12	11.13	11.06	11.26	10.94	11.19	.12	.011	0	0
	50	B	10.13	10.18	9.99	10.32	10.19	10	.14	.014	-.014	-.161
	80	B	9.25	8.72	9.54	9.33	9.4	9.27	.32	.034	.097	.484
GR07	20	B	8.52	9.08	8.43	8.46	8.29	8.32	.32	.038	-.167	-.813
	32	B	7.640	7.75	7.6	7.68	7.38	7.78	.16	.021	-.016	-.158
	50	B	6.79	6.97	6.68	6.64	6.75	6.92	.15	.022	-3E-03	-.034
	80	B	5.91	5.95	5.84	5.7	5.86	6.21	.19	.032	.052	.44
GR08	20	B	5.76	5.95	5.73	5.86	5.65	5.6	.14	.025	-.078	-.849
	32	B	4.89	5.59	4.95	4.95	4.89	4.06	.54	.111	-.311	-.907
	50	B	4.28	4.27	4.27	4.19	4.32	4.37	.06	.015	.024	.58
	80	B	4.04	3.94	3.92	3.97	4.22	4.13	.13	.033	.068	.811
GR09	20	B	12.27	12.05	12.3	12.4	12.29	12.3	.13	.011	.049	.598
	32	B	10.88	10.91	10.65	10.92	11.03	10.91	.14	.013	.038	.43
	50	B	9.53	9.26	9.64	9.91	9.21	9.67	.3	.031	.04	.212
	80	B	9.19	8.97	10.14	8.94	9.21	8.72	.56	.061	-.144	-.409
GR10	20	B	9.48	9.46	9.76	9.43	9.27	9.46	.18	.019	-.049	-.437
	32	B	8.58	8.59	8.6	8.72	8.57	8.4	.11	.013	-.041	-.572
	50	B	7.57	7.48	7.65	7.51	7.59	7.62	.07	.01	.022	.475
	80	B	8.36	8.3	8.16	8.35	8.43	8.54	.14	.017	.075	.829
GR11	20	B	21.73	21.61	21.75	21.84	21.88	21.57	.14	6E-03	6E-03	.074
	32	B	26.92	27.05	26.81	26.94	27.13	26.69	.18	7E-03	-.041	-.365
	50	B	18.57	18.11	18.32	18.73	18.89	18.81	.34	.018	.197	.919
GR12	20	B	24.3	23.83	23.65	23.84	24.92	25.26	.73	.03	.413	.89
	32	B	18.15	17.99	18.13	18.24	18.1	18.27	.12	6E-03	.054	.742
	50	B	17.01	16.81	16.53	17.05	17.18	17.46	.36	.021	.195	.867

Table B.4. Summary of Results from Mays Meter #1 on the Earth Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

MAYS METER #1

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
TE01	20	B	6.67	6.54	6.67	6.56	6.73	6.84	.13	.019	.067	.84
	32	B	5.26	5.19	5.14	5.16	5.24	5.57	.18	.034	.086	.763
	50	B	4.39	4.38	4.35	4.33	4.46	4.43	.05	.012	.021	.611
	80	B	4.19	4.29	4.21	4.21	4.08		.09	.02	-.062	-.936
TE02	20	B	6.44	6.6	6.4	6.3	6.35	6.56	.13	.02	-.014	-.172
	32	B	5.09	4.87	5.24	5.18	5.1	5.06	.14	.027	.024	.272
	50	B	4.07	4.06	3.92	3.98	4.19	4.21	.13	.031	.056	.701
	80	B	3.98	3.95	4.06	3.91	4.02		.07	.018	3E-03	.059
TE03	20	B	12.6	12.41	12.86	12.46	12.73	12.54	.19	.015	.013	.107
	32	B	11.11	11.18	11.02	11.13	11.08	11.14	.06	6E-03	0	0
	50	B	8.3	8.19	8.19	8.38	8.41	8.33	.11	.013	.051	.763
	80	B	7.02	6.91	6.91	7.05	7.08	7.14	.11	.015	.065	.961
TE04	20	B	13.05	13.02	12.67	13.14	13.16	13.24	.23	.017	.094	.656
	32	B	11.24	11.24	11.35	11.11	11.18	11.32	.1	9E-03	-2E-03	-.025
	50	B	8.6	8.59	8.46	8.64	8.73	8.57	.1	.011	.024	.383
	80	B	6.76	6.64	6.73	6.83	6.76	6.86	.09	.013	.048	.866
TE05	20	B	19.09	19.02	19.05	19.13	19.18	19.07	.06	3E-03	.022	.548
	32	B	15.79	14.16	16.13	16.26	16.22	16.18	.91	.058	.413	.716
	50	B	14.75	14.6	14.78	14.7	14.76	14.89	.11	7E-03	.056	.834
TE07	20	B	4.03	3.91	4.06	3.89	4.13	4.16	.13	.031	.057	.722
	32	B	5.11	5.05	5.14	5.18	5.05	5.11	.06	.011	3E-03	.088
	50	B	5.31	5.35	5.22	5.37	5.45	5.16	.12	.022	-.016	-.218
	80	B	3.5	4.33	3.33	3.24	3.32	3.27	.47	.134	-.214	-.724
TE08	20	B	4.85	4.83	4.91	5.03	4.75	4.76	.12	.024	-.029	-.385
	32	B	5.77	5.6	5.78	5.79	5.86	5.83	.1	.017	.052	.838
	50	B	5.56	5.64	5.68	5.62	5.54	5.32	.14	.026	-.078	-.852
	80	B	3.91	4.16	3.97	3.73	3.81	3.86	.17	.043	-.076	-.725
TE09	20	B	12.41	12.43	12.29	12.51	12.27	12.54	.12	.01	.021	.263
	32	B	10.92	10.97	10.8	10.92	10.99	10.91	.07	7E-03	6E-03	.134
	50	B	8.84	8.83	8.73	8.83	8.87	8.92	.07	8E-03	.033	.746
	80	B	5.06	5.6	5.46	5.14	3.79	5.3	.73	.144	-.227	-.492
TE10	20	B	17.77	17.91	18.03	17.84	17.76	17.29	.29	.016	-.151	-.835
	32	B	14.4	14.65	14.26	14.02	14.49	14.59	.26	.018	.011	.067
	50	B	12.23	12.29	12.13	12.21	12.32	12.19	.08	6E-03	0	0
	80	B	7.68	7.78	7.68	7.62	7.54	7.76	.1	.013	-.017	-.277
TE11	20	B	19.6	19.59	19.68	19.56	19.67	19.49	.08	4E-03	-.021	-.413
	32	B	16.6	16.68	16.51	16.48	16.67	16.64	.09	6E-03	6E-03	.106
	50	B	11.34	11.35	11.21	11.4	11.41	11.33	.08	7E-03	.017	.339
	80	B	10.9	10.95	10.86	10.92	10.83	10.95	.06	5E-03	-3E-03	-.087
TE12	20	B	15.92	15.81	16	15.87	16.08	15.84	.11	7E-03	.014	.197
	32	B	14.12	14.16	13.64	14.18	14.29	14.34	.28	.02	.1	.565
	50	B	9.99	10.02	10.16	9.84	9.95	9.99	.11	.011	-.027	-.372
	80	B	9.16	9.37	9.05	9.06	9.24	9.1	.14	.015	-.035	-.405

Table B.5. Summary of Results from Mays Meter #2 on the Asphaltic Concrete Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

MAYS METER #2

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
CA01	20	B	2.56	2.71	2.37	2.19	2.73	2.79	.27	.104	.052	.312
	32	B	3.68	4.06	3.43	3.64	3.41	3.86	.28	.076	-.043	-.241
	50	B	5.03	4.84	5.11	5.06	5	5.13	.12	.023	.046	.629
	80	B	4.91	4.43	4.83	5.08	5.13	5.11	.3	.061	.167	.885
CA02	20	B	3.8	3.84	3.91	3.4	3.97	3.91	.23	.061	.019	.13
	32	B	4.53	5.1	4.3	4.4	4.29	4.56	.34	.074	-.11	-.516
	50	B	5.11	5	5.14	5.03	5.16	5.19	.08	.016	.04	.75
	80	B	5.16	4.76	5.21	5.24	5.24	5.33	.23	.044	.117	.825
CA03	20	B	6.57	6.4	6.73	6.89	6.46	6.38	.23	.034	-.03	-.211
	32	B	7.37	7.18	7.45	7.27	7.27	7.68	.2	.027	.084	.662
	50	B	7.45	7.37	7.33	7.51	7.57	7.490	.1	.014	.049	.772
	80	B	7.78	7.19	7.56	7.91	8.14	8.08	.4	.051	.237	.939
CA04	20	B	5.95	6.21	5.97	5.62	5.94	6	.21	.035	-.044	-.333
	32	B	6.91	6.59	6.91	6.65	7.03	7.35	.31	.045	.165	.848
	50	B	7.11	6.81	7.11	7.18	7.240	7.22	.18	.025	.095	.857
	80	B	6.32	5.87	6.29	6.38	6.67	6.4	.29	.045	.143	.785
CA05	20	B	7.75	7.67	7.67	7.56	7.94	7.91	.17	.021	.075	.71
	32	B	8.32	8.67	8.27	8.08	8.3	8.25	.22	.026	-.079	-.583
	50	B	5.21	4.83	5.14	5.45	5.35	5.3	.24	.047	.116	.756
	80	B	7.68	7.16	7.72	7.75	7.92	7.87	.31	.04	.164	.847
CA06	20	B	8.79	8.97	8.54	8.62	8.95	8.87	.2	.023	.022	.177
	32	B	9.26	9.6	9.06	9.03	9.48	9.13	.26	.028	-.054	-.327
	50	B	8.72	8.59	8.79	8.76	8.72	8.75	.08	9E-03	.024	.472
	80	B	9.32	8.81	9.11	9.56	9.64	9.51	.35	.038	.192	.864
CA07	20	B	2.16	2.57	2.16	2	2.1	1.95	.25	.114	-.13	-.837
	32	B	2.36	2.41	2.19	2.35	2.56	2.27	.14	.059	8E-03	.09
	50	B	2.72	2.75	2.71	2.79	2.64	2.71	.06	.021	-.014	-.39
	80	B	2.85	2.71	2.94	2.87	2.83	2.89	.08	.03	.024	.446
CA08	20	B	1.78	1.89	1.83	1.59	1.76	1.84	.12	.066	-.016	-.214
	32	B	1.71	1.52	1.57	1.73	1.83	1.9	.16	.095	.102	.989
	50	B	2.31	2.32	2.3	2.3	2.3	2.3	.01	3E-03	-3E-03	-.707
	80	B	2.87	2.78	2.71	2.89	2.97	2.98	.12	.041	.067	.893
CA09	20	B	3.65	3.95	3.52	3.6	3.68	3.51	.18	.049	-.073	-.639
	32	B	3.78	3.75	3.81	3.86	3.75	3.71	.06	.015	-.013	-.348
	50	B	3.98	4	3.92	3.97	4.02	3.98	.04	9E-03	6E-03	.275
	80	B	4.29	4.18	4.11	4.41	4.29	4.48	.15	.036	.078	.798
CA10	20	B	2.91	2.92	2.92	2.86	2.89	2.98	.05	.016	.01	.32
	32	B	3.48	3.57	3.38	3.59	3.51	3.35	.11	.031	-.032	-.46
	50	B	3.88	3.87	3.81	3.86	3.91	3.97	.06	.015	.029	.766
	80	B	3.95	3.86	3.91	3.86	3.98	4.13	.11	.029	.062	.861
CA11	20	B	6.66	6.59	6.67	6.73	6.490	6.84	.13	.02	.033	.395
	32	B	7.03	6.89	6.87	7.21	7.18	7	.16	.022	.052	.531
	50	B	6.21	6.08	6.11	6.14	6.32	6.38	.13	.022	.081	.954
	80	B	6.45	6.35	6.27	6.54	6.46	6.62	.14	.022	.073	.82
CA12	20	B	.8	.9	.9	.71	.75	.75	.09	.117	-.048	-.804
	32	B	1.22	1.11	1.49	1.1	1.06	1.33	.19	.153	2E-03	.013
	50	B	1.3	1.25	1.32	1.22	1.38	1.32	.06	.048	.019	.487
	80	B	1.46	1.35	1.44	1.43	1.59	1.48	.09	.059	.04	.725
CA13	20	B	1.11	1.21	1.19	.92	1.02	1.22	.14	.122	-.014	-.167
	32	B	1.38	1.33	1.49	1.14	1.48	1.44	.15	.105	.021	.225
	50	B	1.31	1.25	1.3	1.33	1.35	1.33	.04	.029	.021	.861
	80	B	1.72	1.67	1.64	1.83	1.67	1.79	.09	.05	.029	.527

Table B.6. Summary of Results from Mays Meter #2 on the Surface Treatment Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

MAYS METER #2

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
TS01	20	B	7.69	7.29	7.48	7.67	7.890	8.130	.33	.043	.21	.999
	32	B	6.22	6.03	6.14	6.16	6.3	6.45	.16	.026	.098	.974
	50	B	5.46	5.41	5.54	5.41	5.37	5.59	.09	.017	.017	.291
	80	B	7.01	6.56	6.91	7.16	7.18	7.25	.29	.041	.167	.923
TS02	20	B	9.83	9.64	9.86	9.99	9.89	9.76	.13	.014	.029	.34
	32	B	8.39	8.43	8.03	8.38	8.38	8.72	.24	.029	.092	.6
	50	B	6.63	6.75	6.67	6.41	6.67	6.64	.13	.019	-.022	-.279
	80	B	5.52	5.48	5.33	5.57	5.57	5.64	.12	.021	.056	.748
TS03	20	B	9.56	9.21	9.67	9.7	9.54	9.7	.21	.022	.086	.648
	32	B	8.28	7.76	8.37	8.38	8.45	8.45	.29	.035	.144	.783
	50	B	7.78	7.59	7.91	7.81	7.79	7.81	.12	.015	.033	.451
	80	B	7.1	6.76	7.02	7.19	7.18	7.35	.22	.031	.133	.949
TS04	20	B	8.25	8.25	8.19	8.14	8.45	8.24	.12	.014	.022	.306
	32	B	8.43	8.48	8.6	8.32	8.45	8.3	.12	.015	-.051	-.648
	50	B	6.86	6.4	6.87	6.86	7.02	7.16	.29	.042	.167	.92
	80	B	9.23	8.6	9.33	9.18	9.41	9.64	.39	.042	.214	.872
TS05	20	B	10.66	11.08	10.37	10.41	10.6	10.86	.3	.028	-.021	-.108
	32	B	9.44	9.64	9.08	9.51	9.46	9.49	.21	.022	.01	.072
	50	B	7.72	7.56	7.59	7.76	7.79	7.92	.15	.02	.094	.976
	80	B	11.72	10.94	11.89	11.89	12	11.89	.44	.038	.202	.723
TS06	20	B	4.64	4.54	4.6	4.81	4.78	4.46	.15	.033	2E-03	.017
	32	B	4.22	4.19	4.3	4.05	4.24	4.32	.11	.026	.019	.278
	50	B	3.42	3.52	3.29	3.48	3.48	3.33	.1	.03	-.019	-.292
	80	B	3.11	3.3	2.84	3.33	2.98	3.11	.21	.067	-.024	-.18
TS07	20	B	3.97	3.98	4.06	4.03	3.79	3.95	.1	.026	-.033	-.502
	32	B	4.25	4.03	4.32	4.3	4.35	4.24	.13	.03	.044	.552
	50	B	3.61	3.76	3.62	3.54	3.48	3.65	.11	.03	-.037	-.529
	80	B	3.3	3.35	3.13	3.38	3.27	3.35	.1	.031	.014	.22
TS08	20	B	5.61	5.62	5.54	5.6	5.75	5.52	.09	.016	2E-03	.029
	32	B	4.65	4.6	4.52	4.81	4.79	4.54	.14	.03	.014	.164
	50	B	3.8	4.03	3.67	3.71	3.73	3.87	.15	.039	-.025	-.269
	80	B	4.08	4.06	4	4.11	4.11	4.11	.05	.012	.021	.667
TS09	20	B	5.89	5.51	5.78	6.11	5.95	6.08	.25	.042	.132	.838
	32	B	5.6	5.46	5.67	5.72	5.67	5.49	.12	.021	6E-03	.087
	50	B	5.21	5.06	5.16	5.25	5.3	5.27	.1	.019	.056	.901
	80	B	4.56	4.56	4.52	4.59	4.43	4.7	.1	.022	.019	.307
TS10	20	B	6.06	6.22	5.92	5.95	5.92	6.27	.17	.029	.01	.087
	32	B	5.61	5.49	5.43	5.6	5.68	5.86	.17	.03	.098	.925
	50	B	5.3	5.32	5.21	5.57	5.06	5.35	.19	.035	-8E-03	-.067
	80	B	4.72	4.6	4.67	4.91	4.68	4.75	.11	.024	.03	.415
TS11	20	B	3.57	3.49	3.83	3.41	3.7	3.43	.18	.051	-.025	-.221
	32	B	3.2	3.06	3.11	3.33	3.19	3.29	.11	.036	.052	.728
	50	B	2.51	2.64	2.6	2.32	2.52	2.44	.13	.051	-.046	-.568
	80	B	2.32	2.11	2.4	2.3	2.43	2.35	.12	.054	.051	.643
TS12	20	B	3.47	3.46	3.59	3.59	3.37	3.35	.12	.033	-.044	-.609
	32	B	3.44	3.24	3.62	3.54	3.48	3.3	.16	.047	-2E-03	-.016
	50	B	2.38	2.46	2.37	2.29	2.43	2.37	.07	.028	-.013	-.298
	80	B	2.44	2.46	2.48	2.38	2.46	2.41	.04	.016	-.011	-.441

Table B.7. Summary of Results from Mays Meter #2 on the Gravel Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

MAYS METER #2

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
GR01	20	B	3.72	3.73	3.57	3.79	3.79	3.73	.09	.024	.022	.387
	32	B	3.58	3.65	3.79	3.46	3.46	3.52	.14	.04	-.059	-.647
	50	B	3.24	3.24	3.1	3.3	3.43	3.14	.13	.041	.014	.171
	80	B	2.86	2.75	3.06	2.78	2.92	2.81	.13	.045	-2E-03	-.019
GR02	20	B	4.47	4.56	4.06	4.54	4.56	4.65	.23	.052	.068	.463
	32	B	3.76	4	3.52	3.68	3.91	3.67	.19	.051	-.029	-.234
	50	B	3.33	3.33	3.24	3.33	3.38	3.38	.06	.017	.024	.645
	80	B	3.52	3.49	3.51	3.46	3.7	3.43	.11	.03	6E-03	.095
GR03	20	B	11.4	11.65	11.03	11.26	11.41	11.65	.27	.023	.038	.226
	32	B	9.94	9.65	9.95	9.87	10.02	10.21	.2	.02	.117	.914
	50	B	8.85	8.7	8.68	8.95	8.97	8.92	.14	.016	.073	.815
	80	B	8.11	7.79	8.21	8.14	8.25	8.16	.18	.023	.078	.673
GR04	20	B	9.36	9.52	9.35	9.24	9.4	9.29	.11	.012	-.043	-.614
	32	B	7.9	7.62	7.97	7.91	7.94	8.06	.17	.021	.086	.811
	50	B	7.54	7.32	7.490	7.41	7.640	7.84	.2	.027	.119	.919
	80	B	6.52	6.38	6.45	6.52	6.59	6.67	.11	.017	.071	.999
GR05	20	B	15.42	15.51	15.26	15.4	15.64	15.29	.16	.01	-6E-03	-.064
	32	B	15.17	15.56	14.78	15.26	15.03	15.24	.29	.019	-.038	-.209
	50	B	13.71	13.48	13.7	13.87	13.49	14	.23	.017	.084	.576
	80	B	12.77	12.32	12.08	13.02	13.18	13.26	.53	.042	.297	.879
GR06	20	B	13.39	13.43	13.53	13.56	13.3	13.13	.18	.013	-.083	-.742
	32	B	12.96	12.97	12.89	12.75	13.35	12.84	.23	.018	.021	.14
	50	B	11.69	11.54	11.8	11.75	11.67	11.7	.1	8E-03	.019	.313
	80	B	10.8	10.72	10.27	11.05	10.75	11.22	.36	.034	.149	.648
GR07	20	B	8.22	8.06	8.25	8.51	7.91	8.35	.24	.029	.022	.148
	32	B	7.490	7.6	7.59	7.52	7.41	7.32	.12	.016	-.075	-.97
	50	B	7.18	7.03	7.02	7.22	7.3	7.3	.14	.02	.083	.922
	80	B	6.39	6.14	6.35	6.64	6.33	6.490	.18	.029	.068	.585
GR08	20	B	5.47	5.73	5.45	5.45	5.32	5.41	.15	.028	-.076	-.779
	32	B	4.95	4.87	4.98	5.08	4.91	4.92	.08	.016	2E-03	.031
	50	B	4.35	4.27	4.4	4.14	4.48	4.48	.14	.033	.049	.539
	80	B	4.08	3.97	4.05	3.95	4.18	4.25	.13	.032	.07	.841
GR09	20	B	12.18	12.11	12	12	12.24	12.56	.23	.019	.113	.77
	32	B	10.71	10.78	10.49	10.64	10.78	10.86	.14	.014	.044	.485
	50	B	10	9.94	9.51	10.14	10.21	10.19	.29	.029	.121	.649
	80	B	11.05	10.38	10.92	11.51	11.21	11.24	.43	.039	.2	.738
GR10	20	B	10.09	9.94	10.22	10.14	10.16	9.97	.13	.012	0	0
	32	B	8.87	8.7	8.89	9.3	8.7	8.76	.25	.029	-6E-03	-.04
	50	B	8.68	8.62	8.72	8.62	8.67	8.76	.06	7E-03	.024	.606
	80	B	9.64	9.16	9.48	9.84	9.95	9.78	.32	.033	.171	.841
GR11	20	B	18.65	19.35	18.54	18.68	18.29	18.38	.42	.023	-.219	-.824
	32	B	19.59	19.27	19.76	19.45	19.83	19.64	.23	.012	.079	.547
	50	B	20.31	20	20.16	20.45	20.78	20.18	.31	.015	.097	.501
GR12	20	B	20.21	20.65	20.43	19.88	20.21	19.89	.34	.017	-.175	-.815
	32	B	21.62	21.49	21.37	21.81	22.05	21.35	.31	.014	.04	.205
	50	B	19.58	18.8	19.78	19.61	19.57	20.15	.49	.025	.249	.798

Table B.8. Summary of Results from Mays Meter #2 on the Earth Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

MAYS METER #2

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
TE01	20	B	7.54	7.48	7.65	7.72	7.27	7.6	.18	.023	-.013	-.114
	32	B	5.96	5.65	6.05	5.87	6.02	6.21	.21	.035	.108	.817
	50	B	4.88	4.46	4.62	4.98	5.14	5.18	.32	.066	.195	.963
	80	B	4.49	4.16	4.59	4.57	4.46	4.67	.2	.044	.089	.707
TE02	20	B	7.12	7.11	7.3	7.29	6.89	6.98	.18	.026	-.067	-.58
	32	B	5.76	5.52	5.65	5.76	5.89	5.95	.17	.03	.11	.995
	50	B	4.31	4.02	4.32	4.22	4.44	4.52	.2	.046	.114	.909
	80	B	4.13	3.73	4.02	4.13	4.35	4.41	.27	.066	.17	.979
TE03	20	B	14.04	14.35	14.45	13.75	14.1	13.57	.38	.027	-.191	-.799
	32	B	12.77	12.59	12.68	12.56	13.18	12.83	.25	.02	.097	.608
	50	B	9.26	8.87	9.22	9.18	9.19	9.84	.35	.038	.191	.851
	80	B	8.25	7.97	7.91	8.32	8.46	8.57	.3	.036	.176	.941
TE04	20	B	14.67	15.03	14.65	14.4	14.75	14.53	.24	.016	-.092	-.603
	32	B	12.91	12.76	13.02	12.67	12.97	13.14	.19	.015	.071	.583
	50	B	10.07	9.64	9.84	10.02	10	10.84	.46	.046	.257	.885
	80	B	8.35	7.91	8.29	8.49	8.43	8.62	.27	.033	.157	.906
TE05	20	B	26.88	27.81	26.81	26.43	26.5	26.83	.55	.021	-.229	-.653
	32	B	23.88	22.42	23.43	23.88	24.83	24.84	1.02	.043	.625	.968
	50	B	20.55	19.94	20.67	20.34	20.97	20.81	.41	.02	.205	.786
TE06	20	B	33.45	34.08	33.5	32.75	33.04	33.89	.56	.017	-.084	-.237
	32	B	29.46	27.8	28.8	29.62	30.58	30.53	1.18	.04	.724	.966
	50	B	25.7	24.78	25.54	25.86	26.21	26.11	.58	.022	.333	.915
TE07	20	B	7.61	7.29	7.57	7.79	7.6	7.78	.21	.027	.102	.783
	32	B	7.06	6.98	7.16	7.05	7.16	6.95	.1	.014	-6E-03	-.104
	50	B	5.92	5.51	5.94	6.02	6.02	6.13	.24	.041	.132	.866
	80	B	5.37	5.38	5.3	5.38	5.38	5.38	.04	7E-03	8E-03	.354
TE08	20	B	8.41	8.180	8.19	8.68	8.32	8.67	.25	.03	.111	.7
	32	B	7.54	7.45	7.46	7.67	7.52	7.6	.09	.013	.038	.637
	50	B	6.12	5.57	5.89	6.24	6.46	6.45	.38	.063	.232	.955
	80	B	5.61	5.43	5.57	5.81	5.54	5.68	.15	.026	.048	.518
TE09	20	B	16.13	15.45	16.1	16	16.51	16.59	.46	.028	.27	.931
	32	B	12.76	12.7	12.21	12.54	13.14	13.22	.42	.033	.198	.74
	50	B	9.19	8.68	8.72	9.52	9.45	9.56	.45	.048	.248	.879
	80	B	8.36	7.890	8.24	8.49	8.56	8.62	.3	.036	.178	.938
TE10	20	B	22.23	21.54	22.27	22.46	22.19	22.65	.42	.019	.214	.804
	32	B	17.7	17.41	17.7	17.89	17.89	17.61	.2	.011	.057	.447
	50	B	12.87	12.24	12.21	13.41	13.16	13.32	.6	.046	.311	.826
	80	B	11.25	11.26	11.19	11.51	11.19	11.1	.16	.014	-.032	-.321
TE11	20	B	21.13	21.07	21.11	20.78	21.43	21.26	.24	.011	.07	.457
	32	B	17.22	16.64	16.94	17.67	17.4	17.48	.42	.025	.214	.799
	50	B	12.36	12	12.3	12.62	12.18	12.7	.3	.024	.127	.68
	80	B	10.79	10.48	10.57	10.76	11.05	11.1	.28	.026	.171	.979
TE12	20	B	16.91	16.41	17.07	17.03	17.07	16.97	.28	.017	.111	.628
	32	B	14.62	14.54	14.99	14.29	14.73	14.56	.26	.018	-.022	-.136
	50	B	10.74	10.4	10.46	10.78	10.97	11.08	.3	.028	.187	.981
	80	B	9.89	10.13	9.79	9.6	10.18	9.76	.25	.025	-.035	-.223

Table B.9. Summary of Results from Mays Meter #3 on the Asphaltic Concrete Roads.

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
CA01	20	B	2.65	2.64	2.22	2.54	2.83	3.05	.31	.117	.143	.729
	32	B	3.83	3.91	3.84	3.68	3.97	3.75	.12	.03	-.019	-.26
	50	B	5.55	5.4	5.46	5.49	5.78	5.62	.15	.027	.076	.796
	80	B	5.19	4.95	5.27	5.43	5.05	5.24	.19	.036	.035	.293
CA02	20	B	3.98	4.06	3.91	3.84	3.87	4.22	.16	.04	.029	.283
	32	B	4.11	4.32	4.19	4.06	4.13	3.84	.18	.043	-.102	-.912
	50	B	5.4	5.46	5.68	5.37	5.46	5.05	.23	.043	-.105	-.719
	80	B	5.11	4.64	5.18	4.95	5.33	5.43	.32	.062	.175	.867
CA03	20	B	6.64	6.76	6.89	6.51	6.6	6.45	.18	.028	-.092	-.796
	32	B	4.94	4.98	4.92	4.89	4.83	5.08	.1	.02	.01	.156
	50	B	6.17	6.22	6.51	5.87	6.29	5.97	.25	.041	-.073	-.454
	80	B	6	5.56	5.68	5.68	6.73	6.35	.51	.086	.264	.812
CA04	20	B	5.98	5.52	6.06	6.35	5.91	6.03	.3	.05	.086	.452
	32	B	6.54	6.45	6.7	6.16	6.6	6.79	.25	.038	.06	.383
	50	B	6.740	6.83	6.7	6.67	6.54	6.98	.17	.025	.016	.149
	80	B	5.74	5.37	5.21	6.06	6.1	5.97	.42	.073	.21	.787
CA05	20	B	7.59	7.27	7.91	7.97	7.68	7.11	.38	.05	-.054	-.224
	32	B	6.76	6.48	6.6	6.86	6.7	7.14	.26	.038	.143	.878
	50	B	7.63	7.240	7.37	7.59	7.94	8	.34	.044	.21	.981
	80	B	6.65	6.41	6.57	6.92	7.11	6.22	.36	.055	.016	.069
CA06	20	B	8.74	8.73	8.45	8.92	8.92	8.7	.2	.022	.041	.332
	32	B	8.62	8.67	8.38	8.79	8.86	8.38	.23	.026	-.01	-.067
	50	B	9.14	9.14	8.83	8.86	9.33	9.52	.3	.033	.127	.666
	80	B	8.77	8.29	8.7	8.79	9.02	9.05	.31	.035	.184	.947
CA07	20	B	1.37	1.56	1.62	1.08	1.46	1.14	.25	.179	-.098	-.634
	32	B	3.06	3.94	2.73	2.86	2.89	2.89	.49	.161	-.194	-.62
	50	B	2.81	2.79	2.83	2.92	2.89	2.64	.11	.04	-.025	-.361
	80	B	3.04	3.43	2.95	2.83	3.27	2.73	.3	.098	-.108	-.574
CA08	20	B	1.19	1.49	1.14	1.21	1.08	1.02	.18	.155	-.102	-.87
	32	B	2.06	1.9	2.25	2	2.16	1.97	.14	.07	3E-03	.035
	50	B	2.31	2.29	2.25	2.38	2.32	2.32	.05	.02	.013	.426
	80	B	3.19	2.95	3.4	3.4	2.95	3.24	.22	.07	.013	.09
CA09	20	B	3.86	3.91	3.49	3.97	3.65	4.29	.31	.079	.092	.476
	32	B	3.66	3.84	3.81	3.49	3.78	3.37	.21	.059	-.098	-.725
	50	B	4.13	4.1	4.1	4.35	4.13	4	.13	.031	-.016	-.193
	80	B	4.85	4.51	5.11	5.18	4.83	4.6	.3	.061	-.01	-.051
CA10	20	B	3.09	3.3	3.24	3.02	2.98	2.89	.18	.057	-.108	-.97
	32	B	3.71	3.62	3.78	3.71	3.65	3.78	.07	.02	.019	.416
	50	B	3.87	3.75	3.91	3.91	3.94	3.84	.08	.02	.022	.464
	80	B	4.34	4.06	4.22	4.73	4.35	4.32	.25	.057	.064	.407
CA11	20	B	6.31	6.38	6.41	6.25	6.22	6.25	.09	.014	-.044	-.819
	32	B	6.78	6.67	6.51	6.64	7.11	6.95	.25	.037	.117	.747
	50	B	6.19	5.91	5.59	6.45	6.48	6.54	.42	.068	.216	.808
	80	B	6.83	6.6	6.73	6.76	7.33	6.73	.29	.042	.086	.472
CA12	20	B	.57	.73	.6	.57	.54	.38	.13	.223	-.076	-.958
	32	B	.42	.6	.35	.38	.35	.41	.11	.254	-.038	-.567
	50	B	1.03	1.17	.98	.95	1.02	1.02	.09	.083	-.029	-.527
	80	B	1.66	1.59	1.4	1.75	1.75	1.84	.17	.105	.086	.776
CA13	20	B	.94	1.43	1.17	.83	.76	.51	.36	.386	-.225	-.983
	32	B	.65	.7	.57	.67	.54	.76	.09	.141	.01	.165
	50	B	1.09	1.05	1.08	1.05	.98	1.27	.11	.1	.035	.508
	80	B	1.94	1.84	1.81	2.03	2.16	1.87	.15	.076	.041	.441

Table B.10. Summary of Results from Mays Meter #3 on the Surface Treatment Roads.

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
TS01	20	B	7.58	7.62	7.18	7.94	7.4	7.75	.3	.039	.048	.253
	32	B	5.61	5.43	5.72	5.4	5.87	5.65	.2	.036	.06	.477
	50	B	5.6	5.4	5.52	5.65	5.65	5.78	.14	.026	.089	.971
	80	B	7.41	7.11	7.33	7.87	7.14	7.59	.32	.043	.076	.375
TS02	20	B	8.95	9.02	8.89	9.05	8.92	8.89	.07	8E-03	-.022	-.472
	32	B	7.4	6.98	7.18	7.43	7.81	7.59	.33	.044	.184	.891
	50	B	6.14	6.38	6.41	6.03	5.91	5.97	.24	.039	-.133	-.881
	80	B	5.23	5.43	5.11	4.92	5.18	5.52	.24	.047	.025	.164
TS03	20	B	9.87	9.49	9.87	10.06	10.03	9.91	.23	.023	.098	.683
	32	B	8.07	7.62	7.84	8.41	8.32	8.16	.33	.041	.156	.74
	50	B	8.35	8.48	8.38	8.19	8.32	8.38	.11	.013	-.025	-.381
	80	B	7.16	7.02	7.21	7.56	7.14	6.89	.25	.035	-.032	-.2
TS04	20	B	9.8	9.97	10.13	9.49	9.52	9.91	.28	.029	-.073	-.41
	32	B	8.31	8.45	8.83	8.22	8.25	7.78	.38	.046	-.19	-.792
	50	B	7.18	6.79	7.43	7.27	7.3	7.11	.24	.034	.051	.329
	80	B	9.73	9.27	10.1	10.29	9.97	9.02	.55	.057	-.064	-.182
TS05	20	B	10.95	10.8	11.3	10.99	11.05	10.64	.25	.023	-.057	-.356
	32	B	10.04	9.97	9.87	10.22	10.03	10.1	.13	.013	.041	.496
	50	B	8.040	7.65	8.16	7.97	8.32	8.1	.25	.031	.105	.662
	80	B	11.91	11.72	12.13	12.06	12.45	11.21	.47	.04	-.07	-.234
TS06	20	B	5.51	5.3	5.59	5.4	5.68	5.56	.15	.028	.06	.622
	32	B	4.22	4.1	4.51	4.16	4.06	4.29	.18	.043	-6E-03	-.055
	50	B	3.66	3.81	3.78	3.59	3.59	3.56	.12	.033	-.07	-.92
	80	B	3.47	3.78	3.46	3.46	3.56	3.11	.24	.069	-.124	-.815
TS07	20	B	5.27	5.3	5.4	5.24	5.3	5.11	.11	.02	-.048	-.715
	32	B	4.58	4.32	4.7	4.64	4.83	4.44	.2	.044	.038	.297
	50	B	3.66	3.62	3.52	3.68	3.75	3.71	.09	.024	.041	.741
	80	B	3.64	3.78	3.52	3.75	3.56	3.59	.12	.032	-.035	-.477
TS08	20	B	5.47	5.46	5.21	5.43	6.13	5.11	.4	.073	.022	.088
	32	B	4.48	4.6	4.44	4.6	4.35	4.41	.12	.026	-.048	-.653
	50	B	3.94	4.29	3.3	4.25	3.84	4.03	.4	.102	3E-03	.013
	80	B	4.39	4.38	4.44	4.1	4.25	4.76	.25	.057	.057	.364
TS09	20	B	5.91	6.29	5.46	5.14	6.64	6	.61	.103	.06	.158
	32	B	4.78	5.4	5.05	4.98	4.6	3.87	.58	.121	-.349	-.951
	50	B	5.23	5.46	5.33	5.27	5.21	4.86	.23	.043	-.133	-.932
	80	B	3.04	2.89	3.02	2.89	3.17	3.24	.16	.053	.086	.842
TS10	20	B	5.91	6.25	5.97	5.37	5.75	6.19	.36	.061	-.035	-.153
	32	B	5.12	5.56	5.14	4.83	5.05	5.02	.27	.053	-.117	-.686
	50	B	5.35	5.52	5.11	5.65	5.43	5.02	.27	.051	-.07	-.406
	80	B	2.9	2.92	2.79	2.92	2.95	2.92	.06	.021	.016	.406
TS11	20	B	2.3	2.67	1.9	2.73	2.25	1.94	.39	.17	-.111	-.45
	32	B	1.92	1.59	1.9	1.94	2.06	2.13	.21	.109	.124	.937
	50	B	3.04	3.08	3.05	2.89	3.27	2.92	.15	.05	-.01	-.1
	80	B	2.27	2.16	2.7	3.08	1.71	1.71	.61	.267	-.187	-.489
TS12	20	B	1.58	1.62	1.46	1.56	1.65	1.62	.08	.048	.019	.397
	32	B	1.8	1.46	2.22	1.78	1.81	1.71	.27	.153	.01	.055
	50	B	3.12	2.98	3.05	3.27	3.14	3.14	.11	.035	.041	.601
	80	B	1.92	2.22	2.67	1.78	1.52	1.43	.52	.269	-.273	-.836

Table B.11. Summary of Results from Mays Meter #3 on the Gravel Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

MAYS METER #3

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
GR01	20	B	3.19	3.21	3.33	2.98	3.17	3.27	.13	.041	-3E-03	-.038
	32	B	2.6	3.81	2.22	2.03	2.44	2.48	.7	.27	-.244	-.551
	50	B	2.25	1.97	2.41	2.32	2.29	2.29	.17	.075	.051	.478
	80	B	2.74	1.59	2.73	2.16	3.52	3.71	.9	.328	.505	.888
GR02	20	B	3.3	3.27	3.56	3.46	3.08	3.14	.2	.062	-.073	-.568
	32	B	2.52	4	2.22	2.13	2.16	2.1	.83	.329	-.387	-.739
	50	B	2.08	1.71	1.65	2.6	2.32	2.1	.4	.194	.143	.561
	80	B	3.08	2.06	3.14	3.21	3.27	3.71	.61	.198	.343	.888
GR03	20	B	7.29	7.59	7.18	7.21	7.240	7.240	.17	.023	-.063	-.594
	32	B	5.87	6.32	5.78	5.33	5.87	6.06	.37	.062	-.041	-.179
	50	B	8.19	9.11	7.84	8.1	7.08	8.83	.81	.099	-.133	-.261
	80	B	7.83	6.92	7.81	7.87	7.91	8.64	.61	.078	.352	.915
GR04	20	B	5.79	5.49	5.65	5.68	6.38	5.75	.34	.059	.124	.571
	32	B	4.46	4.25	4.54	4.7	4.38	4.44	.17	.038	.022	.21
	50	B	6.43	7.72	5.87	5.33	5.43	7.78	1.22	.19	-.032	-.041
	80	B	5.68	4.44	4.86	6.92	6.51	5.68	1.05	.185	.413	.62
GR05	20	B	17.67	17.08	18.32	17.72	17.05	18.19	.6	.034	.095	.252
	32	B	16.86	17.11	17.24	16.67	16.64	16.64	.29	.017	-.156	-.838
	50	B	14.58	14.29	14.76	14.57	13.84	15.43	.59	.04	.137	.367
	80	B	12.23	12.38	11.24	13.05	12	12.48	.67	.055	.095	.225
GR06	20	B	15.48	16.51	14.51	15.18	16.07	15.14	.8	.052	-.117	-.233
	32	B	14.08	14.03	14.1	14.22	14.22	13.84	.16	.011	-.025	-.254
	50	B	11.98	12.03	11.97	11.78	11.91	12.19	.15	.013	.025	.263
	80	B	10.3	9.68	9.75	10.73	11.11	10.22	.62	.06	.244	.623
GR07	20	B	9.8	10.03	9.3	9.87	10.19	9.62	.35	.036	6E-03	.029
	32	B	7.92	8.38	8.64	6.67	8.25	7.65	.79	.099	-.184	-.37
	50	B	7.240	6.98	7.3	7.240	7.02	7.65	.27	.037	.105	.617
	80	B	6.5	5.37	6.16	6.92	7.27	6.76	.75	.115	.391	.825
GR08	20	B	7.44	6.95	7.240	7.62	7.3	8.1	.44	.059	.235	.853
	32	B	5.31	5.56	5.56	4.16	5.33	5.97	.69	.129	.06	.139
	50	B	4.48	5.08	4.57	5.11	4	3.62	.66	.147	-.349	-.838
	80	B	3.83	2.89	2.92	4.79	5.24	3.3	1.11	.289	.314	.449
GR09	20	B	13.79	13.3	13.46	14.19	13.46	14.51	.53	.039	.241	.717
	32	B	11.09	11.68	10.73	10.45	10.57	12.03	.72	.065	.054	.119
	50	B	10.12	9.84	9.27	10.32	11.14	10.03	.69	.068	.225	.518
	80	B	11.99	11.49	12.29	12.32	12.64	11.21	.61	.051	-.022	-.058
GR10	20	B	10.88	11.02	10.57	10.89	10.83	11.08	.2	.018	.038	.305
	32	B	9.11	9.4	8.25	8.76	9.59	9.56	.58	.064	.165	.447
	50	B	9.65	10.13	9.84	9.78	9.05	9.43	.42	.043	-.219	-.833
	80	B	9.71	8.7	9.43	10.32	9.4	10.7	.8	.082	.397	.786
GR11	20	B	18.62	19.15	18.57	18.48	18.35	18.54	.31	.016	-.143	-.737
	32	B	20.29	19.97	20.38	20.51	19.97	20.61	.3	.015	.086	.451
	50	B	20.19	20	19.81	20.51	20.48	20.13	.3	.015	.092	.48
GR12	20	B	20.74	21.49	20.86	20.29	20.57	20.48	.47	.023	-.232	-.78
	32	B	20.56	20.51	20.26	20.7	20.95	20.38	.27	.013	.044	.256
	50	B	19.91	19.84	19.46	20.07	20.19	19.97	.28	.014	.098	.557

Table B.12. Summary of Results from Mays Meter #3 on the Earth Roads.

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
TE01	20	B	8.41	8.16	8.79	8.51	8	8.57	.32	.038	3E-03	.016
	32	B	6.43	6.06	6.64	6.41	6.38	6.64	.24	.037	.089	.598
	50	B	4.82	4.32	4.57	5.02	5.46	4.73	.44	.091	.171	.617
	80	B	4.32	4.19	3.65	3.94	4.73	5.08	.58	.135	.286	.776
TE02	20	B	7.890	8.25	8.76	7.59	7.11	7.75	.63	.08	-.267	-.664
	32	B	6.02	6	6.32	5.65	5.94	6.19	.26	.042	0	0
	50	B	4.83	4.76	4.67	4.95	4.79	4.95	.12	.026	.051	.643
	80	B	3.77	3.27	3.62	3.84	3.62	4.48	.45	.119	.241	.853
TE03	20	B	14.94	15.24	15.46	14.92	14.32	14.76	.44	.03	-.21	-.751
	32	B	12.15	11.94	11.94	12.19	12.35	12.32	.2	.016	.117	.927
	50	B	9.12	9.08	9.11	8.22	9.78	9.43	.58	.063	.137	.374
	80	B	7.3	5.97	6.48	8.51	8.45	7.08	1.15	.157	.419	.577
TE04	20	B	15.36	15.53	15.18	15.34	15.56	15.21	.18	.011	-.025	-.228
	32	B	13.12	13.11	12.95	13.33	13.05	13.14	.14	.011	.016	.178
	50	B	9.57	9.43	10.19	8.76	9.46	10	.56	.059	.041	.116
	80	B	7.91	7.84	7.02	8.76	8.03	7.91	.62	.079	.114	.291
TE05	20	B	24.59	24.57	24.51	24.86	24.61	24.38	.17	7E-03	-.029	-.259
	32	B	19.11	18.07	17.53	17.72	17.43	24.8	3.19	.167	1.337	.663
	50	B	21.47	21.56	21.34	21.49	21.65	21.3	.15	7E-03	-.019	-.204
TE06	20	B	32.2	31.56	32.26	32.29	32.48	32.42	.37	.011	.194	.828
	32	B	26.31	25.46	24.8	25.21	25.21	30.86	2.56	.097	1.121	.693
	50	B	28.11	28.13	27.65	27.94	28.32	28.48	.32	.012	.137	.668
TE07	20	B	8.76	8.83	8.76	9.05	8.73	8.41	.23	.026	-.086	-.594
	32	B	7.63	7.56	7.62	7.240	8	7.75	.28	.036	.076	.433
	50	B	6.9	6.13	6.98	7.14	7.18	7.08	.44	.064	.21	.754
	80	B	4.47	4.19	4.38	4.57	4.67	4.54	.19	.042	.098	.832
TE08	20	B	9.94	10.45	9.68	10.03	10.16	9.4	.41	.041	-.162	-.625
	32	B	7.85	7.56	7.68	7.75	8.32	7.97	.3	.038	.146	.772
	50	B	6.94	6.76	6.35	7.08	7.05	7.46	.41	.06	.21	.802
	80	B	4.28	4.32	4.13	4.38	4.25	4.32	.1	.023	.013	.209
TE09	20	B	17.18	17.91	16.1	18	17.14	16.76	.8	.046	-.124	-.245
	32	B	12.81	12.35	12.83	13.46	12.67	12.76	.41	.032	.067	.26
	50	B	10.35	10.13	9.97	10.35	10.73	10.57	.31	.03	.165	.837
	80	B	7.91	7.52	7.72	8	8.29	8.03	.3	.037	.159	.847
TE10	20	B	19.62	19.08	19.43	19.88	19.75	19.97	.36	.019	.21	.91
	32	B	17.08	15.65	19.11	17.88	15.72	17.02	1.47	.086	-.067	-.072
	50	B	13.6	13.46	13.27	13.72	13.46	14.1	.32	.023	.146	.724
	80	B	10.73	10.76	10.86	10.73	10.92	10.35	.22	.021	-.076	-.541
TE11	20	B	16.8	16.73	16.61	16.95	16.61	17.08	.21	.013	.07	.516
	32	B	12.69	13.05	12.54	12.13	13.08	12.64	.39	.031	-.029	-.115
	50	B	11.18	11.18	11.21	10.73	11.4	11.37	.27	.024	.057	.339
	80	B	10.57	10.86	10.6	10.41	10.54	10.45	.18	.017	-.089	-.795
TE12	20	B	17.13	17.14	17.11	16.73	17.4	17.24	.25	.014	.048	.305
	32	B	13.08	13.33	13.21	12.76	13.14	12.95	.22	.017	-.083	-.581
	50	B	9.47	9.08	9.56	9.68	9.56	9.49	.23	.024	.083	.566
	80	B	8.46	8.67	8.41	8.35	8.57	8.29	.16	.019	-.06	-.603

Table B.13. Summary of Results from the Car-Mounted BI on the Asphaltic Concrete Roads.

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
CA01	20	B	2.16	2.22	2.06	2.06	2.22	2.22	.09	.04	.016	.289
	32	B	2.98	3.33	3.17	3.02	2.7	2.7	.28	.095	-.175	-.972
	50	B	3.97	3.81	3.97	3.97	4.13	3.97	.11	.028	.048	.671
	80	B	6.32	6.35	5.72	6.83	6.83	5.87	.52	.082	.016	.048
CA02	20	B	3.11	3.33	3.02	3.02	3.17	3.02	.14	.046	-.048	-.53
	32	B	4.03	4.44	3.97	4.13	3.65	3.97	.29	.072	-.127	-.696
	50	B	4.95	4.92	5.08	4.92	4.92	4.92	.07	.014	-.016	-.354
	80	B	6.35	6.19	6.35	6.35	6.67	6.19	.19	.031	.032	.258
CA03	20	B	6.19	6.03	6.19	6.03	6.19	6.51	.19	.031	.095	.775
	32	B	6.57	6.67	6.35	6.67	6.67	6.51	.14	.022	0	0
	50	B	7.33	6.83	7.3	7.78	7.3	7.46	.34	.047	.127	.583
	80	B	10.57	10.32	9.84	9.84	11.43	11.43	.81	.076	.381	.747
CA04	20	B	5.43	5.24	5.72	5.56	5.24	5.4	.21	.038	-.016	-.121
	32	B	6.13	6.03	6.03	6.19	6.03	6.35	.14	.023	.063	.707
	50	B	6.48	6.03	6.51	6.51	6.83	6.51	.28	.044	.127	.707
	80	B	7.62	7.62	6.98	8.25	7.62	7.62	.45	.059	.063	.224
CA05	20	B	7.27	7.14	7.46	7.3	7.3	7.14	.13	.018	-.016	-.189
	32	B	7.91	7.78	7.78	7.78	8.25	7.94	.21	.026	.079	.606
	50	B	7.87	7.46	8.25	7.46	8.25	7.94	.4	.051	.095	.378
	80	B	10.51	10.32	9.21	10.8	11.27	10.95	.8	.077	.333	.655
CA06	20	B	8.130	8.1	8.1	8.25	7.78	8.41	.24	.029	.032	.213
	32	B	8.6	8.73	8.41	9.05	8.41	8.41	.28	.033	-.063	-.354
	50	B	9.62	9.37	9.52	9.68	9.84	9.68	.18	.019	.095	.832
	80	B	13.72	12.7	13.97	12.54	14.76	14.6	1.04	.076	.46	.697
CA07	20	B	1.78	1.59	1.75	2.22	1.75	1.59	.26	.147	0	0
	32	B	2.35	2.38	2.38	2.38	2.06	2.54	.17	.074	0	0
	50	B	2.57	2.54	2.54	2.54	2.7	2.54	.07	.028	.016	.354
	80	B	4.19	3.65	4.44	4.29	4.44	4.13	.33	.079	.095	.457
CA08	20	B	1.75	1.9	1.75	1.59	2.06	1.43	.25	.144	-.063	-.4
	32	B	1.87	1.75	2.06	1.9	1.75	1.9	.13	.071	0	0
	50	B	2.25	2.38	2.22	2.22	2.22	2.22	.07	.031	-.032	-.707
	80	B	4.29	3.97	4.13	4.76	4.29	4.29	.3	.069	.079	.423
CA09	20	B	3.11	3.17	3.17	3.17	3.02	3.02	.09	.028	-.048	-.866
	32	B	3.52	3.49	3.65	3.49	3.49	3.49	.07	.02	-.016	-.354
	50	B	3.97	3.97	3.97	3.97	3.97	3.97	0	0	0	0
	80	B	5.52	5.72	5.72	5.08	5.4	5.72	.28	.051	-.032	-.177
CA10	20	B	2.51	2.54	2.38	2.54	2.86	2.22	.24	.094	-.016	-.107
	32	B	3.05	3.02	3.02	3.17	3.02	3.02	.07	.023	0	0
	50	B	3.71	3.49	3.65	3.97	3.65	3.81	.18	.049	.063	.555
	80	B	5.24	5.08	5.24	5.4	5.08	5.4	.16	.03	.048	.474
CA11	20	B	6.16	6.19	6.19	5.87	6.19	6.35	.17	.028	.032	.289
	32	B	6.41	6.51	6.19	6.51	6.51	6.35	.14	.022	0	0
	50	B	6.22	6.03	6.03	6.35	6.51	6.19	.21	.033	.079	.606
	80	B	6.7	6.67	6.98	6.51	6.83	6.51	.21	.031	-.048	-.364
CA12	20	B	.95	1.11	.95	.79	.95	.95	.11	.118	-.032	-.447
	32	B	1.27	1.27	1.27	1.27	1.27	1.27	0	0	0	0
	50	B	1.59	1.75	1.43	1.59	1.59	1.59	.11	.071	-.016	-.224
CA13	20	B	.98	1.11	1.27	.79	.95	.79	.21	.21	-.095	-.728
	32	B	1.24	1.27	1.11	1.27	1.27	1.27	.07	.057	.016	.354
	50	B	1.56	1.75	1.43	1.59	1.43	1.59	.13	.085	-.032	-.378

Table B.14. Summary of Results from the Car-Mounted BI on the Surface Treatment Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

CAR-MOUNTED BUMP INTEGRATOR

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
TS01	20	B	6.54	6.35	6.67	6.67	6.51	6.51	.13	.02	.016	.189
	32	B	5.84	6.03	5.72	5.72	5.87	5.87	.13	.023	-.016	-.189
	50	B	5.46	5.4	5.56	5.56	5.4	5.4	.09	.016	-.016	-.289
TS02	20	B	8.19	7.78	8.1	8.41	8.41	8.25	.27	.032	.127	.756
	32	B	7.33	7.46	7.3	6.98	7.3	7.62	.24	.032	.032	.213
	50	B	6.29	6.51	6.19	6.19	6.35	6.19	.14	.023	-.048	-.53
TS03	20	B	8.7	8.57	8.73	8.57	9.21	8.41	.31	.035	.016	.082
	32	B	7.72	7.46	7.78	7.62	7.78	7.94	.18	.023	.095	.832
	50	B	7.240	6.98	7.14	7.3	7.3	7.46	.18	.025	.111	.971
TS04	20	B	7.68	7.46	7.78	7.78	7.78	7.62	.14	.018	.032	.354
	32	B	7.21	7.14	7.14	7.14	7.14	7.46	.14	.02	.063	.707
	50	B	6.76	6.83	6.83	6.67	6.83	6.67	.09	.013	-.032	-.577
TS05	20	B	9.75	9.68	9.84	9.52	10	9.68	.18	.019	.016	.139
	32	B	8	7.94	7.94	8.1	7.94	8.1	.09	.011	.032	.577
	50	B	7.490	7.62	7.46	7.3	7.46	7.62	.13	.018	0	0
TS06	20	B	4.51	4.44	4.44	4.6	4.29	4.76	.18	.04	.048	.416
	32	B	4	3.97	3.97	3.97	3.97	4.13	.07	.018	.032	.707
	50	B	3.49	3.49	3.33	3.49	3.65	3.49	.11	.032	.032	.447
TS07	20	B	4	4.13	3.97	3.97	3.97	3.97	.07	.018	-.032	-.707
	32	B	3.68	3.97	3.65	3.49	3.65	3.65	.17	.047	-.063	-.577
	50	B	3.43	3.33	3.49	3.33	3.49	3.49	.09	.025	.032	.577
TS08	20	B	4.86	4.92	4.92	4.76	4.92	4.76	.09	.018	-.032	-.577
	32	B	4.29	4.13	4.44	4.13	4.29	4.44	.16	.037	.048	.474
	50	B	3.59	3.65	3.49	3.65	3.49	3.65	.09	.024	0	0
TS09	20	B	5.49	5.72	5.72	5.4	5.4	5.24	.21	.039	-.127	-.943
	32	B	5.05	5.24	5.08	5.24	4.76	4.92	.21	.041	-.095	-.728
	50	B	4.83	4.92	5.08	4.76	4.6	4.76	.18	.038	-.079	-.693
TS10	20	B	5.43	5.87	5.4	5.4	5.24	5.24	.26	.048	-.143	-.866
	32	B	5.08	4.92	5.24	5.08	5.08	5.08	.11	.022	.016	.224
	50	B	4.98	5.08	4.92	4.92	5.08	4.92	.09	.017	-.016	-.289
TS11	20	B	2.67	2.7	2.54	2.7	2.7	2.7	.07	.027	.016	.354
	32	B	2.98	3.02	3.17	2.86	3.02	2.86	.13	.045	-.048	-.567
	50	B	2.51	2.54	2.54	2.38	2.54	2.54	.07	.028	0	0
TS12	20	B	3.24	3.02	3.17	3.17	3.49	3.33	.18	.056	.095	.832
	32	B	3.17	3.33	3.02	3.17	3.17	3.17	.11	.035	-.016	-.224
	50	B	2.51	2.54	2.54	2.54	2.54	2.38	.07	.028	-.032	-.707

Table B.15. Summary of Results from the Car-Mounted BI on the Gravel Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

CAR-MOUNTED BUMP INTEGRATOR

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
GR01	20	B	2.98	2.7	3.33	3.02	3.02	2.86	.24	.079	0	0
	32	B	3.14	3.02	3.33	3.17	2.86	3.33	.21	.066	.016	.121
	50	B	3.05	3.02	3.17	3.02	3.02	3.02	.07	.023	-.016	-.354
GR02	20	B	3.59	3.49	3.49	3.65	3.65	3.65	.09	.024	.048	.866
	32	B	3.52	3.65	3.49	3.33	3.65	3.49	.13	.038	-.016	-.189
	50	B	3.27	3.49	3.17	3.33	3.33	3.02	.18	.055	-.079	-.693
GR03	20	B	10.13	10.16	10.48	10.32	9.84	9.84	.28	.028	-.127	-.707
	32	B	8.89	8.57	8.73	9.37	8.57	9.21	.37	.042	.111	.472
	50	B	8.06	7.78	7.78	8.1	7.94	8.73	.4	.049	.206	.826
GR04	20	B	8.45	8.89	8.57	8.25	8.25	8.25	.28	.034	-.159	-.884
	32	B	7.27	7.14	7.14	7.3	7.3	7.46	.13	.018	.079	.945
	50	B	6.98	6.83	7.14	7.3	6.67	6.98	.25	.036	-.016	-.1
GR05	20	B	12.73	12.86	12.7	12.7	12.54	12.86	.13	.01	-.016	-.189
	32	B	12.41	12.38	12.86	11.91	12.54	12.38	.34	.028	-.032	-.146
	50	B	12.16	11.91	12.38	12.06	12.38	12.06	.21	.018	.032	.236
GR06	20	B	12.89	13.02	13.18	12.86	12.54	12.86	.24	.018	-.095	-.64
	32	B	11.43	11.11	11.43	11.43	11.75	11.43	.22	.02	.095	.671
	50	B	11.49	11.59	11.59	11.43	11.27	11.59	.14	.012	-.032	-.354
GR07	20	B	7.4	7.46	7.46	6.98	7.62	7.46	.24	.033	.016	.104
	32	B	6.73	6.98	6.67	6.51	6.83	6.67	.18	.027	-.048	-.416
	50	B	6.57	6.51	6.51	6.51	6.98	6.35	.24	.037	.016	.104
GR08	20	B	4.95	4.92	4.76	4.76	5.24	5.08	.21	.042	.079	.606
	32	B	4.35	4.6	4.13	4.29	4.29	4.44	.18	.042	-.016	-.139
	50	B	4.13	3.81	4.29	4.13	4.13	4.29	.19	.047	.079	.645
GR09	20	B	11.81	11.59	12.06	11.75	11.75	11.91	.18	.015	.032	.277
	32	B	10.13	9.84	9.84	10.32	10.64	10	.34	.034	.111	.511
	50	B	9.4	9.21	9.52	9.37	9.52	9.37	.13	.014	.032	.378
GR10	20	B	8.99	8.89	9.05	8.73	9.21	9.05	.18	.02	.048	.416
	32	B	7.75	7.46	7.78	8.25	7.46	7.78	.33	.042	.032	.154
	50	B	7.37	7.46	7.46	7.46	7.3	7.14	.14	.019	-.079	-.884
GR11	20	B	18.89	19.21	18.73	18.57	19.05	18.89	.25	.013	-.032	-.2
	32	B	18.38	18.73	17.78	18.1	18.26	19.05	.51	.028	.111	.347
	50	B	18	18.73	18.73	17.46	17.62	17.46	.67	.037	-.365	-.862
GR12	20	B	19.21	19.53	19.53	19.05	18.73	19.21	.34	.018	-.143	-.671
	32	B	18.89	18.73	18.73	18.26	19.05	19.68	.53	.028	.222	.667
	50	B	17.49	18.26	16.99	16.99	17.14	18.1	.63	.036	-.016	-.04

Table B.16. Summary of Results from the Car-Mounted BI on the Earth Roads.

CAR-MOUNTED BUMP INTEGRATOR

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
TE01	20	B	6.45	6.83	6.03	6.67	6.35	6.35	.31	.048	-.063	-.324
	32	B	5.68	5.72	5.72	6.03	5.72	5.24	.28	.05	-.095	-.53
	50	B	4.79	4.76	4.92	4.6	5.08	4.6	.21	.043	-.016	-.121
TE02	20	B	6	6.03	6.03	5.87	5.87	6.19	.13	.022	.016	.189
	32	B	5.11	4.92	5.56	4.92	5.08	5.08	.26	.051	-.016	-.096
	50	B	4.38	4.13	4.29	4.44	4.6	4.44	.18	.041	.095	.832
TE03	20	B	12.7	12.86	12.86	12.7	12.7	12.38	.19	.015	-.111	-.904
	32	B	12.16	12.38	12.06	11.75	12.54	12.06	.31	.025	-.016	-.081
	50	B	11.05	10.95	10.95	10.64	11.75	10.95	.41	.037	.079	.303
TE04	20	B	13.84	12.86	13.97	13.81	14.45	14.13	.6	.043	.302	.797
	32	B	13.53	13.02	13.49	13.33	13.49	14.29	.47	.035	.254	.858
	50	B	12.67	13.02	12.38	12.7	12.22	13.02	.36	.029	-.016	-.069
TE05	20	B	24.54	23.97	24.45	24.29	24.92	25.08	.46	.019	.27	.933
	32	B	21.18	19.84	20.48	21.11	22.23	22.23	1.06	.05	.651	.974
	50	B	20.83	19.84	20.16	20.64	21.43	22.07	.91	.044	.572	.988
TE06	20	B	32.51	31.75	32.54	32.23	32.86	33.18	.55	.017	.317	.905
	32	B	27.4	26.19	27.15	27.46	27.62	28.57	.86	.031	.524	.964
	50	B	26.48	25.56	26.19	26.35	27.15	27.15	.68	.026	.413	.964
TE07	20	B	6.92	6.98	6.98	6.83	6.98	6.83	.09	.013	-.032	-.577
	32	B	6.48	6.03	6.51	6.35	6.98	6.51	.34	.053	.143	.656
	50	B	5.81	5.72	5.87	6.03	5.72	5.72	.14	.024	-.016	-.177
TE08	20	B	6.7	6.51	6.67	6.83	6.83	6.67	.13	.02	.048	.567
	32	B	6.22	6.35	6.19	6.19	6.19	6.19	.07	.011	-.032	-.707
	50	B	6.03	5.87	6.03	6.19	6.03	6.03	.11	.019	.032	.447
TE09	20	B	13.68	13.65	13.49	13.81	13.65	13.81	.13	.01	.048	.567
	32	B	10.86	10.8	10.95	10.8	10.95	10.8	.09	8E-03	0	0
	50	B	9.33	9.37	9.52	9.05	9.21	9.52	.21	.022	0	0
TE10	20	B	19.27	19.21	18.89	19.21	19.53	19.53	.27	.014	.127	.756
	32	B	15.43	15.4	15.08	16.03	15.08	15.56	.4	.026	.032	.127
	50	B	13.27	13.18	13.65	13.49	12.7	13.33	.37	.028	-.063	-.275
TE11	20	B	18.7	18.73	18.41	18.89	18.57	18.89	.21	.011	.048	.364
	32	B	14.54	14.45	14.13	14.76	14.45	14.92	.31	.021	.127	.649
	50	B	11.59	11.75	11.59	11.27	11.75	11.59	.19	.017	-.016	-.129
TE12	20	B	13.49	13.65	13.18	13.18	13.49	13.97	.34	.025	.095	.447
	32	B	11.4	11.59	11.11	11.27	11.27	11.75	.26	.023	.048	.289
	50	B	10.16	9.68	10.16	9.84	10.64	10.48	.4	.04	.206	.806

Table B.17. Summary of Results from the NAASRA Meter on the Asphaltic Concrete Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

CAR-MOUNTED NAASRA METER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
CA01	20	B	1.98	1.9	1.8	1.99	2.09	2.09	.12	.063	.066	.849
	32	B	3.02	3.42	3.23	2.95	2.66	2.85	.3	.1	-.171	-.891
	50	B	3.97	3.7	3.89	4.27	3.8	4.18	.25	.062	.085	.55
	80	B	5.61	5.7	5.61	5.7	5.7	5.32	.16	.029	-.066	-.639
CA02	20	B	3.15	3.13	3.04	3.32	3.13	3.13	.1	.033	9E-03	.144
	32	B	3.93	4.18	3.99	4.08	3.8	3.61	.23	.058	-.133	-.919
	50	B	4.69	4.75	4.65	4.75	4.46	4.84	.14	.031	0	0
	80	B	5.72	5.51	5.7	5.8	5.7	5.89	.14	.025	.076	.853
CA03	20	B	6.29	6.08	6.36	6.46	6.17	6.36	.16	.025	.038	.385
	32	B	6.54	6.17	6.740	7.03	6.55	6.17	.37	.057	-.019	-.081
	50	B	6.71	6.46	6.55	6.65	6.84	7.03	.23	.034	.143	.985
	80	B	8.07	8.07	8.17	7.88	8.26	7.98	.15	.019	-9E-03	-.1
CA04	20	B	5.34	5.61	5.32	5.22	5.22	5.32	.16	.029	-.066	-.674
	32	B	6.1	6.17	6.08	6.17	6.08	5.99	.08	.013	-.038	-.756
	50	B	6.18	5.8	6.27	6.17	6.27	6.36	.22	.036	.114	.809
	80	B	6.54	6.46	6.36	6.46	7.03	6.36	.28	.043	.048	.268
CA05	20	B	7.22	7.41	7.12	7.31	7.12	7.12	.13	.019	-.057	-.671
	32	B	7.56	7.22	7.31	7.41	7.98	7.88	.35	.046	.199	.91
	50	B	7.11	6.65	7.5	7.12	7.22	7.03	.31	.044	.048	.242
	80	B	8.19	8.26	7.98	8.07	8.36	8.26	.16	.019	.038	.385
CA06	20	B	8.15	7.69	8.26	8.36	8.07	8.36	.28	.034	.114	.643
	32	B	8.4	8.45	8.17	8.36	8.26	8.74	.22	.026	.066	.481
	50	B	8.42	8.07	8.45	8.17	8.93	8.45	.33	.04	.123	.586
	80	B	9.82	9.31	9.78	9.59	10.07	10.35	.41	.041	.237	.924
CA07	20	B	1.48	1.52	1.52	1.52	1.52	1.33	.08	.057	-.038	-.707
	32	B	2.11	1.99	2.28	2.09	1.9	2.28	.17	.081	.019	.177
	50	B	2.49	2.56	2.37	2.47	2.56	2.47	.08	.032	0	0
	80	B	3.82	3.61	3.8	3.99	3.7	3.99	.17	.044	.066	.619
CA08	20	B	1.41	1.52	1.43	1.33	1.43	1.33	.08	.057	-.038	-.756
	32	B	1.77	1.9	1.71	1.61	1.52	2.09	.23	.129	.019	.131
	50	B	2.15	2.09	1.99	2.37	2.18	2.09	.14	.067	.019	.209
	80	B	3.74	3.7	3.99	3.89	3.7	3.42	.22	.058	-.085	-.618
CA09	20	B	3.02	3.23	2.95	2.85	3.04	3.04	.14	.047	-.028	-.32
	32	B	3.31	3.13	3.32	3.32	3.23	3.51	.14	.043	.066	.746
	50	B	3.72	3.7	3.61	3.8	3.89	3.61	.12	.033	9E-03	.121
	80	B	5	4.94	5.13	4.84	4.94	5.13	.13	.026	.019	.236
CA10	20	B	2.3	2.18	2.28	2.37	2.37	2.28	.08	.035	.029	.567
	32	B	2.87	2.76	2.85	2.85	3.13	2.76	.16	.054	.029	.289
	50	B	3.46	3.42	3.7	3.42	3.51	3.23	.17	.05	-.057	-.522
	80	B	4.64	4.56	4.65	4.46	4.46	5.03	.24	.051	.076	.508
CA11	20	B	6.29	6.17	6.27	6.17	6.27	6.55	.16	.025	.076	.77
	32	B	6.48	6.65	6.17	6.65	6.55	6.36	.21	.032	-.019	-.146
	50	B	5.97	5.99	5.99	6.08	5.99	5.8	.1	.017	-.038	-.577
	80	B	6.42	6.17	7.03	6.27	6.27	6.36	.35	.054	-.038	-.173
CA12	20	B	.8	1.04	.76	.67	.76	.76	.14	.181	-.057	-.626
	32	B	1.03	1.04	.95	.95	1.04	1.14	.08	.077	.029	.567
	50	B	1.39	1.52	1.33	1.43	1.43	1.23	.11	.078	-.047	-.693
CA13	20	B	.78	.76	.85	.76	.76	.76	.04	.055	-9E-03	-.354
	32	B	1.1	1.04	.95	1.23	1.04	1.23	.13	.116	.048	.589
	50	B	1.35	1.33	1.43	1.33	1.43	1.23	.08	.059	-.019	-.378

Table B.18. Summary of Results from the NAASRA Meter on the Surface Treatment Roads.

CAR-MOUNTED NAASRA METER

SITE	SPEED	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000)						SIGMA	S/M	TREND	R
	(K/H)		MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5				
TS01	20	B	6.59	6.55	6.46	6.740	6.740	6.46	.14	.022	9E-03	.104
	32	B	5.66	5.7	5.99	5.51	5.7	5.42	.22	.039	-.085	-.618
	50	B	5.47	5.32	5.51	5.51	5.32	5.7	.16	.029	.057	.567
TS02	20	B	8.21	7.98	7.88	8.45	8.36	8.36	.26	.031	.123	.761
	32	B	7.11	7.22	6.84	6.740	7.31	7.41	.3	.042	.085	.457
	50	B	6.04	6.17	5.99	5.8	6.27	5.99	.19	.031	-9E-03	-.081
TS03	20	B	8.45	8.17	8.55	8.74	8.55	8.26	.23	.028	.019	.129
	32	B	7.79	7.88	8.07	7.22	7.79	7.98	.34	.043	-9E-03	-.045
	50	B	7.18	6.65	6.93	7.69	7.12	7.5	.42	.059	.19	.711
TS04	20	B	7.68	7.69	7.79	7.69	7.79	7.41	.16	.02	-.057	-.577
	32	B	7.05	7.22	7.03	6.93	6.93	7.12	.12	.018	-.028	-.364
	50	B	6.740	6.55	6.36	7.22	7.03	6.55	.36	.054	.066	.291
TS05	20	B	9.5	9.12	9.69	9.5	9.5	9.69	.23	.024	.095	.645
	32	B	7.98	7.88	8.07	7.98	7.88	8.07	.1	.012	.019	.316
	50	B	7.45	7.41	7.6	7.31	7.6	7.31	.14	.019	-.019	-.209
TS06	20	B	4.71	4.65	4.84	5.03	4.46	4.56	.23	.049	-.057	-.394
	32	B	3.86	3.8	3.89	3.8	3.99	3.8	.08	.022	9E-03	.177
	50	B	3.34	3.32	3.23	3.51	3.23	3.42	.12	.037	.019	.243
TS07	20	B	4.12	4.27	4.08	4.37	3.8	4.08	.22	.053	-.066	-.481
	32	B	3.74	3.89	4.08	3.51	3.61	3.61	.24	.064	-.104	-.693
	50	B	3.33	3.61	3.23	3.32	3.32	3.13	.18	.053	-.085	-.761
TS08	20	B	5	5.22	5.03	5.13	5.03	4.56	.26	.051	-.133	-.819
	32	B	4.14	3.8	4.56	4.08	4.37	3.89	.32	.077	0	0
	50	B	3.51	3.51	3.42	3.61	3.32	3.7	.15	.043	.029	.3
TS09	20	B	5.55	5.51	5.89	5.22	5.61	5.51	.24	.043	-.028	-.189
	32	B	4.96	5.22	4.75	5.22	4.56	5.03	.3	.06	-.057	-.305
	50	B	4.67	4.56	4.56	4.84	4.75	4.65	.12	.027	.038	.485
TS10	20	B	5.53	5.8	6.08	5.32	5.22	5.22	.39	.07	-.199	-.813
	32	B	4.98	5.03	4.94	4.84	4.94	5.13	.11	.022	.019	.277
	50	B	4.75	4.84	4.84	4.75	4.75	4.56	.12	.024	-.066	-.904
TS11	20	B	2.6	2.37	2.47	2.76	2.76	2.66	.17	.066	.085	.783
	32	B	2.72	2.76	2.56	2.76	2.66	2.85	.11	.04	.029	.416
	50	B	2.28	2.37	2.18	2.28	2.37	2.18	.1	.042	-.019	-.316
TS12	20	B	3.08	2.95	3.04	3.04	3.13	3.23	.11	.035	.066	.971
	32	B	2.95	3.23	2.95	2.85	2.76	2.95	.18	.06	-.076	-.676
	50	B	2.37	2.56	2.37	2.37	2.37	2.18	.13	.057	-.076	-.894

Table B.19. Summary of Results from the NAASRA Meter on the Gravel Roads.

CAR-MOUNTED NAASRA METER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
GR01	20	B	2.51	2.47	2.56	2.56	2.47	2.47	.05	.021	-9E-03	-.289
	32	B	2.85	2.95	2.85	2.95	2.85	2.66	.12	.041	-.057	-.775
	50	B	2.77	2.76	2.85	2.66	2.85	2.76	.08	.029	0	0
GR02	20	B	3.27	3.13	3.32	3.32	3.23	3.32	.08	.026	.029	.53
	32	B	3.17	3.32	3.13	2.95	3.23	3.23	.14	.045	-9E-03	-.104
	50	B	2.96	3.04	2.95	3.04	3.04	2.76	.12	.042	-.047	-.606
GR03	20	B	9.58	9.59	10.07	9.4	9.4	9.4	.29	.03	-.104	-.573
	32	B	8.32	8.07	8.17	8.64	8.17	8.55	.26	.031	.095	.585
	50	B	7.640	7.6	7.41	7.5	7.5	8.17	.3	.04	.123	.64
GR04	20	B	7.81	8.07	7.79	7.69	7.6	7.88	.18	.023	-.057	-.493
	32	B	6.84	6.740	6.740	6.93	6.93	6.84	.1	.014	.038	.632
	50	B	6.59	6.36	6.65	6.740	6.46	6.740	.17	.026	.057	.522
GR05	20	B	12.29	12.63	12.16	12.44	11.88	12.35	.29	.024	-.085	-.467
	32	B	11.87	12.06	12.25	11.31	11.88	11.88	.36	.03	-.076	-.338
	50	B	11.59	11.5	11.88	11.4	11.78	11.4	.22	.019	-.028	-.202
GR06	20	B	12.67	12.92	13.11	12.44	12.44	12.44	.32	.025	-.161	-.8
	32	B	11.1	10.93	11.12	11.21	11.21	11.02	.12	.011	.029	.364
	50	B	10.94	10.45	11.02	11.12	11.02	11.12	.28	.026	.133	.75
GR07	20	B	7.03	7.41	6.84	6.84	7.03	7.03	.23	.033	-.057	-.387
	32	B	6.4	6.55	6.27	6.27	6.65	6.27	.19	.029	-.019	-.162
	50	B	6.18	6.08	6.36	6.08	6.27	6.08	.13	.022	-9E-03	-.112
GR08	20	B	4.81	4.65	4.65	4.94	5.03	4.75	.17	.036	.057	.522
	32	B	4.1	4.18	3.99	3.99	4.08	4.27	.12	.03	.029	.364
	50	B	3.86	3.89	3.8	3.99	3.7	3.89	.11	.028	-9E-03	-.139
GR09	20	B	11.29	11.21	11.5	11.12	11.21	11.4	.16	.014	9E-03	.096
	32	B	9.78	9.69	9.5	10.07	10.07	9.59	.27	.027	.038	.224
	50	B	8.84	8.45	8.83	9.02	8.93	8.93	.22	.025	.104	.742
GR10	20	B	8.59	8.36	8.83	8.45	8.45	8.83	.23	.027	.057	.394
	32	B	7.56	7.12	7.41	7.98	7.79	7.5	.33	.044	.114	.541
	50	B	7.2	7.31	7.31	7.03	7.22	7.12	.12	.017	-.047	-.606
GR11	20	B	18.9	19.28	18.81	18.71	18.9	18.81	.22	.012	-.085	-.607
	32	B	18.03	18.43	17.29	17.48	18.33	18.62	.6	.033	.143	.374
	50	B	18.51	18.43	18.33	18.81	18.33	18.62	.21	.011	.038	.292
GR12	20	B	18.89	19.28	19.28	18.71	18.33	18.81	.41	.021	-.19	-.741
	32	B	18.24	18.14	18.14	17.67	18.52	18.71	.4	.022	.152	.596
	50	B	17.9	17.67	17.38	17.86	18.05	18.52	.43	.024	.237	.877

Table B.20. Summary of Results from the NAASRA Meter on the Earth Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

CAR-MOUNTED NAASRA METER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
TE01	20	B	6.21	6.36	5.8	6.65	5.89	6.36	.36	.058	9E-03	.042
	32	B	5.05	5.22	5.03	5.13	5.03	4.84	.14	.028	-.076	-.853
	50	B	4.29	4.27	4.46	4.27	4.27	4.18	.1	.024	-.038	-.577
TE02	20	B	5.61	5.7	6.17	5.32	5.32	5.51	.36	.063	-.123	-.549
	32	B	4.96	4.84	5.03	4.94	4.75	5.22	.18	.037	.048	.411
	50	B	4.31	4.08	4.37	4.27	4.18	4.65	.22	.051	.095	.687
TE03	20	B	12.14	12.63	12.25	12.25	11.88	11.69	.37	.031	-.228	-.973
	32	B	11.21	11.4	10.93	11.21	11.21	11.31	.18	.016	9E-03	.085
	50	B	8.91	8.64	8.83	8.93	9.02	9.12	.18	.021	.114	.986
TE04	20	B	13.17	12.54	12.82	13.58	13.39	13.49	.46	.035	.247	.852
	32	B	11.89	12.44	12.06	11.5	11.78	11.69	.37	.031	-.18	-.771
	50	B	9.98	9.78	10.35	9.78	9.88	10.07	.24	.024	9E-03	.062
TE05	20	B	24.23	23.47	24.03	23.94	24.6	25.08	.63	.026	.38	.959
	32	B	20.63	19.57	19.85	20.61	21.38	21.76	.94	.046	.589	.989
	50	B	20.06	19.09	19.28	19.76	20.8	21.38	.99	.049	.608	.973
TE06	20	B	32.34	32.2	32.3	32.11	32.3	32.77	.26	8E-03	.114	.702
	32	B	26.94	26.31	26.69	26.5	27.17	28.02	.68	.025	.39	.901
	50	B	25.88	24.7	25.55	25.84	26.6	26.69	.82	.032	.504	.972
TE07	20	B	6.54	6.55	6.46	6.55	6.55	6.55	.04	7E-03	9E-03	.354
	32	B	6.04	5.8	5.89	5.99	6.36	6.17	.23	.038	.123	.853
	50	B	5.36	5.32	5.51	5.32	5.42	5.22	.11	.02	-.028	-.416
TE08	20	B	6.46	6.36	6.27	6.55	6.740	6.36	.19	.029	.048	.395
	32	B	5.89	5.89	5.89	5.8	5.89	5.99	.07	.011	.019	.447
	50	B	5.68	5.32	5.7	5.8	5.8	5.8	.21	.036	.104	.802
TE09	20	B	13.07	13.01	12.92	13.2	13.01	13.2	.13	.01	.048	.589
	32	B	10.26	10.26	10.45	10.07	10.26	10.26	.13	.013	-.019	-.224
	50	B	8.82	9.02	8.83	8.45	8.64	9.12	.27	.031	0	0
TE10	20	B	18.68	18.52	18.33	18.62	18.9	19	.27	.015	.152	.878
	32	B	14.78	14.44	14.34	15.29	14.82	15.01	.4	.027	.162	.646
	50	B	12.64	12.44	12.73	12.82	12.44	12.73	.18	.014	.029	.254
TE11	20	B	18.33	18.05	17.86	18.71	18.52	18.52	.36	.02	.162	.706
	32	B	13.93	13.87	13.87	13.96	13.87	14.06	.08	6E-03	.038	.707
	50	B	11.02	10.93	11.21	10.93	10.83	11.21	.18	.016	.019	.169
TE12	20	B	13.28	13.3	12.92	13.2	13.58	13.39	.25	.019	.085	.55
	32	B	11.15	11.4	10.83	11.12	11.02	11.4	.25	.022	.019	.121
	50	B	9.84	9.69	9.78	9.59	10.07	10.07	.22	.022	.104	.755

Table B.21. Summary of Results from the BI Trailer on the Asphaltic Concrete Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BUMP INTEGRATOR TRAILER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
CA01	20	R	4.92	4.76	4.92	5.08	.16	.032	.159	1
	20	L	4.82	4.92	4.6	4.92	.18	.038	0	0
	32	R	3.86	3.97	3.81	3.81	.09	.024	-.079	-.866
	32	L	4.02	3.97	3.97	4.13	.09	.023	.079	.866
	50	R	3.49	3.49	3.49	3.49	0	0	0	0
	50	L	3.76	3.81	3.81	3.65	.09	.024	-.079	-.866
CA02	20	R	5.03	5.08	4.92	5.08	.09	.018	0	0
	20	L	5.77	5.72	5.72	5.87	.09	.016	.079	.866
	32	R	4.39	4.29	4.6	4.29	.18	.042	0	0
	32	L	4.97	5.08	4.92	4.92	.09	.018	-.079	-.866
	50	R	3.92	4.13	4.13	3.49	.37	.094	-.317	-.866
	50	L	4.76	4.76	4.92	4.6	.16	.033	-.079	-.5
CA03	20	R	8.57	8.25	8.73	8.73	.27	.032	.238	.866
	20	L	8.47	8.25	8.41	8.73	.24	.029	.238	.982
	32	R	7.83	7.94	7.62	7.94	.18	.023	0	0
	32	L	6.93	7.14	6.67	6.98	.24	.035	-.079	-.327
	50	R	7.04	7.3	6.98	6.83	.24	.034	-.238	-.982
	50	L	6.61	6.67	6.51	6.67	.09	.014	0	0
CA04	20	R	7.25	7.3	7.46	6.98	.24	.033	-.159	-.655
	20	L	7.83	7.78	7.62	8.1	.24	.031	.159	.655
	32	R	6.19	6.19	6.19	6.19	0	0	0	0
	32	L	6.93	6.83	6.98	6.98	.09	.013	.079	.866
	50	R	5.82	5.72	5.72	6.03	.18	.031	.159	.866
	50	L	6.46	6.83	6.19	6.35	.33	.051	-.238	-.721
CA05	20	R	9.15	9.52	8.89	9.05	.33	.036	-.238	-.721
	20	L	9.63	9.21	9.52	10.16	.48	.05	.476	.982
	32	R	8.1	8.1	8.1	8.1	0	0	0	0
	32	L	8.78	8.73	8.73	8.89	.09	.01	.079	.866
	50	R	6.93	6.83	6.98	6.98	.09	.013	.079	.866
	50	L	7.41	7.62	7.3	7.3	.18	.025	-.159	-.866
CA06	20	R	10.37	10.32	10	10.8	.4	.039	.238	.596
	20	L	11.06	11.27	10.64	11.27	.37	.033	0	0
	32	R	9.37	9.37	9.52	9.21	.16	.017	-.079	-.5
	32	L	10.74	10.32	10.95	10.95	.37	.034	.317	.866
	50	R	8.63	8.73	8.41	8.73	.18	.021	0	0
	50	L	9.84	9.84	9.84	9.84	0	0	0	0
CA07	20	R	4.02	3.97	3.97	4.13	.09	.023	.079	.866
	20	L	5.34	5.24	5.4	5.4	.09	.017	.079	.866
	32	R	2.96	3.17	2.86	2.86	.18	.062	-.159	-.866
	32	L	4.18	4.29	4.44	3.81	.33	.079	-.238	-.721
	50	R	2.7	2.7	2.7	2.7	0	0	0	0
	50	L	3.55	3.81	3.49	3.33	.24	.068	-.238	-.982
CA08	20	R	4.18	4.13	4.13	4.29	.09	.022	.079	.866
	20	L	4.71	4.6	4.76	4.76	.09	.019	.079	.866
	32	R	3.07	3.17	3.02	3.02	.09	.03	-.079	-.866
	32	L	4.02	3.97	3.97	4.13	.09	.023	.079	.866
	50	R	2.75	2.86	2.7	2.7	.09	.033	-.079	-.866
	50	L	3.17	3.17	3.17	3.17	0	0	0	0
CA09	20	R	4.97	5.08	4.92	4.92	.09	.018	-.079	-.866
	20	L	6.56	6.83	6.51	6.35	.24	.037	-.238	-.982
	32	R	4.13	4.13	3.97	4.29	.16	.038	.079	.5
	32	L	5.56	5.4	5.72	5.56	.16	.029	.079	.5
	50	R	3.49	3.49	3.65	3.33	.16	.045	-.079	-.5
	50	L	4.5	4.44	4.44	4.6	.09	.02	.079	.866

Table B.21 (Cont.)

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BUMP INTEGRATOR TRAILER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
CA10	20	R	4.44	4.44	4.44	4.44	0	0	0	0
	20	L	6.3	6.35	6.35	6.19	.09	.015	-.079	-.866
	32	R	3.7	3.65	3.81	3.65	.09	.025	0	0
	32	L	5.24	5.08	5.24	5.4	.16	.03	.159	1
	50	R	3.39	3.33	3.33	3.49	.09	.027	.079	.866
	50	L	4.34	4.13	4.44	4.44	.18	.042	.159	.866
CA11	20	R	8.94	9.21	8.89	8.73	.24	.027	-.238	-.982
	20	L	7.94	8.25	7.62	7.94	.32	.04	-.159	-.5
	32	R	7.14	7.14	7.14	7.14	0	0	0	0
	32	L	7.04	6.83	7.14	7.14	.18	.026	.159	.866
	50	R	6.19	6.19	6.03	6.35	.16	.026	.079	.5
	50	L	6.4	6.19	6.51	6.51	.18	.029	.159	.866
CA12	20	R	3.76	3.65	3.97	3.65	.18	.049	0	0
	20	L	4.07	4.29	3.97	3.97	.18	.045	-.159	-.866
	32	R	2.7	2.7	2.7	2.7	0	0	0	0
	32	L	2.54	2.7	2.38	2.54	.16	.063	-.079	-.5
	50	R	2.06	2.06	2.06	2.06	0	0	0	0
	50	L	2.06	2.06	2.06	2.06	0	0	0	0
CA13	20	R	3.55	3.49	3.49	3.65	.09	.026	.079	.866
	20	L	3.86	4.13	3.81	3.65	.24	.063	-.238	-.982
	32	R	2.59	2.54	2.7	2.54	.09	.035	0	0
	32	L	2.7	2.86	2.7	2.54	.16	.059	-.159	-1
	50	R	2.17	2.22	2.22	2.06	.09	.042	-.079	-.866
	50	L	2.22	2.22	2.22	2.22	0	0	0	0

Table B.22. Summary of Results from the BI Trailer on the Surface Treatment Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BUMP INTEGRATOR TRAILER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
TS01	20	R	9.37	9.37	9.52	9.21	.16	.017	-.079	-.5
	20	L	8.94	8.73	9.05	9.05	.18	.02	.159	.866
	32	R	6.77	6.83	6.83	6.67	.09	.014	-.079	-.866
	32	L	6.56	6.83	6.51	6.35	.24	.037	-.238	-.982
	50	R	5.29	5.24	5.08	5.56	.24	.046	.159	.655
	50	L	5.45	5.24	5.72	5.4	.24	.044	.079	.327
TS02	20	R	11.38	11.59	11.43	11.11	.24	.021	-.238	-.982
	20	L	10.69	10.64	10.64	10.8	.09	9E-03	.079	.866
	32	R	8.1	7.94	8.1	8.25	.16	.02	.159	1
	32	L	8.15	8.1	7.94	8.41	.24	.03	.159	.655
	50	R	6.35	6.51	6.19	6.35	.16	.025	-.079	-.5
	50	L	6.14	6.03	6.35	6.03	.18	.03	0	0
TS03	20	R	10.37	10.16	10.48	10.48	.18	.018	.159	.866
	20	L	11.06	11.43	10.8	10.95	.33	.03	-.238	-.721
	32	R	8.25	8.41	8.1	8.25	.16	.019	-.079	-.5
	32	L	8.73	8.89	8.73	8.57	.16	.018	-.159	-1
	50	R	6.77	6.98	6.83	6.51	.24	.036	-.238	-.982
	50	L	7.36	7.46	7.3	7.3	.09	.012	-.079	-.866
TS04	20	R	10.74	10.8	10.8	10.64	.09	9E-03	-.079	-.866
	20	L	9.05	9.05	8.89	9.21	.16	.018	.079	.5
	32	R	8.63	8.57	8.73	8.57	.09	.011	0	0
	32	L	7.41	7.3	7.46	7.46	.09	.012	.079	.866
	50	R	7.36	7.3	7.3	7.46	.09	.012	.079	.866
	50	L	6.35	6.35	6.35	6.35	0	0	0	0
TS05	20	R	11.06	10.95	11.43	10.8	.33	.03	-.079	-.24
	20	L	11.91	12.06	12.06	11.59	.27	.023	-.238	-.866
	32	R	8.89	8.73	9.05	8.89	.16	.018	.079	.5
	32	L	9.84	9.52	10	10	.27	.028	.238	.866
	50	R	7.62	7.62	7.62	7.62	0	0	0	0
	50	L	8.68	8.57	8.89	8.57	.18	.021	0	0
TS06	20	R	5.77	5.87	5.72	5.72	.09	.016	-.079	-.866
	20	L	7.2	7.3	6.98	7.3	.18	.025	0	0
	32	R	4.5	4.6	4.44	4.44	.09	.02	-.079	-.866
	32	L	5.45	5.56	5.4	5.4	.09	.017	-.079	-.866
	50	R	3.7	3.65	3.65	3.81	.09	.025	.079	.866
	50	L	4.13	4.13	4.29	3.97	.16	.038	-.079	-.5
TS07	20	R	5.66	5.72	5.56	5.72	.09	.016	0	0
	20	L	6.35	6.51	6.35	6.19	.16	.025	-.159	-1
	32	R	5.13	5.24	5.24	4.92	.18	.036	-.159	-.866
	32	L	5.08	5.08	5.08	5.08	0	0	0	0
	50	R	4.13	4.13	4.13	4.13	0	0	0	0
	50	L	3.86	3.97	3.81	3.81	.09	.024	-.079	-.866
TS08	20	R	7.990	7.78	7.94	8.25	.24	.03	.238	.982
	20	L	7.73	7.46	7.78	7.94	.24	.031	.238	.982
	32	R	6.24	6.19	6.19	6.35	.09	.015	.079	.866
	32	L	5.93	6.03	5.72	6.03	.18	.031	0	0
	50	R	4.6	4.6	4.6	4.6	0	0	0	0
	50	L	4.39	4.29	4.44	4.44	.09	.021	.079	.866
TS09	20	R	7.83	7.78	7.78	7.94	.09	.012	.079	.866
	20	L	8.1	8.1	8.1	8.1	0	0	0	0
	32	R	6.4	6.35	6.35	6.51	.09	.014	.079	.866
	32	L	6.19	6.35	6.19	6.03	.16	.026	-.159	-1
	50	R	5.29	5.24	5.4	5.24	.09	.017	0	0
	50	L	5.13	5.24	5.08	5.08	.09	.018	-.079	-.866

Table B.22 (Cont.)

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BUMP INTEGRATOR TRAILER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
TS10	20	R	8.2	8.1	8.25	8.25	.09	.011	.079	.866
	20	L	8.41	8.41	8.57	8.25	.16	.019	-.079	-.5
	32	R	6.51	6.67	6.35	6.51	.16	.024	-.079	-.5
	32	L	6.83	6.83	6.83	6.83	0	0	0	0
	50	R	5.13	5.24	4.92	5.24	.18	.036	0	0
	50	L	5.45	5.56	5.4	5.4	.09	.017	-.079	-.866
TS11	20	R	5.66	5.56	5.87	5.56	.18	.032	0	0
	20	L	5.77	5.56	5.72	6.03	.24	.042	.238	.982
	32	R	4.44	4.44	4.44	4.44	0	0	0	0
	32	L	4.39	4.6	4.29	4.29	.18	.042	-.159	-.866
	50	R	3.28	3.17	3.33	3.33	.09	.028	.079	.866
	50	L	3.17	3.33	3.17	3.02	.16	.05	-.159	-1
TS12	20	R	6.14	6.19	6.19	6.03	.09	.015	-.079	-.866
	20	L	6.56	6.51	6.51	6.67	.09	.014	.079	.866
	32	R	4.29	4.13	4.44	4.29	.16	.037	.079	.5
	32	L	4.97	4.92	4.92	5.08	.09	.018	.079	.866
	50	R	3.12	3.17	3.17	3.02	.09	.029	-.079	-.866
	50	L	3.44	3.49	3.33	3.49	.09	.027	0	0

Table B.23. Summary of Results from the BI Trailer on the Gravel Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BUMP INTEGRATOR TRAILER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
GR01	20	R	5.45	5.4	5.4	5.56	.09	.017	.079	.866
	20	L	6.3	6.35	6.35	6.19	.09	.015	-.079	-.866
	32	R	4.02	3.97	3.97	4.13	.09	.023	.079	.866
	32	L	5.24	4.92	5.56	5.24	.32	.061	.159	.5
	50	R	3.39	3.17	3.49	3.49	.18	.054	.159	.866
	50	L	4.55	4.44	4.6	4.6	.09	.02	.079	.866
GR02	20	R	5.93	5.87	5.72	6.19	.24	.041	.159	.655
	20	L	6.4	6.35	6.51	6.35	.09	.014	0	0
	32	R	4.5	4.6	4.44	4.44	.09	.02	-.079	-.866
	32	L	5.45	5.24	5.72	5.4	.24	.044	.079	.327
	50	R	3.39	3.49	3.33	3.33	.09	.027	-.079	-.866
	50	L	4.55	4.44	4.44	4.76	.18	.04	.159	.866
GR03	20	R	12.12	11.91	12.86	11.59	.66	.055	-.159	-.24
	20	L	11.38	11.75	11.27	11.11	.33	.029	-.317	-.961
	32	R	10.11	10.16	10.48	9.68	.4	.04	-.238	-.596
	32	L	11.17	11.27	10.95	11.27	.18	.016	0	0
	50	R	7.78	8.41	7.46	7.46	.55	.071	-.476	-.866
	50	L	10.58	10.48	10.48	10.8	.18	.017	.159	.866
GR04	20	R	10.8	11.27	10.64	10.48	.42	.039	-.397	-.945
	20	L	10.16	10	10.16	10.32	.16	.016	.159	1
	32	R	8.78	8.89	8.57	8.89	.18	.021	0	0
	32	L	9.47	9.84	9.21	9.37	.33	.035	-.238	-.721
	50	R	7.2	7.3	6.98	7.3	.18	.025	0	0
	50	L	9.05	8.73	9.21	9.21	.27	.03	.238	.866
GR05	20	R	13.44	13.49	13.02	13.81	.4	.03	.159	.397
	20	L	16.88	17.3	16.83	16.51	.4	.024	-.397	-.993
	32	R	11.75	11.59	11.59	12.06	.27	.023	.238	.866
	32	L	16.19	16.83	16.35	15.4	.73	.045	-.714	-.982
	50	R	10.95	10.8	11.11	10.95	.16	.014	.079	.5
	50	L	14.76	15.24	15.24	13.81	.82	.056	-.714	-.866
GR06	20	R	14.18	13.97	14.13	14.45	.24	.017	.238	.982
	20	L	15.29	15.4	14.92	15.56	.33	.022	.079	.24
	32	R	13.44	13.49	13.65	13.18	.24	.018	-.159	-.655
	32	L	14.6	14.45	14.45	14.92	.27	.019	.238	.866
	50	R	11.06	11.11	10.95	11.11	.09	8E-03	0	0
	50	L	14.08	13.81	14.29	14.13	.24	.017	.159	.655
GR07	20	R	7.25	6.83	7.46	7.46	.37	.051	.317	.866
	20	L	11.85	11.91	11.59	12.06	.24	.02	.079	.327
	32	R	5.82	5.87	5.72	5.87	.09	.016	0	0
	32	L	10.05	9.68	10.48	10	.4	.04	.159	.397
	50	R	5.08	4.92	5.24	5.08	.16	.031	.079	.5
	50	L	8.52	8.41	8.25	8.89	.33	.039	.238	.721
GR08	20	R	6.77	6.51	6.98	6.83	.24	.036	.159	.655
	20	L	8.41	8.1	8.73	8.41	.32	.038	.159	.5
	32	R	5.08	5.24	4.92	5.08	.16	.031	-.079	-.5
	32	L	6.56	6.67	6.51	6.51	.09	.014	-.079	-.866
	50	R	4.39	4.44	4.29	4.44	.09	.021	0	0
	50	L	6.03	6.03	6.03	6.03	0	0	0	0
GR09	20	R	11.85	11.59	12.22	11.75	.33	.028	.079	.24
	20	L	15.03	14.76	15.4	14.92	.33	.022	.079	.24
	32	R	10.69	10.48	10.64	10.95	.24	.023	.238	.982
	32	L	13.55	13.81	13.49	13.33	.24	.018	-.238	-.982
	50	R	9.31	9.21	9.52	9.21	.18	.02	0	0
	50	L	11.43	11.27	11.75	11.27	.27	.024	0	0

Table B.23 (Cont.)

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BUMP INTEGRATOR TRAILER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
GR10	20	R	8.89	8.57	9.05	9.05	.27	.031	.238	.866
	20	L	12.81	13.02	12.54	12.86	.24	.019	-.079	-.327
	32	R	7.51	7.3	7.94	7.3	.37	.049	0	0
	32	L	11.11	10.95	11.11	11.27	.16	.014	.159	1
	50	R	6.72	6.67	6.83	6.67	.09	.014	0	0
	50	L	10.37	10.48	10.48	10.16	.18	.018	-.159	-.866
GR11	20	R	20.08	20.8	19.37		1.01	.05	-1.429	-1
	20	L	25.64	25.72	25.56		.11	4E-03	-.159	-1
	32	R	19.9	20.64	19.37	19.68	.66	.033	-.476	-.721
	32	L	23.65	23.34	22.23	25.4	1.61	.068	1.032	.64
	50	R	16.35	16.51	16.19		.22	.014	-.317	-1
	50	L	21.99	21.75	22.23		.34	.015	.476	1
GR12	20	R	16.75	16.83	16.67		.11	7E-03	-.159	-1
	20	L	25.08	24.92	25.24		.22	9E-03	.317	1
	32	R	17.09	17.46	16.99	16.83	.33	.019	-.318	-.961
	32	L	24.45	24.45	23.81	25.08	.64	.026	.317	.5
	50	R	13.57	13.49	13.65		.11	8E-03	.159	1
	50	L	22.38	23.65	21.11		1.8	.08	-2.54	-1

Table B.24. Summary of Results from the BI Trailer on the Earth Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BUMP INTEGRATOR TRAILER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
TE01	20	R	7.04	6.67	6.98	7.46	.4	.057	.397	.993
	20	L	10	10	9.84	10.16	.16	.016	.079	.5
	32	R	5.87	5.72	6.03	5.87	.16	.027	.079	.5
	32	L	7.73	7.78	7.46	7.94	.24	.031	.079	.327
	50	R	4.6	4.29	4.6	4.92	.32	.069	.317	1
	50	L	5.98	5.56	6.19	6.19	.37	.061	.317	.866
TE02	20	R	7.73	7.46	7.62	8.1	.33	.043	.317	.961
	20	L	9.52	9.37	9.52	9.68	.16	.017	.159	1
	32	R	5.93	5.87	5.87	6.03	.09	.015	.079	.866
	32	L	7.14	6.98	7.14	7.3	.16	.022	.159	1
	50	R	4.87	4.6	5.08	4.92	.24	.05	.159	.655
	50	L	5.29	5.24	5.24	5.4	.09	.017	.079	.866
TE03	20	R	10.74	10.64	10.32	11.27	.48	.045	.317	.655
	20	L	18.26	18.1	18.57	18.1	.27	.015	0	0
	32	R	8.63	8.57	8.89	8.41	.24	.028	-.079	-.327
	32	L	16.77	17.14	16.35	16.83	.4	.024	-.159	-.397
	50	R	7.62	7.3	7.46	8.1	.42	.055	.397	.945
	50	L	13.86	13.33	14.13	14.13	.46	.033	.397	.866
TE04	20	R	13.92	13.81	13.97	13.97	.09	7E-03	.079	.866
	20	L	16.77	16.83	16.99	16.51	.24	.014	-.159	-.655
	32	R	11.75	11.75	11.43	12.06	.32	.027	.159	.5
	32	L	16.51	16.99	15.87	16.67	.57	.035	-.159	-.277
	50	R	9.95	10	9.68	10.16	.24	.024	.079	.327
	50	L	14.45	14.13	14.45	14.76	.32	.022	.317	1
TE05	20	R	32.17	31.75	32.23	32.54	.4	.012	.397	.993
	20	L	31.59	30.32	32.07	32.38	1.11	.035	1.032	.929
	32	R	27.46	27.46	27.15	27.78	.32	.012	.159	.5
	32	L	25.93	25.08	26.03	26.67	.8	.031	.794	.993
	50	R	23.65	23.5	23.81		.22	9E-03	.317	1
	50	L	21.75	21.91	21.59		.22	.01	-.317	-1
TE06	20	R	37.84	37.78	37.94	37.78	.09	2E-03	0	0
	20	L	40.38	40.48	40.64	40	.33	8E-03	-.238	-.721
	32	R	33.5	33.34	32.86	34.29	.73	.022	.476	.655
	32	L	32.44	31.91	32.23	33.18	.66	.02	.635	.961
	50	R	26.51	26.19	26.83		.45	.017	.635	1
	50	L	26.19	26.51	25.88		.45	.017	-.635	-1
TE07	20	R	8.94	8.73	9.05	9.05	.18	.02	.159	.866
	20	L	9.47	9.68	9.37	9.37	.18	.019	-.159	-.866
	32	R	7.36	7.14	7.62	7.3	.24	.033	.079	.327
	32	L	7.62	7.62	7.62	7.62	0	0	0	0
	50	R	6.24	6.19	6.03	6.51	.24	.039	.159	.655
	50	L	6.67	6.51	6.83	6.67	.16	.024	.079	.5
TE08	20	R	9.58	9.68	9.52	9.52	.09	.01	-.079	-.866
	20	L	9.79	9.68	9.84	9.84	.09	9E-03	.079	.866
	32	R	7.73	7.46	7.78	7.94	.24	.031	.238	.982
	32	L	7.88	7.94	7.78	7.94	.09	.012	0	0
	50	R	6.35	6.35	6.19	6.51	.16	.025	.079	.5
	50	L	6.3	6.19	6.51	6.19	.18	.029	0	0
TE09	20	R	17.25	16.67	17.14	17.94	.64	.037	.635	.99
	20	L	14.29	14.29	14.76	13.81	.48	.033	-.238	-.5
	32	R	12.44	12.22	12.38	12.7	.24	.02	.238	.982
	32	L	13.12	13.02	12.7	13.65	.48	.037	.317	.655
	50	R	7.78	7.62	7.62	8.1	.27	.035	.238	.866
	50	L	9.58	9.21	10.16	9.37	.51	.053	.079	.156

Table B.24 (Cont.)

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BUMP INTEGRATOR TRAILER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
TE10	20	R	21.22	22.38	20.32	20.95	1.06	.05	-.714	-.676
	20	L	24.77	24.76	24.76	24.76	0	0	0	0
	32	R	16.56	16.19	16.51	16.99	.4	.024	.397	.993
	32	L	20.64	20.48	20.48	20.95	.27	.013	.238	.866
	50	R	12.7	12.38	12.86	12.86	.27	.022	.238	.866
	50	L	14.29	14.29	14.76	13.81	.48	.033	-.238	-.5
TE11	20	R	17.41	17.3	17.46	17.46	.09	5E-03	.079	.866
	20	L	23.18	23.34	22.7	23.5	.42	.018	.079	.189
	32	R	13.71	13.97	13.33	13.81	.33	.024	-.079	-.24
	32	L	20.11	20.48	19.68	20.16	.4	.02	-.159	-.397
	50	R	11.8	11.59	11.75	12.06	.24	.021	.238	.982
	50	L	15.98	16.35	16.19	15.4	.51	.032	-.476	-.933
TE12	20	R	20.11	20.32	19.68	20.32	.37	.018	0	0
	20	L	15.24	15.4	15.08	15.24	.16	.01	-.079	-.5
	32	R	18.04	17.94	18.1	18.1	.09	5E-03	.079	.866
	32	L	13.39	13.33	13.33	13.49	.09	7E-03	.079	.866
	50	R	14.02	14.13	13.65	14.29	.33	.024	.079	.24
	50	L	10.69	10.64	10.64	10.8	.09	9E-03	.079	.866

Table B.25. Summary of Results from the BPR Roughometer on the Asphaltic Concrete Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BPR ROUGHOMETER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
CA01	20	R	1.7	1.6	1.59	1.9	.18	.105	.151	.843
	20	L	1.67	1.71	1.6	1.7	.06	.036	-8E-03	-.132
	32	R	2.36	2.24	2.29	2.56	.17	.073	.159	.927
	32	L	2.53	2.7	2.52	2.38	.16	.063	-.159	-.998
	50	R	1.67	1.64	1.57	1.79	.11	.069	.079	.693
	50	L	1.43	1.64	1.6	1.05	.33	.231	-.294	-.889
CA02	20	R	1.45	1.48	1.43	1.44	.02	.017	-.016	-.655
	20	L	2.21	2.25	2.16	2.22	.05	.022	-.016	-.327
	32	R	2.52	2.24	2.44	2.87	.32	.129	.317	.98
	32	L	2.85	3.05	3.03	2.48	.33	.114	-.286	-.878
	50	R	1.78	1.87	1.59	1.87	.16	.093	0	0
	50	L	2.07	2.19	2.19	1.83	.21	.102	-.183	-.866
CA03	20	R	2.97	3.19	2.86	2.87	.19	.063	-.159	-.844
	20	L	4.18	4.27	4.29	3.97	.18	.043	-.151	-.843
	32	R	5.33	5.52	5.06	5.4	.24	.045	-.064	-.267
	32	L	5.82	5.6	6.33	5.51	.45	.078	-.048	-.105
	50	R	4.02	3.75	4.57	3.75	.48	.119	0	0
	50	L	3.55	3.91	3.43	3.32	.31	.088	-.294	-.941
CA04	20	R	2.3	2.56	2.27	2.08	.24	.104	-.238	-.993
	20	L	3.72	3.6	3.97	3.59	.22	.058	-8E-03	-.037
	32	R	4.43	4.48	4.3	4.51	.11	.025	.016	.143
	32	L	5.52	5.6	5.48	5.49	.07	.013	-.056	-.803
	50	R	2.98	3.11	2.84	3	.14	.045	-.056	-.41
	50	L	3.57	3.92	3.51	3.27	.33	.092	-.325	-.988
CA05	20	R	3.74	3.56	3.78	3.87	.16	.044	.159	.974
	20	L	5.49	5.14	5.52	5.79	.33	.06	.325	.995
	32	R	10.75	11.94	10.65	9.65	1.15	.107	-1.143	-.997
	32	L	13.08	12.72	13.45	13.08	.37	.028	.183	.5
	50	R	3.55	3.84	3.41	3.4	.25	.071	-.222	-.881
	50	L	5.31	4.78	4.06	7.08	1.58	.297	1.151	.73
CA06	20	R	4.81	4.98	4.67	4.78	.16	.033	-.103	-.64
	20	L	4.8	5	4.64	4.76	.19	.039	-.119	-.642
	32	R	11.85	11.73	11.53	12.29	.39	.033	.278	.705
	32	L	13.45	13.49	13.33	13.51	.1	7E-03	8E-03	.082
	50	R	4.18	4.11	4.33	4.08	.14	.033	-.016	-.115
	50	L	3.94	5.24	4.59	2	1.71	.435	-1.619	-.945
CA07	20	R	1.06	.95	1.11	1.11	.09	.087	.079	.866
	20	L	1.7	1.97	1.38	1.75	.3	.175	-.111	-.375
	32	R	1.9	1.97	1.86	1.87	.06	.032	-.048	-.792
	32	L	2.13	2.32	1.9	2.16	.21	.098	-.079	-.381
	50	R	.94	.76	.98	1.06	.16	.167	.151	.965
	50	L	1.39	1.32	1.54	1.32	.13	.092	0	0
	80	R	.98	1.06	.98	.89	.09	.089	-.087	-.999
	80	L	1.6	1.35	1.54	1.92	.29	.181	.286	.982
CA08	20	R	1.04	.95	1	1.16	.11	.104	.103	.955
	20	L	1.42	1.3	1.32	1.64	.19	.133	.167	.886
	32	R	1.87	1.86	1.76	1.98	.11	.06	.063	.569
	32	L	2.05	2.21	1.9	2.03	.15	.074	-.087	-.577
	50	R	.77	.75	.78	.79	.02	.031	.024	.982
	50	L	1.15	1.16	1.13	1.16	.02	.016	0	0
	80	R	1.39	1.41	1.44	1.3	.08	.054	-.056	-.741
	80	L	1.31	1.16	1.22	1.54	.2	.156	.191	.933

Table B.25 (Cont.)

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BPR ROUGHOMETER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
CA09	20	R	2.17	2.24	2.17	2.1	.07	.033	-.071	-.998
	20	L	1.56	1.64	1.64	1.41	.13	.082	-.111	-.866
	32	R	1.06	.92	.98	1.27	.19	.176	.175	.939
	32	L	1.64	1.62	1.48	1.81	.17	.102	.095	.569
	50	R	1.11	1.08	1.02	1.24	.11	.103	.079	.693
	50	L	2.3	2.21	2.25	2.44	.13	.055	.119	.945
	80	R	1.22	1.29	1.24	1.14	.07	.06	-.071	-.982
	80	L	2.13	2.03	2.08	2.27	.13	.059	.119	.945
CA10	20	R	1.19	1.11	1.38	1.08	.17	.139	-.016	-.096
	20	L	1.59	1.49	1.62	1.67	.09	.057	.087	.967
	32	R	.8	.81	.73	.86	.06	.08	.024	.371
	32	L	1.83	1.83	1.71	1.95	.12	.065	.063	.533
	50	R	1.21	1.11	1.38	1.13	.15	.126	8E-03	.052
	50	L	1.69	1.56	1.46	2.05	.32	.187	.246	.781
	80	R	1.64	1.68	1.56	1.67	.07	.042	-8E-03	-.115
	80	L	1.65	1.44	2.1	1.41	.39	.233	-.016	-.041
CA11	20	R	3.34	3.21	3.3	3.51	.15	.046	.151	.978
	20	L	3.13	3.21	3.21	2.97	.14	.044	-.119	-.866
	32	R	3.2	3.06	3.13	3.41	.19	.058	.175	.939
	32	L	3.32	2.98	3.41	3.56	.3	.09	.286	.961
	50	R	3.39	3.65	3.51	3	.34	.101	-.325	-.951
	50	L	3.03	3.06	3.03	3	.03	.01	-.032	-1
	80	R	3.34	3.44	3.14	3.43	.17	.051	-8E-03	-.047
	80	L	2.87	2.84	2.67	3.1	.22	.075	.127	.589
CA12	20	R	1.66	1.7	1.65	1.64	.03	.02	-.032	-.961
	20	L	2.05	2.05	2.08	2.03	.02	.012	-8E-03	-.327
	32	R	1.57	1.49	1.6	1.6	.06	.041	.056	.866
	32	L	1.55	1.51	1.62	1.52	.06	.039	8E-03	.132
	50	R	1.21	1.24	1.17	1.22	.03	.027	-8E-03	-.24
	50	L	1.19	1.17	1.21	1.19	.02	.013	8E-03	.5
CA13	20	R	1.59	1.64	1.54	1.6	.05	.03	-.016	-.327
	20	L	1.8	1.86	1.79	1.76	.05	.027	-.048	-.982
	32	R	1.48	1.51	1.46	1.46	.03	.019	-.024	-.866
	32	L	1.59	1.56	1.62	1.59	.03	.02	.016	.5
	50	R	1.29	1.29	1.3	1.27	.02	.012	-8E-03	-.5
	50	L	1.33	1.33	1.32	1.35	.02	.012	8E-03	.5

Table B.26. Summary of Results from the BPR Roughometer on the Surface Treatment Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BPR ROUGHOMETER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
TS01	20	R	5.43	5.59	5.32	5.38	.14	.026	-.103	-.731
	20	L	5.09	4.97	5.08	5.21	.12	.023	.119	.999
	32	R	4.33	4.44	4.06	4.48	.23	.053	.016	.069
	32	L	4.2	4.13	4.29	4.19	.08	.019	.032	.397
	50	R	3.61	3.6	3.51	3.71	.1	.029	.056	.538
	50	L	3.51	3.49	3.6	3.44	.08	.023	-.024	-.292
TS02	20	R	5.92	5.89	5.97	5.89	.05	8E-03	0	0
	20	L	6.42	6.48	6.45	6.35	.07	.01	-.063	-.961
	32	R	5.56	5.6	5.64	5.45	.1	.018	-.079	-.778
	32	L	5.71	5.83	5.86	5.46	.22	.039	-.183	-.828
	50	R	4.06	3.78	4.02	4.4	.31	.077	.31	.991
	50	L	4.08	4.03	4.16	4.05	.07	.017	8E-03	.115
TS03	20	R	6.04	6.13	6.02	5.97	.08	.013	-.079	-.974
	20	L	6.68	6.81	6.65	6.59	.11	.017	-.111	-.971
	32	R	5.11	5.18	5.03	5.11	.07	.014	-.032	-.444
	32	L	6.37	6.6	6.13	6.38	.24	.037	-.111	-.466
	50	R	4.69	4.71	4.78	4.57	.11	.023	-.071	-.676
	50	L	5.23	5.29	5.25	5.14	.08	.014	-.071	-.952
TS04	20	R	8.98	9.32	9.06	8.56	.39	.043	-.381	-.982
	20	L	6.43	5.84	7.35	6.1	.81	.126	.127	.157
	32	R	5.19	5.11	5.3	5.16	.1	.019	.024	.24
	32	L	5.74	5.3	6.14	5.78	.42	.073	.238	.564
	50	R	4.39	4.33	4.37	4.46	.07	.015	.063	.961
	50	L	3.91	3.78	3.91	4.03	.13	.033	.127	1
TS05	20	R	10.17	10.32	10.81	9.38	.73	.071	-.468	-.645
	20	L	9.28	9.21	9.41	9.22	.11	.012	8E-03	.069
	32	R	5.73	5.86	5.62	5.7	.12	.021	-.079	-.655
	32	L	7.08	6.52	7.7	7.02	.59	.083	.246	.417
	50	R	4.93	5.19	4.67	4.92	.26	.053	-.135	-.515
	50	L	5.03	5.1	4.97	5.03	.06	.013	-.032	-.5
TS06	20	R	3.78	3.98	3.71	3.65	.18	.047	-.167	-.942
	20	L	4.47	4.41	4.57	4.43	.09	.02	8E-03	.091
	32	R	3.05	3.03	3.16	2.95	.1	.034	-.04	-.381
	32	L	3.58	3.6	3.6	3.54	.04	.01	-.032	-.866
	50	R	2.36	2.24	2.41	2.43	.11	.045	.095	.901
	50	L	2.66	2.67	2.59	2.73	.07	.027	.032	.444
TS07	20	R	3.8	3.95	3.79	3.67	.14	.038	-.143	-.998
	20	L	4.18	4.41	4.16	3.95	.23	.055	-.23	-.998
	32	R	3.19	3.1	3.25	3.22	.08	.026	.063	.756
	32	L	3.23	3.25	3.22	3.22	.02	6E-03	-.016	-.866
	50	R	2.42	2.46	2.41	2.38	.04	.017	-.04	-.993
	50	L	2.5	2.54	2.46	2.51	.04	.016	-.016	-.397
TS08	20	R	4.79	4.79	4.76	4.83	.03	7E-03	.016	.5
	20	L	4.5	4.49	4.52	4.48	.02	5E-03	-8E-03	-.327
	32	R	3.86	3.91	3.84	3.83	.04	.011	-.04	-.945
	32	L	3.89	3.75	3.97	3.97	.13	.033	.111	.866
	50	R	3.96	3.83	4.05	4	.12	.03	.087	.746
	50	L	4.07	4.13	4.08	4	.06	.016	-.063	-.99

Table B.26 (Cont.)

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BPR ROUGHOMETER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
TS09	20	R	4.57	4.59	4.57	4.56	.02	3E-03	-.016	-1
	20	L	4.61	4.64	4.7	4.51	.1	.021	-.064	-.655
	32	R	3.6	3.57	3.62	3.6	.02	7E-03	.016	.655
	32	L	3.76	3.75	3.76	3.76	.01	2E-03	8E-03	.866
	50	R	3.17	3.17	3.21	3.14	.03	.01	-.016	-.5
	50	L	3.23	3.35	3.16	3.19	.1	.032	-.079	-.778
TS10	20	R	4.51	4.57	4.41	4.56	.09	.019	-8E-03	-.091
	20	L	4.77	4.83	4.76	4.73	.05	.01	-.048	-.982
	32	R	3.56	3.52	3.49	3.67	.09	.026	.071	.768
	32	L	3.85	3.87	3.84	3.83	.02	6E-03	-.024	-.982
	50	R	2.95	2.94	2.94	2.97	.02	6E-03	.016	.866
	50	L	3.27	3.35	3.19	3.27	.08	.024	-.04	-.5
TS11	20	R	3.37	3.4	3.33	3.37	.03	9E-03	-.016	-.5
	20	L	3.27	3.29	3.25	3.27	.02	5E-03	-8E-03	-.5
	32	R	2.58	2.65	2.52	2.57	.06	.025	-.04	-.619
	32	L	2.59	2.54	2.62	2.6	.04	.016	.032	.756
	50	R	1.88	1.92	1.84	1.89	.04	.021	-.016	-.397
	50	L	1.9	1.89	1.89	1.92	.02	.01	.016	.866
TS12	20	R	3.75	3.68	3.79	3.76	.06	.015	.04	.693
	20	L	3.85	3.84	3.83	3.87	.02	6E-03	.016	.655
	32	R	2.66	2.65	2.68	2.64	.02	9E-03	-8E-03	-.327
	32	L	2.93	2.94	2.92	2.94	.01	3E-03	0	0
	50	R	1.88	1.83	1.94	1.89	.06	.03	.032	.569
	50	L	2.1	2.11	2.11	2.08	.02	9E-03	-.016	-.866

Table B.27. Summary of Results from the BPR Roughometer on the Gravel Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BPR ROUGHOMETER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
GR01	20	R	2.91	2.95	2.86	2.91	.05	.016	-.024	-.5
	20	L	3.31	3.29	3.3	3.33	.02	7E-03	.024	.982
	32	R	2.37	2.35	2.37	2.4	.02	.01	.024	.982
	32	L	2.79	2.86	2.73	2.79	.06	.023	-.032	-.5
	50	R	1.9	1.92	1.9	1.89	.02	8E-03	-.016	-1
	50	L	2.42	2.37	2.48	2.41	.06	.023	.024	.427
GR02	20	R	3.22	3.27	3.14	3.25	.07	.021	-8E-03	-.115
	20	L	3.67	3.6	3.86	3.56	.16	.044	-.024	-.147
	32	R	2.67	2.41	2.73	2.87	.24	.088	.23	.977
	32	L	3.03	2.87	3.13	3.08	.14	.045	.103	.764
	50	R	2.15	2.16	2.14	2.14	.01	4E-03	-8E-03	-.866
	50	L	2.67	2.7	2.67	2.65	.02	9E-03	-.024	-.982
GR03	20	R	6.85	6.81	6.79	6.94	.08	.011	.063	.811
	20	L	7.33	7.29	7.41	7.3	.07	9E-03	8E-03	.115
	32	R	5.72	6.05	5.59	5.52	.29	.05	-.262	-.916
	32	L	6.96	6.87	7.16	6.84	.17	.025	-.016	-.091
	50	R	4.04	3.97	4	4.16	.1	.025	.095	.933
	50	L	5.79	5.72	5.84	5.83	.07	.012	.056	.803
GR04	20	R	5.2	5.21	5.25	5.13	.06	.012	-.04	-.619
	20	L	7.16	7.16	7.22	7.11	.06	8E-03	-.024	-.427
	32	R	4.22	4.19	4.21	4.27	.04	.01	.04	.945
	32	L	6.51	6.46	6.57	6.51	.06	9E-03	.024	.427
	50	R	3.59	3.6	3.54	3.64	.05	.013	.016	.327
	50	L	5.78	5.37	5.94	6.05	.37	.063	.341	.932
GR05	20	R	6.66	6.52	6.72	6.75	.12	.018	.111	.924
	20	L	9.61	10.18	9.4	9.26	.5	.052	-.46	-.929
	32	R	6.12	6.3	5.86	6.19	.23	.038	-.056	-.24
	32	L	7.25	7.33	7.1	7.32	.13	.018	-8E-03	-.06
	50	R	4.87	4.81	5.06	4.75	.17	.034	-.032	-.189
	50	L	6.51	6.51			0	0	0	0
GR06	20	R	6.32	6.25	6.46	6.24	.12	.02	-8E-03	-.064
	20	L	7.92	8.11	7.86	7.79	.17	.021	-.159	-.945
	32	R	5.49	5.68	5.54	5.25	.22	.04	-.214	-.982
	32	L	7.33	7.16	7.37	7.48	.16	.022	.159	.985
	50	R	4.27	4.21	4.32	4.27	.06	.013	.032	.569
GR07	20	R	4.65	4.27	4.92	4.76	.34	.073	.246	.725
	20	L	7.19	7.18	7.240	7.14	.05	7E-03	-.016	-.327
	32	R	3.47	3.49	3.41	3.49	.05	.013	0	0
	32	L	6.3	6.24	6.35	6.3	.06	9E-03	.032	.569
	50	R	2.98	3.02	2.97	2.95	.03	.011	-.032	-.961
	50	L	3.84	4.16	3.52		.45	.117	-.635	-1
GR08	20	R	4.16	3.92	4.14	4.41	.25	.059	.246	.998
	20	L	5.45	5.33	5.79	5.22	.3	.056	-.056	-.183
	32	R	3.07	3.08	3	3.14	.07	.023	.032	.444
	32	L	4.06	3.76	4.1	4.33	.29	.071	.286	.995
	50	R	2.55	2.57	2.57	2.49	.05	.018	-.04	-.866
	50	L	3.41	3.37	3.44		.06	.016	.079	1

Table B.27 (Cont.)

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BPR ROUGHOMETER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
GR09	20	R	7.95	7.97	7.95	7.92	.02	3E-03	-.024	-.982
	20	L	9.35	9.29	9.4	9.37	.06	6E-03	.04	.693
	32	R	6.66	6.72	6.68	6.59	.07	.01	-.063	-.961
	32	L	8.61	8.52	8.62	8.7	.09	.01	.087	.999
	50	R	5.55	5.62	5.45	5.59	.09	.017	-.016	-.171
	50	L	6.91	6.91			0	0	0	0
GR10	20	R	6.36	6.48	6.29	6.32	.1	.016	-.079	-.778
	20	L	7.97	7.990	8.020	7.92	.05	6E-03	-.032	-.655
	32	R	4.6	4.65	4.6	4.56	.05	.01	-.048	-1
	32	L	6.95	6.75	7.13	6.98	.19	.028	.119	.619
	50	R	4	4	4.13	3.87	.13	.032	-.063	-.5
	50	L	6.46	6.46			0	0	0	0

Table B.28. Summary of Results from the BPR Roughometer on the Earth Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BPR ROUGHOMETER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
TE01	20	R	4.22	4.08	4.13	4.46	.21	.049	.191	.918
	20	L	5.22	5.19	5.22	5.25	.03	6E-03	.032	1
	32	R	3.55	3.49	3.67	3.48	.11	.03	-8E-03	-.075
	32	L	4.22	4.16	4.32	4.18	.09	.021	8E-03	.091
	50	R	2.7	2.79	2.67	2.64	.08	.031	-.079	-.945
	50	L	3.34	3.4	3.29	3.33	.06	.017	-.032	-.569
TE02	20	R	4.75	4.89	4.75	4.6	.14	.03	-.143	-1
	20	L	4.83	4.78	4.79	4.91	.07	.014	.063	.918
	32	R	3.82	3.89	3.62	3.95	.18	.046	.032	.179
	32	L	3.79	3.79	3.83	3.75	.04	.011	-.024	-.596
	50	R	3.2	3.08	3.37	3.16	.15	.046	.04	.269
	50	L	3.08	3.27	3.02	2.95	.17	.055	-.159	-.945
TE03	20	R	6.47	6.59	6.3	6.52	.15	.023	-.032	-.212
	20	L	10.53	10.51	10.37	10.7	.17	.016	.095	.569
	32	R	5.28	5.41	5.3	5.13	.14	.027	-.143	-.992
	32	L	8.93	8.6	9.16	9.02	.29	.032	.206	.715
	50	R	4.31	4.24	4.25	4.43	.11	.025	.095	.901
	50	L	6.9	7.13	6.62	6.94	.26	.037	-.095	-.371
TE04	20	R	8.24	8.06	8.3	8.37	.16	.019	.151	.948
	20	L	11.21	11.08	11.49	11.05	.25	.022	-.016	-.064
	32	R	6.58	6.22	6.56	6.97	.37	.057	.373	.998
	32	L	9.17	9	8.97	9.54	.32	.035	.27	.84
	50	R	5.41	5.86	4.91	5.48	.48	.089	-.19	-.397
	50	L	7.13	6.86	7.41	7.11	.28	.039	.127	.457
TE05	20	R	19.22	21.65	20.54	15.48	3.29	.171	-3.088	-.938
	32	R	16.45	16.62	16.29		.24	.014	-.333	-1
TE06	20	R	22.05	22.65	25.88	17.62	4.16	.189	-2.516	-.605
	32	R	19.4	18.29	20.51		1.57	.081	2.222	1
TE07	20	R	5.35	5.41	5.35	5.29	.06	.012	-.063	-1
	20	L	5.94	6	6.16	5.67	.25	.042	-.167	-.664
	32	R	4.4	4.51	4.35	4.35	.09	.021	-.079	-.866
	32	L	4.82	4.87	4.79	4.78	.05	.011	-.048	-.933
	50	R	3.48	3.48			0	0	0	0
TE08	20	R	6.02	6	5.92	6.13	.1	.017	.063	.61
	20	L	5.89	5.76	5.86	6.05	.15	.025	.143	.982
	32	R	4.75	4.64	4.76	4.86	.11	.023	.111	.997
	32	L	4.99	4.95	5.14	4.87	.14	.028	-.04	-.286
	50	R	3.54	3.54			0	0	0	0
TE09	20	R	11.63	12.57	11.46	10.84	.88	.075	-.865	-.987
	20	L	12.06	12.26	11.7	12.22	.31	.026	-.016	-.051
	32	R	8.2	7.84	8.27	8.48	.32	.04	.317	.98
	32	L	9.22	8.87	9.37	9.43	.3	.033	.278	.913
	50	R	5.37	5.37			0	0	0	0

Table B.28 (Cont.)

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

BPR ROUGHOMETER

SITE	SPEED (K/H)	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X 1000) MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
TE10	20	R	16.1	16.3	16.35	15.64	.4	.025	-.333	-.835
	20	L	15.01	15.07	15.18	14.8	.2	.013	-.135	-.689
	32	R	11.48	11.45	11.46	11.54	.05	4E-03	.048	.933
	32	L	12.55	13.05	12.22	12.38	.44	.035	-.333	-.761
	50	R	5.84	5.84			0	0	0	0
TE11	20	R	12.14	12.16	12.21	12.06	.07	6E-03	-.048	-.655
	20	L	17.4	17.4			0	0	0	0
	32	R	9.4	9.54	9.49	9.18	.2	.021	-.183	-.92
	32	L	14.07	14.02	14.11		.07	5E-03	.095	1
TE12	20	R	11.73	11.86	11.3	12.02	.38	.032	.079	.212
	20	L	11.4	11.4			0	0	0	0
	32	R	9.23	9.48	9.1	9.13	.21	.023	-.175	-.826

Table B.29. Summary of All ARS Numerics Obtained Directly with RTRRMSs at 20 km/h.

Site	Opala Cars with Modified Maysmeters			Caravan Car with 2 meters		BI Trailer (Wheeltrack)			BPR Roughometer (Wheeltrack)		
	MM 01	MM 02	MM 03	BI	NAASRA	Left	Right	Ave.	Left	Right	Ave.
CA01	2.54	2.56	2.65	2.16	1.98	4.82	4.92	4.87	1.67	1.70	1.69
CA02	3.26	3.80	3.98	3.11	3.15	5.77	5.03	5.40	2.21	1.45	1.83
CA03	6.01	6.57	6.64	6.19	6.29	8.47	8.57	8.52	4.18	2.97	3.57
CA04	5.34	5.95	5.98	5.43	5.34	7.83	7.25	7.54	3.72	2.30	3.01
CA05	7.47	7.75	7.59	7.27	7.22	9.63	9.15	9.39	5.49	3.74	4.61
CA06	7.77	8.79	8.74	8.13	8.15	11.06	10.37	10.72	4.80	4.81	4.80
CA07	2.10	2.16	1.37	1.78	1.48	5.34	4.02	4.68	1.70	1.06	1.38
CA08	2.00	1.78	1.19	1.75	1.41	4.71	4.18	4.44	1.42	1.04	1.23
CA09	3.60	3.65	3.86	3.11	3.02	6.56	4.97	5.77	1.56	2.17	1.87
CA10	2.81	2.91	3.09	2.51	2.30	6.30	4.44	5.37	1.59	1.19	1.39
CA11	6.43	6.66	6.31	6.16	6.29	7.94	8.94	8.44	3.13	3.34	3.23
CA12	1.23	0.80	0.57	0.95	0.80	4.07	3.76	3.92	2.05	1.66	1.86
CA13	1.16	1.11	0.94	0.98	0.78	3.86	3.55	3.70	1.80	1.59	1.70
TS01	7.47	7.69	7.58	6.54	6.59	8.94	9.37	9.15	5.09	5.43	5.26
TS02	9.39	9.83	8.95	8.19	8.21	10.69	11.38	11.03	6.42	5.92	6.17
TS03	8.73	9.56	9.87	8.70	8.45	11.06	10.37	10.72	6.68	6.04	6.36
TS04	8.17	8.26	9.80	7.68	7.68	9.05	10.74	9.90	6.43	8.98	7.70
TS05	9.47	10.66	10.95	9.75	9.50	11.91	11.06	11.48	9.28	10.17	9.73
TS06	4.69	4.64	5.51	4.51	4.71	7.20	5.77	6.48	4.47	3.78	4.13
TS07	3.90	3.97	5.27	4.00	4.12	6.35	5.66	6.01	4.18	3.80	3.99
TS08	5.36	5.61	5.47	4.86	5.00	7.73	7.99	7.86	4.50	4.79	4.65
TS09	5.60	5.89	5.91	5.49	5.55	8.10	7.83	7.96	4.61	4.57	4.59
TS10	5.85	6.06	5.91	5.43	5.53	8.41	8.20	8.31	4.77	4.51	4.64
TS11	3.71	3.57	2.30	2.67	2.60	5.77	5.66	5.72	3.27	3.37	3.32
TS12	3.67	3.47	1.58	3.24	3.08	6.56	6.14	6.35	3.85	3.75	3.80
GR01	3.81	3.72	3.19	2.98	2.51	6.30	5.45	5.87	3.31	2.91	3.11
GR02	4.12	4.47	3.30	3.59	3.27	6.40	5.93	6.16	3.67	3.22	3.45
GR03	10.23	11.40	7.29	10.13	9.58	11.38	12.12	11.75	7.33	6.85	7.09
GR04	8.14	9.36	5.79	8.45	7.81	10.16	10.80	10.48	7.16	5.20	6.18
GR05	13.40	15.42	17.67	12.73	12.29	16.88	13.44	15.16	9.61	6.66	8.14
GR06	12.34	13.39	15.48	12.89	12.67	15.29	14.18	14.74	7.92	6.32	7.12
GR07	8.52	8.22	9.80	7.40	7.03	11.85	7.25	9.55	7.19	4.65	5.92
GR08	5.76	5.47	7.44	4.95	4.81	8.41	6.77	7.59	5.45	4.16	4.80
GR09	12.27	12.18	13.79	11.81	11.29	15.03	11.85	13.44	9.35	7.95	8.65
GR10	9.48	10.09	10.88	8.99	8.59	12.81	8.89	10.85	7.97	6.36	7.17
GR11	21.73	18.65	18.62	18.89	18.90	25.64	20.08	22.86	....	....	....
GR12	24.30	20.21	20.74	19.21	18.89	25.08	16.75	20.92	....	....	....
TE01	6.67	7.54	8.41	6.45	6.21	10.00	7.04	8.52	5.22	4.22	4.72
TE02	6.44	7.12	7.89	6.00	5.60	9.52	7.73	8.63	4.83	4.75	4.79
TE03	12.60	14.04	14.94	12.70	12.14	18.26	10.74	14.50	10.53	6.47	8.50
TE04	13.05	14.67	15.36	13.84	13.17	16.77	13.92	15.35	11.21	8.24	9.73
TE05	19.09	26.88	24.59	24.54	24.23	31.59	32.17	31.88	....	19.22	19.22
TE06	....	33.45	32.20	32.51	32.34	40.38	37.84	39.11	....	22.05	22.05
TE07	4.03	7.61	8.76	6.92	6.54	9.47	8.94	9.21	5.94	5.35	5.65
TE08	4.85	8.41	9.94	6.70	6.46	9.79	9.58	9.68	5.89	6.02	5.95
TE09	12.41	16.13	17.18	13.68	13.07	14.29	17.25	15.77	12.06	11.63	11.84
TE10	17.77	22.23	19.62	19.27	18.68	24.76	21.22	22.99	15.01	16.10	15.55
TE11	19.60	21.13	16.80	18.70	18.34	23.18	17.41	20.29	17.40	12.14	14.77
TE12	15.92	16.91	17.13	13.49	13.28	15.24	20.11	17.67	11.40	11.73	11.56

Table B.30. Summary of All ARS Numerics Obtained Directly with RTRRMSs at 32 km/h.

Site	Opala Cars with Modified Maysmeters			Caravan Car with 2 meters		BI Trailer (Wheeltrack)			BPR Roughometer (Wheeltrack)		
	MM 01	MM 02	MM 03	BI	NAASRA	Left	Right	Ave.	Left	Right	Ave.
CA01	3.13	3.68	3.83	2.98	3.02	4.02	3.86	3.94	2.53	2.36	2.45
CA02	3.78	4.53	4.11	4.03	3.93	4.97	4.39	4.68	2.85	2.52	2.69
CA03	6.12	7.37	4.94	6.57	6.54	6.93	7.83	7.38	5.82	5.33	5.57
CA04	5.86	6.91	6.54	6.13	6.10	6.93	6.19	6.56	5.52	4.43	4.98
CA05	7.27	8.32	6.76	7.91	7.56	8.78	8.10	8.44	13.08	10.75	11.91
CA06	7.50	9.26	8.62	8.60	8.40	10.74	9.37	10.05	13.45	11.85	12.65
CA07	2.11	2.36	3.06	2.35	2.11	4.18	2.96	3.57	2.13	1.90	2.01
CA08	1.75	1.71	2.06	1.87	1.77	4.02	3.07	3.55	2.05	1.87	1.96
CA09	3.47	3.78	3.66	3.52	3.31	5.56	4.13	4.84	1.64	1.06	1.35
CA10	2.98	3.48	3.71	3.05	2.87	5.24	3.70	4.47	1.83	0.80	1.31
CA11	6.72	7.03	6.78	6.41	6.48	7.04	7.14	7.09	3.32	3.20	3.26
CA12	1.32	1.22	0.42	1.27	1.03	2.54	2.70	2.62	1.55	1.57	1.56
CA13	1.14	1.38	0.65	1.24	1.10	2.70	2.59	2.65	1.59	1.48	1.53
TS01	5.72	6.22	5.61	5.84	5.66	6.56	6.77	6.67	4.20	4.33	4.27
TS02	7.44	8.39	7.40	7.33	7.11	8.15	8.10	8.12	5.72	5.56	5.64
TS03	7.68	8.28	8.07	7.72	7.79	8.73	8.26	8.49	6.37	5.11	5.74
TS04	7.85	8.43	8.31	7.21	7.05	7.41	8.63	8.02	5.74	5.19	5.47
TS05	8.53	9.44	10.04	8.00	7.98	9.84	8.89	9.37	7.08	5.73	6.40
TS06	3.84	4.22	4.22	4.00	3.86	5.45	4.50	4.97	3.58	3.05	3.32
TS07	3.72	4.25	4.58	3.68	3.74	5.08	5.13	5.11	3.23	3.19	3.21
TS08	4.51	4.65	4.48	4.29	4.14	5.93	6.24	6.09	3.89	3.86	3.88
TS09	5.25	5.60	4.78	5.05	4.96	6.19	6.40	6.30	3.76	3.60	3.68
TS10	5.15	5.61	5.12	5.08	4.98	6.83	6.51	6.67	3.85	3.56	3.70
TS11	3.11	3.20	1.92	2.98	2.72	4.39	4.44	4.42	2.59	2.58	2.58
TS12	3.15	3.44	1.80	3.18	2.94	4.97	4.29	4.63	2.93	2.66	2.79
GR01	3.68	3.58	2.60	3.14	2.85	5.24	4.02	4.63	2.79	2.37	2.58
GR02	3.90	3.76	2.52	3.52	3.17	5.45	4.50	4.97	3.03	2.67	2.85
GR03	8.70	9.94	5.87	8.89	8.32	11.17	10.11	10.64	6.96	5.72	6.34
GR04	7.25	7.90	4.46	7.27	6.84	9.47	8.78	9.13	6.51	4.22	5.37
GR05	12.71	15.17	16.86	12.41	11.88	16.19	11.75	13.97	7.25	6.12	6.68
GR06	11.12	12.96	14.08	11.43	11.10	14.60	13.44	14.02	7.33	5.49	6.41
GR07	7.64	7.49	7.92	6.73	6.40	10.05	5.82	7.94	6.30	3.47	4.88
GR08	4.89	4.95	5.31	4.35	4.10	6.56	5.08	5.82	4.06	3.07	3.57
GR09	10.88	10.71	11.09	10.13	9.78	13.55	10.69	12.12	8.61	6.66	7.64
GR10	8.58	8.87	9.11	7.75	7.56	11.11	7.51	9.31	6.95	4.60	5.78
GR11	26.92	19.59	20.29	18.38	18.03	23.65	19.90	21.78	....	....	....
GR12	18.15	21.62	20.56	18.89	18.24	24.45	17.09	20.77	....	....	....
TE01	5.26	5.96	6.43	5.68	5.05	7.73	5.87	6.80	4.22	3.55	3.88
TE02	5.09	5.76	6.02	5.11	4.96	7.14	5.93	6.54	3.79	3.82	3.80
TE03	11.11	12.77	12.15	12.16	11.21	16.77	8.63	12.70	8.93	5.28	7.10
TE04	11.24	12.91	13.12	13.53	11.89	16.51	11.75	14.13	9.17	6.58	7.88
TE05	15.79	23.88	19.11	21.18	20.63	25.93	27.46	26.70	....	16.45	16.45
TE06	....	29.46	26.31	27.40	26.94	32.44	33.50	32.97	....	19.40	19.40
TE07	5.11	7.06	7.63	6.48	6.04	7.62	7.36	7.49	4.82	4.40	4.61
TE08	5.77	7.54	7.85	6.22	5.89	7.88	7.73	7.81	4.99	4.75	4.87
TE09	10.92	12.76	12.81	10.86	10.26	13.12	12.44	12.78	9.22	8.20	8.71
TE10	14.40	17.70	17.08	15.43	14.78	20.64	16.56	18.60	12.55	11.48	12.02
TE11	16.60	17.22	12.69	14.54	13.93	20.11	13.71	16.91	14.07	9.40	11.73
TE12	14.12	14.62	13.08	11.40	11.15	13.39	18.04	15.72	....	9.23	9.23

Table B.31. Summary of All ARS Numerics Obtained Directly with RTRRMSs at 50 km/h.

Site	Opala Cars with Modified Maysmeters			Caravan Car with 2 meters		BI Trailer (Wheeltrack)			BPR Roughometer (Wheeltrack)		
	MM 01	MM 02	MM 03	BI	NAASRA	Left	Right	Ave.	Left	Right	Ave.
CA01	3.92	5.03	5.55	3.97	3.97	3.76	3.49	3.62	1.43	1.67	1.55
CA02	4.32	5.11	5.40	4.95	4.69	4.76	3.92	4.34	2.07	1.78	1.92
CA03	5.70	7.45	6.17	7.33	6.71	6.61	7.04	6.83	3.55	4.02	3.79
CA04	5.98	7.11	6.74	6.48	6.18	6.46	5.82	6.14	3.57	2.98	3.28
CA05	6.98	5.21	7.63	7.87	7.11	7.41	6.93	7.17	5.31	3.55	4.43
CA06	7.43	8.72	9.14	9.62	8.42	9.84	8.63	9.23	3.94	4.18	4.06
CA07	2.62	2.72	2.81	2.57	2.49	3.55	2.70	3.12	1.39	0.94	1.16
CA08	2.31	2.31	2.31	2.25	2.15	3.18	2.75	2.96	1.15	0.77	0.96
CA09	3.79	3.98	4.13	3.97	3.72	4.50	3.49	4.00	2.30	1.11	1.71
CA10	3.44	3.88	3.87	3.71	3.46	4.34	3.39	3.86	1.69	1.21	1.45
CA11	5.70	6.21	6.19	6.22	5.97	6.40	6.19	6.30	3.03	3.39	3.21
CA12	1.26	1.30	1.03	1.59	1.39	2.06	2.06	2.06	1.19	1.21	1.20
CA13	1.36	1.31	1.09	1.56	1.35	2.22	2.17	2.20	1.33	1.29	1.31
TS01	5.21	5.46	5.60	5.46	5.47	5.45	5.29	5.37	3.51	3.61	3.56
TS02	5.62	6.63	6.14	6.29	6.04	6.14	6.35	6.24	4.08	4.06	4.07
TS03	6.90	7.78	8.35	7.24	7.18	7.36	6.77	7.06	5.23	4.69	4.96
TS04	6.33	6.86	7.18	6.76	6.74	6.35	7.36	6.85	3.91	4.39	4.15
TS05	7.05	7.72	8.04	7.49	7.45	8.68	7.62	8.15	5.03	4.93	4.98
TS06	3.48	3.42	3.66	3.49	3.34	4.13	3.70	3.92	2.66	2.36	2.51
TS07	3.41	3.61	3.66	3.43	3.32	3.86	4.13	4.00	2.50	2.42	2.46
TS08	3.38	3.80	3.94	3.59	3.52	4.39	4.60	4.50	4.07	3.96	4.01
TS09	5.05	5.21	5.23	4.83	4.67	5.13	5.29	5.21	3.23	3.18	3.20
TS10	4.66	5.30	5.35	4.98	4.75	5.45	5.13	5.29	3.27	2.95	3.11
TS11	2.34	2.51	3.04	2.51	2.28	3.18	3.28	3.23	1.90	1.88	1.89
TS12	2.43	2.38	3.12	2.51	2.38	3.44	3.12	3.28	2.10	1.88	1.99
GR01	2.80	3.24	2.25	3.05	2.77	4.55	3.39	3.97	2.42	1.90	2.16
GR02	3.25	3.33	2.08	3.27	2.96	4.55	3.39	3.97	2.67	2.15	2.41
GR03	7.49	8.85	8.19	8.06	7.64	10.58	7.78	9.18	5.79	4.04	4.92
GR04	6.45	7.54	6.43	6.98	6.59	9.05	7.20	8.12	5.78	3.59	4.69
GR05	11.15	13.71	14.58	12.16	11.59	14.76	10.95	12.86	6.51	4.87	5.69
GR06	10.13	11.69	11.98	11.49	10.94	14.08	11.06	12.57	....	4.27	4.27
GR07	6.79	7.18	7.24	6.57	6.18	8.52	5.08	6.80	3.84	2.98	3.41
GR08	4.28	4.35	4.48	4.13	3.86	6.03	4.39	5.21	3.41	2.55	2.98
GR09	9.53	10.00	10.12	9.40	8.84	11.43	9.31	10.37	6.91	5.55	6.23
GR10	7.57	8.68	9.65	7.37	7.20	10.37	6.72	8.55	6.46	4.00	5.23
GR11	18.57	20.31	20.19	18.00	18.51	21.99	16.35	19.17	....	....	....
GR12	17.01	19.58	19.91	17.49	17.90	22.38	13.57	17.98	....	....	....
TE01	4.39	4.88	4.82	4.79	4.29	5.98	4.60	5.29	3.34	2.70	3.02
TE02	4.07	4.31	4.83	4.38	4.31	5.29	4.87	5.08	3.08	3.20	3.14
TE03	8.30	9.26	9.12	11.05	8.91	13.86	7.62	10.74	6.90	4.31	5.60
TE04	8.60	10.07	9.57	12.67	9.98	14.45	9.95	12.20	7.13	5.41	6.27
TE05	14.75	20.55	21.47	20.83	20.06	21.75	23.65	22.70	....	....	....
TE06	....	25.70	28.11	26.48	25.88	26.19	26.51	26.35	....	....	....
TE07	5.31	5.92	6.90	5.81	5.36	6.67	6.24	6.46	....	3.48	3.48
TE08	5.56	6.12	6.94	6.03	5.68	6.30	6.35	6.32	....	3.54	3.54
TE09	8.84	9.19	10.35	9.33	8.82	9.58	7.78	8.68	....	5.37	5.37
TE10	12.23	12.87	13.60	13.27	12.64	14.29	12.70	13.49	....	5.84	5.84
TE11	11.34	12.36	11.18	11.59	11.02	15.98	11.80	13.89	....	....	....
TE12	9.99	10.74	9.47	10.16	9.84	10.69	14.02	12.36	....	....	....

Table B.32. Summary of All ARS Numerics Obtained Directly with RTRRMSs at 80 km/h.

Site	Opala Cars with Modified Maysmeters			Caravan Car with 2 meters		BI Trailer (Wheeltrack)			BPR Roughometer (Wheeltrack)		
	MM 01	MM 02	MM 03	BI	NAASRA	Left	Right	Ave.	Left	Right	Ave.
CA01	4.29	4.91	5.19	6.32	5.60	....	....	....	....	....	....
CA02	4.50	5.16	5.11	6.35	5.72	....	....	....	....	....	....
CA03	6.18	7.78	6.00	10.57	8.07	....	....	....	....	....	....
CA04	5.55	6.32	5.74	7.62	6.54	....	....	....	....	....	....
CA05	6.50	7.68	6.65	10.51	8.19	....	....	....	....	....	....
CA06	7.53	9.32	8.77	13.72	9.82	....	....	....	....	....	....
CA07	3.00	2.85	3.04	4.19	3.82	....	....	....	1.60	0.98	1.29
CA08	2.89	2.87	3.19	4.29	3.74	....	....	....	1.31	1.39	1.35
CA09	4.25	4.29	4.85	5.52	5.00	....	....	....	2.13	1.22	1.67
CA10	3.72	3.95	4.34	5.24	4.64	....	....	....	1.65	1.64	1.64
CA11	5.95	6.45	6.83	6.70	6.42	....	....	....	2.87	3.34	3.10
CA12	1.96	1.46	1.66	....	....	....	....	....	....	....	....
CA13	2.09	1.72	1.94	....	....	....	....	....	....	....	....
TS01	6.14	7.01	7.41	....	....	....	....	....	....	....	....
TS02	4.92	5.52	5.23	....	....	....	....	....	....	....	....
TS03	5.90	7.10	7.16	....	....	....	....	....	....	....	....
TS04	7.89	9.23	9.73	....	....	....	....	....	....	....	....
TS05	9.58	11.72	11.91	....	....	....	....	....	....	....	....
TS06	3.22	3.11	3.47	....	....	....	....	....	....	....	....
TS07	3.14	3.30	3.64	....	....	....	....	....	....	....	....
TS08	3.74	4.08	4.39	....	....	....	....	....	....	....	....
TS09	3.93	4.56	3.04	....	....	....	....	....	....	....	....
TS10	4.00	4.72	2.90	....	....	....	....	....	....	....	....
TS11	2.82	2.32	2.27	....	....	....	....	....	....	....	....
TS12	2.79	2.44	1.92	....	....	....	....	....	....	....	....
GR01	3.28	2.86	2.74	....	....	....	....	....	....	....	....
GR02	3.18	3.52	3.08	....	....	....	....	....	....	....	....
GR03	6.58	8.11	7.83	....	....	....	....	....	....	....	....
GR04	5.73	6.52	5.68	....	....	....	....	....	....	....	....
GR05	10.79	12.77	12.23	....	....	....	....	....	....	....	....
GR06	9.25	10.80	10.30	....	....	....	....	....	....	....	....
GR07	5.91	6.39	6.50	....	....	....	....	....	....	....	....
GR08	4.04	4.08	3.83	....	....	....	....	....	....	....	....
GR09	9.19	11.05	11.99	....	....	....	....	....	....	....	....
GR10	8.36	9.64	9.71	....	....	....	....	....	....	....	....
GR11	....	....	....	....	....	....	....	....	....	....	....
GR12	....	....	....	....	....	....	....	....	....	....	....
TE01	4.19	4.49	4.32	....	....	....	....	....	....	....	....
TE02	3.98	4.13	3.77	....	....	....	....	....	....	....	....
TE03	7.02	8.25	7.30	....	....	....	....	....	....	....	....
TE04	6.76	8.35	7.91	....	....	....	....	....	....	....	....
TE05	....	....	....	....	....	....	....	....	....	....	....
TE06	....	....	....	....	....	....	....	....	....	....	....
TE07	3.50	5.37	4.47	....	....	....	....	....	....	....	....
TE08	3.91	5.61	4.28	....	....	....	....	....	....	....	....
TE09	5.06	8.36	7.91	....	....	....	....	....	....	....	....
TE10	7.68	11.25	10.73	....	....	....	....	....	....	....	....
TE11	10.90	10.79	10.57	....	....	....	....	....	....	....	....
TE12	9.16	9.89	8.46	....	....	....	....	....	....	....	....

APPENDIX C

CORRELATIONS BETWEEN RTRRMS MEASURES

In this appendix, the average rectified slope (ARS) measures that were obtained from the response-type road roughness measuring systems (RTRRMSs) are compared between instruments and across operating speed. A number of scatter plots are presented that show how the different RTRRMSs "see" roughness, relative to each other.

A simple correlation exercise was performed, in which the ARS measures from each RTRRMS were regressed against those of the others. The squared correlation cofficients (R-squared) are presented for comparative purposes, and are all based on linear regressions.

Purpose of the Comparisons

It is generally recognized that RTRRMSs change with time. The data obtained in the IRRE should not be used to estimate the measures of one RTRRMS from the measure of another, since the mechanical properties of the participating RTRRMSs are now only historical. Recognizing that there is little merit in attempting to estimate one RTRRMS measure from another, the objective of this appendix is to indicate the best agreement that is possible between two RTRRMSs, by comparing measures made at the same time under the same conditions over the same test sites. This level of agreement establishes a standard against which a calibration methodology can be evaluated.

In this report, the source of error (differences in measures obtained from two systems) are classified into three categories:

Repeatability. Whenever repeated measurements are made, there will not be perfect agreement due to sources that are uncontrolled and random. Because the error is random, it can be reduced by averaging, either by using longer test sites or by making repeated runs.

Calibration Error. The measures from one system are consistently higher than those of the other. If the difference is consistent for a class of measurement conditions, it can be determined experimentally and compensated by using a calibration curve. This is done for a RTRRMS by experimentally determining an equation for estimating the reference measure from the RTRRMS measure. The regression equation is the calibration curve, and the method is a calibration by correlation. If the calibration curve is in error then the calibrated measures will be biased.

Reproducibility. Even when two systems are properly calibrated to a reference, and repeat measures are made to eliminate the effect of random error, the measures obtained with one system will generally not be perfectly reproduced by another. This error exists because no two RTRRMSs respond exactly the same to road roughness. If a number of roads are measured with two RTRRMSs, they will be ranked in a different order. No amount of rescaling or manipulating of data can avoid the fact that two roads can be ranked differently by two RTRRMSs.

This appendix deals with the reproducibility error, which cannot be eliminated by calibration. If a calibration reference is "perfect" for one RTRRMS, then it must have a correlation with another RTRRMS that is no better than the correlation that exists directly between the two RTRRMSs. (And since a "perfect" calibration reference has yet to be found for any RTRRMS, the reproducibility will always be less than what is demonstrated in direct comparisons between RTRRMSs.)

Correlations

Tables C.1 - C.10 (located at the end of this appendix) show the correlation matrices of r-squared values for all simple speed combinations of measurements when the results are segregated by surface type. Tables C.11 - C.14 show correlation matrices that are obtained when the data sub-sets are lumped together by surface type and speed. Before calculating linear regression equations between the different measures, the measures obtained from the trailers (Bump Integrator Trailer and BPR Roughometer) for each wheel track were used to calculate an average and difference numeric for each section/speed condition. The average of the measures should approximate the roughness input to a vehicle that causes bounce and pitching motions, while the difference is representative of the roll input to a vehicle.

In addition to the correlation tables, a number of scatter plots were prepared and examined, which more directly show the relationships between the ARS measures obtained from the different systems. Some of these plots are also attached at the end of the appendix.

The scatter plots and the correlation tables lead to these observations:

Measurement speed. Correlations between the measures obtained with different systems are best when the two systems are operated at the same test speed. Correlations are degraded when the difference in speed of the two systems is increased. Figure C.1 compares measures made at different speeds. In all of the plots shown, regression lines are plotted, based on a quadratic regression using the data points shown in the plot. Figures C.2 - C.5 show similar plots made when ARS measures made at the same speeds are compared. (The figures are attached at the end of the appendix.)

Surface type. When the same speed is used for two RTRRMSs, the regression lines obtained for different surface types are nearly the same, indicating that the underlying relationship is not influenced strongly by surface type.

Distribution of Scatter. The variance about the regression lines is fairly uniform over the entire range of roughness. An assumption of equal scatter over the range is a much better approximation than an assumption of scatter proportional to roughness.

Interaction between speed and surface type. When ARS measures made at different speeds are compared (Fig. C.1), the regression lines for different speeds diverge, and would indicate that scatter increases with roughness if the data for the different surface types were combined. Thus, the interrelationship between scatter and roughness that appears when measures are made at different speeds is not due to random effects, but to an interaction between surface type and measurement speed.

Appendix I shows that the spectral contents of road profiles differ with surface type, and Appendix F shows appproximately the waveband seen by a RTRRMS at the different test speeds. On the unpaved roads, there is more short-wave roughness, which is "seen" more by the RTRRMSs at lower speeds. On the asphaltic concrete (CA) roads, there is relatively little short-wave roughness. Therefore, when a paved and unpaved road have the same roughness when measured at a high speed, the unpaved road will have more roughness input to the RTRRMS at a lower speed.

Choice of roadmeter. Figure C.6 compares the ARS measures from the BI and NAASRA meters mounted in the same vehicle. The agreement is nearly perfect except for a few of the 80 km/h tests. (Comparisons with the other systems indicate that the NAASRA readings are more consistent.) Except for the 80 km/h tests, the BI and NAASRA results are equivalent for all practical purposes, and can be considered to be redundant measures made by one system.

The BPR Roughometer. The BPR Roughometer tends to have the lowest correlation with the other instruments. Not suprisingly, its measures usually agree closest with those of the BI Trailer. The problem appears to be that this RTRRMS was not rugged enough for the conditions included in the IRRE, with the result that many of the readings were faulty due to vehicle damage.

Range of conditions for correlation. Any given instrument has certain combinations of speed and surface type that show either high or low correlations with the other instruments, but overall, no trend is evident. Agreement between the different instruments is more-or-less equivalent over all of the test conditions when the test speeds are equal (with the exception of the BPR Roughometer).

Sum and difference measures. The difference measures obtained from the two trailers do not appear useful for predicting measures made with other systems. The simple average of the roughness measures of the right and left wheeltracks has such a high correlation with the other measures that little can be gained by adding the difference measures to a regression.

Correlation across speed. The form of vehicle response to road roughness that is measured by a roadmeter is the rate of motion of the suspension, technically called the average rectified velocity (ARV). ARV is measured by dividing the accumulated axle-body deflection measured by the roadmeter by the elapsed time of the measurement, yielding a numeric with the units "length/time." The ARV thus measures the severity of vibration (in the vehicle suspension) caused by the road roughness.

When the accumulated deflection is divided by the length of the road test section, the result has the units of average rectified slope (ARS). ARS is not a measure of the vertical deviations in the road surface per unit of road length. Rather, it is the ratio of mean suspension (vibration) velocity to travel velocity. The difference is subtle, but explains why ARV should be used when comparing measures made by different RTRRMSs over a range of speeds.

A simple relationship can usually be found between the responsiveness of one RTRRMS relative to another, but due to nonlinearities in the vehicles, the roadmeters, and also the presence of extra vibration from tire and wheel nonuniformities, the relationship will not be linear and may have an offset, such that a zero reading for one system corresponds to a non-zero reading for the other. The nonlinearities are due to vehicle properties, and are primarily influenced by the amplitude of input as perceived by the vehicle, regardless of the travel speed. This is illustrated in Figure C.7, which shows the ARV measures from different RTRRMSs plotted together for three of the IRRE test speeds. The separate regression equations computed for each speed collapse into a single relation. But because ARS is the ARV rescaled by travel speed, the simple offset that appears in the plots in Figure C.7 will vary with speed when the data are compared as ARS measures. Figure C.8 shows that different relations between ARS measures exist for the different measurement speeds.

The data show that a relationship found between two RTRRMSs when both are operated at one speed will usually be valid at other speeds, if the roadmeter numerics are converted to ARV units.

Table C.1. Correlation Tables of R-Squared Values for 20 km/h.

ASPHALTIC CONCRETE TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9914	.973	.9941	.9928	.9846	4.2E-03	.8821	.1645
MM 02	.9914	1	.9882	.995	.9947	.9846	3.9E-03	.8695	.1553
MM 03	.973	.9882	1	.977	.9803	.9633	3.3E-03	.8467	.1554
BI CAR	.9941	.995	.977	1	.9986	.9921	9.6E-03	.8994	.1594
NAASRA	.9928	.9947	.9803	.9986	1	.9886	.0105	.8968	.1559
BI TRL (AVE)	.9846	.9846	.9633	.9921	.9886	1	5.3E-03	.9038	.1221
BI TRL (DIFF)	4.2E-03	3.9E-03	3.3E-03	9.6E-03	.0105	5.3E-03	1	.0767	.0134
BPR (AVE)	.8821	.8695	.8467	.8994	.8968	.9038	.0767	1	.1506
BPR (DIFF)	.1645	.1553	.1554	.1594	.1559	.1221	.0134	.1506	1

TEST SITES WITH SURFACE TREATMENT

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9908	.882	.9587	.958	.9799	.1136	.7554	.2339
MM 02	.9908	1	.8905	.9767	.9723	.9836	.0917	.78	.1955
MM 03	.882	.8905	1	.9372	.9538	.8453	.2415	.7856	.3544
BI CAR	.9587	.9767	.9372	1	.9964	.9587	.1463	.8336	.2461
NAASRA	.958	.9723	.9538	.9964	1	.9526	.1574	.8172	.2532
BI TRL (AVE)	.9799	.9836	.8453	.9587	.9526	1	.0718	.7648	.1932
BI TRL (DIFF)	.1136	.0917	.2415	.1463	.1574	.0718	1	.2257	.7152
BPR (AVE)	.7554	.78	.7856	.8336	.8172	.7648	.2257	1	.4008
BPR (DIFF)	.2339	.1955	.3544	.2461	.2532	.1932	.7152	.4008	1

GRAVEL SURFACED TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9411	.8338	.9636	.9658	.9605	.6771	.9249	.3483
MM 02	.9411	1	.8775	.9829	.9778	.9559	.5338	.8729	.342
MM 03	.8338	.8775	1	.8619	.8671	.8445	.609	.7069	.4743
BI CAR	.9636	.9829	.8619	1	.999	.9839	.5408	.8979	.2936
NAASRA	.9658	.9778	.8671	.999	1	.9883	.5456	.8889	.2976
BI TRL (AVE)	.9605	.9559	.8445	.9839	.9883	1	.5393	.8685	.3303
BI TRL (DIFF)	.6771	.5338	.609	.5408	.5456	.5393	1	.2513	.4732
BPR (AVE)	.9249	.8729	.7069	.8979	.8889	.8685	.2513	1	.3095
BPR (DIFF)	.3483	.342	.4743	.2936	.2976	.3303	.4732	.3095	1

EARTH (CLAY) SURFACE TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9075	.8263	.8823	.8821	.7933	.2283	.8597	.1563
MM 02	.9075	1	.9653	.9887	.9882	.9722	.0207	.989	1E-04
MM 03	.8263	.9653	1	.9675	.9672	.9653	.0109	.9415	6.8E-03
BI CAR	.8823	.9887	.9675	1	.9996	.9806	.0134	.9666	2E-04
NAASRA	.8821	.9882	.9672	.9996	1	.9837	.012	.9656	0
BI TRL (AVE)	.7933	.9722	.9653	.9806	.9837	1	8E-04	.957	.0102
BI TRL (DIFF)	.2283	.0207	.0109	.0134	.012	8E-04	1	8.5E-03	.5384
BPR (AVE)	.8597	.989	.9415	.9666	.9656	.957	8.5E-03	1	4E-04
BPR (DIFF)	.1563	1E-04	6.8E-03	2E-04	0	.0102	.5384	4E-04	1

Table C.2. Correlation Tables of R-Squared Values for 20 and 32 km/h.

ASPHALTIC CONCRETE TEST SITES

20 32	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF
MM 01	.9838	.983	.9761	.9779	.9813	.9569	7E-03	.841	.1698
MM 02	.971	.9864	.9888	.9776	.9796	.961	.0115	.8537	.1676
MM 03	.8881	.9107	.8997	.8819	.876	.8751	4.2E-03	.6783	.083
BI CAR	.9865	.9955	.9863	.9915	.9908	.9784	9.2E-03	.8816	.1768
NAASRA	.9834	.994	.9863	.989	.9897	.9729	.0118	.8662	.1656
BI TRL (AVE)	.9745	.9838	.9695	.9848	.9796	.9929	3.8E-03	.8874	.1161
BI TRL (DIFF)	.0369	.0469	.0488	.038	.0317	.0546	.4335	2.7E-03	.0138
BPR (AVE)	.7157	.7172	.6872	.738	.7193	.7565	.0699	.8654	.1305
BPR (DIFF)	.5086	.5014	.5094	.5016	.478	.5067	7.9E-03	.5307	.2909

TEST SITES WITH SURFACE TREATMENT

20 32	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.9496	.9507	.9209	.9684	.9628	.9475	.1661	.8537	.3474
MM 02	.9534	.9551	.9239	.9743	.9697	.9469	.1729	.8534	.3308
MM 03	.8617	.883	.9739	.9433	.9497	.8476	.2362	.8764	.3658
BI CAR	.9706	.9716	.9271	.9836	.9791	.9623	.1527	.7992	.2919
NAASRA	.9544	.9625	.9386	.986	.9815	.9494	.1524	.7976	.2841
BI TRL (AVE)	.9352	.9568	.8985	.9719	.9646	.9638	.0965	.8437	.2484
BI TRL (DIFF)	.0645	.0596	.118	.1106	.1061	.0641	.6062	.2963	.5324
BPR (AVE)	.946	.9589	.9163	.9746	.9669	.9432	.1755	.8673	.308
BPR (DIFF)	.3762	.4299	.4428	.5201	.4842	.3987	.1786	.5643	.1526

GRAVEL SURFACED TEST SITES

20 32	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.8627	.8094	.7106	.8635	.8762	.9334	.5104	.8895	.3902
MM 02	.9695	.9832	.8846	.9736	.9736	.9663	.5885	.7976	.373
MM 03	.8843	.9006	.9743	.893	.9017	.9046	.6181	.6424	.4723
BI CAR	.9825	.9757	.8606	.9878	.9893	.9886	.5831	.8501	.3354
NAASRA	.9821	.9728	.8655	.9884	.9907	.9914	.587	.8559	.3409
BI TRL (AVE)	.9679	.9601	.8398	.9859	.9895	.9966	.5339	.8258	.2864
BI TRL (DIFF)	.5681	.4836	.5857	.4462	.4453	.4268	.9303	.2481	.5296
BPR (AVE)	.9247	.8762	.646	.9233	.9099	.8831	.1633	.9745	.2271
BPR (DIFF)	.2409	.1823	.1612	.2345	.2301	.1968	.3712	.3294	.3842

EARTH (CLAY) SURFACE TEST SITES

20 32	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.978	.9029	.8373	.8724	.873	.7828	.2218	.8615	.1643
MM 02	.8685	.9891	.9748	.9896	.9905	.9852	.0142	.97	0
MM 03	.7903	.9477	.9853	.9596	.9575	.9528	8.4E-03	.9168	6.3E-03
BI CAR	.8193	.9573	.9626	.9835	.9822	.9683	.0114	.9229	4E-04
NAASRA	.8268	.966	.9697	.9887	.989	.983	8.2E-03	.9345	1E-04
BI TRL (AVE)	.8147	.97	.9722	.9799	.9825	.9945	3.1E-03	.9482	5.5E-03
BI TRL (DIFF)	.338	.0192	5.5E-03	.0131	.0113	1E-03	.8139	8.7E-03	.7005
BPR (AVE)	.835	.9895	.9573	.9838	.9855	.9876	3.6E-03	.9878	2E-03
BPR (DIFF)	.1644	7E-04	3.6E-03	8E-04	3E-04	8.4E-03	.5222	0	.9788

Table C.3. Correlation Tables of R-Squared Values for 20 and 50 km/h.

ASPHALTIC CONCRETE TEST SITES

20 50	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.9414	.9588	.9654	.9382	.936	.917	3.9E-03	.7745	.1727
MM 02	.7592	.8121	.8412	.7841	.7911	.7729	.0103	.582	.0618
MM 03	.8476	.8795	.8995	.8475	.846	.8329	6.4E-03	.6844	.1004
BI CAR	.9422	.9698	.9791	.958	.9586	.9512	.0135	.8415	.1377
NAASRA	.9381	.9651	.9761	.9487	.9506	.934	.0121	.8034	.1463
BI TRL (AVE)	.9557	.9785	.9685	.9753	.9719	.9807	7.7E-03	.8618	.1042
BI TRL (DIFF)	.1026	.1354	.1482	.1049	.0991	.1222	.4018	.0262	2.6E-03
BPR (AVE)	.9355	.9295	.9204	.9467	.9481	.9232	.0572	.9413	.2639
BPR (DIFF)	.2214	.1855	.1866	.1798	.1706	.163	.0599	.1518	.4813

TEST SITES WITH SURFACE TREATMENT

20 50	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.8722	.8872	.9208	.9389	.9371	.8725	.1435	.7616	.2781
MM 02	.9063	.9208	.9216	.952	.9501	.9123	.1125	.7461	.2534
MM 03	.8582	.8791	.8732	.9241	.9076	.8727	.1219	.7691	.2798
BI CAR	.9233	.9311	.9337	.9632	.9605	.9192	.1445	.7876	.2954
NAASRA	.9174	.9256	.9391	.9626	.9596	.9128	.1524	.7969	.308
BI TRL (AVE)	.8904	.9174	.9166	.9612	.953	.9104	.132	.8832	.2938
BI TRL (DIFF)	.3223	.3348	.4505	.4341	.4161	.3263	.4887	.7306	.6305
BPR (AVE)	.8231	.8575	.8418	.8743	.8748	.8629	.0707	.7157	.1972
BPR (DIFF)	.057	.0499	.1121	.0895	.086	.0616	.2846	.0636	.3317

GRAVEL SURFACED TEST SITES

20 50	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.9723	.94	.8503	.9695	.9757	.9922	.6162	.8863	.4085
MM 02	.9699	.9663	.8619	.9749	.9781	.9892	.595	.8309	.4084
MM 03	.9541	.9666	.9146	.9655	.9694	.9715	.6276	.8322	.4515
BI CAR	.9664	.9693	.8713	.9831	.9866	.9926	.5598	.8031	.3705
NAASRA	.9746	.9553	.8519	.9755	.9805	.992	.583	.8079	.3739
BI TRL (AVE)	.9555	.9656	.856	.9841	.9878	.9958	.5209	.8128	.3205
BI TRL (DIFF)	.8514	.7437	.6769	.7355	.7379	.7166	.8316	.517	.4902
BPR (AVE)	.782	.7662	.5243	.7682	.7465	.7355	.1801	.9283	.2207
BPR (DIFF)	.0821	.1072	7.1E-03	.0774	.0647	.0617	.0875	.2267	.0776

EARTH (CLAY) SURFACE TEST SITES

20 50	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.8804	.9893	.96	.9776	.9796	.9603	.0528	.9769	.0407
MM 02	.7427	.9457	.9576	.9678	.972	.9892	1E-04	.9231	8.8E-03
MM 03	.6112	.9014	.9364	.9354	.9397	.9687	6.4E-03	.8823	.0325
BI CAR	.7023	.914	.9482	.9505	.9508	.9581	1.1E-03	.8776	2.6E-03
NAASRA	.7131	.9316	.9573	.9604	.9639	.9846	2E-04	.9051	.0146
BI TRL (AVE)	.7441	.9301	.9297	.951	.9545	.9706	1.7E-03	.9043	1.4E-03
BI TRL (DIFF)	.3005	6.3E-03	2.6E-03	3.8E-03	2.7E-03	4E-04	.6821	1.8E-03	.661
BPR (AVE)	.8033	.7667	.8528	.83	.8188	.7332	.3319	.6908	.42
BPR (DIFF)	.101	.0198	.0453	.0465	.0433	.0136	.6174	0	.9358

Table C.4. Correlation Tables of R-Squared Values for 20 and 80 km/h.

ASPHALTIC CONCRETE TEST SITES

80 \ 20	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.9471	.9661	.9739	.948	.9498	.9375	6.1E-03	.7837	.115
MM 02	.9141	.9413	.9543	.9251	.9264	.9162	.0177	.776	.1168
MM 03	.8652	.8897	.9046	.8587	.8604	.8586	0	.6634	.0343
BI CAR	.7787	.8202	.8312	.8198	.813	.8437	.2109	.8721	.0456
NAASRA	.8553	.8926	.9124	.8848	.8864	.8902	.2171	.9106	.0532
BI TRL (AVE)	0	0	0	0	0	1	0	0	0
BI TRL (DIFF)	0	0	0	0	0	0	1	0	0
BPR (AVE)	.9701	.9632	.882	.9847	.9797	.9804	.0119	.9557	.5472
BPR (DIFF)	.0658	.0726	.0716	.0471	.0534	.0483	.0478	.094	.3066

TEST SITES WITH SURFACE TREATMENT

80 \ 20	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.7165	.7287	.7582	.772	.7575	.7049	.2051	.9364	.4244
MM 02	.7398	.7592	.798	.8104	.7985	.7398	.1806	.9408	.3912
MM 03	.677	.6891	.7652	.7361	.7259	.6451	.2635	.8952	.4565

GRAVEL SURFACED TEST SITES

80 \ 20	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.9397	.9224	.896	.9074	.9096	.9241	.2666	.8659	.3819
MM 02	.9553	.9448	.8607	.9309	.9308	.9389	.2291	.8942	.3358
MM 03	.9358	.8891	.8525	.8943	.8936	.8933	.2867	.9099	.3003

EARTH (CLAY) SURFACE TEST SITES

80 \ 20	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.8758	.7393	.6014	.725	.7438	.7158	.5714	.6732	.4364
MM 02	.9089	.9688	.9334	.9485	.9546	.9698	.3885	.9409	.2366
MM 03	.9461	.9911	.9114	.9923	.9952	.9781	.3968	.9645	.2881

Table C.5. Correlation Tables of R-Squared Values for 32 km/h.

ASPHALTIC CONCRETE TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9869	.9128	.9854	.9905	.9455	.0187	.6527	.4588
MM 02	.9869	1	.915	.9934	.9966	.9619	.0306	.6988	.4923
MM 03	.9128	.915	1	.9088	.9154	.8905	.0693	.5969	.461
BI CAR	.9854	.9934	.9088	1	.9978	.9786	.038	.7415	.5246
NAASRA	.9905	.9966	.9154	.9978	1	.9715	.0303	.7125	.4882
BI TRL (AVE)	.9455	.9619	.8905	.9786	.9715	1	.0741	.7813	.5432
BI TRL (DIFF)	.0187	.0306	.0693	.038	.0303	.0741	1	.0345	.1724
BPR (AVE)	.6527	.6988	.5969	.7415	.7125	.7813	.0345	1	.7036
BPR (DIFF)	.4588	.4923	.461	.5246	.4882	.5432	.1724	.7036	1

TEST SITES WITH SURFACE TREATMENT

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9949	.9364	.9876	.9828	.9761	.127	.969	.4616
MM 02	.9949	1	.9442	.9878	.984	.9725	.1181	.9721	.4568
MM 03	.9364	.9442	1	.9225	.9364	.9296	.1529	.9414	.5103
BI CAR	.9876	.9878	.9225	1	.9969	.969	.102	.9649	.4718
NAASRA	.9828	.984	.9364	.9969	1	.9706	.0996	.9634	.4962
BI TRL (AVE)	.9761	.9725	.9296	.969	.9706	1	.094	.9634	.4842
BI TRL (DIFF)	.127	.1181	.1529	.102	.0996	.094	1	.1286	.3702
BPR (AVE)	.969	.9721	.9414	.9649	.9634	.9634	.1286	1	.5068
BPR (DIFF)	.4616	.4568	.5103	.4718	.4962	.4842	.3702	.5068	1

GRAVEL SURFACED TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.8406	.8114	.8875	.8956	.9144	.3579	.8807	.2125
MM 02	.8406	1	.9314	.991	.9886	.9749	.5296	.7919	.1366
MM 03	.8114	.9314	1	.9146	.9195	.902	.5723	.5888	.1132
BI CAR	.8875	.991	.9146	1	.9995	.994	.4926	.8643	.1742
NAASRA	.8956	.9886	.9195	.9995	1	.9953	.4914	.8669	.1851
BI TRL (AVE)	.9144	.9749	.902	.994	.9953	1	.4282	.8574	.165
BI TRL (DIFF)	.3579	.5296	.5723	.4926	.4914	.4282	1	.1579	.2026
BPR (AVE)	.8807	.7919	.5888	.8643	.8669	.8574	.1579	1	.3098
BPR (DIFF)	.2125	.1366	.1132	.1742	.1851	.165	.2026	.3098	1

EARTH (CLAY) SURFACE TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.8793	.7989	.8173	.826	.8138	.3379	.8371	.1742
MM 02	.8793	1	.9592	.9797	.9878	.9906	.0166	.9896	0
MM 03	.7989	.9592	1	.9657	.9675	.9608	6.8E-03	.9351	3.6E-03
BI CAR	.8173	.9797	.9657	1	.9967	.9804	.0177	.9565	1E-03
NAASRA	.826	.9878	.9675	.9967	1	.9902	.0112	.9697	0
BI TRL (AVE)	.8138	.9906	.9608	.9804	.9902	1	5E-03	.9817	4.7E-03
BI TRL (DIFF)	.3379	.0166	6.8E-03	.0177	.0112	5E-03	1	4.6E-03	.6449
BPR (AVE)	.8371	.9896	.9351	.9565	.9697	.9817	4.6E-03	1	9E-04
BPR (DIFF)	.1742	0	3.6E-03	1E-03	0	4.7E-03	.6449	9E-04	1

Table C.6. Correlations Tables of R-Squared Values for 32 and 50 km/h.

ASPHALTIC CONCRETE TEST SITES

32 50	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.9649	.978	.9507	.9692	.9728	.9322	.0478	.6754	.5244
MM 02	.8178	.8606	.8459	.8165	.8402	.7904	.0499	.4479	.2541
MM 03	.8879	.9189	.9361	.8965	.9044	.8639	.0439	.6383	.4714
BI CAR	.9494	.9836	.9006	.9783	.9783	.9679	.0542	.7383	.5067
NAASRA	.9604	.9874	.9203	.9749	.98	.9482	.045	.6856	.4731
BI TRL (AVE)	.9425	.9697	.9043	.9759	.9746	.9909	.0685	.7527	.4927
BI TRL (DIFF)	.0891	.1189	.227	.1241	.1132	.1623	.7639	.088	.2072
BPR (AVE)	.9293	.936	.7515	.9441	.9391	.9041	4.3E-03	.7538	.5178
BPR (DIFF)	.1879	.1643	.1439	.1884	.1686	.1664	.1147	.177	.4747

TEST SITES WITH SURFACE TREATMENT

32 50	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.9404	.934	.9102	.9507	.9624	.9246	.1094	.8767	.5049
MM 02	.9582	.9539	.9153	.9709	.9805	.9572	.0738	.9058	.4746
MM 03	.9358	.9211	.8821	.9441	.9563	.9315	.1239	.8856	.5936
BI CAR	.9714	.9681	.9284	.9813	.9866	.9573	.1041	.9198	.4893
NAASRA	.9687	.9634	.9319	.9776	.984	.9528	.114	.9198	.4966
BI TRL (AVE)	.9703	.9639	.9531	.9542	.9622	.9799	.1378	.939	.5466
BI TRL (DIFF)	.4803	.472	.5542	.419	.4277	.4429	.6994	.4852	.6377
BPR (AVE)	.8461	.8206	.8354	.8461	.8567	.8937	.0764	.8829	.4485
BPR (DIFF)	.1081	.0932	.1048	.1166	.1258	.0906	.3716	.088	.304

GRAVEL SURFACED TEST SITES

32 50	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.9442	.9624	.9152	.9851	.9888	.9873	.495	.877	.2385
MM 02	.9138	.9857	.9265	.9932	.9943	.9888	.5029	.8193	.1844
MM 03	.8828	.9802	.9578	.9773	.9803	.9668	.5491	.7867	.2033
BI CAR	.9031	.9864	.9299	.9956	.9966	.9953	.4681	.8141	.1748
NAASRA	.9174	.9815	.9202	.9944	.996	.9948	.4791	.8146	.1814
BI TRL (AVE)	.9108	.9773	.916	.9904	.9924	.9967	.4232	.8276	.1625
BI TRL (DIFF)	.6106	.8033	.7211	.7823	.779	.7341	.7744	.4375	.3603
BPR (AVE)	.7567	.6694	.4755	.72	.7219	.6961	.1887	.904	.249
BPR (DIFF)	.0743	.0596	3.8E-03	.0605	.0589	.0433	.0843	.1758	.1651

EARTH (CLAY) SURFACE TEST SITES

32 50	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.898	.9908	.9454	.9428	.9623	.9663	.1427	.978	.0496
MM 02	.7508	.9769	.945	.975	.9864	.9923	5E-04	.9695	7.8E-03
MM 03	.616	.9345	.9324	.9427	.9583	.9598	7.3E-03	.9343	.0273
BI CAR	.7044	.9544	.9535	.9866	.9843	.9727	4.8E-03	.9281	1.9E-03
NAASRA	.7132	.9651	.952	.9742	.9845	.9869	0	.955	.0127
BI TRL (AVE)	.7513	.9693	.918	.9723	.9779	.9848	8.5E-03	.9539	1.8E-03
BI TRL (DIFF)	.3164	7E-03	1.8E-03	.0107	4.5E-03	9E-04	.8607	4E-04	.6378
BPR (AVE)	.8921	.8511	.859	.9345	.9034	.8443	.4539	.7359	.5536
BPR (DIFF)	.1071	.0623	.0506	.159	.117	.0577	.7812	4.7E-03	.875

Table C.7. Correlation Tables of R-Squared Values for 32 and 80 KM/h.

ASPHALTIC CONCRETE TEST SITES

32 / 80	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.9626	.9779	.9304	.9672	.9742	.9497	.0493	.6572	.4453
MM 02	.9302	.9633	.8909	.9483	.9556	.9349	.0518	.6755	.4411
MM 03	.8865	.8992	.9389	.883	.8942	.8845	.0604	.5764	.3885
BI CAR	.7463	.8335	.6977	.8366	.8262	.8819	9E-04	.8377	.4419
NAASRA	.8538	.9203	.7872	.9098	.9089	.9157	8.5E-03	.7896	.4035
BI TRL (AVE)	0	0	0	0	0	0	0	0	0
BI TRL (DIFF)	0	0	0	0	0	0	0	0	0
BPR (AVE)	.976	.9518	.9384	.9675	.9806	.9683	.6757	.6223	.0721
BPR (DIFF)	.0512	.0515	.0454	.0619	.0486	.0423	1E-04	1.2E-03	.0636

TEST SITES WITH SURFACE TREATMENT

32 / 80	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.8	.7879	.8107	.7523	.7481	.77	.2825	.7767	.4933
MM 02	.8309	.819	.8505	.7865	.7875	.8158	.2541	.8025	.509
MM 03	.746	.7351	.8005	.7057	.7068	.7089	.2832	.7633	.4849

GRAVEL SURFACED TEST SITES

32 / 80	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.9645	.923	.8884	.9255	.9373	.9034	.3249	.8299	.206
MM 02	.9713	.9302	.8507	.9417	.9503	.9213	.2848	.8695	.1928
MM 03	.9445	.8657	.8211	.8919	.9037	.8697	.3259	.8841	.2089

EARTH (CLAY) SURFACE TEST SITES

32 / 80	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.8968	.7804	.522	.6923	.7304	.7673	.6397	.7337	.4027
MM 02	.9555	.9932	.9052	.9127	.9529	.9847	.431	.966	.2613
MM 03	.9528	.9854	.8831	.9358	.9666	.9749	.4294	.9817	.3203

Table C.8. Correlation Tables of R-Squared Values for 50 km/h.

ASPHALTIC CONCRETE TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.8665	.9673	.969	.9841	.9403	.1658	.8709	.208
MM 02	.8665	1	.8921	.8811	.9068	.8522	.1831	.6925	.031
MM 03	.9673	.8921	1	.9358	.9557	.8885	.199	.7639	.1449
BI CAR	.969	.8811	.9358	1	.9937	.982	.1673	.9	.1404
NAASRA	.9841	.9068	.9557	.9937	1	.9673	.1586	.8879	.1438
BI TRL (AVE)	.9403	.8522	.8885	.982	.9673	1	.1686	.8926	.1185
BI TRL (DIFF)	.1658	.1831	.199	.1673	.1586	.1686	1	.0314	.0743
BPR (AVE)	.8709	.6925	.7639	.9	.8879	.8926	.0314	1	.1996
BPR (DIFF)	.208	.031	.1449	.1404	.1438	.1185	.0743	.1996	1

TEST SITES WITH SURFACE TREATMENT

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9849	.9715	.9876	.9889	.9582	.4329	.8047	.1485
MM 02	.9849	1	.9725	.993	.988	.963	.3928	.8361	.1377
MM 03	.9715	.9725	1	.9735	.9749	.9558	.4786	.8234	.2064
BI CAR	.9876	.993	.9735	1	.9981	.9699	.4374	.8229	.1426
NAASRA	.9889	.988	.9749	.9981	1	.97	.4517	.8325	.1483
BI TRL (AVE)	.9582	.963	.9558	.9699	.97	1	.5264	.8601	.1107
BI TRL (DIFF)	.4329	.3928	.4786	.4374	.4517	.5264	1	.3529	.2939
BPR (AVE)	.8047	.8361	.8234	.8229	.8325	.8601	.3529	1	.1007
BPR (DIFF)	.1485	.1377	.2064	.1426	.1483	.1107	.2939	.1007	1

GRAVEL SURFACED TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9907	.9759	.9872	.9922	.9835	.7622	.7401	.0672
MM 02	.9907	1	.9884	.9952	.9961	.991	.7785	.7089	.0829
MM 03	.9759	.9884	1	.9814	.9784	.9763	.784	.6924	.0851
BI CAR	.9872	.9952	.9814	1	.9971	.9963	.7543	.6598	.0404
NAASRA	.9922	.9961	.9784	.9971	1	.9934	.7766	.6662	.0466
BI TRL (AVE)	.9835	.991	.9763	.9963	.9934	1	.7224	.6871	.0527
BI TRL (DIFF)	.7622	.7785	.784	.7543	.7766	.7224	1	.3696	.1371
BPR (AVE)	.7401	.7089	.6924	.6598	.6662	.6871	.3696	1	.4031
BPR (DIFF)	.0672	.0829	.0851	.0404	.0466	.0527	.1371	.4031	1

EARTH (CLAY) SURFACE TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9366	.8743	.884	.9196	.9038	.1437	.7966	.0282
MM 02	.9366	1	.981	.9793	.9963	.9867	1E-04	.8606	.0647
MM 03	.8743	.981	1	.9619	.9886	.9445	.0125	.7537	7.8E-03
BI CAR	.884	.9793	.9619	1	.986	.977	3.4E-03	.9553	.2035
NAASRA	.9196	.9963	.9886	.986	1	.9791	9E-04	.8746	.0675
BI TRL (AVE)	.9038	.9867	.9445	.977	.9791	1	4.4E-03	.9014	.1767
BI TRL (DIFF)	.1437	1E-04	.0125	3.4E-03	9E-04	4.4E-03	1	.5127	.9027
BPR (AVE)	.7966	.8606	.7537	.9553	.8746	.9014	.5127	1	.2403
BPR (DIFF)	.0282	.0647	7.8E-03	.2035	.0675	.1767	.9027	.2403	1

Table C.9. Correlation Tables of R-Squared Values for 50 and 80 km/h.

ASPHALTIC CONCRETE TEST SITES

80 \ 50	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.9818	.898	.9546	.9804	.99	.9615	.1606	.8639	.1591
MM 02	.9643	.9108	.9507	.9832	.9882	.9559	.159	.8557	.1334
MM 03	.9331	.8819	.955	.9158	.9305	.9	.217	.7199	.1158
BI CAR	.8233	.735	.8267	.918	.8828	.9009	.0258	.7989	.0212
NAASRA	.9133	.8126	.9117	.9727	.9589	.9372	6.6E-03	.8721	.0238
BI TRL (AVE)	0	0	0	0	0	0	0	0	0
BI TRL (DIFF)	0	0	0	0	0	0	0	0	0
BPR (AVE)	.9357	.9211	.9054	.9303	.9432	.9834	.4048	.9768	.0364
BPR (DIFF)	.064	.0418	.0628	.0485	.051	.0297	.0767	.0594	.4952

TEST SITES WITH SURFACE TREATMENT

80 \ 50	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.7551	.7141	.7546	.7701	.79	.8336	.6775	.6561	.0696
MM 02	.8061	.7673	.8	.8145	.8331	.8795	.6599	.7061	.0759
MM 03	.6914	.6523	.6938	.7094	.7364	.7678	.6696	.6646	.0719

GRAVEL SURFACED TEST SITES

80 \ 50	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.9596	.9476	.9698	.9213	.9291	.9177	.6089	.7662	.0999
MM 02	.9649	.9513	.9584	.9268	.9334	.9269	.5847	.8063	.1142
MM 03	.934	.8925	.9135	.868	.8735	.8651	.5548	.8217	.1083

EARTH (CLAY) SURFACE TEST SITES

80 \ 50	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	.738	.764	.512	.6083	.6852	.8384	.4695	.812	.3032
MM 02	.9951	.9911	.9132	.8576	.9674	.9331	.3234	.827	.0473
MM 03	.9805	.9762	.9024	.8536	.9567	.9136	.3212	.8206	.0431

Table C.10. Correlation Tables of R-Squared Values for 80 km/h.

ASPHALTIC CONCRETE TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9892	.9599	.8721	.955	0	0	.9368	.0743
MM 02	.9892	1	.94	.9275	.9872	0	0	.9502	.0398
MM 03	.9599	.94	1	.7954	.8831	0	0	.9169	.0476
BI CAR	.8721	.9275	.7954	1	.9712	0	0	.8677	.0444
NAASRA	.955	.9872	.8831	.9712	1	0	0	.9178	.0614
BI TRL (AVE)	0	0	0	0	0	1	0	0	0
BI TRL (DIFF)	0	0	0	0	0	0	1	0	0
BPR (AVE)	.9368	.9502	.9169	.8677	.9178	0	0	1	.0116
BPR (DIFF)	.0743	.0398	.0476	.0444	.0614	0	0	.0116	1

TEST SITES WITH SURFACE TREATMENT

	MM 01	MM 02	MM 03
MM 01	1	.9917	.9629
MM 02	.9917	1	.9453
MM 03	.9629	.9453	1

GRAVEL SURFACED TEST SITES

	MM 01	MM 02	MM 03
MM 01	1	.9918	.9751
MM 02	.9918	1	.9821
MM 03	.9751	.9821	1

EARTH (CLAY) SURFACE TEST SITES

	MM 01	MM 02	MM 03
MM 01	1	.7742	.7666
MM 02	.7742	1	.9707
MM 03	.7666	.9707	1

Table C.11. Correlation Tables of R-Squared Values without Segregating Surface Type.

MEASURES MADE AT 20 K/H

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.917	.8778	.9348	.9366	.8867	.5444	.8853	.2745
MM 02	.917	1	.9552	.9901	.9867	.9719	.3169	.956	.0863
MM 03	.8778	.9552	1	.95	.9483	.9219	.359	.8997	.0925
BI CAR	.9348	.9901	.95	1	.9988	.9817	.3087	.9486	.0822
NAASRA	.9366	.9867	.9483	.9988	1	.9834	.2997	.9458	.0762
BI TRL (AVE)	.8867	.9719	.9219	.9817	.9834	1	.2462	.9408	.0382
BI TRL (DIFF)	.5444	.3169	.359	.3087	.2997	.2462	1	.2237	.4801
BPR (AVE)	.8853	.956	.8997	.9486	.9458	.9408	.2237	1	.0666
BPR (DIFF)	.2745	.0863	.0925	.0822	.0762	.0382	.4801	.0666	1

MEASURES MADE AT 32 K/H

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.8866	.8713	.8907	.8978	.8802	.4513	.7267	.3054
MM 02	.8866	1	.9486	.9902	.9912	.9823	.3019	.8458	.0912
MM 03	.8713	.9486	1	.9411	.9417	.9195	.3271	.7459	.0856
BI CAR	.8907	.9902	.9411	1	.9978	.9846	.2927	.8516	.0991
NAASRA	.8978	.9912	.9417	.9978	1	.9862	.2721	.8574	.0866
BI TRL (AVE)	.8802	.9823	.9195	.9846	.9862	1	.253	.8443	.0612
BI TRL (DIFF)	.4513	.3019	.3271	.2927	.2721	.253	1	.1239	.5201
BPR (AVE)	.7267	.8458	.7459	.8516	.8574	.8443	.1239	1	.0998
BPR (DIFF)	.3054	.0912	.0856	.0991	.0866	.0612	.5201	.0998	1

MEASURES MADE AT 50 K/H

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9696	.9571	.9406	.9657	.9365	.5834	.8012	.1511
MM 02	.9696	1	.9814	.9716	.9871	.974	.3435	.7626	.1474
MM 03	.9571	.9814	1	.9677	.9849	.9562	.2882	.7434	.125
BI CAR	.9406	.9716	.9677	1	.9902	.9831	.3058	.7897	.1708
NAASRA	.9657	.9871	.9849	.9902	1	.981	.2916	.7921	.134
BI TRL (AVE)	.9365	.974	.9562	.9831	.981	1	.3293	.8107	.1929
BI TRL (DIFF)	.5834	.3435	.2882	.3058	.2916	.3293	1	.367	.5473
BPR (AVE)	.8012	.7626	.7434	.7897	.7921	.8107	.367	1	.2275
BPR (DIFF)	.1511	.1474	.125	.1708	.134	.1929	.5473	.2275	1

MEASURES MADE AT 80 K/H

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9349	.9178	.8721	.955	0	0	.9368	.0743
MM 02	.9349	1	.9544	.9275	.9872	0	0	.9502	.0398
MM 03	.9178	.9544	1	.7954	.8831	0	0	.9169	.0476
BI CAR	.8721	.9275	.7954	1	.9712	0	0	.8677	.0444
NAASRA	.955	.9872	.8831	.9712	1	0	0	.9178	.0614
BI TRL (AVE)	0	0	0	0	0	1	0	0	0
BI TRL (DIFF)	0	0	0	0	0	0	1	0	0
BPR (AVE)	.9368	.9502	.9169	.8677	.9178	0	0	1	.0116
BPR (DIFF)	.0743	.0398	.0476	.0444	.0614	0	0	.0116	1

Table C.12. Correlation Tables of R-Squared Values without Segregating Measurement Speeds.

ASPHALTIC CONCRETE TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	0	.9539	.9455	.8383	.947	.8492	.0126	.4949	.2605
MM 02	.9539	1	.9203	.8568	.9438	.8067	.0182	.5304	.2065
MM 03	.9455	.9203	1	.8116	.9147	.7658	.0237	.4021	.2121
BI CAR	.8383	.8568	.8116	1	.954	.7913	.0128	.474	.2185
NAASRA	.947	.9438	.9147	.954	1	.8118	.01	.4935	.2254
BI TRL (AVE)	.8492	.8067	.7658	.7913	.8118	1	.0411	.5083	.252
BI TRL (DIFF)	.0126	.0182	.0237	.0128	.01	.0411	1	.0119	.0445
BPR (AVE)	.4949	.5304	.4021	.474	.4935	.5083	.0119	1	.3956
BPR (DIFF)	.2605	.2065	.2121	.2185	.2254	.252	.0445	.3956	1

TEST SITES WITH SURFACE TREATMENT

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	0	.9783	.9119	.9574	.9615	.8889	.2116	.8181	.3172
MM 02	.9783	1	.9227	.978	.975	.8472	.1823	.8038	.2803
MM 03	.9119	.9227	1	.9291	.9401	.7479	.278	.774	.3875
BI CAR	.9574	.978	.9291	1	.9958	.7991	.2103	.7894	.292
NAASRA	.9615	.975	.9401	.9958	1	.8156	.2215	.7945	.3043
BI TRL (AVE)	.8889	.8472	.7479	.7991	.8156	1	.201	.8645	.3005
BI TRL (DIFF)	.2116	.1823	.278	.2103	.2215	.201	1	.2626	.531
BPR (AVE)	.8181	.8038	.774	.7894	.7945	.8645	.2626	1	.4303
BPR (DIFF)	.3172	.2803	.3875	.292	.3043	.3005	.531	.4303	1

GRAVEL SURFACED TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	0	.9004	.8573	.9256	.9245	.9433	.5227	.834	.2148
MM 02	.9004	1	.9384	.986	.9833	.9593	.5777	.743	.1862
MM 03	.8573	.9384	1	.9166	.9187	.8949	.6214	.6178	.2066
BI CAR	.9256	.986	.9166	1	.9979	.9787	.565	.7431	.1622
NAASRA	.9245	.9833	.9187	.9979	1	.9751	.5786	.7448	.1718
BI TRL (AVE)	.9433	.9593	.8949	.9787	.9751	1	.4982	.8065	.1783
BI TRL (DIFF)	.5227	.5777	.6214	.565	.5786	.4982	1	.1374	.2385
BPR (AVE)	.834	.743	.6178	.7431	.7448	.8065	.1374	1	.3193
BPR (DIFF)	.2148	.1862	.2066	.1622	.1718	.1783	.2385	.3193	1

EARTH (CLAY) SURFACE TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	0	.9114	.8411	.8546	.872	.8349	.2491	.8505	.1822
MM 02	.9114	1	.9561	.968	.9792	.9817	.0195	.9813	.0109
MM 03	.8411	.9561	1	.9502	.9619	.9374	4.8E-03	.934	1.1E-03
BI CAR	.8546	.968	.9502	1	.9945	.9639	.0165	.9298	.0134
NAASRA	.872	.9792	.9619	.9945	1	.9736	9.6E-03	.9474	7.6E-03
BI TRL (AVE)	.8349	.9817	.9374	.9639	.9736	1	8.9E-03	.9643	1E-03
BI TRL (DIFF)	.2491	.0195	4.8E-03	.0165	9.6E-03	8.9E-03	1	.0331	.6188
BPR (AVE)	.8505	.9813	.934	.9298	.9474	.9643	.0331	1	8.2E-03
BPR (DIFF)	.1822	.0109	1.1E-03	.0134	7.6E-03	1E-03	.6188	8.2E-03	1

Table C.13. Correlation Tables of R-Squared Values after Conversion to ARV, without segregating Measurement Speeds.

ASPHALTIC CONCRETE TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9708	.9775	.9428	.9837	.9524	.1431	.5061	.293
MM 02	.9708	1	.9542	.9507	.9743	.9199	.159	.5325	.212
MM 03	.9775	.9542	1	.912	.959	.9141	.1813	.448	.2524
BI CAR	.9428	.9507	.912	1	.9806	.9726	.1587	.4621	.2533
NAASRA	.9837	.9743	.959	.9806	1	.9694	.1463	.4875	.2625
BI TRL (AVE)	.9524	.9199	.9141	.9726	.9694	1	.1648	.5901	.2766
BI TRL (DIFF)	.1431	.159	.1813	.1587	.1463	.1648	1	.0583	.1178
BPR (AVE)	.5061	.5325	.448	.4621	.4875	.5901	.0583	1	.3584
BPR (DIFF)	.293	.212	.2524	.2533	.2625	.2766	.1178	.3584	1

TEST SITES WITH SURFACE TREATMENT

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9902	.9589	.9813	.983	.9751	.288	.8782	.1334
MM 02	.9902	1	.9612	.9847	.9839	.977	.2671	.8922	.1228
MM 03	.9589	.9612	1	.9538	.9596	.9378	.3292	.8829	.1753
BI CAR	.9813	.9847	.9538	1	.9974	.9728	.286	.8821	.1076
NAASRA	.983	.9839	.9596	.9974	1	.9752	.2967	.8851	.1179
BI TRL (AVE)	.9751	.977	.9378	.9728	.9752	1	.3038	.8958	.1141
BI TRL (DIFF)	.288	.2671	.3292	.286	.2967	.3038	1	.2835	.3284
BPR (AVE)	.8782	.8922	.8829	.8821	.8851	.8958	.2835	1	.1799
BPR (DIFF)	.1334	.1228	.1753	.1076	.1179	.1141	.3284	.1799	1

GRAVEL SURFACED TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9424	.9286	.9395	.9422	.9529	.6594	.8626	.2495
MM 02	.9424	1	.9744	.9932	.9923	.9848	.7487	.8227	.2384
MM 03	.9286	.9744	1	.9578	.9589	.9495	.7611	.7289	.2219
BI CAR	.9395	.9932	.9578	1	.9975	.9935	.7327	.8157	.2086
NAASRA	.9422	.9923	.9589	.9975	1	.9907	.7442	.8191	.2162
BI TRL (AVE)	.9529	.9848	.9495	.9935	.9907	1	.6903	.8267	.2227
BI TRL (DIFF)	.6594	.7487	.7611	.7327	.7442	.6903	1	.4598	.3116
BPR (AVE)	.8626	.8227	.7289	.8157	.8191	.8267	.4598	1	.4662
BPR (DIFF)	.2495	.2384	.2219	.2086	.2162	.2227	.3116	.4662	1

EARTH (CLAY) SURFACE TEST SITES

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.8912	.8483	.8808	.8977	.8734	.2767	.7517	.115
MM 02	.8912	1	.9542	.97	.9862	.9859	.0202	.9486	7.6E-03
MM 03	.8483	.9542	1	.963	.9772	.9296	4.9E-03	.8343	0
BI CAR	.8808	.97	.963	1	.9905	.9662	.0337	.8428	.0237
NAASRA	.8977	.9862	.9772	.9905	1	.976	.0155	.894	6.7E-03
BI TRL (AVE)	.8734	.9859	.9296	.9662	.976	1	.0216	.9399	2.5E-03
BI TRL (DIFF)	.2767	.0202	4.9E-03	.0337	.0155	.0216	1	.0388	.6738
BPR (AVE)	.7517	.9486	.8343	.8428	.894	.9399	.0388	1	5.7E-03
BPR (DIFF)	.115	7.6E-03	0	.0237	6.7E-03	2.5E-03	.6738	5.7E-03	1

Table C.14. Correlation Tables of R-Squared Values for No Segregation of Data.

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9195	.893	.8916	.9181	.8898	.5078	.8091	.2828
MM 02	.9195	1	.9572	.9684	.9819	.9685	.3171	.8917	.1124
MM 03	.893	.9572	1	.9352	.9518	.9188	.326	.8119	.109
BI CAR	.8916	.9684	.9352	1	.9915	.9635	.3019	.8638	.1117
NAASRA	.9181	.9819	.9518	.9915	1	.9673	.2874	.8762	.1001
BI TRL (AVE)	.8898	.9685	.9188	.9635	.9673	1	.2649	.8939	.0761
BI TRL (DIFF)	.5078	.3171	.326	.3019	.2874	.2649	1	.1809	.508
BPR (AVE)	.8091	.8917	.8119	.8638	.8762	.8939	.1809	1	.1122
BPR (DIFF)	.2828	.1124	.109	.1117	.1001	.0761	.508	.1122	1

Measurements of ARS

	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
MM 01	1	.9484	.9327	.8734	.9295	.9188	.5571	.7347	.2361
MM 02	.9484	1	.9682	.9389	.9778	.9775	.3668	.8234	.1241
MM 03	.9327	.9682	1	.9082	.9576	.9401	.3489	.7216	.1168
BI CAR	.8734	.9389	.9082	1	.9791	.9764	.3452	.7558	.1349
NAASRA	.9295	.9778	.9576	.9791	1	.9784	.3299	.7829	.1163
BI TRL (AVE)	.9188	.9775	.9401	.9764	.9784	1	.3322	.8488	.1055
BI TRL (DIFF)	.5571	.3668	.3489	.3452	.3299	.3322	1	.2031	.5309
BPR (AVE)	.7347	.8234	.7216	.7558	.7829	.8488	.2031	1	.1243
BPR (DIFF)	.2361	.1241	.1168	.1349	.1163	.1055	.5309	.1243	1

Measurements of ARV

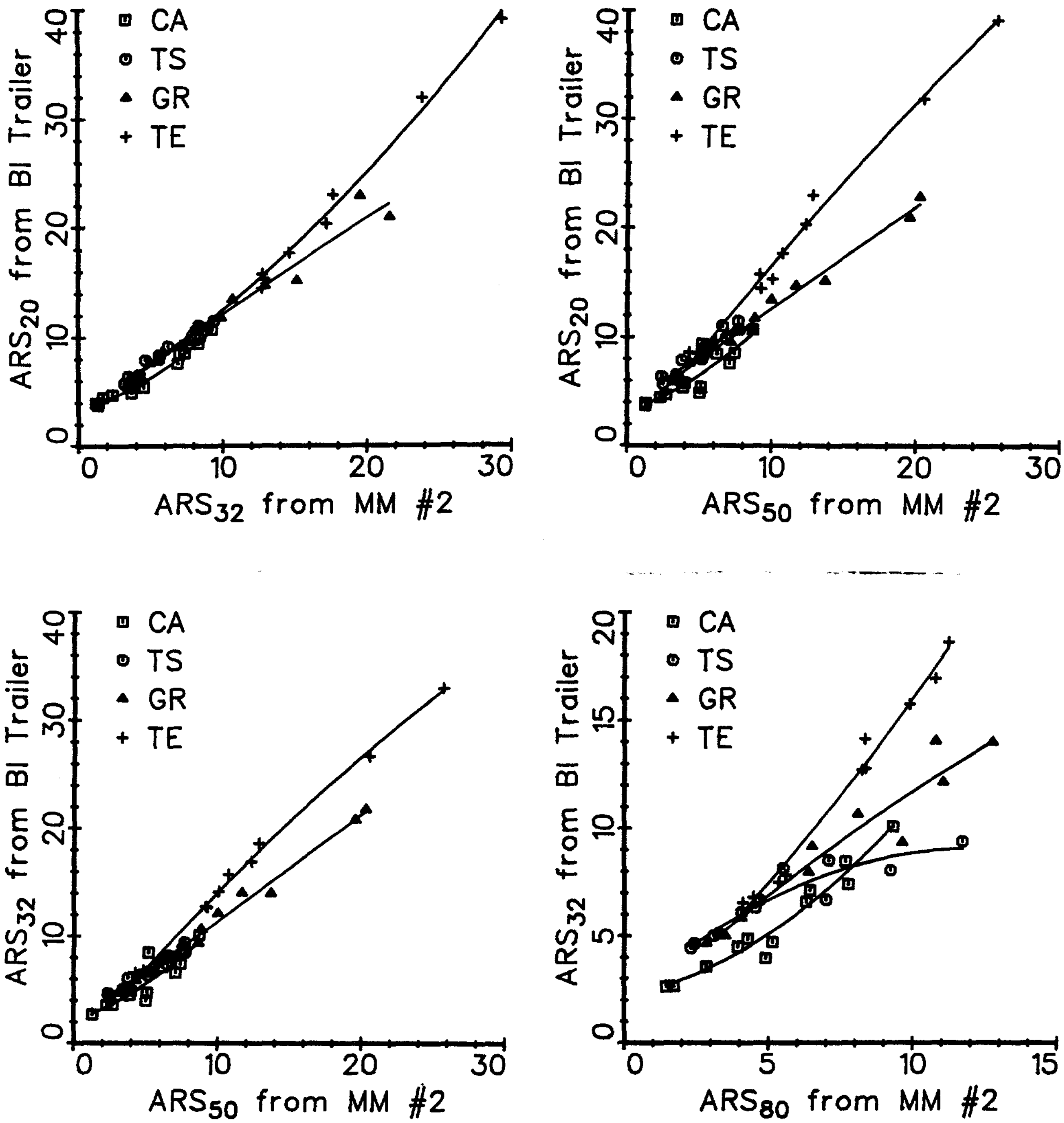


Figure C.1. Comparison of ARS measures made at different speeds by two RTRRMSs.

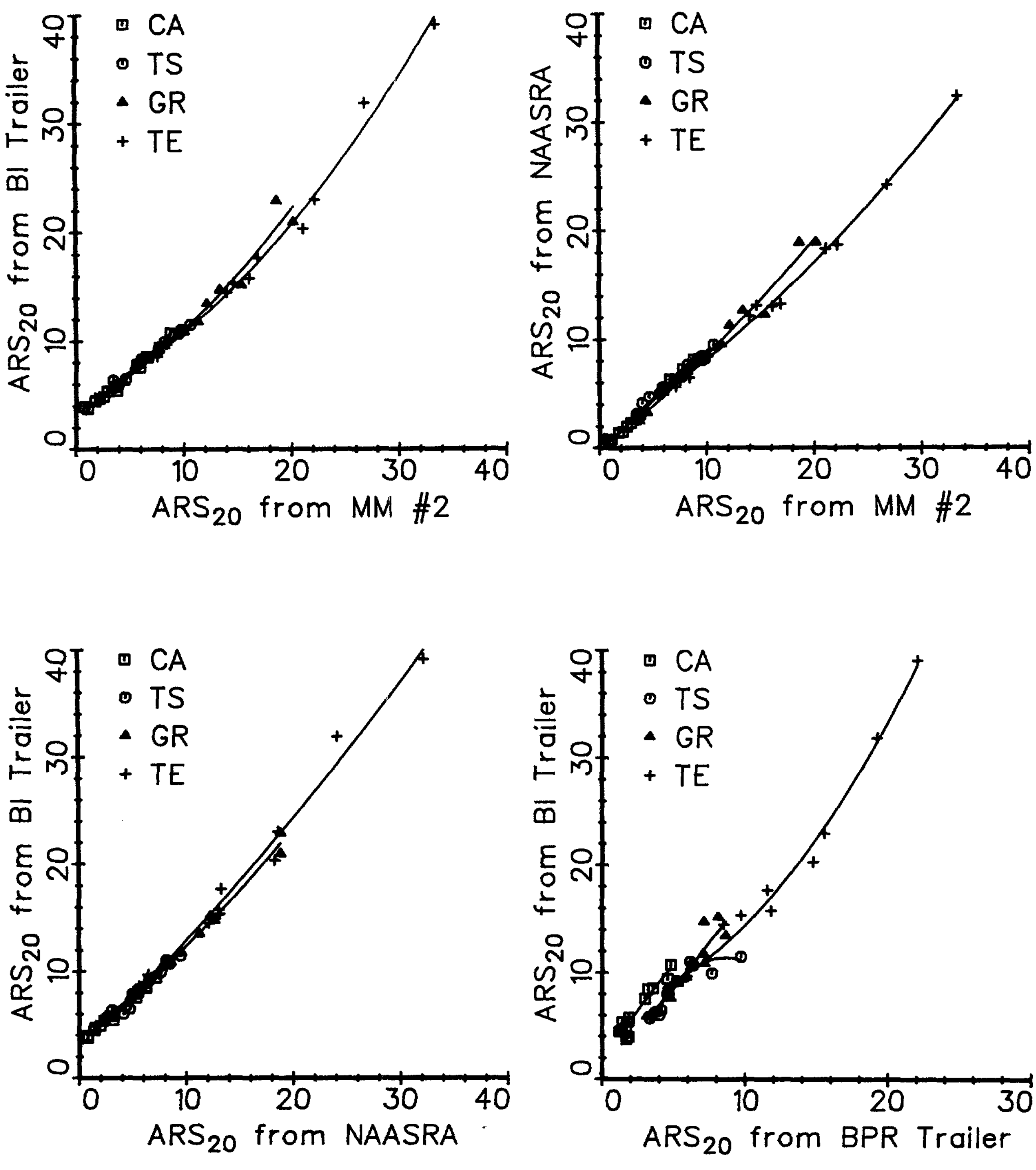


Figure C.2. Comparison of ARS_{20} measures made by four RTRRMSs.

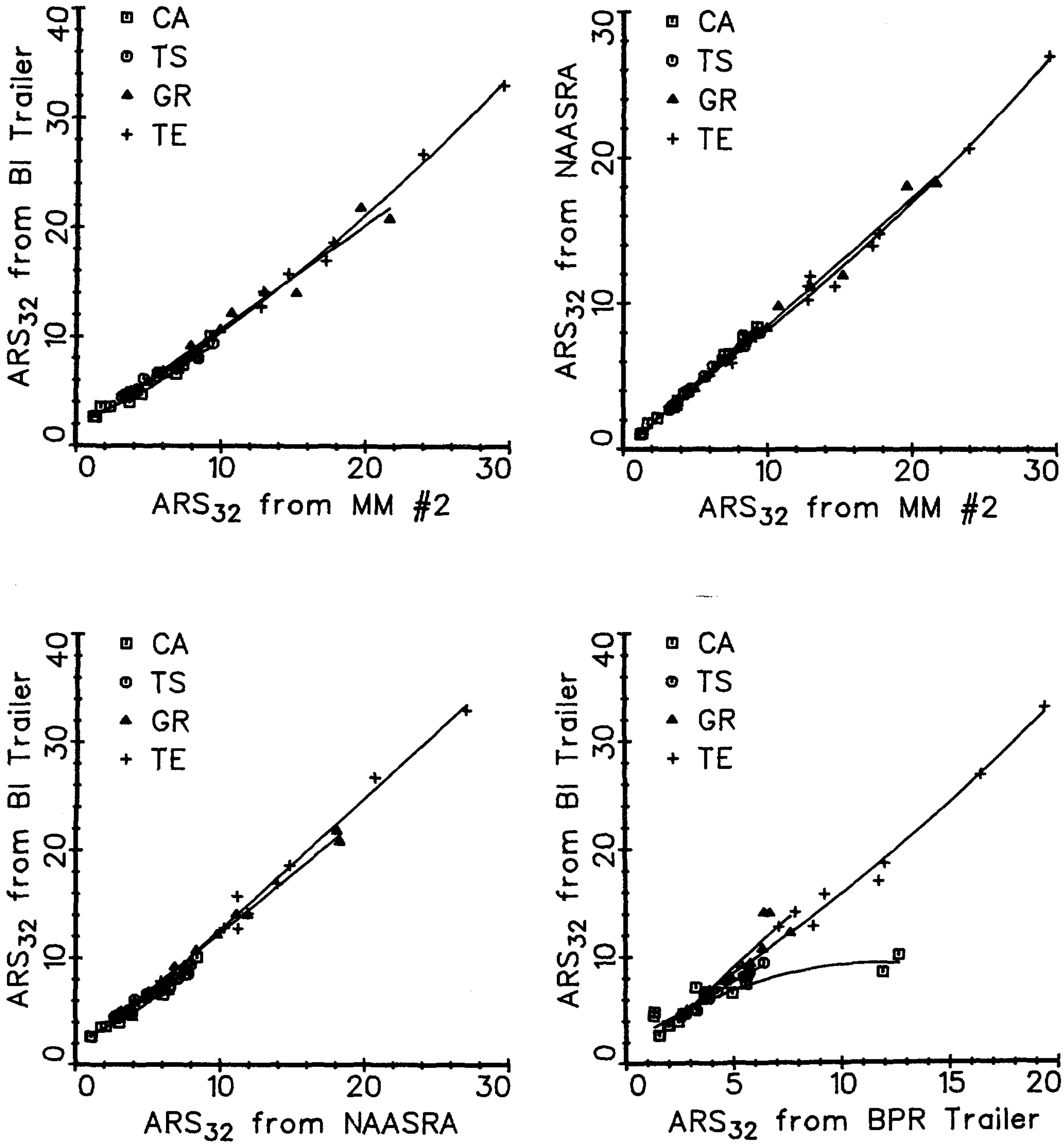


Figure C.3. Comparison of ARS_{32} measures made by four RTRRMSs.

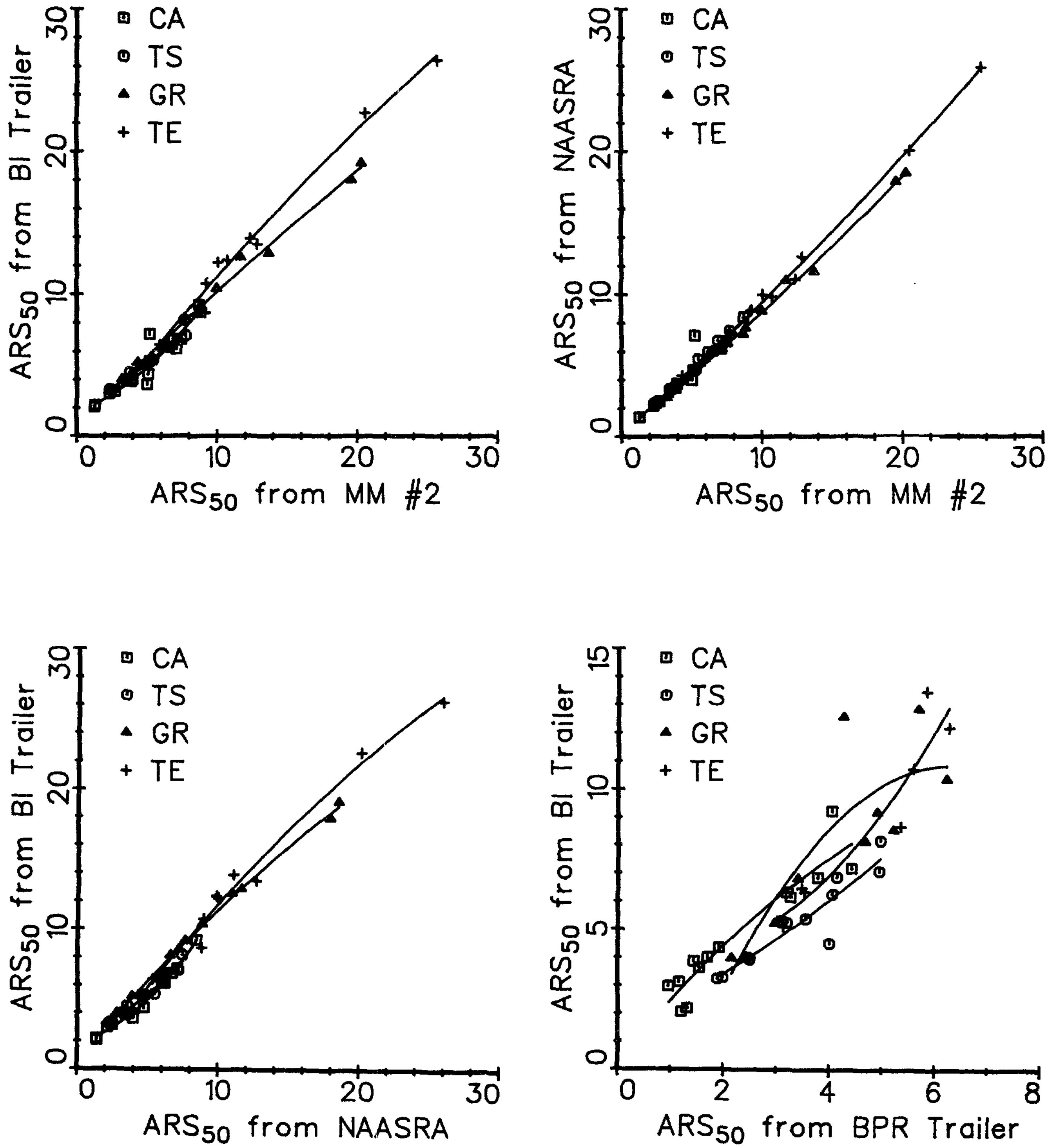


Figure C.4. Comparison of ARS_{50} measures made by four RTRRMSs.

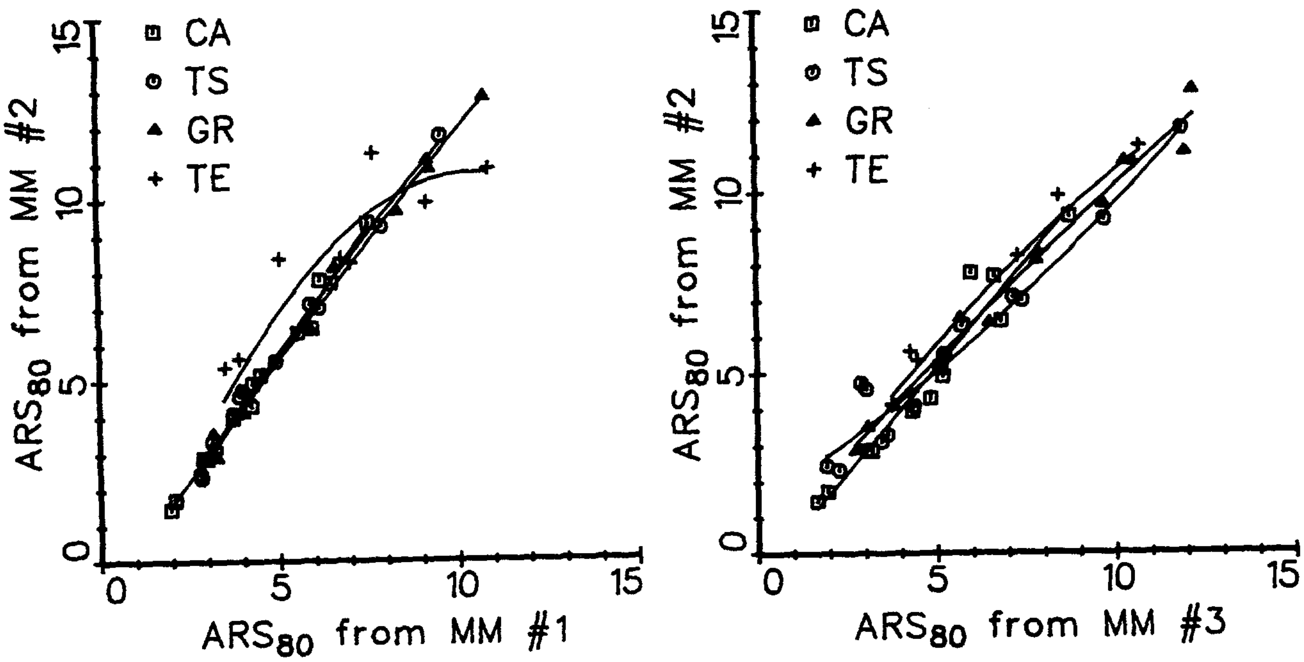


Figure C.5. Comparison of ARS_{80} measures made by three RTRRMSs.

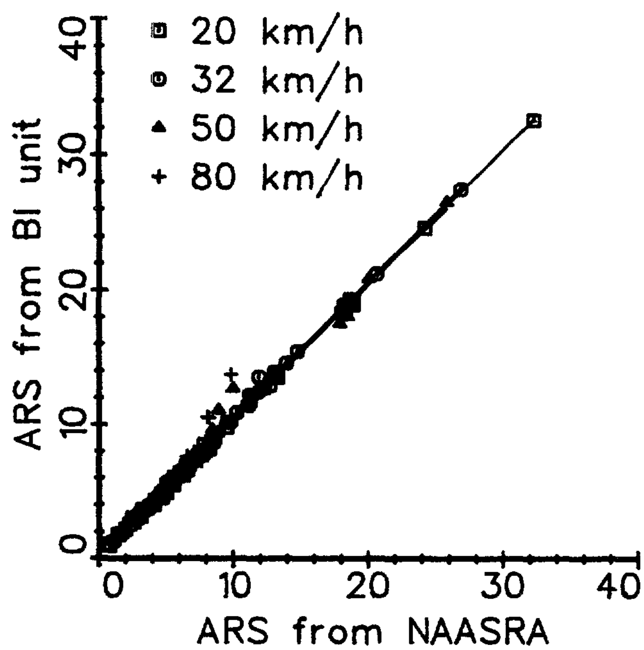
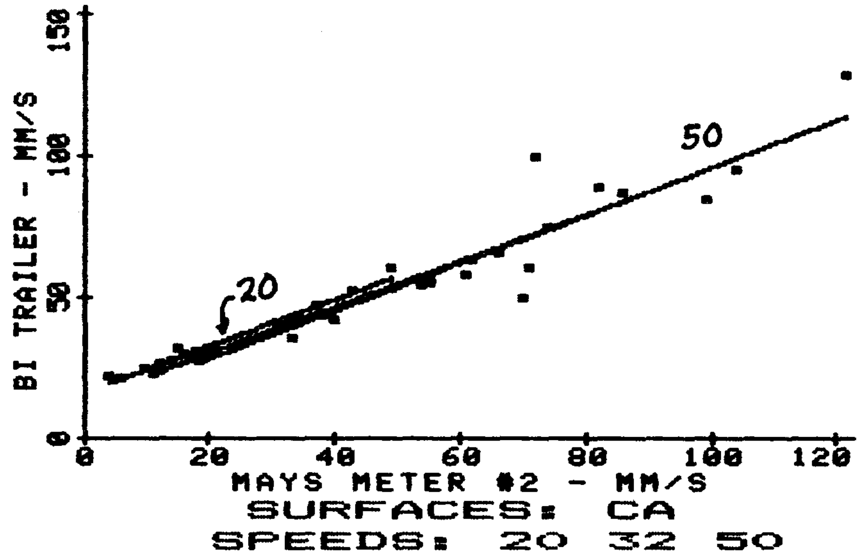
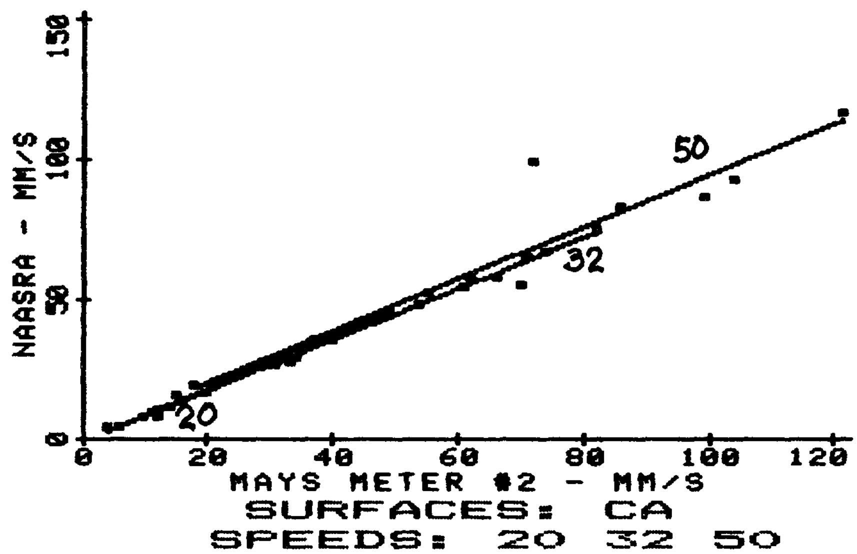


Figure C.6. Comparison of ARS measures made with two roadmeters in the same vehicle.





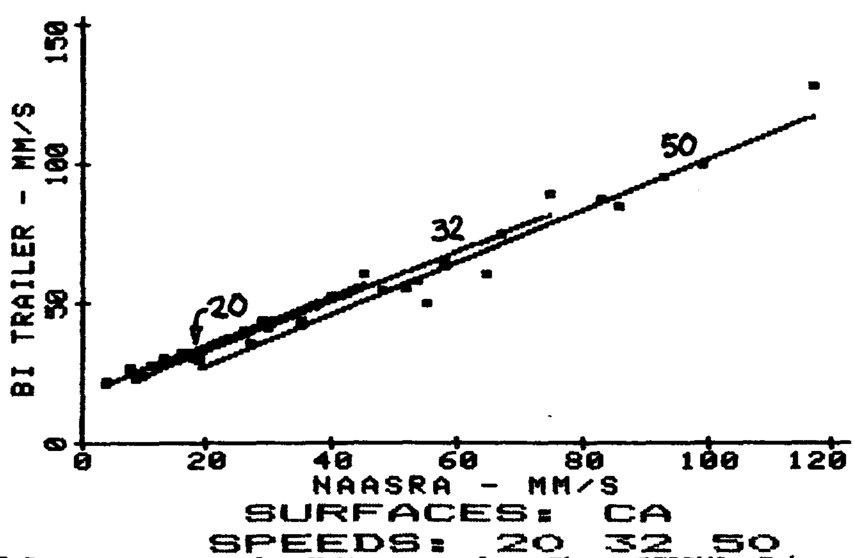


Figure C.7 Comparison of ARV Measures from Three RTRRMSs Taken at Three Speeds on Asphaltic Concrete Roads.

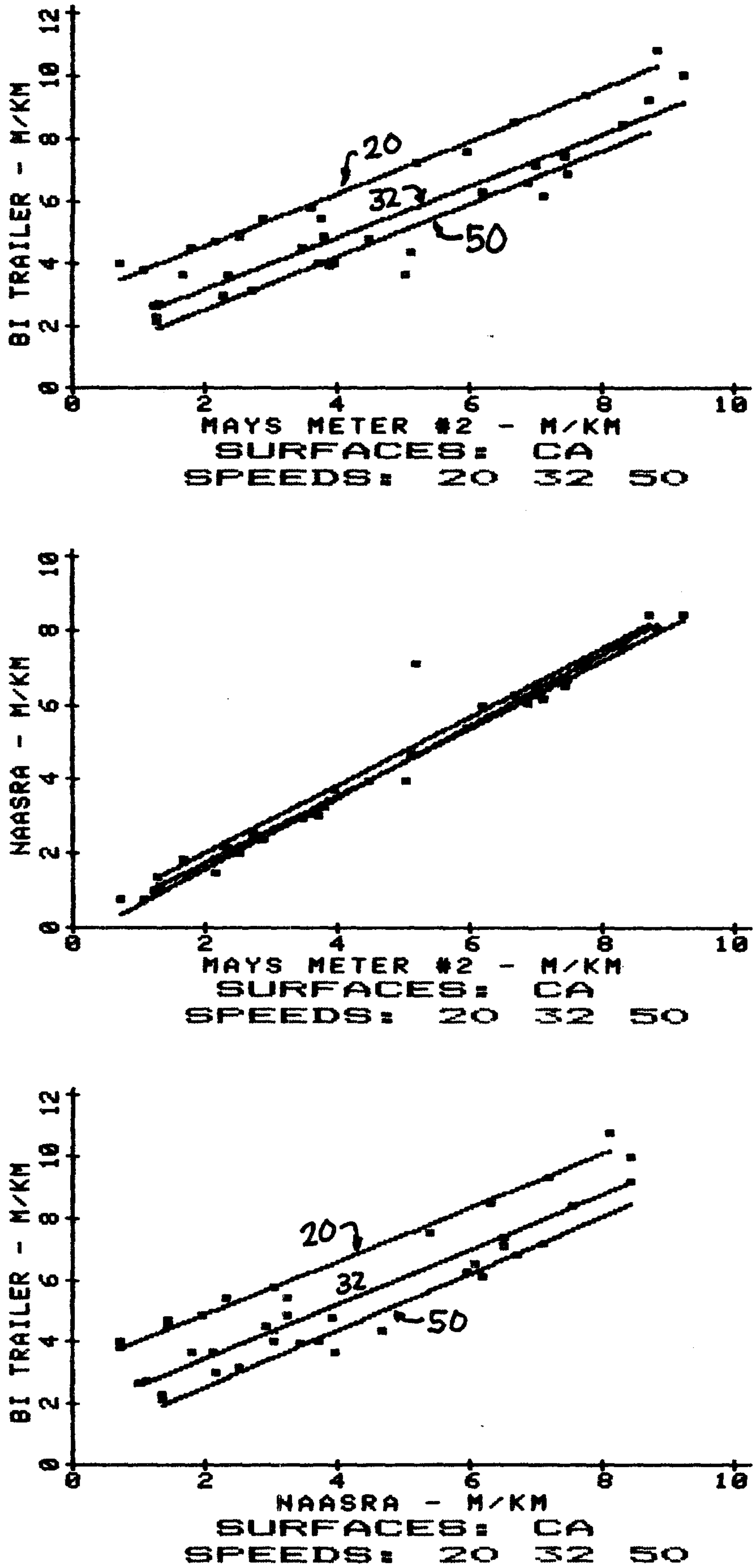


Figure C.8 Comparison of ARS Measures from Three RTRRMSs Taken at Three Speeds on Asphaltic Concrete Roads.

APPENDIX D

SUBJECTIVE RATINGS

Experiment

At the completion of the experiment, a short study was performed in which a panel of 18 persons assigned a subjective ride rating to each test section. The staff at GEIPOT had performed a similar study in late 1978 for the project "Research on the Interrelationships Between Cost of Highway Construction, Maintenance and Utilization" (ICR) to relate the QI scale to user opinion [7]. The procedures used to gather data in the earlier study were repeated, using an international panel of men and women, whose backgrounds are summarized in Table D.1. All of the panel members were driven over the test sections by a staff member familiar with the route in one of three Chevrolet Opala passenger cars. These were the same three cars equipped with Maysmeters that were used in the main experiment. The vehicle speed was 50 km/h for all of the unpaved sections and 80 km/h for all of the paved sections. The panel members rated the section by marking a graphical scale on a field form, which showed as scale ranging from 0 to 5, with 5.0 being a perfect road. Back in the office, the location of the mark was measured with a ruler and entered into the computer, which converted the measure to a value between 0 and 5.

Data Normalization

The data collected in the study are presented in Table D.2. The mean and standard deviation (MEAN and SIGMA) are listed for each test section and for each panel member. The mean value for all ratings is 2.7 and the average standard deviation for all the members is 1. When the ratings from each rater are simply averaged, the results are more influenced by those members who used more of the available scale (signified by larger SIGMA values) than those who used only a small portion. To give each member equal weighting in the final average, the ratings for each member were normalized by the process of subtracting the mean value for that rater from all of his/her ratings, and dividing the results by his/her standard deviation. After normalization, the

Table D.1. Description of panel of raters

Number	Country	Occupation	Sex
1	United States	Mechanical Engineer	Male
2	Brazil	Secretary	Female
3	Brazil	Secretary	Female
4	Brazil	Draftsman	Male
5	Brazil	Accountant	Male
6	United States	Economist/Editor	Male
7	Brazil	Civil Engineer	Male
8	Brazil	Civil Engineer	Male
9	Brazil	Translator	Male
10	Brazil	Clerk	Male
11	Brazil	Draftsman	Male
12	Brazil	Secretary	Female
13	Brazil	Technician	Male
14	New Zealand	Civil Engineer	Male
15	France	Civil Engineer	Male
16	France	Civil Engineer	Male
17	Brazil	Clerk	Male
18	Brazil	Civil Engineer	Female

Table D.2. SUBJECTIVE RATINGS WITH NO CORRECTION

SITE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	MEAN	SIGMA
CA01	3.5	3.4	4.2	3.2	3.4	3.3	3.7	3.7	3.4	4	2.7	4.1	3.4	2.3	2.5	3	3.9	2.8	3.4	.5
CA02	3	3.1	3.5	2.7	3.2	3.2	3.6	3.5	3.5	4.3	2.7	4.2	3.5	2.5	2.5	2.5	3.4	3	3.2	.5
CA03	2.7	2.7	2.6	2.5	2.5	2.8	3.3	3.3	2.6	4.4	2.3	2.7	3.3	2.7	1.5	2	2.5	2.7	2.7	.6
CA04	2.6	2.7	1.7	2.5	2.4	2.5	3.2	3.2	3.2	3.7	2.6	2.8	3.2	3	.5	2.5	3.4	2.4	2.7	.7
CA05	2.5	1.7	1.5	2.4	2.4	2.3	3.2	3	2.5	4	1.7	2.7	3.2	2.6	.	.	2.5	.	2.5	.6
CA06	1.5	1.5	1.8	2.7	2.2	3.2	2.5	2.7	1.6	2.7	1.3	2.7	3.1	2.6	.	.	1.8	1.8	2.2	.6
CA07	3.4	3.4	2.7	3.5	3.2	3.5	4.4	3.5	3.6	4.7	4.3	4.1	3.4	3.5	4.5	4	3.5	3.2	3.7	.5
CA08	3.7	3.2	2.7	3.7	3.5	3.5	4.4	3.5	3.5	4.5	4.4	4.1	3.4	3.5	3.5	4	3.5	3.6	3.7	.4
CA09	2.7	3.2	1.7	3.8	3.3	2.7	2.8	3.7	3.2	4.5	2.5	4.1	3.4	3.2	2.5	4.5	3.4	2.2	3.2	.7
CA10	3.1	2.8	1.2	3.3	3.1	2.5	2.8	3.7	3.5	3.7	3.4	4.1	3.4	3.3	3.5	4	3.6	2.2	3.2	.7
CA11	2.5	3.1	.5	2.2	2.8	2.4	2.6	3.3	2.2	2.6	1.7	3.1	2.7	2.7	1.5	3.5	2.4	1.9	2.4	.7
CA12	4.4	4.3	4.7	4.3	4.3	4.5	4.9	4.5	4.5	4.7	4.5	4.5	4.5	4.3	4.5	5	4.6	4.2	4.5	.2
CA13	4.1	4.5	4.7	4.2	4.3	4.5	4.7	4.4	4.4	4.6	4.5	4.5	4.5	4.1	4.5	5	4.7	4.5	4.5	.2
TS01	2.7	3.1	2.7	3.3	3.3	4.4	3.4	3.6	2.5	4	2.4	3.5	3.4	3.1	4.3	4	3.7	3.2	3.4	.6
TS02	2.3	2.8	2.8	3.1	3.3	3.8	3.4	3.4	3.5	4	2.7	3.5	3.5	3.1	4.3	4	3.8	2.9	3.3	.5
TS03	2.6	2.7	1.7	3	3.4	3.6	3.4	3.2	3.4	4.3	2.6	3.1	3.2	2.8	2.5	3	3.7	2.2	3	.6
TS04	2.5	2.8	1.2	3.1	3.2	3.3	3.3	3.3	2.6	4.1	2.6	3.7	3.2	3	2.2	2.8	3.1	2.5	2.9	.6
TS05	2.1	2.5	1.7	3	3.1	3.3	3.2	3.2	2.7	3.5	2.7	.	3.2	3	2.3	2.7	3.1	2.4	2.8	.5
TS06	3.5	3.1	3.7	3.3	3.7	3.5	3.5	3.5	3.5	4.6	2.7	3.5	3.5	3.5	3.3	3.7	3.3	2.5	3.4	.4
TS07	2.7	2.5	3.7	3.3	3.7	3.5	3.5	3.3	3.5	4.6	2.7	3.5	3.4	3.2	3.3	4	3.5	2.7	3.4	.5
TS08	2.7	3.5	2.8	2.7	3.4	3.6	3.1	3.3	3.3	4.5	2.4	3.5	3.5	3.2	3.3	3	3.4	3.1	3.2	.4
TS09	3	3.2	4.2	3.4	3.7	3.8	4.4	3.5	3.4	4.4	3.7	3.4	3.5	.	.	.	3.6	3.4	3.6	.4
TS10	2.5	3.1	4.5	3.1	3.6	3.9	4.4	3.5	3.6	4.5	3.6	3.4	3.4	.	.	.	3.5	3.3	3.6	.5
TS11	4	4	3.7	3.5	3.9	4.5	4.1	3.7	3.8	4.6	4.6	4.4	3.5	3.7	4.5	4.3	4.1	2.6	4	.5
TS12	3.7	4.1	3.7	3.5	3.8	4.5	4.1	3.7	3.8	4.6	4.4	4.4	3.5	3.5	4.5	4.5	4.1	2.5	3.9	.5
GR01	3.6	1.3	3.5	2.3	3.1	3.3	1.7	2.5	3.4	3.1	3.7	3.5	2.5	3	2.5	4	3.1	1.8	2.9	.7
GR02	3.2	2.1	3.5	2.4	3.1	3.2	1.8	2.5	3.4	3.3	3.7	3.5	2.5	3	2.5	4	2.8	1.8	2.9	.6
GR03	2.3	1.2	2.2	2.2	2.5	2.6	1.6	2.3	2.8	2.7	3.3	3.5	2.5	2.7	3.5	3.5	2.4	1.9	2.5	.6
GR04	2.4	1	2.3	1.9	2.5	2.6	1.5	2.3	2.5	2.8	3.7	3.5	2.5	2.3	1.5	3.2	2.5	1.6	2.4	.7
GR05	2	.6	.2	1.2	2.2	1.5	1.5	2.2	2.3	2.1	2.7	3.1	1.8	2.5	1.5	2.5	2.7	1.7	1.9	.7
GR06	2.5	.5	.5	.8	2.2	1.5	1.3	2	1.4	2.1	2.4	3.2	1.6	2.3	1.4	2.2	2.4	1.6	1.8	.7
GR07	2.5	2.1	2.7	2.2	2.6	2.5	2.7	2.5	2.5	3.5	3.5	3.1	2.3	3.4	2.3	4	2.5	2.5	2.7	.5
GR08	2.1	2.1	3.5	2.4	2.7	3.3	2.5	2.5	2.5	3.5	4.5	3.1	2.4	3.3	2.4	4	2.7	2.8	2.9	.6
GR09	1.6	1.3	2.7	2.3	2.4	2.5	2.2	2.2	1.5	2.7	3.3	2.6	2.3	2.8	1.7	3	2.1	2.4	2.3	.5
GR10	1.5	1.2	2.7	2.1	2.4	2.7	2.4	2.3	1.6	2.7	2.5	2.5	2.5	3	1.7	3	1.9	2.1	2.3	.5
GR11	.6	.3	1.8	1.7	1.5	.2	.6	1.3	1.4	2.3	2.4	1.5	.5	1	.7	1.8	3.1	1.1	1.3	.8
GR12	.4	.2	1.8	1.2	1.4	.4	.6	1.4	1.3	.7	1.6	1.5	.4	1.4	.6	1.5	2.2	.7	1.1	.6
TE01	2.5	2.6	1.2	2.7	3.1	2.6	1.4	2.2	3.3	4.1	3.4	3.5	2.5	2.6	1.5	4	2.5	2.1	2.7	.8
TE02	2.2	2.7	.8	2.7	3	2.5	1.4	2.3	2.7	4.2	3.4	3.5	2.5	2.8	2.5	4	2.6	2.2	2.7	.8
TE03	1.4	2.5	1.3	2.5	2.6	2.5	1.3	2	1.5	3.6	3.4	3.5	2.4	2	1.5	3.5	2.3	1.8	2.3	.8
TE04	1.2	1.8	.7	2.7	2.4	2.5	1.2	1.8	1.5	3.5	3.4	3.5	2.5	1.9	1.5	3	2.4	1.5	2.2	.8
TE05	.6	.2	.6	.7	.4	.5	.5	1	1.5	2.5	1.4	2.1	.3	1.5	1.2	1.5	1.5	.8	1	.6
TE06	.2	.1	.3	.2	.3	.4	.3	.7	1.4	2	.6	1.7	.4	.5	.5	1	1.3	.5	.7	.5
TE07	2.4	1.5	1.3	2.4	2.4	2.5	2.2	2.3	2.7	3.1	3.7	3.1	2.4	3.4	2.4	3.5	3.4	2.2	2.6	.7
TE08	2	1.1	1.7	2.3	2.4	2.5	2.1	2.3	2.5	3.1	1.5	3.1	2.4	3.4	2.4	3.5	3.1	1.9	2.4	.6
TE09	1.4	.8	1.2	1.6	2.3	1.5	1.9	1.7	2.4	2.1	2.7	2.1	1.5	2	1.6	2	2.4	1.8	1.8	.5
TE10	.6	.4	1.2	1.4	1.9	1.2	1.2	1.5	1.3	1.9	3.7	2.1	1.5	1.6	1.5	1.8	2.1	1.5	1.6	.7
TE11	1	.2	.7	1.5	2.4	.7	.8	1.5	1.3	2.5	2.3	1.9	.7	1.3	.9	2	2.4	1.5	1.4	.7
TE12	1.2	.3	.7	1.3	2.3	.6	.7	1.8	1.4	3.2	2.3	1.9	.9	1.7	.8	2	2.6	1.5	1.5	.8
MEAN	2.4	2.1	2.2	2.5	2.8	2.7	2.6	2.7	2.7	3.5	3	3.2	2.6	2.7	2.4	3.2	3	2.3	2.7	.4
SIGMA	1	1.2	1.3	.9	.8	1.1	1.2	.9	.9	1	.9	.8	1	.8	1.2	1	.7	.8	1	.2

ratings of each member had a mean value of zero and a standard deviation of 1.0. The normalized ratings are presented in Table D.3. Ideally, there should be no missing data, because the calculated values of the mean and standard deviation can then be erroneous. In this case, there were ten missing values out of a total of 882. The test sections that were missing were not extremely smooth or extremely rough; hence the errors introduced to the final rating for the sections are assumed to be negligible.

A critical phase of analyzing subjective rating (SR) data is called "anchoring the scale" to assign absolute roughness values to each road section, based on a comparison of the range of SR values obtained from the raters to a reference range. Since the interest here is in seeing the correlation of SR with the other measures and comparing the roughness rankings, the arbitrary normalized scale of Table D.3 was considered sufficient. If desired, the SR numerics can be "anchored" to any one of the many objective roughess measures used in the IRRE.

Example Correlations With Objective Roughness Measures

Figure D.1 shows scatter plots of SR against the roughness measures obtained from one of the response-type road roughness measurement systems (RTRRMSs). The plots also include quadratic regression lines, whose coefficients were computed separately for each surface type. The standard error (SE) is indicated for each regression, and has the same arbitrary units as SR. The plots also include the r^2 value for each of the regressions. The figure reveals that about the same quality of correlation is obtained at all four speeds, and that surface type influences the regressions the most when the RTRRMS was run at 80 km/h. These are unexpected findings, given that the SR values are based on travel speeds of 80 km/h for the paved roads and 50 km/h for the unpaved. Better correlation was expected when the RTRRMS measurement speed matches the travel speed during the SR experiment. In these examples, a single non-linear relationship seems to exist that relates the RTRRMS measure to SR for three of the surface types as a function only of roughness, as measured by either the SR or RTRRMS scale. But a separate relationship is needed for the sections with surface treatment (TS). The SR ratings do not discriminate among these sections as much as the RTRRMS, and the SR is generally high compared to comparable RTRRMS roughness levels for

Table D.3. SUBJECTIVE RATINGS AFTER RE-SCALING

SITE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	MEAN	SIGMA
CA01	1.2	1	1.6	.7	.7	.6	.9	1.1	.9	.5	-.3	1.2	.8	-.6	.1	-.2	1.2	.7	.7	.6
CA02	.7	.8	1	.2	.5	.4	.8	.9	.9	.8	-.3	1.2	.8	-.3	.1	-.7	.6	1	.5	.5
CA03	.4	.4	.3	0	-.4	.1	.6	.7	0	.9	-.7	-.6	.6	-.1	-.7	-1.2	-.6	.6	0	.6
CA04	.3	.5	-.4	0	-.5	-.2	.5	.5	.6	.2	-.3	-.5	.6	.3	-1.5	-.7	.6	.2	0	.6
CA05	.1	-.3	-.6	-.2	-.5	-.3	.5	.3	-.3	.5	-1.4	-.6	.6	-.2	.	.	-.7	.	-.2	.5
CA06	-.9	-.6	-.4	.2	-.7	.5	-.1	0	-1.2	-.8	-1.8	-.6	.4	-.1	.	.	-1.6	-.6	-.5	.6
CA07	1	1.1	.4	1.1	.6	.7	1.5	.9	1	1.3	1.5	1.1	.8	.9	1.8	.8	.7	1.1	1	.3
CA08	1.3	.8	.4	1.3	.9	.7	1.5	.9	.9	1	1.5	1.2	.7	1	.9	.8	.7	1.7	1	.3
CA09	.3	.8	-.4	1.5	.6	0	.2	1.1	.6	1	-.5	1.1	.7	.6	.1	1.3	.6	-.1	.5	.5
CA10	.7	.6	-.8	.9	.4	-.2	.2	1.1	.9	.2	.5	1.1	.7	.7	.9	.8	.8	-.1	.5	.5
CA11	.1	.8	-1.4	-.4	0	-.3	.1	.6	-.5	-.9	-1.4	-.1	0	0	-.7	.3	-.7	-.4	-.3	.6
CA12	2.1	1.7	2	2	1.9	1.6	1.9	2	2	1.2	1.7	1.6	1.8	2	1.8	1.8	2.2	2.3	1.9	.2
CA13	1.7	1.9	2	1.9	1.8	1.5	1.7	1.9	1.9	1.2	1.7	1.6	1.8	1.8	1.8	1.8	2.3	2.7	1.8	.3
TS01	.3	.8	.4	.8	.6	1.5	.7	.9	-.2	.5	-.6	.4	.8	.5	1.6	.8	.9	1.2	.7	.5
TS02	-.1	.6	.5	.7	.6	1	.7	.8	.9	.5	-.3	.4	.8	.5	1.6	.8	1.1	.8	.7	.4
TS03	.2	.5	-.4	.5	.7	.8	.7	.6	.8	.8	-.3	-.1	.6	.2	.1	-.2	1	-.1	.3	.4
TS04	.2	.5	-.8	.6	.6	.5	.6	.6	0	.7	-.3	.7	.6	.3	-.1	-.4	.2	.2	.2	.4
TS05	-.3	.3	-.4	.6	.3	.5	.5	.5	0	0	-.3	.	.6	.3	-.1	-.5	.2	.2	.1	.4
TS06	1.1	.8	1.2	.8	1.2	.7	.8	.9	.9	1.2	-.3	.3	.9	1	.8	.5	.4	.2	.7	.4
TS07	.4	.3	1.2	.8	1.2	.7	.8	.7	.9	1.2	-.2	.3	.8	.7	.8	.8	.7	.6	.7	.3
TS08	.3	1.1	.5	.2	.7	.8	.4	.6	.7	1	-.6	.3	.8	.7	.8	-.2	.6	1	.5	.4
TS09	.6	.8	1.5	1	1.1	.9	1.5	.9	.9	1	.8	.2	.8	.	.	.	.8	1.4	.9	.3
TS10	.1	.8	1.8	.6	1	1	1.5	.9	1.1	1.1	.7	.3	.8	.	.	.	.7	1.3	.9	.4
TS11	1.7	1.6	1.2	1.1	1.3	1.5	1.3	1.1	1.2	1.1	1.7	1.5	.9	1.2	1.8	1.1	1.5	.4	1.3	.3
TS12	1.4	1.6	1.2	1.1	1.2	1.5	1.3	1.1	1.2	1.2	1.6	1.5	.9	1	1.8	1.3	1.6	.2	1.3	.3
GR01	1.2	-.7	1	-.2	.3	.6	-.7	-.2	.8	-.4	.8	.4	-.1	.3	.1	.8	.2	-.6	.2	.6
GR02	.9	-.1	1	-.2	.4	.4	-.6	-.2	.9	-.2	.8	.3	-.2	.3	.1	.8	-.2	-.6	.2	.5
GR03	-.1	-.8	-.1	-.4	-.3	-.1	-.8	-.6	.1	-.9	.4	.3	-.2	0	.9	.3	-.8	-.4	-.2	.5
GR04	0	-.9	0	-.7	-.4	-.1	-.9	-.5	-.2	-.7	.8	.3	-.1	-.5	-.7	0	-.6	-.8	-.3	.4
GR05	-.4	-1.3	-1.6	-1.5	-.7	-1.1	-.8	-.7	-.4	-1.5	-.3	-.1	-.9	-.3	-.7	-.7	-.3	-.8	-.8	.4
GR06	.1	-1.4	-1.3	-2	-.7	-1.1	-1	-.8	-1.4	-1.5	-.6	0	-1.1	-.6	-.8	-1	-.8	-.9	-.9	.5
GR07	.1	0	.4	-.3	-.3	-.2	.1	-.3	-.2	0	.5	-.1	-.3	.8	-.1	.8	-.7	.3	0	.4
GR08	-.3	0	1.1	-.2	-.1	.5	0	-.3	-.2	0	1.6	-.1	-.3	.7	0	.8	-.3	.6	.2	.5
GR09	-.8	-.7	.4	-.3	-.5	-.2	-.3	-.6	-1.3	-.9	.4	-.8	-.3	.1	-.6	-.2	-1.2	.2	-.4	.5
GR10	-.9	-.7	.4	-.5	-.5	0	-.1	-.6	-1.3	-.8	-.4	-.9	-.1	.4	-.6	-.2	-1.4	-.2	-.5	.5
GR11	-1.9	-1.5	-.3	-.9	-1.6	-2.2	-1.5	-1.6	-1.5	-1.3	-.6	-2.2	-2.1	-2.2	-1.4	-1.4	.2	-1.4	-1.4	.6
GR12	-2	-1.6	-.3	-1.5	-1.7	-2	-1.6	-1.6	-1.6	-2.9	-1.4	-2.2	-2.2	-1.6	-1.5	-1.7	-1	-1.9	-1.7	.5
TE01	.1	.4	-.8	.2	.4	0	-.9	-.6	.7	.6	.5	.3	-.1	-.2	-.7	.8	-.7	-.2	0	.5
TE02	-.2	.5	-1.1	.2	.3	-.2	-1	-.5	0	.8	.4	.4	-.2	.1	.1	.8	-.4	-.2	0	.5
TE03	-1	.3	-.8	-.1	-.3	-.2	-1	-.8	-1.3	.1	.5	.3	-.2	-.9	-.7	.3	-.9	-.6	-.4	.5
TE04	-1.2	-.3	-1.2	.2	-.5	-.2	-1.1	-1.1	-1.3	0	.4	.3	-.2	-1	-.7	-.2	-.7	-.9	-.5	.6
TE05	-1.9	-1.6	-1.3	-2.1	-2.9	-2	-1.7	-2	-1.3	-1.1	-1.7	-1.4	-2.3	-1.5	-1	-1.7	-2	-1.8	-1.7	.4
TE06	-2.3	-1.7	-1.6	-2.6	-3	-2	-1.8	-2.4	-1.4	-1.6	-2.6	-1.9	-2.2	-2.8	-1.6	-2.3	-2.3	-2.1	-2.1	.4
TE07	0	-.6	-.8	-.2	-.5	-.2	-.3	-.5	.1	-.4	.8	-.2	-.2	.9	0	.3	.6	-.2	-.1	.4
TE08	-.4	-.8	-.4	-.2	-.5	-.2	-.3	-.5	-.2	-.4	-1.5	-.1	-.3	.8	0	.3	.2	-.5	-.3	.5
TE09	-1	-1.1	-.8	-1	-.6	-1.1	-.6	-1.1	-.3	-1.5	-.2	-1.4	-1.1	-.9	-.6	-1.2	-.7	-.6	-.9	.3
TE10	-1.8	-1.4	-.8	-1.3	-1.1	-1.3	-1.1	-1.4	-1.5	-1.7	.8	-1.4	-1.1	-1.4	-.7	-1.4	-1.2	-1	-1.2	.5
TE11	-1.5	-1.6	-1.2	-1.2	-.5	-1.8	-1.4	-1.4	-1.6	-1.1	-.7	-1.7	-1.9	-1.8	-1.2	-1.2	-.7	-.9	-1.3	.4
TE12	-1.2	-1.5	-1.2	-1.4	-.6	-1.9	-1.5	-1.1	-1.4	-.3	-.7	-1.7	-1.7	-1.3	-1.4	-1.2	-.5	-1	-1.2	.4

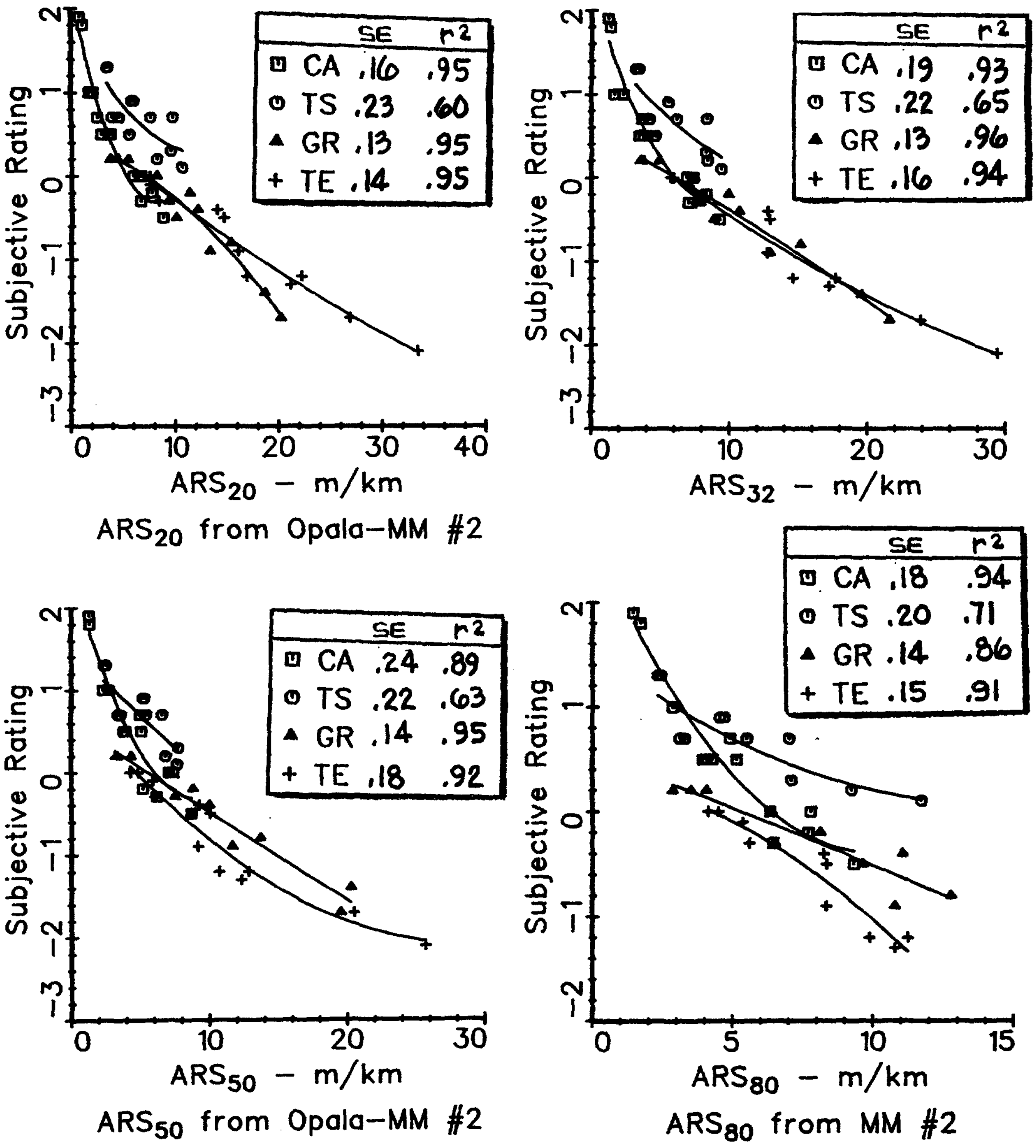


Figure D.1. Correlations between SR and ARS measures from a RTRRMS.

other surface types. The cause of these results over the TS sites is revealed by the PSD functions in Appendix I, which show that the four "roughest" of the TS sections have a periodic variation that is seen by the vehicle at 11 Hz when the speed is 80 km/h. This frequency will typically excite axle motions, because the vehicle has a lightly damped vibration mode in which the mass of the axle and wheels vibrates against the siffness of the tires. These axle vibrations, having small deflection amplitudes but high frequncy, are sensed by the roadmeter but apparently not by the passenger.

Figure D.2 shows similar plots and regression results for the RARS numeric computed from profile using the reference quarter-car simulation (RQCS) described in Appendix F. The regressions are very similar to those obtained from the RTRRMS for the lower speeds, but for the higher speeds, the regression equations collapse approximately into a single relationship. Thus, the sensitivity of the "reference" RTRRMS appears to match the panel judgement better than the ARS measures obtained from the same vehicle used to transport the raters.

Figure D.3 shows the relationships between SR and three other profile-based numerics: the short-wave $CP_{2.5}$, the medium-wave CP_{10}, and QI_r. Just as the RTRRMS speed does not strongly influence the quality of the correlation, the choice of a moving average baselength for the CP analysis does not appear critical unless the analysis emphasizes the longest wavelengths, in which case (not shown) poor correlations exist. The QI_r numeric is seen to be one of the best predictors of SR. The correlation between QI_r and SR on the unpaved roads, is the best obtained, and the correlation for the paved roads is nearly as good as seen for the $RARS_{80}$ numerics. The regression equations for the different surface types collapse approximately into a single relationship between QI_r and SR, as do the regression equations for $RARS_{50}$ and $RARS_{80}$.

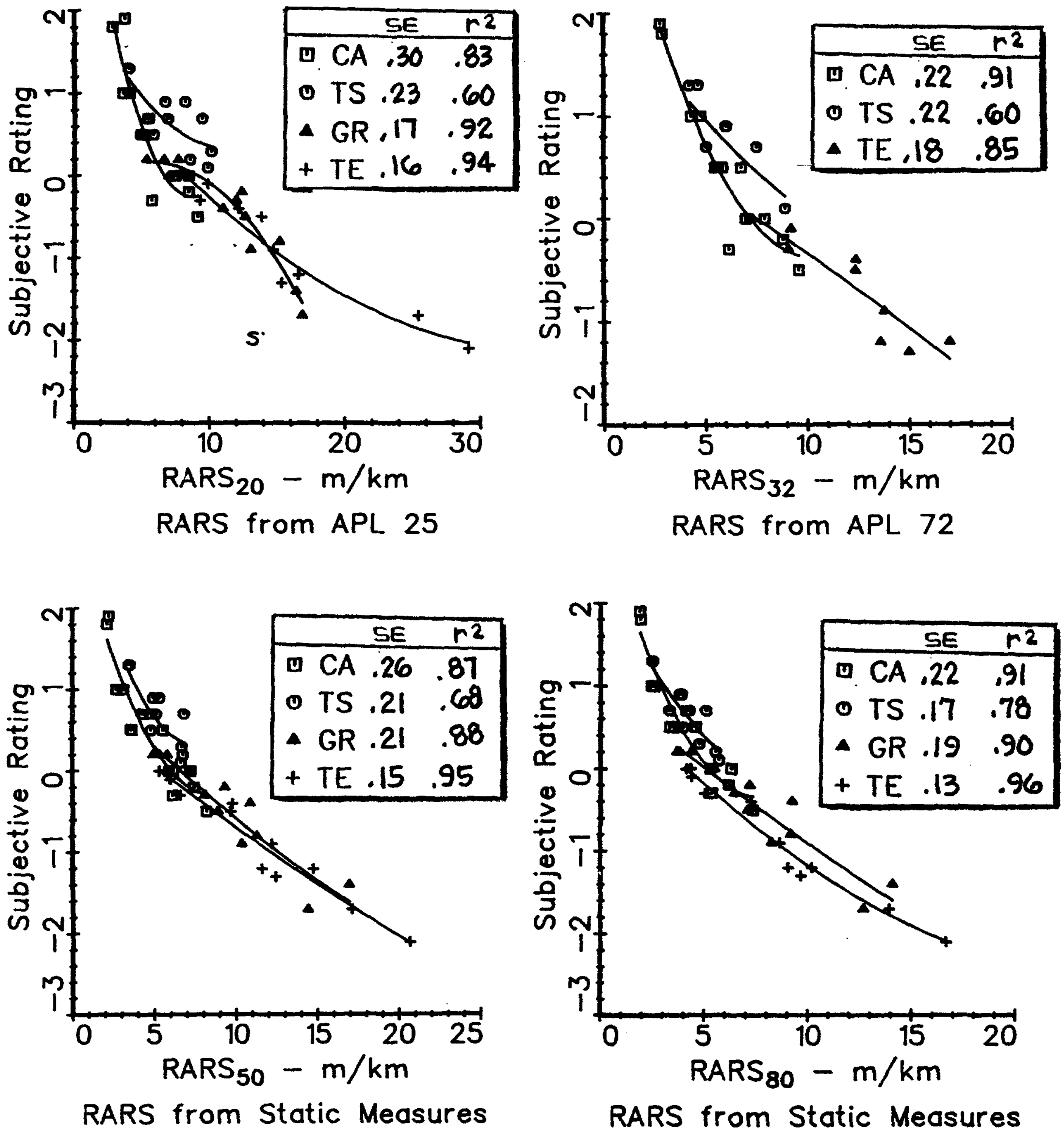
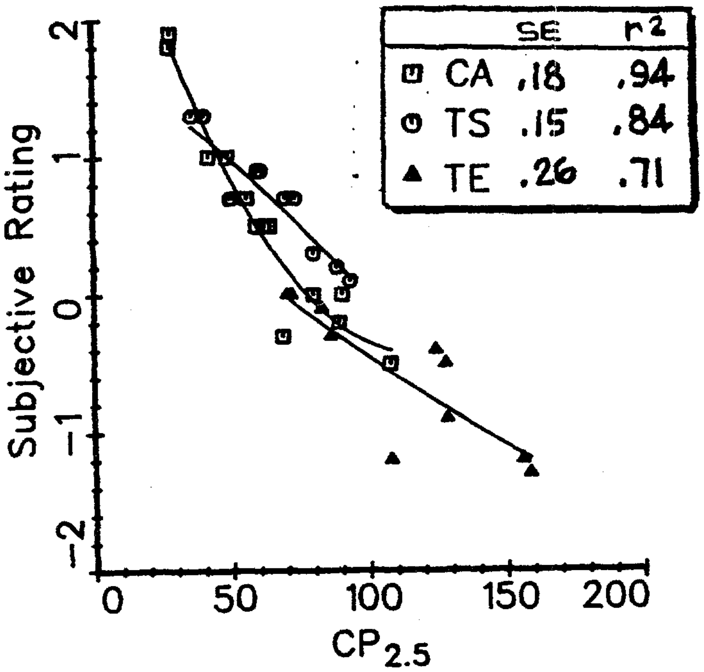
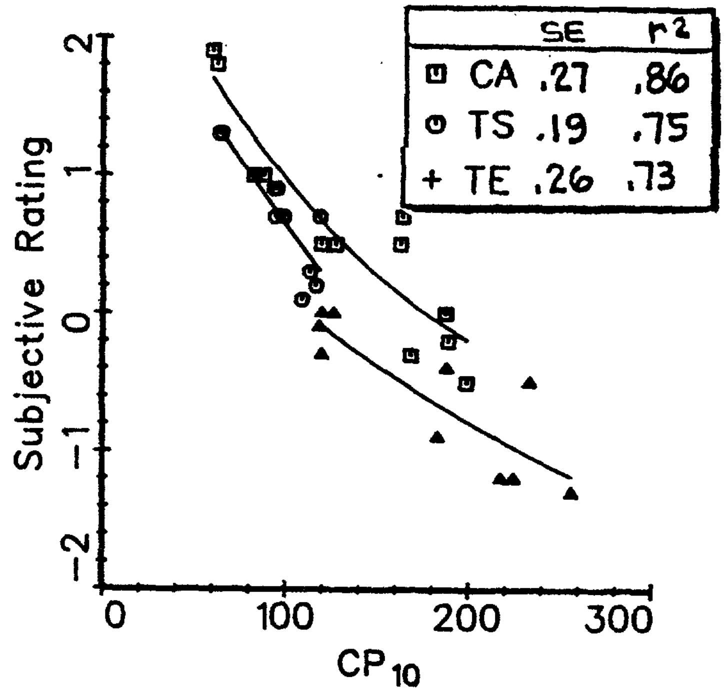


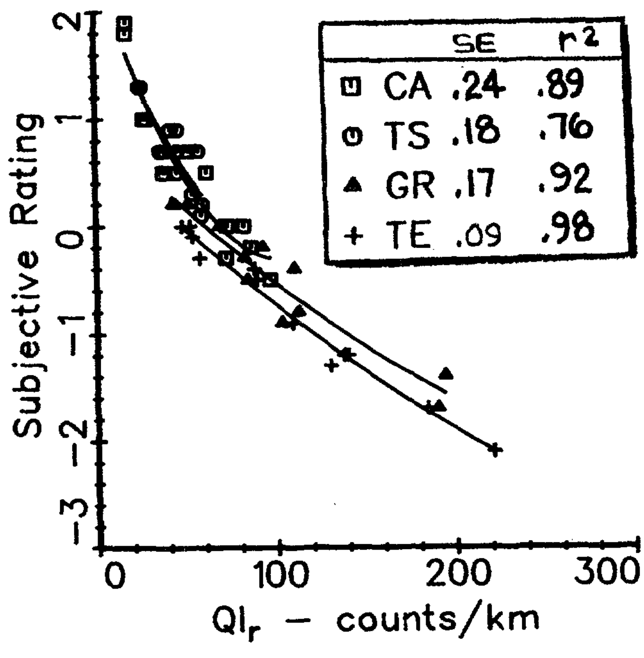
Figure D.2. Correlations between RARS from the QCS and SR.



CP 2.5 from APL 72



CP 10 from APL 72



QI from Static Measures

Figure D.3. Correlations between SR and several profile-based numerics.

APPENDIX E

QI ANALYSIS

prepared by

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QI is the name given to the roughness scale used in Brazil during and after the project, "Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization" (PICR). In actuality, there are several QI scales, which have subtle differences. During the PICR project, the QI scale evolved from a numeric that depended on the specific properties of a reference instrument (designated QI, which stands for Quarter Car Index), to a calibrated measure from a response-type road roughness measuring system (RTRRMS) (the calibrated measure is designated QI^*) [7], to a roughness numeric defined by the true longitudinal profile of the road (designated QI_r) [8].

The QI^* scale is of particular interest, because the cost equations developed in the PICR project that involve road roughness are based on measurements of QI^*.

Although it is not completely equivalent to the QI^* scale, the QI_r scale is also of interest because it is a profile-based roughness measure that has been suggested as a standard for future calibration of RTRRMSs. In addition to the testing reported in this report, the QI_r scale has also seen limited use in Bolivia [26] and South Africa [27]. Further, MO, a nearly identical scale, has been used in Texas [28].

This appendix describes 1) the development of the various versions of QI in Brazil, 2) the mathematical properties of the profile-based QI_r numeric, 3) requirements in profile measurement for valid measurement of QI_r and 4) the compatibility of the QI_r scale with the RTRRMSs that participated in the IRRE.

Many of the details of the procedures used for the QI and QI_r numerics have been reported previously [7, 8], so this appendix mainly covers new findings that have emerged during the IRRE.

DEVELOPMENT OF THE QI ROUGHNESS SCALE

QI: The Quarter-Car Index

The roughness scale initially used in the PICR project was based on the output from a GMR-type Inertial Profilometer (also called a Surface Dynamics Profilometer) used in the project [7]. The Profilometer is equipped with a special purpose analog computer called a Quarter-Car Simulation (QCS) that is intended to replicate the dynamics of a BPR Roughometer [24]. To avoid confusion between this particular QCS and others mentioned in this report, it is designated BPR/QCS. (See Appendix A for descriptions of the two BPR Roughometers that participated in this experiment, and Appendix F for a description of the BPR/QCS.) At the start of the project, both the profilometer speed and the simulation speed were set at 55 km/h, to correspond to the usage of a similar unit at The Pennsylvania State University. The BPR/QCS device produces a number of counts over each 1/10 mile of travel as a measure of road roughness. The scaling is such that each count corresponds to 1/10 inch of accumulated positive suspension deflection of the simulated vehicle. Since the test length is 1/10 mile, the units can also be expressed as "inches/mile," as normally reported for a BPR Roughometer. Because the accumulation in a BPR roadmeter is only for deflection in one direction, the statisic produced is exactly half of the ARS (average rectified slope) numeric produced by roadmeters that accumulate in both directions. This number was multiplied by 0.6214 to convert to kilometers, and the result was reported as "QI" (Quarter-Car Index) with the assumed units "counts/kilometer." The simulator was able to process only one profile at a time, so the QI was found for both the right and left wheel-tracks separately, and these measures were averaged to obtain the official QI for a test section.

The Profilometer and its related equipment experienced constant operational problems during the PICR project. Also, the output of the electronic QCS was found to vary with a number of testing conditions, such as speed, gain setting, and choice of follower-wheel. These variations were consistent and large, indicating that the instrument was not actually measuring "profile" as it is designed to do. (When used only on the smoother paved roads in the United States, the same roughness numeric can be obtained over a range of testing conditions with a GMR-type Inertial Profilometer.) Nonetheless, when operated under the same testing conditions (speed, etc.) the measurements were more time-stable and thus more reliable than those of the RTRRMSs used to gather the bulk of the roughness data for the project. In this regard, the QI measures from the Profilometer helped provide a more time stable roughness scale.

During the project, survey profile measures were made of the control sections (used for calibrating the RTRRMSs) with the rod and level technique, as the Brazilian researchers anticipated even further problems with the equipment. Efforts were made to find an alternative to the BPR/QCS "QI" that could be calculated from the rod and level profile measurements. These efforts were successful, and in 1979, after the Profilometer reached the point where the cost and effort needed to keep it operational were too great, it was "mothballed." From then on, the alternative definition of QI that could be applied to Rod and Level measures was used in the project [8].

QI_r: A Statistic Computed from Rod and Level Profile

Because of the problems associated with the Profilometer, a method for estimating QI from rod and level measurements was developed. Rod and level profiles were made of the control sites, whose QI roughness values were known. Several roughness statistics that had been proposed in the literature were calculated from measured profiles tested for agreement with the QI numerics obtained from the Profilometer:

1. RMSVA (root-mean-square vertical acceleration) [25] calculated for several baselengths,

2. MAVA (mean absolute vertical acceleration = average rectified

acceleration), also calculated for several "characteristic baselengths,"

3. Slope variance, also calculated for several characteristic baselengths, including the one for the published geometry of the CHLOE profilometer, and

4. Waveband analysis, in which profile elevation variance is computed for specific wavebands.

Using each type of analysis, the "best" model for predicting the QI as determined by the Profilometer was developed, using least squares methods to maximize fit and using ridge analyses to choose the independent variables. It was found that excellent correlations were obtained using either a waveband or an RMSVA model. In either case, two independent variables were needed (that is, two different wavebands were needed for the waveband analysis, and two different baselengths were needed for the RMSVA analysis). Computationally, the RMSVA statistic is much simpler to obtain, and thus it was adopted to redefine QI for continuing work [8].

QI^*: Rescaled Measurements from RTRRMSs

During the PICR Project, the roughness scale was defined by either the QI numeric obtained from the BPR/QCS or the QI_r statistic; however, the actual roughness measurements were made with RTRRMSs, composed of Chevrolet Opala passenger cars equipped with modified Maysmeter Roadmeters (see descriptions in Appendix B and Reference [4]). With few exceptions, the RTRRMSs were operated at speeds of 80 km/h on paved roads and at 50 km/h on unpaved roads. A third standard speed of 20 km/h was used on the worst roads, which amounted to only a few percent of the total. When operated at 80 km/h (paved roads), the "raw" measures (as read directly from the roadmeter display) of the RTRRMS were transformed to QI^* through the use of a linear regression equation, which was in essence the calibration for that particular RTRRMS. The measures made at 50 km/h were converted to QI^* through a two-step process: first, the "raw" measure was used to estimate what the RTRRMS would have measured if operated at 80 km/h. Then, the resulting estimated 80 km/h measure was converted to QI^* by using the calibration equation. On those rare occasions that actual measures were made at 20 km/h, a three-step process was used, in which the measure was transformed into an estimate of a 50 km/h measure, which was in turn transformed into an estimate of an 80 km/h measure, which was then transformed into QI^*.

Although the roughness scale has been described in terms of the QI and QI_r scales, the roughness data collected in the PICR project, used as the basis of the roughness-related cost equations, are composed completely of QI^* values: rescaled (calibrated) RTRRMS measures.

MATHEMATICAL DEFINITIONS OF THE QI SCALES

QI: Quarter Car Index

Ideally, the mathematical properties of the QI numeric would be determined by the published response properties of the BPR/QCS device [9, 24]. Due to a number of circumstances, the QI numeric includes a number of equipment-related characteristics as well, which also affect the total roughness definition. In order to understand the significance of the QI numeric, it is necessary to also know something about the factors that influence the operation of the Profilometer and the BPR/QCS.

Calibration Error. The electronic BPR/QCS produces a voltage in proportion to a simulated axle-body velocity, rectifies this signal (takes the absolute value), and integrates the rectified signal over the test length of 0.10 mile (0.160 km) to obtain accumulated displacement. The accumulated displacement signal runs a counter that increments every time a voltage threshold is reached and resets the output of the integrator to zero. The "counts" produced as the output are thus due to 1) the rate at which the signal increases (i.e., average rectified velocity, ARV), and 2) the voltage level used as a reference for "one count." Part of the calibration of the BPR/QCS electronic box involves the careful setting of this threshold, such that each count shown corresponds to .10 inch of accumulated movement in one direction (0.20 inches in both directions). The calibration is achieved by using a sine wave input of specified amplitude and frequency, and adjusting the threshold value until a specified count is obtained. During the PICR project, however, the calibration procedure outlined by the manufacturer was not followed. The speed setting on the QCS was not adjusted correctly, and a square wave was used rather than a sine wave. Not until the Profilometer was prepared for the IRRE were the effects of these errors found [23]:

1. The gain was in error such that the output had the units of .204 inch/count in one direction (.408 inch/count in both directions)

2. The gain pushed the voltage threshold near the limits of the electonic circuitry, where behavior is non-linear due to saturation of the op-amps. The sensitivity of the calibration was reduced, such that fluctuations in performance that would normally be corrected by an accurate calibration were not easily detected. Hence the main purpose of the calibration was partially thwarted.

The square wave input was used rather than the sine wave because the output drifted with a sine wave input, making calibration difficult. The use of a square wave input eliminated the symptom, but not the cause, which was found to be a defective electonic component (replaced) during the course of preparing for the IRRE.

Use of the Profilometer at low speeds. The GMR-type Profilometer senses vehicle-to-road distance using a spring-loaded follower wheel. On medium-quality paved roads, the follower wheel bounces when the Profilometer is operated at highway speeds (50 km/h and higher). In order to prevent bounce of the follower wheel, lower speeds were used during the PICR project. This introduces an additional error into the BPR/QCS numeric, however, because the instrumentation in the Profilometer and the BPR/QCS were designed for higher speeds. Specifically, the BPR/QCS has a high-pass electronic filter that attenuates "very low" frequencies. The cut-off frequency, which is the frequency at which attenuation becomes significant, can be set by the operator to match conditions. The problem is that in order to run the Profilometer without overloading the amplifiers (indicated by lights and beepers), the cut-off filter had to be set at the medium settings, near 0.5 Hz. The corresponding wavelength is determined by the Profilometer travel speed, and is 18 m/cycle at a measurement speed of 32 km/h. The response range of the

BPR/QCS depends on the simulation speed, with the 1.0 Hz lower limit corresponding to a wavelength of 15 m at the simulation speed of 55 km/h.

Although the high-pass filter transmits most of the wavelengths that affect the QI numeric, those near 15 m and longer are attenuated due to the low profilometer speed. Therefore, the QI measures probably did not contain all of the long wavelength content that would be expected if the input to the BPR/QCS had been the "true" profile.

Speed Correction. The BPR/QCS is supposed to correct for profilometer measurement speed. During the PICR project, the circuit was found to be defective, the manufacturer was contacted, and a modification to fix the circuit was developed. The modification was never implemented, however, so that the numerics produced by this particular BPR/QCS had a speed sensitivity. While the overall effect can be corrected by a speed ratio, variations in speed during measurement go undetected and can lead to variability.

Summary of "True" QI. The above factors could possibly be taken into account to determine a quantitative definition of QI. But for all practical purposes, QI can be considered as "the number produced by the BPR/QCS and the Profilometer as operated during the PICR." Because the original QI was so specific to a particular piece of hardware and operational procedures, it cannot be replicated with any assurance.

The Profilometer was only rarely used on surface treatment and unpaved roads. Since very few measurements were obtained, the original QI is effectively undefined for these conditions.

Rather than attempting to determine exactly how to describe the original QI, it has been recommended that the alternative description, designated QI_r and described below, be used as the definition of "true" QI as determined from profile measurement [8].

QI_r: Defined by Profile Geometry

Definition of QI_r. The QI_r statistic is computed directly from measured profiles. First, the profile is "filtered" to yield a variable that has been called "Vertical Acceleration," although it will be shown later that the name is not truly appropriate. The "filter" is defined by the equation:

$$VA(x) = [\ y(x + b) + y(x - b) - 2\ y(x)\ ]\ b^{-2} \qquad \text{(E-1)}$$

where

x = longitudinal distance (m)
y(x) = elevation of wheeltrack at position x (mm)
b = baselength (m).

Given measures of y(x) that are equally spaced, Eq. 1 can be re-written:

$$VA(i) = [\ y(i + k) + y(i - k) - 2\ y(i)\ ]\ b^{-2} \qquad \text{(E-2)}$$

where

$$k = b/dx \qquad \text{(E-3)}$$

and

i = index, corresponding to the i^{th} profile elevation measure
dx = distance between profile measurements

therefore

$$RMSVA_b = [\ 1\ /\ (n - 2\ k) \sum_{i=k+1}^{n-k} VA(i)^2\ ]^{1/2} \qquad \text{(E-4)}$$

where

n = number of measurements

The Estimate of QI that was developed through regression methods is:

$$E\ [QI] = QI_r = -8.54 + 6.17\ RMSVA_{1.0} + 19.38\ RMSVA_{2.5} \qquad (E\text{-}5)$$

where

E [QI] = expected value of QI, and

$RMSVA_b$ has the units: slope x 10^6. (These units arise when b is measured as m and elevations are measured as mm.)

Waveband Response of RMSVA and QI_r. The wavelength sensitivity of the VA "filter" can be calculated using Laplace Transforms, which consider a sinusoidal input:

$$y(w,x) = Y_o\ e^{jwx} = \text{input} \qquad (E\text{-}6)$$

where

$$e^{jwx} = \cos wx + j \sin wx \qquad (E\text{-}7)$$

w = spatial circular frequency (rad/m) = 2π / wavelength = 2π wavenumber, Y_o = sinusoidal amplitude, and $j = \sqrt{-1}$ = the "imaginary" part of a "complex" vector, 90^o out of phase with the "real" part. Eq. 6 describes a variable that is sinusoidal over longitudinal distance.

Combining Eqs. 1 and 6 yields:

$$VA(w,x) = [\ Y_o\ e^{jw(x+b)} + Y_o\ e^{jw(x-b)} - 2\ Y_o\ e^{jwx}\ ]\ b^{-2}$$

$$= Y_o\ [\ e^{jwx}\ e^{jwb} + e^{jwx}\ e^{-jwb} - 2\ e^{jwx}\ ]\ b^{-2}$$

$$= y(w,x)\ [\ e^{jwb} + e^{-jwb} - 2\ ]\ b^{-2}$$

$$= y(w,x)\ [\ \cos(wb) + j \sin(wb) + \cos(-wb) + j \sin(-wb) - 2\ ]\ b^{-2}$$

$$= 2\ y(w,x)\ [\ \cos(wb) -1\ ]\ b^{-2}$$

$$= -\ 4\ y(w,x)\ \sin^2(wb/2)\ b^{-2} \qquad \text{(E-8)}$$

The "gain," $|VA\ /\ Y|$, is therefore:

$$|VA\ /\ Y| = 4\ \sin^2(wb/2)\ b^{-2} \qquad \text{(E-9)}$$

or

$$|VA\ /\ Y| = 4\ \sin^2(\pi b/L)\ b^{-2} \qquad \text{(E-10)}$$

where

$$L = \text{wavelength} = 2\pi/w \qquad \text{(E-11)}$$

This relationship is shown in Figure E.1. The figure also shows the wavelength sensitivity of double differentiation, which defines the true form of vertical acceleration. Differentiation of a variable is very simple in the frequency domain:

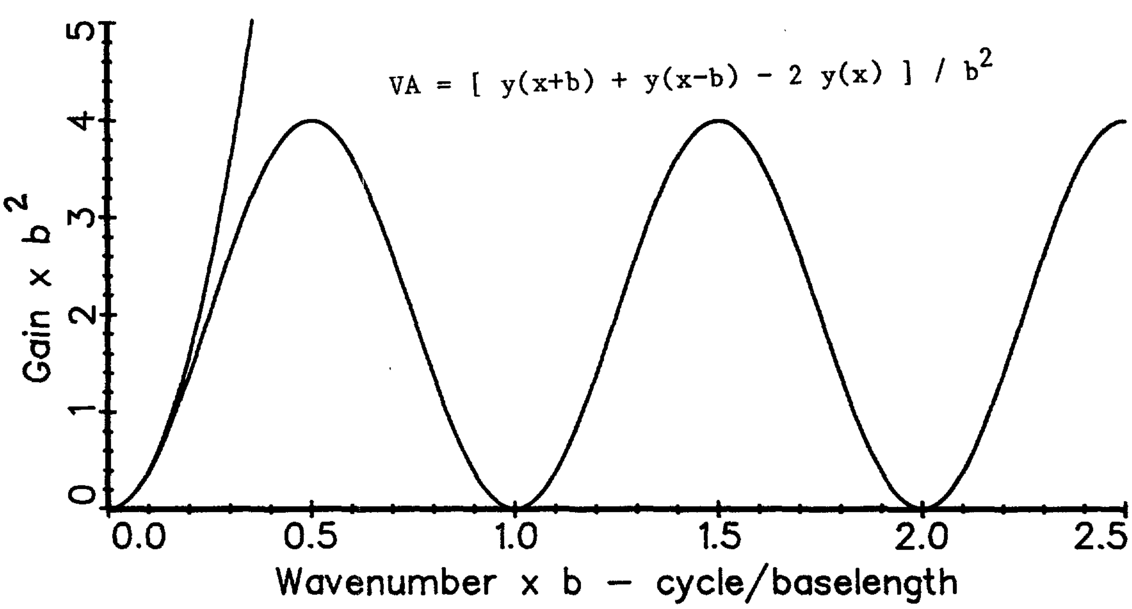
$$y'(w,x) = dy/dx = jw\ Y_o\ e^{jwx} = jw\ y(w,x) \qquad \text{(E-12)}$$

The amplitude response of a double differentiation is obtained by applying Eq. 12 twice:

$$|y''\ /\ y| = |jw\ jw| = |-w^2| = w^2 = (2\pi/L)^2 \qquad \text{(E-13)}$$

When the wavelengths are large relative to the RMSVA baselength, Eq. 10 and 13 yield similar results. In order for the difference to be less than 10%, the wavelengths must be at least 5.6 times longer than the baselength. For the QI_r numeric, which uses a baselength of 2.5 m, this means that the transform approximates vertical acceleration only for wavelengths longer than 14 m, even though most of the "roughness" derives from shorter wavelengths. Thus, the name "RMSVA" is a misnomer, because the roughness statistic has virtually no relation to vertical acceleration of the profile.

Eq. 10 also shows that the VA variable has no response to the wavenumber true vertical acceleration



NOTE: Wavenumber = 1/wavelength

Figure E.1. Sensitivity of RMSVA to Wavenumber

= 1/b and all multiples (harmonics) of this value. It has maximum sensitivity at wavenumbers .5/b, 1.5/b, 2.5/b, ... The VA variable does not have a bandwidth for an arbitrary elevation input, being equally responsive to wave numbers .5/b and 1000.5/b.

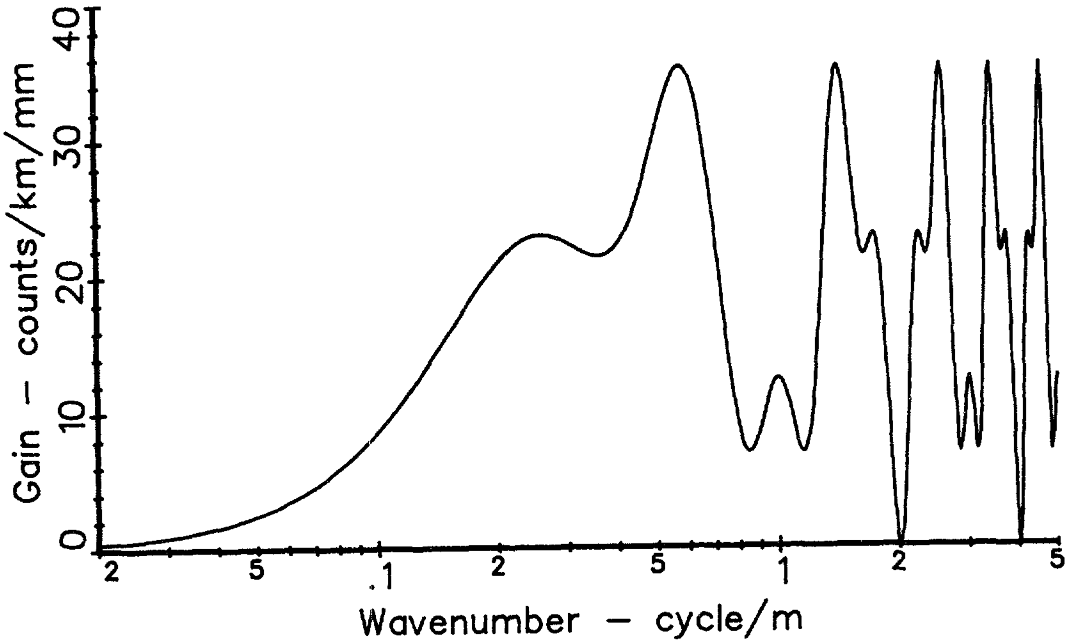
The RMSVA filter is linear, but Eq. 5 is not because it adds two RMS numerics to yield the QI_r statistic. Therefore, QI_r does not have a true waveband response that applies to broad-band road inputs. (That is, if the QI_r numerics that result for two separate inputs are known, there is no relation between those two numerics and the QI_r value that would be obtained from the linear sum of the two inputs.) Nonetheless, the response of the QI_r analysis can be calculated for a purely sinusoidal input by combining eqs. 5 and 10. (Note that the substitution of the ratio of output/input from eq. 10 into eq. 5 implies that the sinusoidal input is characterized by RMS amplitude.)

$(QI_r + 8.54)$ / RMS Y = response to sinusoidal profile input

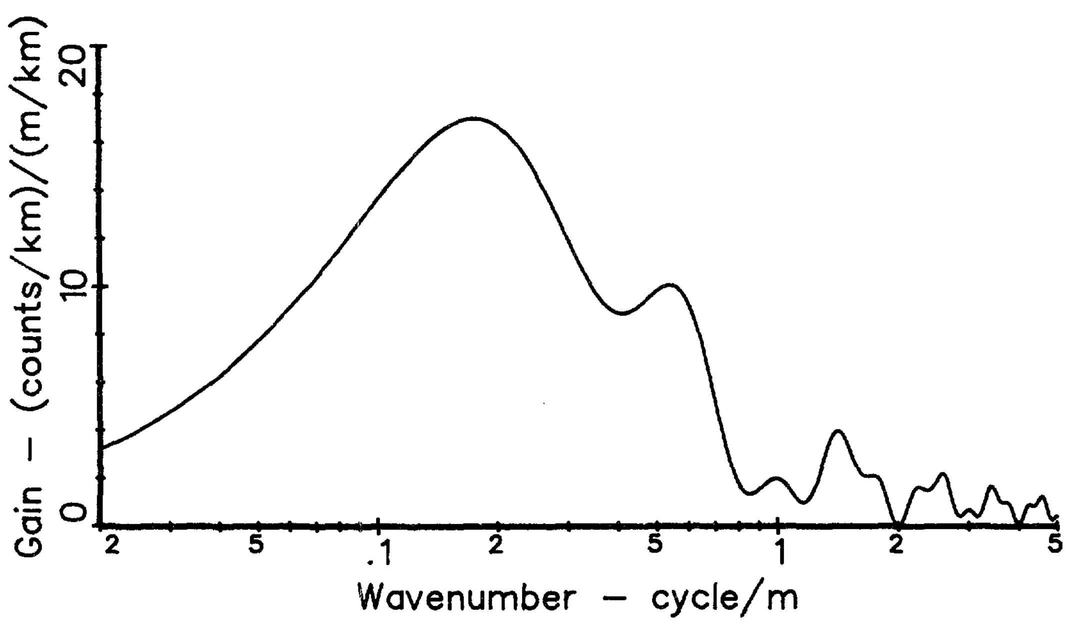
$$= 4 \times 6.17 \ \sin^2(\pi\ 1.0/L)\ 1.0^{-2} + 4 \times 19.38\ \sin^2(\pi\ 2.5/L)\ 2.5^{-2}$$

$$= 24.7 \sin^2(\pi/L) + 12.4 \sin^2(2.5\pi/L) \qquad \text{(E-14)}$$

Eq. 14 is shown plotted in Figure E.2a. While the figure shows that the QI_r analysis amplifies the profile input for shorter wavelengths, it should be noted that there is substantially more road roughness content at long wavelengths when elevation is used to define profile. (See Appendix I, which contains the PSD's of the 49 test sections of the IRRE.) Eq. 14 can be re-written to show the relative importance of wavelengths to the QI_r numeric, by considering a profile input defined by slope. Combining Eqs. 12 and 14 gives:



a. Sensitivity of QIr to pure sinusoidal displacement



b. Sensitivity of QIr to pure sinusoidal slope input

Figure E.2. Sensitivity of QI_r to Wavenumber

$(QI_r + 8.54)$ / RMS Y' = response to sinusoidal slope input

$$= [\ 24.7 \sin^2(\pi/L) + 12.4 \sin^2(2.5\pi/L)\ ] / w$$

$$= L\ [\ 24.7 \sin^2(\pi/L) + 12.4 \sin^2(2.5\pi/L)\ ] / 2\pi$$

$$= L\ [\ 3.95 \sin^2(\pi/L) + 1.97 \sin^2(2.5\pi/L)\ ] \qquad \text{(E-15)}$$

Eq. 15 is plotted in Fig. E.2b.

One of the motives for determining the sensitivity of an analysis to different wavelengths is to help determine whether the analysis is compatible with band-limited measurements. In this case, the question is whether dynamic profilometers such as the APL trailer can be used to directly measure RMSVA and QI_r. In an absolute sense, they cannot. Fig. E.2a shows that the QI_r analysis is not band-limited. The bandwidth of the APL profilometer is limited, however, such that it is not capable of transducing very short wavelengths. If these wavelengths contribute to the RMSVA or QI_r numerics when measured statically, then measures made using the profilometers will be in error since these wavelengths are omitted. If, on the other hand, most of the RMSVA numeric derives from wavelengths that are transduced by the profilometer, then the error can be negligible.

The factor that determines whether or not QI_r can be measured with a dynamic profilometer is the spectral content of the road itself. On roads having less short-wavelength roughness, the errors are slight, while on roads having significant short-wavelength roughness, results obtained from a dynamic profilometer will be more in error. The response to slope input shown in Fig. E.2b gives a fairly reasonable view of the significance of different wavelengths for typical road inputs.

Effect of Measurement Interval. Eqs. 2 - 4 indicate that RMSVA can be computed using any baselength that is a multiple of the measurement interval (the distance between successive profile elevation measurements). The limiting case, of course, is where the baselength equals the measurement interval. When the measurement interval is shorter, such that the baselength is an integer multiple of the measurement interval, Eq. 4 can be re-written:

$$RMSVA_b = [\ 1/(m-2) \sum_{i=1}^{m-1} VA(ik)^2 + 1/(m-2) \sum_{i=1}^{m-1} VA(ik+1)^2 +$$

$$1/(m-2) \sum_{i=1}^{m-1} VA(ik+2)^2 + \ldots\ ]^{1/2}$$

$$= [\ 1/[\ k\ (m-2)] \sum_{j=0}^{k-1} \sum_{i=1}^{m-1} VA(ik+j)^2\ ]^{1/2} \qquad \text{(E-16)}$$

where

$$m = n/k \qquad \text{(E-17)}$$

and it is assumed (for mathematical convenience in this discussion of measurement interval) that the quantity n is an integer multiple of k. Eq. 16 can be further simplified:

$$RMSVA_b = [\ 1/k \sum_{j=0}^{k-1} R_j^{\,2}\ ]^{1/2} \qquad \text{(E-18)}$$

where

$$R_j = [\ 1/(m-2) \sum_{i=1}^{m-1} VA(ik+j)^2\ ]^{1/2} \qquad \text{(E-19)}$$

The above equations have a simple interpretation, since Eq. 19 is equivalent to Eq. 4 for the case of k=1 (baselength = sample interval). The RMSVA value obtained with a small sample interval, in which case $k > 1$, is the RMS sum of all of the possible RMSVA values that can be obtained by skipping data points.

Although the RMSVA formulation has always been presented in terms of a finite number of data points [8, 25, 28], the definition of RMSVA given in Eqs. 2 - 4 can be extended to a limit, where the sample interval dx approaches zero. The "true" $RMSVA_b$ value is thus:

$$\text{"true"}\ RMSVA_b = \lim_{1/k \to 0} [\ 1/k \sum_{j=0}^{k-1} R_j^{\,2}\ ]^{1/2} \qquad \text{(E-20)}$$

Since the selection of the beginning point of the profile measurement is essentially random over a distance lying within the baselength b, as opposed to being systematically selected on the basis of profile properties, the best estimate of any particular R_j value must be independent of the starting point j. That is, the best estimate of R_j will be the same, whether the computation starts at the first profile elevation measurement (j=0), the second (j=1), or any arbitrary position between the start of the data set and a distance corresponding to the baselength b. This is true for a stationary signal, and qualifies as a valid "engineering assumption" as long as the length of the profile is much larger than the baselength.

If the expected value of R_j is independent of j, then all R_j variables computed for a given (long) profile must have the same expected value, and thus:

$$\text{"true" } RMSVA_b = \lim_{1/k \to 0} \{ 1/k \; k \; E[R_j^2] \}^{1/2}$$

$$= E[R_j] \qquad \text{(E-21)}$$

In other words, there is no bias error associated with having a profile measurement interval equal to the RMSVA baselength. The only error is a random one, which is determined by the (random) selection of a starting point for the RMSVA computation. If a profile has the same properties as a stationary random signal, the random error is inversely proportional to the square root of n, the number of independent elevation measures. The error is thus reduced by increasing n in either of two ways: 1) use a shorter sample interval, or 2) use a longer section length. In actuality, no profile is truly stationary, nor random. Therefore, the random error can be decreased by increasing the section length only to the extent that the roughness properties are consistent over the entire length, in accordance with the assumed stationarity. On the other hand, decreasing the sample interval will always bring the estimate of RMSVA closer to the "truth" for that particular segment of profile.

Given the application of RMSVA, in which high accuracy for a short segment is not the primary motive, increasing the section length is preferable to decreasing the measurement interval when possible. This is because the longer profile tends to better approach the assumption of a stationary random signal, and is less dominated by any singularities in its vertical geometry. Since the RMSVA numerics have been suggested as a means for calibrating RTRRMSs, there is another reason to use longer section lengths when possible, because the RTRRMS measurements also include random errors that are decreased with longer sections.

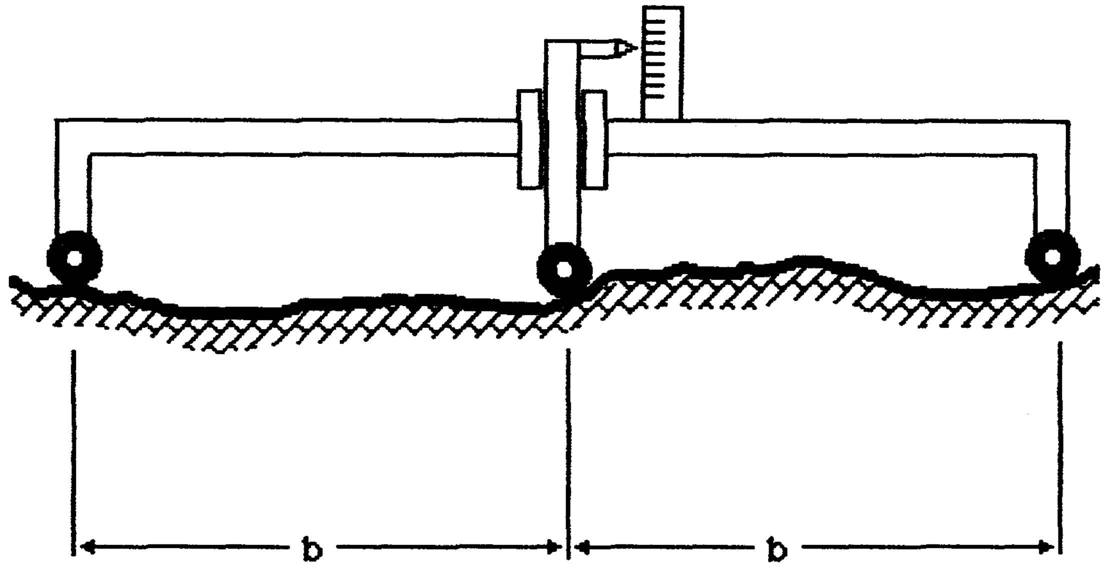
Physical Interpretation of RMSVA and QI_r

RMSVA. Even through the RMSVA statistic is not a measure of vertical acceleration, the VA "filter" has a very simple interpretation: it is equivalent to the mid-chord deviation that would be obtained from a rolling straightedge. As shown in Figure E.3, the deviation of the center of the chord is the difference between the profile elevation at that point and the average of the elevations at the two endpoints of the chord:

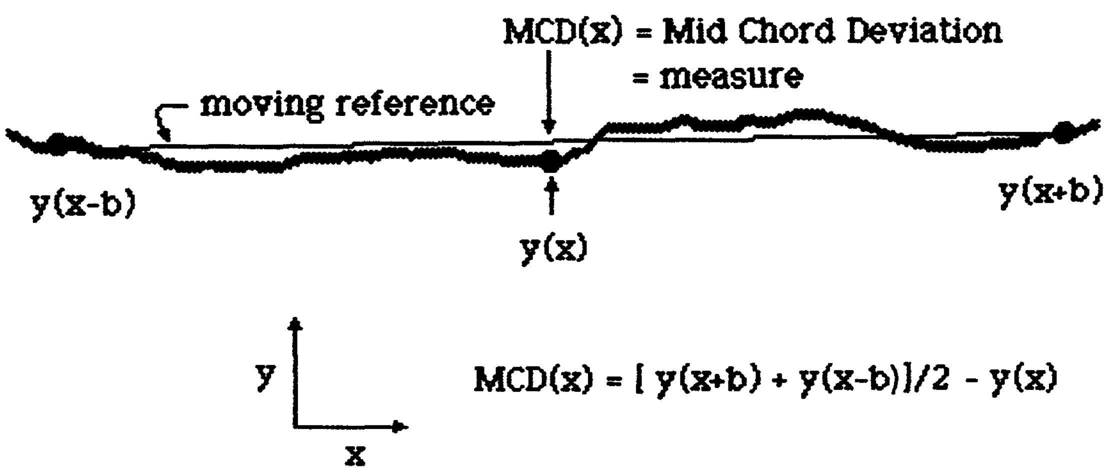
$$MCD(x) = [\ y(x+b) + y(x-b)\ ]/2 - y(x) \qquad \text{(E-22)}$$

In comparing Eq. 22 to Eq. 1, it can be seen that the two differ only by the scale factor $2\ b^{-2}$. Eq. 22 yields a numeric with units of deflection (mm) and the simple interpretation of the figure. "RMSVA" is simply the RMS value of a mid-chord deviation, as would be obtained from a three-point moving straightedge having a length of 2b.

QI_r. The QI_r numeric does not have any direct physical interpretation. It is a weighted sum of two RMS mid-chord deviations, based on chord lengths of 2.0 and 5.0 m. Since it has been used primarily for the calibration of RTRRMSs, it can be thought of as a reference RTRRMS, particularly since the measures are reported as "counts/km." One problem with this interpretation is that the QI_r numeric has certain characteristics that are not reflected in RTRRMSs. For example, wavelengths of 0.5 m are completely "invisible," as can be expected from the concept of RMSVA as shown in Fig. E.3, even though they affect the measure obtained from a RTRRMS. Also, the VA variable defined in Eq. 1 is defined at all times by the profile at three discrete locations. Thus, a singular roughness event, such as a big



a. Schematic Representation of a Mechanical Rolling Straightedge



b. Geometry of Mid Chord Deviation

Figure E.3. Physical Model of RMSVA analysis.

pothole, will cause only three large VA values. A RTRRMS, on the other hand, will respond to the singularity for some time after encountering it.

The QI^* Calibration Method.

All of the road roughness data measured in the PICR Project, as reported and stored in the Brazilian computer data files, are on a scale called QI^*. QI^* is the calibrated roughness measure obtained with the RTRRMSs used in that project, which were the Opala/modified Maysmeter systems described in Appendix A. When operated at 80 km/h (96% of paved road length was measured in the vehicle cost study at 80 km/h [14]), the direct ARS measures (as read directly from the roadmeter display) of the RTRRMS were transformed to QI^* through the use of a linear equation having the form:

$$QI^* = A + B\ ARS_{80} \qquad \text{(E-23)}$$

The values of A and B were found for each RTRRMS during "calibration" by regressing measures of QI (in the early part of the project) or QI_r (in the later part of the project) against the ARS_{80} measures obtained from that RTRRMS on special calibration sites that were periodically re-measured to determine current QI/QI_r roughness levels. The calibration sites were all on paved roads and had mostly asphaltic concrete surfaces. Only a few sections had double surface treatment construction, and these were usually omitted from calibration computations because they were "outliers," deviating from the correlation equation found for the majority of the sites.

On unpaved roads, the RTRRMS was typically operated at 50 km/h (94% of the total length measured in the vehicle operating cost study [14]). A single "speed correction equation"

$$E\ [ARS_{80}] = -0.275 + 1.04\ ARS_{50} \qquad \text{(E-24)}$$

was used for all RTRRMSs, and surface types, to rescale the 50 km/h measurement to an approximation of what the RTRRMS might have measured at 80 km/h. (Eq. 24 requires the ARS measures to have units of m/km, as used for presenting all of the IRRE data. The original version [7] used -275 as the offset, based on ARS measures with the units: mm/km.) To determine QI^*, the estimate of ARS_{80} from Eq. 24 would be re-scaled according to Eq. 23.

When a speed of 50 km/h could not be used, a third standard speed of 20 km/h was allowed. In this case, a third conversion equation was also needed:

$$E\,[ARS_{50}] = 1.023 + 0.658\ ARS_{20} \qquad \text{(E-25)}$$

The estimate of ARS_{50} is then rescaled to an estimate of ARS_{80} using Eq. 24, which is in turn re-scaled to QI^* using the calibration equation determined for that RTRRMS (Eq. 23).

The roughness range used in determining the critical "calibration equation" for Eq. 23 was much less than the range covered by the RTRRMS, because only paved roads were used. The roughness of the calibration sites never exceeded 100 counts/km, while many of the QI^* values obtained for unpaved roads were higher than this, ranging up to 300 counts/km. Therefore, characteristics of the RTRRMS that were dependent on road roughness were not corrected by this procedure. To maintain consistency, all RTRRMSs were based on the same make, model, and year of passenger car. When vehicle components such as shock absorbers were damaged or wore out, they were replaced only with OEM equivalents.

Mathematically, the QI^* roughness scale cannot be completely quantified, because it depends in part on the calibration procedure (Eqs. 23 - 25), and in part on the response properties of those particular RTRRMSs during the PICR. Since different methods were used on different surfaces, the QI^* scale is defined by several procedures, each of which was applied over some of the conditions. By surface type, these are:

Asphaltic Concrete. The QI^* measures are more-or-less equivalent to the QI_r scale, since the calibration equation (Eq. 23) is valid over the roughness range (0 - 100 counts/km), surface type (asphaltic concrete), and measurement speed (80 km/h) that were used to obtain the actual field measurements (96%).

Surface Treatment. The calibration sites included a few surface treatment sites, but the roughness measures were often excluded from the regression equation because there was poor agreement between the ARS_{80} measures from the RTRRMS and the QI/QI_r reference measures. Nearly all of the ARS measures were obtained at 80 km/h in the PICR project; thus, the QI^* values obtained are ARS_{80} measures rescaled according to Eq. 23. Because the calibration sites did not include enough surface treatment sections, QI^* is determined by 1) the response of the Opala (as maintained in the PICR project) at 80 km/h over a surface treatment road, and also 2) its response over asphaltic concrete roads at that speed.

Unpaved Roads. Nearly all (94%) field measurements on unpaved roads in the user cost survey were made at 50 km/h. On these roads, the QI^* values are determined by: 1) the response of the Opala at 50 km/h over unpaved roads, 2) its response at 80 km/h over asphaltic concrete roads, and 3) an aggregate speed conversion equation (Eq. 24).

MEASUREMENT OF QI_r IN THE IRRE

Technical Requirements for Measuring QI_r

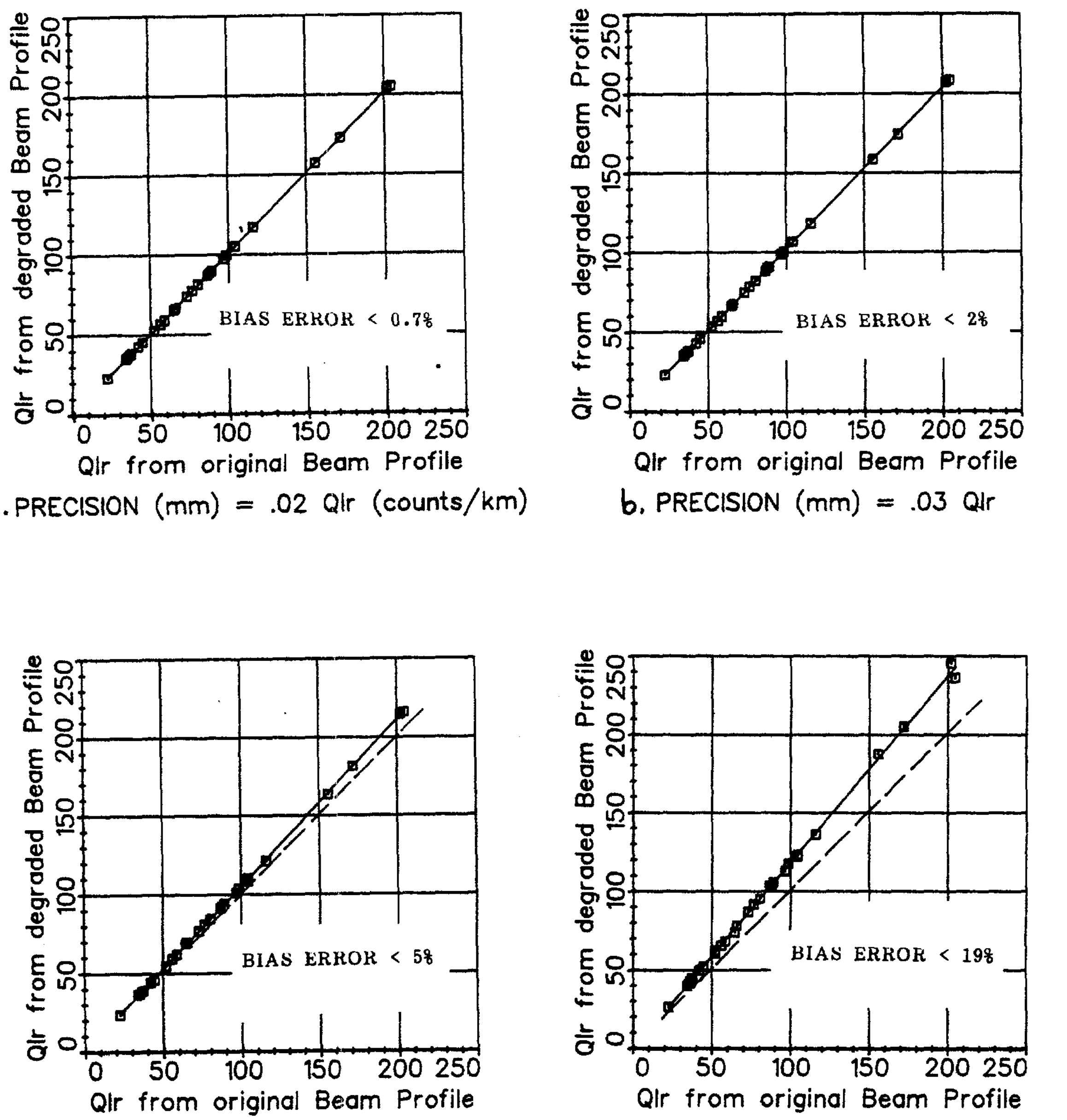
Measurement Interval. The effect of profile measurement interval on the QI_r numeric has been tested and reported previously, with the conclusion that a 500 mm interval is sufficient [8]. The analyses of the QI_r computation method, presented in the previous section (Eqs. 16 - 21), prove that use of alternate intervals cannot bias the expected value of the QI_r numeric, but that repeatability should be improved when a shorter interval is used. Profiles obtained from the TRRL Beam (100 mm intervals) and the APL 72 system (50 mm intervals) were decimated to yield profiles with 500 mm spacings. QI_r numerics computed before and after the decimation agreed closely, as had been found earlier.

Precision in the Elevation Measurement. Based on experience with QCS numerics, it was anticipated that the precision needed in profile measurement for acceptable accuracy in QI_r depends on the roughness. A candidate specification was considered in which the required precision of the profile elevation measurement is simply proportional to the roughness of a road, when expressed as QI_r. An analysis of the profile data obtained from the TRRL Beam was performed to determine: 1) if this type of specification is reasonable, and 2) if it is reasonable, what quantities are involved?

In this analysis, the precision of the measurement was assumed to be limited solely by the quantization of the continuous height variable into digitized quantities, which were originally 1.0 mm. The random measurement errors that also degrade precision were not considered. For each of the 28 measured profiles, the QI_r value obtained with the original profile was used to determine a new quantization level (greater than 1 mm). The profile was then quantized to the nearest multiple of this new level, and re-processed to yield a new QI_r numeric. Figure E.4 shows the results for four levels of increased quantization (degraded precision). In all cases, the effect of the degraded precision is an increase in the computed roughness numeric. The changes were calculated from the difference in the (solid) quadratic regression lines and the (dashed) equality line (x = y), and were found to be nearly constant across the range of roughness when expressed as a percentage. (For example, for the case of precision = 0.03 QI_r, shown in Fig. E.4b, the errors were 1.8% at QI_r = 50, and 1.9% at QI_r =100, 150, and 200 counts/km.) This indicates that the candidate method of specifying required precision in proportion to roughness is valid. For QI_r accuracy within 1.0%, the precision (mm) should be about 0.02 QI_r (counts/km), while for accuracy within 2%, the precision should be less than 0.03 Qi_r. Thus, on the smoothest sites, which had QI_r values near 20 counts/km, the actual measurement precision of 1.0 mm probably led to numerics that are several percent higher than the "true" QI_r values. A measurement precision of 0.5 mm would have been better. At the other end of the scale, where roughness levels were greater than 150 counts/km, a measurement precision of 3 mm (less than 0.02 QI_r) gave the same results as the original precision of 1 mm.

Summary of QI_r Data

The summary QI_r numerics that were obtained from four methods of profile measurement are presented in Table E.1. Some of the paved sections were measured before and during the IRRE via rod and level. Those measured prior are indicated as "RL 1" and those measured during the IRRE are designated "RL



a. PRECISION (mm) = .02 Qlr (counts/km)

b. PRECISION (mm) = .03 Qlr

c. PRECISION (mm) = .05 Qlr (counts/km)

d. PRECISION (mm) = .1 Qlr (counts/km)

Figure E.4. Effect of Profile Measurement Precision on the QI_r numeric

Table E.1 Summary of the QIr Numerics Obtained in the IRRE

Site	Left Wheeltrack						Right Wheeltrack						Both Wheeltracks: Average					
	Static	RL 1	RL 2	Beam	A 72	A 25	Static	RL 1	RL 2	Beam	A 72	A 25	Static	RL 1	RL 2	Beam	A 72	A 25
CA01	47	48	45	....	....	46	57	64	49	....	50	60	52	56	47	....	....	53
CA02	68	67	69	....	59	46	55	58	53	....	70	44	62	63	61	....	64	45
CA03	84	79	89	....	72	77	81	83	78	....	78	69	82	81	84	....	75	73
CA04	78	77	80	77	70	71	68	69	69	66	64	62	73	73	75	71	67	67
CA05	93	98	94	87	96	78	80	80	80	80	69	52	86	89	87	84	82	65
CA06	106	108	106	104	101	83	88	92	84	88	89	72	97	100	95	96	95	78
CA07	32	31	32	....	43	35	25	25	25	....	31	28	28	28	29	....	37	31
CA08	26	26	26	....	31	28	28	28	28	....	30	23	27	27	27	....	30	25
CA09	45	46	43	....	60	37	33	34	31	....	37	35	39	40	37	....	49	36
CA10	39	40	39	....	54	46	36	41*	33	34	44	33	38	40	36	....	49	40
CA11	81	84	78	....	56	46	64	64	64	....	72	44	72	74	71	....	64	45
CA12	18	16	15	22	15	25	17	15	18	....	15	22	17	16	17	....	15	23
CA13	17	17	18	....	16	17	18	19	17	....	17	17	18	18	17	....	16	17
TS01	45	45	....	45	43	40	47	47	....	....	....	40	46	46	....	....	....	40
TS02	59	59	....	....	51	46	56	56	....	....	49	45	57	57	....	....	50	46
TS03	58	58	....	....	55	54	50	50	....	....	....	48	54	54	....	....	....	51
TS04	56	55	....	56	50	54	63	63	....	....	....	49	59	59	....	....	....	51
TS05	64	65	63	65	68	57	53	54	51	....	58	52	59	60	57	....	63	55
TS06	37	39	35	38	35	30	35	34	35	35	31	31	36	36	35	36	33	30
TS07	36	39	33	37	35	32	41	39	42	....	37	33	39	39	38	....	36	32
TS08	43	43	44	....	39	35	47	47	48	....	43	36	45	45	46	....	41	36
TS09	48	55	42	....	39	38	42	43	42	....	42	44	45	49	42	....	41	41
TS10	41	41	....	....	42	35	42	42	....	....	41	34	42	42	....	....	42	34
TS11	25	25	....	....	23	20	26	26	....	....	25	18	26	26	....	....	24	19
TS12	26	26	....	....	23	24	24	24	....	....	22	17	25	25	....	....	23	20
GR01	52	....	52	....	33	44	37	....	32	42	....	38	45	....	42	....	....	41
GR02	45	....	45	....	47	26	41	....	41	....	....	22	43	....	43	....	....	24
GR03	114	....	114	....	74	81	71	....	71	....	....	65	93	....	93	....	....	73
GR04	95	....	95	....	88	73	71	....	71	....	....	60	83	....	83	....	....	66
GR05	117	117*	117	116	119	91	108	112*	108	105	....	92	112	115	112	110	....	92
GR06	108	....	108	....	112	82	98	....	98	....	....	90	103	....	103	....	....	86
GR07	86	....	82	89	62	43	52	....	52	52	....	34	69	....	67	71	....	39
GR08	55	....	55	....	48	41	48	....	48	....	....	33	51	....	51	....	....	37
GR09	119	....	119	....	105	65	102	....	102	....	....	73	110	....	110	....	....	69
GR10	96	....	96	....	102	77	73	....	73	....	....	78	84	....	84	....	....	77
GR11	202	....	202	....	....	158	187	....	187	....	....	136	194	....	194	....	....	147
GR12	205	....	205	205	....	138	176	....	181	172	....	140	190	....	193	188	....	139
TE01	54	....	50	59	49	57	50	48*	51	52	43	50	52	....	50	55	46	54
TE02	49	....	49	....	43	44	47	....	47	....	51	36	48	....	48	....	47	40
TE03	100	....	102	99	99	69	76	....	79	73	75	55	88	....	90	86	87	62
TE04	93	....	93	....	107	82	85	....	85	....	76	67	89	....	89	....	91	75
TE05	185	182*	189	....	....	161	184	182*	185	....	....	154	185	182	187	....	....	157
TE06	240	....	240	....	....	205	202	....	202	202	....	160	221	....	221	....	....	182
TE07	61	....	61	....	56	53	47	....	47	....	53	51	54	....	54	....	55	52
TE08	67	....	67	....	64	58	49	....	49	....	51	41	58	....	58	....	58	49
TE09	109	....	109	....	99	78	110	....	110	....	80	74	109	....	109	....	90	76
TE10	156	....	156	....	135	84	120	....	120	....	98	85	138	....	138	....	117	84
TE11	163	....	170	156	139	118	98	....	98	97	99	71	130	....	134	126	119	94
TE12	164	....	164	....	101	131	117	....	117	....	110	94	140	....	140	....	105	112

* rod and level measures using 100 mm interval between elevation measurements.

2." In addition, 6 wheeltracks were measured by rod and level using a measurement interval of 100 mm. These are also shown in the "RL 1" column, and are identified with an asterisk. The labels "Beam," "A 72," and "A 25" indicate profiles measured with the TRRL Beam, the APL Trailer in the APL 72 configuration, and the APL Trailer in the APL 25 configuration. The results indicated under the headings "Static" are averages of the numerics obtained with the static profile measurements, that is, rod and level and the TRRL Beam. When examining correlations with other measures and statistics, the numbers under the "Static" heading were used.

Accuracy of QI_r Computed from Statically Measured Profiles

Repeatability with Rod and Level. Most of the sources of error that plague roughness measurements using RTRRMSs are eliminated when profiles are measured statically with rod and level: the same roughness computation method can be used, eliminating variations due to different definitions of roughness; and surveying equipment is sufficiently interchangeable to eliminate problems of reproducibility. The only remaining variation is the repeatability that can be achieved in measuring a profile. The repeatability that can be achieved is, in this case, the accuracy of the roughness measurement. Since most of the paved sites were profiled twice with the rod and level method, the IRRE data give an idea of the repeatability achievable in using QI_r as a roughness measure.

Figure E.5a shows the comparison of QI_r measures obtained in two independent rod and level surveys. As in other plots, the dashed line is the line of equality (x=y), while the solid line is the "best fit" as obtained with a quadratic regression. The RMS errors shown in the figures are with reference to the line of equality, rather than the regression line, since regression methods would never be used to "correct" profile-based numerics. Note that the accuracy limits shown in the figures apply only to the IRRE section length of 320 m, and should not be considered universal for all section lengths. For roads whose roughness is more-or-less constant, it can be expected that better accuracy would be obtained for longer test site lengths, because the random sources of variation would tend to average out. The expected change in accuracy is proportional to the square root of length,

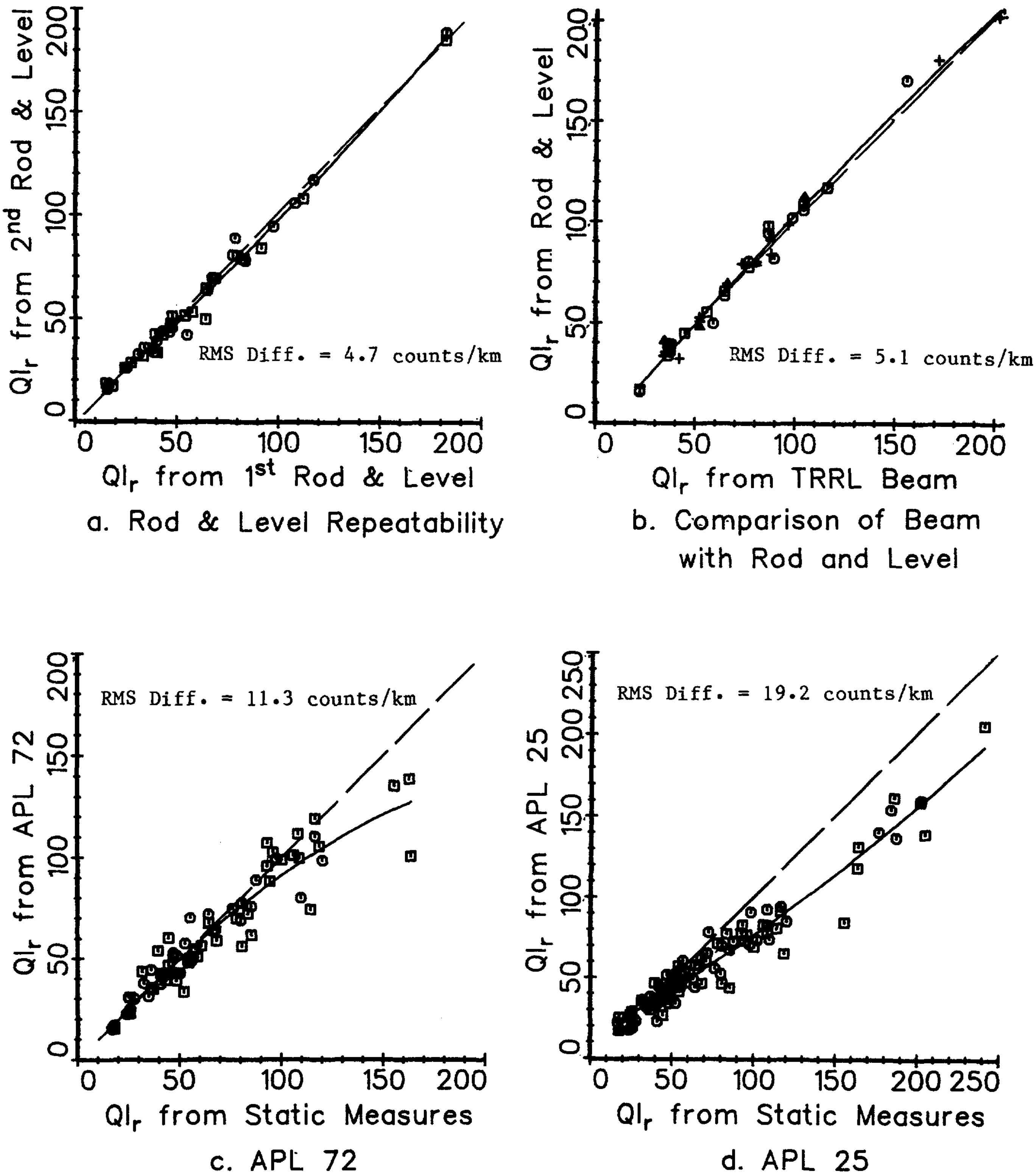


Figure E.5. Comparison of QI_r Measurements from Different Instruments.

such that the random variations indicated in the figure would be cut in half if the section length were increased by a factor of four. On the other hand, larger errors should be expected for shorter sections.

Validation of the TRRL Beam. Figure E.5b compares the QI_r numerics obtained with rod and level and the TRRL beam. Approximately the same repeatability is obtained as with repeated measures with rod and level, indicating that the TRRL Beam is a valid means for measuring longitudinal profile for the purpose of computing QI_r.

Direct Computation of QI_r from Dynamically Measured Profiles

APL 72. Figure E.5c compares the QI_r numerics computed from the profile signals obtained from the APL Trailer in its APL 72 configuration with the QI_r numerics computed from the statically measured profiles. The measures obtained from the APL 72 are lower than those obtained statically, as evidenced by the fact that the quadratic regression line lies below the line of equality. In addition to this bias error (for the rougher sites), the amount of scatter (random error) is much greater than when static profile measurement methods are used.

The results obtained with the APL 72 system can be explained by the power spectral density (PSD) plots presented in Appendix I. At 72 km/h (20 m/sec), the APL Trailer attenuates inputs having wavelengths shorter than 1.0 m, as shown in Figure G.1. When profiles were obtained by the TRRL Beam using an interval of 100 mm, the PSDs obtained from the APL 72 can be compared with static measures for wavelengths shorter than 1.0 m (wavenumbers higher than 1.0 cycle/m). The comparisons verify that the APL 72 is attenuating the profile for those short wavelengths. Since the QI_r numeric is influenced by wavelengths shorter than 1.0 m (Fig. E.2b), it includes the full amplitude of the shorter wavelengths when computed from statically measured profiles, but is "missing" some of the amplitude when measured dynamically, due to the limitations in the response of the APL Trailer.

Note that the wavelengths attenuated by the APL 72 do not influence the APL 72 numerics normally computed by LCPC.

APL 25. Figure E.5d compares the QI_r numerics computed from the profile signals obtained from the APL Trailer in its APL 25 configuration with the QI_r numerics computed from the statically measured profiles. The errors indicated when QI_r is computed directly from the APL 25 signal are also low, resulting in larger errors than with the APL 72. The reason for this can also be seen by examining the PSD plots shown in Appendix I. The APL 25 attenuates wavenumbers below 0.07 (wavelengths longer than 14 m), which are transduced by the static measurement methods, and also the APL 72. The PSD plots also indicate that the APL 25 signals are consistently low for wavenumbers between 0.4 and 2 cycle/m (wavelengths from 0.5 - 2.5 m long). These wavenumbers contribute little to the CAPL 25 numeric, and therefore the erroneous response is probably not a problem when the APL 25 system is used solely for measuring the CAPL 25 coefficient. Overall, the APL 25 profile signal simply doesn't cover the range required by the QI_r analysis.

Other Alternatives for the Calculation of APL QI Values

It is useful to recall that the choice of the two RMSVA baselengths (1 m and 2.5 m) and the numerical coefficients of the QI_r equation (Eq. E.5) were determined empirically during a correlation study (which took place before the IRRE) between the GMR-type Profilometer results and the RMSVA values obtained from rod and level profiles. These regressions reflect the spectral contents of the profiles as measured by the rod and level method, the Profilometer, and the various factors that influenced the original QI numeric.

Because the transfer functions of the APL are different from those of the rod and level system and of the TRRL Beam, the spectral contents of the profiles are also different, and it is not surprising that the differences shown in Figs. E.5c and E.5d were found.

A new statistical analysis has been performed by the French Bridge and Pavement Laboratory (LCPC) in order to determine a better equation for estimating QI when using the APL Trailer. Multilinear regressions were computed between rod and level QI values and the $RMSVA_{1.0}$ and $RMSVA_{2.5}$ values as computed from APL 25 and APL 72 profiles. The statistical population of the test sections on which the computations were carried out is the same as the one which was considered for the comparisons between rod and level QI_r and TRRL Beam QI_r.

Figure E.6 shows that it is possible to find several estimators for QI which are different from those used for the rod and level profiles, while still using the 1.0 and 2.5 m RMSVA baselengths. Note that the standard errors shown for the paved sites are about the same as obtained for the repeated rod and level measures, and for the comparisons between TRRL Beam and rod and level. If QI is measured in the future with APL systems, further improvement might be possible by optimizing the RMSVA baselengths through a study similar to the one which was done for the rod and level method [7].

The $CP_{2.5}$ coefficient, described in Appendix G, can also constitute an estimator for QI. Figure E.7 gives the correlation between QI determined for right and left tracks on all sites CA, TS, GR, TE measured with the TRRL Beam and the $CP_{2.5}$ values obtained from APL 72 signals. The value of the coefficient of correlation reveals a significant linear relationship between the two scales. No bias induced by surface types was visible.

CALIBRATION OF RTRRMSs

A primary purpose of a profile-based roughness numeric such as QI_r is viewed in this report as being for the calibration of RTRRMSs, using a "calibration by correlation." In a calibration by correlation, the "raw" measures from the RTRRMS are used to estimate what the reference measure would be, based on a regression equation. The objective is to produce the most accurate estimates of "true roughness," over the entire range of conditions that will be covered. To this end, one or more regression equations must be used to estimate the "truth" from the RTRRMS "raw" measure. In this case, QI_r is the candidate for "true roughness." Before testing the calibration by correlation method, results are presented using the QI^* procedures described earlier.

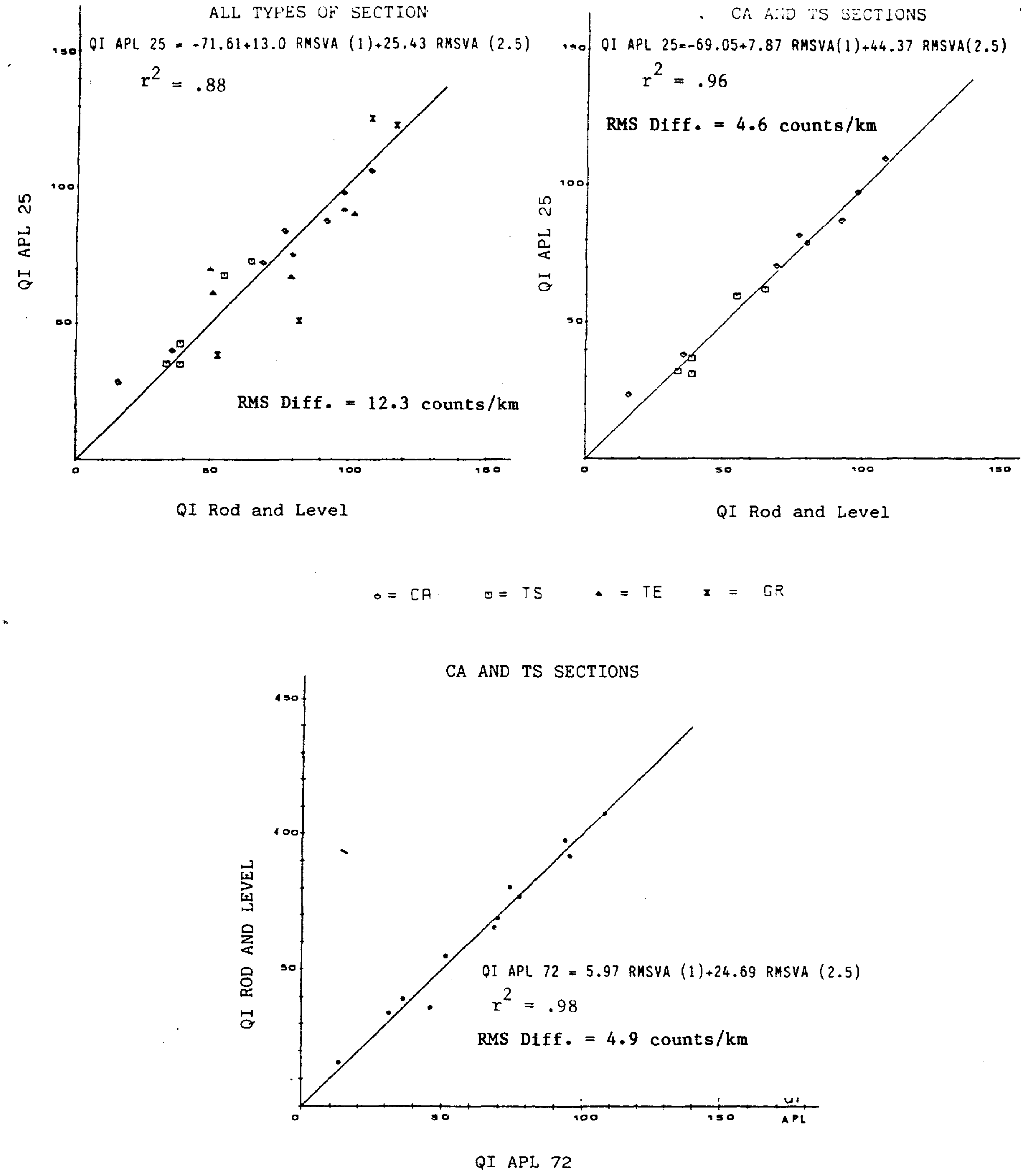


Figure E.6. Comparison of QI values calculated from rod and level with QI values calculated from APL.25 and APL 72 profiles

ALL SECTIONS INCLUDED CA, TS, GR, TE

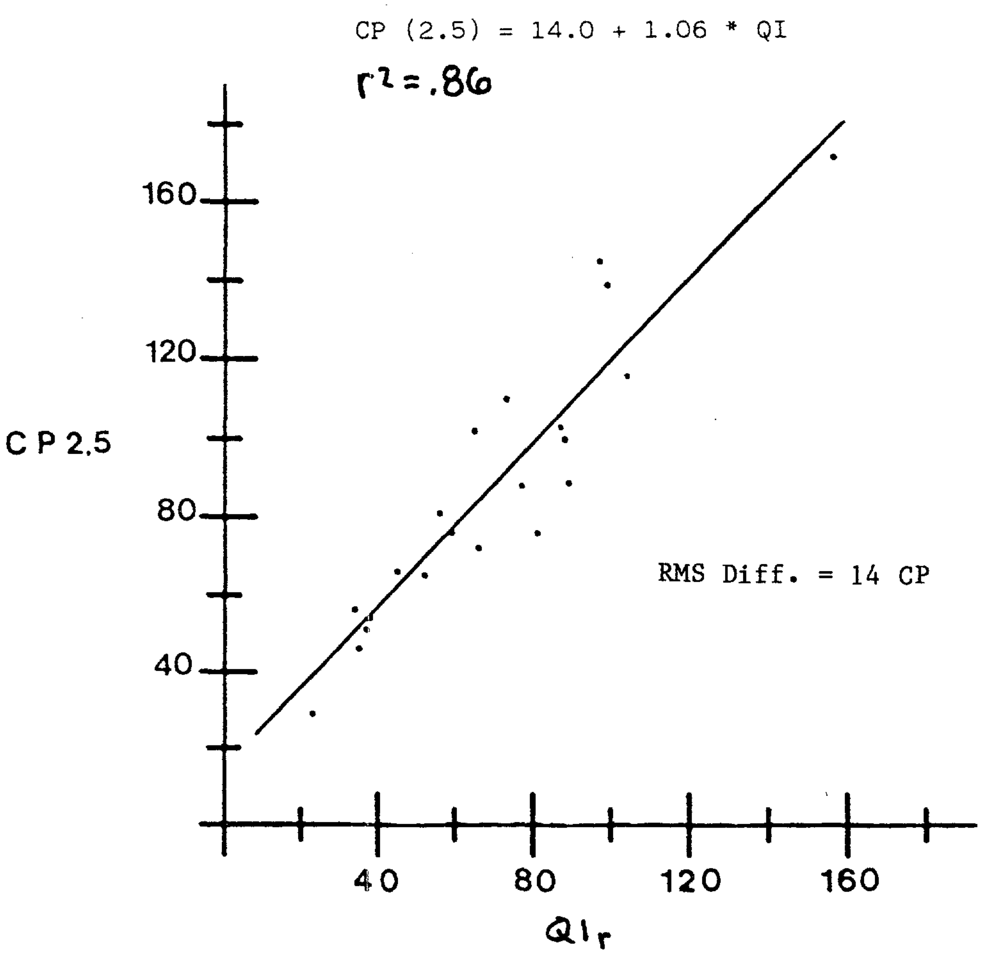


Figure E.7. Comparison of QI values calculated from TRRL Beam profiles with CP (2.5) derived from APL 72 signal

Calibration Using the QI* Method

The QI* calibration method was tested by adopting the procedures followed in the PICR project [7], using the RTRRMS speeds that were used for the majority of the PICR roughness measurements: 80 km/h on paved roads and 50 km/h on unpaved roads [14]. Using the data obtained during the IRRE, a calibration equation was determined for the five Opala and Caravan-based RTRRMSs that were operated at 80 km/h on the Asphaltic Concrete (CA) surfaces (Eq. E-23). ARS_{80} measures on the paved sites were rescaled according to that equation, while ARS_{50} measures on the unpaved surfaces were rescaled according to Eqs. 23 and 24 together. Figure E.8 shows how the QI* numerics compare with the profile-based QI_r reference.

The four plots in Figure E.8 indicate that the QI* calibration method results in a scale that is not equivalent to QI_r on all surface types. Figs. E.8a and E.8b show that the non-equivalence of gravel and earth surfaces (GR and TE) was evident mainly at high roughness levels. This effect can be attributed to the inaccuracy of the speed conversion used [14]. The four outliers on surface treatments are again the result of the tuning of the Opal vehicles to a 2m periodicity (corrugation). The PICR method required that the calibration (linear regression obtained on CA surfaces) be extrapolated to cover other surface types and a wider range of roughness amplitude than was covered in the actual calibration. Also, the single speed correction equation (Eq. 24) introduces bias errors that are unique for each RTRRMS.

The figure also shows that the QI* calibration method does not rescale the ARS measures from the different RTRRMSs the same way; the "calibrated" QI* numerics depend on both the procedure and the response properties of the individual RTRRMS. Thus, the method does not allow comparison of roughness data obtained from different sources. Due to differences that occurred only on the CA sites at 80 km/h, the nearly identical "raw" ARS measures obtained with the BI and NAASRA roadmeters (the measures are compared in Appendix C) on the rougher unpaved roads are rescaled differently, such that the QI* numerics obtained from the BI units tend to be less than the reference QI_r measures, while the QI* numerics from the NAASRA unit are greater than the QI_r measures.

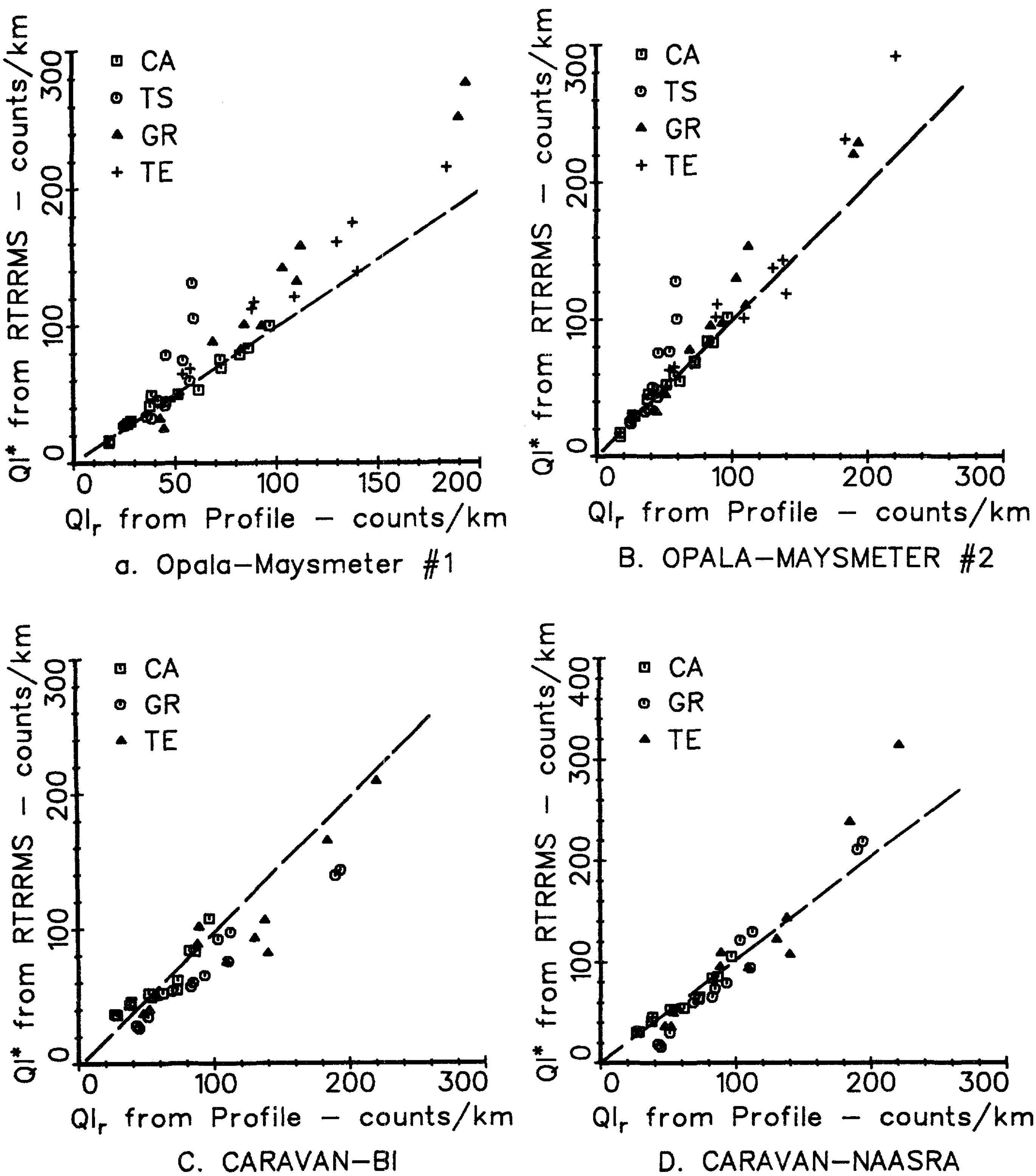


Figure E.8. Comparisons between QI^* from the RTRRMSs and QI_r from profile.

Although the QI^* numerics obtained from the Opala systems differ from those obtained with the Caravan systems, the QI^* calibration method does rescale the three Opala-Maysmeter ARS measures about the same. (The QI^* data from the third Opala-Maysmeter system are not included in the figure, but showed the same relation to QI_r as the other two.) This is the critical finding, in terms of the quality of the PICR roughness data, since it implies that the QI^* data collected in the PICR project from a fleet of Opala-Maysmeter systems is internally consistent. That is, the QI^* calibration succeeds in terms of bringing the measures from different Opala-Maysmeter systems into agreement, even though it fails in bring measures from other RTRRMSs into agreement.

In summary, the QI^* calibration method probably helped to maintain a roughness scale during the PICR project that was consistent and reasonably stable with time. The method requires that the RTRRMS have response properties very similar to the Opala-Maysmeter system as maintained at GEIPOT, so the method is not valid for other RTRRMSs, and should not be used in future work. The QI^* scale is not completely equivalent to the QI_r scale on three of the four surface types that were included in the IRRE. (This has largely been compensated in subsequent work [14].)

Calibration through Correlation

The comparisons between ARS measured with four of the RTRRMSs and QI_r are illustrated in Figures F.9 - 12. Results from the Caravan-BI system (not plotted) are virtually the same as for the Caravan-NAASRA system. Results for the two Opala-Maysmeter systems that are not plotted are generally similar to those of the system that is shown in the figures.

In all plots, the "static" QI_r values from Table E.1 were used. Comparisons with the two single-track RTRRMSs (BI Trailer and BPR Roughometer) are on the basis of single wheeltracks, while those with the two-track RTRRMSs use the average QI_r for both wheeltracks. Thus, the plots involving the trailers generally have twice as many data points. In each figure, the solid curved line is a quadratic regression line obtained from all of the data points shown, based on minimizing the RMS error in estimating QI_r.

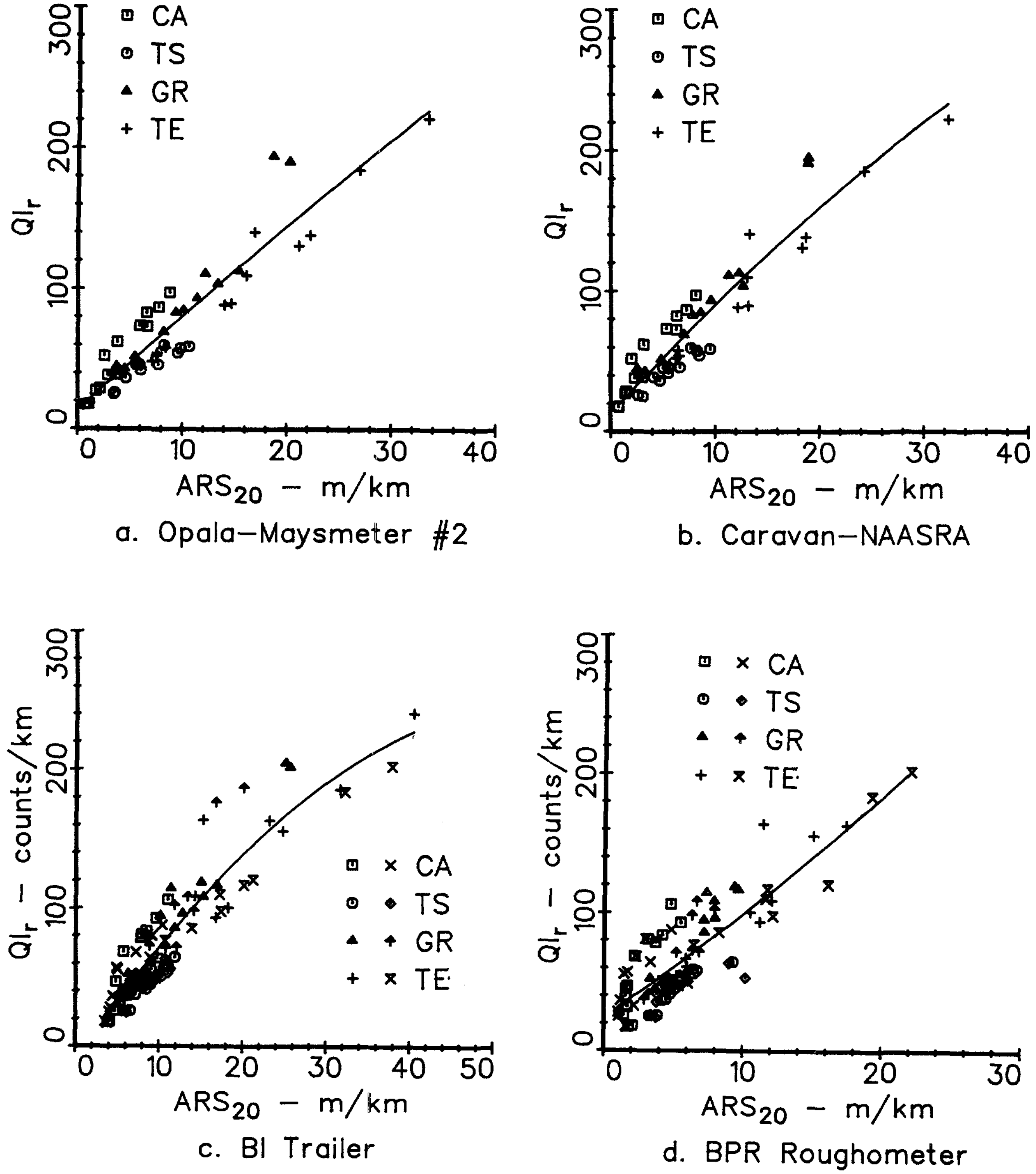


Figure E.9. Example calibration plots to estimate QI_r from ARS_{20}.

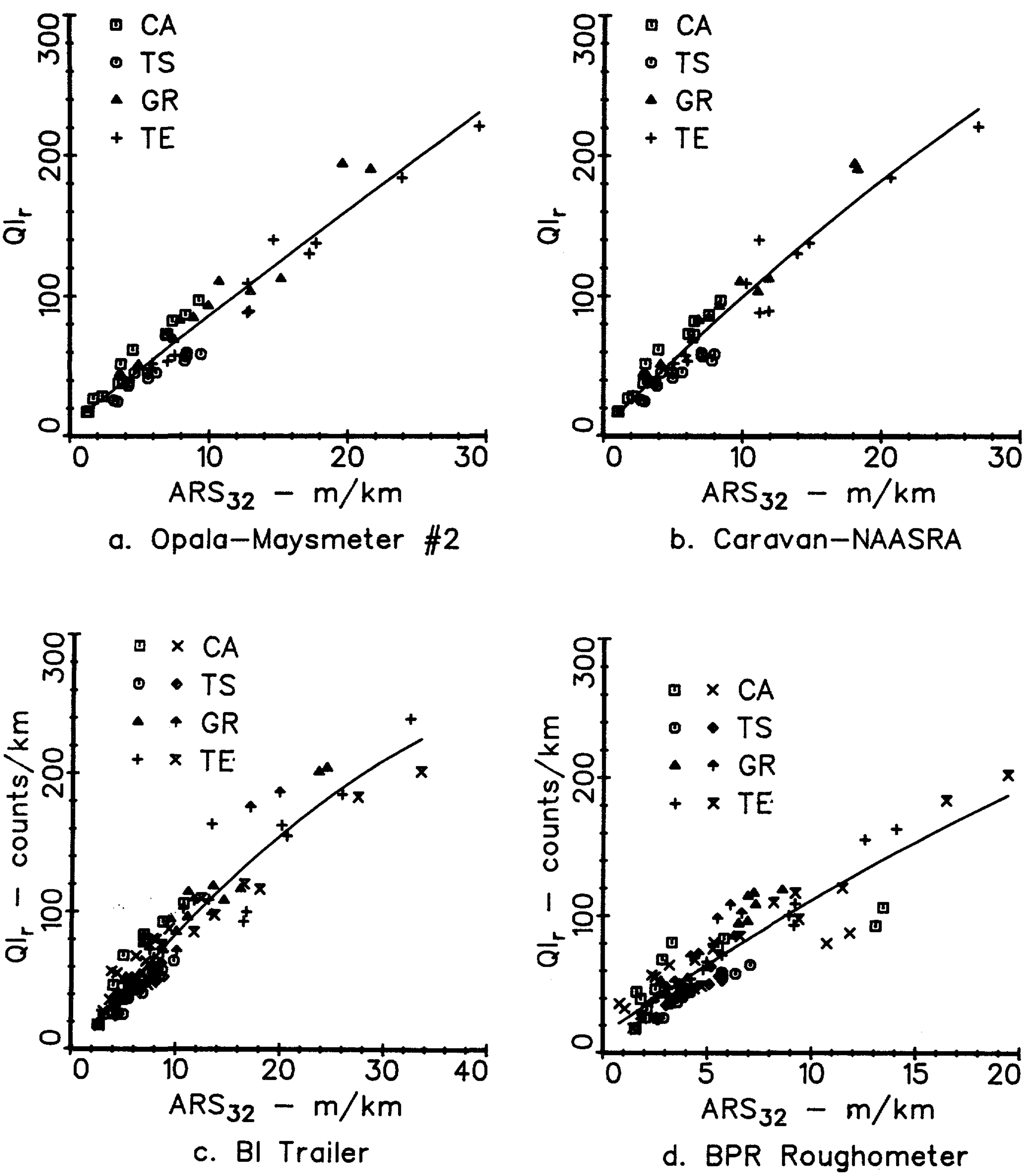


Figure E.10. Example calibration plots to estimate QI_r from ARS_{32}.

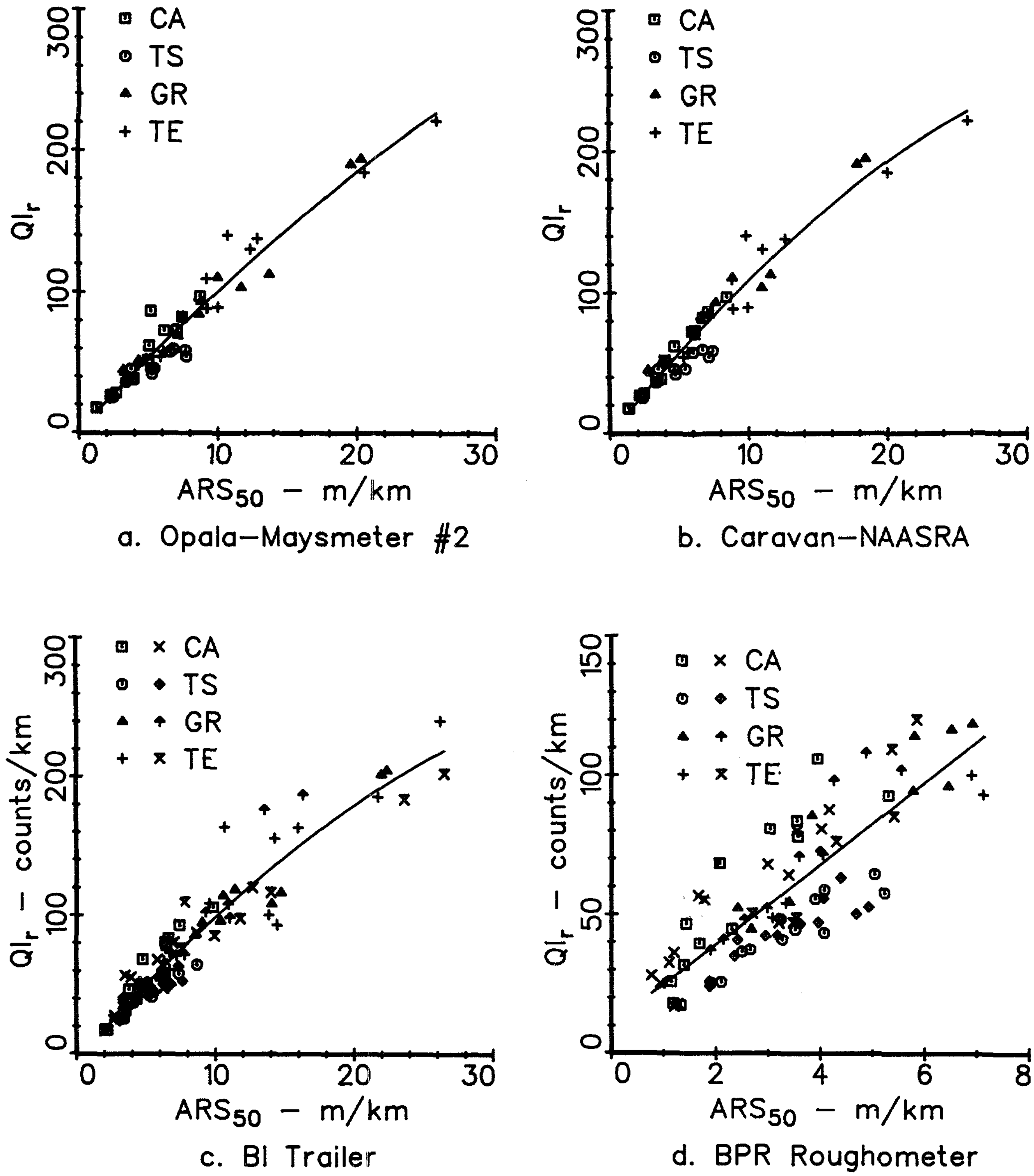


Figure E.11. Example calibration plots to estimate QI_r from ARS_{50}.

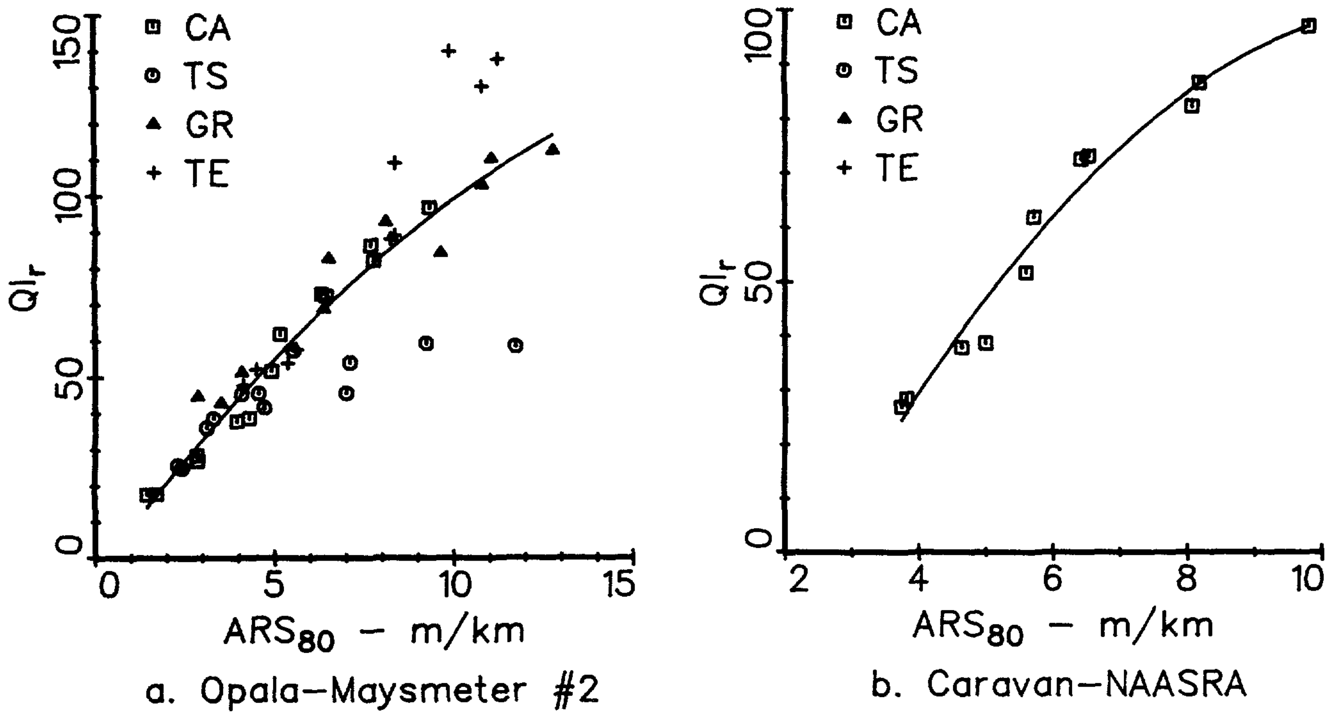


Figure E.12. Example calibration plots to estimate QI_r from ARS_{80}.

These four figures lead to the following observations:

Overall correlation. By and large, QI_r is highly correlated with the ARS numerics obtained from all types of RTRRMSs that participated in the IRRE. Most of the data points lie close to the regression curve in each figure.

Error distribution. Errors, as defined by the scatter about the regression curves in the vertical direction, are fairly uniform across the roughness range. Therefore, least-squares regression models should assume equal significance of error across the scale. Transformations of the variables that change the weighting of error, such as linear regressions of log values, should be avoided (for calibration purposes) because they place less priority on the errors on rougher roads.

Sensitivity to surface type. Surface type systematically affects the regressions in most of the plots. The data points for the asphaltic concrete (CA) roads typically lie above the regression line (indicating that the QI_r analysis is relatively more sensitive than the RTRRMS to roughness on those surfaces), while points for the surface treatment sites (TS) lie below the line (indicating that the QI_r analysis is less sensitive). The implication of this finding is that separate calibrations for each surface type can give better accuracy. The degree of sensitivity to surface type varies with the RTRRMS and the speed, and generally is worse at the lower speeds. The effect is minimal at 50 km/h, such that the bias is less than the random error (scatter about the regression line) associated with individual sites.

The effect of surface type can be expected when considering the sensitivity of the QI_r analysis to wavenumber, shown in Fig. E.2b. The sensitivities of the RTRRMSs are not known precisely, but are generally very similar to that of the RQCS described in Appendix F, particularly in terms of the range of wavenumbers sensed by the RTRRMS. Figure F.2 in that appendix shows the sensitivity of the simulated RTRRMS to wavenumber at all four of the RTRRMS speeds. The bandwidth of a RTRRMS is somewhat broader than that of the QI_r analysis, such that the QI_r numeric reflects a narrower portion of the spectrum than affects a RTRRMS.

The PSD plots in Appendix I indicate that the CA, TS, and unpaved (GR and TE) roads have different aggregate spectral characteristics. The CA surfaces have a higher proportion of roughness contributed at low wavenumbers (longer wavelengths, such as 5 m where the QI_r has its maximum sensitivity (Fig. E.2b). The QI_r "tunes in" to this portion of the spectrum, resulting in an upward bias for this surface type. The TS sites have more of the roughness deriving from higher wavenumbers, to which the QI_r analysis is less sensitive.

Comparison of single-track trailers. Although both the BI Trailer and the "BPR Roughometer" made by Soiltest, Inc., are similar in appearance and are both based on the BPR Roughometer [13], they contrast in performance. The Soiltest BPR Roughometer, which proved to be too fragile for the roads covered in the IRRE (see Appendix A), produced measures that had the least correlation with QI_r. On the other hand, the TRRL BI Trailer measures showed about the same correlations as the RTRRMSs based on passenger cars.

Outliers. The four roughest surface treatment sites appeared as "outliers" when measured by the Opala-Maysmeter systems at 80 km/h (Fig. E.12a). (Although the results are plotted for only one of these systems, all three showed the same behavior.) On these sites (TS01, TS03, TS04, and TS05), the RTRRMS responded much more than the QI_r analysis. The power spectral density (PSD) plots shown in Appendix I for these four sites are similar, and differ from the PSD plots for most of the other test sites. All four have more of the roughness concentrated at higher wavenumbers, to which the QI_r analysis is less sensitive. Further, three of the sites show a singular peak at wavenumber 0.5 cycle/m (2 m wavelength, which appears as a frequency of 11.1 Hz when traversed at 80 km/h).

The presence of a singular peak at 0.5 cycle/m signifies that the road site has a periodic disturbance occurring every 2 m. Although the QI_r analysis shows a near-maximum gain at that wavenumber (Fig. E.2b), it is not as sensitive as the typical passenger car at that frequency [9]. Due to nonlinearities, a passenger car can over-respond when subjected to a purely periodic excitation. This is particularly true with lightly damped vehicles. From the simple comparison of the ARS_{80} and $RARS_{80}$ numerics in Appendix F, the Opala vehicle is seen to be less damped than the RQCS, as evidenced by the higher ARS_{80} numerics. This indicates that stiffer shock absorber could be used with the Opala, with the expected result of bringing the "outliers" closer to agreement with the rest of the ST data.

Correlations and Accuracy. Table E.2 presents the r^2 values obtained when the QI_r numerics are regressed against the ARS numerics from the RTRRMSs using a linear prediction model. The regressions were performed using only the data corresponding to the combination of speed and surface type indicated. When the surface type is indicated as "ALL," then the regression included all measurements made at that speed, and the r^2 describes a calibration across surface type. Table E.3 presents the r^2 values obtained when a quadratic model is used. Both models use a simple least-squares error approach, but the quadratic model is slightly more versatile, as it involves less in the way of assumptions about the linearity of the RTRRMS. In comparing the two tables, it can be seen that there are a number of cases where much better correlation is obtained with the quadratic model, including most of the regressions performed for TS surfaces. Since there is no real penalty for using the quadratic model (other than a more complex computation--typically performed by computer), the quadratic model is recommended to allow for the occasional case in which a linear model would not fit the data or would lead to an erroneous extrapolation.

The correlation coefficients are presented as one basis for comparing the accuracy that can be obtained. Yet it should be understood that r^2 values are only one measure, with limited utility. The r^2 value is essentially the fraction of the variances of the two variables that is accounted for by the (linear or quadratic) regression model. Thus, r^2 values depend both on the agreement between the measures (as related by the regression model) and the range of roughness included in the data set. Since r^2 values can always be improved simply by adding more very smooth and very rough sites, they should never be used as the sole basis for quantifying a calibration quality.

The actual accuracy of an estimate of QI_r based on an ARS measure can be defined as the Standard Error: the RMS difference between the estimate of QI_r and the true QI_r value. The standard errors associated with the quadratic model are presented in Table E.4. Whereas the r^2 values were dimensionless,

Table E.2. R-Squared Values Obtained from Linear Regressions Between QI_r and ARS from the RTRRMSs.

Speed	Surface Type	Opala Passenger Cars with Modified Maysmeters			Caravan Car with 2 meters		Single-Track Trailers	
		MM 01	MM 02	MM 03	BI	NAASRA	TRRL BI	BPR
20	CA	0.9068	0.9343	0.9451	0.9191	0.9242	0.8552	0.7226
	TS	0.8484	0.8439	0.9295	0.8731	0.8984	0.8104	0.6724
	GR	0.9814	0.9262	0.7785	0.9617	0.9636	0.9121	0.8540
	TE	0.8555	0.9675	0.9572	0.9408	0.9444	0.8993	0.8929
	ALL	0.8830	0.8692	0.8437	0.8848	0.8869	0.8404	0.7244
32	CA	0.9435	0.9695	0.8824	0.9517	0.9615	0.8790	0.6621
	TS	0.8975	0.8928	0.9070	0.8792	0.8825	0.8590	0.8475
	GR	0.9175	0.9476	0.8474	0.9770	0.9781	0.9436	0.9121
	TE	0.8697	0.9674	0.9207	0.9096	0.9283	0.8890	0.9674
	ALL	0.8878	0.9324	0.8792	0.9206	0.9271	0.8909	0.8036
50	CA	0.9660	0.8941	0.9476	0.9736	0.9861	0.9167	0.8308
	TS	0.8482	0.8694	0.7841	0.8654	0.8668	0.8492	0.8243
	GR	0.9805	0.9712	0.9403	0.9653	0.9758	0.9137	0.8746
	TE	0.9539	0.9336	0.8823	0.8811	0.9149	0.8510	0.7521
	ALL	0.9448	0.9424	0.9138	0.9234	0.9355	0.8975	0.6957
80	CA	0.9700	0.9780	0.9039	0.8496	0.9395	....	0.8413
	TS	0.6589	0.7048	0.6507	....	....	....	....
	GR	0.9041	0.9317	0.9114	....	....	....	....
	TE	0.7502	0.9365	0.8978	....	....	....	....
	ALL	0.7088	0.7658	0.6709	0.8496	0.9395	....	0.8413

Table E.3. R-Squared Values Obtained from Quadratic Regressions Between QI_r and ARS from RTRRMSs.

Speed	Surface Type	Opala Passenger Cars with Modified Maysmeters MM 01	MM 02	MM 03	Caravan Car with 2 meters BI	NAASRA	Single-Track Trailers TRRL BI	BPR
20	CA	0.9172	0.9402	0.9460	0.9310	0.9351	0.8644	0.7348
	TS	0.8757	0.8912	0.9344	0.9206	0.9279	0.8120	0.8930
	GR	0.9814	0.9587	0.8288	0.9886	0.9864	0.9123	0.8553
	TE	0.8688	0.9675	0.9602	0.9438	0.9493	0.9049	0.8933
	ALL	0.8866	0.8695	0.8478	0.8872	0.8899	0.8567	0.7255
32	CA	0.9481	0.9721	0.8825	0.9605	0.9676	0.8918	0.7996
	TS	0.9346	0.9333	0.9451	0.9128	0.9250	0.8763	0.9058
	GR	0.9538	0.9536	0.8797	0.9835	0.9848	0.9436	0.9158
	TE	0.8738	0.9683	0.9250	0.9120	0.9352	0.8940	0.9692
	ALL	0.8982	0.9326	0.8845	0.9220	0.9294	0.9009	0.8056
50	CA	0.9664	0.8956	0.9492	0.9826	0.9866	0.9339	0.8615
	TS	0.8711	0.8974	0.8602	0.8895	0.8958	0.8893	0.8583
	GR	0.9822	0.9766	0.9576	0.9736	0.9783	0.9155	0.8985
	TE	0.9554	0.9568	0.9229	0.8903	0.9449	0.8556	0.8372
	ALL	0.9448	0.9454	0.9201	0.9303	0.9466	0.9059	0.6958
80	CA	0.9700	0.9785	0.9039	0.9398	0.9709	....	0.8442
	TS	0.8103	0.8533	0.7633	....	....	....	....
	GR	0.9261	0.9441	0.9236	....	....	....	....
	TE	0.8013	0.9398	0.9023	....	....	....	....
	ALL	0.7303	0.7738	0.7032	0.9398	0.9709	....	0.8442

Table E.4. Standard Error for Estimating QI_r with a Quadratic Regression Equation and ARS Measurements.

		Opala Cars with Modified Maysmeters			Caravan Car with 2 meters		Single-Track Trailers	
Speed	Surface Type	MM 01	MM 02	MM 03	BI	NAASRA	BI	BPR
20	CA	7.6	6.4	6.1	6.9	6.7	9.9	13.8
	TS	4.0	3.7	2.9	3.2	3.0	5.0	3.8
	GR	6.5	9.7	19.8	5.1	5.6	14.6	10.4
	TE	15.6	9.6	10.6	12.6	12.0	17.0	15.3
	ALL	14.5	17.1	18.5	15.9	15.7	18.3	19.7
32	CA	6.0	4.4	9.0	5.2	4.7	8.8	12.0
	TS	2.9	2.9	2.7	3.3	3.1	4.1	3.6
	GR	10.3	10.3	16.6	6.1	5.9	11.7	7.9
	TE	15.3	9.5	14.6	15.8	13.6	18.0	8.0
	ALL	13.7	12.3	16.1	13.2	12.6	15.2	16.0
50	CA	4.8	8.5	5.9	3.5	3.0	6.9	10.0
	TS	4.1	3.6	4.2	3.8	3.7	3.9	4.4
	GR	6.4	7.3	9.9	7.8	7.1	14.3	8.7
	TE	9.1	11.1	14.8	17.6	12.5	21.0	10.6
	ALL	10.1	11.1	13.4	12.5	11.0	14.8	15.0
80	CA	4.6	3.9	8.2	5.7	4.0	...	6.8
	TS	4.9	4.3	5.5	...	...	...	...
	GR	6.8	5.9	6.9	...	...	...	...
	TE	15.7	8.6	11.0	...	...	...	...
	ALL	16.4	15.0	17.2	5.7	4.0	...	6.8

a standard error has the units of the QI_r measure: counts/km. In essence, Table E.4 quantifies the accuracy involved when a "raw" ARS measure is re-scaled (according to the quadratic regression equation) to a "Calibrated" QI measure.

The standard error data show that a speed of 50 km/h gives the best accuracy for all of the RTRRMSs. Therefore, RTRRMS measures should be conducted at 50 km/h if the QI_r numeric is used as the calibration reference. The table also indicates the tradeoff in accuracy that occurs when a single calibration is used across all surface types, instead of conducting separate calibrations for each surface type.

APPENDIX F

QUARTER-CAR SIMULATION

The roughness measure from an "ideal" response-type road roughness measurement system (RTRRMS) can be obtained mathematically using a quarter-car simulation (QCS). The roughness numerics obtained via QCS are inherent characteristics of the true longitudinal road profile, and can be obtained with a variety of instrumentation and computation methods. To distinguish the particular set of QCS parameters used in this report from alternate sets used in other QCS applications, the analysis used in the IRRE is called the "Reference Quarter Car Simulation" (RQCS). This appendix describes 1) the development of the RQCS, 2) its mathematical properties, 3) computational details, and 4) the results obtained during the International Road Roughness Experiment (IRRE). Although the use of a QCS to quantify roughness is not new, there is presently no single source in the literature that covers the details of implementing a QCS. Therefore, this appendix includes additional background information in all sections when such information is useful but not readily available elsewhere.

DEVELOPMENT AND HISTORY

Mathematical models of vehicle response have been used since the 1940s by engineers charged with the design and/or evaluation of airplanes and military vehicles. At that time, the effort associated with obtaining a profile with conventional survey methods and converting it into a form compatible with the computation methods of the day (analog computers) was far too great to consider using vehicle simulation for evaluating road roughness. But given the dire consequences of an aircraft failure while traversing a runway, or of a military vehicle traversing rugged terrain, the effort involved in conducting simulations was justified for those applications.

In the early 1960s, General Motors Research (GMR) developed a "Profilometer," using modern instrumentation, that was capable of measuring the "dynamic" portion of a road profile responsible for inducing vehicle ride motions [21]. Shortly after that, the Michigan Dept. of Transportation (MDOT, then called the Mich. Dept. of State Hwys and Transp.) built a second GMR Profilometer in cooperation with GMR [22]. At about the same time, GMR licensed K.J. Law, Inc. to market the Profilometer commercially.

At that time, the most well known roughness measuring system was the BPR Roughometer RTRRMS. In the late 1960s, both MDOT and K.J. Law, Inc. developed electronic "equivalent" BPR Roughometers, which employed a vehicle simulation using an analog computer [22, 24]. Since the BPR Roughometer has but one wheel, that vehicle simulation was called a BPR Roughometer Quarter-Car Simulation (BPR/QCS). The BPR/QCSs used by MDOT and K.J. Law, Inc. have equations identical in form to a textbook mathematical model used to characterize various dynamic systems, and are the first applications of that model for quantifying road roughness. The QCS is in fact that model, with parameter values representative of vehicles. (The two BPR/QCSs used two different sets of parameter values, each based on measurements of a different "standard" BPR Roughometer.) Most of the profilometers produced by K.J. Law, Inc. have included the BPR simulation. Several years later, K.J. Law, Inc. introduced a second set of parameter values for a QCS to simulate a 1968 Chevrolet Impala passenger car.

One of the GMR-type profilometers with a BPR/QCS was the basis for the QI scale used in the PICR project, although, due to a number of factors, the device never actually measured profile during the project with the accuracy normally associated with that instrument. The QI scale is therefore not equivalent to the published characteristics of the BPR/QCS. (See Appendix E for details.)

During the late 1970s, a large-scale NCHRP research project was undertaken at UMTRI (then called The Highway Safety Research Institute) to: 1) study RTRRMSs, 2) determine correlations between the different systems in use, and 3) devise a valid calibration methodology. The research included extensive testing of the RTRRMS in a laboratory environment, along with a formal theoretical analysis of the RTRRMS concept and instrumentation. It became apparent that a main source of the problems lay in the fact that the instruments were invented without a clear concept of what "roughness" is or how it should be measured. Instead, "roughness" had been defined rather loosely as: "Whatever it is that the RTRRMS measures." Since calibration requires comparing the measures from the instrument being calibrated to "true" values of the variables being measured, it was necessary to define, mathematically, a measurable aspect of the true longitudinal profile that would serve as a calibration reference.

The reference that was selected is the QCS, with new model parameters chosen to offer maximum correlation with existing RTRRMSs. In addition to a new set of parameters, the QCS was "upgraded" to a half-car simulation, because nearly all of the RTRRMSs used in the United States are based on two-track vehicles (passenger cars and two-wheeled trailers). The way a tire "envelops" small bumps was found to have a critical influence when the QCS was used to simulate low speeds. Accordingly, tire enveloping was added to the model when low-speed simulations were performed. The RQCS described in this report is nearly identical to the NCHRP reference, differing only in the tire enveloping parameter, which was changed inconsequentially from 1 ft (300 mm) to 250 mm to simplify the measurement requirements for rod and level methods.

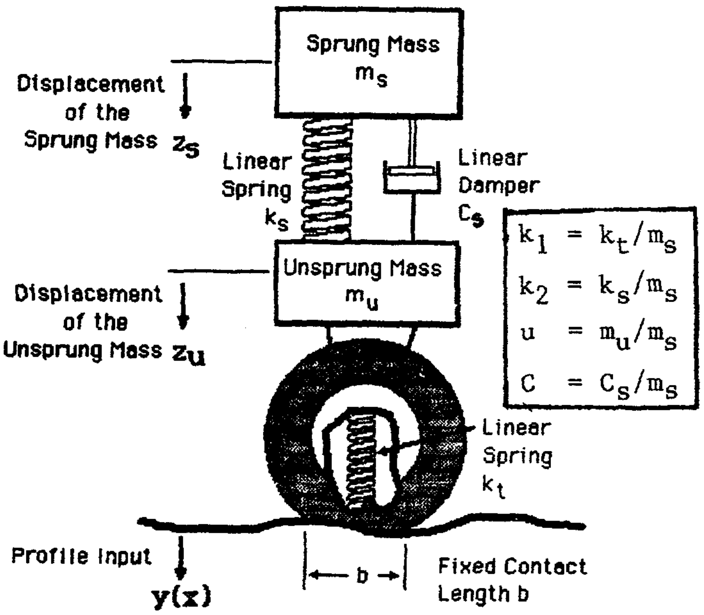
The NCHRP Report 228 recommended a roughness statistic called "reference average rectified velocity" (RARV) which is useful when comparing measurements made by RTRRMSs at more than one measurement speed. The other statistic associated with the RQCS is called "reference average rectified slope" (RARS). Since the RARS numeric obtained with a simulation speed of 80 km/h ($RARS_{80}$) is selected in this report as the best choice for an International Roughness Index, most of the results obtained with the RQCS are reported as RARS values.

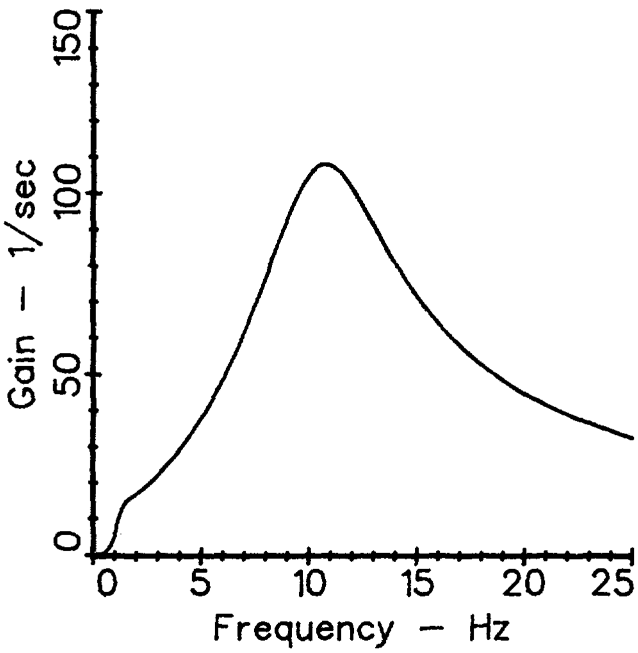
MATHEMATICAL DEFINITION OF THE QUARTER CAR SIMULATION

Summary of the Reference Quarter-Car Simulation (RQCS)

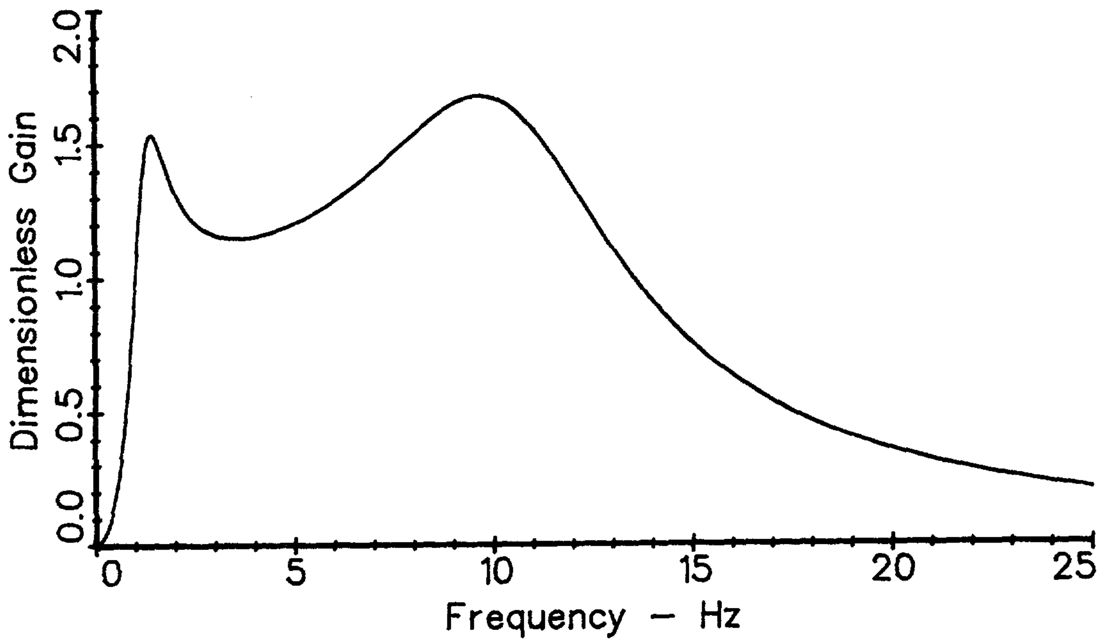
Figure F.1 illustrates the concept of the RQCS analysis in terms of the mechanical model (1a) and its frequency response (1b and 1c). The RQCS consists of three distinct mathematical procedures:

1. **Geometrically smooth the profile.** A pneumatic tire contacts the





b. Frequency Response of RQCS to Elevation Input



c. Frequency Response of RQCS to Slope Input

Figure F.1. The Reference Quarter Car Simulation (RQCS) road over an area, rather than at a single point, and effectively "envelops" small, sharp roughness features. It has been shown that this effect is simulated quite well with a "moving average" smoothing technique, using a "moving average" baselength approximately 50% longer than the contact patch between tire and road [9]. The moving average is defined for a continuous profile measurement by an integral over the baselength of the filter:

$$y_s(x) = 1/b \int_{x-b/2}^{x+b/2} y_r(X)\, dX \qquad \text{(F-1)}$$

where

x = distance travelled

$y_r(x)$ = unfiltered "raw" vertical profile elevation

$y_s(x)$ = smoothed vertical profile elevation

b = baselength of moving average

X = dummy variable of integration

Due to the practical advantage of measuring profile manually at conveniently marked intervals, a baselength of b = 250 mm is proposed in this report, which differs from the 1 ft (300 mm) baselength used in the NCHRP work. The effect of smoothing is often negligible for high simulated speeds, but assumes greater importance for lower speeds, as shown later in this section.

2. Filter the profile signal. The mathematical model shown in Figure F.1a is defined mathematically by two second-order differential equations:

$$\ddot{z}_s + C\,(\dot{z}_s - \dot{z}_u) + K_2\,(z_s - z_u) = 0 \qquad \text{(F-2)}$$

$$\ddot{z}_s + u\,\ddot{z}_u + K_1\,z_u = K_1\,y \qquad \text{(F-3)}$$

where

$$k_1 = 653 \text{ sec}^{-2},\ k_2 = 63.3 \text{ sec}^{-2},\ u = .150,\ C = 6.00 \text{ sec}^{-1} \qquad \text{(F-4)}$$

and

y = profile elevation input

The mechanical system shown in the figure and described by the above equations is a band-pass filter, so-called because it transmits only a band of frequencies, "filtering out" the rest. The figure shows the frequency response plot of the RQCS filter, in the form of "amplitude out"/"amplitude in." Note that the sprung mass, indicated in the Figure as m_s, is used to normalize the other parameters and is itself not used in the filter specification.

Methods that are used to perform the filtering are mentioned later in this section, and computational details are provided in the next section for one approach that is particularly suited for manual profile measurement and computation with microcomputers.

3. **Rectify and average the filtered profile signal.** To simulate a roadmeter, the axle-body velocity from the QCS is rectified and averaged to yield an ARV statistic similar to that obtained from the roadmeter in a RTRRMS. The ARV numeric can be rescaled from units of velocity to units of slope, to yield the ARS numeric. Deriving from the Reference, the statistic is called RARS in this report to differentiate it from the "raw" ARS measure obtained from a mechanical RTRRMS. When the RQCS is implemented as described later in this appendix, the output of the filter has the units of slope, and RARS is computed simply by rectifying and averaging that output.

Half-Car Simulation (HCS)

The QCS is converted to a HCS by adding one more step, which is to average the left- and right-hand wheeltrack profiles, point-by-point, prior to processing with the QCS. This step is included because roadmeters in two-track RTRRMSs are installed at the center of the vehicle axle, where they detect virtually no roll motion of the vehicle body or axle. This step is not equivalent to processing the two profiles independently and then averaging the summary statistics; when the profiles are processed separately, a higher roughness numeric is obtained because the independent profile roughness numerics include crosslevel variations that would not register on a roadmeter at the axle center. The NCHRP Reference is a HCS, while most of the results obtained in the IRRE were for a QCS (each wheeltrack processed independently).

Bandwidth of the RQCS

In order to derive the frequency response functions of the above-described operations, it is convenient to consider complex sinusoidal variables of the form:

$$y(w,x) = Y_o\ e^{jwx} \quad \text{(F-5)}$$

$$y(w,t) = Y_o\ e^{jwt} \quad \text{(F-6)}$$

where

$$e^{jwX} = \cos wX + j \sin wX \quad \text{(F-7)}$$

w = circular frequency = $2\pi f$, and $j = \sqrt{-1}$ = the "imaginary" part of a "complex" vector, 90^o out of phase with the "real" part. Eq. 5 describes a variable that is sinusoidal with distance travelled, x, while Eq. 6 describes a variable that is sinusoidal with time t. Depending on the context, the letter w designates either spatial circular frequency, with units of radians/length in Eq. 5, or temporal circular frequency with units of radians/sec in Eq. 6. Whether the variable is temporal or spatial, differentiation is simple:

$$y' = dy/dx = Y_o\ jw\ e^{jwx} = jw\ y \quad \text{(F-8)}$$

or

$$\dot{y} = dy/dt = Y_o\ jw\ e^{jwt} = jw\ y \quad \text{(F-9)}$$

The Moving Average. The spatial frequency response of a moving average, defined as the ratio of the output "smoothed" profile y_s, to the "raw" profile, y_r, is found by combining Eqs. 1 and 5:

$$y_s/y_r = 1/b\ \left[\int_{x-b/2}^{x+b/2} Y_0\ e^{jwX}\ dX \right] / (Y_o\ e^{jwx}) \quad \text{(F-10)}$$

where X = dummy integration variable. Solving Eq. 10,

$$y_s/y_r = 1/b\ [\ e^{jw(x+b/2)}\ /\ jw - e^{jw(x-b/2)}\ /\ jw\ ]\ e^{-jwx}$$

$$= 1/(jwb)\ [\ e^{jwb/2} - e^{-jwb/2}\ ]$$

$$= 1/(jwb)\ [\ \cos(wb/2) + j\ \sin(wb/2) - \cos(-wb/2) - j\ \sin(-wb/2)\ ]$$

$$= 1/(jwb)\ 2j\ \sin(wb/2)$$

$$= \sin(wb/2)\ /\ (wb/2)$$

$$= \sin(\pi b/L)\ /\ (\pi b/L) \qquad \text{(F-11)}$$

where L = wavelength = $2\pi/w$.

The moving average filter is described in more detail in Appendix J, which includes the effect of sammple interval on the wavenumber sensitivity.

The QCS Filter. Eqs 2 and 3 can be converted to algebraic equations dependent on frequency by substituting jw for the derivatives, as shown in Eq. 9:

$$-w^2\ z_s + jw\ C\ (z_s - z_u) + K_2\ (z_s - z_u) = 0 \qquad \text{(F-12)}$$

$$-w^2\ z_s - w^2\ u\ z_u + K_1\ z_u = K_1\ y \qquad \text{(F-13)}$$

Eqs. 12 and 13 can be solved for the two variables z_u and z_s to yield the temporal frequency response function of the QCS:

$$z_r/y = z_s/y - z_u/y = K_1\ w^2\ /\ D \qquad \text{(F-14)}$$

where

$$z_s/y = K_1\ (K_2 + j\ C\ w)\ /\ D \qquad \text{(F-15)}$$

$$z_u/y = K_1\ (K_2 - w^2 + j\ C\ w)\ /\ D \qquad \text{(F-16)}$$

and

$$D = D_r + j\, D_i \qquad \text{(F-17)}$$

$$D_r = u\, w^4 - [K_1 + K_2\, (1 + u)]\, w^2 + K_1\, K_2 \qquad \text{(F-18)}$$

$$D_i = C\, w\, [K_1 - (1 + u)\, w^2] \qquad \text{(F-19)}$$

Eq. 14 contains both amplitude and phase information. The amplitude of the Frequency Response Function is:

$$|z_r/y| = K_1\, w^2\, /\, (D_r^{\,2} + D_i^{\,2})^{1/2} \qquad \text{(F-20)}$$

Eqs. 14 and 20 are dimensionless, meaning that the output (z_r) will have the same units as the input. Thus, to obtain a slope output, the input should be profile slope. Eq. 20 is shown plotted as a function of frequency in Fig. F.1c. When the input is a profile elevation, then the frequency response function should include the differentiation involved in transforming a displacement to a slope. When the differentiation (jw) is combined with Eq. 20, the result is:

$$|\dot{z}_r/y| = K_1\, w^3\, /\, (D_r^{\,2} + D_i^{\,2})^{1/2} \qquad \text{(F-21)}$$

Eq. 21, with units 1/sec is shown plotted in Fig. F.1b.

Frequency Response of RQCS at four simulation speeds. As shown in Figure F.1c, the bandwidth of the QCS filter covers temporal frequencies between 0.8 - 17 Hz, which can be related to spatial wavenumber (1/L, L = wavelength) by the simulation speed:

$$1/L\ \text{(cycle/m)} = 3600\ \text{(sec/h)}\ .001\ \text{(km/m)}\ f\ \text{(cycle/sec)}\ /\ V\ \text{(km/h)} \qquad \text{(F-22)}$$

In addition, the geometric smoothing limits the response to shorter wavelengths according to Eq. 11, regardless of the simulation speed. Figure F.2 shows the combined effects of the filtering and smoothing for the four speeds used in the IRRE, obtained by combining Eqs. 11, 20, and 22. When expressed as wavelengths, the bands are approximately:

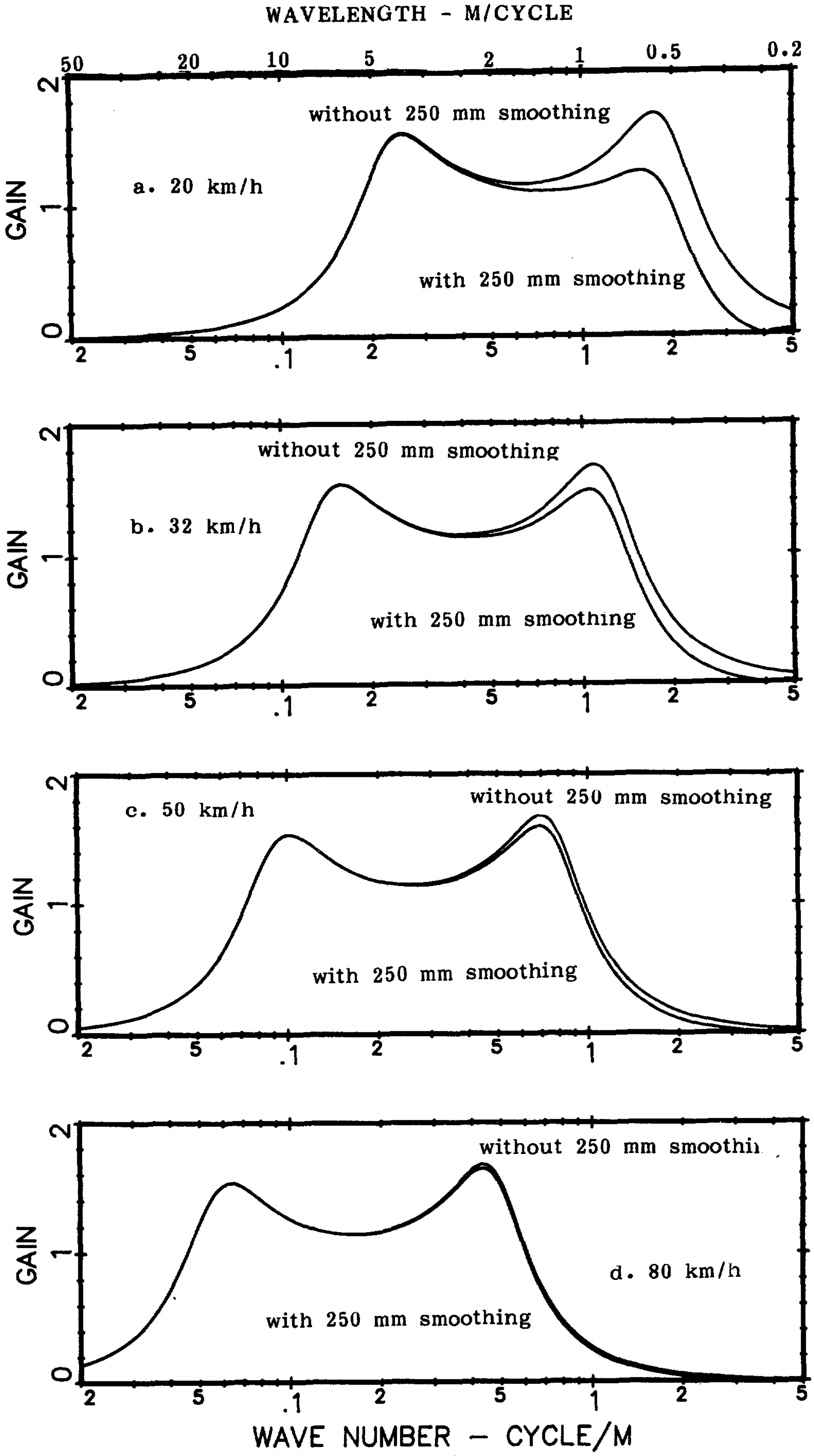


Figure F.2. Sensitivity of RQCS to Different Wavelengths

20 km/h: 0.5 - 7 m

32 km/h: 0.5 - 11 m

50 km/h: 0.8 - 17 m

80 km/h: 1.3 - 28 m (F-23)

Physical Interpretation of the RARS Statistic.

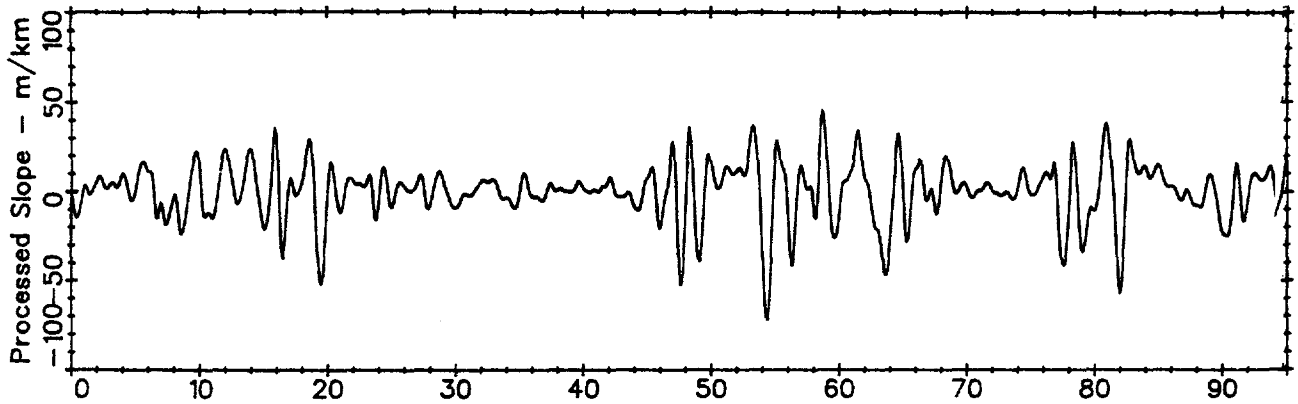
The RQCS analysis described above has three simple interpretations:

Reference RTRRMS. As shown in Figure F.1a, the analysis simulates an idealized RTRRMS, sometimes called the "Golden Car," equivalent in concept to a gold-plated reference measure. The RQCS has the same approximate sensitivity to surface type, roughness, and (simulated) measurement speed as observed with a RTRRMS, but has none of the nonlinearities that exist with most vehicles and roadmeters. The RQCS gives the operator of a RTRRMS an opportunity to see how the RTRRMS compares with an "ideal" system, in terms of such performance features as: suspension damping, roadmeter nonlinearity, and tire/wheel nonuniformity.

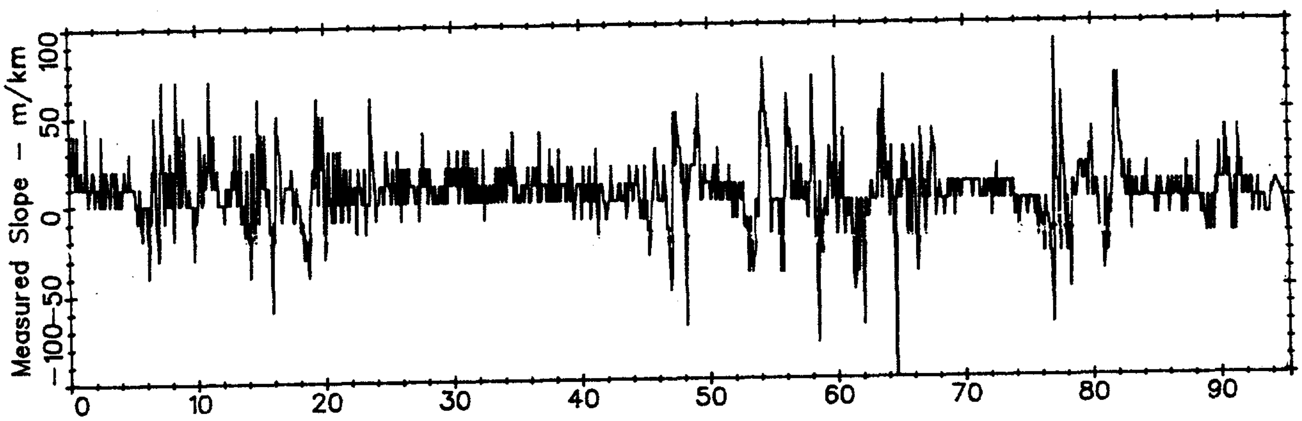
Profile Slope. Alternatively, the RQCS can be viewed as providing a statistic summarizing profile geometry. RARS is, as the name implies, the average rectified slope of the profile when wavelengths are attenuated that fall outside the range specified in Eq. 23.

Vehicle Excitation. When the roughness statistic is converted to RARV, it is proportional to the vertical excitation perceived by a vehicle traversing that road at the simulation speed. Thus, roads can be compared in terms of their roughness as perceived by the vehicle, even when different speeds are involved, by using a simulation speed that corresponds to the traffic speed. A higher number always implies more vehicle excitation, regardless of the simulation speed.

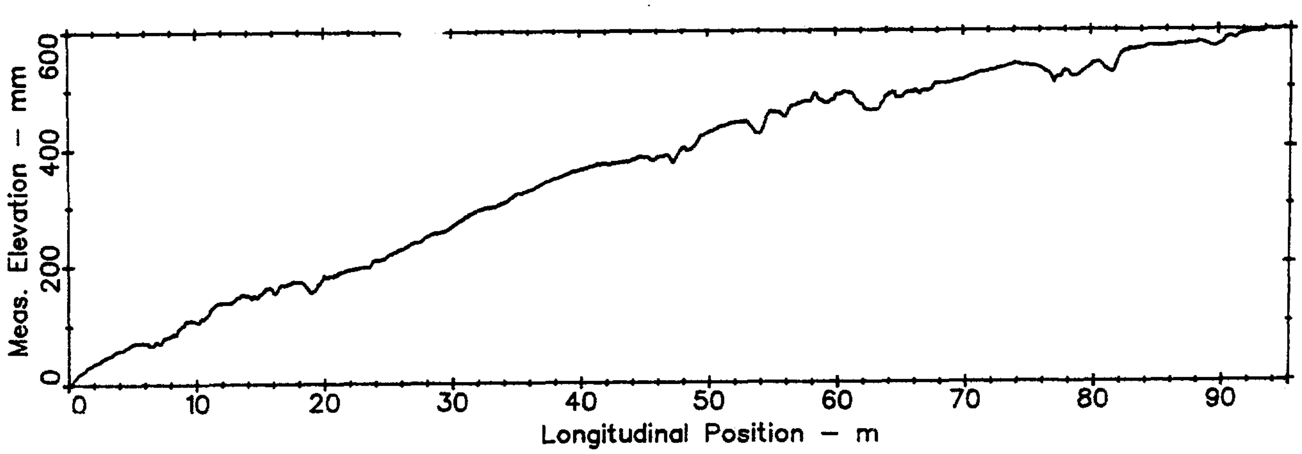
Examples of the RQCS "Filter." To illustrate the nature of the RQCS, Figures F.3 and F.4 show the profile inputs and the resulting QCS output. Figure F.3 shows three plots derived from a single profile measured with the TRRL Beam during the IRRE. Note that the roughness information is not very



c. Slope Profile as Filtered by the RQCS

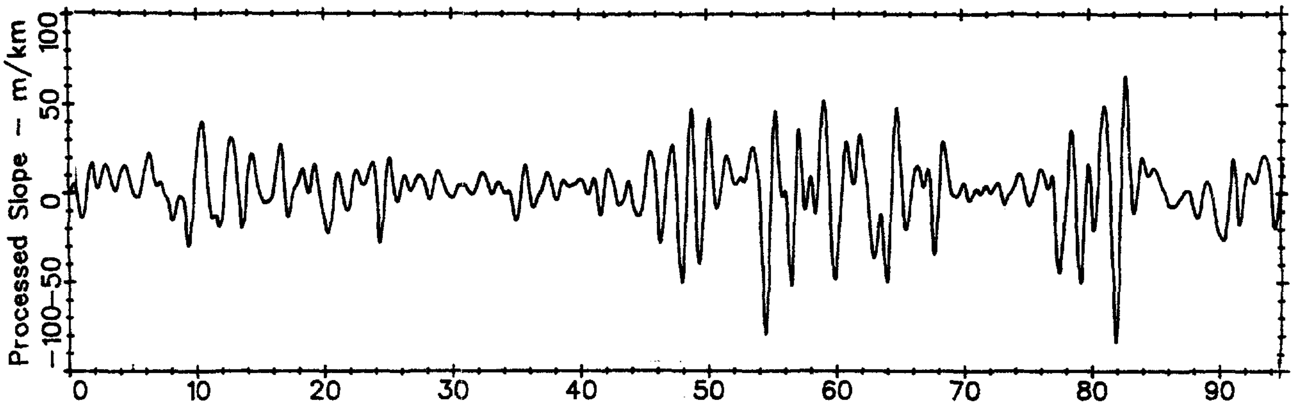


b. Approximate Slope: Elevation change per Measurement Interval

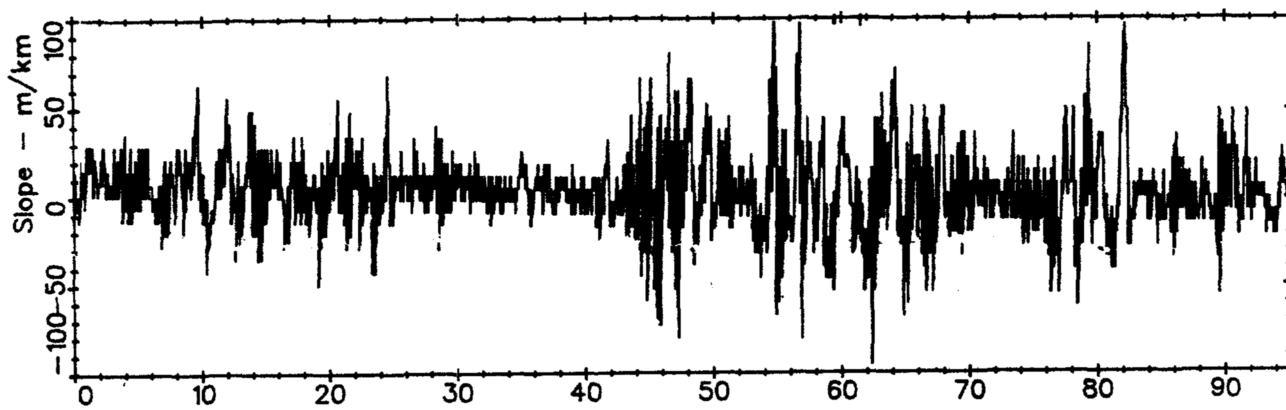


a. Original Elevation Measurement

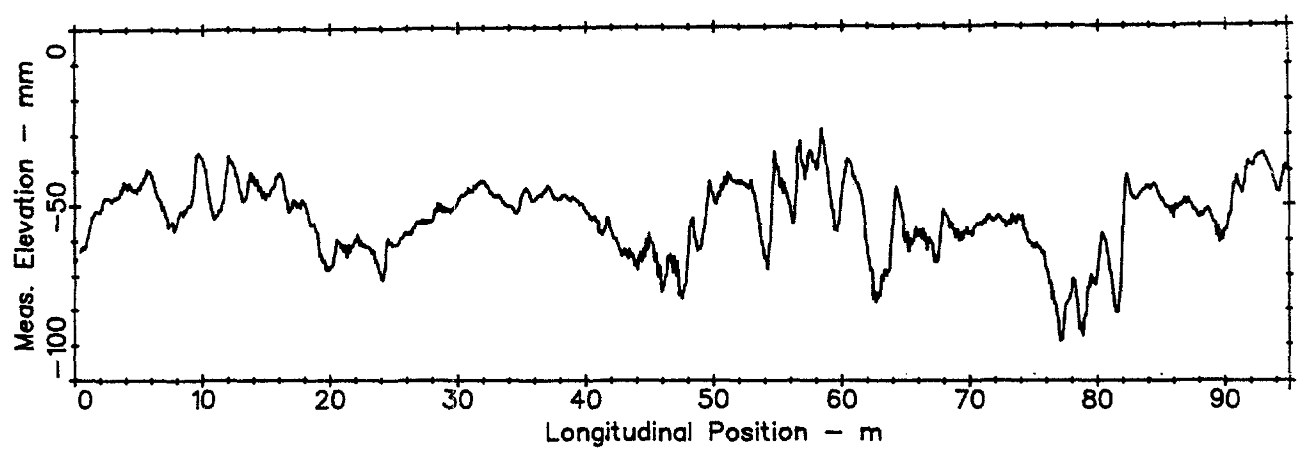
Figure F.3. Analysis of Profile Obtained With TRRL Beam. (Left Wheeltrack, Section CA06)



c. Slope Profile as Filtered by the RQCS



b. Approximate Slope: Elevation Change per Measurement Interval



a. Original Elevation Measurement

Figure F.4. Analysis of Profile Obtained with APL 72. (Left Wheeltrack, Section CA06) clear from the elevation profile (Fig. F.3a) due to 1) the underlying slope of the road, and 2) the fact that road elevation profiles are dominated by the longest wavelengths included in the measurement. The plot of profile slope (Fig. F.3b), obtained by taking point-by-point differences in elevation, normalized by the measurement interval, more clearly shows "roughness." The filtered slope, as seen through the RQCS (Fig. F.3c), is very similar to the "raw" slope, however, the high frequency "hash" is removed by the RQCS bandpass filter. Also, the non-zero mean slope is removed with the longer wavelengths.

Figure F.4 shows corresponding measurements obtained with the APL Trailer (in the APL 72 configuration), described in Appendices A and G. Figures F.3 and F.4 show that direct comparison of the elevation "profile" signals (Figs. 3a and 4a) is meaningless, since the APL signal does not include wavelengths longer than 40 m. Direct comparison of the slope "profile" signals (Figs. 3b and 4b) is much closer, yet the signals are still not comparable due to differences in the instrumentation approaches of the TRRL Beam and APL Trailer. After the signals are filtered by the RQCS, the waveband of the slope profile has been limited to the band that excites the RQCS at the simulation speed of 50 km/h. While exact agreement is not obtained, the signals now appear much more similar, and have close RARS values.

COMPUTATIONAL DETAILS

Due to the way the RQCS is formulated, the output of the model has the same units as the input. Thus, a single RQCS algorithm can provide RARS directly from a slope input or RARV directly from a vertical velocity input, without modification.

Since this report emphasizes the RARS statistic, rather than the RARV statistic, spatial descriptors are used when possible.

Computational Methods for Simulating Vehicle Dynamics

The RQCS can be implemented any number of ways, since the analysis is defined by Eqs. 2 and 3, rather than a specific means of their solution. Four approaches that have been used successfully are mentioned here:

Analog Computer. As noted earlier, the first QCSs used for roughness evaluation were electronic [22, 24]. An electronic filter is designed that follows Eqs. 2 and 3, thus defining an electronic analog of the ideal mechanical system. An analog computer requires that the profile be measured continuously, to provide a voltage proportional to profile over the proper frequency range. Therefore, it cannot easily be used with measurement methods that only provide the profile numerically at discrete intervals, such as the Rod and Level and TRRL Beam. An analog computer has several potential advantages: 1) it operates in "real time," and therefore does not require that profile be stored on magnetic tape, 2) summary results are obtained immediately, and 3) it is ideally suited to an analog dynamic profilometer, such as the APL 72 (digitization is not necessary). In practice, the analog QCSs have proven troublesome to maintain. (For example, problems with the BPR/QCS used as the basis of the QI, are mentioned in Appendix E.)

Numerical Integration. The differential equations can be numerically integrated on a digital computer, using one of many possible integration approximations (Euler, Runge-Kutta, Hammings Predictor-Corrector, etc.). The variables are calculated at discrete times, spaced closely by the small "time step." At each time step, the derivatives are evaluated (according to Eqs. 2 and 3) and used to estimate the variables at the next step. While numerical integration is an approximation, the errors can be kept at negligible levels by proper choice of the time step interval [36].

Estimation through Correlation. A number of alternative analyses can be devised that yield statistics correlated with RARS. While a rigorous mathematical relationship might not exist, a statistical relation can be developed through regression analyses. The QI_r analysis, described in Appendix E, estimates the output of a BPR/QCS using mid-chord deviations (RMSVA) from two baselengths. The RMSD analysis, described in Appendix H, estimates the ARS numeric obtained from a BI Trailer as it existed in July

1982 during the IRRE. Although alternate statistics combined with regression equations are not universally equivalent to direct computation of a QCS numeric from the profile data, the alternate statistics can sometimes be "converted" to the RARS roughness scale with little loss in accuracy.

State Transition Matrix. Because the differential equations of the QCS are linear, the exact solution can be calculated if the profile input has a known shape between measurements. The solution method is called the state transition matrix (STM) method, because the differential equations are used to define two fixed matrices of constant coefficients that are used to compute the transition of the QCS over each time step [37]. This method is described below.

Filtering the Profile: The State Transition Matrix

The state of the mathematical model shown in Fig. F.1 can be described completely (for purposes of determining RARS) by the four state variables z_s', z_s'', z_u', and z_u''. The displacements of the sprung and unsprung masses, z_s and z_u, can also be computed, but are not necessary for determining the suspension motion detected by a roadmeter.

Because the RQCS is linear, the new value of each variable can be calculated at a position x along the road if the values of the four variables are known at a previous position, and if the profile shape is known over the measurement interval. For assumed constant profile slope between measurements, and a constant measurement interval, the values of the state variables at a given point are computed as:

$$Z_s' = s_{11}\, z_s' + s_{12}\, z_s'' + s_{13}\, z_u' + s_{14}\, z_u'' + p_1\, y' \qquad \text{(F-24)}$$

$$Z_s'' = s_{21}\, z_s' + s_{22}\, z_s'' + s_{23}\, z_u' + s_{24}\, z_u'' + p_2\, y' \qquad \text{(F-25)}$$

$$Z_u' = s_{31}\, z_s' + s_{32}\, z_s'' + s_{33}\, z_u' + s_{34}\, z_u'' + p_3\, y' \qquad \text{(F-26)}$$

$$Z_u'' = s_{41}\, z_s' + s_{42}\, z_s'' + s_{43}\, z_u' + s_{44}\, z_u'' + p_4\, y' \qquad \text{(F-27)}$$

where

Z_s', Z_s'', Z_u', and Z_u'' are the values of the state variables for the current position,

z_s', z_s'', z_u', and z_u'' are the values known for the previous position, and

y' = profile slope input.

The coefficients s_{jk} and p_j ($j,k = 1...4$) are constants, which are fixed by the "time step," which is the time that would be needed for a vehicle to advance over one profile measurement interval at the simulation speed.

In essence, the RQCS consists of Eqs. 24 - 27. Table F.1 lists the coefficients required for simulation speeds of 50 and 80 km/h, and measurement intervals of 50, 100, 250, and 500 mm.

The above computation method is recursive, meaning that it "marches" through the profile, basing new computed values on both the new input and the previous values. As such, it is always responding to past excitation, just as a physical vehicle does.

Computation of the RQCS Coefficients

When a simulation speed/measurement interval combination is required that is not included in Table F.1, the necessary coefficients can be computed directly. To simplify the mathematical expressions, matrix notation will be used below. In the following equations, all one-dimensional (1x4) matrices are indicated in bold print, while two-dimensional matrices (4x4) are both underlined and shown in bold print. Although the state transition computation method can be used to give a slope output, Eqs. 2 and 3 have time derivatives. To solve those equations, it is more convenient if all derivatives are temporal, and therefore only time derivatives are indicated in this section.

Eqs. 24 - 27 can be re-written in matrix form with temporal derivatives as:

Table F.1 RQCS Coefficients

dt = 3.6×10^{-3} sec, dx = 50 mm, V = 50 km/h (Valid for any road surface)

$$\underline{ST} = \begin{bmatrix} .999611699 & 3.56272188 \times 10^{-3} & 1.92070642 \times 10^{-4} & 3.71002355 \times 10^{-5} \\ -.209863995 & .979719377 & .0483543033 & .0200843925 \\ 2.57625371 \times 10^{-3} & 2.47334903 \times 10^{-4} & .970650997 & 3.32009264 \times 10^{-3} \\ 1.38542279 & .13389595 & -15.8388928 & .839331301 \end{bmatrix} \quad \mathbf{PR} = \begin{bmatrix} 1.96228971 \times 10^{-4} \\ .161509692 \\ .0267727492 \\ 14.4534699 \end{bmatrix}$$

dt = 7.2×10^{-3} sec, dx = 100 mm, V = 50 km/h (Valid for road surfaces not having isolated "bumps" shorter than 150 mm)

$$\underline{ST} = \begin{bmatrix} .998527757 & 7.0568212 \times 10^{-3} & -3.69240955 \times 10^{-5} & 1.40418015 \times 10^{-4} \\ -.38744038 & .961803551 & -.223846046 & .0366872825 \\ 9.6237219 \times 10^{-3} & 9.36120101 \times 10^{-4} & .889589221 & 6.01437205 \times 10^{-3} \\ 2.4788086 & .244581883 & -28.661375 & .65463106 \end{bmatrix} \quad \mathbf{PR} = \begin{bmatrix} 1.50916745 \times 10^{-3} \\ .611286426 \\ .100787057 \\ 26.1825663 \end{bmatrix}$$

dt = .018 sec, dx = 250 mm, V = 50 km/h (Valid for road surfaces not having isolated "bumps" shorter than 300 mm)

$$\underline{ST} = \begin{bmatrix} .992040026 & .0171948155 & -.0124196184 & 7.08544757 \times 10^{-4} \\ -.789425935 & .917212924 & -2.29510558 & .0624074845 \\ .0465278304 & 4.72363171 \times 10^{-3} & .453113538 & 9.9465964 \times 10^{-3} \\ 3.89845779 & .416049897 & -47.1993075 & .0835914715 \end{bmatrix} \quad \mathbf{PR} = \begin{bmatrix} .0203795897 \\ 3.0845315 \\ .500358633 \\ 43.3008497 \end{bmatrix}$$

dt = .036 sec, dx = 500 mm, V = 50 km/h (Valid for road surfaces not having significant "short wave roughness." Less accurate than when dx = 250 mm.)

$$\underline{ST} = \begin{bmatrix} .972753756 & .0330653765 & -.0908549945 & 1.71168531 \times 10^{-3} \\ -1.37070714 & .842828908 & -6.08082958 & .0390698522 \\ .102287289 & .0114112354 & -.275579675 & 5.66614513 \times 10^{-3} \\ 1.66878205 & .260465682 & -26.3354005 & -.433758069 \end{bmatrix} \quad \mathbf{PR} = \begin{bmatrix} .118101242 \\ 7.45153671 \\ 1.17329239 \\ 24.6666185 \end{bmatrix}$$

dt = 2.25×10^{-3} sec, dx = 50 mm, V = 80 km/h (Valid for all road surfaces)

$$\underline{ST} = \begin{bmatrix} .999845186 & 2.23520857 \times 10^{-3} & 1.06254529 \times 10^{-4} & 1.47639955 \times 10^{-5} \\ -.135258296 & .987024495 & .0709857026 & .0129269461 \\ 1.03017325 \times 10^{-3} & 9.84266368 \times 10^{-5} & .988294046 & 2.14350069 \times 10^{-3} \\ .898326884 & .0861796409 & -10.2296999 & .903144578 \end{bmatrix} \quad \mathbf{PR} = \begin{bmatrix} 4.8559593 \times 10^{-5} \\ .0642725938 \\ .0106757814 \\ 9.33137299 \end{bmatrix}$$

dt = 4.5×10^{-3} sec, dx = 100 mm, V = 80 km/h (Valid for road surfaces not having isolated "bumps" shorter than 150 mm)

$$\underline{ST} = \begin{bmatrix} .999401438 & 4.44235095 \times 10^{-3} & 2.18885407 \times 10^{-4} & 5.72179098 \times 10^{-5} \\ -.257054857 & .975036049 & 7.96622337 \times 10^{-3} & .0245842747 \\ 3.96037912 \times 10^{-3} & 3.81452732 \times 10^{-4} & .954804848 & 4.05558755 \times 10^{-3} \\ 1.68731199 & .163895165 & -19.3426365 & .794870062 \end{bmatrix} \quad \mathbf{PR} = \begin{bmatrix} 3.79676767 \times 10^{-4} \\ .249088634 \\ .041234773 \\ 17.6553245 \end{bmatrix}$$

dt = .01125 sec, dx = 250 mm, V = 80 km/h (Valid for road surfaces not having isolated "bumps" shorter than 300 mm)

$$\underline{ST} = \begin{bmatrix} .996607069 & .0109151441 & -2.08327474 \times 10^{-3} & 3.19014531 \times 10^{-4} \\ -.55630449 & .943876786 & -.832472102 & .0506470087 \\ .0215317589 & 2.12676354 \times 10^{-3} & .750871363 & 8.22188868 \times 10^{-3} \\ 3.33501289 & .337646725 & -39.1276349 & .434756397 \end{bmatrix} \quad \mathbf{PR} = \begin{bmatrix} 5.47620359 \times 10^{-3} \\ 1.38877659 \\ .227596878 \\ 35.792622 \end{bmatrix}$$

dt = .0225 sec, dx = 500 mm, V = 80 km/h (Valid for road surfaces not having significant "short wave roughness")

$$\underline{ST} = \begin{bmatrix} .988172567 & .0212839445 & -.0252093147 & 9.92316691 \times 10^{-4} \\ -.928516044 & .900161568 & -3.39136929 & .0628016846 \\ .0638632609 & 6.61544461 \times 10^{-3} & .240289418 & 9.86268262 \times 10^{-3} \\ 3.74329442 & .418677898 & -46.6788394 & -.114525219 \end{bmatrix} \quad \mathbf{PR} = \begin{bmatrix} .0370367529 \\ 4.31988533 \\ .695847322 \\ 42.935545 \end{bmatrix}$$

$$Z(i) = \underline{\mathbf{ST}}\ \mathbf{Z}(i-1) + \mathbf{PR}\ \dot{y}(i) \quad \text{(F-28)}$$

where

$$Z^T = [\ \dot{z}_s,\ \ z_s,\ \ \dot{z}_u,\ \ z_u\ ] \quad \text{(F-29)}$$

and

$\underline{\mathbf{ST}}$ = 4x4 State Transition Matrix (with coefficients s_{11} ... s_{44})

$\mathbf{PR}$ = 1x4 Partial Response Matrix (with coefficients p_1 ... p_4)

i = present time step , i-1 = previous time step

To make Eqs. 2 and 3 compatible with Eqs. 24 - 27, both sides of Eqs. 2 and 3 are differentiated with respect to time. They can then be expressed in the following matrix form using the four state variables of the **Z** vector, defined in Eq. 29:

$$\mathbf{Z}(t) = \underline{\mathbf{A}}\ \ \mathbf{Z}(t) + \mathbf{B}\ y(t) \quad \text{(F-30)}$$

$$\underline{\mathbf{A}} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -K_2 & -C & K_2 & C \\ 0 & 0 & 0 & 1 \\ K_2/u & C/u & -(K_1+K_2)/u & -C/u \end{bmatrix} \qquad \mathbf{B} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ K_1/u \end{bmatrix} \quad \text{(F-31)}$$

The form of the solution for Eqs. 30 and 31 has already been presented (Eq. 28). For a constant time step, over which the input $\dot{y}(i)$ is a constant, the $\underline{\mathbf{ST}}$ and $\mathbf{PR}$ matrices can be computed from the $\underline{\mathbf{A}}$ and **B** matrices:

$$\underline{\mathbf{ST}} = e^{\underline{\mathbf{A}}\ dt} \quad \text{(F-32)}$$

$$\mathbf{PR} = \underline{\mathbf{A}}^{-1}\ (\underline{\mathbf{ST}} - \underline{\mathbf{I}}\ )\ \mathbf{B} \quad \text{(F-33)}$$

where

$$dt\ (sec) = dx\ (m)\ 3600\ (sec/h)\ .001\ (km/m)\ /\ V\ (km/h) \quad \text{(F-34)}$$

and $\underline{I}$ is a 4 x 4 identity matrix. The **PR** matrix as defined in Eq. 33 is based on the assumption of an input that remains constant over the profile measurement interval. That is why the generalized input in Eqs. 24 - 27 should be a slope, rather than elevation: an assumption of constant slope between profile measures is more reasonable than an assumption of constant elevation. (Note that if an elevation input is used, the output signal will also be an elevation, and that a simple average would not yield RARS.)

Eq. 33 requires a matrix inversion, which is not detailed here because it is such a common computer subroutine. The matrix exponent in Eq. 32 is less common, but can be evaluated with a Taylor series expansion:

$$e^{x} = 1 + x + x^2/2 + x^3/(3\ 2) + x^4/4! + \ldots$$

$$e^{\underline{\mathbf{A}}\,dt} = \underline{I} + \underline{\mathbf{A}}\,dt + \underline{\mathbf{A}}\,\underline{\mathbf{A}}\,dt^2\ /\ 2 + \underline{A}^3\,dt^3\ /\ 3! + \ldots$$

$$= \underline{I} + \sum_{i=1}^{N} \underline{A}^i\,dt^i\ /\ i! \qquad \text{(F-35)}$$

For Eq. 35 to be perfectly exact, N must approach infinity. In practice, however, the series converges rapidly to the precision of a computer when dt is small. In calculating the coefficients shown in Table F.1, the computer program checked the coefficients after each new term in the series was added to determine if a change in $e^{\underline{\mathbf{A}}\,dt}$ could be detected; when a change was not detected for any of the 16 coefficients, then the program stopped since the coefficients were precise to the limits of the computer. This generally occurs after about 10 terms (N=10).

Conversion of Elevation Profiles to a Smoothed Slope Input.

As mentioned earlier, the RQCS includes a smoothing of the input profile, using a 250 mm "moving average," and also uses elevation changes (slope) as the input to the QCS filter. When the two operations are combined, the resulting operation is very simple: The slope input used for the QCS filter is the change in elevation over the moving average baselength. If the profile is measured continuously, then

$$y'(x) = [y_r(x + b) - y_r(x)] \; / \; b \qquad \text{(F-36)}$$

where $y'(x)$ = smoothed slope input to the RQCS

$y_r(x)$ = raw profile elevation

(It is recognized that Eq. 35 introduces a phase shift, equivalent to the distance b/2 = 250/2 = 125 mm). This has no effect on the roughness numerics and simplifies the conversion of the equations into computer code. For zero phase, the equation would be: $y'(x) = [y_r(x+b/2) - y_r(x-b/2)] \; / \; b$.)

When profile elevations are measured at constant intervals, there are two possible relations between dx, the measurement interval, and b, the baselength of the moving average:

1. dx $\geq$ b. In this case, the input to the RQCS should be:

$$y'(i) = [y(i+1) - y(i)] \; / \; dx \qquad \text{(F-37)}$$

The input is the equivalent of a profile smoothed with a moving average equal to dx. If dx = b = 250 mm, then the resulting slope input values agree perfectly with the definition of the RQCS. Should dx be greater than b (for example, 500 mm), then the result is equivalent to the filter portion of the RQCS with a longer moving average baselength, equal to dx.

2. dx < b. (Example: dx=100, b=250 mm.) If b is not an integer multiple of dx, then interpolation of profile points is needed to employ the correct baselength in the moving average:

$$y'(i) = [\; A\, y(i+k) + B\, y(i+k+1) - y(i) \;] \; / \; b \qquad \text{(F-38)}$$

where

$$k = \mathrm{INT}(\; b/dx \;) \;,\; B = (\; b - k\, dx)\; /dx \;,\; \text{and } A = 1 - B \qquad \text{(F-39)}$$

The function INT in Eq. 39 is the INTeger function in the BASIC and FORTRAN computer languages, and designates truncation.

If b is an integer multiple of dx (for example, dx=50, b=250 mm), then Eq. 38 is simplified because A=1 and B=0. Eq. 38 then reduces to:

$$y'(i) = [y(i+k) - y(i)] / b \qquad \text{(F-40)}$$

Initialization.

Because the RQCS is always responding to both new profile input and its present "state" (as defined by the spatial equivalents of vertical acceleration and vertical velocity of the simulated body and axle), the assumed initial values of the four state variables can influence the RARS numeric. This replicates the behavior of a physical RTRRMS which is responding to the road surface immediately prior to the test site upon entry.

In order to obtain the true initial state of the RQCS, the profile must be measured for some distance prior to the start of the test site. The simulation should begin on the lead-in, to determine the proper values of the variables z_s', z_s'', z_u', and z_u'' at the start of the test site.

In the IRRE, lead-in data were not available from the static profile measures obtained from Rod and Level and the TRRL Beam, and initial conditions had to be assumed. The assumed initial conditions are:

$$z_s'' = z_u'' = 0 \qquad \text{(F-41)}$$

$$z_s' = z_u' = [y(i + k) - y(i)] / (k\ dx) \qquad \text{(F-42)}$$

where

$$k = \text{INT}(\ 0.5 / dt) \qquad \text{(F-43)}$$

The above initial conditions assumed for the RQCS have a physical interpretation: it is as if the Reference RTRRMS is approaching the test site on a perfectly smooth road, with a grade equal to the average grade of the profile over the first 0.5 second of simulated travel time. Note that Eq. 42

initializes the RQCS for a slope input, suitable for direct computation of RARS. When RARV is computed, the dx variable in Eq. 42 is replaced with dt to yield an initial vertical velocity. Also, the primes used to indicate spatial derivative should be replaced with dots to indicate time derivatives. The profiles obtained during the IRRE were analyzed to determine the errors introduced using Eqs. 41 and 42 and, as shown in the next section, they were negligible.

(A different initialization was used at first in the IRRE analyses, which used only the first two profile points (k=1 in Eq. 42). The resulting RQCS numerics, included in the December 1982 draft of this report, showed slightly higher and more erratic results for the profiles measured with the Beam and APL 72 system. The shorter measurement intervals made that initialization more sensitive to the values of the first two elevation measures, introducing a random effect that degraded the agreement between RQCS numerics obtained by different profile measurement methods.)

A Demonstration Computer Program.

Figure F.5 presents a demonstration computer program to calculate $RARS_{80}$, using the BASIC computer language. The profile values needed to compute the slope input are kept in a buffer, which is the array, Y. The State Transition Matrix is stored in the ST array (and read by the program from the DATA statements at the bottom); the Particular Response Matrix is stored in the array PR (these coefficients are also read from the DATA statements); DX is the measurement interval (0.25 m in the program); the Z array contains the current values of the four state variables; and the Z1 array contains the old values of the state variables, from the previous time step. Although smoothing is not needed, due to the sample length of 0.25 m, the program has provision for smoothing with smaller intervals. When DX is changed to values smaller than 0.25, then more elements in the Y buffer are used for smoothing. The program was written as a demonstration and is not particularly efficient. For example, it should be modified to read the profile from a file, rather than for keyboard input. In order to convert the program for other sample intervals and/or simulation speeds, lines 1510-1550 should be replaced with new values.

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

Fig. F.5   Demonstration program for computing IRI with a microcomputer

MEASUREMENT OF RQCS NUMERICS IN THE IRRE

The profile data obtained in the IRRE provided a number of new quantitative findings concerning the accuracy of RQCS numerics obtained using different methods.

Alternatives in the Quarter-Car Model

Tire Enveloping. The tire enveloping (moving average) smoothing portion of the RQCS is not always used in the United States. This is justified by an earlier finding that the smoothing had a very slight effect on paved roads at the highway speeds (60 - 80 km/h) normally associated with RTRRMS use in the United States [9]. To determine the significance of the smoothing over the much broader range of surface type and speed covered in the IRRE, the profiles obtained from the TRRL beam and the APL 72 trailer were processed with and without the smoothing. Fig. F.6 shows the RARS statistics as obtained with and without the 250 mm moving average. As predicted from the plots shown earlier in Fig. F.2, the effect is slight at high speeds, but more significant at lower speeds. Figs. 6a and 6b show that smoothing must be included for the simulation speeds of 20 and 32 km/h. Figs. 6c and 6d show that a small but noticeable effect is present for 50 km/h. For a simulation speed of 80 km/h (data not shown), there was no visible difference between RARS numerics obtained with and without smoothing.

Half-Car or Quarter Car. When possible, the ARS statistic was computed from both wheeltracks together, simulating a half-car. This computation requires that the profiles of both wheeltracks begin at the same point, so that the point-by-point averaging can be performed. Because of this requirement, only the static profile measures were processed in this way. Figure F.7 compares the measures obtained processing both wheeltracks together with the measures obtained by processing the profiles separately and then averaging the RARS obtained for each. The figure shows that for the conditions covered in the IRRE, the two methods give highly correlated results, which can be approximately "converted" using a regression equation determined from the IRRE data:

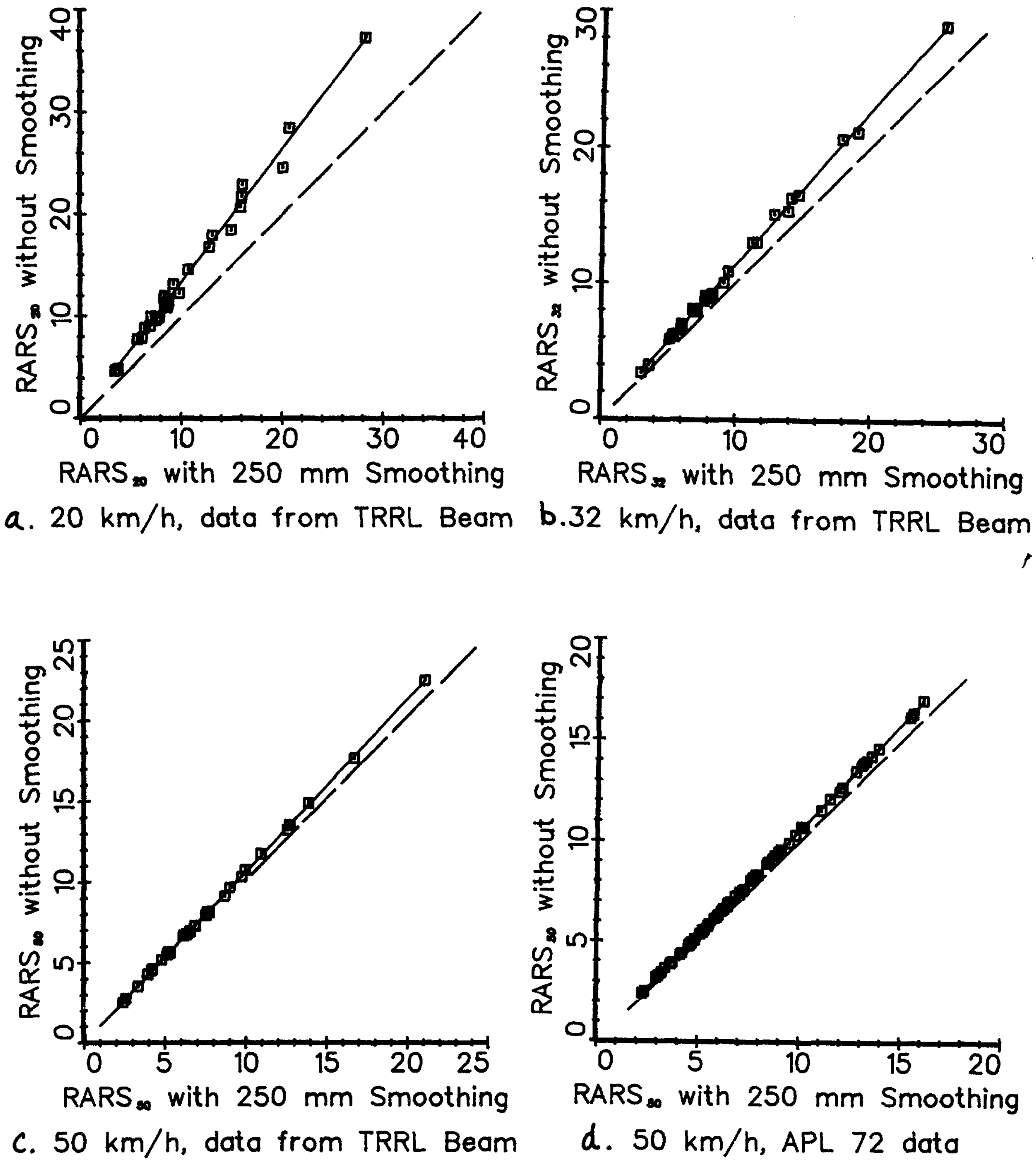


Figure F.6. Effect of Smoothing (Enveloping) on the RARS Numeric

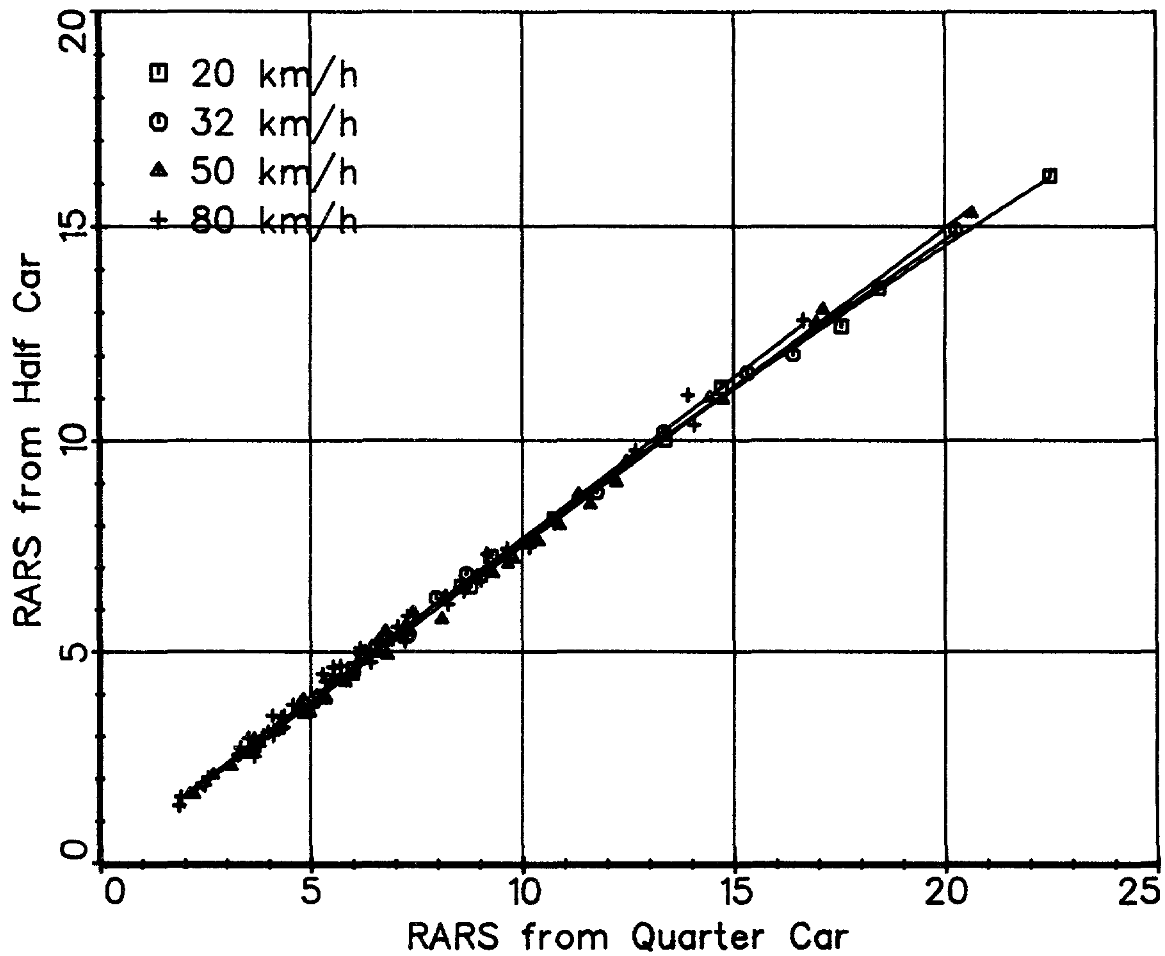


Figure F.7. Comparison of the RARS Obtained from Quarter-Car and Half-Car Simulations

$$ARS_h = 0.760\ RARS_A \tag{F-44}$$

where

ARS_h = numerics computed from point-by-point average of both wheeltrack profiles (HCS), and

$RARS_A$ = Average of two RARS numerics computed independently from the two wheel track profiles.

Eq. 44 reflects the fact that most of the test sites used in the IRRE had very similar roughness levels in the two wheeltracks. When one wheeltrack is substantially rougher than the other, this equation will not be valid. In fact, the case for one wheeltrack much rougher than the other is relatively easy to analyze. In the limit, where one wheeltrack is perfectly smooth, then $ARS_h = RARS_A$. When one wheeltrack is much smoother than the other, but not perfectly smooth, the ratio of ARS_h to $RARS_A$ should be expected to lie between 0.76 and 1.0.

Technical Requirements for Profile Measurement

Initialization and/or Lead-In. To obtain the "true" RARS numeric, the profile preceding a test site must be measured. To determine the amount of lead-in required, the errors introduced by the assumed initial conditions of Eqs. 41 - 43 were evaluated. One of the test sites was divided into 16 consecutive sections, 20 m long. The RQCS was run over the site, starting first at x=0, and finishing at x=320. The $RARS_{50}$ numeric was printed for each of the 20 m sections, rather than simply for the total length. This was repeated 14 times, starting at x=20, x=40, ... x=300. The results are shown in Table F.2. The test site, CA05, was chosen because it was known to have highly variable roughness over its length. In the table, the first (top) numeric in each column is based on the assumed initial conditions of Eqs. 41 - 43, while all subsequent numerics are initialized "correctly" (the initial condition for the 20 m section is the ending condition for the preceding 20 m section), as the RQCS proceeded continuously. The table shows that the effect

Table F.2. Effect of RQCS Initialization

Sub-Section Starting Position	Position where RQCS was started (m) 0	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300
0	8.20	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
20	5.11	5.21	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
40	7.19	7.19	7.13	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
60	4.10	4.10	4.09	3.50	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
80	5.34	5.34	5.34	5.34	5.21	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
100	4.05	4.05	4.05	4.05	4.05	3.93	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
120	6.08	6.08	6.08	6.08	6.08	6.08	5.76	.....	.....	.....	.....	.....	.....	.....	.....	.....
140	9.80	9.80	9.80	9.80	9.80	9.80	9.81	9.72	.....	.....	.....	.....	.....	.....	.....	.....
160	6.11	6.11	6.11	6.11	6.11	6.11	6.11	6.11	6.01	.....	.....	.....	.....	.....	.....	.....
180	4.93	4.93	4.93	4.93	4.93	4.93	4.93	4.93	4.94	4.61	.....	.....	.....	.....	.....	.....
200	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	.....	.....	.....	.....	.....
220	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.68	6.30	.....	.....	.....	.....
240	14.88	14.88	14.88	14.88	14.88	14.88	14.88	14.88	14.88	14.88	14.88	14.87	13.86	.....	.....	.....
260	11.37	11.37	11.37	11.37	11.37	11.37	11.37	11.37	11.37	11.37	11.37	11.37	11.35	10.89	.....	.....
280	10.67	10.67	10.67	10.67	10.67	10.67	10.67	10.67	10.67	10.67	10.67	10.67	10.67	10.68	10.27	.....
300	6.56	6.56	6.56	6.56	6.56	6.56	6.56	6.56	6.56	6.56	6.56	6.56	6.56	6.56	6.57	6.33

NOTE: The above results are for the left wheeltrack of site CA05. Simulation speed = 50 km/h.

of the initialization is extremely slight, and disappears after 20 m (at the simulation speed of 50 km/h). That is, the same roughness numerics are obtained for each 20 m section, as long as the RQCS is started on a preceding 20 m section. Even the roughness numerics computed for the first 20 m section in each of the 15 runs show only slight errors. The large variations in roughness between some of the sections (from 4.05 to 14.88) are actual variations in road roughness, duly reflected in the $RARS_{50}$ statistic.

The section of CA05 from 60 - 80 m appears in the Table as one in which there is the greatest difference between $RARS_{50}$ using the assumed initialization of Eqs. 41- 43 and the correct value. Therefore, it was used to show the differences between the output of the RQCS filter as it is affected by initialization in Figure F.8. The figure shows three filtered profiles: 1) the RQCS output signal for the theoretically correct initialization, determined by the 60 m of profile preceding this 20 m section, and designated "true RQCS output" in the figure; 2) the signal obtained using the initial conditions of Eqs. 41 - 43; and 3) a deliberately erroneous initialization, obtained by stopping the computer simulation in progress and changing one of the variables drastically before restarting. The third trace shows that even with an unreasonable initialization, which might be caused by a computer programming error, the output of the RQCS reached the "correct" response within the 16 m shown in the plots.

These results indicate that, for all practical purposes, no lead-in is required if: 1) the initializations of Eqs. 41 - 43 are used, and 2) calibration sites are selected such that the preceding 20 m have similar roughness qualities.

Measurement Interval. The "true" RARS value is obtained with a sample interval approaching zero. In order to show the effects of sample interval on the roughness statistics, the 28 profiles obtained with the TRRL beam were decimated to yield profiles having intervals that were multiples of the original 100 mm. Some of the data obtained are plotted in Figure F.9 to show the effect of sample interval on the $RARS_{50}$ numeric. In each plot, the dashed line is the line of equality, on which the data points should lie for perfect agreement. The solid lines are quadratic regression curves, which indicate trends in the data. The plots indicate that as the measurement

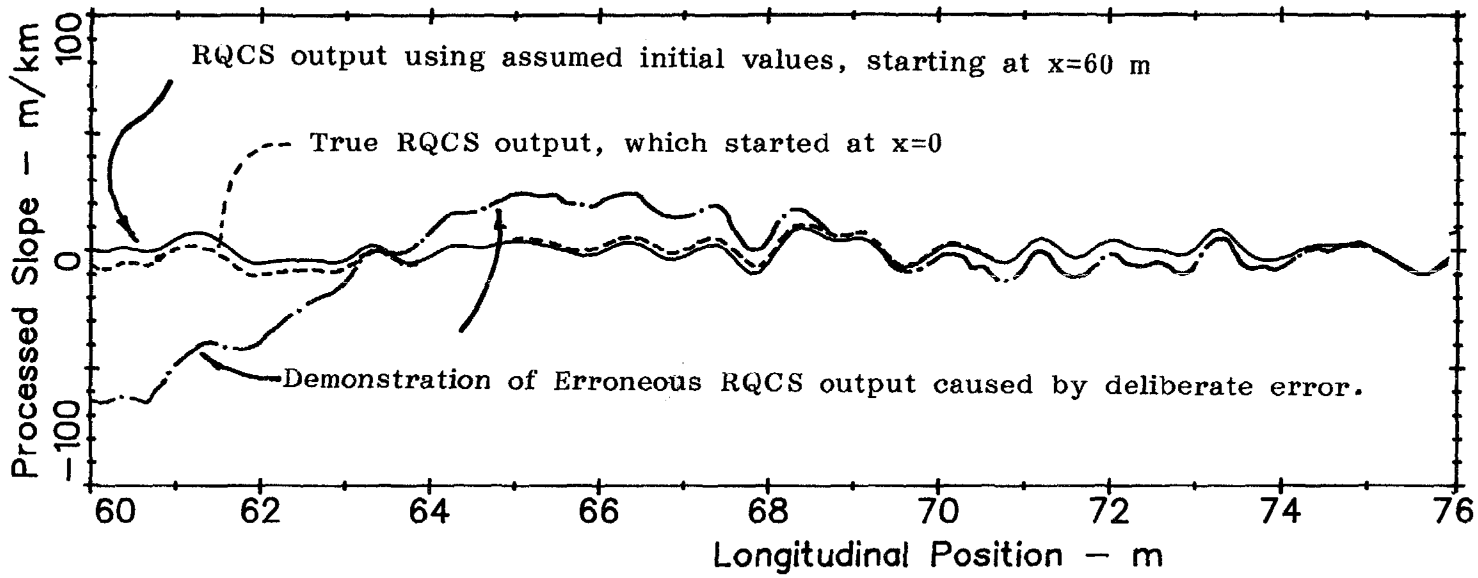


Figure F.8. Initialization of RQCS

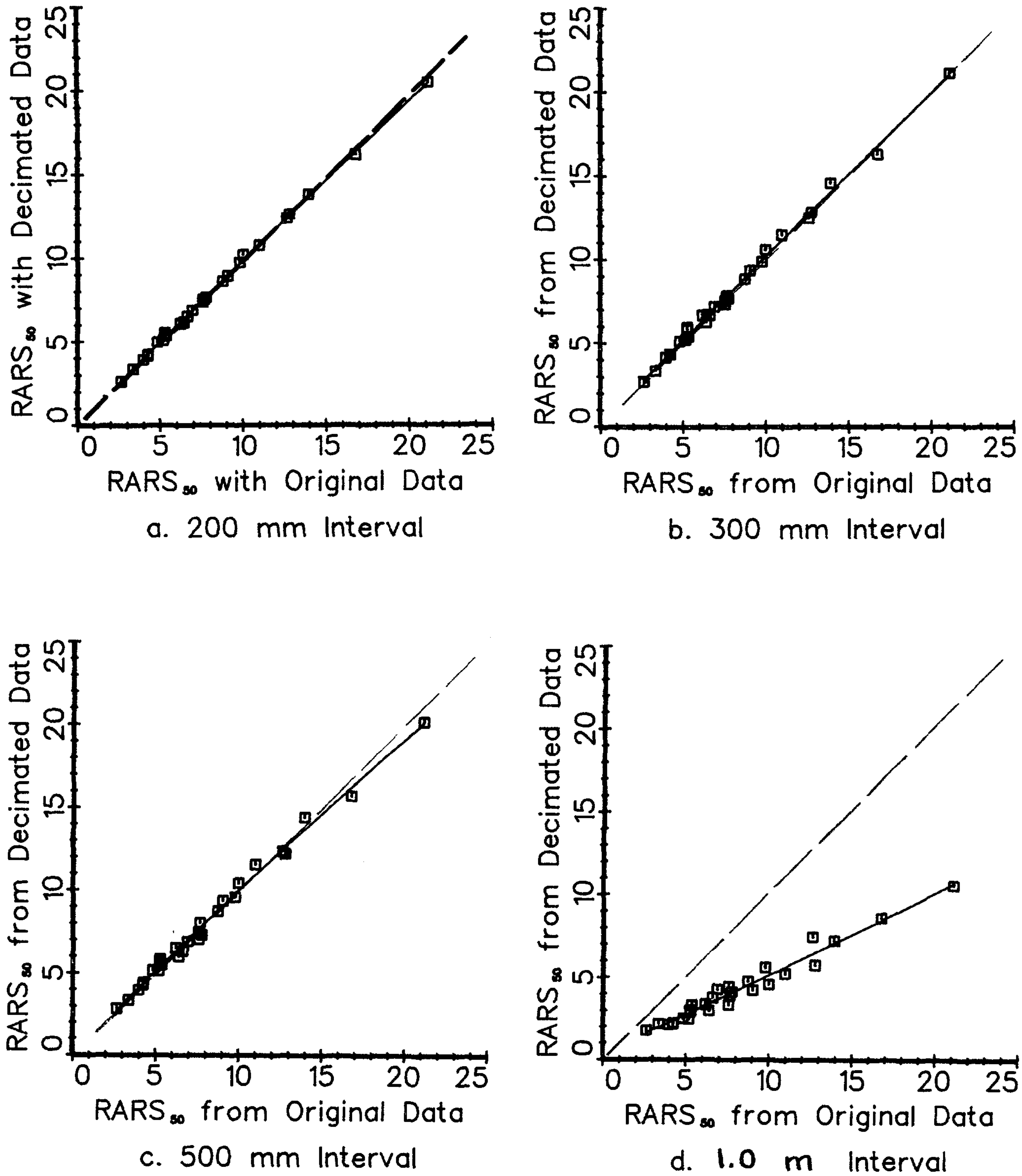


Figure F.9. Effect of Measurement Interval on $RARS_{50}$.

interval increases up to 500 mm, there is negligible bias introduced, but that the random error (scatter) increases slightly. (A possible exception might be the two roughest measures shown in Fig. 9c, in which the $RARS_{50}$ values from the decimated profile data are slightly lower; however, it is not possible to say whether this bias is due to a characteristic of rough unpaved roads, or simply chance, since the error is of the same magnitude as the random scatter.) Fig. 9d illustrates the bias error that occurs when the sample interval is so large that significant variations in profile between measurements are missed: $RARS_{50}$ numerics calculated from a profile with the 1.0 m spacing are low by 50%.

The data shown in Figure 9, along with similar data from the APL Trailer (not shown), indicate that random error in the $RARS_{50}$ computation can be held to negligible levels by using a measurement interval less than 250 mm, while unbiased but less accurate measures can be obtained using an interval of 500 mm.

The interaction of speed and required measurement interval is illustrated in Figure F.10, which shows that a sample interval of 500 mm is not adequate for the lower simulation speeds of 20 and 32 km/h, but that good results are obtained for a simulation speed of 80 km/h. For the higher speeds of 50 and 80 km/h, there is negligible bias error, but the random error still exists, indicating that a shorter interval (250 mm) is needed for the best accuracy.

Precision in the Elevation Measurement. It has been known that the precision needed in profile measurement for analysis through QCS is a function of the roughness, with better precision needed on smoother roads [38]. A statement of necessary precision therefore depends on the range of roughness being evaluated. A candidate specification was considered in which the required precision is simply proportional to the roughness of a road, when expressed as $RARS_{50}$. An analysis of the profile data obtained from the TRRL Beam was performed to determine: 1) if this type of specification is reasonable, and 2) if it is reasonable, what quantities are involved?

In this analysis, the precision of the measurement was assumed to be limited solely by the quantization of the continuous height variable into digitized quantities, which were originally 1.0 mm. The random measurement

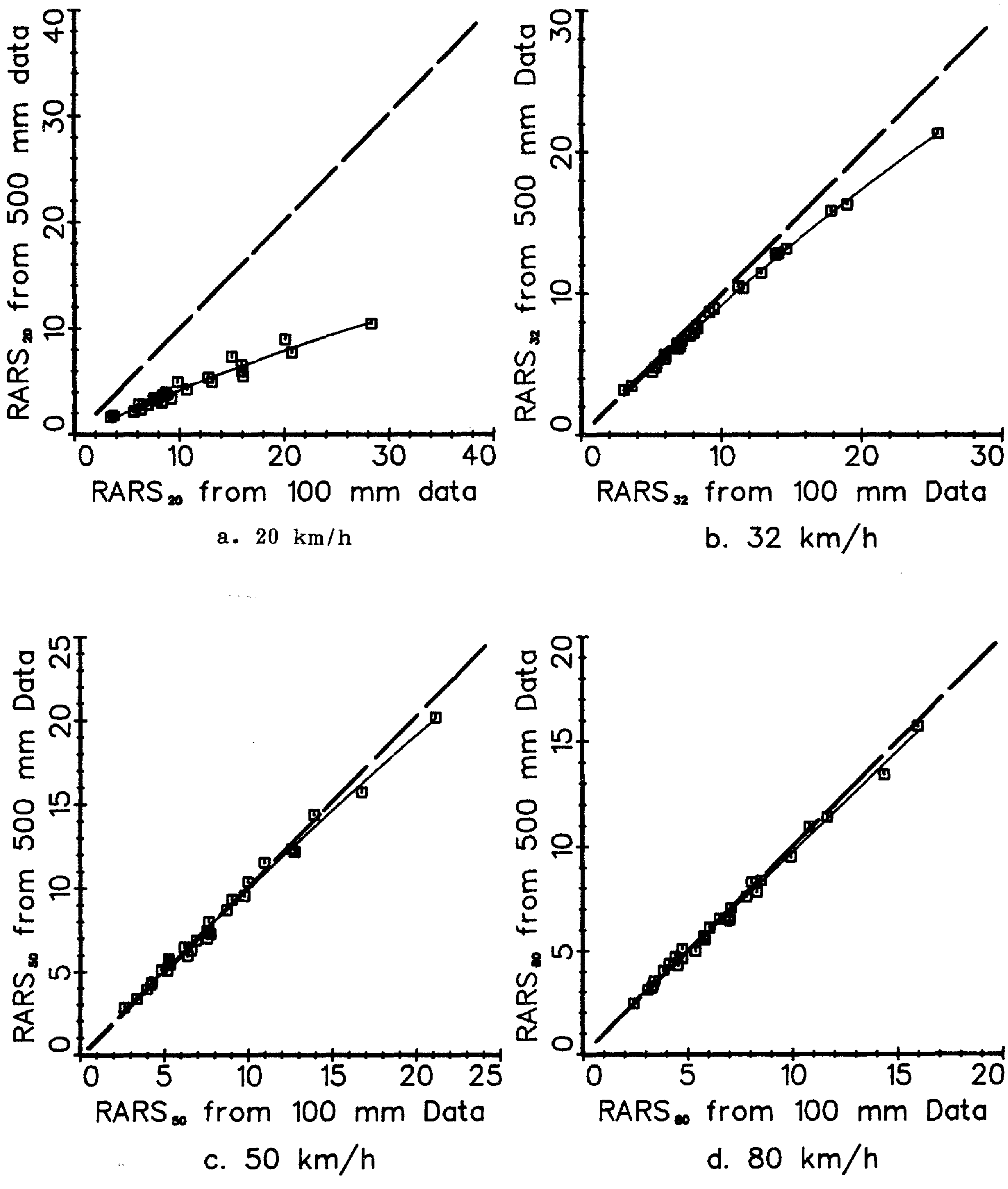
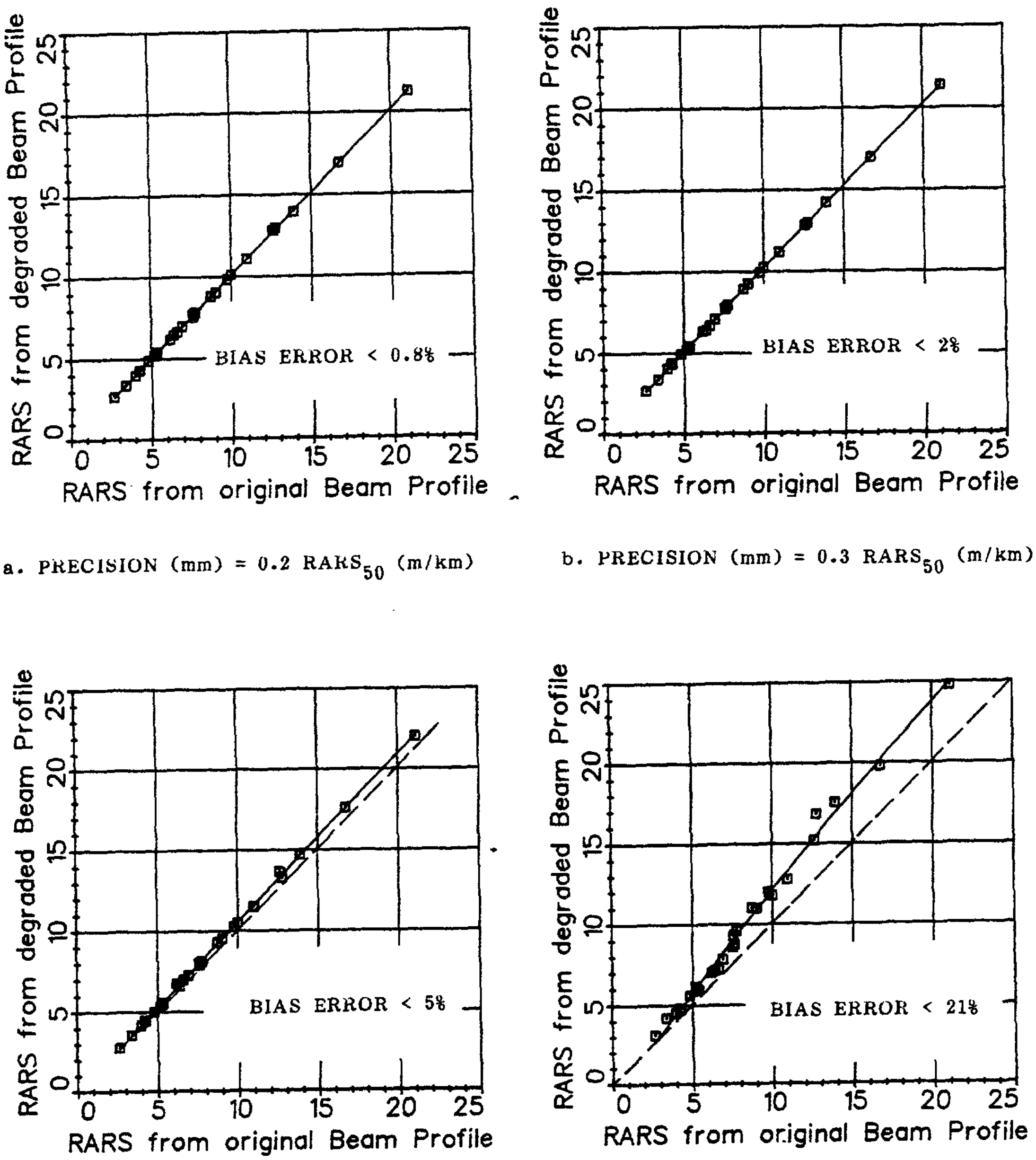


Figure F.10. Interaction of Measurement Interval and Simulation Speed on the RARS Computation.

errors that also degrade precision were not considered. For each of the 28 measured profiles, the $RARS_{50}$ value obtained with the original profile was used to determine a new quantization level (greater than 1 mm). The profile was then quantized to the nearest multiple of this new level, and re-processed to yield a new $RARS_{50}$ numeric. Figure F.11 shows the results for four levels of increased quantization (degraded precision). In all cases, the effect of the degraded precision is an increase in the computed roughness numeric. The changes were calculated from the difference in the (solid) quadratic regression lines and the (dashed) equality line (x = y), and were found to be nearly constant across the range of roughness when expressed as a percentage. (For example, for the case of precision = 0.3 RARS, shown in Fig. F.11c, the errors were 1.7% at $RARS_{50}$ = 5, 2.0% at $RARS_{50}$ = 10, 1.7% at $RARS_{50}$ = 15, and 1.2% at $RARS_{50}$ = 20.) This indicates that the candidate method of specifying required precision in proportion to roughness is valid. For $RARS_{50}$ accuracy within 1.0%, the precision (mm) should be less than 0.2 $RARS_{50}$ (m/km), while for accuracy within 2%, the precision should be less than 0.3 $RARS_{50}$. Thus, on the smoothest sites, which had $RARS_{50}$ values near 2 m/km, the actual measurement precision of 1.0 mm probably led to numerics that are several percent higher than the "true" $RARS_{50}$ values. A measurement precision of 0.5 mm would have been better. At the other end of the scale, where roughness levels were greater than 15 m/km, a measurement precision of 3 mm (better than .2 $RARS_{50}$) gave the same results as the original precision of 1 mm.

Summary of RQCS Data

The summary RARS numerics that were obtained from four methods of profile measurement are presented in Tables 3 - 6. All of the RARS numerics have the units: slope x 10^{-3} (m/km, mm/m, etc.). Only those numerics are presented for which the profile bandwidth covered the RQCS bandwidth, as defined in Eq. 23. For the lower speeds of 32 and 20 km/h, the 500 mm spacing used with the rod and level is inadequate, and the RARS numerics are not shown. But at the higher simulation speeds of 50 and 80 km/h, the 500 mm spacing used with the rod and level was adequate (although a shorter interval is recommended for future work to improve repeatability), and thus at least one RARS numeric computed from a statically measured profile is presented for



a. PRECISION (mm) = 0.2 $RARS_{50}$ (m/km)

b. PRECISION (mm) = 0.3 $RARS_{50}$ (m/km)

c. PRECISION (mm) = 0.5 $RARS_{50}$ (m/km)

d. PRECISION (mm) = 1.0 $RARS_{50}$ (m/km)

Figure F.11. Effect of Profile Measurement Precision on the $RARS_{50}$ numeric

Table F.3. Summary of the $RARS_{20}$ Data.

	Left Wheeltrack						Right Wheeltrack						Both Wheeltracks				Average (L + R)/2
Site	Static	RL 1	RL 2	Beam	A 72	A 25	Static	RL 1	RL 2	Beam	A 72	A 25	Static	RL 1	RL 2	Beam	Static
CA01	....	....	....	....	....	5.0	....	....	....	....	....	5.8	....	....	....	....	....
CA02	....	....	....	....	....	5.4	....	....	....	....	....	4.9	....	....	....	....	....
CA03	....	....	....	....	....	8.8	....	....	....	....	....	8.1	....	....	....	....	....
CA04	7.5	....	....	7.5	....	7.4	6.1	....	....	6.1	....	7.3	5.3	....	....	5.3	6.8
CA05	8.8	....	....	8.8	....	9.2	8.4	....	....	8.4	....	7.7	6.5	....	....	6.5	8.6
CA06	9.9	....	....	9.9	....	9.8	8.7	....	....	8.7	....	8.5	7.3	....	....	7.3	9.3
CA07	....	....	....	....	....	4.3	....	....	....	....	....	3.8	....	....	....	....	....
CA08	....	....	....	....	....	3.8	....	....	....	....	....	3.3	....	....	....	....	....
CA09	....	....	....	....	....	5.6	....	....	....	....	....	4.3	....	....	....	....	....
CA10	....	....	....	....	....	6.5	4.1	4.5	....	3.7	....	4.0	3.1	....	....	....	4.5
CA11	....	....	....	....	....	5.8	....	....	....	....	....	5.6	....	....	....	....	....
CA12	3.5	....	....	3.5	....	3.9	....	....	....	....	....	3.5	2.6	....	....	....	3.6
CA13	....	....	....	....	....	2.7	....	....	....	....	....	3.0	....	....	....	....	....
TS01	6.9	....	....	6.9	....	7.1	....	....	....	....	....	6.6	5.1	....	....	....	7.1
TS02	....	....	....	....	....	9.3	....	....	....	....	....	9.5	....	....	....	....	....
TS03	....	....	....	....	....	10.9	....	....	....	....	....	9.3	....	....	....	....	....
TS04	7.8	....	....	7.8	....	8.5	....	....	....	....	....	8.6	6.6	....	....	....	8.2
TS05	8.6	....	....	8.6	....	9.8	....	....	....	....	....	9.9	6.4	....	....	....	8.2
TS06	6.4	....	....	6.4	....	5.9	5.7	....	....	5.7	....	4.8	4.6	....	....	4.6	6.0
TS07	5.7	....	....	5.7	....	6.2	....	....	....	....	....	4.7	4.3	....	....	....	5.8
TS08	....	....	....	....	....	5.8	....	....	....	....	....	6.0	....	....	....	....	....
TS09	....	....	....	....	....	8.2	....	....	....	....	....	8.1	....	....	....	....	....
TS10	....	....	....	....	....	7.0	....	....	....	....	....	6.4	....	....	....	....	....
TS11	....	....	....	....	....	4.0	....	....	....	....	....	3.9	....	....	....	....	....
TS12	....	....	....	....	....	4.6	....	....	....	....	....	3.5	....	....	....	....	....
GR01	....	....	....	....	....	6.4	7.0	....	....	7.0	....	6.9	5.8	....	....	....	8.2
GR02	....	....	....	....	....	5.4	....	....	....	....	....	5.3	....	....	....	....	....
GR03	....	....	....	....	....	14.0	....	....	....	....	....	10.7	....	....	....	....	....
GR04	....	....	....	....	....	13.7	....	....	....	....	....	10.2	....	....	....	....	....
GR05	15.8	15.7	....	16.0	....	15.6	13.6	14.4	....	12.8	....	14.7	11.2	11.6	....	10.9	14.7
GR06	....	....	....	....	....	12.9	....	....	....	....	....	13.1	....	....	....	....	....
GR07	13.1	....	....	13.1	....	7.7	8.4	....	....	8.4	....	6.3	8.1	....	....	8.1	10.8
GR08	....	....	....	....	....	8.3	....	....	....	....	....	7.1	....	....	....	....	....
GR09	....	....	....	....	....	11.0	....	....	....	....	....	10.9	....	....	....	....	....
GR10	....	....	....	....	....	12.8	....	....	....	....	....	12.4	....	....	....	....	....
GR11	....	....	....	....	....	17.7	....	....	....	....	....	15.1	....	....	....	....	....
GR12	20.1	....	....	20.1	....	18.8	15.0	....	....	15.0	....	14.9	12.7	....	....	12.7	17.6
TE01	9.2	....	....	9.2	....	8.7	8.3	7.8	....	8.3	....	7.8	6.5	....	....	6.5	8.8
TE02	....	....	....	....	....	9.2	....	....	....	....	....	6.5	....	....	....	....	....
TE03	16.0	....	....	16.0	....	14.1	10.7	....	....	10.7	....	10.2	10.0	....	....	10.0	13.4
TE04	....	....	....	....	....	15.7	....	....	....	....	....	12.0	....	....	....	....	....
TE05	21.5	21.5	....	....	....	25.5	23.5	23.5	....	....	....	25.3	16.2	16.2	....	....	22.5
TE06	....	....	....	....	....	31.2	28.3	....	....	28.3	....	27.0	21.4	....	....	....	29.7
TE07	....	....	....	....	....	9.2	....	....	....	....	....	10.5	....	....	....	....	....
TE08	....	....	....	....	....	10.0	....	....	....	....	....	8.5	....	....	....	....	....
TE09	....	....	....	....	....	14.8	....	....	....	....	....	14.6	....	....	....	....	....
TE10	....	....	....	....	....	16.9	....	....	....	....	....	16.3	....	....	....	....	....
TE11	20.8	....	....	20.8	....	17.5	16.1	....	....	16.1	....	13.1	13.6	....	....	13.6	18.4
TE12	....	....	....	....	....	18.0	....	....	....	....	....	15.0	....	....	....	....	....

Table F.4. Summary of the $RARS_{32}$ Data.

	Left Wheeltrack						Right Wheeltrack						Both Wheeltracks				Average (L + R)/2
Site	Static	RL 1	RL 2	Beam	A 72	A 25	Static	RL 1	RL 2	Beam	A 72	A 25	Static	RL 1	RL 2	Beam	Static
CA01	....	....	....	....	....	4.7	....	....	....	....	5.2	5.3	....	....	....	....	....
CA02	....	....	....	....	6.0	4.9	....	....	....	....	7.5	4.5	....	....	....	....	....
CA03	....	....	....	....	8.2	7.3	....	....	....	....	7.6	7.0	....	....	....	....	....
CA04	7.2	....	....	7.2	7.2	6.6	5.9	....	....	5.9	6.7	6.5	5.1	....	....	5.1	6.5
CA05	8.2	....	....	8.2	9.6	7.4	7.7	....	....	7.7	8.0	6.5	6.3	....	....	6.3	8.0
CA06	9.1	....	....	9.1	10.2	7.9	8.3	....	....	8.3	9.0	7.0	6.8	....	....	6.8	8.7
CA07	....	....	....	....	5.2	3.8	....	....	....	....	4.3	3.4	....	....	....	....	....
CA08	....	....	....	....	4.3	3.5	....	....	....	....	4.3	3.0	....	....	....	....	....
CA09	....	....	....	....	6.8	4.6	....	....	....	....	4.9	3.7	....	....	....	....	....
CA10	....	....	....	....	5.8	5.6	3.9	4.2	....	3.6	5.1	3.8	3.0	....	....	....	4.3
CA11	....	....	....	....	6.4	5.2	....	....	....	....	5.9	4.9	....	....	....	....	....
CA12	3.0	....	....	3.0	2.9	3.4	....	....	....	....	2.7	3.2	2.2	....	....	....	3.0
CA13	....	....	....	....	2.9	2.6	....	....	....	....	2.9	2.7	....	....	....	....	....
TS01	6.0	....	....	6.0	6.3	5.5	....	....	....	....	....	5.3	4.4	....	....	....	6.0
TS02	....	....	....	....	7.5	6.8	....	....	....	....	7.5	7.2	....	....	....	....	....
TS03	....	....	....	....	8.4	8.3	....	....	....	....	....	7.5	....	....	....	....	....
TS04	7.1	....	....	7.1	7.2	6.9	....	....	....	....	....	6.9	6.0	....	....	....	7.6
TS05	8.0	....	....	8.0	9.2	7.6	....	....	....	....	8.6	7.7	5.9	....	....	....	7.5
TS06	5.4	....	....	5.4	5.4	4.5	5.1	....	....	5.1	4.7	4.2	3.9	....	....	3.9	5.2
TS07	5.3	....	....	5.3	4.9	4.8	....	....	....	....	5.1	4.2	4.0	....	....	....	5.5
TS08	....	....	....	....	5.6	4.5	....	....	....	....	5.6	4.7	....	....	....	....	....
TS09	....	....	....	....	6.3	6.4	....	....	....	....	5.7	6.5	....	....	....	....	....
TS10	....	....	....	....	6.3	5.6	....	....	....	....	5.7	5.2	....	....	....	....	....
TS11	....	....	....	....	4.2	3.3	....	....	....	....	4.3	3.2	....	....	....	....	....
TS12	....	....	....	....	4.8	3.8	....	....	....	....	4.5	2.9	....	....	....	....	....
GR01	....	....	....	....	5.7	5.1	6.0	....	....	6.0	....	5.1	5.0	....	....	....	6.8
GR02	....	....	....	....	6.9	4.1	....	....	....	....	....	4.1	....	....	....	....	....
GR03	....	....	....	....	10.4	10.3	....	....	....	....	....	8.1	....	....	....	....	....
GR04	....	....	....	....	11.3	10.2	....	....	....	....	....	7.9	....	....	....	....	....
GR05	14.6	14.6	....	14.6	15.5	12.1	12.1	12.6	....	11.6	....	11.2	10.2	10.4	....	10.0	13.4
GR06	....	....	....	....	15.1	10.1	....	....	....	....	....	10.1	....	....	....	....	....
GR07	11.2	....	....	11.2	8.6	6.2	6.8	....	....	6.8	....	5.1	6.8	....	....	6.8	9.0
GR08	....	....	....	....	7.5	6.3	....	....	....	....	....	5.5	....	....	....	....	....
GR09	....	....	....	....	12.0	8.2	....	....	....	....	....	8.3	....	....	....	....	....
GR10	....	....	....	....	11.4	9.2	....	....	....	....	....	9.3	....	....	....	....	....
GR11	....	....	....	....	....	15.6	....	....	....	....	....	12.6	....	....	....	....	....
GR12	19.0	....	....	19.0	....	14.5	13.9	....	....	13.9	....	12.2	12.0	....	....	12.0	16.4
TE01	7.8	....	....	7.8	7.8	6.6	6.9	6.5	....	6.9	6.5	6.0	5.4	....	....	5.4	7.3
TE02	....	....	....	....	7.0	6.6	....	....	....	....	7.6	5.2	....	....	....	....	....
TE03	14.1	....	....	14.1	14.8	10.5	9.4	....	....	9.4	10.0	7.8	8.8	....	....	8.8	11.8
TE04	....	....	....	....	15.0	12.6	....	....	....	....	9.8	9.0	....	....	....	....	....
TE05	19.1	19.1	....	....	....	18.0	21.5	21.5	....	....	....	19.4	14.9	14.9	....	....	20.3
TE06	....	....	....	....	....	23.0	25.4	....	....	25.4	....	20.7	19.2	....	....	....	25.4
TE07	....	....	....	....	9.4	7.1	....	....	....	....	8.9	7.6	....	....	....	....	....
TE08	....	....	....	....	9.3	7.6	....	....	....	....	8.8	6.6	....	....	....	....	....
TE09	....	....	....	....	15.0	10.9	....	....	....	....	12.5	10.7	....	....	....	....	....
TE10	....	....	....	....	18.9	12.6	....	....	....	....	15.0	12.1	....	....	....	....	....
TE11	17.8	....	....	17.8	17.1	13.7	12.8	....	....	12.8	12.8	9.7	11.6	....	....	11.6	15.3
TE12	....	....	....	....	12.8	14.2	....	....	....	....	14.3	11.7	....	....	....	....	....

Table F.5. Summary of the $RARS_{50}$ Data.

Site	Left Wheeltrack						Right Wheeltrack						Both Wheeltracks				Average (L + R)/2
	Static	RL 1	RL 2	Beam	A 72	A 25	Static	RL 1	RL 2	Beam	A 72	A 25	Static	RL 1	RL 2	Beam	Static
CA01	4.5	4.5	4.5	....	....	....	5.1	5.4	4.9	....	5.3	....	3.9	4.0	3.7	....	4.8
CA02	6.0	5.9	6.1	....	5.9	....	5.1	5.3	5.0	....	7.3	....	4.3	4.3	4.3	....	5.6
CA03	7.4	7.2	7.7	....	8.0	....	7.0	7.4	6.6	....	7.2	....	5.5	5.4	5.5	....	7.2
CA04	6.6	6.6	6.7	6.6	7.0	....	5.7	6.1	5.8	5.4	6.3	....	5.0	5.2	4.9	4.8	6.2
CA05	7.8	8.0	7.8	7.6	9.5	....	7.1	7.2	7.2	6.9	7.2	....	5.9	5.9	6.0	5.8	7.4
CA06	8.7	8.7	8.6	8.7	10.2	....	7.7	8.1	7.3	7.8	9.0	....	6.3	6.1	6.2	6.5	8.2
CA07	2.9	2.7	3.0	....	4.7	....	2.5	2.4	2.7	....	3.7	....	2.1	1.9	2.2	....	2.7
CA08	3.1	3.1	3.1	....	3.7	....	3.2	3.3	3.1	....	3.7	....	2.3	2.3	2.3	....	3.1
CA09	4.1	4.3	3.9	....	6.3	....	3.3	3.4	3.1	....	4.2	....	2.9	3.0	2.8	....	3.7
CA10	3.8	4.0	3.7	....	5.5	....	3.4	3.8	3.1	3.4	4.8	....	2.7	....	2.7	....	3.6
CA11	6.4	6.7	6.1	....	6.5	....	5.9	6.0	5.8	....	5.3	....	4.8	4.9	4.7	....	6.1
CA12	2.3	2.2	2.1	2.6	2.4	....	2.2	2.1	2.3	....	2.3	....	1.6	1.6	1.6	....	2.2
CA13	2.2	2.2	2.1	....	2.3	....	2.1	2.2	2.0	....	2.3	....	1.6	1.7	1.5	....	2.1
TS01	5.2	5.2	....	5.2	5.6	....	5.1	5.1	....	....	....	....	3.9	3.9	....	....	5.1
TS02	6.9	6.9	....	....	6.2	....	6.7	6.7	....	....	6.5	....	4.9	4.9	....	....	6.8
TS03	7.3	7.3	....	....	7.7	....	6.2	6.2	....	....	....	....	5.0	5.0	....	....	6.7
TS04	6.4	6.4	....	6.4	6.6	....	7.2	7.2	....	....	....	....	5.5	5.5	....	....	6.8
TS05	7.3	7.4	6.9	7.6	8.7	....	6.0	6.1	5.8	....	7.7	....	5.3	5.4	5.1	....	6.6
TS06	4.4	4.7	4.3	4.3	4.6	....	4.1	4.2	4.1	4.0	4.1	....	3.1	3.2	3.0	3.1	4.2
TS07	4.2	4.5	4.0	4.2	4.6	....	4.4	4.4	4.4	....	4.6	....	3.2	3.3	3.1	....	4.3
TS08	4.7	4.7	4.7	....	4.9	....	5.0	5.2	4.8	....	5.1	....	3.5	3.5	3.5	....	4.8
TS09	5.6	5.8	5.4	....	6.0	....	5.1	5.3	4.9	....	5.5	....	3.9	4.0	3.7	....	5.3
TS10	5.0	5.0	....	....	6.0	....	5.0	5.0	....	....	5.5	....	3.6	3.6	....	....	5.0
TS11	3.5	3.5	....	....	3.1	....	3.4	3.4	....	....	3.2	....	2.6	2.6	....	....	3.5
TS12	3.8	3.8	....	....	3.4	....	3.3	3.3	....	....	3.0	....	2.6	2.6	....	....	3.5
GR01	5.4	....	5.4	....	5.3	....	4.5	....	4.2	4.8	....	....	3.5	....	3.5	....	5.0
GR02	5.6	....	5.6	....	6.2	....	5.1	....	5.1	....	....	....	3.9	....	3.9	....	5.4
GR03	10.6	....	10.6	....	9.1	....	8.0	....	8.0	....	....	....	6.9	....	6.9	....	9.3
GR04	9.0	....	9.0	....	9.8	....	7.2	....	7.2	....	....	....	5.8	....	5.8	....	8.1
GR05	12.6	13.0	12.0	12.8	15.4	....	10.1	10.3	10.1	9.8	....	....	8.7	9.0	8.5	8.7	11.3
GR06	11.0	....	11.0	....	13.5	....	9.8	....	9.8	....	....	....	7.6	....	7.6	....	10.4
GR07	8.8	....	8.6	9.0	7.9	....	5.7	....	6.2	5.3	....	....	5.6	....	5.7	5.5	7.3
GR08	6.3	....	6.3	....	6.5	....	5.4	....	5.4	....	....	....	4.3	....	4.3	....	5.8
GR09	11.8	....	11.8	....	11.9	....	10.0	....	10.0	....	....	....	8.0	....	8.0	....	10.9
GR10	10.1	....	10.1	....	11.1	....	7.7	....	7.7	....	....	....	6.7	....	6.7	....	8.9
GR11	19.2	....	19.2	....	....	....	14.7	....	14.7	....	....	....	12.7	....	12.7	....	17.0
GR12	16.0	....	15.1	16.8	....	....	12.9	....	13.2	12.6	....	....	11.0	....	11.2	10.8	14.4
TE01	6.0	....	5.9	6.2	7.0	....	5.3	5.2	5.5	5.3	5.8	....	4.3	....	4.4	4.2	5.7
TE02	5.4	....	5.4	....	6.2	....	5.3	....	5.3	....	6.8	....	3.9	....	3.9	....	5.3
TE03	11.4	....	11.8	11.0	12.8	....	8.2	....	8.8	7.7	9.0	....	7.2	....	7.4	7.0	9.8
TE04	10.6	....	10.6	....	13.8	....	8.8	....	8.8	....	8.8	....	7.1	....	7.1	....	9.7
TE05	16.4	15.9	16.9	....	....	....	17.8	18.2	17.5	....	....	....	13.0	13.1	13.0	....	17.1
TE06	20.6	....	20.6	....	....	....	20.7	....	20.3	21.1	....	....	15.3	....	15.3	....	20.6
TE07	6.5	....	6.5	....	8.4	....	5.4	....	5.4	....	7.8	....	4.4	....	4.4	....	6.0
TE08	7.0	....	7.0	....	8.4	....	6.1	....	6.1	....	7.6	....	5.0	....	5.0	....	6.6
TE09	12.5	....	12.5	....	13.1	....	12.0	....	12.0	....	10.1	....	9.0	....	9.0	....	12.2
TE10	15.5	....	15.5	....	16.1	....	14.0	....	14.0	....	13.0	....	11.0	....	11.0	....	14.8
TE11	14.5	....	15.1	13.9	15.6	....	10.4	....	10.8	10.0	12.1	....	9.5	....	9.9	9.0	12.5
TE12	11.9	....	11.9	....	11.5	....	11.3	....	11.3	....	13.2	....	8.5	....	8.5	....	11.6

Table F.6. Summary of the $RARS_{80}$ Data.

	Left Wheeltrack						Right Wheeltrack						Both Wheeltracks				Average (L + R)/2
Site	Static	RL 1	RL 2	Beam	A 72	A 25	Static	RL 1	RL 2	Beam	A 72	A 25	Static	RL 1	RL 2	Beam	Static
CA01	3.8	3.8	3.7	....	....	....	4.4	4.6	4.2	....	4.7	....	3.5	3.5	3.4	....	4.1
CA02	4.9	4.9	4.9	....	4.8	....	4.3	4.4	4.1	....	6.0	....	3.7	3.8	3.7	....	4.6
CA03	6.4	6.2	6.6	....	6.6	....	6.2	6.3	6.1	....	6.0	....	5.0	5.0	5.0	....	6.3
CA04	5.7	5.6	5.8	5.8	5.7	....	4.8	5.0	4.8	4.8	5.2	....	4.5	4.6	4.5	4.4	5.3
CA05	6.7	6.8	6.6	6.6	7.5	....	5.7	5.7	5.5	5.8	5.6	....	5.1	5.1	5.1	5.1	6.2
CA06	7.9	7.8	7.6	8.3	8.5	....	6.7	6.8	6.3	7.0	8.5	....	5.8	5.7	5.5	6.2	7.3
CA07	2.7	2.6	2.8	....	3.8	....	2.2	2.2	2.3	....	3.0	....	1.9	1.8	1.9	....	2.5
CA08	2.6	2.6	2.6	....	3.2	....	2.6	2.6	2.5	....	2.9	....	2.0	2.0	2.0	....	2.6
CA09	3.9	4.1	3.8	....	5.0	....	3.1	3.2	3.1	....	3.5	....	2.9	3.0	2.9	....	3.5
CA10	3.5	3.5	3.5	....	5.0	....	3.2	3.3	3.0	3.3	4.2	....	2.7	2.7	2.7	....	3.3
CA11	5.6	5.8	5.4	....	5.5	....	5.1	5.2	5.1	....	4.6	....	4.3	4.3	4.3	....	5.4
CA12	1.9	1.7	1.7	2.5	1.9	....	1.8	1.8	1.9	....	1.9	....	1.4	1.3	1.4	....	1.9
CA13	2.0	2.0	2.0	....	1.9	....	1.9	2.0	1.8	....	1.9	....	1.6	1.6	1.5	....	1.9
TS01	4.3	4.1	....	4.5	4.5	....	4.2	4.2	....	....	....	....	3.2	3.2	....	....	4.3
TS02	5.1	5.1	....	....	4.7	....	5.0	5.0	....	....	4.6	....	3.7	3.7	....	....	5.1
TS03	5.1	5.1	....	....	5.5	....	4.4	4.4	....	....	....	....	3.7	3.7	....	....	4.7
TS04	5.2	4.9	....	5.4	5.1	....	5.9	5.9	....	....	....	....	4.6	4.6	....	....	5.5
TS05	6.5	6.2	6.2	7.0	7.6	....	4.9	5.0	4.8	....	6.1	....	4.7	4.7	4.6	....	5.7
TS06	3.4	3.5	3.3	3.4	3.5	....	3.2	3.1	3.2	3.1	3.2	....	2.5	2.5	2.5	2.7	3.3
TS07	3.3	3.5	3.1	3.3	3.6	....	3.4	3.3	3.4	....	3.5	....	2.6	2.6	2.5	....	3.3
TS08	3.9	3.9	3.9	....	3.8	....	4.1	4.1	4.1	....	4.1	....	3.1	3.1	3.1	....	4.0
TS09	3.9	4.0	3.7	....	4.4	....	3.9	4.1	3.8	....	4.1	....	3.0	3.1	2.9	....	3.9
TS10	3.8	3.8	....	....	4.5	....	3.8	3.8	....	....	4.2	....	2.8	2.8	....	....	3.8
TS11	2.5	2.5	....	....	2.3	....	2.5	2.5	....	....	2.4	....	1.9	1.9	....	....	2.5
TS12	2.6	2.6	....	....	2.4	....	2.4	2.4	....	....	2.2	....	1.8	1.8	....	....	2.5
GR01	4.0	....	4.0	....	3.6	....	3.4	....	2.9	3.9	....	....	2.5	....	2.5	....	3.7
GR02	3.9	....	3.9	....	4.6	....	3.7	....	3.7	....	....	....	2.8	....	2.8	....	3.8
GR03	8.3	....	8.3	....	6.9	....	6.1	....	6.1	....	....	....	5.4	....	5.4	....	7.2
GR04	7.0	....	7.0	....	7.3	....	5.9	....	5.9	....	....	....	4.7	....	4.7	....	6.4
GR05	9.8	10.1	9.2	10.0	11.6	....	8.6	8.9	8.4	8.5	....	....	7.3	7.6	6.8	7.5	9.2
GR06	8.6	....	8.6	....	10.3	....	7.9	....	7.9	....	....	....	6.1	....	6.1	....	8.3
GR07	6.6	....	6.2	7.1	5.9	....	4.3	....	4.5	4.1	....	....	4.3	....	4.2	4.4	5.5
GR08	4.7	....	4.7	....	4.7	....	4.0	....	4.0	....	....	....	3.2	....	3.2	....	4.4
GR09	10.1	....	10.1	....	10.2	....	8.3	....	8.3	....	....	....	7.0	....	7.0	....	9.2
GR10	8.2	....	8.2	....	9.5	....	5.9	....	5.9	....	....	....	5.6	....	5.6	....	7.1
GR11	15.2	....	15.2	....	....	....	13.0	....	13.0	....	....	....	10.4	....	10.4	....	14.1
GR12	13.7	....	13.0	14.4	....	....	11.6	....	11.6	11.7	....	....	9.8	....	9.6	9.9	12.7
TE01	4.5	....	4.2	4.7	4.6	....	4.2	3.9	4.2	4.4	4.1	....	3.4	....	3.2	3.7	4.3
TE02	4.1	....	4.1	....	4.5	....	4.1	....	4.1	....	4.8	....	3.0	....	3.0	....	4.1
TE03	8.1	....	8.2	8.1	9.0	....	6.3	....	6.6	6.1	6.7	....	5.2	....	5.3	5.1	7.2
TE04	7.6	....	7.6	....	9.8	....	6.9	....	6.9	....	6.7	....	5.4	....	5.4	....	7.3
TE05	13.7	13.8	13.6	....	....	....	14.1	14.4	13.9	....	....	....	11.1	11.3	10.8	....	13.9
TE06	17.5	....	17.5	....	....	....	15.8	....	15.5	16.0	....	....	12.8	....	12.8	....	16.6
TE07	4.8	....	4.8	....	5.4	....	4.0	....	4.0	....	5.0	....	3.5	....	3.5	....	4.4
TE08	5.5	....	5.5	....	5.9	....	4.5	....	4.5	....	5.3	....	3.9	....	3.9	....	5.0
TE09	8.4	....	8.4	....	8.8	....	8.8	....	8.8	....	7.5	....	6.4	....	6.4	....	8.6
TE10	10.7	....	10.7	....	10.7	....	9.6	....	9.6	....	9.0	....	7.5	....	7.5	....	10.2
TE11	11.3	....	11.8	10.8	11.6	....	8.0	....	8.1	7.8	9.5	....	7.4	....	7.8	7.1	9.6
TE12	9.3	....	9.3	....	8.3	....	8.8	....	8.8	....	9.9	....	6.7	....	6.7	....	9.0

each of the 98 wheeltracks. The APL Trailer speeds were such that the $RARS_{20}$ numerics are not shown when the profiles were measured in the APL 72 configuration (at 72 km/h), while neither the $RARS_{50}$ nor the $RARS_{80}$ numerics are shown when the profiles were measured in the APL 25 configuration (21.6 km/h). Results for all four simulation speeds are shown for the 28 profiles obtained statically with the TRRL Beam.

Some of the paved sections were measured before and during the IRRE via rod and level. Those measured prior are indicated as "RL 1" and those measured during the IRRE are designated "RL 2." In addition, 6 wheeltracks were measured by rod and level using a measurement interval of 100 mm. These are also shown in the "RL 1" column, and can be identified because they are the only rod and level results given for the lower simulation speeds of 20 and 32 km/h. The labels "Beam," "A 72," and "A 25" indicate profiles measured with the TRRL Beam, the APL Trailer in the APL 72 configuration, and the APL Trailer in the APL 25 configuration. The results indicated under the headings "Static" are averages of the numerics obtained with the static profile measurements, that is, rod and level and the TRRL Beam. When examining correlations with other measures and statistics, the numbers under the "Static" heading were used. One other column is included, "Ave.," that lists the average of the "Static" RARS value from the left and right wheeltracks. These average RARS numerics are used in comparisons with two-track RTRRMS measues.

In order to obtain eight more RARS estimates for correlation analyses with the two-track RTRRMSs at the lower speeds, the "Ave" RARS numerics shown in Tables F.3 and F.4 include eight estimates based on the single RARS numeric computed from the TRRL Beam, pro-rated according to the ratio between the right- and left-hand wheeltrack roughness as computed from rod and level data at that speed.

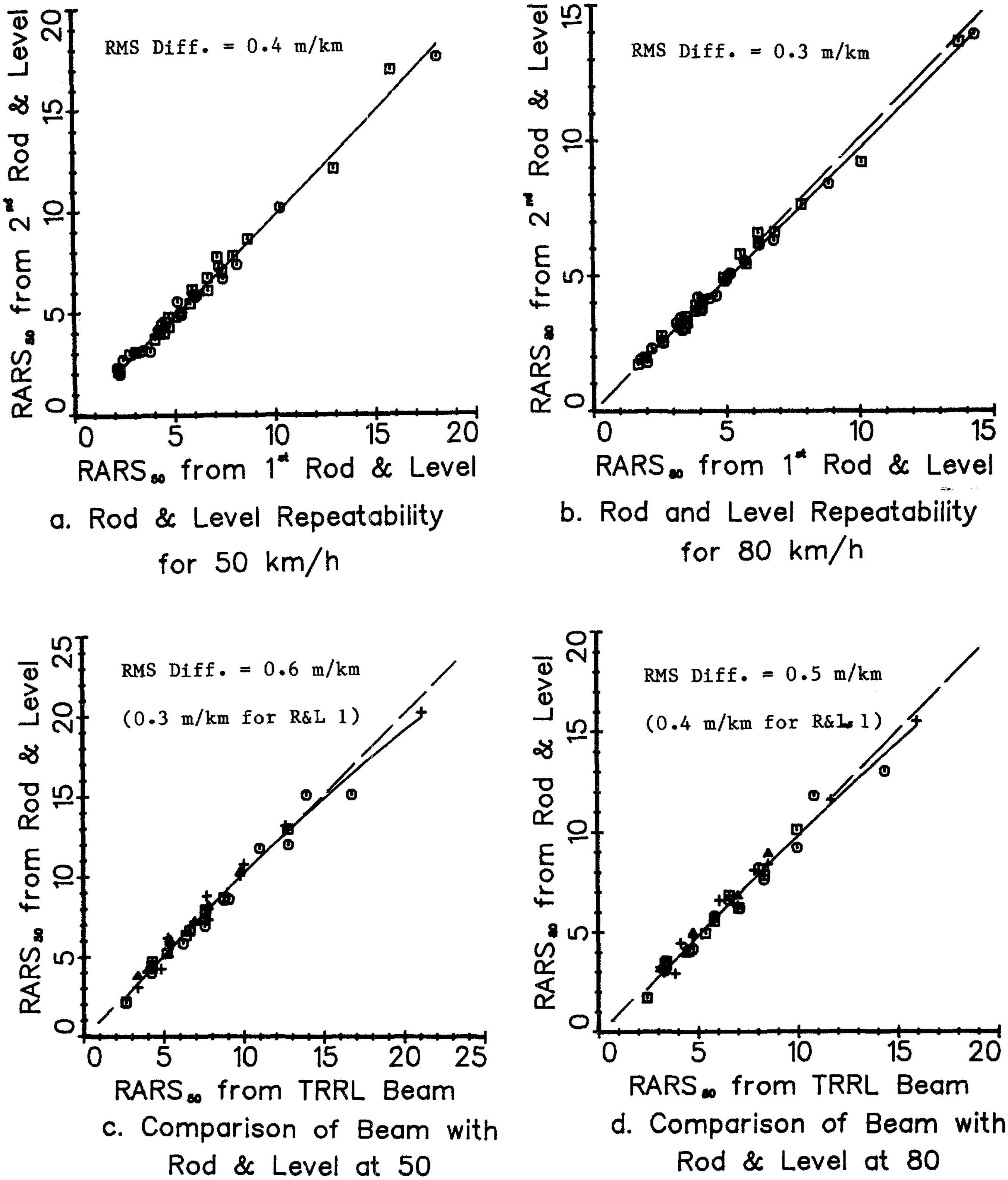
Accuracy of RARS Computed from Statically Measured Profiles

Repeatability with Rod and Level. Most of the sources of error that plague roughness measurements using RTRRMSs are eliminated when profiles are measured statically with rod and level: the same roughness computation method can be used, eliminating variations due to different definitions of roughness;

and surveying equipment is sufficiently interchangeable to eliminate problems of reproducibility. The only remaining variation is the repeatability that can be achieved in measuring a profile. The repeatability that can be achieved is, in this case, the accuracy of the roughness measurement. Since most of the paved sites were profiled twice with the rod and level method, the IRRE data give an idea of the repeatability achievable in using RARS as a roughness measure. Figure F.12 shows the comparison of RARS measures obtained in two independent rod and level surveys (12a and 12b). As in other plots, the dashed line is the line of equality (x=y), while the solid line is the "best fit" as obtained with a quadratic regression. The RMS errors shown in the figures are with reference to the line of equality, rather than the regression line, since regression methods would never be used to "correct" profile-based numerics. Note that the accuracy limits shown in the figures apply only to the IRRE section length of 320 m, and should not be considered universal for all section lengths. For roads whose roughness is more-or-less constant, it can be expected that better accuracy would be obtained for longer test site lengths, because the random sources of variation would tend to average out. The expected change in accuracy is proportional to the square root of length, such that the random variations indicated in the figure would be cut in half if the section length were increased by a factor of four. On the other hand, larger errors should be expected for shorter sections.

Validation of the TRRL Beam. Figure F.12 also compares the RARS numerics obtained with road and level and the TRRL beam. Approximately the same repeatability is obtained as with repeated measures with rod and level, indicating that the TRRL Beam is a valid means for measuring longitudinal profile for the purpose of computing RARS.

(Although greater scatter is evident in the Beam/Rod and Level comparisons than in the conparisons between repeat rod and level measures, the Beam data sets include the roughest sites, while the repeat rod and level measures were made only on paved roads. When only the measures on paved roads are considered, the same degree of repeatability is seen.)



a. Rod & Level Repeatability for 50 km/h

b. Rod and Level Repeatability for 80 km/h

c. Comparison of Beam with Rod & Level at 50

d. Comparison of Beam with Rod & Level at 80

Figure F.12. Repeatability (and thus Accuracy) of RARS as Measured Statically

Accuracy of RARS Computed from Dynamically Measured Profiles

APL 72. Figure F.13 compares the RARS numerics computed from the profile signals obtained from the APL Trailer in its APL 72 configuration with RARS numerics computed from the statically measured profiles. For simulation speeds of 50 and 80 km/h, the APL measures are slightly higher than the "true" (statically measured) values, as evidenced by the quadratic regression line lying above the line of equality. This error is slight, however, in comparison with the random error seen. These results indicate that the APL Trailer, used according to the APL 72 procedures, can indeed measure RARS, but with less accuracy than would be obtained using a static profile measurement method.

The plots indicate that while the accuracy associated with the APL 72 system is not as good as the static profile measurement methods, the APL system is consistent over all four road surface types and the entire roughness range. There are no outstanding "outliers." Results presented later for the RTRRMS calibration indicate that the RARS measures obtained with the APL 72 system have about the accuracy same as can be obtained with a RTRRMS that has been calibrated by correlation. Since the APL Trailer is independently calibrated according to methods specified by LCPC, the problems of reproducibility and time stability associated with RTRRMSs are eliminated.

It should be noted that during the IRRE, the LCPC research team was primarily interested in obtaining the APL numerics used in France (see Appendix G), and had a number of problems to overcome, such as the incompatibility between the standard APL 72 test length of 200 m and the 320 m length of the IRRE sites. During the IRRE, the APL 72 profiles were digitized solely for the purpose of preparing graphical plots of the longitudinal profile, rather than for any analyses. (A computer program had to be written in Brasilia to store the digitized signals on floppy disks.) It is very possible that the accuracy shown in the figure could be improved if the measurement and data recording procedures were designed with the RQCS analysis in mind.

While the effort and cost associated with obtaining a profile is proportional to its length when low-speed manual methods are used, there is

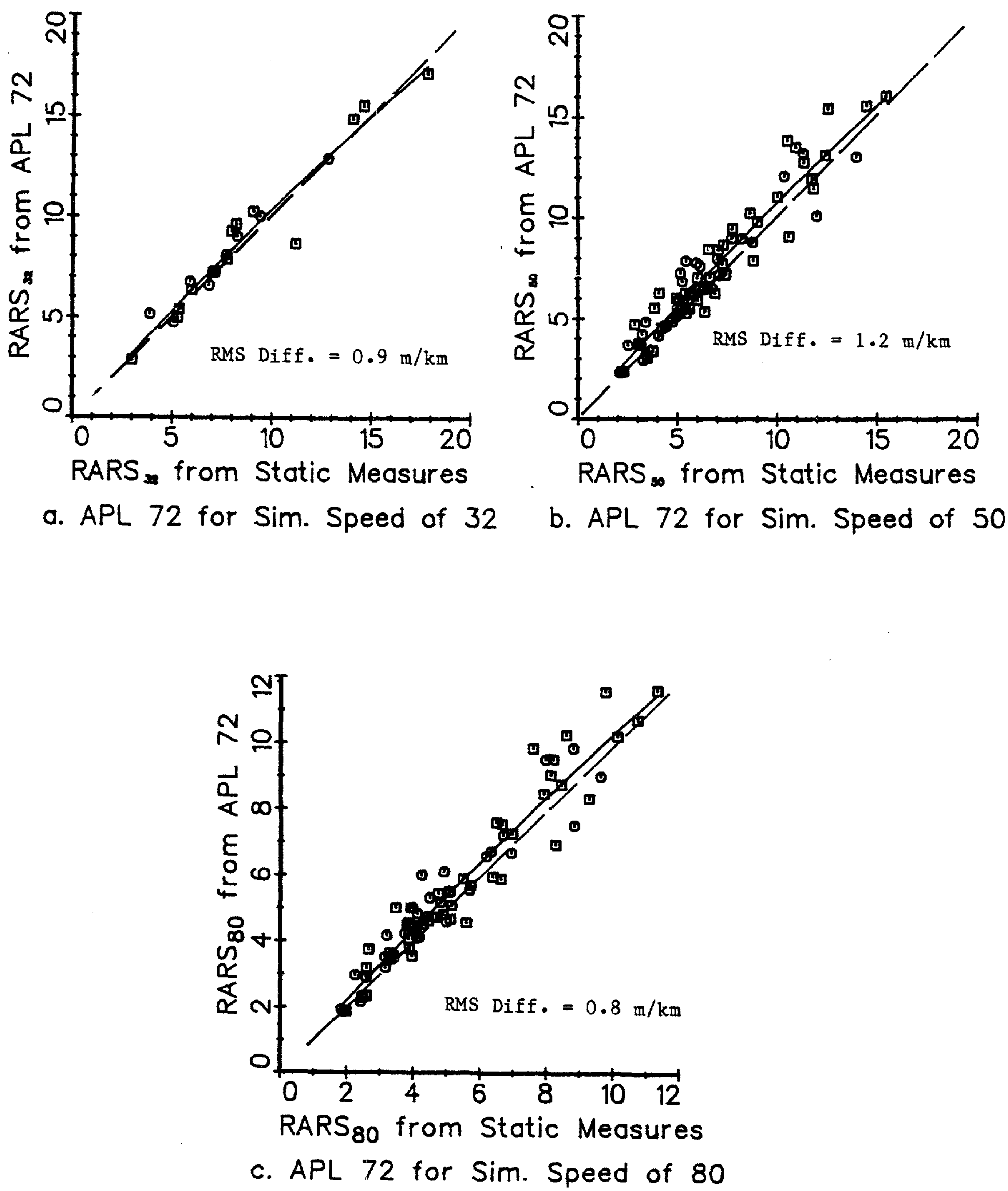


Figure F.13. Accuracy of RARS as measured with APL 72.

only a slight cost penalty associated with longer lengths (or repeated measurements) when an automated high-speed system such as the APL Trailer is used. Hence, it is possible that accuracy could be improved by running repeated measurements or using longer test lengths to reduce random error. Although most of the IRRE sites were measured several times with the APL 72 system, time constraints after the IRRE prevented the LCPC team from preparing more than one digitized profile per wheeltrack, so it was not possible to determine whether averaging of repeat runs would improve accuracy.

APL 25. Figure F.14 compares the RARS numerics computed from the profile signals obtained from the APL Trailer in its APL 25 configuration with RARS numerics computed from the statically measured profiles. For the simulation speeds of 32 and 50 km/h, the RARS numerics obtained with the APL Trailer are consistently lower than those obtained from the static profile measurements. For the higher simulation speed of 50 km/h, this is to be expected, since the frequency response of the APL Trailer is not broad enough to include the longer wavelengths that affect $RARS_{50}$ when the trailer is towed at only 20.7 km/h. Yet, the same effect is also seen for a simulation speed of 32 km/h, even though the APL signal theoretically has the required bandwidth. Only for a simulation speed of 20 km/h is the bias error negligible. The reasons for the invalid RARS measures from the APL 25 system were not investigated.

CALIBRATION OF RTRRMSs

A primary purpose of a profile-based numeric such as RARS is viewed in this report as being for the calibration of RTRRMSs, using a "calibration by correlation." In a calibration by correlation, the "raw" measures from the RTRRMS are used to estimate what the reference measure would be, based on a regression equation. The objective is to produce the most accurate estimates of "true roughness," over the entire range of conditions that will be covered. To this end, one or more regression equations must be used to estimate the "truth" from the RTRRMS "raw" measure. The estimate of the "truth," in this case RARS, is defined as "the calibrated RTRRMS measure," and designated E[RARS] for estimates of RARS.

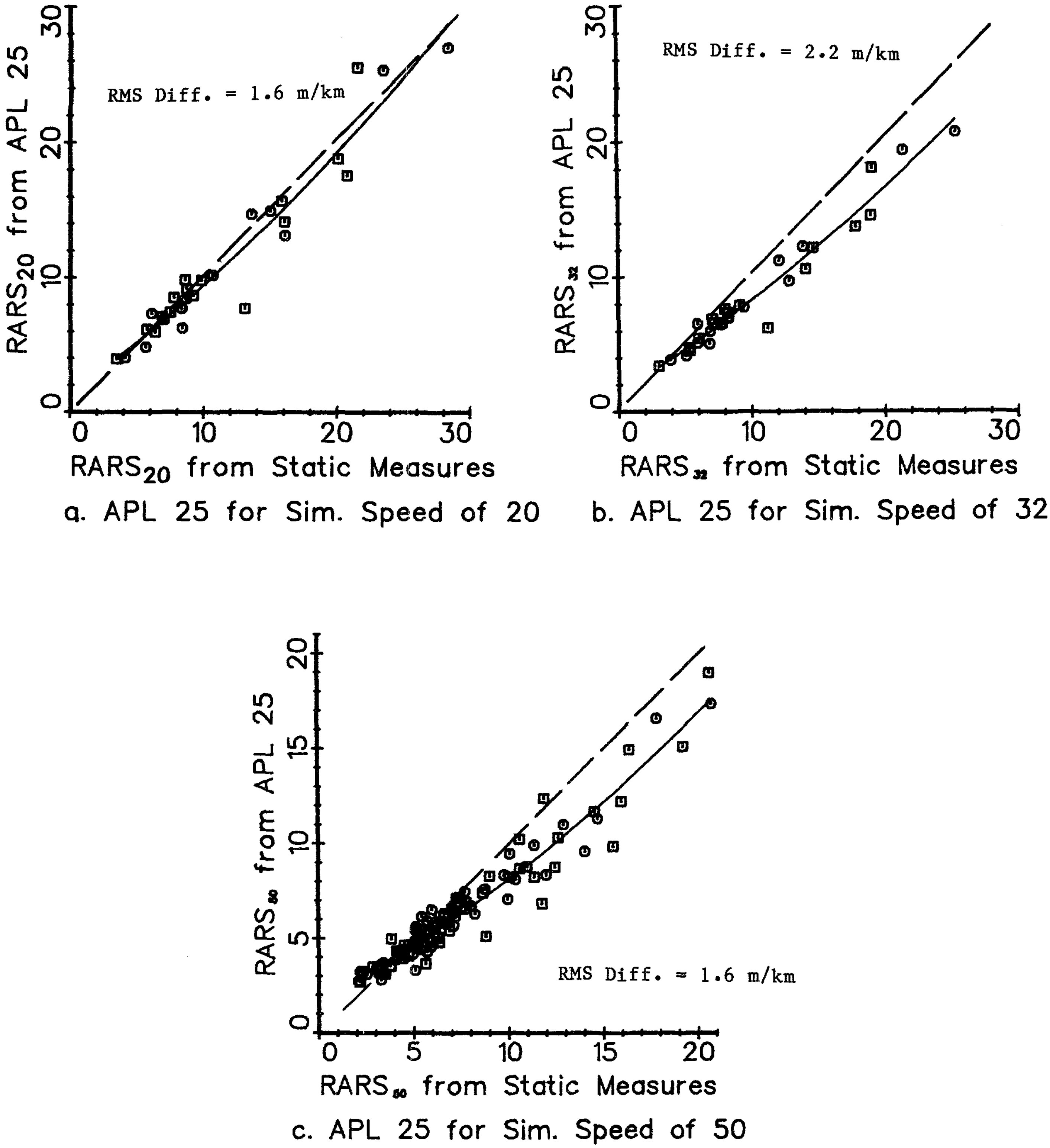


Figure F.14. Accuracy of RARS as measured with APL 25.

Calibration when Simulation Speed = Measurement Speed.

The comparisons between ARS measured with four of the RTRRMSs and RARS are illustrated in Figures F.15 - 18. Results from the Caravan-BI system (not plotted) are virtually the same as for the Caravan-NAASRA system. Results for the two Opala-Maysmeter systems that are not plotted are generally similar to those of the system that is shown in the figures.

In each comparison, the simulated speed of the RQCS matches the RTRRMS speed. For the passenger car-based systems, the "Ave." RARS values from Tables F.3 - F.6 were used. Comparisons with the two single-track RTRRMSs (BI Trailer and BPR Roughometer) are on the basis of single wheeltracks. Thus, the plots involving the trailers generally have twice as many data points. In each figure, the solid curved line is a quadratic regression line obtained from all of the data points shown, based on minimizing the RMS error in estimating RARS.

For the lower speeds of 20 and 32 km/h, there are only valid static measures of RARS on 19 of the test sites (30 wheeltracks), and therefore the RARS numerics computed wfrom the APL signals are shown. (For the speeds of 50 and 80 km/h, RARS was measured statically for all 49 test sites (98 wheeltracks).)

These four figures lead to the following observations:

Overall correlation. By and large, the RARS numeric is highly correlated with the ARS numerics obtained from all types of RTRRMSs that participated in the IRRE. Most of the data points lie very close to the regression curve in each figure, and the measures on all four types of surface are uniformly distributed about the curve in most cases (exceptions are noted below).

Error distribution. Errors, as defined by the scatter about the regression curves in the vertical direction, are fairly uniform across the roughness range. Therefore, least-squares regression models should assume equal significance of error across the scale. Transformations of the variables that change the weighting of error, such as linear regressions of

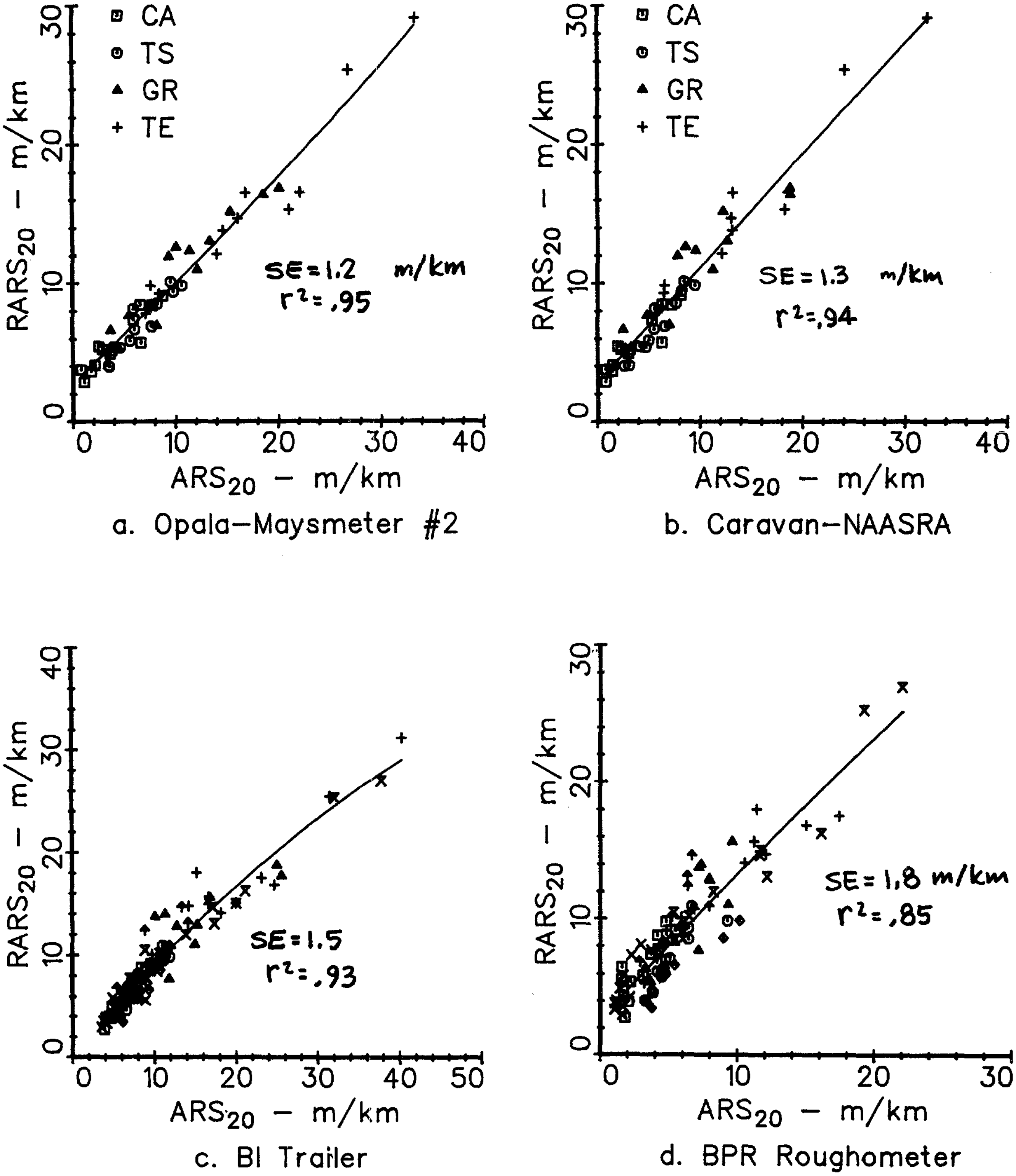


Figure F.15. Example calibration plots to estimate $RARS_{20}$ from ARS measures. The $RARS_{20}$ numerics were measured with the APL 25.

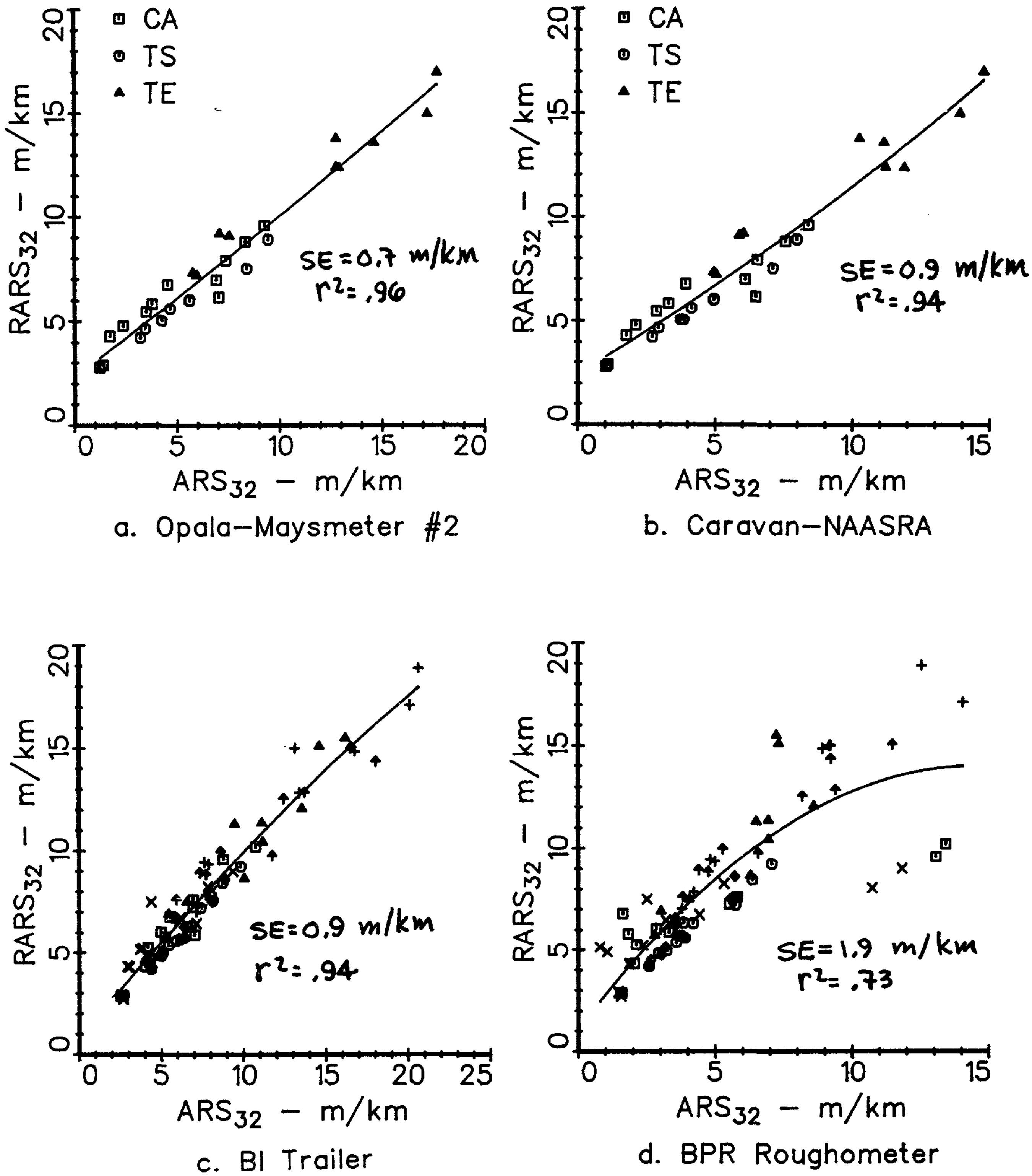


Figure F.16. Example calibration plots to estimate $RARS_{32}$ from ARS measures. The $RARS_{32}$ numerics were measured with the APL 72.

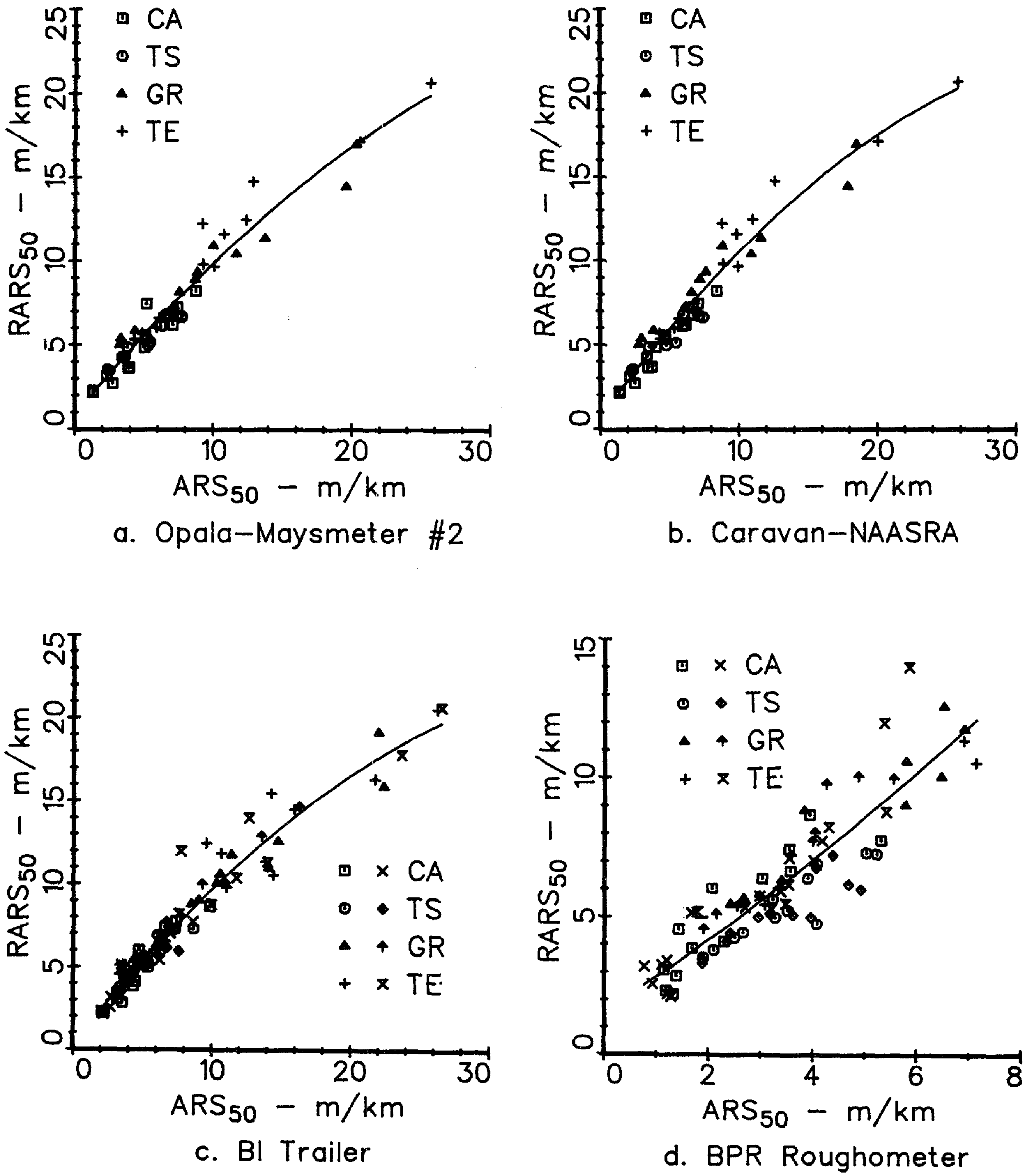


Figure F.17. Example calibration plots to estimate $RARS_{50}$ from ARS_{50} measures.

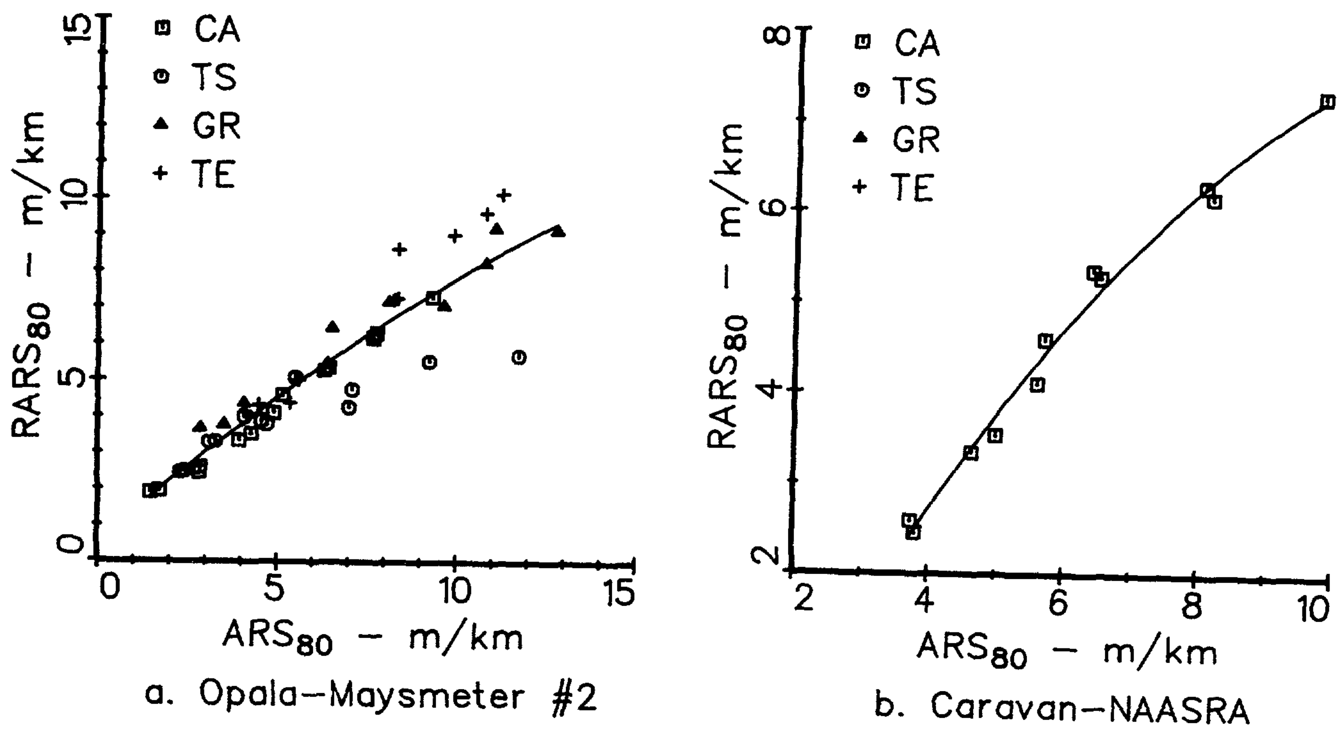


Figure F.18. Example calibration plots to estimate $RARS_{80}$ from ARS_{80} measures.

log values, should be avoided because they place less priority on the errors on rougher roads.

Sensitivity to surface type. Surface type sometimes systematically affects the regressions. In many of the plots, the data points for the unpaved roads lie above the regression line (indicating that the RQCS responds more than the RTRRMS on those surfaces), while points for the surface treatment sites lie below the line (indicating that the RQCS responds less). These differences are only apparent on the smoother surfaces, where RARS values are less than 10 m/km. This behavior is evidenced mainly at the lower speeds by three of the RTRRMSs. The implication of this finding is that separate calibrations for each surface type can give better accuracy. The degree of sensitivity to surface type varies with the RTRRMS. For example, the scatter for the BI Trailer is not visibly affected by surface type at speeds of 32 and 50 km/h.

Comparison of single-track trailers. Although both the BI Trailer and the "BPR Roughometer" made by Soiltest, Inc., are similar in appearance and are both based on the BPR Roughometer [13], they contrast in performance. The Soiltest BPR Roughometer, which proved to be too fragile for the roads covered in the IRRE (see Appendix A), produced the most erratic results. On the other hand, the TRRL BI Trailer produced high quality results, particularly at its design speed of 32 km/h.

Outliers. The four roughest surface treatment sites appeared as "outliers" when measured by the Opala-Maysmeter systems at 80 km/h (Fig. F.18a). (Although the results are plotted for only one of these systems, all three showed the same behavior.) On these sites (TS01, TS03, TS04, and TS05), the RTRRMS responded much more than the RQCS. The power spectral density (PSD) plots shown in Appendix I for these four sites are similar, and differ from the PSD plots for most of the other test sites. All four have relatively low amplitudes at wavenumber 0.1 cycle/m (10 m wavelength, which appears as a frequency of 2.2 Hz at 80 km/h), with most of the roughness concentrated at higher wavenumbers. Further, three of the sites show a singular peak at wavenumber 0.5 cycle/m (2 m wavelength, which appears as a frequency of 11.1 Hz).

The presence of a singular peak at 0.5 cycle/m signifies that the road site has a periodic disturbance occurring every 2 m. Although the RQCS has its maximum sensitivity at that wavelength, as shown in Figure F.2d, the RQCS was designed to be less responsive than the typical passenger car at that frequency [9]. Unlike the RQCS, a passenger car is not linear, and can over-respond when subjected to a purely periodic excitation. This is particularly true with lightly damped vehicles. From the simple comparison of the ARS_{80} and $RARS_{80}$ numerics in Fig. F.18a, the Opala vehicle is seen to be less damped than the RQCS, as evidenced by the higher ARS_{80} numerics. This indicates that stiffer shock absorbers could be used with the Opala, with the expected result of bringing the "outliers" into agreement with the rest of the data.

The ARS_{80} measures on these four TS sites were "outliers" relative to all of the profile-based numerics tested, and the $RARS_{80}$ numeric actually comes the closest to matching these measures.

Correlations and Accuracy. Table F.7 presents the r^2 values obtained when the RARS numerics from the statically measured profiles are regressed against the ARS numerics, using a linear prediction model. The regressions were performed using only the data corresponding to the combination of speed and surface type indicated. When the surface type is indicated as "ALL," then the regression included all measurements made at that speed, and the r^2 describes a calibration across surface type. Table F.8 presents the r^2 values obtained when a quadratic model is used. Both models use a simple least-squares error approach, but the quadratic model is slightly more versatile, as it involves less in the way of assumptions about the linearity of the RTRRMS. In comparing the two tables, it can be seen that most of the time there is little difference. This indicates that a linear regression is usually suitable for estimating the "truth" (as defined by RARS) from a RTRRMS measure. However, there are a few cases where much better correlation is obtained with the quadratic model, such as the Caravan-BI system at 80 km/h on the CA surfaces. Since there is no real penalty for using the quadratic model (other than a more complex computation--typically performed by computer), the quadratic model is recommended to allow for the occasional case in which a linear model would not fit the data or would lead to an erroneous extrapolation.

Table F.7. R-Squared Values Obtained from Linear Regressions Between RARS from RQCS and ARS from RTRRMSs.

Speed	Surface Type	Opala Passenger Cars with Modified Maysmeters MM 01	MM 02	MM 03	Caravan Car with 2 meters BI	NAASRA	Single-Track Trailers TRRL BI	BPR
20	ALL	0.8699	0.9709	0.9482	0.9689	0.9637	0.9529	0.9216
32	ALL	0.9070	0.9730	0.9194	0.9749	0.9716	0.9767	0.6663
50	CA	0.9468	0.8781	0.9320	0.9650	0.9739	0.9104	0.8316
	TS	0.8998	0.9321	0.8715	0.9249	0.9178	0.8863	0.8132
	GR	0.9757	0.9655	0.9474	0.9623	0.9611	0.9554	0.8967
	TE	0.9696	0.9251	0.8969	0.8962	0.9161	0.8854	0.7529
	ALL	0.9323	0.9349	0.9158	0.9330	0.9321	0.9325	0.8090
80	CA	0.9807	0.9935	0.9223	0.8994	0.9723	....	0.8793
	TS	0.8013	0.8332	0.7807	....	....	....	....
	GR	0.9328	0.9576	0.9506	....	....	....	....
	TE	0.7095	0.9662	0.9560	....	....	....	....
	ALL	0.7750	0.8505	0.7712	0.8994	0.9723	....	0.8793

Note: for all regressions, the simulation speed was equal to the RTRRMS measurement speed.

Table F.8. R-Squared Values Obtained from Quadratic Regressions Between RARS from the RQCS, and ARS from the RTRRMSs.

Speed	Surface Type	Opala Passenger Cars with Modified Maysmeters MM 01	MM 02	MM 03	Caravan Car with 2 meters BI	NAASRA	Single-Track Trailers TRRL BI	BPR
20	ALL	0.8829	0.9758	0.9589	0.9697	0.9645	0.9656	0.9216
32	ALL	0.9076	0.9774	0.9275	0.9758	0.9721	0.9798	0.6887
50	CA	0.9481	0.8787	0.9351	0.9708	0.9739	0.9264	0.8589
	TS	0.9017	0.9332	0.9050	0.9271	0.9220	0.9064	0.8175
	GR	0.9783	0.9666	0.9479	0.9626	0.9646	0.9596	0.9073
	TE	0.9697	0.9574	0.9581	0.9145	0.9583	0.8948	0.8234
	ALL	0.9421	0.9437	0.9275	0.9432	0.9488	0.9451	0.8105
80	CA	0.9817	0.9936	0.9227	0.9603	0.9883	....	0.8838
	TS	0.8798	0.9030	0.8264	....	....	....	....
	GR	0.9409	0.9606	0.9520	....	....	....	....
	TE	0.7883	0.9662	0.9624	....	....	....	....
	All	0.7923	0.8532	0.7850	0.9603	0.9883	....	0.8838

Note: All regressions were performed with the RQCS simulation speed equal to the RTRRMS measurement speed.

The correlation coefficients are presented as one basis for comparing the accuracy that can be obtained using the RQCS as a definition of "truth" with the accuracy obtainable using other numerics. Yet it should be understood that r^2 values are only one measure, with limited utility. The r^2 value is essentially the fraction of the variances of the two variables that is accounted for by the (linear or quadratic) regression model. Thus, r^2 values depend both on the agreement between the measures (as related by the regression model) **and** the range of roughness included in the data set. Since r^2 values can always be improved simply by adding more very smooth and very rough sites, they should never be used as the sole basis for quantifying a calibration quality.

The actual accuracy of an estimate of RARS, E[RARS], based on an ARS measure can be defined as the standard error: the RMS difference between E[RARS] (the estimate of RARS obtained using the regression equation and an ARS measure) and the true RARS value. The standard errors associated with the quadratic model are presented in Table F.9. Whereas the r^2 values were dimensionless, a standard error has the units of the measure: m/km. In essence, Table F.9 quantifies the accuracy involved when a "raw" ARS measure is re-scaled (according to the quadratic regression equation) to a "Calibrated ARS" (CARS) measure. The SE values obtained when the APL signals are processed are indicated in Figures 15 and 16.

Calibration to $RARS_{80}$

The RQCS was developed for maximum correlation with RTRRMSs when the simulation speed is set to the measurement speed of the vehicle. Therefore, for calibration to a common index, the index should be based on a standard speed best matched to that used in actual practice. A speed of 50 km/h was initially considered (and proposed in an earlier draft of this report) for the standard because of its good correlation to RTRRMS performance, and the fact that it falls midway in the range of speeds used with RTRRMS equipment. Yet the fact that the majority of tests are conducted at 80 km/h argues for the choice of that speed as the standard for an International Roughness Index (IRI).

Table F.9. Standard Error for Estimating RARS with a Quadratic Regression Equation and ARS Measurements.

		Opala Cars with Modified Maysmeters			Caravan Car with 2 meters		Single-Track Trailers	
Speed	Surface Type	MM 01	MM 02	MM 03	BI	NAASRA	BI	BPR
20	ALL	1.72	1.02	1.33	1.14	1.24	1.14	1.65
32	ALL	1.36	0.86	1.53	0.88	0.95	0.79	2.91
50	CA	0.46	0.70	0.51	0.34	0.32	0.55	0.76
	TS	0.38	0.31	0.37	0.32	0.33	0.38	0.53
	GR	0.51	0.63	0.79	0.67	0.65	0.74	0.73
	TE	0.65	0.95	0.95	1.35	0.94	1.53	1.25
	ALL	0.88	0.97	1.10	0.97	0.92	0.97	1.13
80	CA	0.23	0.14	0.47	0.30	0.16	...	0.36
	TS	0.36	0.32	0.43	...	...	...	...
	GR	0.48	0.39	0.44	...	...	...	...
	TE	1.03	0.41	0.44	...	...	...	...
	ALL	1.00	0.84	1.02	0.30	0.16	...	0.36

Note: Simulation speed for RQCS matched the RTRRMS measurement speed for all of the above regression results.

Recognizing that there are sometimes circumstances preventing RTRRMS use at 80 km/h, the data collected in the IRRE were also analyzed to determine the accuracy associated with estimating $RARS_{80}$ when a different RTRRMS speed is used. Figures F.19 - F.21 show the comparisons between $RARS_{80}$ and ARS measured at speeds of 20, 32, and 50 km/h. The corresponding standard errors obtained are presented in Table F.10, and the r^2 values are shown in Table F.11. Since the standard error units are "m/km" for $RARS_{80}$, they are directly comparable to the $RARS_{80}$ standard error results in Table F.9. However, comparisons of the results in Table F.10 with Table F.9 are not valid for simulation speeds other than 80 km/h, since RARS numerics are speed dependent.

Table F.10 provides a good picture of the nominal accuracy with which the $RARS_{80}$ can be estimated from measurements with RTRRMS when operated at a speed of 80 km/h. When calibrated separately on each surface type, an accuracy better than 0.5 m/km is feasible. The only exception to this is MM01 on the earth (TE) surfaces. Slightly higher errors are indicated when estimating $RARS_{80}$ from measurements at other speeds. At 50 km/h errors on the order of 0.75 m/km are more typical.

While overall accuracy sometimes suffers when a low RTRRMS speed is used, the ARS_{20} and ARS_{32} numerics from all of the RTRRMSs show good correlation with $RARS_{80}$ when the regressions were performed separately for different surface types. For example, Fig. F.20a (for an Opala-Maysmeter system) shows that $RARS_{80}$ numerics are consistently "high" for the CA and GR surfaces (relative to the regression line obtained for all surface types), and "low" for the TS and TE surfaces. Table F.10 indicates that the standard error associated with that figure is as low as 0.25 (TS surfaces), when separate regressions are used. But since separate calibrations are needed for each surface type to obtain this accuracy, the accuracy that would be obtained using a single calibration across surface type would not be as good, since the $CARS_{80}$ numerics would include the bias error (seen in the figure as the average distance that the TS data points lie above the regression line).

The surface type sensitivity that appears when low RTRRMS speeds are used together with $RARS_{80}$ as the calibration reference is expected. It occurs

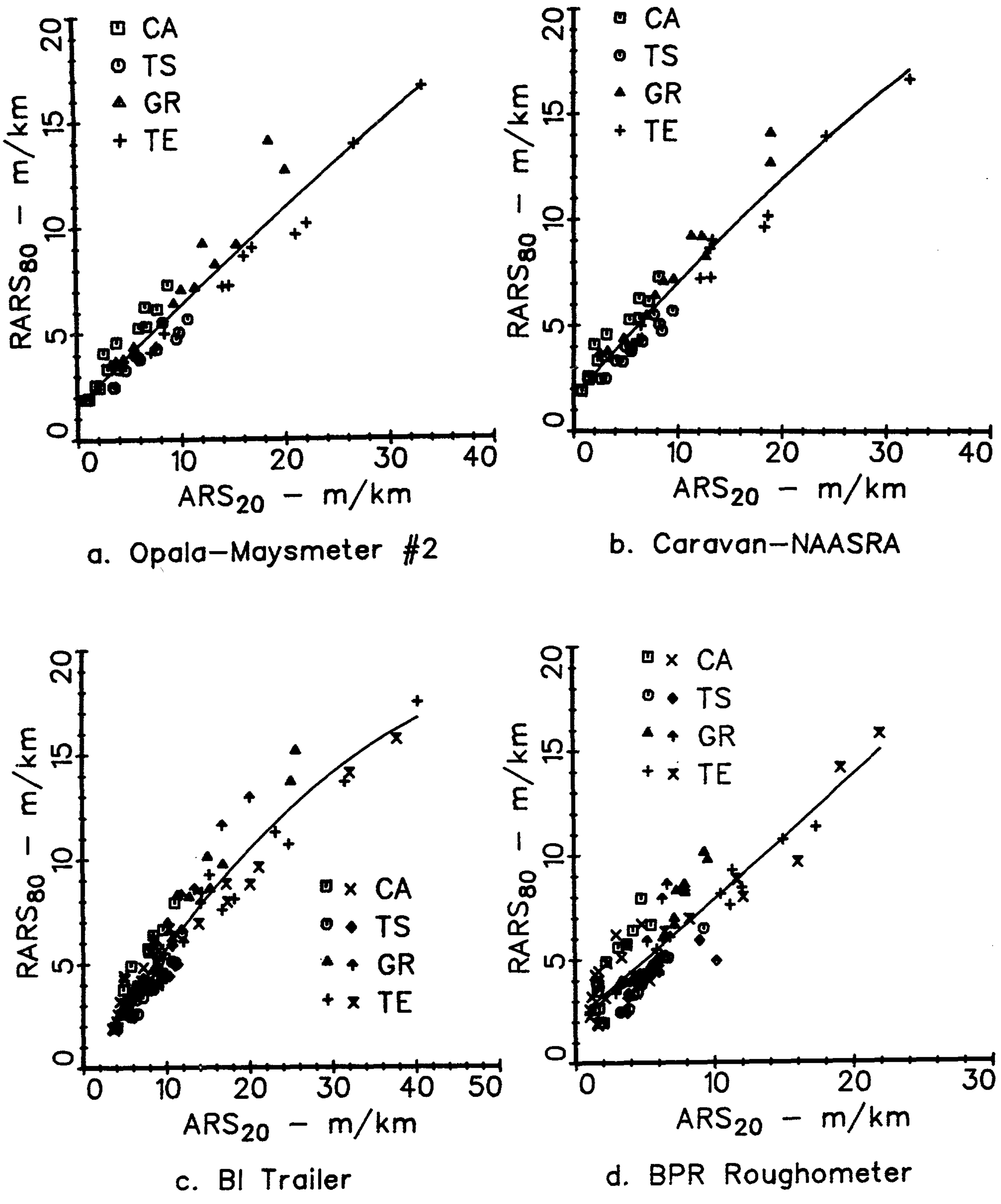


Fig. F.19. Example calibration plots to estimate $RARS_{80}$ from ARS_{20} measures.

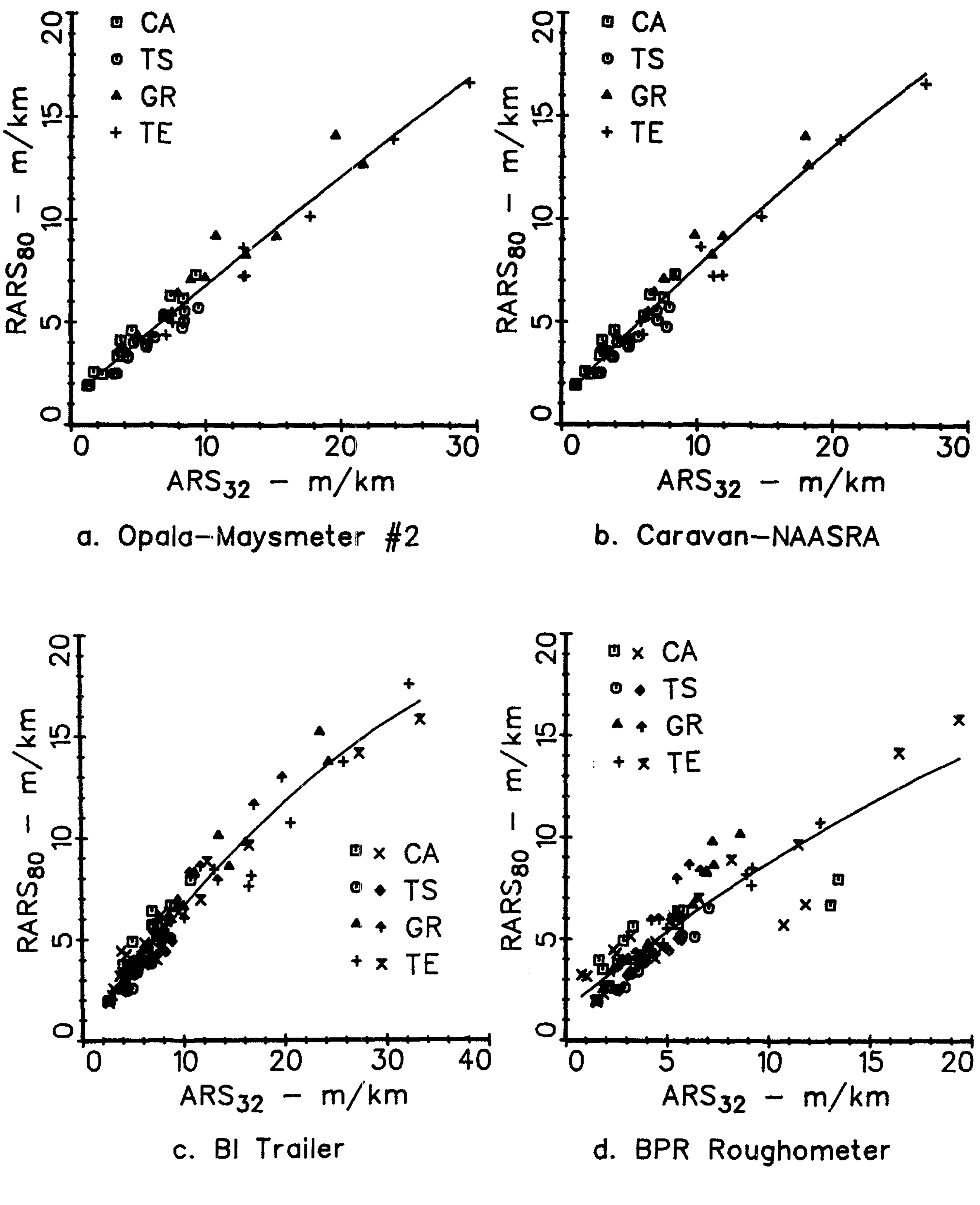


Fig. F.20. Example calibration plots to estimate $RARS_{80}$ from ARS_{32} measures.

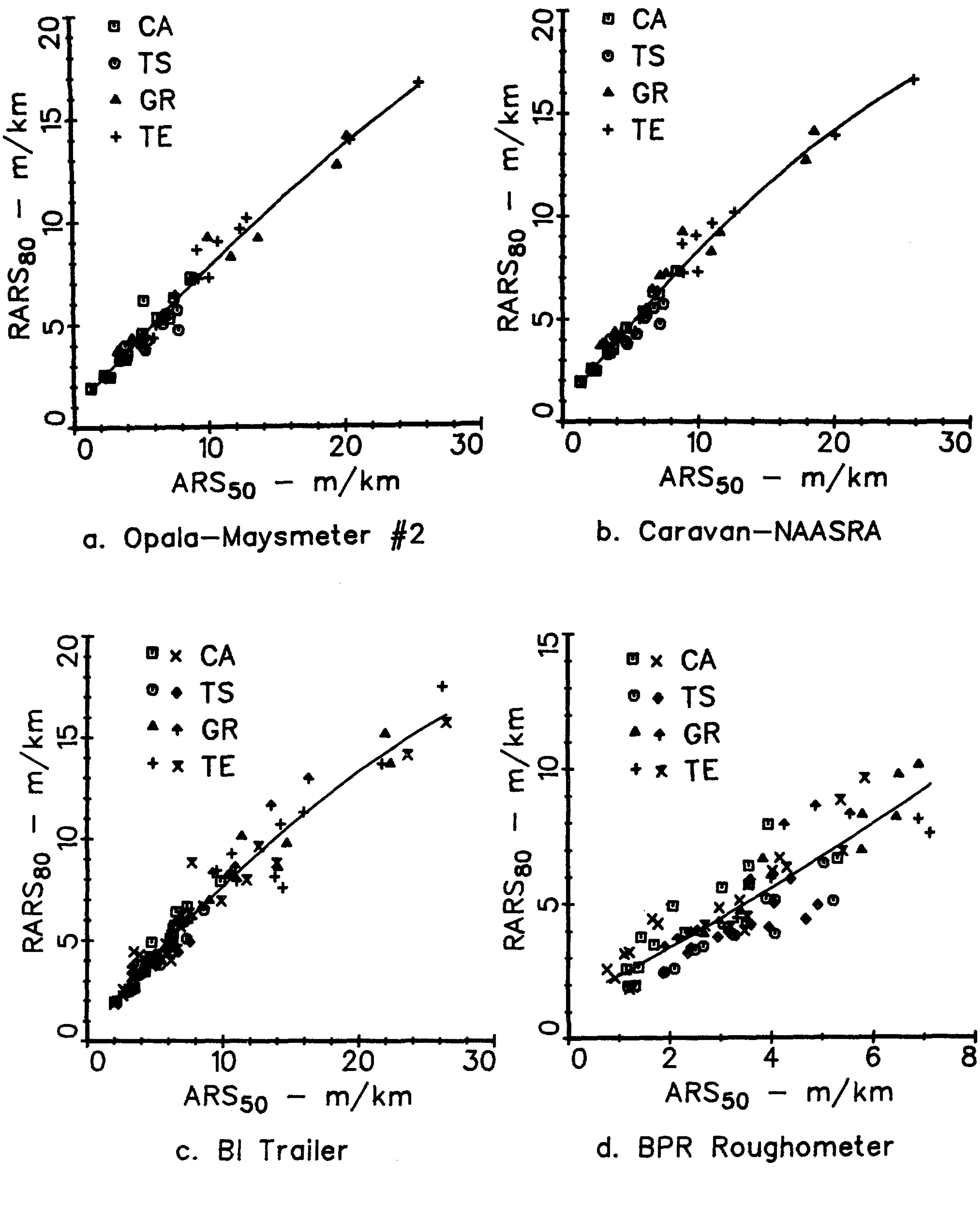


Fig. F.21. Example calibration plots to estimate $RARS_{80}$ from ARS_{50} measures.

Table F.10 Standard Errors for Estimating $RARS_{80}$ from Quadratic Regression Equations and ARS Measurements.

speed	Surface Type	Opala Cars with Modified Maysmeters MM 01	MM 02	MM 03	Caravan Car with 2 meters BI	NAASRA	Single-track Trailers BI	BPR
20	CA	0.49	0.41	0.36	0.44	0.43	0.59	0.87
	TS	0.33	0.33	0.25	0.29	0.27	0.42	0.30
	GR	0.61	0.74	1.28	0.51	0.51	0.73	0.70
	TE	1.14	0.45	0.48	0.59	0.56	0.68	0.64
	ALL	0.95	1.02	1.09	0.90	0.89	1.01	1.22
32	CA	0.42	0.31	0.61	0.36	0.33	0.52	0.81
	TS	0.24	0.25	0.24	0.29	0.29	0.34	0.32
	GR	0.43	0.78	1.10	0.56	0.53	0.64	0.61
	TE	1.16	0.40	0.81	0.80	0.65	0.83	0.51
	ALL	0.81	0.70	0.96	0.74	0.69	0.81	1.17
50	CA	0.35	0.51	0.40	0.19	0.18	0.40	0.65
	TS	0.38	0.36	0.38	0.33	0.32	0.33	0.44
	GR	0.44	0.56	0.69	0.59	0.58	0.75	0.67
	TE	0.43	0.51	0.68	0.93	0.57	1.07	0.77
	ALL	0.58	0.59	0.74	0.68	0.58	0.76	0.95
80	CA	0.23	0.14	0.47	0.30	0.16	...	0.36
	TS	0.36	0.32	0.43	...	...	...	...
	GR	0.48	0.39	0.44	...	...	...	...
	TE	1.03	0.41	0.44	...	...	...	...
	ALL	1.00	0.84	1.02	...	...	...	...

Table F.11. r^2 Values Obtained from Quadratic Regressions Between $RARS_{80}$ and the ARS Measurements.

speed	Surface Type	Opala Cars with Modified Maysmeters MM 01	MM 02	MM 03	Caravan Car with 2 meters BI	NAASRA	Single-track Trailers BI	BPR
20	CA	0.9186	0.9415	0.9557	0.9325	0.9365	0.8848	0.7478
	TS	0.8951	0.8989	0.9401	0.9227	0.9291	0.8445	0.9197
	GR	0.9633	0.9457	0.8373	0.9745	0.9742	0.9501	0.8922
	TE	0.8487	0.9859	0.9833	0.9754	0.9779	0.9683	0.9597
	ALL	0.8949	0.9035	0.8901	0.9246	0.9262	0.9074	0.7852
32	CA	0.9385	0.9679	0.8720	0.9547	0.9616	0.9113	0.7827
	TS	0.9462	0.9423	0.9459	0.9176	0.9180	0.8976	0.9100
	GR	0.9812	0.9390	0.8791	0.9687	0.9722	0.9614	0.9183
	TE	0.8437	0.9887	0.9529	0.9547	0.9705	0.9530	0.9755
	ALL	0.9224	0.9539	0.9140	0.9494	0.9561	0.9407	0.8005
50	CA	0.9583	0.9107	0.9454	0.9878	0.9892	0.9464	0.8614
	TS	0.8660	0.8796	0.8611	0.8943	0.9008	0.9057	0.8255
	GR	0.9806	0.9684	0.9524	0.9647	0.9669	0.9469	0.8994
	TE	0.9781	0.9813	0.9668	0.9382	0.9769	0.9210	0.8517
	ALL	0.9609	0.9677	0.9495	0.9568	0.9690	0.9472	0.7753
80	CA	0.9817	0.9936	0.9227	0.9603	0.9883	.....	0.8838
	TS	0.8798	0.9030	0.8264	.....	.....	.....	.....
	GR	0.9409	0.9606	0.9520	.....	.....	.....	.....
	TE	0.7883	0.9662	0.9624	.....	.....	.....	.....
	ALL	0.7923	0.8532	0.7850	.....	.....	.....	.....

because the wavebands covered by the RTRRMS no longer match that of the RQCS, due to the speed difference. The relationship between the two depends on the relative spectral content of the road, which differs with surface type.

One physical reason for the fairly good results obtained at lower speeds is that some of the random errors in the RTRRMS measurement are reduced by greater averaging, since a longer time is spent making the measurement. The same effect can be obtained for higher speeds by using longer calibration sites.

A second reason for better results at low speeds appears to apply to the BPR Roughometer. When operated at the lower speeds, the RTRRMS is subjected to less excitation (ARV). Errors due to vibration levels exceeding the design limits of the vehicle and roadmeter are reduced by reducing the vibration levels. Of course, this effect disappears when more rugged RTRRMSs are used.

Calibration Across Speed

The IRI selected in this report is based on the concept that a given road has only a single "true" roughness value, regardless of how it is used by the public. An alternative concept is that a road roughness measure should reflect how the road is used, such that a high-quality road used at high speeds might be rated the same in terms of perceived roughness as a lower quality road used at low speeds.

When ARS numerics are used to estimate RARS over a range of speeds, there is a question of how many calibration curves are needed. Should a separate curve be used for every speed encountered? Or can a single calibration curve be used across speed? Prior to the IRRE, it has been shown that substantial calibration errors can be introduced when ARS measures taken at different speeds are compared to the corresponding RARS measures, and that the errors are eliminated by using ARV as the roughness numeric [9, 29]. Figure F.22 confirms that a single ARS/RARS calibration across speed does not exist for the RTRRMSs that participated in the IRRE. On paved roads, substantial errors would be introduced by using a ARS-to-RARS regression obtained for one speed for ARS-to-RARS rescaling at a different speed.

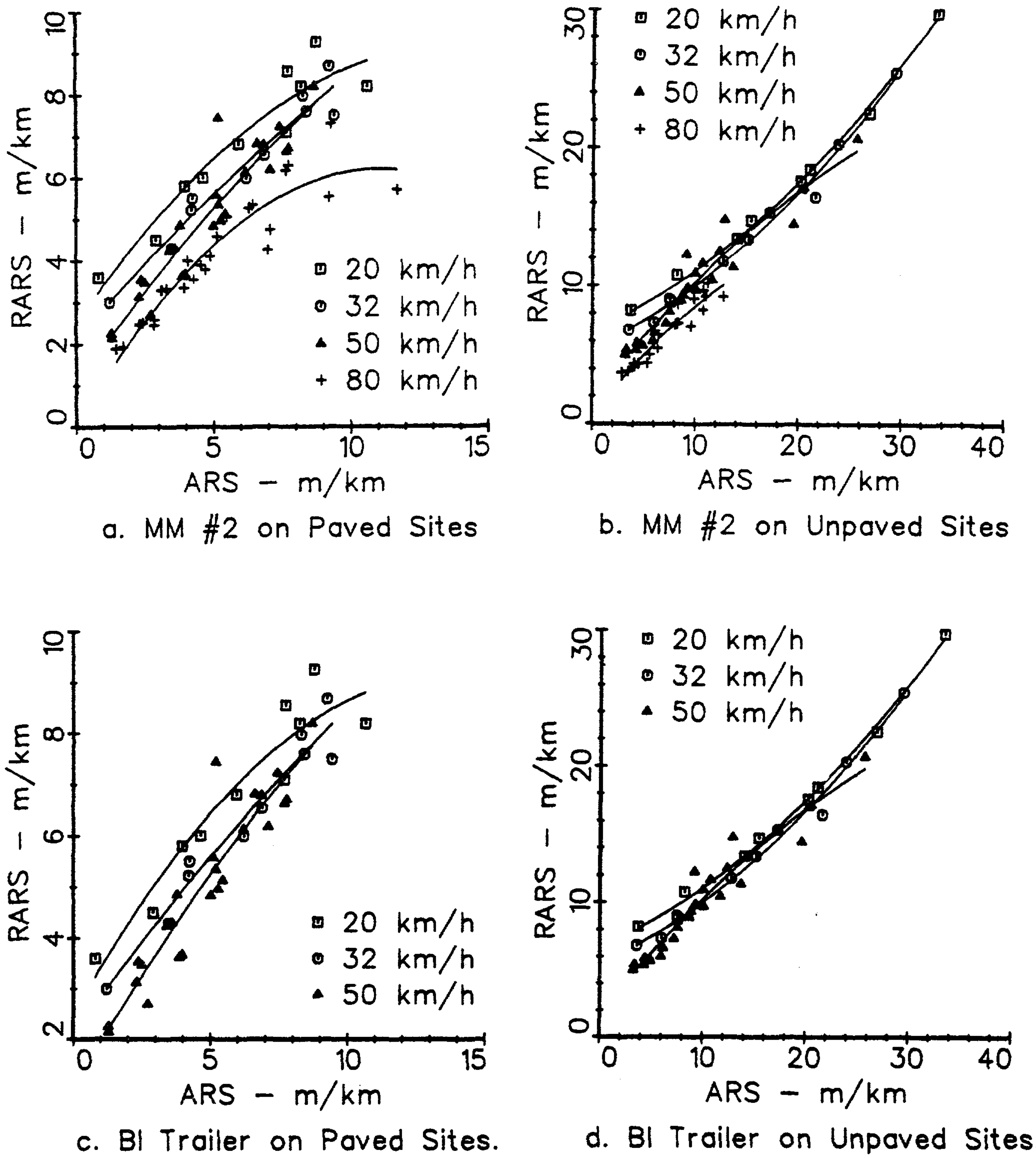


Figure F.22. Calibration across speed using ARS and RARS numerics.

Figure F.23 shows the same data points, rescaled to ARV units (mm/sec). When converted to ARV, the agreement is much better, such that it would be reasonable to use a single calibration across speed. This is because the ARV is the vehicle response variable actually measured by the RTRRMS. It is easy to show that if a valid ARV relation exists, then a corresponding ARS relation cannot exist except under certain conditions. A valid ARV calibration across speed would have the form:

$$E\ [RARV] = CARV = A + B\ ARV + C\ ARV^2 \qquad \text{(F-45)}$$

Since ARV and ARS are related by measurement speed, Eq. 45 can be converted to an ARS equation:

$$CARS = CARV\ /\ V = A\ /\ V + B\ ARV\ /\ V + C\ ARV^2\ /\ V$$

$$= A\ /\ V + B\ ARS + C\ V\ ARS^2 \qquad \text{(F-46)}$$

Eq. 46 cannot be independent of speed unless the offset A and the curvature C are both zero.

Although a calibration across speed can be demonstrated for the RTRRMSs that participated in the IRRE, an ARV calibration across speed is not guaranteed due to the presence of nonlinearities in RTRRMSs [9]. Often, however, the factors that introduce a speed dependency are small enough that a calibration equation obtained at one speed (e.g., 50 km/h) can be used at another speed (e.g., 32 km/h) if the RTRRMS and RQCS measures are converted to ARV units.

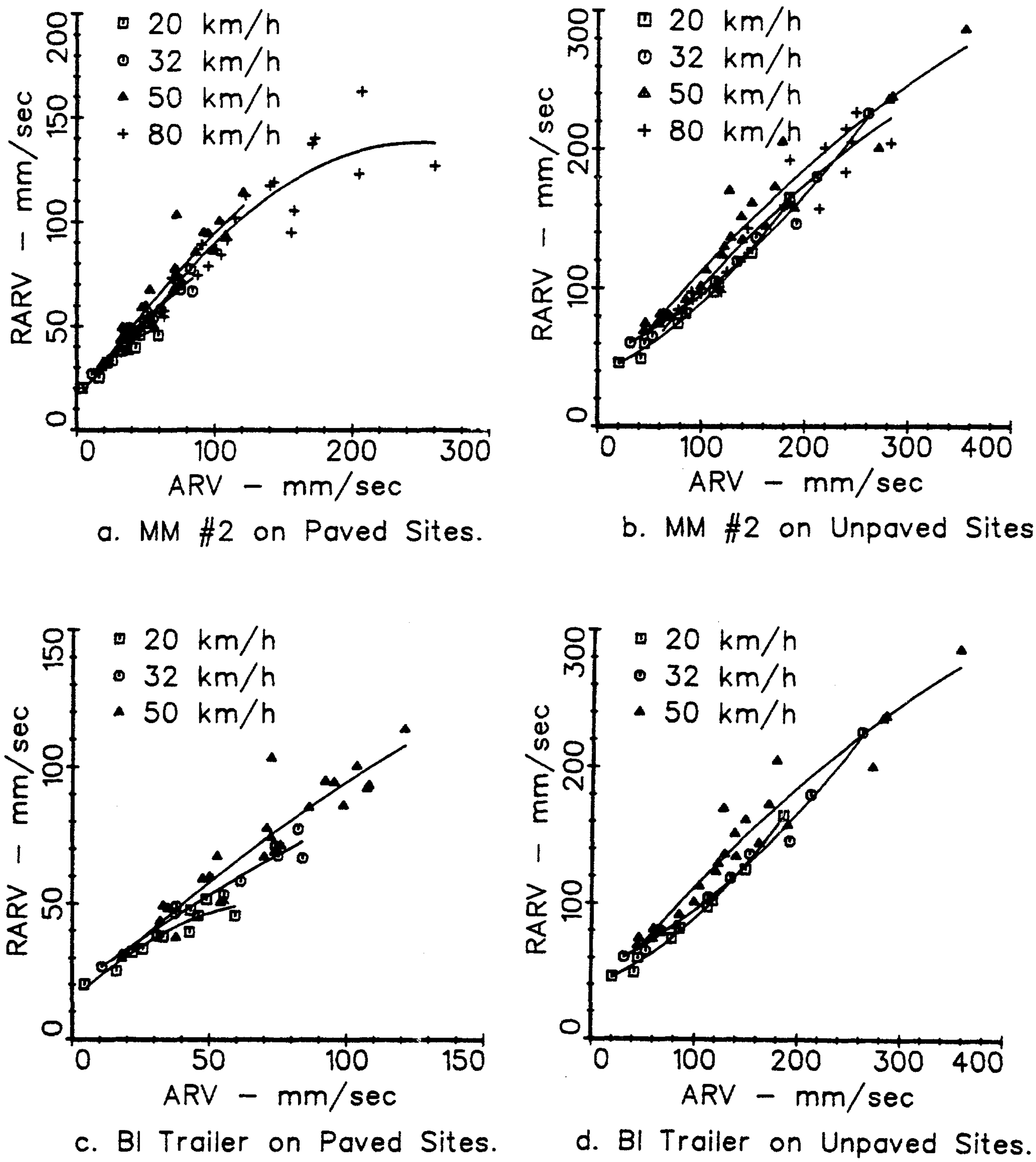


Figure F.23. Calibration across speed using ARV and RARV numerics.

APPENDIX G

APL ANALYSES USED IN EUROPE

prepared by

The French Bridge and Pavement Laboratory (LCPC),
The Belgian Road Research Center (CRR),
The University of Michigan Transportation Research Institute (UMTRI), and
The Brazilian Road Research Institute (IPR/DNER).

The Longitudinal Profile Analyser (APL) Trailer, developed by LCPC, produces a profile signal which replicates the frequency content of the longitudinal profile of a pavement section over the frequency range 0.5 - 20 Hz. The profile signal obtained from the APL Trailer can then be processed any number of ways to provide simple and quantified roughness information appropriate to a particular application. The CAPL 25 measurement is used for low-speed (21.6 km/h) evaluation of road quality during construction, while the APL 72 system provides for the high-speed measurement (72 km/h) of three independent roughness numerics to describe the condition of existing roads in greater detail. A very similar roughness analysis, which results in three evenness coefficients (CP), is used by CRR in Belgium.

Appendix A describes the APL instrument itself and the methods used to record profile data during the International Road Roughness Experiment (IRRE). This appendix presents: 1) mathematical properties of the CAPL 25, APL 72, and CP numerics, 2) the measures of these numerics obtained in the IRRE, 3) correlations between these measures and those obtained from response-type road roughness measuring systems (RTRRMSs), and 4) examples of how plotting the APL profile can be used to visually diagnose pavement condition. Plots of power spectral density (PSD) functions obtained from the APL Trailer are included in Appendix I along with similar plots obtained from static profile measurements. Additional CP-type analyses are presented in Appendix J, in which the moving average analysis is applied to both the APL 72 profiles and statically measured profiles.

The results reported in this appendix were obtained during two analysis operations. The first was done in Brazil by the LCPC team during the IRRE, and provided the CAPL 25 coefficients and the APL 72 indices. Further analyses were performed in Europe by carrying out spectral density analysis, energy analysis (LCPC method), and coefficient of evenness (CP) analysis (CRR method).

DESCRIPTION OF THE APL SUMMARY NUMERICS

CAPL 25

The APL 25 configuration of the APL trailer was originally designed to evaluate the quality of roughness of road layers during construction. It had to meet the objectives of great ease of use and of simplicity of data analysis. A relatively low standard speed of 21.6 km/h (6.0 m/sec) is used because high-speed measurements can give rise to problems on a construction site. The name of the measure is based on the standard test length of 25 meters which is used for the calculation of a roughness numeric called the APL 25 coefficient (CAPL 25).

During testing, the transducer signal is recorded graphically (scale 1/200) on an analog paper recorder, and at the same time, digitized every 0.25 meter. The digitizing equipment is set so that the value varies about zero, with the value zero being obtained when the system is at rest. The absolute values of the samples are summed, and averaged over the 25 m test section (100 samples). This average is the CAPL 25 coefficient, which can be converted to millimeters by a scale factor associated with an amplifier gain setting. Physically, the CAPL 25 is the average rectified displacement of the arm on the trailer supporting the follower wheel, relative to the horizontal pendulum used as an inertial reference. The computation of the CAPL 25 coefficients is carried out during the measurement and their values are printed on the recorder strip chart. When the sections that are measured are several kilometers long, it is more convenient to record the digitized signal on magnetic tapes and have it processed with a mini-computer. Further information about the APL 25 methodology is available in Reference [15].

The transducer signal processed to yield the CAPL 25 result is filtered only by the mechanical properties of the APL trailer, which are shown by the Bode plot in Figure G.1. At the 6.0 m/s towing speed, the bandwidth of the APL signal (approximately 0.4 - 20 Hz) includes wavelengths from 0.3 to 15 m, as shown in the figure. The normal spectral content of roads is such that when profile is characterized by a displacement (elevation) measure such as the CAPL 25 numeric, the measure will be dominated by the lowest wave numbers (longest wavelengths) within the response range of the trailer. (See Appendix I for more information on spectral content of simple roughness numerics.)

It will be seen later that the mode for quantifying roughness represented by the CAPL 25, which is very well adapted to judge the quality of a road construction or to evaluate the present state of a road network, is not the best method available to provide an appreciation of the typical dynamic response of the vehicle.

But in the same way that coefficients of roughness were determined (CRR method, described later) from APL 72 signals, it would have been possible to obtain analog coefficients with the APL 25 signal offering better correlations with the RTRRMSs. For example, CRR uses both the APL 25 signal and the APL 72 signal to compute CP numerics. However, these analyses were not performed during the IRRE because they would have been redundant to those applied to the APL 72.

APL 72 Analyses used in France

The APL 72 analyses are the most commonly used in France by the Road Administrations for the purpose of routine surveying of the road networks [16]. The measures are taken at 72 km/h (20 m/sec), because at this speed, the APL Trailer detects profile variations for wavelengths between 1 and 40 m (Fig. G.1). As described in Appendix A, the profiles are stored on magnetic tape, to be played back later in the laboratory for analysis.

The APL 72 analysis used in France is based on the global energy (mean square value) of a signal. Road roughness is characterized by three numerics,

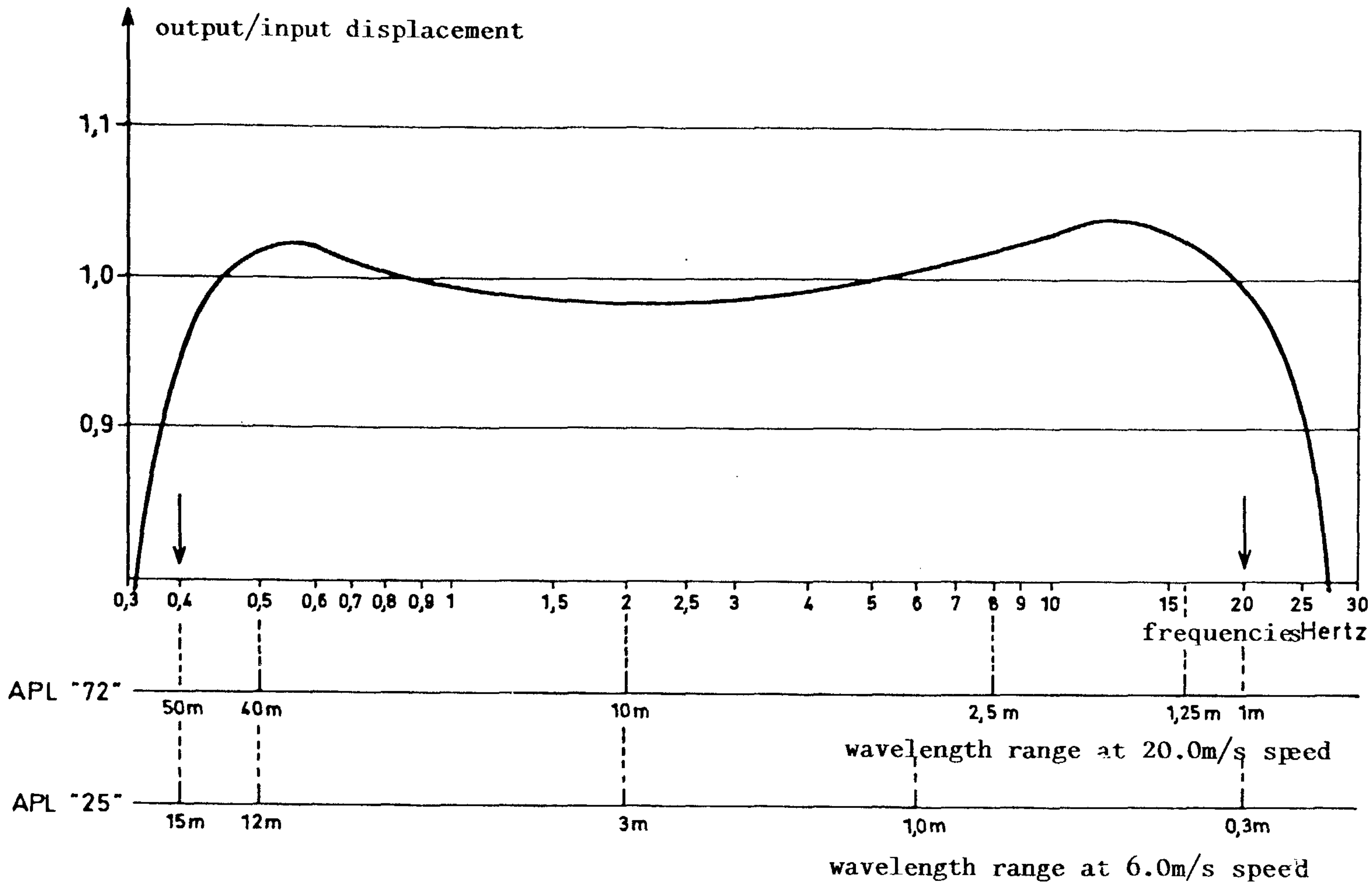


Figure G.1. Frequency Response of APL Trailer
to displacement input

computed for every 200 m. The three values are obtained by playing the signal back from the tape recorder through three electronic band-pass filters. During playback, the tape speed is increased to reduce processing time and to avoid the need for filters with extremely low frequency characteristics.

The filters are set to separate the short, medium, and long wavelength roughness content. These ranges (wavebands) were chosen to distinguish between profile roughness affecting user safety (shorter wavelengths) and those affecting user comfort (longer wavelengths). The three wavebands are:

1.0 - 3.3 m/cycle	Short Wavelength (SW)
3.3 - 13 m/cycle	Medium Wavelength (MW)
13 - 40 m/cycle	Long Wavelength (LW)

The intermediate limits (3.3 m and 13 m) where chosen to be related to the characteristics of devices used previously in France (3 m straightedge, viagraphe).

The signal delivered by each filter is squared and integrated over a length of 200 meters. Thus, for every 200 meters of road three mean-square values of energy (W) are obtained for the signal (one for each wavelength range). To each of these energy values, one can associate a value of "equivalent amplitude" (Y) expressed in mm, which would be the amplitude of a sinusoidal signal, the wavelength of which is the median value of the filter range, and which would deliver the same energy.

More usually, the energy values (W) are spread within 10 classes (called Index (I) for the IRRE) graded, from 1--the worst level of roughness to 10--the best level, in an approximately logarithmic way. Further details of this APL 72 Analysis are available in Reference [17].

In normal operation, the profiles of the right and left wheel-tracks are measured simultaneously with two APL trailers. In this experiment, the tracks were analyzed separately, and roughness measures were reported for each wheeltrack.

APL Analyses used in Belgium

The characterization of evenness (roughness) that is used is based on a geometric type of representation of the longitudinal profile. This representation makes use of a numerical filtering of the measured profile with a moving average technique. The option taken through this choice of representation offers the advantage of providing a straightforward geometrical interpretation, useful in practice [20].

The characterization of the measured profile is obtained by evaluating the difference of the surface profile from the reference line obtained by smoothing the same profile. The process of applying a moving average to the signal acts as a filter attenuating short length irregularities. For its application, this technique requires the numerically sampled signal recorded from the APL trailer. The distance marks for sampling are provided by a pulse train issued from the measuring wheel of the APL mounted as an odometer. The sample interval 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 over a given section is determined. This mean value, divided by two and expressed per unit length, 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 base length, e.g., $CP_{2.5}$. For a given baselength, the roughness level increases as the CP increases.

The computations performed at the Belgian Road Research Center (CRR) used the APL 72 signals recorded in Brazil at a measurement speed of 72 Km/h (20 m/s). The sampling step length used is 1/3 meter, and the coefficients of evenness (CP) were determined for the baselengths of 2.5 m, 10 m, and 40 m, which are the conventional values used. The CP is normally evaluated for hectometric (100 meters) sections. In the IRRE, the CP of each 320 m profile was therefore chosen as the mean value of the CP of three contiguous hectometric blocs, starting at the beginning of each section track.

As mentioned earlier, the same CP statistic is applied in Belgium to APL 25 measurements performed at the speed of 6 m/s (21.6 Km/h). The sampling step length used in that case is of 1/6 meter and the baselengths considered for the moving average are mainly 15 m and 2.5 m.

The moving average filter is analyzed in detail in Appendix J, to derive its frequency response, including the effects of sample interval.

FINDINGS FROM THE IRRE

Measures of APL Summary Statistics

CAPL 25. The APL 25 system produces CAPL 25 numerics for every 25 m of travelled road. Therefore, each 320 test section had 12 or 13 associated CAPL 25 numerics for each wheeltrack. To facilitate comparisons with other numerics, each profile is characterized by the mean of the 12 or 13 CAPL 25 values.

The APL 25 results that were obtained in the IRRE are presented in Tables G.1 - G.4. In these tables, the four surface types are: asphaltic concrete, surface treatment, gravel, and earth. They are abbreviated according to their spelling in Portuguese as CA, TS, GR, and TE, respectively.

APL 72. During the IRRE, all the paved sections (CA and TS) were measured by the APL 72 in each track (right and left), several times for some

Table G.1. Summary of APL Results for the Asphaltic Concrete Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

APL TRAILER

SITE	MEAS.	TRACK	ROUGHNESS MEASUREMENTS MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
CA01	25	R	18.5	18	19		.7	.038	1	1
	25	L	15	15	15		0	0	0	0
	72 SW	R	4	4	4	4	0	0	0	0
	72 SW	L	3.3	3	3	4	.6	.173	.5	.866
	72 MW	R	3	3	3	3	0	0	0	0
	72 MW	L	3	3	3	3	0	0	0	0
	72 LW	R	3.3	4	3	3	.6	.173	-.5	-.866
	72 LW	L	3	4	2	3	1	.333	-.5	-.5
CA02	25	R	14	14			0	0	0	0
	25	L	16	16			0	0	0	0
	72 SW	R	2.7	2	3	3	.6	.217	.5	.866
	72 SW	L	2.7	2	3	3	.6	.217	.5	.866
	72 MW	R	3.7	3	4	4	.6	.157	.5	.866
	72 MW	L	2.7	2	3	3	.6	.217	.5	.866
	72 LW	R	4	4	4	4	0	0	0	0
	72 LW	L	4.3	4	5	4	.6	.133	0	0
CA03	25	R	16.5	17	16		.7	.043	-1	-1
	25	L	18	18	18		0	0	0	0
	72 SW	R	1.5	1	2		.7	.471	1	1
	72 SW	L	1	1	1		0	0	0	0
	72 MW	R	3	3	3		0	0	0	0
	72 MW	L	3	3	3		0	0	0	0
	72 LW	R	3.5	4	3		.7	.202	-1	-1
	72 LW	L	4	5	3		1.4	.354	-2	-1
CA04	25	R	15.5	16	15		.7	.046	-1	-1
	25	L	18	18	18		0	0	0	0
	72 SW	R	2	2	2		0	0	0	0
	72 SW	L	1.5	1	2		.7	.471	1	1
	72 MW	R	2.5	2	3		.7	.283	1	1
	72 MW	L	2	2	2		0	0	0	0
	72 LW	R	3	3	3		0	0	0	0
	72 LW	L	3	3	3		0	0	0	0
CA05	25	R	16	16	16		0	0	0	0
	25	L	20	20	20		0	0	0	0
	72 SW	R	2.5	3	2		.7	.283	-1	-1
	72 SW	L	1.5	2	1		.7	.471	-1	-1
	72 MW	R	3	4	2		1.4	.471	-2	-1
	72 MW	L	2.5	3	2		.7	.283	-1	-1
	72 LW	R	3.5	3	4		.7	.202	1	1
	72 LW	L	3.5	3	4		.7	.202	1	1
CA06	25	R	18	18			0	0	0	0
	25	L	20	20			0	0	0	0
	72 SW	R	2	2			0	0	0	0
	72 SW	L	1	1			0	0	0	0
	72 MW	R	4	4			0	0	0	0
	72 MW	L	4	4			0	0	0	0
	72 LW	R	3	3			0	0	0	0
	72 LW	L	3	3			0	0	0	0
CA07	25	R	7	7	7		0	0	0	0
	25	L	7	7	7		0	0	0	0
	72 SW	R	4	4	4		0	0	0	0
	72 SW	L	3	3	3		0	0	0	0
	72 MW	R	6	6	6		0	0	0	0
	72 MW	L	6	6	6		0	0	0	0
	72 LW	R	6	6	6		0	0	0	0
	72 LW	L	8	8	8		0	0	0	0

Table G.1 (Cont.)

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

APL TRAILER

SITE	MEAS.	TRACK	ROUGHNESS MEASUREMENTS MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
CA08	25	R	7	7	7		0	0	0	0
	25	L	7	7	7		0	0	0	0
	72 SW	R	4	5	3		1.4	.354	-2	-1
	72 SW	L	4	4	4		0	0	0	0
	72 MW	R	6.5	7	6		.7	.109	-1	-1
	72 MW	L	7	7	7		0	0	0	0
	72 LW	R	7	7	7		0	0	0	0
	72 LW	L	6	6	6		0	0	0	0
CA09	25	R	12	12	12		0	0	0	0
	25	L	10	10	10		0	0	0	0
	72 SW	R	3.5	4	3		.7	.202	-1	-1
	72 SW	L	3	4	2		1.4	.471	-2	-1
	72 MW	R	5.5	5	6		.7	.129	1	1
	72 MW	L	5	5	5		0	0	0	0
	72 LW	R	4.5	5	4		.7	.157	-1	-1
	72 LW	L	4	4	4		0	0	0	0
CA10	25	R	11	11	11		0	0	0	0
	25	L	11	11	11		0	0	0	0
	72 SW	R	3.5	3	4		.7	.202	1	1
	72 SW	L	2	2	2		0	0	0	0
	72 MW	R	5.5	5	6		.7	.129	1	1
	72 MW	L	5	5	5		0	0	0	0
	72 LW	R	6	6	6		0	0	0	0
	72 LW	L	5	5	5		0	0	0	0
CA11	25	R	17	17			0	0	0	0
	25	L	15	15			0	0	0	0
	72 SW	R	2	2			0	0	0	0
	72 SW	L	3	3			0	0	0	0
	72 MW	R	2	2			0	0	0	0
	72 MW	L	4	4			0	0	0	0
	72 LW	R	4	4			0	0	0	0
	72 LW	L	5	5			0	0	0	0
CA12	25	R	5	5	5		0	0	0	0
	25	L	5	5	5		0	0	0	0
	72 SW	R	6	6	6	6	0	0	0	0
	72 SW	L	6	6	6		0	0	0	0
	72 MW	R	8	8	8	8	0	0	0	0
	72 MW	L	8.5	8	9		.7	.083	1	1
CA13	25	R	5	5	5		0	0	0	0
	25	L	6	6	6		0	0	0	0
	72 SW	R	6	6	6	6	0	0	0	0
	72 SW	L	6	6	6	6	0	0	0	0
	72 MW	R	7	7	7	7	0	0	0	0
	72 MW	L	8	8	8	8	0	0	0	0
	72 LW	R	6	6	6	6	0	0	0	0
	72 LW	L	6	6	6	6	0	0	0	0

Table G.2. Summary of APL Results for the Surface Treatment Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

APL TRAILER

SITE	MEAS.	TRACK	ROUGHNESS MEASUREMENTS MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
TS01	25	R	7.6	7.6	7.5		.1	9E-03	-.1	-1
	25	L	7.3	7.5	7.3	7.2	.2	.021	-.15	-.982
	72 SW	R	2	2	2	2	0	0	0	0
	72 SW	L	2	2	2	2	0	0	0	0
	72 MW	R	6.7	7	7	6	.6	.087	-.5	-.866
	72 MW	L	6	6	6	6	0	0	0	0
	72 LW	R	6.7	7	7	6	.6	.087	-.5	-.866
	72 LW	L	7	7	7	7	0	0	0	0
TS02	25	R	9.4	9.4			0	0	0	0
	25	L	9.6	9.6			0	0	0	0
	72 SW	R	2	2			0	0	0	0
	72 SW	L	2	2			0	0	0	0
	72 MW	R	5	5			0	0	0	0
	72 MW	L	6	6			0	0	0	0
	72 LW	R	4	4			0	0	0	0
	72 LW	L	6	6			0	0	0	0
TS03	25	R	10.8	10.8	10.8		0	0	0	0
	25	L	10	9.8	10.2		.3	.028	.4	1
	72 SW	R	2	2	2	2	0	0	0	0
	72 SW	L	1.3	2	1	1	.6	.433	-.5	-.866
	72 MW	R	6	6	6	6	0	0	0	0
	72 MW	L	6	6	6	6	0	0	0	0
	72 LW	R	4	4	4	4	0	0	0	0
	72 LW	L	5	5	5	5	0	0	0	0
TS04	25	R	10	10			0	0	0	0
	25	L	8.7	8.7			0	0	0	0
	72 SW	R	1	1	1	1	0	0	0	0
	72 SW	L	1.7	2	2	1	.6	.346	-.5	-.866
	72 MW	R	6	6	6	6	0	0	0	0
	72 MW	L	6	6	6	6	0	0	0	0
	72 LW	R	6	6	6	6	0	0	0	0
	72 LW	L	6.3	6	7	6	.6	.091	0	0
TS05	25	R	8.5	8.5			0	0	0	0
	25	L	9.4	9.4			0	0	0	0
	72 SW	R	1	1	1		0	0	0	0
	72 SW	L	1	1	1		0	0	0	0
	72 MW	R	6	6	6		0	0	0	0
	72 MW	L	6.5	7	6		.7	.109	-1	-1
	72 LW	R	8.5	9	8		.7	.083	-1	-1
	72 LW	L	8.5	8	9		.7	.083	1	1
TS06	25	R	7.9	7.9			0	0	0	0
	25	L	8.4	8.2	8.5		.2	.025	.3	1
	72 SW	R	4	4			0	0	0	0
	72 SW	L	3	3			0	0	0	0
	72 MW	R	6	6			0	0	0	0
	72 MW	L	6	6			0	0	0	0
	72 LW	R	7	7			0	0	0	0
	72 LW	L	6	6			0	0	0	0
TS07	25	R	8	8			0	0	0	0
	25	L	8.9	8.8	9		.1	.016	.2	1
	72 SW	R	4	4			0	0	0	0
	72 SW	L	4	4			0	0	0	0
	72 MW	R	5	5			0	0	0	0
	72 MW	L	5	5			0	0	0	0
	72 LW	R	6	6			0	0	0	0
	72 LW	L	6	6			0	0	0	0

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

APL TRAILER

SITE	MEAS.	TRACK	ROUGHNESS MEASUREMENTS MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
TS08	25	R	11.6	11.5	11.7		.1	.012	.2	1
	25	L	10.3	10.4	10.1		.2	.021	-.3	-1
	72 SW	R	3	3	3		0	0	0	0
	72 SW	L	3	3	3		0	0	0	0
	72 MW	R	4	4	4		0	0	0	0
	72 MW	L	4	4	4		0	0	0	0
	72 LW	R	3	3	3		0	0	0	0
	72 LW	L	3	3	3		0	0	0	0
TS09	25	R	8.8	8.9	8.7		.1	.016	-.2	-1
	25	L	6.8	6.8	6.8		0	0	0	0
	72 SW	R	2	2			0	0	0	0
	72 SW	L	3	3			0	0	0	0
	72 MW	R	7	7			0	0	0	0
	72 MW	L	7	7			0	0	0	0
	72 LW	R	5	5			0	0	0	0
	72 LW	L	6	6			0	0	0	0
TS10	25	R	7.4	7.4	7.4		0	0	0	0
	25	L	7	7	7		0	0	0	0
	72 SW	R	3	3			0	0	0	0
	72 SW	L	2	2			0	0	0	0
	72 MW	R	6	6			0	0	0	0
	72 MW	L	7	7			0	0	0	0
	72 LW	R	8	8			0	0	0	0
	72 LW	L	9	9			0	0	0	0
TS11	25	R	4.5	4.5	4.5		0	0	0	0
	25	L	4.7	4.7	4.6		.1	.015	-.1	-1
	72 SW	R	4	4	4		0	0	0	0
	72 SW	L	5	5	5		0	0	0	0
	72 MW	R	8	8	8		0	0	0	0
	72 MW	L	7	7	7		0	0	0	0
	72 LW	R	9	9	9		0	0	0	0
	72 LW	L	8	8	8		0	0	0	0
TS12	25	R	5.5	5.4	5.5		.1	.013	.1	1
	25	L	4.8	4.7	4.8		.1	.015	.1	1
	72 SW	R	5	5	5		0	0	0	0
	72 SW	L	5.5	6	5		.7	.129	-1	-1
	72 MW	R	8.5	9	8		.7	.083	-1	-1
	72 MW	L	10	10	10		0	0	0	0
	72 LW	R	3	3	3		0	0	0	0
	72 LW	L	5	5	5		0	0	0	0

Table G.3. Summary of APL Results for the Gravel Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

APL TRAILER

SITE	MEAS.	TRACK	ROUGHNESS MEASUREMENTS MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
GR01	25	R	5.5	5.5			0	0	0	0
	25	L	6.1	6.1			0	0	0	0
	72 SW	L	3	3	3		0	0	0	0
	72 MW	L	7	7	7		0	0	0	0
	72 LW	L	6	6	6		0	0	0	0
GR02	25	R	6.8	6.8			0	0	0	0
	25	L	7.2	7.2			0	0	0	0
	72 SW	L	3	3	3		0	0	0	0
	72 MW	L	7	7	7		0	0	0	0
	72 LW	L	3.5	3	4		.7	.202	1	1
GR03	25	R	14.7	13.8	15.5		1.2	.082	1.7	1
	25	L	19.2	19.9	18.4		1.1	.055	-1.5	-1
	72 SW	L	1	1			0	0	0	0
	72 MW	L	3	3			0	0	0	0
	72 LW	L	3	3			0	0	0	0
GR04	25	R	14.6	14.8	14.4		.3	.019	-.4	-1
	25	L	14.6	12.5	16.7		3	.203	4.2	1
	72 SW	L	1	1			0	0	0	0
	72 MW	L	3	3			0	0	0	0
	72 LW	L	5	5			0	0	0	0
GR05	25	R	20.9	21.5	20.2		.9	.044	-1.3	-1
	25	L	19	19.7	18.3		1	.052	-1.4	-1
	72 SW	B	1	1			0	0	0	0
	72 MW	B	3	3			0	0	0	0
	72 LW	B	5	5			0	0	0	0
GR06	25	R	19.4	19.9	18.9		.7	.036	-1	-1
	25	L	21	20.4	21.6		.8	.04	1.2	1
	72 SW	B	1	1			0	0	0	0
	72 MW	B	3	3			0	0	0	0
	72 LW	B	5	5			0	0	0	0
GR07	25	R	7	7	7		0	0	0	0
	25	L	8.5	7.9	9.1		.8	.1	1.2	1
	72 SW	L	1	1	1		0	0	0	0
	72 MW	L	4.5	4	5		.7	.157	1	1
	72 LW	L	6	6	6		0	0	0	0
GR08	25	R	6.9	7	6.7		.2	.031	-.3	-1
	25	L	7.2	7.2	7.2		0	0	0	0
	72 SW	L	2	2	2		0	0	0	0
	72 MW	L	6.5	6	7		.7	.109	1	1
	72 LW	L	6.5	6	7		.7	.109	1	1
GR09	25	R	17.4	17.6	17.1		.4	.02	-.5	-1
	25	L	16.4	16.2	16.5		.2	.013	.3	1
	72 SW	L	1	1			0	0	0	0
	72 MW	L	3	3			0	0	0	0
	72 LW	L	3	3			0	0	0	0
GR10	25	R	10.9	10.9	10.9		0	0	0	0
	25	L	15.6	15.6	15.5		.1	5E-03	-.1	-1
	72 SW	L	1	1			0	0	0	0
	72 MW	L	3	3			0	0	0	0
	72 LW	L	6	6			0	0	0	0
GR11	25	R	14.5	14.2	14.7		.4	.024	.5	1
	25	L	12.4	12.4	12.3		.1	6E-03	-.1	-1
GR12	25	R	22	28.9	15.2		9.7	.439	-13.7	-1
	25	L	13.9	14.3	13.5		.6	.041	-.8	-1

Table G.4. Summary of APL Results for the Earth Roads.

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

APL TRAILER

SITE	MEAS.	TRACK	ROUGHNESS MEASUREMENTS				SIGMA	S/M	TREND	R
			MEAN	RUN 1	RUN 2	RUN 3				
TE01	25	R	10.1	9.5	10.4	10.4	.5	.051	.45	.866
	25	L	12.8	12.6	13	12.9	.2	.016	.15	.721
	72 SW	R	3	3	3		0	0	0	0
	72 SW	L	2	2	2		0	0	0	0
	72 MW	R	5	5	5		0	0	0	0
	72 MW	L	4.5	4	5		.7	.157	1	1
	72 LW	R	4	4	4		0	0	0	0
	72 LW	L	3	3	3		0	0	0	0
TE02	25	R	11.5	11.4	11.7	11.5	.2	.013	.05	.327
	25	L	9.8	9.3	9.9	10.2	.5	.047	.45	.982
	72 SW	R	2	2	2		0	0	0	0
	72 SW	L	2.5	3	2		.7	.283	-1	-1
	72 MW	R	5	5	5		0	0	0	0
	72 MW	L	7	7	7		0	0	0	0
	72 LW	R	5	5	5		0	0	0	0
	72 LW	L	4.5	5	4		.7	.157	-1	-1
TE03	25	R	13.3	13.5	13.2	13.1	.2	.016	-.2	-.961
	25	L	15.7	15.2	16.4	15.5	.6	.04	.15	.24
	72 SW	R	1	1	1		0	0	0	0
	72 SW	L	1	1	1		0	0	0	0
	72 MW	R	4.5	5	4		.7	.157	-1	-1
	72 MW	L	3	3	3		0	0	0	0
	72 LW	R	5	5	5		0	0	0	0
	72 LW	L	5	5	5		0	0	0	0
TE04	25	R	20.8	21.3	20	21.2	.7	.035	-.05	-.069
	25	L	16.4	16.2	16.8	16.3	.3	.02	.05	.156
	72 SW	R	1	1	1		0	0	0	0
	72 SW	L	1	1	1		0	0	0	0
	72 MW	R	1	1	1		0	0	0	0
	72 MW	L	2.5	2	3		.7	.283	1	1
	72 LW	R	3	3	3		0	0	0	0
	72 LW	L	2.5	2	3		.7	.283	1	1
TE05	25	R	15.8	15.8			0	0	0	0
	25	L	17.9	18.5	17.3		.8	.047	-1.2	-1
TE06	25	R	20.1	20.1			0	0	0	0
	25	L	23.3	23	23.6		.4	.018	.6	1
TE07	25	R	8.4	8.3	8.5		.1	.017	.2	1
	25	L	10.6	11.7	9.4		1.6	.154	-2.3	-1
	72 SW	R	2	2			0	0	0	0
	72 SW	L	1	1			0	0	0	0
	72 MW	R	6	6			0	0	0	0
	72 MW	L	5	5			0	0	0	0
	72 LW	R	7	7			0	0	0	0
	72 LW	L	6	6			0	0	0	0
TE08	25	R	8	8.3	7.6		.5	.062	-.7	-1
	25	L	10	10	10		0	0	0	0
	72 SW	R	2	2			0	0	0	0
	72 SW	L	1	1			0	0	0	0
	72 MW	R	6	6			0	0	0	0
	72 MW	L	5	5			0	0	0	0
	72 LW	R	5	5			0	0	0	0
	72 LW	L	6	6			0	0	0	0

Table G.4 (Cont.)

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRASILIA - JUNE 1982

APL TRAILER

SITE	MEAS.	TRACK	ROUGHNESS MEASUREMENTS MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
TE09	25	R	13.7	14	13.4		.4	.031	-.6	-1
	25	L	15.7	15.4	16		.4	.027	.6	1
	72 SW	R	1	1			0	0	0	0
	72 SW	L	1	1			0	0	0	0
	72 MW	R	4	4			0	0	0	0
	72 MW	L	3	3			0	0	0	0
	72 LW	R	6	6			0	0	0	0
	72 LW	L	5	5			0	0	0	0
TE10	25	R	15	14.8	15.2		.3	.019	.4	1
	25	L	19.5	21.3	17.8		2.5	.127	-3.5	-1
	72 SW	R	1	1			0	0	0	0
	72 SW	L	1	1			0	0	0	0
	72 MW	R	3	3			0	0	0	0
	72 MW	L	2	2			0	0	0	0
	72 LW	R	5	5			0	0	0	0
	72 LW	L	4	4			0	0	0	0
TE11	25	R	13	13.7	12.2		1.1	.082	-1.5	-1
	25	L	20.6	26.9	14.3		8.9	.433	-12.6	-1
	72 SW	R	1	1			0	0	0	0
	72 SW	L	1	1			0	0	0	0
	72 MW	R	4	4			0	0	0	0
	72 MW	L	1	1			0	0	0	0
	72 LW	R	5	5			0	0	0	0
	72 LW	L	3	3			0	0	0	0
TE12	25	R	20.3	20.1	20.4		.2	.01	.3	1
	25	L	15.9	21.5	10.3		7.9	.498	-11.2	-1
	72 SW	R	1	1			0	0	0	0
	72 SW	L	1	1			0	0	0	0
	72 MW	R	2	2			0	0	0	0
	72 MW	L	2	2			0	0	0	0
	72 LW	R	3	3			0	0	0	0
	72 LW	L	4	4			0	0	0	0

of them. It was also the case for the TE sections (earth roads) with the exception of sections TE 05 and TE 06 which were not measured. For the gravel road sections, the measurement was carried out only in the left track (L) of sections GR 01 - GR 04, GR 9, and GR 10, and between tracks (represented by the letter B) for the sections GR 05 to GR 08. Sections GR 11 and GR 12 were not measured.

Tables G.1 to G.4 show the APL 72 indices (I) as they were calculated during the IRRE in Brazil. The values provided are for only a 200 m continuous segment entirely included in each 320 m test section. Of course, when the test sections are not homogeneous along their lengths, the reported values may not truly represent the average APL 72 index of the whole section. But in these cases, the choice of only one numeric to characterize the whole section roughness would not, itself, be very representative.

The tables show that nearly all of the earth sections have an APL 72 SW index near 1 (the category for the worst roads), as do more than half of the gravel sections. Indeed, the APL 72 index scales used during the IRRE were derived to match the range of observed roughness in the French road network, but they could be modified in order to give representation over a larger roughness range (this was not done in the IRRE). The fact that the APL 72 (I) numeric does not distinguish roughness levels for the unpaved roads is the result of the category definitions, rather than the measurement and analyses preceding the categorization. When the APL 72 index is not used, the roads can be quantified by the mean-square energy (W) and equivalent amplitude (Y) numerics.

Tables G.5 and G.6 show the complementary APL 72 results as they are obtained in France by LCPC and in Belgium by CRR. They give (for one run only):

- The values of the total (mean square) energy (W) and the equivalent displacement (Y) for a 200-m continuous segment entirely included in each 320-m test section (LCPC method). Both W and Y values are given for the three wavebands described earlier: Short wavelengths (abbreviated as SW), Medium wavelengths (MW), and Long wavelengths (LW)

SECTIONS		(W) APL 72			(Y) APL 72			(CP) APL 72		
		SW	MW	LW	SW	MW	LW	2,5 m	10 m	40 m
CA 01	R	8.8	124.6	1434.4	2.9	11.1	37.8	58	176	536
	L	9.9.	119.9	1571.9	3.1	10.9	39.6	54	153	499
CA 02	R	12	83.9	785.4	3.4	9.1	28	62	158	386
	L	12.1	76.9	754.6	3.4	8.7	27.4	67	169	453
CA 03	R	31	120.6	829.7	5.5	10.9	28.8	91	184	468
	L	27.2	117.6	554.7	5.2	10.8	23.5	90	191	579
CA 04	R	17	143.9	1246.5	4.1	11.9	35.3	72	184	530
	L	25.4	139.1	978.7	5	11.7	31.2	88	192	501
CA 05	R	27.8	147.2	318.4	5.2	12.1	17.8	76	172	507
	L	33.4	172	665.6	5.7	13.1	25.8	103	207	504
CA 06	R	22.8	82.6	1026.4	4.7	9	32	100	193	507
	L	26.6	75.2	1179.1	5.1	8.6	34.3	116	206	493
CA 07	R	6.8	37	298.2	2.6	6	17.2	42	87	218
	L	5.7	20.1	102.8	3.6	5.3	10.1	56	89	219
CA 08	R	6	18.3	162	2.4	4.2	12.7	41	78	221
	L	7.7	16.6	252.4	2.7	4	15.8	43	87	247
CA 09	R	8.5	38.3	478.7	2.9	6.1	21.8	49	114	302
	L	12.8	27.9	759.1	3.5	5.2	27.5	70	126	370
CA 10	R	11.6	42	247.3	3.4	6.4	15.7	56	128	332
	L	21.4	49	495.9	4.6	7	22.2	69	128	319
CA 11	R	21.7	189.7	845.9	4.6	13.7	29	76	181	421
	L	13.9	82.9	546.2	3.7	9.1	23.3	62	157	443
CA 12	R	3.6	14	434.5	1.9	3.7	20.8	28	61	228
	L	3.1	8.3	328.4	1.7	2.8	18.1	29	59	262
CA 13	R	3	12.9	313.3	1.7	3.6	17.7	29	63	236
	L	2.9	8.1	273.9	1.7	2.8	16.5	27	62	217
TS 01	R	23.2	18.6	214	4.8	4.3	14.6	74	97	238
	L	15.1	18.1	158.7	3.9	4.2	12.6	66	92	210
TS 02	R	18.7	42.8	638.8	4.3	6.5	25.2	73	121	402
	L	18.2	36.9	361.1	4.2	6	19	74	117	353
TS 03	R	20.1	27.7	674.9	4.4	5.2	25.9	75	109	377
	L	23.4	27	447	4.8	5.1	21.1	85	118	346
TS 04	R	30.2	29.3	314.3	5.5	5.4	17.7	96	126	261
	L	21.5	20.7	215.1	4.6	4.5	14.6	81	107	271
TS 05	R	25	18.3	102.3	5	4.2	10.1	85	101	179
	L	33.7	23.4	95.3	5.8	4.8	9.7	102	117	172
TS 06	R	7.3	23.6	221.4	2.7	4.8	14.8	46	97	304
	L	10.3	30.9	374.9	3.2	5.5	19.3	54	101	282
TS 07	R	9	48.6	277	3	6.9	16.6	50	99	276
	L	9.5	39.4	236.9	3	6.2	15.3	51	99	268
TS 08	R									
	L	11.6	61.5	1173.1	3.4	7.8	34.2	50	80	239
TS 09	R	15.9	20.1	438.3	3.9	4.4.	20.9	61	101	252
	L	13.9	16	289.1	3.7	4	17	59	87	215
TS 10	R	13.4	32	104.5	3.6	5.6	10.2	59	101	212
	L	18.5	19.4	82.9	4.3	4.4.	9.1	63	90	171
TS 11	R	7.2	11.8	90.7	2.6	3.4	9.5	35	65	218
	L	5.5.	15.5	114.7	2.3	3.9	15.5	37	63	249
TS 12	R	4.1	9.8	1043.1	2	3.1	32.2	40	69	354
	L	5.1	5.7	564.1	2.2	2.4	5.7	41	61	272

TABLE G.5 : COMPLEMENTARY APL 72 RESULTS OBTAINED ON THE PAVED ROADS (CA AND TS SECTIONS)

SECTIONS		(W) APL 72			(Y) APL 72			(CP) APL 72		
		SW	MW	LW	SW	MW	LW	2,5 m	10 m	40 m
TE 01	R	13.2	50.8	844.1	3.6	7.1	29	65	117	367
	L	21.9	52.6	1328.8	4.6	7.2	36.4	76	136	462
TE 02	R	18.9	50.2	410.2	4.3	7	20.2	76	133	351
	L	16.5	20.6	806.3	4	4.5	28.3	68	107	395
TE 03	R	32.4	55.7	498.8	5.7	7.4	22.3	110	171	558
	L	37.2	131.7	582	6.1	11.4	24.1	139	206	490
TE 04	R	30.1	225	1138.3	5.4	15	33.7	107	249	575
	L	37.2	138.8	1558.4	6.1	11.7	39.4	149	219	592
TE 05	R			NO MEASUREMENT						
	L									
TE 06	R			NO MEASUREMENT						
	L									
TE 07	R	21.7	35.4	227.6	4.6.	5.9	15	80	111	295
	L	24.1	52.3	335.3	4.9	7.2	18.3	86	126	251
TE 08	R	20.9	21.3	477.8	4.5	4.6	21.8	82	110	366
	L	24.9	39.6	296.2	4.9	6.3	17.2	91	130	305
TE 09	R	32.8	85.5	374	5.7	9.3	19.3	115	164	341
	L	37.2	128.9	507.4	6.1	11.3	22.5	142	203	397
TE 10	R	37.2	109.9	504.5	6.1	10.4	22.4	141	196	408
	L	37.2	199.3	866.6	6.1	14.1	29.4	171	254	479
TE 11	R	37.2	85.6	509.3	6.1	9.2	22.5	145	193	316
	L	37.2	225	1281.7	6.1	15	35.8	172	320	635
TE 12	R	37.2	148.8	1036	6.1	12.2	32.1	136	228	479
	L	37	147.3	626.7	6	12.1	25	80	208	406
GR 01	R									
	L	13.3	17.4	355.2	3.6	4.1	18.8	58	85	348
GR 02	R									
	L	12.9	14.2	733.6	3.5	3.7	27	58	91	428
GR 03	R									
	L	33.4	94.6	1079.9	5.7	9.7	32.8	103	184	464
GR 04	R									
	L	36	109.9	574.5	6	10.4	23.9	113	176	404
GR 05	R									
	B	37.2	104.1	464.4	6.1	10.2	21.5	169	217	402
GR 06	R.									
	B	37.2	117.8	525.4	6.1	10.8	22.9	153	231	393
GR 07	R									
	B	30.6	42.4	270.9	5.5	6.5	16.4	89	121	298
GR 08	R									
	B	15.3	16.9	179.1	3.9	4.1	13.3	75	108	329
GR 09	R									
	L	37.2	98.6	965.5	6.1	9.9	31	139	200	482
GR 10	R									
	L	37.2	94.6	359.2	6.1	9.7	18.9	134	202	372
GR 11	R			NO MEASUREMENT						
	L									
GR 12	R			NO MEASUREMENT						
	L									

Table G.6 : Complementary APL 72 results obtained on the unpaved roads (GR and TE sections)

- The values of the (CP) coefficients determined by the CRR method for a set of three bases (of moving average), namely, the conventional values in practice in Belgium which are 2.5 m, 10 m, and 40 m

Additional analyses were performed by LCPC and CRR related to the QI roughness scale, and these results are reported in Appendix E. Additional computations were performed at UMTRI using (approximately) the CP moving average technique, applied to both APL and statically measured profile signals. These results are reported in Appendix J.

Comparison of APL Results with RTRRMS Results

Linear regressions were calculated between the APL numerics and those obtained from the RTRRMSs. The correlations, defined by the square of the correlation coefficient (R-squared) are summarized in the correlation matrices presented in Tables G.7 - G.10. In performing these regressions, the test data were segregated by speed and surface type. For the APL 72 energy values (W) and the APL 72 equivalent displacement (Y), linear regressions were calculated only with Maysmeter 02 and Bump Integrator trailer results. Linear regressions were used as a first step in the analysis, even while recognizing that higher correlations could often be obtained by nonlinear regression models.

The overall examination of Tables G.7 - G.10 shows that the quality of the correlations obtained depends naturally on the type of test sections, the types of RTRRMSs, and their measuring velocity, but that this quality is most of all influenced by the model of processing the APL signal, particularly by the choice of the wavelength range that is used. The correlations obtained for each type of APL analysis are discussed below.

CAPL 25. Scatter plots between CAPL 25 and RTRRMS numerics (not included) show that the relationship between the CAPL 25 and a RTRRMS measure is strongly dependent on surface type. As indicated by the correlation matrices in the tables, good correlations are found only on the asphaltic concrete surfaces; correlations are poorest for the surface treatment and gravel sections. As was seen earlier, the CAPL treatment is an amplitude

ASPHALTIC CONCRETE TEST SITES (CA)

APL numérics \ RTRRMS		M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25		.7323	.7606	.8057	.7280	.7356	.6952	.5646
APL 72 I	SW	.7035	.7405	.7511	.7041	.7005	.6847	.4270
	MW	.5551	.5806	.6155	.5385	.5468	.5825	.3346
	LW	.4908	.5195	.6054	.4935	.5047	.4608	.4604
APL 72 W	SW		.8509				.8278	
	MW		.5752				.4985	
	LW							
APL 72 Y	SW		.8439				.8051	
	MW		.6088				.5238	
	LW							
APL 72 CP	2,5	.8676	.9101	.9296	.8898	.8864	.8845	.7334
	10	.7539	.7908	.8357	.7584	.7736	.7118	.5728
	40	.6004	.6225	.6816	.6069	.6253	.5650	.5166

TEST SITES WITH SURFACE TREATMENT (TS)

APL numérics \ RTRRMS		M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25		.3670	.3820	.5322	.4248	.4570	.3763	.2719
APL 72 I	SW	.8383	.8416	.9148	.8611	.8849	.8253	.7046
	MW	.0911	.0968	.2248	.1000	.1267	.0757	.0483
	LW	.0031	.0044	.0095	.0034	.0003	.0002	.0363
APL 72 W	SW		.8553				.8453	
	MW		.0063				.0062	
	LW							
APL 72 Y	SW		.8583				.8444	
	MW		.0259				.0223	
	LW							
APL 72 CP	2,5	.8738	.8747	.9302	.9289	.9283	.8764	.8871
	10	.6477	.6371	.8219	.7002	.7348	.5774	.4690
	40	.0231	.0138	.0035	.0113	.0085	.0132	.0174

GRAVEL SURFACED TEST SITES (GR)

APL numérics \ RTRRMS		M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25		.3891	.6054	.4973	.5391	.5188	.4491	.7478
APL 72 I	SW	.7373	.6982	.4966	.7344	.7260	.6901	.8130
	MW	.8005	.8135	.4780	.8373	.8165	.7892	.8533
	LW	.0881	.0961	.0020	.1078	.0977	.0848	.1037
APL 72 W	SW		.8103				.7929	
	MW		.8042				.8012	
	LW							
APL 72 Y	SW		.8007				.7857	
	MW		.8207				.8099	
	LW							
APL 72 CP	2,5	.9009	.9173	.8412	.9076	.9068	.9242	.8295
	10	.8759	.8943	.6173	.9223	.9181	.9030	.8328
	40	.1636	.1855	.0244	.1980	.1841	.1730	.1899

EATH (CLAY) SURFACE TEST SITES (TE)

APL numérics \ RTRRMS		M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25		.8120	.7481	.7463	.7331	.7261	.6669	.7046
APL 72 I	SW	.4963	.6086	.7319	.6174	.6102	.6034	.6002
	MW	.7848	.7279	.7800	.7392	.7402	.7228	.6709
	LW	.2376	.1060	.0912	.1140	.1175	.1049	.0684
APL 72 W	SW		.8557				.8376	
	MW		.7569				.7491	
	LW							
APL 72 Y	SW		.8408				.8235	
	MW		.8035				.7920	
	LW							
APL 72 CP	2,5	.8175	.9103	.8366	.9539	.9438	.8822	.8860
	10	.9168	.8582	.8017	.8884	.8860	.8288	.7970
	40	.4142	.2773	.2951	.3380	.3219	.2603	.1816

TABLE G.7 : CORRELATION MATRIX OF R. SQUARED VALUES FOR THE APL RESULTS AND RTRRMS MEASURES MADE AT 20 KM/H

ASPHALTIC CONCRETE TEST SITES (CA)

APL numerics \ RTRRMS			M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25			.8094	.8353	.8044	.7860	.8072	.7170	.4705
APL 72	I	SW	.7361	.7600	.7859	.7403	.7492	.7080	.3701
		MW	.6580	.6597	.6750	.6047	.6320	.4936	.2424
		LW	.5685	.6107	.5433	.5513	.5693	.4854	.3467
	W	SW		.8722				.8375	
		MW		.6568				.4892	
		LW							
	Y	SW		.8632				.8205	
		MW		.6682				.5062	
		LW							
	CP	2,5	.8742	.9267	.8768	.9152	.9120	.9196	.6707
		10	.8341	.8652	.8355	.8202	.8350	.7433	.4726
		40	.6905	.7274	.6264	.6678	.6840	.5786	.4033

TEST SITES WITH SURFACE TREATMENT (TS)

APL numerics \ RTRRMS			M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25			.3872	.3776	.4861	.3924	.4140	.4146	.4586
APL 72	I	SW	.8713	.8523	.8683	.8660	.8669	.8647	.8044
		MW	.0832	.0825	.1802	.0824	.0924	.0994	.1216
		LW	.0062	.0081	.0164	.0038	.0034	.0055	.0022
	W	SW		.9024				.9095	
		MW		.0023				.0097	
		LW							
	Y	SW		.8931				.8920	
		MW		.0188				.0292	
		LW							
	CP	2,5	.9580	.9535	.9482	.9368	.9424	.9189	.9177
		10	.6798	.7218	.7765	.7163	.7267	.6294	.6704
		40	.0776	.0132	.0004	.0205	.0176	.0013	.0195

GRAVEL SURFACED TEST SITES (GR)

APL numerics \ RTRRMS			M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25			: 2476	.5071	.4338	.4719	.4645	.4623	.8044
APL 72	I	SW	.6823	.6118	.4355	.6645	.6695	.6410	.7862
		MW	.7622	.7185	.4496	.7729	.7738	.7678	.8774
		LW	.0726	.0598	.0014	.0934	.0836	.1029	.1744
	W	SW		.7277				.7705	
		MW		.7289				.8062	
		LW							
	Y	SW		.7197				.7602	
		MW		.7399				.8082	
		LW							
	CP	2,5	.9239	.9147	.8464	.9154	.9252	.9068	.7917
		10	.8548	.8493	.6561	.8862	.8905	.9030	.8464
		40	.1448	.1300	.0228	.1719	.1644	.1958	.2813

EATH SURFACED TEST SITES (TE)

APL numerics \ RTRRMS			M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25			.7911	.7312	.7478	.7404	.7177	.7123	.6847
APL 72	I	SW	.6246	.7015	.7261	.6961	.7006	.6673	.6198
		MW	.7964	.7727	.7584	.8121	.7903	.8261	.7024
		LW	.1736	.1084	.0828	.1529	.1289	.1557	.0850
	W	SW		.9157				.8979	
		MW		.7926				.8467	
		LW							
	Y	SW		.9044				.8824	
		MW		.7702				.8571	
		LW							
	CP	2,5	.8326	.9106	.8352	.9314	.9383	.8635	.8979
		10	.9275	.8934	.7654	.6661	.9135	.9026	.8374
		40	.3668	.3245	.3139	.4839	.4254	.3536	.2214

TABLE G.8 : CORRELATION MATRIX OF R. SQUARED VALUES FOR THE APL RESULTS AND RTRRMS MEASURES MADE AT 32 KM/H

ASPHALTIC CONCRETE TEST SITES (CA)

APL numérics \ RTRRMS			M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25			.8832	.8711	.9352	.8380	.8789	.7534	.6939
APL 72	I	SW	.8119	.8123	.7845	.7702	.8036	.7387	.5931
		MW	.7335	.7247	.7672	.6246	.6942	.5327	.5220
		LW	.6610	.6898	.7429	.6236	.6568	.5184	.5225
	W	SW		.6890				.8294	
		MW		.5764				.5061	
		LW							
	Y	SW		.7362				.8194	
		MW		.6629				.5497	
		LW							
	CP	2,5	.9337	.8777	.9135	.9609	.9557	.9366	.7972
		10	.9106	.8998	.9430	.8634	.9038	.7807	.7123
		40	.7529	.7784	.7992	.7182	.7563	.6204	.6326

TEST SITES WITH SURFACE TREATMENT (TS)

APL numérics \ RTRRMS			M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25			.3632	.3940	.3348	.3654	.3746	.3781	.6432
APL 72	I	SW	.9021	.8964	.8361	.9018	.9042	.8854	.8169
		MW	.0694	.0911	.0463	.0770	.0800	.0826	.2370
		LW	.0157	.0115	.0124	.0171	.0142	.0205	.0161
	W	SW		.9063				.9568	
		MW		.0019				.0007	
		LW							
	Y	SW		.9193				.9368	
		MW		.0220				.0125	
		LW							
	CP	2,5	.9442	.9244	.9198	.9578	.9639	.9594	.7691
		10	.7141	.7189	.6290	.7233	.7104	.6392	.5263
		40	.0010	.0048	.0032	.0037	.0026	.0006	.0043

GRAVEL SURFACED TEST SITES (GR)

APL numérics \ RTRRMS			M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25			.0384	.4411	.4615	.4699	.4246	.4846	.7031
APL 72	I	SW	.7047	.6647	.6638	.6402	.6493	.6409	.6863
		MW	.7698	.7642	.7169	.7388	.7487	.7626	.8251
		LW	.0625	.0501	.0167	.0630	.0564	.0664	.1529
	W	SW		.7883				.7660	
		MW		.7657				.8100	
		LW							
	Y	SW		.7807				.7565	
		MW		.7825				.8092	
		LW							
	CP	2,5	.9329	.9399	.9440	.9214	.9316	.9360	.7511
		10	.8671	.8753	.8462	.8706	.8815	.6393	.7759
		40	.1258	.1210	.0699	.1340	.1254	.1588	.3187

EATH (CLAY) SURFACE TEST SITES (TE)

APL numérics \ RTRRMS			M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25			.6472	.6486	.5546	.6841	.6408	.6807	.8532
APL 72	I	SW	.6968	.7251	.7425	.7410	.7321	.6852	.7685
		MW	.7533	.8040	.6265	.8225	.7999	.8504	.8629
		LW	.0893	.1186	.0205	.1602	.1180	.2044	.1024
	W	SW		.9128				.8718	
		MW		.8218				.8791	
		LW							
	Y	SW		.9031				.8599	
		MW		.7297				.6336	
		LW							
	CP	2,5	.8934	.9057	.9068	.8628	.9044	.8264	.8901
		10	.8511	.8998	.7167	.8742	.8832	.9447	.9410
		40	.2612	.3353	.1848	.5365	.3710	.4641	.5270

TABLE G.9 : CORRELATION MATRIX OF R. SQUARED VALUES FOR THE APL RESULTS AND RTRRMS MEASURES MADE AT 50 KM/H

ASPHALTIC CONCRETE TEST SITES (CA)

APL numérics \ RTRRMS		M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25		. 8782	. 8891	. 8793	. 6597	. 7828		. 8896
APL 72	I SW	. 8020	. 8070	. 7601	. 7019	. 7453		. 5921
	I MW	. 6920	. 6873	. 6745	. 2952	. 4312		. 9197
	I LW	. 6476	. 6593	. 6501	. 5012	. 5994		. 4383
	CP 2,5	. 9432	. 9578	. 8852	. 9348	. 9438		. 6085
	CP 10	. 8943	. 9047	. 8688	. 6807	. 8035		. 8615
	CP 40	. 7385	. 7637	. 6913	. 5526	. 6660		. 8291

TEST SITES WITH SURFACE TREATMENT (TS)

APL numérics \ RTRRMS		M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25		. 1952	. 2330	. 2677				
APL 72	I SW	. 7306	. 7809	. 6806				
	I MW	. 0323	. 0449	. 0825				
	I LW	. 0738	. 0671	. 0394				
	CP 2,5	. 8866	. 9164	. 8359				
	CP 10	. 4126	. 4526	. 4217				
	CP 40	. 0523	. 0542	. 0281				

GRAVEL SURFACED TEST SITES (GR)

APL numérics \ RTRRMS		M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25		. 7873	. 8283	. 7546				
APL 72	I SW	. 6217	. 6335	. 6157				
	I MW	. 7264	. 7576	. 7221				
	I LW	. 0368	. 0733	. 0836				
	CP 2,5	. 9631	. 9535	. 9055				
	CP 10	. 8675	. 8884	. 8388				
	CP 40	. 1179	. 1723	. 1683				

EARTH (CLAY) SURFACE TEST SITES (TE)

APL numérics \ RTRRMS		M M O 1	M M O 2	M M O 3	BI CAR	NAASRA	BI TRL (AVE)	BPR (AVE)
CAPL 25		. 6828	. 7457	. 7692				
APL 72	I SW	. 4207	. 7202	. 6219				
	I MW	. 6819	. 7760	. 7771				
	I LW	. 2676	. 0987	. 1301				
	CP 2,5	. 6151	. 8723	. 9196				
	CP 10	. 8363	. 8658	. 9011				
	CP 40	. 3962	. 2822	. 3222				

TABLE G.10 : CORRELATION MATRIX OF R. SQUARED VALUES FOR THE APL RESULTS AND THE RTRRMS MEASURES MADE AT 80 KM/H analysis of the road spectral wavelengths lying between 0.3 m and 15 m (high and medium wavenumbers), dominated by the influence of the longer wavelengths. When the spectrum is very rich in small wavelengths, which is particularly the case for surface treatment sections (TS), the CAPL 25 will less evidently bring out these effects than would the RTRRMS or other APL numerics.

APL 72 Index (I). Scatter plots between the SW and MW indices and the RTRRMS measures (not shown) indicate that a definite relationship is evident between the SW index and the RTRRMS measures on the smoother surfaces that is not strongly dependent on surface type. But the correlation is degraded on the rougher surfaces because the roughness range for the SW index does not extend far enough for the unpaved roads. (The SW index is 1--the bottom of the scale--for most of the unpaved roads and many of the surface treatment sites.) For the MW index, relationships can be seen with the RTRRMS measures, which are different for the different surface types. Compared to other correlations observed in the IRRE, the correlations between the MW index and the RTRRMS measures are not very good. For the LW indices, there is virtually no relationship with the RTRRMS measures, as indicated in the correlation matrices. Only on the CA sections do correlations exist, and even these are poor. Good correlations could not be expected because the RTRRMSs do not "see" these long wavelengths.

Overall, the comparison of the correlations obtained with the CAPL 25 coefficients or the APL 72 index show that when the small wavelengths are isolated from the rest, the results are clearly better. The remark made earlier for the TS sections (regarding correlation with the CAPL 25 numeric) is illustrated in Tables G.7 to G.10 by the differences obtained between correlations with the SW index and the MW index.

APL 72 Energy Values (W) and APL 72 Equivalent Displacement (Y). Some of the problems with correlating RTRRMS measures with the indices are eliminated by considering the W and Y values, which lie on a continuous roughness scale, rather than the discrete intervals 1 - 10.

The linear regressions were calculated only with the Maysmeter 02 and the Bumnp Integrator trailer since the principle of global energy (W) and equivalent displacement analysis is not different from the APL 72 Index (I), and that the values (W), (Y), (I) are not independent. Nevertheless, the values of (W) and (Y) are expressed in scales approximately linear and continuous. Tables G.7 to G.9 show that the correlations with the RTRRMSs are generally better for (W) and (Y) than for (I).

Figure G.2 shows example scatter plots for the SW energy (W) values, against the ARS measures obtained from one of the RTRRMSs. The regression lines are also shown. The relationship with the SW numerics is dependent on surface type for the lower RTRRMS speeds, but diminishes for the speed of 50 km/h. The correlations shown are good enough, particularly for the RTRRMS speed of 50 km/h, that the SW energy (W) numeric could be considered as a calibration reference for the RTRRMS.

Figure G.3 shows similar plots for the MW energy (W) numeric. In this case, the relationships are not as good, and are strongly influenced by surface type. The correlation with the RTRRMS is almost nonexistent for the surface treatment (TS) sites.

The results shown in Figs. G.2 and G.3 derive from the differences in wavenumber sensitivity between the APL numerics and the RTRRMS. In comparing the APL 72 wavebands to the Reference Quarter Car Simulation (RQCS) in Fig. F.2 in Appendix F (qualitatively similar to that of any RTRRMS), it can be seen that the RTRRMS responds to a broad band of wavenumbers, whereas the APL numerics selectively isolate narrow bands. Only the SW numerics (W, Y, I) include the shorter wavelengths, which constitute a major portion of the RTRRMS measures on all but the CA roads. The waveband data shown in Tables G.5 and G.6 (and also the Power Spectral Density (PSD) functions plotted in Appendix I) all indicate that the CA surfaces had proportionately more medium wavelength content than the other surface types. At the higher speed of 50 km/h, the RTRRMS is more influenced by the medium wavelengths, which leads to the observed reduced correlation with the SW numerics but improved correlation with the MW numerics (relative to the correlations observed for the lower speeds of 20 and 32 km/h).

APL 72 CP Coefficients. Examination of Tables G.7 - G.10 reveals that:

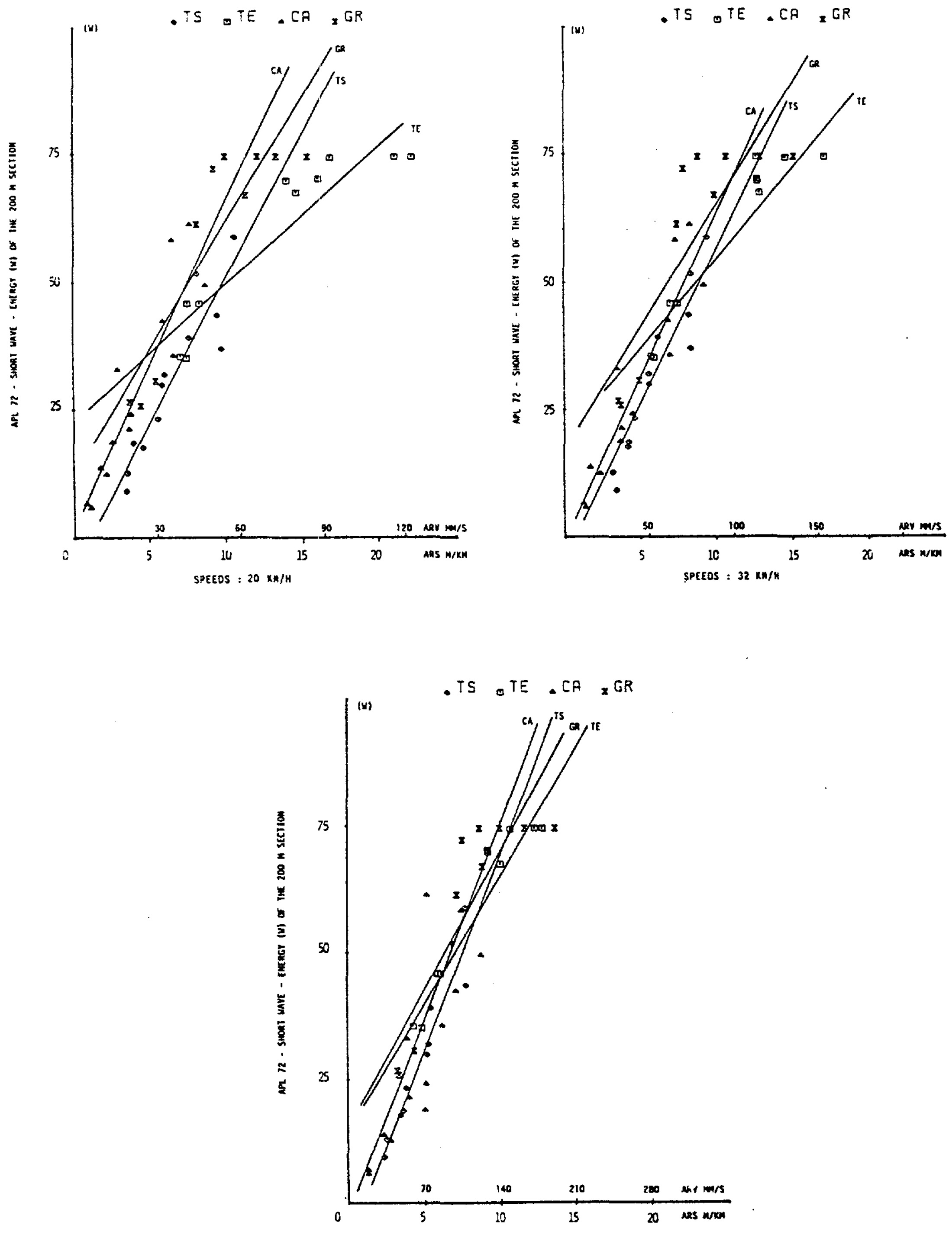


Figure G.2. Comparison of APL 72 short wave energy results (W) with Mays Meter 02 results

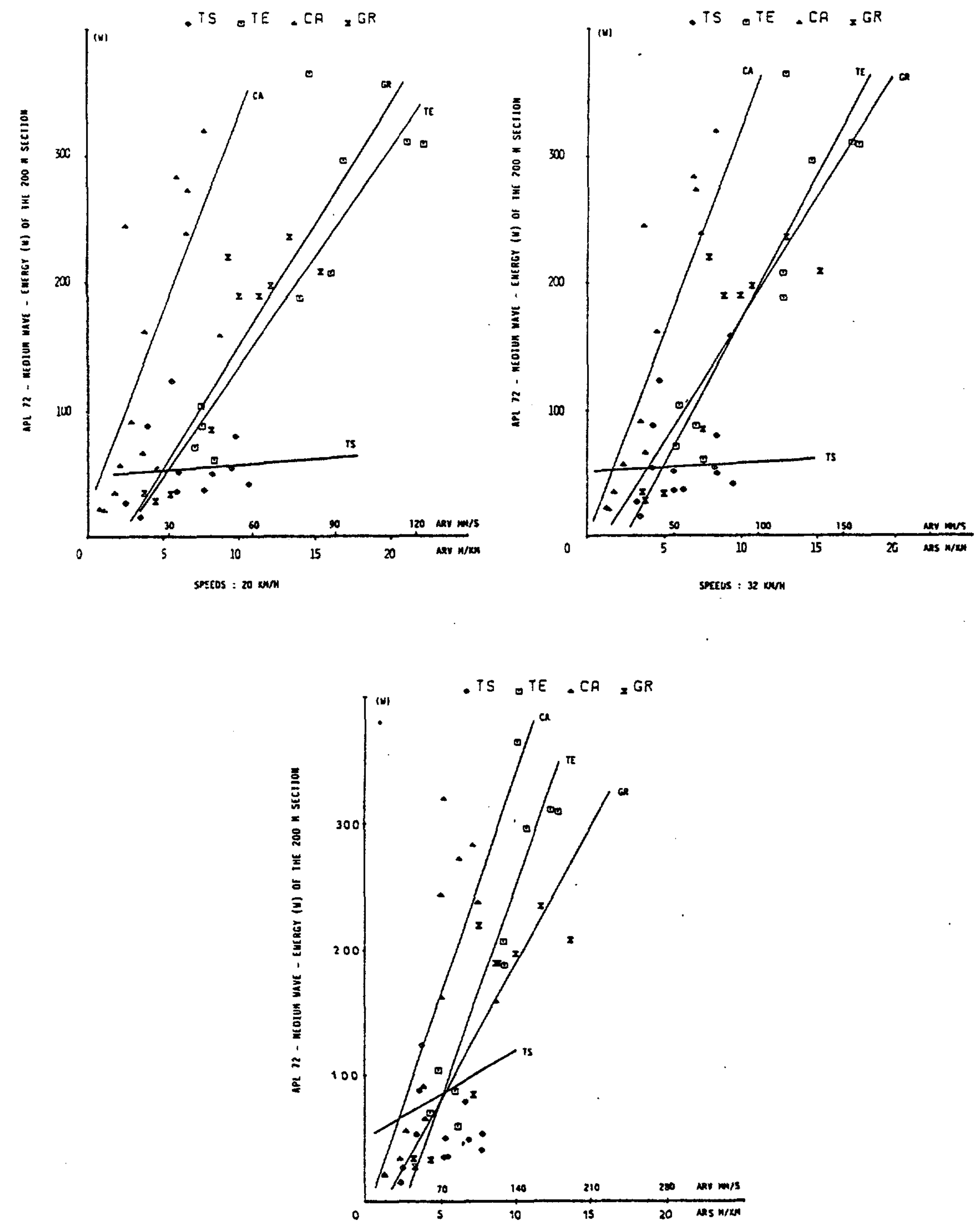


Figure G.3. Comparison of APL 72 medium wave energy results (W) with Mays Meter 02 results

- The R-squared value of the coefficients of correlation reduces, in general, as the base length for determination of the CP values increases.

- Significant and high correlation values are obtained for CP (base 2.5 m) with all RTRRMS devices on all test sites and for all the test speeds.

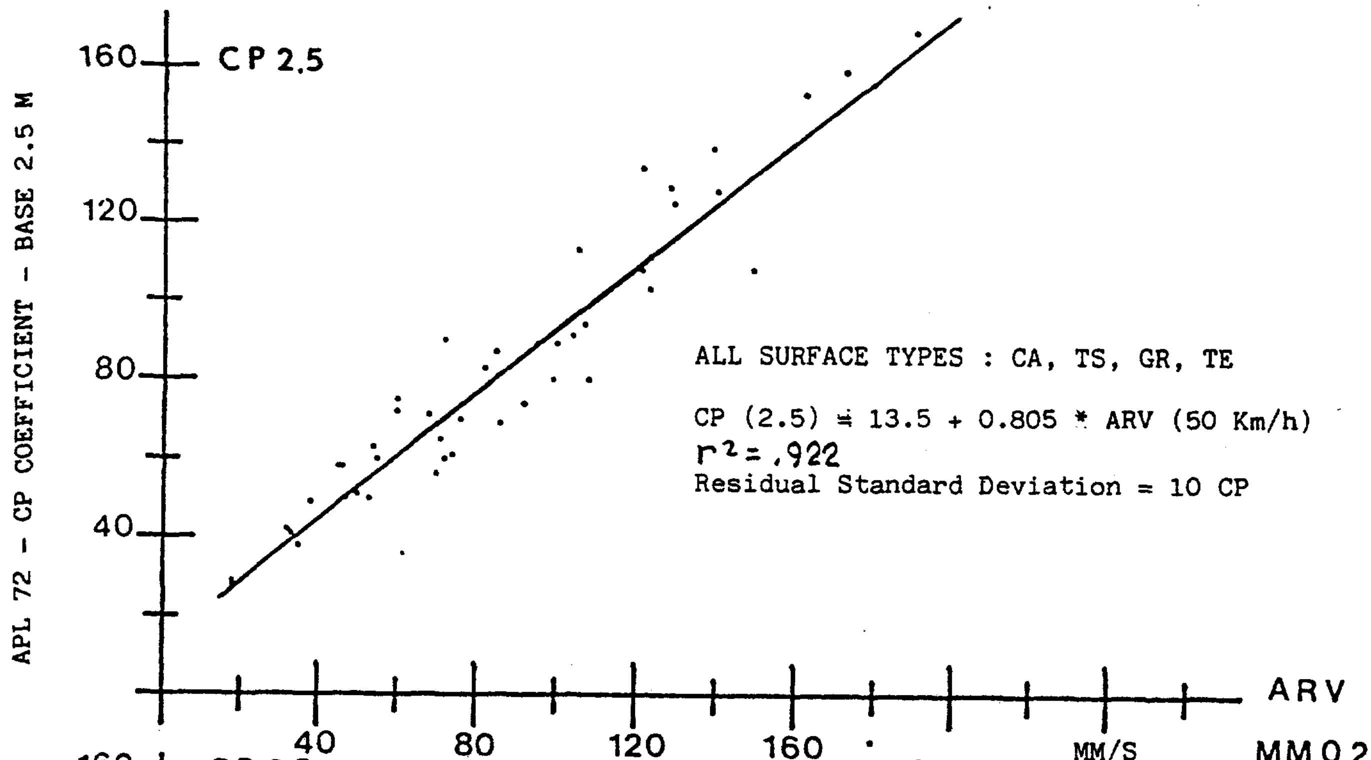
By merging all data belonging to a given RTRRMS device and calculating the linear regression coefficients and the correlation coefficient for each test speed, one can expect to evaluate the effects of speed and site factors that could influence a calibration plot that would be needed to estimate the CP (2.5) numerics from measurements made with one RTRMMS. This case has been examined for both the Maysmeter 02 and Bump Integrator trailers. It has been found that the best fit for the CP (2.5) values is obtained through correlation with both devices traveling at 50 Km/h and that no site type influences the correlation.

The two examples are illustrated in Figure G.4. Both correlations are significantly high ($r^2 > 0.90$) and yield nearly identical linear regression equations.

Figure G.5 shows the influence of the value of the moving average base (2.5 m or 10 m) and the velocity of measurement of the Maysmeter 02 on the correlations between CP values and Maysmeter 02 values. These CP (10) values bring out, just as do the APL 72 MS (W) values, the peculiarity of TS sections. But, in a general way, they confirm the greater sensitivity of the RTRRMSs to the smaller wavelengths.

Of all the APL results reported in this appendix, the CP (2.5) numerics produce the best correlations with the RTRRMSs, and that agreement is best for a RTRRMS speed of 50 km/h.

No effort was made to improve the correlations by using alternate baselengths, although it is likely that better correlation could be obtained by adjusting the baselength to obtain appropriate filtering. This hypothesis is supported by the analyses performed by TRRL, reported in Appendix H, where it was found that a baselength of 1.8 m gave improved correlations.



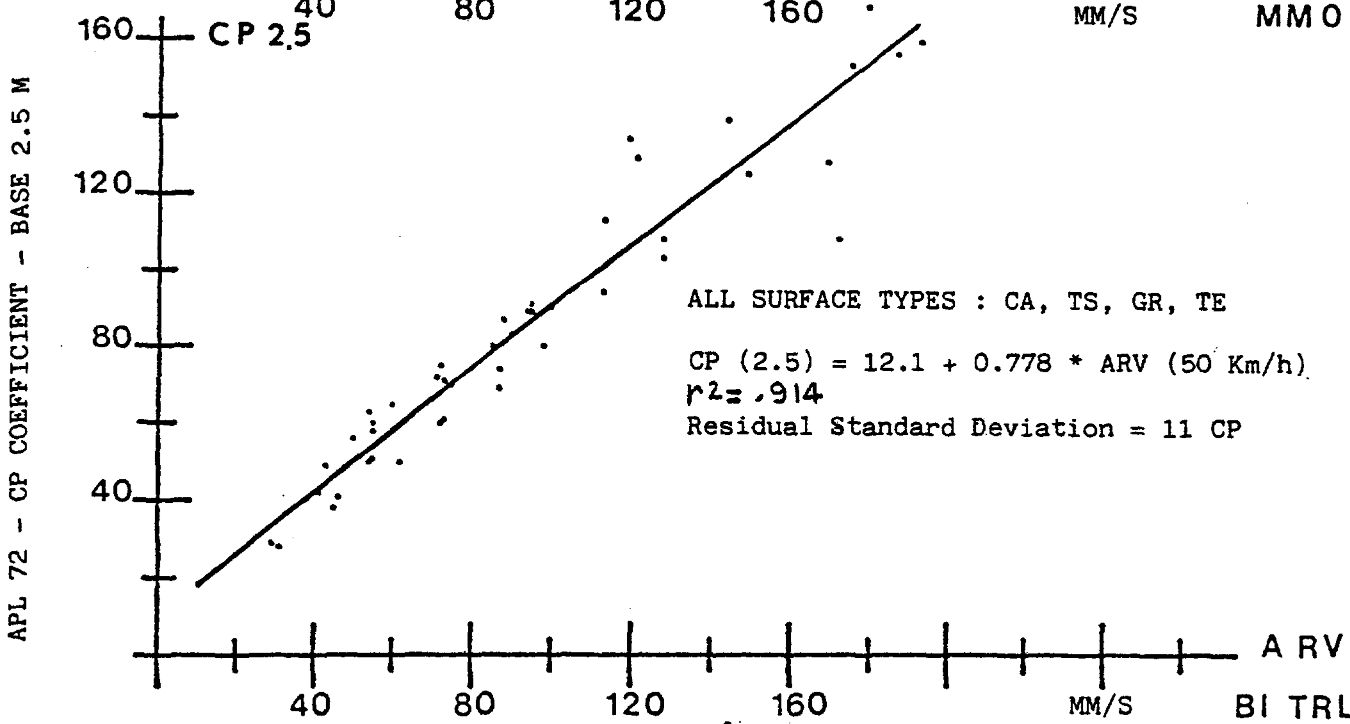
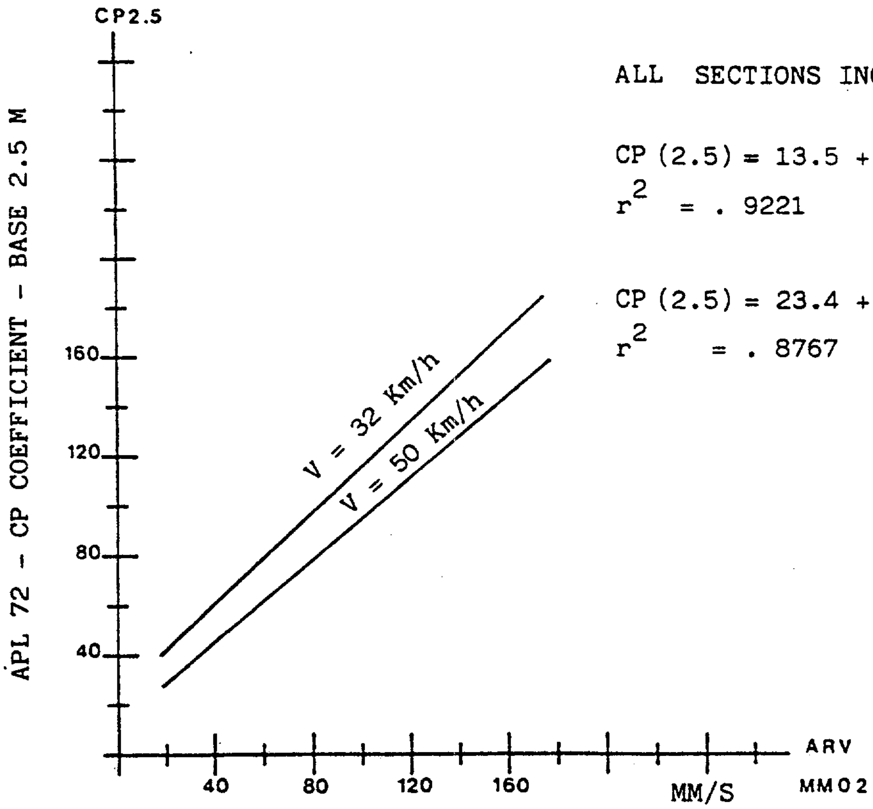


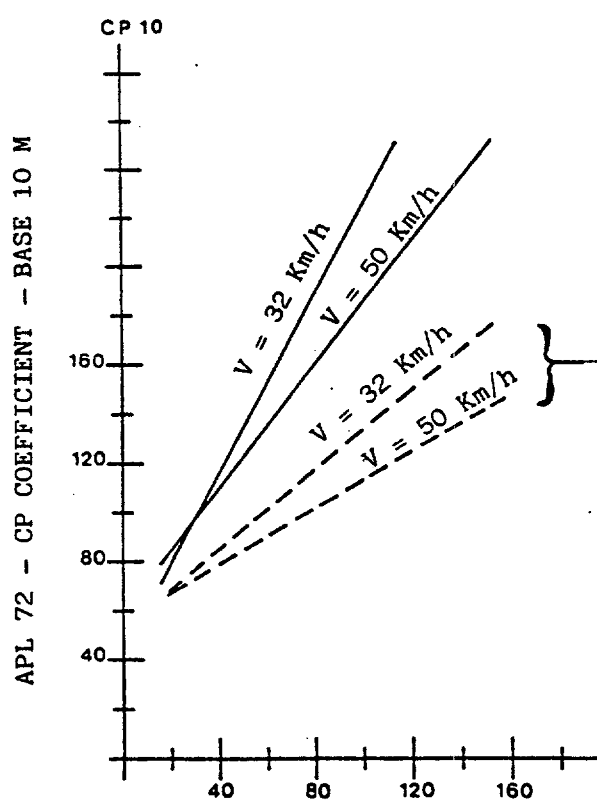
Figure G.4. Comparison of APL 72 CP (2.5) values with RTRRMS Measures made at 50 km/h



ALL SECTIONS INCLUDED CA, TS, GR, TE :

CP (2.5) = 13.5 + 0.805 * ARV (50 Km/h)
r^2 = . 9221

CP (2.5) = 23.4 + 0.929 * ARV (32 Km/h)
r^2 = . 8767



ALL SECTIONS INCLUDED CA, TS, GR, TE :

CP(10)= 44 + 1.11 * ARV (50 Km/h)
r^2 = . 7749

CP(10)= 59.3 + 1.25 * ARV (32 Km/h)
r^2 = . 7078

....

SECTIONS TS ONLY :

CP(10)==52.8 + 0.811 * ARV (32 Km/h)
r^2 = 0.7218

CP(10)= 54.8 + 0.587 * ARV (50 Km/h)
r^2 = . 7189

Figure G.5. Comparison of APL 72 CP (2.5) and APL 72 CP (10) with Mays Meter Ø 2 results

EXAMPLE APL PROFILES

Adding to the summary results presented, LCPC and CRR have provided a graphical representation of the test section profiles which were run by the APL trailer, since it was the only apparatus present during the IRRE which conveniently produced such results.

For each track of each test section measured, but for one run only, the graphs of APL 25 and APL 72 signals were represented for road lengths of about 1000 meters containing these test sections, and were made available to the participants in the IRRE. This representation was achieved with the help of a plotter recorder linked to a micro-computer which treated the digitized signals. (Sample intervals were 250 mm for the APL 25 signal and 50 mm for the APL 72 signal.)

In addition to the profile plots, PSD functions were computed immediately after the IRRE from all of the APL 72 signals for which the CP numerics were calculated. PSD functions were also computed at that time for the profiles measured statically with the TRRL Beam, and both sets were distributed to the participants in the IRRE. More recently, PSD functions were computed for all of the profile measurements obtained in the IRRE, and those plots are included in Appendix I.

Some examples of graphical representations of the APL profiles are included in this appendix and discussed below.

Figure G.6 shows the representations of APL 25 and APL 72 signals recorded on the same test section (CA 01 right track). Figure G.6a gives the complete graphical representation of the APL 72 analog signal (lower part of the figure) and the same signal for which the wavelength components above 18 meters have been eliminated by electronic filtering. Figure G.6b shows that this electronic filtering results in a signal that is nearly identical to the APL profile obtained with the APL 25 system at a lower speed in a different run. Figure G.6c shows the perfect (within the plotting precision) agreement between the digitized representation of the full APL 72 signal and its analog

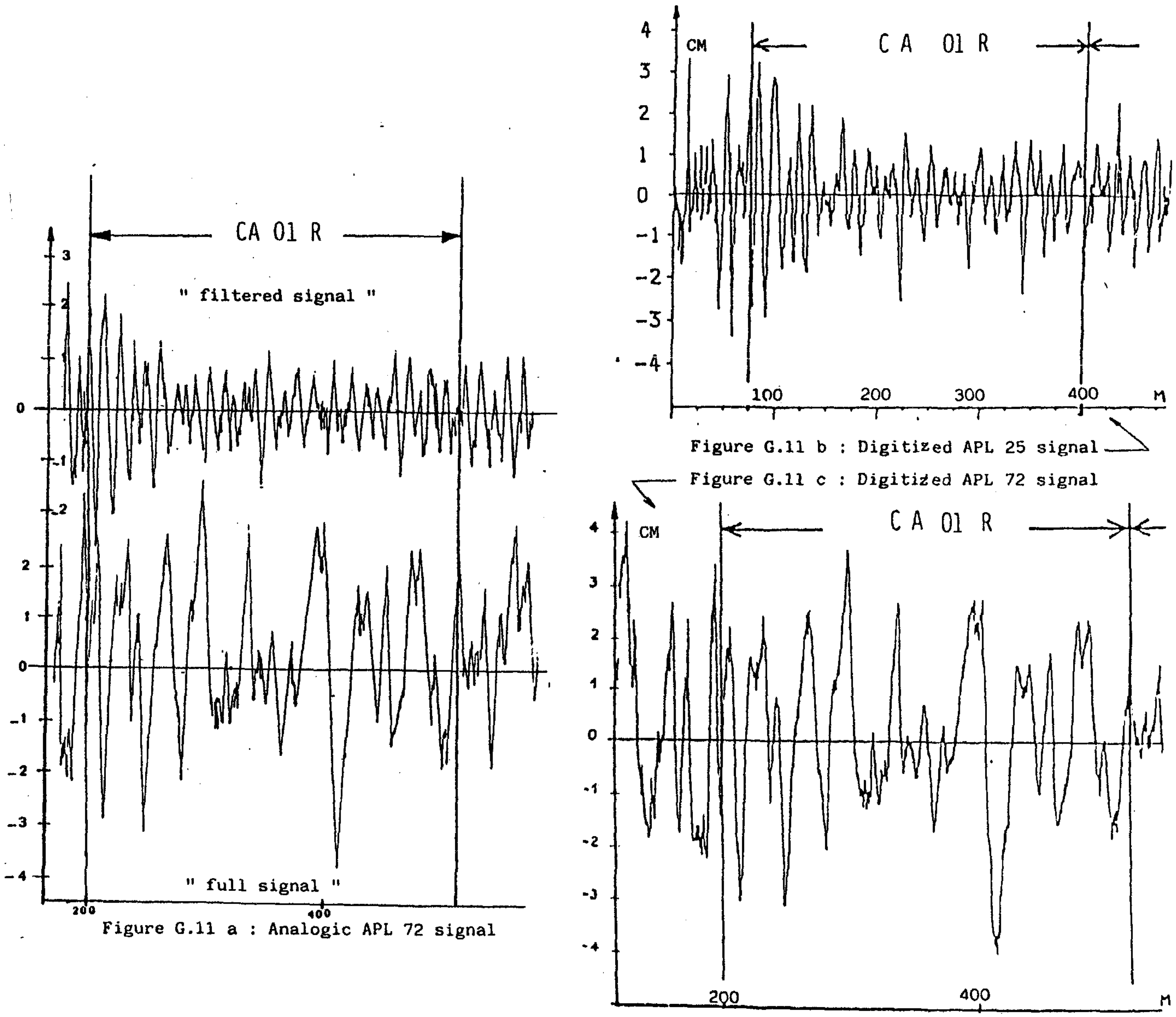


Figure G.11 a : Analogic APL 72 signal

Figure G.11 b : Digitized APL 25 signal

Figure G.11 c : Digitized APL 72 signal

Figure G.6. Different presentations of APL signals recorded on the section CA 01 Right Track representation.

Figure G.7 shows the profiles obtained from the APL 25 and 72 systems, and also the complete record of CAPL 25 numerics as they were measured over the length of the left-hand wheeltrack of test site TS 05. Figure G.8 presents similar measures for the left-hand wheeltrack of site TS 11. Figure G.9 compares the PSD functions of these two TS sections. (In preparing the PSD plots, a sample interval of 1/3 m was used. No extra filtering or windowing functions were applied. A section length of 340 m was transformed, in order to obtain 1024 samples as required by the Fast Fourier Transform (FFT) program used.) The PSD plots show the distribution of the mean square of the APL 72 signal across wavnumber. Thus, the vertical scale has units of displacement^2/(cycle/m) = m^3. The horizontal scale, which is plotted as wavenumber (cycle/m), is labelled with wavelength (m/cycle) for convenience in the following discussion. (PSDs of all APL profiles are provided in Appendix I.)

The content of the spectrum of section TS 05 L reveals the important presence of short wavelengths which appear also on the representation of the road profile as shown in Figure G.9. In contrast, section TS 11 L has a more regular spectrum where the shorter wavelengths do not prevail, which is also confirmed by the profile representation (Fig. G.10). Along with the RTRRMS measures, the APL 72 SW energy and the APL 72 CP (2.5) (Table G.5) reflect this difference between sections TS 05 and TS 11, and illustrate the sensitivity of these modes of roughness quantification for higher wavenumbers (shorter wavelengths). In fact, the TS 05 site was an "outlier" when RTRRMS measures made at 80 km/h were compared to the profile-based numerics. By inspecting the APL profile and PSD, the cause of the high value obtained from the RTRRMSs could be determined (the remarkably rich roughness content at a 2 m wavelength).

Figure G.10 shows how the APL profiles identify heterogeneities. Section TS 08 is located at the start of a steep slope (in the direction of measurement) and the road is built partially on an embankment which has settled over a length of about 50 meters. The APL 72 signal reveals the steep slope of the profile over the 200 meters that precede the beginning of the test section. APL 25 and APL 72 signals, together with the elementary values

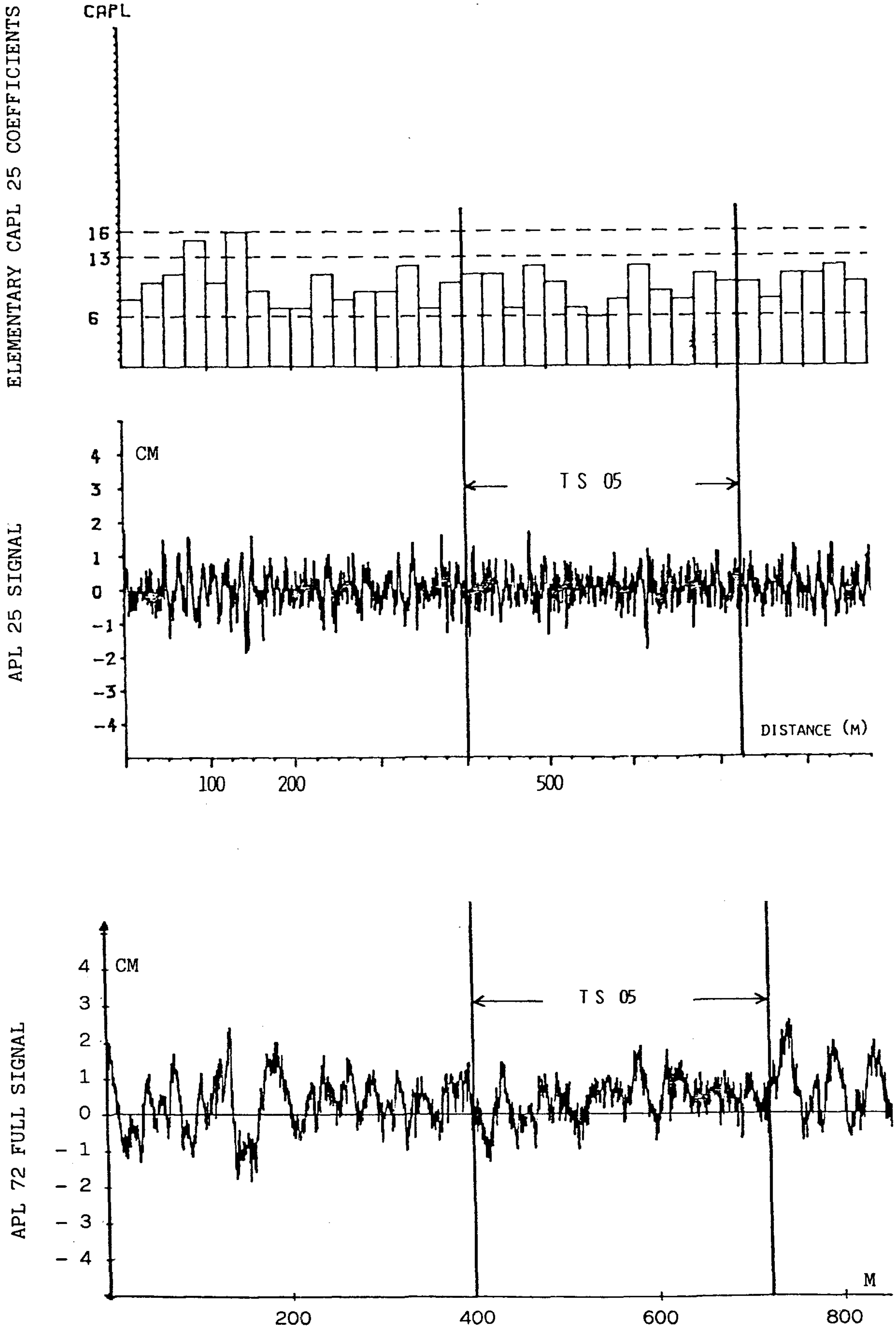


Figure G.7. APL signals measured on section test TS 05 left track

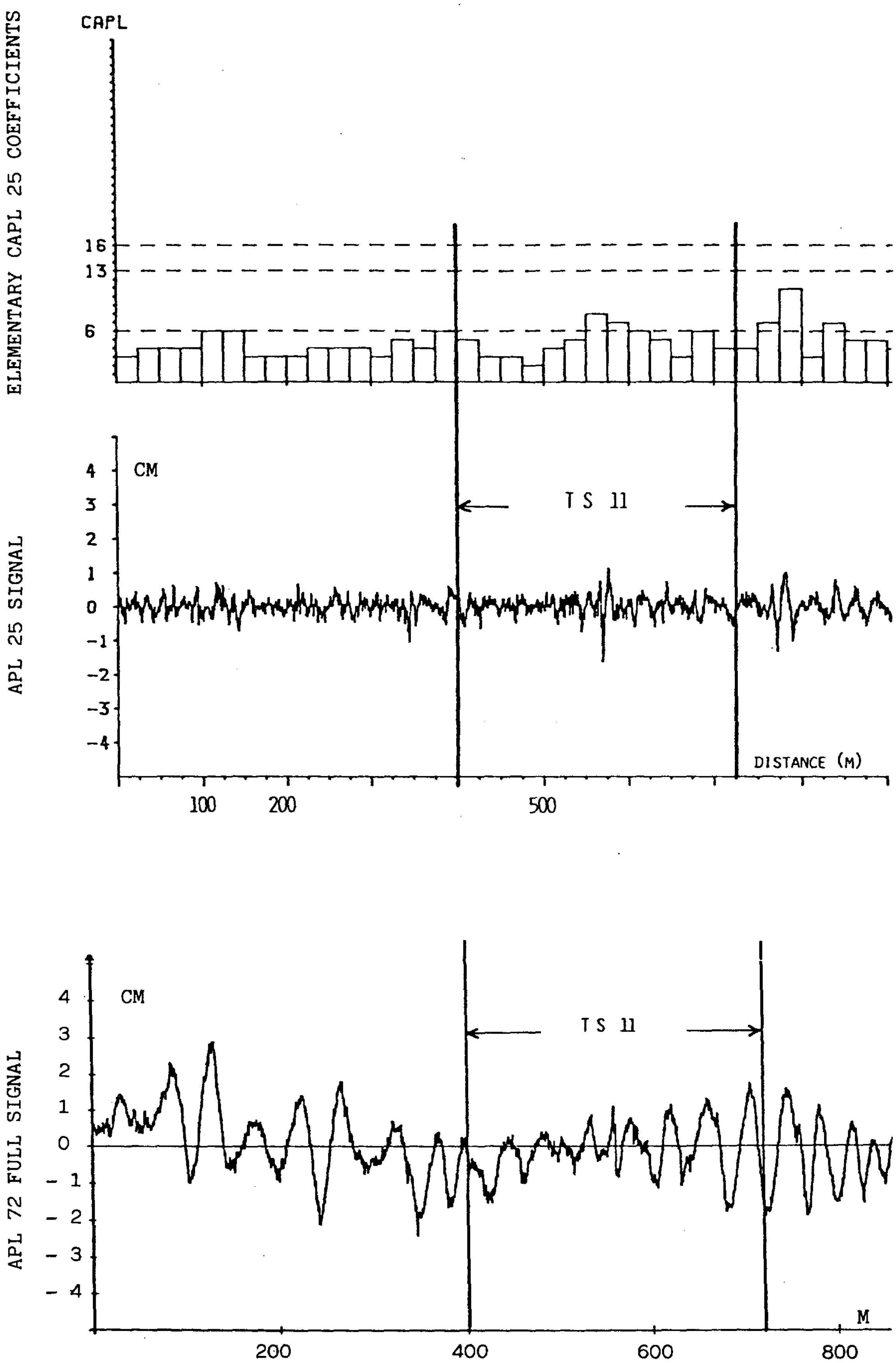


Figure G.8. APL signals measured on section test TS 11 left track

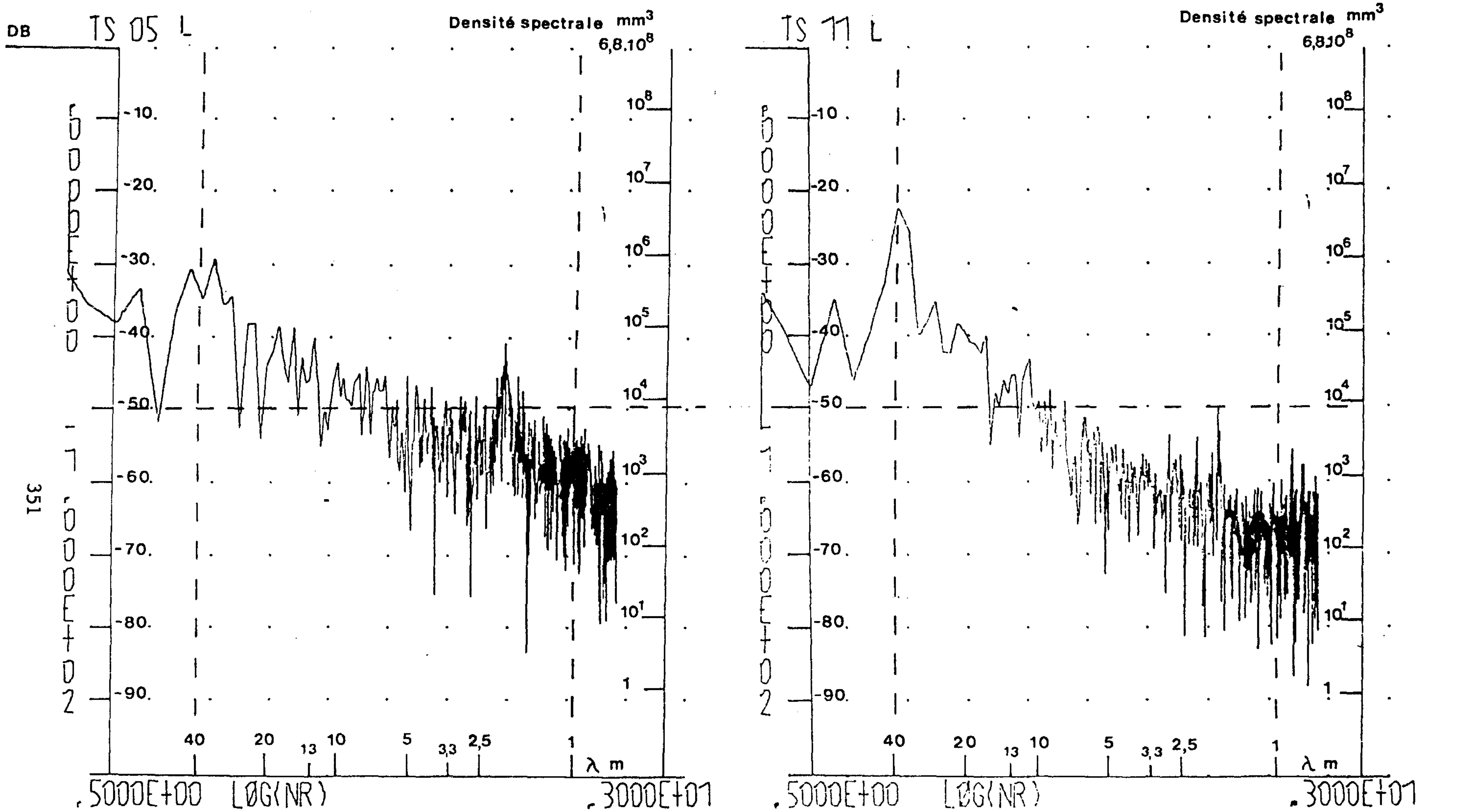
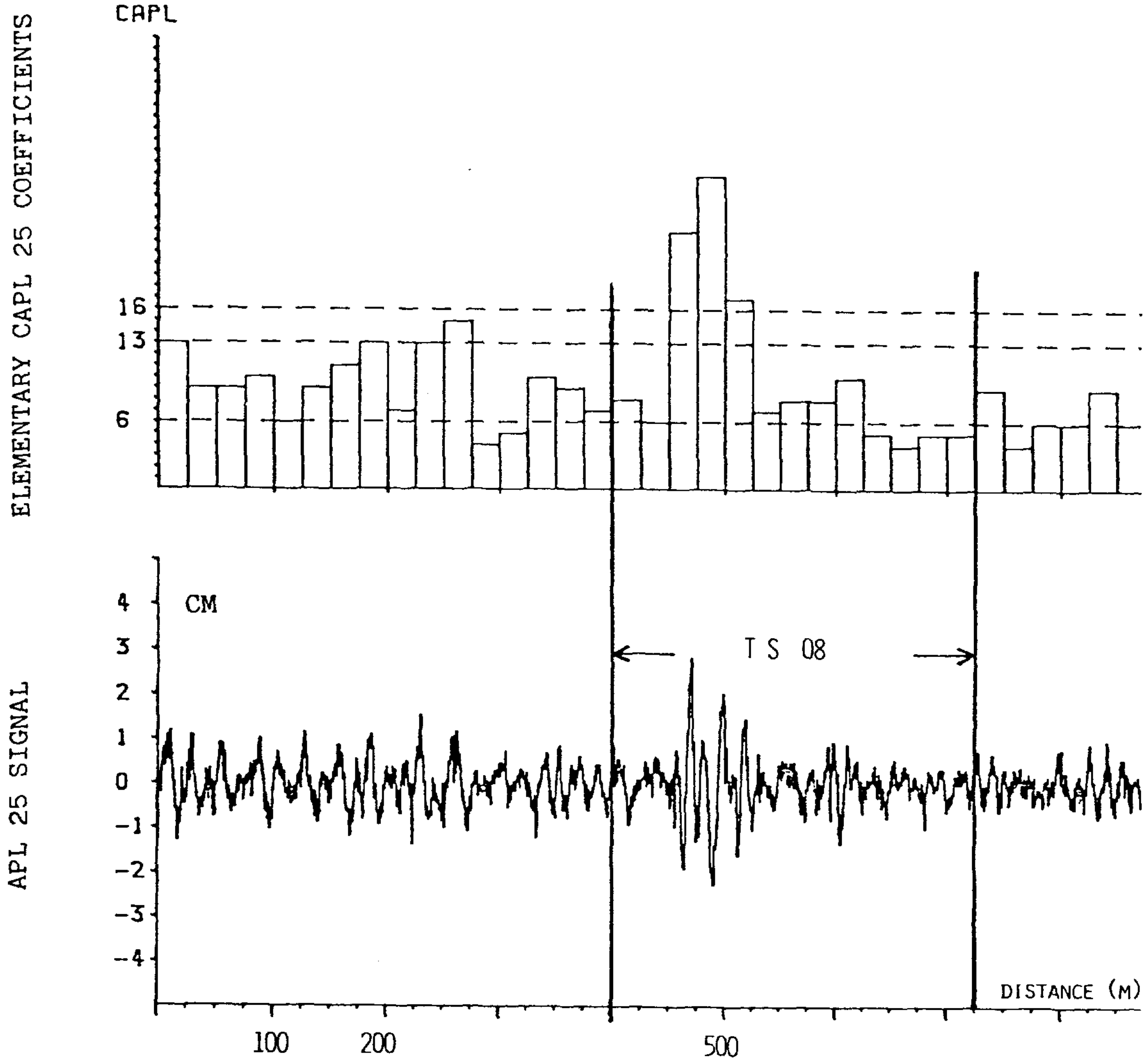


Figure G.9. POWER SPECTRAL DENSITY FROM APL 72 SIGNAL OF TS 05 LEFT TRACK AND TS 11 LEFT TRACK



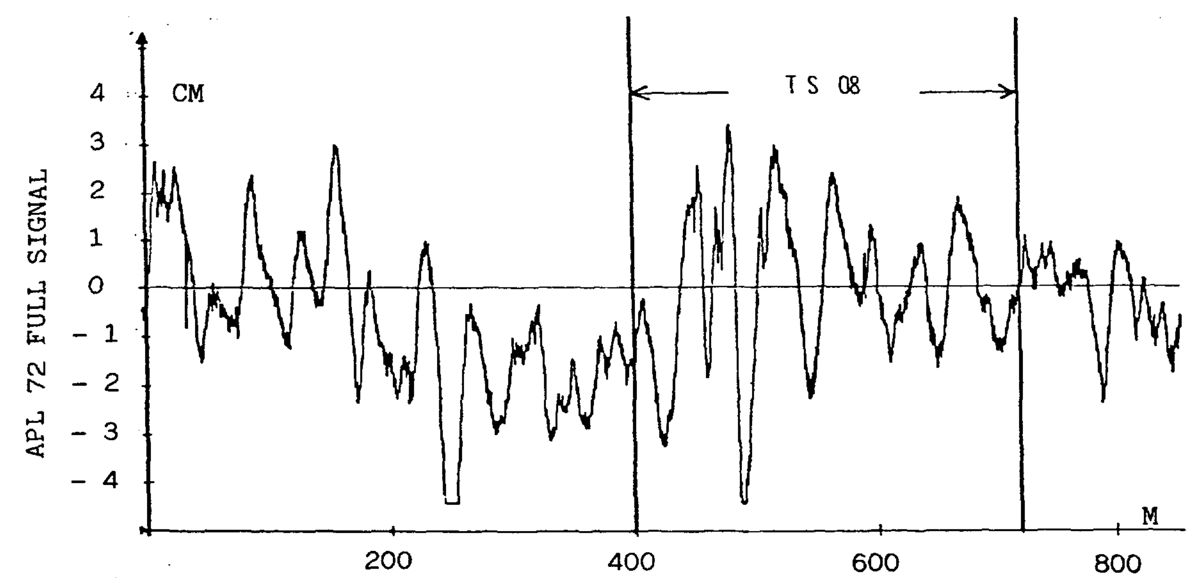


Figure G.10. APL signals measured on section test TS 08 left track

of CAPL 25 representation, clearly show this embankment settlement effect.

CONCLUSIONS

Considered as a profilometer, the APL Trailer is not comparable to static or quasi-static leveling systems which take the absolute profile of a road through an altimetric process based on a fixed horizontal reference. Nevertheless, the profilometric qualities of the APL are largely sufficient to give a significant representation of a road profile in the range of wavelengths from 0.5 m to 40 meters, as shown by the laboratory measurements of the APL frequency response in Fig. G.1 and in the comparisons of PSD functions in Appendix I. This range is, in itself, sufficient to characterize all the defects related to a road.

Moreover, the APL Trailer is a dynamic device with automatic modes of recording and of signal processing that allow efficient data collection. During the IRRE, where it experienced practially no failure, the APL Trailer proved that it could be used successfully on all surface types of roads included in the IRRE, paved and unpaved, and under severe environmental conditions. Because it is autonomous and requires little technological support, it can be run in all parts of the world.

The quality of correlations between the RTRRMSs measurements and the APL numerics depends on the way the APL signals have been processed and, in particular, on the selection of the wavelength ranges which compose them. For this experimentation, the LCPC and the CRR have applied methods of analysis which are used in a standardized way in France and in Belgium. These methods have been developed for the purpose of evaluating the quality of road construction or for surveying road evolution and its state of deterioration. They were not particularly oriented to represent the response of a vehicle riding on that road and even less to constitute a calibration scale for the RTRRMSs. Nevertheless, analyses based on a separation of the smaller wavelengths produce APL numerics very well correlated with the RTRRMS measures. This is particularly the case for the CP (2.5) numerics, and the results reported in Appendix H indicate that the baselength can be optimized to obtain still higher correlations.

In Appendix E, it is shown that it is possible to obtain estimates of QI_r, provided that the parameters of the model are properly adjusted to the spectral contents of the APL profiles. In Appendix J, it is shown that the methods of analysis developed for the APL can be applied successfully to profiles obtained by other means. And in Appendix F, it is shown that the RARS numeric (from the RQCS) can be computed directly from the APL signals, using the APL 25 signals for the 20 km/h RTRRMS speed and the APL 72 signal for the other speeds of 32, 50, and 80 km/h. The correlations obtained using the RQCS analysis are the highest obtained.

The APL Trailer, like all other profilometer-type systems, offers increased metrological and analysis possibilities when compared to RTRRMSs. As a matter of fact, the continuous representation of a profile, even if it reflects only part of its wavelength spectral content, allows a more precise analysis of the state of degradation of a road and of the variations of its riding quality: it brings into light particular zones, and gives information on the homogeneity of the section tested. Moreover, one can compute from the recording of a profile different roughness indexes adapted to the applications in view and choose the length of the road characterized by this index. This last property is very useful for quantifying local defects of roughness in the studies concerning the safety of road users. These supplementary metrological possibilities become an appreciable advantage when the profilometers have operational qualities equivalent to those of the RTRRMSs.

Regardless of the qualities of a device used for measuring a roughness index of a road, the interpretation of that index in view of determining a global level of quality for that road cannot be performed independently from its other characteristics: nature of degradations (stated visually or photographically), state and constitution of the structure, importance of past and future traffic, frequency of maintenance works--and for the regions where the problem exists, the quality of skid resistance of pavements. This remark, which applies to all types of numerical parameters measured by a device on the road, is illustrated by the case of the surface treatment sections. The RTRRMSs ARS values, the APL 72 SW Index, and the CP (2.5) values all award to sections TS 01 to TS 05 a level of quality equivalent to those of sections CA 01 to CA 06 which are very degraded and highly circulated. These 5 surface treatment sections are on a road without degradation of which the constitutions seem to be adapted to the very low volume of traffic, which requires no maintenance, and which has an acceptable level of ride quality. The short wavelengths that dominate their profiles are those of the ancient gravel road which was not trimmed when the surface dressing was added; the short wavelengths cannot be attributed to an evolution of the state of deterioration of this road.

APPENDIX H

TRRL PROPOSALS FOR ROAD ROUGHNESS CALIBRATION AND STANDARDIZATION

prepared by

The British Transport and Road Research Laboratory (TRRL)

1. INTRODUCTION

The report presents the analysis and findings from the TRRL beam profile data as analyzed by the TRRL, and describes a complete instrument package developed at TRRL to enable users to obtain calibrated and standardized roughness measures directly from field measurements using RTRRMS's. The report also presents the results of a short validation exercise that was conducted in the Caribbean island of St. Lucia.

Of the 49 test sections selected for the IRRE, the TRRL beam profiled only 18 sections because of the late arrival of the beam in Brasilia. On ten of these sections both wheelpaths were profiled, the nearside wheelpath (right wheeltrack) only on three sections and the offside wheelpath (left wheeltrack) on the remaining five sections. Seven RTRMMS's were used in the experiment, but in this report only four of these systems were considered for analysis. They are the TRRL Towed fifth wheel B.I. trailer, the car mounted Bump Integrator, the NAASRA meter, and the Maysmeter 02. Maysmeters 01 and 03 and the BPR Roughometer were excluded from the analysis, as the data gathered from these instruments were very variable.

2. TRRL BEAM PROFILE ANALYSIS

Objectives

The TRRL experimental beam was developed to provide a RTRRMS calibrating capability. This development was based on past TRRL experience in the field of roughness measurement in developing countries. The concept of 'ride comfort' as adopted in the developed world as a direct measure of the unevenness of a road surface as perceived by the road user was not applicable to the road conditions met in developing countries.

In such countries ride comfort and level of service do not have the same importance as in the developed countries, as the greater need is for more roads to provide the basic means of transportation and communication which are operable throughout the year. Because of shortage of resources for building and maintaining all weather roads, a lower serviceability rating is tolerated by the user. However, the lower quality of the road surface manifests itself in higher vehicle operating costs through greater wear and tear of the mechanical components of the vehicles. Comfort to the vehicle rather than to the rider takes on a greater importance.

There is very little evidence to suggest what measure of roughness is most appropriate to relate to the effects of 'vehicle comfort'. Measures in use have been generally selected on the basis of convenience, simplicity and past experience of investigators, and the most popular measure has been the output of RTRRM's which measure the displacement of the axle relative to the body of the vehicle induced by the roughness of the road it is traversing. The magnitude of these response type measurements varies according to the suspension characteristics of the vehicle used and also with time due to a change in these characteristics through usage. Such measurements are acceptable only if they could be calibrated to a given standard enabling measurements with different vehicles at different periods in time and space to be related to that standard. Despite these serious drawbacks RTRRMS's enjoy a greater popularity with practising engineers and researchers and are in widespread use throughout the world. It is to be accepted that this method of measurement will prevail for some years to come and therefore the necessity to provide a viable and readily available calibration system is urgent.

An alternative to the RTRRMS measure of roughness is a profilometry based measure of roughness, and this is an obvious candidate for providing a calibration reference for calibrating measurements of TRRMS. A major requirement of any profilometer based system is that it should have the ability to accurately measure the longitudinal profiles of test sections of road, and also be able to be calibrated independently of other measuring systems. It also requires a method of processing the profile data to yield a single roughness statistic to describe the profile for subsequent correlation with RTRRMS measures.

A successful calibration system based on profilometry for use in developing countries needs to satisfy three important conditions. The calibration system/instrument must be easily transportable particularly from country to country. Appraisal studies undertaken by consultants for developing countries are usually of short duration. This means that unless the instrument is easily transportable to the country and the site, it will not be used by practising engineers and consultants, however good the instrument may be. Secondly the instrument must be reasonably simple to operate, and data management, analysis and interpretation must be available immediately after measurement. Manual data processing cannot be undertaken by field staff, therefore the generation of profiles alone in the field and the creation of a large data bank without the capability of instant computation, analysis and presentation of calibrated results is not acceptable as a viable method of calibrating roughness measurements. The last and equally important consideration is the cost of such an instrument. The instruments available at present are highly sophisticated, and very expensive to acquire, which effectively puts them out of the reach of the practitioner.

These three conditions guided the TRRL's approach to the IRRE data analysis, the computation of a suitable numeric for correlation with RTRRMS measurements and the subsequent development of the beam as a viable roughness calibrating and standardising instrument, independent of external computational requirements.

Method of Analysis

When analysing the data, consideration had to be given to the effect of different surface types and speeds of measurement, and also to the effect of variability between wheelpaths. These three factors have been fully examined in the main report, conclusions reached, and analysis proceeded with, on the basis of these conclusions. In this report alternative methods have been examined with a view to simplifying the analysis for practical use but without impairing the calibration accuracy. In this report three numerics have been developed as candidate statistics for correlation with RTRRMS, and their performance is discussed and compared with the other reference statistics developed by UMTRI and LCPC/CRR. The three numerics are a profile variance about a moving average datum curve (M. Avg), a root mean square of vertical elevation (RMSVE) from a straight line datum and a root mean square of deviation (RMSD) from a linear regression line. All three numerics were examined for various baselengths and profile intervals.

Early drafts of the main report (UMTRI-82-45-1) discussed the effect of measuring roughness with RTRRMS's at different speeds and suggested the use of an Average Rectified Velocity (ARV) unit in place of the more popularly used Average Rectified Slope (ARS) unit as this enabled comparison of RTRRMS measurements over more than a single test speed. However, the analysis discussed in this report uses the ARS unit of measurement, as the calibration method proposed is confined to a single standard test speed. This decision was made in the light of analysis results obtained, and is discussed in Chapter 3. Subsequent UMTRI proposals to adopt a single standard speed of measurement resulted also in the choice of an ARS unit, in preference to a traffic speed concept ARV measure.

Root Mean Square of Vertical Elevation (RMSVE)

This numeric was developed as a method of finding an approximate value of an area under a given datum line to reflect the unevenness of the road profile, and was derived from the formula used to find the root mean square value of a function as used in electrical engineering to describe the properties of alternating currents. The calculation was performed using 'Simpson's Rule' for approximate integration of an area under a curve when equally spaced points are available as was the case with profiles generated by the beam at 100mm intervals. The root mean square of vertical elevation for a baselength b was calculated using the formula:

$$RMSVE_b = \sqrt{\frac{\frac{h}{3}\left[y_o^2 + y_n^2 + 4(y_1^2 + y_3^2 \ldots y_{n-1}^2) + 2(y_2^2 + y_4^2 \ldots y_{n-2}^2)\right]}{h(n-1)}}$$

where h is the distance between elevation points, and
n is the number of elevation points considered in the baselength, b.

The RMSVE for the test section of road containing N baselengths of length b is given by:

$$RMSVE = \sqrt{\frac{\sum RMSVE_b^{\,2}}{N}}$$

The RMSVE numeric was calculated for a number of different baselengths ranging from 0.4 metres through to 10.0 metres and for profile intervals from 100mm to 1000mm in steps of 100mm. These were then correlated with the RTRRMS's measurements, and the R^2 values are tabulated in Tables H.1-H.4 for the four different measurement speeds and for profile intervals up to 500mm. Their performance is discussed in Chapter 3.

Moving Average Variance

This numeric presents the profile unevenness in terms of the variance of the deviation of the measured profiles about datum curves derived from moving averages. The points $(\bar{y})$ of a moving average datum curve n points in length are calculated using the measured profile data points (y) as follows:

$$\bar{y}_{i+\frac{n-1}{2}} = \frac{1}{n}\sum_{j=i}^{i+n-1} y_j \qquad \text{for } i \geq 1$$

For calculation of the profile deviations from the moving average datum, n is always chosen to be an odd number. The profile deviations (d) relative to a moving average datum are given by:

$$d_k = y_k - \bar{y}_k, \text{ where } k = i + \frac{n-1}{2} \quad \text{for } i \geq 1$$

The variance $(\sigma_b^{\,2})$ of these deviations over a given sequence of N profile points for a given moving average of length b (n x profile interval) is:

$$\sigma_b^{\,2} = \frac{1}{N-n-1}\sum_{k=1}^{N-n} (d_k - \bar{d})^2$$

The variance $\sigma_b^{\,2}$ reflects the unevenness in the road profile that is associated with profile features that are approximately b meters in length or less.

The profiles of the test sections measured by the TRRL beam are defined at points spaced 100mm apart. Moving average variances were calculated for a number of different baselengths (b) ranging from 0.4 metres to 10.0 metres and for profile intervals of 100mm, 200mm and 300mm. The previous RMSVE analysis indicated that profile intervals greater than 300mm produced weaker correlations, and therefore intervals greater than 300mm were not analyzed. These variances were then correlated with the RTRRMS's measurements made at speeds of 20 km/h, 32 km/h and 50 km/h (and at 80 km/h with the MM02 only) to examine the relationship between the two for use as a calibration measure. The results of these correlations are given in Tables H.5 - H.8, and discussed in Chapter 3 along with the other numerics.

Root Mean Square of Deviation (RMSD)

The root mean square of deviation is a very simple numeric that suggested itself after examination of the performance of the previous two numerics. It is derived by determining the deviations from a simple linear regression line for a given baselength b, in meters, and profile interval dx, in millimetres, and then calculating the root mean square of these deviations. For a given baselength b, with n profile points, the regression line $y = A + Bx$ is calculated and the deviations D_i evaluated.

$$RMSD_b = \sqrt{\frac{\sum Di^2}{n}}$$

The RMSD for the test section of road containing N baselengths of length b and profile interval dx is given by:

$$RMSD_{dx,b} = \sqrt{\frac{\sum RMSD_b 2}{N}}$$

$RMSD_{dx,b}$ was calculated for discrete baselengths as well as for contiguous baselengths. For the discrete baselength analysis the baselengths used were consecutive and the last profile point of the first baselength was also the first profile point of the next consecutive baselength, whereas in the contiguous baselength analysis all profile points were used successively to form a baselength. For documentation purposes these $RMSD_{dx,b}$ values are tabulated in Tables H.9 - H.12 for all combinations of baselengths and profile intervals examined for all the test sections and wheelpaths measured in Brazil. Tables of R^2 values generated through correlation of RTRRMS's measurements with $RMSD_{dx,b}$ for the nearside wheelpath only for both methods of analysis (i.e., discrete contiguous baselengths) are given in Tables H.13 and H.14. Table H.15 tabulates the R^2 values for the offside wheelpath for the discrete baselength analysis only. A detailed examination of these tables is made in Chapter 3.

3. INTERPRETATION AND DISCUSSION OF RESULTS

Measurement variables

The object of the profile analysis detailed in the previous chapter and tabulated in Tables H.1-H.15 was to develop a suitable statistic to accurately characterize a road profile such that it could be correlated with the response of a roughness measuring vehicle travelling on it, and thereby produce a stable calibrating equation. The analysis also serves the purpose of examining the effect of different surface types on RTRRMS's, the effect of measuring at different speeds, and also the effect of the variation in wheelpath roughness on RTRRMS.

1. Surface types: The main IRRE report examines the effect of surface type in detail and concludes that because of the interaction of surface type and measurement speed it would be necessary to provide separate calibration equations for paved and unpaved roads at 50 km/h or less, and also separate calibrations for asphaltic concrete and surface treated roads at 80 km/h. In this report surface type was not examined separately as it was felt desirable to consider the phenomenon of roughness as being universal for all roads irrespective of surface type. This could be achieved (as was mentioned in the main report) if the influence of measurement speed could be eliminated.

2. Measurement speed: Examination of the R^2 values calculated for all combinations of baselengths, profile intervals, and wheelpaths with the four

RTRRMS's show that all three calibration statistics correlate consistently better at a measurement speed of 32 km/h than at any other alternative measurement speed. One reason for this feature may be that it is easier to propel the vehicle steadily at this speed without interference from spurious acceleration and deceleration inputs and also that the wheelpath can be consistently adhered to. As the primary objective of the IRRE was to develop a calibration standard that was robust and could be easily applied universally it is suggested that the standard speed for calibration measurement should be 32 km/h for RTRRMS's irrespective of the actual speeds at which the normal roughness measurements are made. Two immediate benefits that accrue from calibrating at a speed of 32 km/h are the creation of statistically stronger calibration relationships and the elimination of any possible effects due to road surface type on RTRRMS measurements. Routine roughness measurements at speeds other than 32 km/h, although not recommended, could still be undertaken provided the relationship between measurements at 32 km/h and any other desired speed of measurement is established during the calibration period.

3. Effect of wheelpath variation on RTRRMS correlation: When RTRRMS's measure roughness on a road the effect of the unevenness of both wheelpaths are assumed to provide inputs to the numerical measure of roughness. Correlation with single wheel trailers is usually improved by measuring both wheelpaths with the trailers and correlating the average measure of the two wheelpaths with RTRRMS measures. This is feasible when measurements are made at reasonable speeds, but profilometry with manual systems such as the Rod and Level and the TRRL beam discourages the measurement of both wheelpaths as these measurements are time consuming. Detailed analysis was therefore undertaken to establish whether any particular wheelpath had a stronger influence on RTRRMS measures or whether it was the rougher or smoother wheelpath that influenced the RTRRMS. A brief examination of correlations of all the rougher wheelpaths and all the smoother wheelpaths measured did not provide any conclusive results for preferring one to the other. Table H.13 tabulates the $RMSD_{dx,b}$, R^2 values for the nearside wheelpath, and Table H-15 tabulates the comparable R^2 values for the offside wheelpath for all combinations of speed, profile interval, baselength and RTRRMS's. Of the 213 R^2 values generated for each wheelpath in these tables, in every single case the R^2 value for the nearside wheelpath is superior to the offside wheelpath,

suggesting that profiles of the nearside wheelpath only need to be measured when using manual profiling methods. [The 1984 version of the TRRL beam permits a 320 metre wheelpath to be surveyed in one hour, reducing the survey effort considerably. Improved correlations between RTRRMS and profile based reference numerics can be achieved by using the mean values of the two wheelpaths.]

Examination of profile interval and baselength

In all the three analyses (i.e., Moving Average, RMSVE and RMSD) many combinations of profile intervals and baselengths have been analysed and correlated with RTRRMS measures. Examination of the R^2 values derived through the M. Avg. statistic (Tables H.5 - H.8) show that the best R^2 value tends to vary between response vehicles as well as between measurement speed. There is no consistent pattern evident in the improvement of the R^2 value with any particular combination of profile intervals or speed, and this makes it difficult to decide on a 'best' profile interval or speed to choose for calibration purposes. Also the R^2 values are inferior to those produced by the other two statistics.

The RMSVE statistic on the other hand shows a definite trend towards peaking of the R^2 value around certain profile intervals and baselengths at different measurement speeds, with the 32 km/h speed consistently the best. The Table H.16a summarizes the best R^2 values produced at a measurement speed of 32 km/h for the three best profile intervals and baselengths. The best average R^2 value for the four RTRRMS's used in the IRRE exercise is 0.970 for a baselength of 1.8 metres using a profile interval of 300mm. Thus the RMSVE statistic is capable of producing a calibration relationship with a very high level of statistical significance using profile points at 300mm intervals for a baselength of 1.8 metres.

Development of the RMSD profile statistic

The successful establishment of an RMSVE profile statistic to characterize the unevenness of a road surface calculated on a baselength of 1.8 metres using 300mm spaced profile intervals was the result of successive stages of examination of the highly complex theory of waveform analysis. The relative simplicity of the computation of the RMSVE statistic based on profile elevations over a short baselength suggested that this principle could be simplified even further by calculating the root mean square of the deviations of the profile heights from an ideal flat smooth road surface. Thus the RMSD, calculated from the deviations from a linear regression line was considered for correlation with RTRRMS measures. Tables H.9 and H.10 show the $RMSD_{dx,b}$ values computed for discrete baselengths and Tables H.11 and H.12 list the $RMSD_{dx,b}$ values computed for contiguous baselengths. The R^2 values obtained after regression with the RTRRMS is given in Table H.13 for discrete baselengths, and Table H.14 for contiguous baselengths. Comparing the discrete baselength R^2 values with the equivalent R^2 values from the RMSVE analysis (Tables H.1-H.4) it is seen that the R^2 values, though very similar, are marginally better for the RMSD statistic. (Direct comparison is not always possible for every baselength, because the RMSD analysis was conducted on baselengths closer to the 'window' of interest (1.8 metres) than the broader spaced baselengths examined in the earlier RMSVE analysis). Table H.16b summarises R^2 values produced over the three best profile interval/baselength combinations for the four RTRRMS's operated at 32 km/h. This shows that the RMSD analysis produces results on a pattern almost identical to the RMSVE analysis and again the overall 'best' baselength/profile interval combination emerges at 1.8 meters and 300mm, producing an average R^2 value of 0.970.

Comparison of discrete and contiguous baselength analyses

Given a large number of consecutive elevation points, baselengths could be defined as discrete or contiguous as explained earlier and it was necessary to examine the results produced by the two different definitions. Therefore the complete RMSD analysis was conducted using both definitions of baselength and the R^2 values produced can be compared between Table H.13 and Table H.14. Here again the pattern of improvement or degradation of the R^2 values with various combinations of profile interval, baselength and speed are almost identical, and overall it is observed that the more complicated contiguous baselength analysis is only marginally better in about fifty per cent of the cases than the much simpler discrete baselength analysis by a few points in the third decimal place. In the particular case of the 1.8 metres baselength which has so far emerged as the most favoured for correlation with RTRRMS, the discrete baselength analysis produces better R^2 values in three out of four cases.

It is therefore proposed to use the simpler method of calculating the RMSD statistic using discrete baselengths, and $RMSD_{300,1.8}$ has been selecte as the most appropriate reference numeric for correlation with RTRRMS's operating at a speed of 32 km/h.

4. A STANDARD INTERNATIONAL ROUGHNESS INDEX

The analysis and discussion so far has concentrated on producing stable calibration relationships for calibrating RTRRMS over a period of time. The second and equally important requirement is to establish a standard roughness scale to which all RTRRMS's throughout the world could be calibrated, enabling the effect of road roughness on highway use and maintenance to be assessed on a universal basis. The main report discusses the need for an International Roughness Index, outlines the requirements such an index has to satisfy, and finally suggests the use of an $RARS_{80}$ index as processed via a Quarter Car Simulation (QCS).

An alternative Standard International Roughness Index is discussed below, based on the need for a practical and viable system, and on a scale which is familiar and easily understood by the world highway community.

In the previous discussion on calibration relationships, it was established that a statistic generated through road profile, such as $RMSD_{dx,b}$, provides a satisfactory numeric for correlation with RTRRMS measures. RMSD is thus a statistic that uniquely characterizes a particular road profile and could therefore serve as a common standard roughness index. But such a statistic has several drawbacks when considered as a common roughness index. Its descriptive name would not be commonly understood, its absolute numerical value is small and spread over a very narrow range (0.3 to 7.0 to represent roughness ranging from 800mm/km to 15,000mm/km respectively) and it has no universal association with surface unevenness. The most popular measure of roughness is the output of RTRRMS based on the dynamic motions in the suspension of a passenger car type of vehicle.

The measurements obtained with these instruments are in the form of discrete counts where each count corresponds to a certain length of cumulative deflection of the vehicle suspension. As the counts themselves are not comparable for different instruments, they need to be re-scaled to a reference, which should logically be a linear distance per distance such as inches per mile or millimeters per kilometer. The TRRL Towed Bump Integrator Trailer which was developed from the BPR Roughometer was specially designed as a standard response measuring instrument, with known response characteristics and is well known and used in many parts of the world. Roughness measurements obtained from the Bump Integrator Trailer in mm/km are easily identified by practitioners with perceived levels of roughness of roads and have been extensively used in the past to assess road and vehicle performance and should therefore appear as a strong candidate for providing a standard roughness scale. Moreover, the mm/km roughness statistic has a historical base due to its predominant use in past roughness evaluation studies and is an important input parameter for the RTIM2 and HDM-II road investment models. However, because of the inherent drawback of response measuring systems, the trailer itself cannot be considered as a standard system/instrument, but an equation derived from an RMSD profile statistic to estimate the Bump Integrator Trailer response characteristics would provide an acceptable standard reference roughness measure on a scale familiar to practitioners. One important qualification for such an acceptance though is that Bump Integrator Trailer measurements should in practice correlate well with other RTRRMS's. Figs. H.1, H.2 and H.3 show the near perfect correlation between the Trailer measurements and the three response instruments used in the IRRE study. Similar correlations have been achieved in previous studies with other RTRRMS's. Therefore a standard reference roughness equation based on the BI Trailer response characteristics would be deemed suitable.

Such a standard reference roughness equation has been developed from the IRRE data and is shown in Fig. H.4, where the equation developed is in a quadratic form with an R^2 value of 0.961. The quadratic form marginally improves the goodness of fit at the upper end of the roughness scale. The standard reference roughness equation is:

$$\text{ROUGHNESS (mm/km)} = 472 + 1437\ (\text{RMSD}_{300,1.8}) + 225\ (\text{RMSD}_{300,\ 1.8})^2$$

The above standard reference roughness equation will remain a permanent road roughness estimator through time and space, and will not be subject to any change in the future.

5. PROPOSED METHOD OF CALIBRATING AND STANDARDIZING OF RTRRMS's

In Chapter 3 the analysis of the three profile generated statistics were interpreted and discussed together with the performance pattern of the R^2 values with respect to the influence of surface type, speed of measurement and effect of wheelpath roughness variations.

Surface type

It was argued that roughness should not be discriminated by surface type as it should be regarded as a phenomenon manifesting itself on all surface types in the same manner and affecting vehicle operation and road performance in the same way. Any influence of surface type on roughness measures caused by variations in measurement speed are probably attributable to suspension characteristics rather than surface type. It is proposed in this report that surface type should not be discriminated especially in view of the further proposal that measurement speed should also be held constant.

Measurement speed

The analysis of the IRRE data suggests that measurements made at 32 km/h provide consistently better correlations than at any other measurement speed. Calibration and standardization procedures require robust and stable relation nships, and every stage of conversion of relationships between speeds tends to weaken the stability of the relationship. It is therefore proposed that for calibration and standardization purposes the measurement speed be maintained at 32 km/h, so that the final calibrated and standardized roughness measure will always be expressed in terms of a measurement speed of 32 km/h and thus directly comparable universally. Users desiring to make routine measures of roughness with RTRRMS's at speeds other than the standard speed of 32 km/h will need to correlate the roughness measures at two different speeds with a particular response system, and then use the equivalent 32 km/h measure for calibration and standardization.

Variation in wheelpath roughness

Slow manual methods of profilometry have discouraged the measurement of both wheelpaths, if the measurement of one wheelpath alone was sufficient to produce a strong correlation. The analysis has shown that the nearside wheelpath profile statistics always correlated better with RTRRMS than the offside wheelpaths. However, where profiles of both wheelpaths are available, the $RMSD_{300,1.8}$ of the two wheelpaths should be used to correlate with RTRRMS at 32 km/h.

Choice of Profile Statistic

Three profile based statistics were generated with the TRRL beam profilometer, and a further three statistics were developed and presented in the main report. It was shown in the analysis in this Appendix that the overall best combination of profile interval and baselength was observed to be the 300mm interval for a baselength of 1.8 metres. Table H.17 compares the R^2 values produced by these six different statistics when they were correlated against the four RTRRMS's used in the Brazil IRRE on the 28 wheelpaths measured by the TRRL beam. All the statistics produced good to excellent correlations with the four RTRRMS's, but the computational effort required to produce them varied widely. The statistic requiring the least computational effort and also producing the best correlation with the RTRRMS is the $RMSD_{300,1.8}$, and therefore the use of this statistic is proposed for calibration and standardization of response type roughness measurements made at 32 km/h.

Calibrating and standardizing process

The procedure for calibration is to select a number of sections of road approximately 200-300 metres in length, covering a range of roughness levels and containing as many road surface types as possible (a minimum of ten sections is recommended). These sections are then profiled on the nearside wheelpath (and on the offside wheelpath where possible) with the TRRL beam and the Root Mean Square of Deviation statistic ($RMSD_{300,1.8}$) computed for each section. The sections are also measured with the response type vehicle mounted roughness measuring instrument at a speed of 32 km/h and the results expressed in mm/km. A linear regression of the form y = a+bx is calculated using RMSD as the independent variable (x) and the RTRRMS measured as the dependent variable (y). This equation now constitutes the calibration equation for that particular RTRRMS. Routine field roughness measurements can now be made with the response instrument.

The routine measurements need to be standardized in the following manner. Substitute each field measurement for y in the equation y = a+bx and calculate x from x = (y-a)/b, to produce an estimate of $RMSD_{300,1.8}$ as perceived by that particular RTRRMS. This estimated value of $RMSD_{300,1.8}$ is then input to the Standard Reference Roughness equation

$$\text{ROUGHNESS (mm/km)} = 472 + 1437\ (RMSD_{300,1.8}) + 225\ (RMSD_{300,1.8})^2$$

to produce a standardized roughness value. All the field measurements are standardized in this manner.

6. VALIDATION STUDY IN ST LUCIA

The calibrating and standardizing methodology was developed from data collected from the International Road Roughness Experiment conducted in Brazil in May 1982. It was decided to validate this methodology by obtaining data from a different geographical environment, and using different RTRRMS, and therefore a study was conducted in St. Lucia in the Eastern Caribbean in March 1983.

Time and financial constraints restricted this study to two weeks field work, with the use of two locally hired vehicles, a Datsun 120 station wagon and a Cortina estate car, which were both instrumented with Bump Integrator units. The experimental conditions were not as controlled as in the IRRE study, as the TRRL staff were working quite independently without any institutional backup. There was little choice in the selection of the hire vehicles and their mechanical conditions was an unknown factor. One vehicle was driven by the hire car driver himself who was less amenable to experimental control than would be desirable, and the lack of reliable tire pressure gauges led to the vehicles being operated in a partially uncontrolled condition. These drawbacks, although not desirable, were in retrospect welcome because in the real world transport practitioners are likely to have to operate under similar conditions and the calibration methodology needs to be sufficiently robust to cope with these situations.

Nineteen test sections of road were measured with the TRRL beam and the two RTRRMS's, and the details of these sections together with the RTRRMS measures are given in Table H.18. The test section profiles were analyzed in exactly the same manner as the IRRE, Brazil data, and direct comparisons are therefore possible.

Table H.19 tabulates the R^2 values obtained using the RMSVE statistic, and Table H.20 shows the R^2 values obtained with the Moving Average Variance.

As the preferred statistic is the RMSD, a fuller documentation of the analysis is given in the following tables. Tables H.21 and H.22 tabulate the root mean square of deviation using the discrete baselength method, and Tables H.23 and H.24 the results obtained using the contiguous baselength method. These $RMSD_{dx,b}$ statistics were correlated against the Datsun and Cortina measures of roughness and the resulting R^2 values are presented in Tables H.25 and H.26 for discrete and contiguous baselengths respectively. It will be observed that the pattern of improvement or degradation of the R^2 values is identical to that observed in the IRRE analysis. Table H.16b summarised the R^2 values obtained for the Datsun and Cortina when correlated with the $RMSD_{dx,b}$ statistic, for profile interval/baselength combinations selected from the IRRE study. The correlations are slightly weaker than those obtained in the IRRE study, but confirm that the calibration methodology derived from the IRRE study is applicable in different environments and with different RTRRMS's.

Tables H.27 and H.28 tabulate the uncalibrated and calibrated roughness measurements for the IRRE and St. Lucia study respectively, using the calibrating and standardizing methodology described in the previous section.

7. OPERATION OF THE TRRL ROUGHNESS CALIBRATION AND STANDARDIZATION BEAM

The TRRL beam has now been developed as a compact, self contained road roughness calibration and standardization system. The road profiles measured by the beam are processed automatically through its internal micro-processor and the $RMSD_{300,1.8}$ is printed out on completion of the measurement of the test section. After measuring all the test sections, the operator is required to input the $RMSD_{300,1.8}$ values for each section together with the corresponding RTRRMS measure through the built-in key-pad for computation of the calibration equation. The equation is printed together with the R^2 value. The equation is output for the operator's information only, as he does not need to use it. The R^2 value will be printed with a warning that the correlation is not satisfactory if the value falls below 0.90. After the equation has been computed and printed, the operator inputs his routine field roughness measurements in mm/km and the processor will print the calibrated standard measure of roughness which will be expressed in mm/km for standard speed for 32 km/h.

A flow-chart of the operation of the beam is given in Fig. H.5.

TABLE H.1

TABLE OF R SQUARE VALUES OF RMS VERTICAL ELEVATION vs RTRRMS

(USING DISCRETE BASELENGTHS) BRASIL IRRE DATA

NEARSIDE WHEELPATH

20 Km/hr

100mm INTERVAL

	0.4m	0.8m	1.0m	1.2m	1.6m	2.0m	3.0m	4.0m	5.0m	6.0m	7.0m	8.0m	9.0m	10.0m
TRAILER	0.765	0.879	0.899	0.911	0.928	0.919	0.896	0.865	0.823	0.817	0.789	0.823	0.817	0.762
CAR BI	0.859	0.925	0.948	0.954	0.967	0.969	0.939	0.915	0.879	0.867	0.840	0.840	0.844	0.813
NAASRA	0.849	0.920	0.944	0.950	0.965	0.967	0.938	0.915	0.879	0.868	0.840	0.842	0.847	0.814
MM-02	0.879	0.932	0.952	0.957	0.962	0.964	0.929	0.901	0.864	0.848	0.826	0.920	0.820	0.792

200mm INTERVAL

	0.8m	1.2m	1.6m	2.0m	3.2m	4.0m	4.8m	6.0m	6.8m	8.0m	8.8m	10.0m
TRAILER	0.910	0.927	0.931	0.921	0.898	0.863	0.854	0.816	0.816	0.820	0.796	0.759
CAR BI	0.947	0.962	0.963	0.965	0.940	0.908	0.902	0.860	0.849	0.834	0.826	0.810
NAASRA	0.943	0.959	0.962	0.964	0.940	0.908	0.903	0.862	0.850	0.836	0.827	0.811
MM-02	0.947	0.960	0.955	0.956	0.925	0.892	0.887	0.840	0.829	0.812	0.804	0.789

300mm INTERVAL

	1.2m	1.8m	2.4m	3.0m	4.2m	4.8m	6.0m	7.2m	7.8m	9.0m	10.2m
TRAILER	0.932	0.925	0.901	0.894	0.869	0.849	0.819	0.810	0.814	0.819	0.792
CAR BI	0.972	0.972	0.956	0.938	0.912	0.905	0.871	0.848	0.847	0.847	0.825
NAASRA	0.970	0.971	0.955	0.937	0.912	0.906	0.872	0.849	0.848	0.849	0.827
MM-02	0.968	0.962	0.945	0.927	0.897	0.891	0.851	0.829	0.829	0.822	0.800

400mm INTERVAL

	1.6m	2.4m	3.2m	4.0m	4.8m	5.6m	7.2m	8.0m	8.8m	9.6m
TRAILER	0.923	0.892	0.892	0.860	0.849	0.823	0.805	0.811	0.793	0.811
CAR BI	0.863	0.834	0.835	0.828	0.807	0.795	0.779	0.786	0.780	0.795
NAASRA	0.858	0.830	0.833	0.826	0.805	0.794	0.779	0.787	0.781	0.796
MM-02	0.862	0.829	0.828	0.817	0.797	0.783	0.761	0.767	0.759	0.773

500mm INTERVAL

	2.0m	3.0m	4.0m	5.0m	6.0m	7.0m	8.0m	9.0m	10.0m
TRAILER	0.906	0.888	0.862	0.815	0.811	0.780	0.813	0.813	0.755
CAR BI	0.849	0.856	0.835	0.792	0.793	0.766	0.789	0.791	0.744
NAASRA	0.844	0.852	0.833	0.790	0.793	0.766	0.790	0.793	0.746
MM-02	0.850	0.852	0.828	0.782	0.778	0.753	0.773	0.768	0.723

TABLE H.2

TABLE OF R SQUARE VALUES OF

RMS VERTICAL ELEVATION Vs RTRRMS

(USING DISCRETE BASELENGTHS) BRASIL IRRE DATA

NEARSIDE WHEELPATH

32 Km/hr

100mm INTERVAL

	0.4m	0.8m	1.0m	1.2m	1.6m	2.0m	3.0m	4.0m	5.0m	6.0m	7.0m	8.0m	9.0m	10.0m
TRAILER	0.722	0.856	0.887	0.907	0.944	0.945	0.940	0.920	0.889	0.881	0.858	0.887	0.879	0.834
CAR BI	0.811	0.887	0.921	0.928	0.965	0.974	0.971	0.960	0.938	0.931	0.915	0.909	0.911	0.889
NAASRA	0.800	0.881	0.917	0.925	0.965	0.974	0.972	0.961	0.941	0.933	0.916	0.914	0.916	0.892
MM-02	0.806	0.872	0.908	0.915	0.955	0.966	0.965	0.954	0.937	0.926	0.913	0.897	0.894	0.876

200mm INTERVAL

	0.8m	1.2m	1.6m	2.0m	3.2m	4.0m	4.8m	6.0m	6.8m	8.0m	8.8m	10.0m
TRAILER	0.895	0.927	0.951	0.951	0.944	0.920	0.914	0.882	0.881	0.885	0.863	0.831
CAR BI	0.920	0.945	0.970	0.975	0.970	0.957	0.955	0.926	0.921	0.904	0.898	0.888
NAASRA	0.916	0.943	0.971	0.976	0.973	0.958	0.958	0.929	0.924	0.909	0.902	0.891
MM-02	0.901	0.928	0.958	0.963	0.958	0.949	0.947	0.919	0.910	0.891	0.886	0.874

300mm INTERVAL

	1.2m	1.8m	2.4m	3.0m	4.2m	4.8m	6.0m	7.2m	7.8m	9.0m	10.2m
TRAILER	0.938	0.955	0.943	0.940	0.925	0.909	0.883	0.878	0.877	0.880	0.852
CAR BI	0.960	0.978	0.979	0.972	0.959	0.958	0.934	0.916	0.917	0.912	0.897
NAASRA	0.959	0.980	0.981	0.974	0.963	0.960	0.936	0.920	0.921	0.918	0.902
MM-02	0.945	0.965	0.971	0.966	0.953	0.952	0.929	0.909	0.909	0.895	0.882

400mm INTERVAL

	1.6m	2.4m	3.2m	4.0m	4.8m	5.6m	7.2m	8.0m	8.8m	9.6m
TRAILER	0.950	0.937	0.939	0.918	0.910	0.887	0.875	0.879	0.860	0.874
CAR BI	0.877	0.872	0.878	0.886	0.871	0.863	0.854	0.864	0.853	0.865
NAASRA	0.873	0.870	0.877	0.885	0.871	0.864	0.857	0.868	0.856	0.868
MM-02	0.883	0.880	0.883	0.891	0.878	0.871	0.859	0.863	0.853	0.858

500mm INTERVAL

	2.0m	3.0m	4.0m	5.0m	6.0m	7.0m	8.0m	9.0m	10.0m
TRAILER	0.944	0.936	0.918	0.881	0.878	0.850	0.879	0.876	0.827
CAR BI	0.876	0.901	0.891	0.860	0.860	0.843	0.864	0.860	0.831
NAASRA	0.872	0.898	0.890	0.861	0.861	0.845	0.868	0.864	0.835
MM-02	0.885	0.909	0.898	0.873	0.868	0.853	0.863	0.853	0.826

TABLE H.3

TABLE OF R SQUARE VALUES OF RMS VERTICAL ELEVATION vs RTRRMS

(USING DISCRETE BASELENGTHS) BRASIL IRRE DATA

NEARSIDE WHEELPATH

50 Km/hr

100mm INTERVAL

	0.4m	0.8m	1.0m	1.2m	1.6m	2.0m	3.0m	4.0m	5.0m	6.0m	7.0m	8.0m	9.0m	10.0m
TRAILER	0.686	0.831	0.867	0.890	0.937	0.951	0.947	0.931	0.909	0.891	0.875	0.895	0.882	0.845
CAR BI	0.759	0.850	0.889	0.900	0.948	0.959	0.971	0.964	0.948	0.944	0.936	0.942	0.946	0.923
NAASRA	0.738	0.833	0.876	0.887	0.945	0.958	0.978	0.973	0.962	0.960	0.947	0.954	0.956	0.930
MM-02	0.748	0.826	0.867	0.875	0.931	0.944	0.969	0.958	0.955	0.950	0.941	0.941	0.937	0.918

200mm INTERVAL

	0.8m	1.2m	1.6m	2.0m	3.2m	4.0m	4.8m	6.0m	6.8m	8.0m	8.8m	10.0m
TRAILER	0.870	0.913	0.944	0.954	0.953	0.930	0.930	0.889	0.886	0.892	0.868	0.840
CAR BI	0.892	0.925	0.959	0.966	0.973	0.963	0.968	0.942	0.945	0.939	0.928	0.923
NAASRA	0.879	0.914	0.958	0.966	0.980	0.973	0.977	0.959	0.955	0.952	0.941	0.930
MM-02	0.866	0.898	0.942	0.947	0.958	0.956	0.964	0.947	0.945	0.939	0.928	0.917

300mm INTERVAL

	1.2m	1.8m	2.4m	3.0m	4.2m	4.8m	6.0m	7.2m	7.8m	9.0m	10.2m
TRAILER	0.930	0.965	0.958	0.949	0.939	0.928	0.893	0.893	0.891	0.883	0.849
CAR BI	0.940	0.969	0.972	0.971	0.970	0.966	0.946	0.940	0.946	0.946	0.934
NAASRA	0.930	0.966	0.976	0.980	0.979	0.974	0.962	0.955	0.954	0.956	0.943
MM-02	0.912	0.947	0.960	0.970	0.966	0.961	0.951	0.947	0.940	0.937	0.925

400mm INTERVAL

	1.6m	2.4m	3.2m	4.0m	4.8m	5.6m	7.2m	8.0m	8.8m	9.6m
TRAILER	0.955	0.956	0.953	0.932	0.931	0.903	0.891	0.890	0.868	0.873
CAR BI	0.844	0.852	0.863	0.878	0.865	0.858	0.859	0.879	0.857	0.874
NAASRA	0.842	0.856	0.866	0.884	0.873	0.870	0.876	0.891	0.874	0.883
MM-02	0.847	0.862	0.863	0.882	0.875	0.869	0.872	0.880	0.861	0.858

500mm INTERVAL

	2.0m	3.0m	4.0m	5.0m	6.0m	7.0m	8.0m	9.0m	10.0m
TRAILER	0.952	0.943	0.927	0.899	0.886	0.866	0.888	0.879	0.838
CAR BI	0.848	0.883	0.881	0.854	0.851	0.842	0.879	0.870	0.850
NAASRA	0.845	0.886	0.888	0.869	0.868	0.858	0.890	0.880	0.858
MM-02	0.849	0.889	0.884	0.875	0.864	0.855	0.878	0.857	0.834

TABLE H.4

TABLE OF R SQUARE VALUES OF RMS VERTICAL ELEVATION vs RTRRMS

(USING DISCRETE BASELENGTHS) BRASIL IRRE DATA

NEARSIDE WHEELPATH

80 Km/hr

100mm INTERVAL

	0.4m	0.8m	1.0m	1.2m	1.6m	2.0m	3.0m	4.0m	5.0m	6.0m	7.0m	8.0m	9.0m	10.0m
MM-02	0.586	0.683	0.741	0.758	0.845	0.869	0.909	0.906	0.906	0.903	0.897	0.875	0.869	0.857

200mm INTERVAL

	0.8m	1.2m	1.6m	2.0m	3.2m	4.0m	4.8m	6.0m	6.8m	8.0m	8.8m	10.0m
MM-02	0.738	0.792	0.868	0.880	0.904	0.909	0.913	0.903	0.889	0.875	0.868	0.859

300mm INTERVAL

	1.2m	1.8m	2.4m	3.0m	4.2m	4.8m	6.0m	7.2m	7.8m	9.0m	10.2m
MM-02	0.809	0.875	0.907	0.913	0.912	0.909	0.904	0.887	0.880	0.869	0.859

400mm INTERVAL

	1.6m	2.4m	3.2m	4.0m	4.8m	5.6m	7.2m	8.0m	8.8m	9.6m
MM-02	0.774	0.813	0.813	0.838	0.831	0.828	0.834	0.835	0.820	0.821

500mm INTERVAL

	2.0m	3.0m	4.0m	5.0m	6.0m	7.0m	8.0m	9.0m	10.0m
MM-02	0.791	0.838	0.837	0.836	0.831	0.825	0.829	0.814	0.805

TABLE H.5

TABLE OF R SQUARE VALUES OF MOVING AVERAGE vs RTRRMS

NEARSIDE WHEELPATH BRASIL IRRE DATA

20 Km/hr

100mm INTERVAL

	0.4m	1.0m	1.6m	2.0m	3.0m	5.0m	7.0m	10.0m
TRAILER	0.831	0.956	0.955	0.931	0.877	0.822	0.801	0.794
CAR BI	0.868	0.892	0.911	0.914	0.891	0.837	0.812	0.787
NAASRA	0.867	0.895	0.915	0.918	0.894	0.840	0.815	0.792
MM-02	0.859	0.864	0.878	0.880	0.856	0.801	0.775	0.745

200mm INTERVAL

	1.2m	1.6m	2.0m	2.4m	3.2m	4.0m	5.2m
TRAILER	0.964	0.949	0.924	0.900	0.866	0.843	0.816
CAR BI	0.891	0.905	0.906	0.899	0.875	0.851	0.827
NAASRA	0.895	0.909	0.910	0.902	0.879	0.855	0.831
MM-02	0.857	0.869	0.869	0.862	0.838	0.814	0.791

300mm INTERVAL

	1.2m	1.8m	2.4m	3.0m	3.6m	4.2m	4.8m	5.4m
TRAILER	0.961	0.927	0.887	0.863	0.847	0.832	0.819	0.810
CAR BI	0.903	0.912	0.901	0.884	0.867	0.852	0.841	0.831
NAASRA	0.907	0.916	0.905	0.887	0.871	0.855	0.844	0.835
MM-02	0.869	0.876	0.865	0.848	0.831	0.816	0.805	0.796

TABLE H.6

TABLE OF R SQUARE VALUES OF MOVING AVERAGE vs RTRRMS

NEARSIDE WHEELPATH BRASIL IRRE DATA

32 Km/hr

100mm INTERVAL

	0.4m	1.0m	1.6m	2.0m	3.0m	5.0m	7.0m	10.0m
TRAILER	0.770	0.935	0.966	0.959	0.924	0.881	0.861	0.846
CAR BI	0.800	0.852	0.893	0.910	0.913	0.885	0.869	0.841
NAASRA	0.801	0.859	0.901	0.919	0.921	0.892	0.876	0.850
MM-02	0.768	0.807	0.852	0.874	0.884	0.861	0.843	0.806

200mm INTERVAL

	1.2m	1.6m	2.0m	2.4m	3.2m	4.0m	5.2m
TRAILER	0.961	0.966	0.955	0.941	0.917	0.899	0.876
CAR BI	0.865	0.892	0.907	0.910	0.903	0.891	0.879
NAASRA	0.873	0.901	0.916	0.919	0.911	0.898	0.886
MM-02	0.817	0.849	0.869	0.877	0.873	0.883	0.854

300mm INTERVAL

	1.2m	1.8m	2.4m	3.0m	3.6m	4.2m	4.8m	5.4m
TRAILER	0.968	0.958	0.933	0.916	0.903	0.890	0.880	0.871
CAR BI	0.882	0.910	0.916	0.910	0.902	0.894	0.889	0.883
NAASRA	0.890	0.919	0.924	0.918	0.909	0.901	0.895	0.890
MM-02	0.837	0.874	0.886	0.883	0.875	0.869	0.865	0.860

TABLE H.7

TABLE OF R SQUARE VALUES OF MOVING AVERAGE vs RTRRMS

NEARSIDE WHEELPATH BRASIL IRRE DATA

50 Km/hr

100mm INTERVAL

	0.4m	1.0m	1.6m	2.0m	3.0m	5.0m	7.0m	10.0m
TRAILER	0.712	0.898	0.951	0.953	0.927	0.881	0.857	0.828
CAR BI	0.775	0.854	0.903	0.923	0.930	0.911	0.902	0.886
NAASRA	0.766	0.854	0.911	0.937	0.953	0.938	0.928	0.910
MM-02	0.741	0.811	0.868	0.897	0.921	0.913	0.905	0.877

200mm INTERVAL

	1.2m	1.6m	2.0m	2.4m	3.2m	4.0m	5.2m
TRAILER	0.935	0.951	0.950	0.940	0.918	0.899	0.874
CAR BI	0.877	0.906	0.923	0.927	0.924	0.915	0.906
NAASRA	0.881	0.916	0.938	0.947	0.948	0.941	0.933
MM-02	0.833	0.870	0.898	0.910	0.915	0.911	0.909

300mm INTERVAL

	1.2m	1.8m	2.4m	3.0m	3.6m	4.2m	4.8m	5.4m
TRAILER	0.948	0.955	0.938	0.921	0.907	0.894	0.883	0.874
CAR BI	0.893	0.924	0.931	0.928	0.922	0.916	0.913	0.909
NAASRA	0.899	0.939	0.952	0.952	0.947	0.943	0.939	0.936
MM-02	0.853	0.898	0.918	0.921	0.919	0.917	0.915	0.914

TABLE H.8

TABLE OF R SQUARE VALUES OF MOVING AVERAGE vs RTRRMS

NEARSIDE WHEELPATH BRASIL IRRE DATA

80 Km/hr

100mm INTERVAL

	0.4m	1.0m	1.6m	2.0m	3.0m	5.0m	7.0m	10.0m
MM-02	0.582	0.681	0.764	0.809	0.849	0.845	0.836	0.801

200mm INTERVAL

	1.2m	1.6m	2.0m	2.4m	3.2m	4.0m	5.2m
MM-02	0.720	0.773	0.815	0.836	0.846	0.843	0.843

300mm INTERVAL

	1.2m	1.8m	2.4m	3.0m	3.6m	4.2m	4.8m	5.4m
MM-02	0.744	0.813	0.847	0.853	0.849	0.848	0.847	0.846

TABLE H.9

ROOT MEAN SQUARE OF DEVIATION

(USING DISCRETE BASELENGTHS) BRASIL IRRE DATA

100mm INTERVAL

SECTION	1.5m		1.8m		2.0m		2.2m		2.4m		2.6m	
	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s
CA04	1.154	1.453	1.356	1.617	1.449	1.690	1.440	--	1.707	--	1.638	--
CA05	1.695	1.780	1.869	1.981	1.990	2.154	2.034	--	2.186	--	2.292	--
CA06	1.851	2.169	2.100	2.430	2.196	2.671	2.328	--	2.521	--	2.517	--
CA10	0.686	--	0.787	--	0.865	--	0.901	--	0.965	--	0.996	--
CA12	--	0.599	--	0.704	--	0.748	--	0.784	--	0.843	--	0.876
TS01	--	1.197	--	1.360	--	1.390	--	1.472	--	1.576	--	1.599
TS04	--	1.368	--	1.584	--	1.659	--	1.694	--	1.816	--	1.868
TS05	--	1.566	--	1.858	--	1.931	--	2.063	--	2.145	--	2.183
TS06	0.995	1.103	1.069	1.180	1.137	1.228	1.169	--	1.178	--	1.242	--
TS07	--	1.029	--	1.074	--	1.150	--	1.166	--	1.220	--	1.249
TE01	1.529	1.759	1.637	1.889	1.659	1.965	1.745	--	1.803	--	1.839	--
TE03	1.982	2.910	2.163	3.147	2.217	3.239	2.318	--	2.390	--	2.426	--
TE06	5.015	--	5.483	--	5.616	--	5.914	--	6.073	--	6.282	--
TE11	2.970	4.038	3.103	4.269	3.245	4.407	3.284	--	3.394	--	3.398	--
GR01	1.345	--	1.438	--	1.481	--	1.538	--	1.577	--	1.578	--
GR05	2.419	3.121	2.672	3.386	2.774	3.464	2.932	--	2.963	--	3.104	--
GR07	1.586	2.610	1.682	2.724	1.737	2.885	1.776	--	1.843	--	1.843	--
GR12	3.044	4.371	3.494	5.100	3.770	5.096	4.081	--	4.327	--	5.022	--

200mm INTERVAL

SECTION	1.6m		1.8m		2.0m		2.2m		2.4m	
	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s
CA04	1.231	1.591	1.373	1.654	1.456	1.720	1.455	--	1.740	--
CA05	1.777	1.831	1.895	1.999	2.011	2.182	2.045	--	2.213	--
CA06	2.085	2.213	2.143	2.467	2.246	2.715	2.375	--	2.571	--
CA10	0.748	--	0.782	--	0.863	--	0.915	--	0.973	--
CA12	--	0.657	--	0.695	--	0.749	--	0.794	--	0.849
TS01	--	1.279	--	1.368	--	1.398	--	1.485	--	1.582
TS04	--	1.501	--	1.601	--	1.676	--	1.710	--	1.821
TS05	--	1.759	--	1.902	--	1.965	--	2.091	--	2.165
TS06	0.994	1.104	1.048	1.157	1.122	1.212	1.158	--	1.157	--
TS07	--	1.059	--	1.081	--	1.147	--	1.169	--	1.221
TE01	1.557	1.808	1.632	1.900	1.664	1.985	1.761	--	1.807	--
TE03	2.021	2.987	2.161	3.123	2.200	3.281	2.316	--	2.402	--
TE06	5.260	--	5.513	--	5.698	--	6.002	--	6.147	--
TE11	2.937	3.973	3.021	4.192	3.151	4.360	3.203	--	3.310	--
GR01	1.356	--	1.401	--	1.458	--	1.524	--	1.562	--
GR05	2.483	3.209	2.643	3.386	2.762	3.423	2.885	--	2.944	--
GR07	1.577	2.650	1.631	2.759	1.673	2.943	1.736	--	1.810	--
GR12	3.553	4.511	3.590	5.179	3.839	5.187	4.204	--	4.427	--

TABLE H.10

ROOT MEAN SQUARE OF DEVIATION

(USING DISCRETE BASELENGTHS)   BRASIL IRRE DATA

300mm INTERVAL

SECTION	1.5m		1.8m		2.1m	
	n/s	o/s	n/s	o/s	n/s	o/s
CA04	1.187	1.501	1.422	1.675	1.392	1.853
CA05	1.702	1.817	1.899	2.036	2.094	2.264
CA06	1.873	2.231	2.137	2.500	2.312	2.727
CA10	0.656	--	0.788	--	0.855	--
CA12	--	0.574	--	0.721	--	0.799
TS01	--	1.199	--	1.387	--	1.489
TS04	--	1.371	--	1.603	--	1.712
TS05	--	1.634	--	1.951	--	2.055
TS06	0.973	1.059	1.054	1.152	1.136	1.224
TS07	--	1.023	--	1.087	--	1.172
TE01	1.366	1.645	1.517	1.832	1.626	1.892
TE03	1.984	2.904	2.195	3.103	2.299	3.249
TE06	5.057	--	5.434	--	5.721	--
TE11	2.857	3.833	3.005	4.085	3.205	4.317
GR01	1.239	--	1.359	--	1.482	--
GR05	2.363	3.164	2.651	3.433	2.892	3.701
GR07	1.476	2.550	1.608	2.723	1.680	2.880
GR12	3.172	4.552	3.687	5.263	3.849	5.733

500mm INTERVAL

SECTION	1.5m		2.0m		2.5m		3.0m	
	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s
CA04	1.073	1.467	1.463	1.728	1.579	2.139	2.034	2.299
CA05	1.667	1.831	1.991	2.275	2.334	2.459	2.533	2.752
CA06	1.881	2.189	2.249	2.762	2.508	3.085	2.863	3.263
CA10	0.617	--	0.859	--	1.028	--	1.169	--
CA12	--	0.528	--	0.772	--	0.897	--	1.073
TS01	--	1.148	--	1.401	--	1.603	--	1.765
TS04	--	1.363	--	1.695	--	1.869	--	2.031
TS05	--	1.543	--	1.922	--	2.153	--	2.160
TS06	0.826	0.932	1.033	1.124	1.152	1.243	1.221	1.327
TS07	--	0.889	--	1.037	--	1.133	--	1.236
TE01	1.321	1.511	1.540	1.836	1.715	2.016	1.945	2.145
TE03	1.712	2.699	1.988	3.192	2.273	3.457	2.429	3.713
TE06	4.678	--	5.516	--	6.094	--	6.628	--
TE11	2.566	3.715	2.950	4.423	3.145	4.890	3.405	5.087
GR01	1.119	--	1.331	--	1.513	--	1.685	--
GR05	2.247	3.020	2.708	3.439	3.087	3.814	3.374	4.051
GR07	1.291	2.481	1.570	2.768	1.720	3.089	1.881	3.135
GR12	3.120	4.418	3.940	5.276	4.694	5.509	5.229	6.180

TABLE H.11

ROOT MEAN SQUARE OF DEVIATION

(USING CONTIGUOUS BASELENGTHS) BRASIL IRRE DATA

100mm INTERVAL

SECTION	1.5m		1.8m		2.0m		2.2m		2.4m		2.6m	
	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s
CA04	1.189	1.426	1.324	1.594	1.415	1.703	1.508	--	1.602	--	1.696	--
CA05	1.692	1.757	1.863	1.955	1.973	2.079	2.078	--	2.181	--	2.279	--
CA06	1.905	2.136	2.127	2.422	2.255	2.597	2.368	--	2.469	--	2.562	--
CA10	0.712	--	0.794	--	0.850	--	0.904	--	0.959	--	1.012	--
CA12	--	0.639	--	0.701	--	0.744	--	0.788	--	0.830	--	0.872
TS01	--	1.224	--	1.345	--	1.418	--	1.485	--	1.545	--	1.599
TS04	--	1.412	--	1.561	--	1.647	--	1.722	--	1.788	--	1.847
TS05	--	1.633	--	1.838	--	1.953	--	2.045	--	2.118	--	2.172
TS06	1.021	1.115	1.081	1.180	1.121	1.222	1.159	--	1.197	--	1.233	--
TS07	--	1.042	--	1.107	--	1.149	--	1.188	--	1.225	--	1.260
TE01	1.552	1.789	1.631	1.883	1.682	1.942	1.732	--	1.781	--	1.827	--
TE03	2.015	2.957	2.147	3.134	2.229	3.238	2.306	--	2.377	--	2.445	--
TE06	5.050	--	5.429	--	5.655	--	5.866	--	6.065	--	6.255	--
TE11	2.950	4.049	3.114	4.291	3.212	4.441	3.298	--	3.373	--	3.440	--
GR01	1.357	--	1.435	--	1.482	--	1.526	--	1.568	--	1.608	--
GR05	2.438	3.117	2.642	3.364	2.771	3.506	2.896	--	3.016	--	3.131	--
GR07	1.615	2.602	1.688	2.786	1.737	2.896	1.786	--	1.835	--	1.883	--
GR12	3.142	4.248	3.583	4.772	3.854	5.084	4.107	--	4.344	--	4.567	--

200mm INTERVAL

SECTION	1.6m		1.8m		2.0m		2.2m		2.4m	
	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s
CA04	1.244	1.510	1.339	1.626	1.434	1.739	1.530	--	1.626	--
CA05	1.764	1.845	1.881	1.978	1.994	2.102	2.102	--	2.206	--
CA06	2.032	2.286	2.176	2.474	2.301	2.646	2.412	--	2.511	--
CA10	0.739	--	0.797	--	0.855	--	0.912	--	0.968	--
CA12	--	0.655	--	0.701	--	0.748	--	0.794	--	0.838
TS01	--	1.273	--	1.355	--	1.429	--	1.496	--	1.557
TS04	--	1.484	--	1.581	--	1.665	--	1.739	--	1.803
TS05	--	1.749	--	1.878	--	1.986	--	2.072	--	2.138
TS06	1.017	1.110	1.061	1.159	1.103	1.204	1.143	--	1.182	--
TS07	--	1.060	--	1.105	--	1.148	--	1.188	--	1.226
TE01	1.573	1.836	1.631	1.903	1.688	1.965	1.742	--	1.794	--
TE03	2.047	2.993	2.140	3.119	2.226	3.231	2.304	--	2.376	--
TE06	5.255	--	5.503	--	5.732	--	5.945	--	6.146	--
TE11	2.899	4.033	3.014	4.209	3.116	4.369	3.205	--	3.282	--
GR01	1.347	--	1.405	--	1.457	--	1.505	--	1.550	--
GR05	2.479	3.189	2.617	3.346	2.746	3.489	2.868	--	2.987	--
GR07	1.573	2.692	1.629	2.817	1.684	2.929	1.783	--	1.791	--
GR12	3.384	4.520	3.677	4.854	3.947	5.158	4.199	--	4.434	--

TABLE H.12

ROOT MEAN SQUARE OF DEVIATION

(USING CONTIGUOUS BASELENGTHS) BRASIL IRRE DATA

300mm INTERVAL

SECTION	1.5m		1.8m		2.1m	
	n/s	o/s	n/s	o/s	n/s	o/s
CA04	1.238	1.454	1.390	1.635	1.542	1.811
CA05	1.715	1.808	1.900	2.020	2.072	2.208
CA06	1.938	2.227	2.161	2.524	2.340	2.779
CA10	0.700	--	0.799	--	0.894	--
CA12	--	0.637	--	0.721	--	0.803
TS01	--	1.230	--	1.361	--	1.472
TS04	--	1.427	--	1.587	--	1.719
TS05	--	1.708	--	1.912	--	2.062
TS06	1.000	1.072	1.076	1.152	1.146	1.222
TS07	--	1.031	--	1.108	--	1.176
TE01	1.414	1.686	1.523	1.813	1.622	1.928
TE03	2.019	2.915	2.169	3.117	2.301	3.278
TE06	5.053	--	5.449	--	5.804	--
TE11	2.827	3.874	3.026	4.155	3.190	4.408
GR01	1.267	--	1.371	--	1.460	--
GR05	2.404	3.185	2.631	3.458	2.837	3.684
GR07	1.505	2.552	1.611	2.753	1.711	2.928
GR12	3.312	4.445	3.769	4.966	4.169	5.416

500mm INTERVAL

SECTION	1.5m		2.0m		2.5m		3.0m	
	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s
CA04	1.147	1.416	1.431	1.737	1.710	2.029	1.975	2.302
CA05	1.670	1.805	2.006	2.189	2.289	2.481	2.539	2.732
CA06	1.975	2.197	2.328	2.682	2.597	3.043	2.825	3.327
CA10	0.682	--	0.857	--	1.013	--	1.149	--
CA12	--	0.624	--	0.774	--	0.901	--	1.005
TS01	--	1.195	--	1.434	--	1.604	--	1.722
TS04	--	1.420	--	1.676	--	1.856	--	1.994
TS05	--	1.622	--	1.929	--	2.082	--	2.173
TS06	0.868	0.956	1.020	1.123	1.145	1.253	1.254	1.367
TS07	--	0.904	--	1.040	--	1.153	--	1.259
TE01	1.365	1.553	1.576	1.799	1.736	1.999	1.875	2.163
TE03	1.769	2.722	2.052	3.115	2.267	3.396	2.441	3.613
TE06	4.681	--	5.454	--	6.072	--	6.574	--
TE11	2.563	3.785	2.941	4.343	3.187	4.779	3.389	5.168
GR01	1.160	--	1.353	--	1.502	--	1.622	--
GR05	2.267	3.028	2.695	3.477	3.041	3.810	3.332	4.063
GR07	1.356	2.438	1.567	2.777	1.735	3.044	1.877	3.241
GR12	3.262	4.285	4.015	5.134	4.632	5.773	5.170	6.293

TABLE H.13

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING DISCRETE BASELENGTHS) BRAZIL IRRE DATA
NEARSIDE WHEELPATH

Interval	Type	20 km/h						32 km/h						50 km/			
100 mm	Base	1.5m	1.8m	2.0m	2.2m	2.4m	2.6m	1.5m	1.8m	2.0m	2.2m	2.4m	2.6m	1.5m	1.8m	2.0m	2.2m
	Trailer	0.922	0.922	0.917	0.921	0.913	0.874	0.938	0.950	0.947	0.949	0.946	0.922	0.916	0.931	0.919	0.95
	Car BI	0.967	0.970	0.968	0.963	0.957	0.934	0.957	0.970	0.974	0.975	0.975	0.967	0.937	0.958	0.962	0.96
	NAASRA	0.965	0.968	0.966	0.961	0.956	0.933	0.956	0.971	0.975	0.975	0.977	0.968	0.931	0.955	0.961	0.96
	MM-02	0.964	0.964	0.961	0.955	0.947	0.922	0.944	0.958	0.965	0.966	0.966	0.963	0.913	0.937	0.945	0.95
200 mm	Base	1.6m	1.8m	2.0m	2.2m	2.4m		1.6m	1.8m	2.0m	2.2m	2.4m		1.6m	1.8m	2.0m	2.2m
	Trailer	0.925	0.919	0.916	0.919	0.910		0.952	0.951	0.950	0.952	0.047		0.912	0.931	0.921	0.95
	Car BI	0.963	0.967	0.964	0.958	0.950		0.971	0.974	0.974	0.974	0.974		0.960	0.965	0.967	0.96
	NAASRA	0.962	0.966	0.963	0.957	0.949		0.972	0.975	0.976	0.975	0.976		0.961	0.963	0.968	0.97
	MM-02	0.954	0.959	0.954	0.947	0.937		0.959	0.960	0.963	0.962	0.963		0.943	0.943	0.948	0.95
300 mm	Base	1.5m	1.8m	2.1m				1.5m	1.8m	2.1m				1.5m	1.8m	2.1m	
	Trailer	0.924	0.912	0.898				0.952	0.948	0.940				0.932	0.929	0.930	
	Car BI	0.974	0.968	0.964				0.973	0.980	0.975				0.959	0.972	0.967	
	NAASRA	0.973	0.967	0.963				0.974	0.982	0.976				0.955	0.972	0.966	
	MM-02	0.965	0.959	0.957				0.959	0.970	0.965				0.933	0.953	0.945	
500 mm	Base	1.5m	2.0m	2.5m	3.0m			1.5m	2.0m	2.5m	3.0m			1.5m	2.0m	2.5m	3.0m
	Trailer	0.901	0.897	0.883	--			0.940	0.942	0.933	--			0.920	0.913	0.886	--
	Car BI	0.957	0.947	0.927	0.908			0.969	0.970	0.963	0.953			0.963	0.970	0.967	0.96
	NAASRA	0.958	0.948	0.927	0.908			0.971	0.973	0.966	9.955			0.964	0.978	0.977	0.97
	MM-02	0.949	0.935	0.915	0.894			0.958	0.962	0.957	0.946			0.941	0.958	0.958	0.95

TABLE H.14

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING CONTIGUOUS BASELENGTHS) BRAZIL IRRE DATA
NEARSIDE WHEELPATH

Interval	Type	20 km/h				32 km/h				50 km/h			
100 mm	Base	1.5m	1.8m	2.0m		1.5m	1.8m	2.0m		1.5m	1.8m	2.0m	
	Trailer	0.928	0.924	0.919		0.941	0.948	0.948		0.937	0.949	0.952	
	Car BI	0.969	0.968	0.965		0.963	0.971	0.974		0.945	0.958	0.963	
	NAASRA	0.967	0.967	0.964		0.962	0.972	0.975		0.939	0.956	0.963	
	MM-02	0.965	0.962	0.958		0.949	0.961	0.965		0.923	0.940	0.947	
200 mm	Base	1.6m	1.8m	2.0m		1.6m	1.8m	2.0m		1.6m	1.8m	2.0m	
	Trailer	0.930	0.924	0.918		0.952	0.952	0.951		0.951	0.954	0.955	
	Car BI	0.967	0.964	0.961		0.970	0.973	0.974		0.960	0.965	0.968	
	NAASRA	0.966	0.964	0.960		0.971	0.974	0.976		0.957	0.965	0.970	
	MM-02	0.958	0.955	0.950		0.955	0.960	0.963		0.937	0.945	0.951	
300 mm	Base	1.5m	1.8m	2.1m		1.5m	1.8m	2.1m		1.5m	1.8m	2.1m	
	Trailer	0.927	0.917	0.907		0.953	0.951	0.947		0.957	0.959	0.958	
	Car BI	0.972	0.966	0.958		0.977	0.979	0.979		0.965	0.970	0.973	
	NAASRA	0.971	0.965	0.958		0.978	0.981	0.980		0.963	0.971	0.976	
	MM-02	0.963	0.956	0.948		0.964	0.969	0.970		0.944	0.953	0.959	
500 mm	Base	1.5m	2.0m	2.5m	3.0m	1.5m	2.0m	2.5m	3.0m	1.5m	2.0m	2.5m	3.0m
	Trailer	0.908	0.897	0.885	0.873	0.943	0.940	0.934	0.927	0.950	0.950	0.946	0.938
	Car BI	0.954	0.942	0.929	0.914	0.970	0.969	0.965	0.958	0.967	0.969	0.969	0.966
	NAASRA	0.954	0.943	0.929	0.914	0.972	0.971	0.967	0.961	0.969	0.975	0.978	0.977
	MM-02	0.943	0.931	0.916	0.900	0.960	0.961	0.957	0.951	0.949	0.957	0.960	0.960

TABLE H.15

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING DISCRETE BASELENGTHS) BRAZIL IRRE DATA
OFFSIDE WHEELPATH

Interval	Type	20 km/h				32 km/h				50 km/h			
100 mm	Base	1.5m	1.8m	2.0m		1.5m	1.8m	2.0m		1.5m	1.8m	2.0m	
	Trailer	--	--	--		--	--	--		--	--	--	
	Car BI	0.880	0.884	0.882		0.897	0.912	0.909		0.850	0.869	0.870	
	NAASRA	0.870	0.874	0.873		0.884	0.899	0.898		0.835	0.859	0.856	
	MM-02	0.899	0.899	0.898		0.916	0.932	0.928		0.870	0.893	0.887	
200 mm	Base	1.6m	1.8m	2.0m		1.6m	1.8m	2.0m		1.6m	1.8m	2.0m	
	Trailer	--	--	--		--	--	--		--	--	--	
	Car BI	0.899	0.883	0.882		0.920	0.914	0.912		0.878	0.874	0.875	
	NAASRA	0.890	0.874	0.874		0.908	0.902	0.901		0.865	0.866	0.862	
	MM-02	0.915	0.897	0.896		0.936	0.934	0.929		0.897	0.900	0.890	
300 mm	Base	1.5m	1.8m	2.1m		1.5m	1.8m	2.1m		1.5m	1.8m	2.1m	
	Trailer	--	--	--		--	--	--		--	--	--	
	Car BI	0.884	0.875	0.860		0.913	0.913	0.905		0.875	0.877	0.872	
	NAASRA	0.874	0.866	0.852		0.901	0.902	0.895		0.862	0.870	0.867	
	MM-02	0.899	0.888	0.874		0.932	0.935	0.929		0.895	0.904	0.902	
500 mm	Base	1.5m	2.0m	2.5m	3.0m	1.5m	2.0m	2.5m	3.0m	1.5m	2.0m	2.5m	3.0m
	Trailer	--	--	--	--	--	--	--	--	--	--	--	--
	Car BI	0.864	0.870	0.878	0.878	0.898	0.906	0.910	0.919	0.869	0.869	0.876	0.889
	NAASRA	0.856	0.861	0.870	0.871	0.887	0.894	0.900	0.909	0.848	0.857	0.862	0.878
	MM-02	0.881	0.885	0.895	0.890	0.922	0.928	0.931	0.937	0.883	0.885	0.891	0.903

TABLE H.16a

BEST R SQUARE VALUES OF RMSVE vs RESPONSE INSTRUMENTS for DIFFERENT PROFILE INTERVALS & BASE LENGTHS at 32 Km/H

PROFILE INTERVAL	100 mm			200 mm			300 mm		
BASE (m)	1.6	2.0	3.0	1.6	2.0	3.2	1.8	2.4	3.0
BRASIL IRRE									
TRAILER	.944	.945	.940	.951	.951	.944	.955	.943	.940
CAR BI	.965	.974	.971	.970	.975	.970	.978	.979	.972
NAASRA	.965	.974	.972	.971	.976	.973	.980	.981	.974
MM-02	.955	.966	.965	.958	.963	.958	.965	.971	.966
Average R^2	.957	.965	.962	.963	.966	.961	.970	.969	.963
ST LUCIA									
DATSUN	.866	.908	.909	.887	.917	.925	.906	.891	.894
CORTINA	.893	.916	.954	.884	.906	.960	.911	.938	.945

TABLE H.16b

BEST R SQUARE VALUES OF RMSD vs RESPONSE INSTRUMENTS for DIFFERENT PROFILE INTERVALS & BASE LENGTHS at 32 Km/H

PROFILE INTERVAL	100 mm			200 mm			300 mm		
BASE (m)	2.0	2.2	2.4	1.8	2.0	2.2	1.5	1.8	2.1
BRASIL IRRE									
TRAILER	.947	.949	.946	.951	.950	.952	.952	.948	.940
CAR BI	.974	.975	.975	.974	.974	.974	.973	.980	.975
NAASRA	.975	.975	.977	.975	.976	.975	.974	.982	.976
MM-02	.965	.966	.966	.960	.963	.962	.959	.970	.965
Average R^2	.965	.966	.966	.965	.966	.966	.965	.970	.964
ST LUCIA									
DATSUN	.916	.939	.916	.933	.927	.941	.902	.926	.925
CORTINA	.918	.949	.948	.912	.916	.947	.913	.924	.947

TABLE H.17

COMPARISON OF R SQUARE VALUES OF DIFFERENT STATISTICS CORRELATED AGAINST RTRRMS

	R SQUARE VALUES					
	RMSD*	RMSVE*	M Avg*	APL $CP_{2.5}$	$RARS_{32}$	QI
BRASIL_IRRE						
TRAILER	.948	.955	.958	.924	.974	.889
CAR BI	.980	.978	.910	.933	.954	.934
NAASRA	.982	.980	.919	.943	.958	.938
MM-02	.970	.965	.874	.951	.931	.933
Average R^2	.970	.970	.915	.938	.954	.924
ST LUCIA						
DATSUN	.926	.906	.856	---	---	---
CORTINA	.924	.911	.855	---	---	---

* - computed for 1.8m baselength using 300 mm profile intervals

Measurement Speed for RTRRMS is 32 Km/hr

TABLE H.18

RTRRMS MEASUREMENTS (MM/KM)

ST LUCIA 1983

SECTION	DATSUN 20Km/hr	DATSUN 32Km/hr	DATSUN 50Km/hr	CORTINA 20Km/hr	CORTINA 32Km/hr	CORTINA 50Km/hr
1	2875	2979	2861	--	--	--
2	1196	1012	828	859	614	695
3 *	3250	2564	1938	1491	934	835
4	2951	2908	3036	2651	2266	2266
5	2566	2865	2908	2181	2095	2053
6 *	7582	6908	7600		REGRAVELLED	
7	4832	4714	4447	3806	3335	3122
8	5003	5195	4952	4062	3848	3763
9	4139	4423	4170	3580	3412	3117
10	4682	4714	4779	--	--	--
11	2654	2654	2569	2233	2022	1980
12 **	762	889	889	960	818	847
13	2275	2190	2106	1853	1769	1980
14 ***	9730	8309	7077	6908	5897	5097
15	4391	4328	3665		PATCHED	
16	1832	1801	1706	1727	1432	1348
17	5452	5965	6254	4746	4704	4575
18		PATCHED		4779	4971	4843
19 ***	6982	6252	5471	5210	4298	3929

* - UNPAVED ROAD

** - CONCRETE TEST TRACK

*** - DISUSED PAVED ROAD

TABLE H.19

TABLE OF R SQUARE VALUES OF RMS VERTICAL ELEVATION vs RTRRMS

(USING DISCRETE BASELENGTHS) NEARSIDE WHEELPATH

ST. LUCIA DATA

Interval	Type	20 km/h				32 km/h				50 km/h			
100 mm	Base	1.6m	1.8m	2.0m	3.0m	1.6m	1.8m	2.0m	3.0m	1.6m	1.8m	2.0m	3.0m
	Datsun	0.892	0.908	0.893	0.855	0.886	0.917	0.908	0.909	0.794	0.845	0.869	0.913
	Cortina	0.944	0.955	0.953	0.941	0.893	0.912	0.916	0.954	0.841	0.864	0.869	0.933
200 mm	Base	1.6m	2.0m	3.2m		1.6m	2.0m	3.2m		1.6m	2.0m	3.2m	
	Datsun	0.897	0.908	--		0.887	0.917	0.925		0.788	0.865	--	
	Cortina	0.938	0.952	--		0.884	0.906	0.960		0.830	0.856	--	
300 mm	Base	1.8m	2.4m	3.0m		1.8m	2.4m	3.0m		1.8m	2.4m	3.0	
	Datsun	0.887	--	--		0.906	0.891	0.894		0.847	--	--	
	Cortina	0.946	--	--		0.911	0.938	0.945		0.868	--	--	
500 mm	Base	2.0m	3.0m			2.0m	3.0m			2.0m	3.0m		
	Datsun	0.861	0.819			0.890	0.877			0.865	0.885		
	Cortina	0.956	0.932			0.944	0.954			0.910	0.937		

TABLE H.20

TABLE OF R SQUARE VALUES OF MOVING AVERAGE vs RTRRMS

ST LUCIA DATA

Speed	Interval	Type	Nearside Wheelpath					Offside Wheelpath				
20km/h	200 mm	Base	1.6m	2.0m	2.4m	3.2m		1.6m	2.0m	2.4m	3.2m	
		Datsun	0.887	0.890	0.867	0.834		0.859	0.884	0.892	0.882	
		Cortina	0.859	0.893	0.908	0.904		0.884	0.905	0.916	0.923	
	300 mm	Base	1.2m	1.8m	2.4m	3.0m	3.6m	1.2m	1.8m	2.4m	3.0m	3.6m
		Datsun	0.861	0.872	0.830	0.808	0.790	0.831	0.879	0.886	0.878	0.862
		Cortina	0.854	0.896	0.399	0.891	0.871	0.879	0.913	0.925	0.924	0.917
32km/h	200 mm	Base	1.6m	2.0m	2.4m	3.2m		1.6m	2.0m	2.4m	3.2m	
		Datsun	0.840	0.867	0.863	0.860		0.839	0.881	0.898	0.898	
		Cortina	0.767	0.842	0.879	0.891		0.808	0.847	0.874	0.902	
	300 mm	Base	1.2m	1.8m	2.4m	3.0m	3.6m	1.2m	1.8m	2.4m	3.0m	3.6m
		Datsun	0.813	0.856	0.837	0.835	0.837	0.810	0.882	0.900	0.896	0.888
		Cortina	0.785	0.855	0.890	0.907	0.910	0.794	0.858	0.889	0.902	0.912
50km/h	100 mm	Base	1.6m	2.0m	2.4m	3.2m		1.6m	2.0m	2.4m	3.2m	
		Datsun	0.750	0.829	0.867	0.900		0.735	0.811	0.856	0.877	
		Cortina	0.717	0.782	0.830	0.882		0.742	0.791	0.826	0.866	
	300 mm	Base	1.2m	1.8m	2.4m	3.0m	3.6m	1.2m	1.8m	2.4m	3.0m	3.6m
		Datsun	0.701	0.827	0.864	0.886	0.897	0.693	0.819	0.868	0.876	0.874
		Cortina	0.717	0.801	0.850	0.881	0.898	0.728	0.806	0.847	0.867	0.887

TABLE H.21

ROOT MEAN SQUARE OF DEVIATION

(USING DISCRETE BASELENGTHS) ST LUCIA DATA

100mm INTERVAL

SECTION	1.5m		1.8m		2.0m		2.2m		2.4m		2.6m	
	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s
1	1.668	1.370	1.777	1.449	1.970	1.641	1.956	--	2.241	--	2.222	--
2	1.005	1.011	1.118	1.096	1.185	1.202	1.233	--	1.271	--	1.312	--
3	1.399	2.209	1.430	2.287	1.472	2.316	1.459	--	1.501	--	1.540	--
4	1.888	1.942	2.067	2.175	2.224	2.280	2.302	--	2.401	--	2.623	--
5	1.798	1.942	1.877	2.175	2.089	2.280	2.063	--	2.228	--	2.229	--
6	3.685	3.356	4.062	3.675	4.695	4.278	4.849	--	5.088	--	5.490	--
7	2.715	2.087	3.022	2.302	3.163	2.345	3.206	--	3.218	--	3.555	--
8	2.642	2.733	3.047	3.003	3.039	3.419	3.428	--	3.639	--	3.729	--
9	2.069	3.000	2.419	3.212	2.570	3.479	2.781	--	2.890	--	2.873	--
10	2.733	3.000	3.003	3.100	3.419	3.354	3.458	--	3.894	--	3.906	--
11	1.782	1.930	2.003	2.137	2.040	2.204	2.031	--	2.303	--	2.319	--
12	0.562	0.562	0.689	0.689	0.760	0.760	0.766	--	0.852	--	0.903	--
13	1.451	1.475	1.463	1.741	1.650	1.777	1.791	--	1.738	--	1.830	--
14	5.017	5.017	5.225	5.225	5.510	5.510	5.685	--	5.660	--	5.753	--
15	3.312	2.876	3.558	2.504	3.781	2.564	3.787	--	3.961	--	4.153	--
16	1.068	1.141	1.178	1.276	1.336	1.318	1.390	--	1.460	--	1.522	--
17	2.617	3.411	3.144	3.784	3.462	4.244	3.793	--	3.655	--	3.975	--
18	3.279	3.261	3.382	3.411	3.521	3.549	3.897	--	4.096	--	4.061	--
19	3.105	4.526	3.257	4.809	3.319	5.092	3.488	--	3.526	--	3.565	--

200mm INTERVAL

SECTION	1.6m		1.8m		2.0m		2.2m		2.4m	
	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s
1	1.722	1.511	1.808	1.463	2.011	1.656	1.996	--	2.276	--
2	1.036	1.031	1.072	1.081	1.162	1.186	1.199	--	1.246	--
3	1.405	2.198	1.487	2.281	1.518	2.307	1.509	--	1.569	--
4	2.089	1.944	2.140	2.198	2.296	2.282	2.352	--	2.464	--
5	1.870	2.058	1.919	2.198	2.121	2.282	2.111	--	2.257	--
6	3.787	3.408	4.175	3.617	4.739	4.230	4.945	--	5.139	--
7	2.873	2.204	3.073	2.303	3.228	2.320	3.259	--	3.285	--
8	2.764	2.955	3.070	3.089	3.074	3.474	3.468	--	3.630	--
9	2.304	3.073	2.532	3.359	2.654	3.592	2.868	--	2.984	--
10	2.955	3.409	3.089	3.301	3.474	3.420	3.539	--	3.955	--
11	1.841	2.026	1.961	2.125	2.012	2.198	2.022	--	2.270	--
12	0.626	0.626	0.701	0.701	0.784	0.784	0.784	--	0.869	--
13	1.606	1.612	1.562	1.752	1.748	1.826	1.883	--	1.836	--
14	5.190	5.190	5.322	5.322	5.601	5.601	5.787	--	5.708	--
15	3.438	2.478	3.515	2.547	3.680	2.652	3.752	--	3.908	--
16	1.135	1.233	1.186	1.320	1.357	1.365	1.414	--	1.483	--
17	2.929	3.631	3.186	3.883	3.530	4.323	3.847	--	3.751	--
18	3.350	3.415	3.372	3.511	3.528	3.619	3.938	--	4.101	--
19	3.143	4.509	3.267	4.616	3.367	4.964	3.491	--	3.558	--

TABLE H.22

ROOT MEAN SQUARE OF DEVIATION

(USING DISCRETE BASELENGTHS) ST LUCIA DATA

300mm INTERVAL

SECTION	1.5m		1.8m		2.1m	
	n/s	o/s	n/s	o/s	n/s	o/s
1	1.735	1.408	1.847	1.506	2.049	1.676
2	0.928	0.953	1.053	1.079	1.153	1.218
3	1.227	1.680	1.324	1.748	1.333	1.806
4	1.972	1.922	2.207	2.196	2.400	2.462
5	1.808	1.922	1.930	2.196	2.034	2.248
6	3.912	3.394	4.275	3.786	4.906	4.376
7	2.759	2.115	3.071	2.389	3.250	2.525
8	2.796	2.919	3.243	3.190	3.509	3.498
9	2.142	3.031	2.501	3.366	2.693	3.856
10	2.919	3.031	3.190	3.344	3.498	3.531
11	1.743	1.991	1.967	2.197	2.147	2.345
12	0.558	0.558	0.713	0.713	0.790	0.790
13	1.383	1.504	1.369	1.739	1.591	1.825
14	4.655	4.655	5.139	5.139	5.379	5.379
15	3.316	2.276	3.482	2.518	3.517	2.700
16	1.059	1.184	1.195	1.346	1.431	1.451
17	2.620	3.461	3.208	3.832	3.626	4.231
18	3.338	3.287	3.423	3.558	3.895	3.890
19	2.935	4.340	3.127	4.639	3.228	4.818

500mm INTERVAL

SECTION	1.5m		2.0m		2.5m		3.0m	
	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s
1	1.661	1.348	2.024	1.658	2.419	2.078	2.540	2.231
2	0.832	0.882	1.122	1.145	1.237	1.284	1.401	1.540
3	1.331	1.755	1.527	1.983	1.615	2.107	1.807	2.229
4	1.838	1.934	2.284	2.280	2.637	2.503	2.907	3.040
5	1.873	1.934	2.175	2.280	2.360	2.625	2.686	3.040
6	3.974	3.493	4.946	4.471	5.595	4.928	5.808	5.111
7	2.452	1.923	2.971	2.195	3.247	2.609	3.737	2.872
8	2.649	2.891	3.077	3.636	3.891	4.026	4.119	4.516
9	2.137	3.040	2.624	3.512	2.959	3.800	3.295	4.183
10	2.891	3.040	3.636	3.495	4.026	3.815	4.516	4.193
11	1.802	1.808	2.146	2.099	2.419	2.383	2.721	2.680
12	0.530	0.530	0.811	0.811	0.905	0.905	1.138	1.138
13	1.370	1.469	1.623	1.920	1.789	2.151	2.006	2.479
14	4.158	4.158	5.223	5.223	5.392	5.392	6.007	6.007
15	3.437	2.225	3.819	2.481	4.168	2.845	4.425	2.975
16	1.021	1.077	1.365	1.341	1.576	1.585	1.807	1.759
17	2.667	3.529	3.692	4.246	4.104	4.366	4.761	4.833
18	3.360	3.235	3.691	3.637	4.319	4.327	4.800	4.856
19	2.780	3.939	3.108	4.790	3.429	5.109	3.530	5.383

TABLE H.23

ROOT MEAN SQUARE OF DEVIATION

(USING CONTIGUOUS BASELENGTHS) ST LUCIA DATA

100mm INTERVAL

SECTION	1.5m		1.8m		2.0m	
	n/s	o/s	n/s	o/s	n/s	o/s
1	1.628	1.379	1.819	1.523	1.933	1.616
2	1.049	1.034	1.123	1.114	1.173	1.169
3	1.367	2.257	1.420	2.319	1.454	2.355
4	1.863	1.874	2.071	2.077	2.202	2.206
5	1.764	1.874	1.935	2.077	2.031	2.206
6	3.583	3.328	4.164	3.816	4.513	4.116
7	2.723	2.119	2.955	2.284	3.097	2.383
8	2.715	2.693	3.038	3.059	3.235	3.286
9	2.086	3.016	2.347	3.327	2.504	3.503
10	2.693	3.016	3.059	3.327	3.286	3.503
11	1.790	1.940	1.960	2.122	2.063	2.228
12	0.602	0.602	0.678	0.678	0.732	0.732
13	1.435	1.518	1.574	1.698	1.662	1.811
14	5.032	5.032	5.281	5.281	5.430	5.430
15	3.377	2.325	3.622	2.487	3.756	2.528
16	1.091	1.144	1.219	1.267	1.301	1.348
17	2.732	3.500	3.114	3.857	3.364	4.061
18	3.199	3.200	3.493	3.539	3.678	3.746
19	3.114	4.604	3.269	4.829	3.362	4.967

200mm INTERVAL

SECTION	1.6m		1.8m		2.0m	
	n/s	o/s	n/s	o/s	n/s	o/s
1	1.733	1.454	1.857	1.551	1.970	1.647
2	1.029	1.040	1.084	1.101	1.138	1.163
3	1.435	2.277	1.476	2.324	1.515	2.366
4	1.999	1.977	2.135	2.116	2.267	2.248
5	1.859	1.977	1.965	2.116	2.058	2.248
6	3.855	3.423	4.238	3.763	4.739	4.072
7	2.867	2.160	3.020	2.269	3.162	2.372
8	2.840	2.893	3.055	3.132	3.252	3.356
9	2.284	3.230	2.451	3.422	2.604	3.591
10	2.893	3.230	3.132	3.422	3.356	3.591
11	1.808	1.990	1.921	2.110	2.024	2.218
12	0.637	0.637	0.693	0.693	0.749	0.749
13	1.584	1.613	1.675	1.733	1.761	1.847
14	5.186	5.186	5.363	5.363	5.523	5.523
15	3.391	2.437	3.546	2.545	3.678	2.640
16	1.158	1.229	1.244	1.312	1.327	1.393
17	2.915	3.716	3.178	3.946	3.434	4.149
18	3.299	3.413	3.494	3.629	3.684	3.832
19	3.170	4.490	3.280	4.650	3.381	4.806

TABLE H.24

ROOT MEAN SQUARE OF DEVIATION

(USING CONTIGUOUS BASELENGTHS)   ST LUCIA DATA

300mm INTERVAL

SECTION	1.5m		1.8m		2.1m	
	n/s	o/s	n/s	o/s	n/s	o/s
1	1.705	1.436	1.897	1.597	2.065	1.753
2	0.965	0.994	1.070	1.105	1.165	1.213
3	1.206	1.684	1.289	1.774	1.360	1.854
4	1.981	1.934	2.200	2.149	2.408	2.351
5	1.785	1.934	1.951	2.149	2.092	2.351
6	3.787	3.417	4.379	3.786	4.864	4.376
7	2.805	2.160	3.037	2.331	3.245	2.484
8	2.857	2.881	3.181	3.250	3.464	3.583
9	2.158	3.123	2.419	3.418	2.646	3.661
10	2.881	3.123	3.250	3.418	3.583	3.661
11	1.764	2.011	1.949	2.191	2.112	2.341
12	0.615	0.615	0.709	0.709	0.802	0.802
13	1.344	1.556	1.498	1.742	1.638	1.914
14	4.734	4.734	5.060	5.060	5.341	5.341
15	3.306	2.330	3.552	2.523	3.745	2.673
16	1.117	1.207	1.259	1.338	1.392	1.466
17	2.772	3.494	3.174	3.841	3.559	4.124
18	3.282	3.295	3.591	3.643	3.889	3.957
19	2.904	4.387	3.090	4.672	3.247	4.921

500mm INTERVAL

SECTION	1.5m		2.0m		2.5m		3.0m	
	n/s	o/s	n/s	o/s	n/s	o/s	n/s	o/s
1	1.649	1.373	1.968	1.667	2.222	1.933	2.445	2.159
2	0.883	0.922	1.069	1.123	1.220	1.298	1.343	1.446
3	1.360	1.794	1.526	2.005	1.643	2.144	1.735	2.254
4	1.870	1.911	2.254	2.295	2.617	2.636	2.949	2.923
5	1.885	1.911	2.149	2.295	2.370	2.636	2.594	2.923
6	3.864	3.468	4.787	4.314	5.359	4.864	5.750	5.243
7	2.515	2.000	2.974	2.306	3.315	2.565	3.591	2.761
8	2.686	2.842	3.264	3.491	3.718	4.009	4.101	4.424
9	2.164	3.084	2.587	3.541	2.954	3.903	3.289	4.192
10	2.842	3.084	3.491	3.541	4.009	3.903	4.424	4.192
11	1.860	1.825	2.165	2.148	2.418	2.392	2.620	2.606
12	0.602	0.602	0.772	0.772	0.918	0.918	1.039	1.039
13	1.313	1.547	1.587	1.885	1.808	2.168	2.004	2.415
14	4.345	4.345	5.034	5.034	5.520	5.520	5.885	5.885
15	3.480	2.247	3.903	2.542	4.199	2.767	4.423	2.927
16	1.100	1.135	1.351	1.368	1.562	1.573	1.737	1.755
17	2.895	3.522	3.602	4.104	4.219	4.506	4.746	4.843
18	3.337	3.291	3.881	3.918	4.369	4.448	4.781	4.924
19	2.821	4.012	3.152	4.615	3.400	5.018	3.607	5.333

TABLE H.25

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING DISCRETE BASELENGTHS) ST. LUCIA DATA

Speed	Interval	Type	Nearside Wheelpath						Offside Wheelpath			
20km/h	100 mm	Base	1.5m	1.8m	2.0m	2.2m	2.4m	2.6m	1.5m	1.8m	2.0m	
		Datsun	0.917	0.915	0.901	0.911	0.883	0.872	0.889	0.889	0.895	
		Cortina	0.933	0.957	0.955	0.966	0.958	0.956	0.886	0.894	0.895	
	200 mm	Base	1.6m	1.8m	2.0m	2.2m	2.4m		1.6m	1.8m	2.0m	
		Datsun	0.910	0.922	0.912	0.914	0.890		0.888	0.884	0.893	
		Cortina	0.945	0.956	0.955	0.964	0.962		0.908	0.907	0.901	
	300 mm	Base	1.5m	1.8m	2.1m				1.5m	1.8m	2.1m	
		Datsun	0.891	0.897	0.887				0.884	0.885	0.879	
		Cortina	0.943	0.953	0.951				0.925	0.936	0.931	
	500 mm	Base	1.5m	2.0m	2.5m	3.0m			1.5m	2.0m	2.5m	3.0m
		Datsun	0.851	0.860	0.831	0.823			0.855	0.876	0.882	0.862
		Cortina	0.939	0.949	0.938	0.919			0.897	0.905	0.917	0.921
32km/h	100 mm	Base	1.5m	1.8m	2.0m	2.2m	2.4m	2.6m	1.5m	1.8m	2.0m	
		Datsun	0.900	0.925	0.916	0.939	0.916	0.908	0.881	0.889	0.090	
		Cortina	0.877	0.913	0.918	0.949	0.948	0.944	0.812	0.826	0.836	
	200 mm	Base	1.6m	1.8m	2.0m	2.2m	2.4m		1.6m	1.8m	2.0m	
		Datsun	0.909	0.933	0.927	0.941	0.925		0.892	0.893	0.912	
		Cortina	0.899	0.912	0.916	0.947	0.952		0.845	0.859	0.850	
	300 mm	Base	1.5m	1.8m	2.1m				1.5m	1.8m	2.1m	
		Datsun	0.902	0.926	0.925				0.909	0.914	0.920	
		Cortina	0.913	0.924	0.947				0.881	0.895	0.905	
	500 mm	Base	1.5m	2.0m	2.5m	3.0m			1.5m	2.0m	2.5m	3.0m
		Datsun	0.877	0.896	0.887	0.888			0.904	0.913	0.927	0.921
		Cortina	0.936	0.942	0.959	0.950			0.879	0.875	0.905	0.919
50km/h	100 mm	Base	1.5m	1.8m	2.0m	2.2m	2.4m	2.6m	1.5m	1.8m	2.0m	
		Datsun	0.812	0.859	0.880	0.908	0.897	0.906	0.769	0.799	0.846	
		Cortina	0.825	0.865	0.871	0.913	0.914	0.914	0.755	0.775	0.790	
	200 mm	Base	1.6m	1.8m	2.0m	2.2m	2.4m		1.6m	1.8m	2.0m	
		Datsun	0.830	0.871	0.893	0.914	0.908		0.796	0.806	0.847	
		Cortina	0.850	0.863	0.869	0.912	0.918		0.792	0.799	0.804	
	300 mm	Base	1.5m	1.8m	2.1m				1.5m	1.8m	2.1m	
		Datsun	0.851	0.887	0.920				0.838	0.851	0.881	
		Cortina	0.873	0.883	0.917				0.839	0.854	0.869	
	500 mm	Base	1.5m	2.0m	2.5m	3.0m			1.5m	2.0m	2.5m	3.0m
		Datsun	0.851	0.895	0.911	0.911			0.868	0.884	0.906	0.891
		Cortina	0.908	0.908	0.936	0.936			0.851	0.843	0.882	0.901

TABLE H.26

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING CONTIGUOUS BASELENGTHS) ST. LUCIA DATA

Speed	Interval	Type	Nearside Wheelpath			Offside Wheelpath		
20 km/h	200 mm	Base	1.6m	1.8m	2.0m	1.6m	1.8m	2.0m
		Datsun	0.923	0.921	0.916	0.883	0.889	0.892
		Cortina	0.949	0.955	0.960	0.897	0.904	0.910
	300 mm	Base	1.5m	1.8m	2.1m	1.5m	1.8m	2.1m
		Datsun	0.893	0.886	0.876	0.881	0.877	0.885
		Cortina	0.949	0.952	0.951	0.925	0.929	0.931
32 km/h	200 mm	Base	1.6m	1.8m	2.0m	1.6m	1.8m	2.0m
		Datsun	0.920	0.928	0.931	0.886	0.900	0.909
		Cortina	0.898	0.915	0.928	0.836	0.852	0.864
	300 mm	Base	1.5m	1.8m	2.1m	1.5m	1.8m	2.1m
		Datsun	0.909	0.914	0.913	0.905	0.910	0.921
		Cortina	0.919	0.934	0.945	0.879	0.894	0.904
50 km/h	200 mm	Base	1.6m	1.8m	2.0m	1.6m	1.8m	2.0m
		Datsun	0.841	0.868	0.895	0.790	0.818	0.839
		Cortina	0.848	0.869	0.887	0.782	0.803	0.819
	300 mm	Base	1.5m	1.8m	2.1m	1.5m	1.8m	2.1m
		Datsun	0.854	0.883	0.902	0.833	0.849	0.880
		Cortina	0.878	0.899	0.916	0.835	0.855	0.870

TABLE H.27

COMPARISON OF CALIBRATED AND UNCALIBRATED ROUGHNESS MEASUREMENTS

(MM/KM)

BRASIL IRRE

SECTION	RMSD (300,1.8)	CAR BI		NAASRA		MM-02		REFERENCE ROUGHNESS
		Uncal	Cal	Uncal	Cal	Uncal	Cal	
CA04	1.422	3064	3151	3050	3248	6906	3161	2970
CA05	1.899	3953	3852	3781	3839	8315	3668	4012
CA06	2.137	4302	4140	4199	4192	9261	4023	4570
CA10	0.788	1524	2045	1434	2057	3480	2029	1744
CA12	0.721	635	1470	513	1449	1219	1362	1625
TS01	1.387	2921	3042	2831	3077	6217	2921	2898
TS04	1.603	3604	3571	3525	3628	8430	3711	3354
TS05	1.951	4001	3892	3990	4014	9436	4090	4132
TS06	1.054	2000	2372	1929	2404	4220	2261	2237
TS07	1.087	1842	2262	1871	2363	4248	2270	2300
TE01	1.517	2842	2983	2527	2845	5959	2833	3170
TE03	2.195	6080	5718	5605	5456	12767	5434	4710
TE06	5.434	13700	14577	13471	14756	28635	13724	14925
TE11	3.005	7271	6879	6963	6793	17224	7447	6822
GR01	1.359	1572	2078	1425	2050	3578	2060	2840
GR05	2.651	6207	5838	5938	5773	15173	6490	5863
GR07	1.608	3366	3384	3202	3368	7490	3368	3364
GR12	3.687	9446	9212	9120	9145	21615	9672	8829

TABLE H.28

COMPARISON OF CALIBRATED AND UNCALIBRATED ROUGHNESS MEASUREMENTS (MM/KM)

ST LUCIA STUDY

SECTION	RMSD (300,1.8)	DATSUN Uncal	DATSUN Cal	CORTINA Uncal	CORTINA Cal	REFERENCE ROUGHNESS
1	1.847	2979	4071	---	---	3894
2	1.053	1012	1672	614	1620	2235
3	1.324	2564	3513	934	2052	2769
4	2.207	2908	3974	2266	4123	4739
5	1.930	2865	3915	2095	3832	4084
6	4.275	6908	10730	---	---	10727
7	3.071	4714	6705	3335	6105	7007
8	3.243	5195	7521	3848	7158	7499
9	2.501	4423	6229	3412	6259	5473
10	3.190	4714	6705	---	---	7346
11	1.967	2654	3632	2022	3711	4169
12	0.713	889	1542	818	1892	1611
13	1.369	2190	3034	1769	3299	2861
14	5.139	8309	13706	5897	12015	13799
15	3.482	4328	6077	---	---	8204
16	1.195	1801	2559	1432	2774	2511
17	3.208	5965	8905	4704	9060	7397
18	3.423	---	---	4971	9690	8027
19	3.127	6252	9445	4298	8135	7166

FIG. H.1

BI TRAILER (Average) vs CAR BI

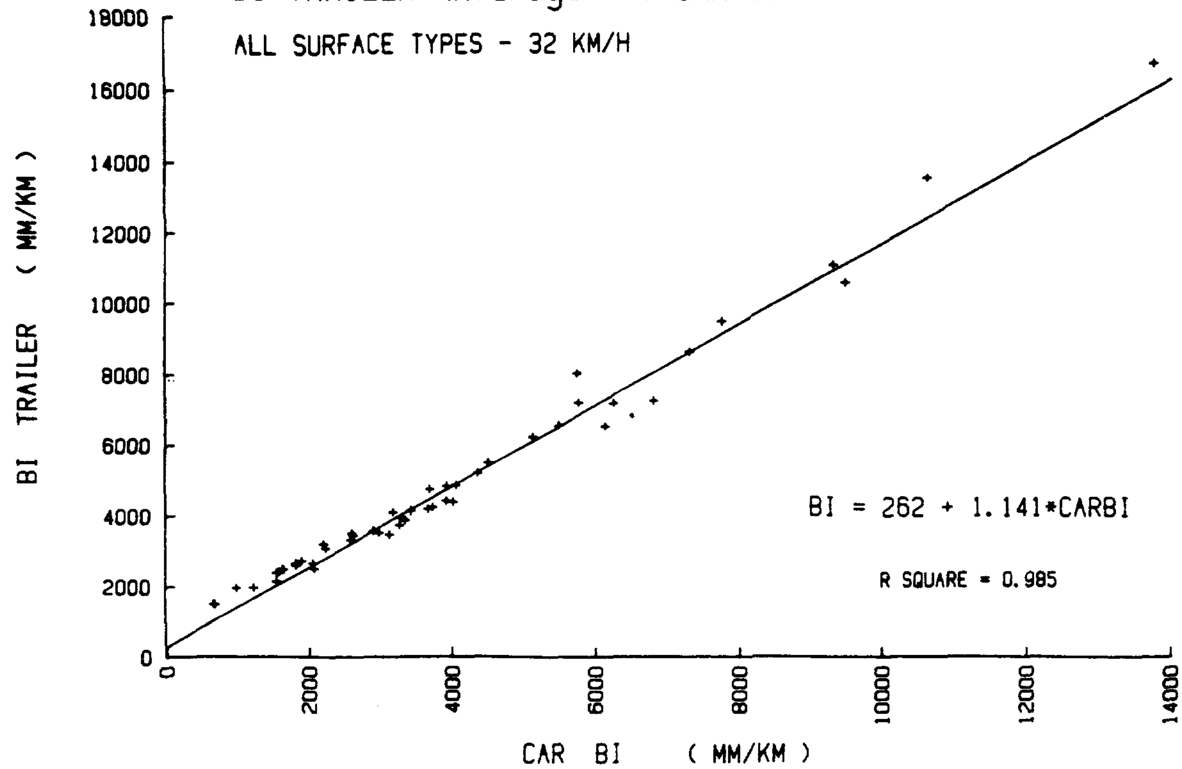


FIG. H.2

BI TRAILER (Average) vs NAASRA

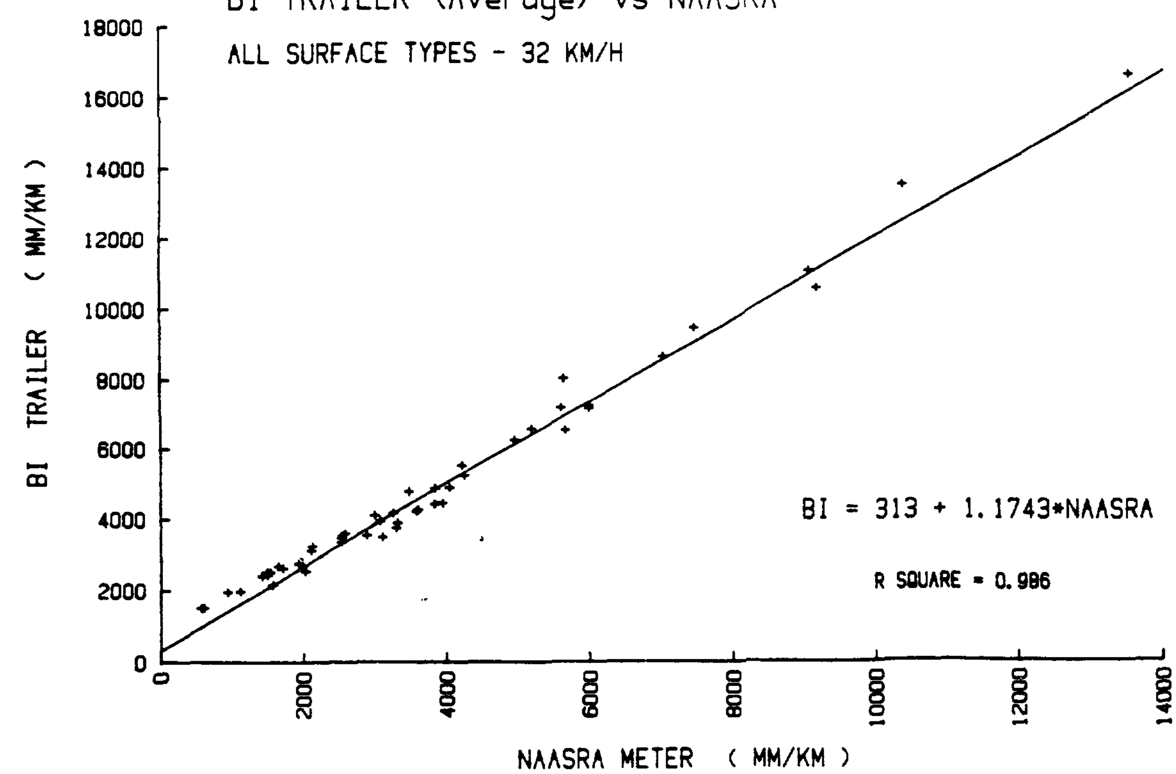


FIG. H.3

BI TRAILER (Average) vs MM-02

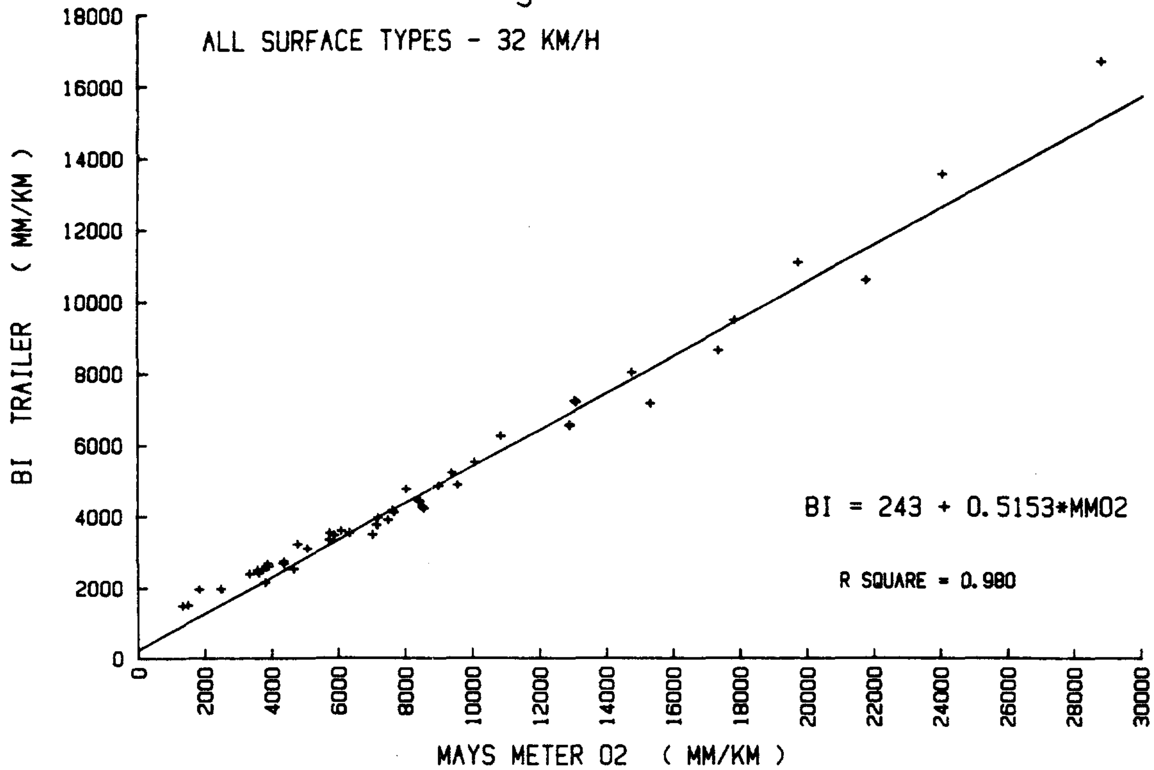


FIG. H.4

STANDARDISED REFERENCE ROUGHNESS EQUATION

(DERIVED FROM BI TRAILER / RMSD (300, 1.8) CORRELATION)

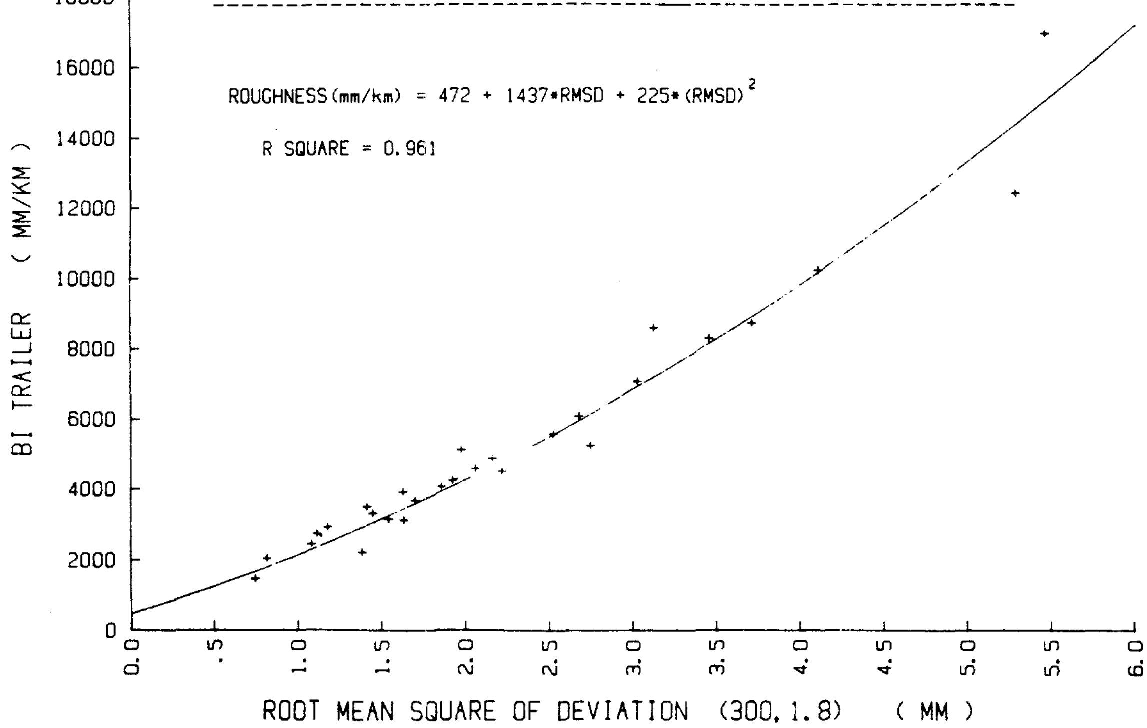
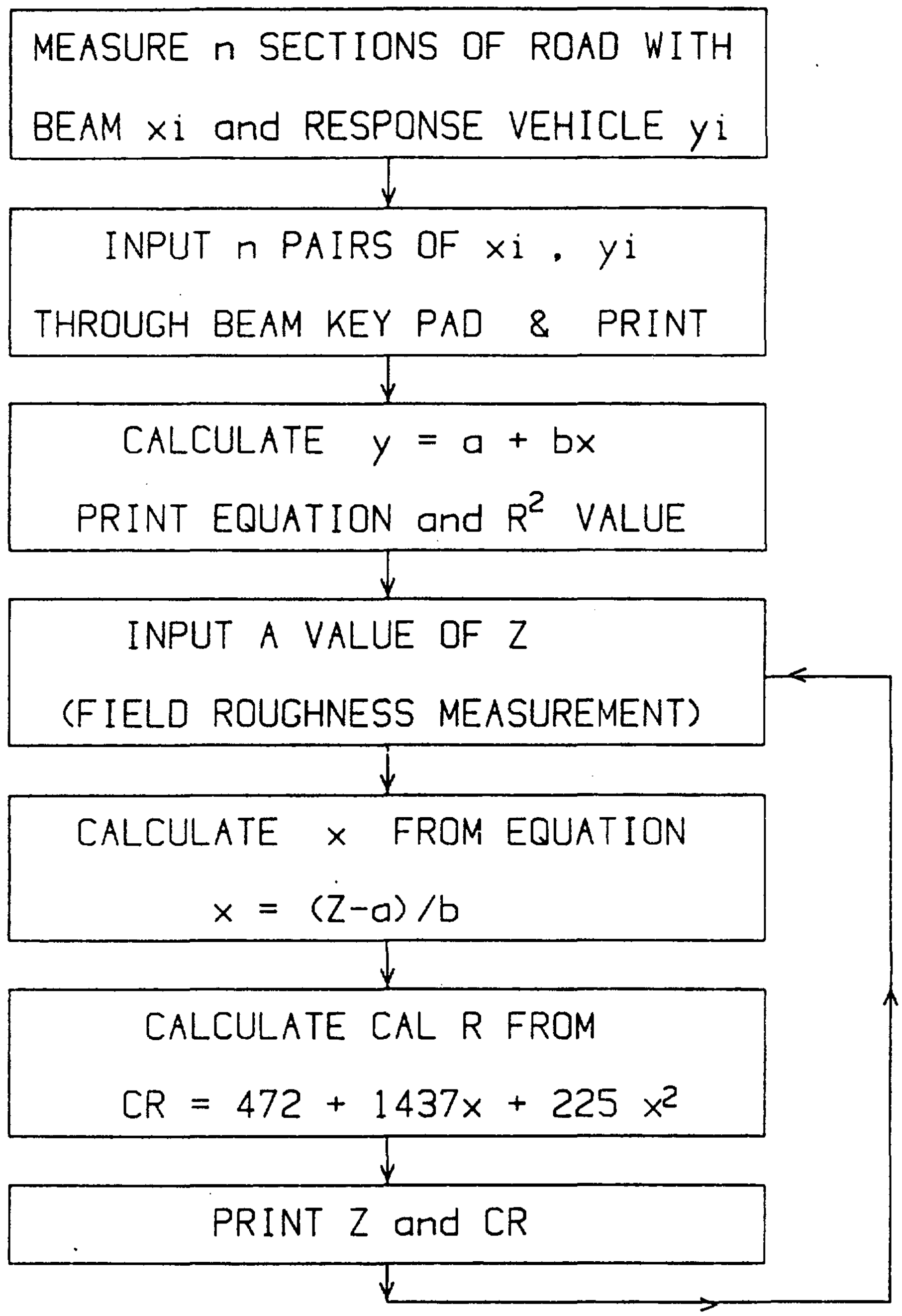


FIG. H. 5

FLOW DIAGRAM OF THE OPERATION OF THE TRRL ROUGHNESS CALIBRATION BEAM



APPENDIX I

SPECTRAL CONTENT OF ROAD PROFILES

The many measures that have been used to quantify road roughness at first appear to have little in common, yet often result in highly correlated summary statistics. The correlations between dissimilar numerics are determined in part by the mathematical properties of the analyses, and in part by the statistical properties of the road profiles. Much of the correlation between numerics can be caused by correlations within the road profile input and can vary with the type of road. Therefore, information about the nature of the longitudinal profiles of actual roads can give considerable insight to some of the experimental findings dealing with different roughness numerics.

The purpose of this appendix is to present a few plots of the spectral characteristics of the 98 wheeltrack profiles (49 lanes) that were obtained in the IRRE. Each wheeltrack profile was measured up to 6 times, using rod and level, the TRRL Beam, and the APL Trailer in both the APL 25 and APL 72 modes of operation. The plots presented serve to quantify the nature of road roughness in great detail over the four surface types included in the IRRE, and also to show the differences resulting from alternative measurement methods.

Power Spectral Density (PSD) Functions

A longitudinal road profile is fixed in space and, in the short term, is also fixed with time. That is, the same profile should be observed when exactly the same path is followed within a reasonably short period of time (perhaps years for paved roads, and perhaps minutes for unpaved roads during heavy rain). Although a road profile is deterministic, it does have the appearance of a random signal, and statistical descriptions commonly used for random signals have proven to be useful for characterizing road profile. By analyzing the profile using statistical methods, the very large amount of information (hundreds or thousands of independent elevation measurements) are reduced to a manageable number of summary statistics.

For reasons that will be discussed below, virtually every roughness numeric computed from profile that has proven useful involves isolating a band of wavenumbers (wavenumber = 1/wavelength) from the original profile signal. It is therefore helpful to view the variations in profile in terms of wavenumber amplitudes, using the statistical power spectral density (PSD) function.

Physically, a PSD function is the variance of the variable being measured (elevation, slope, etc.) distributed over wavenumber, having the units: quantity measured^2/wavenumber. Thus, an elevation profile measured with the units of mm would have PSD units: mm^2 m/cycle, since the quantity measured is mm and a wavenumber (spatial frequency) has units: cycle/m. The integral of a PSD function over a band of wavenumbers (waveband) corresponds to the contribution of that band to the total variance, while the integral over all wavenumbers is equal to the total variance of the variable measured. (An alternate PSD definition, called a "double-sided PSD," is sometimes used in which case negative wavenumbers are also considered. For a double-sided PSD function, the wavenumbers must be integrated from -oo to +oo to obtain the variance. All PSD functions presented in this appendix are single-sided, meaning that the variance is distributed only over wavenumbers ranging from 0 to +oo.)

Further information about the usage of PSD functions and other spectral analyses of random (and random-like) signals can be obtained in Reference [39], which also includes formal mathematical definitions of the PSD function.

Although PSD functions were developed for describing random signals, error analyses that assume the signal to be random are not appropriate for road profiles, since the profile is not random. The PSD function of a road profile is not an estimate, but rather, an alternate description containing almost as much (up to half) of the information as the original profile measurement.

Spectral Contents of Road Profiles

Figure I.1 shows three PSD functions, all of which are computed from a single measured profile. Since road profile is measured as an elevation, it is natural to compute the PSD function directly from that measure. As Fig. I.1a shows, the contribution to elevation variance is much greater at the lower wavenumbers (longer wavelengths).

A PSD function computed for a measured variable such as road elevation can be converted to the PSD function of any other variable, if the two variables are related by a linear operation. Since most of the roughness analyses involve linear filters (the RQCS, RMSVA, moving average, CP, APL 72 energy (W), etc.), the PSD function of the filtered profile can be computed directly from the PSD function of the road profile, together with the frequency response plot of the linear filter. Since differentiation and integration are linear operations, the PSD function can also be computed for the derivatives of the elevation measurement: slope, slope derivative (spatial acceleration, etc.), as shown by Figs. I.1b and I.1c.

As a means for characterizing road profiles, the PSD function of slope offers two advantages:

1) The plots can be scaled to show more detail. Note that the elevation and acceleration functions cover a wider range of amplitudes than the slope PSD over the wavenumber range .025 - 1 (wavelengths 1 - 40 m), requiring that the plots be scaled down.

2) Alternate roughness analyses can be compared more readily using their wavenumber response plots. When response plots are calculated for displacement inputs, one must always remember that there is much more input at the lower wavenumbers, and that even if the analysis is less responsive at those wavenumbers, they can constitute much of the numeric. But when response plots are calculated for slope inputs, what you see is what you get. A high sensitivity (gain) at any wavenumber band, high or low, indicates that that band contibutes heavily to the summary numeric.

All road PSD functions that follow in this appendix are presented in

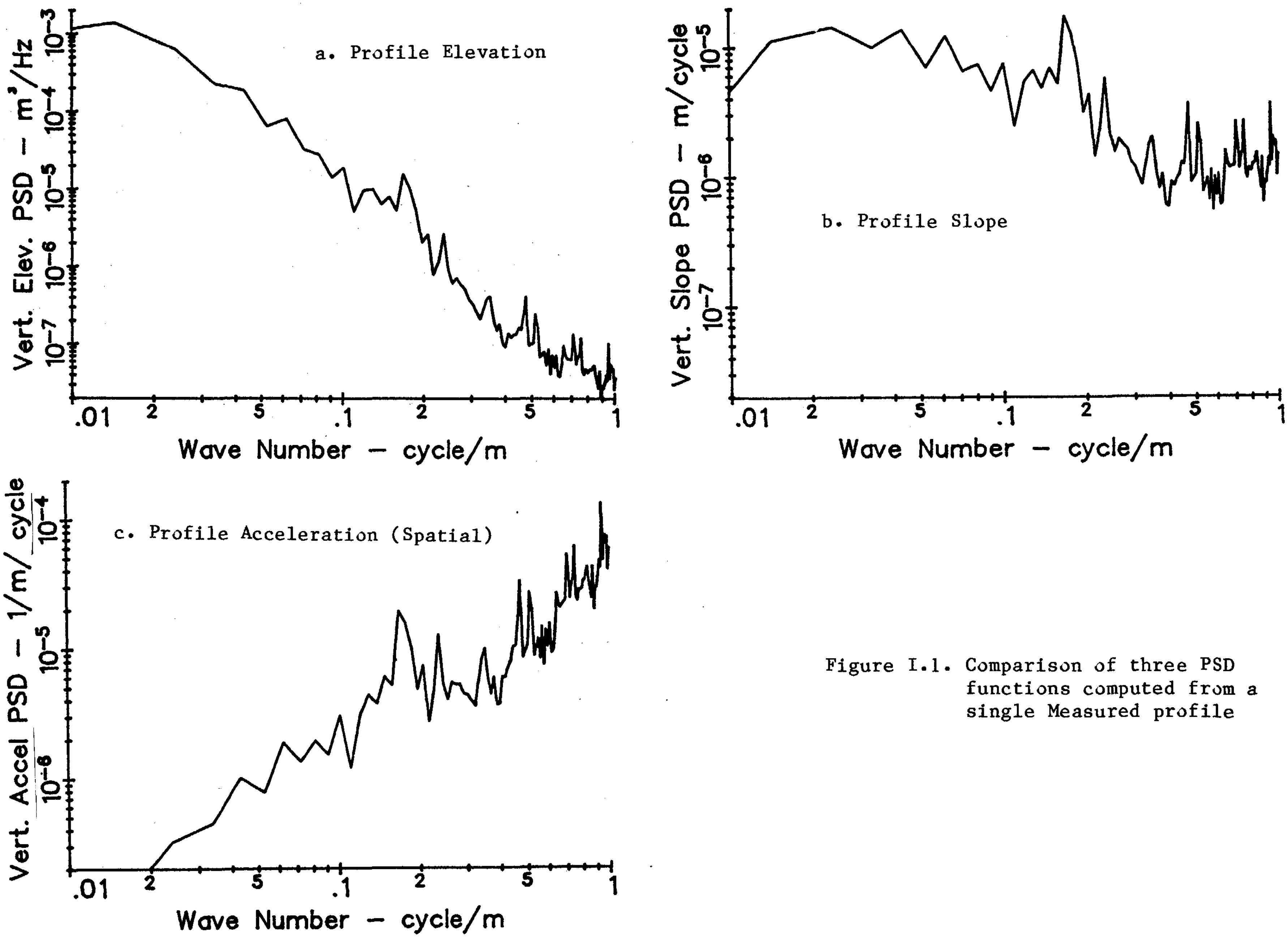


Figure I.1. Comparison of three PSD functions computed from a single Measured profile terms of profile slope.

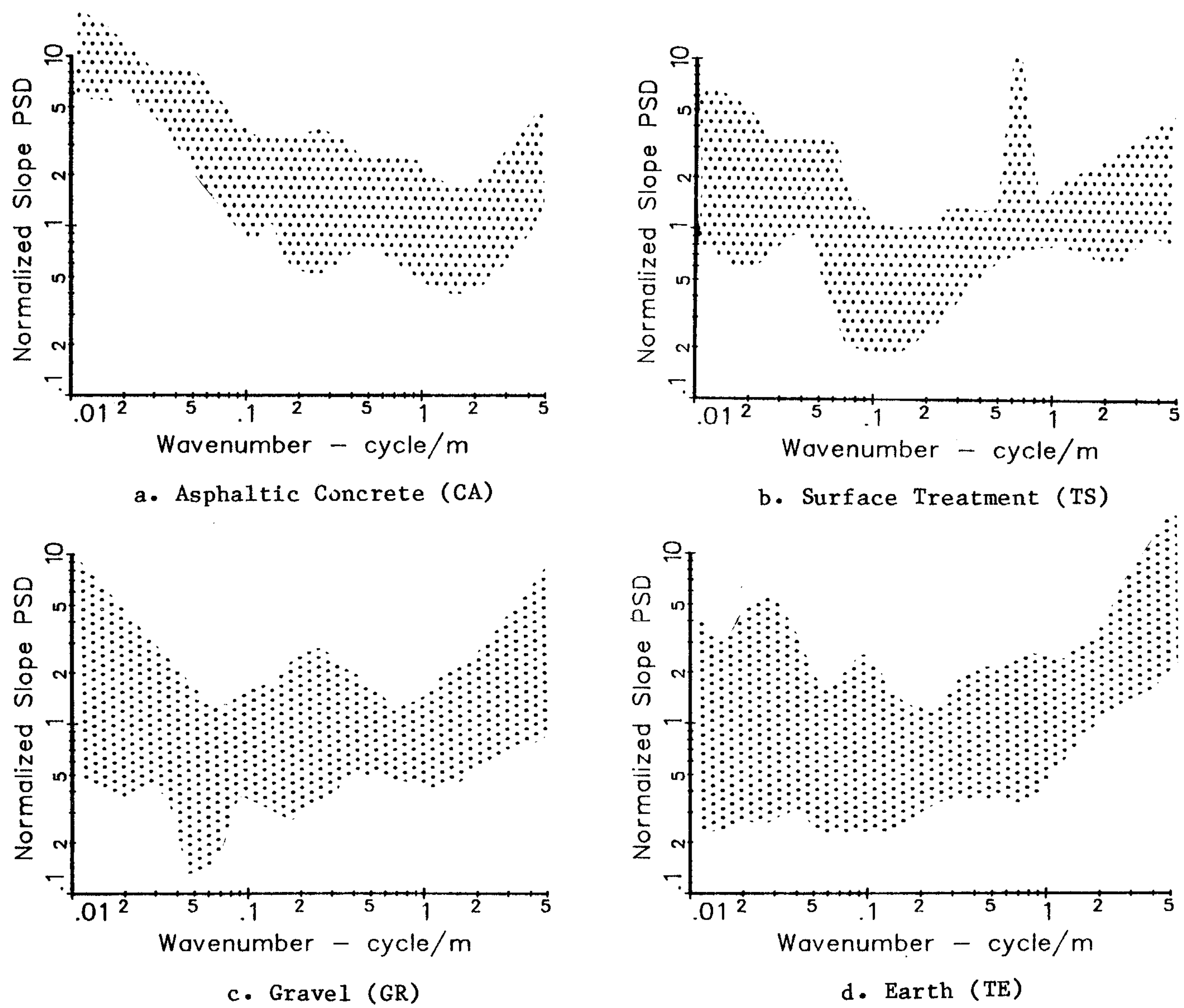
Figure I.2 presents aggregate PSD functions, obtained by graphically overlaying the PSD functions for individual profiles obtained with the TRRL Beam. The amplitudes of each individual plot were normalized by the squared $RARS_{50}$ roughness value known for that particular wheeltrack. When the PSD functions are normalized in this fashion, many appear to have the same shape, particularly when segregated by surface type. The plots show that:

1) The asphaltic concrete (CA) sites had the least roughness concentrated in the high wavenumbers of any of the surface types. Also, there is little vertical scatter when the PSD functions are normalized, indicating that most of the CA sites had very similar spectral distributions. The PSD shape shown constitutes a "signature" for that type of surface.

2) The surface treatment (TS) sites also had a signature, distinguished by a relative minimum over wavenumbers 0.1 - 0.4 (wavelengths 2.5 - 10 m), with increased roughness content for wavenumbers outside this range. Also, several of the TS sites displayed a spectral peak at wavenumber 0.5, indicating a periodic roughness component occurring at 2.0 m intervals.

3) The PSD functions for the unpaved gravel (GR) and earth (TE) sites show more variation in content than do the paved roads, but this is not unexpected since they also cover a greater range of roughness. Although they do show a slight minimum in the center near wavenumber 0.1, their roughness distribution is more uniform over the spectrum of wavenumbers, with the earth roads showing somewhat more roughness content at the highest wavenumbers than the gravel roads.

4) In all cases, the amplitudes rise at the highest wavenumbers covered (wavenumbers 2 - 5). This is due in part to aliasing, and is discussed below.



a. Asphaltic Concrete (CA)

b. Surface Treatment (TS)

c. Gravel (GR)

d. Earth (TE)

Figure I.2. Aggregate PSD "Signatures" for Four Surface Types

Sensitivity of Simple Variance to Measurement Methods

Although different types of roads may have unique "signatures," all come closer to having a uniform slope input than a uniform elevation input or uniform acceleration input. This has certain implications regarding the measurement of simple variance and RMS statistics:

1) RMS displacement measures are determined almost completely by the lowest wavenumbers (longest wavelengths) included in the measurement. The lower the wavenumber, the larger will be the RMS displacement. When the measuring instrument does not explicitly filter the profile (e.g., rod and level), then the lowest wavenumber is approximately determined by the length of the profile, and RMS elevation will increase with length.

2) RMS acceleration measures are determined almost completely by the highest wavenumbers (shortest wavelengths) included in the measurement. The higher the wavenumber range, the higher will be the RMS acceleration. When the acceleration is computed from a measured elevation profile, the highest wavenumber can be limited by either the instrument (for a dynamic profilometer), or the sample interval. A shorter sample interval will give higher RMS acceleration numerics.

3) RMS slope measures are determined by the width of the waveband included in the measurement. RMS slope numerics can be increased either by including higher wavenumbers or by including lower wavenumbers. For statically measured profiles, the waveband is not increased so much with profile length as by sample interval. Decreasing the sample interval will increase the slope numeric, although not nearly as rapidly as for an acceleration numeric.

Note that simple RMS elevation, slope, and acceleration numerics all can be increased without bound by increasing the measurement waveband. Therefore, road roughness cannot be meaningfully characterized by a numeric such as "true slope variance" or "true RMS acceleration," since the measured numerics depend more on the bandwidth of the measurement than on the road. (In fact, "true" slope variance and RMS accelerations are infinite.) Instead, the numeric must either require a standardized measurement method, or else include a means for limiting the bandwidth through processing of the measurement. When terms such as "slope variance" are used, the numerics are inevitably more complicated and specialized than implied by their names.

Summary of the PSD Data from the IRRE

The remaining figures in this appendix, Figs. I.3 - I.10 show the PSD functions measured for each wheeltrack of 8 of the 49 test sites used in the IRRE. Each Figure can have up to eight individual PSD plots, corresponding to measures made by rod and level, the APL 25 system, the APL 72 system, and the TRRL Beam. In order to facilitate comparisons, all plots are made on log-log axes, and cover the same wavenumber range. The vertical scaling was determined automatically by the computer program to include the highest PSD amplitudes. In every case, the vertical scale covers a range of 100:1. Since the plots are logarithmic, they can be shifted up or down to match the y-axis scaling in order to overlay different plots.

The same analysis was applied to all of the profiles:

1) The 320 m long profile was converted from an elevation to a slope profile (approximately) by taking the differences in adjacent elevation values, normalized by the sample interval. This step eliminates the mean values, trends, and large amplitudes for the long-wavelength variations that appear when profiles are measured statically.

2) The slope profile was "padded" with zeros to increase the number of data points to the next power of two, which depended on the sample interval used. For the rod and level data, the 641 data points were padded to obtain a total of 1024; for the APL 72 data, the 6401 data points were padded to obtain a total of 8192.

3) The profile was processed via the Fast Fourier Transform (FFT), and the amplitudes of the resulting complex coefficients were squared

and scaled to PSD engineering units.

4) The frequency response of the numerical differentiation used in step 1 was used to correct the PSD amplitudes at the higher wavenumbers to the results that would have been obtained by true differentiation.

5) Adjacent PSD values were averaged over a wavenumber interval of .01 cycle/m, which typically meant that 3 - 5 "raw" PSD values were averaged together to obtain the values plotted.

Comparison of the Different Measurement Methods

Rod and Level. The known limitations of rod and level are in the precision of the individual measures, the need for a large sample interval (to keep the effort reasonable), and the potential for human error. Both precision limits and aliasing can cause the PSD functions to increase erroneously when the wavenumbers approach the upper limit of 1.0 (half the sample frequency of 2 samples/m). Past experience with the precision requirements indicates that the 1 mm interval is adequate for the roughness range covered in the IRRE [38]. Therefore, the fact that the PSD functions obtained by rod and level rise more with wavenumber than the PSD functions obtained by the other methods, including the TRRL Beam, reflects aliasing.

The very good agreement with the TRRL Beam for many of the sites indicate that human error was reduced or eliminated by the routine procedures used in Brazil.

TRRL Beam. These measures match those of the rod and level almost perfectly in many of the plots, up until the higher wavenumbers influenced by aliasing. Since the highest wavenumbers for the rod and level measures appear to be artificially high due to aliasing, this is probably true also for the Beam PSD function, for wavenumbers above 2 or 3 cycle/m. The 3 m length of the Beam affects some of the PSD plots for the smoothest roads, appearing as a spectral peak at wavenumber .33 (3 m wavelength). This would be caused by the slight setup error that occurs periodically in the measurement process. The amount of variance contained within that peak is quite small, however, due to its narrow width. Therefore, the setup error, quantified by the PSD, can be seen to be negligible. (The spectral peak is not even visible for the rougher roads.)

APL Trailer. The APL Trailer, which is designed to measure profile over the frequency range of 0.5 - 20 Hz, covers a wavenumber range determined by its travel speed. At 72 km/h (APL 72), this wavenumber range is .025 - 1, while for the speed of 21.6 km/h (APL 25) this range is .08 - 3.3. The sample interval for the APL 25 signals was 250 mm, which puts the maximum wavenumber at 2.0, and means that aliasing can be present for wavenumbers above 1.

For many of the sites, the agreement between the APL 72 and APL 25 signals and the static measures is nearly perfect over the waveband of the instrument. The PSD plots illustrate very clearly the fidelity that can occur within that range, while also showing how lower wavenumbers are attenuated by the trailer.

Like the TRRL beam, the APL spectra show peaks on the smoother sites that are caused by the measurement process. The first peaks occur at wavenumber 0.6 and its harmonics (1.2, 1.8, ...). This is caused by a slight periodic disturbance introduced by the trailer wheel (circumference = 1/.6 = 1.7 m), and, because the peak is too narrow to include much variance, is negligible in terms of roughness measurement.

In the case of the APL 72 data, the PSD functions also consistently show a peak lying outside of the design range of the trailer, approximately at wavenumber 3.5. This corresponds to a frequency of 70 Hz during measurement. Most of the analyses are barely influenced by wavenumbers this high, so it also is negligible.

The fact that many of the PSD functions from the APL Trailer match those obtained statically is proof that the APL Trailer a valid profilometer (in terms of amplitude response) over the design waveband range. Yet some of the time, the match is not as good between the trailer and the statically measured profiles. These differences may, in many cases, be caused by imprecision in the lateral positioning of the towing vehicle on the test sites, or by starting the signal before or after the markings on the road. In a sense, the careful matching of the rod and level profiles and the TRRL profiles is artificial, since the wheelpaths were marked beforehand and followed almost exactly for repeated static measurements. In actual practice, the choice of where the travelled wheeltrack lies can influence the measurement obtained. The design of the IRRE removed this source of variation from the static measures, but not from the APL measures.

Validation for Specific Analyses. Although the good match between the PSD functions tends to confirm that all of the methods used can give "valid" measures of profile, the actual accuracy associated with each method must be determined for the specific application. This is particularly true when high accuracy requirements are set, since very small differences are difficult to see in PSD plots, unless more complicated processing methods are used.

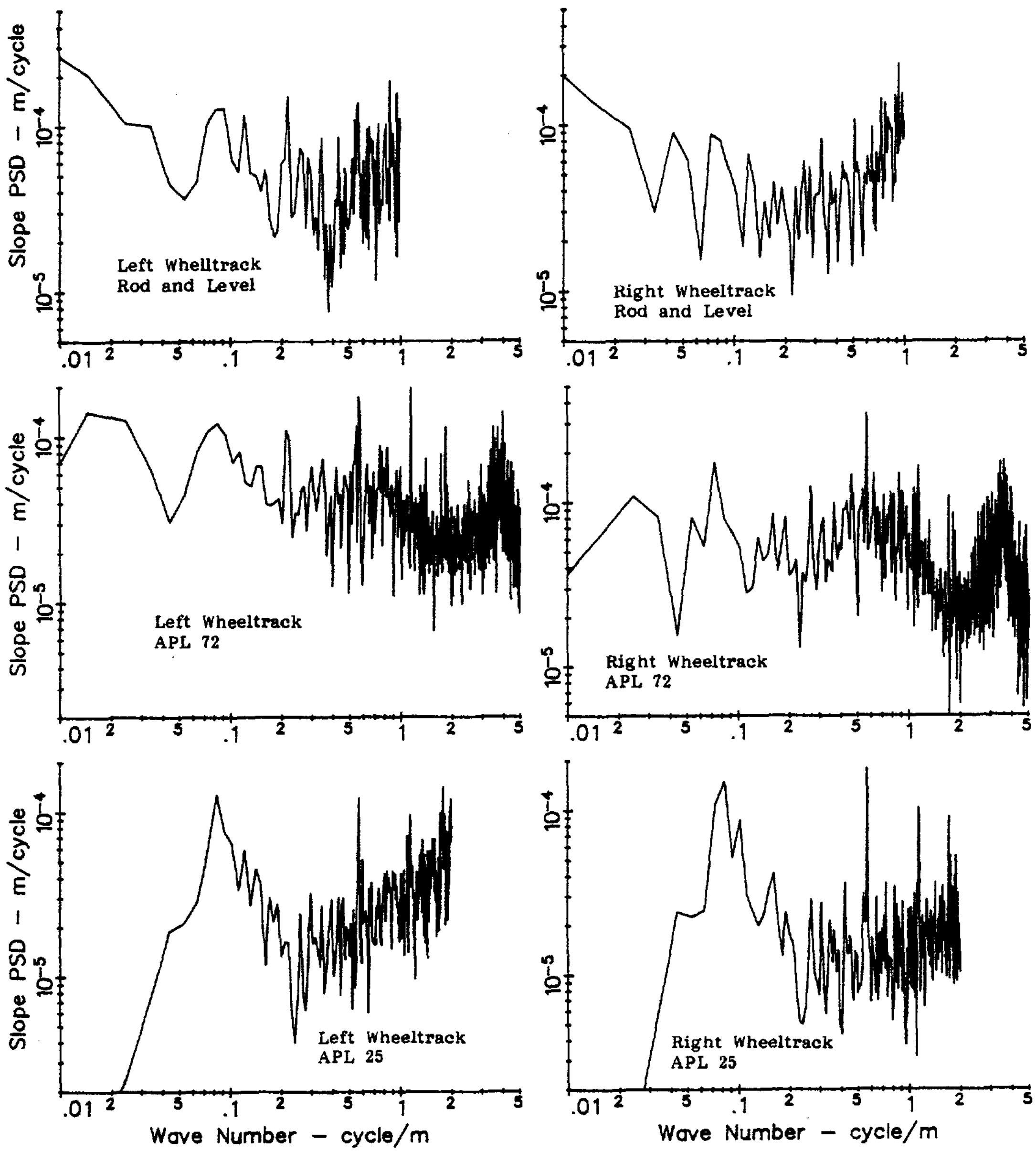


Figure I.3. PSD functions for Site CA02.

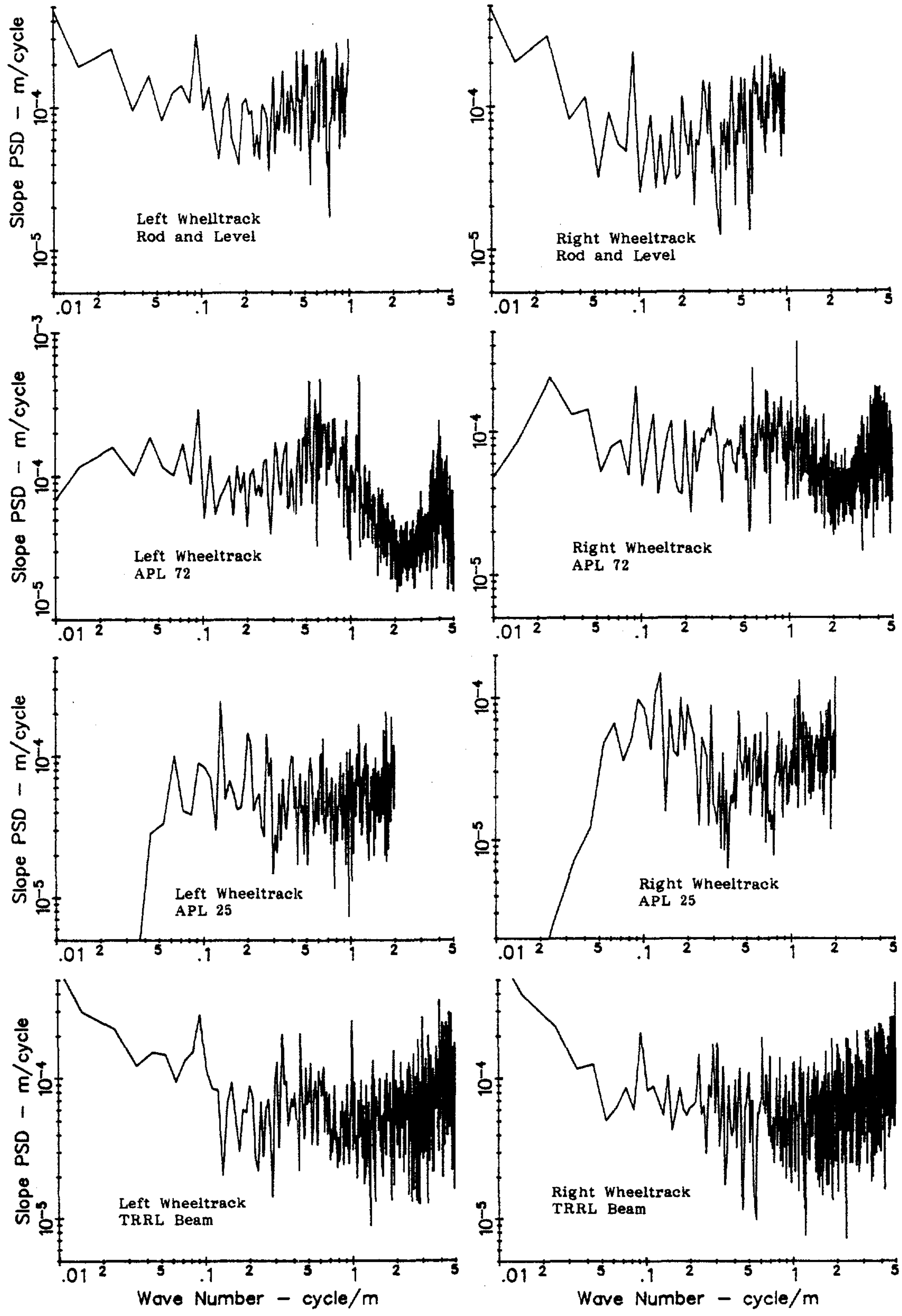


Figure 1.4. PSD functions for Site CA05

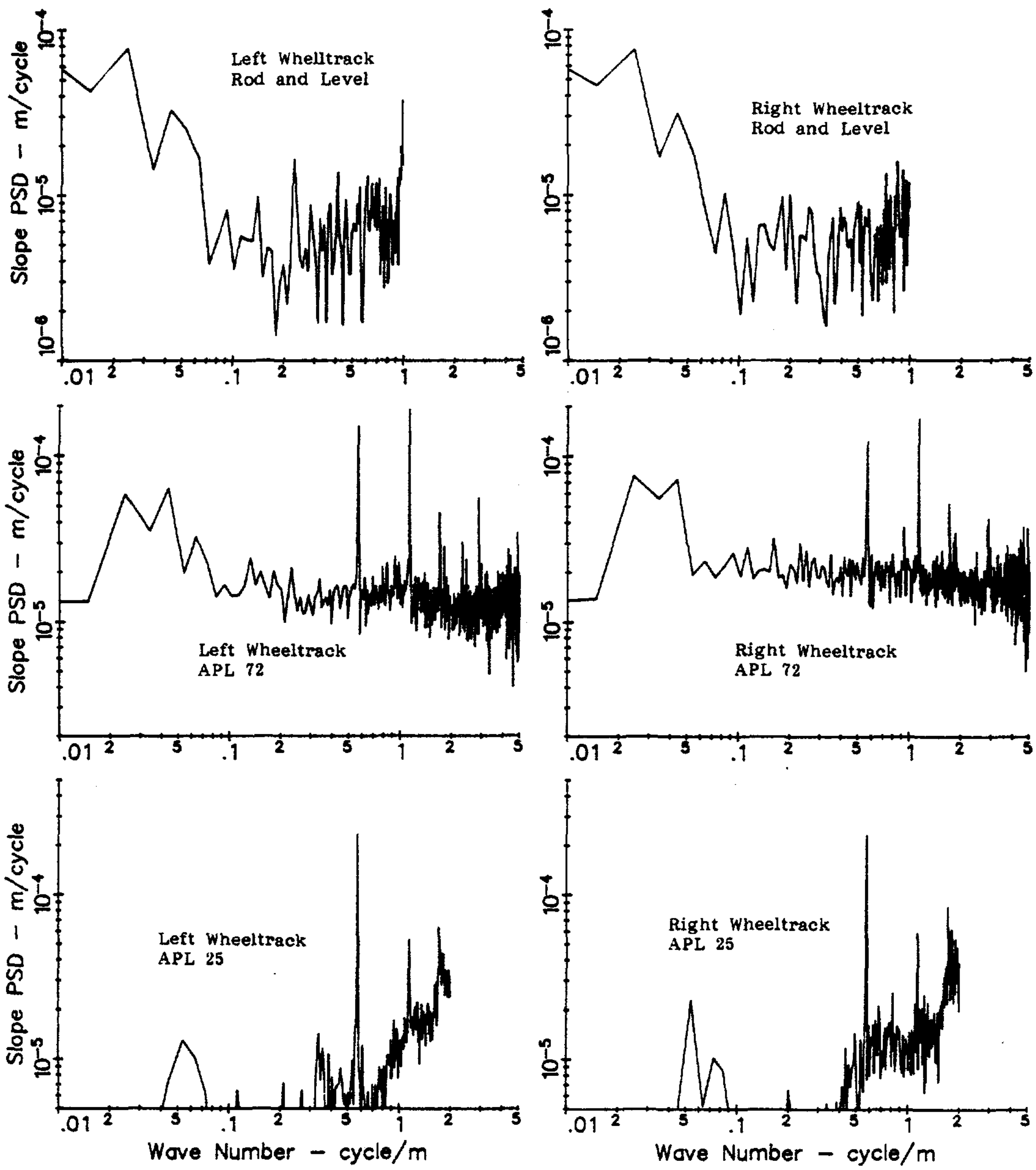


Figure 1.5. PSD functions for Site CA13.

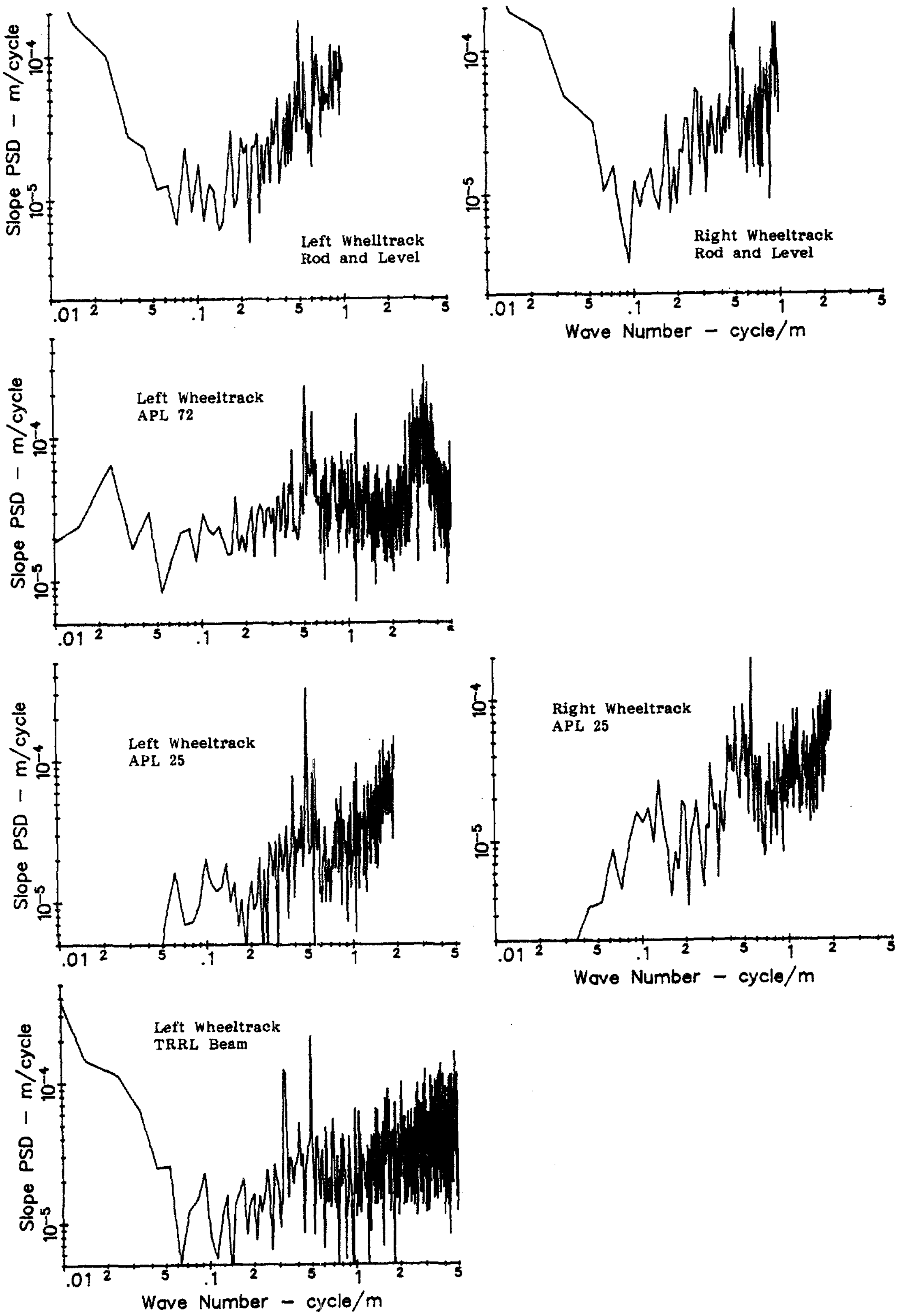


Figure I.6 PSD functions for Site TS01.

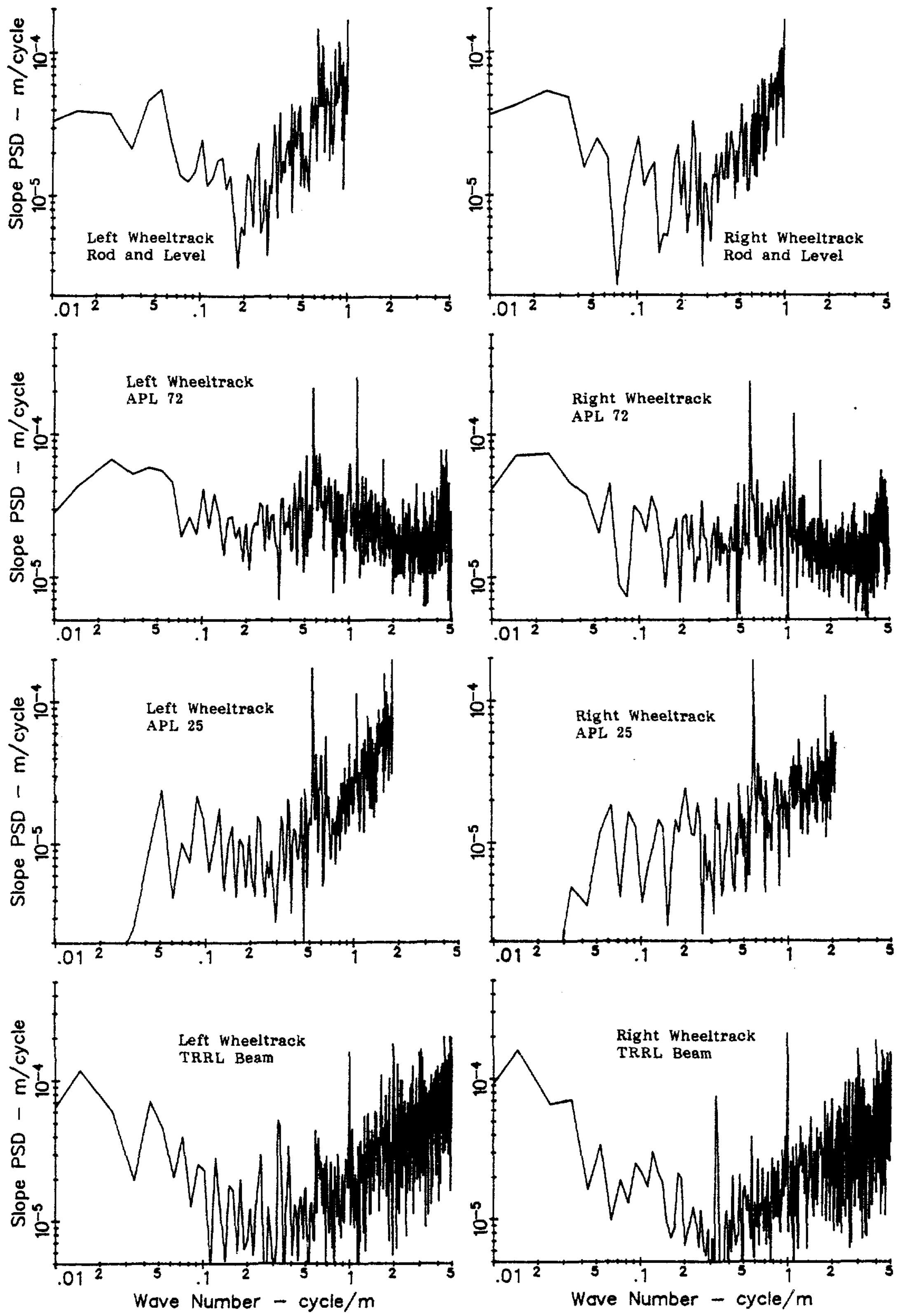


Figure I.7. PSD functions for Site TS06.

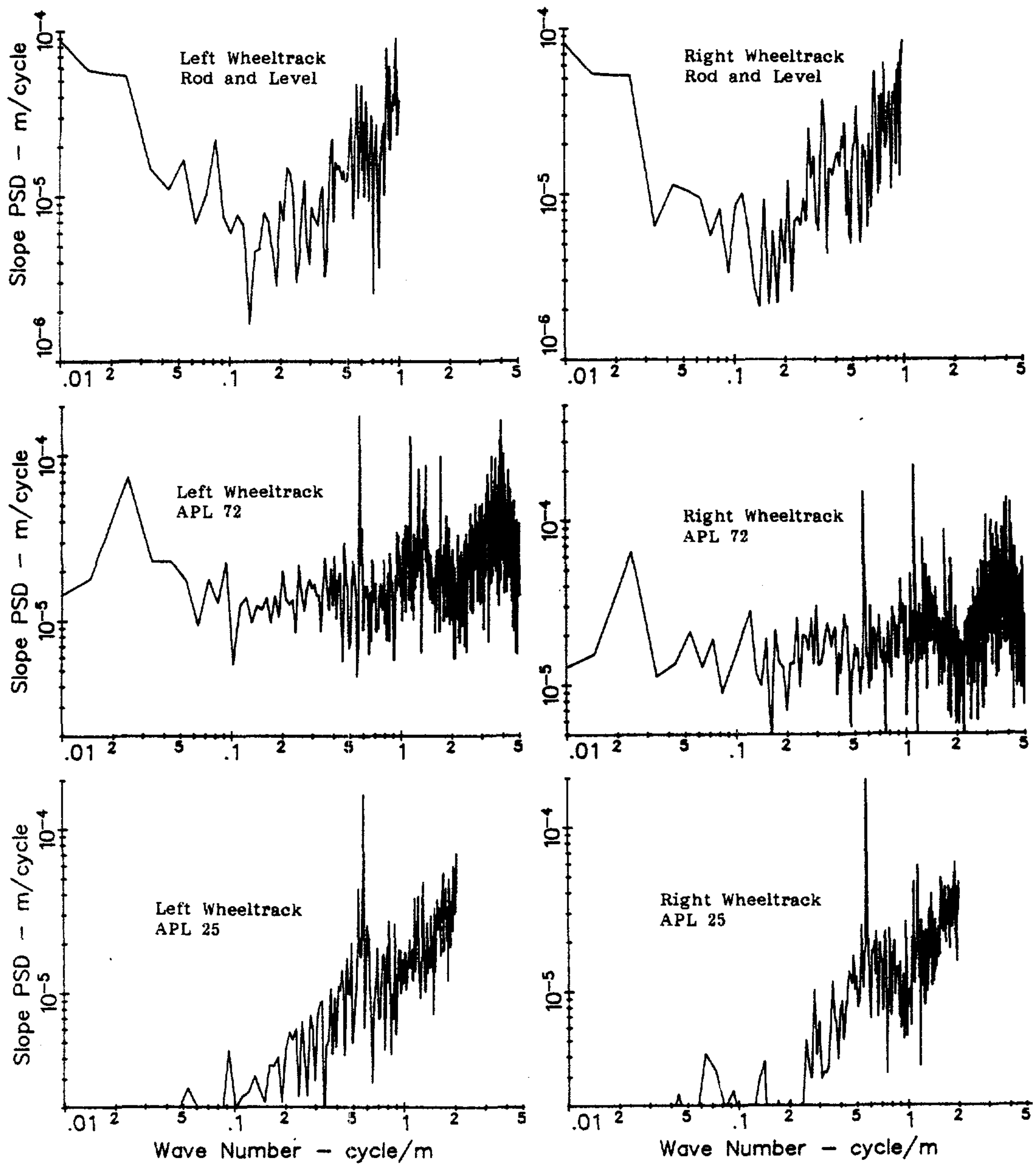


Figure I.8. PSD functions for Site TS11.

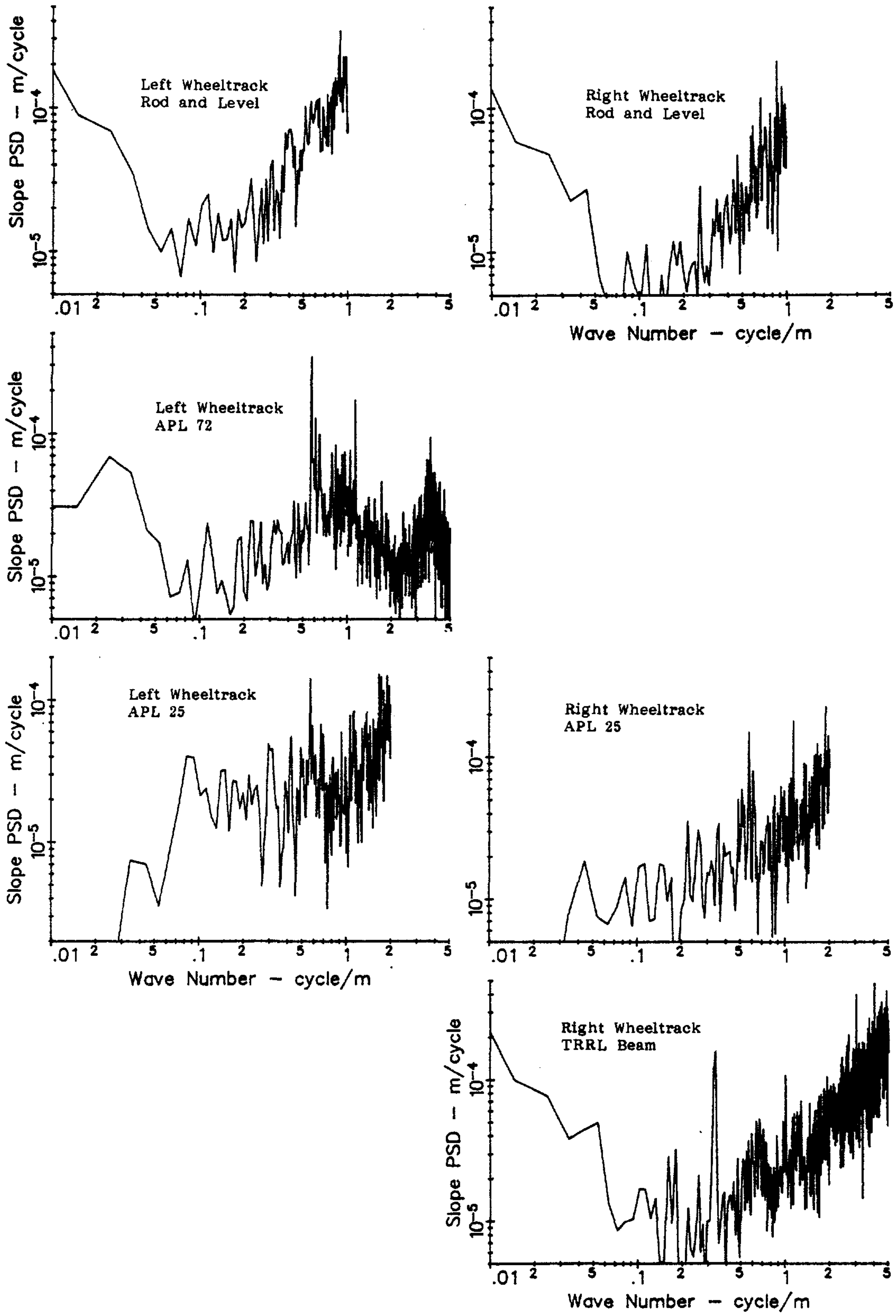


Figure I.9. PSD functions for Site GR01.

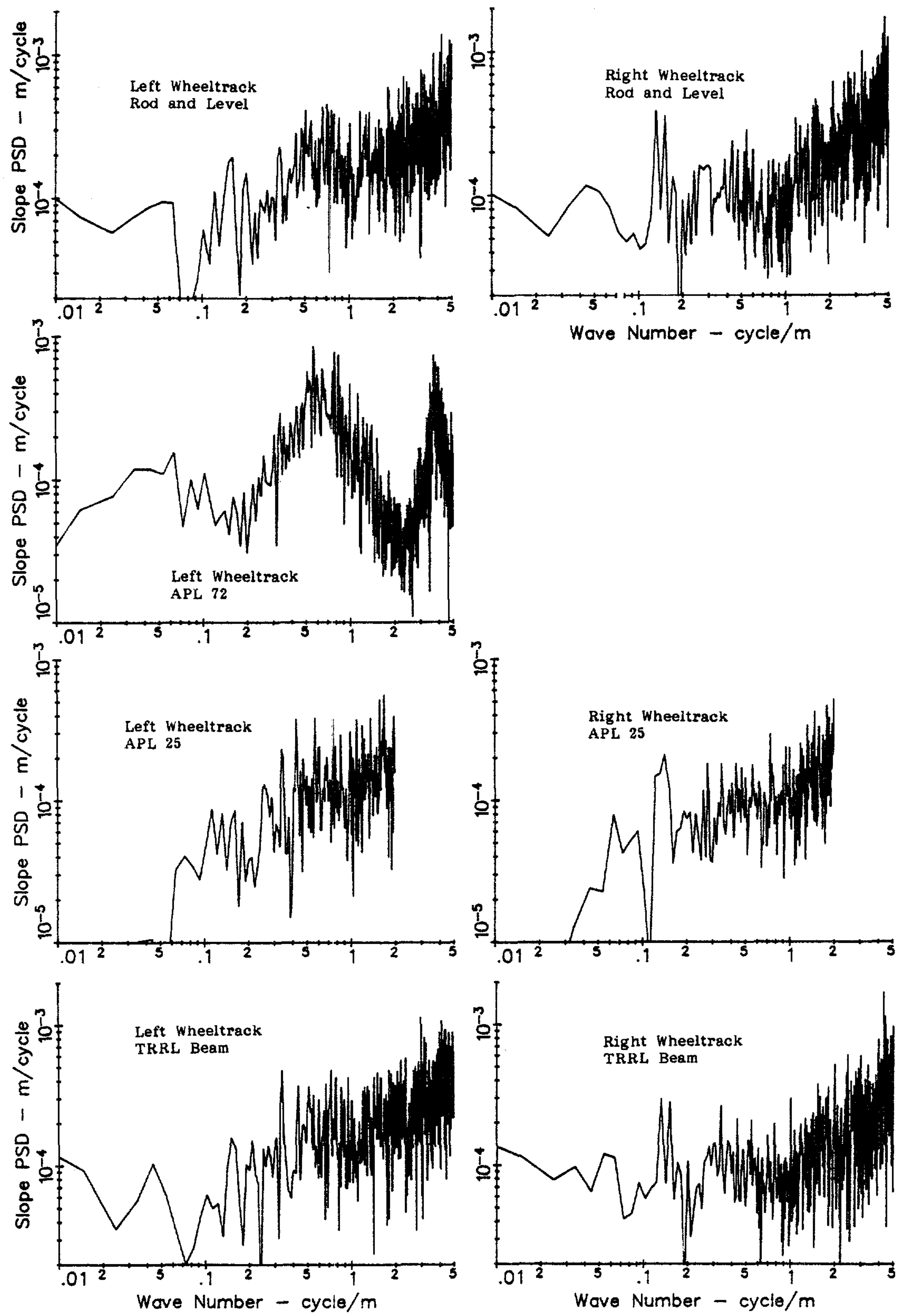


Figure I.10. PSD functions for Site GR05.

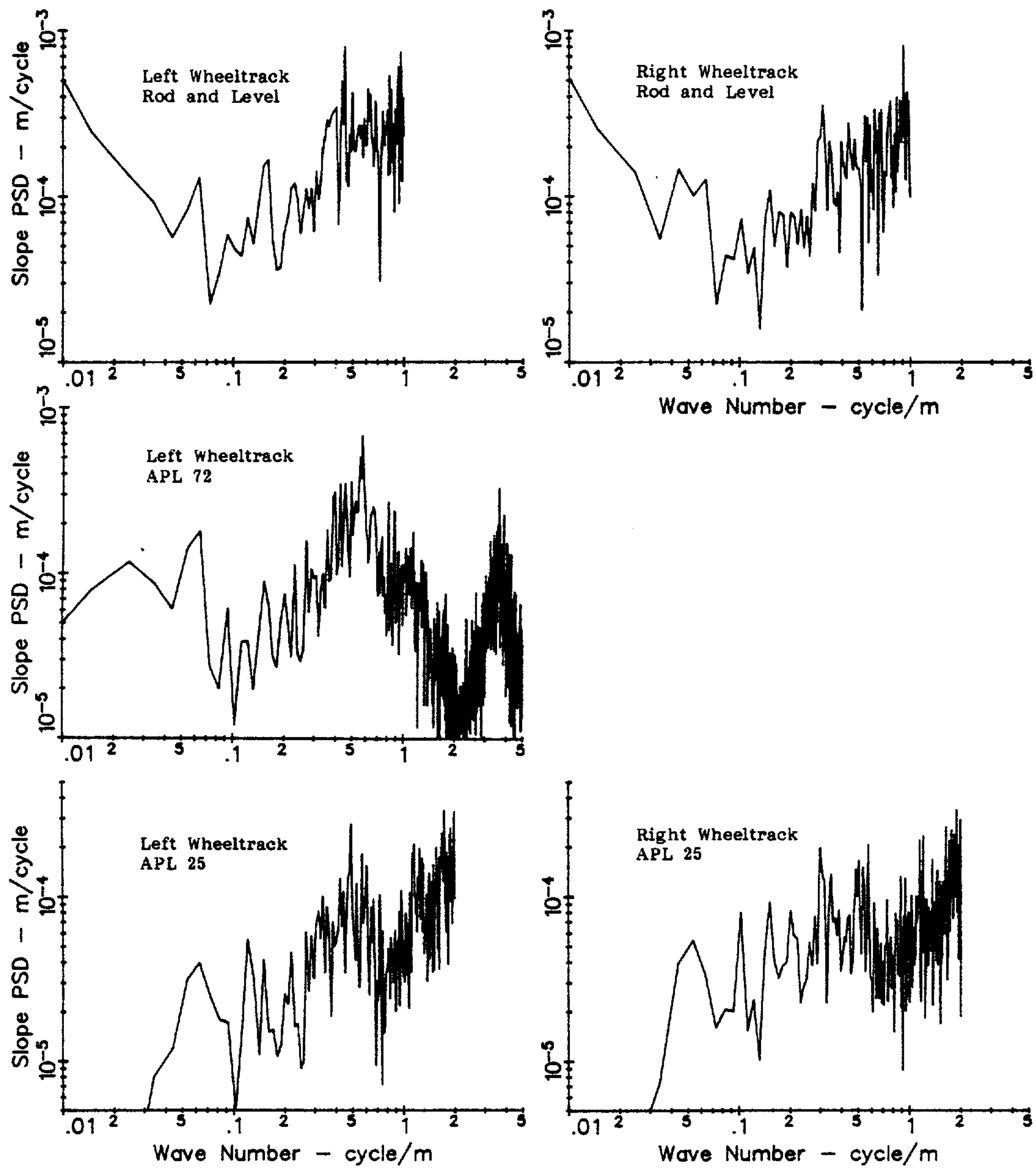


Figure I.11. PSD functions for Site GR09.

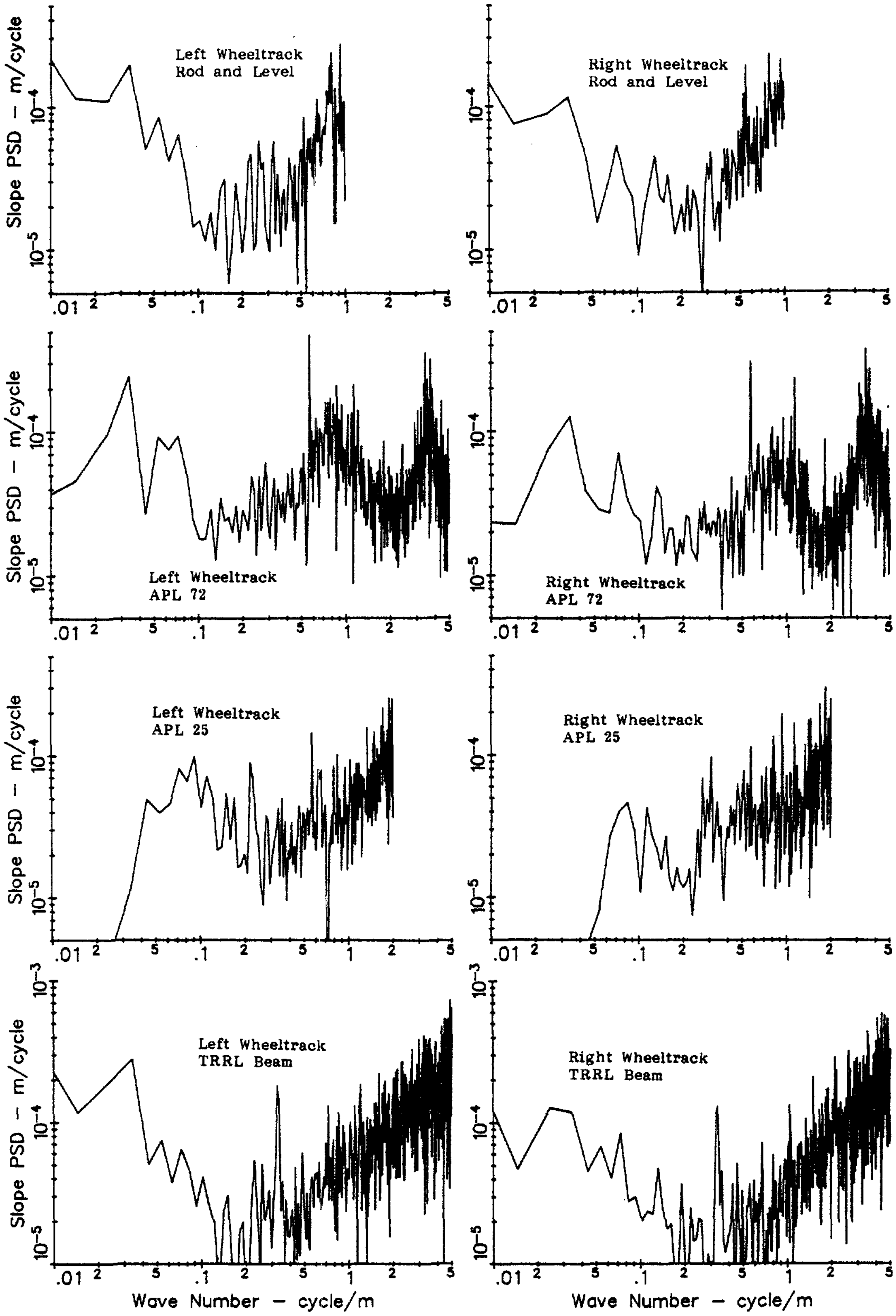


Figure I.12. PSD functions for Site TE01.

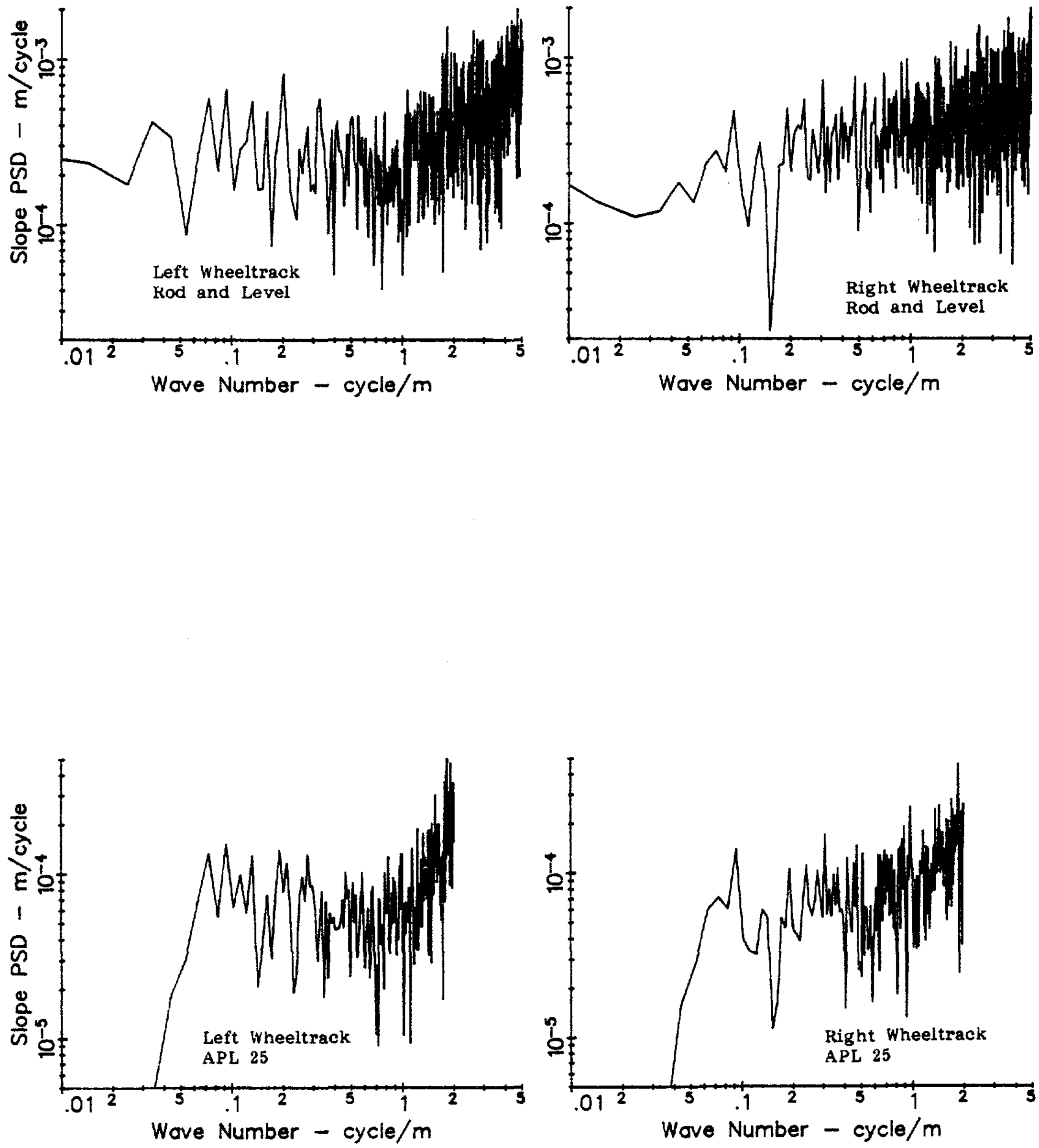


Figure I.13. PSD functions for Site TE05.

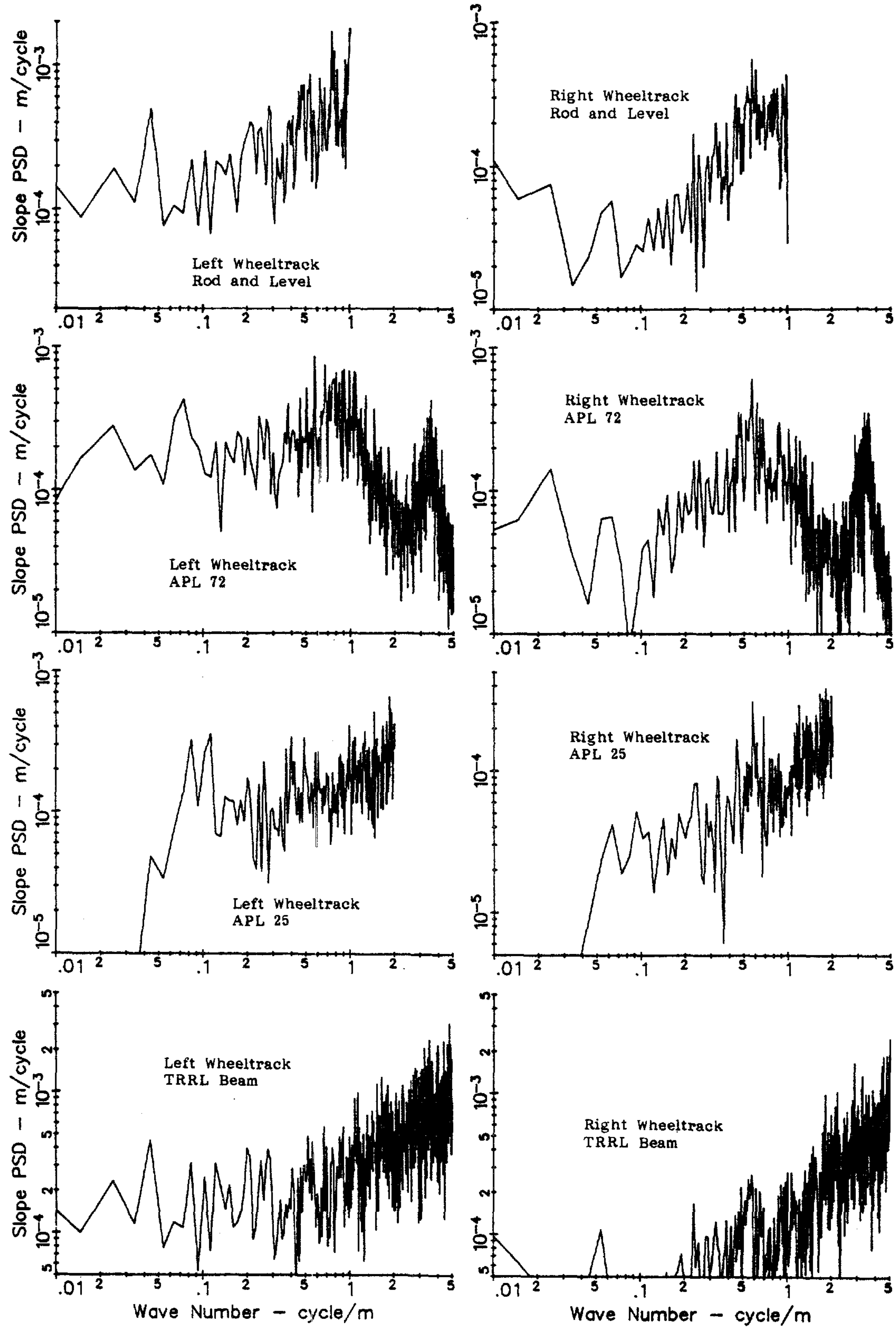


Figure I.14. PSD functions for Site TE 11.

APPENDIX J

ADDITIONAL ANALYSES WITH THE MOVING AVERAGE

A moving average analysis has been applied to measured profiles by CRR (Appendix G) and by TRRL (Appendix H), to obtain roughness numerics that correlate very well with the measures obtained with response-type road roughness measuring systems (RTRRMSs). In each case, the analyses were applied to profiles obtained with a single measurement method, and the reproducibility of the numerics with different profile measurement methods had not been established.

The purpose of this appendix is to derive the response properties of the moving average, as was done for the QI_r and RARS numerics (Appendices E and F), and also to apply several of the moving average analyses to profiles measured statically and dynamically.

Mathematical Definition of the Moving Average

The moving average analysis consists of three steps:

1. **Geometrically smooth the profile.** A profile can be smoothed at each point by considering an average over a baselength:

$$y_s(x) = 1/b \int_{x-b/2}^{x+b/2} y_r(X)dX \qquad (J-1)$$

where

- x = distance travelled
- $y_r(x)$ = unfiltered "raw" vertical profile elevation at position x
- $y_s(x)$ = smoothed profile elevation at position x
- b = baselength of moving average
- X = dummy variable of integration

When the profile is sampled, the integral in Eq. 1 is replaced with a summation:

$$y_s(i) = 1/(2m + 1) \sum_{k=-m}^{m} y_r(i+k) \qquad \text{(J-2)}$$

where

$$m = \text{INT} [(b / dx) /2] \qquad \text{(J-3)}$$

and

i = index, indicating the i^{th} sample.

dx = interval between samples (m)

INT = INTeger function used in FORTRAN and BASIC, indicating truncation.

Eqs. 2 and 3 require that the baselength correspond to an **odd** integer multiple of dx. Thus, for an interval of 500 mm, moving average baselengths can be 1.0 m (3 points), 2.0 m (5 points), 3.0 m (7 points), and so on. When the baselength requires an **even** integer multiple of dx, then the smoothed average would correspond to a position between samples, and a slightly different equation can be used:

$$y_s(i-.5) = 1/(2m) \sum_{k=-m}^{m-1} y_r(i+k) \qquad \text{(J-4)}$$

where the index (i-.5) indicates that the smoothed value should occur halfway between samples i and i-1.

2. Subtract the smoothed profile from the original profile.

$$y_f(i) = y_r(i) - y_s(i) \qquad \text{(J-5)}$$

where $y_f(i)$ is the final, filtered profile. When the number of points included in the average is even, then the smoothed value should lie between samples, and an alternate to Eq. 5 can be used:

$$y_f(i-.5) = y_r(i-.5) - y_s(i-.5)$$

$$= [\ y_r(i) + y_r(i-1)\ ] / 2 - y_s(i-.5) \qquad (J-6)$$

With this step, the smoothed profile is used as a reference or datum, from which deviations can be summarized in the next step.

3. Summarize the filtered profile. The y_f variable will vary about zero, and must either be rectified or squared before averaging to obtain a non-zero roughness numeric. In Belgium, the value is rectified and multiplied by 50 (assuming the profile had been scaled in mm) to obtain the CP numeric. In Appendix H, the RMS value is used.

Bandwidth of the Moving Average.

In order to derive the sensitivity of the moving average filter to wavenumber, it is convenient to consider complex sinusoidal variables of the form:

$$y(w,x) = Y_o\ e^{jwx} \qquad (J-7)$$

where

$$e^{jwx} = \cos(wx) + j\ \sin(wx) \qquad (J-8)$$

$$w = 2\pi/L \qquad (J-9)$$

and

L = wavelength
$j = \sqrt{-1}$

The sensitivity of the moving average smoothing filter to wavelength is found by substituting Eq. 7 into the definition (for a continuous signal) of Eq. 1:

$$y_s/y_r = 1/b \; [\int_{x-b/2}^{x+b/2} Y_o \, e^{jwX} \, dX \; / \; (Y_o \, e^{jwx}) \qquad \text{(J-10)}$$

Where X = dummy variable of integration. Solving Eq. 10,

$$y_s/y_r = 1/b \; [\; e^{jw(x+b/2)} \; / \; jw \; - \; e^{jw(x-b/2)} \; / \; jw \;] \; e^{-jwx}$$

$$= 1/(jwb) \; [\; e^{jwb/2} \; - \; e^{-jwb/2} \;]$$

$$= 1/ \; (jwb) \; [\; \cos(wb/2) + j \; \sin(wb/2) - \cos(-wb/2) - j \; \sin(-wb/2) \;]$$

$$= 1/(jwb) \; 2j \; \sin(wb/2)$$

$$= \sin(wb/2) \; / \; (wb/2)$$

$$y_s/y_r = \sin(\pi b/L) \; / \; (\pi b/L) \qquad \text{(J-11)}$$

Therefore, the sensitivity of the final filtered variable y_f to wavelength is:

$$y_f/y_r = (y_r - y_s)/y_r$$

$$= 1 - y_s/y_r$$

$$= 1 - \sin(\pi b/L) \; / \; (\pi b/L) \qquad \text{(J-12)}$$

Effect of Sample Interval

The numerical equivalents to a moving average given in Eqs. 2 and 4 approach the "true" moving average definition (Eq. 1) when the sample interval is much smaller than the baselength, such that there are 10 or more samples included in the moving average. But the results reported in Appendix H indicate that when the baselength b is not much larger than the sample interval dx, such that there are fewer samples within the moving average, the resulting roughness measure depends on both b and dx.

The sensitivity of the numerical equivalents (Eqs. 5 and 6) to wavelength can also be calculated, by substituting Eq. 7 into Eqs. 2 and 4. Noting that

$$e^{jwx} + e^{-jwx} = 2 \cos(wx) \qquad \text{(J-13)}$$

and that all x values are integer multiples of dx, Eq. 5 can be converted to the wavenumber domain as:

$$y_f/y_r = 1 - 1/(2m + 1) \; [\; 1 + \sum_{k=1}^{m} 2 \cos(k \; w \; dx) \qquad \text{(J-14)}$$

(for b/dx = **odd** integer number)

while Eq. 6 can be converted as:

$$y_f/y_r = \cos(.5w \; dx) - 1/2m \sum_{k=1}^{m} 2 \cos(\{k-.5\} \; w \; dx) \qquad \text{(J-15)}$$

(for b/dx = **even** integer number)

Eqs. 14 and 15 were used to prepare the four plots shown in Figs. J.1, using the baselength of 2.5 m with measurement intervals of 50 and 500 mm, and the baselength 1.8 m with 100 amd 300 mm intervals. Note that the moving average filter attenuates wavelengths longer than the baselength, and transmits wavelengths that are much shorter than the baselength with a unity gain. For wavelengths slightly shorter than the baselength, the gain is variable, ranging from 1.2 to 0.85. When the sample interval is larger, the properties of the filter are affected, because wavelengths that would be attenuated by the smoothing of a true moving average can appear as a longer wavelength (with less attenuation) due to aliasing. Since these wavelengths are still present in the smoothed signal, they cancel when subtracted from the original, causing the lowered reponse shown in the plots.

Although the moving average analysis is a high-pass filter, generally passing wavenumbers higher than the cut-off, the summary numeric is primarily influenced by the longest wavelengths that are transmitted, due to the

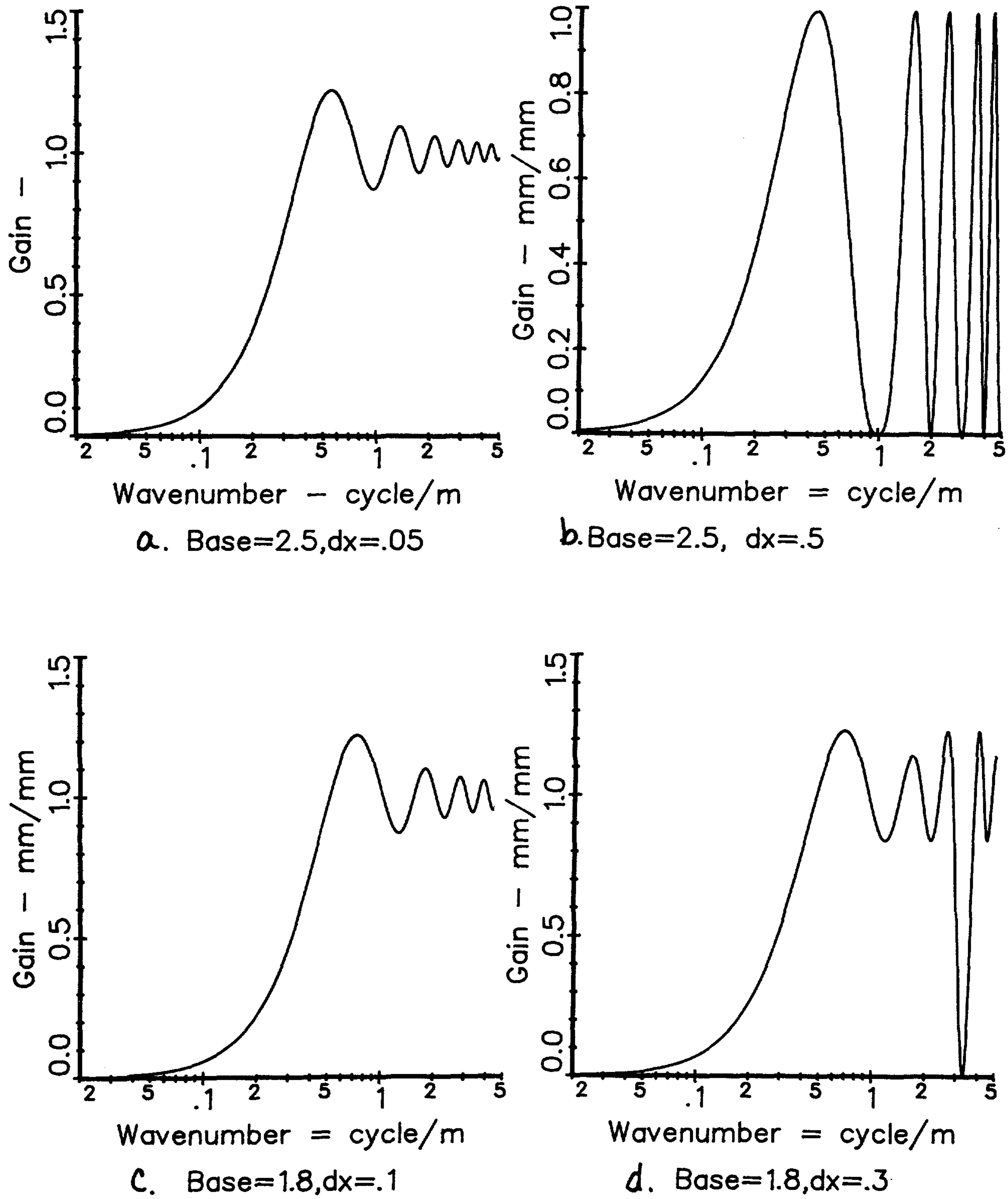


Figure J.1. Wavenumber Response Functions of the Moving Average for Baselengths and Sample Intervals Used in the IRRE, for an Elevation Input.

spectral content of roads (Appendix I). To better show the actual influence of different wavelengths on the roughness numeric, the plots can be converted for the case of a slope input. For the sinusoidal input, differentiation can be expressed algebraically:

$$y' = dy/dx = jw = j(2\pi/L) \qquad (J\text{-}16)$$

Thus,

$$|y_f/y_r'| = |y_f/y_r| \;/\; w = |y_f/y_r| \; L/2\pi \qquad (J\text{-}17)$$

Eq. 17 was used to rescale the four plots in Figure J.1 for the case of a slope input, to obtain the plots shown in Figure J.2.

Upon examining the plots for the 2.5 m baselength used for the CP statistic, it can be seen that the CP moving average analysis used by CRR is quite different from the Butterworth band-pass filter as used by LCPC. But when road inputs are considered which have a fairly uniform spectral content in terms of slope input, then the CP filter properties appear more like a band-pass. This is why the LCPC and CRR analyses give highly correlated results when comparing the SW coefficients to $CP_{2.5}$, the MW coefficients to CP_{10}, and the LW coefficients to CP_{40} (Appendix G).

The plots shown for the 1.8 m baselength correspond to the RMSD numeric described in Appendix H, although not completely since that analysis uses a linear regression line over a length of 1.8 m rather than a simple mean. The RMSD numeric does not have a true linear wavenumber response, but is so similar to a moving average that generalizations about the wavenumber sensitivity of one should hold for the other. The plots in the two figures indicate why the RMSD numeric is dependent on sample interval, and why it is lowered with increasing interval.

Comparison of Dynamic and Static Measures of CP

Although the moving average analysis was employed by both CRR and TRRL (see Appendix H), time constraints prevented the direct comparison of summary

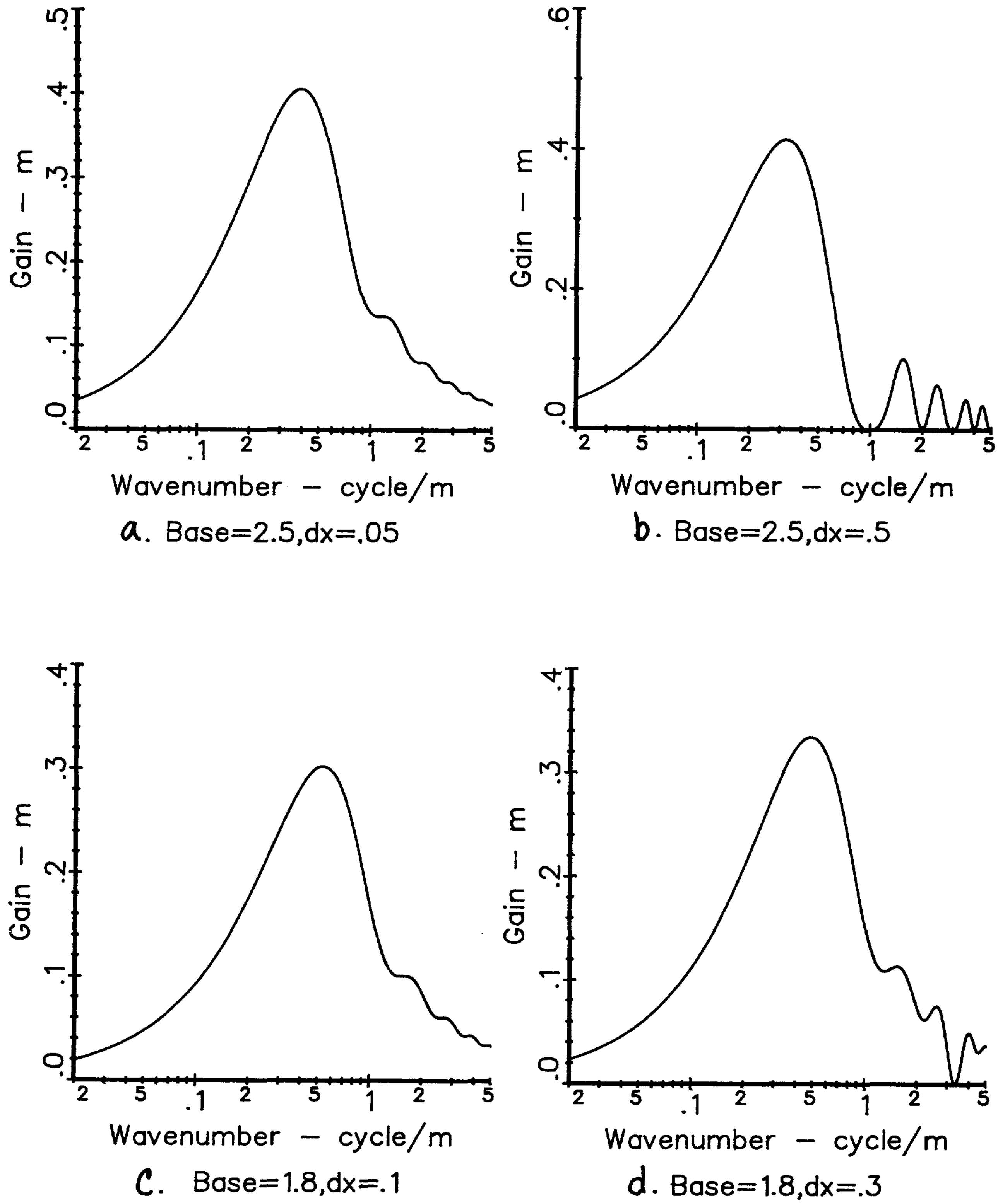


Figure J.2. Wavenumber Response Functions of the Moving Average for Baselengths and Sample Intervals Used in the IRRE, for a Slope Input.

numerics based on the moving average filter, as computed from statically measured profiles (rod and level or the TRRL Beam) and from the dynamically measured APL profiles, by either of those agencies. Since the results reported from CRR and from TRRL were both very encouraging, the moving average analysis was performed more recently at UMTRI on both the APL 72 profiles supplied by LCPC and the rod and level profiles supplied by The Brazilian Transportation Planning Company (GEIPOT), using the same computer program (modified) that produced the QI_r and RARS numerics reported in Appendices E and F. These results, scaled with CP units, are listed in Table J.1

The APL 72 signals were the same ones used to compute QI_r and RARS numerics, and were obtained at 50 mm intervals as described in Appendix A. The numerical methods used for both the APL and the rod and level profiles are those described in this appendix, and therefore may not exactly match the procedure used at CRR. For example, the data processing at CRR was routinely performed using three adjacent sections 100 m long, whereas the processing at UMTRI was performed continuously for each 320 m site; also a sample interval of 1/3 m is normally used at CRR in contrast to the 50 mm interval used by LCPC.

In comparing the numerics in Table J.1 to the CP numerics in Appendix G, very good agreement is seen when the baselength was 2.5 m, although agreement is not as close for baselengths of 10 and 40 m. (The numerics reported in this appendix tend to be higher by 5% - 10%.) Even though this indicates that the results in this appendix are not completely equivalent to the CP numeric as computed by CRR, they appear to be similar enough to compare the static and dynamic measurements, as long as the comparisons are limited to the results presented in this appendix. (Unfortunately, time constraints for this report prevented collaboration between UMTRI and CRR to resolve the differences.) For convenience, the numerics are referred to as CP in the following discussion, even though they are "unofficial."

For the $CP_{2.5}$ numeric, the 500 mm sample interval used with the rod and level measures causes the digital filter to behave differently than a true moving average, as indicated in Figs. J.1b and J.2b. Therefore, the 28 profiles from the TRRL Beam were processed to obtain the $CP_{2.5}$ numeric, and these results are listed in the Table, rather than those obtained from rod and

Table J.1. Summary of Moving Average (CP) Numerics Obtained at UMTRI from Statically Measured Pprofiles and from the APL Trailer.

Test Site	CP(2.5)				CP(10)				CP(40)			
	Left		Right		Left		Right		Left		Right	
	Beam	APL	Beam	APL	R&L	APL	R&L	APL	R&L	APL	R&L	APL
CA 01	...	...	...	57	176	...	199	190	520	...	549	579
CA 02	...	65	...	84	208	173	171	180	573	487	480	432
CA 03	...	84	...	92	228	176	221	197	672	521	584	474
CA 04	90	77	77	70	235	207	212	195	632	562	559	556
CA 05	100	103	94	80	249	235	217	186	644	590	658	568
CA 06	112	116	95	102	241	216	226	200	667	525	667	523
CA 07	...	58	...	44	96	96	92	93	259	239	247	241
CA 08	...	46	...	46	101	94	94	83	296	266	240	201
CA 09	...	73	...	50	141	135	133	128	423	406	354	344
CA 10	...	69	41	57	138	135	135	139	384	323	368	306
CA 11	...	61	...	75	192	160	200	185	426	448	440	436
CA 12	35	...	...	29	69	...	77	62	304	...	334	281
CA 13	...	27	...	27	80	66	78	67	242	246	254	261
TS 01	67	70	...	...	107	96	111	...	276	212	317	...
TS 02	...	76	...	74	145	125	142	127	444	365	522	439
TS 03	...	88	...	...	133	123	130	...	425	364	485	...
TS 04	106	80	...	...	120	105	133	...	321	261	285	...
TS 05	98	109	...	93	127	126	111	110	205	188	236	191
TS 06	62	53	57	47	112	104	101	99	302	310	328	339
TS 07	57	52	...	50	114	104	118	109	307	268	337	287
TS 08	...	55	...	57	140	123	149	135	534	547	578	586
TS 09	...	61	...	65	99	92	114	106	239	236	269	273
TS 10	...	67	...	61	105	99	118	106	207	187	234	221
TS 11	...	40	...	41	78	66	75	69	235	233	239	209
TS 12	...	44	...	39	78	67	83	73	308	298	399	397
GR 01	...	57	60	...	108	82	86	...	466	300	426	...
GR 02	...	69	...	...	116	112	106	...	405	416	359	...
GR 03	...	105	...	...	306	189	175	...	578	544	575	...
GR 04	...	110	...	...	218	186	181	...	582	410	574	...
GR 05	152	173	122	...	251	230	264	...	442	424	443	...
GR 06	...	153	...	...	220	243	235	...	418	427	484	...
GR 07	112	93	66	...	163	126	125	...	364	286	358	...
GR 08	...	76	...	...	124	112	110	...	407	346	370	...
GR 09	...	143	...	...	254	214	235	...	565	516	574	...
GR 10	...	134	...	...	197	208	155	...	387	399	372	...
GR 11	...	...	...	...	317	...	389	...	510	...	581	...
GR 12	201	...	157	...	354	...	349	...	539	...	678	...
TE 01	82	74	78	65	153	142	138	119	579	504	456	385
TE 02	...	69	...	77	128	112	131	137	413	415	392	373
TE 03	138	143	99	103	228	216	198	170	552	521	662	577
TE 04	...	153	...	96	217	229	238	217	713	627	713	572
TE 05	...	...	...	...	477	...	399	...	1025	...	624	...
TE 06	...	...	253	...	595	...	505	...	992	...	856	...
TE 07	...	90	...	84	158	138	119	123	362	291	301	295
TE 08	...	93	...	85	147	138	119	117	349	321	382	396
TE 09	...	140	...	118	227	212	210	173	411	426	416	369
TE 10	...	172	...	144	289	263	249	204	570	508	490	439
TE 11	...	167	128	140	337	327	197	190	691	681	417	354
TE 12	...	122	...	145	307	226	257	243	522	441	550	499

level.

Figure J.3 compares the moving average measures statically and from APL profiles. The four scatter plots show that:

1. The $CP_{2.5}$ numerics computed from the APL 72 signals are higher than those computed from rod and level. This is to be expected from the wavenumber sensitivity plots shown in Figs. J.1 and J.2. The results shown here and in Appendix H indicate that a moving average analysis must require either that the sample interval be fixed (as suggested in Appendix H), or that it be sufficiently small that aliasing will not be significant. A problem with specifying a fixed sample interval is that the magnitude of the aliasing effect depends on the spectral contents of the profile, which is limited by the bandwidth of the APL trailer. Hence, specifying a fixed sample interval could give different relationship between measures obtained with the APL and those obtained statically. A more practical problem is that a specified interval decreases the options available for measuring profile.

On the other hand, aliasing can be eliminated simply by using a smaller interval. Fig. J.3 indicates good agreement between the APL and Beam measures, which used a 100 mm interval.

2. The CP_{10} numerics as computed from the APL 72 are nearly identical to those obtained from the rod and level, with the exception of two of the roughest unpaved roads, which appear as "outliers." Excluding the two "outliers," the plot shows the remaining 73 data points lying very close to the line of equality, matching the repeatability of the statically measured RARS numerics, although the APL measures are about 5% lower than the rod and level measures.

The "outliers" (GR 03 and TE 12) both have corresponding PSD functions that are quite different in the two wheeltracks (see Appendix I), such that the lateral positioning of the APL Trailer appears to be critical on these sections. For the worst "outlier" (GR 03), the left wheeltrack has a periodic component that occurs exactly at the 10 m wavelength. This peak is seen in the PSD measured with rod and level but not the PSD obtained with the trailer, explaining why the rod and level measure is so much higher.

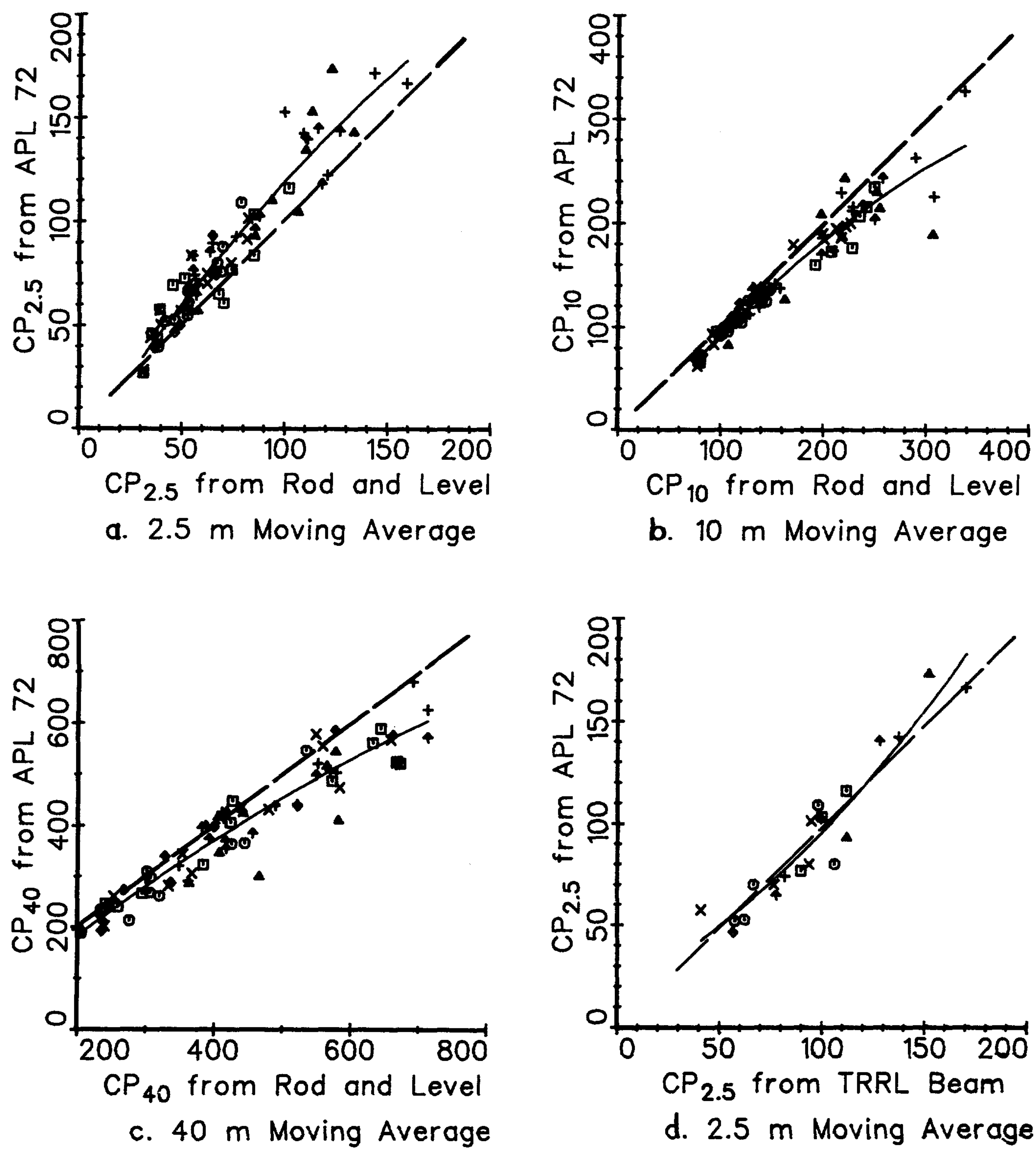


Figure J.3. Comparison of CP Numerics from Statically Measured Profiles and from the APL Trailer.

3. The CP_{40} measures obtained from the APL are about 10% lower than those obtained from the rod and level. In viewing the response plot of the CP analysis (Fig. J.2), it can be seen that wavelengths longer than the baselength are not completely attenuated. For example, the gain at wavenumber 0.2 (wavelength = 5 m) is 3/4 of the gain at wavenumber 0.4 (wavelength = 2.5 m = baselength). For the case of 40 m baselength, this means that the analysis is affected by wavelengths longer than 40 m. But the APL 72 response (Fig. G.1 in Appendix G) does not include these longer wavelengths, whereas the static rod and level method does. Appendix I, which contains PSD functions obtained from the APL Trailer, TRRL Beam, and rod and level, show the difference in slope input at the very long wavelengths (low wavenumbers). The differences shown in Fig. G.4c may reflect the bandwidth limitation of the APL Trailer.

In summary, the $CP_{2.5}$ and CP_{10} can be obtained either with a statically measured profile or with an APL Trailer, without any significant error beyond the normal repeatability associated with profile measurement. The sample interval must be small, however, to obtain good agreement with the $CP_{2.5}$ numeric. However, the CP_{40} numeric is influenced, in part, by the response properties of the APL Trailer because the rod and level measure includes a slight effect of wavenumbers that are too low to be sensed by the APL Trailer.

APPENDIX K

SUBJECTIVE ESTIMATION OF ROUGHNESS BY SCALE DESCRIPTOR METHOD

Prepared by

William D.O. Paterson (World Bank)

Experiment

Immediately after the completion of the main experiment a small study was performed in which 4 individual observers estimated the roughness of each test section directly using the 'Scale Descriptor Method'. This method, developed during World Bank studies in Brazil following the PICR project, provides a set of descriptors of the road shape and ride sensations at six levels of roughness on a reference ARS scale from 0 to 25 m/km. Observers match the ride and their assessment of surface shape with the descriptors and estimate roughness directly in m/km units. The method is distinctly different from the subjective panel rating (Appendix D). In the panel rating, observers rate the ride comfort on a 0 to 5 scale representing their individual perceptions of poor to perfect road conditions. The subjective panel rating is thus an unanchored scale which is influenced by the observers' preconceptions of satisfactory ride comfort and is known to vary from region to region and country to country. The scale descriptor method however employs an anchored scale which is nominally directly equivalent to a RARS scale.

The observers were given a set of instructions and two charts summarizing the scale for paved roads and unpaved roads respectively, as shown in Figs. K.1 and K.2. The scale was the same for both categories of road, only some of the descriptors differed in examples of typical roads and the types of distress associated with each level of roughness. The scale in the method used for the survey was constructed on the calibrated ARS at 80 km/h of the Opalas used in the PICR. Included with the set of instructions was a set of two photographs of examples of road surface appearance at each of the six levels of roughness (these were not of sections included in the experiment), but in fact the observers made little reference to these and used primarily the written descriptors.

The observers were driven in one of the Opala sedan cars that had been used for a Maysmeter in the main experiment, over all 49 test sections in approximately the same random sequence as the main experiment. A speed of approximately 80 km/h was maintained on the paved roads and a speed of approximately 50 km/h on the unpaved roads. There was no stopping at the individual sites and all sections were observed in the course of one day. The observer's estimate of roughness in m/km was written on a field form with the test section number and occasionally a brief comment, for example whether the surface texture was 'noisy', whether the vehicle was 'bottoming' on the suspension, etc. None of the observers had applied the method previously, although two of the four had had some previous experience of the scale. The characteristics of the observers are summarized in Table K.1.

Data Analysis

The data collected in the study are presented in Table K.2, together with the $RARS_{50}$ reference value of roughness for each test section from Table F.5, Appendix F. These reference values were not known to any of the observers and had not been computed at the time of the survey. Also presented in the table are the means of the observers' estimates and the absolute deviations from the reference value.

The results are plotted for all observers in Fig. K.3 and by individual observer in Fig. K.4 showing surface type effects. The results are summarized by the statistics presented in Table K.3 and are discussed under the aspects of systematic bias, accuracy and correlation. They are evaluated with the expectation that normally only one observer would undertake an estimation survey and that averaging across observers is not the norm.

Systematic bias is the measure of how the observer's scale compared with the reference scale and indicates whether, on average, there was any systematic underestimation or overestimation. The mean reference roughness was 7.58 m/km, and the observers' means ranged from 7.00 to 8.64 m/km, with an average of 7.80 m/km. This is equivalent to a bias ranging from -7.6 to +14.0 percent with an average of +3.0 percent. The observers' perceived scales based on the survey scale are therefore very close to the reference $RARS_{50}$ scale.

The bias would be further reduced in applications of the method as the observer gained experience and if a preliminary 'calibration' survey were conducted for the observer. The method is thus successful in both anchoring and controlling the scale. The significance of a low bias is that an observer in the course of a long survey will tend to produce an average result which is within approximately 10 percent of the reference. It is also significant in that the $RARS_{50}$ scale can be substituted for the survey scale in the method without need for adjustment of the descriptors.

The accuracy of estimation of roughness on an individual section is quantified through the root mean square deviation between the observer's estimate and the reference value. For the four observers this ranged from 27 to 48 percent, since the error is proportional to the mean and is best expressed as a percentage. The two observers with some previous experience (A and B) rated slightly better than the two without any previous experience (C and D), i.e. 27 - 35 percent and 35 - 48 percent, respectively. The maximum individual errors were deviations of 3.2 m/km, or 55 percent for the most accurate observer and +7.6 m/km or 140 percent for the least accurate. For a subjective method such as this, given that the bias is approximately random and generally less than 10 percent, an error of the order of 36 percent average (and less upon experience) is perfectly acceptable and highly satisfactory. It compares with an error of the order of 14 percent for calibrated RTRRMSs and 6 percent for static profilometry methods.

The correlation between the observers' estimates and the reference is a measure of the observer's accuracy in ranking the sections by roughness and of how well the estimate relates to roughness. The coefficients of determination (R^2-values) range from 0.86 to 0.92 which demonstrates that the method is highly effective in these respects.

Although the sample size in this study was small, the results presented are probably representative of what could be expected from competent personnel. The results are sufficient to indicate that the method is able to give satisfactory estimates of roughness with an error of approximately 36 percent, free from significant bias and with high reliability for ranking the roughness of individual sections over a wide range.

Following the selection of $RARS_{80}$ as the International Roughness Index (IRI), the rating scale requires linear adjustment by the factor of 0.80 (which is the ratio of the means of $RARS_{80}$ and $RARS_{50}$ in the IRRE data). This relationship between the two scales is not mathematical but empirical: there are differences due to the different wavebands sensed at 50 and 80 km/h but, as these have negligible effects on the primary conclusions, the analysis was not re-run. In order for the rating scales in Figs. K.1 and K.2 to be used for the direct estimation of IRI therefore, the scale values need to be multiplied by 0.80; the new ranges are thus 0 to 10 for paved roads and 0 to 24 for unpaved roads.

Table K.1: Description of observers for roughness estimation

Code	Country	Occupation	Sex
A	United States	Mechanical Engineer	Male
B	New Zealand	Civil Engineer	Male
C	Thailand	Systems Engineer	Male
D	United Kingdom	Econometrician	Male

Table K.2: IRRE survey data from roughness estimation by scale descriptor method (Roughness in m/km)

SEC	OBS A	OBS B	OBS C	OBS D	MEAN OBS	RARS50	DEVN A	DEVN B	DEVN C	DEVN D
CA01	4.5	7.5	3.5	4	4.88	4.8	-0.3	2.7	-1.3	-0.8
CA02	3.5	7.5	4.0	4	4.75	5.6	-2.1	1.9	-1.6	-1.6
CA03	4.5	8.0	5.0	5	5.63	7.2	-2.7	0.8	-2.2	-2.2
CA04	5.0	7.5	5.0	5	5.63	6.2	-1.2	1.3	-1.2	-1.2
CA05	7.5	8.0	6.0	6	6.88	7.4	0.1	0.6	-1.4	-1.4
CA06	7.0	9.0	7.0	7	7.50	8.2	-1.2	0.8	-1.2	-1.2
CA07	2.5	3.0	2.5	2	2.50	2.7	-0.2	0.3	-0.2	-0.7
CA08	3.0	3.5	2.5	2	2.75	3.1	-0.1	0.4	-0.6	-1.1
CA09	3.5	3.5	3.5	3	3.38	3.7	-0.2	-0.2	-0.2	-0.7
CA10	4.5	4.0	4.5	3	4.00	3.6	0.9	0.4	0.9	-0.6
CA11	4.5	7.0	7.5	5	6.00	6.1	-1.6	0.9	1.4	-1.1
CA12	2.0	1.6	1.5	2	1.78	2.2	-0.2	-0.6	-0.7	-0.2
CA13	1.5	2.0	2.0	2	1.88	2.1	-0.6	-0.1	-0.1	-0.1
TS01	2.5	5.0	2.5	3	3.25	5.1	-2.6	-0.1	-2.6	-2.1
TS02	2.5	6.0	4.0	3	3.88	6.8	-4.3	-0.8	-2.8	-3.8
TS03	4.0	4.0	4.0	3	3.75	6.7	-2.7	-2.7	-2.7	-3.7
TS04	4.5	4.0	6.0	4	4.63	6.8	-2.3	-2.8	-0.8	-2.8
TS05	4.0	4.0	6.0	4	4.50	6.6	-2.6	-2.6	-0.6	-2.6
TS06	3.5	3.0	3.5	2	3.00	4.2	-0.7	-1.2	-0.7	-2.2
TS07	3.5	3.5	3.0	2	3.00	4.3	-0.8	-0.8	-1.3	-2.3
TS08	3.5	5.0	4.0	2	3.63	4.8	-1.3	0.2	-0.8	-2.8
TS09	3.5	5.0	4.0	.	4.17	5.3	-1.8	-0.3	-1.3	.
TS10	3.0	4.8	4.0	.	3.93	5.0	-2.0	-0.2	-1.0	.
TS11	2.0	3.0	2.5	2	2.38	3.5	-1.5	-0.5	-1.0	-1.5
TS12	2.0	3.5	2.5	2	2.50	3.5	-1.5	0.0	-1.0	-1.5
GR01	3.5	8.0	12.0	5	7.13	5.0	-1.5	3.0	7.0	0.0
GR02	3.0	8.0	13.0	5	7.25	5.4	-2.4	2.6	7.6	-0.4
GR03	4.0	9.0	12.0	5	7.50	9.3	-5.3	-0.3	2.7	-4.3
GR04	3.5	10.0	12.0	5	7.63	8.1	-4.6	1.9	3.9	-3.1
GR05	13.0	12.0	12.0	14	12.75	11.3	1.7	0.7	0.7	2.7
GR06	16.0	13.0	13.0	16	14.50	10.4	5.6	2.6	2.6	5.6
GR07	12.0	10.0	11.0	7	10.00	7.3	4.7	2.7	3.7	-0.3
GR08	10.0	9.0	11.0	7	9.25	5.8	4.2	3.2	5.2	1.2
GR09	13.0	11.0	10.0	8	10.50	10.9	2.1	0.1	-0.9	-2.9
GR10	11.0	10.0	10.0	7	9.50	8.9	2.1	1.1	1.1	-1.9
GR11	18.0	18.0	19.0	18	18.25	17.0	1.0	1.0	2.0	1.0
GR12	20.0	22.0	19.0	20	20.25	14.4	5.6	7.6	4.6	5.6
TE01	5.0	4.0	8.0	4	5.25	5.7	-0.7	-1.7	2.3	-1.7
TE02	5.0	5.0	9.0	4	5.75	5.3	-0.3	-0.3	3.7	-1.3
TE03	6.0	8.0	10.0	5	7.25	9.8	-3.8	-1.8	0.2	-4.8
TE04	8.0	9.0	12.0	6	8.75	9.7	-1.7	-0.7	2.3	-3.7
TE05	19.0	22.0	18.0	20	19.75	17.1	1.9	4.9	0.9	2.9
TE06	21.0	24.0	20.0	22	21.75	20.6	0.4	3.4	-0.6	1.4
TE07	9.0	8.0	14.0	9	10.00	6.0	3.0	2.0	8.0	3.0
TE08	9.0	7.0	14.0	9	9.75	6.6	2.4	0.4	7.4	2.4
TE09	11.0	10.0	16.0	10	11.75	12.2	-1.2	-2.2	3.8	-2.2
TE10	13.0	11.0	16.0	10	12.50	14.8	-1.8	-3.8	1.2	-4.8
TE11	18.0	16.0	17.0	18	17.25	12.5	5.5	3.5	4.5	5.5
TE12	16.0	17.0	15.0	18	16.50	11.6	4.4	5.4	3.4	6.4

Table K.3: Summary statistics of accuracy of subjective estimation of roughness by the 'Scale Descriptor Method' (class 4) in the IRRE

Method/observer parameter	unit	Reference $RARS_{50}$	Estimation by observer A	B	C	D	Average Estimation
No. observations		49	49	49	49	47	194
Mean roughness	m/km	7.58	7.33	8.24	8.64	7.00	7.80
Mean bias	m/km	0	-0.25	+0.66	+1.06	0.58	+0.22
Mean bias	fraction	0	-.033	+.088	+.140	-.076	+.030
RMS Error	m/km	0	2.6	2.3	3.0	2.8	2.7
RMS Error	fraction	0	0.35	0.27	0.48	0.35	0.36
R^2	fraction	1.00	0.89	0.92	0.86	0.89	

Ride comfortable over 120 km/h. Undulations barely perceptible at 80 km/h in range 1,5-2,0. No depressions, potholes or corrugations are noticeable; depressions < 2mm/3m. Typical high quality AC 1,5--2,5, high quality ST 2,0-3,5.

Ride comfortable at 100-120 km/h. At 80 km/h moderately sharp movements or large undulations may be felt. Defective surface: occasional depressions or potholes (e.g. 12-25mm/3m or 20-40mm/5m with freq. 3-1 per 50m), or many shallow potholes (e.g. on ST showing extensive ravelling). Surface without defects: moderate corrugations or large undulations.

Ride comfortable at 70-90km/h, Frequent sharp movements and swaying. Nearly always associated with severe defects: frequent deep and uneven depressions (e.g. 20-40mm/3m or 40-80mm/5m with freq. 5-3 per 50m), or frequent potholes (e.g. 4-6 per 50m). Surface without defects: strong undulations or corrugations.

Necessary to reduce velocity below 50km/h. Many deep potholes and severe disintegration (e.g. 40-80 mm deep with freq. 10-20 per 50m).

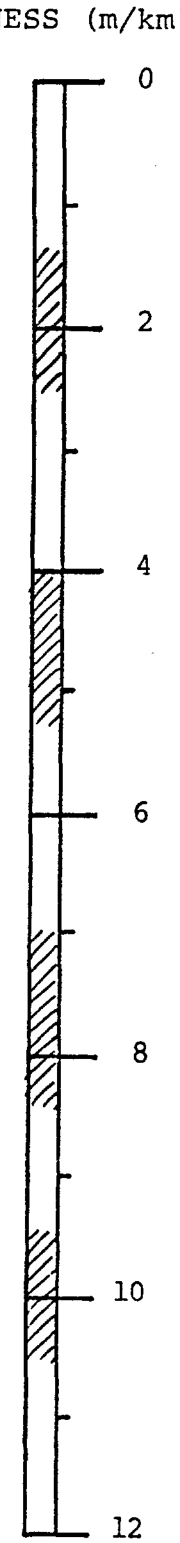
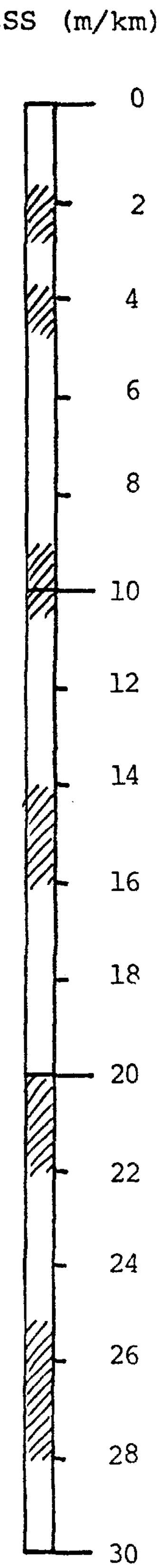


Figure K.1: Road roughness estimation scale for paved roads with asphaltic concrete or surface treatment surfacings



Recently bladed surface of fine gravel or soil surface with excellent longitudinal and transverse profile.

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

Ride comfortable at 70-80 km/h but aware of sharp movements and some wheel bounce. Frequent shallow-moderate depressions or shallow potholes (e.g. 6-20mm/3m with freq. 5-10 per 50m). Moderate corrugations (e.g. 6-20mm/0,7-1,5m).

Ride comfortable at 50km/h (40-70 km/h on specific sections). Frequent moderate transverse depressions (e.g. 20-40mm/3-5m at freq. 10-20 per 50m) or occasional deep depressions or potholes (e.g. 40-80mm/3m). Strong corrugations (e.g. > 20mm/0,7-1,5m).

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

Ride comfortable at 20-30 km/h. Speeds higher than 40-50 km/h would cause extreme discomfort, and possibly damage to the car. On a good general profile: frequent deep depressions and/or potholes (e.g. 40-80 mm/1-5m at freq. 10-15 per 50m) and occasional very deep depressions (e.g. > 80mm/0,6-2m).
On a poor general profile: frequent moderate defects and depressions (e.g. poor earth surface).

Figure K.2: Road roughness estimation scale for unpaved roads with gravel or earth surfaces

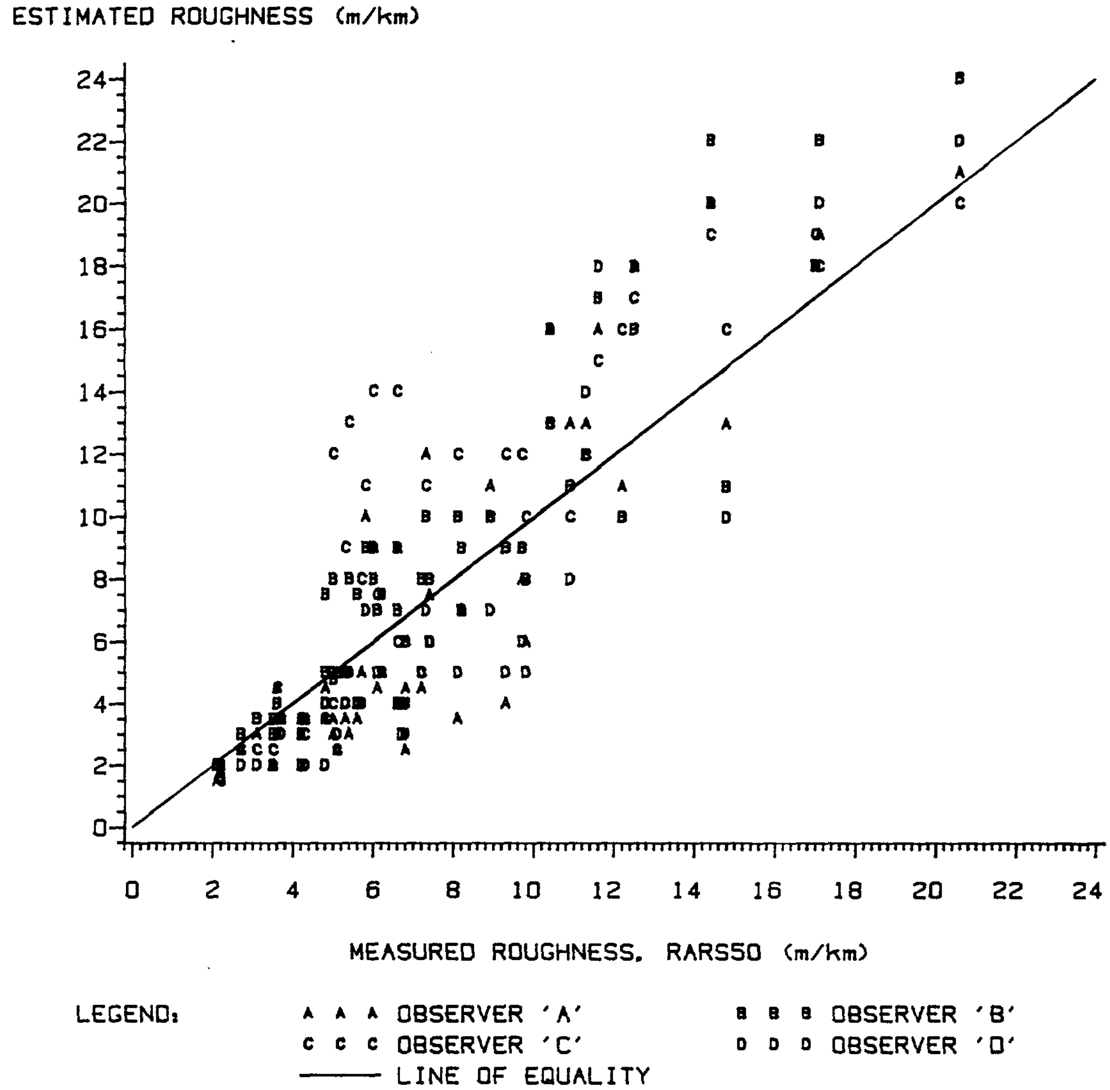


Figure K.3: Comparison of observer-estimates of roughness with measured $RARS_{50}$ index: collectively.

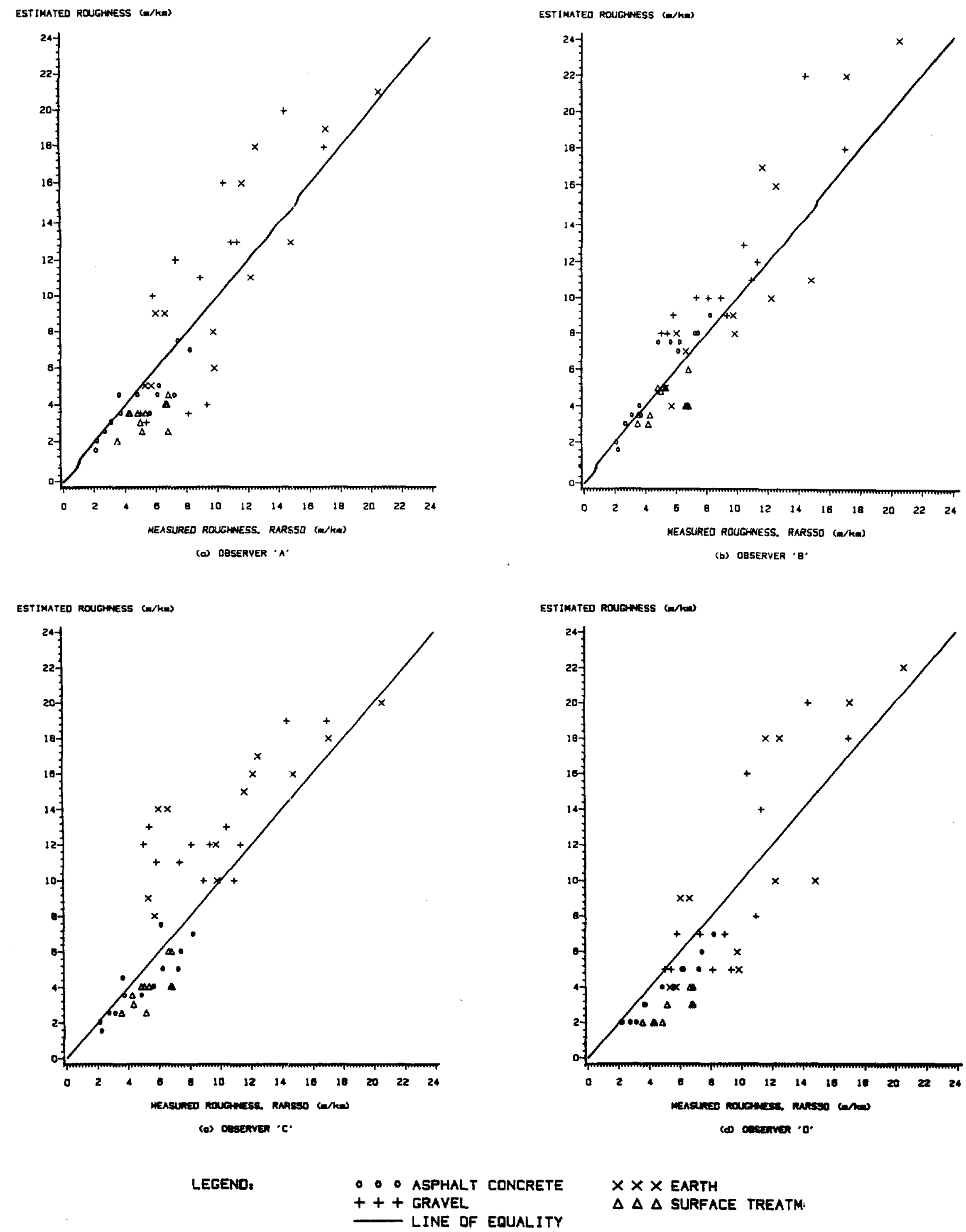


Figure K.4: Comparison of observer-estimates of roughness with measured $RARS_{50}$: for each observer separately.

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