# OUTLINE OF A GENERALIZED ROAD ROUGHNESS INDEX FOR WORLDWIDE USE

W. R. Hudson, The University of Texas at Austin

The solution to the problems of providing uniformity in roughness measurements is not an easy one. No perfect answer exists, only a set of intelligent alternatives. It is vital, however, that some type of framework be set up so that coordination can begin. A multifaceted approach is proposed as follows:

1. Develop a Generalized Roughness Index (GRI) which has a sound basis and can provide a pseudo-standard for comparison of all methods.
2. Evaluate the use of an artificial calibration method (such as developed by the Transport and Road Research Laboratory) with a variety of instruments and cases to determine its value, problems, and utility.
3. Apply the concept of a standard rating panel to provide an additional methodology for defining and reproducing the GRI in countries all over the world without the cost of purchasing a stable profilometer, such as the General Motors device.
4. Evaluate the use of rod and level surveys and recommend field equipment to simplify and speed up such surveys for establishing calibration points on a GRI.

It is recommended that a GRI be implemented to test these concepts. Cooperation will be needed among several countries and agencies. Particular attention should be given to coordination of research data from the Kenya, Brazil and India projects, in which the World Bank is involved.

## Background

One of the primary operating characteristics of a highway or pavement at any particular time is the level of service that it provides to its users. In turn, the variation of this level of service, or serviceability, with time provides a measure of the road's performance. This performance and the cost and benefit implications thereof are the primary outputs of a pavement management system. User costs are particularly related to road roughness on very rough roads. It was shown by Carey and Irick (5) in 1960 that road surface roughness was the primary variable needed to explain the driver's opinion of the quality of serviceability, or level of service, provided by a road surface, e.g., its desirability for use.

Road roughness can be thought of in many ways. some people talk about smoothness, others, serviceability. The Canadians use riding comfort and there are national committees in the United States to evaluate "riding quality." Still others talk of surface profile. In the European committees of PIARC, the Permanent International Association of Road Congresses, the English term "roughness" has come to be associated with surface texture and skid resistance or hydroplaning. Herein, roughness and smoothness can be defined as opposite ends of the same scale. A general definition of roughness must describe those surface characteristics of a road which affect the riding quality as perceived by the road user.

The availability of a roughness scale is important in terms of evaluating a road and its performance, but it is also very important in terms of evaluating vehicle operation and user costs. A common roughness scale for worldwide use regardless of the level of roughness, e.g., gravel surface or paved surface, is highly important.

## Surface Roughness

Serviceability, or ride quality, is largely a function of roughness. Studies made at the AASHO Road Test (8) showed that about 95 percent of the information about the serviceability of a road is contributed by the roughness of its surface profile. That is, the correlation coefficients in the present serviceability, or PSI, equation studies improved only about 5 percent when other factors were added to the index (8). Francis Hveem discusses this problem in several papers. He states that "there is no doubt that mankind has long thought of road smoothness or roughness as being synonymous with pleasant or unpleasant." Road surface roughness is not easily described or defined, and the effects of a given degree of roughness vary considerably with the speed and characteristics of the vehicle using the pavement.

### Roughness Defined

Road roughness is a phenomenon present in a road surface that is experienced by the operator and passengers of any vehicle travelling over that surface. Surface roughness is a function of the road surface profile and certain parameters of the vehicle, including tires, suspension, body mounts, seats, etc., as well as the sensibilities of the passenger to acceleration and speed. All of these factors undoubtedly affect the phenomenon of roughness. Safety considerations also influence our acceptance of roughness. Hudson and Haas (10) refer to "pavement roughness" as the "distortion of the pavement surface which contributes to an undersirable or uncomfortable ride." This definition refers to the road surface and divorces itself from other considerations. For purposes of this paper, this definition involving surface distortion will suffice in terms of "road roughness."

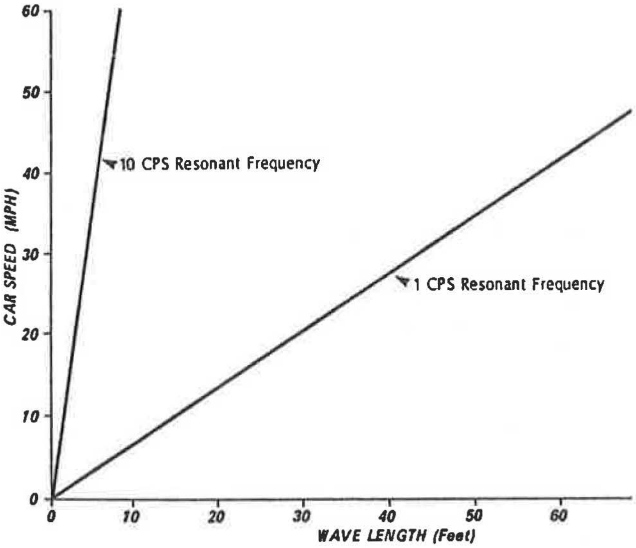
## Components of Roughness

To define completely a roughness function some evaluation of the roughness of the entire surface area of the pavement should be made. However, for practical purposes this roughness can be divided into three components; transverse variations, longitudinal variations, and horizontal variations of pavement alignment. In other words, any functional roadway parameter which imparts accelerations to the vehicle or to the riders must be examined. More particularly of interest are those functions which influence the comfort and safety of the rider and/or the deterioration of the vehicle. Previous studies have shown that longitudinal roughness is probably the major contributing factor to undersirable vehicle forces (8). The next greater offender is transverse roughness (e.g., the roll component transmitted to the vehicle). The horizontal curvature of the roadway, which imparts yaw forces to the vehicle, is considered to be the least offensive and the one which is normally handled by following good highway alignment practices. Since most vehicles (approximately 70 percent) travel in a well-defined wheel path with their right wheel located approximately one meter (2-1/2 to 3-1/2 feet) from the outside lane line we conclude that measurements of longitudinal profile in the two respective wheel paths 1.83 meters (six feet) apart might provide the best sampling of roadway surface roughness. Furthermore, comparison between the two wheel paths can provide some measurement of the cross slope or transverse variations which are also important.

A rider in a vehicle passing over a road surface experiences a ride sensation. This ride sensation is a function of the road profile, the vehicle parameters, and the vehicle speed. A variation of any one of these three variables can make a rough road profile appear smooth or vice versa. Therefore, we might say that, from a passenger's viewpoint, roughness is an unfortunate combination of road profile, vehicle parameters, and speed. Riding characteristics of airplanes are also affected by the properties of the pavements and of the aircraft. Accelerations of sufficient magnitude to critically affect safety of aircraft operations are sometimes obtained over poor pavements.

Although some vehicles have hard suspension and others soft, the vehicle parameters (tires, suspension body mounts, seats, etc.) do not vary sufficiently to make a significant change in passenger comfort. With the limitation of relatively fixed vehicle parameters it is apparent that ride sensation is most dependent upon the car excitation generated by the various combinations of road profile and vehicle speed. Most drivers have experienced the sensation of either slowing down or speeding up to improve their ride on a particular road. This indicates that the road has a wave length content which, when driven over at a particular speed, produces an excitation in the vehicle at one of the vehicles resonant frequencies. The typical passenger car has resonant frequencies at between one and ten cycles per second. The relationship between wavelength, car speed, and car resonant frequency is shown in Figure 1. This relationship indicates that at many speeds there is a road wavelength that will cause an excitation at one of the car resonant frequencies. If the amplitude of that wavelength is large, the car ride will be noticeably affected.

Figure 1. Relationship between resonant frequencies of cars, car speed, and pavement surface wavelength.



In general, most passenger car ride characteristics are very much alike, and for any particular road most cars will be driven at about the same speed. With two of these variables held relatively fixed, the excitations into the car and thus the riding characteristics of the car become primarily a function of the wavelength content of the road profile surface.

## Surface Roughness Evaluation

Roughness evaluation has received considerable attention from many highway and airport agencies in North America. Roughness is the primary component of serviceability and a large number of different roughness measures are in current use. This concept of preception by the highway user is important. This definition of roughness excludes surface texture and microtexture of surface aggregates since these are not perceived by the user to affect riding quality. Instead they affect skid resistance and other operational characteristics but will be excluded in this paper. The diameter of the surface stone used in pavement surface treatments which causes "noise," is discernible to the user, has an effect on the user's perception, and is roughness by this definition.

## Surface Profile

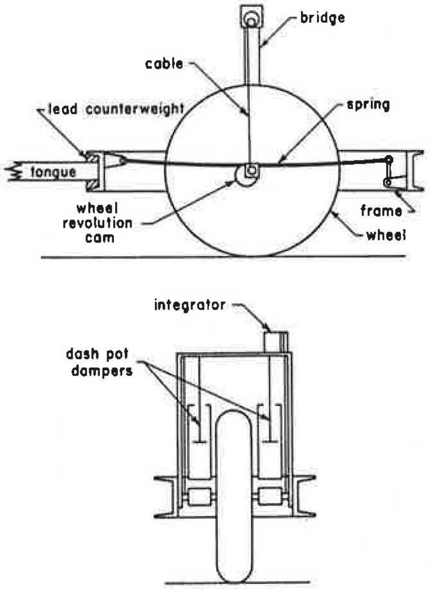
Many authors, such as Darlington (6) and Carey (3), feel that a surface profile is the best way to characterize roughness. In terms of profile, roughness can be defined as "the summation of variations in the surface profile." Profiles in this sense do not include the overall geometry in the road but are limited to wave lingths in the surface that are less than approximately 152.4 meters (500 feet) in length. In Darlington's terms, roughness is "the analysis of the profile or of the random signal known as profile."

Carey in (3) points out four fundamental uses of surface profiles or roughness measurements: as construction quality control tools, to locate abnormal changes in the highway such as drainage or subsurface problems, extreme construction deficiencies, etc., to establish a systemwide basis for allocation of pavement maintenance resources, and to identify pavement serviceability-performance histories.

In summary, a profile is a detailed recording of surface characteristics and roughness or smoothness is a statistic which summarizes these characteristics. Thus, roughness-smoothness is a statistic or number which summarizes the riding quality or surface profile of a road.

How rough is rough? Once the surface characteristics are summarized, it is essential to establish a scale for this statistic or summary value. This can be done in many ways, as pointed out by Darlington (6). Traditionally there are two ways of determining this statistic; mechanical integration and mathematical integration or analysis. The first of these methods is the most common, that is, the use of some mechanical instrument or device, such as the BPR roughometer in Figure 2, to mechanically filter and summarize the data in a specified way. The second method involves recording the profile as faithfully as possible and then analyzing and/or integrating this profile mathematically with some standard mathematical procedure, such as that outlined by Walker and Hudson (31 and 32), Roberts and Hudson (24 and 25), and Darlington (6). The most common methods in current use for mechanical measurement and summary include the BPR Roughometer (15 and 16), the PCA Roadmeter (1 and 2), the Mays Meter (32 and 33), the Chloe Profilometer (4), and the land plane or Profilograph (rolling straight edge) (28).

Figure 2. Schematic Diagram - BPR Roughometer



A number of studies have been made to compare these instruments and a number of references are available, including (6, 11, 16, and 22).

Since so much has been written about the various instruments available, we will not attempt in this short paper to review all these measurement methods in detail. See (14, 16, and 39) for details.

## Comparison of Measurement and Summary Techniques

Regardless of the measurement and type of summary techniques used, it is essential that a good reference be established and maintained. It is equally important that accuracy be maintained in summation.

Darlington (6) points out that three basic reference methods have been used historically to measure roughness: the so-called rolling straight edge or land plane, as illustrated in Figure 3, the inertial mass as used in the BPR Roughometer, illustrated in Figure 2, the Mays meter and the PCA meter which the automobile serves as the inertial mass and, finally, an inertial reference profilometer, such as the Surface Dynamics or General Motors Profilometer, where an external reference is provided.

Figure 3. Land plane roughness device sometimes called Profilograph or rolling straight edge.

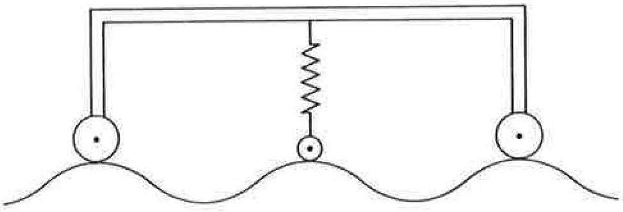


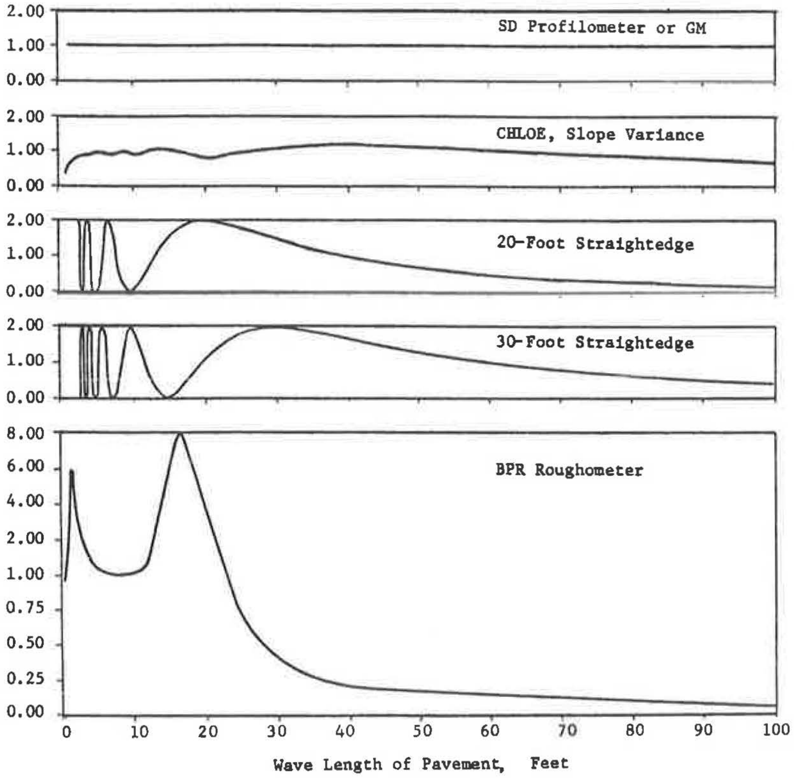
Figure 4 illustrates by means of a Bode plot the transfer function or response of several types of instruments to the input of road roughness. The problem is that the straight edge or land plane device is so erratic in its response that it is relatively useless. This is illustrated in Figure 4, where the effect of roughness wavelengths which are any multiple of the length of the straight edge results in zero output from the device.

Darlington simulated the response of the BPR roughometer (or vibrometer, or seismic reference device) on an analog computer using measured physical characteristics of the instrument. His analysis shows that the roughometer type device yields reasonable results for wave length in the region of approximately 1.22 to 4.26 meters (4 to 14 feet). Wave lengths in the range of 4.26 to 5.48 meters (14 to 18 feet) are badly distorted, and wave lengths beyond 6.70 meters (22 feet) rapidly attenuate to zero response.

## The need for compatibility or Generality

As outlined above, diverse measurements of roughness are used around the world. It is not feasible to talk of equality among these measurements since it is not possible to provide compatibility among the various measuring systems if proper consideration is given. This compatibility involves two levels of concern: "External" compatability -- relating to whether the results of one agency's or country's work has quantitative relationship or meaning to those of another agency, and "Internal" Compatibility -- relating to correlating results, achieving repeatability, etc., within an agency.

Figure 4. Theoretical differences between SD Profilometer, Chloe, rolling straight-edges and seismic roughometer



This second aspect of compatibility is well illustrated by the Brazil Project (18) for it is essential that measurements made in all parts of Brazil be compatible with each other even though it is not possible to make all the measurements with a single instrument.

The problem of external compatibility is best illustrated by the fact that results of studies in Kenya can be compared to the findings in Brazil only if there is compatibility between the two sets of roughness data. I feel this can best be accomplished by establishing a "generalized roughness index" which can be used as a compatible base of comparison. This is preferable to selecting any particular measurement system, which itself may be changing and which may not be available to a particular potential using agency.

If a Generalized Roughness Index (GRI) is used, the the matter resolves to one of providing some way of determing the GRI in any particular instance.

In his opening remarks to a National Conference on roughness measurements and correlation in 1972, Mr. W. N. Carey, Jr., Executive Director of the U.S. Transportation Research Board speaks to these problems (3).

> A third use of profile measurements is to establish a systematic statewide basis for allocation of pavement maintenance resources. A word of caution here is in order. In the interest of finding low-cost tools that can be easily available to each highway department district, there is a tendencey to suggest highly simplistic devices. I believe that reliance on these devices may lead to serious mistakes in the development of priorities for maintenance expenditures. . .

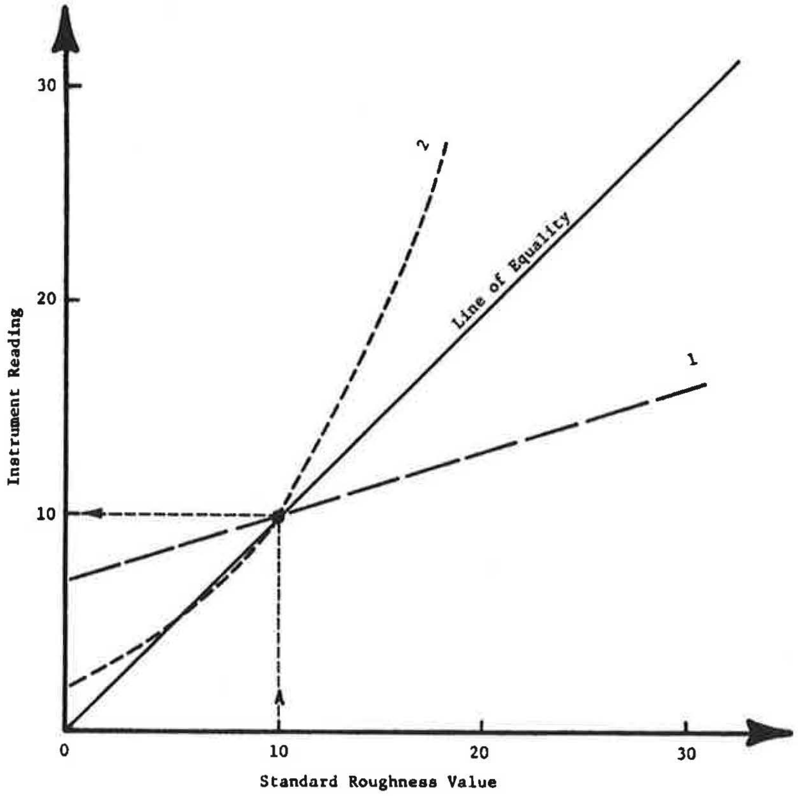
Carey's comment can easily be extended to include low-volume and unpaved road planning in developing countries where roughness can be used not only for allocating maintenance resources but also for ascertaining and considering user and vehicle operating costs. Although the absolute accuracy required for these various purposes may differ in all cases, relative accuracy and compatibility are important.

## History of Roughness Calibration and Correlation

The earliest roughness measurements were reported by Hogentogler, as far back as 1923 (42) and early development of the Roughometer was reported in 1926 (19). Even in these early developments the need for calibration was readily recognized. From 1941. when the BPR Roughometer became "standardized," the Bureau of Public Roads (now the Federal Highway Administration) maintained a "standard calibration section" for testing any new or modified BPR Roughometer. It was observed from the beginning that instruments manufactured as nearly alike as possible did not record the same roughness value for the same pavement. The fallacy of a single calibration section is discussed by Hudson and Hain (15).

It is not possible to calibrate a dynamic instrument at a single point over its range and expect the calibration to be satisfactory for use of the instrument over a full range of roughness. This is illustrated in Figure 5 where a standard roughness section with a value of 10 has been set up. We might assume that any other instrument which reads 10 would be calibrated to the standard value. In fact, this assumption is depicted by the solid "line of equality" in the figure. This line assumes that if an instrument reads 10, it is "calibrated" and thus will read 20 when the standard instrument reads 20, 30 when the standard instrument reads 30, etc. Alternatively line No. 1 illustrates a plausible case of a linear relationship where instrument No. 1 is

Figure 5. Single point BPR calibration problems.



calibrated to the standard instrument on the section with value 10. Without additional test points we would not realize that the slope of the calibration line is really different from the assumed line of equality. Dotted line No. 2 illustrates a more complex case of nonlinear relationship which would, of course, also be missed with the single point calibration. Some twenty-four state agencies had BPR Roughometers in use in 1960. Many of these devices have been calibrated by this one-point method and by no other method.

### Roughometer Calibration Course - AASHO Road Test

As reported by Hudson and Hain (15) there was a need to use the Roughometer in the AASHO Road Test but it became obvious very early, with the AASHO Profilometer to compare to, that the BPR Roughometer was a variable instrument, difficult to keep in calibration. In our work at the AASHO Road Test we were not only involved in measuring the roughness of all pavements with the AASHO Profilometer and in developing and operating the BPR Roughometer, but also in checking and calibrating at least six roughometers from states such as Michigan, North Dakota, Minnesota, and Wisconsin which brought their instruments to the Road Test for calibration against the AASHO Profilometer for determining serviceability.

Basically the method involved the installation of aluminum bars on the surface of a smooth rigid pavement to establish four separate test sections of different but known roughness. The roughometer could then be checked against the standard sections at any required time.

### TRRL Pipe Calibration Course

Another artificial calibration technique has been proposed and used by the Transport and Road Research Laboratory in England. This concept appears to have promise for use as a calibrating device or standardization method around the world. A short note on the moethod is presented in (39). Briefly, the method involves the selection of a smooth pavement section approximately 300 meters (985 feet) long as a standard. This smooth section becomes the smoothest section in a series of 6 calibration sections. Subsequently rougher sections are created by adding artificial bumps to the surface of the standard sections by means of pipes with external diamter of 3.413 centimeters (1.34 inches). A total of six levels of roughness are created. Thus, the problem of one-point calibration is alleviated and yet the calibrating agency need find only one smooth, relatively unchanging pavement section. The absolute profile of this basic smooth standard section can likewise be checked with precise rod and levels on a quarterly or semiannual basis as necessary.

### Use of a "Standard" Device for Calibration

Probably the most widely used method of calibration and correlation has been the use of some type of so-called standard device. Really this approach should be divided into two types. The first involves the selection of one replicate from the group of similar devices being used and the use of this replica only for calibration purposes so that it presumably does not "wear out." This is the approach that the BPR took with the check section as outlined earlier. I liken this approach to gold-plating a crowbar. If you have two dozen crowbars and select one of them because it appears to be more perfect in shape and weight than the others and plate it with gold, what do you have? Still a crowbar, albeit a shiny and expensive one. There is little evidence that this type of "standard" device has been successful in true calibration and correlation.

The second type of standard device involves the use of a master device which is itself calibratible or which has a standard of accuracy which is perhaps a magnitude greater than the other devices for which it is to be the master control. The AASHO Road Test Profilometer was such a device which became a standard against which dozens of Chloe Profilometers and BPR Roughometers were calibrated during and soon after the AASHO Road Test. This approach is discussed below as the Texas Calibration Course.

## Use of Hydraulic Shaker Table

The General Motors Profilometer was originally developed for obtaining road profile input which could be fed into a vehicle ride simulator for testing vehicle suspensions at the General Motors Proving Ground (26 and 27). Some authorities feel that a similar approach can be used for inputting standard roughness to a machine in an analytically controlled manner to calibrate other devices. This method involves observing the responses of a measuring device in a laboratory with a servo-controlled hydraulic ram resting under each wheel. Known excitation is applied through the hydraulic rams to the vehicle to determine its response. More specifically, the wheels of the vehicle are vibrated by a shaker table in a manner to simulate operation of the vehicle on each of a set of standard test sections. Road profile data obtained with an instrument such as GM Profilometer are used to drive the shaker table. The profile data tape could be used for any number of successive recalibrations over any period of time and, in that sense, would not change.

There is, of course, some question about the correspondence between readings obtained by shaker table and roughness measurements obtained in the field. The major source of discrepancy remains in the fact that the vehicle is moving and wheels are rotating while measurements are being made in the field but not while operating on a shaker table. The dynamic vs. static tire conditions are of particular concern. At the present time the National Cooperative Highway Research Program is undertaking a research project which will undoubtedly investigate the shaker table approach to calibration of roughness devices (21). In general, this method does not seem possible for use worldwide since the shaker table is cumbersome and expensive. If a simple version could be devised it could be duplicated and purchased by interested goups but a great deal of research and development is required and we must await the results of the NCHRP study.

## Texas Calibration Course

The Center for Highway Research and the Texas State Department of Highways and Public Transportation use the SDP or General Motors Profilometer as a master calibration device for a series of Mays Meters which are used routinely throughout the state. This approach is reported by Walker, Hudson and Williamson (32, 33, and 34). To some degree, a similar approach has been taken by the Michigan Highway Department, as reported by Holbrook and Darlington (12 and 13). The same approach is being taken at the present time in the UNDP Brazil Study (18). A SDP was purchased and is used for measuring a set of calibration sections. These sections are run regularly by eight Mays Meters to insure that their calibration remains stable. A control chart procedure and regular check procedure similar to that outlined by Williamson is followed (32, 33, and 34).

Basically, Texas maintains a group of 25 pavement sections which vary from smooth to rough. Every three months the profiles of all these sections are measured and analyzed with the SDP Profilometer. In this way, a set of pavements with known roughness are always available for use in checking and calibrating any other roughness instrument. Any instrument which appears to be giving erroneous readings is regularly run on several check sections and the values plotted on a standard control chart. If a device is "out-of-control" on three or four sections then it is thoroughly checked, mechanically repaired, and, if necessary, recalibrated.

## Rod and Level Surveys

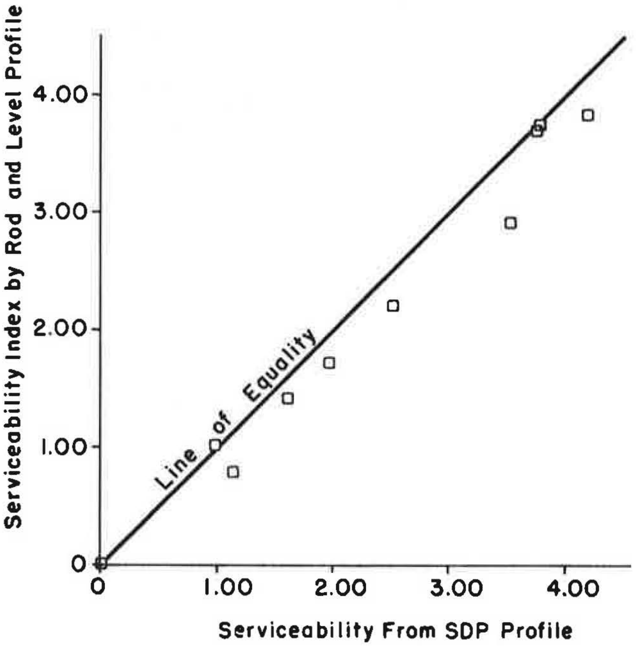
Many people feel that it is possible to establish vehicle roughness calibrations over standard pavement sections by running control rod and level surveys of the calibration sections to see if and how their profiles are changing. There are two basic problems associated with this methodology. First, the response of the vehicle and most roughness measuring instruments to a profile is an integration of everything the measuring instrument sees on the road surface. This is a continuous process and not one involving discrete points such as are used in a rod and level survey. This problem is magnified by the fact that even the best manual leveling techniques make it expensive to make measurements of test sections 300 meters (985 feet) long at spacings closer than about 1/2 meter (1.6 feet). Even in this case a total of 600 measuring points is required each time a calibration section is checked.

Perhaps more difficult than the accuracy and detailed problem outlined above is the need to integrate and/or summarize and anlyze the profile. To date, little has been done in this area. Recently we have investigated the use of second derivations of the profile to yield estimates of vertical accelerations present in the profile. A relationship has, in turn, been developed between vertical accelerations and SI.

Calculations are simple and do not require a large computer facility as is the case with existing profile analyzing methods such as power spectral density, Fourier transform, and digital filtering. Road profile root mean square vertical accelerations have a strong correlation with Mays Meter roughness readings as shown in the study by McKenzie and Srinarawat (40). Figure 6 illustrates a very good agreement in terms of serviceability index from 10 road surface profiles obtained by rod and level method and the Surface Dynamics Profilometer (SDP) (41). This plot also suggests that road profile data from rod and level and SDP are interchangeable and rod and level can be used to provide commonality among road roughness scales presently in use.

Certainly, these discrete rod and level surveys have some practical advantages, particularly in developing countries where labor-intenseive methods are economical. It might be far more practical to obtain detailed, discrete profiles with rod and levels of, say, ten or twelve pavement test sections on a regular basis than to maintain a high-technology, expensive electronic device for continuous profile measurements. Such a method will be practical if data analysis techniques can be developed and automated for easy use of the data.

Figure 6. Comparison of serviceability indices derived from rod and level profile and SDP profile.



Rating Panel Approach - Canadian Good Roads Association

Immediately following the AASHO Road Test, the Canadian Good Roads Association desired to put the findings of the AASHO Road Test into practice. In order to do this, they ran a rather complete survey of the existing roughness of their pavement system. They did not agree totally with the serviceability concept outlined at the AASHO Road Test and they chose to develop a Riding-Comfort Index Scale with values from 1 to 10. This index is basically an evaluation of pavement riding quality or roughness (7, 9, and 10).

After carefully establishing their Riding Comfort Index, a standard procedure was adopted using a small panel of well-trained raters to go from location to location evaluating the riding quality of these pavements and recording this riding quality in a data management system. A great deal of work has been done on rating scales and other subjective evaluations (5, 17, 20, and 24). There are some shortcomings to this approach, but it has the benefits of being practical, relatively inexpensive, and reasonably stable although its precision may be questioned. It certainly fulfills the concept and answers the question, however, raised by Carey in the quote referenced earlier in this paper. This approach deserves further consideration.

Standard Rating Panel

While it is not in present use, I believe that the concept of using a standard panel of pavement riding quality raters to establish a time-and-condition-stable standard roughness scale offers great promise as a practical solution. Yoder and Milhous (37) show in thier studies of rating panels and various instrumentation that rating panels of fifteen persons or more are quite stable in predicting pavement serviceability. Since roughness is so highly correlated with serviceability, there is little doubt that such panels would be equally stable in predicting pavement roughness. Carey and Irick (5) report similar results when comparing panels at the AASHO Road Test, as do Roberts and Hudson (24 and 25).

One major problem exists, what about panels from different cultures? For example, a panel from the United States rides predominately on paved roads. Can it rate accurately on the same scale as a panel from a developing country which rides predominately on gravel roads? How could this dichotomy be solved? Perhaps if as many as three members could be made available to participate in panel ratings in each of the major areas of the world, goegraphic and cultural stability could be evaluated.

This method would never have the precision or detail of physical calibration. However, it might be accurate in terms of insuring that different classes of road roughness are adequately separated.

The following section presents a discussion of the relative merits of these methods for use in establishing a General Roughness Index.

## Possible Approaches for Calibration

Evaluation of the concepts for calibration outlined in the last section indicates that three basic methods have strong potential: the use of a shaker table to input artificial roughness in a laboratory, the use of artificial roughness calibration sections, and the use of standard road sections along with a method of evaluating the roughness of these standard calibration sections from time to time.

However, the practical limitations of the problem set forth in this paper apparently preclude any possibility of using a hydraulic shaker table with known roughness inputs to calibrate roughness devices. No such equipment is presently in use for this purpose, even in the United States, and the development and employment of such equipment in the field seems completely infeasible at this point. Therefore, the other two major approaches are discussed in further detail: artificial calibration sections and standard pavement calibration sections.

## Artificial Roughness Course

The concept of introducing well defined artificial roughness onto a selected section of smooth pavement in identifiable stages follows the approach of Abaynayaka and TRRL. The approach is certainly feasible since any country in the world could develop at least one smooth, strong section of pavement to serve as the base section. They could then find several pieces of standardized pipe or other material approximately 2 meters (6.6 feet) long to introduce roughness. These two ingredients can be combined in several stages to provide up to six or even more test sections of increasing roughness. The method therefore warrants careful consideration.

The major problems associated with this method are the artificiality of the roughness introduced and the potential of generating resonance or harmonic motion in the measuring vehicle being calibrated. As indicated by the anlysis of Darlington (figure 4), the transfer function of a roughness measuring device is highly dependent upon the wavelength characteristics and amplitude of the roughness in the roadway surface. It yields reasonable readings for wavelengths in the range of 1.22 to 4.28 meters (4 to 14 feet) and it has two resonance frequencies at 0.61 meters (2 feet) and 5.18 meters (17 feet). The response of the instrument to step-inputs might be on the first peak present at very short wavelengths. If some type of resonance is generated in the system, say for roughness level six, then the multiplication amplitude could be even higher. It is entirely possible that the response of an instrument to the roughest calibration section would be, for example, a very large roughness number and yet the instrument might respond different to a very rough gravel road with natural potholes, etc. There is certainly also the possibility that the calibration course can be set up in such a way as to cover the range of interest for most very rough roads and thus to serve adequately as a calibration procedure. The only way to ascertain the answer to this question is to study the problem theoretically and to apply the concept in the field where an alternative method of calibration and checking, such as the SDP or General Motors Profilometer, exists for comparison. This type of comparison check is being made in Brazil and results will be reported soon.

The other problem with this method is that it does not yield to traditional analysis of random data or profiles as outlined by Darlington, Williamson and Walker (6, 36, 30, and 31). It is possible that another type of analysis could be used to evaluate the step function inputs to the roughness profile which will be made by the pipes or artificial bumps. It is desirable that someone follow up on the required analytical approach as a part of the evaluation methodology for this procedure.

Finally, this concept is attractive in the sense that only about six test sections are needed to cover a wide range of roughness and only one basic strong pavement section is needed to provide the base section. Considerable thought, however, needs to be given to the possibility of replication of roughness levels within the artificial calibration course. This could be done by adding two additional roughness levels whose roughness corresponds with a previously selected level, but with new roughness being introduced by an alternate pattern or an alternate means such as a few wider bumps or a rearrangement of the location of the bumps to interrupt regular patterns.

## Natural Pavement Calibration Sections

The use of existing pavement sections for calibration of roughness devices is an attractive alternative, but there are problems. The attractiveness seems obvious since the sections are typical of the pavements to be measured in the real world; they contain normal roughness inputs of varying wavelengths and amplitudes over a wide spectrum of conditions. The problems, however, are multifold and must be considered. They include finding sections at extremes of roughness, the changing of roughness with time on a selected test section, the large number of sections usually required, and the considerable time and effort required to check the sections which are normally fairly widely spaced geographically.

Obviously it is not possible to set up a normal pavement section calibration course on which the test pavement roughness will remain constant. All of the pavements are in various degress of deterioration. Most of them were built smooth but they are in the process of change and experience shows that rough pavements change more rapidly than smooth pavements. It is absolutely essential then that for this approach some method of determining the roughness history of each test section with time be developed. This can be done in at least three ways; by true profiles measured "continuously" with instruments such as the SDP profilometer, true profiles measured at discrete increments with precise rod and level techniques, and repeated evaluation of the roughness of the calibration section by a standard rating panel.

Evaluation of the True Profiles - "Continuous." Of the three listed methods, the most attractive seems to be the use of existing pavement with an evaluation of their true profiles. This technique was chosen for use in the Brazil Project where adequate research funding was available to provide a standard profilometer, in this case the SDP profilometer, for making continuous measurements for calibration.

It seems, however, that this approach is impractical at the present time for use worldwide as a calibration standard. The use of a standard roughometer or other "gold-plated" version of a typical machine carried around the world as a standard device is not realistic as shown by experience at the AASHO Road Test and the work by the Center for Highway Research for the Texas Highway Department.

Evaluation of True Profiles - Discrete. It is possible that analytical techniques can be developed to accurately evaluate a discrete rod and level profile of pavement test sections set up for standardization. Field work is underway by Srinarawat and Hudson to evaluate this approach and to compare the accuracy required and the spacing or detail of the measurement points needed to provide adequate information (41).

If the approach is feasible from an analytical point of view, it is possible that field practice can show what type of level instrument and perhaps even what special level rod could be most useful to speed up the process and make it more practically applicable. The U.S. Air Force, for example, has developed a laser profiling system which works on the same basis as a rod and level but which takes automatic readings using a laser beam for a light source (38).

Another point favoring the rod and level approach is the hand labor which is normally available in many of the developing countries for which a roughness calibration is needed. The rod and level crews could make the necessary measurements on a quarterly or triannual basis with relatively little expense whereas in the United States, for example, such an approach might not be as economical as a profilometer.

Thusfar, work by Srinarawat and Hudson seems to indicate that it is possible to interchange machine and rod-level measurements (41).

Roughness Panel. A third approach to establishing and maintaining standard roughness evaluations of calibration test sections is appealing and should be carefully considered. It involves setting up a standard rating panel and developing a Generalized Roughness Index (GRI) which could be used not only for rating and establishing the roughness level of the calibration sections but as a standardized roughness scale for comparing instruments against each other all over the world without having to select any one particular instrument as the "standard."

This approach is far from thoroughly formulated and a great deal of additional thought will be needed before it can be accepted or rejected. However, it is worthy of consideration. If the method works, its value is readily evident. If adequate accuracy and details can be obtained, calibration sections could be set up and evaluated regularly without the expense and detail required for rod and level surveys.

Likewise, the potential pitfalls to the method are obvious. The method would basically be subjective rather than objective, which we, as engineers, always strongly desire. The potential value of the method lies in the question of whetehr or not we can make the subjective rating process objective by carefully selecting and establishing rating panels and rating procedures using up-to-date modern scaling and psychological techniques to overcome some of the subjectivity of the rating approach.

The basic value and acceptability of ratings for judging pavement quality was well established at the AASHO Road Test by Carey and Irick (5) and subsequently by Yoder and Milhous in the significant NCHRP study (37). As outlined previously herein, the Canadian Good Roads Association has also made an excellent practical application of the rating concept (5 and 35).

Another major problem with the roughness rating approach is possible cultural differences amongst countries. One country, for example, such as the United States, has a population accustomed to riding on paved roads which are basically smooth. On the other hand, other countries such as many of the countries in Africa and Latin America, are accumstomed to riding on unpaved roads. There is considerable concern that this cultural or historic difference, which is also by the way aggravated by traditional types and quality of vehicles used, would greatly affect any relationship developed by a rating scheme, and thus would completely invalidate the concept of relative ratings.

## Generalized Roughness Index

After a thorough evaluation of the problem of establishing a common basis for comparing roughness measurements all over the world, and specifically comparing roughness measurements in Kenya, Brazil, and India in terms of using data taken from these three research studies and combining it for use in developing improved joint models, it is recommended that a Generalized Roughness Index or a universal roughness index be developed to serve as a basis for comparison instead of the output of any particular roughness device. On the surface this seems an arbitrary intermediate step; however, experience shows otherwise.

At the present time, no simple, robust roughness measuring and evaluation technique exists which is constant enough to become the appropriate "standard." The SDP profilometer might be considered, but work in adopting and using this instrument in Brazil and in comparing it to the Texas instrument manufactured ten years ago shows considerable difference in hardware and data processing techniques. Many people feel we are on the threshold of developing a non-constact probe to replace the road-following wheel for the SDP device. When this happens, you can be assured that the transfer function of this transducer will be different from that of the road-following wheel. Thus, the "standard" would change again. Many other examples could be cited, but for simplicity let it suffice to say that no real "standard" exists.

An example of a similar situation existed in 1962 concerning specifications and measurement of subgrade strength for pavement design. The American Association of State Highway Officials at that time desired to establish a standard design method which would be useable and used by all or at least a large majority of the State Highway Departments. There were many candidate measuring techniques, such as CBR, Texas Triaxial strength, shear modulus, California R-Value, and others. Majority vote would have selected CBR since it was used by more states than any other method. However, comparison of the CBR between states showed that even this so-called "standard" was far from standard since each state made slight modifications in the empirical test procedure. In the face of this diversity, Mr. T. S. Huff, Chief Highway Design Engineer for the Texas Highway Department and Chairman of the AASHTO Committee, recommended that a "soil support value" with a range from zero to ten be set up as the "standard." Each State Highway Department then related its soil test method to the soil support value rather than to some state test procedure. Nationwide information on standard test materials obtained from the AASHO Road Test was used to establish common points.

At this time, 15 years of experience in using the AASHO Interim Design Guide has shown the wisdom of selecting the what-seemed-at-the-time "arbitrary" Soil Support value.

## GRI - A Combined Approach

Examination of alternatives indicates that the practical approach to solving this problem will involve some combination of the factors discussed above. To provide realism in the calibration, it is essential that 10 to 12 real pavement sections be included in a calibration course. These can be evaluated on a semiannual basis by rod and level surveys. A detailed methodology will be published by Srinarawat and Hudson within the next year.

To provide a large number of calibration sections of varying roughness and a calibration technique with some commonality around the world, a TRRL calibration course should be added to the calibration procedure. The methodology currently outlined by Abayanaka and the TRRL should be used until a more definitive consensus procedure is developed. Finally, the overall reasonableness of the scale can be assured at any time using a rating panel to ensure that reasonable roughness ratings are establisted for uniformity. These ratings should involve panels on at least all three or four major research efforts in the world and should include at least three or four common members in each panel in the initial stages of development. These common members could be employees of the World Bank or other research personnel who are involved in one or more of the world-wide research projects and who could beneficially visit other activities, thus providing the necessary commonality of ratings.

The GRI itself should have a relatively large scale, perhaps 0 to 100 and should be generalized with smoothness of existing new highways falling in the range of 10 to 15 and roughness on some of the roughest roads now perceived falling in the 70 to 80 range. This gives adequate room at both ends of the scale for changes and variations not yet observed and in no way detracts from the use of the Index.

Some readers will undoubtedly be disappointed that a firm Index in full detail is not presented here; however, work over the past 10 years shows that there will be several steps required to solve this problem and we believe this paper is a necessary first step in defining the problem so that an intelligent compromise can be reached.

## Summary and Recommendations

Solving the problems of providing uniformity in roughness measurements is not easy. No perfect answer exists, only a set of intelligent alternatives. It is vital, however, that a framework be set up so that coordination and use can begin. I proposed a multifacted approach.

1. Develop a GRI which has a sound basis and can provide a pseudo-standard for comparison with any roughness scale existing now or to be developed.
2. Evaluate the use of the TRRL artificial calibration method for a variety of roughness devices and cases to determine its value, problems, and utility.
3. Apply the concept of a standard rating panel to provide an additional methodology for defining and reproducing the GRI in countries all over the world without the cost of purchasing an SDP profilometer or similar equipment.
4. Use rod and level surveys and recommend field equipment to simplify and speed up such surveys for establishing calibration points on a GRI.

It is recommended that action be taken to implement a GRI and to test the concepts set forth above. Cooperation will bee needed among several countries and agencies and a leader, such as the World Bank, is needed. Particular attention should be given to coordination of research data from the Kenya, Brazil, and India projects.

## Acknowledgments

Much of the information presented here comes from past associations and joint efforts with people like Bill Carey, Paul Irick, Freddy Roberts, Roger Walker, Hugh Williamson, et al. I thank them for their support and intellectual stimulation through the years. Thanks are due to Dr. Clell Harral and Per Fossberg of the World Bank for support in collecting these ideas and assisting with revisions. The work was supported by a grant from the World Bank.

## References

1. M. P. Brokaw. Development of the PCA Road Meter: A Rapid Method fo Measuring Slope Variance. Highway Research Board, Special Report 116, 1971, pp. 137-149.
2. M. P. Brokaw. A 5-Year Report on Evaluation of Pavement Serviceability with Several Road Meters. Highway Research Board, Special Report 116, 1971, pp. 80-91.
3. W. N. Carey, Jr. Uses of Surface Profile Measurements. Introductory Remarks, SR 133, Pavement Evaluation Using Road Meters, Highway Research Board, Washington, D. C., 1973.
4. W. N. Carey, Jr., H. C. Huckins, and R. C. Leathers. Slope Variance as a Measure of Roughness and the CHLOSE Profilometer. Highway Research Board, Special Report 73, 1962, pp. 126-137.
5. W. N. Carey, Jr., and P. E. Irick. The Pavement Serviceability Performance Concept. Highway Research Board, Bulletin 250, 1960, pp. 40-58.
6. J. R. Darlington. Evaluation and Application Study of the General Motors Corporation Rapid Travel Profilometer. Michigan Department of State Highway, Report R-731, April 1973.
7. Field Performance Studies of Flexible Pavements in Canada. Proceedings, Second International Conference on Structural Design of Asphalt Pavements, University of Michigan, 1967.
8. J. P. Guilford. Psychometric Methods, McGraw Hill, 1954.
9. R. C. G. Haas and B. G. Hutchinson. A Management System for Highway Pavements. Prepared for Presentation to Australian Road Research Board, September 1970.
10. R. C. G. Hass and W. R. Hudson. Pavement Management Systems. New York: McGraw-Hill, Chapters 6, 7, and 8, 1978. (in press)
11. R. C. G. Hass and W. R. Hudson. The Importance of Rational and Compatible Pavement Performance Evaluation. Highway Research Board, Special Report 116, 1971, pp. 92-109.
12. L. F. Holbrook. Prediction of Subjective Response to Road Roughness by Use of the Rapid Travel Profilometer. Highway Research Record 291, 1969, pp. 212-226.
13. L. F. Holbrook and J. R. Darlington. Analytical Problems Encountered in the Correlation of Subjective Response and Pavement Power Spectral Density Functions. Highway Research Record 471, 1973, pp. 83-90.
14. W. R. Hudson and R. C. G. Haas. Compatibility Between Pavement Roughness and Serviceability Measuring Systems. Minutes of Joint Subcommittee of Highway Research Board Committees DB-4 and DB-5, January, 1970.
15. W. R. Hudson and R. C. Hain. Calibration and Use of the BPR Roughometer at the AASHO Road Test. Highway Research Board Special Report 66, 1961, pp. 19-38.
16. W. R. Hudson, W. E. Teske, Karl H. Dunn, and E. B. Spangler. State of the Art of Pavement Condition Evaluation. Subcommittee Report to Pavement Condition Evaluation Committee of Highway Research Board, Special Report 95, 1968.
17. B. G. Hutchinson. Principles of Subjective Rating Scale Construction. Highway Research Record 46, 1964, pp. 60-70.
18. Inception Report, Report No. 1, Research Concepts and Procedures. Project entitled Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization. Republica Federativa Do Brasil and United Nations Development Program, April 1976, 155 pp.
19. An Instrument for the Measurement of Relative Road Roughness. Public Roads, Vol. 7, No. 7, September 1926, p. 144.
20. V. F. Nakamura and H. L. Michael. Serviceability Ratings of Highway Pavements. Highway Research Record 40, 1963, pp. 21-36.
21. Request for Proposals on Calibration and Correlation of Response-Type Road Roughness Measuring Systems. NCHRP Project 118, Transportation Research Board, Washington, D.C., January 1977.
22. Pavement Evaluation Using Road Meters. HRB Special Report 133, Highway Research Board, Washington, D. C., 1973.
23. B. E. Quinn and J. L. Zable. Evaluating Highway Elevation Power Spectra from Vehicle Performance. Highway Research Record 121, 1966, pp. 15-26.
24. F. L. Roberts and W. R. Hudson. Pavement Serviceability Equations Using the Surface Dynamics Profilometer. Research Report No. 73-3, Center for Highway Research, The University of Texas at Austin, April 1970.
25. F. L. Roberts and W. R. Hudson. Pavement Serviceability Equations Using the Surface Dynamics Profilometer. Highway Research Board, Special Report 116, 1971, pp. 68-71.
26. E. B. Spangler and W. J. Kelly. Servo Seismic

Method of Measuring Road Profile. Highway Research Board, Bulletin 328, 1962, pp. 33-51.

27. E. B. Spangler and W. J. Kelly. GMR Road Profilometer - A Method for Measuring Road Profile. Highway Research Record 121, 1966, pp. 27-54.
28. State of the Art of Pavement Condition Evaluation. Highway Research Board, Special Report 95, 1968, pp. 49-68.
29. Symposium on Pavement Design and Evlaution. Proceedings, Canadian Good Roads Association, 1960 and 1961.
30. R. S. Walker, W. R. Hudson, and F. L. Roberts. Development of a System for High-Speed Measurement of Pavement Roughness - Final Report. Research Report No. 73-5F, Center for Highway Research, The University of Texas at Austin, May 1971.
31. R. S. Walker and W. R. Hudson. Practical Uses of Spectral Analysis with the Surface Dynamics Road Profilometer. Highway Research Record 362, 1971, pp. 113-125.
32. R. S. Walker and W. R. Hudson. A Correlation Study of the Mays Road Meter with the Surface Dynamics Profilometer. Research Report No. 156-1, Center for Highway Research, The University of Texas at Austin, August 1972.
33. R. S. Walker and W. R. Hudson. Method for Measuring Serviceability Index with the Mays Road Meter. Highway Research Board, Special Report 133, 1973, pp. 68-72.
34. R. S. Walker and W. R. Hudson. Use of Profile Wave Amplitude Estimates for Pavement Serviceability Measures. Highway Research Record 471, 1973, pp. 110-117.
35. E. B. Wilkins. Outline of a Proposed Management System for the Canadian Good Roads Association Pavement Design and Evaluation Committee. Proceedings, Canadian Good Road Association, 1968.
36. Hugh J. Williamson, W. R. Hudson, and C. Dale Zinn. A Study of the Relationships Between Various Classes of Road-Surface Roughness and Human Ratings of Riding Quality. Research Report No. 156-5F, Center for Highway Research, The University of Texas at Austin, August 1975.
37. E. J. Yoder, and R. T. Milhous. Comparisons of Different Methods of Measuring Pavement Condition - Interim Report. NCHRP Report 7, 1964.
38. Neal P. Baum, Trudy Ann Stough. Evaluation of Inertial and Laser Profilometer Systems. Research Report No. FAA-RD-74-188 and AFWL-TR-74-289, U.S. Department of Transportation and U.S. Department of Defense, April 1975.
39. W. R. Hudson. A Generalized Roughness Index for Worldwide Use. Working Paper Prepared for the World Bank, September 1978.
40. D. McKenzie and M. Srinarawat. Root Mean Square Vertical Acceleration (RMSA) as a Basis for Mays Meter Calibration. Brazil Project Tech Memo BR-23, University of Texas at Austin, February 1978.
41. M. Srinarawat. Generalized Roughness Index. (Draft Unpublished - PhD Thesis, The University of Texas at Austin).
42. C. A. Hogentogler, Apparatus Used in Highway Research Projects. Bulletin of the National Research Council, Vol. 6, Part 4, No. 35, August 1923, pp. 14-16.