Road Roughness: Its Elements and Measurement

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The purpose of this paper is to summarize the importance of rational and compatible measurements of road roughness and to point out some of the problems of and possible methods for making such compatible measurements. Some ideas are also set forth for a general roughness index that could be used on a worldwide basis for comparing roughness of both paved and unpaved surfaces and for evaluating both road serviceability and vehicle operating costs. It is intended to provide an assessment of the current state of the art and a comparative evaluation of alternative surface (paved and unpaved) roughness measurement methodologies, with particular attention to evaluating and using the important relationships between vehicle operating costs and road surface condition. There is a need for a common scale for measuring roughness. First, we must be able to compare results of research on vehicle operating cost relationships from several research studies (for example, in Kenya, Brazil, and India) and to evaluate the magnitude and nature of errors associated with applying relationships developed in one country to other countries. Second, if we apply the vehicle operating costs and road deterioration relationships to other countries (which is already being done), then we obviously need to measure roughness on a common scale.

One of the primary operating characteristics of a road, whether paved or unpaved, 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 one measure of the road's performance. This performance, and the cost and benefit implications thereof, are the primary outputs of a pavement management system. In 1960, Carey and Irick (1) showed that surface roughness was the primary variable needed to explain the driver's opinion of the quality of the serviceability provided by a pavement surface, (i.e., its desirability for use). More recently, research has shown that user costs are also related to roughness, particularly on rougher-paved and unpaved roads. The Kenya highway design standards study, conducted by the Transport and Road Research Laboratory (TRRL) and the World Bank from 1971 to 1975 demonstrated the relation of vehicle operating costs to road roughness (2). Preliminary results of a similar study in Brazil give the same general conclusions.

What is road roughness and how can it best be defined? Some people talk about smoothness; others, serviceability. The Canadians talk of 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 the Permanent International Association of Road Congresses (PIARC), the English term roughness translates as unevenness, because their literal translation of roughness has come to be associated with surface texture and skid resistance or hydroplaning. In this paper, road roughness and smoothness are defined as being opposite ends of the same scale. A general definition of roughness must describe those surface characteristics of a pavement that affect vehicle operating costs and the riding quality of that pavement as perceived by the highway user.

The measuring of roughness is important in terms of evaluating road surfaces and their performance. It is also very important in terms of evaluating vehicle operating costs, as outlined above. The accuracy in measurement required for these various purposes may vary, as it may also vary between very rough roads (such as gravel and earth roads) and relatively smooth, or paved, roads. In the face of these diverse needs, it is important that a compatible roughness scale be made available for worldwide use.

NEED FOR COMPATIBILITY OR GENERALITY

Diverse measurements of roughness are used around the world. Comparison of equality among these measurements is not feasible because no roughness measuring system is capable of giving equal results for all conditions. Rather, it is essential to ensure that we have compatible measurements. Given proper consideration, compatibility among the various measuring systems can be provided. This compatibility involves two levels of concern:

1. External compatibility, which is related to whether the results of one agency's or country's work have a quantitative relationship or meaning with those of another agency or country, and
2. Internal compatibility, which is related to correlation of results and repeatability, within an agency or country.

This second aspect of compatibility is well illustrated by the Brazilian project. It is essential that all measurements made in Brazil be compatible with each other, even though it is not possible to make all the measurements with a single instrument.

As an illustration of the problem of external compatibility, results of studies in Kenya can be compared with the findings in Brazil only if the two sets of roughness data are compatible. It will be important to compare data from Kenya, Brazil, and India to examine transferability of data. This can best be accomplished by establishing a General Roughness Index (GRI) that can be used as a compatible base of comparison. This is preferable to selecting any particular measurement system, which itself may be changing and may not be available to a particular potential user agency.

If a GRI is used, then the matter resolves to the providing of a way to determine the GRI in a particular instance.

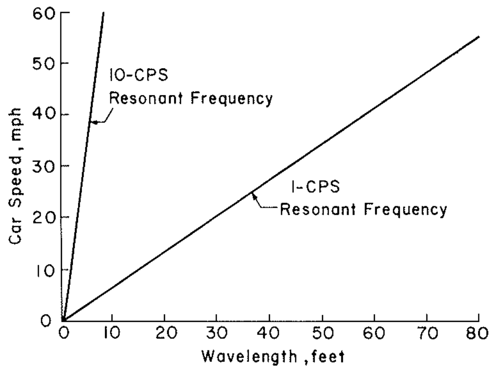
ROAD ROUGHNESS

Road serviceability, or riding quality, is largely a function of road roughness. Studies made at the American Association of State Highway Officials (AASHO) road test (1) have shown that about 95 percent of the road user's perception of the serviceability of a road results from the roughness of its surface profile. That is to say, the correlation coefficients in the present serviceability index (PSI) equation studies improved only about 5 percent when other factors were added (1) to the index. Hveem discusses this problem in several papers (3). He states that "there is no doubt that mankind has long thought of road smoothness or roughness as being synonymous with pleasant or unpleasant." New economic engineering research has shown that the effect of roughness on transportation costs may be more important than the effect on riding comfort. This aspect is of overwhelming importance in low-income, developing countries. Roughness of the road surface 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 that uses the road.

Definition of Roughness

Road roughness is a phenomenon that results from the

Figure 1. Relation among resonant frequencies of cars, car speed, and pavement surface wavelength.



interaction of the road surface profile and any vehicle that travels over that surface. It is experienced by the vehicle, its operator, and any passengers or cargo. Roughness is a function of the road surface profile and certain parameters of the vehicle, including tires, suspension, body mounts, and seats as well as of the sensibilities of the passengers and driver to acceleration and speed.

Hudson and Haas (4) refer to "pavement roughness" as the "distortion of ride quality." This definition is intended to refer to the road surface, whether paved or unpaved. Safety considerations influence the acceptance of roughness, and the important economic aspects of roughness on vehicle operating costs should be recognized. For this paper, the following definition of road roughness is suggested: the distortion of the road surface that contributes to an undesirable, unsafe, uneconomical, or uncomfortable ride. A slightly different definition might be as follows: the distortion of the road surface that imparts undesirable vertical accelerations and forces to the vehicle or to its riders and thus contributes to an undesirable, uneconomical, unsafe, or uncomfortable ride.

A rider in a vehicle that passes over a road surface experiences a ride sensation. This ride sensation is a function of (a) the longitudinal road profile, (b) the vehicle parameters, and (c) the vehicle speed. A variation of any one of these three variables can make a rough road profile appear smooth or rough. Therefore, we might say that, from a passenger's viewpoint, roughness is an undesirable combination of road profile, vehicle parameters, and speed. Riding characteristics of airplanes are also affected by the properties of airfield surfaces and of the aircraft. Vertical accelerations of sufficient magnitude to critically affect safety of aircraft operations are sometimes obtained over poor surfaces.

Most drivers have experienced the sensation of improving a ride on a particular road by either slowing down or speeding up. This indicates that the road surface profile contains roughness waves or undulations of a length that, when driven over at a particular speed, produce an excitation in the vehicle at one of the vehicle's resonant frequencies. Since a normal vehicle is a simple mechanical vibrating system made up of the mass of the vehicle, the springs on which it rides, and the shock absorbers, at a particular frequency of vibration or bouncing of any vehicle, the vibrations tend to increase in amplitude. This is normally called the resonant frequency. The typical passenger car has resonant frequencies of between 1 and 10 cycles/s (Figure 1). This relationship indicates that, at any particular speed of travel, there is a road profile wavelength that will excite the vehicle at one of its resonant frequencies and thus cause excessive vibration or bouncing. If the amplitude of that resonant wavelength is large, the vibration or vertical accelerations imparted to the vehicle may be quite noticeable. Since vertical accelerations impart significant vertical force, these wavelengths result in significant forces applied to the vehicle, which can result in damage to vehicle components and increased operating costs, as well as in an unsafe and uncomfortable ride.

In general, most vehicles in a particular class (e.g., passenger cars as one class and trucks as another class) possess similar characteristics and, for any particular road surface, most vehicles in the same class will be driven at about the same speed. With two of these variables held relatively fixed, the excitation of the vehicle, and thus the riding quality and vertical forces on the vehicle, becomes primarily a function of the wavelength content of the road profile surface.

Evaluation

Roughness evaluation has received considerable attention from many highway and airport agencies in North America in the last three decades. Roughness is the primary component of pavement serviceability, and a large number of different roughness measures are in current use to evaluate such serviceability. Some of the more widely used methods for measuring roughness, correlating measurements, and applying the results are outlined elsewhere (5). Many of these measurements have involved roughness perception by the highway user as a very important factor, and thus roughness measurements have generally excluded surface texture and microtexture of surface aggregates because these are not perceived by the user to affect riding comfort.

The diameter of surface stone used in gravel and surface-treated roads that causes noise discernable to the user does have an effect on user perception and affects road roughness by this definition. It is not yet known whether these kinds of microvariations affect vehicle operating costs and safety.

Road Profile

Many authors, such as Darlington (6) and Carey (7), think that pavement profile does the best job of characterizing roughness. In terms of pavement profile, roughness can be defined as the summation of variations in the surface profile of the pavement. Profiles in this sense do not include the overall geometry of the road but are limited to wavelengths in the surface of the pavement between approximately 0.031 and 152.4 m (0.1 and 500 ft) in length. In Darlington's terms, roughness is "the analysis of the pavement profile or of the random signal known as profile."

Carey (7) points out four fundamental uses of pavement surface profiles or roughness measurements:

1. To maintain construction quality control;
2. To locate abnormal changes in the highway, such as drainage, subsurface problems, or extreme construction deficiencies;
3. To establish a systemwide basis for allocation or road maintenance resources; and
4. To identify road serviceability-performance life histories for evaluation of alternative designs.

In summary, then, a road profile is a detailed recording of surface characteristics, and roughness or smoothness is a statistic that summarizes these characteristics and provides a measure of riding quality of a road.

Once the surface characteristics of a road 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, the two basic ways of determining this statistic are

1. Mechanical integration and
2. 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 Bureau of Public Roads (BPR) Roughometer (Figure 2) or TRRL Bump Integrator 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 or integrating this profile mathematically with some standard mathematical procedure, such as that outlined by Walker and Hudson (8 ,9), Roberts and Hudson (10,11), Quinn (12), and Darlington (6). The most common methods in current use for mechanical measurement and summary include the BPR Roughometer (13),5), the very similar TRRL Bump Integrator (14), the Portland Cement Association (PCA) Roadmeter (15), the Mays Meter (9,16), the Carey Huckins, Leathers, and other Engineers (CHLOE) Profilometer (17), and the land plane, Profilograph, or rolling straightedge (Figure 3) (17). A number of studies have been made to compare these instruments, as outlined elsewhere (5,6).

A word of elaboration is needed on the term mechanically filtered, outlined above for the BPR Roughometer. Instruments such as the BPR Roughometer, the PCA Road Meter, and the Mays Meter use the vehicle itself as a mechanical filter for processing the profile and summarizing, in effect, the response of a particular vehicle (in its specific condition) to the road profile.

If the mechanical characteristics of the measuring vehicle could be set and maintained at a desired preselected level, then the resulting summary statistics could be directly related to the economics or safety of a specific vehicle class. Unfortunately, due to the many parameters and the great variability involved, the use of the Bump Integrator or BPR Roughometer results, rather than the profile itself, introduces great measurement and analytical complications.

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. Summaries are included elsewhere (5,18).

COMPARISON OF MEASUREMENT AND SUMMARY TECHNIQUES

Regardless of the type of measurement and summary techniques used, it is essential that a good reference be established and maintained. It is equally important that accuracy in summation be maintained. Every different instrument has a different readout scale, and even seemingly identical instruments must be calibrated so that the observed readout is meaningful. This readout scaling and consistency are central to this paper.

Darlington (6) points out that three basic reference methods have been used historically:

1. A so-called rolling straightedge, or land plane, as illustrated in Figure 3;
2. An inertial mass, as used in the BPR Roughometer (Figure 2), the Mays Meter, and the PCA Road Meter (in the latter two cases, the automobile forms the inertial mass); and
3. An inertial reference profilometer, such as the Surface Dynamics or General Motors Profilometer, where an external reference is provided.

Figure 4 illustrates by means of a Bode plot the transfer function or response of several types of profilers to the input of road roughness. The problem is that the straightedge, or land plane device, is so erratic in its response as to be relatively useless. The course shown in Figure 4 reflects that roughness wavelengths that are any multiple of the length of the straightedge result in zero output from the device.

Darlington simulated the response of the BPR Roughometer, vibrometer, or seismic reference device (whichever you prefer to call it) on an analog computer, by using measured physical characteristics of the instrument. His analysis shows that the roughometer-type device yields reasonable results for wavelengths in the range of 1.22-4.26 m (4-14 ft). Wavelengths in the range of 4.26-5.48 m (14-18 ft) are badly distorted, and wavelengths beyond 6.70 m (22 ft) rapidly attenuate to zero effect.

Figure 2. Schematic diagram of BPR roughometer.

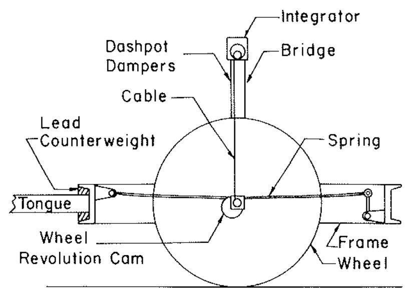


Figure 3. Land plane roughness device sometimes called profilograph or rolling straightedge.

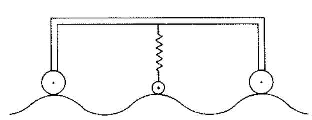


Figure 4. Theoretical differences between SD Profilometer, CHLOE, rolling straightedges, and seismic roughometer.

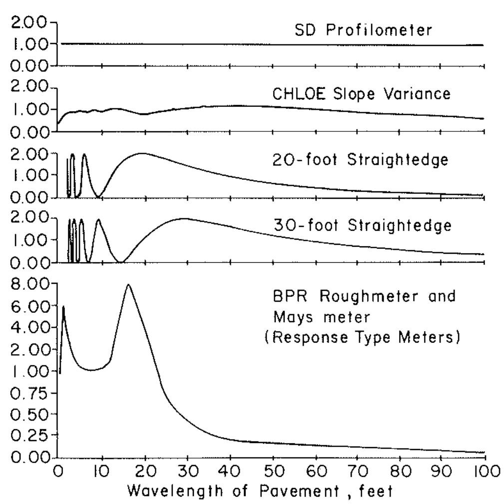
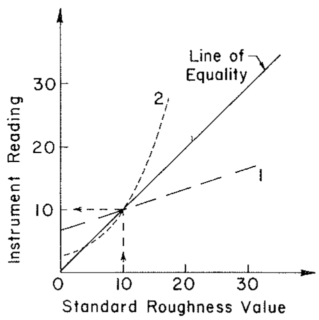


Figure 5. Single-Point BPR calibration problems.



ROUGHNESS CALIBRATION AND CORRELATION

The earliest roughness measurements were reported by Hogentogler as far back as 1923. 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, BPR (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 this calibration section is discussed by Hudson and Hain (13).

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 that has a value of 10 has been set up. We might assume that any other instrument that 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, and 30 when the standard instrument reads 30. Alternatively, line 1 illustrates a plausible case of a linear relationship, where instrument 1 is calibrated to the standard instrument on the section of 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. Dashed line 2 illustrates a more complex case of nonlinear relationship that would, of course, also be missed with the single-point calibration.

Roughometer Calibration Course: AASHO Road Test

As reported by Hudson and Hain (11), there was a need to use the Roughometer in the AASHO road test. But, it became obvious very early, with the AASHO Profilometer as a comparison, that the BPR Roughometer was a variable instrument difficult to keep in calibration. In work at the AASHO road test we were not only involved in measuring the roughness of all pavement with the AASHO Profilometer and in developing and operating the BPR Roughometer, but we also checked and calibrated at least six additional 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 roughometers 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 TRRL in England. This concept appears to have promise for use as a calibrating device or standardization method around the world. Briefly, the method involves the selection of a smooth, standard pavement section approximately 300 m (985 ft) long. This smooth section becomes the smoothest section in a series of calibration sections. Subsequent rough sections are created by adding artificial bumps to the surface of the standard section by means of pipes that have an external diameter of 3.413 cm (1.344 in). 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.

This method has great attraction and may be a practical all-around method, but it also has pitfalls that make it fall short for ultimate use. For example, all of the roughness introduced in this way is artifical roughness of a step-input nature, whereas much of the roughness in a normal road profile is composed of a combination of sinusoids. As pointed out by Darlington (6), these real profiles lend themselves to analysis by a variety of analytical methods. The step-input roughness of the TRRL calibration track does not yield to analysis so readily. Nevertheless it is a practical method and a prime candidate for consideration. The other major observation relates to use of the method. To date it has been used primarily as a calibration tool for the towed one-wheel trailer Bump Integrator or BPR Roughometer-type device, and apparently works well for this situation. The problems of using the method on an automobile-mounted device, such as the Mays Meter, where all four wheels of the vehicle and the resulting vehicle motions will become involved, are yet to be determined. Finally, as pointed out in the Bode plot or transfer function for the BPR Roughometer, that the instruments respond and stay calibrated in wavelengths from 1.22 to 4.28 m (4 to 14 ft) does not tell us how they will respond at other wavelengths. Note from the computer simulation of Darlington that the response of the instrument to step-inputs should be on the first peak (i.e., very short wavelengths). If some type of resonance is generated in the measurement system, say for roughness level six, then the multiplication amplitude could be even higher. Nevertheless, this method certainly bears further evaluation.

Use of a Standard Device for Calibration

Probably the most widely used method of calibration and correlation has involved some type of so-called standard device. Really, this approach should be divided into two parts. The first involves the selection of one replicate from a group of similar devices being used and using this copy of the device for calibration purposes, so that it presumably does not wear out. I liken this approach to gold plating a crowbar. If you have two dozen crowbars and select the one that appears to be more perfect in shape and weight than any of the others and plate it with gold as a reference, what do you have? Still a crowbar, albeit a shiny and expensive one.

The only validity of this approach is lack of wear in routine use. However, many of the errors we must deal with do not result from wear alone. There is little evidence that this type of standard device has been successful in use for calibration and correlation.

The second part involves the use of a master device, which is itself calibratible or has a standard of accuracy that 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; it 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 (GM) profilometer was originally developed for obtaining road profile input that could be fed into a vehicle-ride simulator for testing vehicle suspensions at the GM proving ground (20, 21). Some authorities think 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 in a laboratory of a wheeled measuring device that has a servo-controlled hydraulic ram resting under each wheel. Known excitation is applied through the hydraulic rams to the device to determine its response. More specifically, the wheels of the device are vibrated by the shaker table in a manner to simulate operation of the device on each of a set of standard test sections. Road profile data obtained with an instrument such as the 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 never change.

There is, of course, some question about the correspondence between readings obtained by using a shaker table and roughness measurements obtained in the field. The major source of discrepancy remains in the fact that the vehicle is normally moving and the wheels are rotating while measurements are being made in the field but not while it is on a shaker table. The dynamic versus static tire conditions are of particular concern. The National Cooperative Highway Research Program (NCHRP) has just completed a research project that has investigated the shaker table approach to calibration of roughness devices. In general, this method does not seem feasible for use worldwide because the shaker table is cumbersome and expensive.

Texas Calibration Course With Surface Dynamics Profilometer

The Center for Transportation Research and the Texas State Department of Highways and Public Transportation use the Surface Dynamics Profilometer (SDP) or GM Profilometer as a master calibration device for a series of Mays Meters that are used routinely throughout the state. This approach is reported by Walker, Hudson, and Williamson (9,16,22). To some degree, a similar approach has been taken by the Michigan Highway Department, as reported by Holbrook and Darlington (23). A similar approach is also being taken at the present time in the United Nations Development Program Brazil study (24). A SDP was purchased and is used for measuring a set of calibration sections. These sections are run regularly by four Mays Meters to ensure that their calibration remain stable. A control chart procedure and regular check procedure similar to that outlined by Williamson are followed.

Basically, Texas maintains a group of 25 pavement sections that together exhibit a range of roughness. Every three months the profile of each of these sections is measured and analyzed with the SDP. In this way a set of pavements with known roughness is always available for use in checking and calibrating any other roughness instrument. Any instrument that appears to be giving erroneous readings is run regularly on several check sections and the values are plotted on a typical control chart. If a device is out-of-control on three or four sections, it is thoroughly checked mechanically and recalibrated.

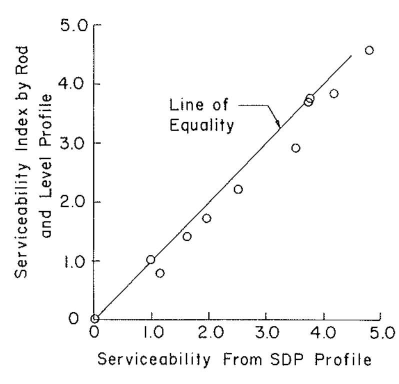
Rod and Level Surveys

Many people think 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 that involves discrete points such as are used in a rod and level survey. This problem is magnified because even the best manual leveling techniques make it expensive to make measurements of test sections 300 m (985 ft) long at spacings closer than about 0.5 m (1.6 ft). 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 the detailed problem outlined above is the need to integrate and summarize and analyze the profile. To date, little has been done in this area. Recently, we have investigated the use of second derivatives of the profile to yield estimates of vertical accelerations present in the profile. A relationship has, in turn, been developed between vertical accelerations and serviceability index (SI).

Calculations are simple and do not require a large computer facility, as do existing profile analysis 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, and they have been employed successfully as a Mays Meter calibration standard in Texas (25). Figure 6 illustrates a very good agreement in terms of SI from 10 road surface profiles obtained by rod and level method and the SDP. This plot also suggests that road profile data from rod and level and

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



SDP are interchangeable and that rod and level can be used to provide commonality among road roughness scales currently in use.

Certainly these discrete rod and level surveys have some practical advantages, particularly in developing countries where labor-intensive methods are economical. It might be far more practical to obtain detailed, discrete profiles with rod and levels of, say, 10 or 12 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.

Rating Panel Approach: Canadian Good Roads Association

Immediately following the AASHO road test, the Canadian Good Roads Association wanted to put the findings of the AASHO road test into practice. In order to do this, they thought it was essential to run a 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 from 1 to 10. This index is basically an evaluation of pavement riding quality or roughness (26).

After they carefully established their riding comfort index, a standard procedure was adopted by using a small panel of well-trained raters to go from location to location and evaluate the riding quality of these pavements and record this riding quality in a data management system. A great deal of work has been done on rating scales and other subjective evaluation (1,10,27-30). There are some shortcomings to this approach, but it has the benefits of being practical, relatively inexpensive, and reasonably stable, although its detailed accuracy may be questioned. This approach deserves further consideration.

Standard Rating Panel

Although it is not in current 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 promise as a practical solution. Yoder and Milhous (18) show in their studies of rating panels and various instrumentation that rating panels of 15 persons or more are quite stable in predicting pavement serviceability. Since roughness is so highly correlated with serviceability, there is little doubt that the panel would be equally stable in predicting pavement roughness. Carey and Irick (1) report similar results when comparing panels at the AASHO road test, as do Roberts and Hudson (10,11).

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 used by a panel from a developing country, who rides predominately on gravel roads? How could this dichotomy be solved? If as many as three common members could be made available to participate in panel ratings in each of the major areas of the world, then I believe adequate geographic and cultural stability could be obtained.

This method will never have the precision or detail of physical calibration; however, it could help ensure that different classes or road roughness are adequately separated with a good degree of confidence.

DISCUSSION OF RESULTS

Ultimately, the best practical approach that can be used to provide a GRI may involve some combination of the factors discussed above. For example, a GRI could be set up that has a scale based on second derivatives of a rod and level profile such that, for example, the number of vertical accelerations that exceed some specified value might be used as an indicator of the GRI or roughness number. In such cases, the pavement sections might be surveyed with a rod and level once or twice a year to provide objective support for this subjective rating.

Major problems with the roughness rating approach are the possibilities of cultural differences among countries, as discussed above. There is considerable concern that these cultural or historic differences, which are also, by the way, aggravated by traditional types and quality of vehicles used, would affect any relationship developed by a rating scheme and thus would completely invalidate the concept of relative ratings.

I feel, however, that, as suggested previously, reasonable roughness ratings could be established and that the problem of comparing one rating panel with another could be alleviated by ensuring that basic rating panels, at least among major research efforts, have at least three members in common in the initial stages of development. These common members could be employees or advisors of the World Bank or other research personnel who would be involved in one or more of the research projects and who could visit the other activities to provide the necessary commonality of ratings.

At the present time, no roughness measuring and evaluation technique exists that alone is constant enough to become the appropriate standard. The SDP might be considered, but work in adopting and using this instrument in Brazil and in comparing it with the Texas instrument manufactured 10 years ago shows considerable difference in hardware and data processing techniques. Many people feel we are on the threshold of developing a noncontact probe to replace 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.

Similar problems exist with the TRRL laser profilometer, the Swedish device, the automatic road analyzer (ARAN) unit, and others. All have potential but none has generality and stability at the present time.

SUMMARY AND RECOMMENDATIONS

The purpose of this paper has been to set forth information on the elements of roadway roughness and its measurement. As pointed out, the major problem associated with such use is the problem of providing simple, direct, and relatively inexpensive roughness measurements that remain stable from day to day, year to year, and country to country around the world. A number of seemingly simple devices exist, but close examination of the devices in service, as pointed out here, shows many deficiencies in practice.

Efforts should continue in this important area, but a coordinated funded effort is needed to develop the high quality of measurement equipment and calibration techniques required for regular effective worldwide use. Support for this research effort is strongly solicited.

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