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16. Abstract

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

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

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

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UMTRI-84-12-2

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

M. Sayers
T.D. Gillespie
C. Queiroz

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APPENDIX

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

Appendix H, included in this volume, was prepared by S. W. Abaynayaka and Linda Parsley of TRRL. Appendices E and G were prepared jointly by UMTRI, IPR/DNER, CRR, and LCPC.

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: H. Hide, and G. Morosiuk formed the research team from TRRL; M. Boulet, A. Viano, and F. Marc formed the research team from LCPC; M. I. Izabel (GEIPOT) supervised the subjective rating study and aided in the data entry; I. L. Martins (GEIPOT), Z. M. S. Mello (IPR/DNER), and H. Orellana (GEIPOT) aided in the data entry and analysis; L. G. Campos (GEIPOT) was responsible for selection of test sites and, together with O. Viegas (IPR/DNER), provided day-to-day supervision and control of the IRRE; M. Paiva (GEIPOT) repaired and calibrated the GMR Profilometer, and worked together with S. H. Buller (GEIPOT) to provide technical support during the IRRE.

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

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. (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, rather than the instrumentation.) 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].

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, 16, 17]. 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 Brazilia 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	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000)									
	(K/H)		MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	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	.839
	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)						SIGMA	S/M	TREND	R
			MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5				
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	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3)									
	(K/H)		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	3.79	.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	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3)									
	(K/H)		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.

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MAYS METER #3

SITE	SPEED	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3)									
	(K/H)		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)						SIGMA	S/M	TREND	R
			MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5				
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	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000)									
	(K/H)		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	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000)									
	(K/H)		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	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000)									
	(K/H)		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	.989
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	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000)									
	(K/H)		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)									
	(K/H)		MEAN	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	SIGMA	S/M	TREND	R
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	TRACK	ROUGHNESS MEASUREMENT (SLOPE X 1000)									
	(K/H)		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	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3)							
	(K/H)		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	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3)							
	(K/H)		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	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3)							
	(K/H)		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	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3)							
	(K/H)		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	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3)							
	(K/H)		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	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3)							
	(K/H)		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	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3)							
	(K/H)		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	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X E3)							
	(K/H)		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	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X 1000)							
	(K/H)		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	TRACK	ROUGHNESS MEASUREMENTS (SLOPE X 1000)							
	(K/H)		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	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
50									
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	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
50									
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	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
50									
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	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL (AVE)	BI TRL (DIFF)	BPR (AVE)	BPR (DIFF)
50									
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

20 80	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

20 80	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

20 80	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

20 80	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	.6393	.4714
BI CAR	.9494	.9836	.9006	.9783	.9783	.9679	.0542	.7383	.5067
NAASRA	.9604	.9974	.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	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL	BI TRL	BPR	BPR
80						(AVE)	(DIFF)	(AVE)	(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	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL	BI TRL	BPR	BPR
80						(AVE)	(DIFF)	(AVE)	(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	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL	BI TRL	BPR	BPR
80						(AVE)	(DIFF)	(AVE)	(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	MM 01	MM 02	MM 03	BI CAR	NAASRA	BI TRL	BI TRL	BPR	BPR
80						(AVE)	(DIFF)	(AVE)	(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	.9069	.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

50 80	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

50 80	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

50 80	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

50 80	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	.1649	1	.0583	.1178
BPR (AVE)	.5061	.5325	.449	.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	.3039	.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

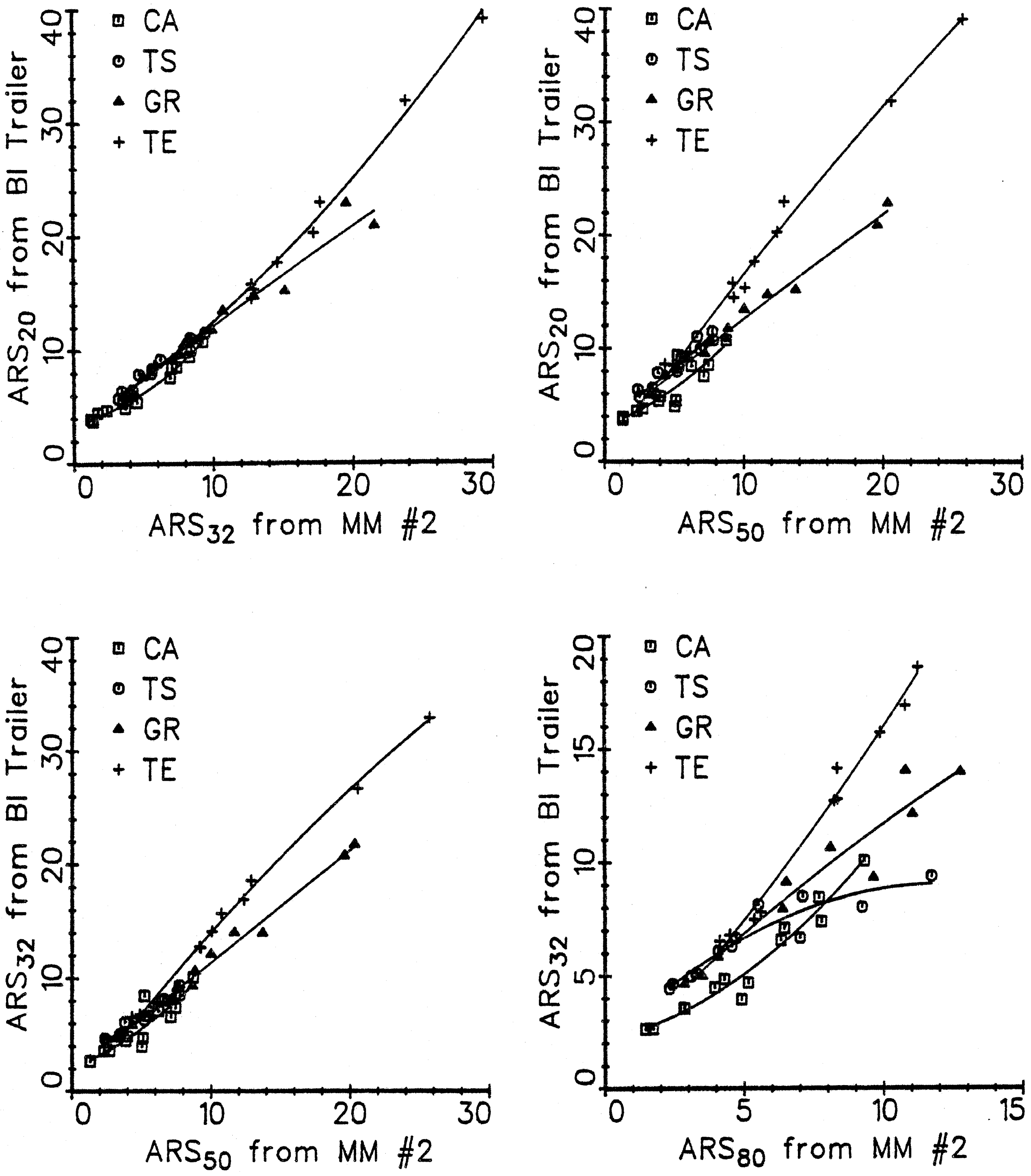


Figure C.1. Comparison of ARS measures made at different speeds by two RTRRMSs.

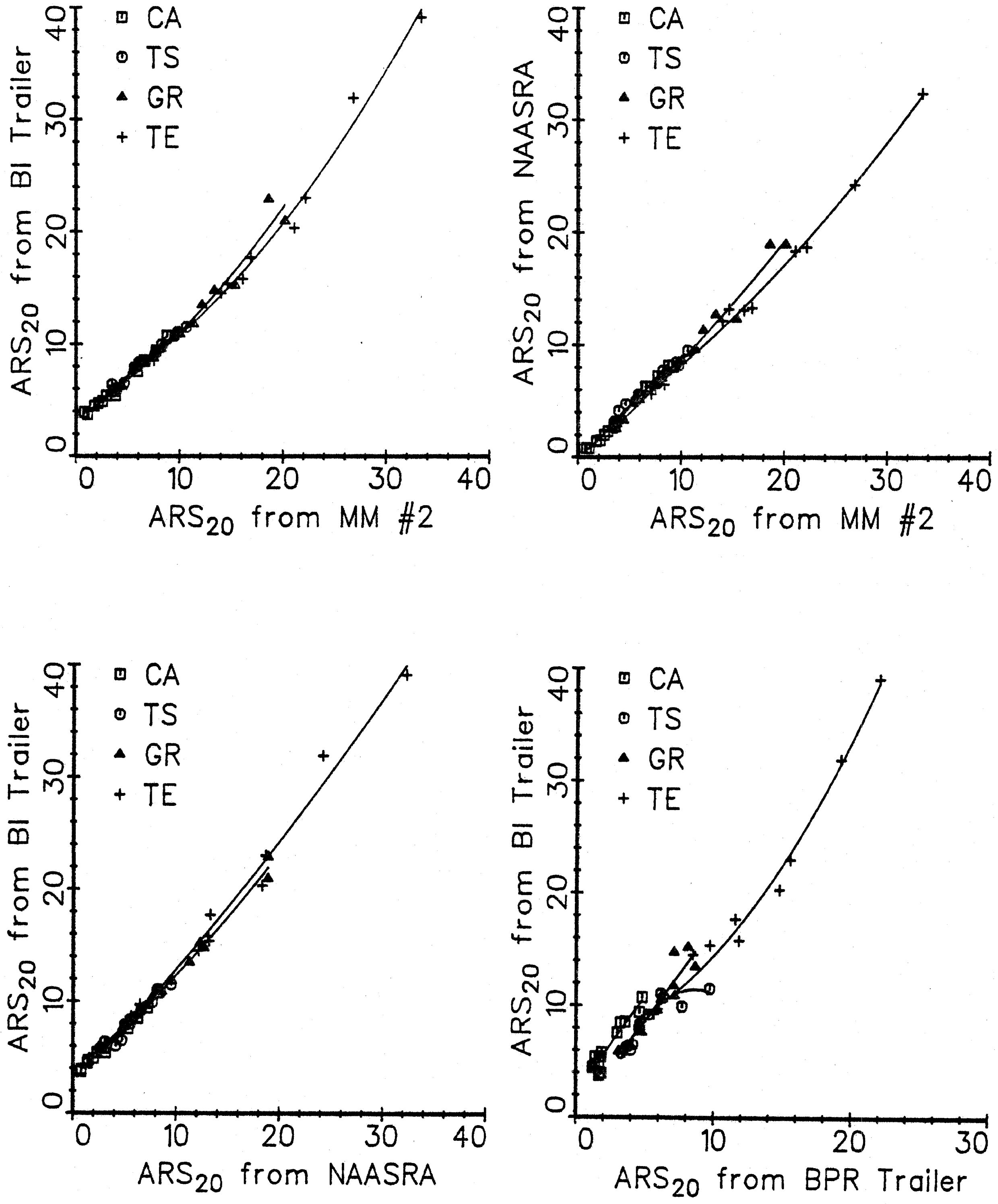


Figure C.2. Comparison of ARS_{20} measures made by four RTRRMSs.

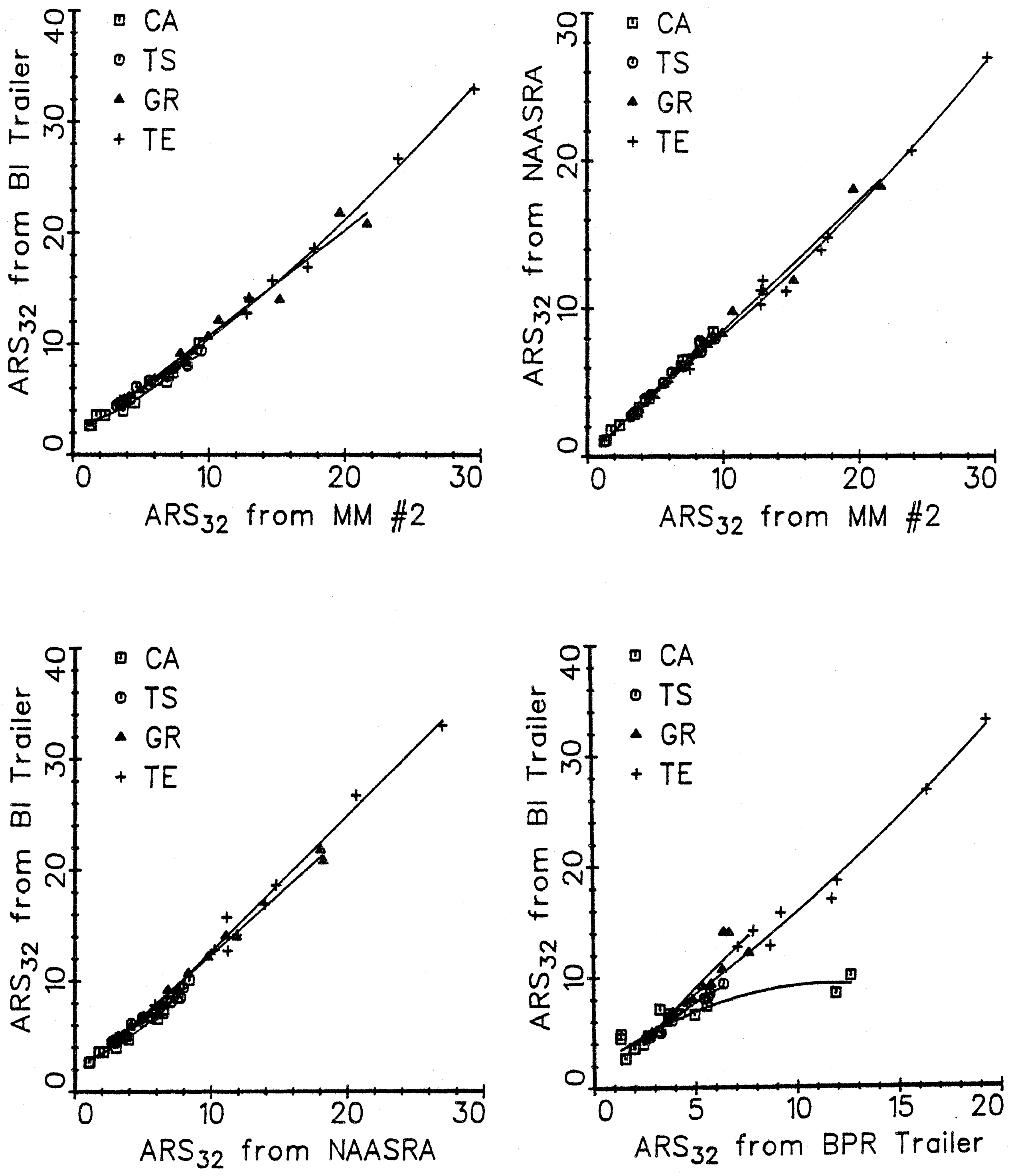


Figure C.3. Comparison of ARS$_{32}$ measures made by four RTRRMSs.

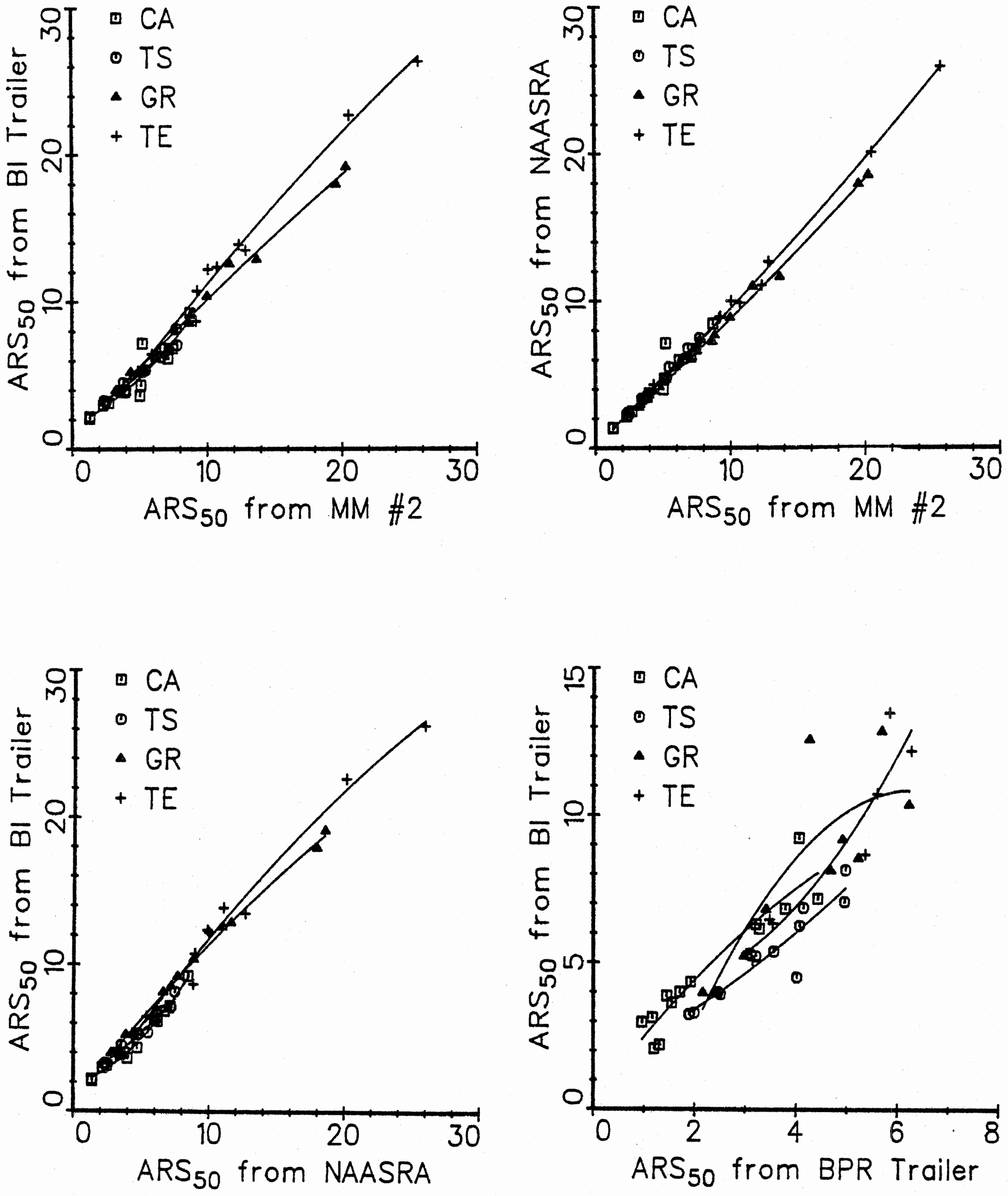


Figure C.4. Comparison of ARS_{50} measures made by four RTRRMSs.

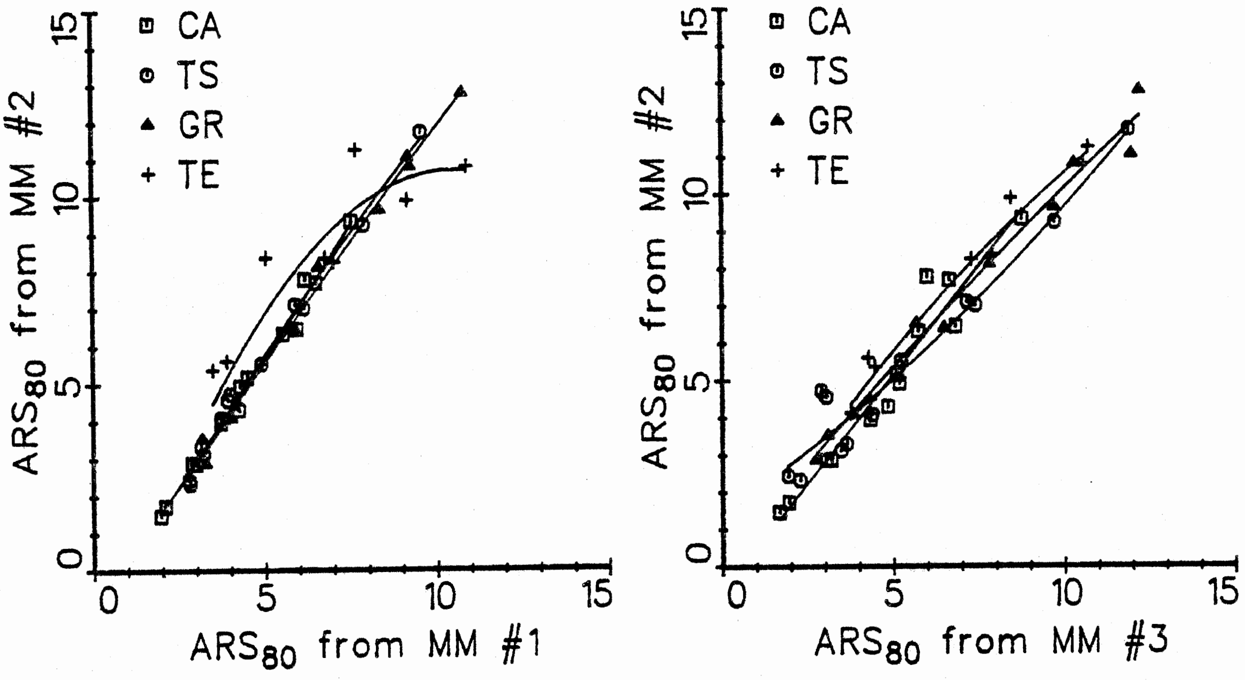


Figure C.5. Comparison of ARS_{80} measures made by three RTRRMSs.

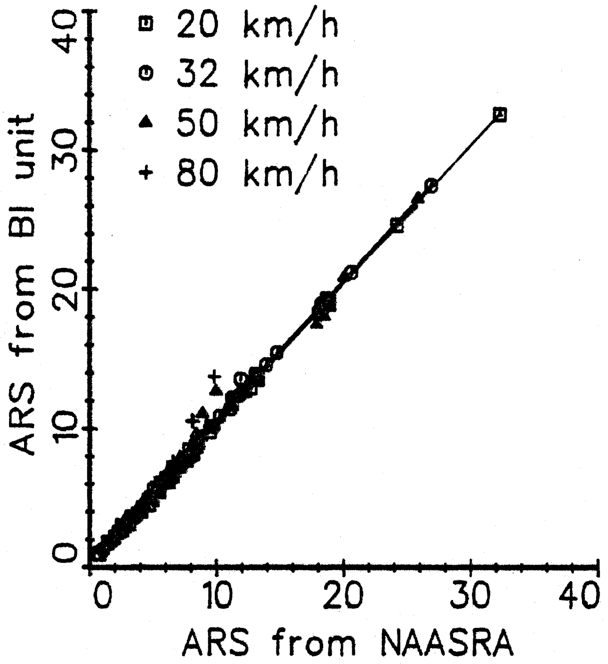
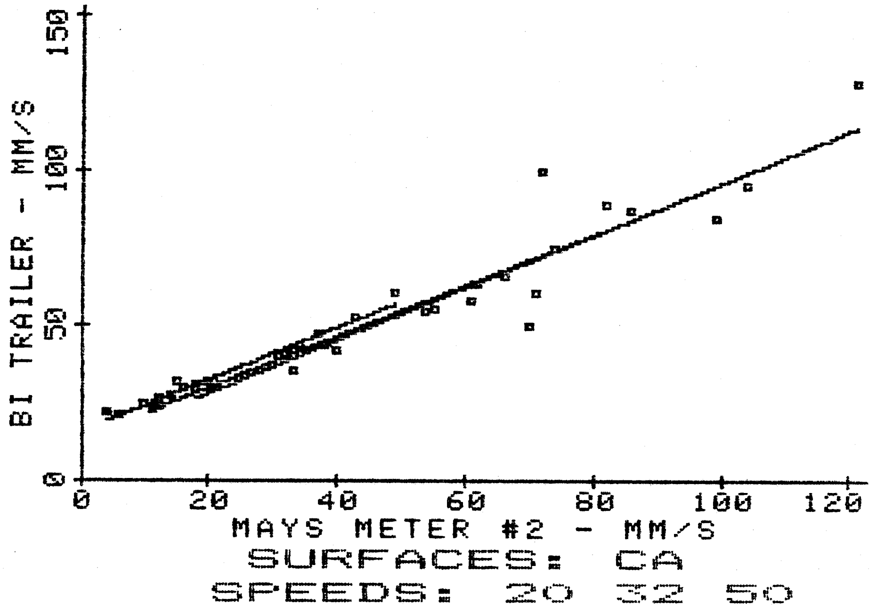
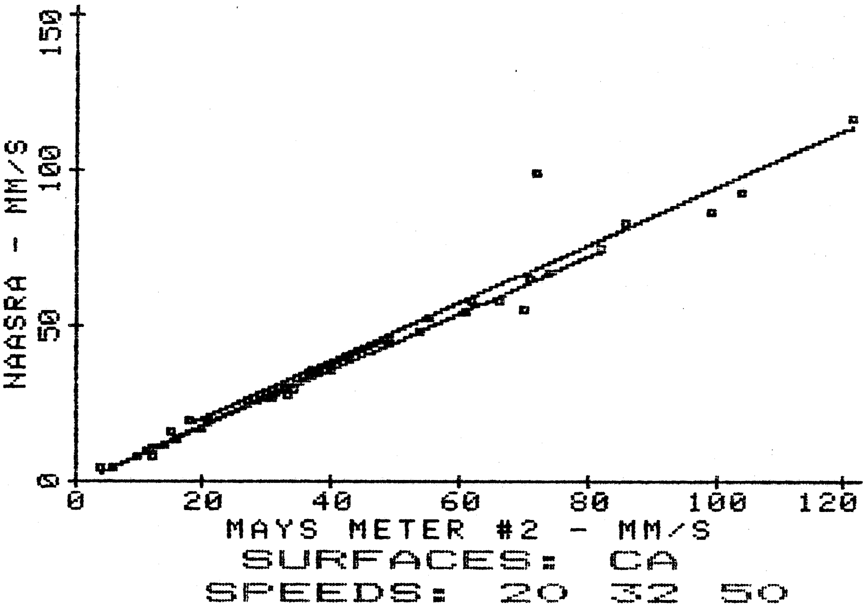


Figure C.6. Comparison of ARS measures made with two roadmeters in the same vehicle.





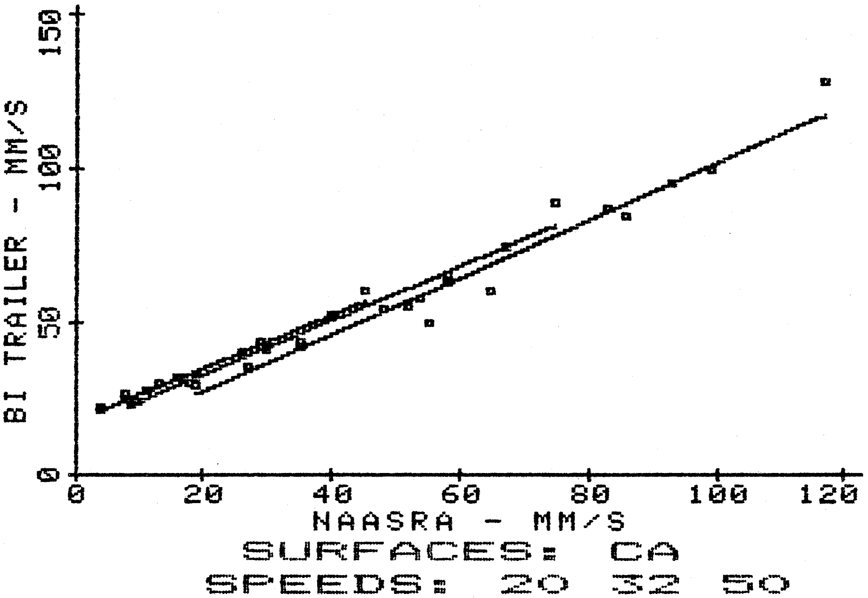
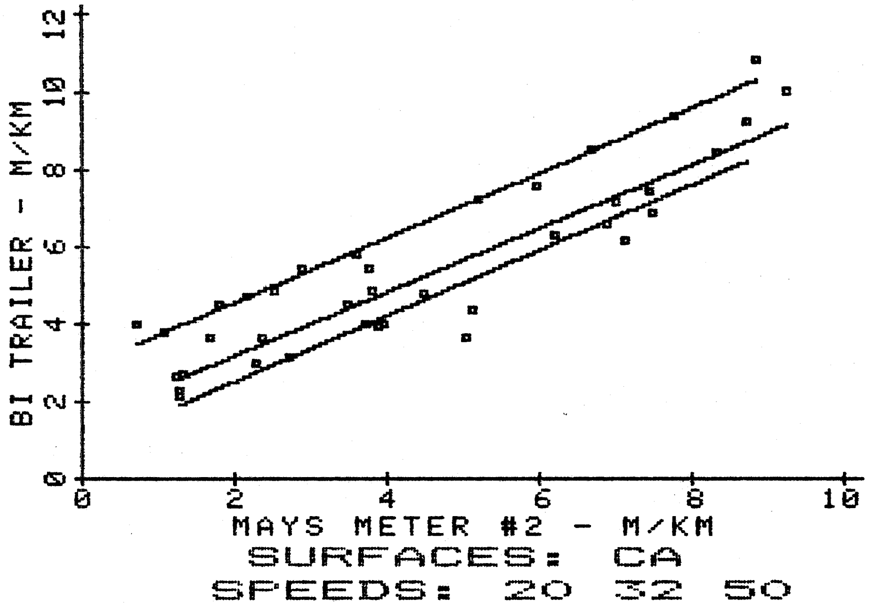
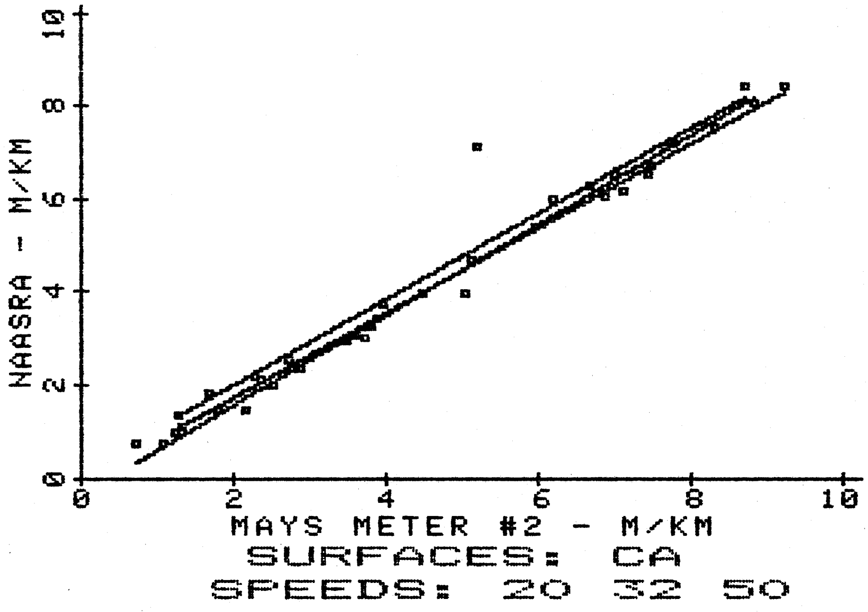


Figure C.7 Comparison of ARV Measures from Three RTRRMSs Taken at Three Speeds on Asphaltic Concrete Roads.





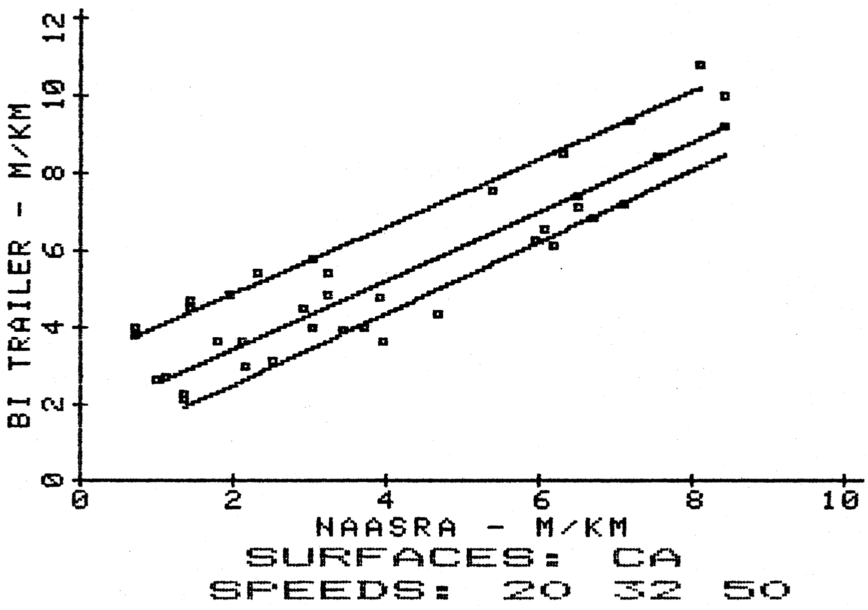


Figure C.8 Comparison of ARS Measures from Three RTRRMSs Taken at Three Speeds on Asphaltic Concrete Roads.

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

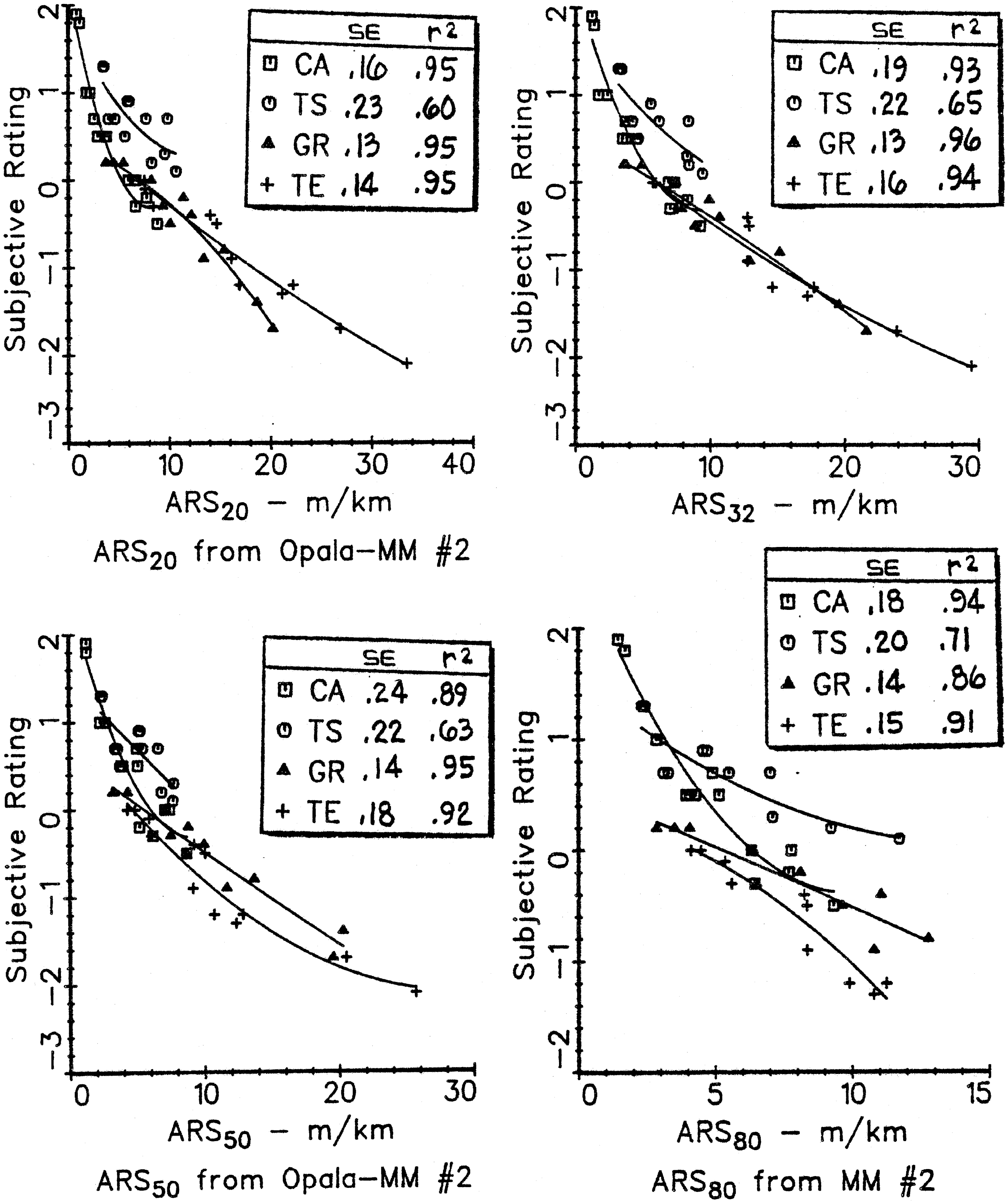


Figure D.1. Correlations between SR and ARS measures from a RTRRMS.

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 aparantly 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 regresion equations for $RARS_{50}$ and $RARS_{80}$.

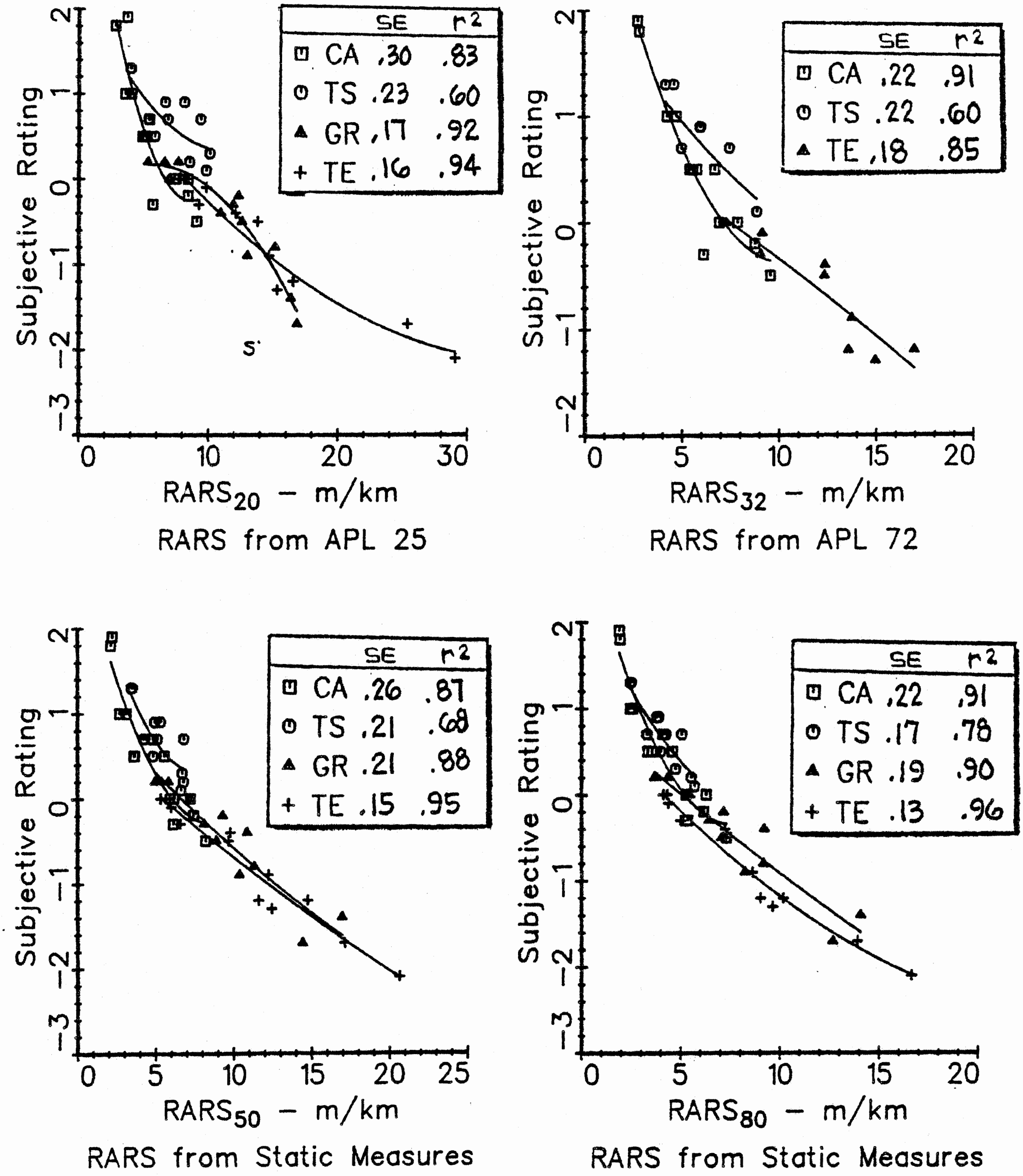
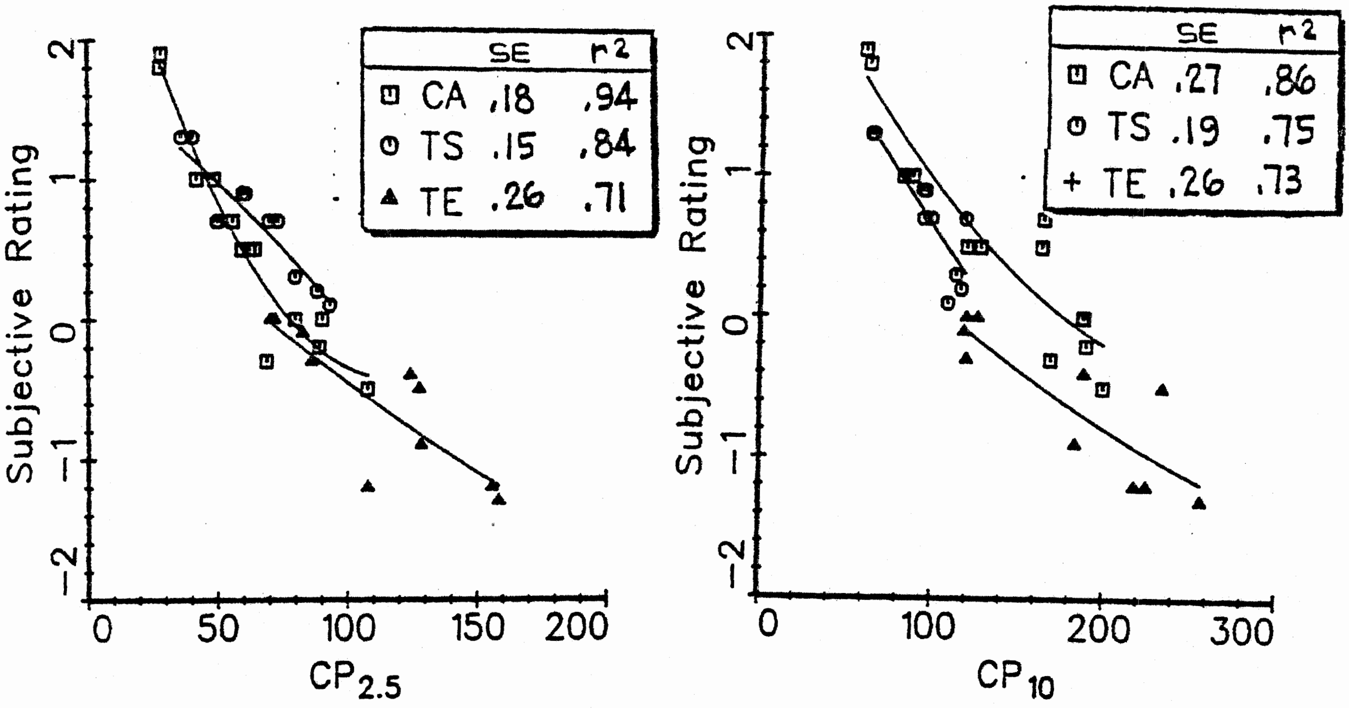
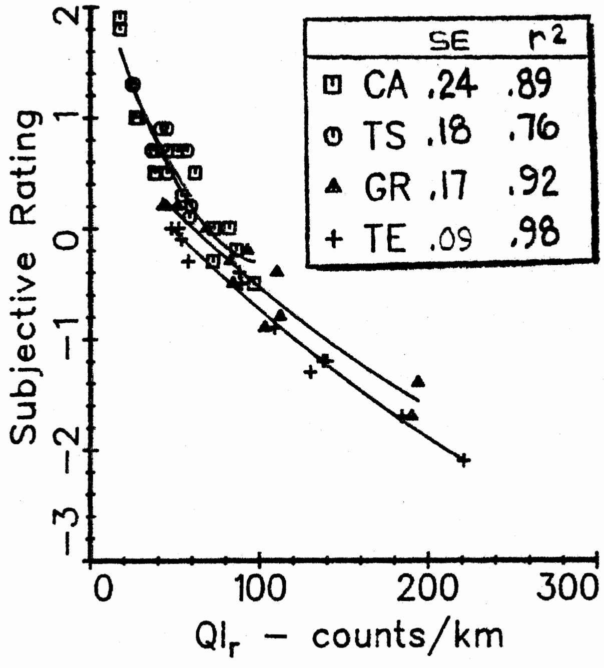


Figure D.2. Correlations between RARS from the QCS and SR.



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

The University of Michigan Transportation Research Institute (UMTRI).
The Brazilian Road Research Institute (IPR/DNER),
The French Bridge and Pavement Laboratory (LCPC), and
The Belgian Road Research Center (CRR)

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" (ICR). In actuality, there are several QI scales, which have subtle differences. During the ICR 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 numeric partly defined by a reference instrument and partly defined by the response properties of the Opala passenger car (designated QI^*) [7], to a roughness 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 ICR 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 response-type road roughness measuring systems (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 QIr numeric, 3) requirements in profile measurement for valid measurement of QIr, and 4) the compatibility of the QIr 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 ICR 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 ICR 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 ICR 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 ICR 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). The integrated 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 ICR 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 ICR 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 ICR 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 ICR." 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 never used on unpaved roads, and only rarely used on surface treatment roads. Therefore, the original QI is 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

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

where

n = number of measurements

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

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

where

E [QI] = expected value of QI, and

$RMSVA_b$ has the units: 1/mm 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:

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

where

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

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° 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:

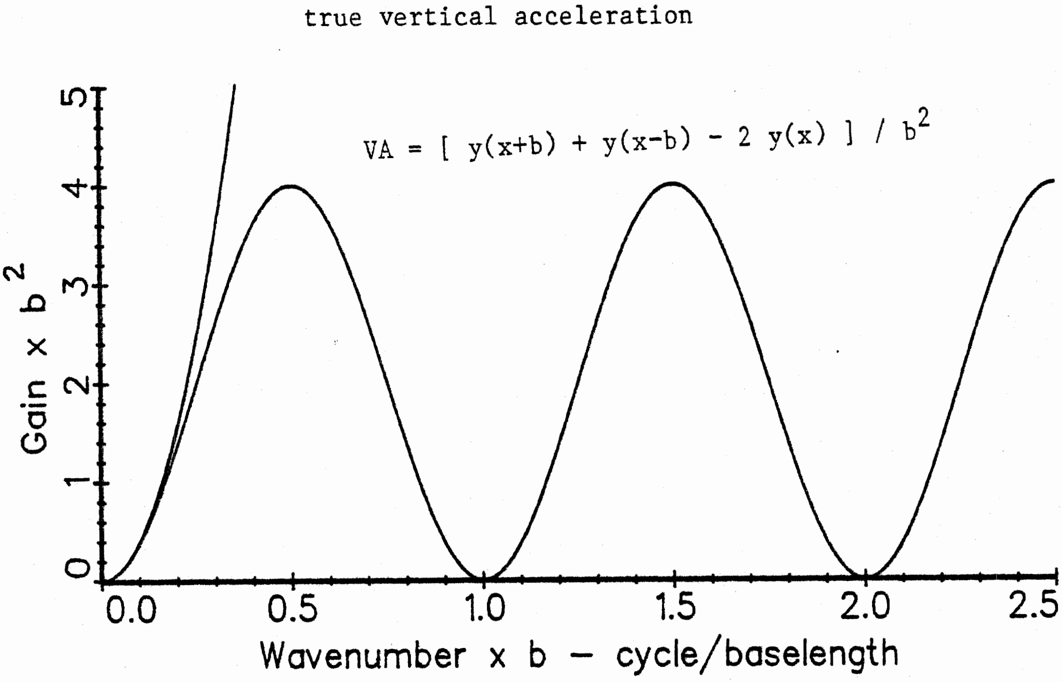
$$y'(w,x) = dy/dx = jw\ Y_o\ e^{jwx} = jw\ y(w,x) \qquad \text{(E-12)}$$

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 yeild 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



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. 4, 5, and 11:

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

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

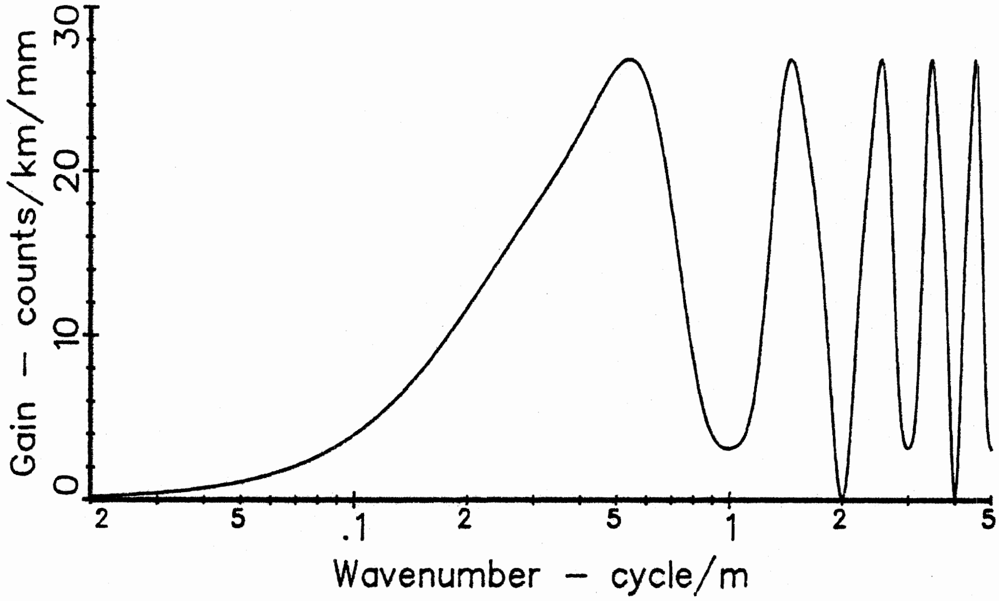
$$= 24.7 \sin^2(\pi/L) + 3.1 \sin^2(2.5\pi/L) \qquad \text{(E-14)}$$

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:

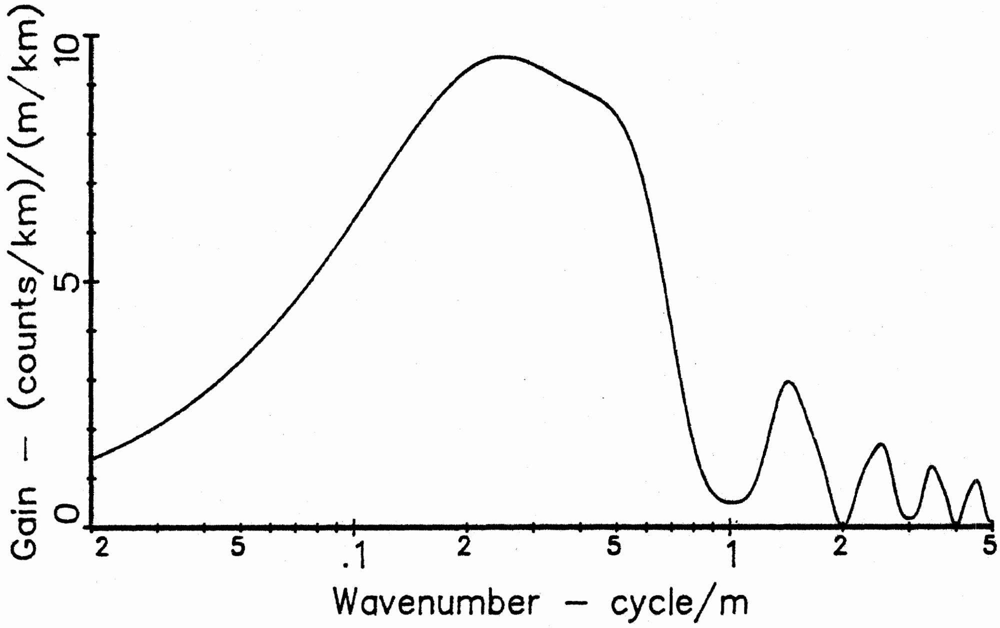
$|(QI_r + 8.54) / Y'|$ = response to sinusoidal slope input

$$= [\ 24.68 \sin^2(\pi/L) + 3.1 \sin^2(2.5\pi/L)\ /\ w$$

$$= L\ [\ 24.68 \sin^2(\pi/L) + 3.1 \sin^2(2.5\pi/L)\ /\ 2\pi$$



a. Sensitivity of QIr to pure sinusoidal displacement



b. Sensitivity of QIr to sinusoidal slope input

Figure E.2. Sensitivity of QI_r to Wavenumber

$$= L \, [\, 3.95 \sin^2(\pi/L) + 0.50 \sin^2(2.5\pi/L) \,] \qquad \text{(E-15)}$$

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:

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

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

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

where

$$m = n/k \tag{E-17}$$

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:

$$\mathrm{RMSVA}_b = [\ 1/k \sum_{j=0}^{k-1} R_j{}^2\ ]^{1/2} \tag{E-18}$$

where

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

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:

$$\text{"true" } \mathrm{RMSVA}_b = \lim_{1/k \to 0} [\ 1/k \sum_{j=0}^{k-1} R_j{}^2\ ]^{1/2} \tag{E-20}$$

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.

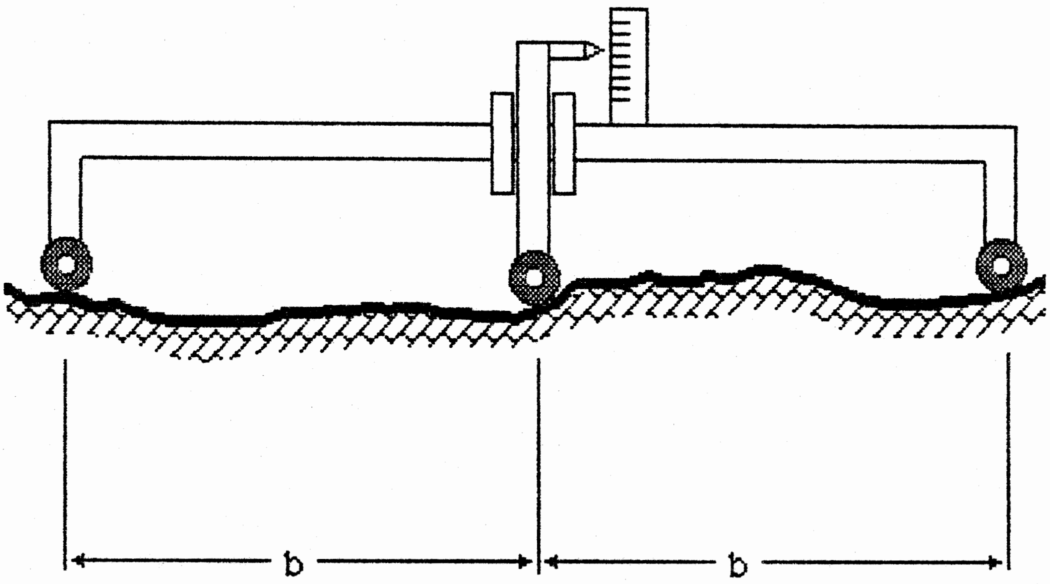
Physical Interpretation of RMSVA and QI_r

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:

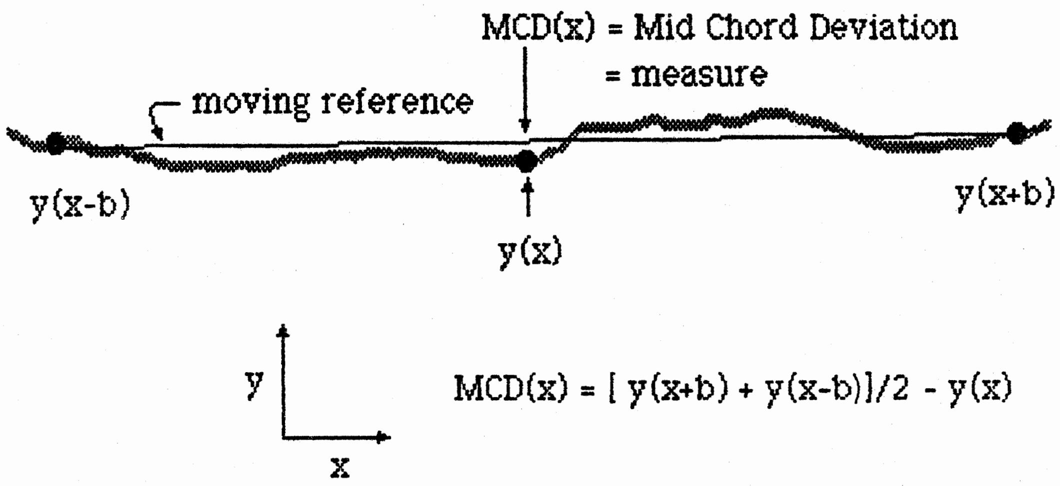
$$MCD(x) = [\ y(x+b) + y(x-b)\ ]/2 - y(x) \qquad \text{(E-22)}$$

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 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.



a. Schematic Representation of a Mechanical Rolling Straightedge



b. Geometry of Mid Chord Deviation

Figure E.3. Physical Model of RMSVA analysis.

The QI^* Calibration Method.

All of the road roughness data measured in the ICR 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:

$$QI^* = A + B\ ARS_{80} \tag{E-23}$$

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"

$$E\ [ARS_{80}] = -0.275 + 1.04\ ARS_{50} \tag{E-24}$$

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 ICR. 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 ICR 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 ICR 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 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 agregate speed conversion equation (Eq. 24).

MEASUREMENT OF QI_r IN THE IRRE

Technical Requirements for Measuring QI_r

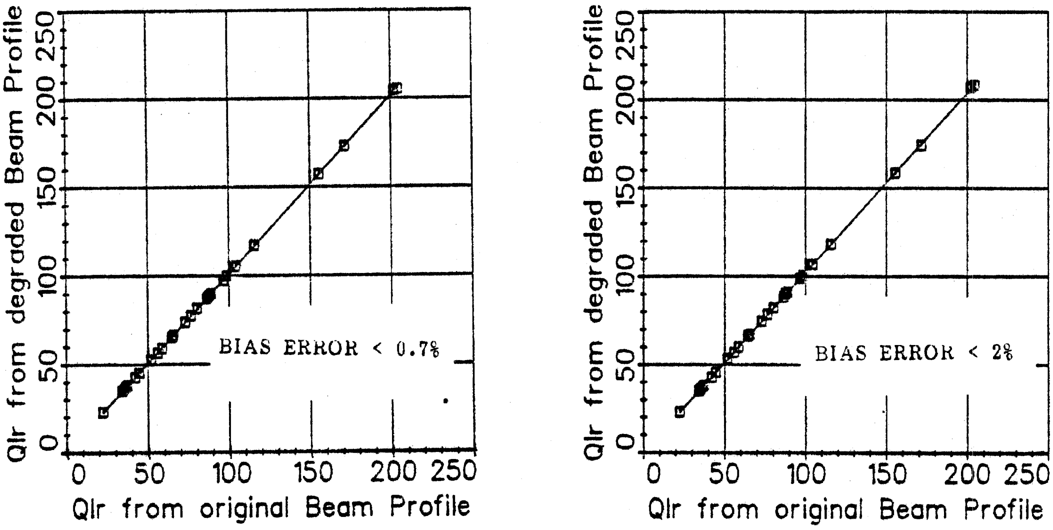
Measurement Interval. The effect of profile measurement interval on the QI_r numeric has been tested and reported previously, with the conclusion that a 500 mm interval is adequate [7]. The analyses of the QI_r computation method, presented in the previous section (Eqs. 16 - 21), prove that use of alternate 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?

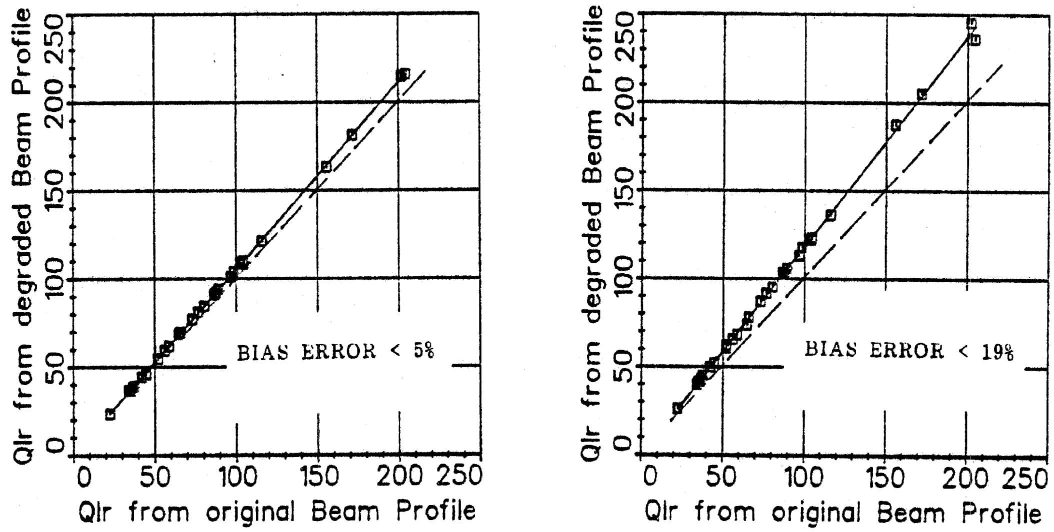
In this analysis, the precision of the measurement was assumed to be limited solely by the quantization of the continuous height variable into digitized quantities, which were originally 1.0 mm. The random measurement errors that also degrade precision were not considered. For each of the 28 measured 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 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"



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

	Left Wheeltrack						Right Wheeltrack						Both Wheeltracks: Average					
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	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

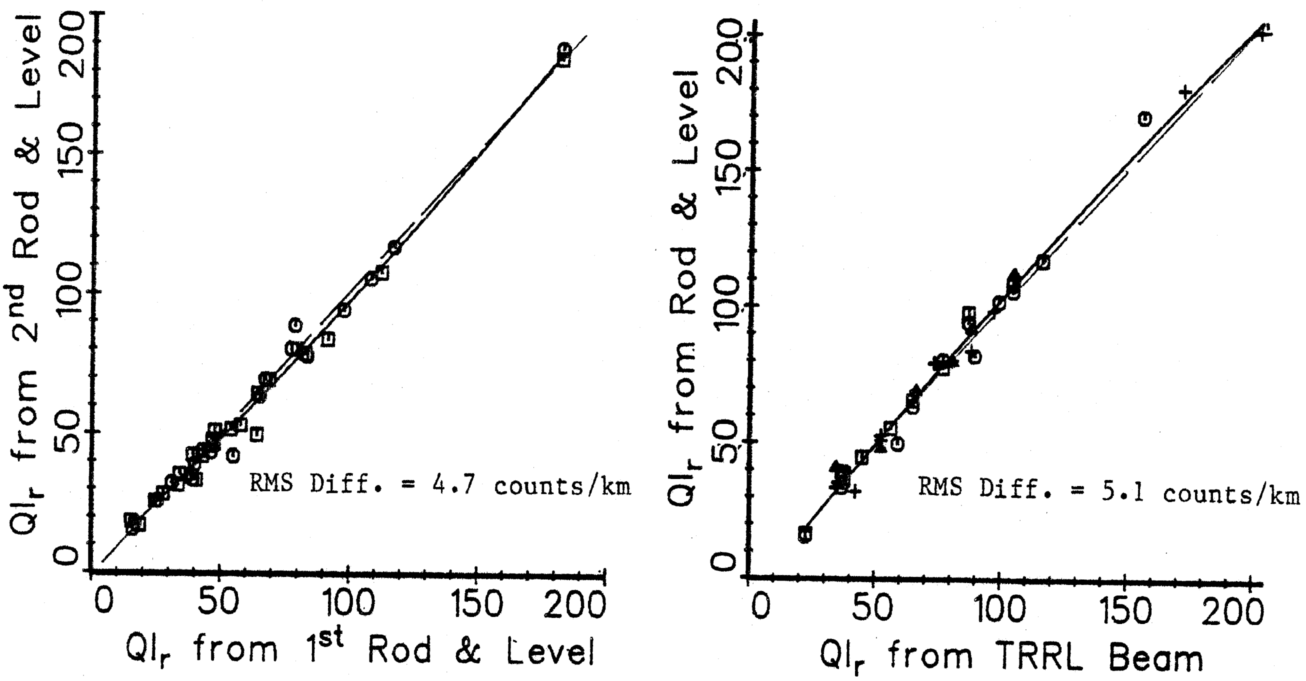
* rod and level measures using 100 mm interval between elevation measurements.

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

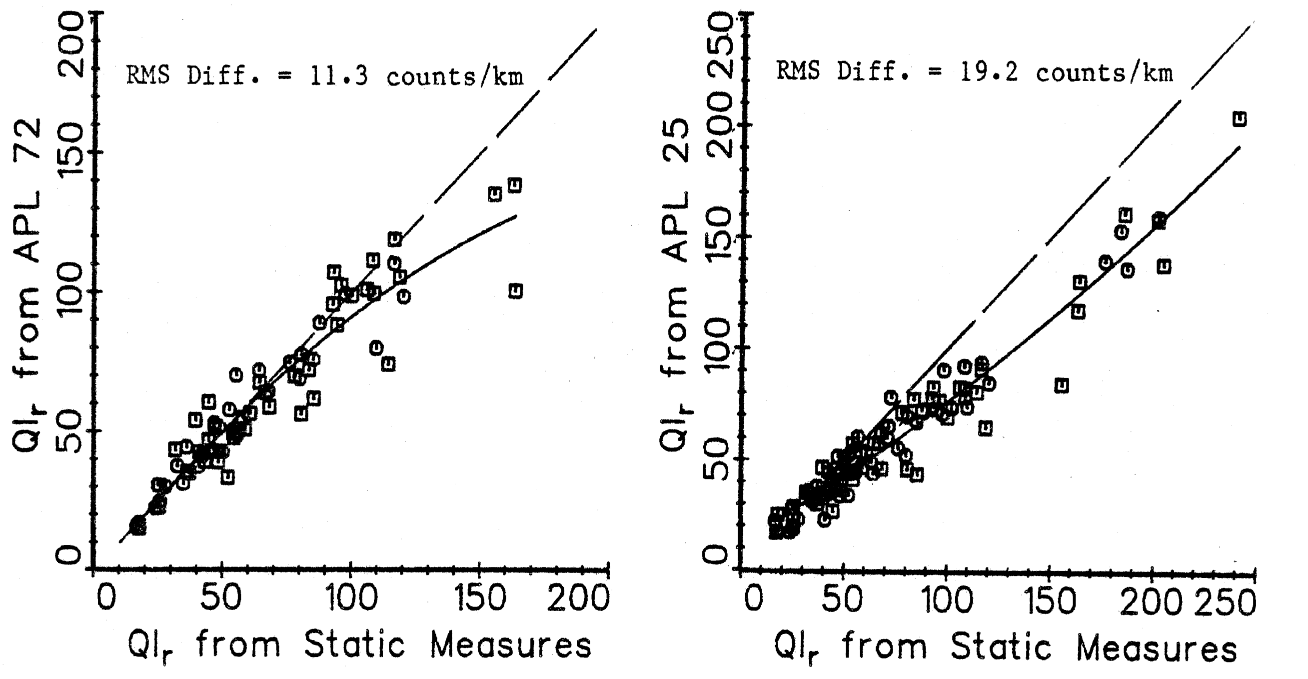
Repeatability with Rod and Level. Most of the sources of error that plague roughness measurements using RTRRMSs are eliminated when profiles are measured statically with rod and level: the same roughness computation method can be used, eliminating variations due to different definitions of roughness; 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, 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.



a. Rod & Level Repeatability

b. Comparison of Beam with Rod and Level



c. APL 72

d. APL 25

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

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.

Calibration Using the QI^* Method

The QI^* calibration method was tested by adopting the procedures followed in the ICR project [7], using the RTRRMS speeds that were used for the majority of the ICR roughness measurements: 80 km/h on paved roads and 50

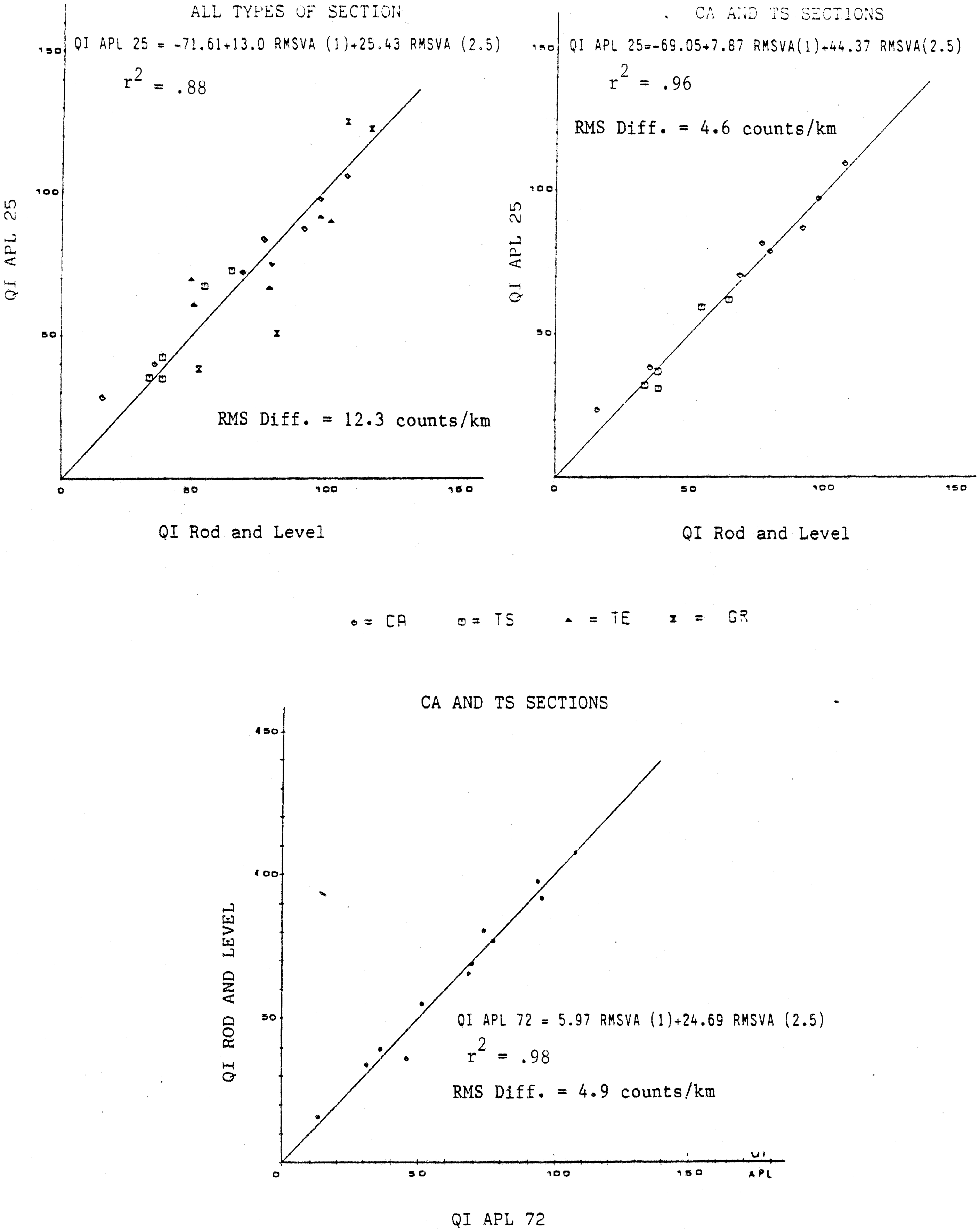


Figure E.6. Comparison of QI values calculated from rod and level with QI values calculated from APL.25 and APL 72 profiles

ALL SECTIONS INCLUDED CA, TS, GR, TE

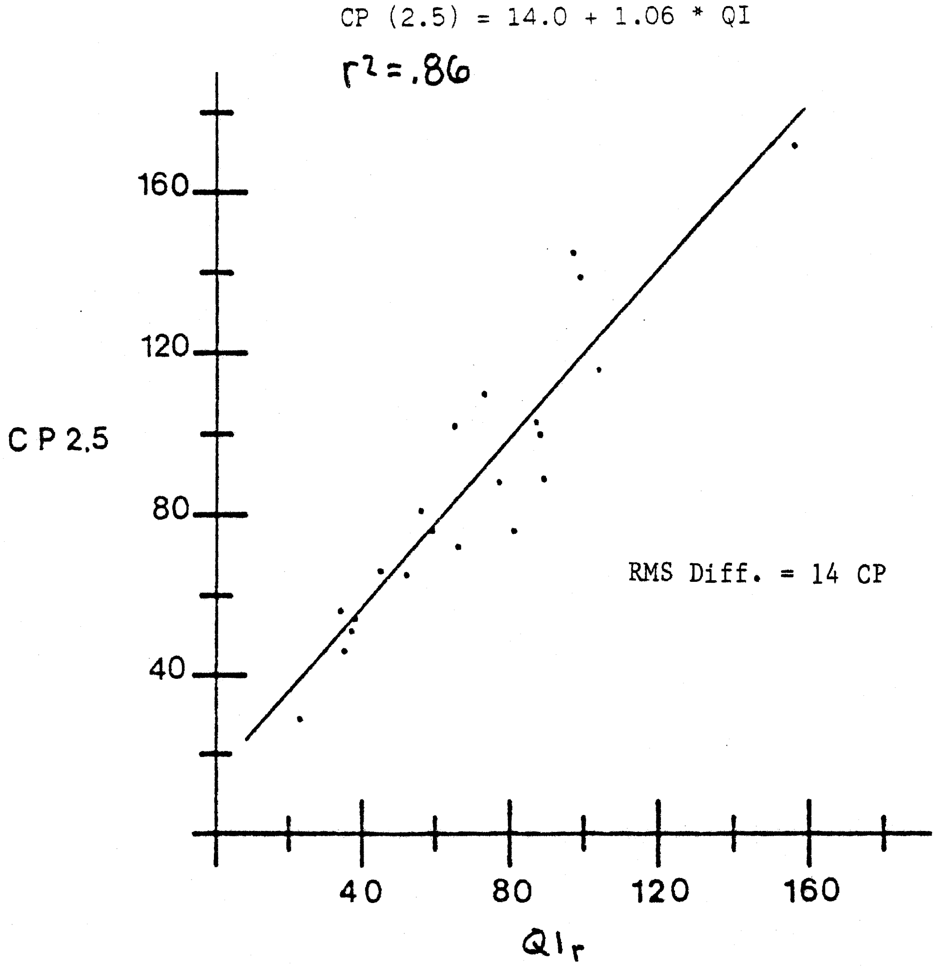
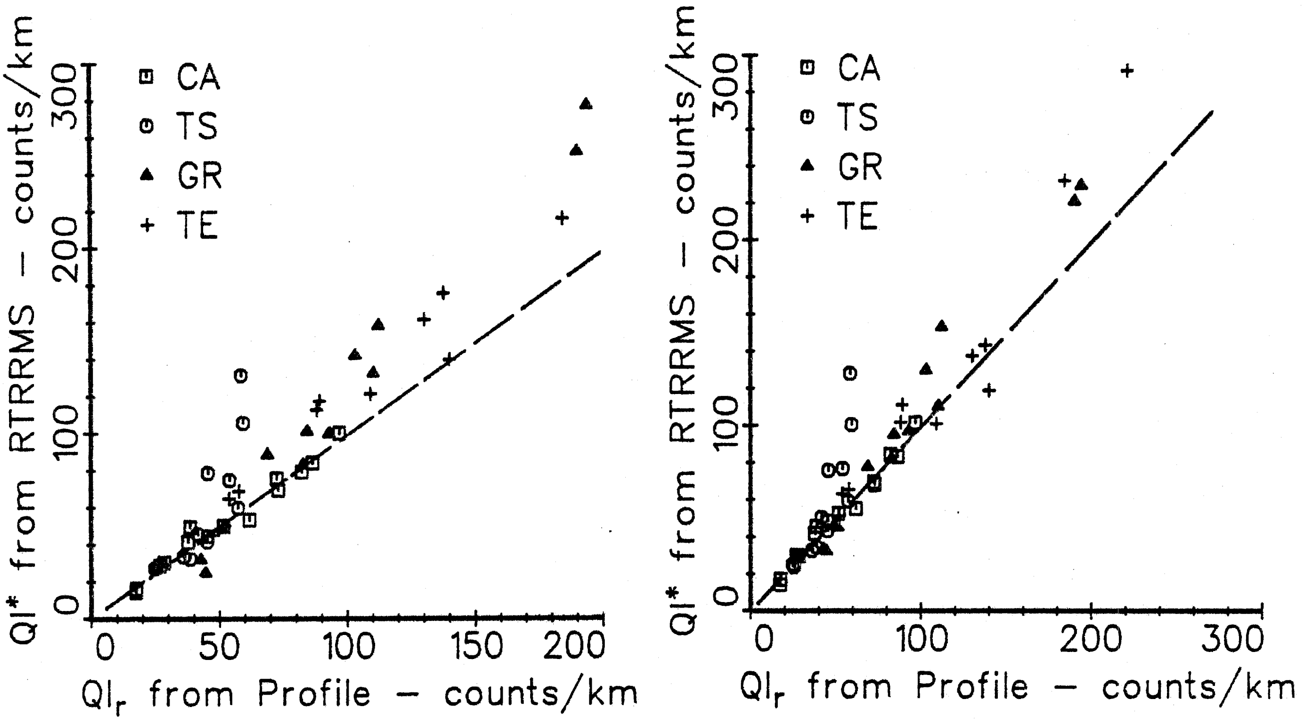


Figure E.7. Comparison of QI values calculated from TRRL Beam profiles with CP (2.5) derived from APL 72 signal km/h on unpaved roads [14]. Using the data obtained during the IRRE, a calibration equation was determined for the five Opala and Caravan-based RTRRMSs that were operated at 80 km/h on the 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.

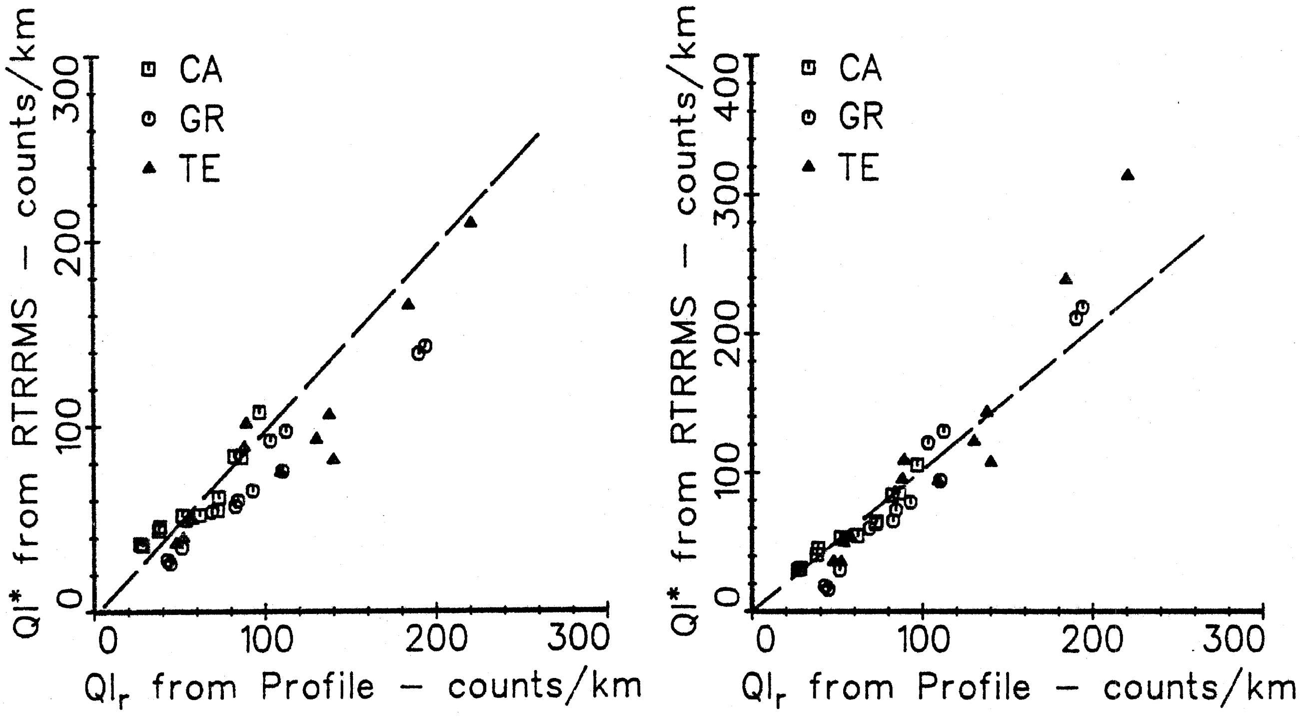
The four plots in Figure E.8 indicate that the QI^* calibration method results in a scale that is not equivalent to QI_r on all surface types. The method requires that the calibration (linear regression obtained on CA surfaces) be extrapolated to cover other surface types and a wider range of roughness 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.

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 ICR roughness data, since it implies that the QI^* data collected in the ICR 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



a. Opala–Maysmeter #1 B. OPALA–MAYSMETER #2



C. CARAVAN–BI D. CARAVAN–NAASRA

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

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 ICR project that was consistent and reasonably stable with time. The method requires that the RTRRMS have response properties very similar to the Opal-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 equivalent to the QI_r scale on three of the four surface types that were included in the IRRE.

Calibration through Correlation

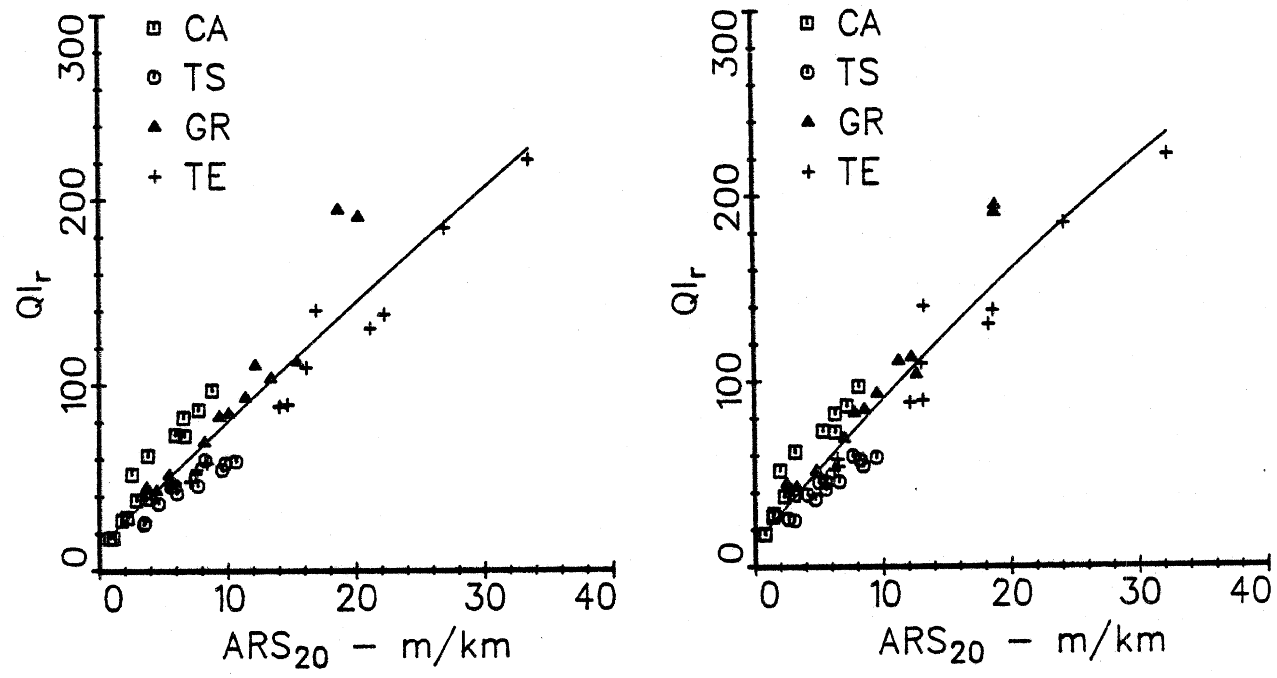
The comparisons between ARS measured with four of the RTRRMSs and QI_r are illustrated in Figures F.9 - 12. Results from the Caravan-BI system (not plotted) are virtually the same as for the Caravan-NAASRA system. Results for the two Opala-Maysmeter systems that are not plotted are generally similar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

These four figures lead to the following observations:

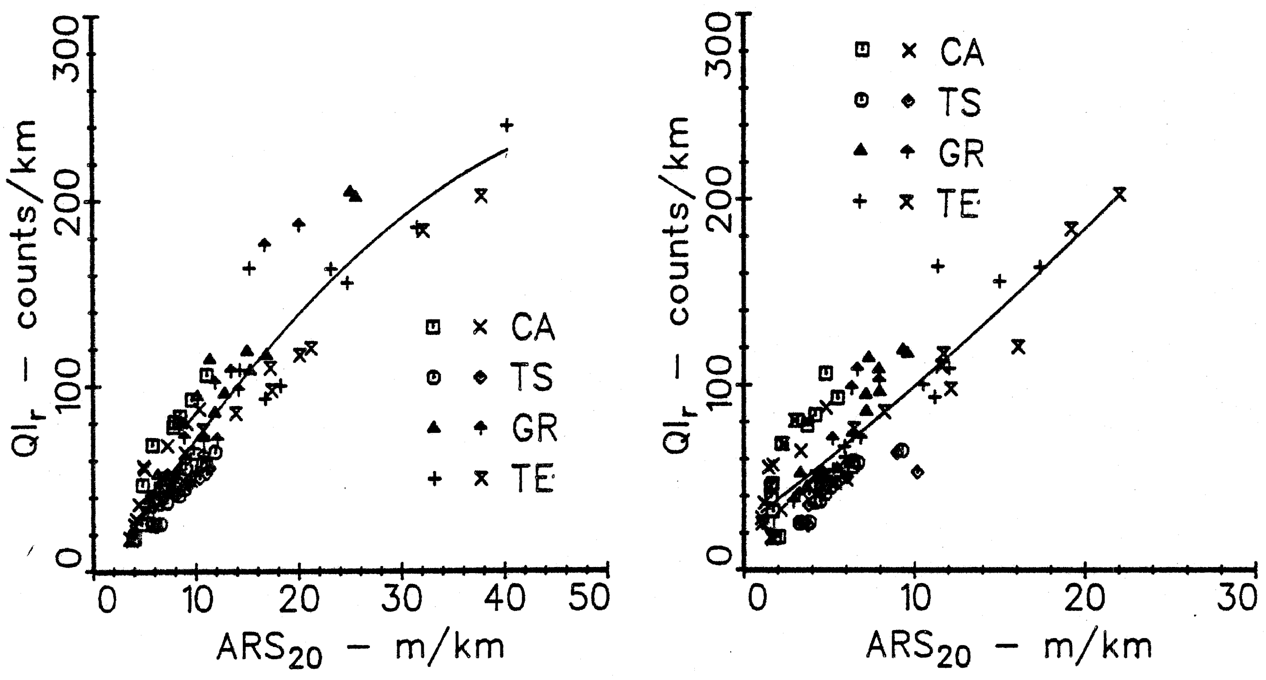
Overall correlation. By and large, QI_r is highly correlated with the ARS numerics obtained from all types of RTRRMSs that participated in the IRRE. Most of the data points lie close to the regression curve in each figure.

Error distribution. Errors, as defined by the scatter about the regression curves in the vertical direction, are fairly uniform across the



a. Opala–Maysmeter #2

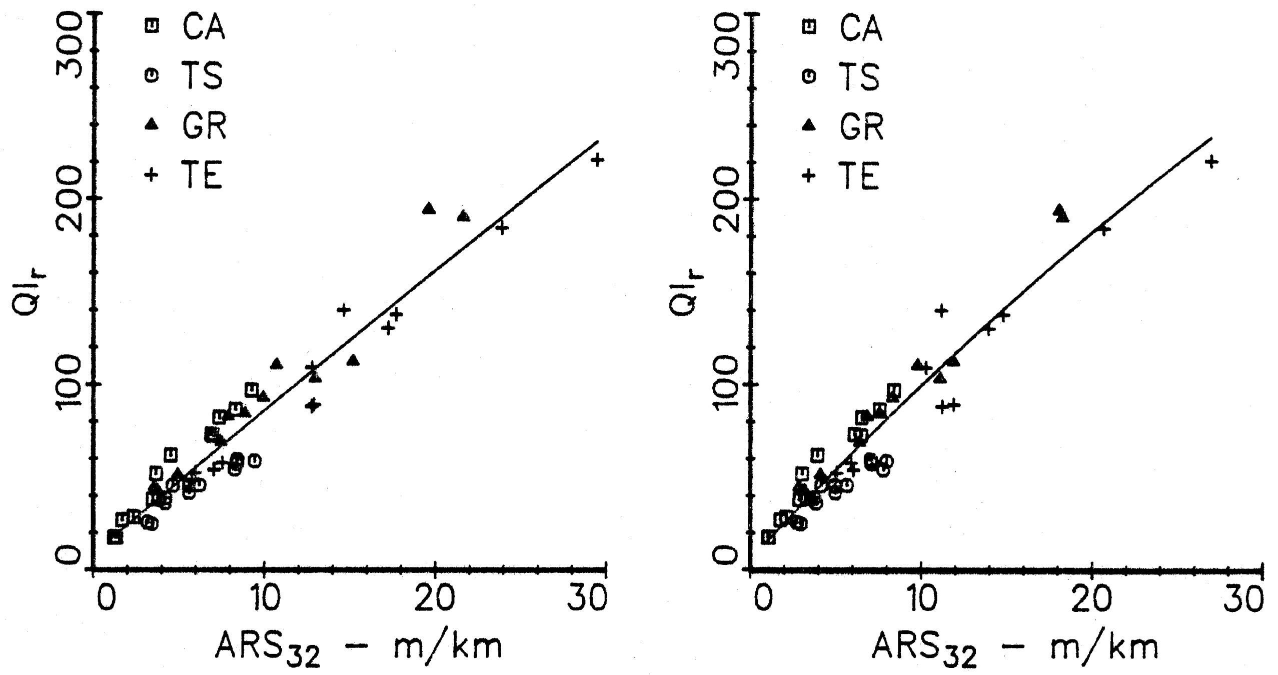
b. Caravan–NAASRA



c. BI Trailer

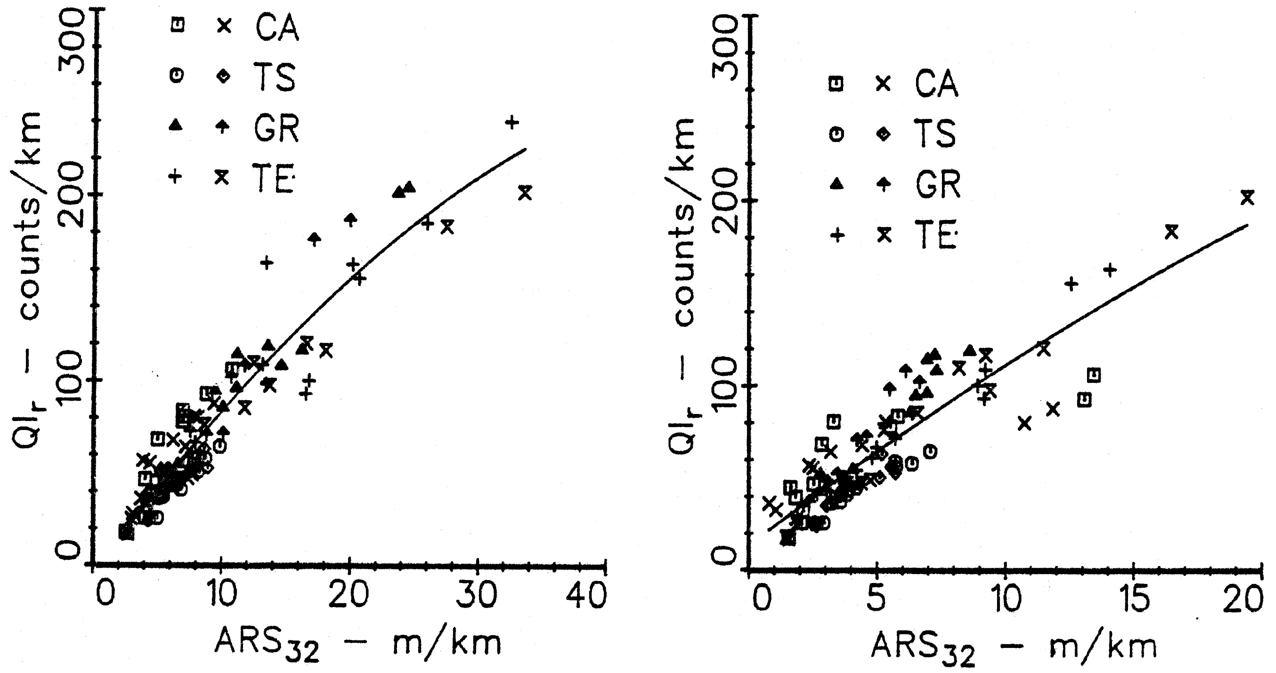
d. BPR Roughometer

Figure E.9. Example calibration plots to estimate QI$_r$ from ARS$_{20}$.



a. Opala–Maysmeter #2

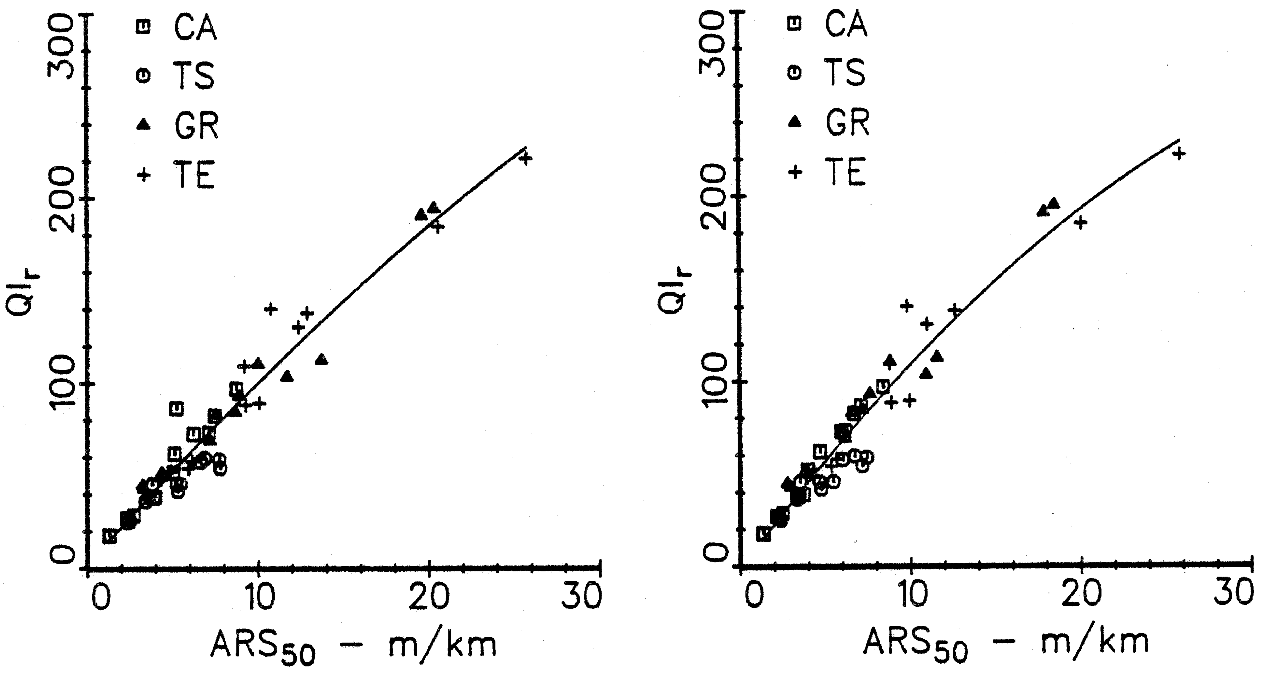
b. Caravan–NAASRA



c. BI Trailer

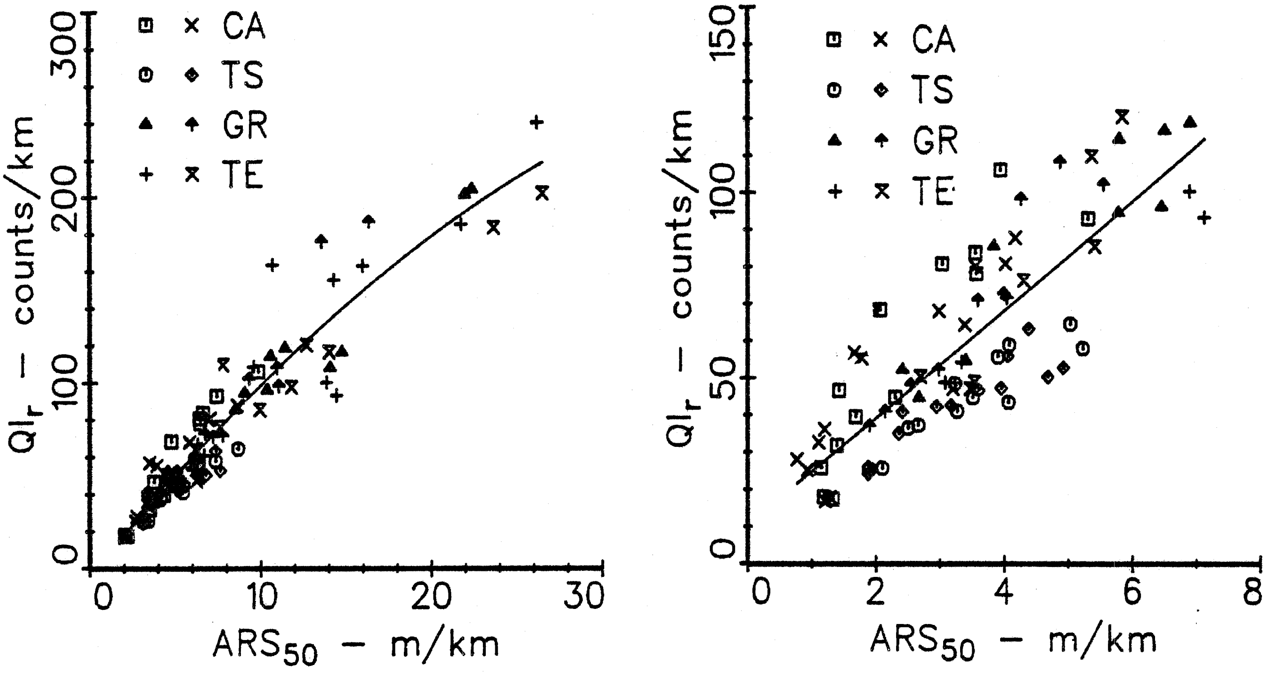
d. BPR Roughometer

Figure E.10. Example calibration plots to estimate QI$_r$ from ARS$_{32}$.



a. Opala–Maysmeter #2

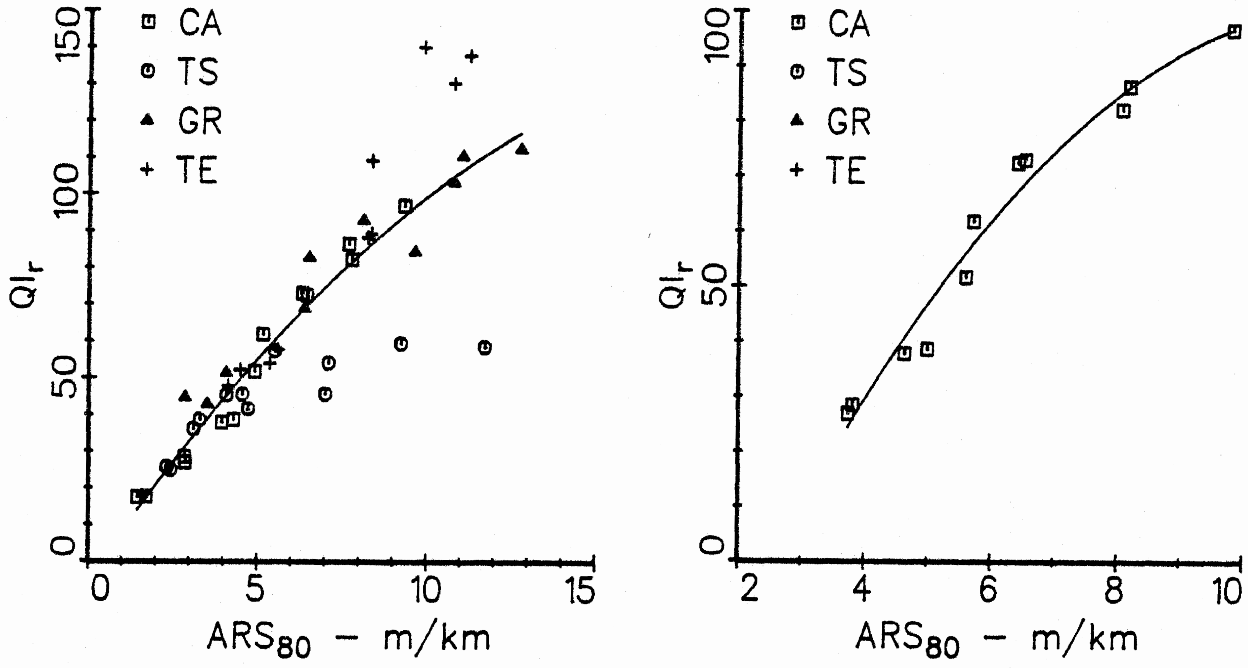
b. Caravan–NAASRA



c. BI Trailer

d. BPR Roughometer

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



a. Opala–Maysmeter #2

b. Caravan–NAASRA

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

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

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

		Opala Passenger Cars with Modified Maysmeters			Caravan Car with 2 meters		Single-Track Trailers	
Speed	Surface Type	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

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, 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.

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

		Opala Passenger Cars with Modified Maysmeters			Caravan Car with 2 meters		Single-Track Trailers	
Speed	Surface Type	MM 01	MM 02	MM 03	BI	NAASRA	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

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 ICR 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.

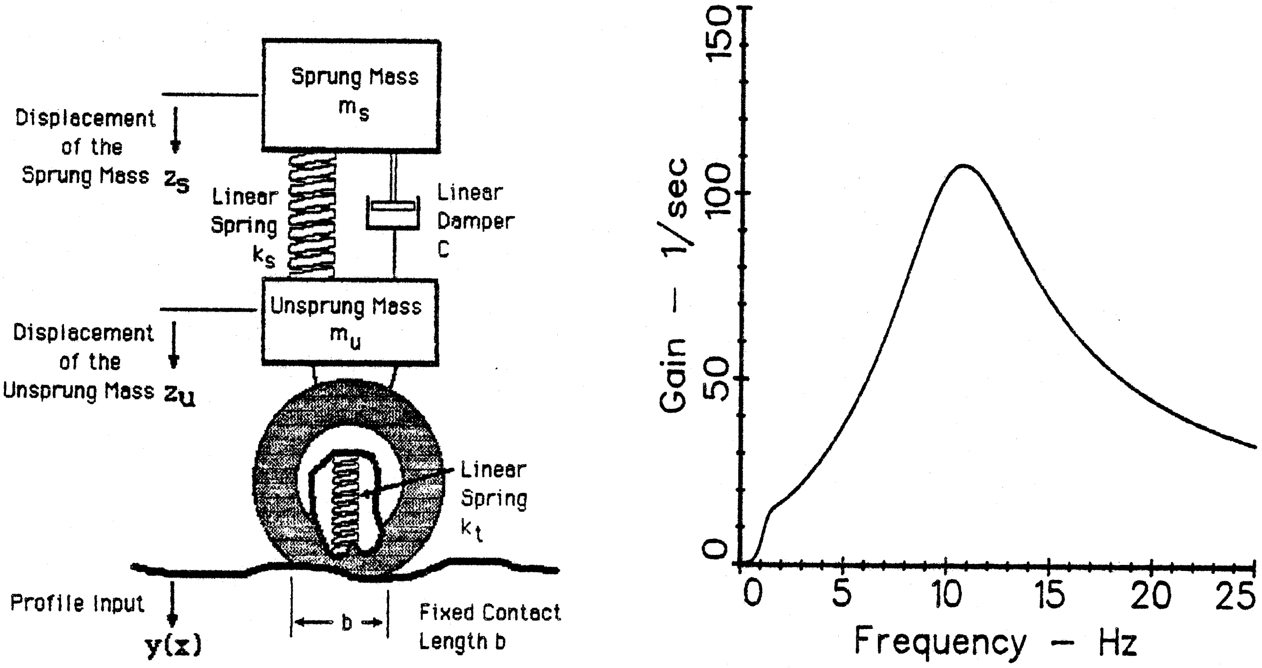
The NCHRP Report 228 recommended a roughness statistic called "reference average rectified velocity" (RARV) which is useful when comparing measurements made by RTRRMSs at more than one measurement speed. The other statistic associated with the RQCS is called "reference average rectified slope" (RARS). Since the RARS numeric obtained with a simulation speed of 50 km/h ($RARS_{50}$) 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)

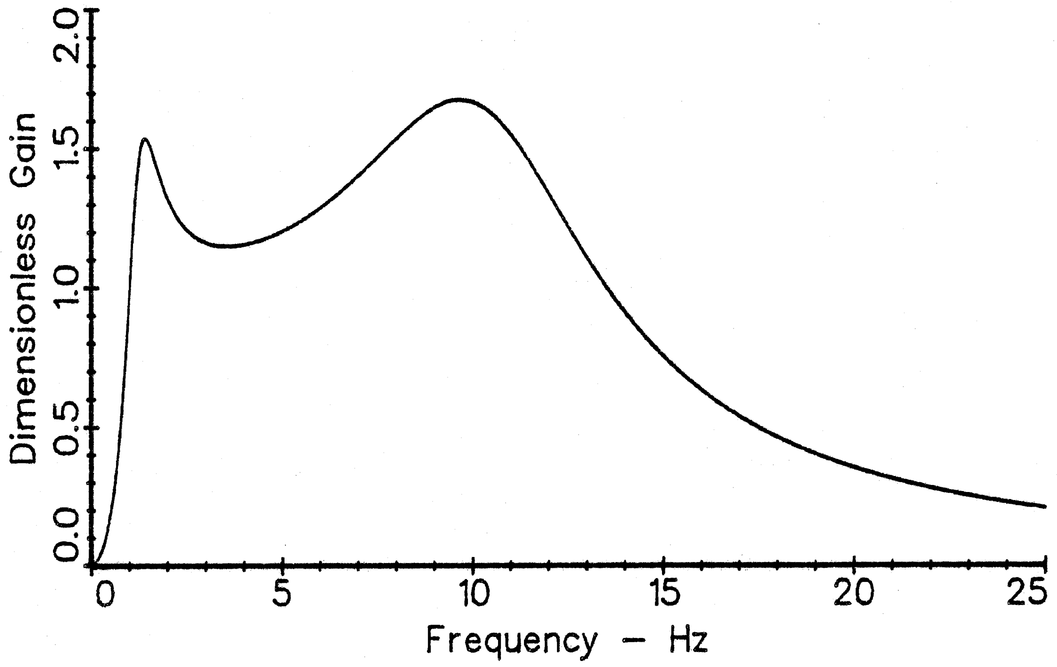
Figure F.1 illustrates the concept of the RQCS analysis in terms of the mechanical model (1a) and its frequency response (1b and 1c). The RQCS consists of three distinct mathematical procedures:

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



a. Mechanical Representation of RQCS

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 "envelopes" 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."

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:

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

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

where

$$e^{jwX} = \cos wX + j\ \sin wX \tag{F-7}$$

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:

$$y' = dy/dx = Y_o\ jw\ e^{jwx} = jw\ y \tag{F-8}$$

or

$$\dot{y} = dy/dt = Y_o\ jw\ e^{jwt} = jw\ y \tag{F-9}$$

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:

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

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 samnple 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

$$D = D_r + j\ D_i \tag{F-17}$$

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

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

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

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

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:

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

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:

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

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:

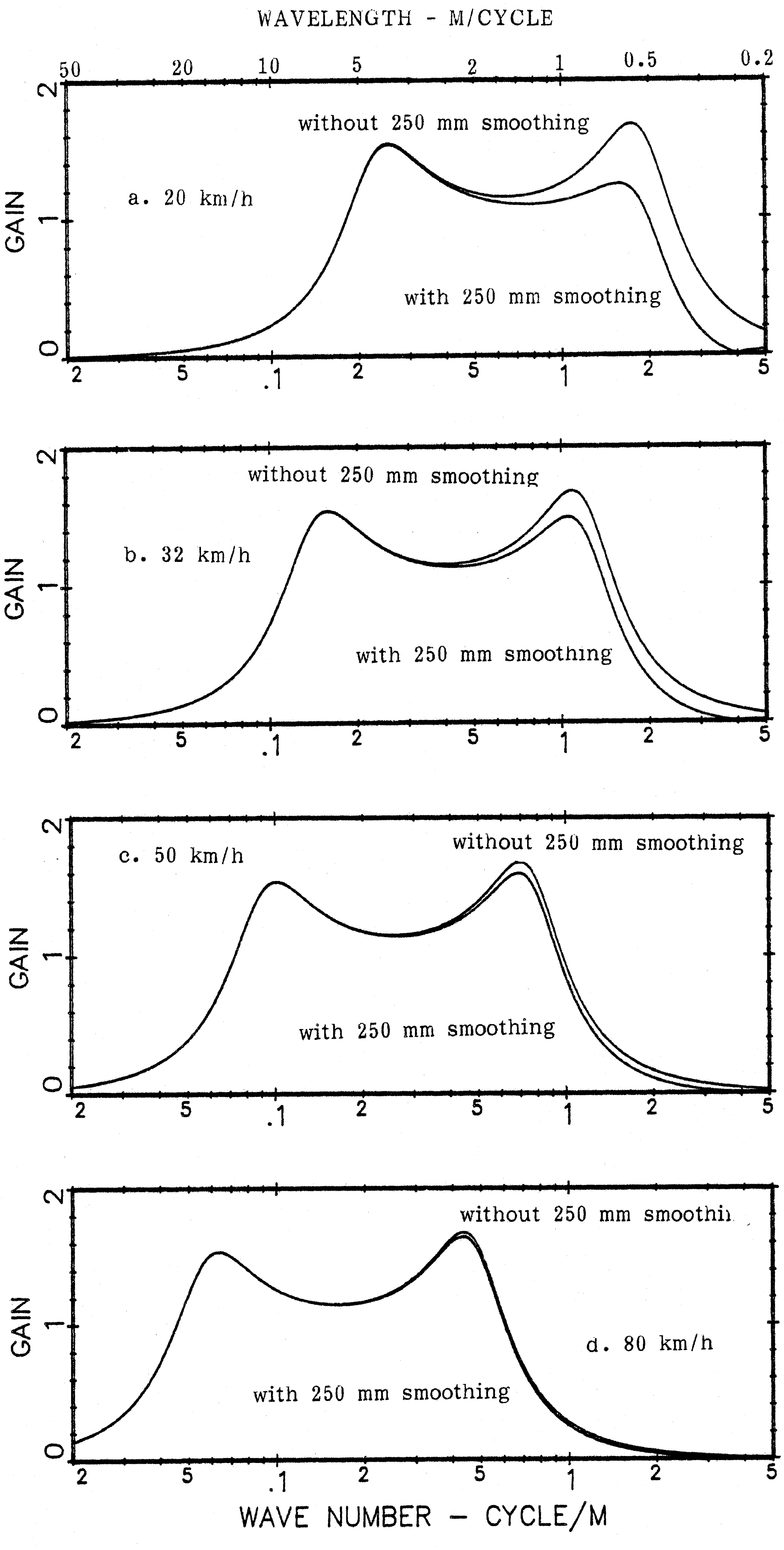


Figure F.2. Sensitivity of RQCS to Different Wavelengths

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.

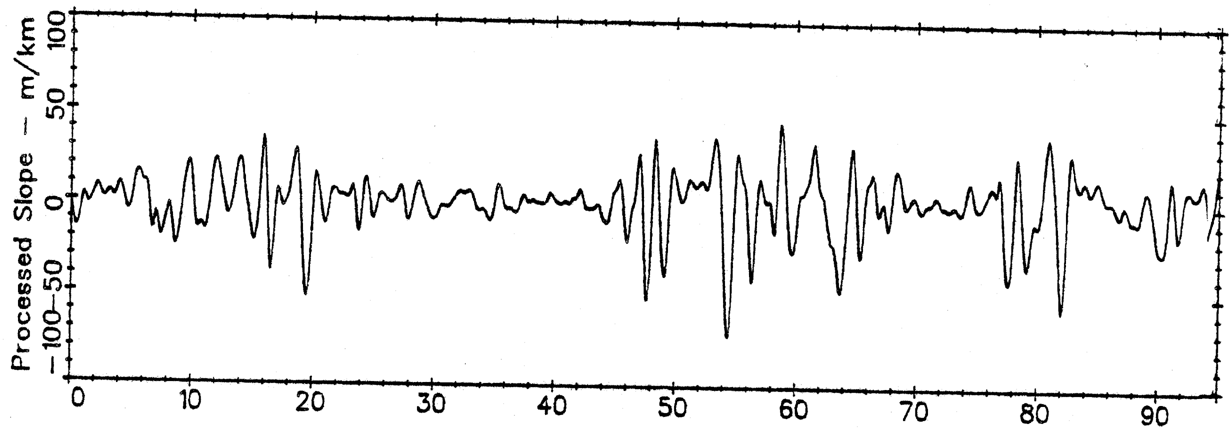
The RQCS analysis described above has three simple interpretations:

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.

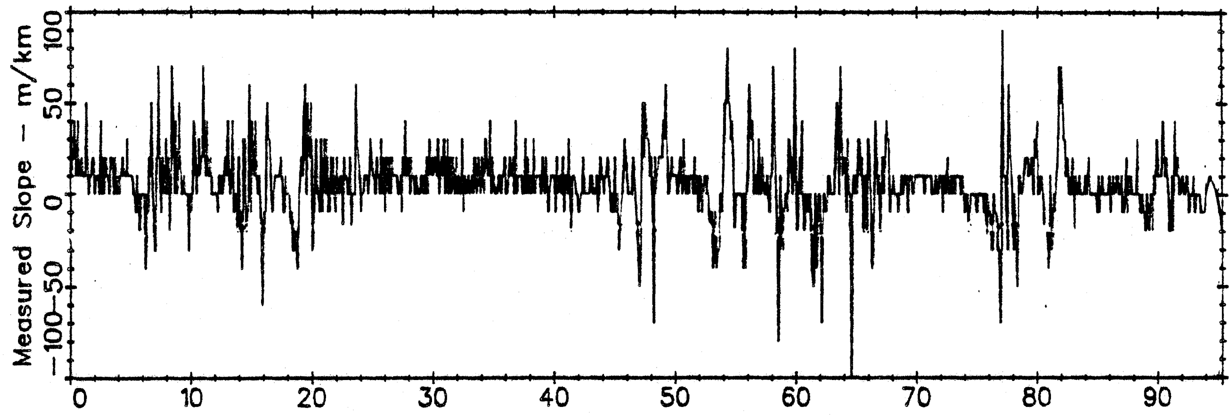
Profile Slope. Alternatively, the RQCS can be viewed as providing a statistic summarizing profile geometry. RARS is, as the name implies, the average rectified slope of the profile when wavelengths are attenuated that fall outside the range specified in Eq. 23.

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.

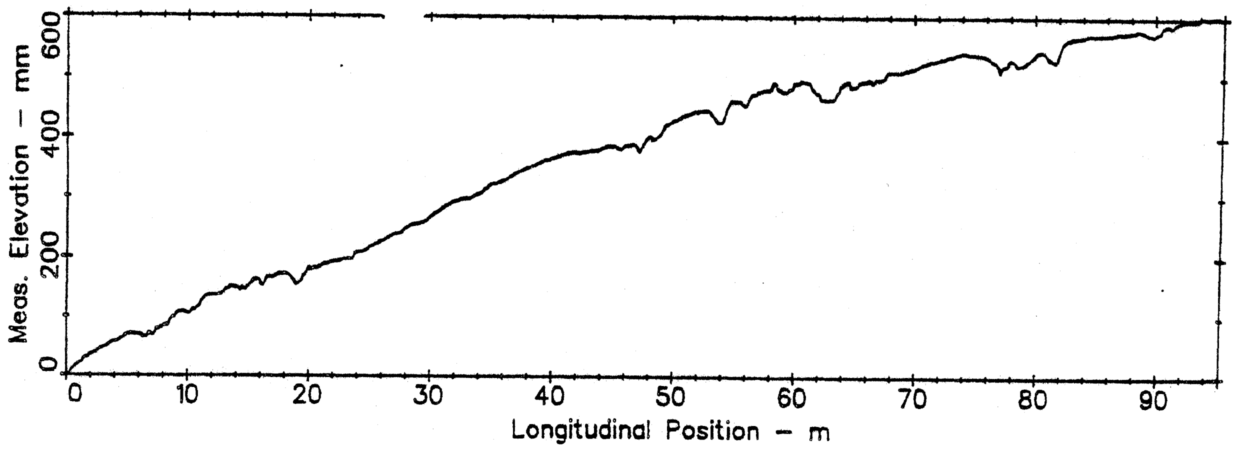
Examples of the RQCS "Filter." To illustrate the nature of the RQCS, Figures F.3 and F.4 show the profile inputs and the resulting QCS output. Figure F.3 shows three plots derived from a single profile measured with the TRRL Beam during the IRRE. Note that the roughness information is not very



c. Slope Profile as Filtered by the RQCS

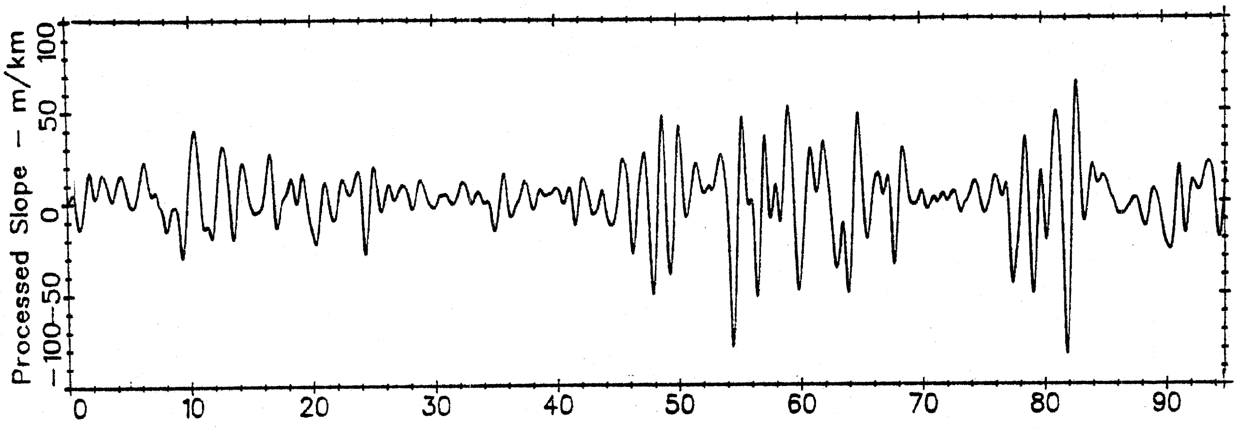


b. Approximate Slope: Elevation change per Measurement Interval

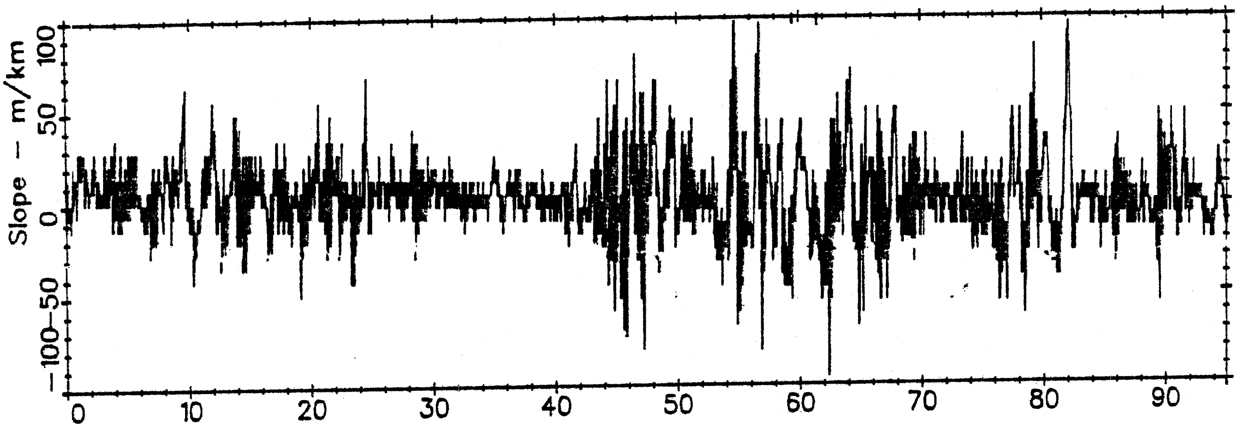


a. Original Elevation Measurement

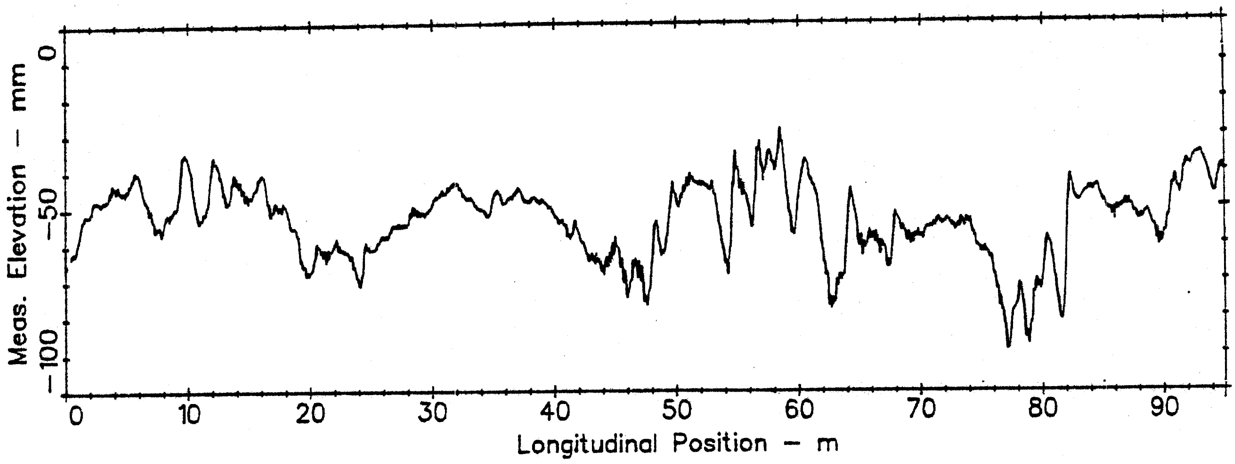
Figure F.3. Analysis of Profile Obtained With TRRL Beam. (Left Wheeltrack, Section CA06)



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. 2a and 3a) is meaningless, since the APL signal does not include wavelengths longer than 40 m. Direct comparison of the slope "profile" signals (Figs. 2b and 3b) 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 ($j,k = 1\ldots4$) 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

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

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

$dt = 7.2 \times 10^{-3}$ 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.)

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

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

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

$dt = 4.5 \times 10^{-3}$ 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")

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

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

where

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

and

$\underline{\mathbf{ST}}$ = 4x4 State Transition Matrix (with coefficients $s_{11} \cdots s_{44}$)
$\mathbf{PR}$ = 1x4 Partial Response Matrix (with coefficients $p_1 \cdots p_4$)
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:

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

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

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 $\mathbf{B}$ matrices:

$$\underline{\mathbf{ST}} = e^{\underline{\mathbf{A}}\ dt} \tag{F-32}$$

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

where

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

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:

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

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

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

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 $e^{\underline{A}\,dt}$ 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

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

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:

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

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:

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

where

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

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

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

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 $RARS_{50}$, using the BASIC computer language. The profile values are stored in 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); N is the number of profile points; DX is the measurement interval (set at 0.25 m in the demonstration), V is the simulation speed (50 km/h), N1 is the number of points needed to proceed for 0.5 seconds to initialize the vertical velocity variables; 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 includes a "one size fits all" Eq. 38 (line #420 in the program listing) to compute the profile slope input to the RQCS filter. The program was written for ease of understanding, and is not particularly efficient. Note that the "one size fits all" smoothing equation is overly complex when DX = 0.25 m, since K=1, A=1, and B=0.

Figure F.5. Demonstration Computer Program for the RQCS

```
100  REM      This program is a demonstration of the RQCS. Simulation
110  REM      speed is 50 km/h and the measurement interval is 0.25 m.
120  REM      The profile elevations should have units: mm.
130  REM
140  DIM Y(1281),Z(4),Z1(4),ST(4,4),PR(4)
150  READ V,DX,BL
160  FOR I = 1 TO 4
170  FOR J = 1 TO 4
180  READ ST(I,J)
190  NEXT J
200  READ PR(I)
210  NEXT I
220  INPUT "NUMBER OF PROFILE ELEVATION POINTS = ";N
230  FOR I = 1 TO N
240  PRINT "POINT #";I;
250  INPUT " ELEVATION = ";Y(I)
260  NEXT I
270 K =  INT (BL / DX)
280 B = (BL - K * DX) / DX
290 A = 1 - B
300 N1 =  INT (.5 * V / 3.6 / DX) + 1
310  REM
320  REM     Initialize RQCS with average slope over the first 0.5 sec.
330  REM
340 Z1(1) = (Y(N1 + 1) - Y(1)) / N1 / DX
350 Z1(2) = 0
360 Z1(3) = Z1(1)
370 Z1(4) = 0
380 RS = 0
390  REM     Calculate Roughness RS
400  REM
410  FOR I = 1 TO  INT (N - K - B)
420 YP = (A * Y(I + K) + B * Y(I + K + 1) - Y(I)) / BL
430  FOR J = 1 TO 4
440 Z(J) = PR(J) * YP
450  FOR JJ = 1 TO 4
460 Z(J) = Z(J) + ST(J,JJ) * Z1(JJ)
470  NEXT JJ
480  NEXT J
490  FOR J = 1 TO 4
500 Z1(J) = Z(J)
510  NEXT J
520 RS = RS +  ABS (Z(1) - Z(3))
530  NEXT I
540  PRINT "RARS = ";RS /  INT (N - K - B)
550  END
560  DATA   50,.25,.25
570  REM
580  DATA .992040026, .0171948155, -.0124196184, 7.08544757E-04, .0203795897
590  DATA -.789425935, .917212924, -2.29510558, .0624074845, 3.0845315
600  DATA .0465278304, 4.72363171E-03, .453113538, 9.9465964E-03, .500358633
610  DATA 3.89845779, .416049897, -47.1993075, .0835914715, 43.3008497
```

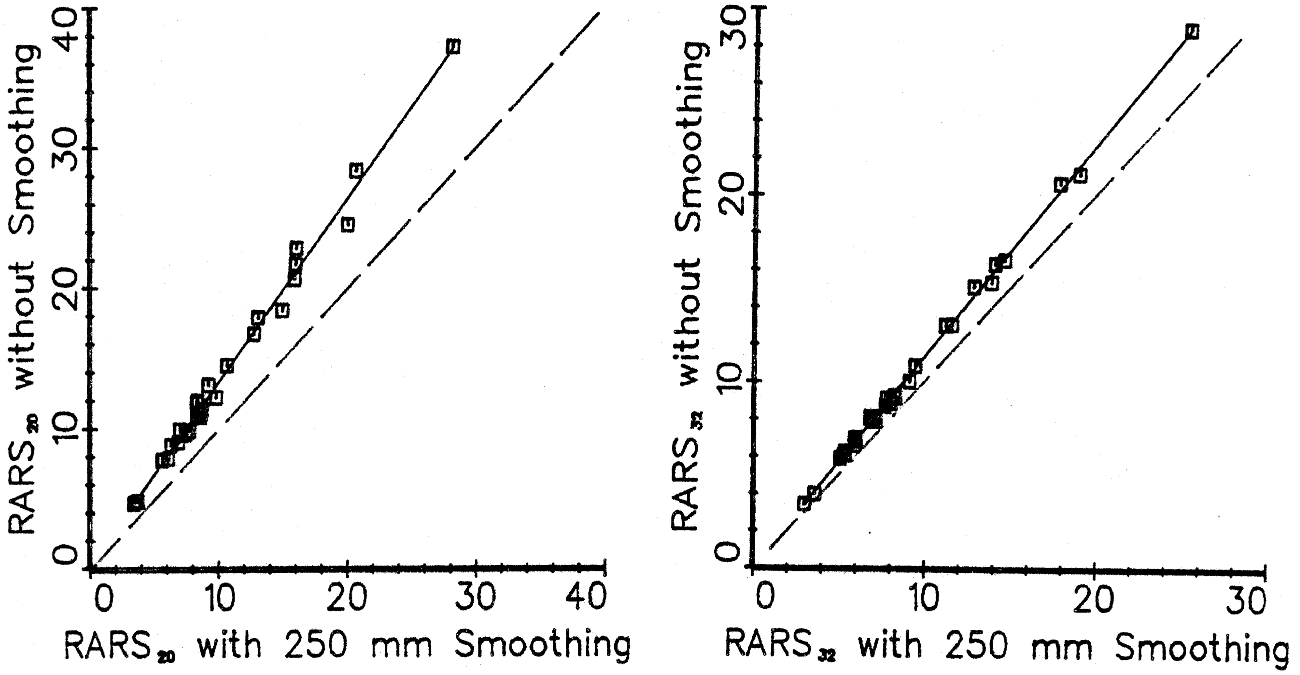
MEASUREMENT OF RQCS NUMERICS IN THE IRRE

The profile data obtained in the IRRE provided a number of new quantitative findings concerning the accuracy of RQCS numerics obtained using different methods.

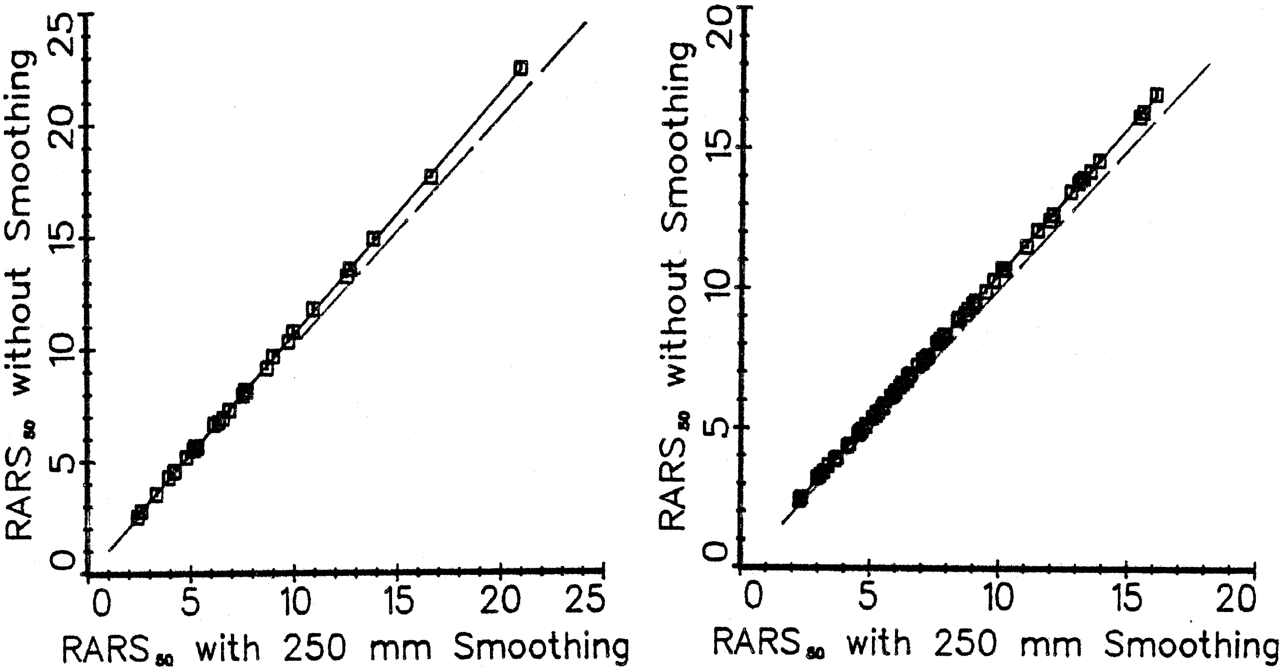
Alternatives in the Quarter-Car Model

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:



a. 20 km/h, data from TRRL Beam b. 32 km/h, data from TRRL Beam



c. 50 km/h, data from TRRL Beam d. 50 km/h, APL 72 data

Figure F.6. Effect of Smoothing (Enveloping) on the RARS Numeric

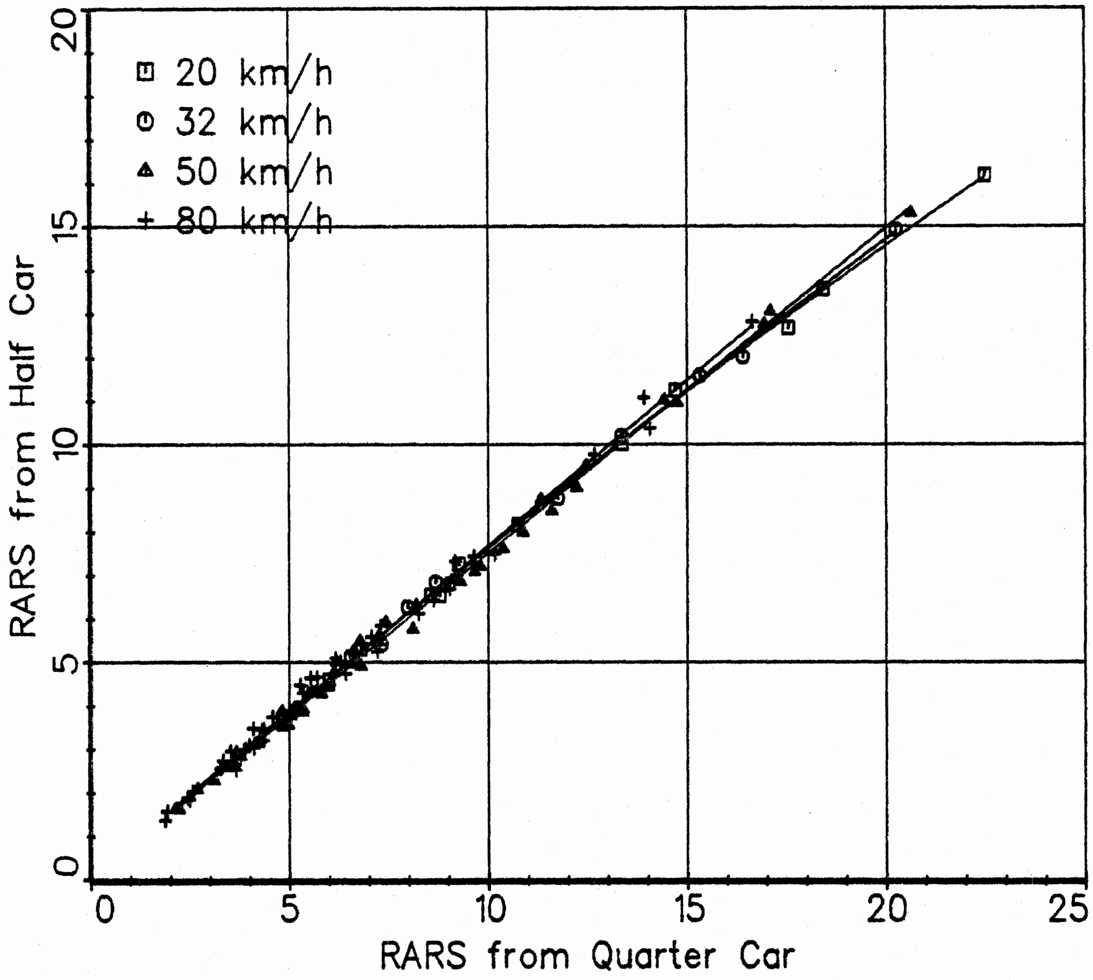


Figure F.7. Comparison of the RARS Obtained from Quarter-Car and Half-Car Simulations

$$ARS_h = 0.760\ RARS_A \qquad \text{(F-44)}$$

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

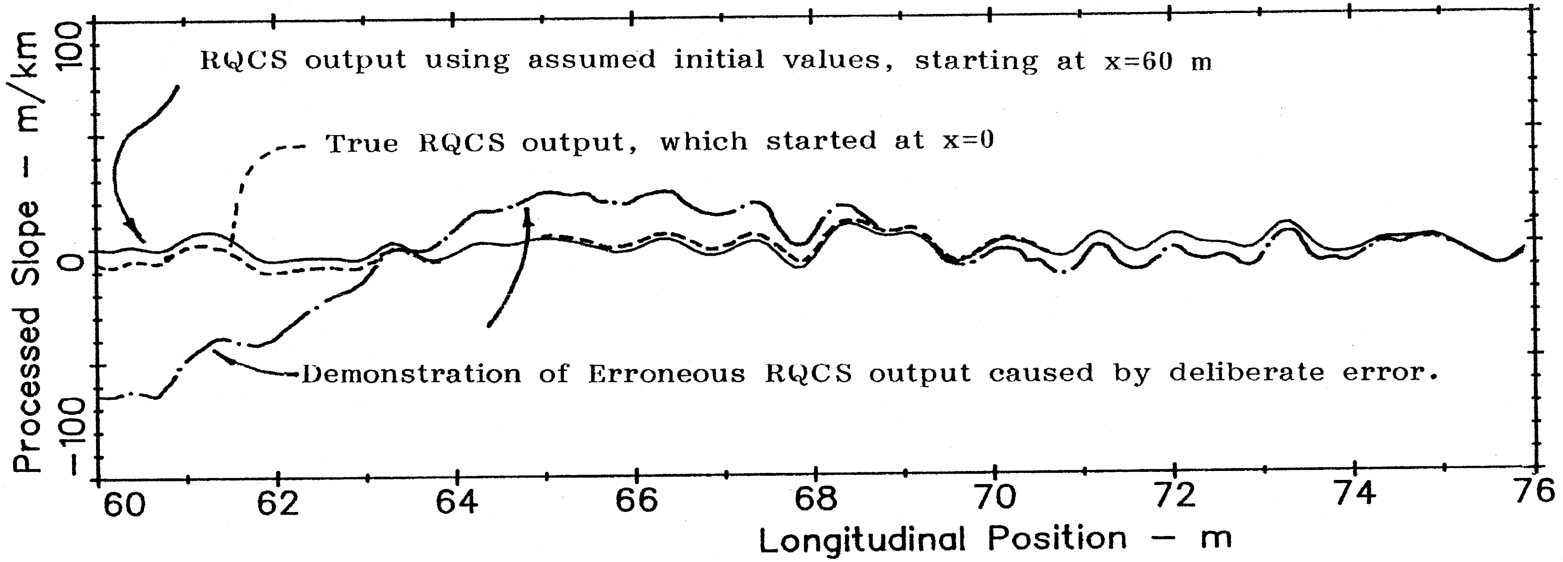
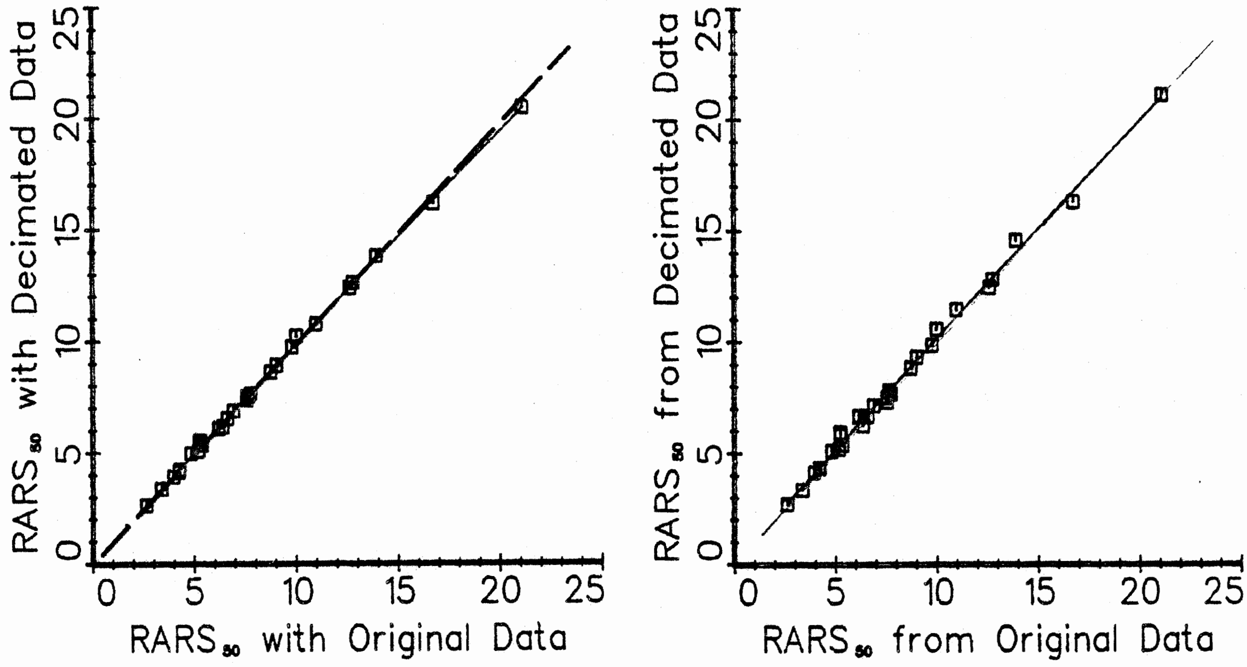
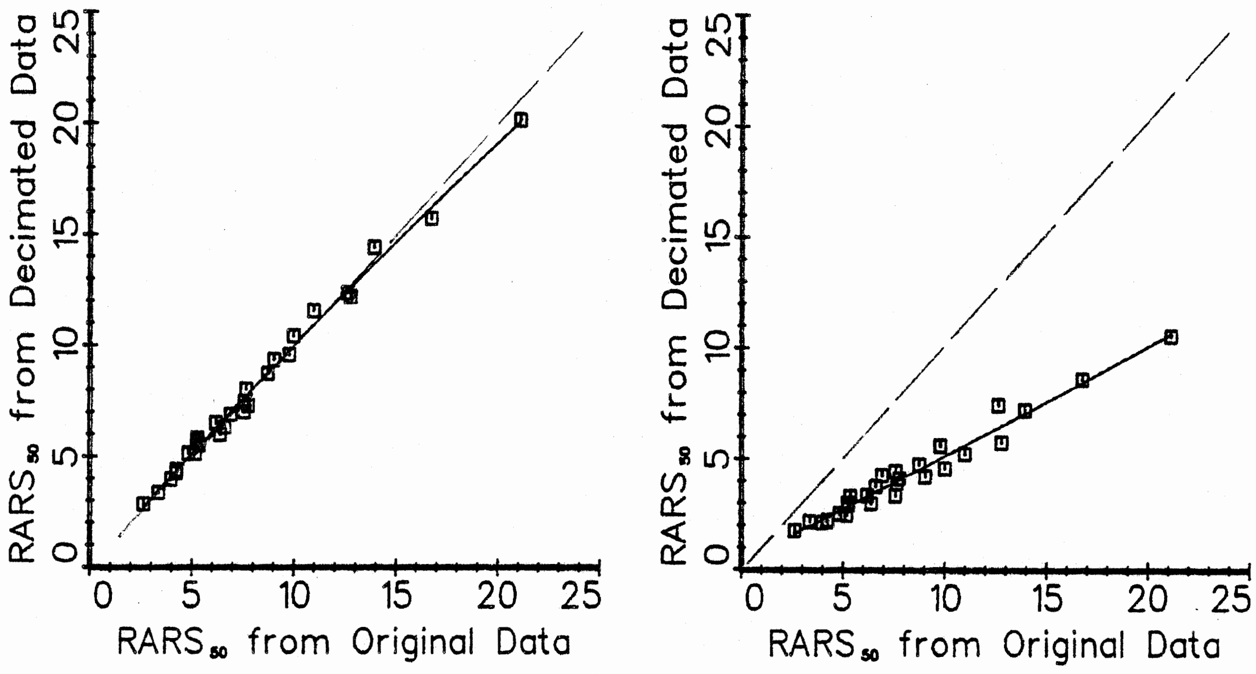


Figure F.8. Initialization of RQCS



a. 200 mm Interval

b. 300 mm Interval



c. 500 mm Interval

d. 1.0 m Interval

Figure F.9. Effect of Measurement Interval on $RARS_{50}$.

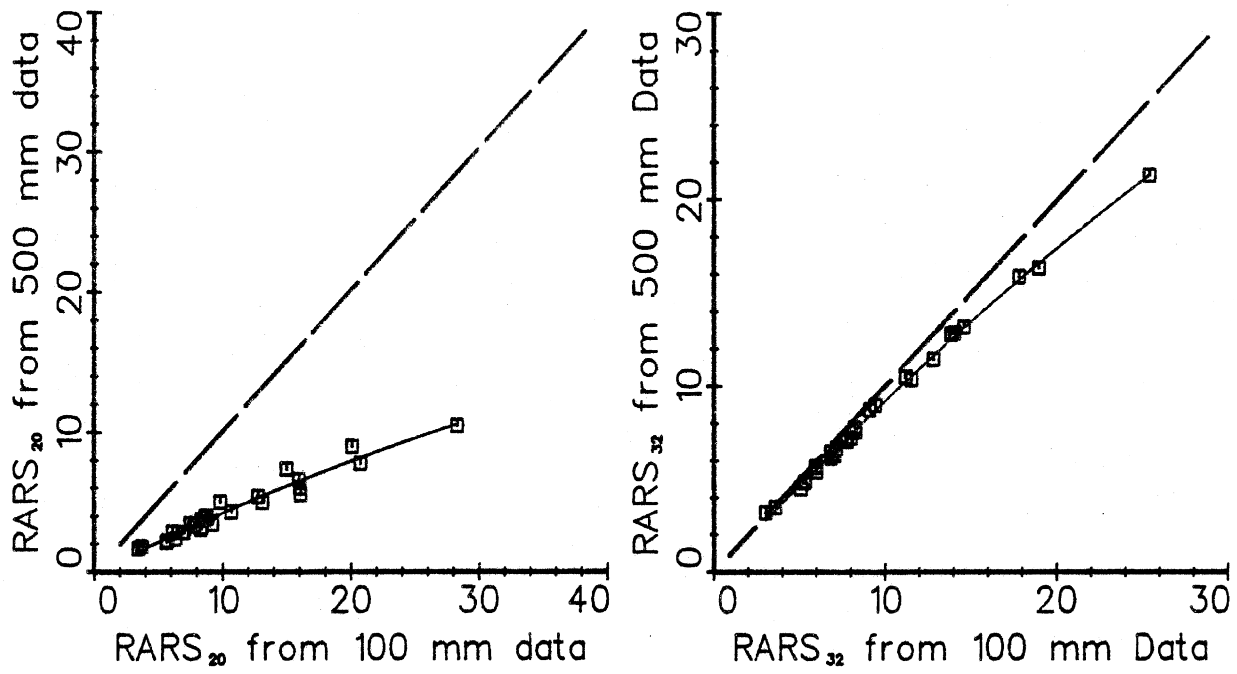
interval increases up to 500 mm, there is negligible bias introduced, but that the random error (scatter) increases slightly. (A possible exception might be the two roughest measures shown in Fig. 9c, in which the $RARS_{50}$ values from the decimated profile data are slightly lower; however, it is not 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.

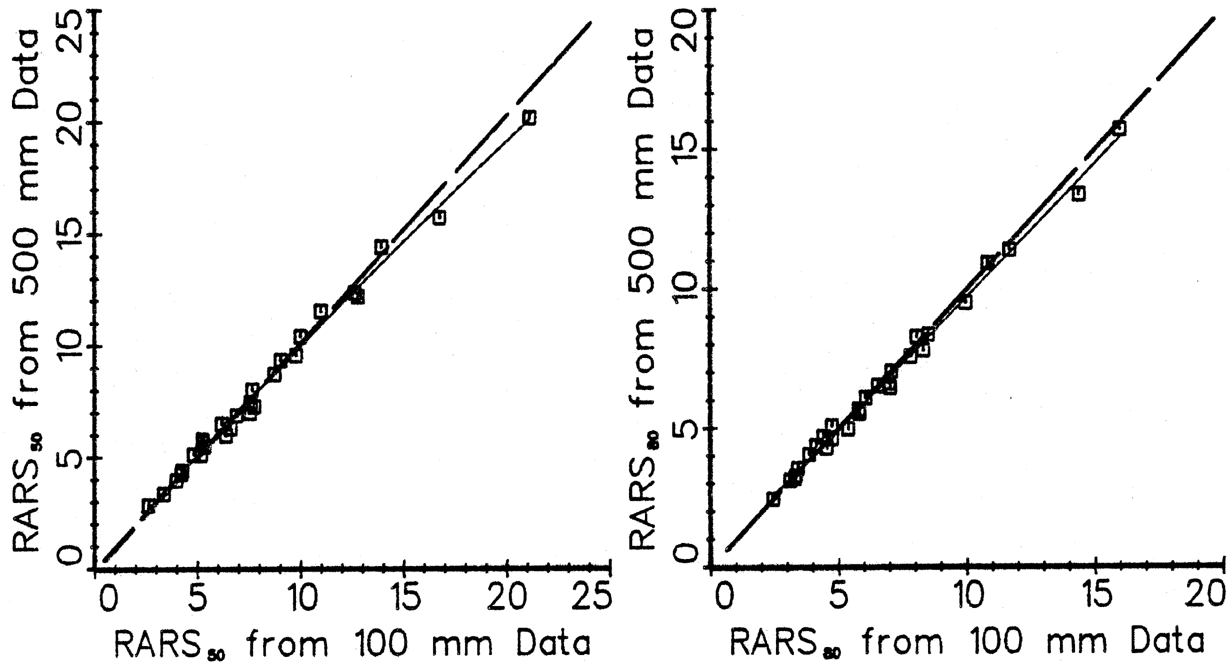
Precision in the Elevation Measurement. It has been known that the precision needed in profile measurement for analysis through QCS is a function of the roughness, with better precision needed on smoother roads [38]. A statement of necessary precision therefore depends on the range of roughness being 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



a. 20 km/h

b. 32 km/h



c. 50 km/h

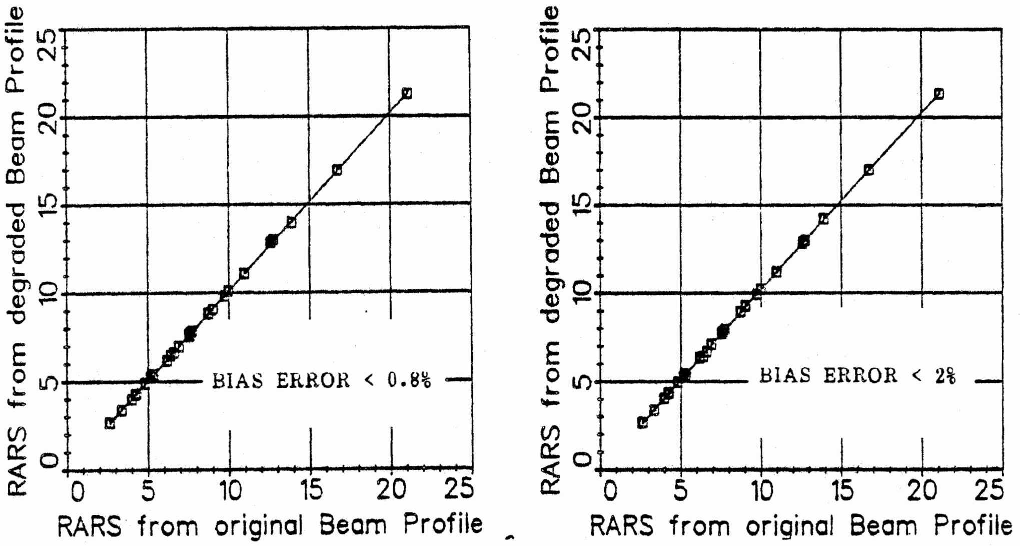
d. 80 km/h

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.

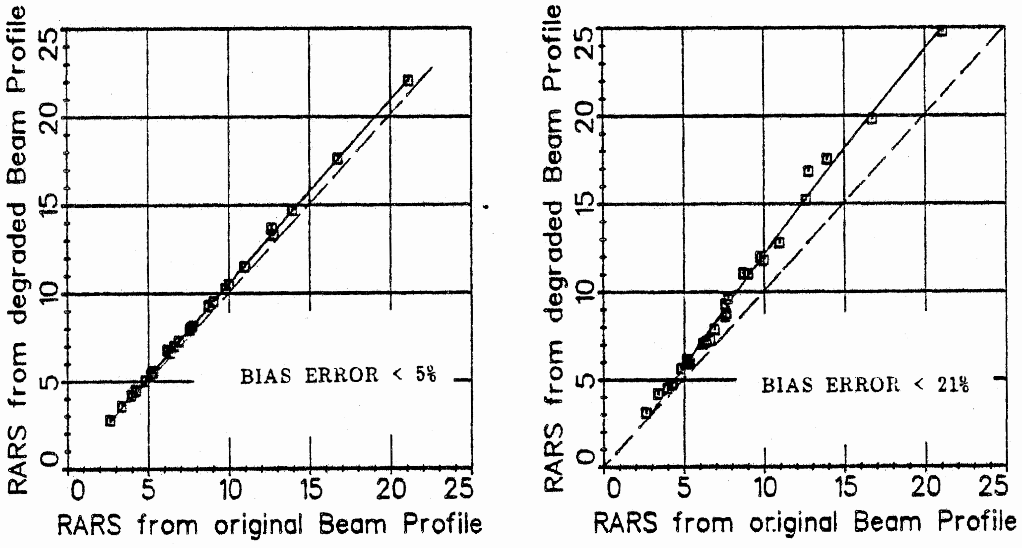
Summary of RQCS Data

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.

	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	4.5	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.

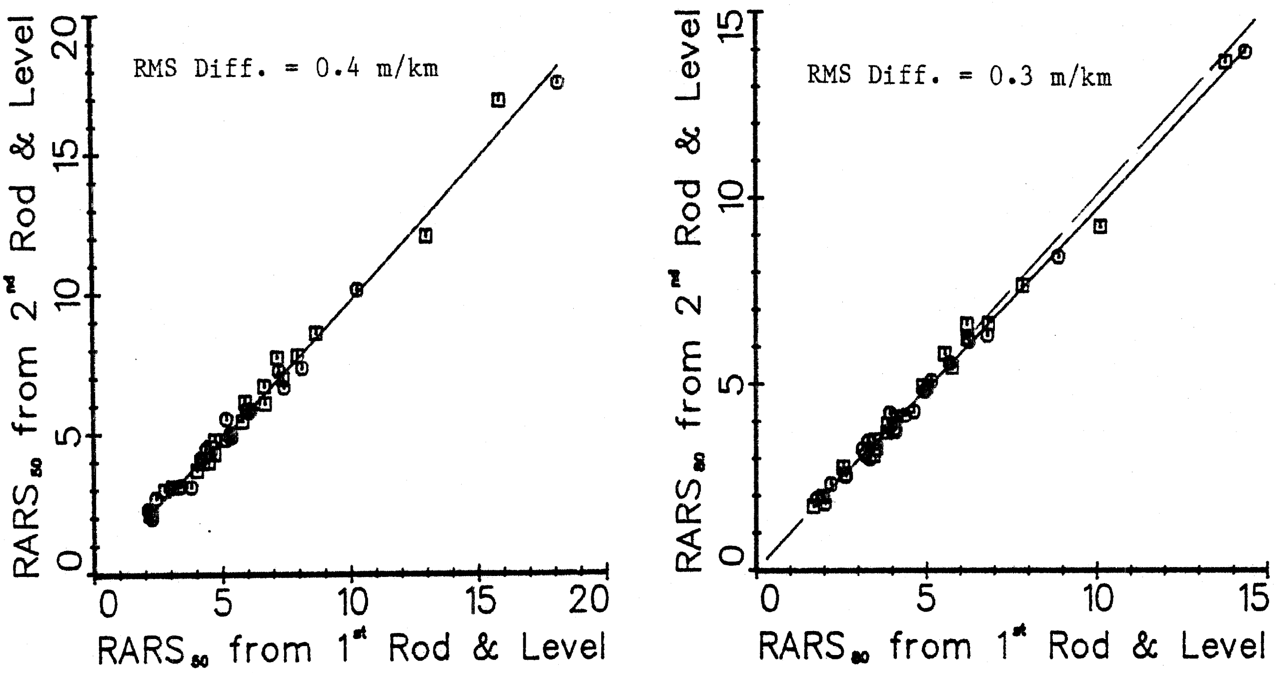
Accuracy of RARS Computed from Statically Measured Profiles

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.

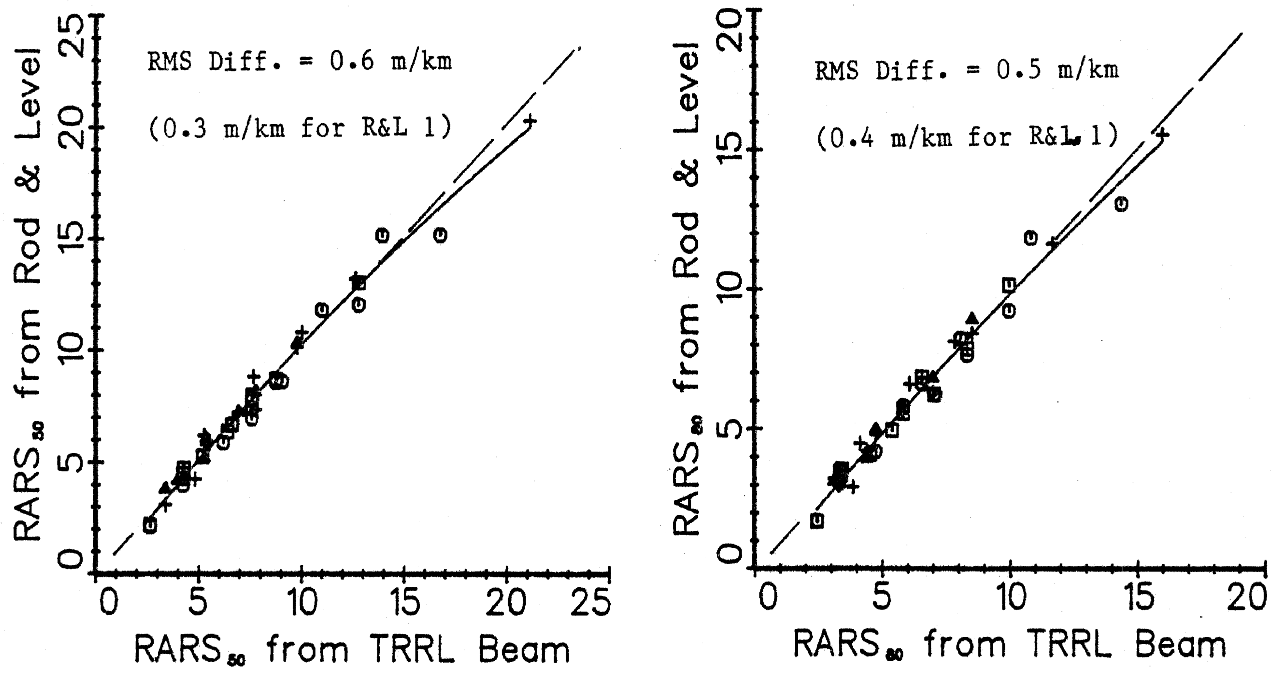
Validation of the TRRL Beam. Figure F.12 also compares the RARS numerics obtained with road and level and the TRRL beam. Approximately the same repeatability is obtained as with repeated measures with rod and level, indicating that the TRRL Beam is a valid means for measuring longitudinal profile for 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

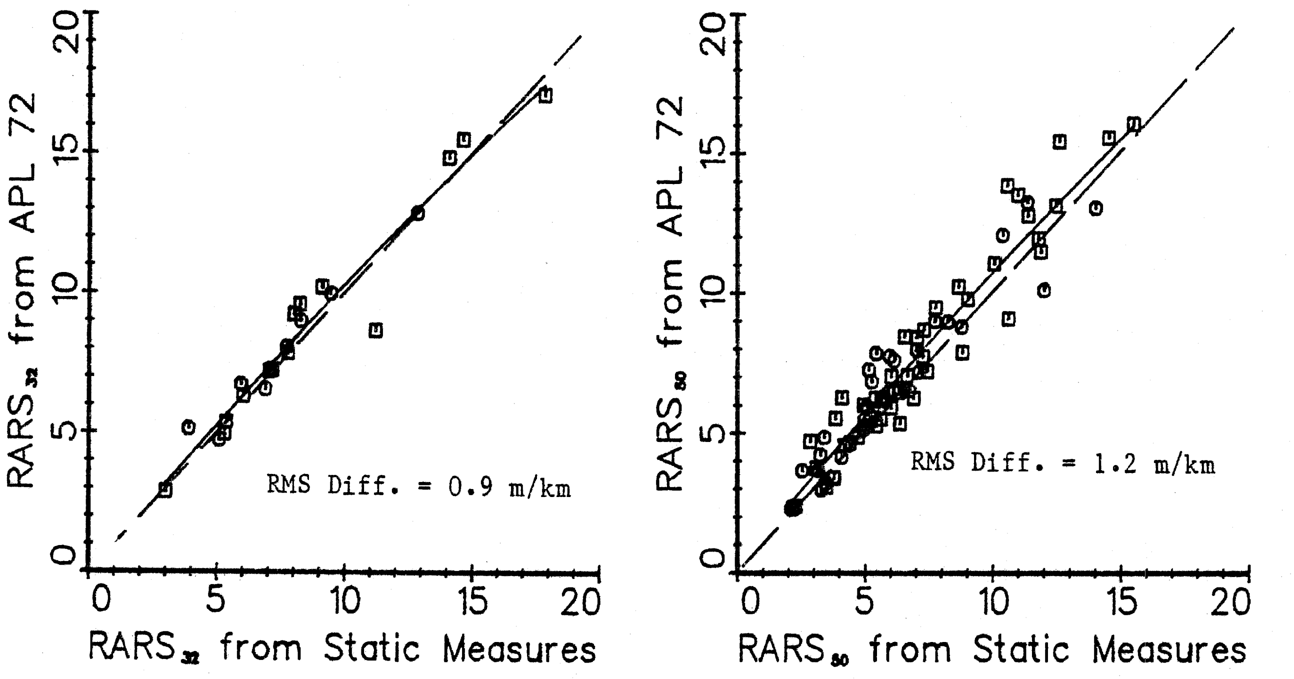
Accuracy of RARS Computed from Dynamically Measured Profiles

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.

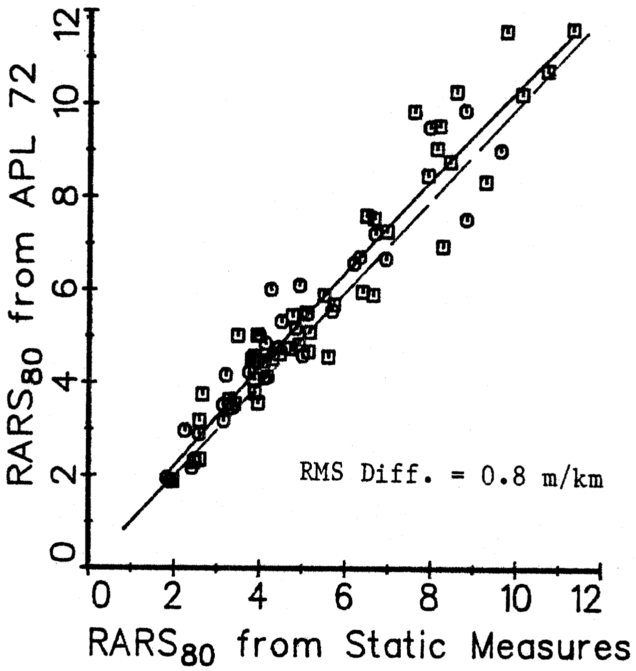
It should be noted that during the IRRE, the LCPC research team was primarily interested in obtaining the APL numerics used in France (see Appendix G), and had a number of problems to overcome, such as the incompatibility between the standard APL 72 test length of 200 m and the 320 m length of the IRRE 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



a. APL 72 for Sim. Speed of 32

b. APL 72 for Sim. Speed of 50



c. APL 72 for Sim. Speed of 80

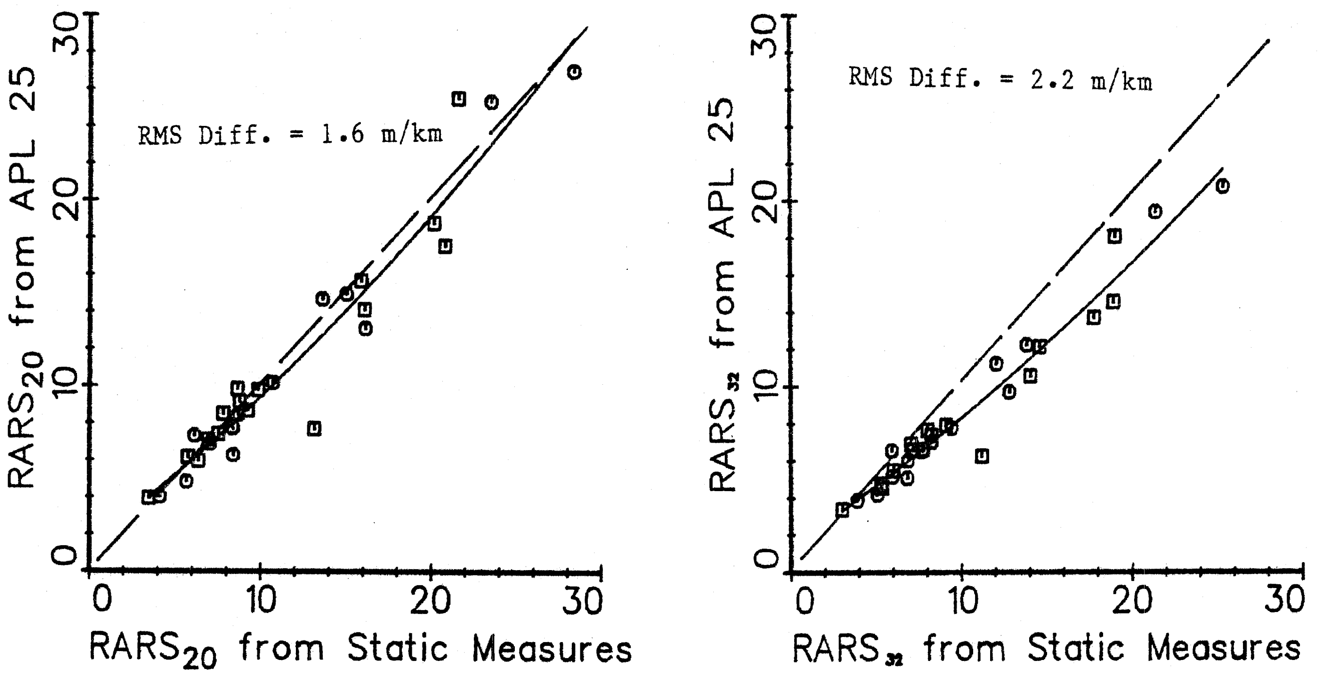
Figure F.13. Accuracy of RARS as measured with APL 72.

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.

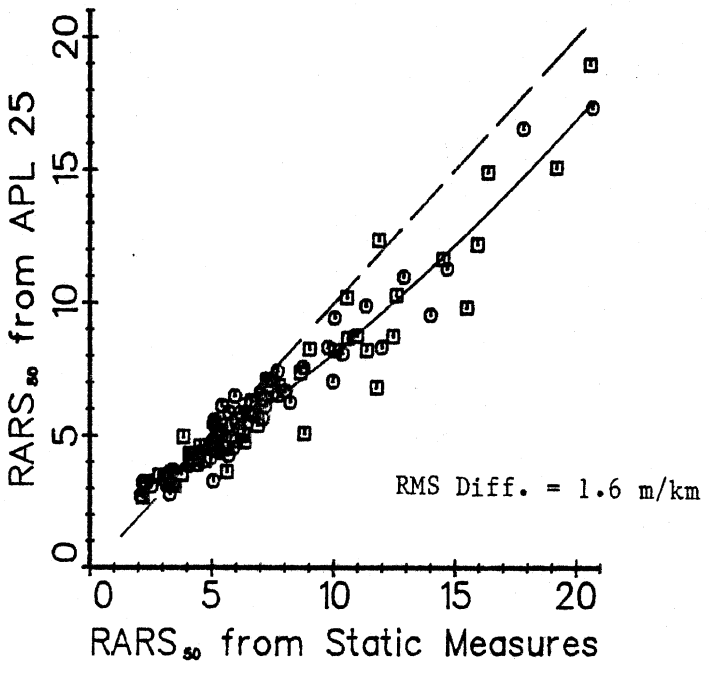
APL 25. Figure F.14 compares the RARS numerics computed from the profile signals obtained from the APL Trailer in its APL 25 configuration with RARS numerics computed from the statically measured profiles. For the simulation speeds of 32 and 50 km/h, the RARS numerics obtained with the APL Trailer are 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 CARS for Calibrated ARS.



a. APL 25 for Sim. Speed of 20 b. APL 25 for Sim. Speed of 32



c. APL 25 for Sim. Speed of 50

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.

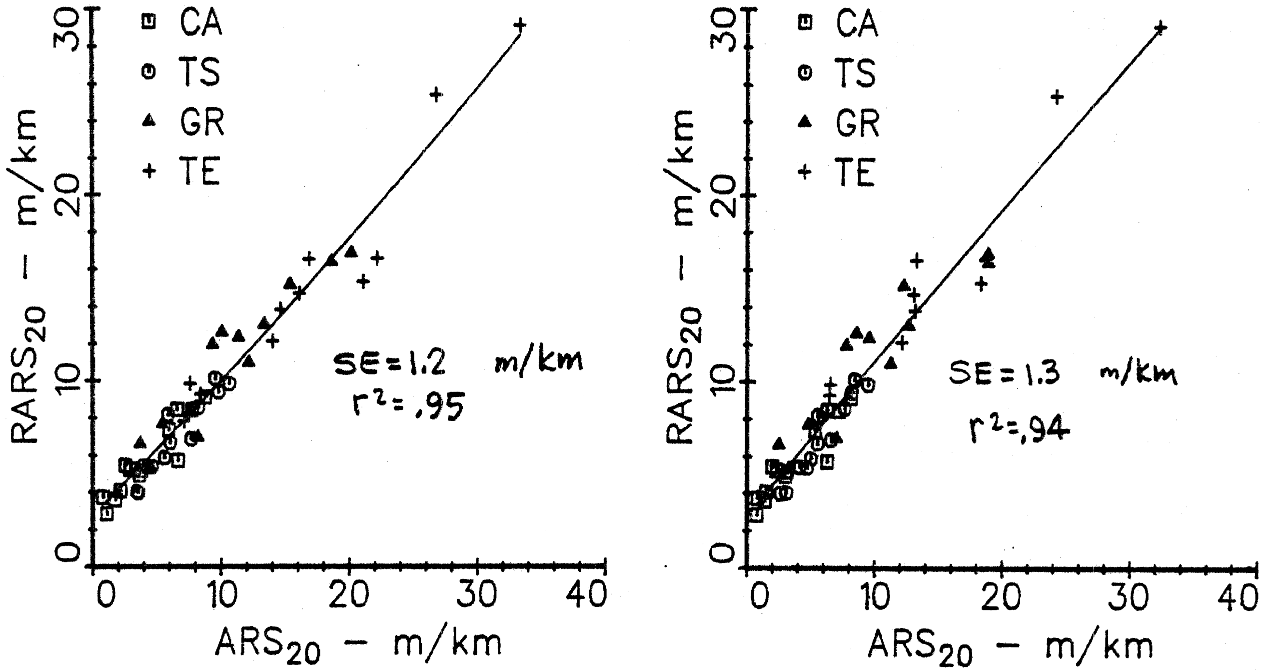
In each comparison, the simulated speed of the RQCS matches the RTRRMS speed. For the passenger car-based systems, the "Ave." RARS values from Tables F.3 - F.6 were used. Comparisons with the two single-track RTRRMSs (BI Trailer and BPR Roughometer) are on the basis of single wheeltracks. Thus, the plots 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:

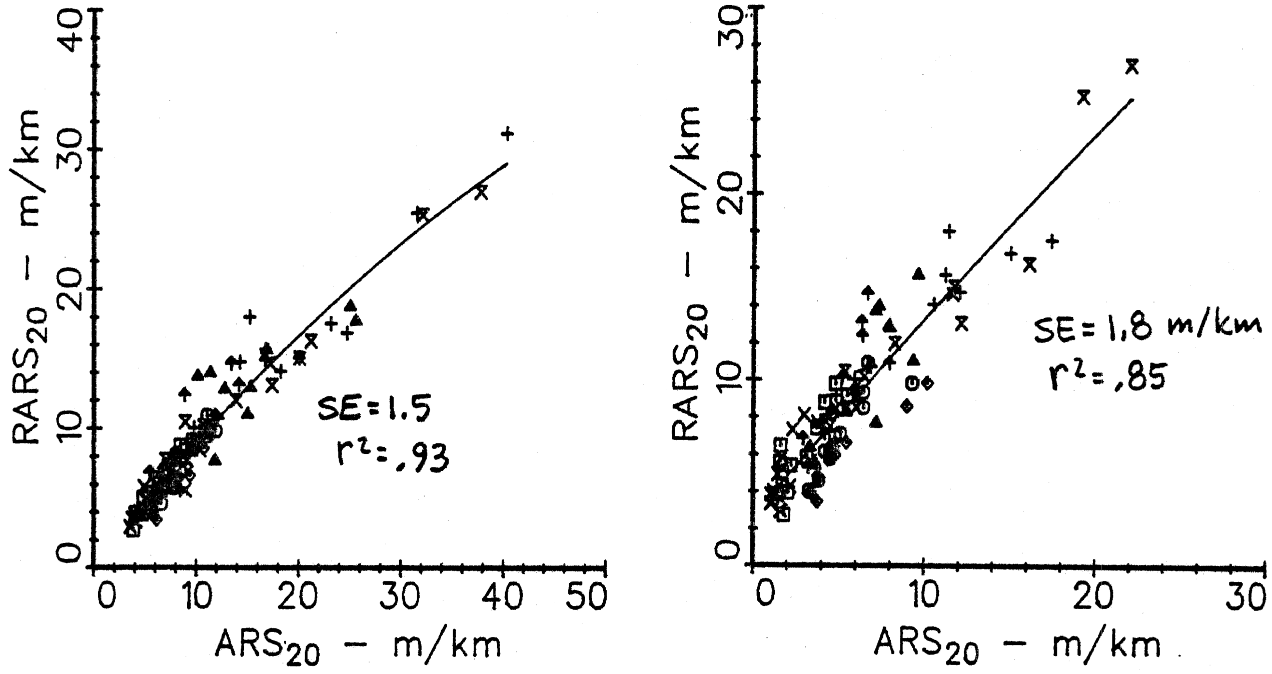
Overall correlation. By and large, the RARS numeric is highly correlated with the ARS numerics obtained from all types of RTRRMSs that participated in the IRRE. Most of the data points lie very close to the regression curve in each figure, and the measures on all four types of surface are uniformly distributed 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



a. Opala–Maysmeter #2

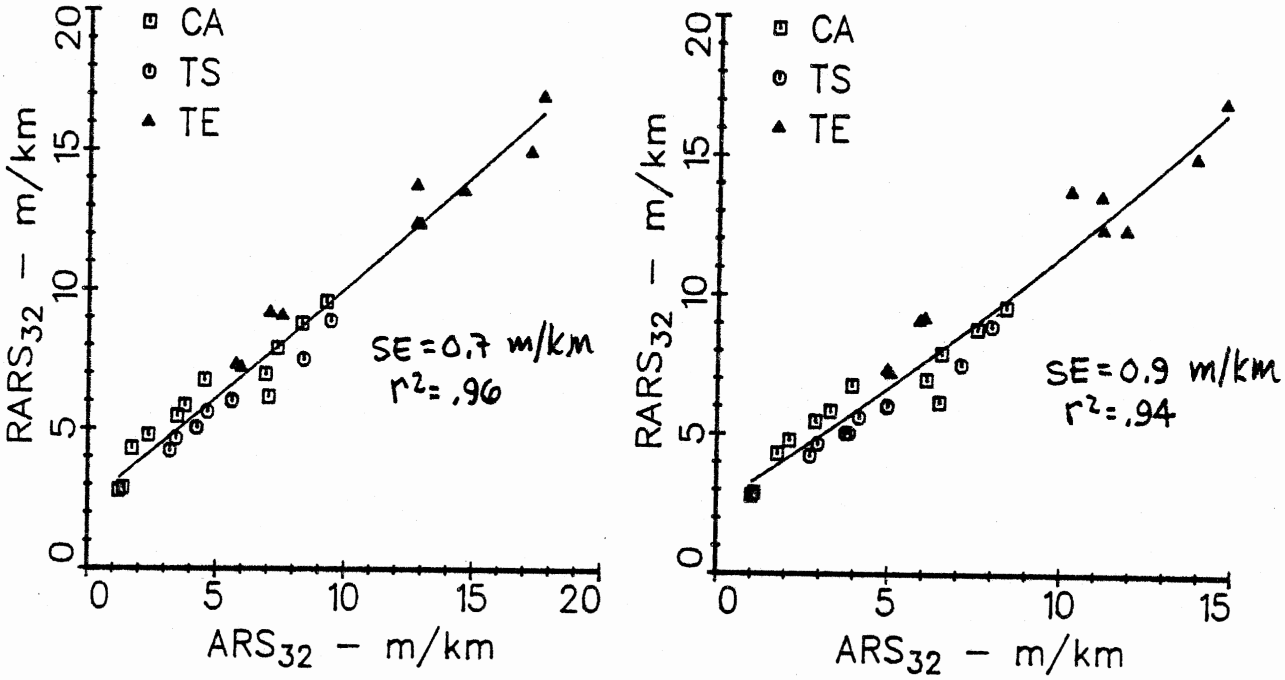
b. Caravan–NAASRA



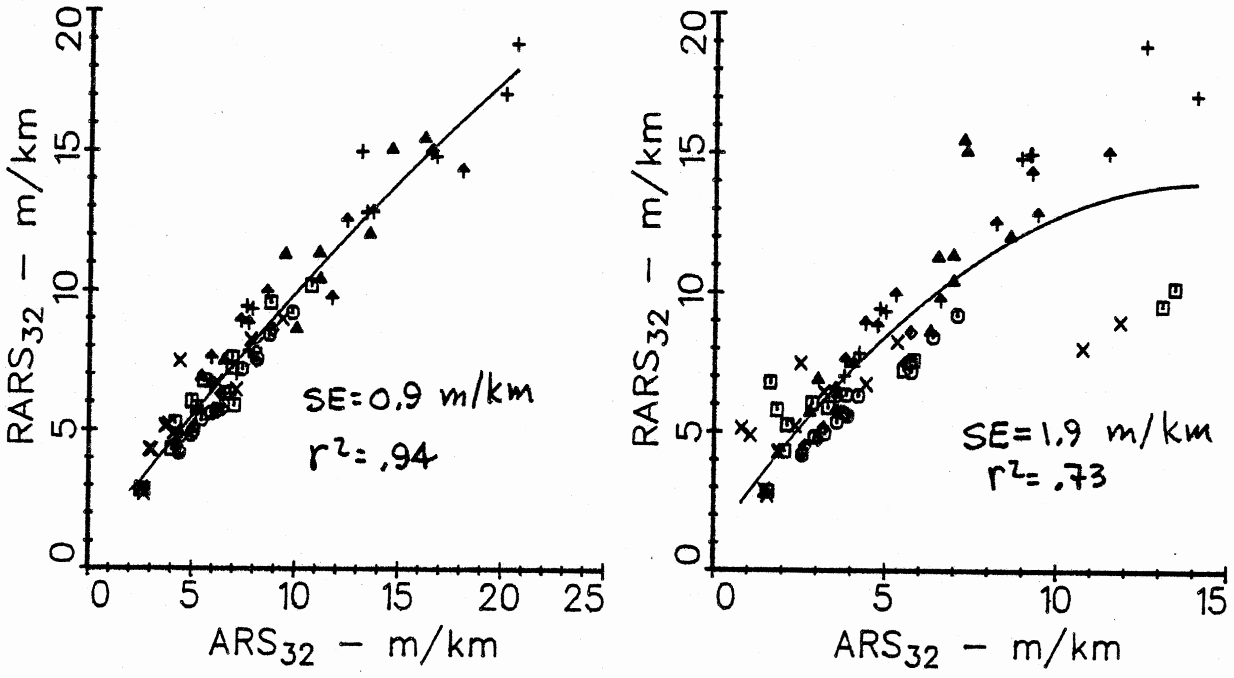
c. BI Trailer

d. BPR Roughometer

Figure F.15. Example calibration plots to estimate $RARS_{20}$ from ARS measures. The $RARS_{20}$ numerics were measured with the APL 25.

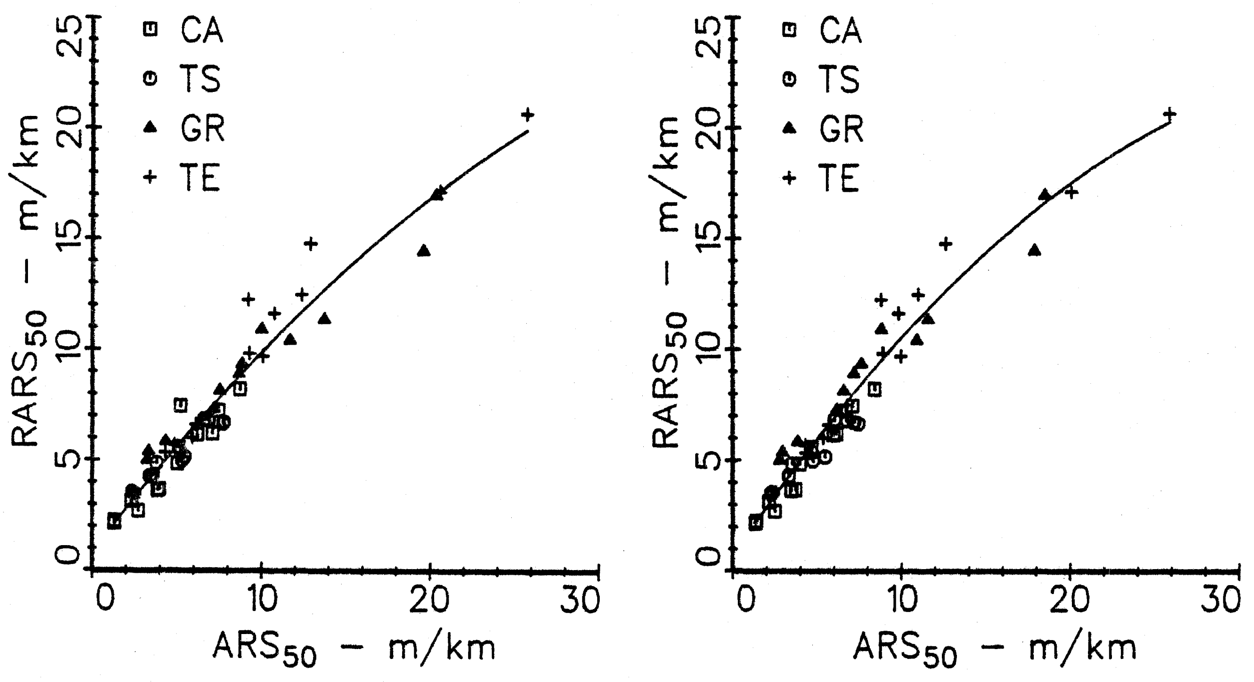


a. Opala–Maysmeter #2 b. Caravan–NAASRA



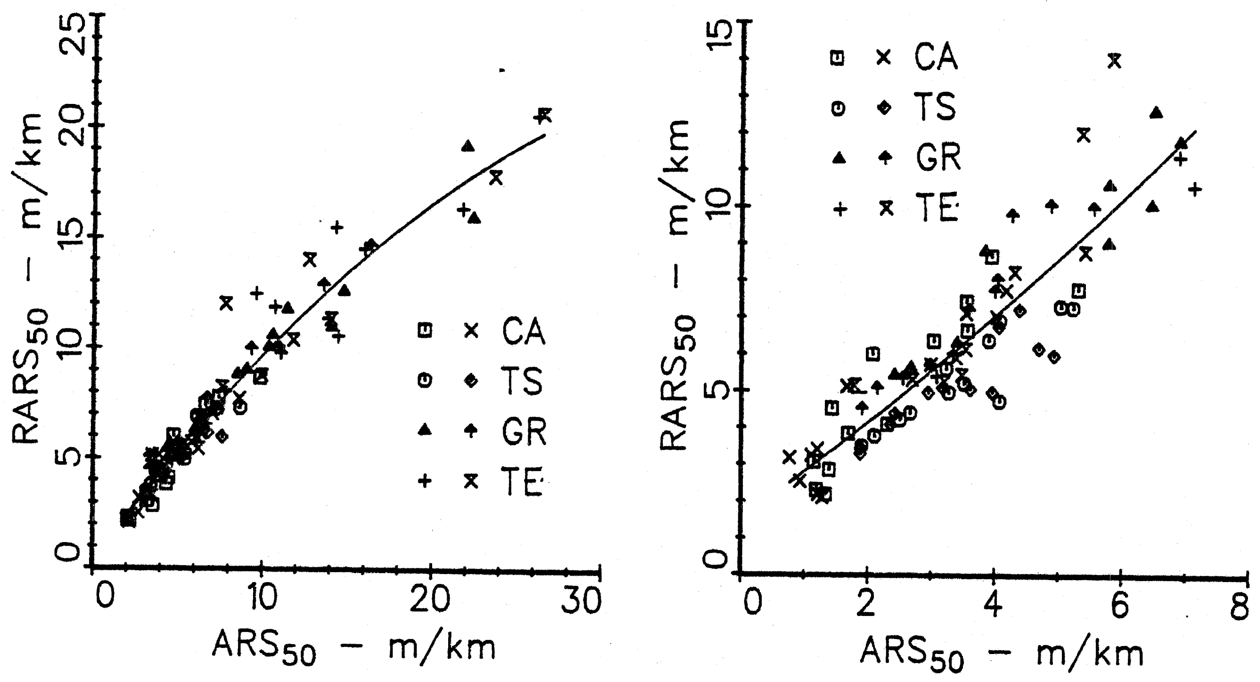
c. BI Trailer d. BPR Roughometer

Figure F.16. Example calibration plots to estimate $RARS_{32}$ from ARS measures. The $RARS_{32}$ numerics were measured with the APL 72.



a. Opala—Maysmeter #2

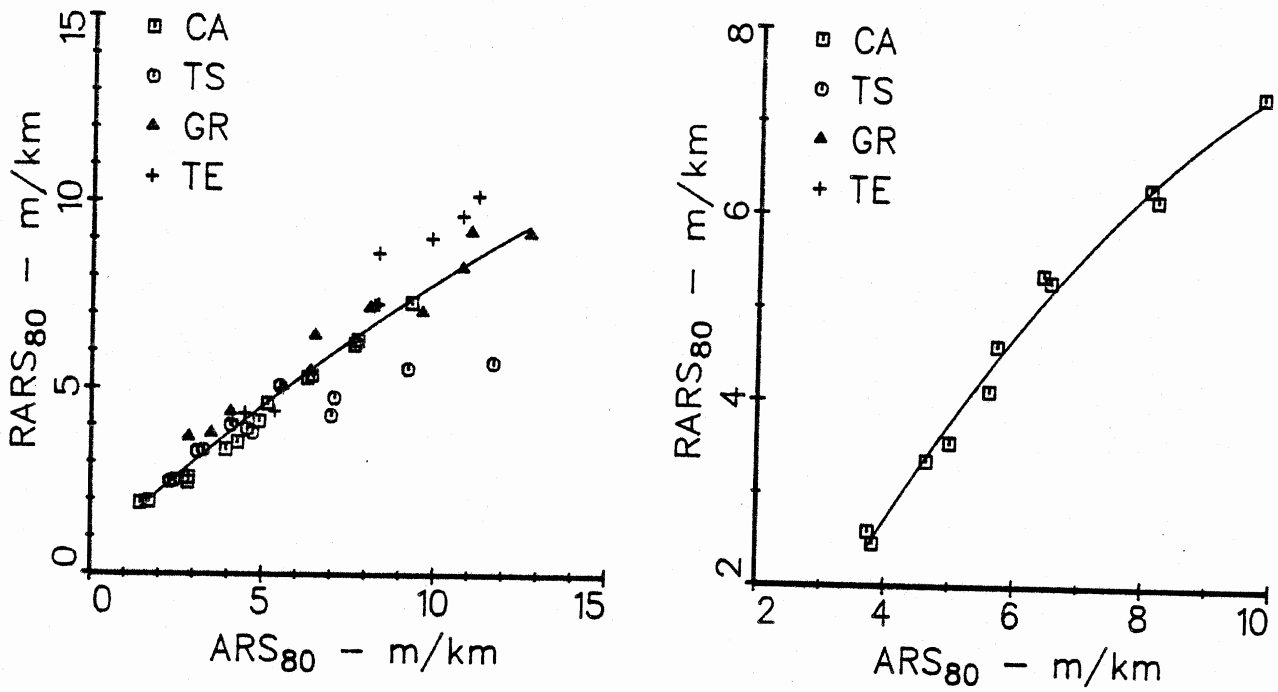
b. Caravan—NAASRA



c. BI Trailer

d. BPR Roughometer

Figure F.17. Example calibration plots to estimate $RARS_{50}$ from ARS_{50} measures.



a. Opala–Maysmeter #2

b. Caravan–NAASRA

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.

		Opala Passenger Cars with Modified Maysmeters			Caravan Car with 2 meters		Single-Track Trailers	
Speed	Surface Type	MM 01	MM 02	MM 03	BI	NAASRA	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			Caravan Car with 2 meters		Single-Track Trailers	
		MM 01	MM 02	MM 03	BI	NAASRA	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 based on an ARS measure can be defined as the standard error: the RMS difference between CARS (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.

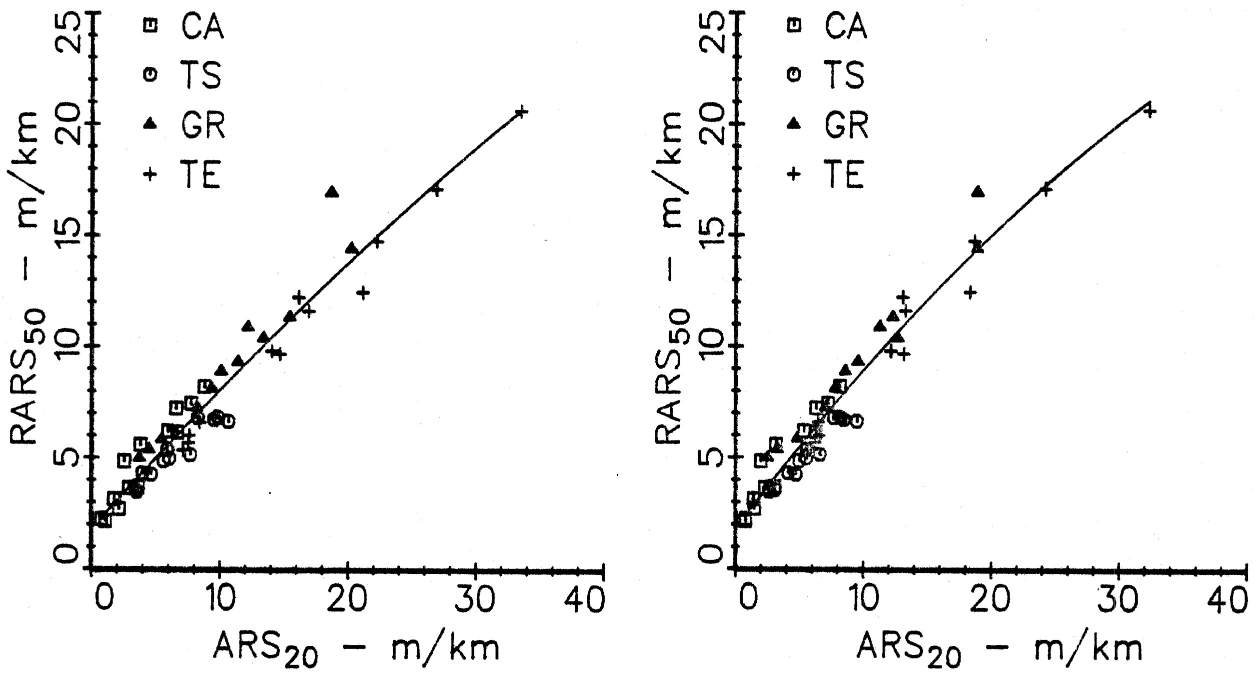
Calibration when Simulation Speed = 50 km/h

The RQCS was developed for maximum correlation with RTRRMSs when the simulation speed is set to the measurement speed of the vehicle. A "standard" RTRRMS speed of 50 km/h is selected in this report as the best single speed to be used as a basis for an International Roughness Index (IRI). From this decision, the best candidate RQCS numeric is $RARS_{50}$, which is recommended in this report as the most suitable for the IRI. Recognizing that there are sometimes circumstances preventing RTRRMS use at 50 km/h, the data collected in the IRRE were also analyzed to determine the accuracy associated with estimating $RARS_{50}$ when a different RTRRMS speed is used. Figures F.19 - F.21 show the comparisons between $RARS_{50}$ and ARS measured at speeds of

Table F.9. Standard Error for Estimating RARS with a Quadratic Regression Equation and ARS Measurements.

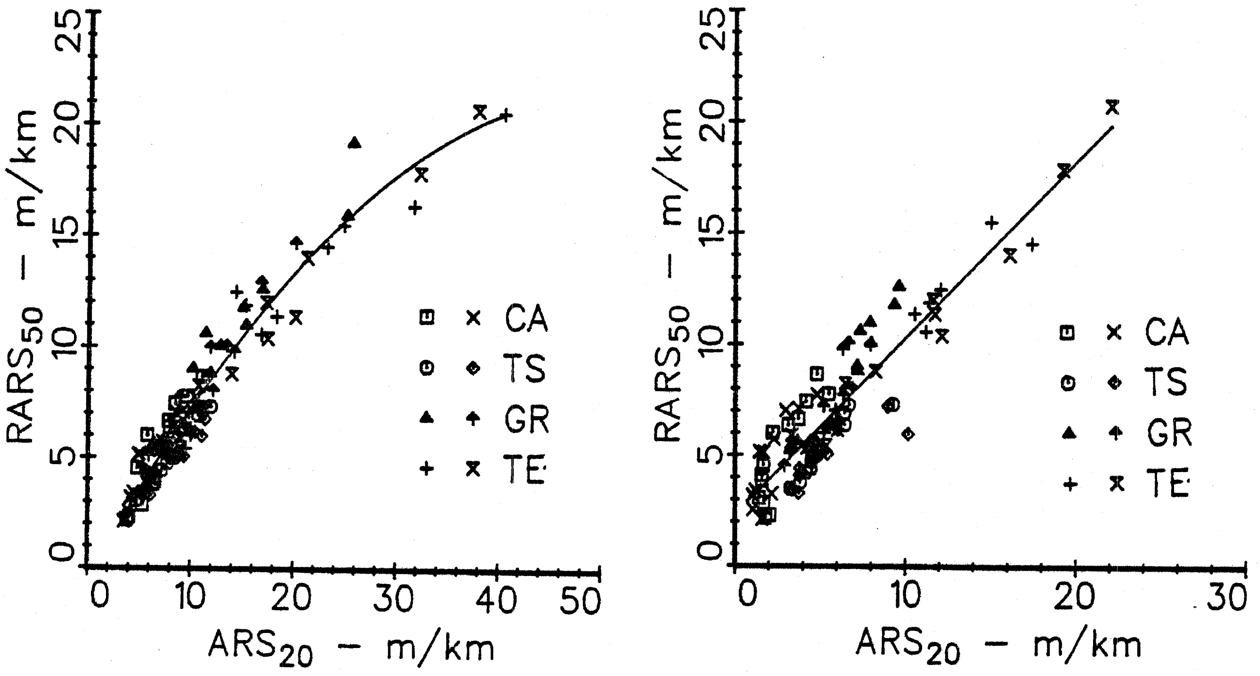
		Opala Cars with Modified Maysmeters			Caravan Car with 2 meters		Single-Track Trailers	
Speed	Surface Type	MM 01	MM 02	MM 03	BI	NAASRA	BI	BPR
20	ALL	1.72	1.02	1.33	1.14	1.24	1.14	1.65
32	ALL	1.36	0.86	1.53	0.88	0.95	0.79	2.91
50	CA	0.46	0.70	0.51	0.34	0.32	0.55	0.76
	TS	0.38	0.31	0.37	0.32	0.33	0.38	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.



a. Opala–Maysmeter #2

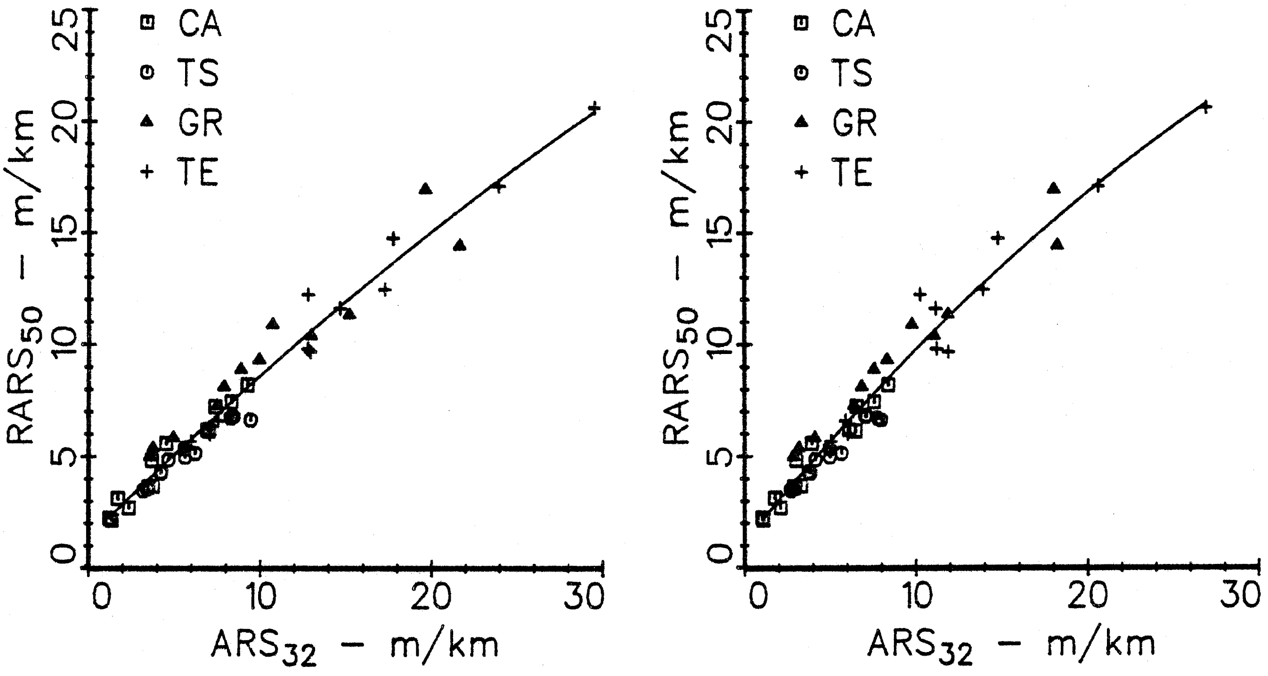
b. Caravan–NAASRA



c. BI Trailer

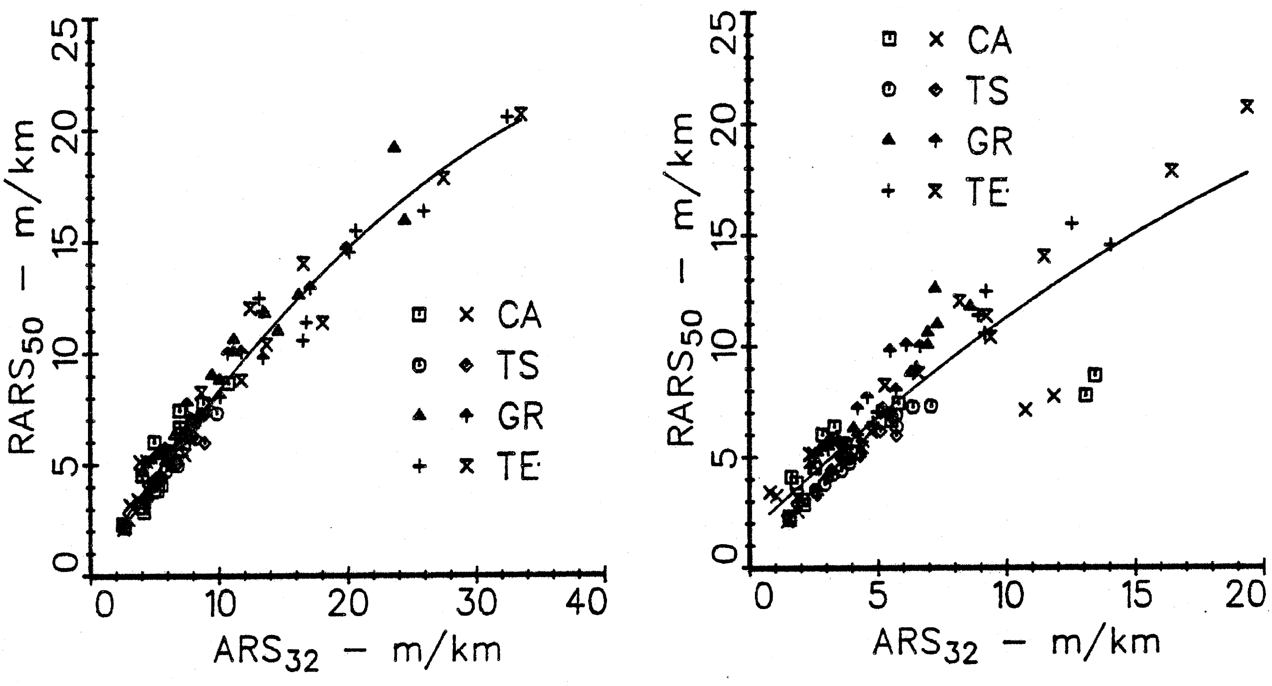
d. BPR Roughometer

Figure F.19. Example calibration plots to estimate $RARS_{50}$ from ARS_{20} measures.



a. Opala–Maysmeter #2

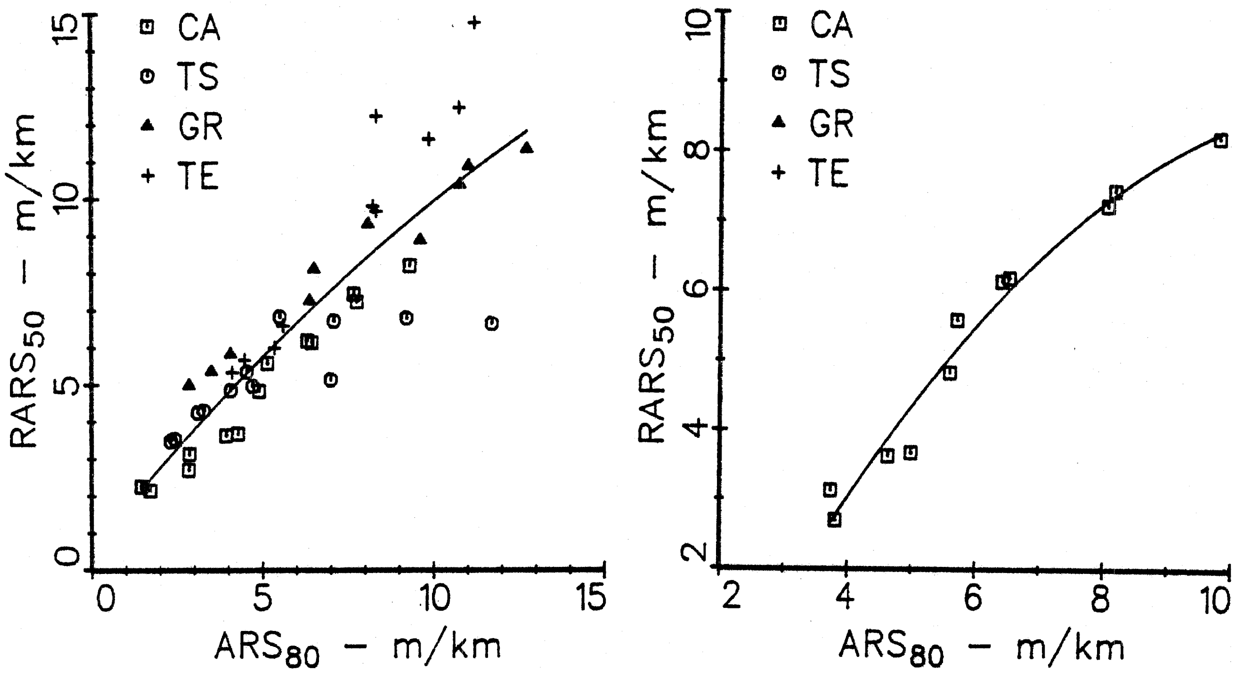
b. Caravan–NAASRA



c. BI Trailer

d. BPR Roughometer

Figure F.20. Example calibration plots to estimate $RARS_{50}$ from ARS_{32} measures.



a. Opala–Maysmeter #2

b. Caravan–NAASRA

Figure F.21. Example calibration plots to estimate $RARS_{50}$ from ARS_{80} measures.

20, 32, and 80 km/h. The corresponding standard errors obtained are presented in Table F.10. Since the standard error units are m/km for $RARS_{50}$, they are directly comparable to the $RARS_{50}$ 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 50 km/h, since RARS numerics are speed dependent.

The figures and tables show that a RTRRMS speed of 80 km/h degrades the correlation with $RARS_{50}$, which means that the $CARS_{50}$ measures obtained at 80 km/h would be less accurate. On the other hand, better results are sometimes obtained when a lower RTRRMS speed is used. The Caravan-based systems gave better accuracy when operated at 20 and 32 km/h than when operated at 50, and correlations with the BI Trailer were best at 32 km/h. This finding is encouraging, because it means that the $RARS_{50}$ numeric can be estimated quite well when field conditions prevent operation of the RTRRMS at 50 km/h.

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 $RARS_{50}$ when the regressions were performed separately for different surface types. For example, Fig. F.20a (for an Opala-Maysmeter system) shows that $RARS_{50}$ 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 0.22 (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 $CARS_{50}$ 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 $RARS_{50}$ as the calibration reference is expected. It occurs 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.

Table F.10. Standard Error for Estimating RARS$_{50}$ with a Quadratic Regression Equation and ARS Measurements.

Speed	Surface Type	Opala Cars with Modified Maysmeters			Caravan Car with 2 meters		Single-Track Trailers	
		MM 01	MM 02	MM 03	BI	NAASRA	BI	BPR
20	CA	0.64	0.57	0.53	0.59	0.57	0.75	1.02
	TS	0.35	0.35	0.36	0.31	0.31	0.43	0.37
	GR	0.77	0.88	1.48	0.64	0.63	0.79	0.70
	TE	1.47	0.58	0.56	0.78	0.77	0.99	0.77
	ALL	1.10	0.97	1.17	0.88	0.90	1.03	1.35
32	CA	0.55	0.44	0.79	0.49	0.46	0.68	0.84
	TS	0.21	0.22	0.37	0.25	0.25	0.37	0.34
	GR	0.34	0.91	1.25	0.68	0.64	0.76	0.65
	TE	1.46	0.75	0.83	1.14	0.97	1.08	0.73
	ALL	0.95	0.80	1.20	0.86	0.83	0.86	1.57
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	0.41	0.32	0.67	0.39	0.30	...	0.39
	TS	0.53	0.49	0.66	...	...	...	...
	GR	0.51	0.38	0.49	...	...	...	...
	TE	1.72	0.81	0.80	...	...	...	...
	ALL	1.64	1.40	1.63	0.39	0.30	...	0.39

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.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:

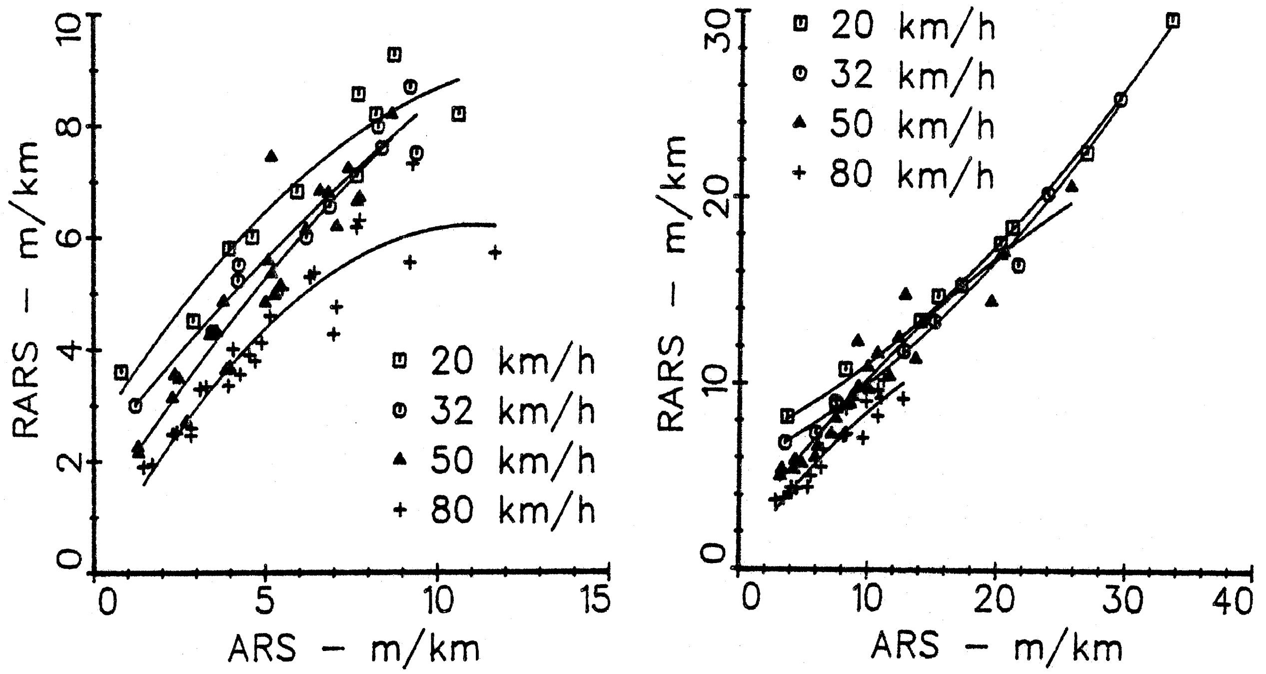
$$E\ [RARV] = CARV = A + B\ ARV + C\ ARV^2 \qquad \text{(F-45)}$$

Since ARV and ARS are related by measurement speed, Eq. 45 can be converted to an ARS equation:

$$\begin{aligned} CARS &= CARV / V = A / V + B\ ARV / V + C\ ARV^2 / V \\ &= A / V + B\ ARS + C\ V\ ARS^2 \qquad \text{(F-46)} \end{aligned}$$

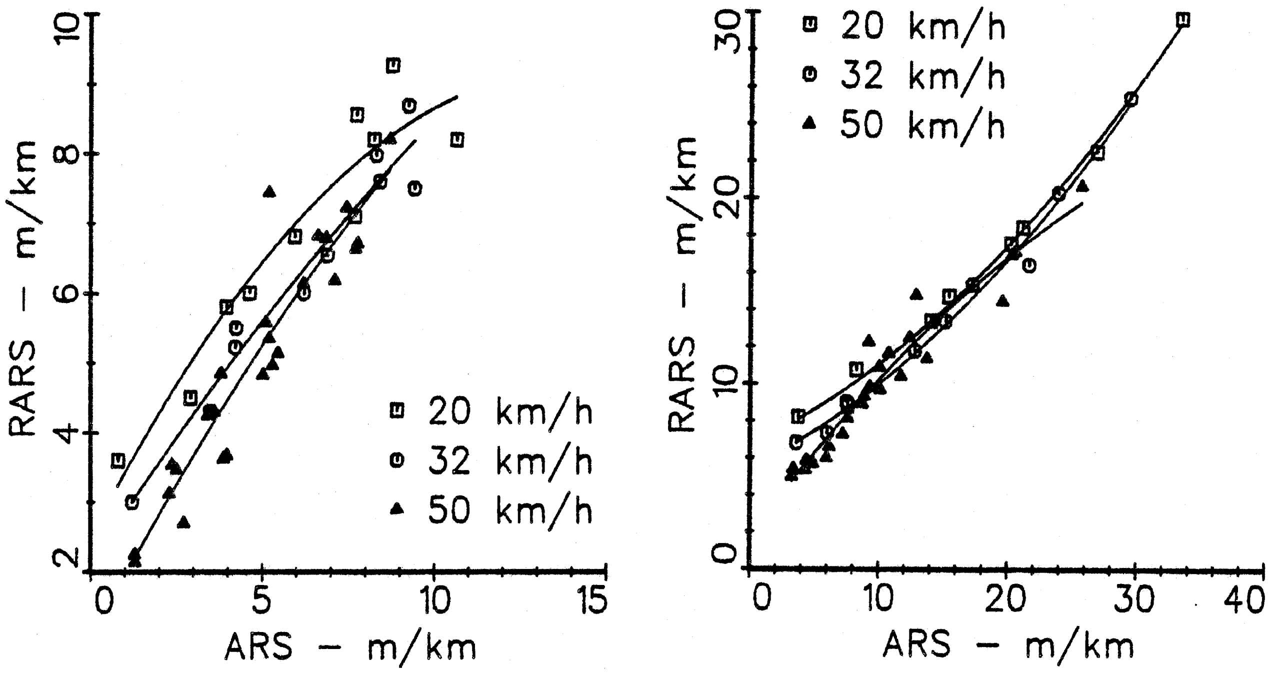
Eq. 46 cannot be independent of speed unless the offset A and the curvature C are both zero.

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.



a. MM #2 on Paved Sites

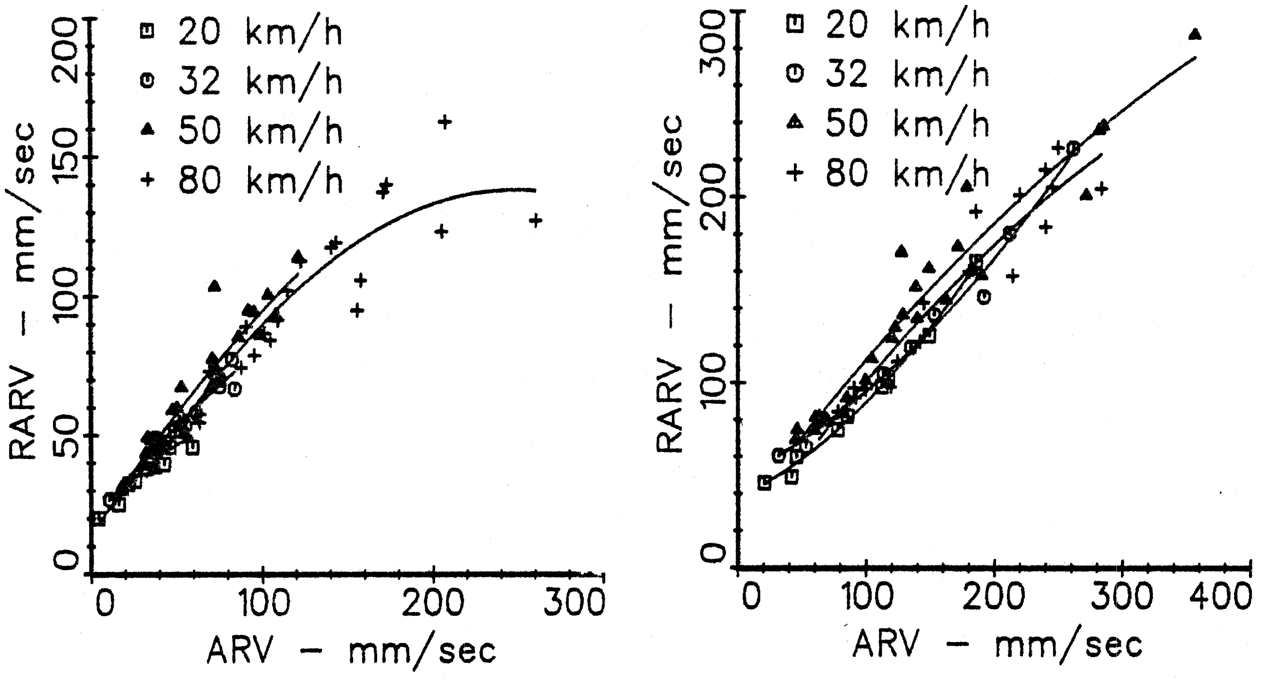
b. MM #2 on Unpaved Sites



c. BI Trailer on Paved Sites.

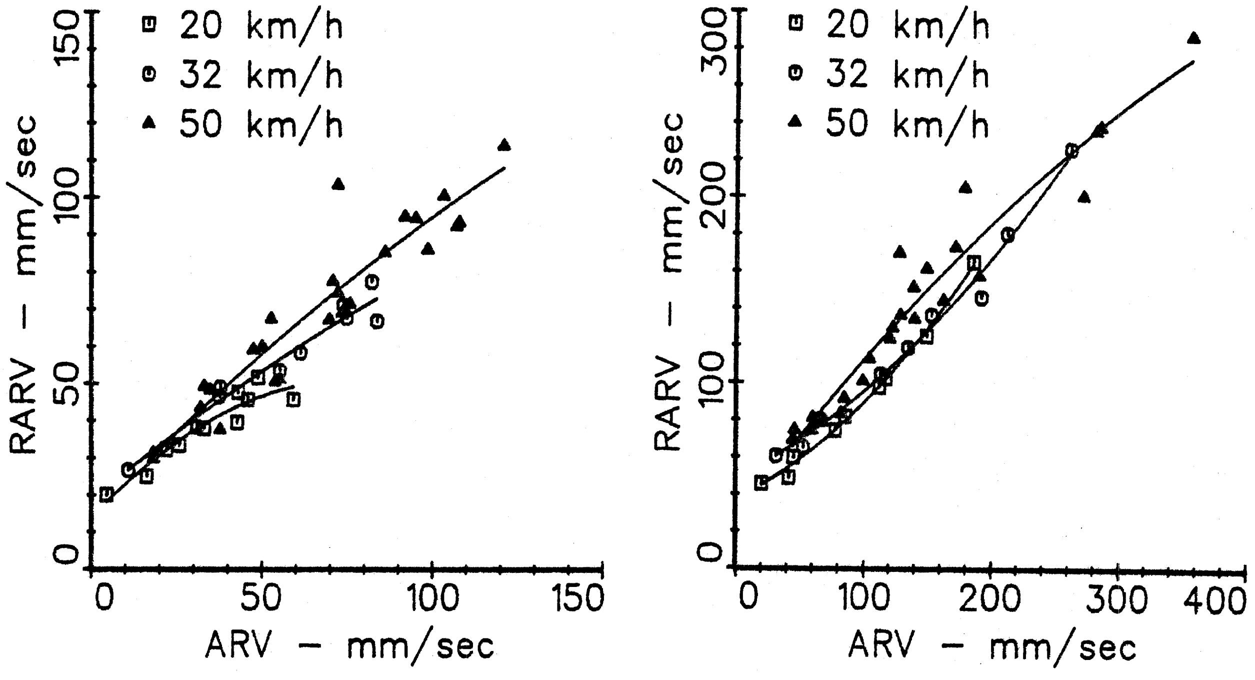
d. BI Trailer on Unpaved Sites.

Figure F.22. Calibration across speed using ARS and RARS numerics.



a. MM #2 on Paved Sites.

b. MM #2 on Unpaved Sites



c. BI Trailer on Paved Sites.

d. BI Trailer on Unpaved Sites.

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).

DESCRIPTIONS 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 laboratatory 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,

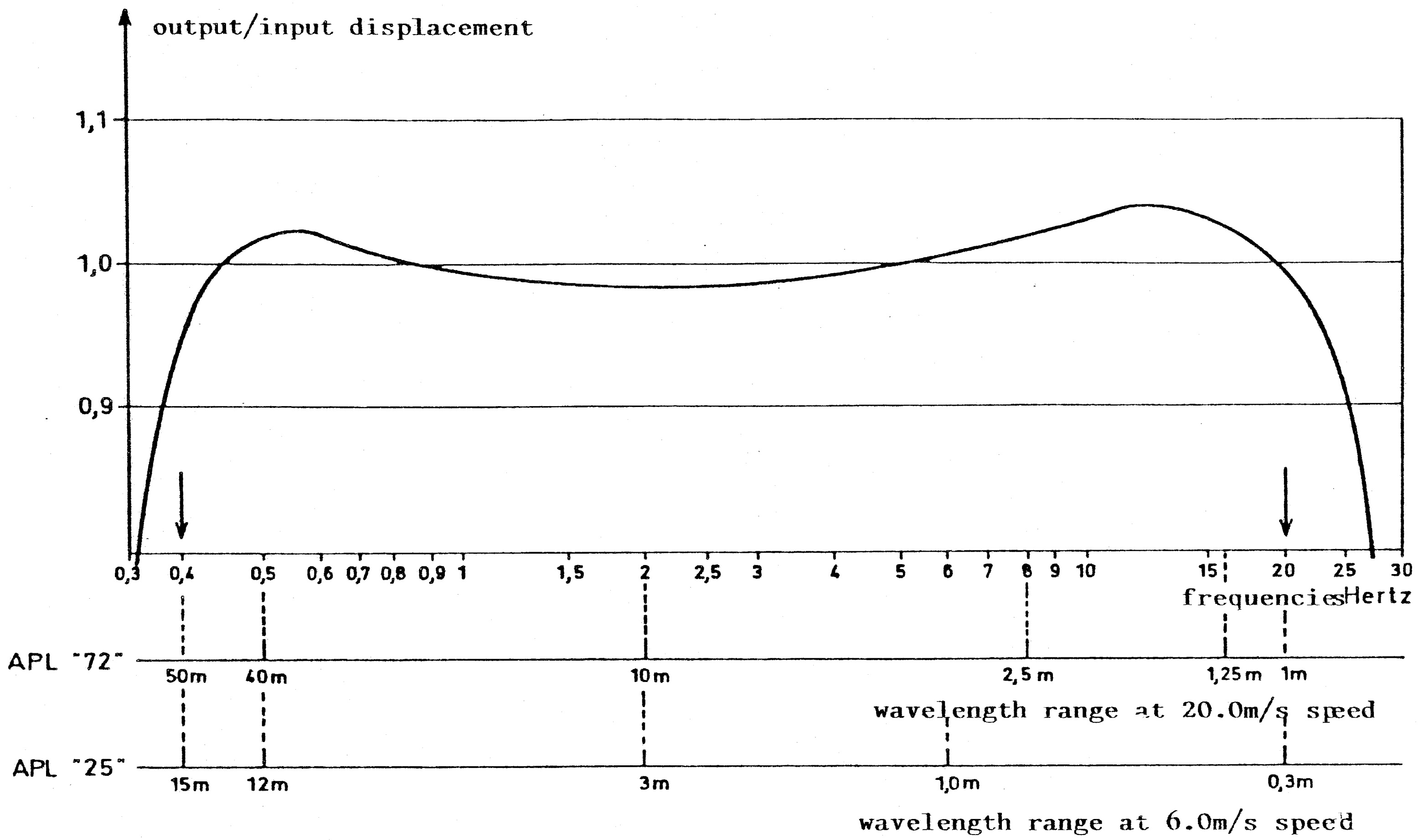


Figure G.1. Frequency Response of APL Trailer to displacement input computed for every 200 m. The three values are obtained by playing the signal back from the tape recorder through three electronic band-pass filters. During playback, the tape speed is increased to reduce processing time and to avoid 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 availabale 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

Table G.2 (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
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							
			MEAN	RUN 1	RUN 2	RUN 3	SIGMA	S/M	TREND	R
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)

RTRRMS APL numérics			MMO1	MMO2	MMO3	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
	W	SW		. 8509				. 8278	
		MW		. 5752				. 4985	
		LW							
	Y	SW		. 8439				. 8051	
		MW		. 6088				. 5238	
		LW							
	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)

RTRRMS APL numérics			MMO1	MMO2	MMO3	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
	W	SW		. 8553				.8453	
		MW		. 0063				.0062	
		LW							
	Y	SW		. 8583				. 8444	
		MW		. 0259				. 0223	
		LW							
	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)

RTRRMS APL numérics			MMO1	MMO2	MMO3	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
	W	SW		. 8103				. 7929	
		MW		. 8042				. 8012	
		LW							
	Y	SW		. 8007				. 7857	
		MW		. 8207				. 8099	
		LW							
	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)

RTRRMS APL numérics			MMO1	MMO2	MMO3	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
	W	SW		. 8557				. 8376	
		MW		. 7569				. 7491	
		LW							
	Y	SW		. 8408				. 8235	
		MW		. 8035				. 7920	
		LW							
	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 numérics \ 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 numérics \ 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 numérics \ 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 numérics \ 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)

RTRRMS APL numérics			MMO1	MMO2	MMO3	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)

RTRRMS APL numérics			MMO1	MMO2	MMO3	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)

RTRRMS APL numérics			MMO1	MMO2	MMO3	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)

RTRRMS APL numérics			MMO1	MMO2	MMO3	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		MM01	MM02	MM03	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		MM01	MM02	MM03	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		MM01	MM02	MM03	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		MM01	MM02	MM03	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 ndex 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:

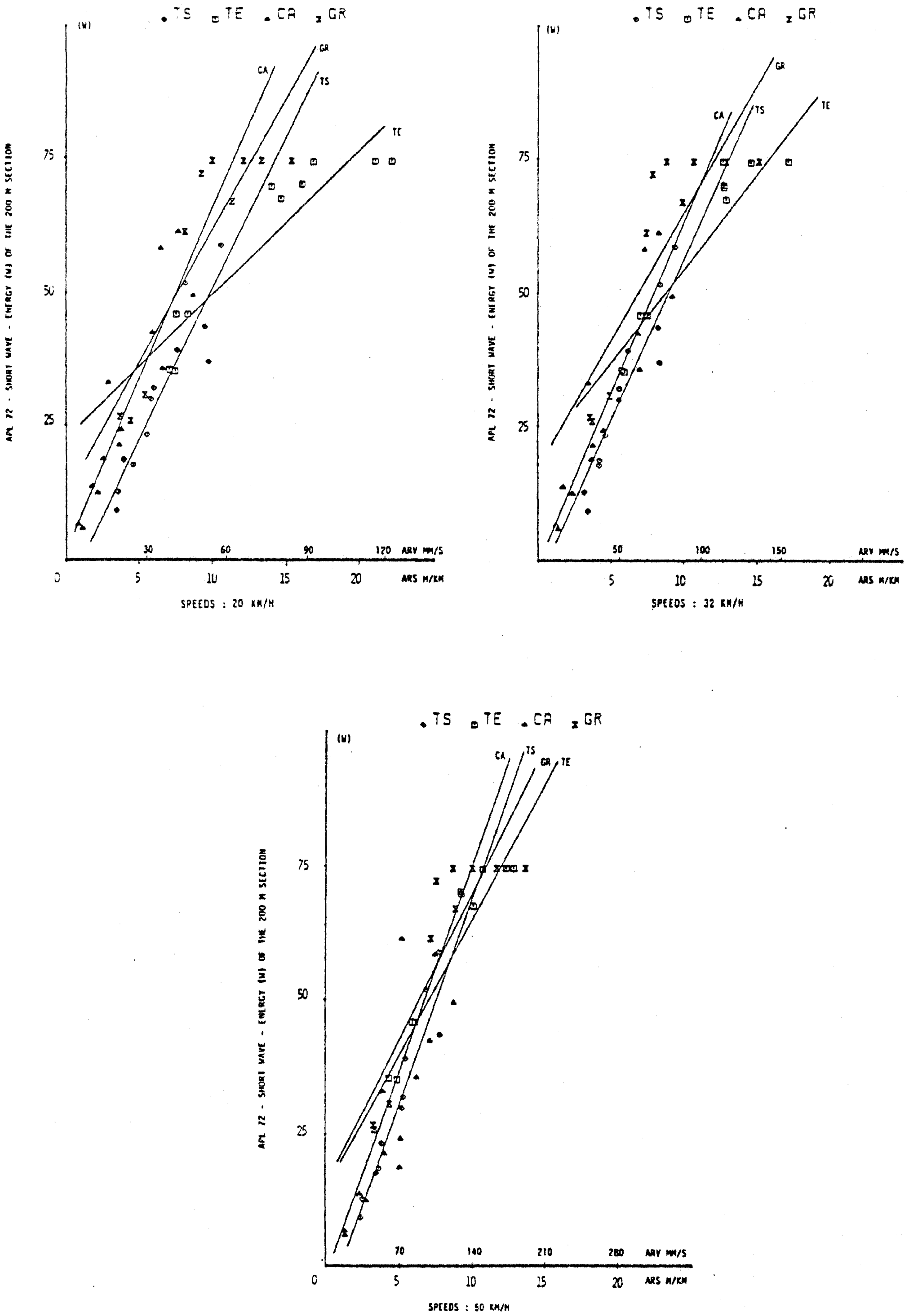


Figure G.2. Comparison of APL 72 short wave energy results (W) with Mays Meter 02 results

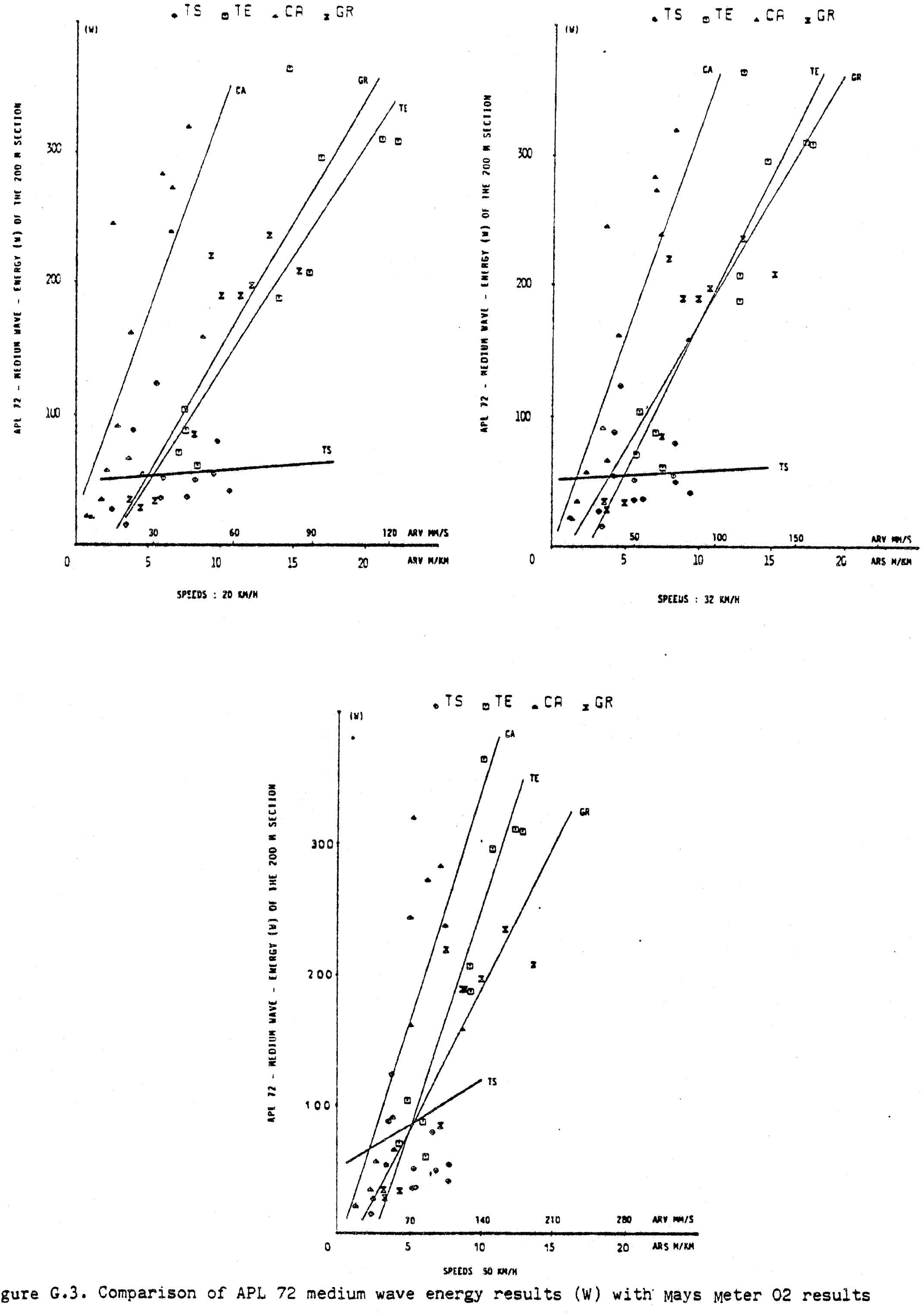


Figure G.3. Comparison of APL 72 medium wave energy results (W) with Mays Meter 02 results

- 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.

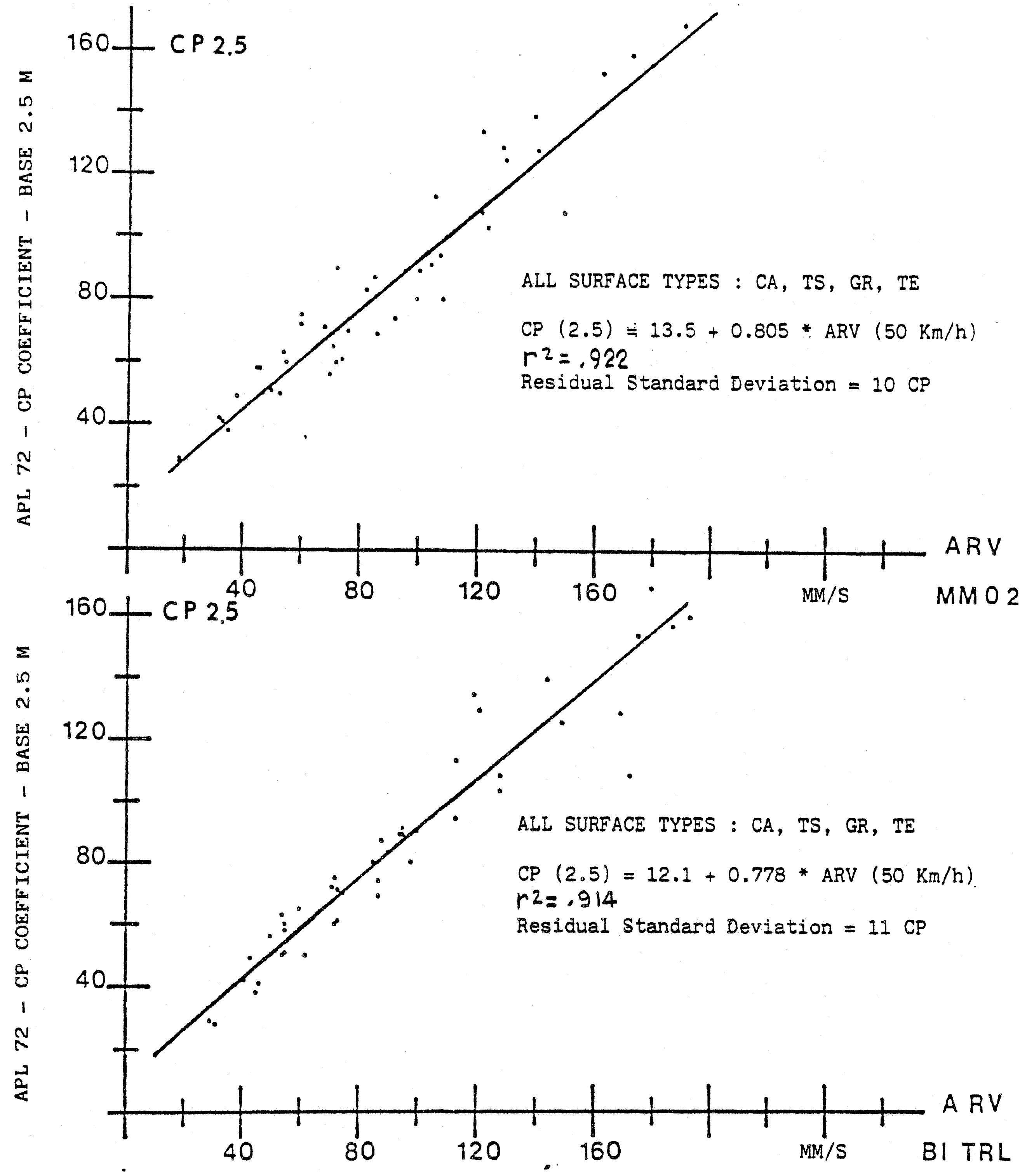
By merging all data belonging to a given RTRRMS device and calculating the linear regression coefficients and the correlation coefficient for each test speed, one can expect to evaluate the effects of speed and site factors that could influence a calibration plot that would be needed to estimate the 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.



ALL SURFACE TYPES : CA, TS, GR, TE

CP (2.5) ≑ 13.5 + 0.805 * ARV (50 Km/h)

$r^2 = .922$

Residual Standard Deviation = 10 CP

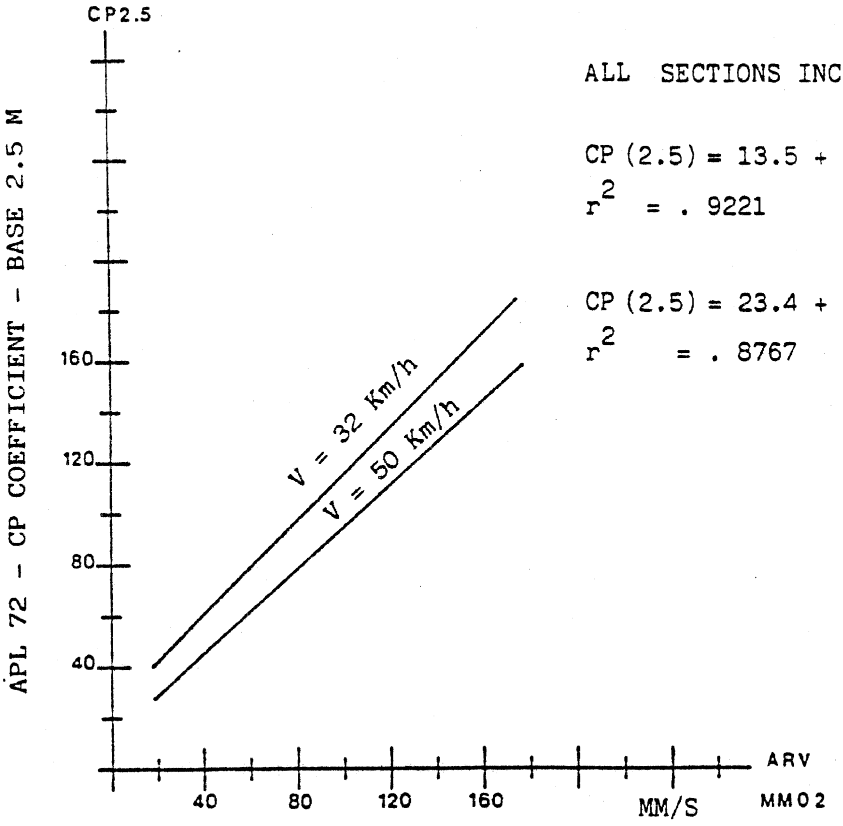
ALL SURFACE TYPES : CA, TS, GR, TE

CP (2.5) = 12.1 + 0.778 * ARV (50 Km/h)

$r^2 = .914$

Residual Standard Deviation = 11 CP

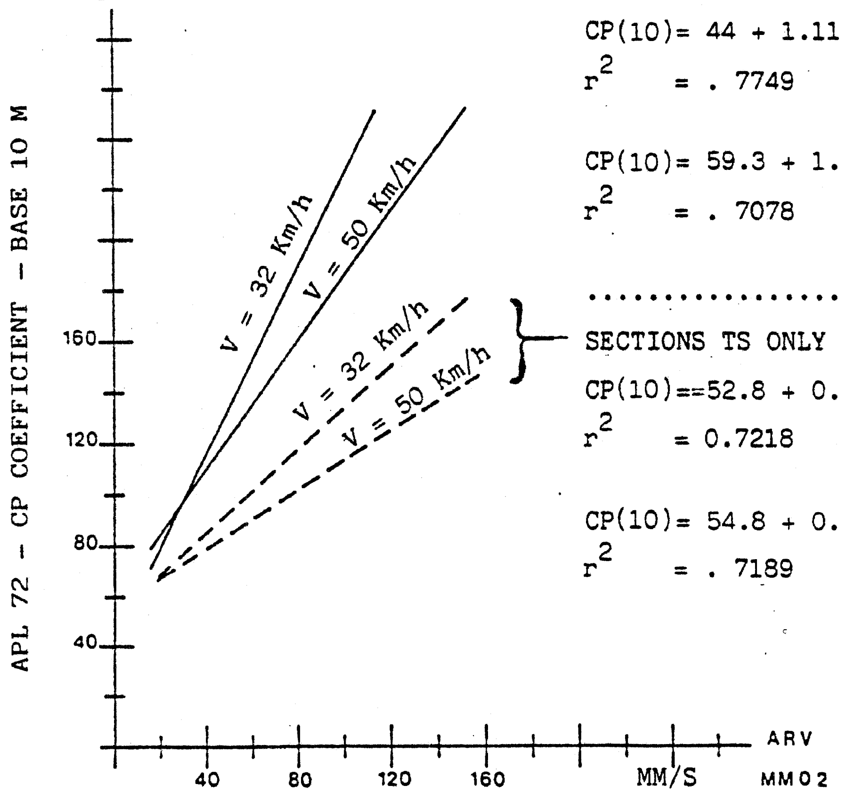
Figure G.4. Comparison of APL 72 CP (2.5) values with RTRRMS Measures made at 50 km/h



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 0 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

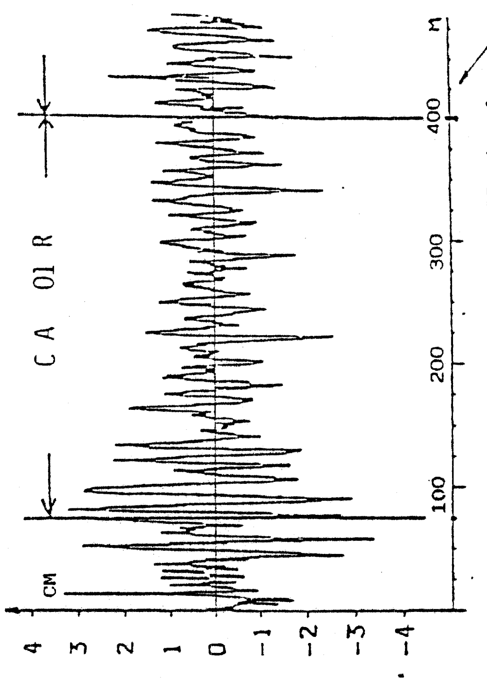


Figure G.11 b : Digitized APL 25 signal

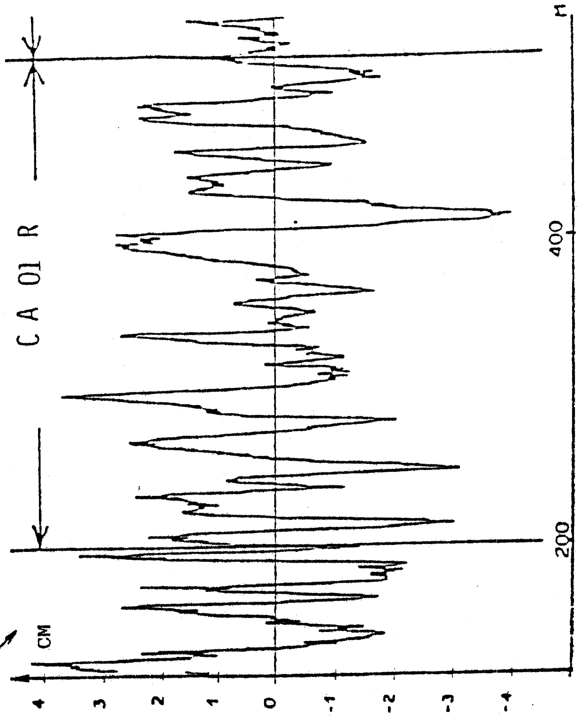


Figure G.11 c : Digitized APL 72 signal

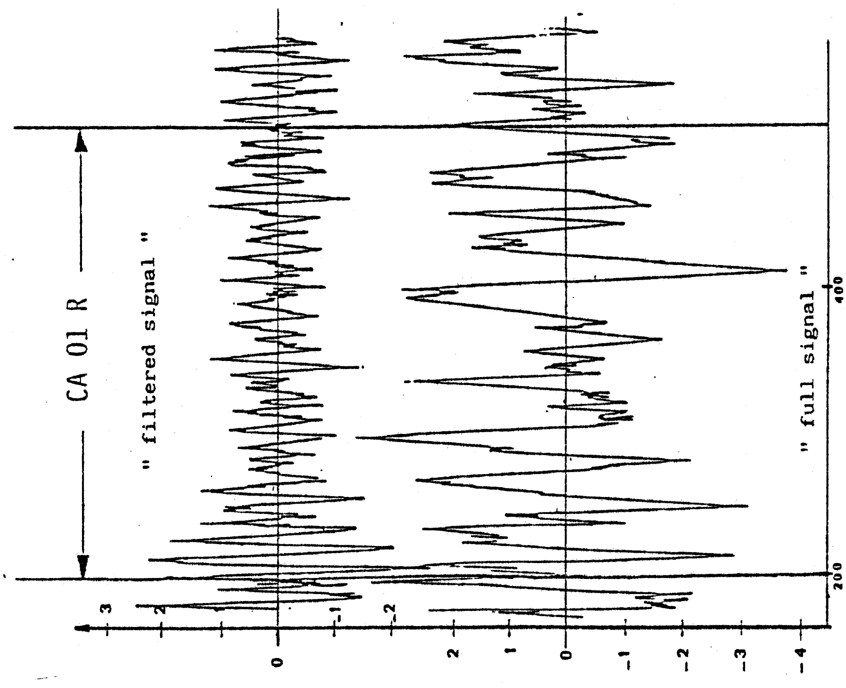


Figure G.11 a : Analogic APL 72 signal

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

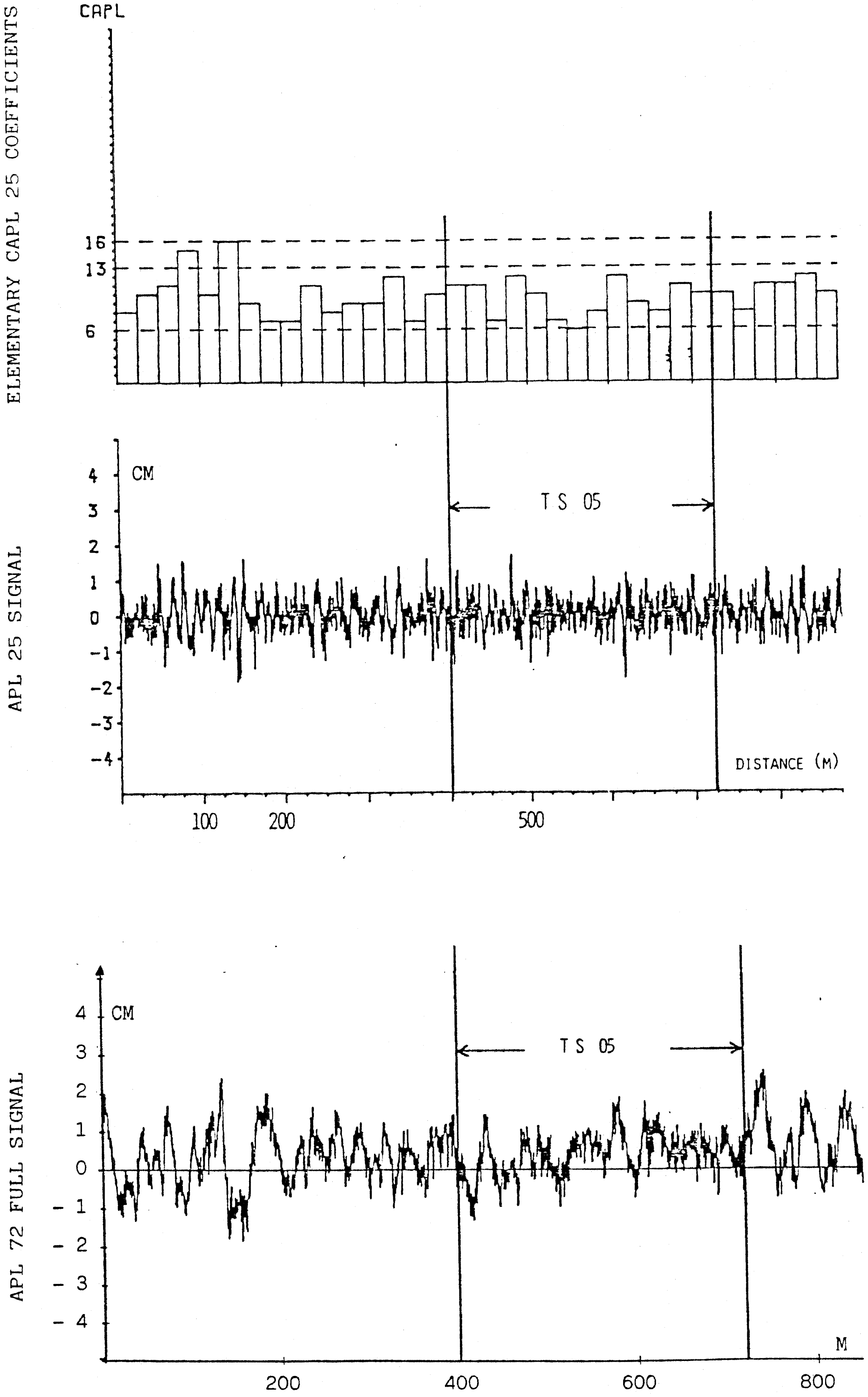


Figure G.7. APL signals measured on section test TS 05 left track

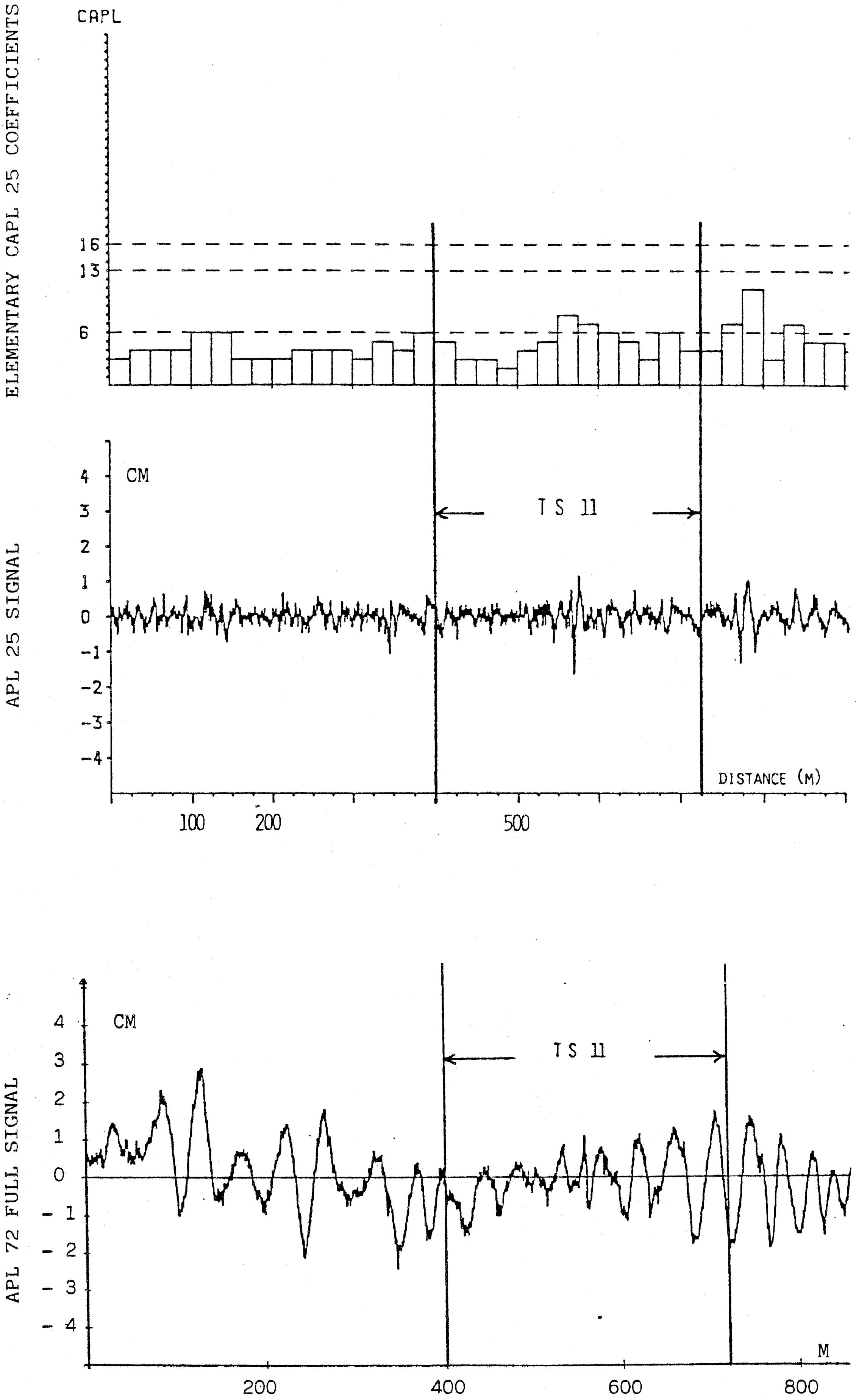


Figure G.8. APL signals measured on section test TS 11 left track

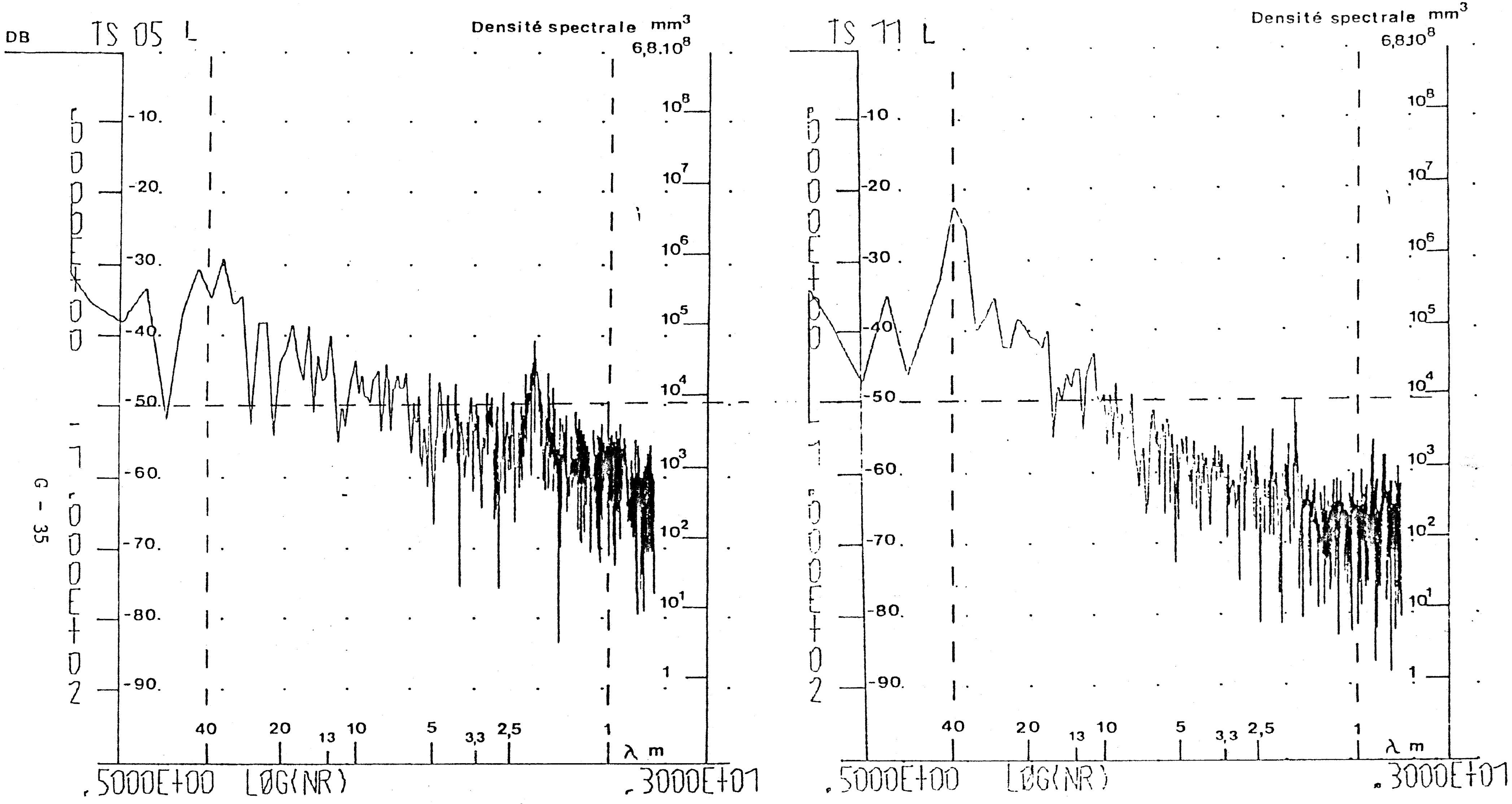


Figure G.9. POWER SPECTRAL DENSITY FROM APL 72 SIGNAL OF TS 05 LEFT TRACK AND TS 11 LEFT TRACK

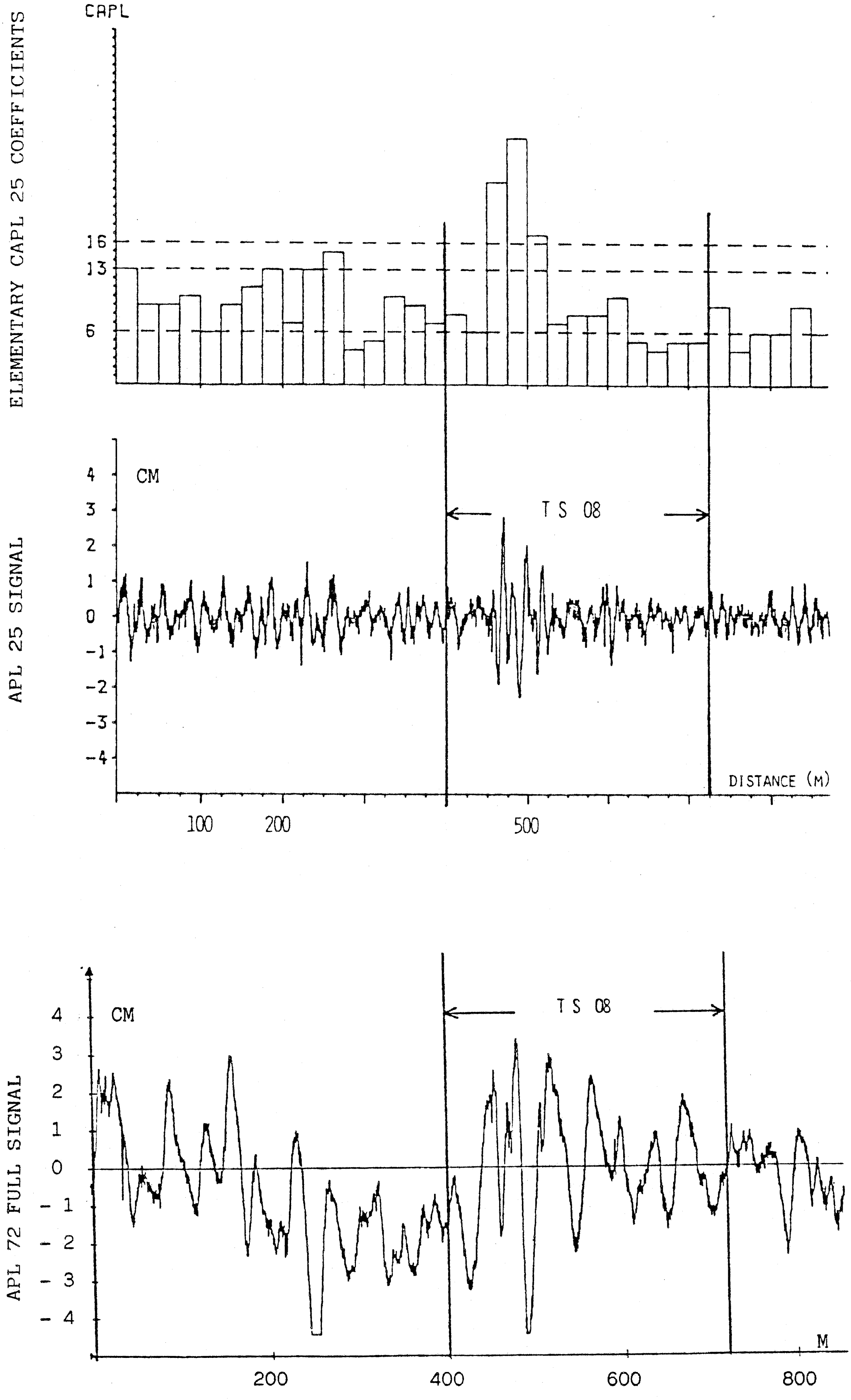


Figure G.10. APL signals measured on section test TS 08 left track

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

THE TRANSPORT AND ROAD RESEARCH LABORATORY PROPOSALS FOR ROAD ROUGHNESS CALIBRATION AND STANDARDISATION

by

S W Abaynayaka and Linda Parsley

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Chapter

INTERNATIONAL ROAD ROUGHNESS EXPERIMENT - BRAZIL 1982

TRRL proposals for calibrating response instruments and providing a universal standard measure of roughness

1. INTRODUCTION

The International Road Roughness Experiment conducted in Brazil in May 1982 has been fully documented and reported by the University of Michigan in their draft report to the World Bank (UMTRI-82-45-1). The report detailed the objectives of the experiment and presented the analysis and findings together with conclusions and interim recommendations for calibrating and standardising roughness measurements. These findings and recommendations were based on the analyses conducted by the team on a limited number of profile based numerics, ie the QI developed during the Brazil ICR project, the RARV based on the Quarter Car Simulation model, the CAPL 25 coefficient produced through the APR 25 trailer, and the APL72 Wave band indicies. Correlations between these profile based numerics and the response type road roughness measuring systems (RTRRMS's) were calculated to determine the accuracy and minimum complexity needed for calibrating the RTRRMS's. The conclusions reached were that:-

1. RARV as processed via a QCS provided the best calibration reference for RTRRMS's provided separate calibrations were available for paved and unpaved roads at 50 km/h or less, and also that separate calibrations were available for asphaltic concrete and surface treated roads at 80 km/h.

2. QI, though not as effective a calibration reference as RARV, is based on an analysis (RMSVA) that is simple, easily understood and therefore worthy of further consideration and development.

3. The APL 25 and 72 roughness numerics showed poor correlation with the RTRRMS and were therefore unacceptable as calibration references. (However, an LCPC and CRR revised draft of Appendix G suggests the use of CP units ('coefficient de planéité') as an improved calibration reference).

This report presents the analysis and findings from the TRRL beam profile data as analysed by the TRRL, and describes a complete instrument package developed at TRRL to enable users to obtain calibrated and standardised 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 10 of these sections both wheelpaths were profiled, the nearside wheelpath only on 3 sections and the offisde wheelpath on the remaining 5 sections. Seven RTRRMS's were used in the experiment, but in this report only 4 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 Mays Meter 02. Mays Meters 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

2.1 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 RTRRMS'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 enjoy a great popularity with practising engineers and researchers and are in widespread use throughout the world. It has 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 is an obvious candidate for providing a calibration reference for calibrating measurements of RTRRMS. 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 instruments can be easily transportable to the country and the site, they will not be used, by practising engineers and consultants, however good the instruments may be. Secondly the instrument must be reasonably simple to operate, and data management, analysis and interpretation available immediately after measurement. Manual data processing cannot be undertaken by field staff, therefore the generation of profiles alone on the field und 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.

2.2 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. The main report considered two candidate numerics for correlation with RTRRMS's namely the QI derived from RMSVA and RARV derived from the Quarter Car Simulation model. The revised draft of Appendix G of the report submitted by LCPC and CRR of France provided a third numeric, namely the APL-CP 2.5m derived from a moving average datum curve. In this report three further numerics have been computed as candidate statistics for correlation with RTRRMS, and their performance is discussed and compared with the other three statistics. 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.

The main report 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.

2.2.1 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 ℓ was calculated using the formula:

$$\mathrm{RMSVE}_{\ell} = \sqrt{\frac{\frac{h}{3}\left[y_o^2 + y_n^2 + 4(y_1^2 + y_3^2 \ldots y_{n-1}^2) + 2(y_2^2 + y_4^2 \ldots y_{n-2}^2)\right]}{h(n-1)}}$$

where h is the distance between elevation points
and n is the number of elevation points considered in the baselength, ℓ.

The RMSVE for the test section of road containing N baselengths of length ℓ is given by:

$$\mathrm{RMSVE} = \sqrt{\frac{\sum \mathrm{RMSVE}_{\ell}^{2}}{N}}$$

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 1-4 for the four different measurement speeds and for profile intervals up to 500mm. Their performance is discussed in Chapter 3.

2.2.2 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:

$$\bar{y}_{(i + \frac{n-1}{2})} = \frac{1}{n}\sum_{j=i}^{i+n-1} y_j \qquad \text{for } i \geqslant 1$$

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:

$$d_k = y_k - \bar{y}_k \text{ , where } k = i + \frac{n-1}{2} \quad \text{for } i \geqslant 1$$

The variance (σ_ℓ^2) of these deviations over a given sequence of N profile points for a given moving average of length ℓ (n x profile interval) is:

$$\sigma_\ell^2 = \frac{1}{N-n-1}\sum_{k=1}^{N-n} (d_k - \bar{d})^2$$

The variance σ_ℓ^2 reflects the unevenness in the road profile that is associated with profile features that are approximately ℓ metres in length or less.

The profiles of the test sections measured by the TRRL beam are defined at points spaced 100 mm apart. Moving average variances were calculated for a number of different wavelengths(ℓ) ranging from 0.4 metres to 10.0 metres and for profile intervals of 100 mm

200 mm and 300 mm. The previous RMSVE analysis indicated that profile intervals greater than 300 mm produced weaker correlations, and therefore intervals greater than 300 mm were not analysed. 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 5-8 and discussed in Chapter 3 along with the other numerics.

2.2.3 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 and then calculating the root mean square of these deviations. For a given baselength ℓ, with n profile points, the regression line $y = a + bx$ is calculated and the deviations D_i evaluated.

$$RMSD_\ell = \sqrt{\frac{\sum Di^2}{n}}$$

The RMSD for the test section of road containing N baselengths of length ℓ is given by:

$$RMSD = \sqrt{\frac{\sum RMSD_\ell^2}{N}}$$

RMSD 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 values are tabulated in Tables 9-12 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 for the nearside wheelpath only for both methods of analysis (ie discrete and contiguous baselengths) are given in Tables 13-18. Tables 19-21 tabulate 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

3.1 Measurement variables

The object of the profile analysis detailed in the previous chapter and tabulated in Tables 1-21 was to develop a suitable statistic to accurately characterise a road profile such that it could be correlated to 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 could still be undertaken provided the relationship between measurements at 32 km/h and any other desired speed of measurement is established prior to calibration.

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. Tables 13-15 tabulate the RMSD, R^2 values for the nearside wheelpath, and Tables 19-21 tabulate 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.

3.2 Examination of profile interval and baselength

In all three analyses (ie 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 5-8) 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 interval 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. Table 22 summarises 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 1.8m 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.

3.3 Development of the RMSD profile statistic

The successful establishment of an RMSVE profile statistic to characterise 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 9 and 10 show the RMSD values computed for discrete baselengths and Tables 11 and 12 list the RMSD values computed for contiguous baselengths. The R^2 values obtained after regression with the RTRRMS is given in Tables 13-15 for discrete baselengths, and Tables 16-18 for contiguous baselengths. Comparing the discrete baselength R^2 values with the equivalent R^2 values from the RMSVE analysis (Tables 1-4) 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 23 summarises R^2 values produced over the three best profile interval/baselength combinations for the four RTRRMS 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 metres and 300mm, producing an average R^2 value of 0.970.

3.4 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 of baselength. Therefore the complete RMSD analysis was conducted using both definitions of baselength and the R^2 values produced can be compared between Tables 13-15 and Tables 16-18. 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 metre 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.

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 to, 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 RARV 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 profiles, such as RMSD, provides a satisfactory numeric for correlation with RTRRMS measures. RMSD is thus a statistic that uniquely characterises 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 15,000 mm/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 millimetres per kilometre. 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. 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 equivalent measure 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. Figs 1, 2 and 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. Therefore a standard reference roughness equation based on the BI Trailer measurement standard would be deemed suitable.

Such a standard reference roughness equation has been developed from the IRRE data and is shown in Fig 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:-

$$\text{ROUGHNESS} = 472 + 1437\,(\text{RMSD}_{1.8/300}) + 225\,(\text{RMSD}_{1.8/300})^2$$

The above standard reference roughness equation will remain a permanent road roughness estimator through time and space.

5. PROPOSED METHOD OF CALIBRATING AND STANDARDISING OF RTRRMS

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 variation.

5.1 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.

5.2 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 standardisation procedures require robust and stable relationships, 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 standardisation purposes the measurement speed should be maintained at 32 km/h, so that the final calibrated and standardised 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 the two different speeds with a particular response system, and then use the equivalent 32 km/h measure for calibration and standardisation.

5.3 Variation in wheelpath roughness

The analysis has shown that the nearside wheelpath profile statistics always correlated better with RTRRMS than the offside wheelpaths. Slow manual methods of profilometry discourage the measurement of both wheelpaths, if the measurement of one wheelpath alone is sufficient to produce a strong correlation. No rational reason can be given for the consistently better performance of the nearside wheelpath correlation, but in view of the overwhelming evidence produced by the analysis, it is proposed that the nearside wheelpaths only need to be profiled to obtain profile statistics for correlation with RTRRMS.

5.4 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 report that the overall best combination of profile interval and baselength was observed to be the 300 mm interval for a baselength of 1.8 metres. Table 24 compares the R^2 values produced by these six different statistics when they were correlated against the four RTRRMS used in the Brazil IRRE. All the statistics produced good to excellent correlations with the four RTRRMS, 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, and therefore the use of this statistic is proposed for calibration and standardisation of response type roughness measurements.

5.5 Calibrating and standardising 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 10 sections is recommended). These sections are then profiled on the nearside wheelpath with the TRRL beam and the Root Mean Square of Deviation (RMSD) statistic 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 measure 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 standardised 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 as perceived by that particular RTRRMS. This estimated value of RMSD is then input to the Standard Reference Roughness equation

$$\text{ROUGHNESS} = 472 + 1437\ (\text{RMSD } 1.8/300) + 225\ (\text{RMSD } 1.8/300)^2$$

to produce a standardised roughness value. All the field measurements are standardised in this manner.

6. VALIDATION STUDY IN ST LUCIA

The calibrating and standardising 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 back-up. There was little choice in the selection of the hire vehicles and their mechanical condition 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 tyre 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 25. The test section profiles were analysed in exactly the same manner as the IRRE, Brazil data and direct comparisons are therefore possible.

Tables 26-28 tabulate the R^2 values obtained using the RMSVE statistic, and Tables 29-31 show 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 32 and 33 tabulate the root mean square of deviation using the discrete baselength method, and Tables 34 and 35 the results obtained using the contiguous baselength method. These RMSD statistics were correlated against the Datsun and Cortina measures of roughness and the resulting R^2 values are presented in Tables 36-38 and Tables 39-41 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 23 summarised the R^2 values obtained for the Datsun and Cortina when correlated with the RMSD 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 42 and 43 tabulate the uncalibrated and calibrated roughness measurements for the IRRE and St Lucia study respectively, using the calibrating and standardising methodology described in the previous section.

7. OPERATION OF THE TRRL ROUGHNESS CALIBRATION AND STANDARDISATION BEAM

The TRRL beam has now been developed as a compact, self contained road roughness calibration and standardisation system. The road profiles measured by the beam are processed automatically through its internal micro-processor and the RMSD 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 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 value of R^2. 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 a standard speed of 32 km/h.

A flow-chart of the operation of the beam is given in Fig 15.

TABLE 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	0.744	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	0.878	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 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	0.770	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	0.758	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	0.893	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	0.873	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	0.893	0.873	0.868	0.853	0.863	0.853	0.826

TABLE 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
HAASRA	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
HAASRA	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	0.859	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 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	0.703	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 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	0.894	0.867	0.852	0.841	0.831
HAASRA	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 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	0.825	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	0.872	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 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	0.939	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	0.916	0.921	0.919	0.917	0.915	0.914

TABLE 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	0.651	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 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	—
BR01	1.345	—	1.438	—	1.481	—	1.538	—	1.577	—	1.578	—
BR05	2.419	3.121	2.672	3.386	2.774	3.464	2.932	—	2.963	—	3.104	—
BR07	1.586	2.610	1.682	2.724	1.737	2.885	1.776	—	1.843	—	1.843	—
BR12	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	—
BR01	1.356	—	1.401	—	1.458	—	1.524	—	1.562	—
BR05	2.483	3.209	2.643	3.386	2.762	3.423	2.885	—	2.944	—
BR07	1.577	2.650	1.631	2.759	1.673	2.943	1.736	—	1.810	—
BR12	3.553	4.511	3.590	5.179	3.839	5.187	4.204	—	4.427	—

TABLE 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 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	1.785	—	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 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	4.235	4.015	5.134	4.632	5.773	5.170	6.293

TABLE 13

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING DISCRETE BASELENGTHS)   BRASIL IRRE DATA

NEARSIDE WHEELPATH

20 Km/hr

100mm INTERVAL

	1.5m	1.8m	2.0m	2.2m	2.4m	2.6m
TRAILER	0.922	0.922	0.917	0.921	0.913	0.874
CAR BI	0.967	0.970	0.968	0.963	0.957	0.934
NAASRA	0.965	0.968	0.966	0.961	0.956	0.933
MM-02	0.964	0.964	0.961	0.955	0.947	0.922

200mm INTERVAL

	1.6m	1.8m	2.0m	2.2m	2.4m
TRAILER	0.925	0.919	0.916	0.919	0.910
CAR BI	0.963	0.967	0.964	0.958	0.950
NAASRA	0.962	0.966	0.963	0.957	0.949
MM-02	0.954	0.959	0.954	0.947	0.937

300mm INTERVAL

	1.5m	1.8m	2.1m
TRAILER	0.924	0.912	0.898
CAR BI	0.974	0.968	0.964
NAASRA	0.973	0.967	0.963
MM-02	0.965	0.959	0.957

500mm INTERVAL

	1.5m	2.0m	2.5m	3.0m
TRAILER	0.901	0.897	0.883	--
CAR BI	0.957	0.947	0.927	0.908
NAASRA	0.958	0.948	0.927	0.908
MM-02	0.949	0.935	0.915	0.894

TABLE 14

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING DISCRETE BASELENGTHS)   BRASIL IRRE DATA

NEARSIDE WHEELPATH

32 Km/hr

100mm INTERVAL

	1.5m	1.8m	2.0m	2.2m	2.4m	2.6m
TRAILER	0.938	0.950	0.947	0.949	0.946	0.922
CAR BI	0.957	0.970	0.974	0.975	0.975	0.967
NAASRA	0.956	0.971	0.975	0.975	0.977	0.968
MM-02	0.944	0.958	0.965	0.966	0.966	0.963

200mm INTERVAL

	1.6m	1.8m	2.0m	2.2m	2.4m
TRAILER	0.952	0.951	0.950	0.952	0.947
CAR BI	0.971	0.974	0.974	0.974	0.974
NAASRA	0.972	0.975	0.976	0.975	0.976
MM-02	0.959	0.960	0.963	0.962	0.963

300mm INTERVAL

	1.5m	1.8m	2.1m
TRAILER	0.952	0.948	0.940
CAR BI	0.973	0.980	0.975
NAASRA	0.974	0.982	0.976
MM-02	0.959	0.970	0.965

500mm INTERVAL

	1.5m	2.0m	2.5m	3.0m
TRAILER	0.940	0.942	0.933	--
CAR BI	0.969	0.970	0.963	0.953
NAASRA	0.971	0.973	0.966	0.955
MM-02	0.958	0.962	0.957	0.946

TABLE 15

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING DISCRETE BASELENGTHS)   BRASIL IRRE DATA

NEARSIDE WHEELPATH

50 Km/hr

100mm INTERVAL

	1.5m	1.8m	2.0m	2.2m	2.4m	2.6m
TRAILER	0.916	0.931	0.919	0.954	0.953	0.923
CAR BI	0.937	0.958	0.962	0.965	0.970	0.961
NAASRA	0.931	0.955	0.961	0.967	0.973	0.972
MM-02	0.913	0.937	0.945	0.952	0.957	0.960

200mm INTERVAL

	1.6m	1.8m	2.0m	2.2m	2.4m
TRAILER	0.912	0.931	0.921	0.955	0.952
CAR BI	0.960	0.965	0.967	0.968	0.973
NAASRA	0.961	0.963	0.968	0.972	0.976
MM-02	0.943	0.943	0.948	0.954	0.958

300mm INTERVAL

	1.5m	1.8m	2.1m
TRAILER	0.932	0.929	0.930
CAR BI	0.959	0.972	0.967
NAASRA	0.955	0.972	0.966
MM-02	0.933	0.953	0.945

500mm INTERVAL

	1.5m	2.0m	2.5m	3.0m
TRAILER	0.920	0.913	0.886	–
CAR BI	0.963	0.970	0.967	0.962
NAASRA	0.964	0.978	0.977	0.973
MM-02	0.941	0.958	0.958	0.959

TABLE 16

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING CONTIGUOUS BASELENGTHS)   BRASIL IRRE DATA

NEARSIDE WHEELPATH

20 Km/hr

100mm INTERVAL

	1.5m	1.9m	2.0m
TRAILER	0.928	0.924	0.919
CAR BI	0.969	0.968	0.965
NAASRA	0.967	0.967	0.964
MM-02	0.965	0.962	0.958

200mm INTERVAL

	1.6m	1.8m	2.0m
TRAILER	0.930	0.924	0.918
CAR BI	0.967	0.964	0.961
NAASRA	0.966	0.964	0.960
MM-02	0.958	0.955	0.950

300mm INTERVAL

	1.5m	1.8m	2.1m
TRAILER	0.927	0.917	0.907
CAR BI	0.972	0.966	0.958
NAASRA	0.971	0.965	0.958
MM-02	0.963	0.956	0.948

500mm INTERVAL

	1.5m	2.0m	2.5m	3.0m
TRAILER	0.908	0.897	0.885	0.873
CAR BI	0.954	0.942	0.929	0.914
NAASRA	0.954	0.943	0.929	0.914
MM-02	0.943	0.931	0.916	0.900

TABLE 17

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING CONTIGUOUS BASELENGTHS)   BRASIL IRRE DATA

NEARSIDE WHEELPATH

32 Km/hr

100mm INTERVAL

	1.5m	1.8m	2.0m
TRAILER	0.941	0.948	0.948
CAR BI	0.963	0.971	0.974
NAASRA	0.962	0.972	0.975
MM-02	0.949	0.961	0.965

200mm INTERVAL

	1.6m	1.8m	2.0m
TRAILER	0.952	0.952	0.951
CAR BI	0.970	0.973	0.974
NAASRA	0.971	0.974	0.976
MM-02	0.955	0.960	0.963

300mm INTERVAL

	1.5m	1.8m	2.1m
TRAILER	0.953	0.951	0.947
CAR BI	0.977	0.979	0.979
NAASRA	0.978	0.981	0.980
MM-02	0.964	0.969	0.970

500mm INTERVAL

	1.5m	2.0m	2.5m	3.0m
TRAILER	0.943	0.940	0.934	0.927
CAR BI	0.970	0.969	0.965	0.958
NAASRA	0.972	0.971	0.967	0.961
MM-02	0.960	0.961	0.957	0.951

TABLE 18

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING CONTIGUOUS BASELENGTHS)   BRASIL IRRE DATA

NEARSIDE WHEELPATH

50 Km/hr

100mm INTERVAL

	1.5m	1.8m	2.0m
TRAILER	0.937	0.949	0.952
CAR BI	0.945	0.958	0.963
NAASRA	0.939	0.956	0.963
MM-02	0.923	0.940	0.947

200mm INTERVAL

	1.6m	1.8m	2.0m
TRAILER	0.951	0.954	0.955
CAR BI	0.960	0.965	0.968
NAASRA	0.957	0.965	0.970
MM-02	0.937	0.945	0.951

300mm INTERVAL

	1.5m	1.8m	2.1m
TRAILER	0.957	0.959	0.958
CAR BI	0.965	0.970	0.973
NAASRA	0.963	0.971	0.976
MM-02	0.944	0.953	0.959

500mm INTERVAL

	1.5m	2.0m	2.5m	3.0m
TRAILER	0.950	0.950	0.946	0.938
CAR BI	0.967	0.969	0.969	0.966
NAASRA	0.969	0.975	0.978	0.977
MM-02	0.949	0.957	0.960	0.960

TABLE 19

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING DISCRETE BASELENGTHS)   BRASIL IRRE DATA

OFFSIDE WHEELPATH

20 Km/hr

100mm INTERVAL

	1.5m	1.8m	2.0m
TRAILER	—	—	—
CAR BI	0.880	0.884	0.882
NAASRA	0.870	0.874	0.873
MM-02	0.899	0.899	0.898

200mm INTERVAL

	1.6m	1.8m	2.0m
TRAILER	—	—	—
CAR BI	0.899	0.883	0.882
NAASRA	0.890	0.874	0.874
MM-02	0.915	0.897	0.896

300mm INTERVAL

	1.5m	1.8m	2.1m
TRAILER	—	—	—
CAR BI	0.884	0.875	0.860
NAASRA	0.874	0.866	0.852
MM-02	0.899	0.888	0.874

500mm INTERVAL

	1.5m	2.0m	2.5m	3.0m
TRAILER	—	—	—	—
CAR BI	0.864	0.870	0.878	0.878
NAASRA	0.856	0.861	0.870	0.871
MM-02	0.881	0.885	0.895	0.890

TABLE 20

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING DISCRETE BASELENGTHS) BRASIL IRRE DATA

OFFSIDE WHEELPATH

32 Km/hr

100mm INTERVAL

	1.5m	1.8m	2.0m
TRAILER	—	—	—
CAR BI	0.897	0.912	0.909
NAASRA	0.884	0.899	0.898
MM-02	0.916	0.932	0.928

200mm INTERVAL

	1.6m	1.8m	2.0m
TRAILER	—	—	—
CAR BI	0.920	0.914	0.912
NAASRA	0.908	0.902	0.901
MM-02	0.936	0.934	0.929

300mm INTERVAL

	1.5m	1.8m	2.1m
TRAILER	—	—	—
CAR BI	0.913	0.913	0.905
NAASRA	0.901	0.902	0.895
MM-02	0.932	0.935	0.929

500mm INTERVAL

	1.5m	2.0m	2.5m	3.0m
TRAILER	—	—	—	—
CAR BI	0.898	0.906	0.910	0.919
NAASRA	0.887	0.894	0.900	0.909
MM-02	0.922	0.928	0.931	0.937

TABLE 21

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING DISCRETE BASELENGTHS)   BRASIL IRRE DATA

OFFSIDE WHEELPATH

50 Km/hr

100mm INTERVAL

	1.5m	1.8m	2.0m
TRAILER	—	—	—
CAR BI	0.850	0.869	0.870
NAASRA	0.835	0.859	0.856
MM-02	0.870	0.893	0.887

200mm INTERVAL

	1.6m	1.8m	2.0m
TRAILER	—	—	—
CAR BI	0.878	0.874	0.875
NAASRA	0.865	0.866	0.862
MM-02	0.897	0.900	0.890

300mm INTERVAL

	1.5m	1.8m	2.1m
TRAILER	—	—	—
CAR BI	0.875	0.877	0.872
NAASRA	0.862	0.870	0.867
MM-02	0.895	0.904	0.902

500mm INTERVAL

	1.5m	2.0m	2.5m	3.0m
TRAILER	—	—	—	—
CAR BI	0.860	0.869	0.876	0.889
NAASRA	0.848	0.857	0.862	0.878
MM-02	0.883	0.885	0.891	0.903

TABLE 22

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 23

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 24

COMPARISON OF R SQUARE VALUES OF DIFFERENT STATISTICS CORRELATED AGAINST RTRRMS

	R SQUARE VALUES					
	RMSD*	RMSVE*	M Avg*	APL $CP_{2.5}$	RARV	QI
BRASIL IRRE						
TRAILER	.948	.955	.958	.924	.964	.889
CAR BI	.980	.978	.910	.933	.935	.934
NAASRA	.982	.980	.919	.943	.940	.938
MM-02	.970	.965	.874	.951	.908	.933
Average R^2	.970	.970	.915	.938	.937	.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 25

RTRRMS MEASUREMENTS (MM/KM)

ST LUCIA 1983

SECTION	DATSUN			CORTINA		
	20Km/hr	32Km/hr	50Km/hr	20Km/hr	32Km/hr	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 26

TABLE OF R SQUARE VALUES OF RMS VERTICAL ELEVATION Vs RTRRMS

(USING DISCRETE BASELENGTHS) ST LUCIA DATA

NEARSIDE WHEELPATH

20 Km/hr

100mm INTERVAL

	1.6m	1.8m	2.0m	3.0m
DATSUN	0.892	0.908	0.893	0.855
CORTINA	0.944	0.955	0.953	0.941

200mm INTERVAL

	1.6m	2.0m	3.2m
DATSUN	0.897	0.908	--
CORTINA	0.938	0.952	--

300mm INTERVAL

	1.8m	2.4m	3.0m
DATSUN	0.887	--	--
CORTINA	0.946	--	--

500mm INTERVAL

	2.0m	3.0m
DATSUN	0.861	0.819
CORTINA	0.956	0.932

TABLE 27

TABLE OF R SQUARE VALUES OF RMS VERTICAL ELEVATION Vs RTRRMS

(USING DISCRETE BASELENGTHS)　　ST LUCIA DATA

NEARSIDE WHEELPATH

32 Km/hr

100mm INTERVAL

	1.6m	1.8m	2.0m	3.0m
DATSUN	0.886	0.917	0.908	0.909
CORTINA	0.893	0.912	0.916	0.954

200mm INTERVAL

	1.6m	2.0m	3.2m
DATSUN	0.887	0.917	0.925
CORTINA	0.884	0.906	0.960

300mm INTERVAL

	1.8m	2.4m	3.0m
DATSUN	0.906	0.891	0.894
CORTINA	0.911	0.938	0.945

500mm INTERVAL

	2.0m	3.0m
DATSUN	0.890	0.877
CORTINA	0.944	0.954

TABLE 28

TABLE OF R SQUARE VALUES OF RMS VERTICAL ELEVATION vs RTRRMS

(USING DISCRETE BASELENGTHS)   ST LUCIA DATA

NEARSIDE WHEELPATH

50 Km/hr

100mm INTERVAL

	1.6m	1.8m	2.0m	3.0m
DATSUN	0.794	0.845	0.869	0.913
CORTINA	0.841	0.864	0.869	0.933

200mm INTERVAL

	1.6m	2.0m	3.2m
DATSUN	0.768	0.865	--
CORTINA	0.830	0.856	--

300mm INTERVAL

	1.8m	2.4m	3.0m
DATSUN	0.847	--	--
CORTINA	0.868	--	--

500mm INTERVAL

	2.0m	3.0m
DATSUN	0.865	0.885
CORTINA	0.910	0.937

TABLE 29

TABLE OF R SQUARE VALUES OF MOVING AVERAGE Vs RTRRMS

ST LUCIA DATA

20 Km/hr

NEARSIDE WHEELPATH | OFFSIDE WHEELPATH

200mm INTERVAL

	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	DATSUN	0.859	0.884	0.892	0.882
CORTINA	0.859	0.893	0.908	0.904	CORTINA	0.884	0.905	0.916	0.923

300mm INTERVAL

	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	DATSUN	0.831	0.879	0.886	0.878	0.862
CORTINA	0.854	0.896	0.899	0.891	0.871	CORTINA	0.879	0.913	0.925	0.924	0.917

TABLE 30

TABLE OF R SQUARE VALUES OF MOVING AVERAGE vs RTRRMS

ST LUCIA DATA

32 Km/hr

NEARSIDE WHEELPATH　　　　OFFSIDE WHEELPATH

200mm INTERVAL

	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	DATSUN	0.839	0.881	0.898	0.898
CORTINA	0.767	0.842	0.879	0.891	CORTINA	0.808	0.847	0.874	0.902

300mm INTERVAL

	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	DATSUN	0.810	0.882	0.900	0.896	0.888
CORTINA	0.785	0.855	0.890	0.907	0.910	CORTINA	0.794	0.858	0.889	0.902	0.912

TABLE 31

TABLE OF R SQUARE VALUES OF MOVING AVERAGE vs RTRRMS

ST LUCIA DATA

50 Km/hr

200mm INTERVAL

NEARSIDE WHEELPATH					OFFSIDE WHEELPATH				
	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	DATSUN	0.735	0.811	0.856	0.877
CORTINA	0.717	0.782	0.830	0.882	CORTINA	0.742	0.791	0.826	0.866

300mm INTERVAL

NEARSIDE WHEELPATH						OFFSIDE WHEELPATH					
	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	DATSUN	0.693	0.819	0.858	0.876	0.874
CORTINA	0.717	0.801	0.850	0.881	0.898	CORTINA	0.728	0.806	0.847	0.867	0.887

TABLE 32

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	3.893	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 33

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	2.220	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 34

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	n/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 35

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	2.464
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 36

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING DISCRETE BASELENGTHS)　　ST LUCIA DATA

20 Km/hr

NEARSIDE WHEELPATH　　OFFSIDE WHEELPATH

100mm INTERVAL

NEARSIDE WHEELPATH

	1.5m	1.8m	2.0m	2.2m	2.4m	2.6m
DATSUN	0.917	0.915	0.901	0.911	0.883	0.872
CORTINA	0.933	0.957	0.955	0.966	0.958	0.956

OFFSIDE WHEELPATH

	1.5m	1.8m	2.0m
DATSUN	0.889	0.889	0.895
CORTINA	0.886	0.894	0.895

200mm INTERVAL

NEARSIDE WHEELPATH

	1.6m	1.8m	2.0m	2.2m	2.4m
DATSUN	0.910	0.922	0.912	0.914	0.890
CORTINA	0.945	0.956	0.955	0.964	0.962

OFFSIDE WHEELPATH

	1.6m	1.8m	2.0m
DATSUN	0.888	0.884	0.893
CORTINA	0.908	0.907	0.901

300mm INTERVAL

NEARSIDE WHEELPATH

	1.5m	1.8m	2.1m
DATSUN	0.891	0.897	0.887
CORTINA	0.943	0.953	0.951

OFFSIDE WHEELPATH

	1.5m	1.8m	2.1m
DATSUN	0.884	0.885	0.879
CORTINA	0.925	0.936	0.931

500mm INTERVAL

NEARSIDE WHEELPATH

	1.5m	2.0m	2.5m	3.0m
DATSUN	0.851	0.860	0.831	0.823
CORTINA	0.939	0.949	0.938	0.919

OFFSIDE WHEELPATH

	1.5m	2.0m	2.5m	3.0m
DATSUN	0.855	0.876	0.882	0.862
CORTINA	0.897	0.905	0.917	0.921

TABLE 37

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING DISCRETE BASELENGTHS)   ST LUCIA DATA

32 Km/hr

NEARSIDE WHEELPATH   OFFSIDE WHEELPATH

100mm INTERVAL

	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	DATSUN	0.891	0.889	0.909
CORTINA	0.877	0.913	0.918	0.949	0.948	0.944	CORTINA	0.812	0.826	0.836

200mm INTERVAL

	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	DATSUN	0.892	0.893	0.912
CORTINA	0.899	0.912	0.916	0.947	0.952	CORTINA	0.845	0.850	0.850

300mm INTERVAL

	1.5m	1.8m	2.1m		1.5m	1.8m	2.1m
DATSUN	0.902	0.926	0.925	DATSUN	0.909	0.914	0.920
CORTINA	0.913	0.924	0.947	CORTINA	0.881	0.895	0.905

500mm INTERVAL

	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	DATSUN	0.904	0.913	0.927	0.912
CORTINA	0.936	0.942	0.959	0.950	CORTINA	0.879	0.875	0.905	0.919

TABLE 38

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING DISCRETE BASELENGTHS)   ST LUCIA DATA

50 Km/hr

NEARSIDE WHEELPATH   OFFSIDE WHEELPATH

100mm INTERVAL

	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	DATSUN	0.769	0.799	0.846
CORTINA	0.825	0.865	0.871	0.913	0.914	0.914	CORTINA	0.755	0.775	0.790

200mm INTERVAL

	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	DATSUN	0.796	0.806	0.847
CORTINA	0.850	0.863	0.869	0.912	0.918	CORTINA	0.792	0.799	0.804

300mm INTERVAL

	1.5m	1.8m	2.1m		1.5m	1.8m	2.1m
DATSUN	0.851	0.887	0.920	DATSUN	0.838	0.851	0.881
CORTINA	0.873	0.883	0.917	CORTINA	0.839	0.854	0.869

500mm INTERVAL

	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	DATSUN	0.868	0.884	0.906	0.891
CORTINA	0.908	0.908	0.944	0.936	CORTINA	0.851	0.843	0.882	0.901

TABLE 39

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING CONTIGUOUS BASELENGTHS)   ST LUCIA DATA

20 Km/hr

NEARSIDE WHEELPATH   OFFSIDE WHEELPATH

200mm INTERVAL

	1.6m	1.8m	2.0m		1.6m	1.8m	2.0m
DATSUN	0.923	0.921	0.916	DATSUN	0.883	0.889	0.892
CORTINA	0.949	0.955	0.960	CORTINA	0.897	0.904	0.910

300mm INTERVAL

	1.5m	1.8m	2.1m		1.5m	1.8m	2.1m
DATSUN	0.893	0.886	0.876	DATSUN	0.881	0.877	0.885
CORTINA	0.949	0.952	0.951	CORTINA	0.925	0.929	0.931

TABLE 40

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING CONTIGUOUS BASELENGTHS) ST LUCIA DATA

32 Km/hr

NEARSIDE WHEELPATH OFFSIDE WHEELPATH

200mm INTERVAL

NEARSIDE WHEELPATH	1.6m	1.8m	2.0m
DATSUN	0.920	0.928	0.931
CORTINA	0.898	0.915	0.928

OFFSIDE WHEELPATH	1.6m	1.8m	2.0m
DATSUN	0.886	0.900	0.909
CORTINA	0.836	0.852	0.864

300mm INTERVAL

NEARSIDE WHEELPATH	1.5m	1.8m	2.1m
DATSUN	0.909	0.914	0.913
CORTINA	0.919	0.934	0.945

OFFSIDE WHEELPATH	1.5m	1.8m	2.1m
DATSUN	0.905	0.910	0.921
CORTINA	0.879	0.894	0.904

TABLE 41

TABLE OF R SQUARE VALUES OF RMS DEVIATION vs RTRRMS

(USING CONTIGUOUS BASELENGTHS) ST LUCIA DATA

50 Km/hr

NEARSIDE WHEELPATH OFFSIDE WHEELPATH

200mm INTERVAL

NEARSIDE WHEELPATH

	1.6m	1.8m	2.0m
DATSUN	0.841	0.868	0.895
CORTINA	0.848	0.869	0.887

OFFSIDE WHEELPATH

	1.6m	1.8m	2.0m
DATSUN	0.790	0.818	0.839
CORTINA	0.782	0.803	0.819

300mm INTERVAL

NEARSIDE WHEELPATH

	1.5m	1.8m	2.1m
DATSUN	0.834	0.883	0.902
CORTINA	0.878	0.899	0.916

OFFSIDE WHEELPATH

	1.5m	1.8m	2.1m
DATSUN	0.833	0.849	0.880
CORTINA	0.835	0.855	0.870

TABLE 42

COMPARISON OF CALIBRATED AND UNCALIBRATED ROUGHNESS MEASUREMENTS

BRASIL IRRE

SECTION	RMSD	CAR BI		NAASRA		MM-02		REFERENCE ROUGHNESS
		Uncal	Cal	Uncal	Cal	Uncal	Cal	
CA04	1.422	3064	3151	3050	3248	6906	3161	2970
CA05	1.299	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 43

COMPARISON OF CALIBRATED AND UNCALIBRATED ROUGHNESS MEASUREMENTS

ST LUCIA STUDY

SECTION	RMSD	DATSUN		CORTINA		REFERENCE ROUGHNESS
		Uncal	Cal	Uncal	Cal	
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	4.273	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 1

BI TRAILER (Average) vs CAR BI

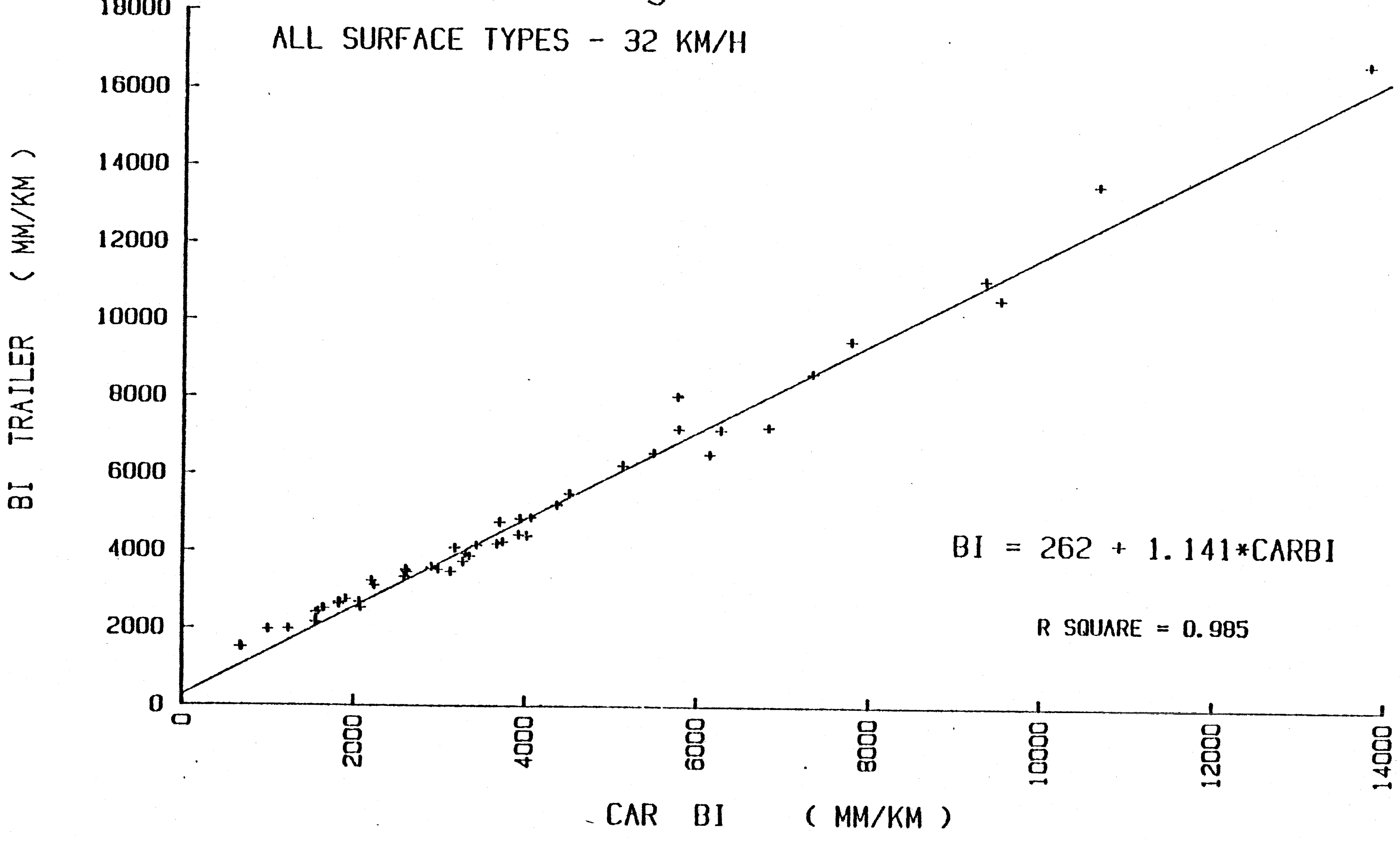


FIG 2

BI TRAILER (Average) vs NAASRA

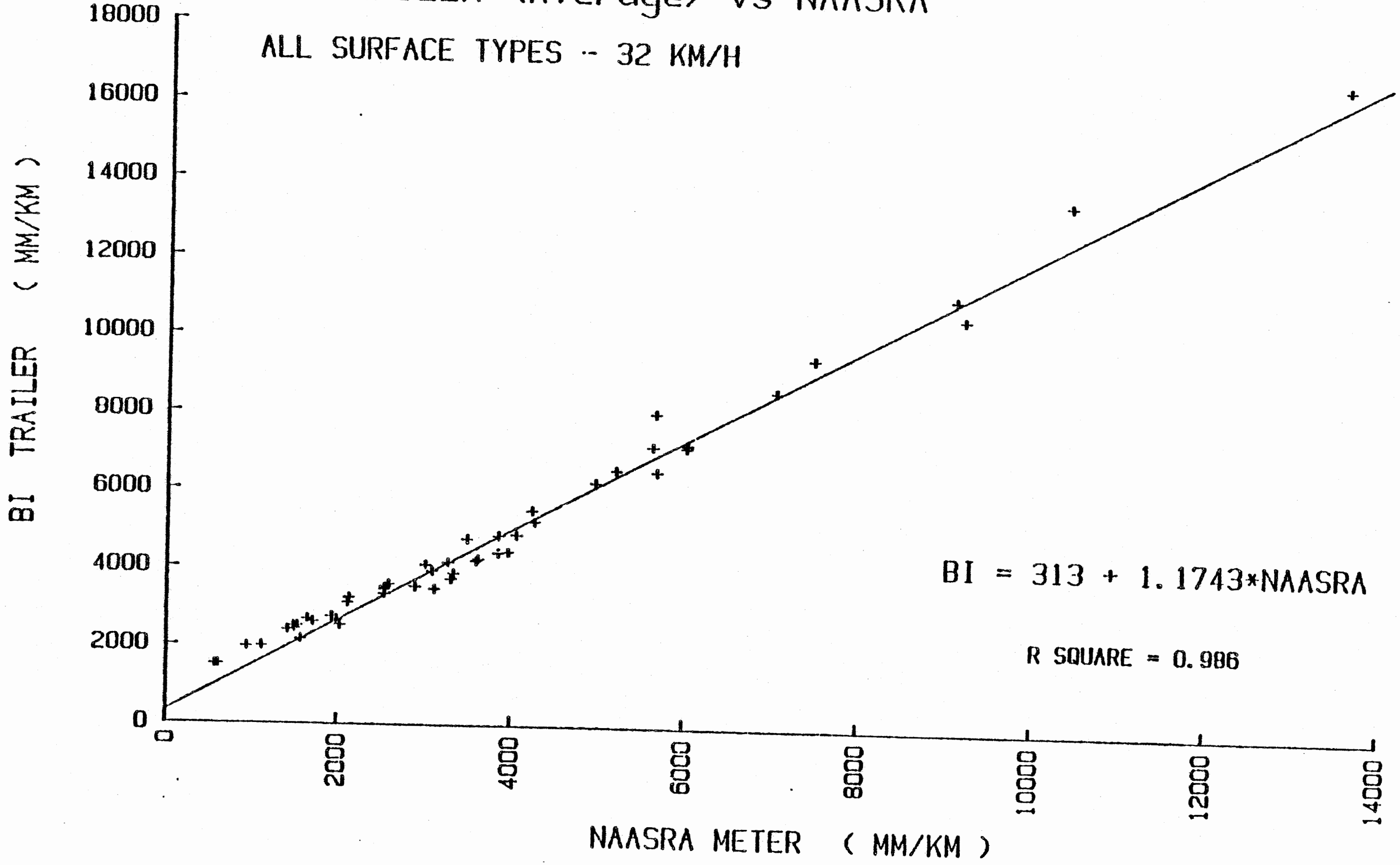


FIG 3

BI TRAILER (Average) vs MM-02

ALL SURFACE TYPES - 32 KM/H

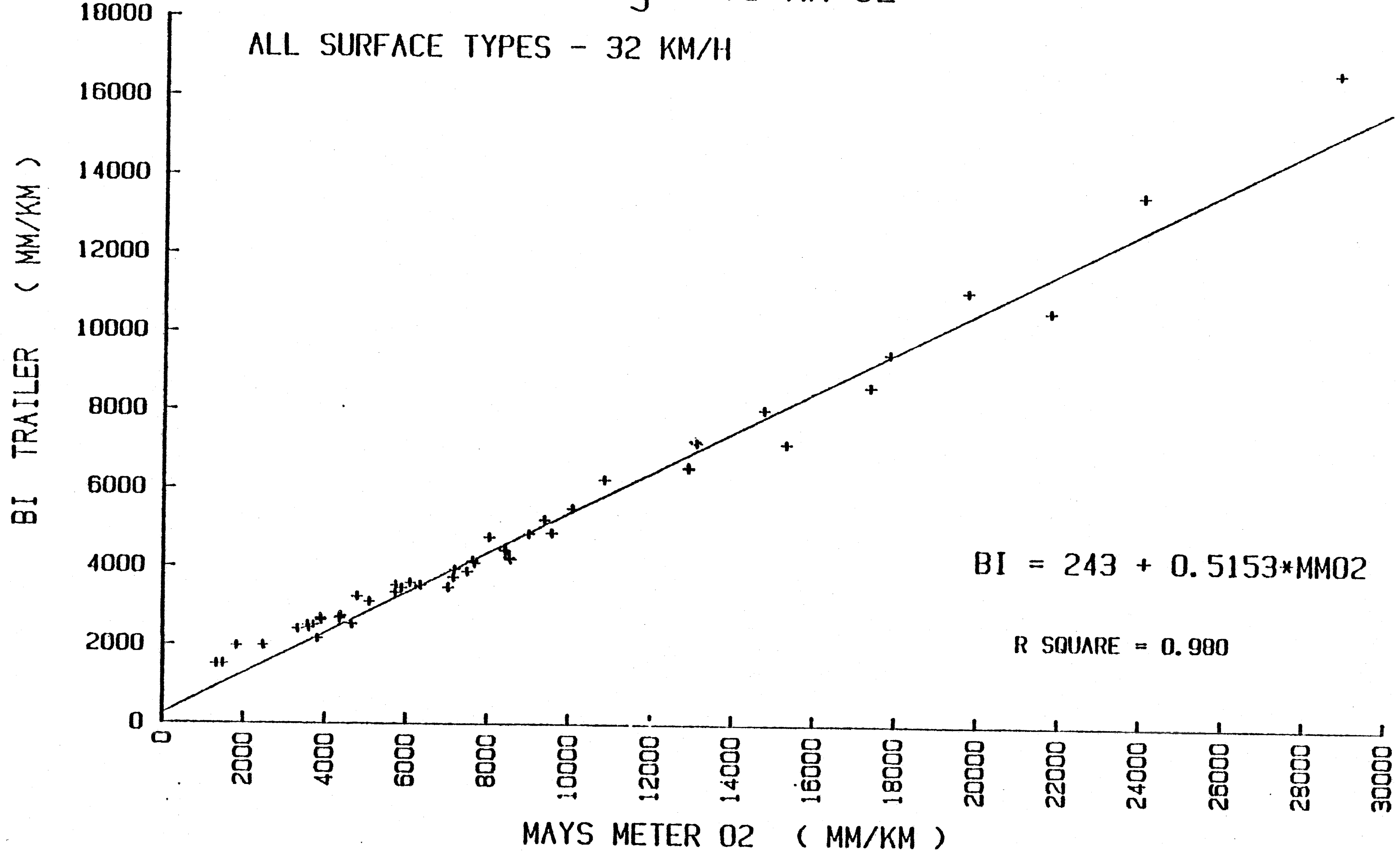


FIG 4

STANDARDISED REFERENCE ROUGHNESS EQUATION

(DERIVED FROM BI TRAILER / RMSD(1.8/300) CORRELATION)

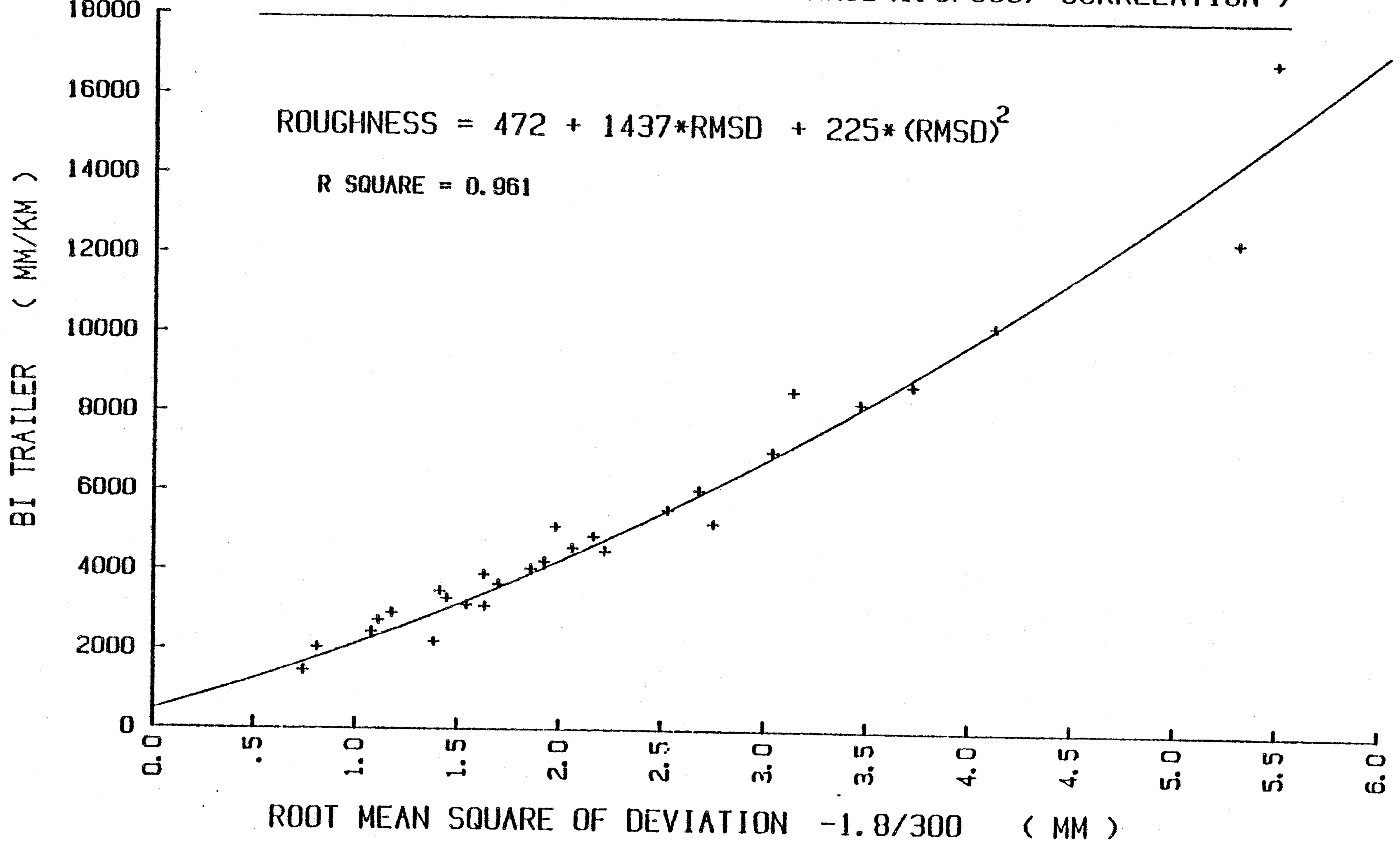


FIG 5

UNCALIBRATED CAR BI ROUGHNESS

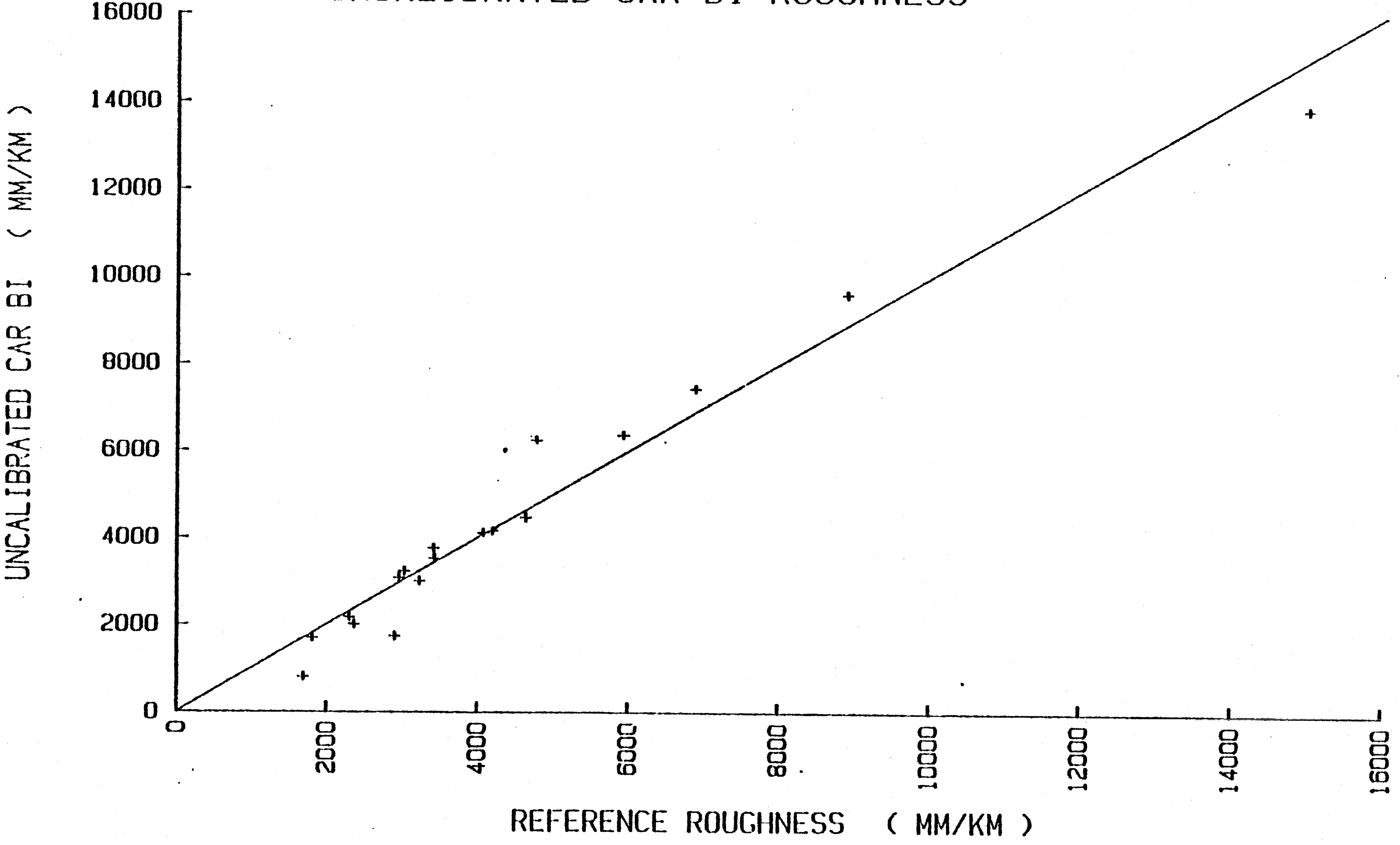


FIG 6

CALIBRATED CAR BI ROUGHNESS

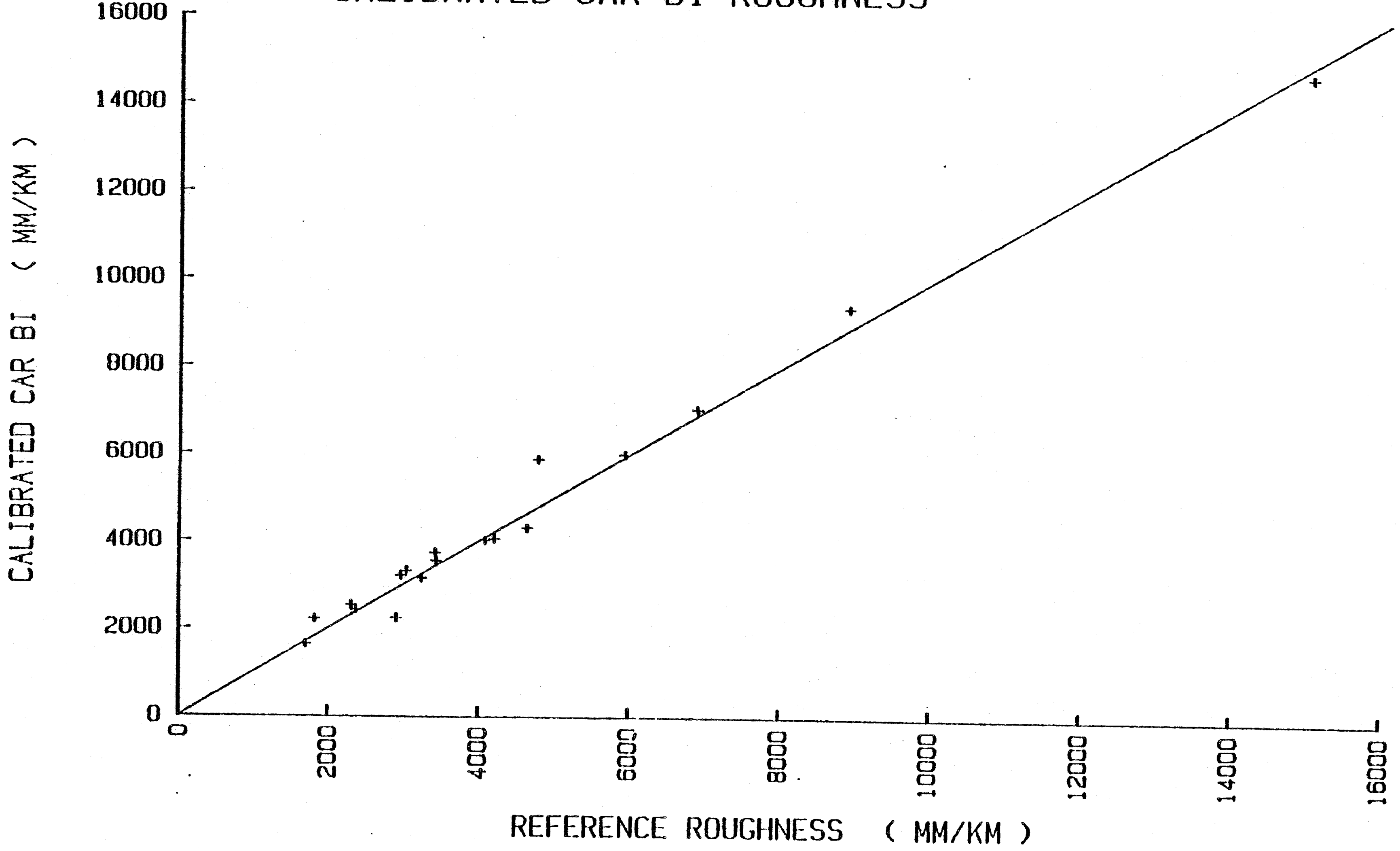


FIG 7

UNCALIBRATED NAASRA ROUGHNESS

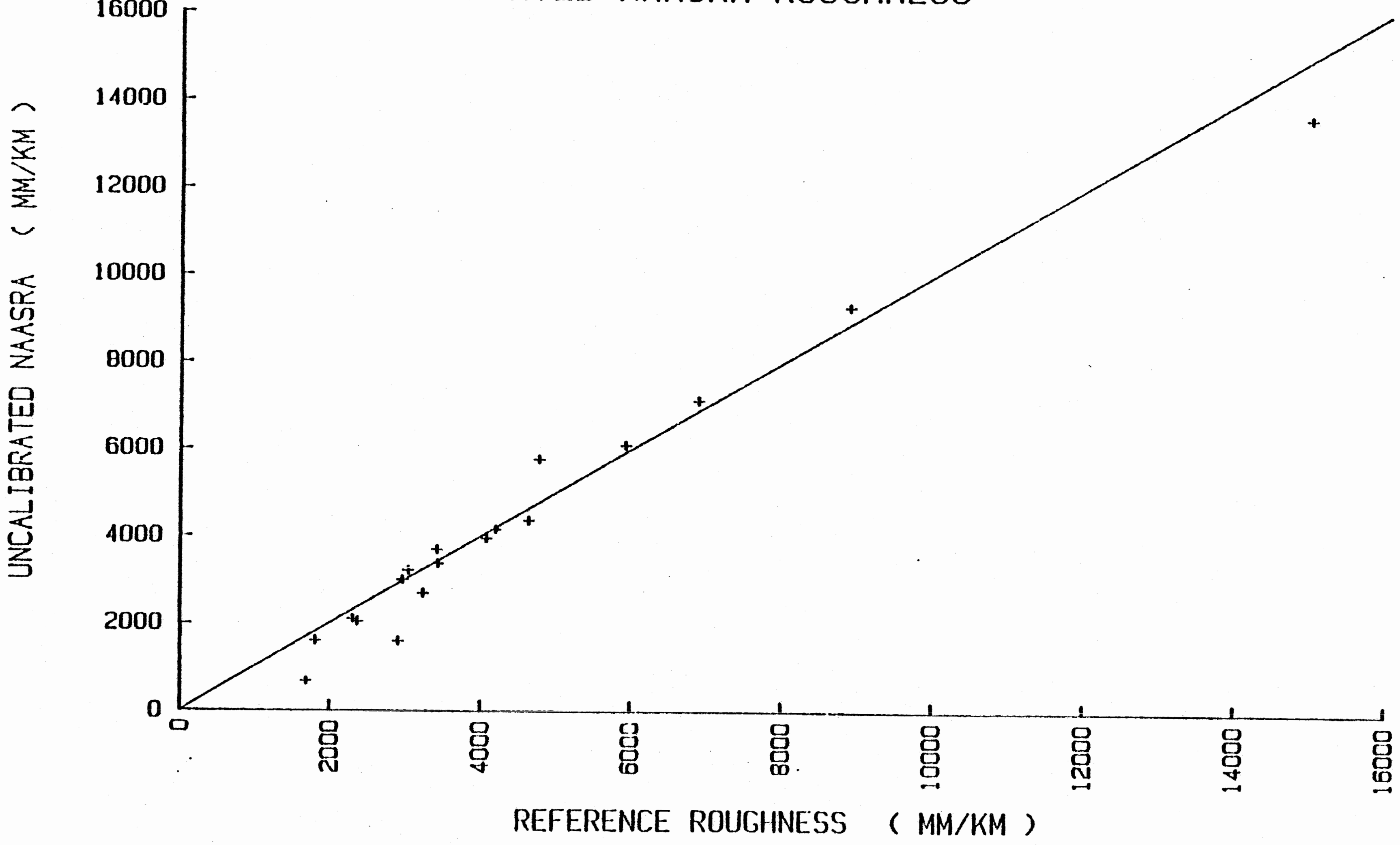


FIG 8

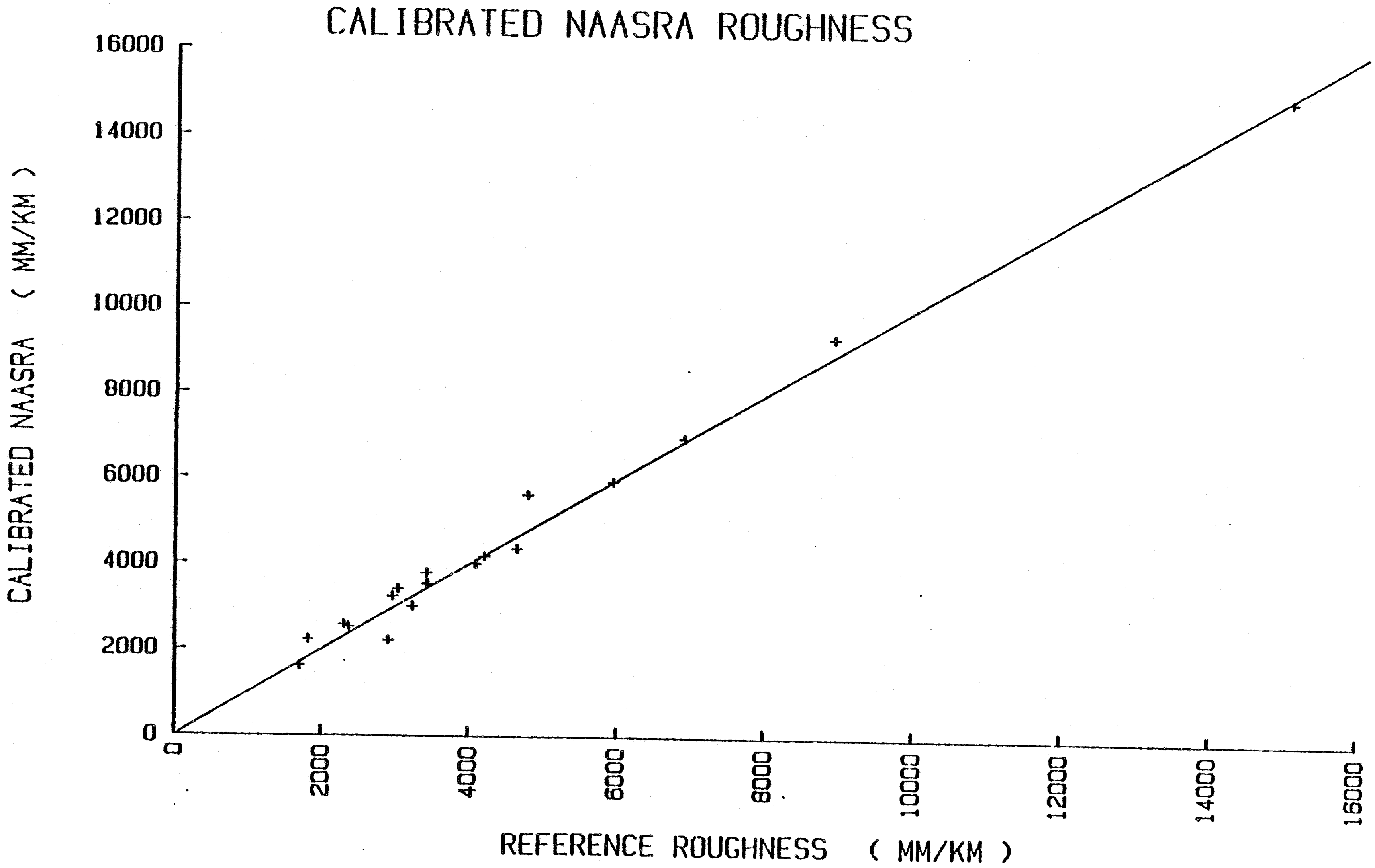

CALIBRATED NAASRA ROUGHNESS
CALIBRATED NAASRA (MM/KM)
16000
14000
12000
10000
8000
6000
4000
2000
0
0
2000
4000
6000
8000
10000
12000
14000
16000
REFERENCE ROUGHNESS (MM/KM)

FIG 9

UNCALIBRATED MM-02 ROUGHNESS

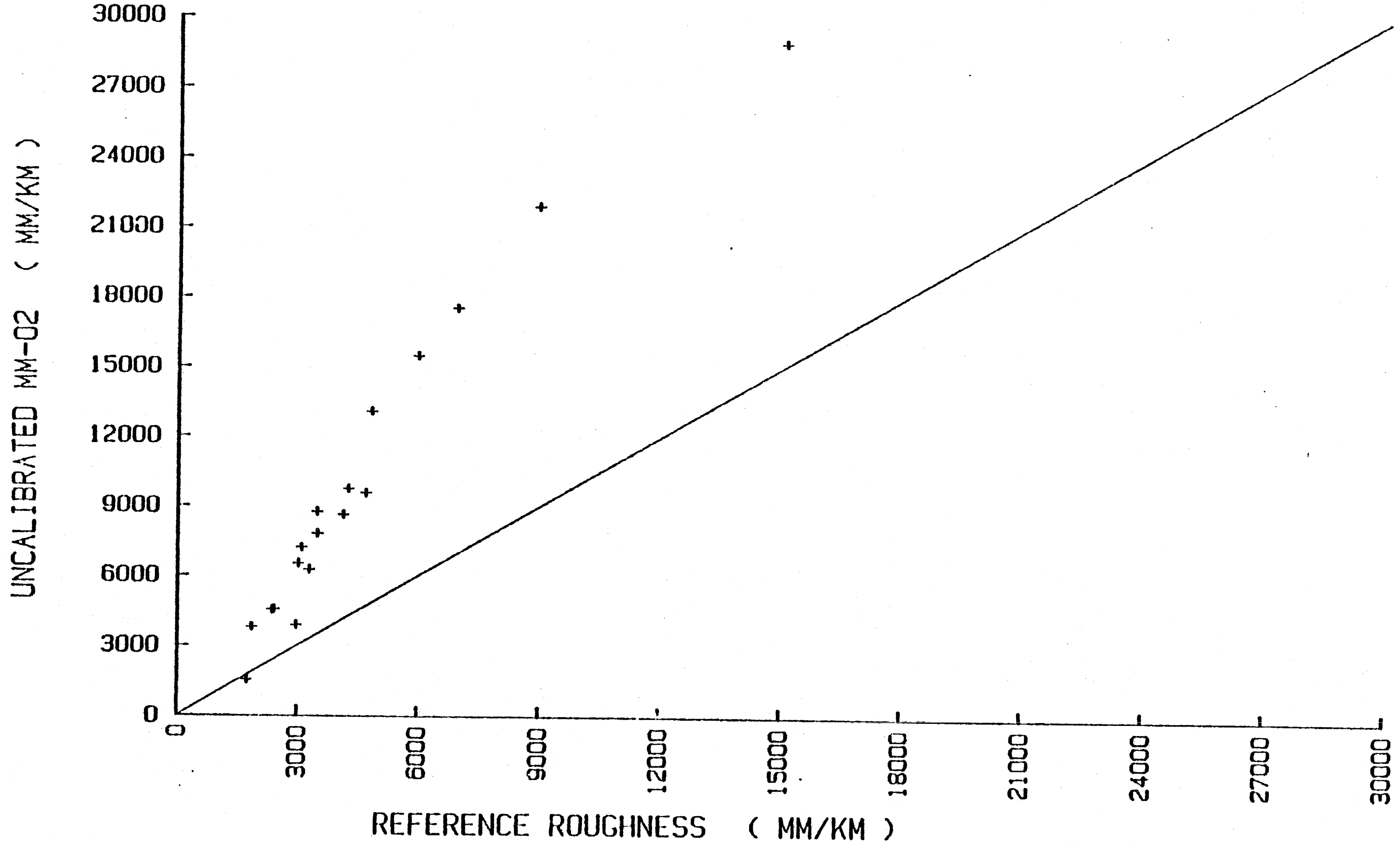


FIG 10

CALIBRATED MM-02 ROUGHNESS

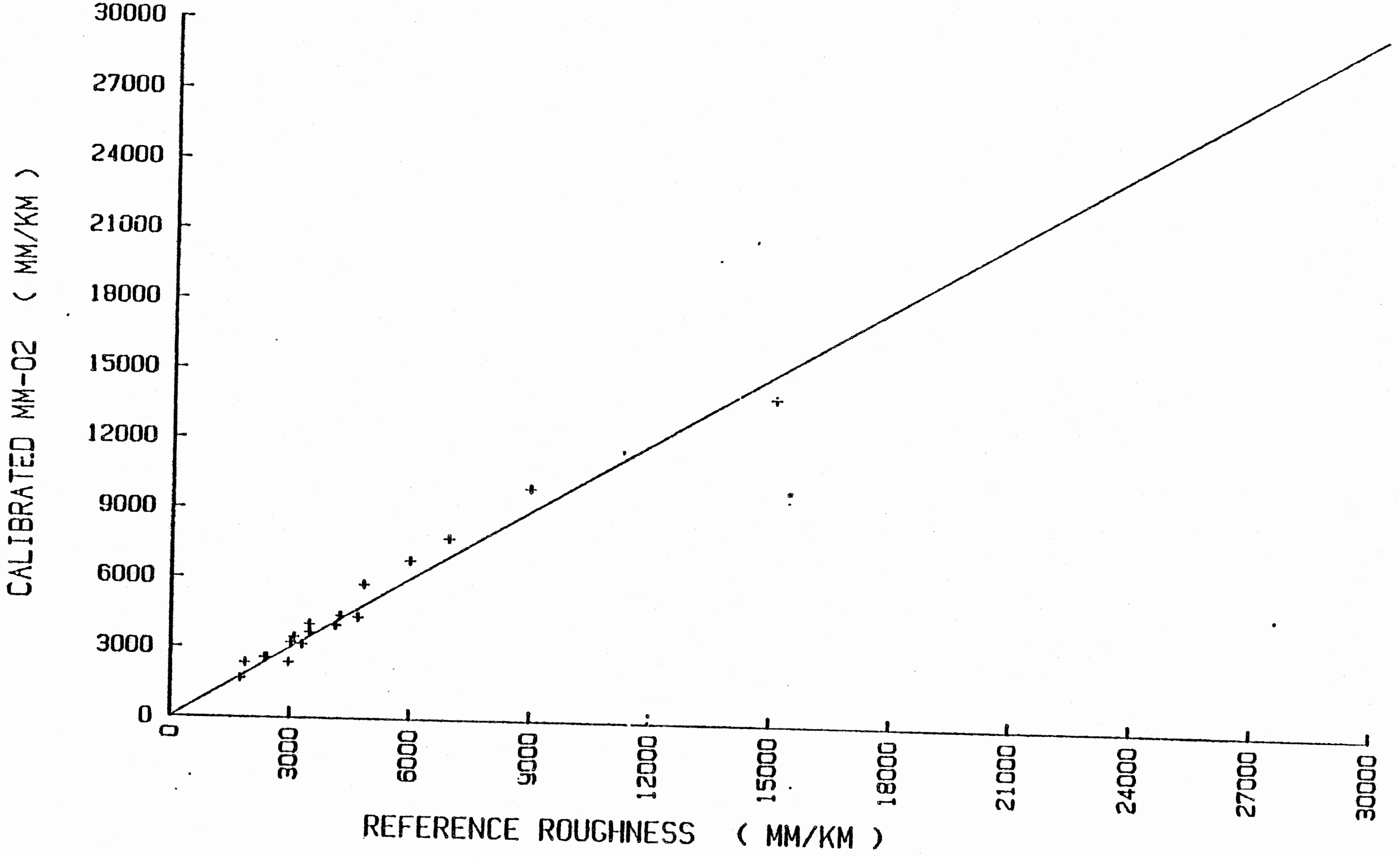
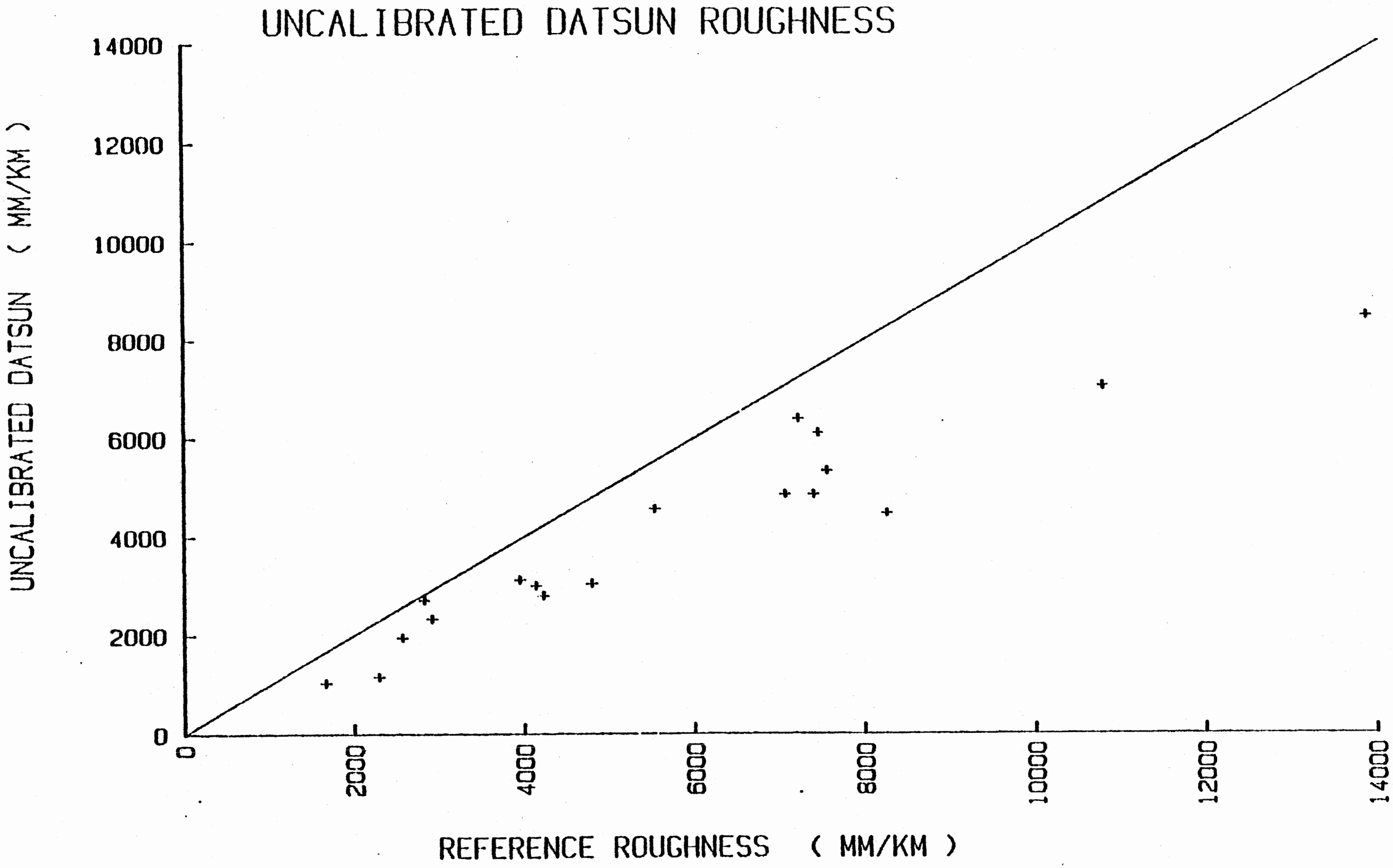


FIG 11



UNCALIBRATED DATSUN ROUGHNESS

FIG 12

CALIBRATED DATSUN ROUGHNESS

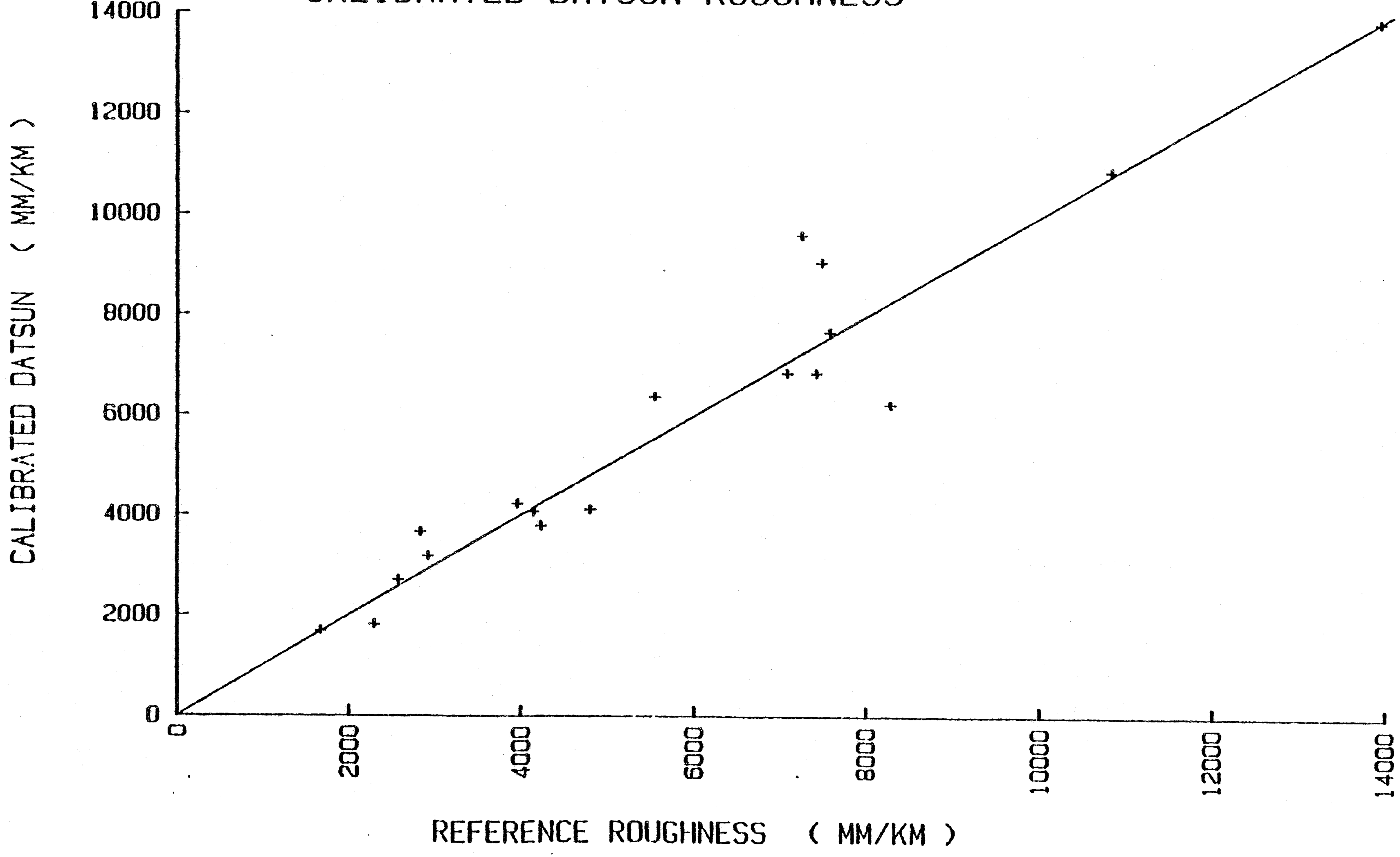


FIG 13

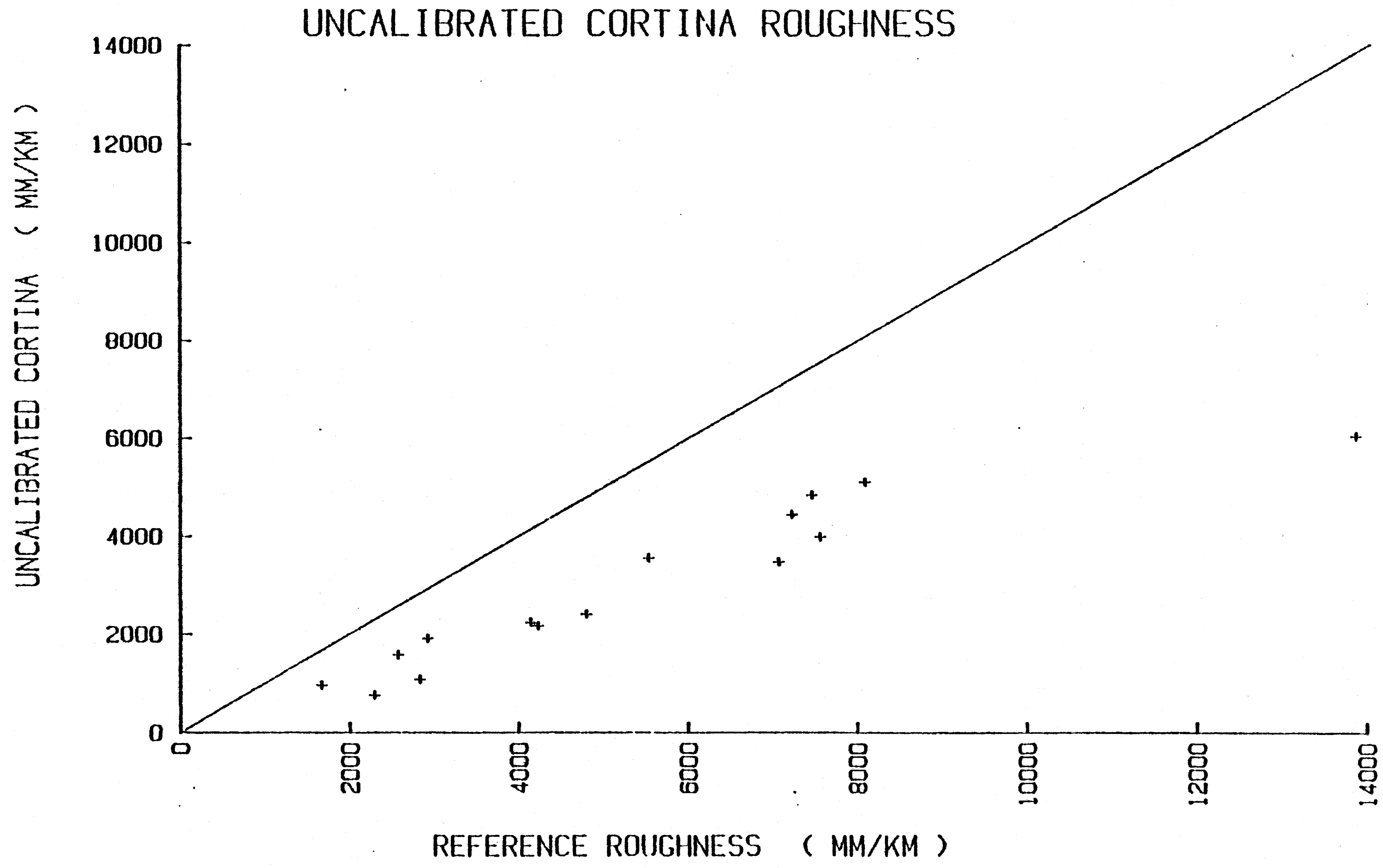
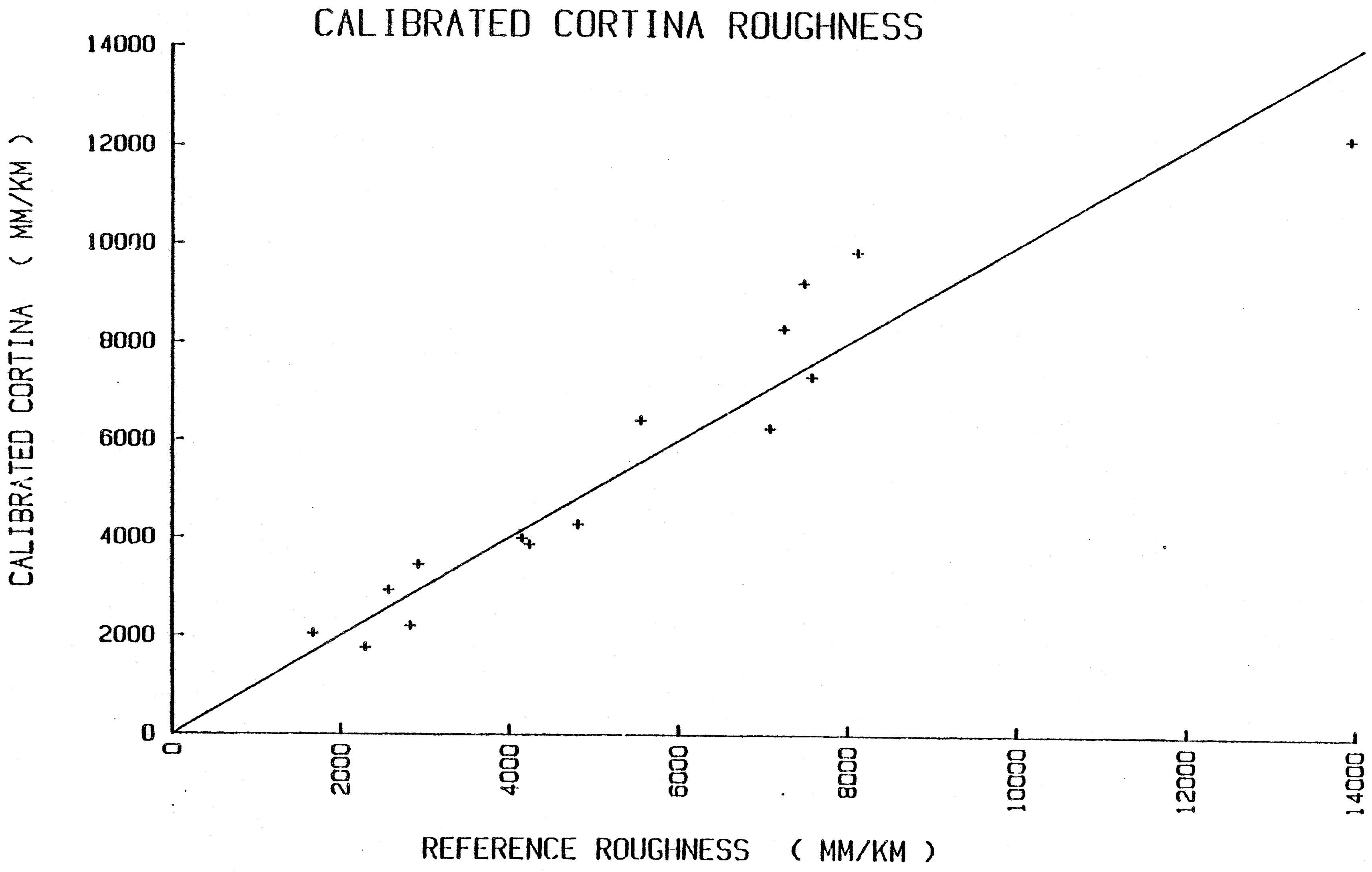

UNCALIBRATED CORTINA ROUGHNESS

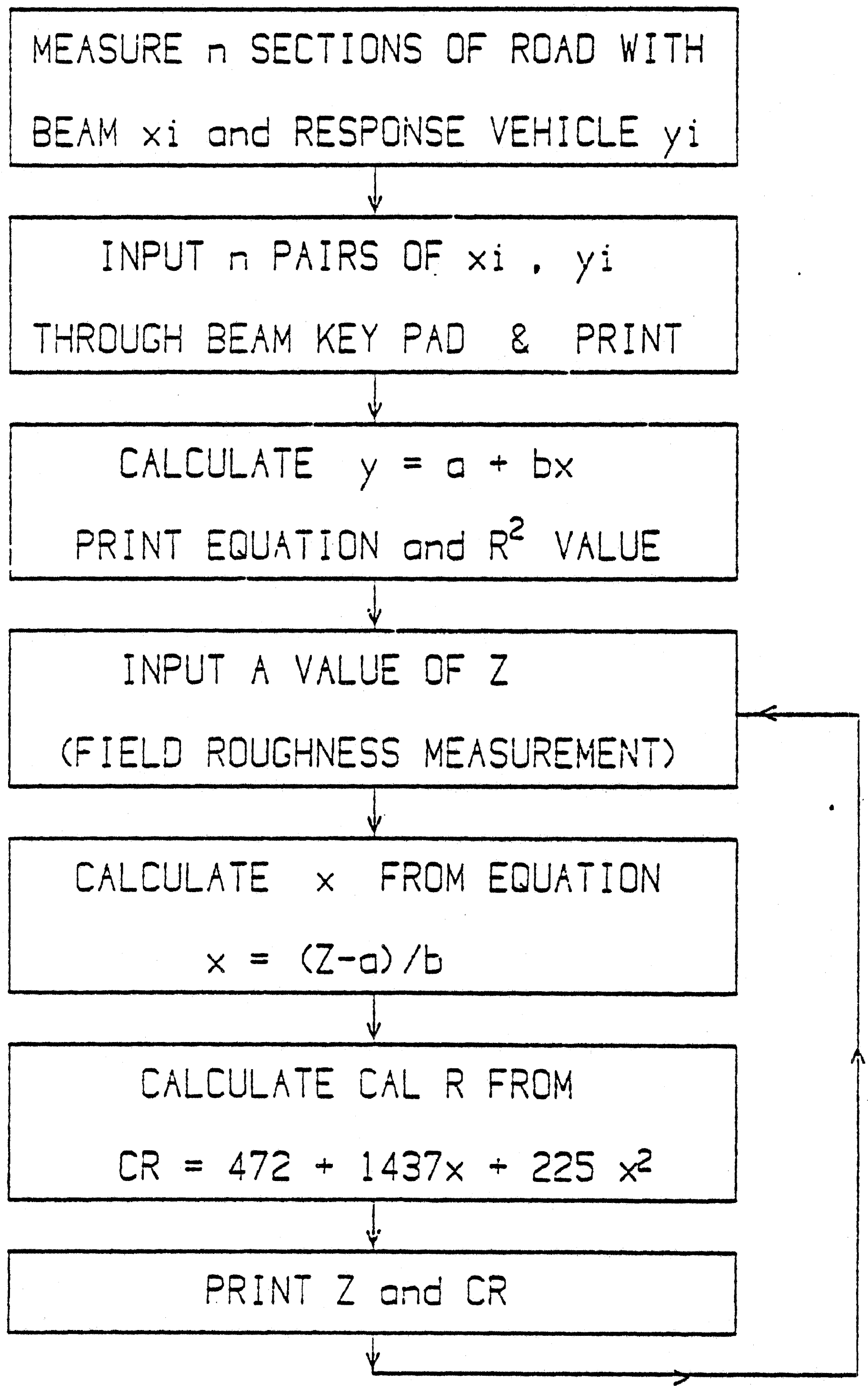
FIG 14



CALIBRATED CORTINA ROUGHNESS

FIG 15

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 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

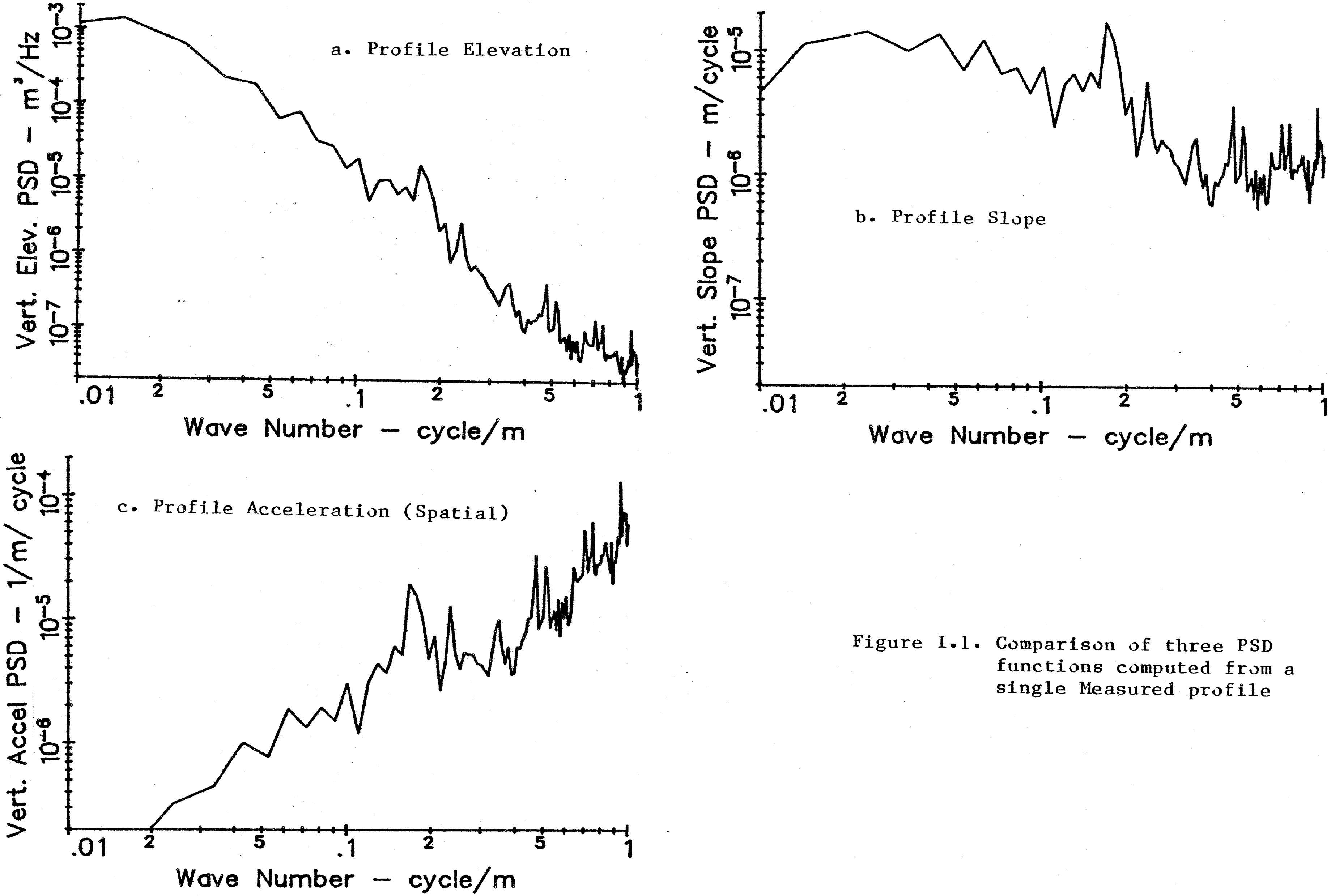


Figure I.1. Comparison of three PSD functions computed from a single Measured profile terms of profile slope.

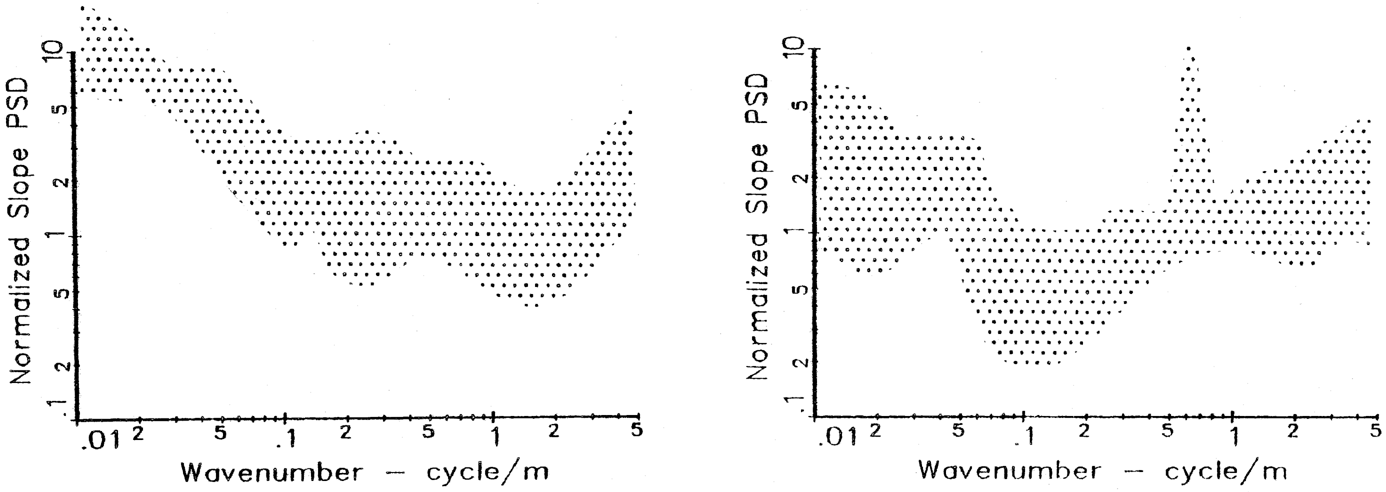
Figure I.2 presents aggregate PSD functions, obtained by graphically overlaying the PSD functions for individual profiles obtained with the TRRL Beam. The amplitudes of each individual plot were normalized by the squared $RARS_{50}$ roughness value known for that particular wheeltrack. When the PSD functions 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.

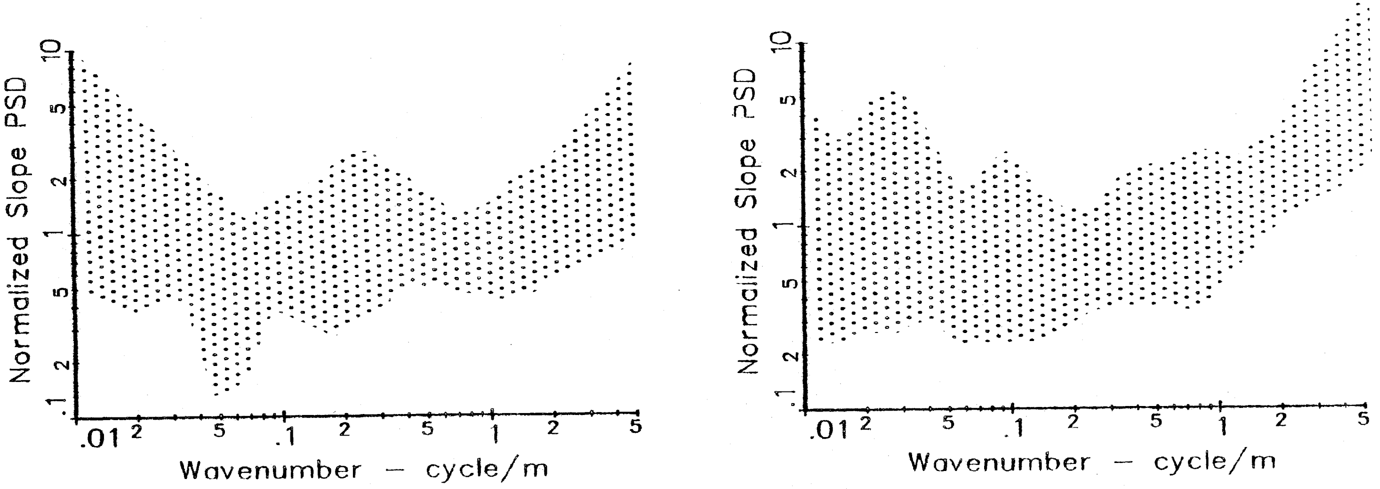
3) The PSD functions for the unpaved gravel (GR) and earth (TE) sites show more variation in content than do the paved roads, but this is not unexpected since they also cover a greater range of roughness. Although they do show a slight minimum in the center near wavenumber 0.1, their roughness distribution 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.51, show the PSD functions measured for each wheeltrack of 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 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.

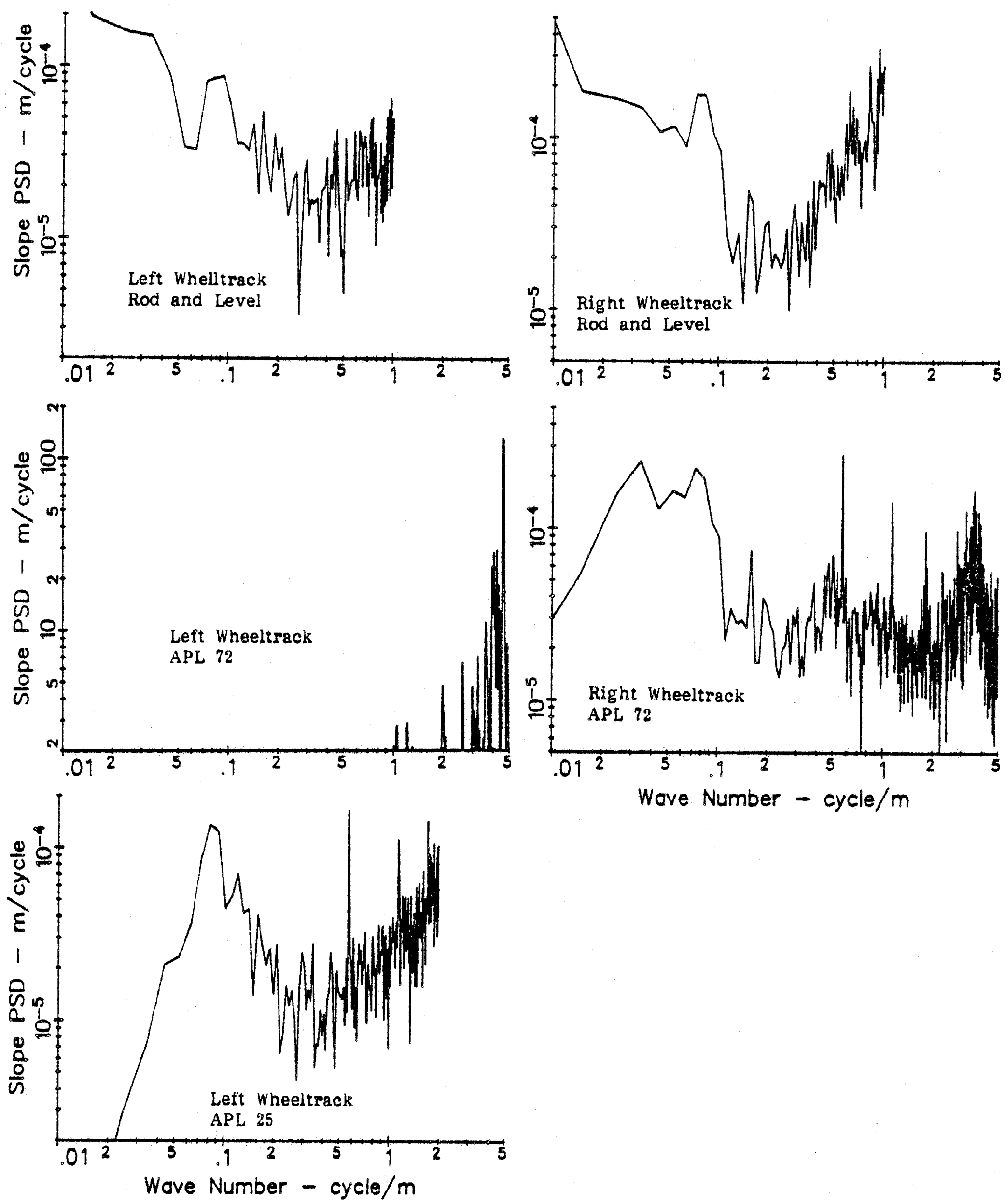


Figure I.3. PSD functions for Site CA01.

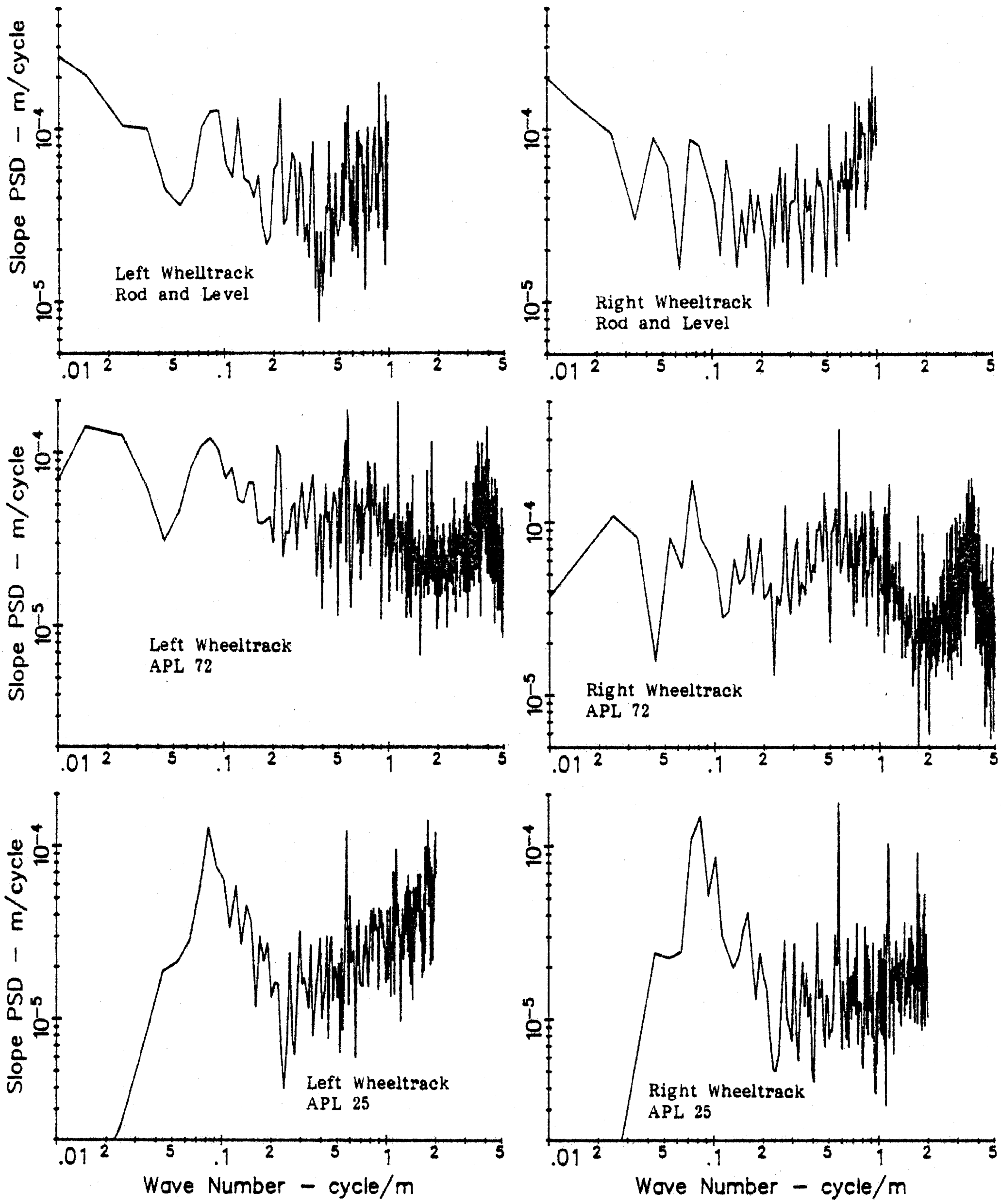


Figure I.4. PSD functions for Site CA02.

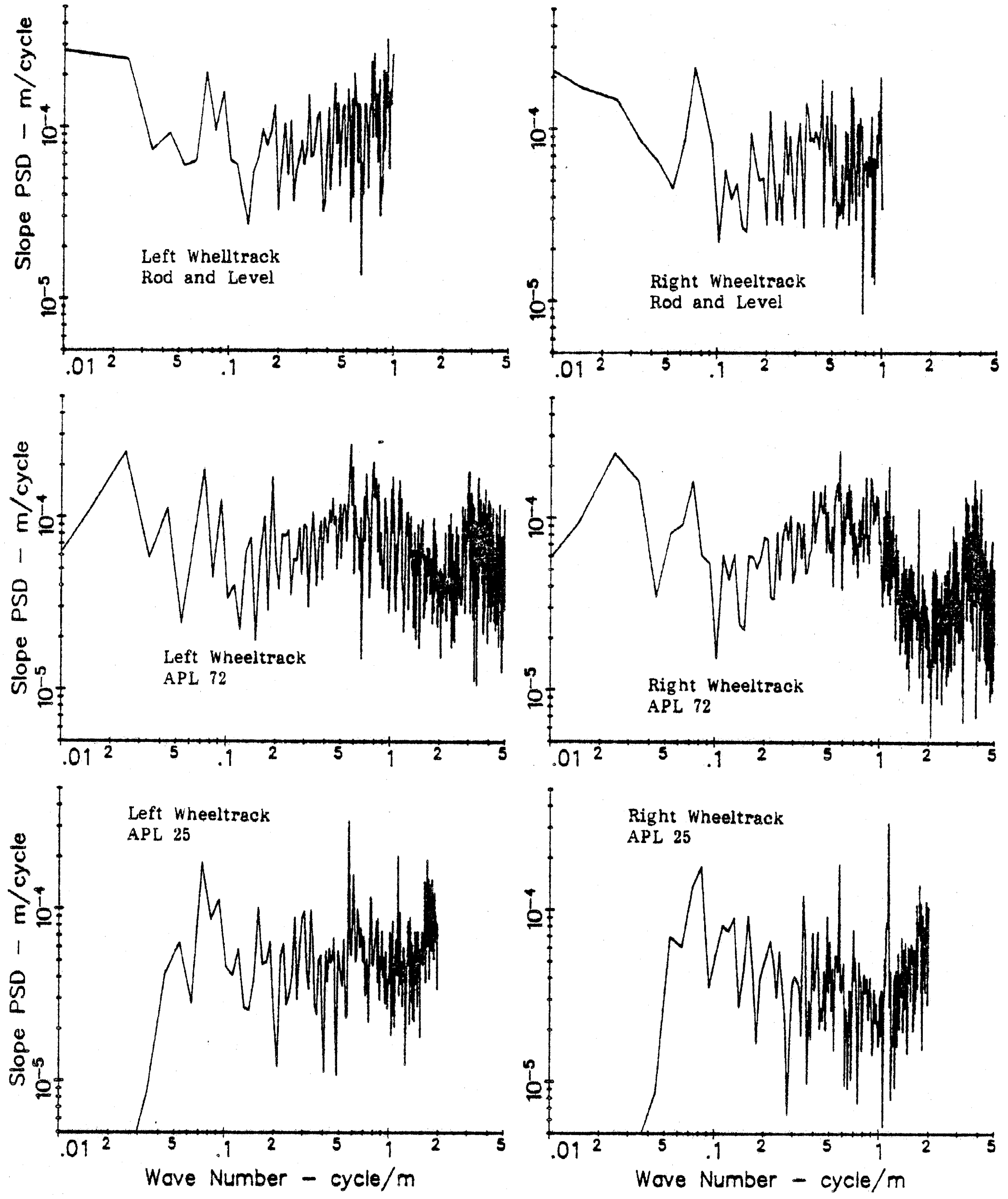


Figure I.5. PSD functions for Site CA03.

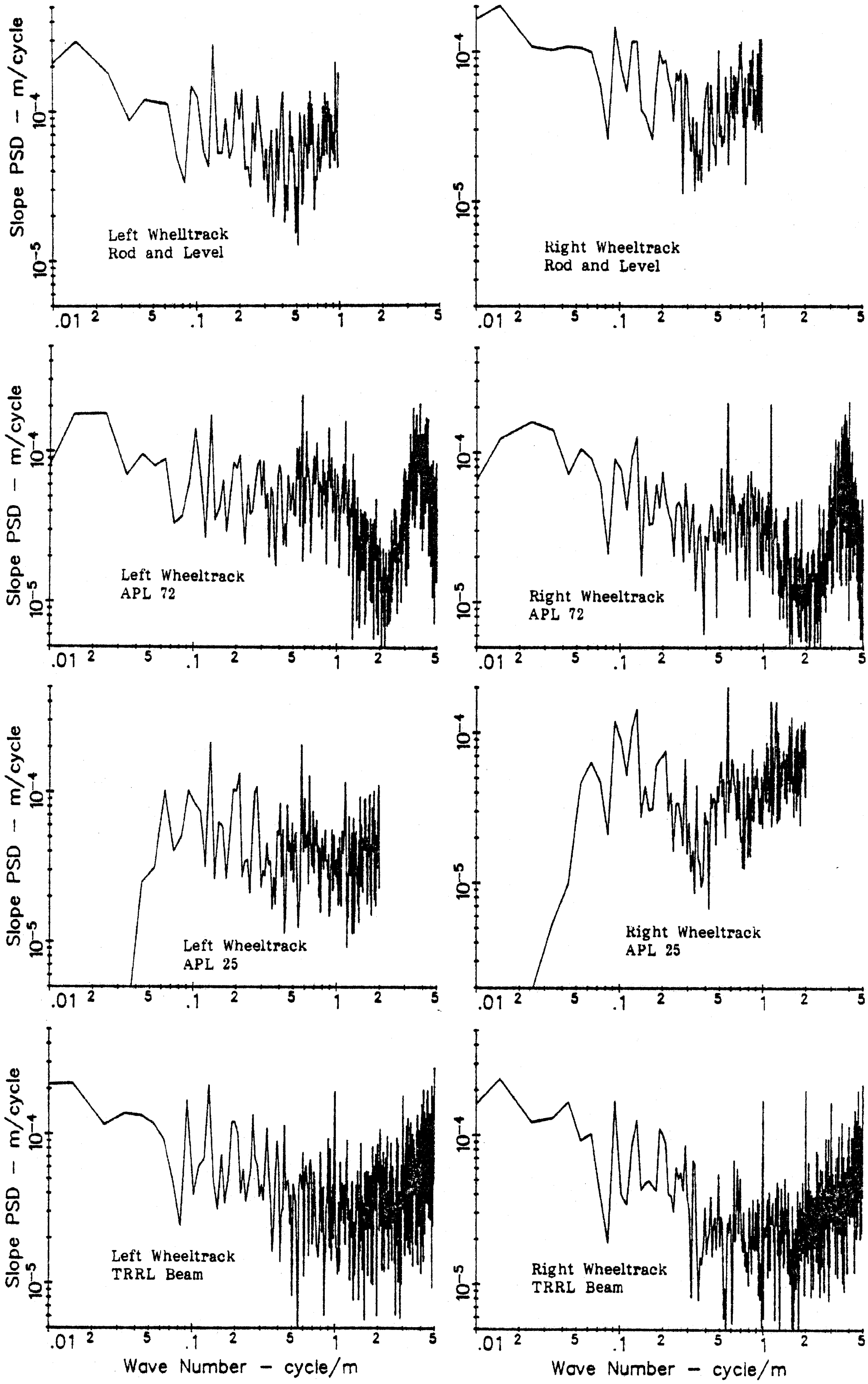


Figure I.6. PSD functions for Site CA04.

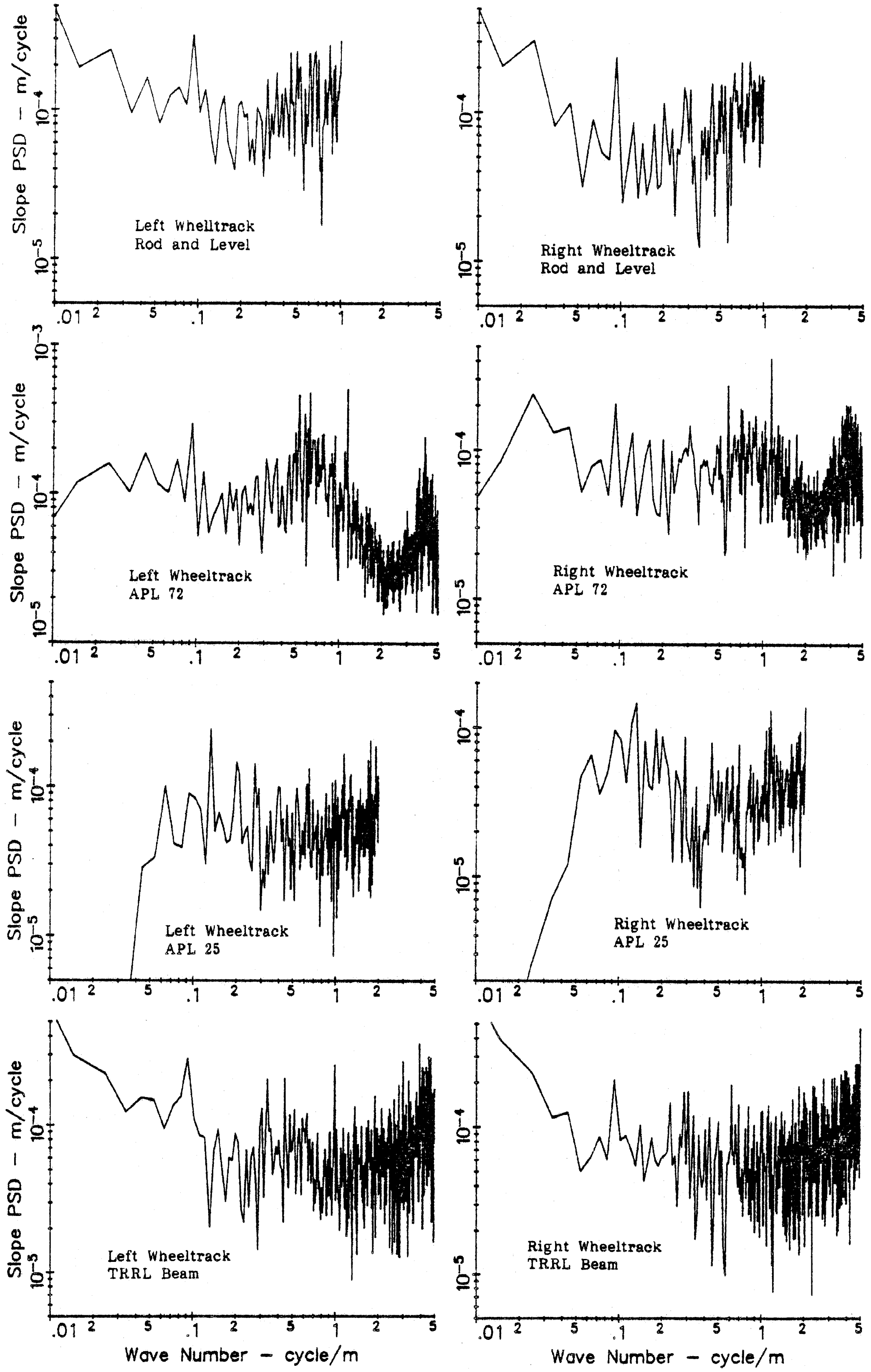


Figure I.7. PSD functions for Site CA05.

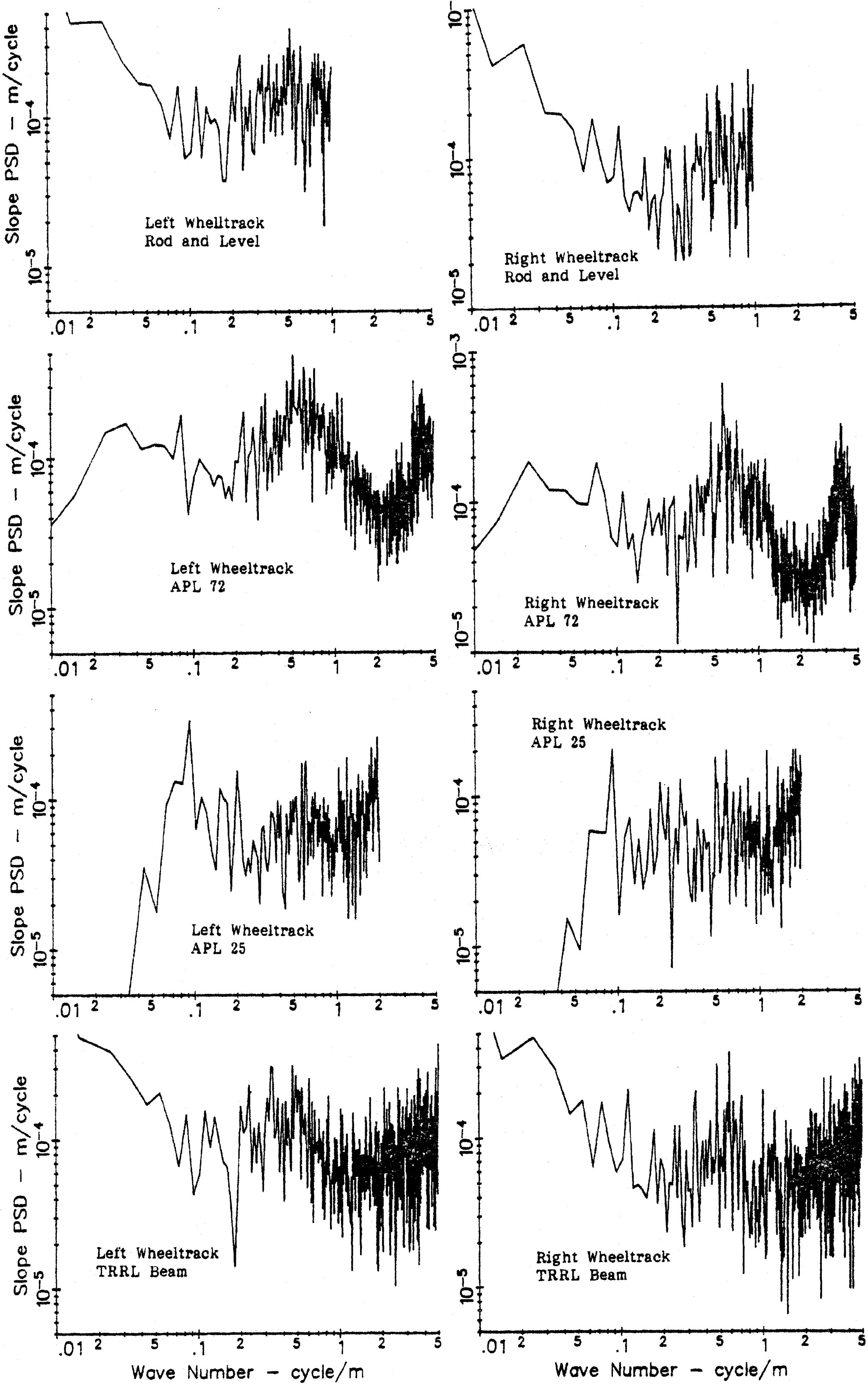
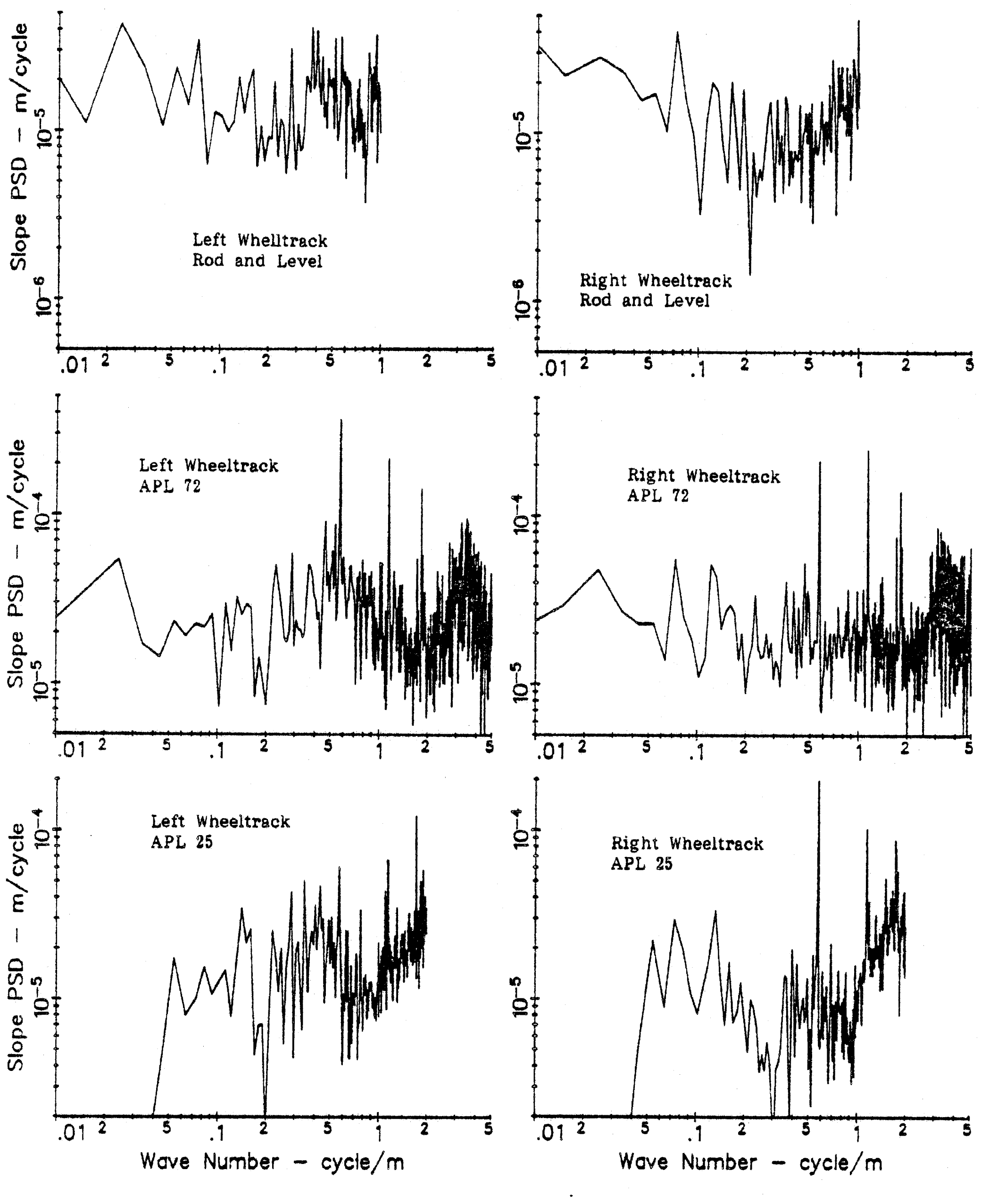


Figure I.8. PSD functions for Site CA06.



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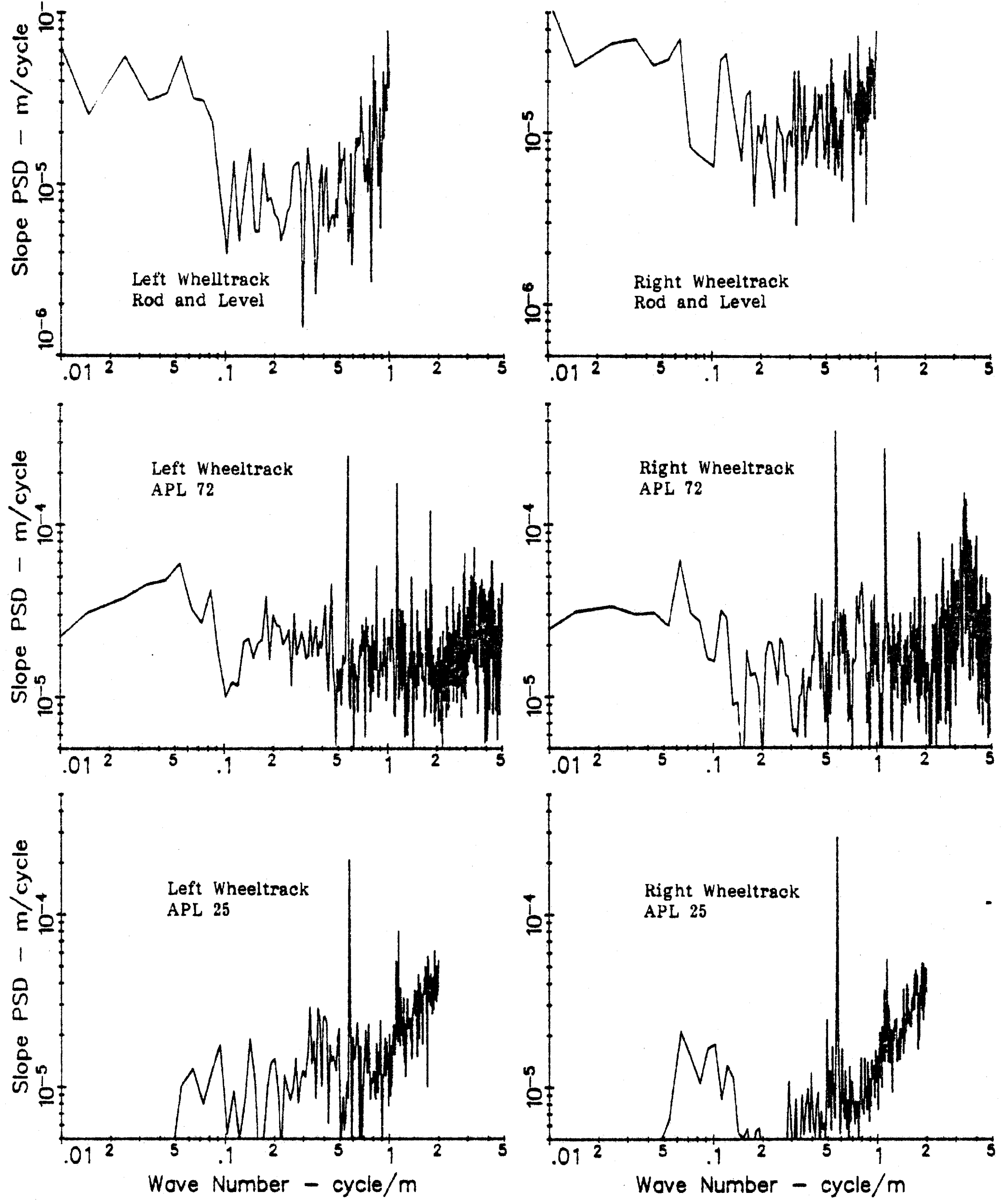

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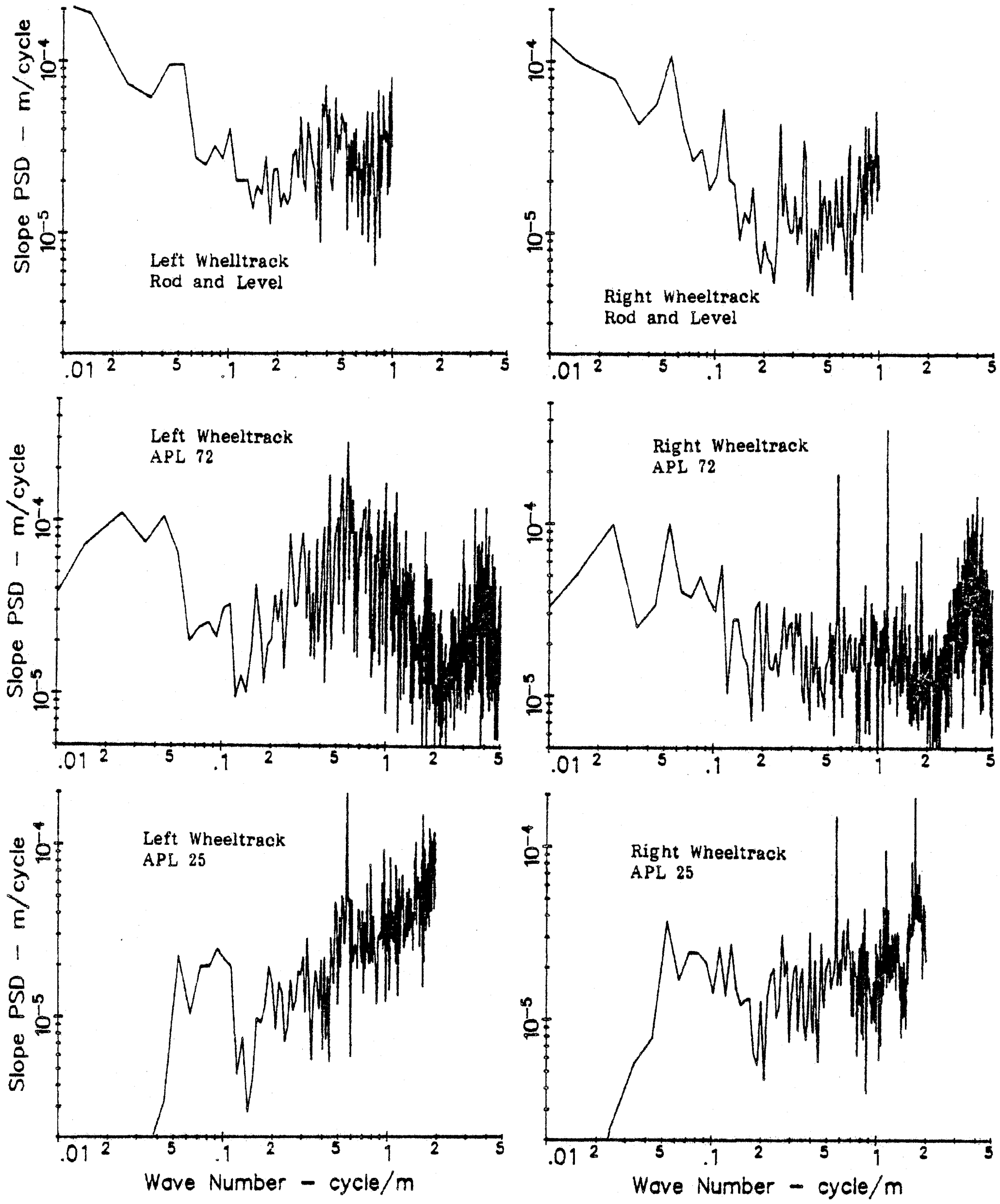


Figure I.11. PSD functions for Site CA09.

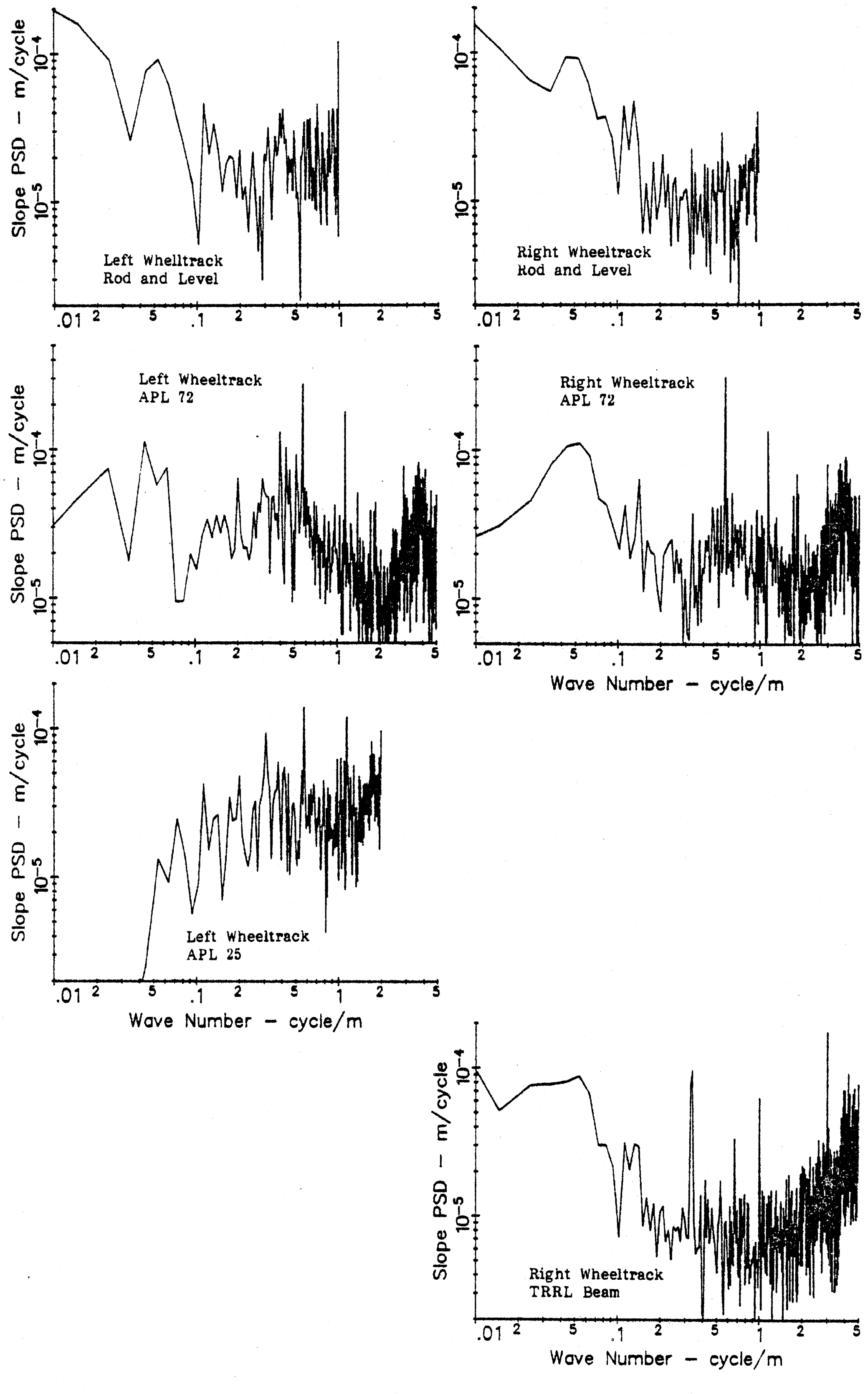


Figure I.12. PSD functions for Site CA10.

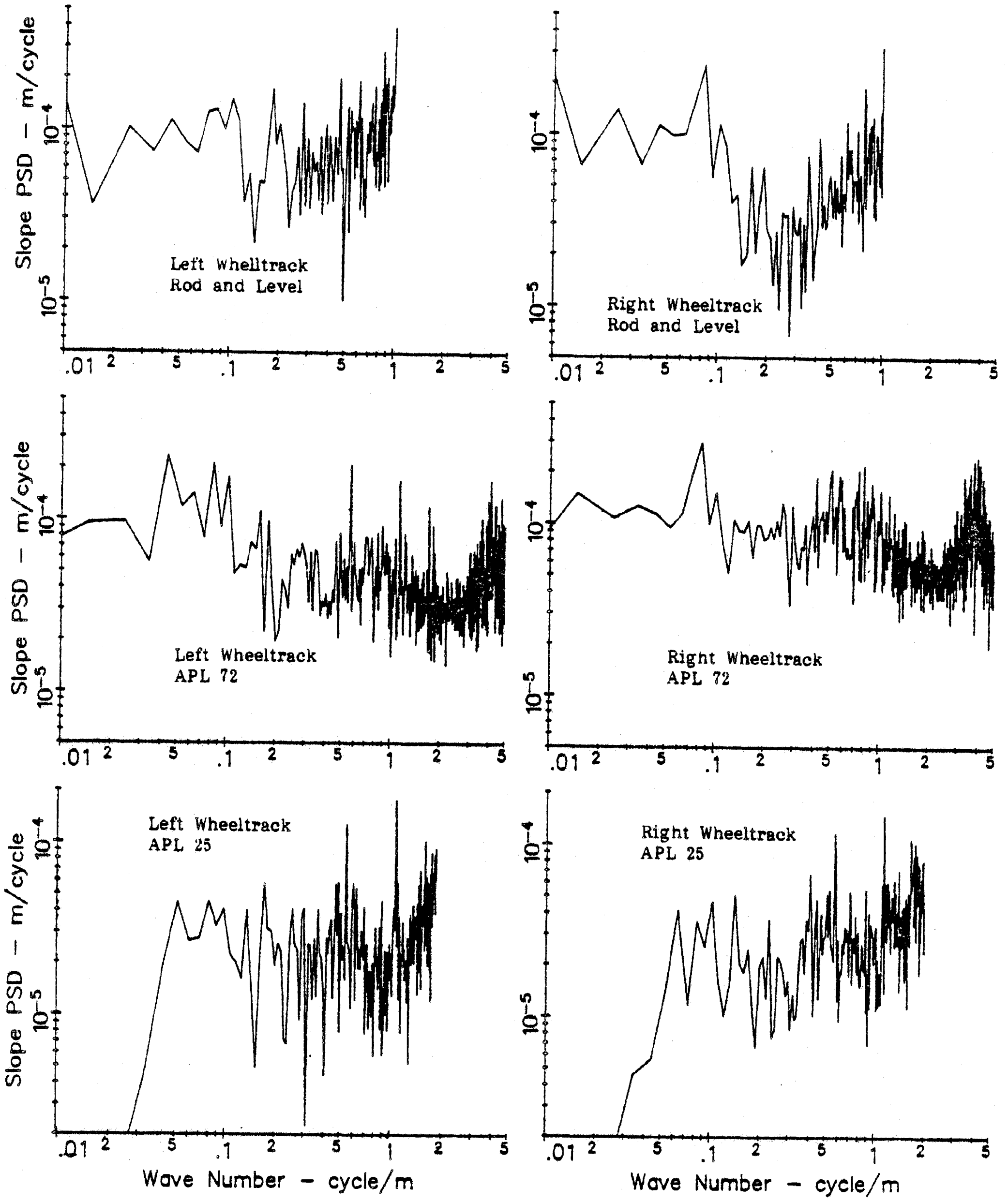
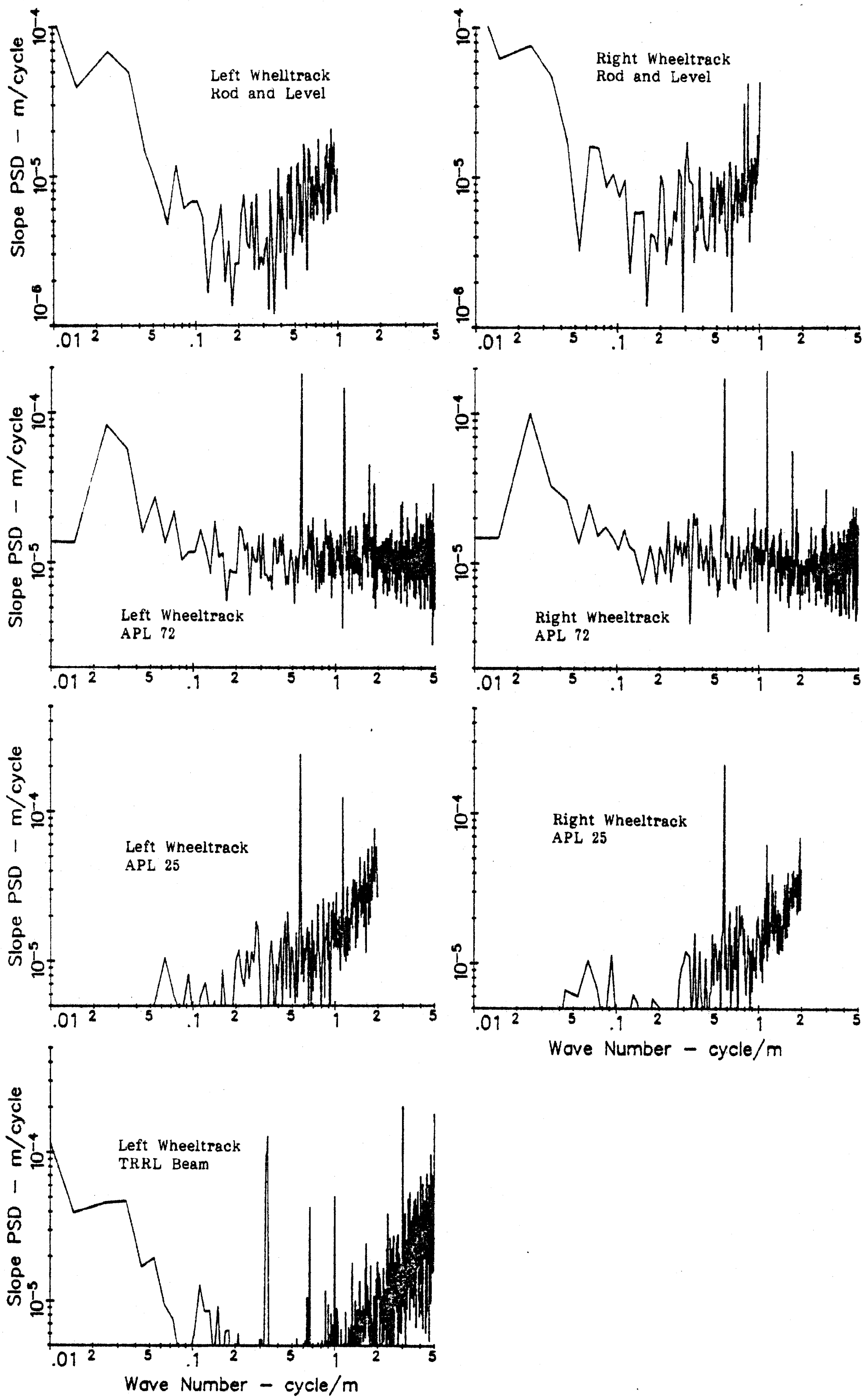


Figure I.13. PSD functions for Site CA11.



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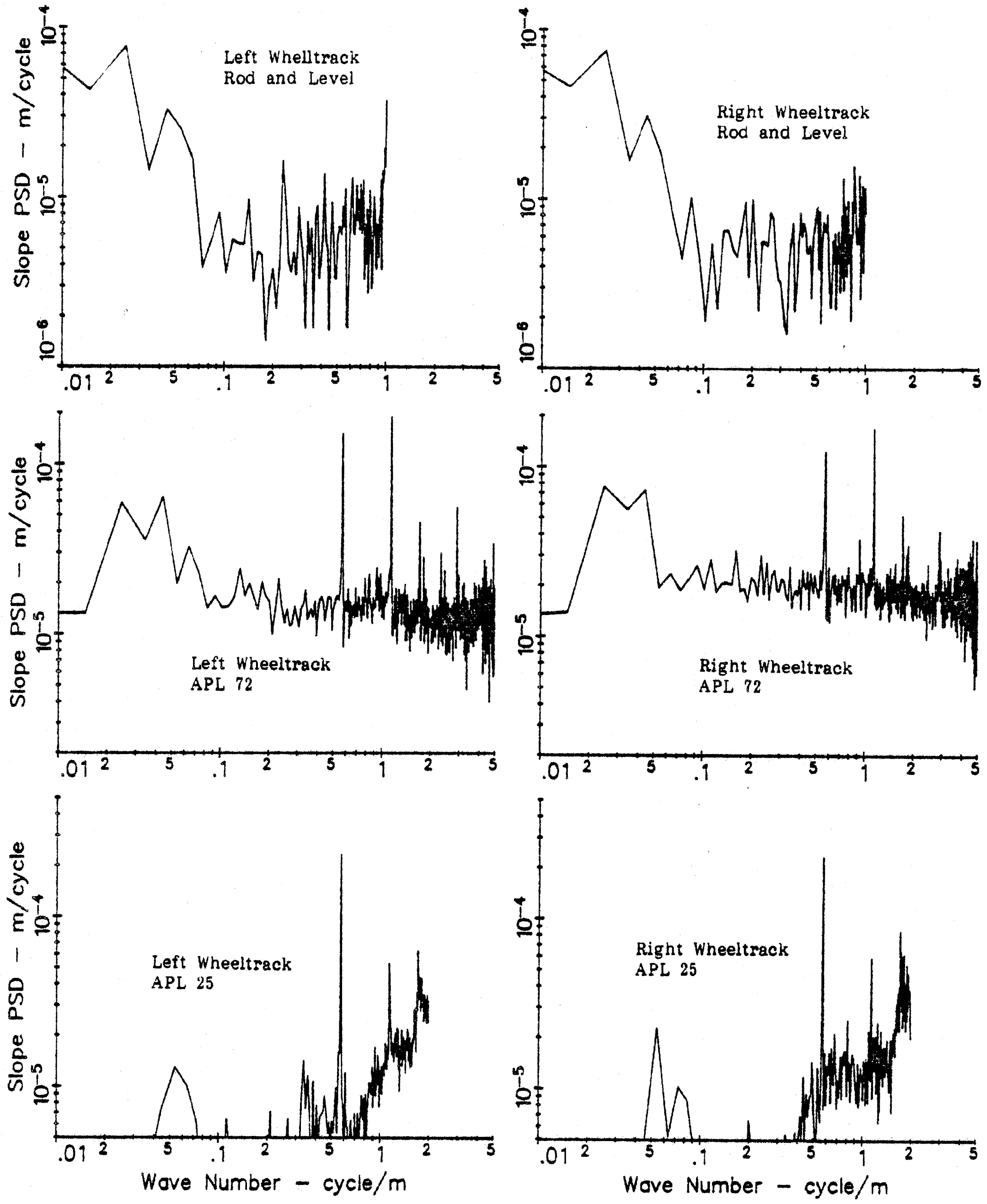


Figure I.15. PSD functions for Site CA13.

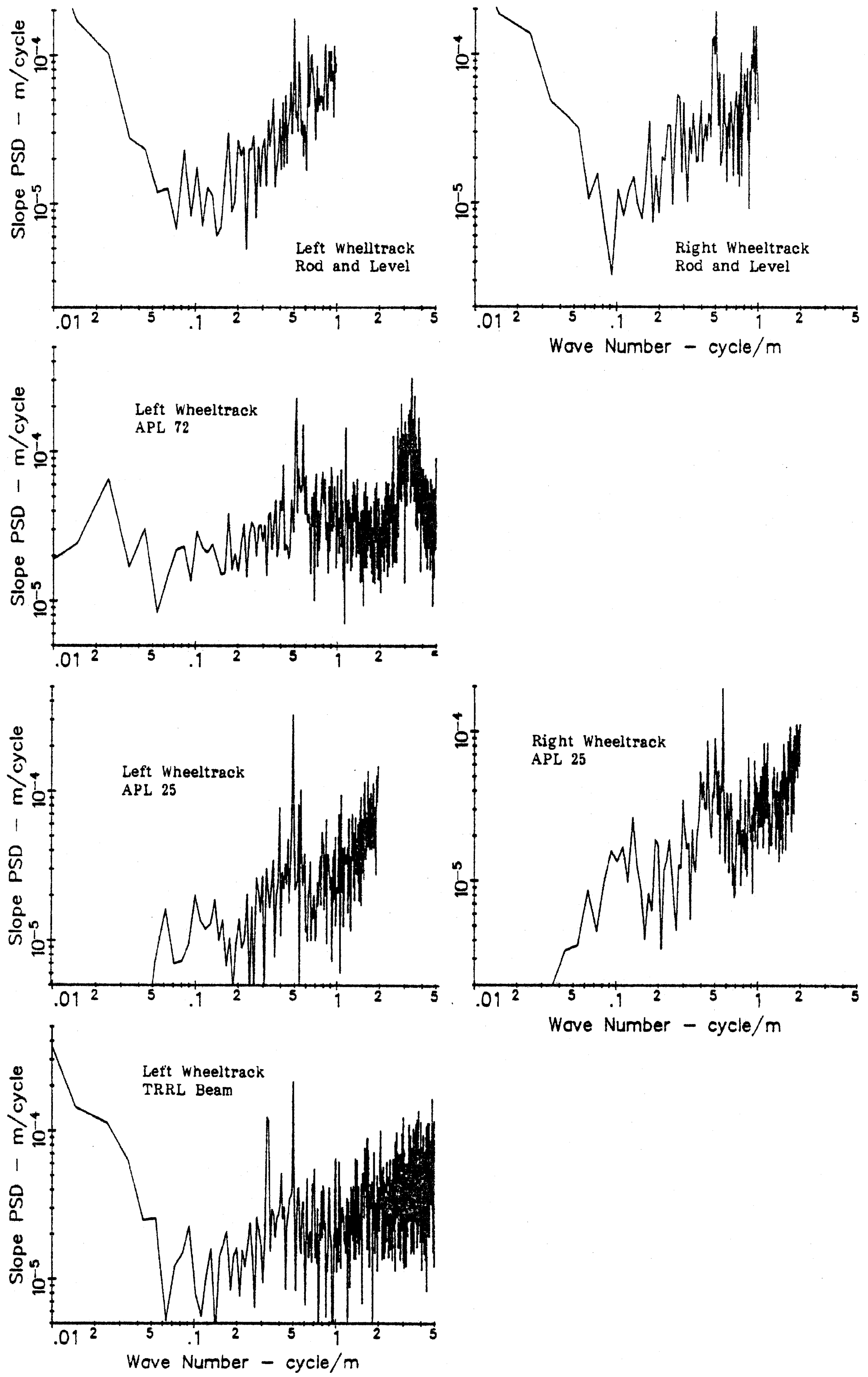


Figure I.16. PSD functions for Site TS01.

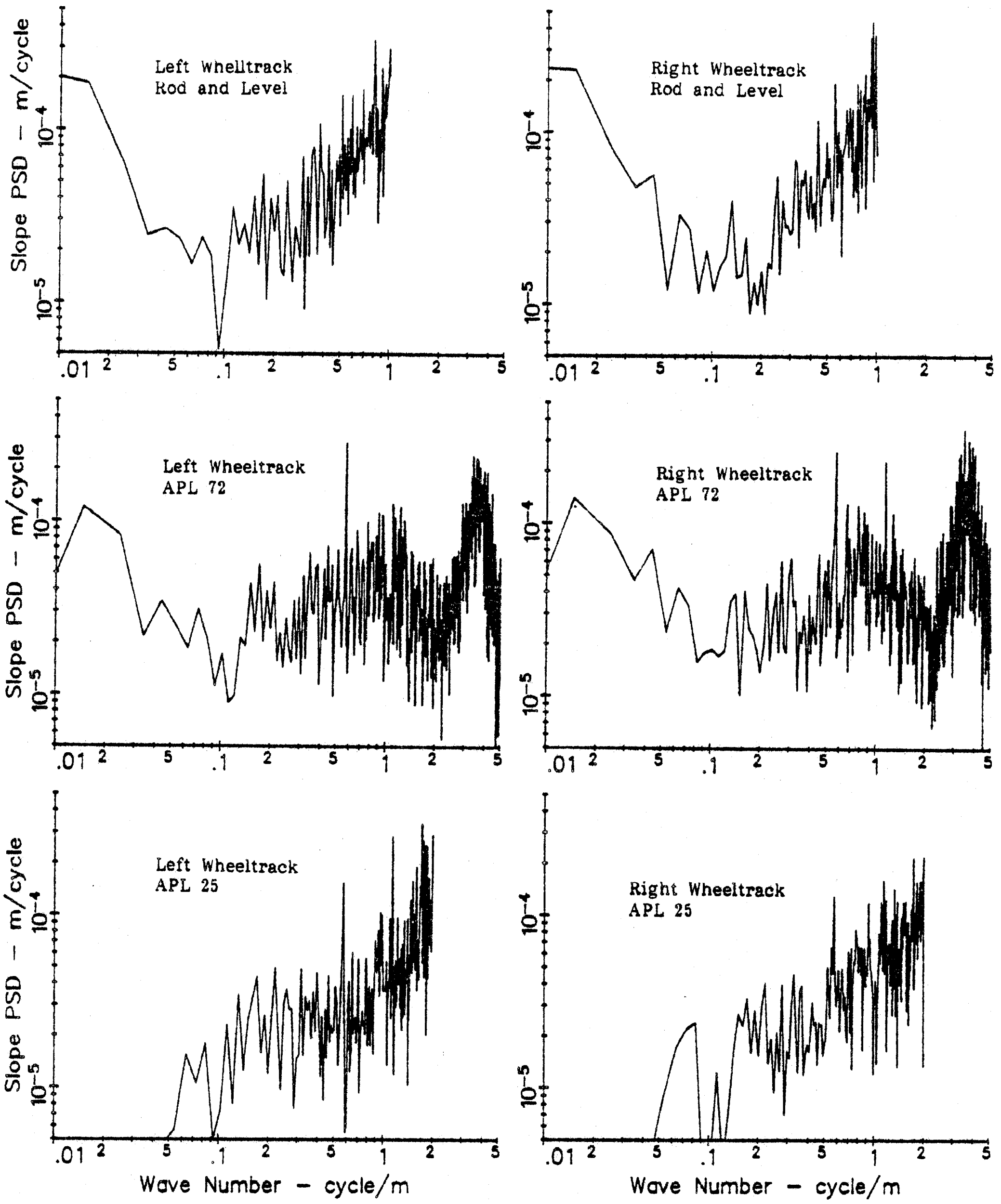


Figure I.17. PSD functions for Site TS02.

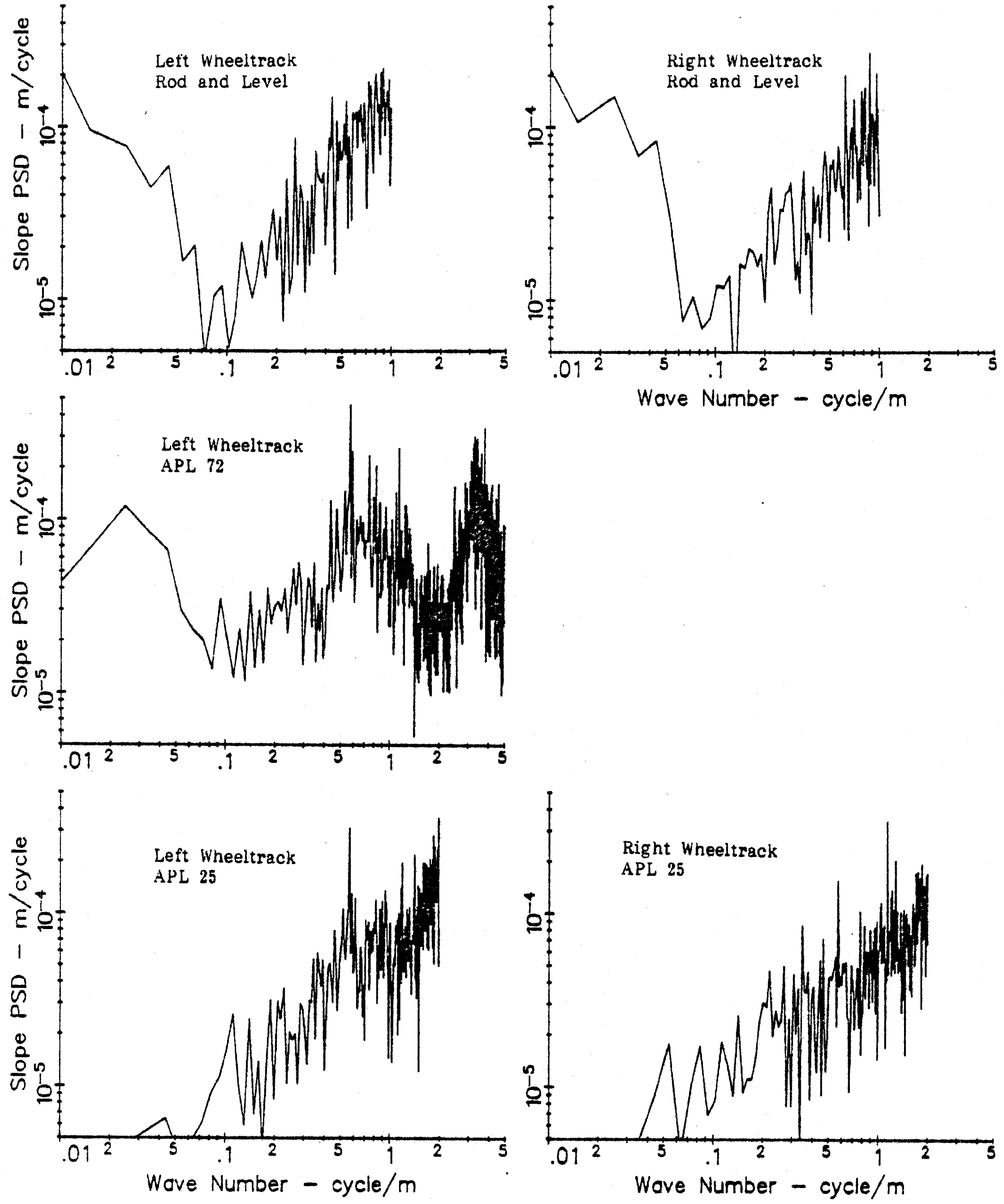


Figure I.18. PSD functions for Site TS03.

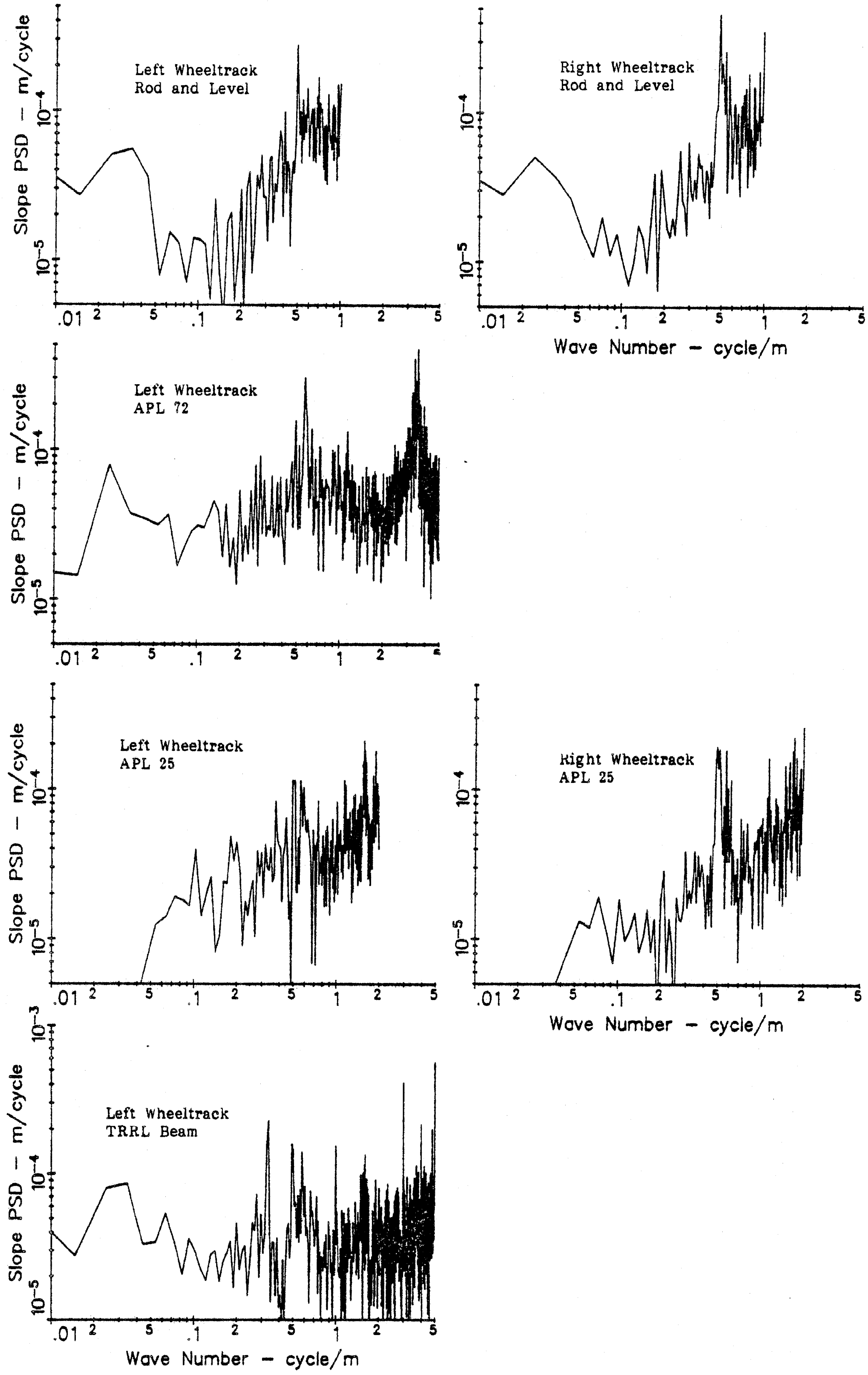


Figure I.19. PSD functions for Site TS04.

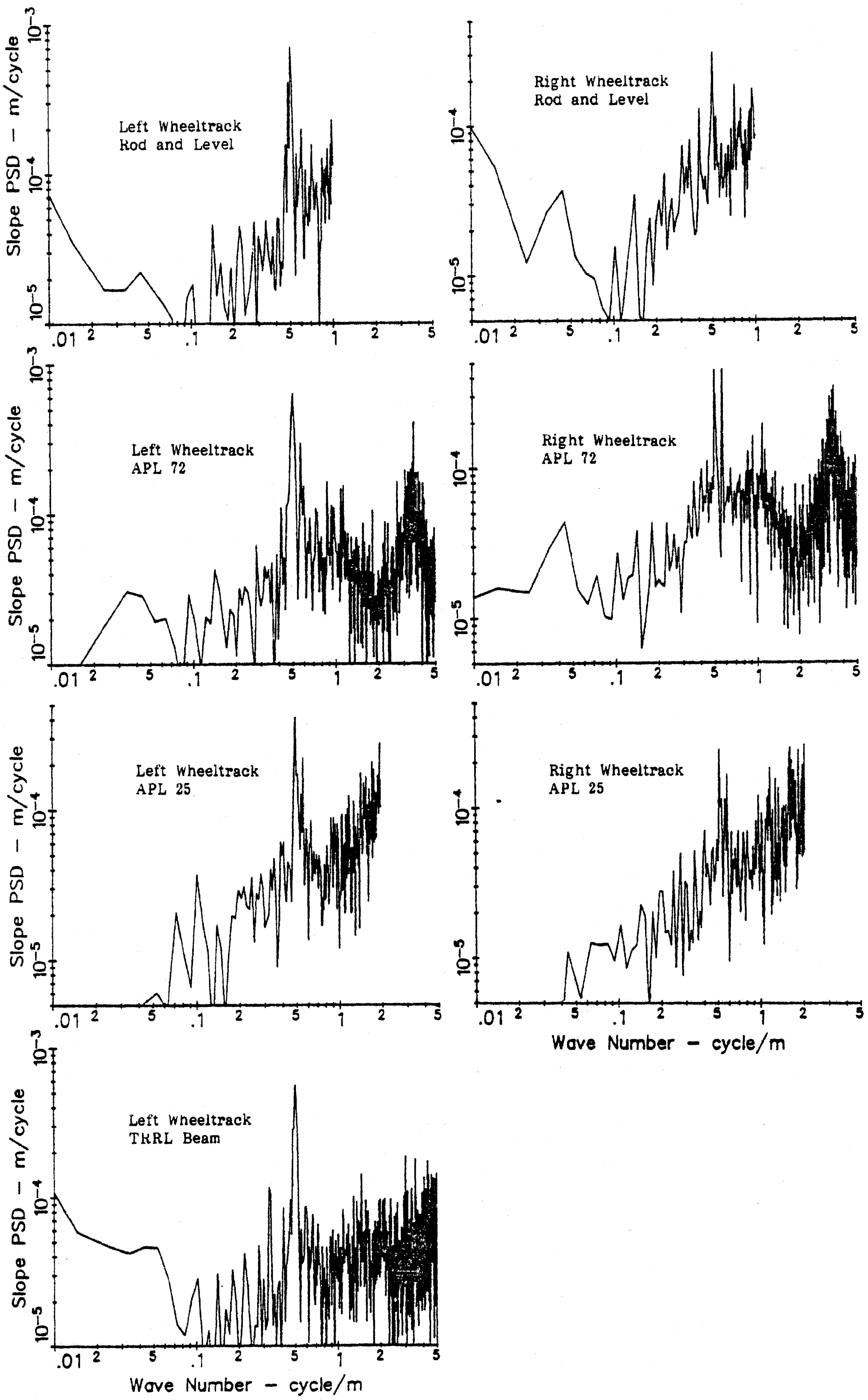


Figure I.20. PSD functions for Site TS05.

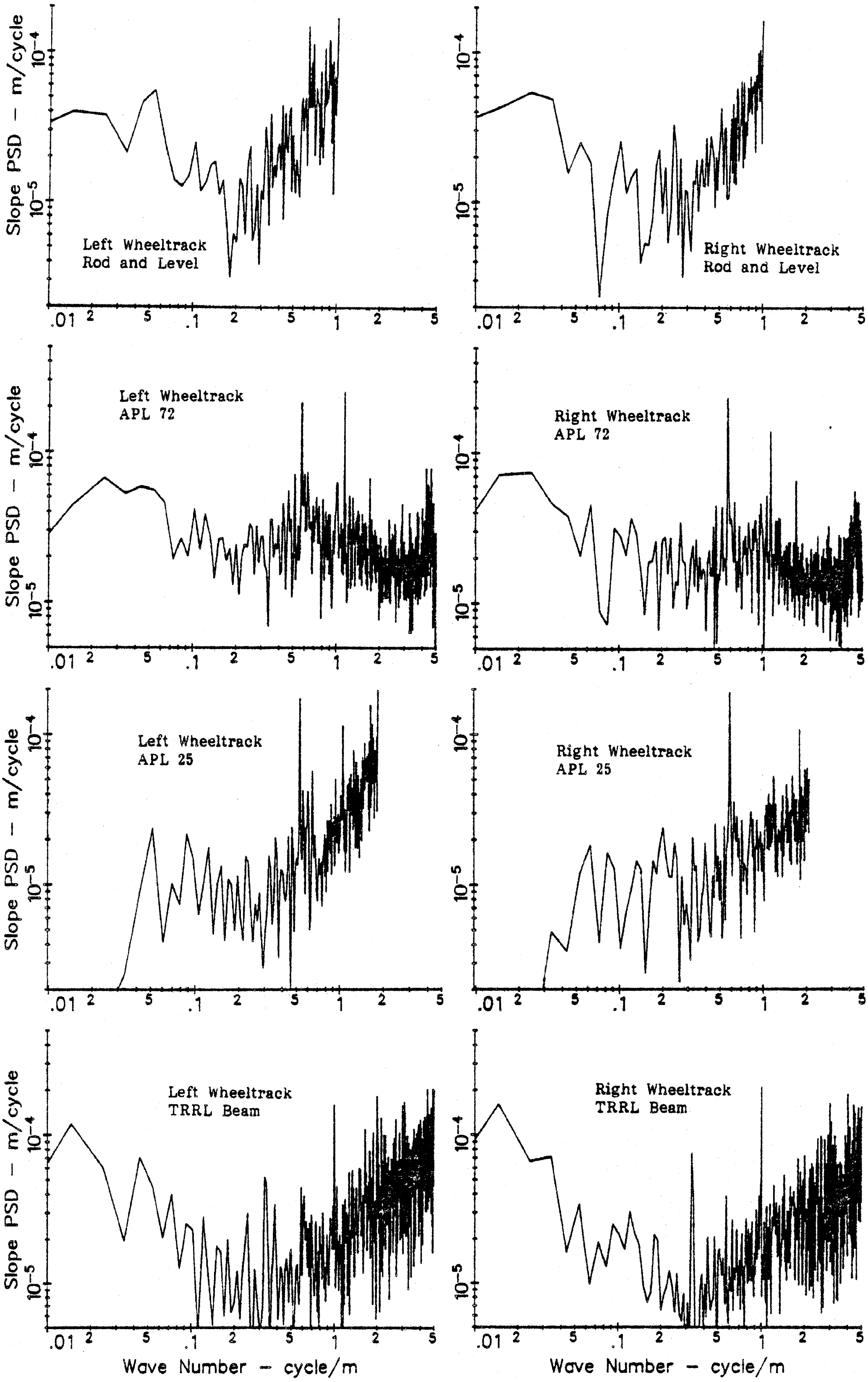
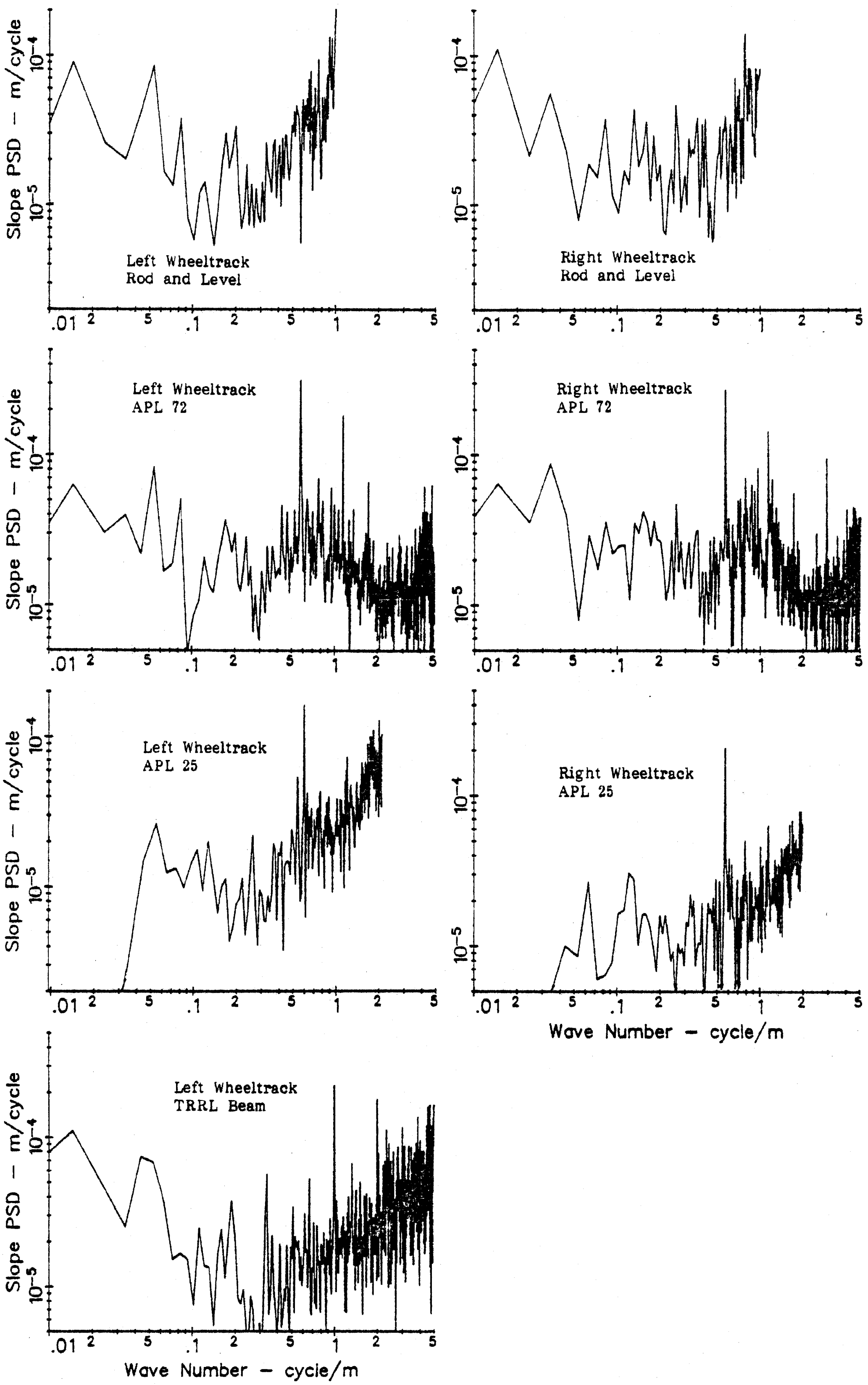


Figure I.21. PSD functions for Site TS06.



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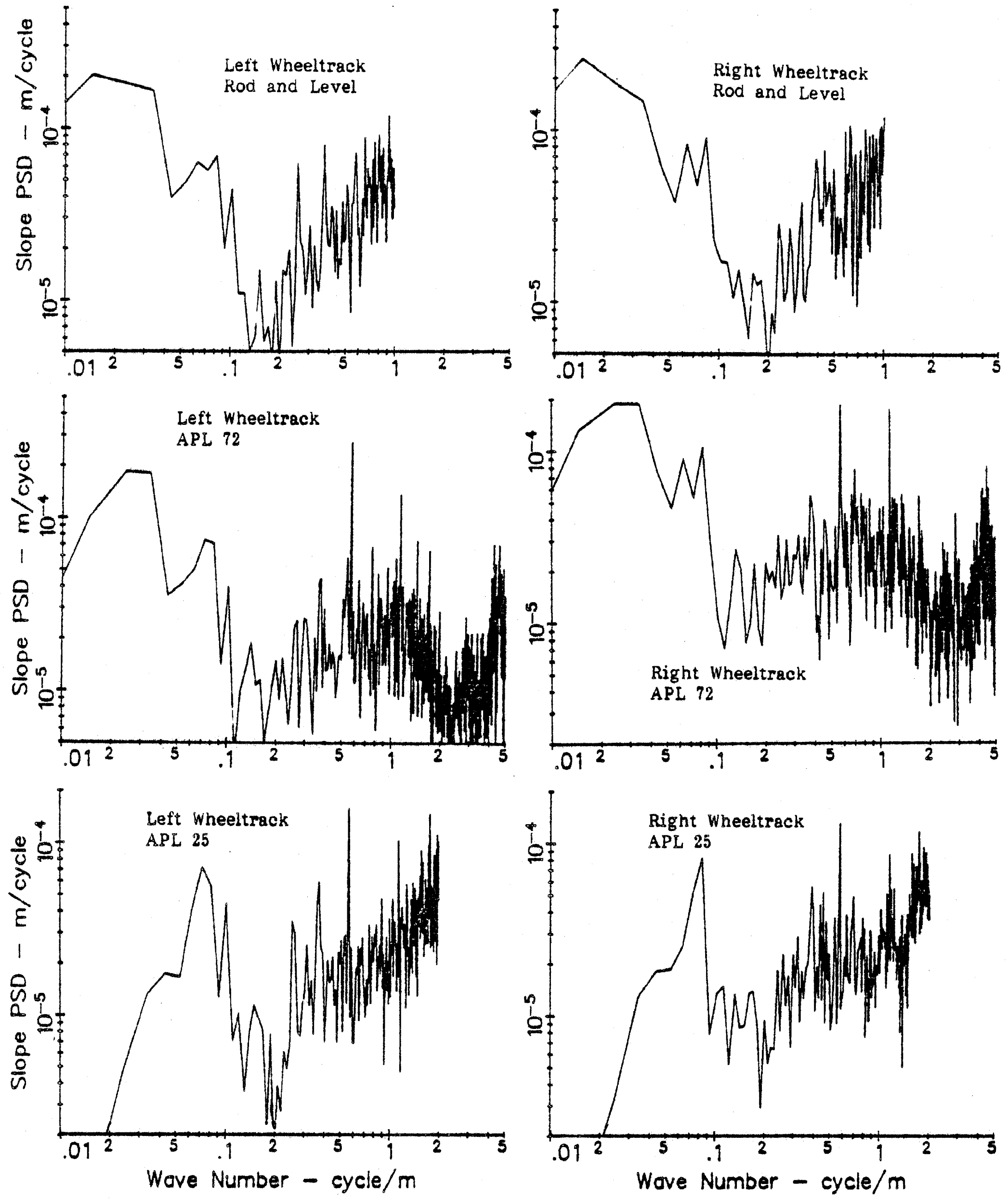

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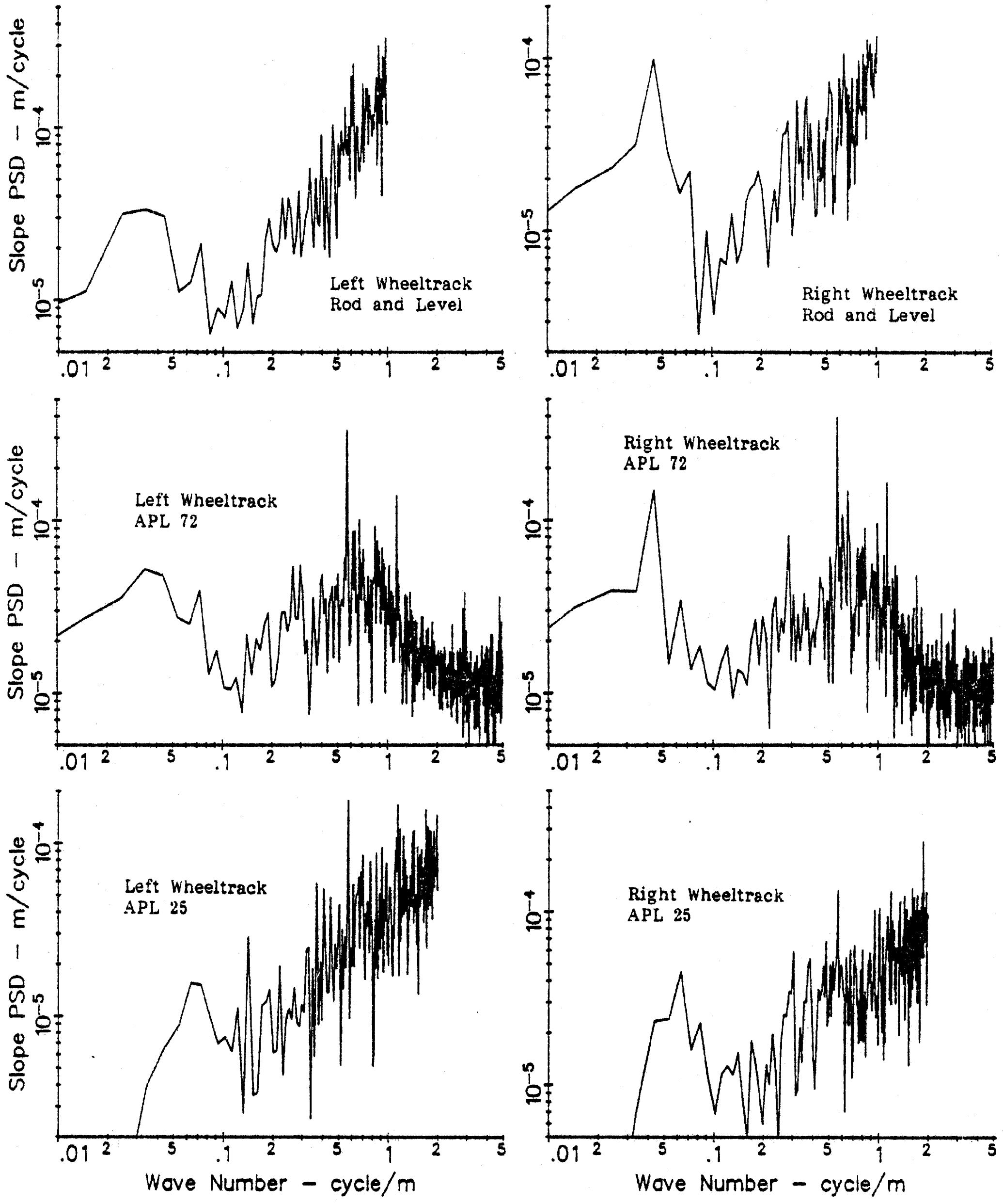
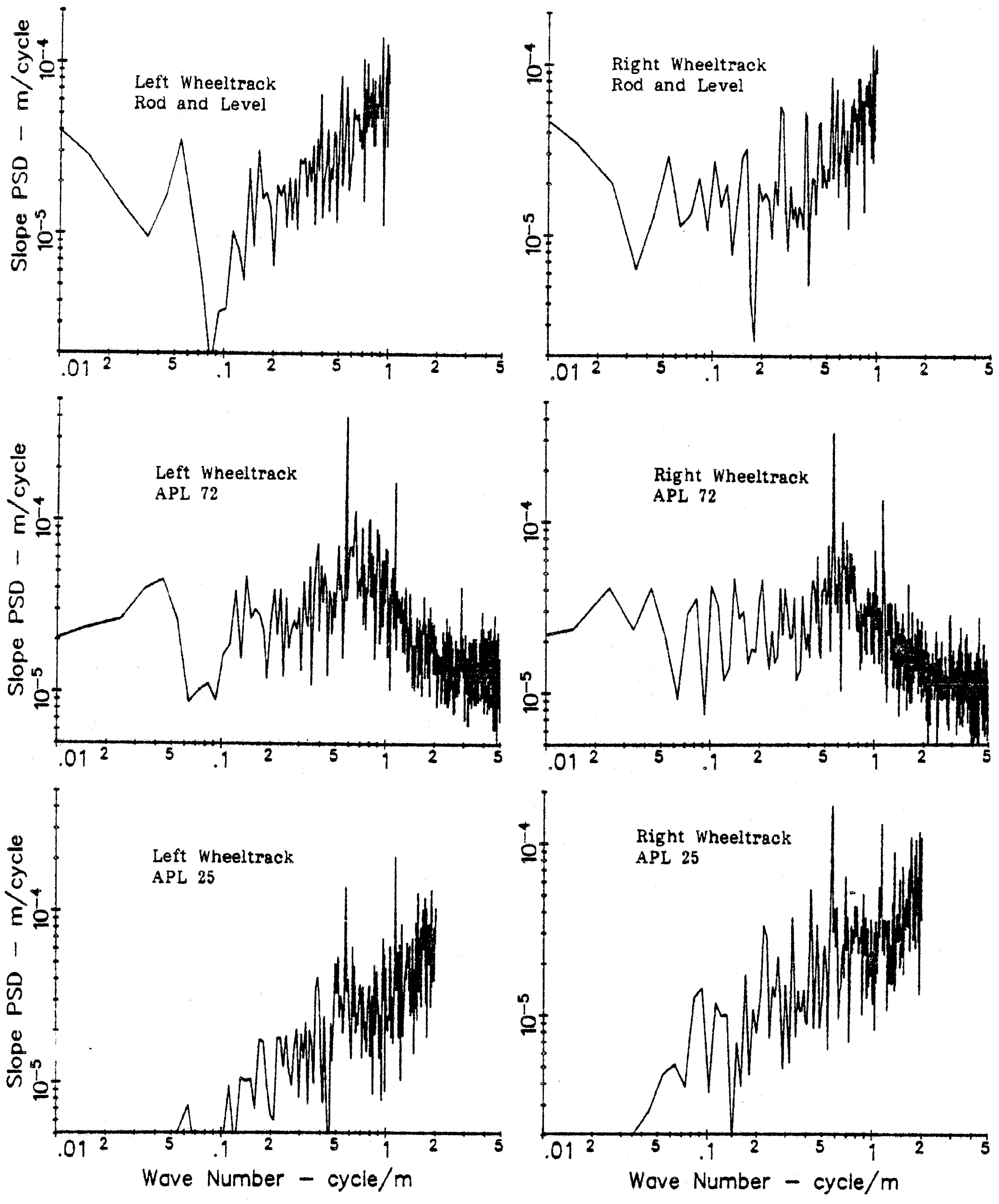


Figure I.24. PSD functions for Site TS09.



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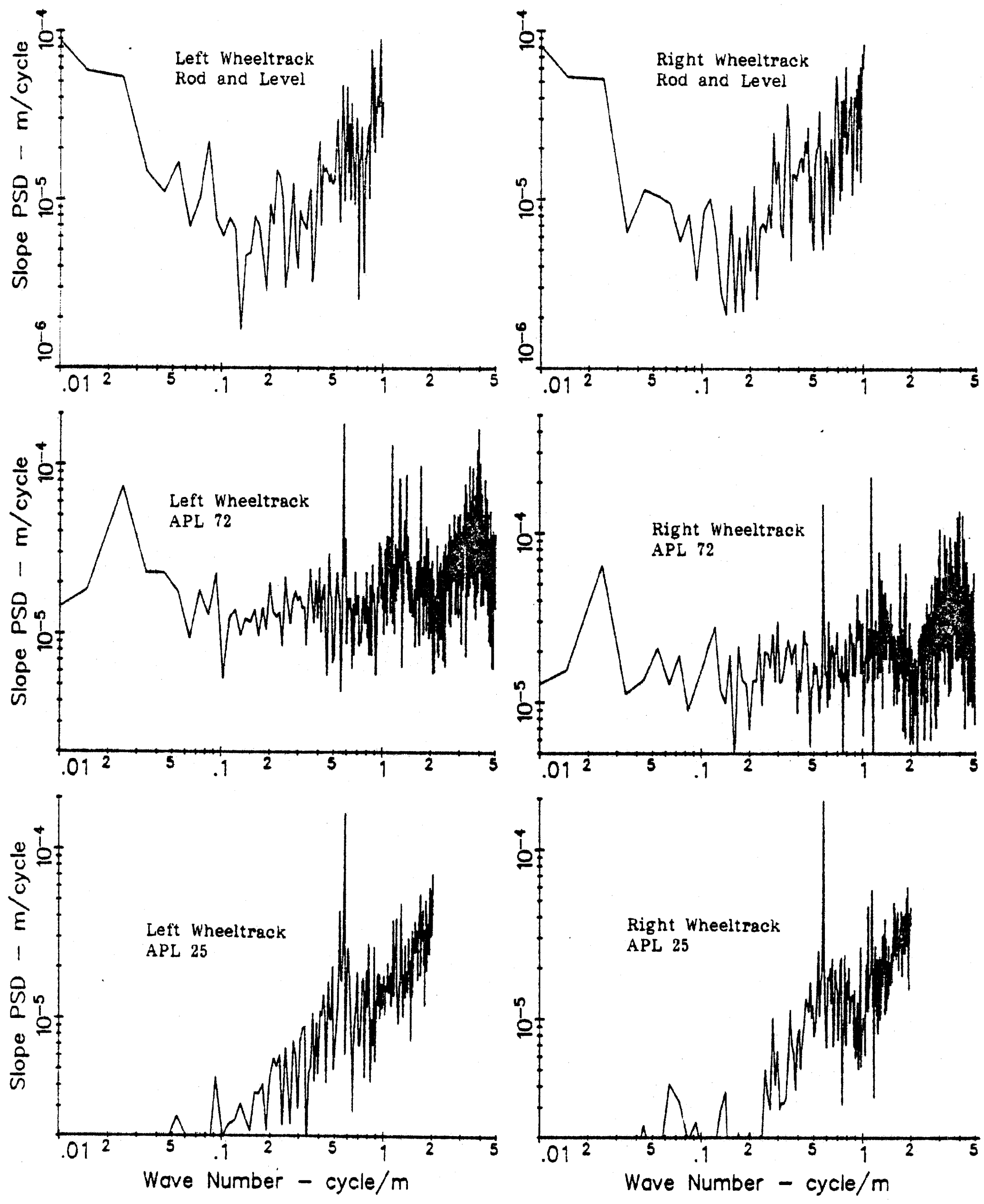

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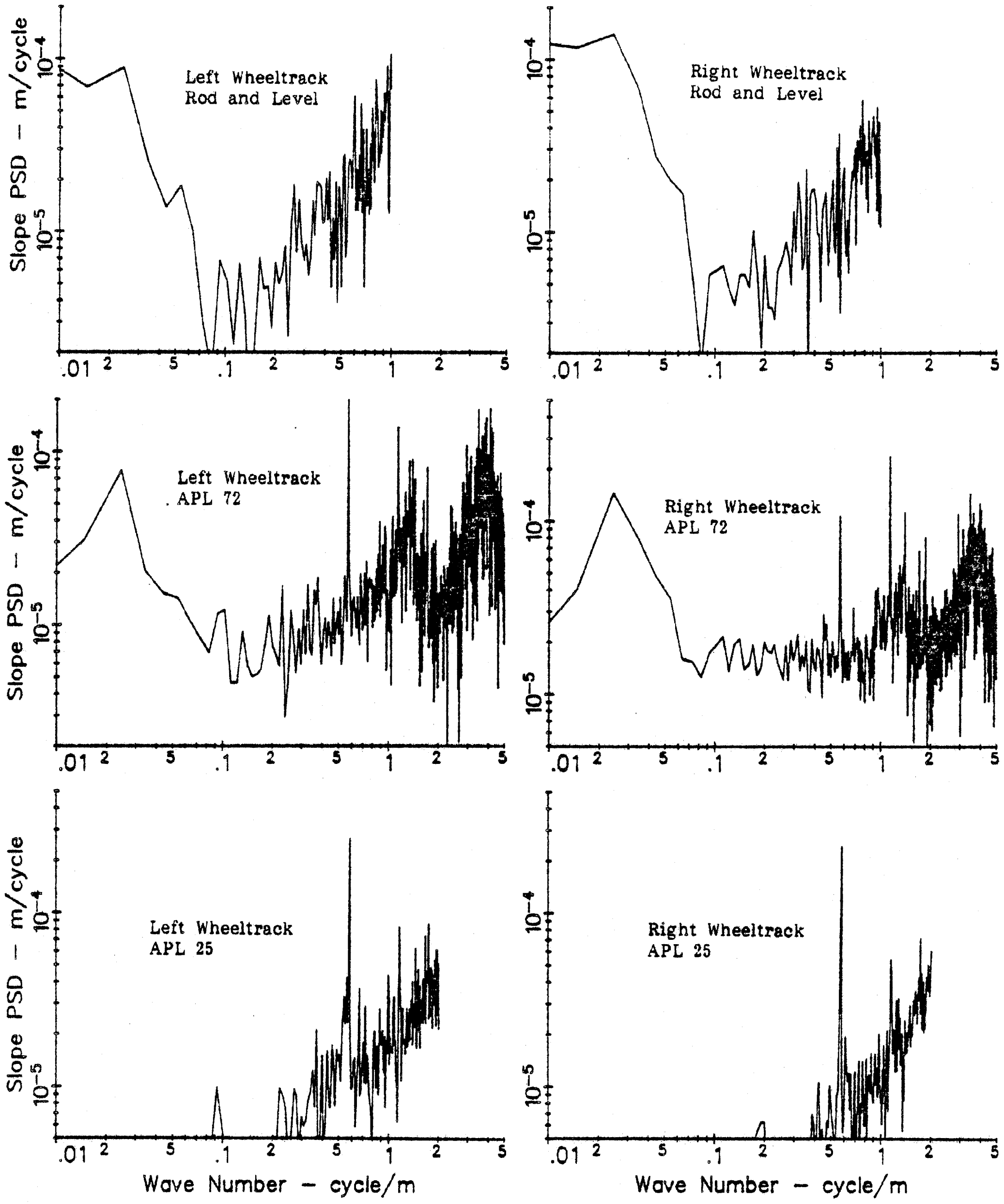

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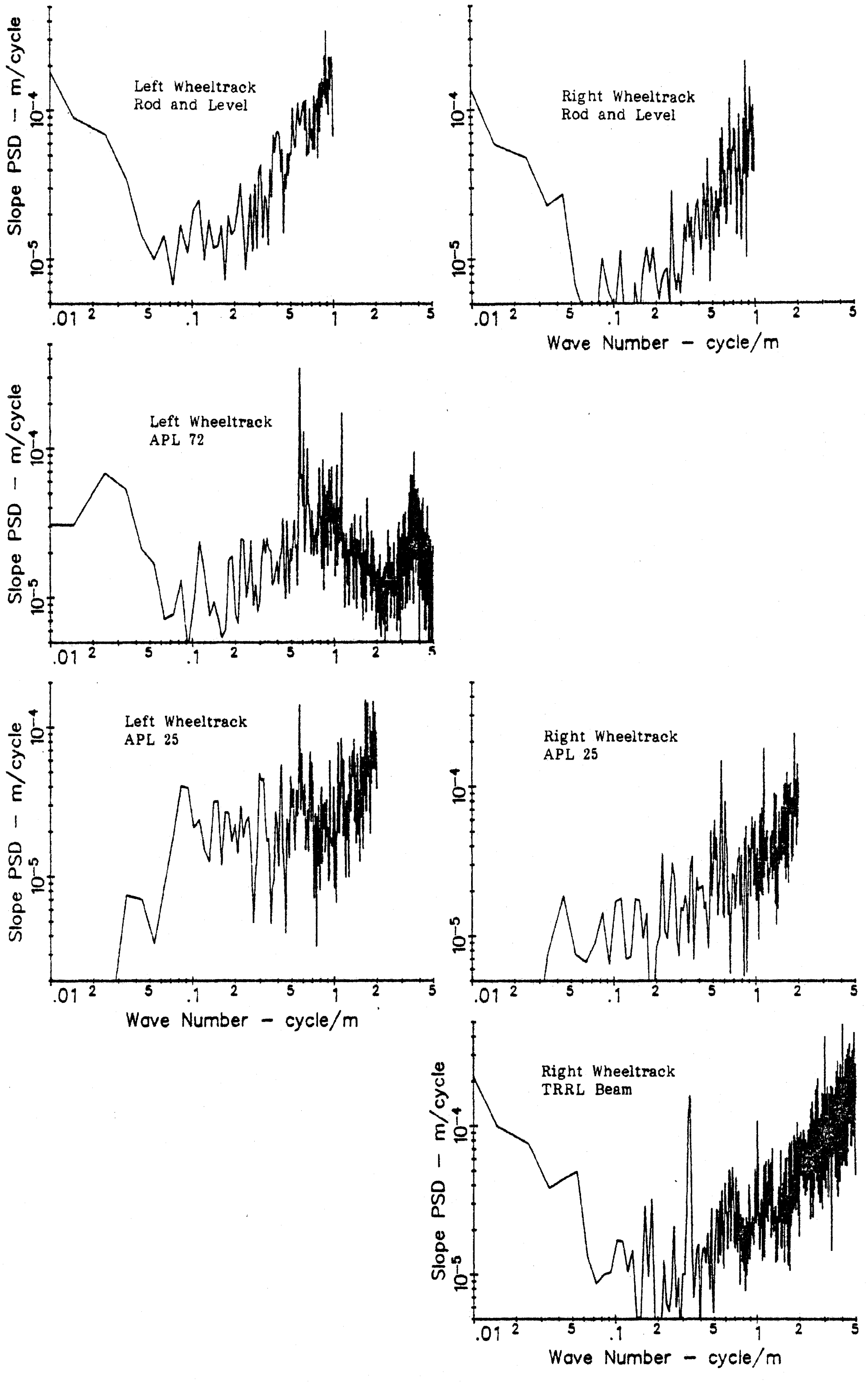


Figure I.28. PSD functions for Site GRU1.

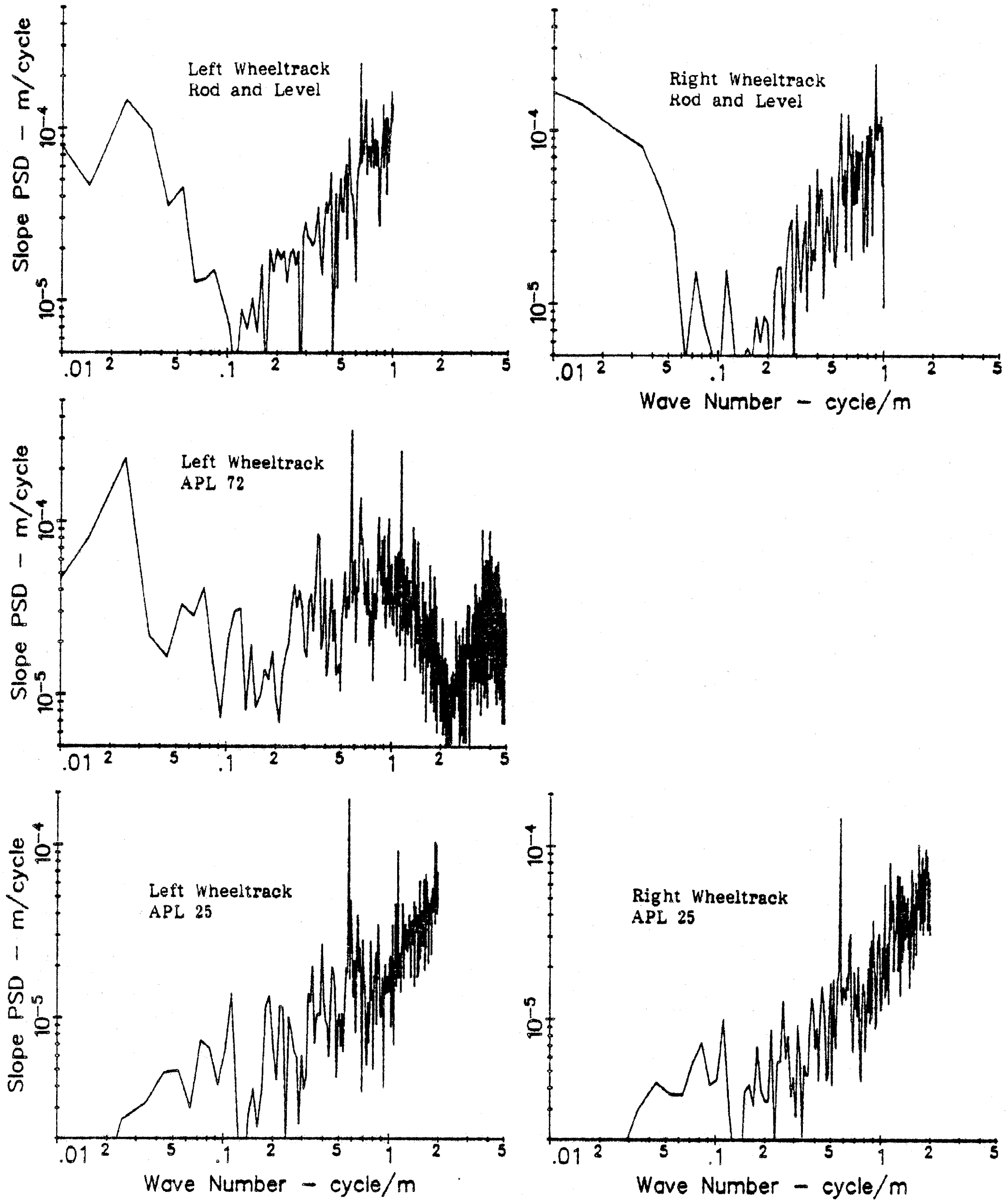


Figure I.29. PSD functions for Site GR02.

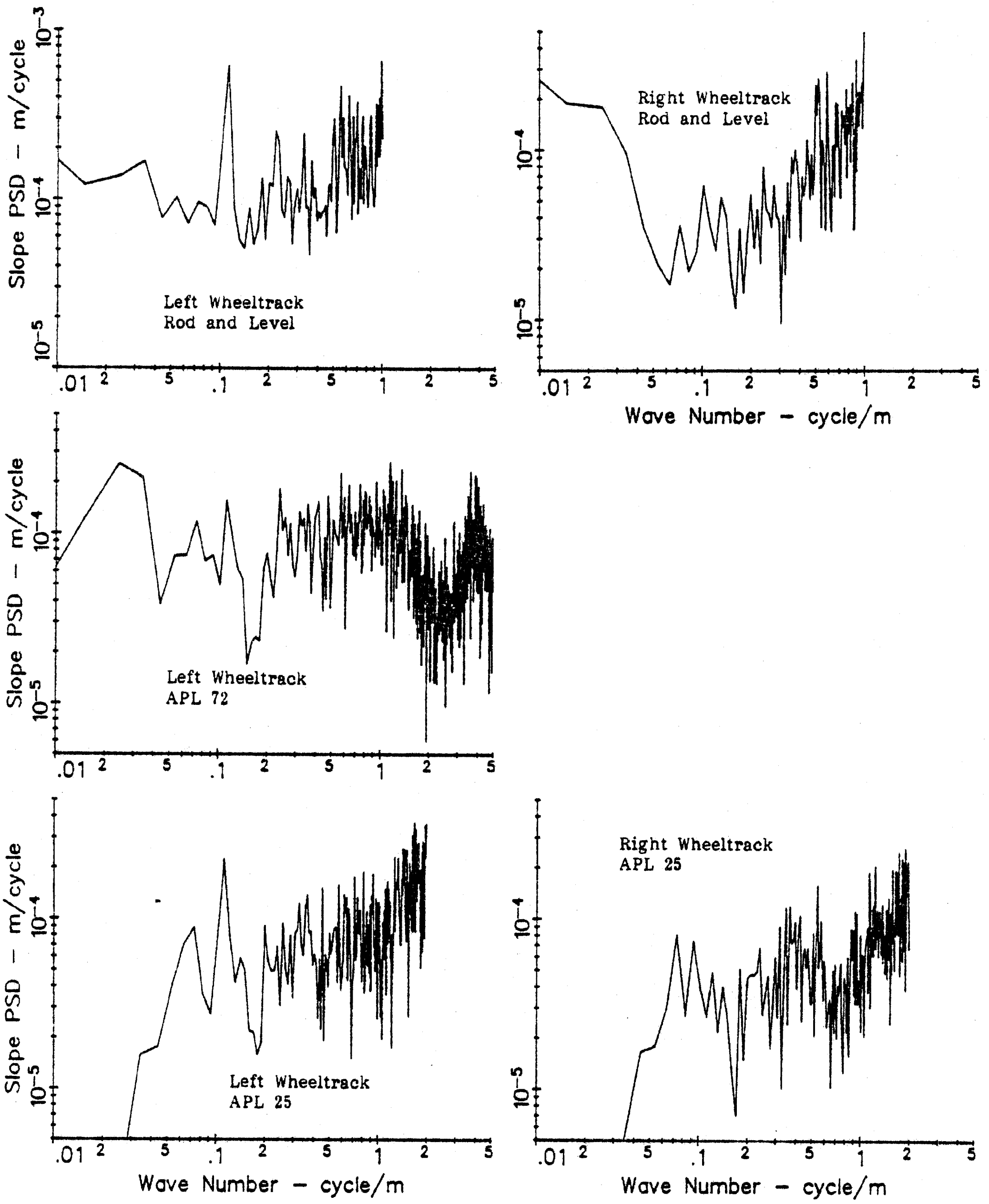


Figure I.30. PSD functions for Site GR03.

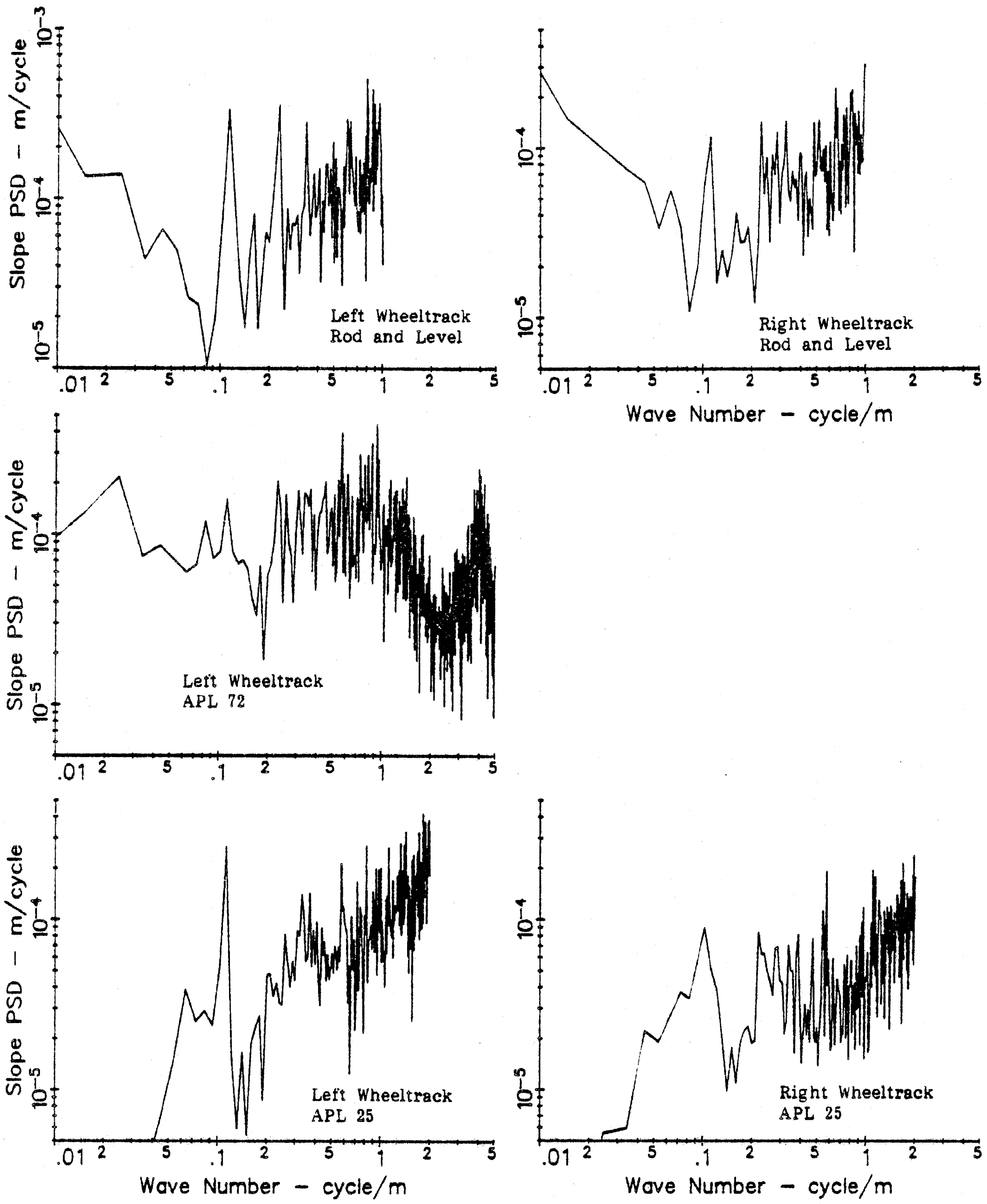


Figure I.31. PSD functions for Site GR04.

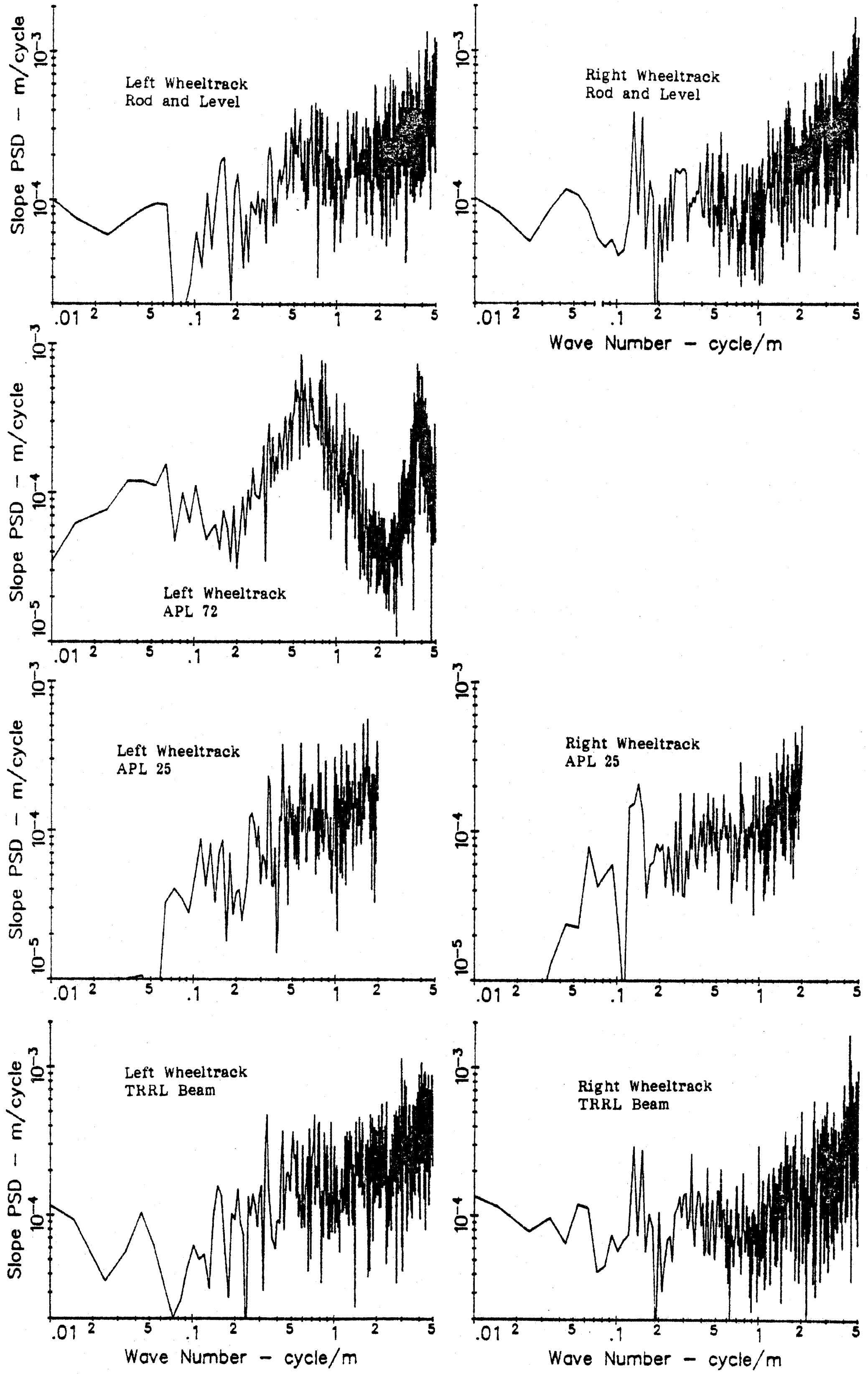


Figure I.32. PSD functions for Site GR05.

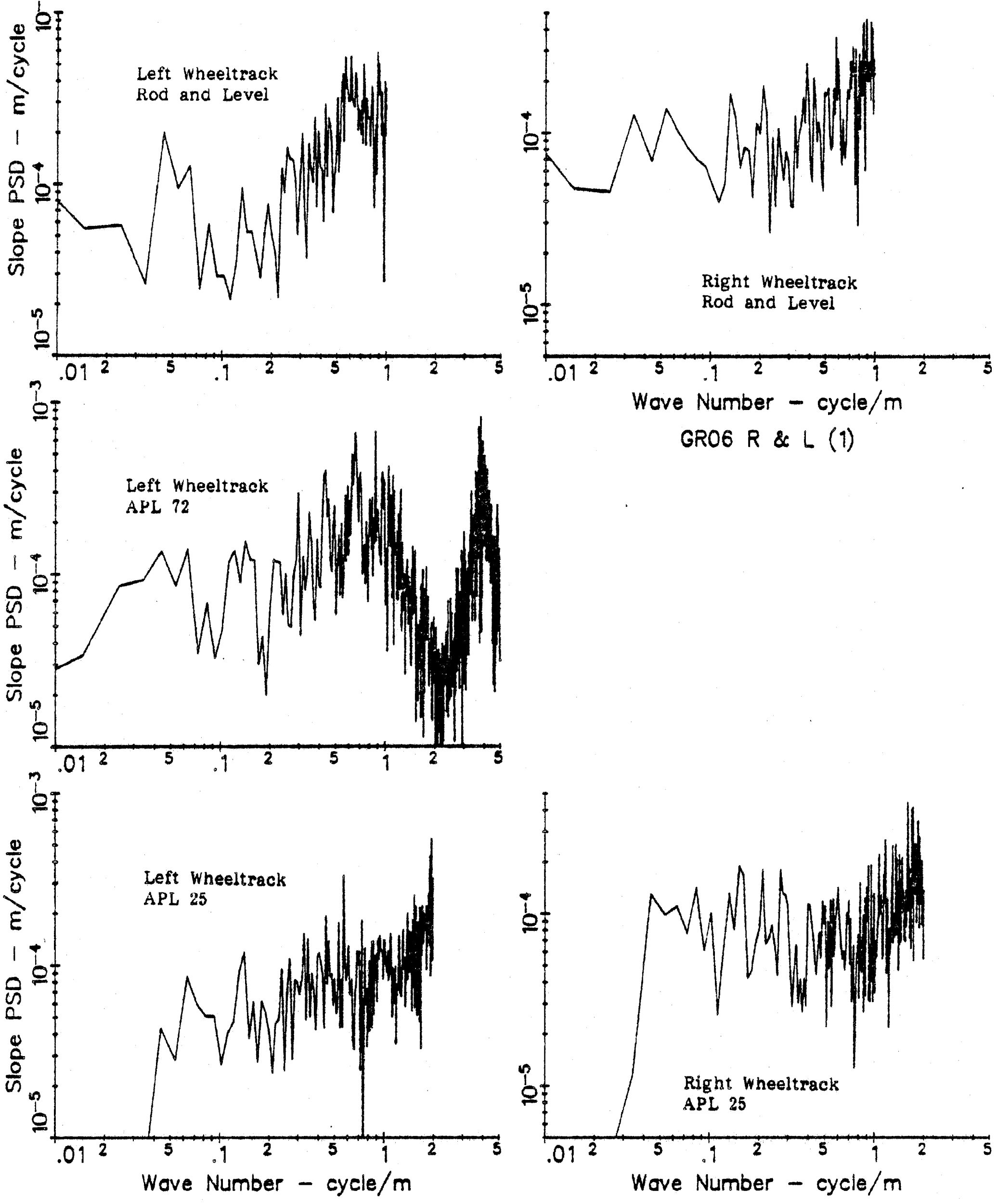


Figure I.33. PSD functions for Site GR06.

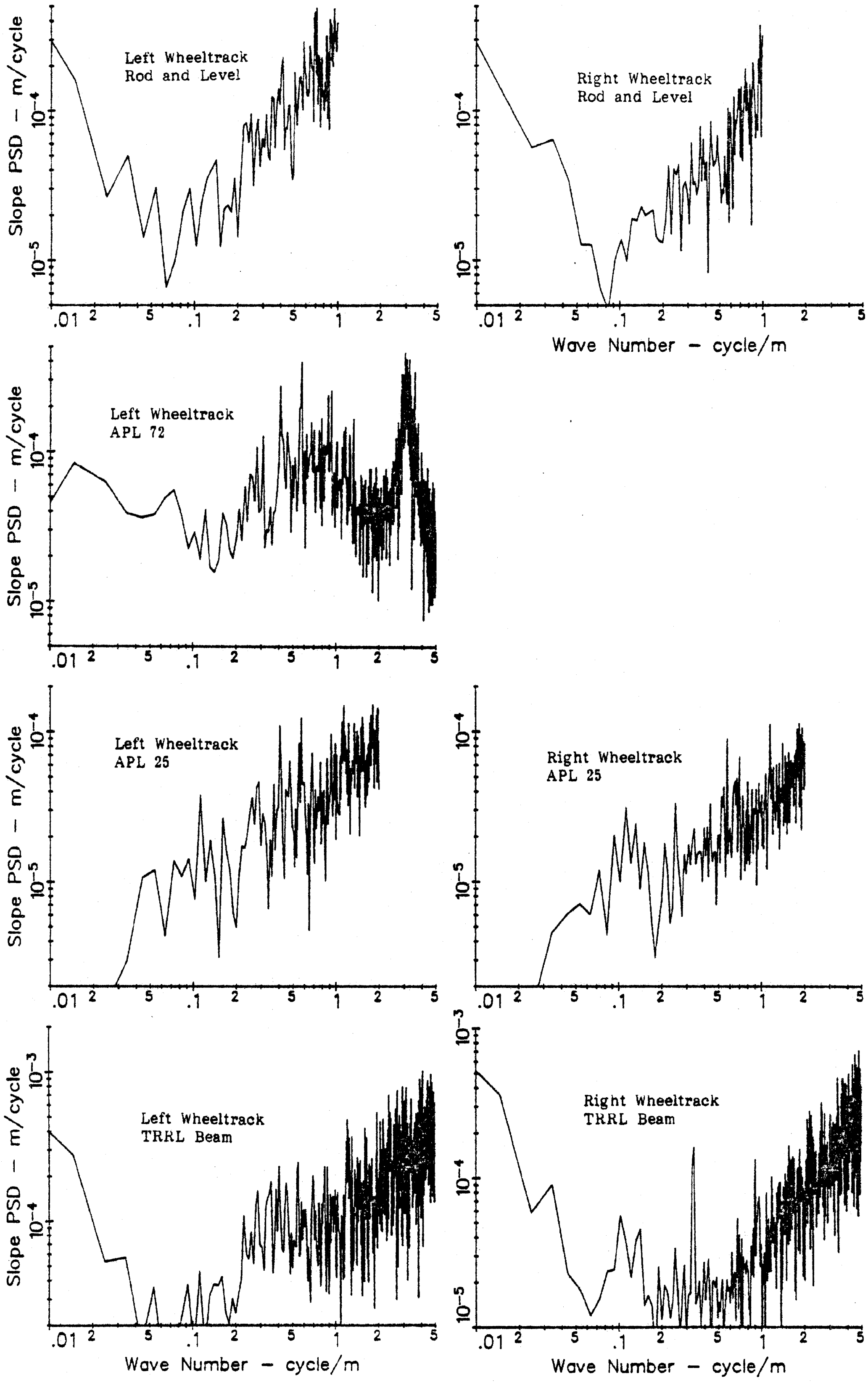


Figure I.34. PSD functions for Site GR07.

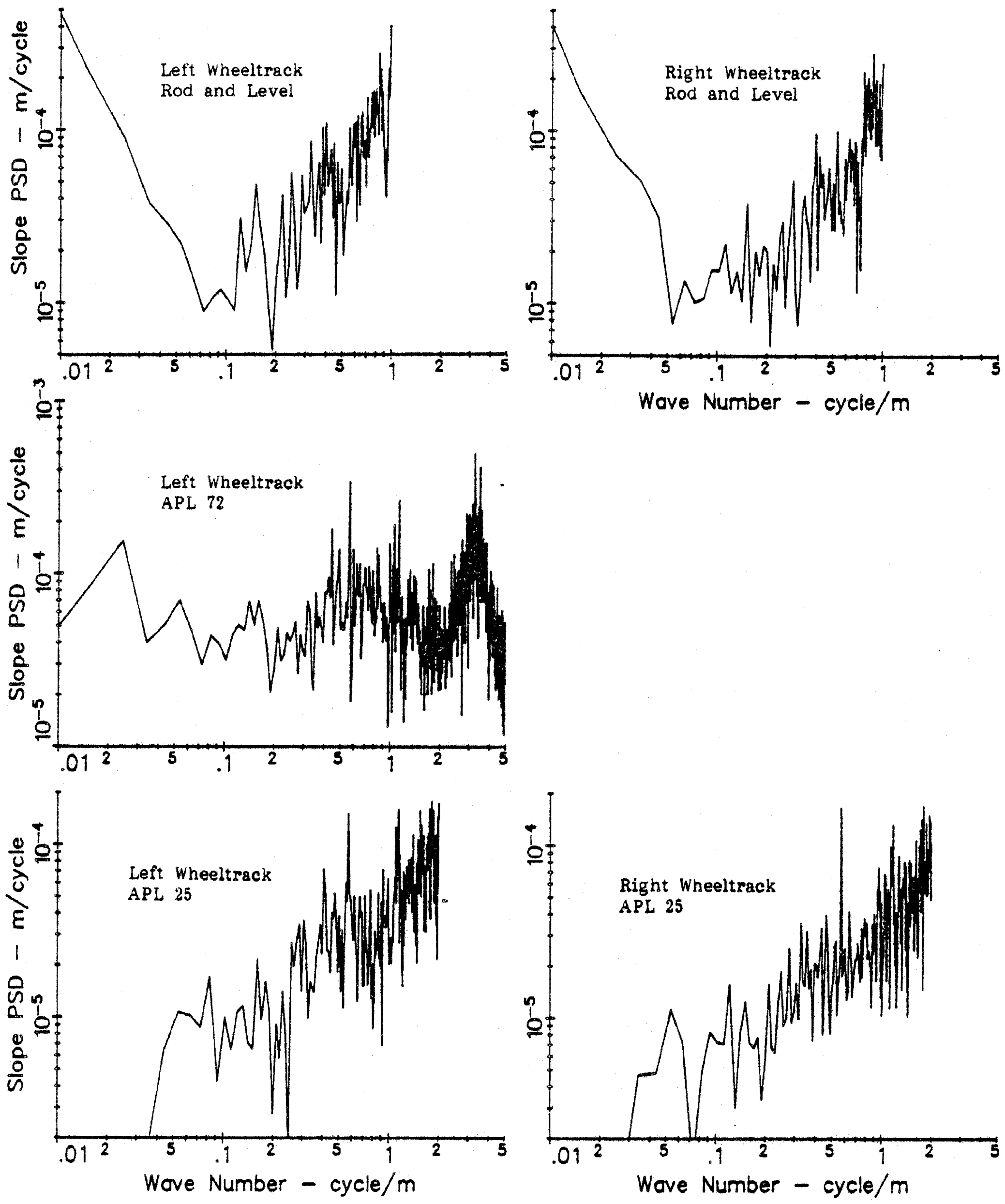


Figure I.35. PSD functions for Site GR08.

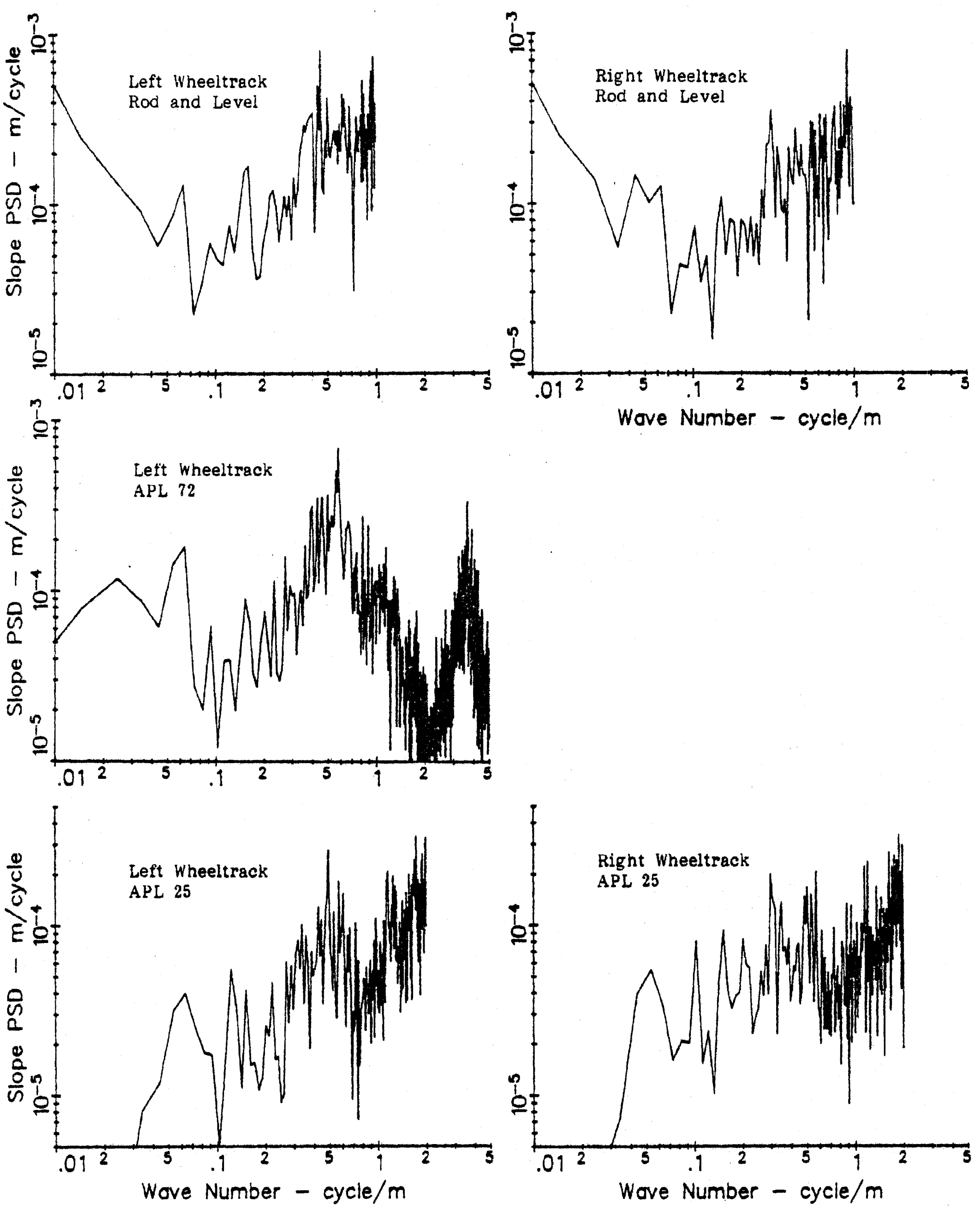


Figure I.36. PSD functions for Site GR09.

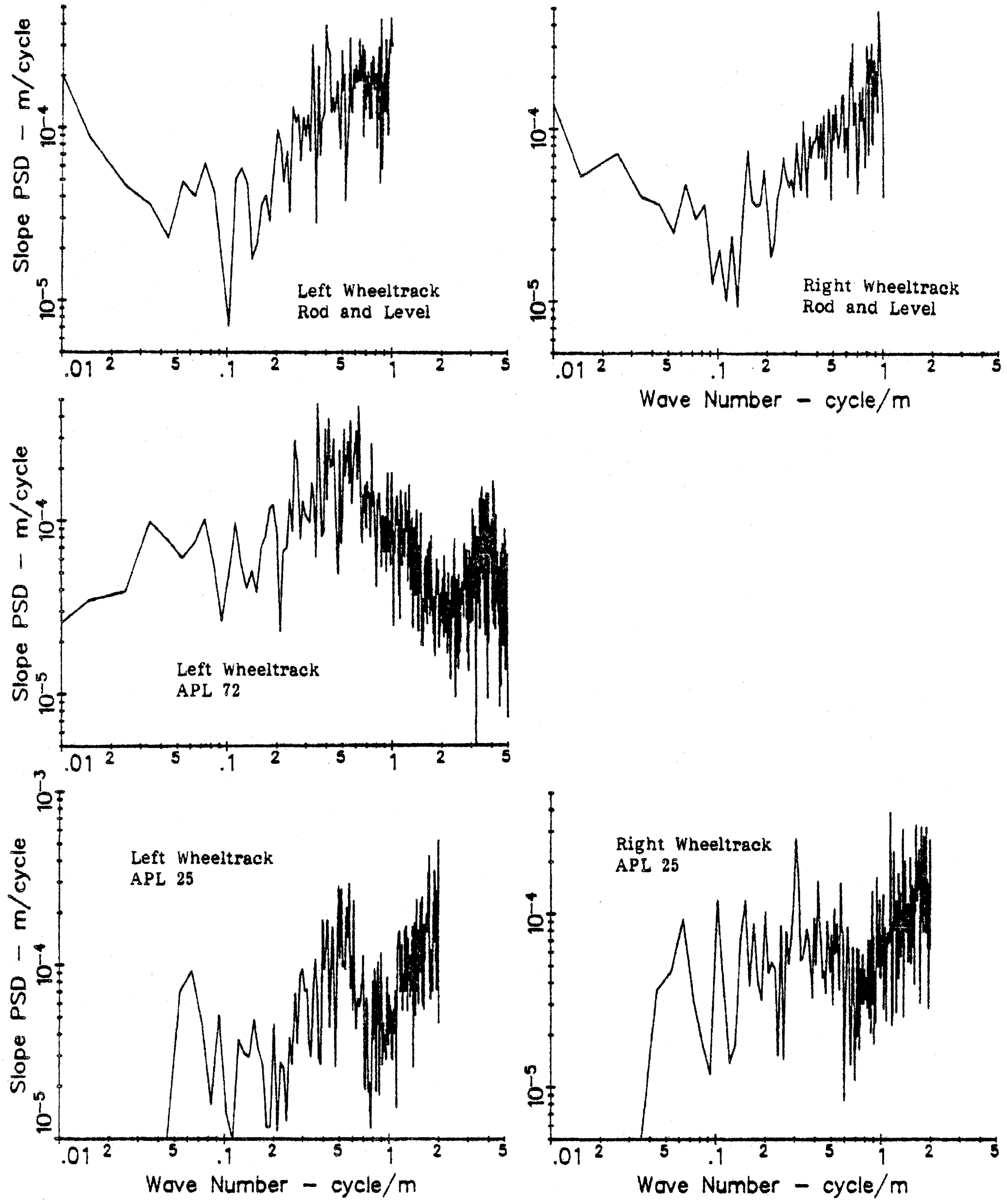


Figure I.37. PSD functions for Site GR10.

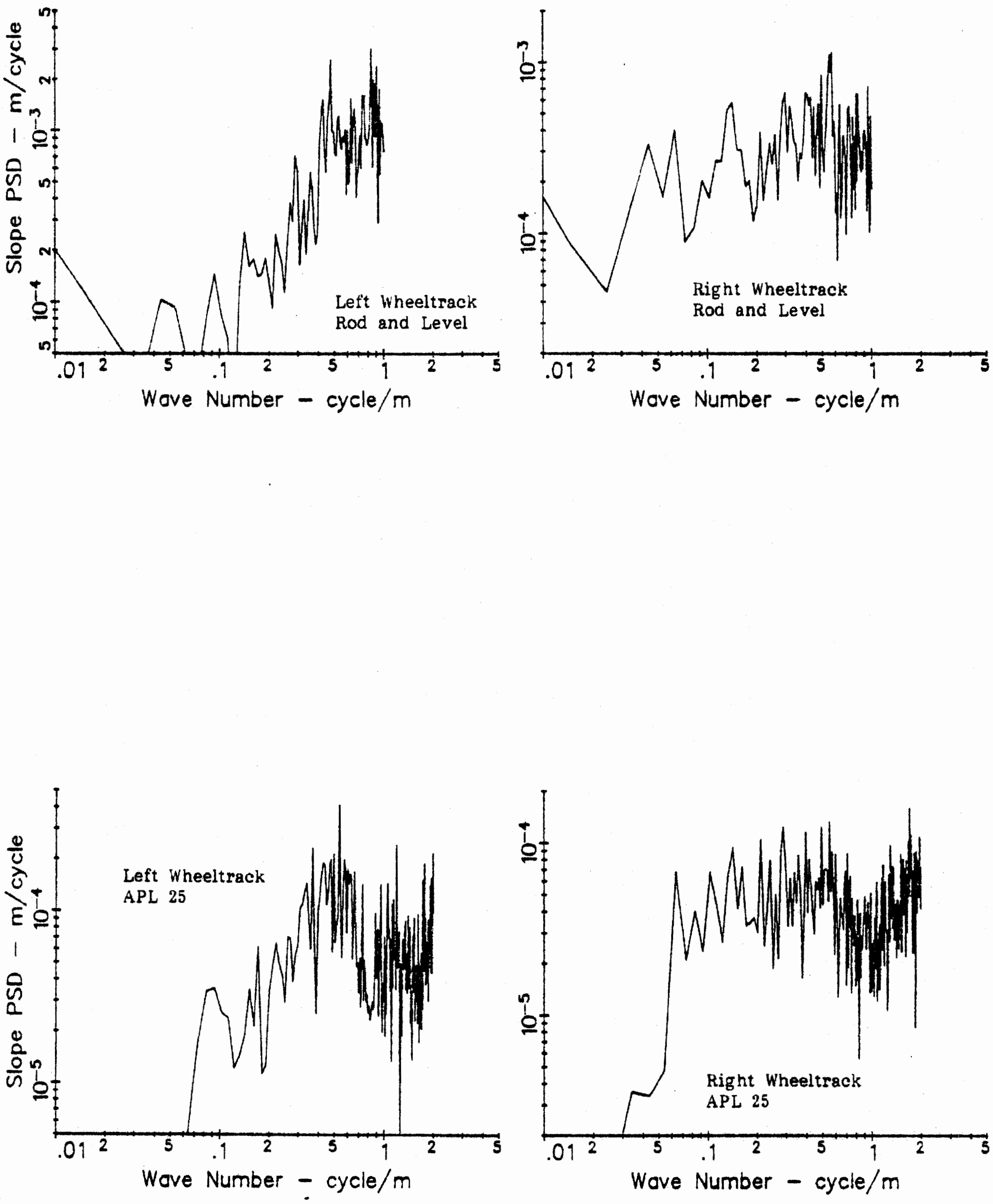


Figure 1.38. PSD functions for Site GR11.

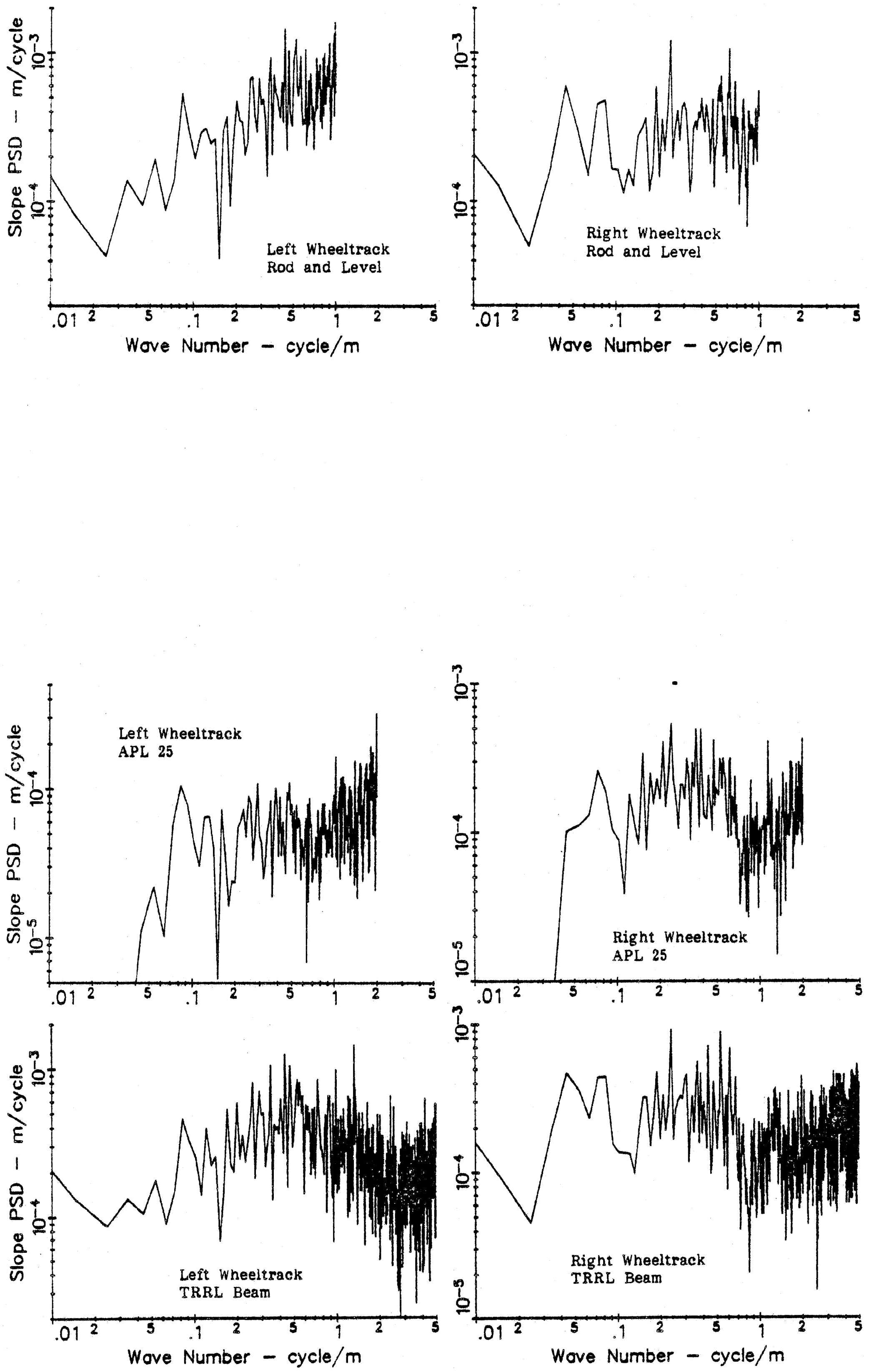


Figure I.39. PSD functions for Site GR12.

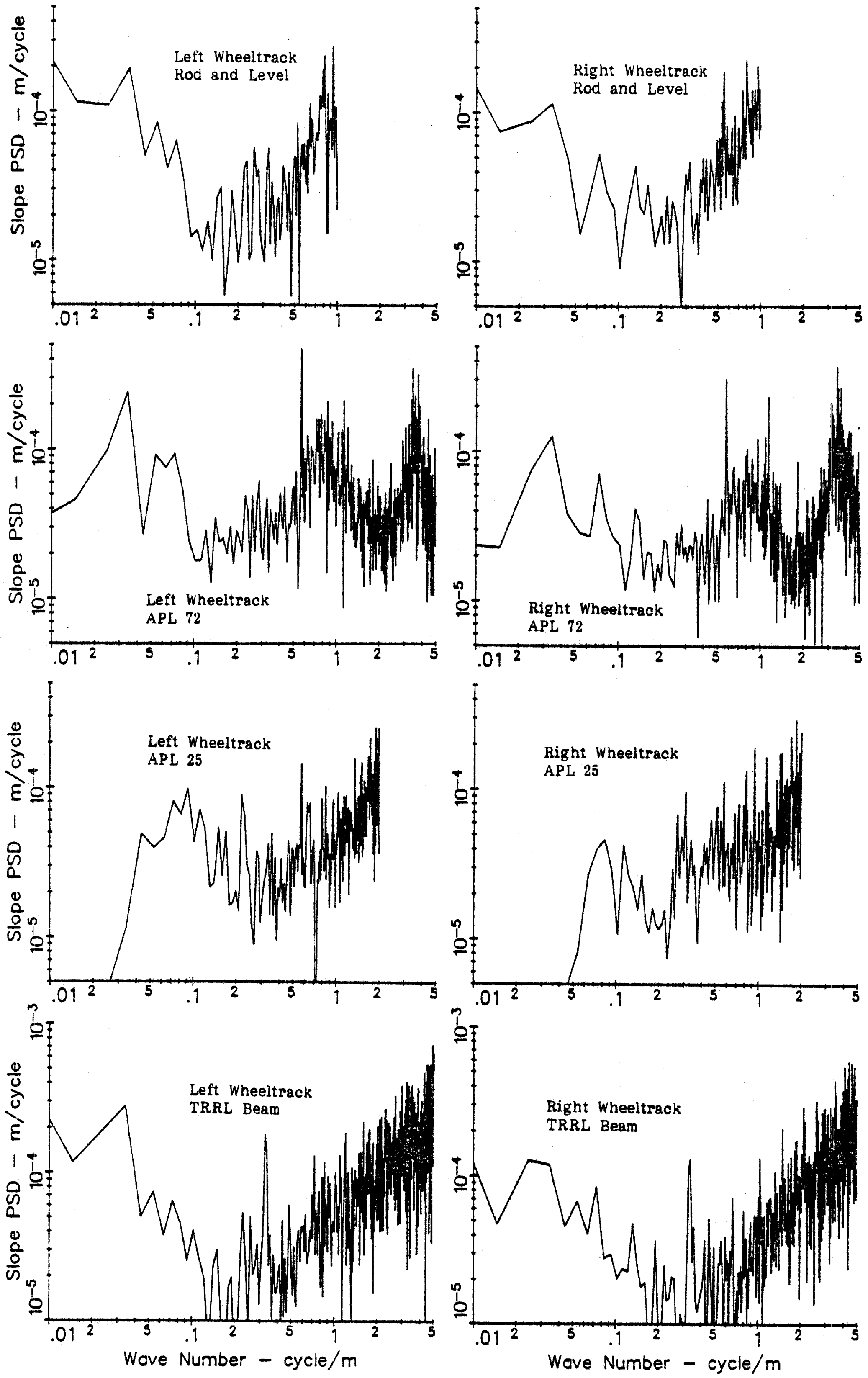


Figure I.40. PSD functions for Site TE01.

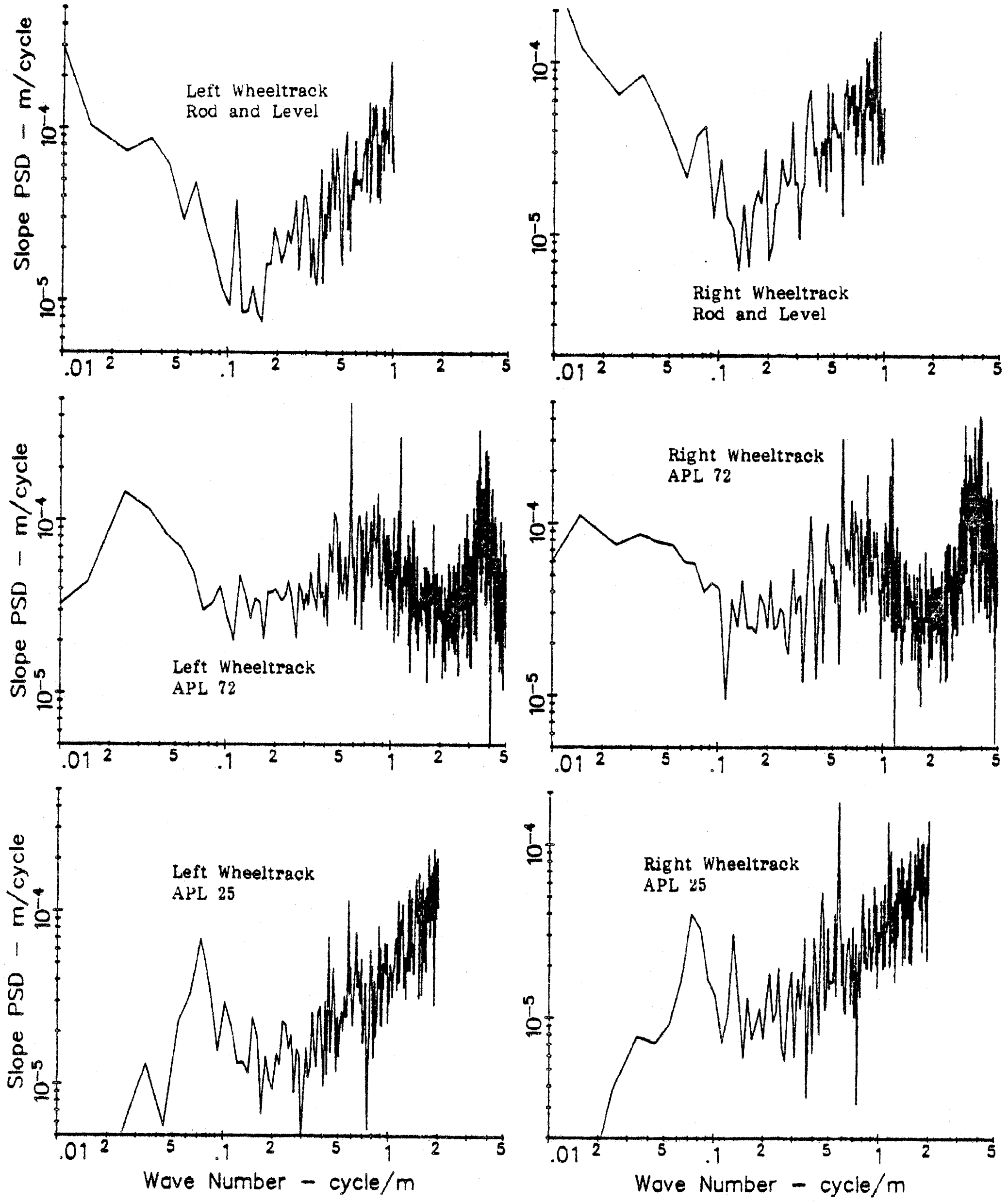


Figure I.41. PSD functions for Site TE02.

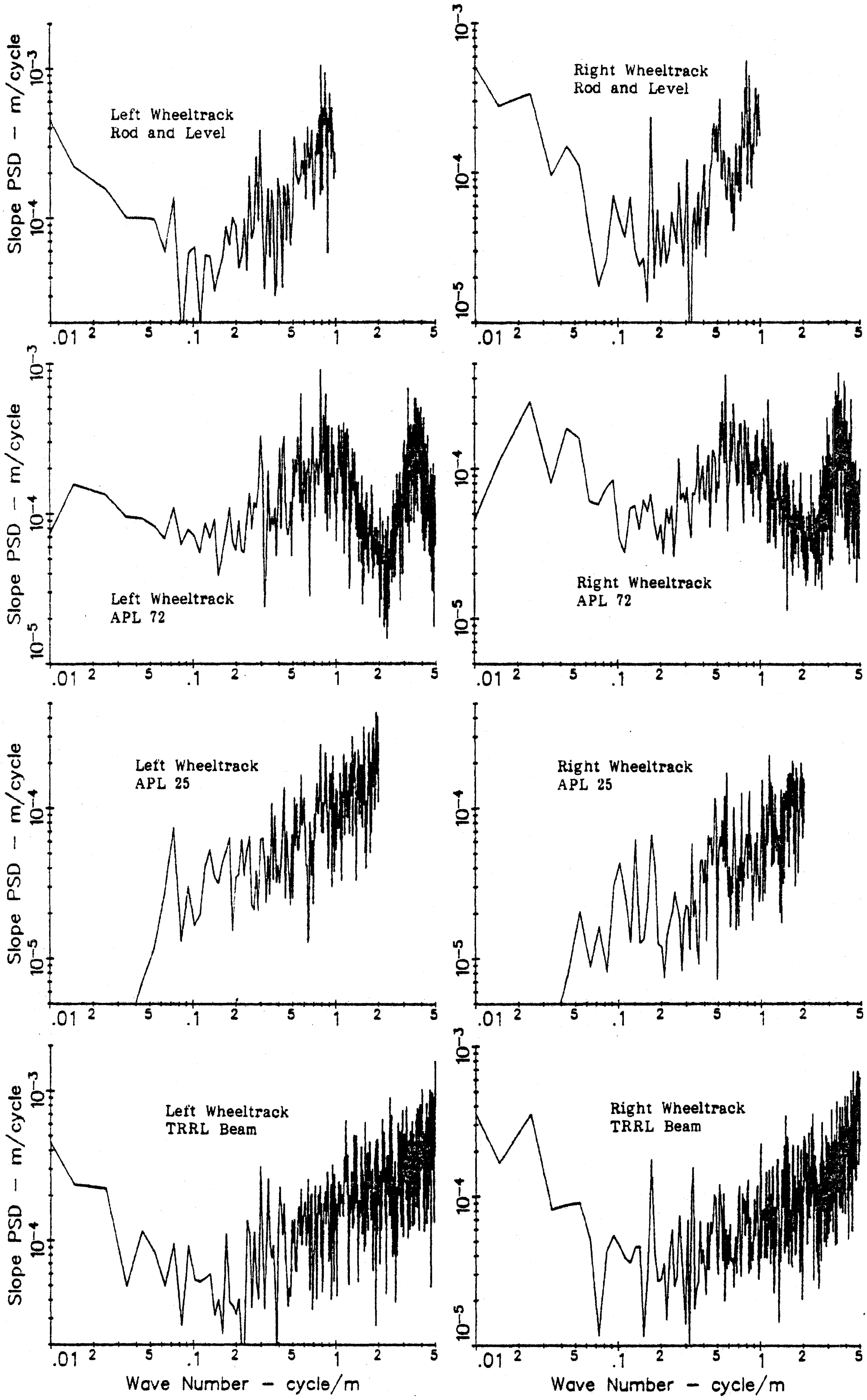


Figure I.42. PSD functions for Site TE03.

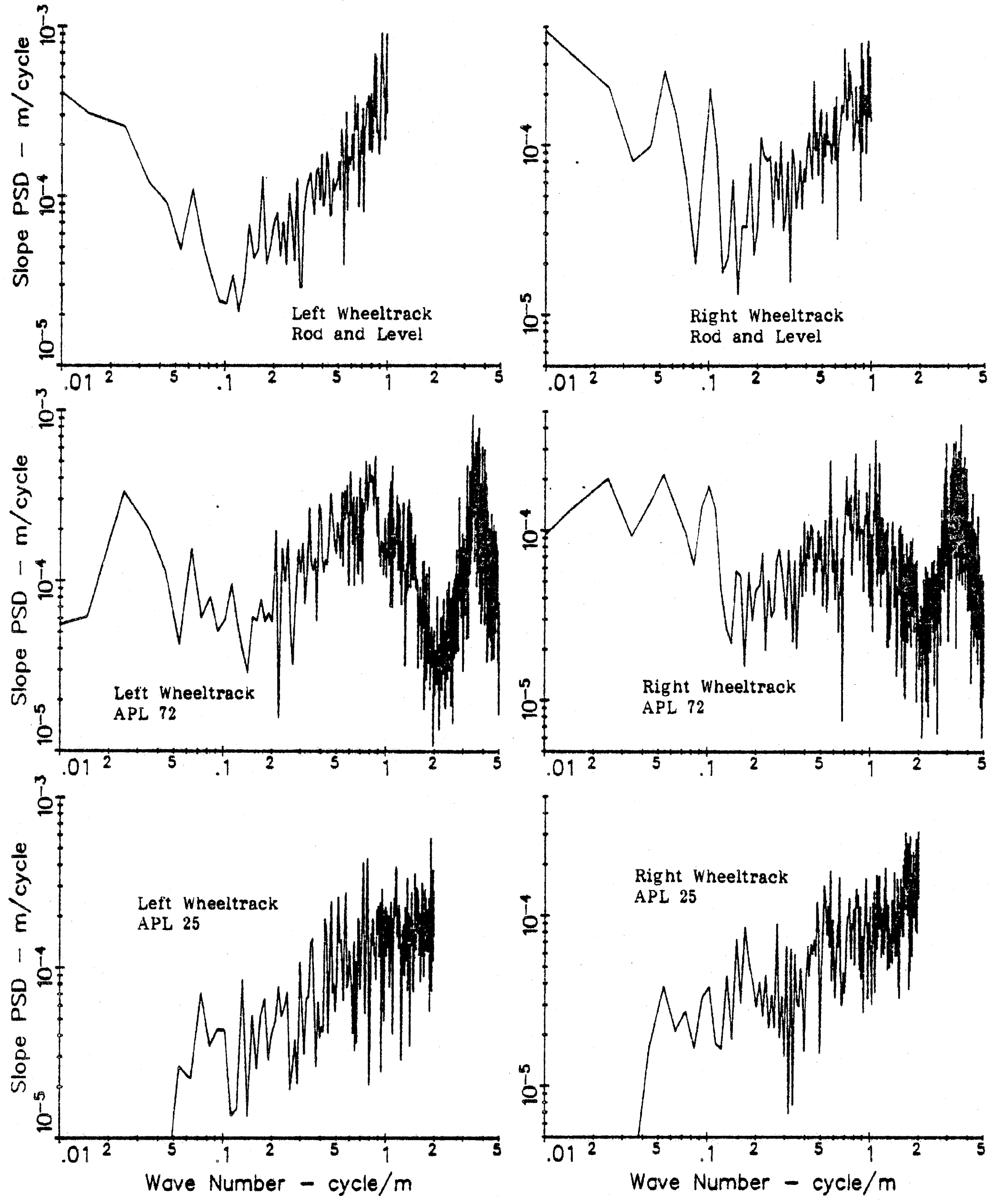


Figure I.43. PSD functions for Site TE04.

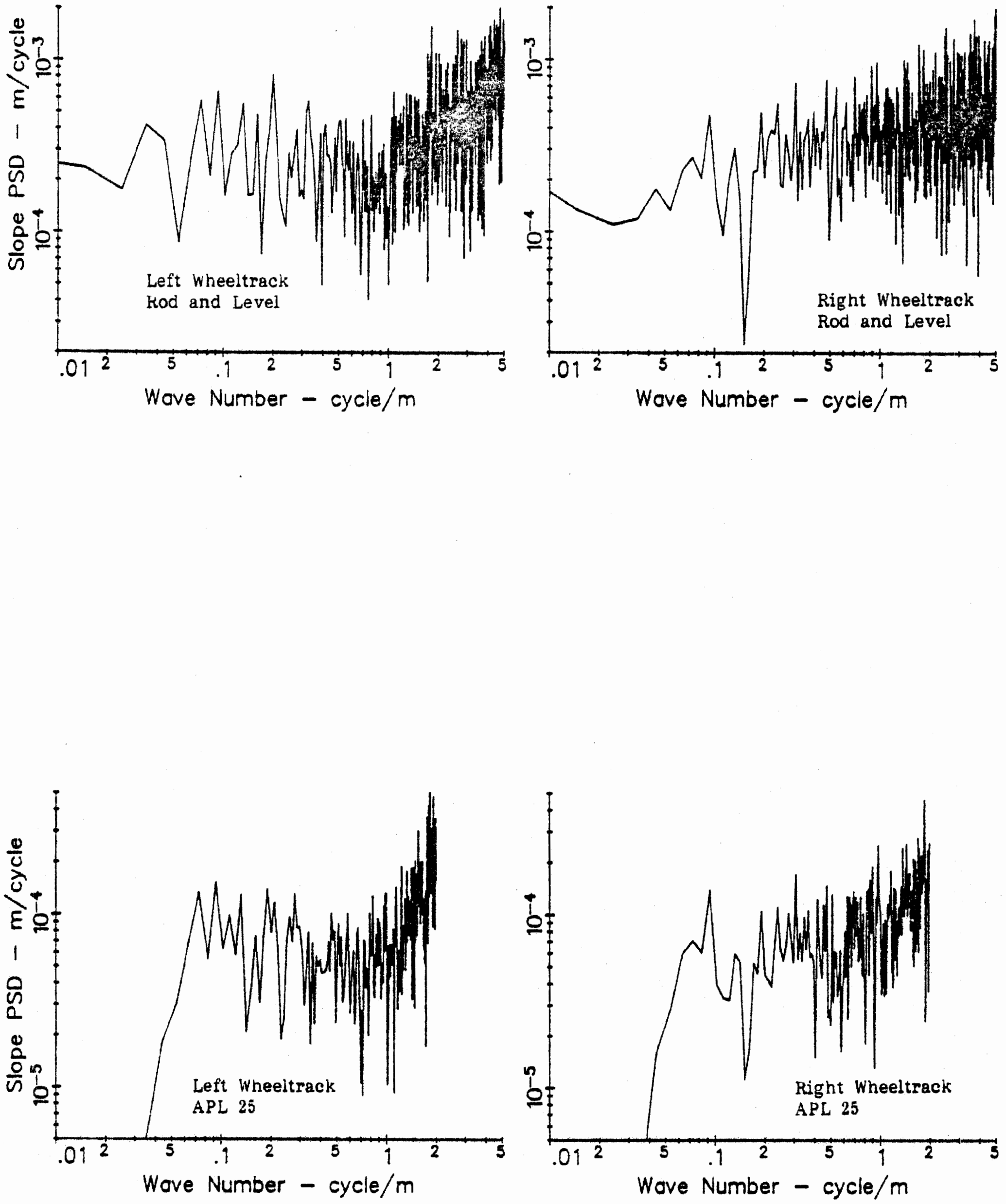


Figure I.44. PSD functions for Site TE05.

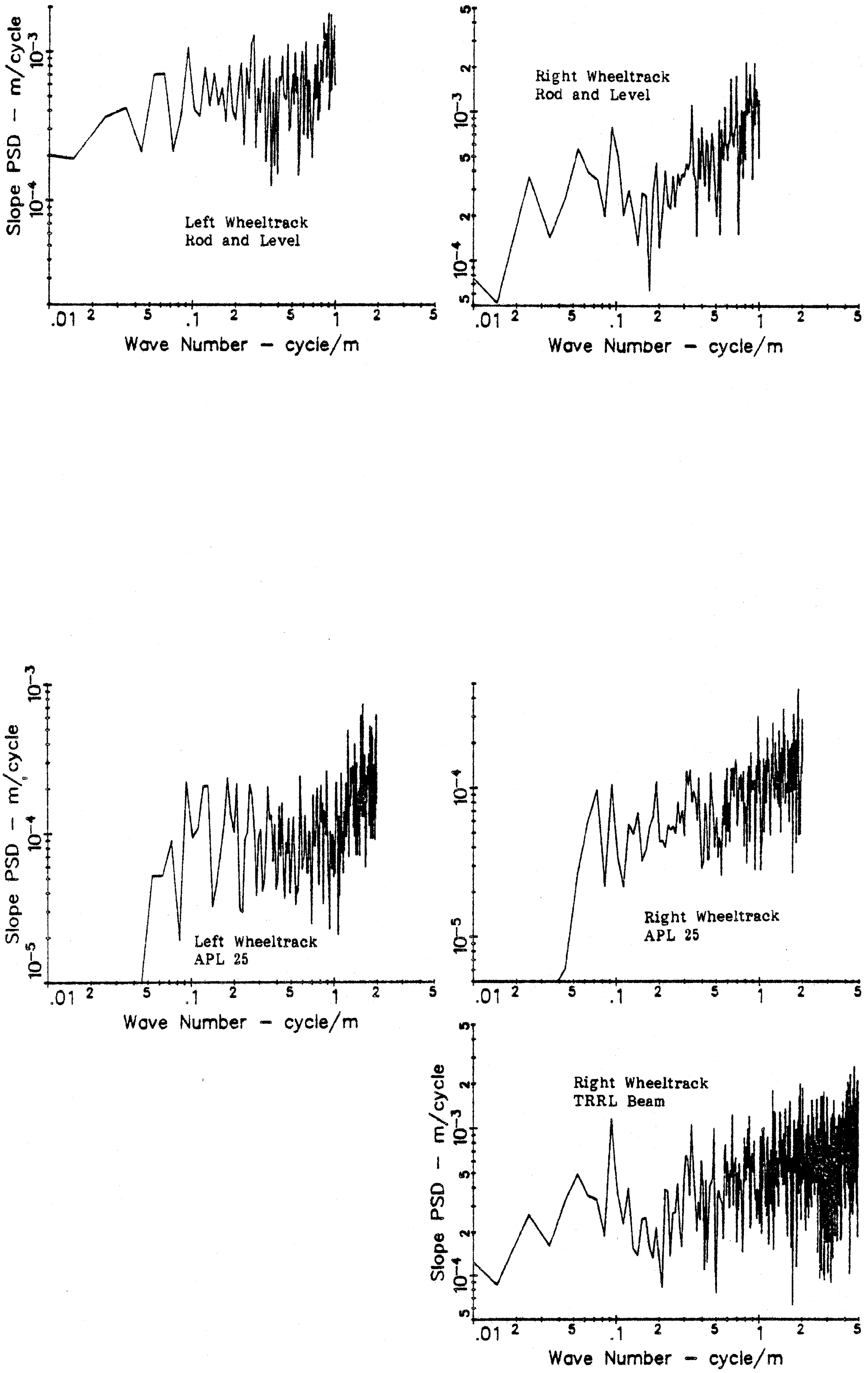
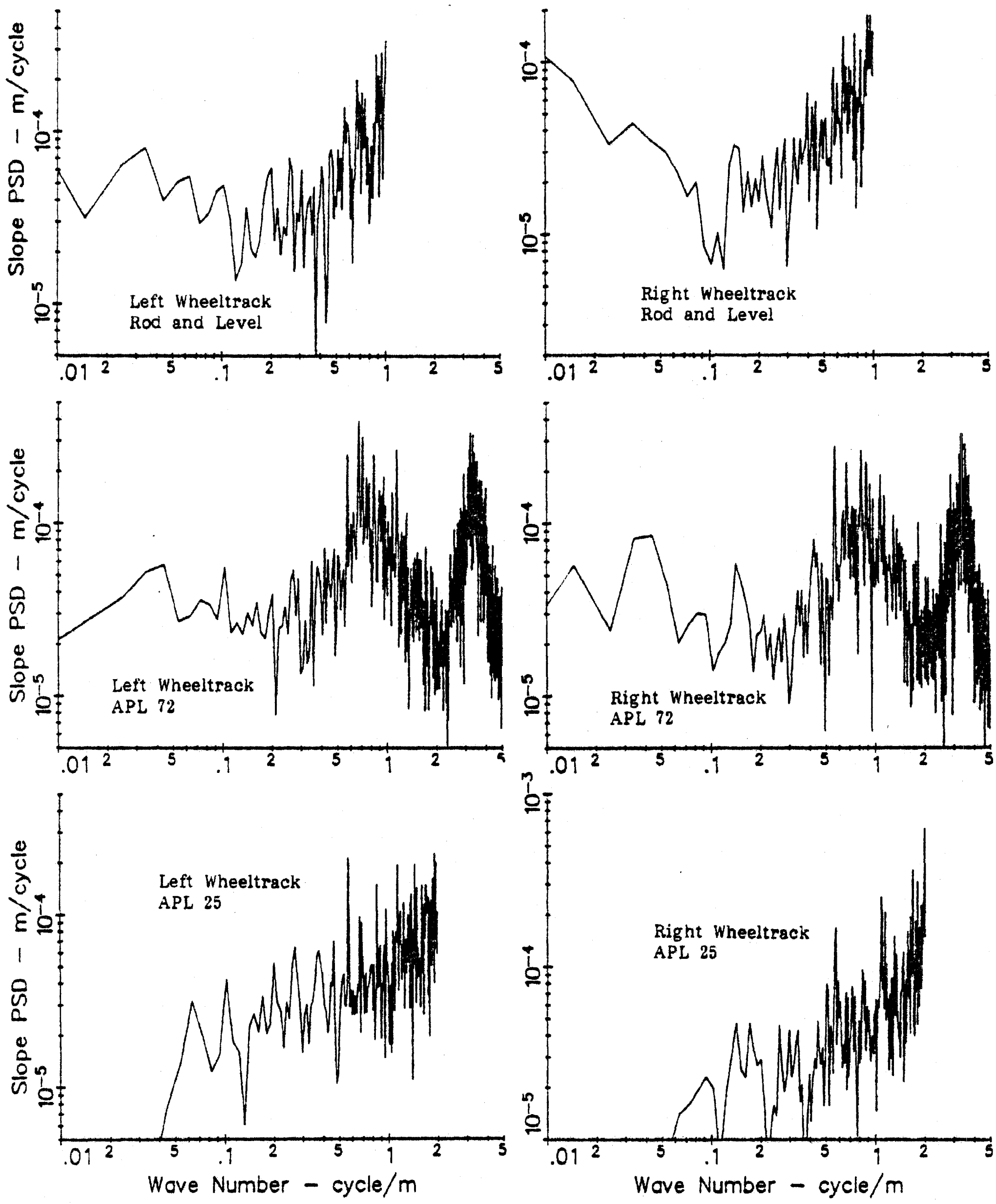


Figure I.45. PSD functions for Site TE06.



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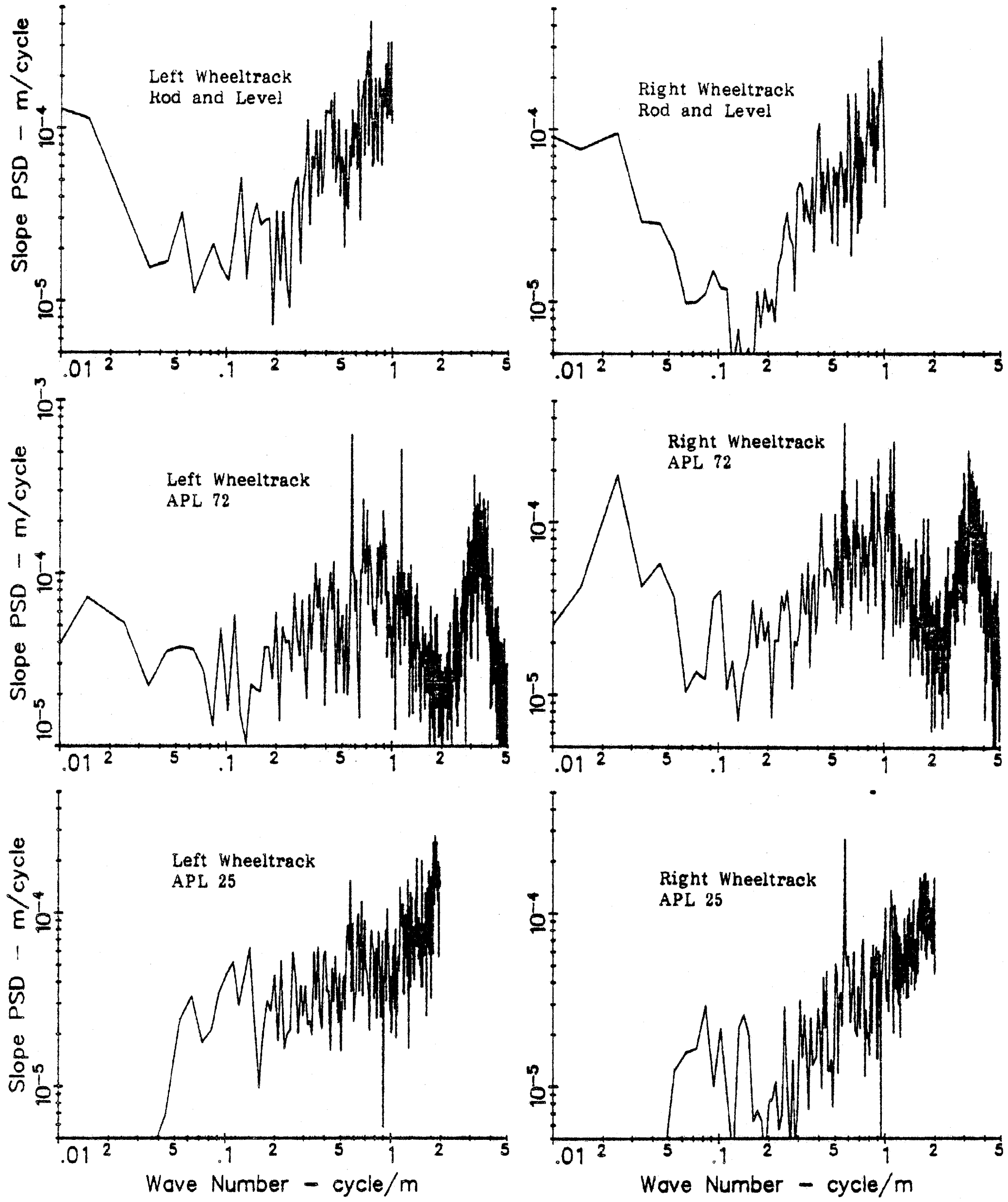

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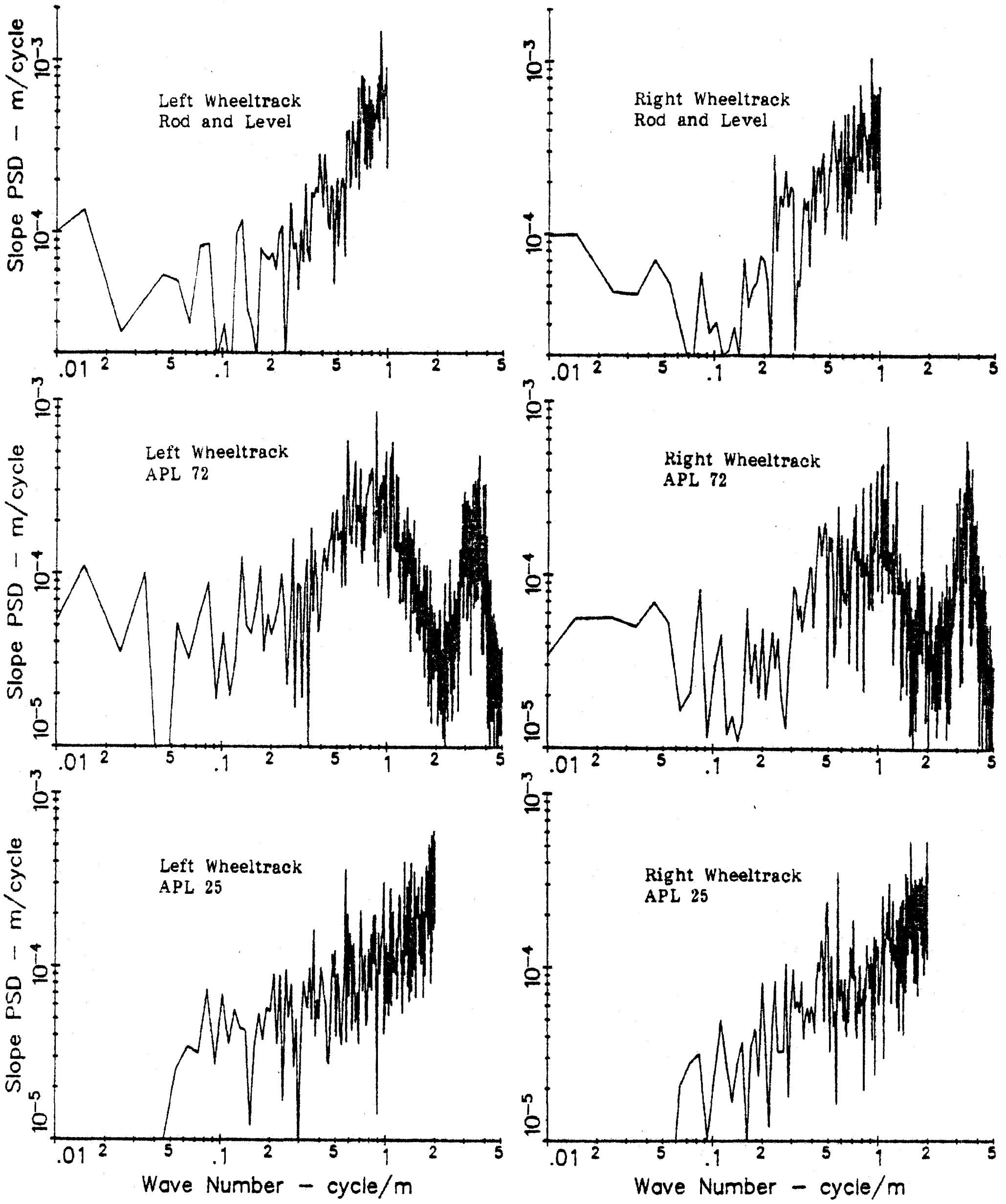

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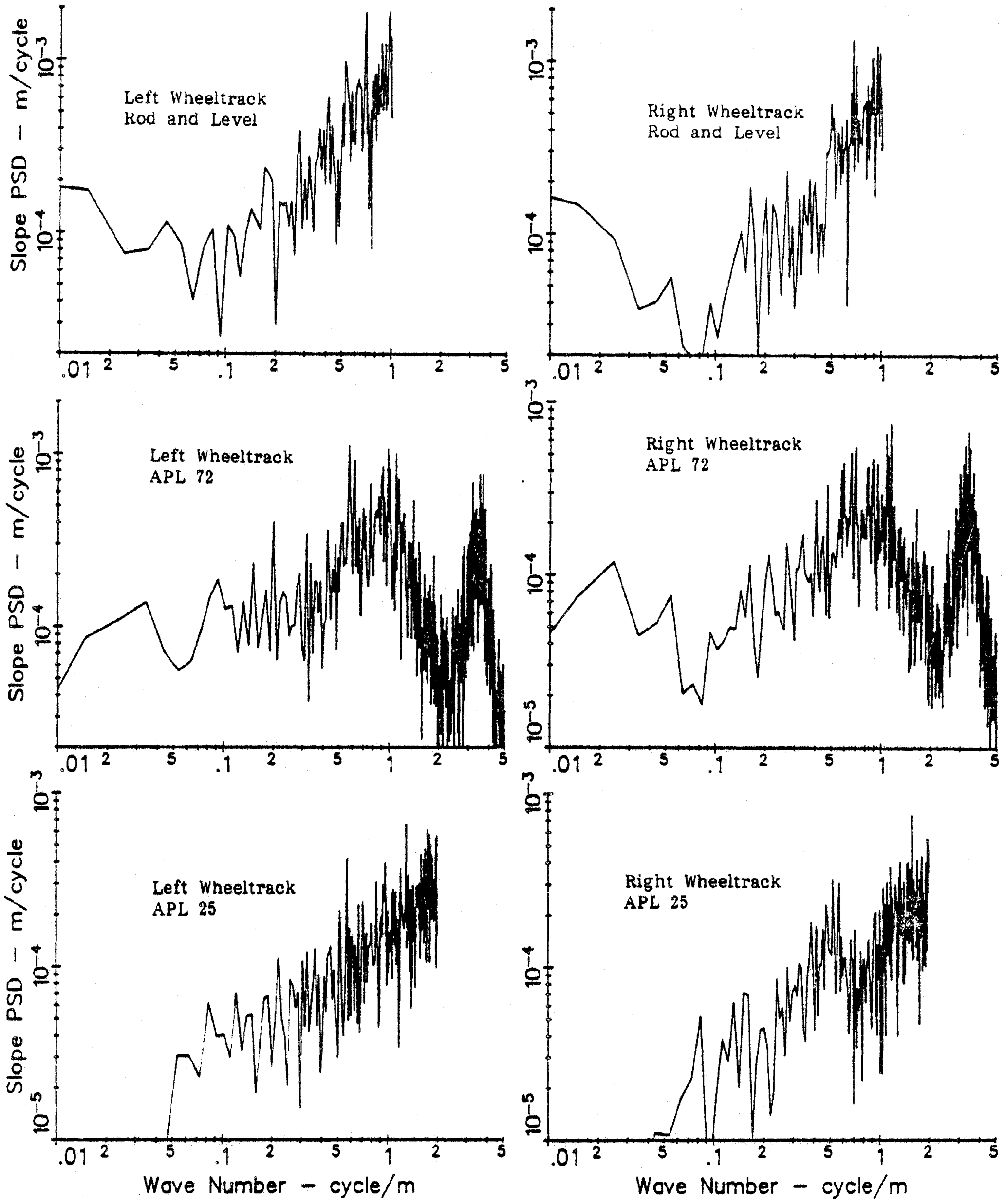


Figure I.49. PSD functions for Site TE10.

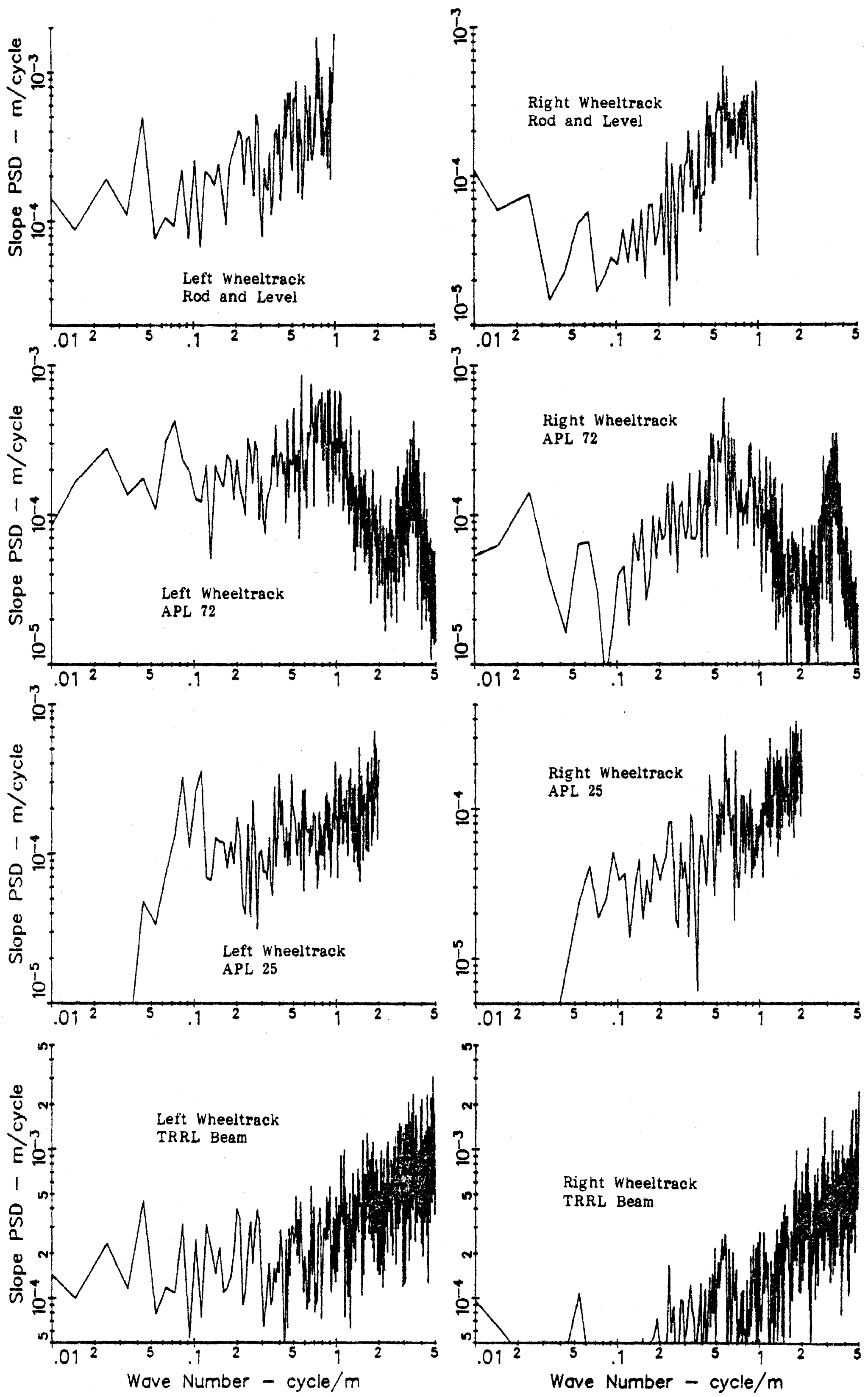


Figure I.50. PSD functions for Site TE11.

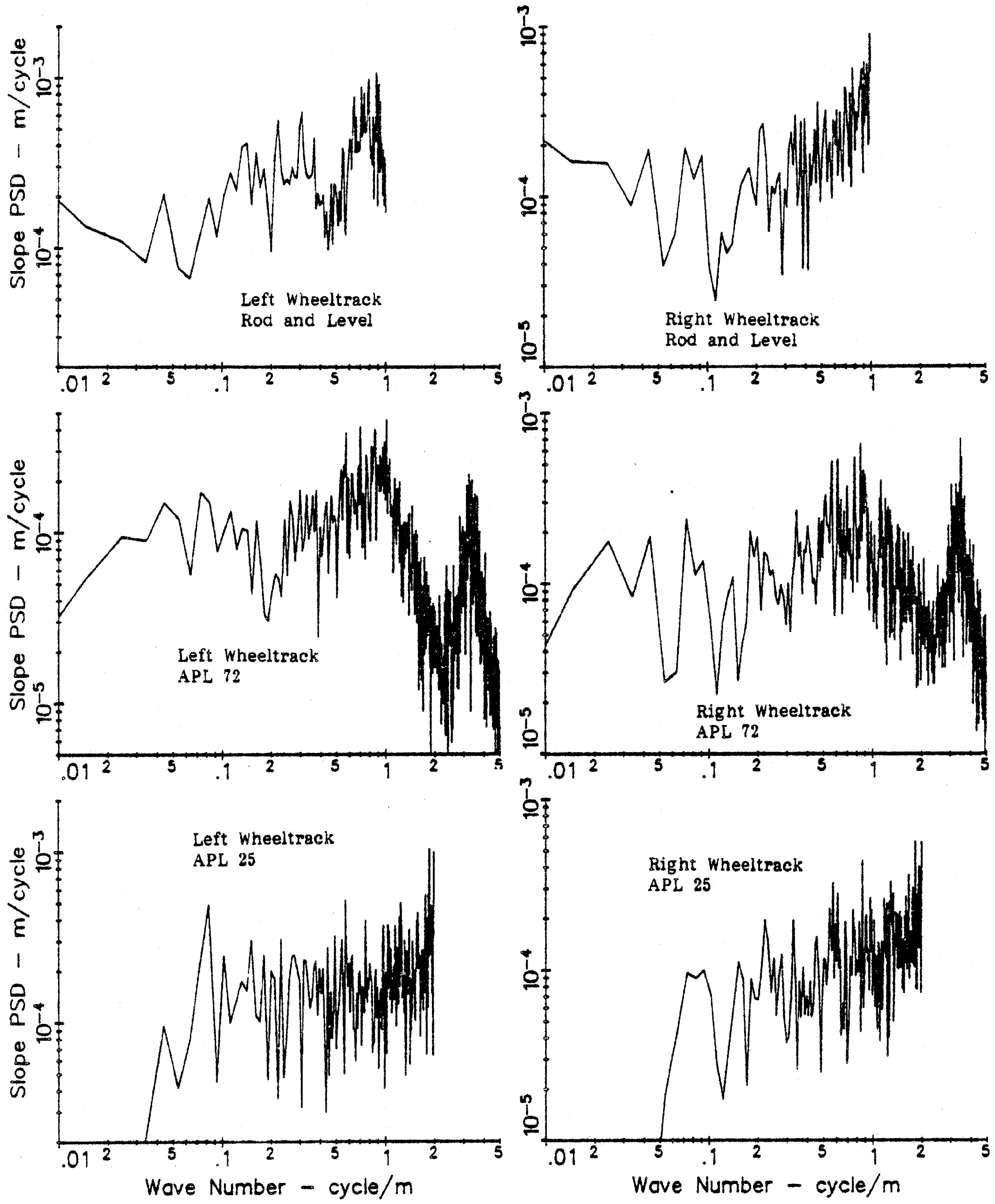


Figure I.51. PSD functions for Site TE12.

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:

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

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:

$$y_s(i) = 1/(2m + 1) \sum_{k=-m}^{m} y_r(i+k) \qquad (J-2)$$

where

$$m = \mathrm{INT}\ [\ (b\ /\ dx)\ /2\ ] \qquad (J-3)$$

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:

$$y_s(i-.5) = 1/(2m) \sum_{k=-m}^{m-1} y_r(i+k) \qquad (J-4)$$

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.

$$y_f(i) = y_r(i) - y_s(i) \qquad (J-5)$$

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:

$$y_f(i-.5) = y_r(i-.5) - y_s(i-.5)$$

$$= [\ y_r(i) + y_r(i-1)\ ] / 2 - y_s(i-.5) \qquad \text{(J-6)}$$

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:

$$y(w,x) = Y_o\ e^{jwx} \qquad \text{(J-7)}$$

where

$$e^{jwx} = \cos(wx) + j\ \sin(wx) \qquad \text{(J-8)}$$

$$w = 2\pi/L \qquad \text{(J-9)}$$

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)

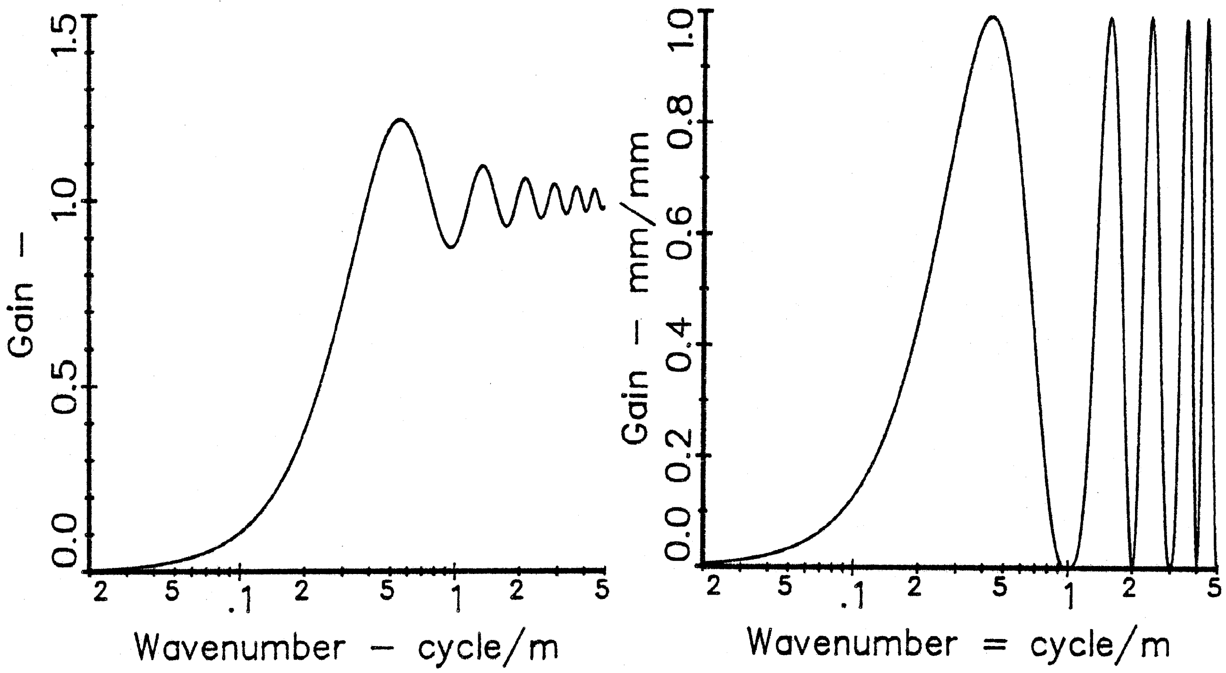
while Eq. 6 can be converted as:

$$y_f/y_r = \cos(.5w\ dx) - 1/2m \sum_{k=1}^{m} 2\cos(\{k-.5\}\ w\ dx) \qquad \text{(J-15)}$$

(for b/dx = **even** integer number)

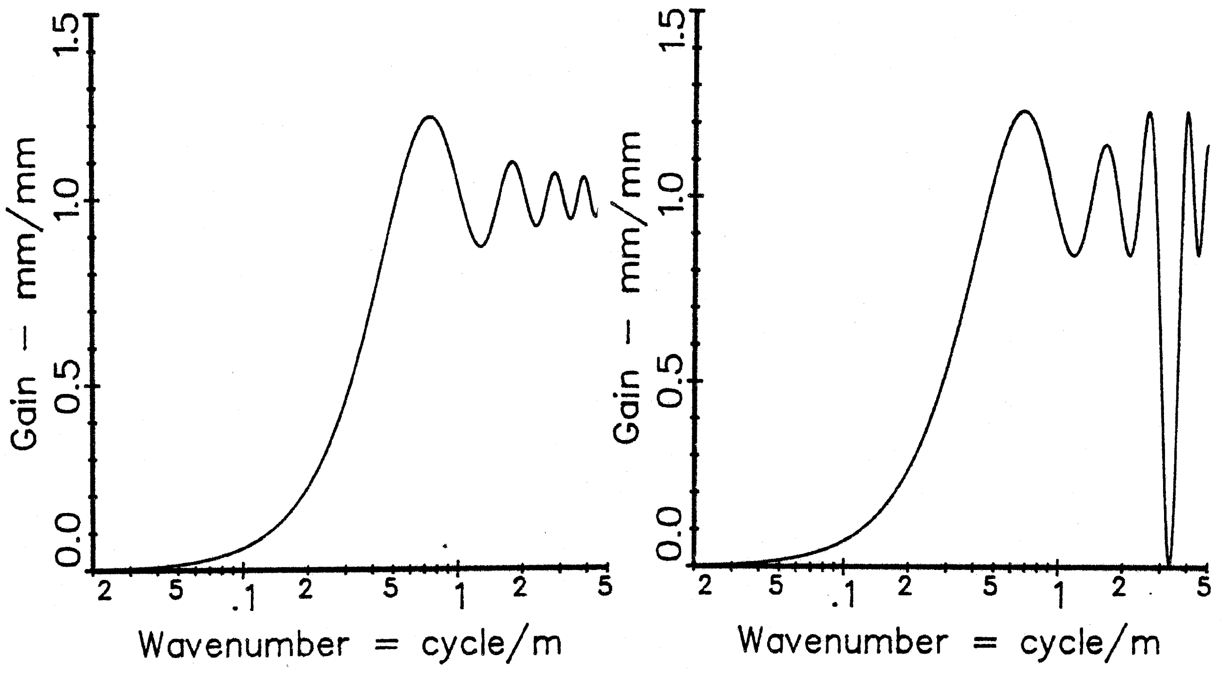
Eqs. 14 and 15 were used to prepare the four plots shown in Figs. J.1, using the baselength of 2.5 m with measurement intervals of 50 and 500 mm, and the baselength 1.8 m with 100 amd 300 mm intervals. Note that the moving average filter attenuates wavelengths longer than the baselength, and transmits 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



a. Base=2.5,dx=.05

b. Base=2.5, dx=.5



c. Base=1.8,dx=.1

d. Base=1.8,dx=.3

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:

$$y' = dy/dx = jw = j(2\pi/L) \tag{J-16}$$

Thus,

$$|y_f/y_r'| = |y_f/y_r| \;/\; w = |y_f/y_r| \; L/2\pi \tag{J-17}$$

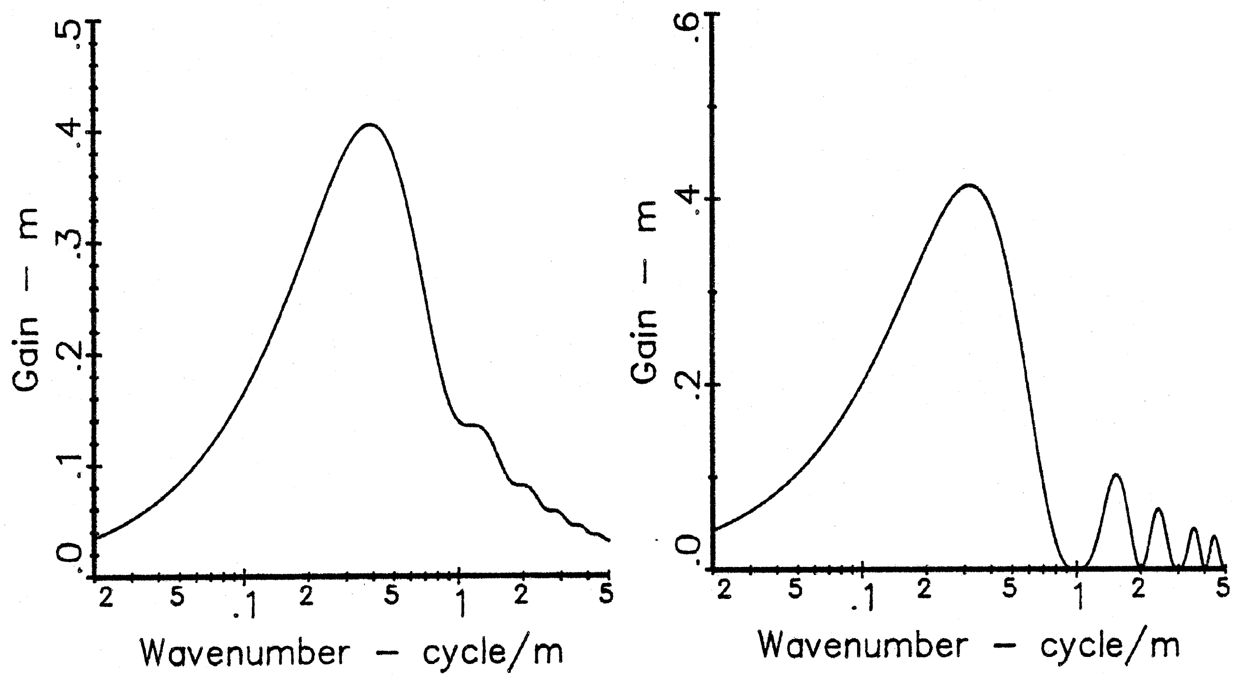
Eq. 17 was used to rescale the four plots in Figure J.1 for the case of a slope input, to obtaine the plots shown in Figure J.2.

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.

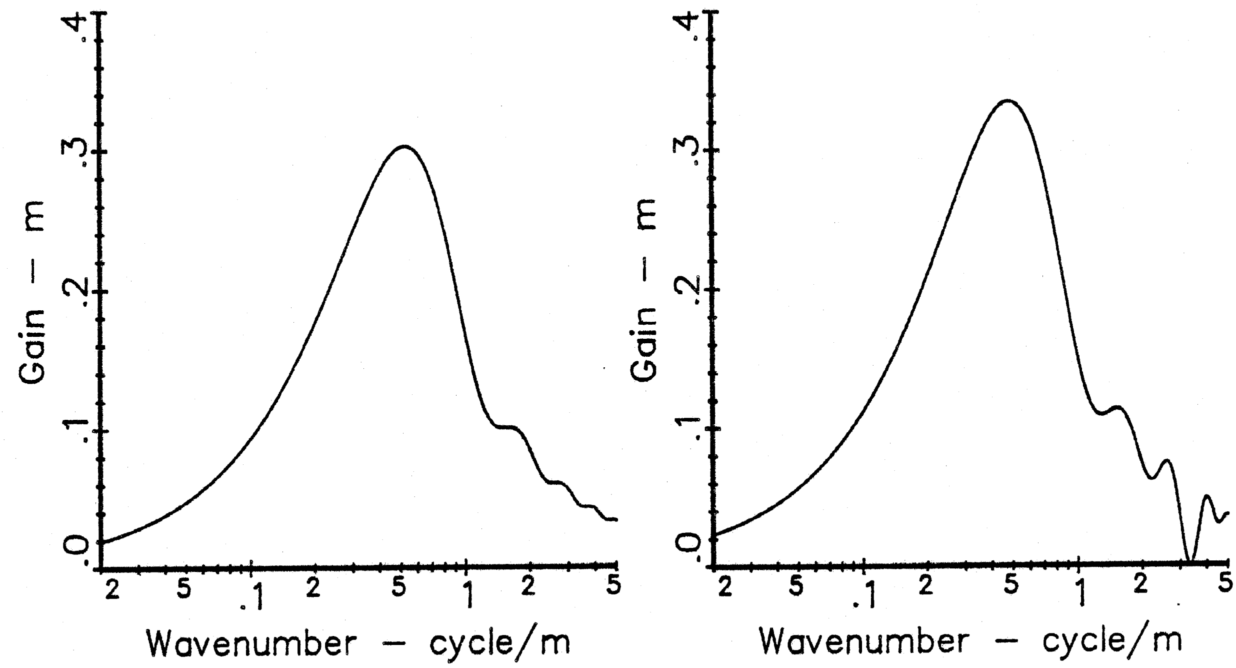
Comparison of Dynamic and Static Measures of CP

Although the moving average analysis was employed by both CRR and TRRL (see Appendix H), time constraints prevented the direct comparison of summary



a. Base=2.5,dx=.05

b. Base=2.5,dx=.5



c. Base=1.8,dx=.1

d. Base=1.8,dx=.3

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.

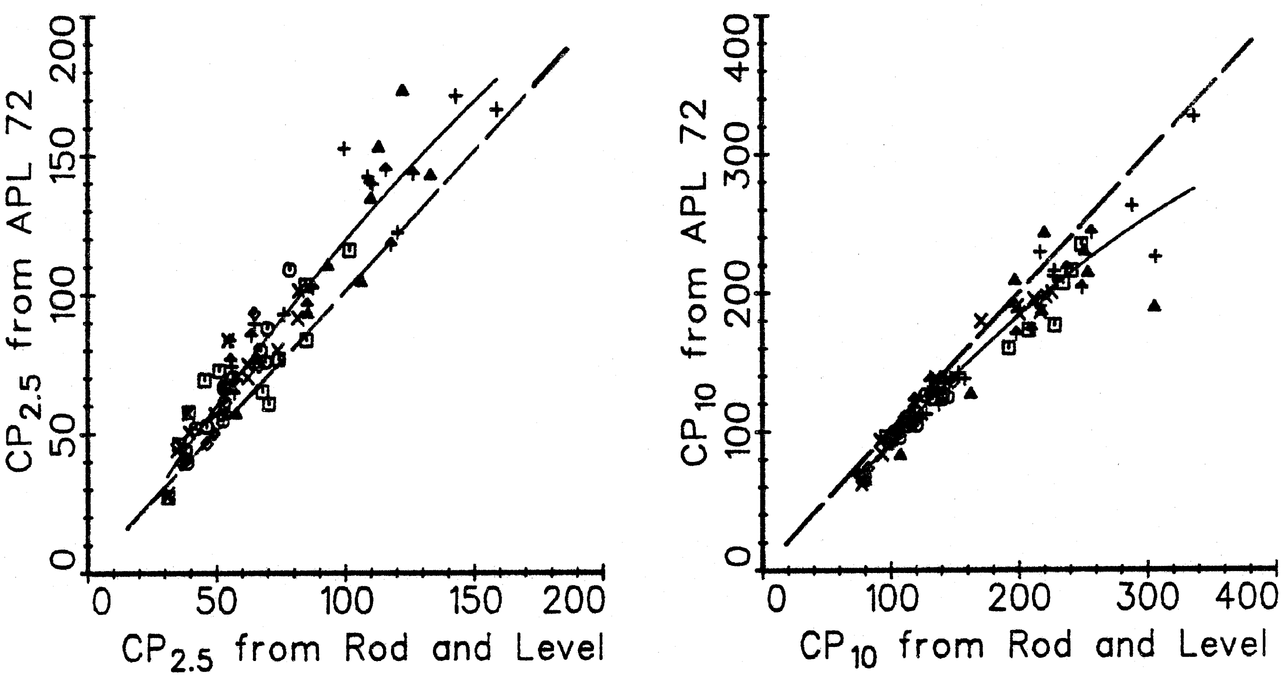
Figure J.3 compares the moving average measures statically and from APL profiles. The four scatter plots show that:

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.

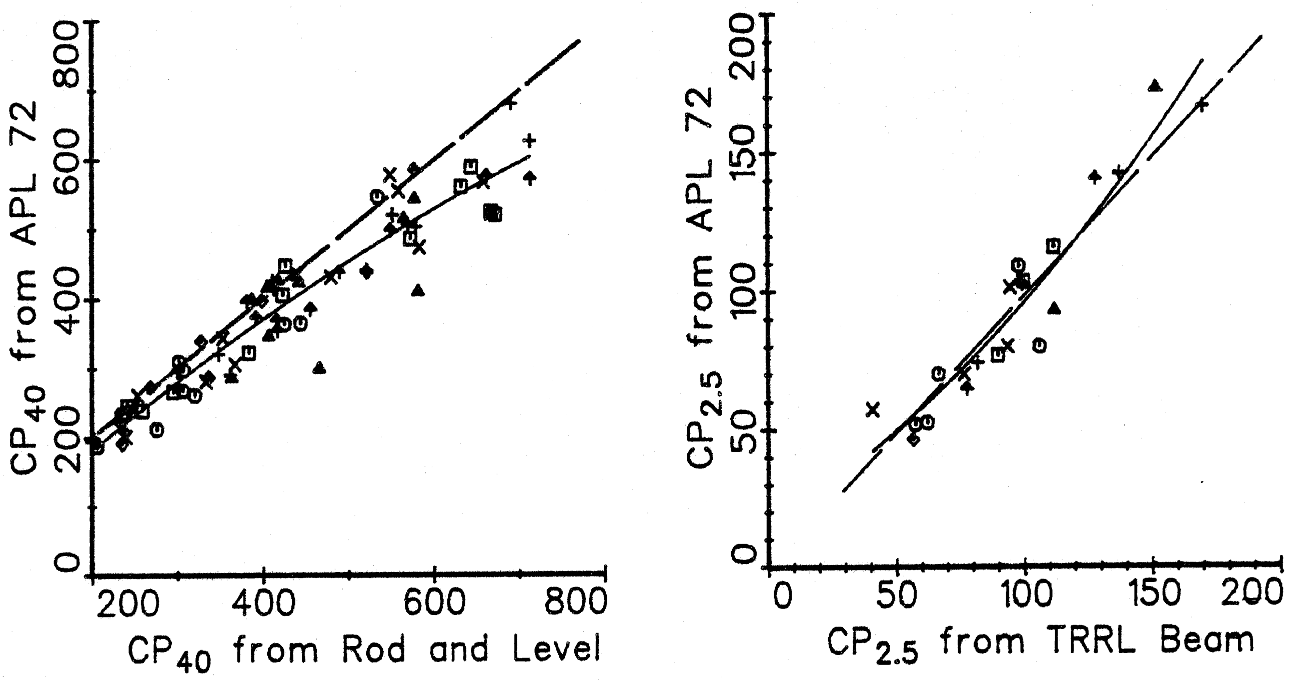
2. The CP_{10} numerics as computed from the APL 72 are nearly identical to those obtained from the rod and level, with the exception of two of the roughest unpaved roads, which appear as "outliers." Excluding the two "outliers," the plot shows the remaining 73 data points lying very close to the line 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.



a. 2.5 m Moving Average

b. 10 m Moving Average



c. 40 m Moving Average

d. 2.5 m Moving Average

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.