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TECHNICAL CONSIDERATIONS IN THE WORLDWIDE STANDARDIZATION OF ROAD ROUGHNESS MEASUREMENT

A Report to the World Bank

by

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16. Abstract

Road roughness is of interest to highway engineers worldwide because of its direct influence on the road users' comfort, safety and vehicle wear; all of which ultimately impacts on road user costs. A persistent problem in advancing this technology is how to best characterize roughness and calibrate the worldwide measurements to a standard.

This report presents a technical discussion of road roughness and the measurement processes commonly in use today. The rationale for an objective selection of a roughness measurement standard must reflect the related interaction with road-using vehicles and the effects of travel speed. On that basis the measures of suspension deflections obtained with roadmeters, as practiced today, is seen as reasonable if valid calibration methods are developed. Among alternative approaches to calibration methods, the most straightforward is a direct measurement of the road profile which can be processed to extract the roughness measurement, such as the profilometer/quarter-car simulation method that has been used in the U.S.

Recommendations for developing standard calibration methods for worldwide use are presented.

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Introduction

The roughness of road surfaces has been long recognized as an important measure of its performance. Roughness has a direct influence on ride comfort, safety, and vehicle wear [1], by dynamic excitation of the vehicle. In turn, the dynamic wheel loads produced are implicated as causative factors in roadway deterioration. The term "roughness," as used here, means the variations in surface elevation along a road which excite vibrations in traversing vehicles.

As a consequence, the characterization and measurement of road roughness is of interest to highway engineers worldwide. In the United States, ride comfort has been emphasized because it is the manifestation of roughness most evident to the public. This philosophy has resulted in the concept of Present Serviceability Rating [2] used broadly throughout the United States to judge road roughness quality.

In less developed countries, this same emphasis is not as appropriate. Faced with limited resources, they must choose between quantity and quality in the development of public road systems. Optimizing road transport efficiency involves trade-offs between the high initial costs of smooth roads and the high user operating costs of poor roads. Hence, studies of the road user cost relationship to roughness are underway in India [3], Brazil [4], Kenya [5], and other locations. User costs are generally quantified in terms of fuel, oil, tires, maintenance parts, maintenance labor and vehicle depreciation, though often excluding other costs consequences of roughness associated with speed limitations, accidents and cargo damage.

A presistent problem in these studies, as well as elsewhere in the world, is how to characterize the roughness of a road in a universal, consistent and relevant manner. The popular methods currently in use have been developed from a practical approach to the problem without a thorough technical understanding. As a result, the relationship between different measurement methods is uncertain, as is also the relevancy to ride comfort or road user costs. The deficiencies in technical understanding have been manifest in inability to control the measurement process, so that measurements from different locales, different times or different equipment cannot be compared. To solve this problem, universal standards for road roughness measurement are needed so that the measurement systems may be appropriately calibrated. Only then, by relating the measurements to a standard, will they become comparable, achieving the objectives of having transportable and time-stable road roughness measures.

In response to this problem in the United States, research has been conducted [6] which has resulted in a new level in understanding the roughness measurement process to the point that a standard has been proposed, along with means for calibrating measurement systems to that standard. This paper applies the findings of that research to the worldwide problems incident to standardization of road roughness measurement. The discussion first examines the practices used in roughness measurement to clarify the differences. Thence, a standard for roughness measurement is proposed, and alternative methods for calibrating to the standard on a worldwide basis are evaluated. The main areas in which the technology can be applied to improve roughness measurement practice are highlighted in a series of recommendations at the end.

Background

Road roughness is envisioned most readily as the profile of the vertical-longitudinal dimensions along the wheel tracks in the road. Generally speaking, the profile is random in nature, but may be characterized by the amplitudes and wavelengths it contains. Using methods of random signal analysis, the profile can be equated to the superposition of a series of sine waves having specific amplitudes and phase relationships. Thence, the roughness can be described by a Power Spectral Density (PSD) which represents the amplitude distribution across the wavelength spectrum. Figure 1a shows the PSD of a typical road elevation profile. In the plot, wave number (1/wavelength) is used to represent the spacial frequency. The profile can also be represented

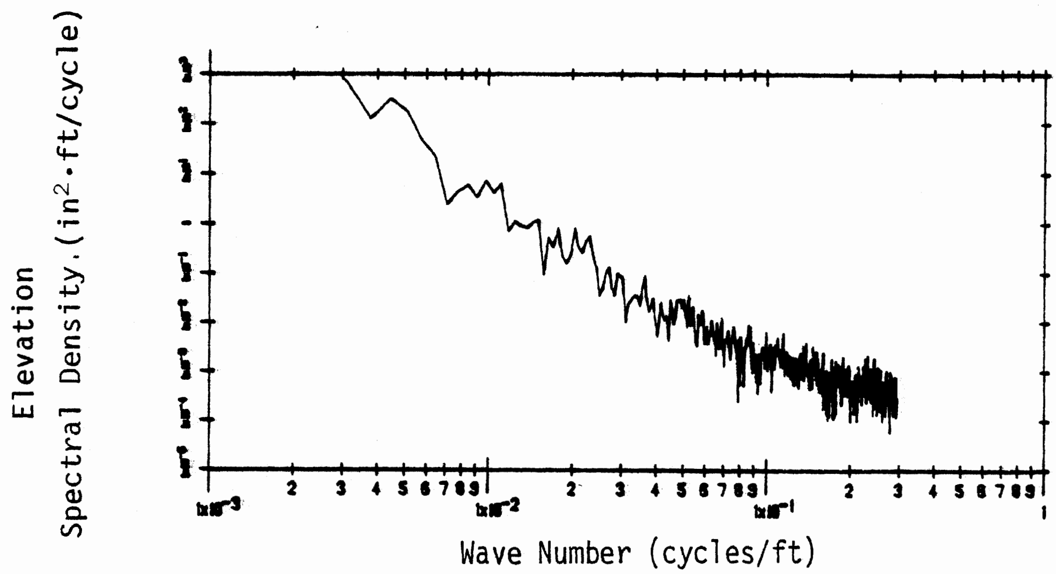


Figure 1a. Typical PSD of Road Profile Elevation

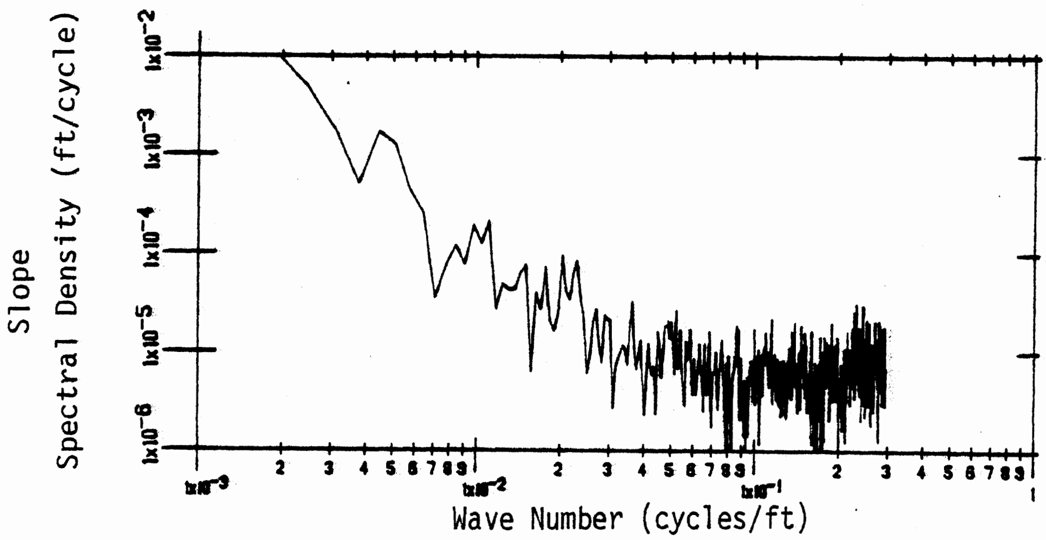


Figure 1b. Typical PSD of Road Slope

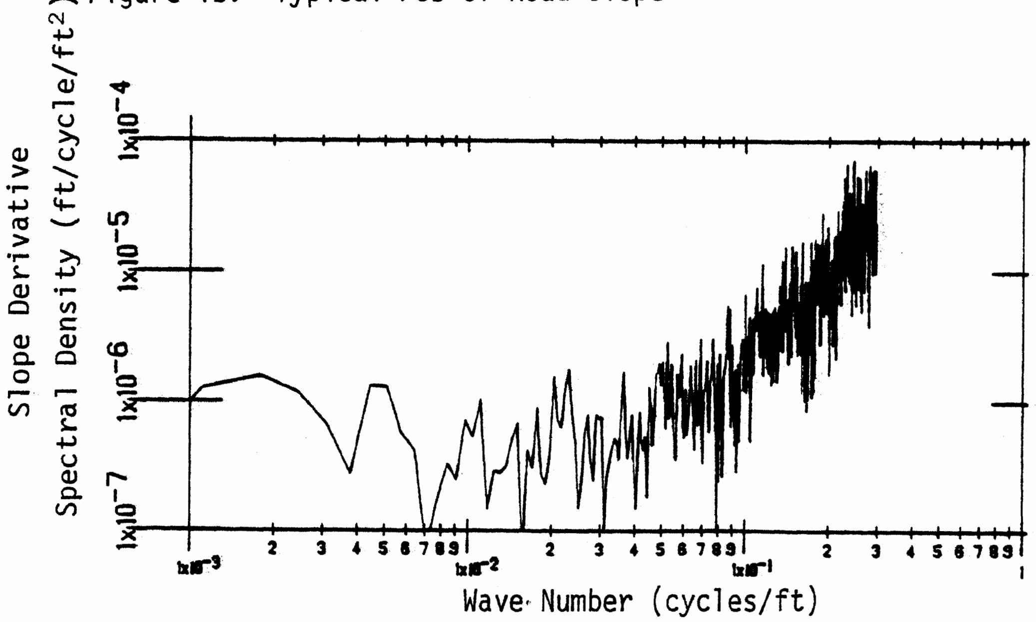


Figure 1c. Typical PSD of Road Slope Derivative

equally well by the PSD of slope (the spacial derivative of elevation) as shown in Figure 1b, or the derivative of slope as in Figure 1c. When the PSD is plotted on linear-linear coordinates, the area under the curve is the mean square value of the amplitude variable. Understanding this relationship adds great insight to the interpretation of road roughness measurements. For example, the mean square value of the total PSD will be infinity unless it is specifically constrained to a limited wave number band. Thus any measure of roughness amplitude will only be meaningful if it is limited to a specific wave number band. Though not recognized in this way, all roughness measurement devices, of necessity, cover a limited wave number band which is variable with the devices. Further, they do not measure uniformity over the band, but vary in their response as a function of wave number. And, lastly, they do not measure the mean square statistic, but alternate forms often involving rectified signals.

Review of Roughness Measurement Practice

In an effort to quantify road roughness properties, highway engineers have devised many types of equipment, each generally falling into one of two classes—direct and vehicle-response-type measurement systems. Direct measurement devices are intended to measure specific properties of the road surface independent of the operating speed (even though, in fact, the operating speed must be controlled to ensure the system functions properly). Such devices are the CHLOE, rolling straight edges and various types of profilometers. Vehicle-response systems, as the name implies, are intended to quantify roughness by a measure of the roughness-induced vibration response of an automotive vehicle (or similar system) even though known to be influenced by speed and other factors. This latter class includes the Mays Meters, PCA Meters, Bump Integrators and such devices, and in the U.S. have been labeled Response-Type Road Roughness Measurement Systems (RTRRMS). In general, all systems are response-type systems inasmuch as they have specific response properties that determine their measurement capabilities, but the response-type designation implicitly refers to a direct speed dependence in the measurement.

Direct Measurement Systems - At the outset, highway engineers tried to describe roughness by the vertical deviations of the surface from the flat plane it was intended to be. From this came the concept of measuring the vertical deviations and summing their absolute values. The sum per unit length (equivalent to an average rectified slope) was an indicator of the roughness magnitude. Though numerically different from a mean square (or root mean square) statistic, these two types of measures are related closely enough that the response of the measurement systems can be compared using methods only properly valid for mean square treatment.

To obtain a measure of this type, engineers devised the rolling straight edge [7], as illustrated in Figure 2, with lengths of 10, 20 or perhaps 30 feet. With such devices, the vertical deviations are measured relative to the datum plane established by the end wheels and hence have a highly variable response behavior. As shown in Figure 3a for a 30-foot straight edge, the variability in response includes complete insensitivity to certain wave numbers. In cognizance of this, land plane profilometers [8] were constructed in which a multiplicity of wheels were used to support the beam and thus establish an average datum for measurement. A 30-foot device of this type still has variable response, as shown in Figure 3b. A further variation on this approach was obtained with the CHLOE [9] in which a main frame (datum) is towed by a vehicle and the relative road slope, as detected by a set of closely spaced wheels, is measured to obtain mean slope statistics. The CHLOE's response is given in Figure 3c. Finally, surpassing all of these devices, inertial profilometers [10] have been developed, allowing measurement of road profiles relative to a reasonably accurate inertial reference, as evidenced by the typical response shown in Figure 3d. Their low wave number response is limited by accelerometer sensitivity, but can easily extend to 100m wavelengths. The high wave number limitation depends on the road-follower-wheel design and will be discussed in more detail later. With such consistent, broadband response, the data obtained are suitably accurate to allow processing to calculate any number of roughness parameters.

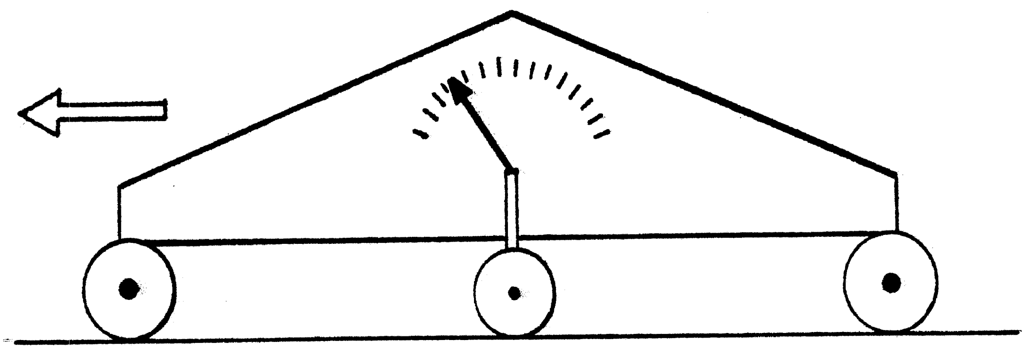


Figure 2. Illustration of a rolling straight edge.

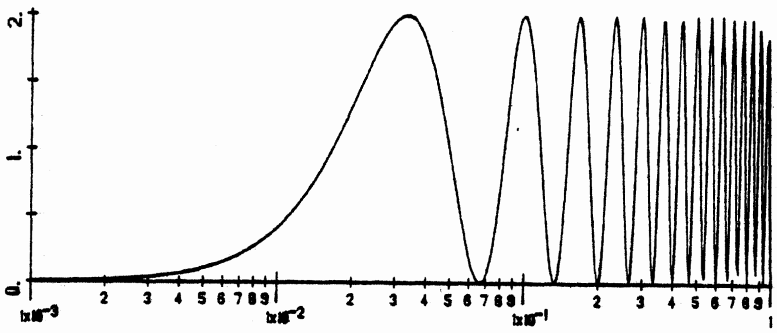


Figure 3a. Response Gain of a 30-foot Rolling Straight Edge

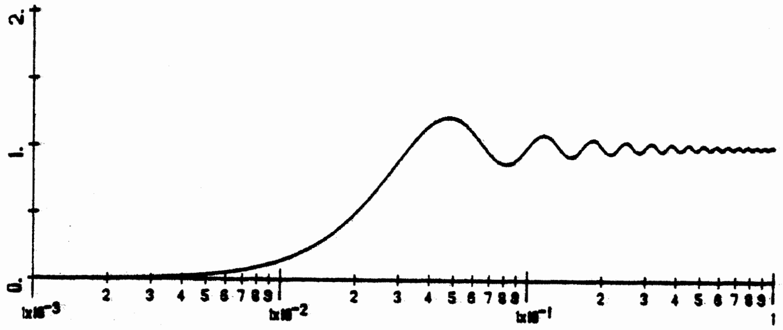


Figure 3b. Response Gain of a 30-foot Land Plane Profilometer

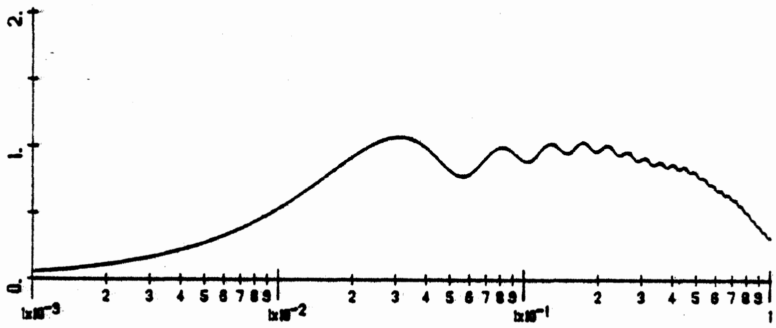


Figure 3c. Response Gain of a CHLOE Profilometer

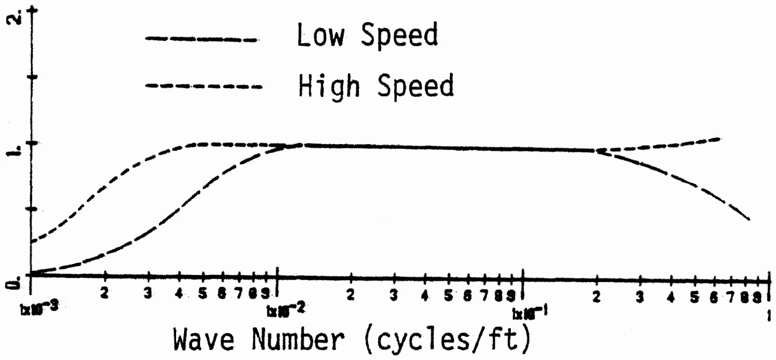


Figure 3d. Response Gain of an Inertial Profilometer

Even though all these devices obtain a measure related to road slope, it is obvious from Figure 3 that all devices will not obtain equivalent results. Each should be recognized as a distinctive device responding to specific portions of the road roughness spectrum which may or may not be common to other devices. Hence, the correlation among devices is only a coincidental result of correlation among road roughness properties.

Vehicle-Response Measurement Systems - As an alternative to the above, highway engineers devised means of measuring road roughness from the response induced in an automotive vehicle. The method incorporates the heuristic satisfaction of measurement directly on a vehicle akin to the user's along with the conveniences of high speed, and simplicity. The approach has been implemented by installation of Mays Meters [11], PCA Meters [12], or Bump Integrator [13] hardware on conventional passenger cars. Transducing the rear suspension motion, the Mays Meter and Bump Integrator type devices have a response behavior as shown in Figure 4a. (The PCA Meter has a more complex response that will not be discussed here, but can be found in Reference [6].) By their nature, this type of device has a response which is dependent on temporal frequency even though the road only contains spacial frequencies. The road spacial frequencies are related to temporal frequency by the travel speed, hence the response to road input will vary with speed, as shown in the figure. In addition, because the vehicle response is time dependent, the accumulated roughness measurement also depends on how long it takes to traverse a length of road. At higher speeds, less time is available for the roughness measure to accumulate.

With the obvious sensitivity of these systems to the specific dynamic properties of the host vehicle, means have been sought for obtaining this type measurement on a more controlled device. The BPR Roughometer [14] and the TRRL Bump Integrator [13] are single-wheel devices intended to replicate the essential dynamics of passenger cars in a more controlled fashion. Their behavior, shown in Figure 4b, is more responsive than typical passenger cars, and as a consequence, it has been necessary to limit them to a low test speed currently standardized at 32 km/h.

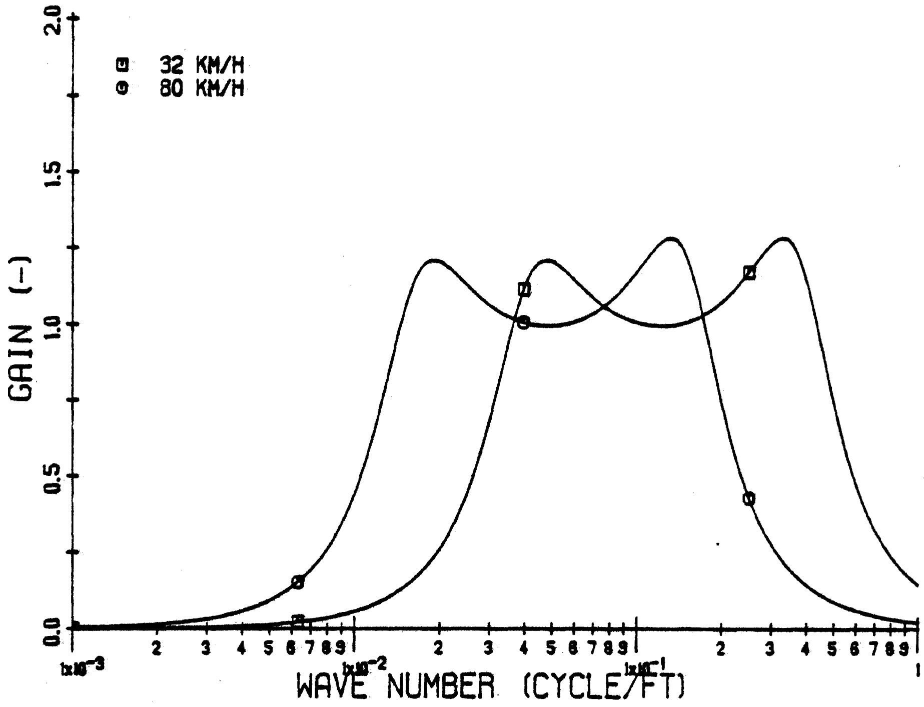


Figure 4a. Response Gain of Typical Vehicle-Response Systems

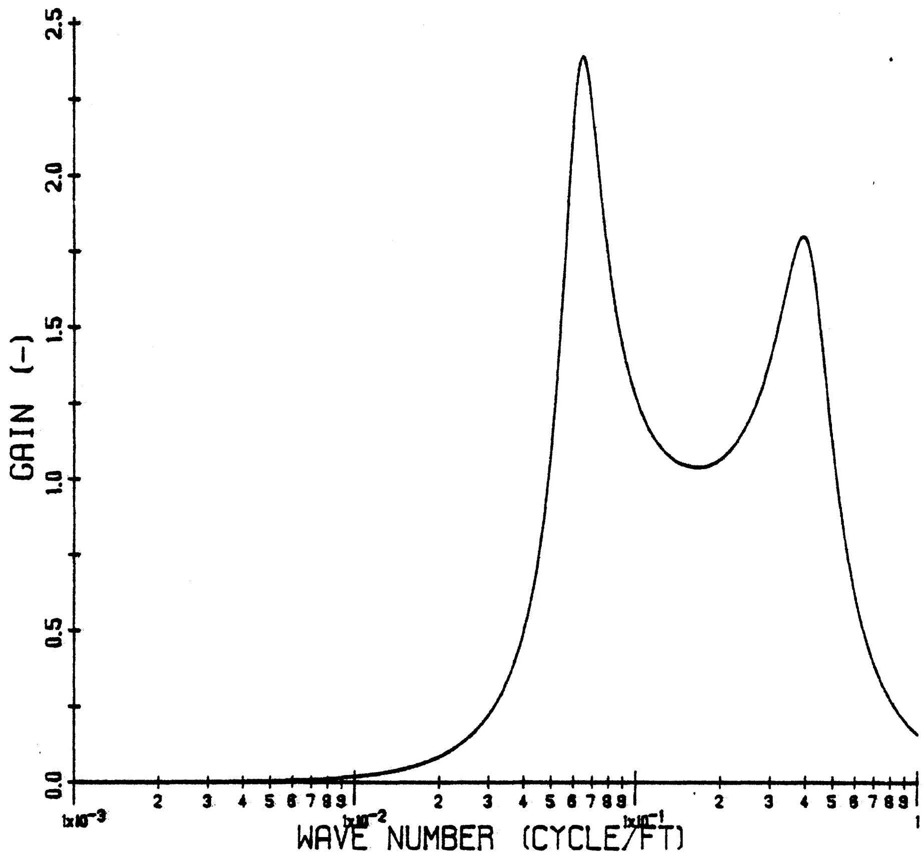


Figure 4b. Response Gain of TRRL Bump Integrator

A Proposed Roughness Standard

The variety of approaches toward road roughness measurement in existence generally inhibit the development and refinement of a standardized methodology. Standardization is necessary to facilitate transfer of information and technology among practitioners worldwide. Yet the choice of a standard must be based on sound logic reflecting sensitivity to both the objectives in measurement and the level of technology broadly available.

To establish a rational basis for proposing a worldwide standard, one must first define the roughness properties of interest and thoroughly understand the relationship of those properties to the behavior of different vehicles, at different speeds, on different roads. It is assumed here that vehicle vibrations are the manifestation of road roughness that is the legitimate primary interest. Vehicle-response type systems measure suspension motions reflecting both sprung and unsprung mass vibrations. The magnitude and spectral content of the suspension velocity are similar to the sprung mass accelerations from which ride comfort is perceived. Hence, in the United States, where the objective is to obtain a measure of roughness closely related to ride comfort, a suspension velocity measure has been recommended [6]. There is basis to suggest that this measure closely relates to many user cost factors, as well, and is discussed in Appendix B to this report.

In effect, the velocity is measured by vehicle-response type devices in which an accumulated suspension displacement measurement is obtained. The accumulated (rectified) displacment is normalized by the distance traveled, yielding an Average Rectified Slope statistic, ARS, expressed variously in units of "mm/km," "counts/km" or "Inches/Mile." The equivalent velocity representation is the Average Rectified Velocity, ARV, which may be expressed, for example, in units of "mm/sec." The ARV and ARS are related by the travel speed, V, according to the equation:

$$ARV = ARS \times V \tag{1}$$

Thus the ARV is not a new statistic to replace the ARS statistics in roughness measurement, nor does it lose continuity with a roughness data base accrued in the past. Rather, it is an alternative form of the measurements now obtained which merits understanding and appreciation by use in the practice. Its advantages are:

1) It is a direct measure of the vibration amplitude induced in a vehicle by road roughness.

2) It has a meaningful interpretation regardless of test speed.

The ARV is therefore proposed as a meaningful statistic to quantify roughness of a road at a given speed on a given vehicle. To contend with the dependence of roughness on speed, standardized test procedures must be established; and to contend with the dependence on vehicles, each must be calibrated to a standard scale.

Selection of Test Speed

The ARV is directly related to the Average Rectified Slope statistics, ARS, by the test speed, V, through the relationship:

$$ARV_{vt} = ARS_{vt} \times V \tag{2}$$

where the subscript "vt" has been added to emphasize that the relationship is valid only for a given vehicle system and a given test. The ARV is the measure of vehicle response to roughness, whereas the ARS is to some extent a more direct measure of roughness itself.

The relationship and utility of these two statistics can be illustrated rather simply. For a given road and test vehicle, the acceleration levels, and hence the ARV, exhibited by the vehicle will vary with speed. The ARV generally increases with operating speed at a rate that is nominally proportional to roughness magnitude of the road. The relationship for a typical rough and smooth road is illustrated in Figure 5. In individual cases, the exact shape of the curve is

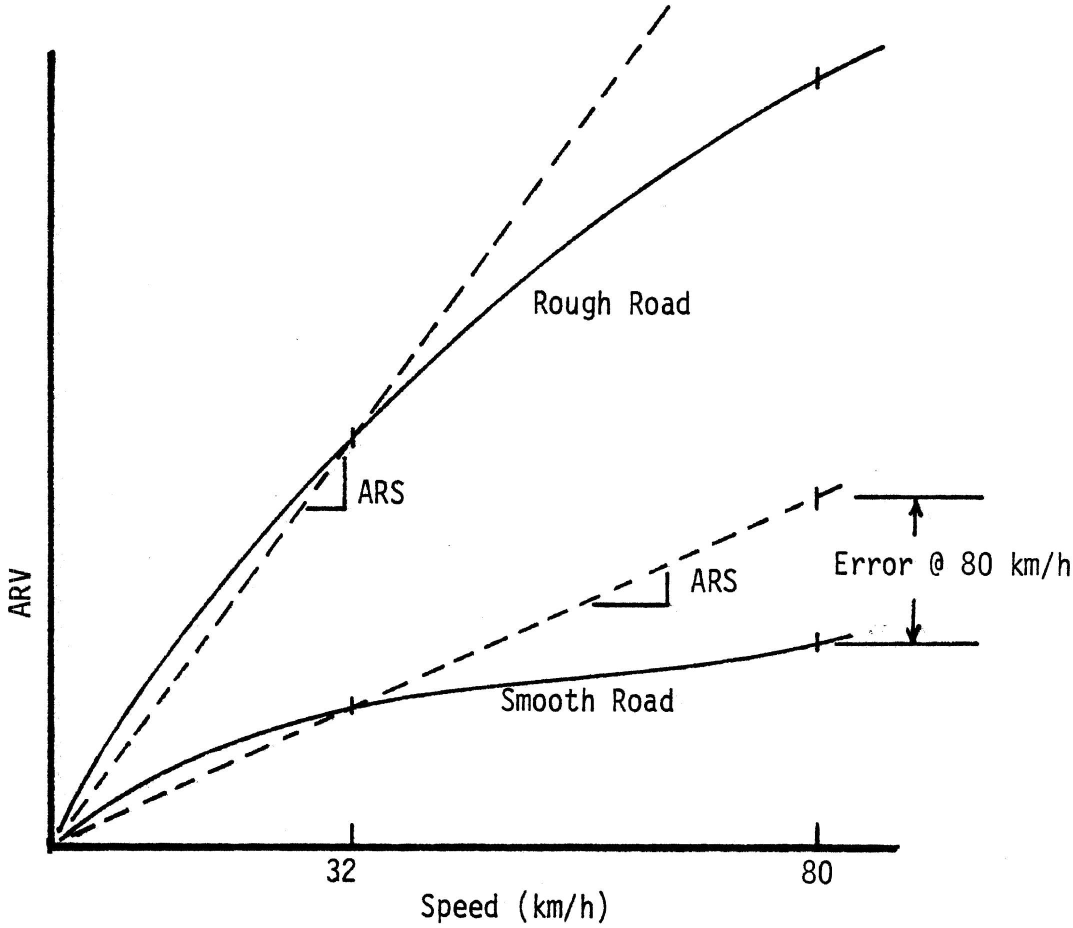


Figure 5. Relationship Between ARV and ARS Statistics.

dependent on the specific road and vehicle considered, but on the average, it will increase monotonically with speed. Further, it is a fairly linear function of speed, when speed is taken as an exponential power between 1/2 and 1. That is, theoretically, the ARV is fairly linear with the square root of speed as observed by Jordan [13]. But with the typical nonlinearities of many of the actual measuring systems, it may be more directly linear with speed, rather than the square root.

The common practice of measuring and quantifying road roughness by some ARS statistic obtained at 32 km/h is seen as a method which estimates the general slope of ARV-speed relationship. Thus it is a first-order estimate of the roughness of the road, suitable for comparing (or ranking) roads, one to another, on the basis of roughness as perceived at 32 km/h. However, comparing road roughness properties at 32 km/h is not the purpose for roughness measurement in most cases. More commonly, the purpose is to quantify the roughness in proportion to propensity for causing vibrations in the user vehicles at the prevailing traffic speeds. Inasmuch as the prevailing speeds vary between high-density urban roads and low-density rural roads, the measure at a uniform speed of 32 km/h is not always the most relevant. The roughness of a road is most critical to the high-speed user vehicles. As shown in Figure 5, on any particular road a roughness measurement at 32 km/h is not a good predictor of the roughness level at the high speed of 80 km/h, as such a prediction may easily be in error by 100 percent, or even 200 percent. Therefore, the direction for progressing to more relevant roughness measurements must allow for measurement at other speeds. Implementing that practice, however, requires adaptation of a uniform practice for selecting that test speed. Within the developed countries, the posted speed limit is the logical choice.

In countries where roughness is not, or cannot be, measured at different speeds representative of traffic, methods can be suggested for speed compensation of a large data base. Despite the fact that accurate speed corrections cannot be predicted on individual roads, average corrections for the roads in a network can be determined from experimental tests on a limited sample. In general, the form of the compensation equation should be

$$ARV_s = ARV_t(v_s/v_t)^n \tag{3}$$

or

$$ARS_s = ARS_t(v_t/v_s)^n \tag{4}$$

where the subscript "s" refers to the traffic speed condition, and the subscript "t" refers to the test speed condition. The exponent "η" may vary with the measurement equipment and the roughness spectrum characteristic of the roads. An average value for the exponent may be determined by running tests at two speeds on a representative sample of roads, and should generally fall in the range between 0.5 and 2.0.

The speed compensation equation obtained is then an average correction. When applied to a statistically large population of roughness data the prediction for some roads is high and others low, but the average error is zero. For many broad statistical analyses, such as road user cost studies or road network surveys, no net error results when the data is thus corrected to the travel speed prevailing on each road segment. In this way, a data base is obtained that more closely relates to the roughness level experienced by the users.

The Choice of Calibration Methods

The numerical value of the ARS or ARV statistics obtained in the measurement of roughness by vehicle-response systems is directly linked to the responsiveness of the individual system. Hence, the values cannot be validly compared to those measured by other systems or even the same system at other points in time because that response is known to vary uncontrollably. As a result, it is common practice to attempt to relate the individual systems to a reference, which may be one selected system maintained for that purpose, or even the mean value obtained with a number of similar systems. Yet, comparing or correlating to a reference is not a valid calibration unless the accuracy of the reference can be defined; nor does it standardize measurements without demonstrating that the reference is a replicable standard. As an example, the TRRL Bump Integrator is often used as a reference because of its more precisely defined specifications for design and performance. Yet, the many Bump Integrators distributed throughout the world should not be accepted as a standard because it has not been established that they measure equivalently. To the contrary, being hardware devices, they are potentially sensitive to enough variables in the towing vehicle, maintenance practices, and operating procedures that implied usage as a standard should be discouraged.

In order to calibrate a roughness measurement system, it is necessary either to scale its measurements on surfaces of standard roughness or to scale its measurements to standard measures on arbitrary surfaces. The dynamic nature of the devices is too complex to allow practical calibration by simple measures of response as attempted with the Bump Integrator [13]. Rather, the calibration must be based on their performance when subject to broadband excitation as occurs on the road. Thus, calibration must be based either on a standard measure of roughness or on surfaces of standard roughness qualities.

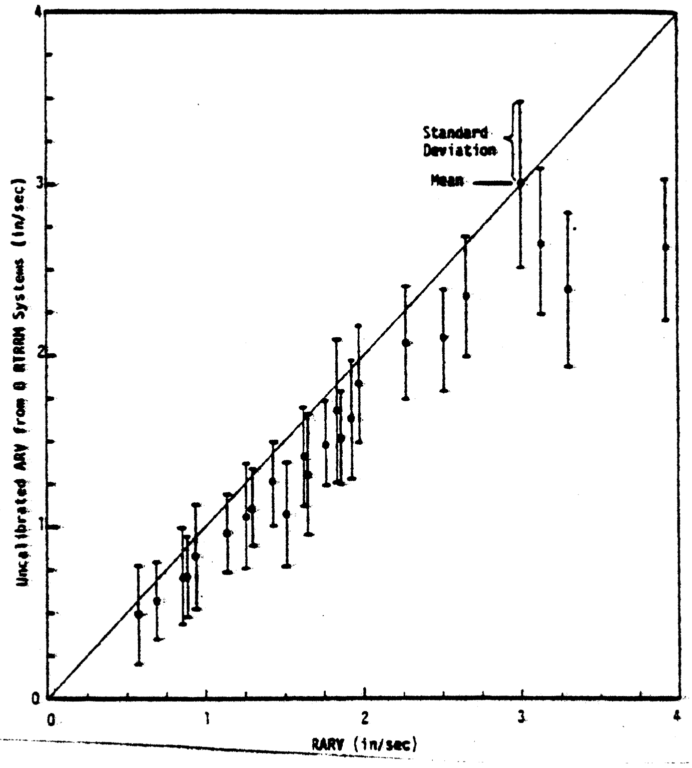
Profilometer/Quarter-Car Simulation

Among the alternatives available for standardization of roughness measurements, the profilometer/quarter-car simulation method has been proposed as the most viable [6]. Recognizing that it is virtually impossible to design and maintain vehicle-response hardware controlled to an appropriate degree of accuracy, a computer simulated system was chosen. By obtaining road profiles to a specified level of accuracy, the simulated measurement for an idealized system can be determined. The correlation of an actual measurement system against that of the idealized simulation for a selection of local roads provides the calibration to a standard. The actual measurements corrected to that standard can then be compared validly to any other measurements also related to the standard, whether elsewhere in the world or years later in time. A standard method for the calibration process has been developed and is the primary calibration method described in the attached Appendix A.

In applying a calibration to such devices, it must be recognized that the systems may be nonlinear in amplitude response. Thence their response may depend on the general amplitude of suspension motions obtained in the calibration. Because the ARV is a direct measure of that motion amplitude, the calibration should be established in ARV units. Calibration in ARS units is equivalent and valid only if limited to discrete fixed test speeds. However, techniques such as the artificial surface calibration method described later are only possible by resort to the ARV statistic. The use of the ARV concept is encouraged for the benefits obtained in understanding the acquisition and use of road roughness measurements.

The calibration requires that suitably accurate profile measurements be available along with relatively minimal capability for computer simulation. The assumed system for profile measurement in the calibration is with the GMR (inertial) type profilometer, but is not essential to the method.

A major advantage of this approach is its demonstrated capabilities in calibration. Figure 6 illustrates the uncalibrated versus calibrated results obtained with eight vehicle-response type (RTRRM) systems from Reference [6]. The method proves capable of calibrating the systems to a level of error that is within the normal variability of the devices over the roughness range up to more than two inches/second in RARV units. At the same time, the figure illustrates the major functional limitation on the profilometer method; namely, at high levels of roughness, the profilometer measurements depart from those obtained from the vehicle-response systems. Many causes for this disparity can be postulated, most focusing on the limitations in the follower wheels used to track the surface with the profilometer. A more thorough discussion of the functional limitations of inertial profilometers is presented in Appendix D. Nevertheless, the peculiar sensitivity of profilometers at high roughness levels is cause for profilometer measurements on highly textured (as, for example, gravel or surface treatment) or highly faulted roads to be disproportionately high with the data reduction methods currently in use. In such cases, data filtering analogous to the tire envelopment phenomena experienced by vehicle-response systems



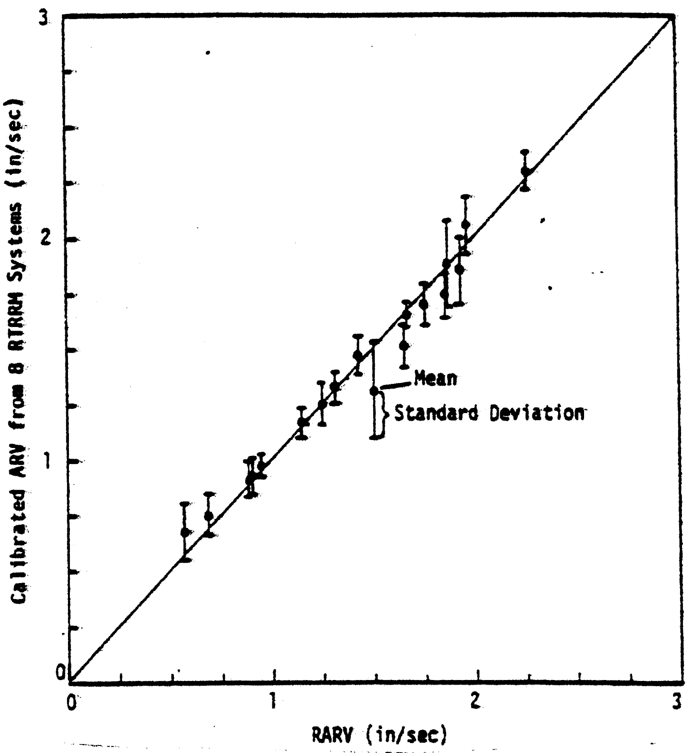


Figure 6. Comparison of Roughness Measurements from Eight RTRRM Systems; Uncalibrated and Calibrated by Profilometer/Quarter-Car Simulation (RARV).

is recommended, although it is not clear that it has ever been implemented by profilometer users. In less developed countries with more of these surface types, this procedure appears even more essential.

The major shortcoming with the inertial profilometer approach is the cost and complexity of the system. Low cost profilometer systems for calibration purposes can be envisioned, but without an impetus may take years to be realized. Low cost (on the order of 25 percent of current profilometer systems) may be achieved by several routes:

1) Use of non-contacting road follower systems, eliminating the adaptation of follower wheels to a specialized profilometer vehicle, and eliminating the follower-wheel durability problems on rough surfaces.

2) Reduction of on-board computational power to only that needed for calculation of the roughness statistic.

3) Elimination of expensive profile recording systems.

The entire calibration profilometer can be in the form of an instrumented box which can be mounted on any available vehicle. With low cost, a spare parts inventory can be maintained in less developed countries to overcome the problems with equipment failure.

Any means for profile measurement is adequate if it can meet the accuracy requirements specified. A device operating on the principle of the TRRL Horizontal Bar has the potential for profile measurement by labor intensive methods with certain modifications and precautions in its use. An analysis of the TRRL Horizontal Bar has been made and is included as Appendix C to the report. Enough precautions in its use are indicated that consideration might be given to design of a similar device specifically intended for manual measurement of road profiles before using the current design for this purpose.

Rod and level methods of profile measurement might also be considered. Recent data [15] has been published giving evidence to the viability of this approach and is hence discussed in a separate section of the report.

It has often been questioned whether axle accelerations can be obtained on a vehicle as a measure of road profile appropriate for calibration. No research has been done to establish the practicality of a method, although current knowledge can be applied to identify potential problem areas. Measurement of the vertical accelerations on the axle of an automotive vehicle is not a good indicator of the underlying profile of the road. The excitation inputs to the axle include not only the road, but the effects of nonuniformities in the tire/wheel assembly, vibrations of the body and other wheels transmitted down through the suspension, as well as possible driveline vibrations. In addition, the dynamic response of the axle has a marked frequency sensitivity characterized by a resonance near 10 Hz that is dependent on mass, stiffness and damping properties, as shown in Figure 7. Correction for the dynamic behavior would require an effort no less than that necessary to compensate for variables in a typical vehicle-response system. The problems of variations in suspension properties, especially the shock absorber damping, can be compensated by concurrently measuring sprung mass accelerations just above the axle with a second accelerometer (see Reference [16] for a more extensive discussion of this method), but a calibration for certain other variables, most notably the tire variables, must still be performed. Recognizing these problems, and that the method has never been critically treated, it cannot be recommended at this time.

The vehicle variables can be eliminated by mounting the accelerometer directly on a follower wheel towed along the pavement surface similar to that currently used with profilometers. A characteristic resonance like that seen in Figure 7 will still exist, though it theoretically can be pushed to a much higher frequency (above the range of spacial frequencies of interest when towed at a slow speed). The implementation of a system of this type would require careful compromises in design to achieve the low-frequency accelerometer sensitivity necessary to measure the longer wavelengths in the presence of the high-magnitude, high-frequency accelerations that exist in the surface. Unfortunately, this method has also not been critically tested, and hence

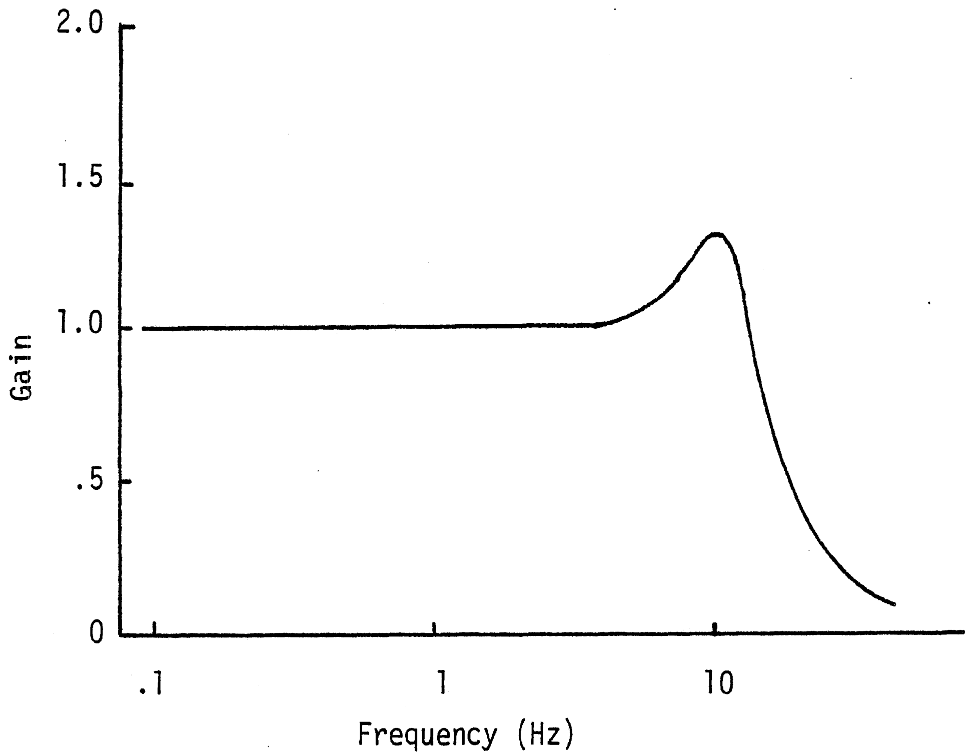


Figure 7. Response Gain on the Axle of a Typical Vehicle.

there is no basis for recommending it because of the potential for high development effort being required.

Rod and Level Surveys

Considering that an accurate profile measurement is a data base suitable for calibration, the logical question is whether the traditional rod and level measurements can prove adequate. As often, the best evidence of adequacy is determined by actual test. Rod and level measurements have been obtained in Brazil [15] at 10 cm intervals over road test sites. The measurements were processed to obtain amplitude values for selected wave number bands which were correlated to ARS measurements obtained from vehicle-response systems. Though correlations against only two such systems are reported, high correlations are indicated suggesting that profile measurements can be accomplished in practice with suitable accuracy.

With this encouragement, rod and level methods appear to offer high promise, although some improvements in methodology can be suggested. The reduction of the profile into content in wave number bands is computationally more involved that the calculations for a quarter-car simulation. Inasmuch as the quarter-car simulation shares a closer physical relationship to vehicle-response systems rather than simply an empirical correlation, it is more satisfying as a calibration standard. The comparative response of the two measurement processes are shown in Figure 8. The response of the vehicle in this case has been plotted on the basis of road profile elevation as the input and suspension velocity as the output.

The Brazilian work is further limited to correlation against ARS measurements obtained at only one test speed. For other speeds, other wave number bands and correlation analyses would be called for. With the quarter-car simulation method, the simulation speed can be varied quite simply to match the test speeds.

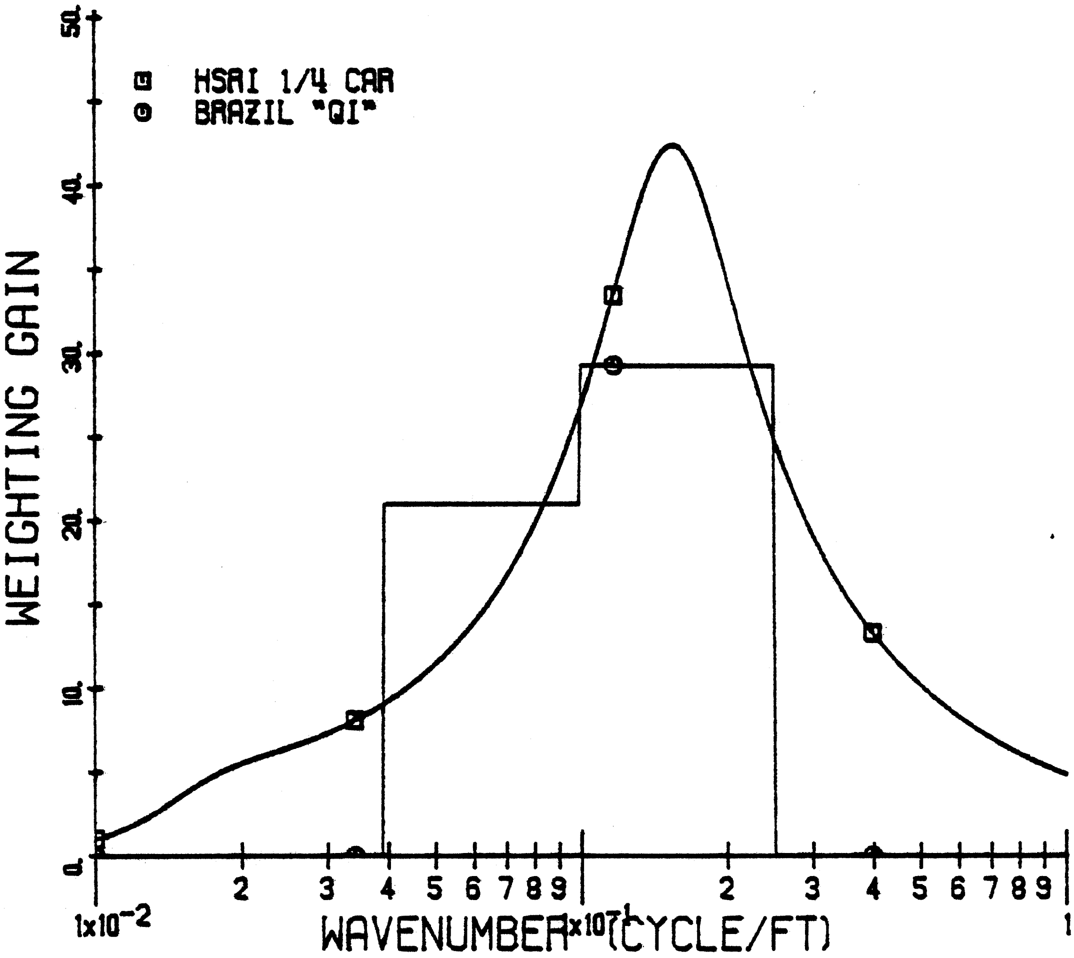


Figure 8. Comparison of Roughness Weighting Used in Rod and Level Study to That of Quarter-Car Standard at 80 km/h.

Artificial Surfaces - Vehicle-response systems must be calibrated by scaling their performance on surfaces similar to roads. The profilometer/quarter-car simulation method is a means to accomplish this on locally available roads by computing the standard statistic for each of the roads. Alternatively, calibration can be accomplished by constructing roads to have a given roughness value on the standard scale. Constructing full-scale roads to precise tolerances is both economically and physically difficult. Thus an artificial surface method was devised to allow construction of a known roughness level using commonly available materials [6]. This method is also described in Appendix A. By calibrating at low speed, the surface length can be minimized and the vertical features can be exaggerated to allow easy maintenance of tolerances. As specified in the Appendix, the surfaces have a random roughness property with spectral content similar to average road properties observed in the USA and Europe.

In applying this method in less developed countries, it should be recognized that the spectral content of the roughness properties may differ somewhat because of the greater use of manual labor in construction of the road surface in these countries. The result may be a slightly greater random error in the direct comparison of measurements from calibrated systems. The roughness levels represented by the current surface design are not high enough to cover the normal measurement range encountered in less developed countries. The design provided yields an ARV of 1.98 inches/second which is nominally equivalent to 5000 mm/km at a 32 km/h test speed. Hence it may be necessary to scale the vertical dimensions up by roughly 50 percent or more to get a calibration point near the upper limits of roughness. Though scaling changes greater than 10 percent were discouraged in the original specification of the method to ensure uniformity in its implementation, an appropriately higher level (suggested as 50 percent greater than the vertical dimensions shown in the design) could be adopted in less developed countries.

Though, as reported in Reference [6], this calibration method did not prove foolproof in every case, it was surprisingly effective in calibrating five out of eight systems to a level of error which was insignificant in comparison to the random error within the systems. In evaluation by other users, this method has proven capable of correlating a number of vehicle-response type measuring systems to an accuracy better than five percent (again, much less than the random error); although, in the absence of a profilometer, it could not be established how accurately they were calibrated to the standard scale. In light of these successes, the artificial surface method described in Appendix A can be recommended as an approach toward calibration with a much sounder basis and higher prospects for success than any other known artifical surface course, including the TRRL pipe course.

The primary weakness of this artifical surface method is the fact that it does not fully correct for nonuniformities (imbalance and runout) in the wheel assemblies of the test vehicle due to the low test speed required. In general, with good wheel maintenance practice, these effects constitute a significant error only on smoother roads (nominally 3000 mm/km and less). In such cases, the wheel vibrations add to the measured roughness, and readings at this low level should always be used cautiously. Inasmuch as smoother roads are of less interest as a roughness problem, this weakness is not viewed as a major deterrent to use of the artificial surface method.

Recommendations

From the perspective on the problems of standardization of road roughness measurement reflected in the preceding discussions, certain concrete recommendations can be proffered. The recommendations aim toward improving the practice of road roughness measurement throughout the world.

1) Calibration Methods - A comprehensive evaluation of calibration methods for vehicle-response type roughness measurement systems should be performed. The calibration methods should be evaluated concurrently in order to allow a comparison of their results. Historically, the calibration of these devices has been approached on an empirical and piecemeal basis. The NCHRP Project [6] yielded a technical foundation for designing calibration processes, but was oriented toward

the environment of developed countries. A comparable research/evaluation program directed to the problem in less developed countries is called for if further delays and piecemeal solutions are to be avoided.

a) Based on current knowledge, three calibration approaches should definitely be included in the evaluation:

   - Profilometer/quarter-car simulation
   - Rod and level profilometry combined with a quarter-car simulated standard
   - Artificial surfaces as a roughness standard

b) The program should not be limited to only these methods but should allow latitude for testing of one or more alternatives offering promise for better accuracy or practicality in routine calibration. Alternatives such as the non-contacting profilometer, French APL, modified horizontal bar devices, or accelerometer devices should be evaluated in terms of the current state-of-the-art and their practicality for use in the environment of less developed countries to determine if they offer advantages in solving the worldwide calibration problem.

2) <u>Calibration Standard</u> - The simulated quarter-car model defined in Appendix A should be adopted as the standard to which measurements of all vehicle-response type systems are calibrated. Measurements corrected to that scale have the transportable and time-stable quality needed to allow interchange of data among different programs and countries.

3) <u>Roughness Index</u> - The ARV representation of roughness should be adopted as the generalized roughness index appropriate to vehicle-response type systems. When measured at road user speeds and calibrated to a standard scale, the ARV measure adds meaning to the quantification of roughness and offers potential for better correlation to road user cost effects. The ARV is compatible with current practice, and by its use familiarizes the practitioner with the underlying significance of road roughness effects at different operating speeds.

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APPENDIX A

RTRRM SYSTEM CALIBRATION METHODS

Two calibration methods for response-type road roughness measuring systems (RTRRM systems) have been devised and tested. The first calibration method is based on correlation of an RTRRM system to standard roughness measurements on a selection of available roads. This method requires the use of a GMR-type profilometer to measure road profiles that are subsequently processed through a quarter-car-type simulation of the reference RTRRM system to obtain standard roughness values for the tested roads. Recommended procedures for this calibration have been prepared in the format of an ASTM test method and are contained in this appendix.

GMR profilometers are currently unavailable to most RTRRM users, so a calibration method that does not require their use was developed. This method subjects the RTRRM systems to excitation that has an associated absolute level of roughness, provided by easily fabricated artificial road bumps whose roughness levels are defined by their geometry. A calibration method based on these bumps, also prepared in the format of an ASTM test method, is presented in this appendix.

As an aid to users of the artificial surfaces, the analysis supporting their design is provided in a section that discusses the properties that such a type of excitation should have, and some of the design trade-offs that are required to implement this method. This section develops the concept of an "average road," presents research findings concerning tire enveloping (a phenomenon that must be addressed when considering low-speed calibration procedures), and then discusses the process of designing an artificial surface (with an associated known roughness level) to be used for calibrating RTRRM systems. Also, the results are presented for a variety of computer simulations that were conducted to anticipate the sensitivity of the calibration to unavoidable differences in the dynamics of vehicles used in RTRRM systems. And, finally, suggestions are provided for the further development of the method.

STANDARD METHOD FOR PRIMARY CALIBRATION OF RTRRM SYSTEMS

1. *Scope*

1.1 This method constitutes the primary means to calibrate the pavement roughness measurement of a response-type road roughness measuring system (RTRRM system) to a standard roughness scale.

1.2 An RTRRM system is defined as an automobile or two-wheel trailer with a solid axle, with instrumentation to measure the accumulated axle displacement relative to the vehicle body caused by road roughness, and the time required to traverse a test section. The roughness measurement obtained is the ratio of the two measurements and is the average rectified velocity (ARV) in units of inches/second. The ARV statistic is related to the conventional inches/mile statistic according to the relationship inches/mile $= 3600 \times \text{ARV}/V$, where V is the test speed in miles per hour.

1.3 The standard scale is the ARV obtained by processing the true pavement profile through the reference RTRRM system simulation defined herein. It is designated as reference ARV (RARV).

2. *Summary of Method*

2.1 The test apparatus consists of a GMR-type road profilometer, capable of measuring left and right wheel profiles, and a simulation of the reference RTRRM system described herein.

2.2 The profilometer is operated over a selection of road surfaces, concurrently with the RTRRM system being calibrated, to record the road profiles.

2.3 The road profiles are processed through the reference RTRRM simulation at the speed equivalent to the nominal RTRRM system test speed on each roadway to produce the RARV statistic for the test section.

2.4 The calibration is obtained by linear regression of the RTRRM system ARV measurements against the RARV measurements.

2.5 The pavement roughness measured in ARV units by the RTRRM test system on actual roads is corrected via the calibration obtained above to estimate RARV. The corrected values are designated calibrated ARV (CARV), and should include the measurement speed as a subscript.

3. *Apparatus*

3.1 *Profilometer*—The profilometer shall be capable of measuring the road profile in the left and right wheel tracks over a frequency band of 0.5 to 25 Hz at simulated calibration speeds. At normal operating speed, the profile measurements in this bandwidth shall be obtained with a resolution of 0.01 in., a hysteresis not to exceed 0.001 in., and a gain accuracy of 1 percent of the full-scale amplitude. Calibration of the profilometer shall be confirmed at the beginning of each series of road tests.

3.2 *Simulation*—The simulation of the reference RTRRM system shall be a quarter-car model as shown in Figure A-1, with the parameter values indicated therein. Input to the simulation shall be the average elevation of the left and right wheel tracks. The simulated speed shall be the same as the RTRRM test speed. Output shall be the calculated accumulated axle-body displacement. The final value of the output is divided by the time needed to traverse the road section at the speed being simulated to yield the RARV for that section. Whether the simulation is implemented digitally or analog, the frequency response function of the simulation shall be within 1 percent of the reference response function shown in Figure A-1 over the frequency range of 0.5 to 25 Hz.

3.3 *Test Sections*—At least 10 road sections of each construction type (i.e., flexible, rigid) to be included in the calibration shall be selected in the local vicinity such that all can be tested in the period of one day. All test sections shall be 0.5 miles or greater in length with the beginning and ending points clearly identified by landmarks or temporary markers. The road sections shall be substantially straight, and homogeneous both longitudinally and laterally in roughness characteristics. The 10 roads shall represent a range of roughness levels from the smoothest available to the roughest extreme to be calibrated at the selected test speed, but not exceeding an RARV level of 2.75 in./sec.

4. *Calibration Procedure*

4.1 *Speed*—Calibrate the RTRRM test vehicle speed indicator at the test speeds by traversing an accurately measured pavement of a length appropriate for the method of timing. The road should be reasonably level and straight, and speed should be held constant. Load the vehicle to its normal operating weight and set all tires at the normal operating inflation pressure level. Other methods of equivalent accuracy may be used.

4.2 *Preparation*—Turn on all electronic equipment, allow time for warm-up, and check the calibrations and that all systems are functioning properly. Warm up the RTRRM system by driving on the highway at normal speeds for a distance of at least 5 miles.

4.3 *Test Sections*—Proceed to each test section with the RTRRM test system and the profilometer, ensuring that the RTRRM system has been warmed up on the road prior to test and has not sat stationary for more than a few minutes between warm-up and the actual test.

4.3.1 *RTRRM System*—Check and reset tire pressure as necessary prior to each test to the nominal operating pressure, plus or minus one psi. Proceed over the test section at the prescribed test speed recording the accumulation of axle-body displacement from the beginning to the end of the test section. At the end of the test section record the test speed, the accumulated inches of axle-body displacement, the time to traverse the test section, and the ambient weather conditions. Proceed to the other test sections and repeat this process.

4.3.2 *Profilometer*—Proceed over the test section measuring the profiles and/or accumulation of the simulated axle-body displacement from the beginning to the end of the test section. At the end of the test section, determine the RARV by taking the ratio of accumulated inches to the simulated time used traversing the test section. If the test surface is rough, such that bounce of the road-follower wheel could occur, repeat the test for the same simulated speed, but at a lower profilometer speed, to confirm the RARV measurement obtained.

$$M_s\ddot{Z}_s - C_s(\dot{Z}_s-\dot{Z}_u) + K_s(Z_s-Z_u) = 0$$

$$M_s\ddot{Z}_s + M_u\ddot{Z}_u + K_tZ_u = K_tZ$$

$K_s/M_s = 62.3\ 1/sec^2$

$K_t/M_s = 653\ 1/sec^2$

$M_u/M_s = .150$

$C_s/M_s = 6.00\ 1/sec$

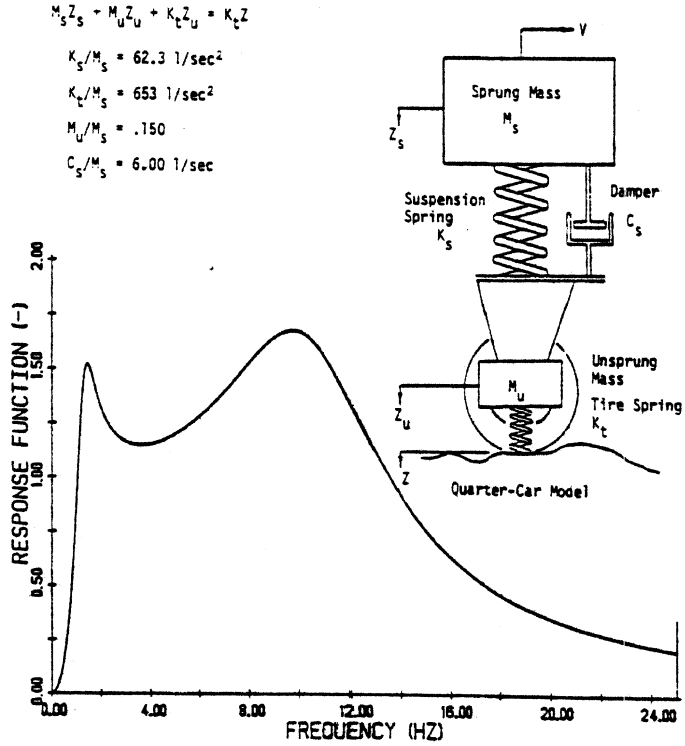


Figure A-1. Dynamics of reference road roughness measurement system.

5. *Data Reduction*

5.1 *Calibration*—For each test section obtain the RARV measured by the profilometer/simulation and the ARV measured with the RTRRM test system. Develop the calibration relationship by a linear regression of the appropriate data pairs.

5.1.1 *Measured ARV*—This quantity is obtained by dividing the accumulated inches of axle-body displacement by the time needed to traverse that test section. On Mays meter devices, the inches of displacement are equivalent to 6.4 times the chart paper travel generated over the test section length. On PCA meter devices, the inches of displacement are the sum of counts from all registers, multiplied by the quantization interval (normally ⅛ in.). Other devices may require other types of data interpretation.

5.1.2 *Linear Regression*—The calibration of an RTRRM system may vary with test speed and type of roadway (flexible or rigid). At the option of the user, separate calibrations may be developed for the system at each intended test speed and for each roadway type. Alternatively, one calibration may be obtained covering both flexible and rigid pavements with an expected reduction in stated precision of the RTRRM system. A minimum of 10 data pairs is needed to establish a calibration. A calibration at each operating speed is necessary unless it can be shown that equivalent calibrations can be obtained at each speed. The calibration is obtained by a linear regression of the RARV against the measured ARV, resulting in an equation of the form: $RARV = C1 + C2 \times ARV$. The standard error, with the units inches/second, is calculated along with the regression equation and recorded with the calibration as an indication of its accuracy.

The calibration is recorded in the form of the foregoing derived equation, substituting the letters "CARV" for "RARV." The symbol CARV then denotes the calibrated ARV estimate of the reference ARV, based on measurements made with that system in subsequent road tests.

The calibration is identified by recording the date, RTRRM test system, tire inflation pressure, profilometer/simulation system, actual and indicated test speed, pavement type(s), ambient weather conditions, and standard error. The calibration may be plotted on rectilinear graph paper as a straight line relating CARV to measured ARV for ease in subsequent use.

5.2 *Pavement Roughness Measurement*—The calibration obtained above is used to convert on-road ARV roughness measurements to CARV units. Because RTRRM systems may have varying degrees of sensitivity to test speed, pavement type, and ambient temperature, calibrations should be performed frequently to identify the particular sensitivities. The conversion of on-road measurements to CARV should then be obtained from the calibration most closely related to the on-road conditions.

STANDARD METHOD FOR CALIBRATION OF RTRRM SYSTEMS ON AN ARTIFICIAL SURFACE

1. *Scope*

1.1 This method provides a means to calibrate the pavement roughness measurement of a response-type road-roughness measurement system (RTRRM system) to a standard roughness scale.

1.2 An RTRRM system is defined as an automobile or two-wheel trailer with a solid axle, with instrumentation to measure the accumulated axle displacement relative to the vehicle body caused by road roughness, and the time required to traverse a test section. The roughness measurement obtained is the ratio of the two measurements and is the average rectified velocity (ARV) in units of inches/second. The ARV statistic is related to the conventional inches/mile statistic according to the relationship $\text{inches/mile} = 3600 \times ARV/V$, where V is the test speed in miles per hour.

1.3 The standard scale is the ARV obtained by processing the true pavement profile through the reference RTRRM system simulation defined in the primary calibration method. It is designated as reference ARV (RARV).

1.4 The method of calibrating on an artificial surface is an indirect method of calibrating that yields an estimate of the calibration that would be obtained by correlation of the subject RTRRM system against a profilometer/reference RTRRM system simulation on a large sample of roads (i.e., the primary calibration). The calibration on an artificial surface is a means of estimating the primary calibration with sufficient accuracy to be useful in the absence of an available profilometer system, and is a means to monitor RTRRM system performance changes between primary calibrations due to changes in the vehicle, environment, etc. This calibration method does not include certain effects specific to vehicle speed and pavement types and hence has limited applicability.

2. *Summary of Method*

2.1 The test apparatus consists of a prepared surface fabricated from laminations of flat stock materials to yield a defined profile containing a relative roughness/wave number content that is related to the average properties of actual roads. The prepared surface is deployed on an existing base surface in a fashion to allow the RTRRM system (to be calibrated) to approach and drive over this surface with either both left and right wheels on the surface or just the wheels on the left or right side on the surface. The base surface is sufficiently smooth that the roughness level in the approach area, under the artificial surfaces, and in the departure area, is insignificant when compared to the roughness of the artificial surface.

2.2 The RTRRM system to be calibrated is driven five times over the test surface at each of five speeds by two methods as follows: (1) with both left and right wheels passing over the artificial surface simultaneously to yield a rough surface calibration point, and (2) with alternately the left wheels only and then the right wheels only passing over the artificial surface to yield a calibration point at a moderate roughness level. The inches of accumulated axle-body displacement, accrued during travel over the artificial surface and during the subsequent decay of vehicle bouncing after leaving the surface, are recorded.

2.3 A calibration plot for relating the subject RTRRM system to the standard scale is developed on rectilinear graph paper by plotting two points that are connected by a straight line. The two points are: (1) the average measured roughness for all tests with both left and right wheels on the artificial surface corresponding to a given RARV value; and (2) the average measured roughness for all tests with the left and right wheels individually on the artificial surface corresponding to one-half the given RARV value.

2.4 The pavement roughness measured in ARV units by the subject RTRRM test system on actual roads is corrected via the calibration plot to obtain calibrated ARV (CARV) values.

3. *Apparatus*

3.1 *Artificial Surfaces*—The artificial surface is created by placing two basic profile patterns on an existing smooth pavement. The two patterns, designated A and B, are defined by the profile elevation views shown in Figure A-2. The surfaces must be of sufficient width to yield at least 12 in. (30 cm) of surface to the outside of the vehicle tires to allow for tracking variations. The suggested width of the surface is 96 in. (2.44 m); or they may be constructed of two pieces centered on the wheel tracks with a recommended width of at least 30 in. (76 cm).

3.2 *Surface Installation*—The artificial surface is prepared by construction and installation of profile segments as shown in the layout pattern of Figure A-3. The surface consists of four profile segments in the sequential series of patterns A-B-A-B with 12 ft (3.658 m) of space between the end of one and the beginning of the next. All segments should be installed with the leading edges in the same direction, although the surface may be used in either direction of travel with the same results expected.

The base surface on which the artificial surface is installed shall be in an area free of traffic. The base surface shall have low roughness on the area in which the artificial surface is installed, in the approach and departure areas for at least 100 ft (30.5 m) on either end of the artificial surface, and in the lane on either side of the artificial surface.

On selection of a test area, the area should be cleaned to remove any loose gravel or other protuberances that would prevent the profile segments from lying over their entire length on the base surface. The profile segments shall be emplaced and installed securely on the base surface either by adhesives or fasteners to ensure that they present a firm surface to the tires of the vehicle being calibrated.

3.3 *Tolerances*—In construction of the profile patterns as shown in Figure A-2, the vertical dimensions directly determine the equivalent pavement roughness represented by the artificial surface. For the dimensions shown, a four wheel traverse of the complete surface at the calibration speed replicates a pavement RARV value equivalent to 1.98 in./sec at a test speed of 50 mph. To ensure calibration accuracy, all vertical dimensions should be held to within 1 percent of those specified. If, however, the availability of materials, construction methods, or other factors are such that the resultant vertical dimensions must be scaled differently from that shown, the RARV value is scaled proportionately. In no case should the constructed profile be scaled by more than a 10 percent difference from that shown.

The longitudinal dimensions of the profile pattern should be maintained within 0.25 in. (0.64 cm) of the design dimension. As emplaced on the base surface (Fig. A-3), all profile elements should be maintained within 1.0 in. (2.54 cm) of the design locations.

4. *Calibration Procedure*

4.1 *Speed*—Calibrate the RTRRM test vehicle speed indicator at the test speeds by traversing an accurately measured pavement of a length appropriate for the method of timing. The road should be reasonably level and straight, and speed should be held constant. Load the vehicle to its normal operating weight and set all tires at the normal operating inflation pressure level. Other methods of equivalent accuracy may be used.

4.2 *Artificial Surface Tests*—Prior to calibration set all tires to 28 psi (192 k Pa). Operate the RTRRM system vehicle for at least 5 miles (8 km) on local roads at an average speed of about 40 mph (64.4 km/h). Immediately after this preconditioning, reset all tires to an inflation pressure of 32 ± 1 psi (220 + 7 k Pa). Align the vehicle with the artificial surfaces and perform tests with all wheels of the vehicle passing over the surface simultaneously. Perform 5 tests each at speeds of 13, 14, 15, 16, and 17 mph (21, 22.5, 24, 25.5, and 27 km/h) using the following procedure:

1. Align the RTRRM system vehicle with the surface and accelerate to the test speed prior to reaching the surface.
2. Initiate the roughness measurement as the front wheels reach the artificial surface.
3. Maintain uniform vehicle speed and path while traversing the artificial surface and beyond.
4. As the rear axle leaves the artificial surface, wait for the vehicle bouncing to subside and then terminate the roughness measurement.
5. Record the test number, the test speed, and the inches of accumulated axle-body displacement measured.
6. Repeat the procedure as necessary until all tests are completed. Recheck tire pressures periodically to ensure maintenance of the specified pressure.

At the completion of tests with both wheel tracks on the artificial surface, repeat tests in the same number, speeds, and with the same procedures, in which wheels on only one side of the vehicle pass over the artificial surface. Alternate between the left and right side wheels of the vehicle.

The profile patterns are prescribed for a mean calibration speed of 15 mph (24 km/h); calibration at another speed is not valid.

5. *Data Reduction*

5.1 *Calibration*—The calibration for the RTRRM system is obtained by plotting two points on rectilinear graph paper and passing a straight line through the points. The plot is prepared by labeling the ordinate "CARV," and the abscissa "Measured ARV." A legend for the graph should include additional information, including the vehicle identification, operator, date, etc.

From the test data for four-wheel operation on the artificial surface, determine the average inches of roughness for all 25 tests (5 tests each at 5 speeds). Convert the average inches to measured ARV by dividing by the "effective time" factor, 6.73 sec. That is, measured ARV = average inches/6.73 sec. Plot a point on the calibration plot corresponding to this value of measured ARV and a CARV value of (nominally) 1.98 in./sec.

From the test data for two-wheel operation on the artificial surface, determine the average inches of roughness for all 25 tests covering both left and right wheel track tests. Convert to measured ARV as above and plot as a point corresponding to a CARV value of (nominally) 0.99 in./sec. A straight line drawn through these points is the calibration.

5.2 *Pavement Roughness Measurement*—The calibration plot obtained previously may be used to correct the on-road ARV measurements of the RTRRM system to CARV units. No standard error can be associated with CARV measurements that are based on this calibration method.

5.3 *Notice of Possible Errors*—This calibration may be used for correcting on-road measurements to CARV in lieu of a primary calibration when a profilometer/simulation

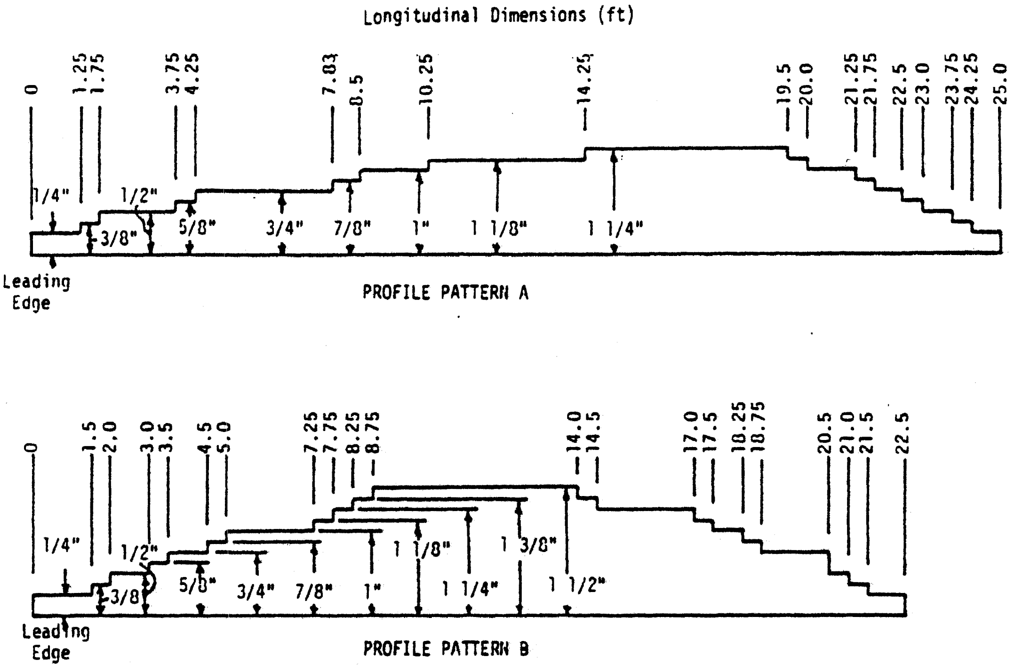


Figure A-2. Elevation view of artificial surface profile patterns.

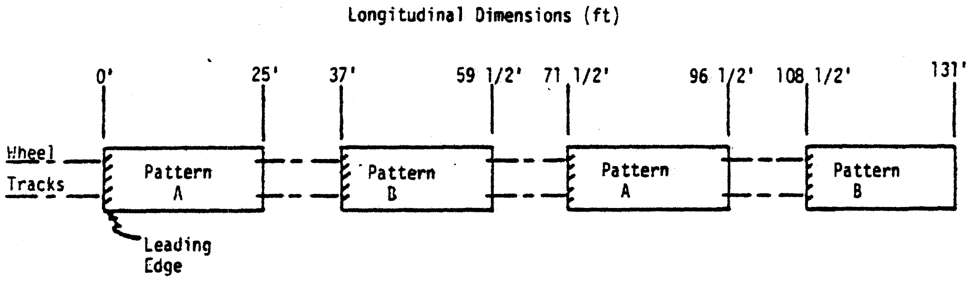


Figure A-3. Layout plan for artificial surface profile elements.

is not available. However, the calibration accuracy is not assured. Insufficient damping in the rear suspension is a known cause of inaccuracy and is indicated when the average accumulated axle-body travel in a calibration exceeds the limit shown in Figure A-4. As shown, the limit depends on the level of meter hysteresis, which is found by measuring the difference in axle-body position when the meter enters a register (i.e., it "clicks") with motion in one direction, and leaves it with motion in the other direction. The figure is valid for a surface RARV value of 1.98 in./sec; if the actual surface has a different RARV value, the ordinate should be rescaled accordingly.

Ultimately, the calibration obtained with this method may in some cases exhibit a systematic difference from that obtained in a primary calibration. Hence it should be used as a secondary calibration prior to, or between, primary calibrations. At such time that a primary calibration is obtained, the secondary calibration should be performed concurrently to establish an individual "effective time" factor for each RTRRM system. This calibration does not compensate for the effects of tire/wheel nonuniformities which strongly influence roughness measurements of smooth roads, such as new pavement constructions. Hence the calibration is not valid for road surfaces with CARV values less than 1.0 in./sec.

DEVELOPMENT OF ARTIFICIAL SURFACE CALIBRATION METHOD

The calibration method presented in the preceding section follows the basic notion of calibrating an instrument by using the instrument to measure a standard unit of roughness. Because this approach presumes the existence of a standard unit of measure, the first step in the development of this method was the definition of a "standard road" that could provide the same calibration as the primary profilometer method presented earlier. The fabrication of a standardized surface is simplified if the calibration speed is reduced, such that the surface provides excitation at low speed that is typical of real roads being traversed by RTRRM systems at their normal operating speeds. The advantages are that the surface does not have to be as long and also that background roughness deriving from the underlying surface and from fabrication imprecision is easier to maintain at negligible levels. In effect, this is accomplished by compressing the profile in proportion to the ratio: (calibration speed)/(simulated operating speed).

The pneumatic tire is, however, unable to completely respond to changes in pavement elevation if they occur within distances that are comparable to the length of the contact patch between tire and pavement. Small surface features are "enveloped" by the tire, resulting in less force being transmitted to the vehicle. If the calibration speed is too low, the tire enveloping will attenuate too much of the roughness for the calibration to be valid. Thus the calibration must be based on an adequate understanding of tire enveloping as well as on an understanding of the properties of normal roads. Accordingly, the phenomenon of tire enveloping was investigated, and the findings are presented in this section.

The actual design of an artificial surface used to calibrate RTRRM systems is the result of a number of trade-offs. The main concern during this project was to develop a surface that was easy and cheap to fabricate and to devise a calibration method that was simple to follow and required no auxiliary instrumentation other than the road meter in the RTRRM system. As a result, the calibration method is subject to errors. Because of this, and the fact that the method has not been fully demonstrated in the field, some of the properties of the bumps are described to aid those users of RTRRM systems who might further develop the calibration methodology. Also, suggestions are made for the immediate direction that the further development should follow.

Properties of the Standard Road

Pavement elevation changes randomly along the length of most roads, requiring that descriptions of profile be statistical. In the past 20 years, spectral density functions have been found to be useful descriptors of highway and airfield runway pavements. The spectral density of an individual pavement section is generally unique, but when the spectral densities of a large number of roads are compared, they are seen to have similar shapes. The uniqueness of the spectral density of any given section of pavement is the reason that measurements made with different RTRRM systems do not agree perfectly, and why a large number of roads must be included in an on-road calibration. (On the other hand, the commonality between spectral densities of different pavement sections is the underlying reason that even dissimilar roughness measurements are correlated.) A calibration could be performed with just two surfaces if both were known to have only "average" properties and none of the unique features common to real roads which bias the calibration. Clearly the development of an artificial surface for calibration of RTRRM systems begins with the question, What is the spectral density of the average road?

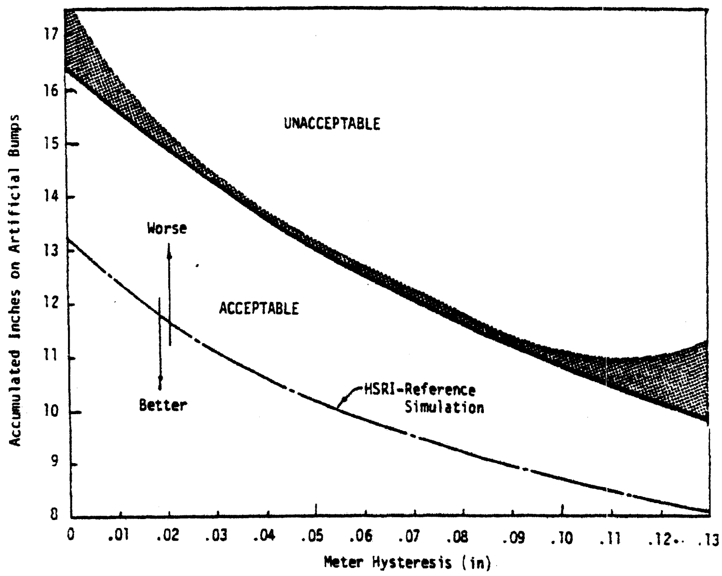


Figure A-4. Shock absorber acceptability criterion.

Analytic expressions have been suggested by various researchers to use as a road model, for calculations, when measured profiles are not available. Houboult (*25*) suggested a model for airfield runways that is the most well-known road model and is defined as

$$Gz(\nu) = Go/\nu^2 \qquad \text{(A-1)}$$

where $Gz(\nu)$ is the (model) road spectral density, ν is wave number (wave number = 1/wavelength), and Go, the sole parameter in the model, is a scaling factor that indicates the level of roughness. As more highway pavements were profiled, it became apparent that real road spectral densities have higher amplitudes at low wave numbers than predicted by the model. More recent models that have been suggested have included additional parameters to provide the capability for better matching measured spectral densities. But parameter values that allow the models to represent average roads have not been estab-

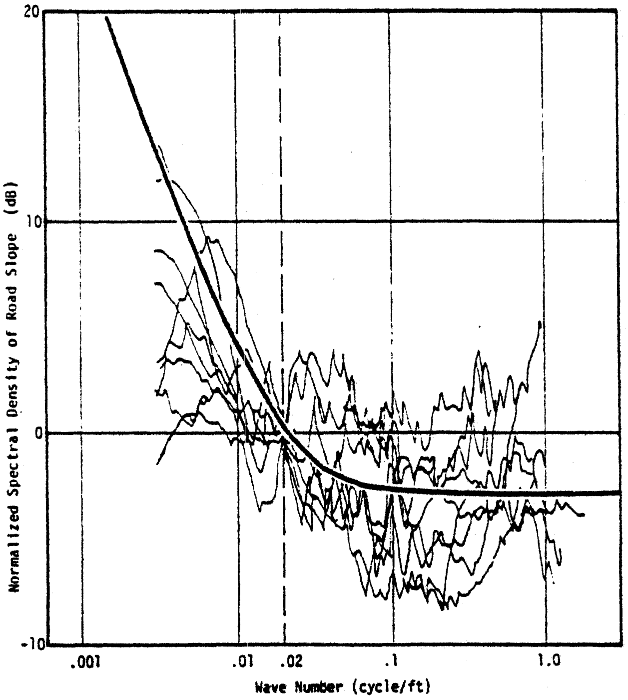


Figure A-5. Normalized spectral densities of European concrete roads.

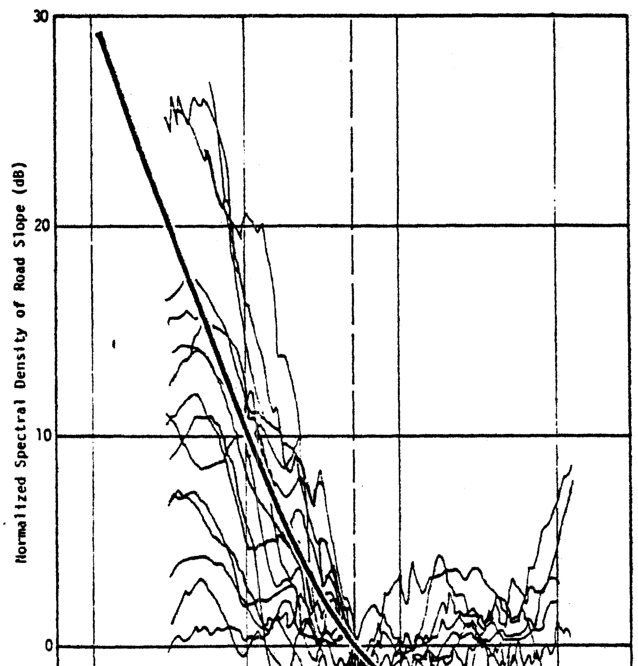


Figure A-6. Normalized spectral densities of European bituminous roads.

lished. A suitable model should have just one parameter that establishes the roughness, and the model should be validated by comparison with a large number of measured spectral densities. Given that highway personnel have traditionally differentiated between roughness measurements of flexible and rigid pavements, it is likely that separate models are needed for different construction types.

Figures A-5 and A-6 show measured spectral densities of a number of European roads (*26*). The figures show slope spectral densities rather than elevation spectral densities, because slope spectral densities do not change as much with wave number and peculiarities of individual spectra are thus easier to distinguish. Each measured curve was normalized (rescaled) in the figures to better show the common shape of the different curves. The heavy black lines depict an analytic spectral density function that was selected to best match the measured curves and define the average road model. The equation of each line is

$$Gz'(\nu) = Go[1 + (\nu o/\nu)^2] \ (\text{ft/ft})^2\text{ft/cycle} \quad \text{(A-2)}$$

The only difference between the models for rigid and flexible pavements is the value given to the parameter νo; a value of 0.02 cycle/ft is suggested for rigid constructions and a value of 0.05 cycle/ft is suggested for flexible construction. No trend is apparent that would indicate that the shape of the model spectral density should be different for smooth and rough roads; thus the single equation is offered for all levels of roughness that were included in the survey. The model was found to also agree with measured spectra for Texas roads (*27*) and with the 18 Ann Arbor roads profiled during the Correlation Program.

When a road is traversed by a vehicle, it is perceived as a moving elevation. A standard calibration excitation should provide the same input to the RTRRM system vehicle as a road with properties specified by the foregoing equation, when said road is traversed at the normal RTRRM system measurement speed. On the basis of the transformations in Appendix C, the spatial spectral density of the calibration surface should be

$$Gz'(\nu) = GoC[1 + (C\nu o/\nu)^2] \ (\text{ft/ft})^2\text{ft/cycle} \quad \text{(A-3)}$$

where C is the ratio of the simulated measurement speed to the calibration speed.

Tire Enveloping

Background

All of the forces that act on a vehicle in response to road roughness must be transmitted by the pneumatic tires, starting at the contact patch between tire and pavement. Although it is true that a tire acts much like a linear spring when the entire contact patch area is moved up and down, the force transmissibility actually varies throughout the contact patch. Thus, when the tire rolls over a bump or other pavement feature, the force transmitted to the spindle changes with the position of the bump within the contact patch. Figure A-7 illustrates the relationship between vertical spindle force and longitudinal position, when the tire is rolled over a very small cleat that extends across the width of the contact patch (perpendicular to the direction of travel) but is narrow compared to the length of the contact patch. Lippman (*28*) has shown that tire enveloping can be treated as a linear behavior by successfully predicting force responses to various cleat shapes from the force responses to simple step inputs. (The response shown here would be predicted by adding the response to a positive step input with the response to a negative step input, with the two edges of the steps separated by the width of the cleat.)

Because the tire linearly relates spindle force to displacement throughout the contact patch, the simple concept of the tire as a linear spring need not be abandoned; rather it can be supplemented by the addition of a separate model of the contact patch enveloping. The displacement seen by the simple tire spring would still be a single-valued elevation, but instead of being the pavement elevation at the center of the contact patch, it would be a weighted average of the profile under the entire contact patch. This weighting function can be measured by rolling the tire over a cleat narrow enough to approximate an impulse function input, as illustrated in the figure. (A more precise way of measuring the weighting function is by rolling the tire over a step, and then differentiating the response, because the derivative of a step input is an impulse function with a magnitude exactly equal to the height of the step.)

Tire enveloping can also be characterized as a wave number response function to better illustrate how the phenomenon affects RTRRM system calibration. The wave number response function is equivalent to a spatial frequency response function, obtained by calculating the Fourier transform of the weighting function. Figure A-8 shows the wave number response function calculated from the weighting function shown in the previous figure. The gain of the function is scaled to the unity for a wave number of zero (a flat surface), under which condition changes in vertical spindle force are simply the result of the tire spring rate. But for increasing wave numbers, the enveloping function attenuates the input, such that the amplitude of variations in the vertical force will be less than predicted by the tire spring rate. And, at certain wave numbers, the enveloping completely attenuates the input such that no force variations would be observed if the tire were rolled over a sinusoidal surface having the "nodal" wave number indicated in the figure.

An artificial surface should not be designed to contain excitation vital for a valid calibration at wave numbers near the first node in the tire enveloping function. Ideally, all of the significant excitation should be at wave numbers that are low enough that the enveloping does little to attenuate the input. Alternatively, the input can be boosted at wave numbers near the first node, anticipating the attenuation. Thus the vehicle is ultimately given the proper excitation which corresponds to traversing an average road at the normal RTRRM system measurement speed.

The little published information on tire enveloping is not adequate to quantify the enveloping mechanism to the extent needed for proper design of a low-speed artificial surface for RTRRM system calibration. Measuring the weighting functions or wave number response functions for a selection of tires was beyond the scope of the research, but analysis of the enveloping phenomenon revealed

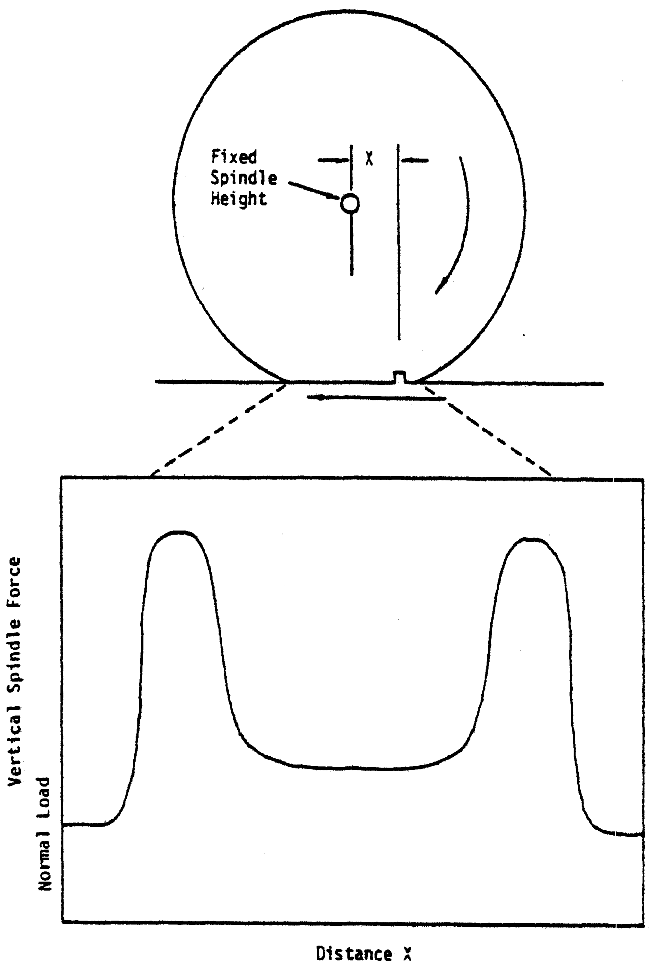


Figure A-7. Illustration of tire envelopment.

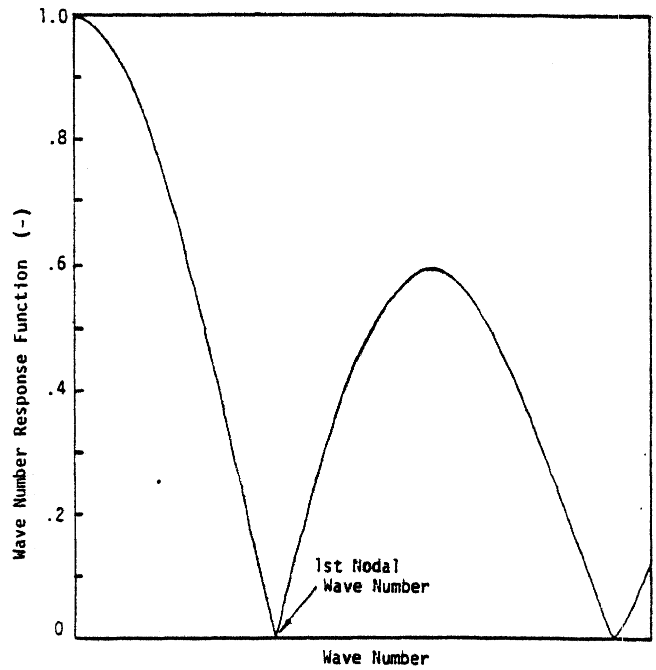


Figure A-8. Fourier transform of weighting function shown in Figure A-7.

that the necessary information could be obtained with relatively few tests.

Tire Enveloping Tests

A tire rolling over a pavement irregularity generates vertical force that is perceived by the vehicle as a function of time. The weighting function and wave number response function, shown in Figures A-7 and A-8, are seen as functions of time and frequency, and are related to the spatial functions by the speed of the vehicle. The first nodal wave number needs to be established to ensure that the calibration speed is selected to keep the corresponding frequency above the effective response limit of RTRRM systems.

Accordingly, a series of tests was designed and conducted to locate this node. The Highway Safety Research Institute test vehicle (1976 Pontiac station wagon) was instrumented with necessary recording equipment, along with an accelerometer mounted on the rear axle, near the right-hand wheel. The car was then driven over small bumps, such as welding rods and pieces of angle iron attached to the pavement. The resulting axle motion was the combined result of the dynamic response to the bump and pavement and of the attenuation of the excitation due to tire enveloping. The signal from the accelerometer was processed by a real-time spectrum analyzer to determine the frequency content of the axle motion.

A number of tests were conducted, with speed (measured with a fifth wheel) and tire pressure varied. In all of the resulting frequency response plots, a node was evident. The node was seen to be at the same wave number when only the test speed was varied—evidence that it was caused by tire enveloping. As Figure A-9 shows, the nodal wave number was sensitive to tire pressure; hence, a (hot) tire pressure of 32 psi was selected and maintained for RTRRM system vehicles during calibration. (This corresponds approximately to a cold tire pressure of 28 psi.) At 32 psi, the nodal wavelength is 0.95 ft.

Tire Enveloping Model

A model of the tire-enveloping attenuation up to the first nodal wave number was needed for analysis and design of the artificial bumps. The simple model of a constant weighting function shown in Figure A-10 proved sufficient. In the model, the sensitivity of the tire to pavement irregularities is uniform for a certain length and zero elsewhere. The figure also shows the wave number response function that is associated with this assumed weighting function. The advantage of this model is that it is completely defined by a single parameter—the weighting function length—which is also the first nodal wavelength.

Analyses were made to estimate the magnitudes of errors that could be expected from using this model in lieu of the exact wave number response function. Published data indicate that a much better model of the tire-enveloping weighting function would be the difference between two uniform weighting functions. Figure A-11 compares the two models with a real tire (*28*) by showing the vertical force resulting when the tire is rolled over a step input.

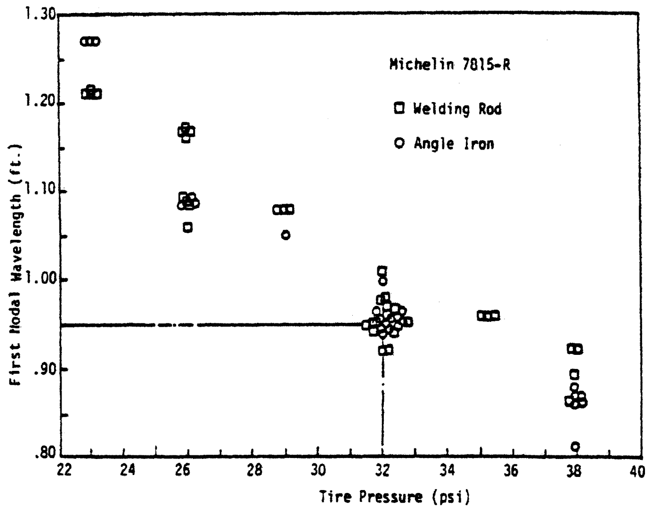


Figure A-9. Measured modal wavelengths.

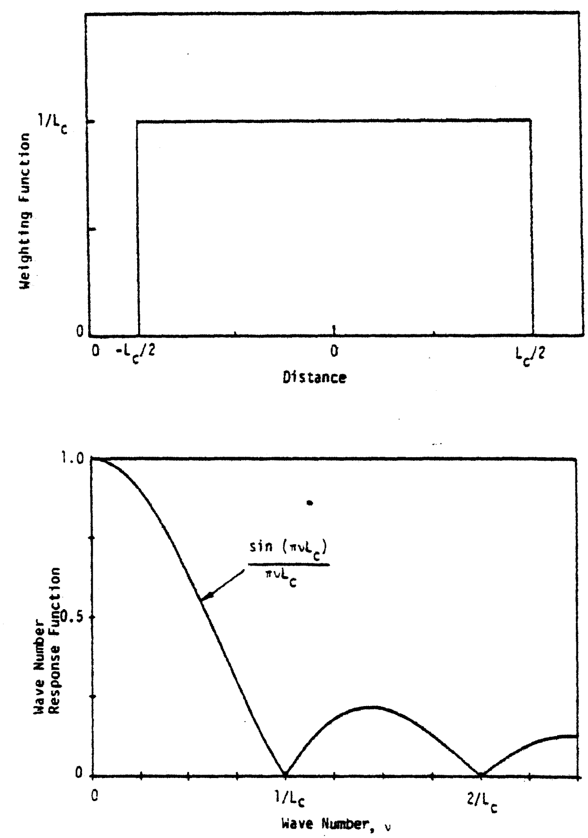


Figure A-10. Simple tire enveloping model.

The figure also shows the three weighting functions and the corresponding wave number response functions. Note that the more complex model requires three parameter values; thus perfect agreement between the two models is impossible. The frequency response functions for a variety of parameter combinations were calculated and compared with the simple model. It was found that when the correct nodal wavelength is provided to the simple model, there is good agreement for wave numbers below the first node, as shown by the example in Figure A-11; accordingly, the

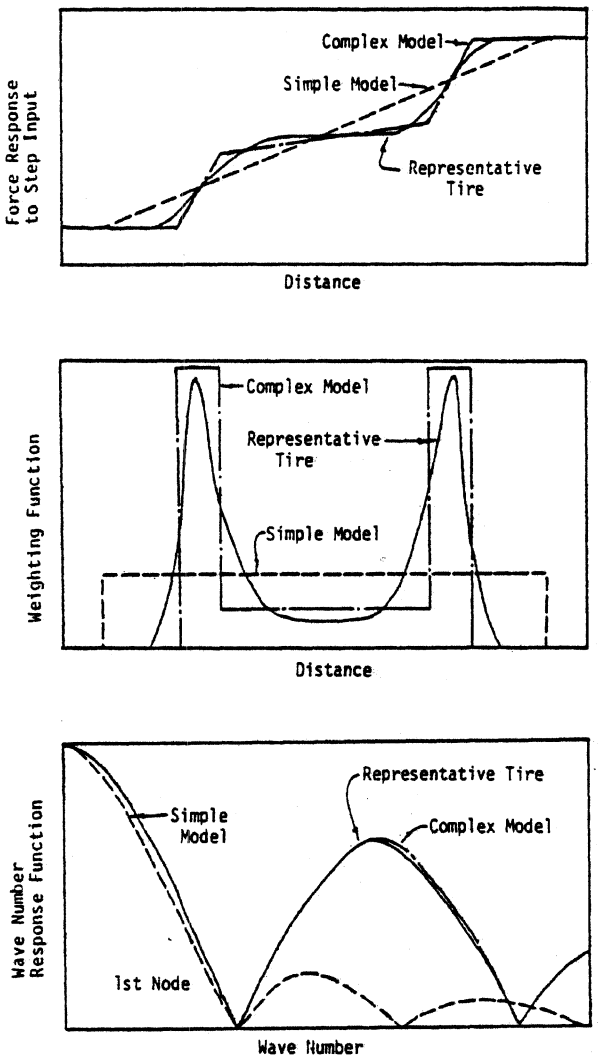


Figure A-11. Comparison of two tire-enveloping models with representative measurement.

simple model was used to predict tire-enveloping effects when needed during the project. (Agreement between the models suffers at wave numbers that are higher than the first node, but this wave number range has little effect on RTRRM system performance.)

Design of Artificial Bumps

The artificial surface that was developed was intended to simulate a rough bituminous pavement being traversed at 50 mph. On the basis of the tire-enveloping data, a calibration speed of 15 mph was selected. At this speed, the first node is at 23 Hz, which frequency is generally above the frequency range that affects RTRRM system measurements. The main consideration was keeping the attenuation less than 50 percent for frequencies less than 15 Hz, which resulted in the minimum speed of 15 mph. Still, 50 percent is a significant attenuation. Accordingly, the model road spectral density function was divided by the tire enveloping wave number response function for wave numbers up to 0.75, thereby boosting the high wave number roughness to compensate for the increased tire enveloping effects at the low calibration speed. The road model shows large spectral density amplitudes at very low wave numbers, so the low frequency end was limited for wave numbers less than 0.023 cycle/ft, a value that corresponds to 0.5 Hz and is below the response limit of RTRRM system vehicles.

A spectral density function contains no phase information, and as a result any number of profiles could be constructed to match the specified spectral density. A number of profiles were generated on the computer by summing a series of sine waves with very small amplitudes and with phase angles set randomly.

To simplify the task of fabricating an artificial surface, the different surface profiles generated on the computer were examined for sections that could be created by placing bumps on an existing smooth pavement. This required that the profile begin and end at a minimum elevation. It was also necessary that the roughness be more-or-less uniformly distributed over its length. For initial tests, a total length of 60 ft was desired. For ease of handling, candidate sections that could be provided by two bumps, 20 to 30 ft long, placed on an existing flat pavement were preferred. To further simplify the task of fabricating the bumps, the different candidate sections were quantized to changes in elevation of ⅛ in., so that they could be constructed from plywood and masonite or other flat stock materials.

An unwanted result of the modifications of the computer-generated surfaces is that the actual spectral density of the artificial bumps does not match the design spectral density. In effect, the spectral density quality has been traded off to provide a bump design that is easier for the RTRRM system user to deal with. A variety of simple bumps designed as previously described were analyzed to select the pair that had a spectral density closest to the original design.

Preliminary testing, with just two bumps, showed that measurement precision was a problem. The source of this problem was the small amount of axle-body travel accumulated in a single pass together with the quantization levels in commercial road meters. Accordingly, a second set of bumps was fabricated to double the magnitude of the measurements from the road meters. However, a random error still exists; thus the calibration procedure suggested in the previous section requires a number of passes to average out this error. More bumps could be added by users performing daily calibration checks in order to achieve a good calibration with fewer passes. Note that if a longer artificial surface is anticipated from the start, a larger set of unique bumps could be designed which would match the design spectral density better than the two bumps defined in Figure A-2.

Properties of the Artificial Bumps

Figure A-12 compares the actual spectral density of the artificial bumps with the design spectral density. Comparing this figure with Figures A-5 and A-6 indicates that the artificial bumps deviate less from the average road curve than do most individual roads, although it is also clear that the match is not perfect. The notable peculiarities are that the bumps provide too much excitation at wave numbers corresponding to frequencies of 0.7, 6, 11, and 13 Hz

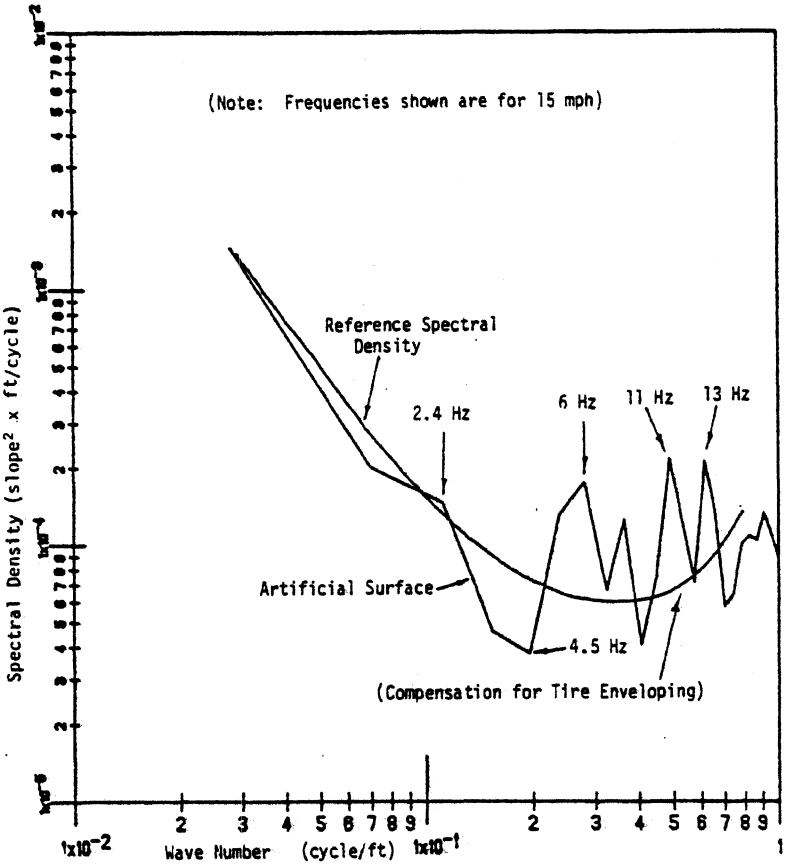


Figure A-12. Spectral density of artificial surface.

(at 15 mph). But the proper excitation is provided near the body resonance of RTRRM system vehicles (1 to 1.5 Hz), and the excesses near the axle resonance are compensated by less excitation at adjacent frequencies also near the axle responance. To minimize the effects of these imperfections, the suggested calibration procedure requires testing at several speeds to effectively "smear" the peaks and troughs in the spectral density together.

The actual response of the HSRI reference to the artificial bumps is shown in Figure A-13 (with the simulation modified to include the tire-enveloping model). The figure also breaks down the total simulated inches of axle-body travel as averaged over speeds of 13, 14, 15, 16, and 17 mph. These values can be used to calculate the accumulated inches that would be simulated for a different number of bumps, with the relation:

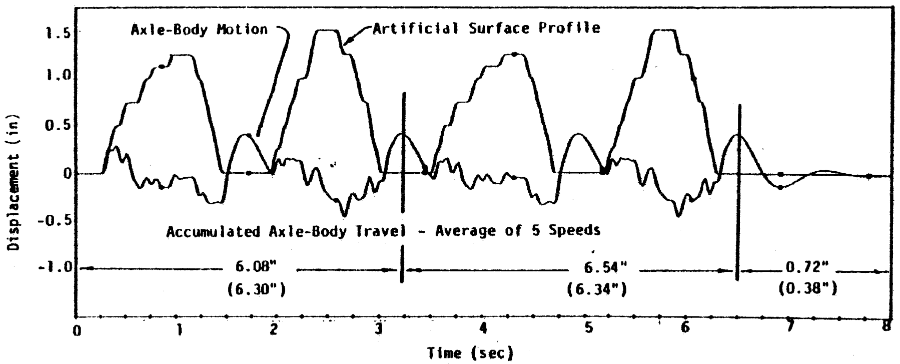
$$\text{Inches of travel} = 6.80 + (n\text{-}1) \times 6.54 \qquad \text{(A-4)}$$

where n is the number of sets of bumps used (all spaced at 12-ft intervals). Thus, when two sets are used, as specified in the previous section, the HSRI reference should accumulate 13.34 in. of axle-body travel. The design RARV value for the bumps is 1.98 in./sec. Inches of accrued axle-body travel that are measured with RTRRM systems are converted to ARV by dividing the measured value by an "effective time" that is found by ratioing the simulated inches of axle-body travel of the HSRI reference by the RARV value. A time of 6.73 sec is obtained when two sets of bumps are used.

If the actual dimensions of the bumps differ from the specified geometry, the inches of travel, calculated by the foregoing equation, and the RARV value should be scaled accordingly. When only one side of the vehicle is driven over the bumps the RARV value should be reduced by 50 percent, but the "effective time" is unaffected.

RTRRM systems will display a speed sensitivity when operated on the bumps. Also, the measurements will be more sensitive to tire pressure than during on-road operation, because the tire pressure affects not only the tire spring rate but also the tire-enveloping behavior. Table A-1 gives the sensitivities of the HSRI reference simulation to both speed and the first nodal wavelength in the enveloping model described earlier to indicate the sensitivities that can be expected.

To estimate errors that could be obtained by calibrating RTRRM systems with vehicles that do not have response properties identical to the HSRI reference, a number of different vehicles were simulated on the bumps. Figure A-14 illustrates the response functions of the different simulated vehicles and also shows the measurements that would be obtained, along with the percent errors, if they were calibrated according to the method specified in the previous section. In general, the figure shows that the well-damped version of each of the five basic vehicle types is given a smaller error.



(Numbers in parentheses are for traveling in the opposite direction over the bumps.)

Figure A-13. Response of HSRI-reference to artificial surface.

TABLE A-1

RESPONSE OF HSRI-REFERENCE WITH TIRE ENVELOPING MODEL TO TWO SETS OF BUMPS

Calibration Speed (mph)	Enveloping Nodal Wavelength (ft)	Accumulated Inches
13	.95	13.13
14		13.26
15		13.36
16		13.41
17		13.52
ave.		13.34
15	.50	15.38
	.60	14.96
	.70	14.58
	.80	14.01
	.90	13.57
	1.00	13.08
	1.10	12.60
	1.20	12.12

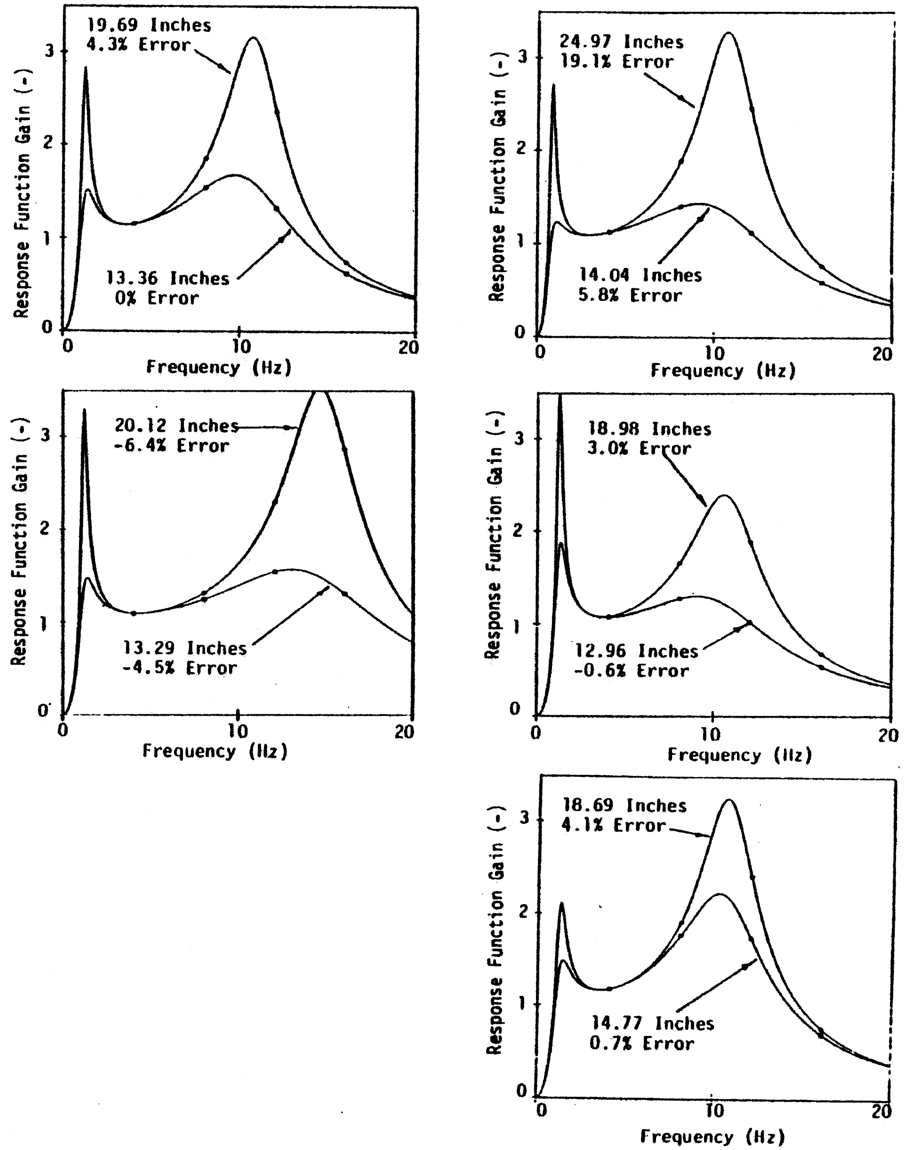


Figure A-14. Response of various simulated vehicles to artificial surfaces.

Recommendations for Further Improvements

Clearly the artificial bump calibration method can benefit from further developments. Basically, there are two directions that can be taken. First, the artificial bump design and calibration method can be improved. A better surface could be developed by using more than two bump patterns, with the result of a closer agreement between the actual spectral density and the intended spectral density. Also, different surfaces could be generated to simulate PCC roads and speeds other than 50 mph. The second direction is to take the existing method and gather a more substantial amount of experience with its use. Given the current state of development and the limited results from the Correlation Program, the latter direction would be more fruitful. Some of the questions about this calibration method that can only be answered by first-hand experience in the daily calibration of RTRRM systems are:

1. What is the reliability of this method with different RTRRM systems? Can it be counted on to provide the same calibration as a profilometer?
2. What is the trade-off between the number of bumps used during calibration, the number of passes at each speed, and the precision of the calibration?
3. What improvement in the precision is obtained by reducing or eliminating meter nonlinearities?
4. Does the selection of tires for the vehicle portion of the RTRRM system overly influence the calibration?

Ultimately, the artificial bump calibration method is presented as a short-term solution for agencies that have no access to a profilometer. An intensive effort to optimize the artificial bump calibration method is not recommended, because it is hoped that the long-term solution lies in the availability of road roughness measurement systems, based on profilometer technology, that will make RTRRM systems as they now exist obsolete.

APPENDIX B

ROAD ROUGHNESS EFFECTS ON VEHICLES

The primary interest in road roughness today is its excitation of vibrations in the road-using vehicles affecting the ride comfort and causing vehicle deterioration. The vibrations induced are random in nature and can be described by any one of a large choice of variables. Selecting a variable by which to quantify roughness should be approached from an understanding of the vehicle dynamics mechanisms involved.

Choice of a Roughness Variable

Applying this approach to selecting a roughness variable related to ride comfort results in the logical choice of the Average Rectified Velocity (ARV) statistic measured for the suspension motions on vehicle-response-type measuring systems. That measure appears suitable for quantifying many of the vehicle vibration effects influencing costs to the road user, as described in the next section.

The basis for choosing the ARV statistic derives from the relationship between vibrations and ride comfort. Ride vibrations are traditionally measured in terms of the accelerations produced at various points on the body of a motor vehicle. Characteristically, those accelerations have an amplitude and frequency content similar to the spectrum shown in Figure B-1, obtained from measurements on a typical passenger car. The ISO curves shown in the figure approximate the rider sensitivities to accelerations throughout the spectrum. Such data would indicate that the ride comfort experienced is predominately determined by the acceleration amplitudes beginning near 1 Hz (the body bounce frequency) and extending through the peak at 10 Hz (axle resonance frequency). Though the evidence is sparse, there is indication that the discomfort experienced is, at least to a first-order approximation, linearly related to the general amplitude of the acceleration spectrum [17].*

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*See References in main text.

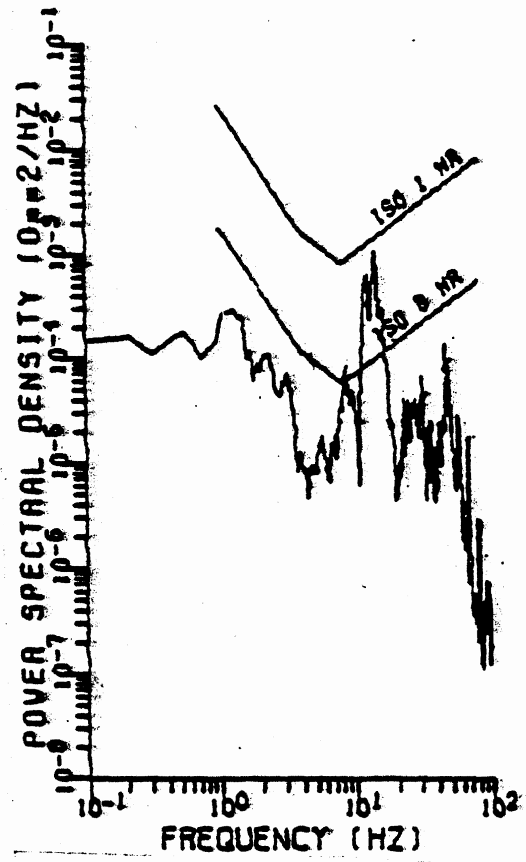

Figure B-1. Comparison of measured spectral density of passenger acceleration with ISO vibration standards.

The measurement of road roughness by vehicle response systems is based on measurement of the suspension motions on the vehicle. The suspension motions are also a random signal having a characteristic spectral shape. The motion can be quantified by displacement, velocity or acceleration measures. Of these three, the velocity signal (see Figure B-2) has a spectral content most similar to the ride accelerations, and its amplitude is proportional to that of the accelerations.

Thus a full measure of the suspension velocity signal over this frequency range is the most logical correlate to vehicle accelerations and ride comfort. With most roughness measurement schemes, the suspension deflections are accumulated while traversing a test section. Common practice is to divide this total displacement by the test section length to obtain a measure of the suspension displacement caused by roughness per unit distance traveled. If instead, the accumulated displacement is divided by the length of time required to traverse the test section, an Average Rectified Velocity (ARV) is obtained. That numeric is then effectively equivalent to the integral for the vehicle response spectrum shown in Figure B-2.

Applicability of ARV to Road User Costs

There are many potential ways in which road roughness may contribute to user costs associated with operation on a highway. Among these are:

1) Increase in tire wear and road hazard failures
2) Steering and suspension wear
3) Component failures (springs, brackets, etc.)
4) Cargo damage
5) Slower transport speeds.

Many other ways undoubtedly can be postulated. The ability to discover the relationship between these cost factors and road roughness from empirical data can be confounded by an inappropriate choice of a roughness statistic. In every case it is advisable to consider the physical mechanisms that may be involved before choosing the roughness statistic

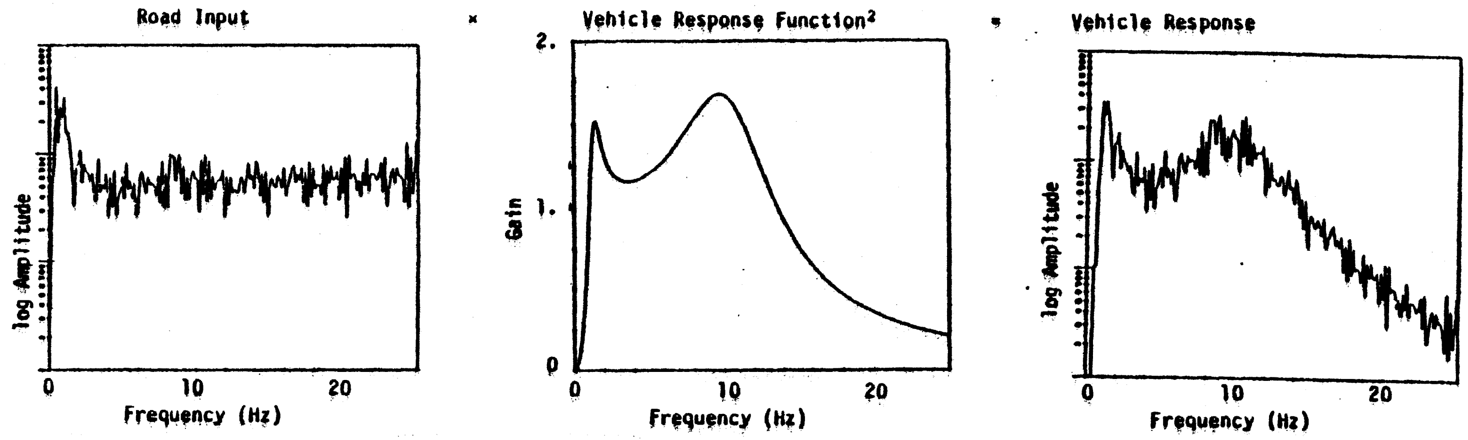

Figure B-2. Contribution of vehicle and road to spectral density of axle-body velocity.

to be tested in a correlation analysis. It is suggested that the little recognized ARV statistic may be the best choice for many of the analyses performed.

The ARV statistic is numerically proportional to the acceleration levels on a vehicle induced by the roughness at any speed. This is not true of the "mm/km" type statistics currently in use. Consider a rural and urban road each with the same "mm/km" value as measured at 32 km/h. Though these two roads may be considered equivalent in roughness, if the mean traffic speed on the urban road is 30 km/h and that on the rural road is 60 km/h, they are not equivalent to the user. In actuality, the effective roughness on the rural road will be on the order of 50-100 percent greater than that of the urban road because of the higher travel speed. Even worse, if the "mm/km" statistic were measured at 30 km/h on the urban road and 60 km/h on the rural road, in most cases the rural road would yield a lower numerical value, erroneously implying that the rural road is in fact better. Only when the roughness is measured as an ARV statistic at the appropriate traffic speed is a true evaluation of the effective roughness obtained.

The ARV statistic is then the measure that closely relates to vibration levels on using vehicles. Hence, it is directly related to ride discomfort and the associated phenomenon—cargo damage. Where roughness magnitudes are so high that travel speeds are limited, the driver stimulus that controls the speed is most certainly the discomfort and the perception of excessive vibrations in the vehicle. Within the U.S. military establishment, research has determined relationships between the acceleration levels imposed on a driver and maximum travel speeds [18,19]. It is doubtful that these limits apply directly to civilian transport, especially in the case of the owner/driver where perception of vehicle damage may be the controlling factor. Nevertheless, methodology has been established indicating the potential for relating a direct vibration measure, such as the ARV, to limitations on transport speed.

Wear in vehicle suspension and steering system components is logically related to force levels and motions on the components. Force levels are proportional to accelerations and hence the ARV. The rate at which motion occurs is again proportional to ARV. Component failures occur as a result of repeated applications of force, and the life of a component is classically bounded by the relationship of stress (force) level and cycles to failure, as illustrated in Figure B-3. Components are ideally designed to keep stress levels below the material's endurance limit, so that the component life is effectively infinite. Therefore, the failure rate of vehicle components is expected to relate directly to force magnitudes imposed by road roughness.

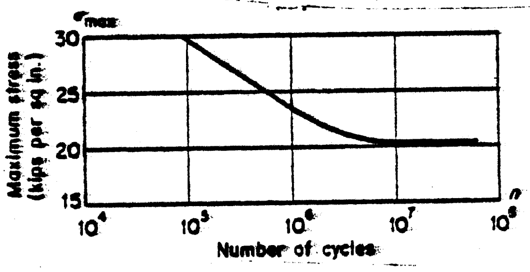

Figure B-3. Cycle life as a function of maximum stress, typical of mild steels.

Tire wear can be linked to roughness through the scrub action associated with suspension motions and wheel bouncing. Bead, tread and sidewall failures may be linked with severe loadings and excessive deflections. In both of these cases, the ARV is a logical correlate of the effects.

Thus the ARV concept is seen to have a broad basis for integration into analysis of road-user costs. The emphasis here is on concept because it is not the statistic itself so much as the vehicle behavior that it reflects which is important. In the main report, it has been indicated that the ARV is simply a complementary form of an ARS statistic, such as the "mm/km." Its primary value lies in clarifying the systematic relationship between ARS statistics, travel speed and vehicle vibrations. From that understanding it is possible to rationalize the benefits of measuring roughness at different speeds, how and where speed corrections can be applied to roughness data, and how roughness data may be best employed in road-user cost studies. Extensive information on road roughness exists throughout the world. It is not necessary to discard this valuable data, but recognize that its value in application may be greatly enhanced on occasion by translation to the ARV form.

APPENDIX C

APPRAISAL OF TRRL HORIZONTAL BAR

Introduction

The TRRL Overseas Unit is currently in the process of developing a simple electromechanical device for the purpose of providing an objective measure of road roughness properties, which has been tentatively labeled the "Horizontal Bar." The device consists of a three-meter rigid bar which is positioned horizontally, or optionally-parallel, to the road surface. A movable carriage on the bar supports a small (~8-inch diameter) pneumatic tire which is rolled along the road surface directly beneath the bar. The vertical motion of the wheel center is sensed relative to the datum line of the bar.

In essence, the device is a simple manual profilometer, largely mechanical in nature, considered appropriate technology for use in less developed countries. Two potential applications are envisioned for the device:

1) The measurement of a summary surface roughness statistic

2) The direct measurement of road surface profiles by labor intensive methods.

The first application was the primary TRRL motive for development of the system. In light of the understanding of road roughness measurement problems developed in the research behind NCHRP Report #228, a number of pitfalls are evident. The applications of the Horizontal Bar device are therefore discussed here to point out the problems that may be anticipated, and potential approaches to solution.

Measurement of a Summary Roughness Statistic

The Horizontal Bar was conceived as a means for objectively measuring the vertical deviations of a road surface as an indicator of roughness, analogous to the "mm/km" measure obtained with the Bump

Integrator, but without its problems of variations in dynamic response. This type of measure is termed a "summary statistic" because it reduces a complex roughness waveform to a single numerical value. It first should be understood that this statistic is a measure of the road slope deviations from zero (i.e., the deviations from a flat, smooth road). Though not numerically equivalent to the RMS slope, the "mm/km" is very similar to—and highly correlated with—the RMS slope. The benefit of recognizing this is that it is possible to predict its properties from a knowledge of the RMS properties which are well established mathematically for random signals of the nature of road roughness profiles.

From comprehensive studies of road roughness characteristics, it has been determined that the road slope properties vary with wave number on the average, as shown in Figure C-1. (Note that wave number is the spacial frequency in cycles/ft, and is equal to 1/wavelength.) The PSD plot indicates that the road slope amplitude content is greatest at low wave number (long wavelength), but relatively constant thereafter with wave number. The mean square value is equal to the area under the curve, hence its value is directly related to the wave number band that is measured.

From this understanding, it may be projected that the summary roughness measurement of "mm/km" obtained with the Horizontal Bar will be directly proportional to its wave number bandwidth, and will vary with the factors that determine its bandwidth. At the low wave number extreme (i.e., long wavelength), the low cutoff wave number is determined by the procedures and accuracy with which the datum plane is established by placement of the bar. Whether recognized or not, a low cutoff limit will exist and cause variations in the measurement which depend on the accuracy with which the level of the bar is established. Under no circumstances should the bar be placed "parallel" to the road in an uncontrolled manner, as it may be expected that the low cutoff limit, and hence the summary roughness measure, will be subject to variation as a consequence of the specific procedures used in each measurement.

At the high wave number extreme of the measurement bandwidth, similar limitations arise. The upper limit is dependent on the radius

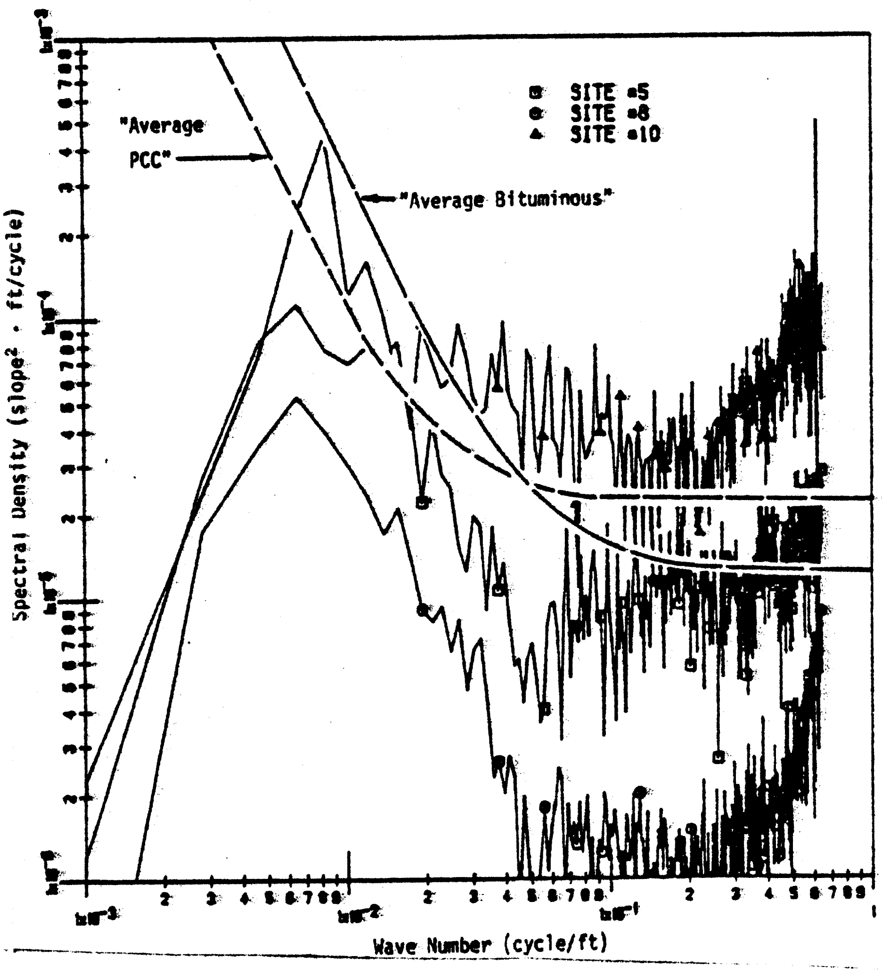

Figure C-1. Typical spectral densities of pavement slope (average of two tracks).

of the follower wheel used, its hardness (inflation pressure), and the loading against the ground. As with pneumatic-tired vehicles, the exact measurement obtained will depend on the envelopment properties of the tire, only in this case, the effect will be far different from that of vehicle tires because of the radically different dimensional size and stiffness. All in all, it may be anticipated that the Horizontal Bar may respond to wave numbers perhaps an order of magnitude higher than that seen by vehicles. Hence, the Horizontal Bar will be especially sensitive to pavement texture characteristics to a degree far in excess of that of a vehicle. Thus a high degree of random error will occur in efforts to correlate fifth wheel or vehicle-mounted devices with the Horizontal Bar, and it can be projected that such efforts would ultimately lead to separate relationships for different classes of road textural properties.

Theoretically, the Horizontal Bar device will obtain a roughness measurement that is roughly proportional to the area under the curve shown in Figure C-2. To be most effective, its roughness response bandwidth should closely match that of road vehicles, but it is quite unlikely that such equivalence can be obtained with a simple mechanical device.

As it turns out, TRRL has already observed empirically the sensitivity of this device to high wave number roughness (i.e., an exaggerated sensitivity to road texture characteristics). Development has been initiated for means to diminish this sensitivity. One method, softening the tire by going to an inflatable pneumatic tire, is constructive inasmuch as it strives to approach the envelopment behavior of vehicle tires, but obviously must overcome the nagging problems of maintaining consistent performance with normal variations of inflation pressure, temperature, wear, etc.

Additionally, the instrumentation system has been modified, introducing quantization of 2.5 mm and hysteresis of 1 mm, to suppress the observed sensitivity. The research behind the NCHRP Report #228 (see pp. 12-15) suggests this approach will contribute undesirable variations

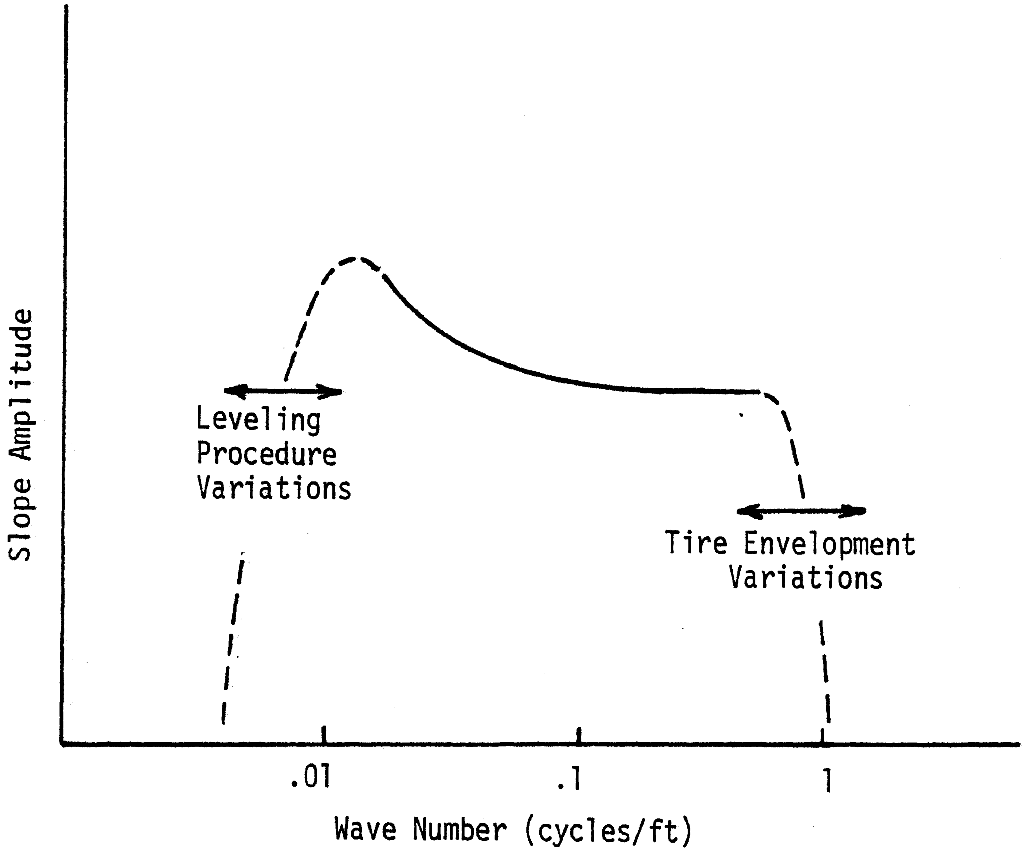

Figure C.2. Measurement Quantity with Horizontal Bar Device.

to the performance of the system, without eliminating the unwanted sensitivity. Specifically, quantization will add random errors to the measurements obtained and will be most serious as a problem on smoother roads. On the other hand, hysteresis will consistently act to diminish the magnitude of the measured roughness statistic by a percentage that varies with the roughness amplitude. Perhaps the most problemmatical aspect of introducing quantization and hysteresis is that they render the system nonlinear (i.e., the output measurement is not always exactly proportional to the wheel motion input). Linear systems can be readily calibrated by measuring the input/output amplitude relationship under arbitrary conditions which may be rather artificial in nature. However, with nonlinear systems, the relationship obtained is sensitive to both the calibration input amplitude and the input spectral qualities. Hence, the problems in calibration of Horizontal Bar devices instrumented similar to the current prototype, may be expected to closely parallel the past experiences with the Bump Integrator.

Measurement of Road Profiles

The Horizontal Bar device offers potential capability for measurement of road profiles (albeit, a labor-intensive method) in less developed countries, with some modifications. Road profiles, obtained within a reasonable degree of accuracy over an appropriate bandwidth for a series of road test sections, are an adequate data base from which to establish the calibration of fifth wheel and vehicle-mounted Bump Integrators, or comparable equipment. To be suited to this application, equipment and procedures of the following nature would be needed:

1) Bar leveling - The horizontal bar serves as a segmented datum line in the measurement of the profile. Its position must be known accurately during measurement of each profile segment. Its longitudinal position for each measurement setup can be established relative to a beginning benchmark point with acceptable accuracy using a simple tape measure. Its vertical positioning is critical inasmuch as random errors will introduce fictitious components to the profile at six-meter and longer wavelengths. While the exact level of accuracy needed is yet to

be determined, it will probably be on the order of a fraction of a millimeter end-to-end on the bar. The bar can either be leveled to this accuracy or, alternatively, placed at a convenient slope, the slope being measured to the same accuracy and suitably recorded with the data.

2) Profile elevation - The profile elevation relative to the bar is obtained from the rolling wheel. The device should be configured to produce an analog elevation signal with a resolution of 0.25 mm and with hysteresis components less than 0.025 mm. This will require that the follower wheel be carefully prepared to run true and that the vertical transducer be of reasonably high quality with precision linkages. Of special concern in this respect is deflection of the bar. The bar is the datum line; hence, forces imposed on it by the operator pushing the carriage, friction in the wheel suspension or other sources, will produce errors in the profile. Bar deflections that will occur with suspension friction are hysteretic effects, and even though not easily noticeable, they will deteriorate the quality of the measured profile if too much in excess of the hysteresis limits proposed. If operator hand forces on the bar produce vertical deflections more than a fraction of a millimeter, he will inadvertently add periodic components to the profile at the wavelength of his stride. Furthermore, if the bar deviates from being absolutely straight, it will add an apparent component to the roughness profile equivalent to its shape. Hence, great care must be exercised to ensure that the bar is the intended straight-line datum free from sags or bends in its shape.

3) Longitudinal position - In order to obtain the longitudinal position dimension of the profile, it will be necessary to add a longitudinal transducer to the carriage. The output should be an analog signal that can be resolved to better than 10 mm of distance. This high resolution is needed because of concern that high wave number vertical profile components may be present due to the follower wheel response to surface texture. Since the profile must ultimately be digitized to be useful, the digital samples must be taken at a rate of 3-4 times the

the highest wave number in order to avoid a technical phenomenon called aliasing.* The way in which aliasing will be prevented will depend on the data reduction method finally selected, but means can be assured by having the longitudinal resolution on the order of 10 mm.

Recommendations

The use of the Horizontal Bar to obtain objective measurement of a useful summary statistic is prone to many problems. Many of the problems are comparable to those existing with vehicle-based systems. The fact that the Horizontal Bar will measure roughness properties that differ significantly from those to which vehicle-based systems are sensitive, forecasts a limited utility as a calibration device.

The application of the Horizontal Bar to hand measurement of profiles is possible. Yet many modifications and corrective actions may be needed to ensure necessary accuracy. Rather than rework an existing device, it may be more efficient to develop an alternative device more specifically designed to serve this function.

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*Aliasing occurs when a periodic signal is sampled at less than twice per cycle. In the digital data that signal appears "aliased" down to a lower frequency. (See Appendix D.)

APPENDIX D

ROAD PROFILE MEASUREMENT AND INTERPRETATION

by

M. Sayers

In the history and development of road roughness measurement systems, the GMR profilometer has set the standard of precision reliability and versatility to which all other systems are compared. Because the GMR profilometer performs so much better than RTRRM systems and the earlier "profilometers" such as the CHLOE, there has not seemed to be good reason for its users to seriously examine the performance limits. Yet, any instrument does have inherent limitations. In the NCHRP Project 1-18, for example, a state-of-the-art GMR profilometer was used together with a quarter-car simulation to provide roughness measures for 24 surfaces. These measures were to be used for the calibration of eight RTRRM systems and Figure 1, taken from Reference [6], shows the resulting comparison. While a more-or-less linear trend exists up to fairly high roughness levels (RARV ≈ 2.7 in/sec), indicating excellent linear correlation, the profilometer produces unusually high readings for the rougher surfaces. The disparities at high roughness levels were thought to be due to some performance limitation of the profilometer, but the physical mechanisms responsible for the excessive response, not being critical to the research, were never clarified. Similar performance has been observed in the Brazilian project. Before a universal roughness measure is adopted, it is vital that the profile measurement process be well understood.

To provide insight into this concern, consider the design and operation of an inertial (GMR-type) profilometer system. Conceptually, an inertial profilometer is a simple device, using two common transducers and some minimal electronics to convert pavement elevation of a wheel track into a signal that is either stored or processed to obtain a summary statistic for the pavement. An accelerometer is attached to the body of a vehicle, measuring the vertical acceleration of the body. A signal proportional to acceleration is produced and integrated twice, either electronically or with a digital computer. This yields a signal that is ideally proportional to the vertical position of the vehicle body, relative

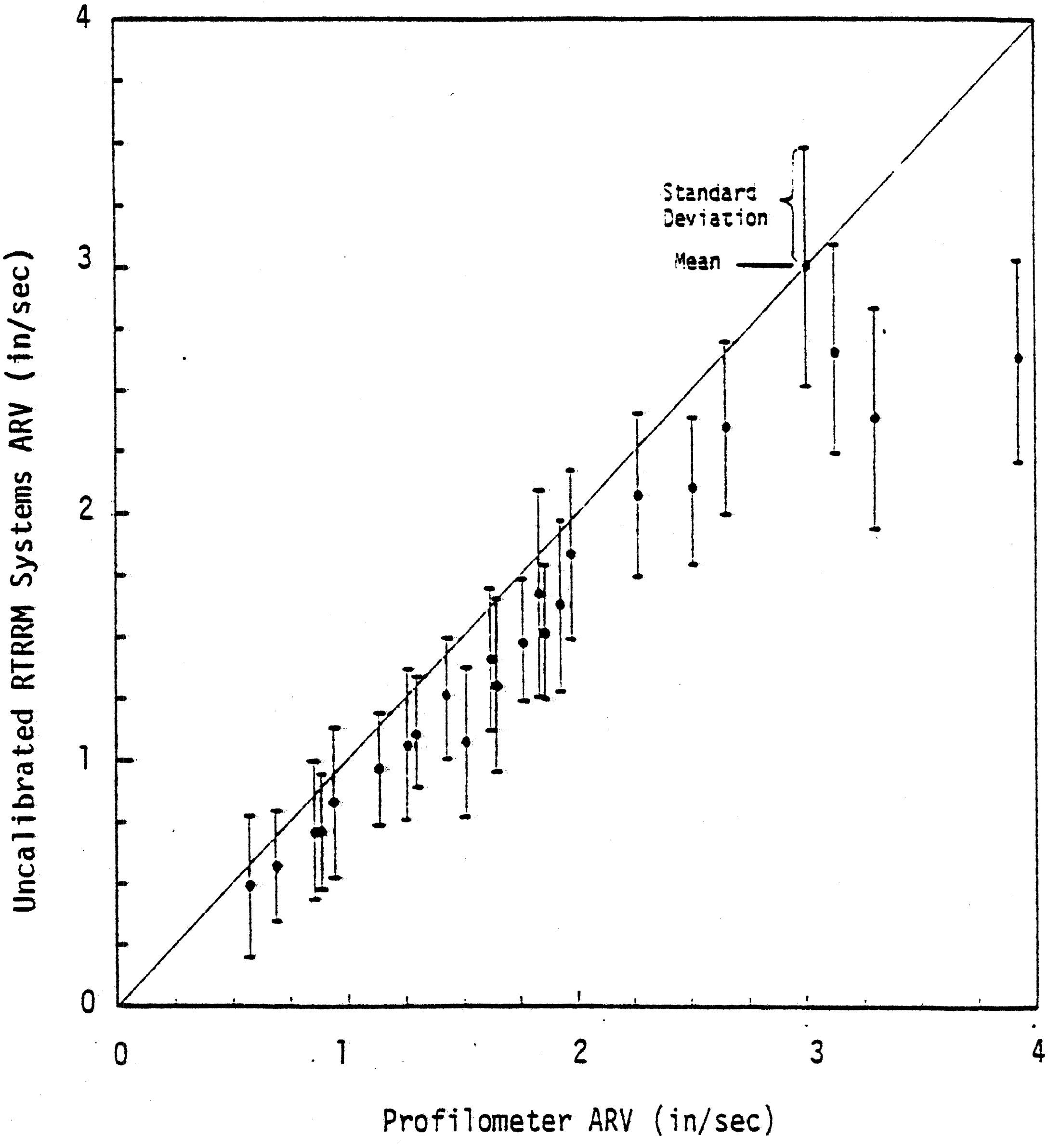


Figure 1. Comparison of roughness measurements from GMR profilometer and eight RTRRM systems.

to an inertial reference. A second transducer simultaneously measures the distance between the vehicle body and the pavement, at a location directly under the accelerometer. The signal from this transducer is subtracted from the twice-integrated accelerometer signal, thus yielding a signal proportional to the pavement elevation relative to an inertial reference. While both transducers contribute to the overall signal, most of the low-frequency content is provided by the accelerometer, with the high-frequency content coming from the displacement transducer.

The accelerometer senses two phenomena—acceleration in the direction of its mounting axis and the component of gravity also acting in the axis direction. Acceleration is a purely dynamic variable; it is a function of time and frequency, but by itself is completely unrelated to distance and wavelength. Thus, the profile properties measured by the accelerometer are converted analytically, using the vehicle speed. As Figure 2 shows, the frequency content of the acceleration signal is primarily in the range of 1-15 Hz for a typical passenger car or light truck. At lower frequencies, the content is low and the classic concern about the signal/noise ratio becomes important as the signal amplitude drops. The double integration process acts to weight the frequency content of the acceleration signal by a factor inversely proportional to the frequency squared. This strongly attenuates the high-frequency content of the signal, while greatly amplifying the low-frequency content (see Figure 3). Since this factor is infinite at zero frequency, any DC offset, no matter how small, will rapidly accumulate and grow. Also, any electronic noise existing at low frequencies, which effectively limits the transducer resolution will also be greatly amplified. For example, a resolution of 0.01 inches (after integration) at 1 Hz corresponds to an acceleration resolution of 0.001 g's. Yet at 0.1 Hz, the same acceleration resolution, when doubly integrated, results in a displacement resolution of 1.0 inches. In practice, this high amplification of low-frequency content appears as a drifting problem, with the ultimate result that it is impossible to measure the very low-frequency components of road profile. To reduce the unwanted drifting, GMR-type profilometers have high-pass filters that cut out the low-frequency content, such that the low-frequency limitations are mainly dependent on the filter response

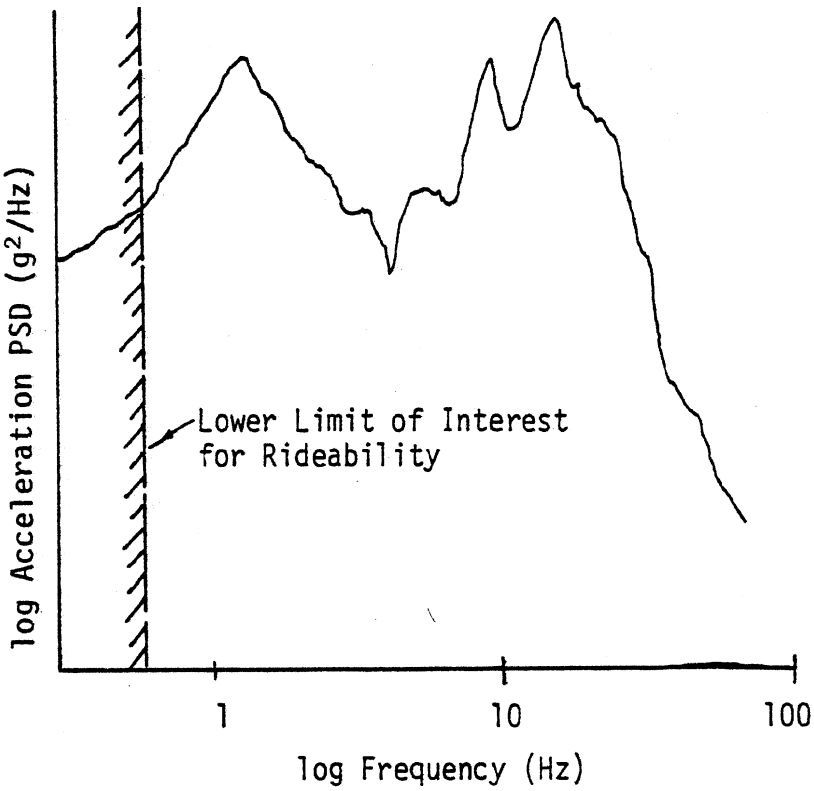


Figure 2. Example of PSD of accelerometer signal on GMR Profilometer.

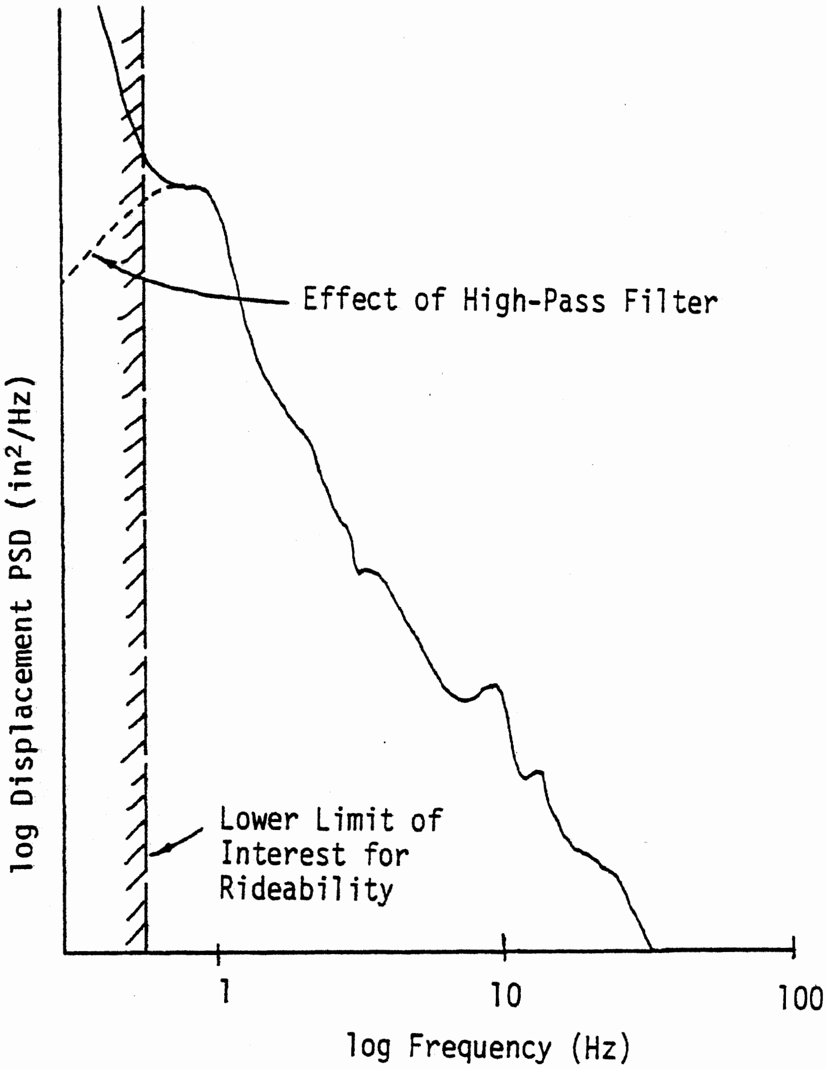


Figure 3. Example of PSD of doubly-integrated accelerometer signal from profilometer.

properties. Since the transducer limitations are frequency dependent, the corresponding limitation expressed as wavelength is dependent on the operating speed of the profilometer. For example, if the practical limit of the accelerometer is 0.2 Hz, the corresponding wavelength is 400 ft/cycle when the profilometer travels at 55 mph. But if the profilometer is traveling only at 20 mph, the physical limitations still keep the lower frequency limit at 0.2 Hz, although this now corresponds to a 150-foot wavelength.

The second variable included in the accelerometer signal is the gravity component, proportional to the cosine of the angle of the measurement axis, relative to horizontal. The angle of the measurement axis is actually the combined effect of pitch and roll of the vehicle body. These effects are always small and thus negligible compared to the vertical acceleration, except at low frequencies. Since the low-frequency response is already limited by the high-pass filters, the tilting of the accelerometer is normally not a problem in practice.

All in all, the nature of the accelerometer signal, together with the double integration process, limits the capability of the measured profile at low frequencies. A GMR profilometer is not suitable for accurately measuring the large, slow changes in profile attributable to hills and such. Likewise, a two-track GMR profilometer is not suitable for measuring the underlying road camber. Still, higher frequency roll features are replicated. Public opinion on road roughness is thought to be related to ride vibrations above 0.5 Hz, and the accelerometers on a GMR profilometer should certainly be capable of providing both the vertical and roll components of roughness above 0.5 Hz for the application needed in Project 1-23 if the profilometer is used at normal highway speeds.

The other transducer in the GMR profilometer, which measures the pavement-to-vehicle-body distance, has both frequency and geometric limitations. The traditional device used for measuring this distance involves a small follower wheel, held on the pavement with a static force of several hundred pounds, and a linear displacement transducer such as a potentiometer. This device performs its job well when properly designed and maintained, but does have properties—summarized in Figure 4—that ultimately limit its performance. The follower wheel is a mechanical system with mass and compliance, and thus has resonance properties (see Figure 4a). The follower wheel assembly typically resonates at a frequency near 100 Hz, regardless of the profilometer speed. Thus, at 100 Hz, the measured displacement will be much greater than the actual displacement, but at frequencies less than 50 Hz, the amplification should be slight, giving good agreement between the actual and measured motions. At 55 mph, the 50 Hz limit corresponds to a wavelength of 0.61 ft/cycle. In order to locate the resonance at this frequency, the tire is made of solid urethane to increase its stiffness and the whole assembly is made as light as possible. The follower wheel also distorts the true displacement signal because of geometric effects. Due to its finite curvature, it will roll over sharp corners, rather than following them exactly, adding its radius to that of the bumps. Also, it will respond to small bumps more than it will to small depressions (Figure 4b). Obviously, this effect is reduced by designing the follower wheel to be as small as possible. No tire or wheel is truly round, and an apparent sinusoidal component will be added at the wavelength corresponding to the circumference of the follower wheel, which is typically 1.5 ft (Figure 4c). This error is reduced by grinding the tire to tolerances of .001 inch or less. The upper frequency response limit of the profilometer is determined by these three effects together.

Probably the most serious problem with a follower wheel is that it can bounce and actually leave the ground (Figure 4d). Once off the ground, the mass of the wheel is no longer coupled to the high stiffness of the urethane tire, but only to the static loading of several hundred pounds. Bounce of the follower wheel is not correctable by post-processing of data; rather, it can only be eliminated by increasing the static load (and thus increasing wear of the tire), or by running the profilometer at a reduced speed (and thus losing fidelity for long wavelengths due to the accelerometer limitations). It should be noted that the limited compliance of the solid tire is needed to reduce the bounce problem by absorbing some of the very high frequency roughness (associated

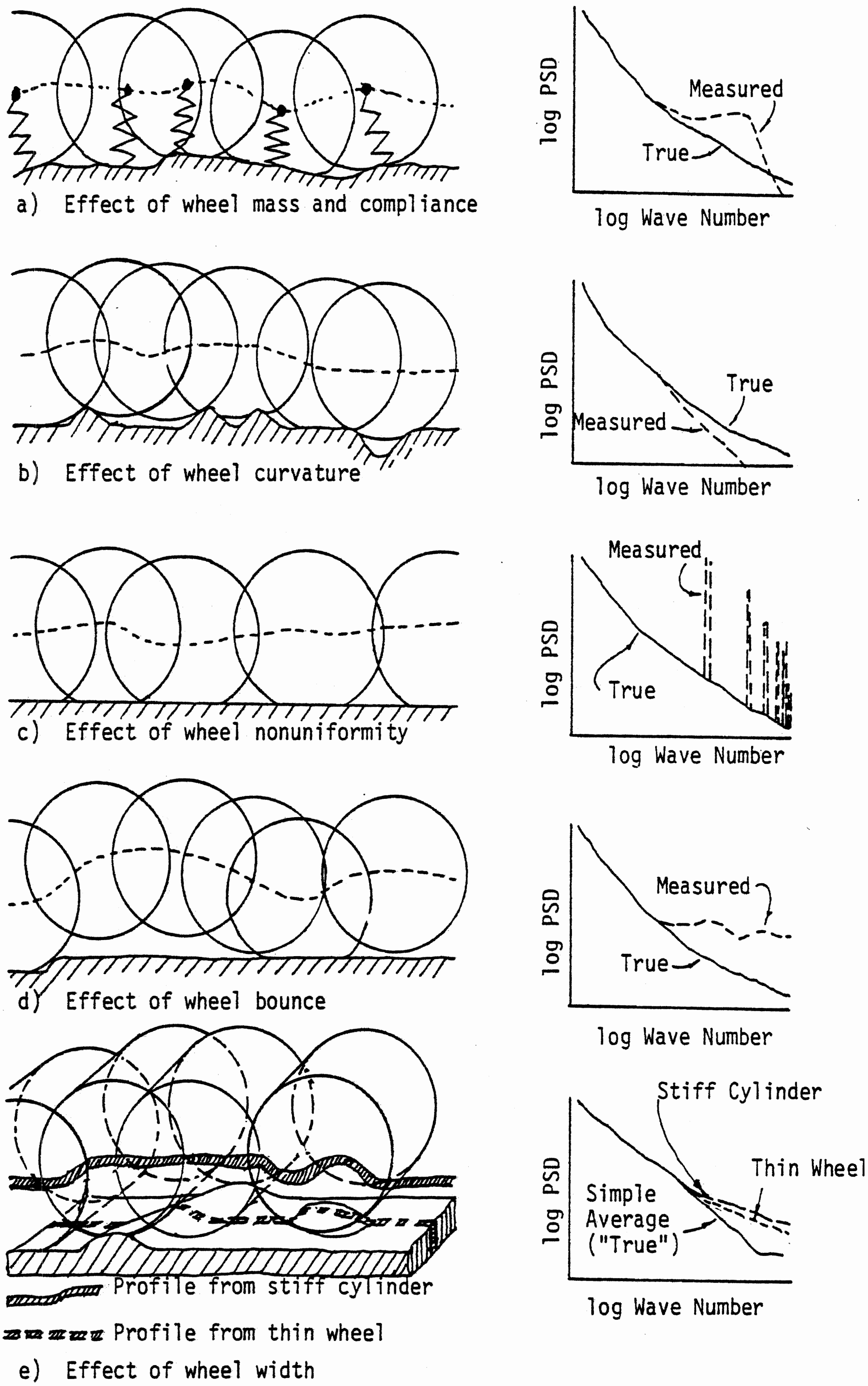


Figure 4. Illustration of measurement errors due to follower wheel, with resulting effects on profile PSD.

with edges and sharp corners in the profile) which are more likely to cause bouncing. But the compliance must be kept low enough to keep the mechanical resonance frequency well above the frequency range of interest.

Finally, the response of the follower wheel to the distribution of roughness over its width is not clear. Figure 4e compares three possible responses to three-dimensional bumps. The soft pneumatic tires of passenger cars tend to envelop bumps and transmit forces somewhat proportional to the total deflections under the contact patch. Note that the profile that would be measured with a very narrow follower wheel does not differentiate between the thin bump and wide bump. On the other hand, the wide follower wheel gives a harsher representation than the pneumatic tire because it always responds to the highest point underneath it, rather than the overall average.

Road follower wheels are being abandoned in many of the new GMR profilometers in favor of displacement transducers which do not physically contact the ground. These so-called non-contacting probes operate either by reflections of a light beam on the pavement, detecting its angular position relative to a sensor (see Figure 5), or by broadcasting sound waves and detecting the echoes. Each of these devices have accuracy limitations due to resolution, frequency response, and geometry. Devices that involve timing of light or sound pulses will have inherent frequency limitations. Obviously, the signal can be updated only as frequently as the pulses are generated, which results in a theoretical maximum frequency content of one-half of the pulsing frequency. The devices that operate on an optical image projected on the ground have the potentially desirable feature that the image area results in an average elevation over an area that can be easily adjusted by varying the image. The acoustic devices, on the other hand, are expected to have a displacement sensitivity over an area that may or may not be easily adjusted, but nonetheless needs to be quantified (see Figure 6). The non-contacting probes, being intrinsically more complicated than a linear potentiometer, could potentially have quantization, hysteresis, and signal-to-noise problems that act together to reduce the overall resolution.

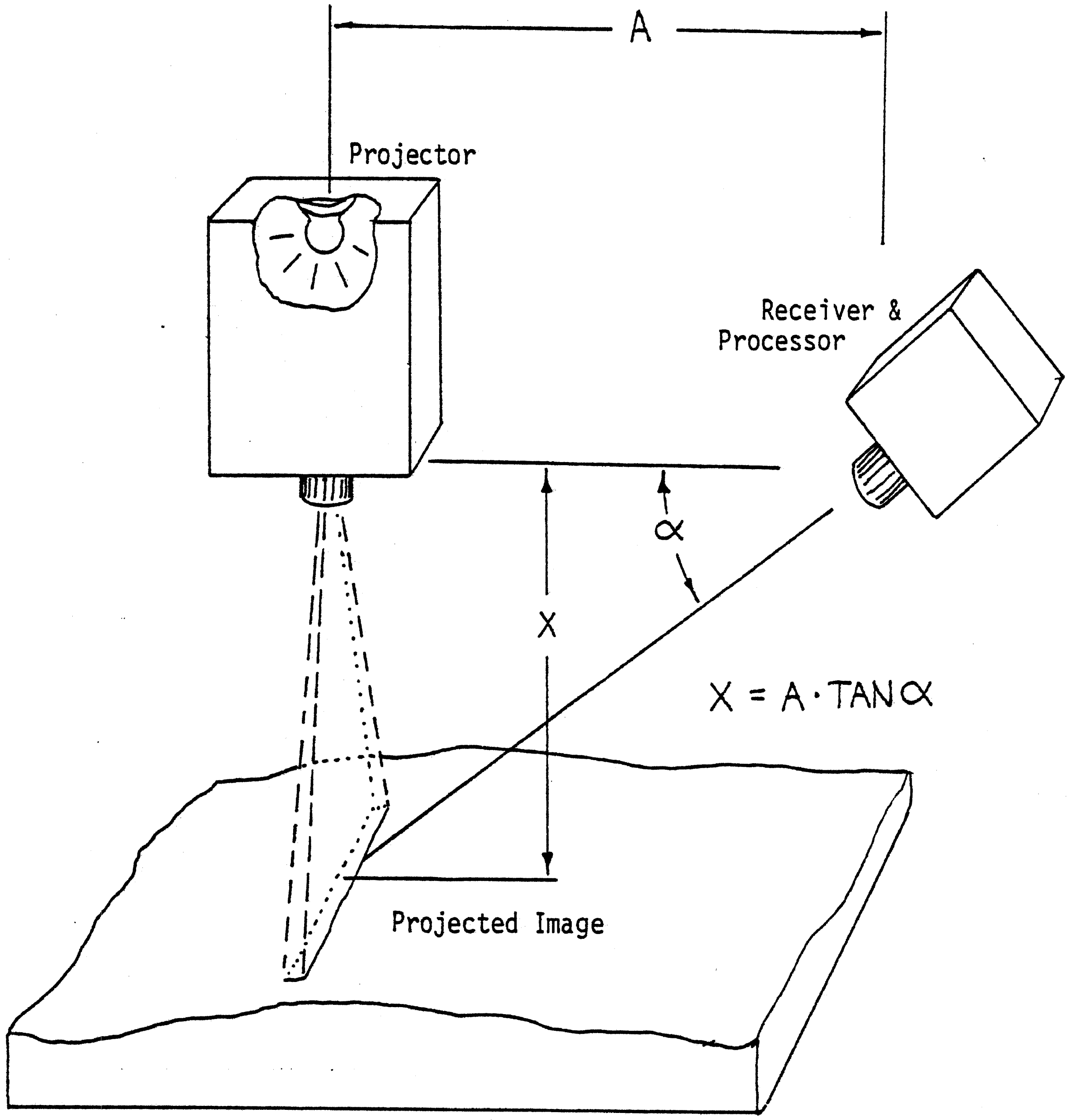
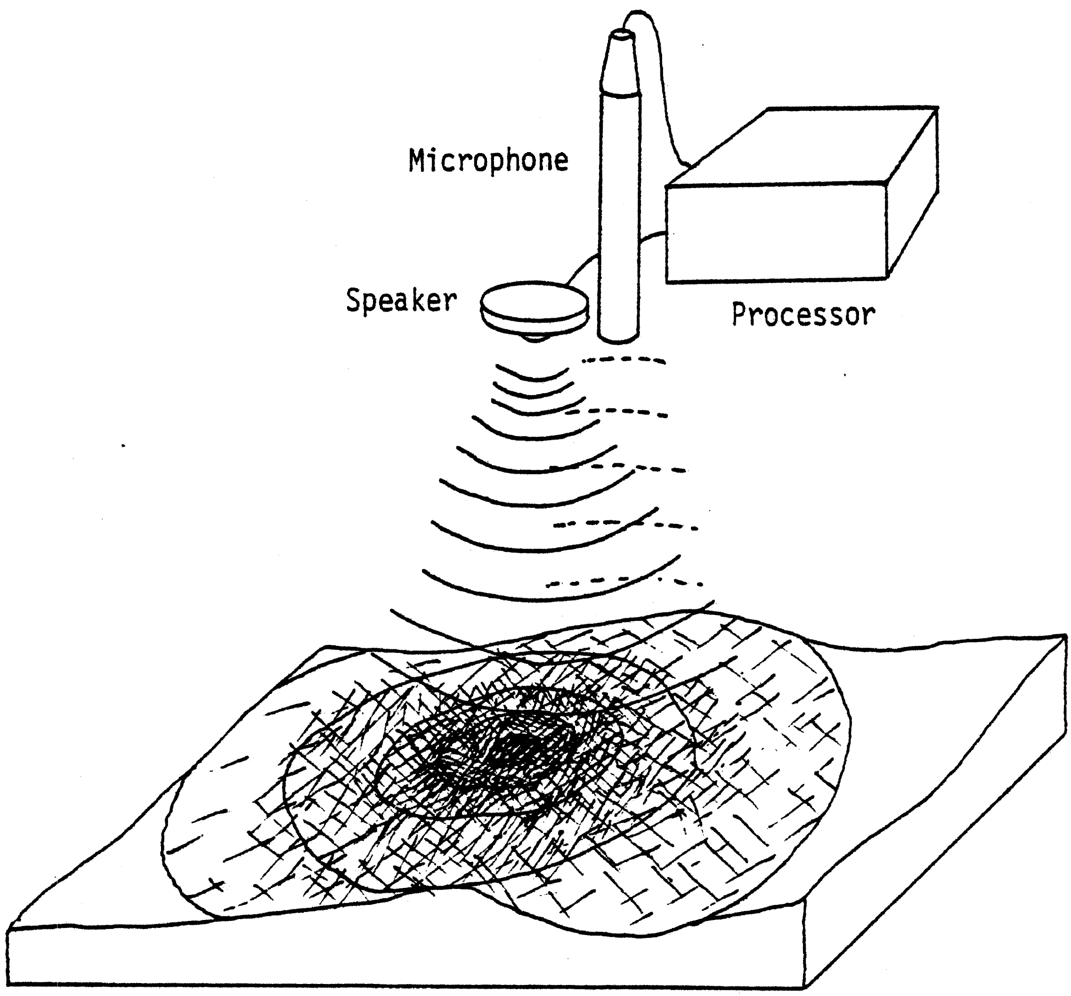


Figure 5. Simple diagram of optical non-contacting probe operation.



Note: Sensitivity of probe to surface elevation is shown by shading, with the darkest shading indicating maximum sensitivity.

Figure 6. Simple diagram of acoustic non-contacting probe operation.

Any signal that is generated periodically, or sampled periodically, can have aliasing problems if the frequency content of the variable being measured extends above one-half of the sampling frequency (see Figure 7). Rather than showing the high-frequency "harsh" roughness, that contributes only slightly to overall roughness ratings, the measured profile shows fictitious features with lower frequency content that is more important to overall roughness measures.

In concluding this discussion on profile measurement, consider the basic job of a profilometer, which is the task of reducing a three-dimensional pavement surface to a two-dimensional profile description. Figures 8a and 8b compare two different, but equally valid, profile descriptions of a road surface. The first represents the surface by two line profiles. The second shows the profiles as being taken for slices of pavement, where the profile elevation at each longitudinal point is an average of the surface elevation taken over the width of the slice. Given that the pneumatic tires of a passenger car contact pavement over a small area—the so-called contact patch—the second concept of a profile is more representative of the actual roughness input imposed on a vehicle. Clearly, a profile that is an average over a wide area will have less "harshness" than the profile of a narrow track, as the narrow track will include small features that are averaged out in the wide track. As a result, the high-frequency content of the narrow track profile should be greater than that of the wide track (see Figure 8c). Clearly, a roughness numeric with a frequency weighting based on "narrow" profiles will not be guaranteed to be correct when applied to "wide" profiles unless the numeric is based only on wavelengths much longer than the width.

Along the same line, a potential complication in interpreting "road profile" is that the road is described by two profiles, which both affect vehicle ride equally, and furthermore, which are strongly correlated in amplitude and have a high coherence over some frequencies. (That is, a definite phase angle relationship exists over a broad range of wave numbers. For small wave numbers (long wavelengths), both tracks are in phase and have a high coherence. For higher wave numbers, the two profiles are partially in phase, and at even higher wave numbers corresponding

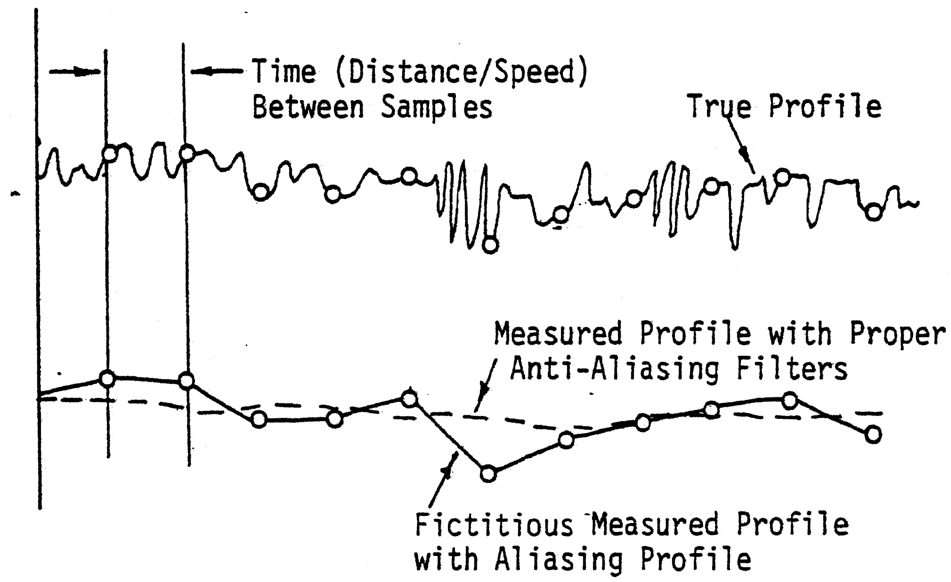


Figure 7. Example of fictitious profile measurement caused by aliasing when profile is measured at discrete intervals.

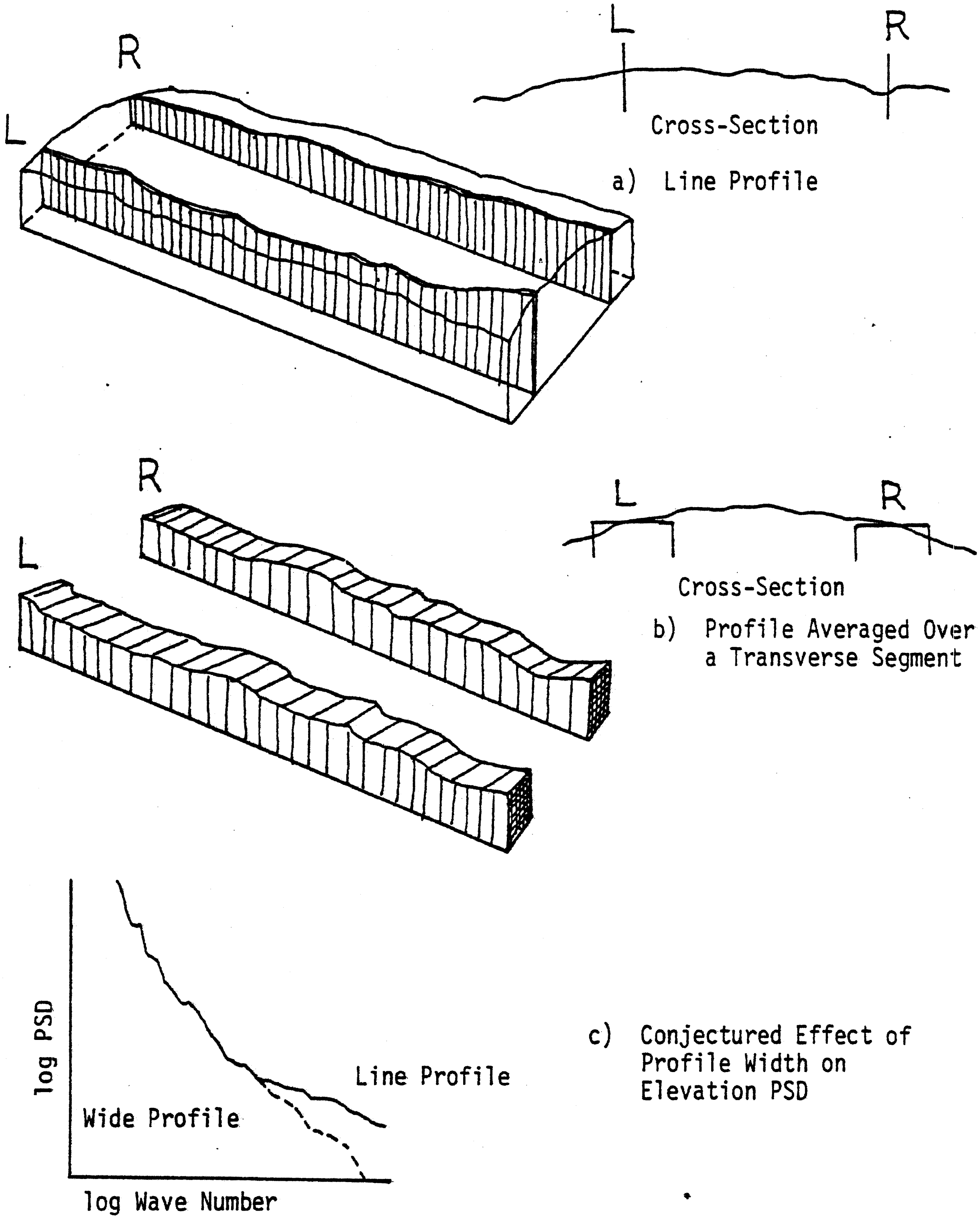


Figure 8. Illustration of profile width.

texture, the two profiles are independent. Usually, though, the amplitudes, as characterized by PSDs, are similar over the entire wave number range.)

To some extent, the effort needed to analyze the contributions of each track profile to vehicle ride—and hence public opinion—can be reduced by considering the road input differently. Due to the symmetry of a passenger car between the left- and right-hand sides, the bouncing and pitching motions are essentially decoupled from the rolling and side-to-side motions when the vehicle is traveling in a straight line. The bouncing and pitching motions are excited by a single input which is the average of the right- and left-hand track inputs, and termed "vertical profile" in this discussion. (This function is time delayed between the front and rear axles by a time equal to the wheelbase divided by vehicle speed.) The roll and lateral motions, on the other hand, are excited only by an input which is the elevation difference between the two track profiles and termed "roll profile." (The roll profile is also time delayed between the front and rear axles.) For an isotropic surface, the vertical profile input is independent of the roll profile input, defining a coherence function of zero. Two-track profile measurements made during the 1-18 project showed that most of the road sections used in the correlation program did in fact show little coherence between the vertical and roll components (see Figure 9). Taken together, this means that often vehicle ride motions in the vertical direction have no coherence with the roll motions (that is, at any frequency there is no consistent phase angle between the two inputs) and thus separate frequency-amplitude weightings can be easily applied. (An exception to this is the case of a road where one track is significantly rougher than the other. When the vertical profile increases, it is usually due to the rougher track which simultaneously causes a roll that is therefore in phase with the vertical input.)

Although the vertical and roll profiles usually have low coherence, it is true that a surface with a "rough" vertical profile will usually have a "rough" roll profile. When the PSD of the roll profile is ratioed to the PSD of the vertical profile, as shown in Figure 10, a certain

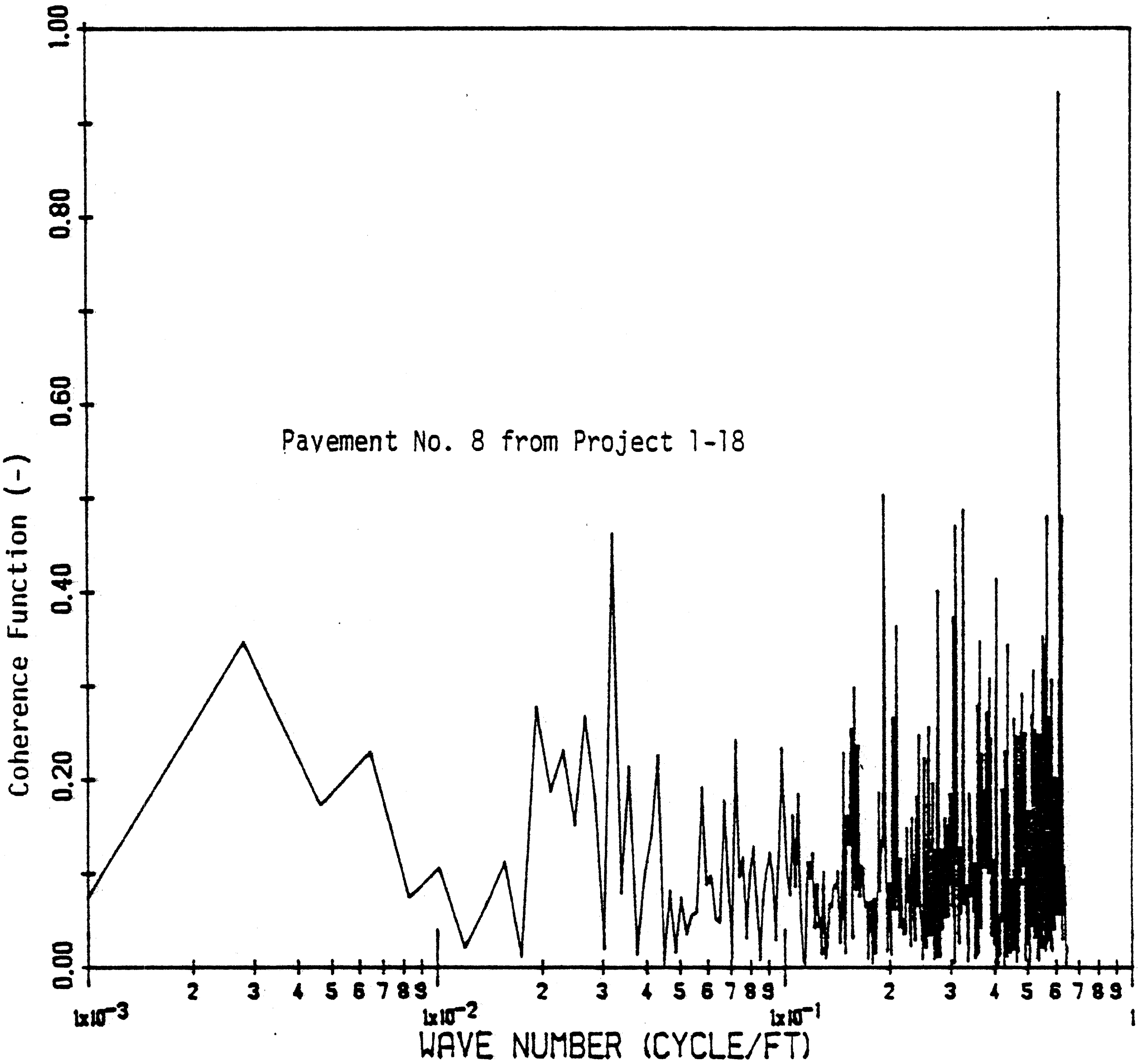


Figure 9. Coherence between roll and vertical profiles of typical road.

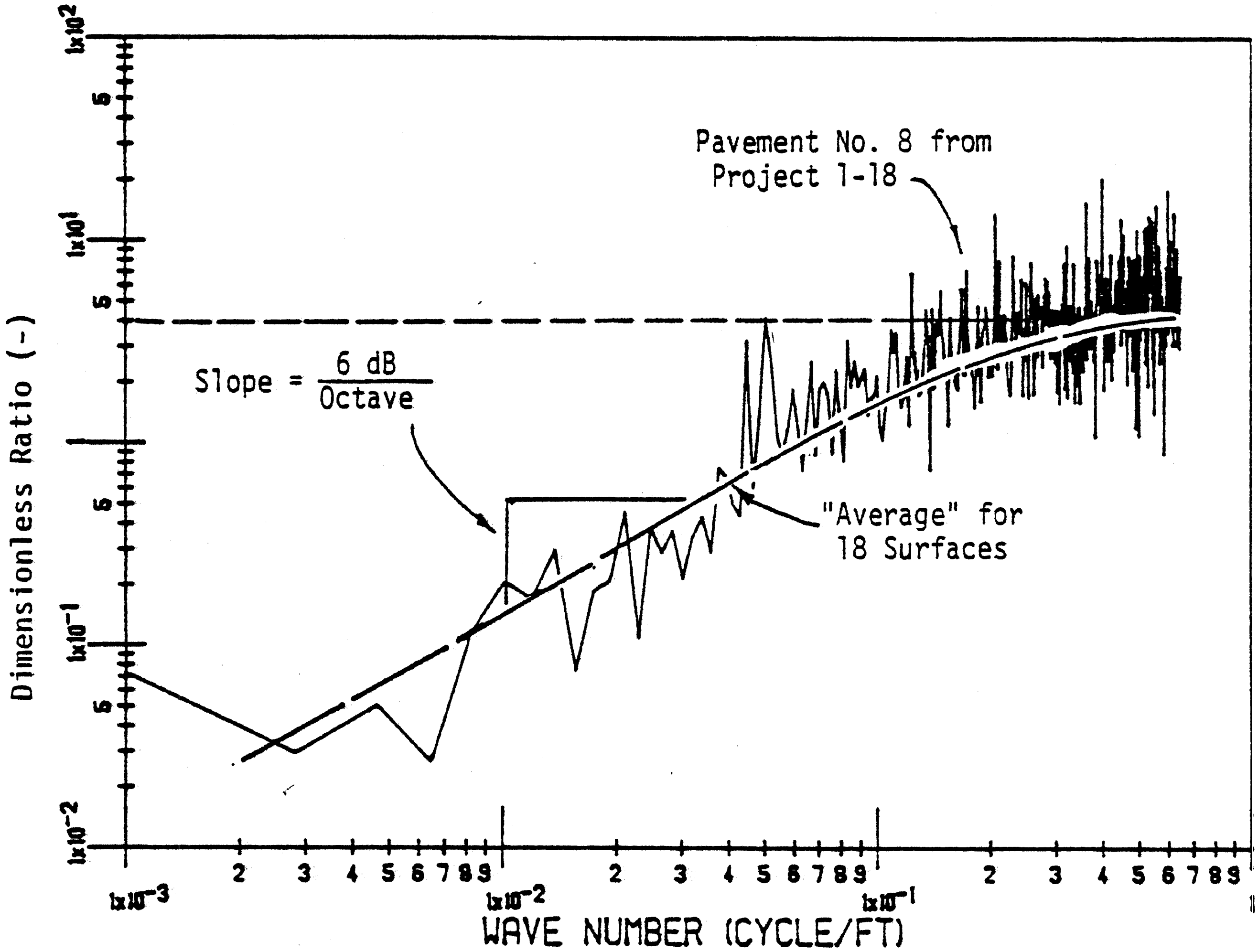


Figure 10. Ratio of roll PSD to vertical PSD for typical road.

commonality is observed when a number of roads are compared. That is, although the roll and vertical profiles usually have no phase relationship, simple numerics based on their amplitudes will be correlated for a sample of roads. This relationship between PSDs can lead to problems when trying to relate the two numerics to a subjective rating scale if statistical methods are adopted that assume independent variables; however, since only two signals are involved, the problem is manageable. If numerics based on the vertical profile are found to consistently correlate either better or worse with subjective ratings than numerics based on roll profile, an ordered stepped regression analysis would be a reasonable and consistent measure of performance of the candidate transforms.

Since the original AASHO road serviceability test, highway engineers have been careful to distinguish between rigid and flexible types of pavement when contending with roughness properties. One of the interesting accomplishments of the NCHRP 1-18 project was the characterization of rigid and flexible pavements by representative PSDs. Essentially, rigid pavements have relatively more high wave number roughness and less low wave number roughness than flexible pavements. Thus, roughness measures that respond to the high wave number content are biased against rigid pavements and need a correction term in empirically derived regression equations. Likewise, devices that respond more to the low wave number roughness, such as the PCA meter mounted in a passenger car, are biased in favor of rigid pavements. The fact that separate regression equations used in the past must be provided for different pavement types is evidence that the objective measures that were used did not have a frequency bandwidth that matched that of a passenger car-passenger combination. A roughness numeric should be equally valid for both pavement types if it is developed correctly to truly reflect public opinion.