State of the Art of Measurement and Analysis of Road Roughness

J. C. WAMBOLD, L. E. DEFRAIN, R. R. HEGMON, K. MCGHEE, J. REICHERT, AND E. B. SPANGLER

This paper is a review of the state of the art of the measurement and analysis techniques used to evaluate road roughness. A summary of some European work is included in this review; however, the emphasis of this paper is on work done in the United States. Road roughness is defined as the deviations of a pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic pavement loads, and pavement drainage. Road roughness is measured by two general types of equipment: profilometers, which measure these characteristic dimensions directly, and response-type equipment, which measure surface roughness as a dynamic response of the measuring equipment to that roughness. This paper discusses (a) the characteristic of road roughness, operating characteristics, and output of each type of roughness measuring equipment and (b) the various methods of analysis and their application to highway safety, ride comfort, dynamic pavement loading, and pavement serviceability. These methods of analysis have been categorized into two general groups: those that provide a single number of index such as root mean square, slope variance, or present serviceability index and those that statistically provide more detail than a single index, such as harmonic analysis or power spectral density. Finally, a summary of present research projects on new equipment and analysis methods is given.

The nation's aging highway system, together with increased traffic and growing competition for the tax dollar, make transportation administration more difficult. As a result, better management systems are needed to enable administrators to make objective assessments. Among the major functions of a highway or transportation department are the planning of maintenance schedules for a system of existing roads and the acceptance or rejection of newly built or resurfaced roads. The decision to resurface a particular section of road, in preference to others, is not a simple one in view of the many factors that should be taken into consideration. However, considerable information is available to support an objective evaluation, and research is under way to permit the development of improved pavement-management systems.

For maintenance management purposes, an evaluation of the condition of a pavement must include at least four factors: (a) safety, (b) pavement performance, (c) pavement distress, and (d) structural capacity. Each of these factors is used in the decision-making process to determine the nature and extent of pavement rehabilitation.

Of these four, pavement performance is most generally related to road roughness in one manner or another. This was initially accomplished with the present serviceability index (PSI), as developed at the American Association of State Highway Officials (AASHO) road test. In its original form, the PSI was developed as a measure of the rider's evaluation, and thus the pavement-performance factor was the only one to reflect the consumer's evaluation of pavement condition.

Passenger's evaluation is used here instead of the usual reference to ride comfort. In much of the work on road roughness, it has been determined that there is a dichotomy between ride quality (a subjective quantity) and pavement serviceability (an objective measure). Ride quality is primarily a measure of acceptance of the roadway as a method of conveyance. Serviceability is a measure of the physical characteristics of the pavement surface. Although some attempts have been made to correlate these quantities, little information exists to define this relation.

The nature of the roughness, for example the extent of rutting, cracking, and patching, was included in the calculation of PSI. In the interest of expediency, many states have dropped one or more of these terms or simply substituted a constant. The PSI procedure has gone through many such changes, and a variety of other indices have been developed so that now there is no standard practice for quantifying pavement performance.

The measurement of road roughness is of interest to the maintenance manager in determining pavement safety, serviceability, and potential for assessing pavement distress, as well as to the highway or transportation department that wants an acceptance criterion for newly constructed or repaved roads. Some departments already have acceptance criteria for newly constructed or paved roads. In such cases, roughness is not to exceed a specified value as measured by a specified measurement method. Thus, it is recognized that paving equipment and methods are imperfect and some roughness is to be expected in new pavements. In a few cases, the initial roughness is so high as to make the pavement appear to be distressed.

The initial road roughness will normally increase with exposure to traffic and weather. Deformations in the pavement foundation caused by poor drainage, swelling soils, or nonuniform initial compaction will lead to roughness in the surface course. Freeze-thaw cycles cause seasonal changes in roughness and some permanent deformations. Shear forces generated during braking of heavy vehicles may cause shifting of the surface course and initiate a washboard-type roughness, which is then aggravated by dynamic wheel forces excited by the roughness.

Relatively large faults in the riding surface may develop across pavements to bridge deck joints. Similar faults may develop in the railroad grade crossings. Shifting in the foundations causes the development of roughness (as discussed above) in flexible pavements. In rigid portland cement concrete (PCC) pavements, whole slabs may tilt and result in faults at the joints. Finally, local failures such as potholes may develop and contribute to the overall roughness of the road surface.

Continuing developments in measuring equipment and analysis techniques have greatly expanded the available information. For example, a new commercially available all-digital inertial profilometer system not only provides a more accurately measured road profile but is also able to provide real-time data analysis of the measured road profile, which makes analysis information immediately available as the road profile is measured. Research is in progress to further simplify the inertial profilometer system by the development of an operational noncontacting sensor to replace the road-following wheel in the present inertial profilometers. These developments include acoustic, infrared, and white-light sensors being developed by the Federal Highway Administration (FHWA) and commercially in the United States. Other similar systems are being developed in Europe (1,2). Thus, there will soon be a choice of the noncontact sensors.

ROAD ROUGHNESS

Before we begin an in-depth discussion of equipment

Figure 1. Typical transfer function for passenger car body relative to axle vibrations at 87 km/h.

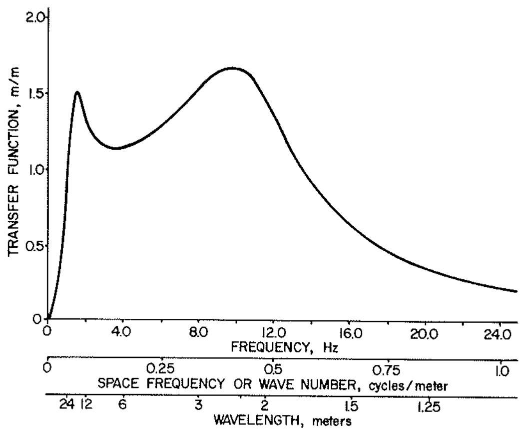


Figure 2. Road that induces automobile body shake.

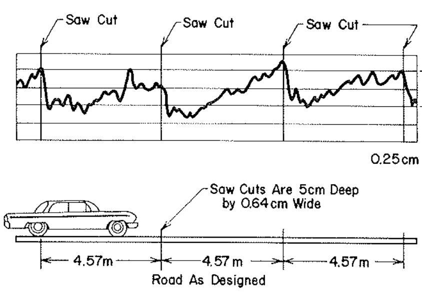
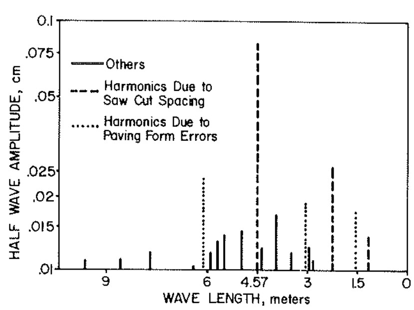


Figure 3. Harmonic analysis of road that causes automobile body shake.



for measuring road roughness, let us define road roughness itself. Road roughness is defined as deviations of a traveled surface from a true planar surface that has characteristic dimensions that affect ride quality, vehicle dynamics, dynamic pavement loads, and pavement drainage. To quantify these characteristic dimensions it is necessary to discuss the dynamic characteristics of the vehicle, vehicle speed, and the wavelength and amplitude content of the road profile over which the vehicle travels.

The dynamic characteristics of a typical vehicle can be represented by a transfer function shown in Figure 1. The plot shows the response of the vehicle in the frequency range from 1 to 24 Hz in terms of the amplitude ratio. For example, a sinusoidal road input to the vehicle at a frequency of 10 Hz would cause the vehicle to oscillate at the same frequency but at an amplitude 1.7 times greater than the input amplitude. As can be seen from the plot, amplitude ratios greater than 1 extend from below 1 Hz to almost 14 Hz in a typical automotive vehicle.

Vehicle frequency response in the time domain (hertz) is related to spatial frequency in the highway profile by the velocity at which the vehicle travels over the highway profile.

A vehicle that travels at 24 m/s on a road of wavelength of 3 m will experience an 8-Hz excitation; a vehicle that travels at 12 m/s on a 1.5-m wavelength will experience the same 8-Hz excitation. Spatial frequency is defined as the reciprocal wavelength so that it can be converted to a frequency in hertz. Thus, by using a vehicle speed in the proper units, we can convert the spatial frequency to time-domain frequency, as shown by the second scale along the abscissa of Figure 1 (an example case with a vehicle velocity of 24 m/s). With this relationship, we can see that spatial frequencies from 0.04 to 1.0 cycles/m will cause the vehicle body to oscillate at an amplitude greater than the amplitude present in road profile. A third scale in wavelength is also given for the readers' convenience.

With these relationships, we can examine the characteristic dimensions of the road profile content that contribute to road roughness. An example of the short wavelength roughness contribution is the road profile shown in Figure 2, which caused a vehicle to vibrate objectionably at 10 Hz when the vehicle was driven over it at 88 km/h. An analysis of this road profile [Figure 3, (3)] suggests that the objectionable vibration was caused by the short-wavelength, periodic inputs centered about the 2.29-m component, which is half of the slab length.

It also suggests that, in the measurement of short-wavelength road roughness, sufficient resolution will be necessary to measure accurately the amplitudes for the wavelength shown in Figure 3. Currently, it is considered necessary that profiling equipment be capable of measuring amplitudes down to 0.025 cm.

MEASUREMENT OF ROAD ROUGHNESS

Road roughness is measured by two types of equipment, that which measures the response to roughness (response-type equipment) and that which measures actual profiles (profilometers). Ideally, the profiling methods give accurate, scaled reproductions of the pavement profile along a straight line. In practice, the range and resolution of any profiling devices are limited, but within these limits the measurement may be called absolute.

The response-type measurement records the dynamic response of mechanical systems as they travel over the rough road at some constant speed. It is, therefore, a relative measurement and depends on the characteristics of the mechanical system and the speed of travel.

Response-Type Equipment

As early as 1917, the Bureau of Public Roads (BPR), now FHWA, investigated devices to measure the road roughness of highways. In the early 1920s, the Via-Log was used to some extent by New York highway officials, but it was not generally adopted by other highway departments. Of interest is a 1925 file letter that states that its price ($750) may have been the principal reason for its limited use.

Various devices to measure road roughness were tried up to May 1925, when the first BPR roughometer (4,5) was introduced. The roughometer is a single-wheel trailer that measures the unidirectional vertical movements of the damped, leaf-sprung wheel (with respect to the frame) by a mechanical integrator. The results are recorded on counters to produce an inches-per-mile count of roughness. Several highway departments (6,7) have added a cumulative tape recorder and an oscillograph. Another modification of the BPR roughometer, developed at Purdue University (8), is designed to provide more information than the original version. It uses several resonance beams that are excited at different frequencies; thus, at a given speed an indication of the wavelength content of the surface is given.

Due to the slow response of the electromechanical counter, measurements with the roughometer are generally made at 32 km/h. Testing at this low speed is a disadvantage in that it is not very safe when other traffic is operating at normal highway speeds. Illinois has reported (9) that this limitation can be corrected by replacing the electromechanical counter by an electronic one for operation at higher speeds. However, the higher speed modifies the operational characteristics of this device.

Another type of response equipment is the group generally called roadmeters (10-13). Two commonly used meters are the Portland Cement Association (PCA) meter (14) and the Mays meter (15). These meters measure the vertical movements of the rear axle of an automobile relative to the vehicle frame. Because of its low-cost and high-speed operation, this method is now in widespread use. The performance and capabilities of the roadmeter were the subject of a workshop held at Purdue University in 1972 (16). This method of measurement is clearly the simplest and least expensive. However, the response-type equipment in use today is known to be time unstable, and the data from these devices will only be usable if suitable calibration procedures are developed to overcome this limitation. Significant progress has been recently made under a National Cooperative Highway Research Program (NCHRP) contract (17) to identify the time-unstable elements in these systems and to develop calibration procedures to account for their changing performance.

All roadmeters measure a dynamic effect of the roughness, but this type of measurement does not define the profile of the roughness. Some wavelengths will be amplified and others will be attenuated; thus, the selection of the mechanical system is critical. Roadmeters are useful for survey work in predicting the users' response regarding the quality of the road. However, to examine further the condition of a road or to determine what characteristics of the road cause the poor condition, profiling equipment (commonly called profilometers) need to be used.

Profiling Equipment

The advantages of a profiling system are evident. It contains complete information about the pavement profile (within the limits of the particular device) that can be evaluated according to specific needs. Such systems are expensive, however, either in initial cost or in operation, and require some data processing.

The simplest profilometer is a straight edge (18), and modifications, such as putting it on wheels, have been made. Several straight-edge spans are used, including 10, 12, 15, 16, and 30 ft. This equipment is operated either statically or at very low speed. It is not suitable for profiling because it cannot measure wavelengths longer than its span and can distort wavelengths that are harmonics of its span. Low-speed systems such as the Carey, Huckins, Leathers, and other engineers (CHLOE) are moving reference planes that have little or no dynamic effects because of their slow speed (19,20).

A low-speed profilometer system developed by the Air Force (21) consists of a horizontal laser beam, which is transmitted as a reference, and a tracking vehicle, which moves slowly along the runway and measures the undulations of the pavement. Profiles of wavelengths up to 120 m are measured with precision but at slow speeds of about 5 km/h. The operation of the equipment requires highly trained technicians.

The first modern profiling equipment, the General Motors Research (GMR) Laboratories profilometer (3,22,23), was developed by GMR Laboratories in the 1960s by using an internal reference concept. The GMR profilometer (see Figure 4) uses two spring-loaded, road-following wheels, instrumented with a linear potentiometer to measure relative displacements between the vehicle frame and the road surface. The accelerometers, mounted on the frame over each of the follower wheels, are used to measure the vehicle frame motion by double integration of the signal. The frame motion is then added to the relative displacements motion to yield two voltage signals, which in theory are the road profiles of the wheel paths (see Figure 4). This method of using a road wheel displacement signal plus the double integration of the body accelerations, rather than just the double integrations of wheel accelerations, is used as a means of covering a wider range in the measurement of road roughness. The vehicle suspension acts as a mechanical filter and transmits low-frequency (long wavelengths) vibrations but attenuating high-frequency (short wavelengths) vibrations. Thus, frequencies below 1 Hz are measured primarily by the accelerometers, mounted on the vehicle bodies, whereas the frequencies above 2 Hz are measured primarily by the linear potentiometers, mounted between the body and the follower wheels.

For frequencies between 1 and 2 Hz, the profile is a combination of the two signals. This method has been shown to be extremely useful because it has good resolution of both the short wavelengths, which have low amplitudes, and the long wavelengths, which have much greater amplitudes. The GMR profilometer was originally manufactured with analog processing equipment; however the most recent profilometer has been manufactured with an on-board minidigital computer.

In the digital computer version (see Figure 5), the road profile computation is performed by a digital minicomputer on board the profilometer vehicle, and the computed road profile data points are stored on a digital magnetic tape recorder for later data processing. In this system the sensor signals, acceleration, and displacement are sampled and immediately converted to digital values for use in the profile computation. The sampling and computation of the road profile are performed as a function of distance instead of time, as in the earlier analog system, which makes these independent of vehicle speed and much easier to interpret. The digital system, through the programmability of the minicomputer, reduces considerably the technical expertise previously required to operate and maintain the analog computer system. System calibration, signal scaling, and data formatting for storage of magnetic tape data are functions performed under software program control.

Computation of road profile is scaled so that a wide range of road profile values can be computed and stored on magnetic tape without concern about system overload. Although road profile data points are computed several times per data record point, data points are typically stored on magnetic tape every 6 in of distance traveled for the two-track-wheel paths.

The GMR profilometer system has become known

Figure 4. Diagram of measurement system for GMR profilometer.

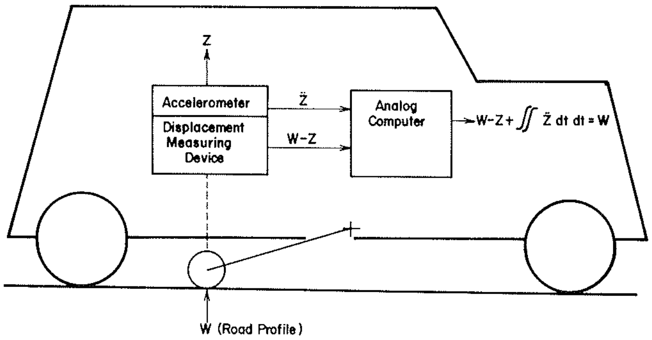
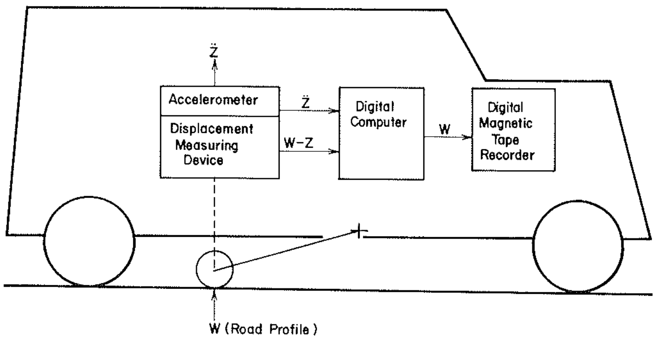


Figure 5. Digital version of GMR profilometer.



under several names: General Motor profilometer, rapid travel profilometer (RTP), and surface dynamics profilometer (SDP). The system is commercially available but is currently being used by only five states: Kentucky, Michigan, Pennsylvania, Texas, and West Virginia. The last system, built for West Virginia, is the new digital system with the application software just described. In addition, Texas is in the process of replacing its early analog system with the new digital design.

There are several reasons that the GMR-type profilometer is not more widely used in the highway community. Certainly its high purchase cost is an important factor, although more than 40 states have skid testers that have almost the same price tag. Another important factor may be the limited use that has been made in the past of the information contained in the roughness profile. Both of these reasons could moderate as more cost-saving application software, like the bituminous fill program, becomes available to the highway community and the output of the profilometer becomes an important input to a well-designed pavement management system. (The bituminous fill program allows one to simulate an overlay and to compute the new profile developed.) Another factor that should improve profilometer performance and assist in user community acceptance will be the replacement of the present road-following wheel with a noncontacting device.

Among various profiling apparatuses developed in Europe, we should mention the French designed dynamic profile analyzer (24) [l'analyseur du profil en long bitrace (APL) du Laboratoire central francais des Ponts et Chaussees] (see Figure 6). It provides for the measurement of two tracks of longitudinal profile. Each of the single-wheel trailers (see Figures 6 and 7) that constitutes the measuring device is made up of

1. A profile pick-up wheel that is mechanically conditioned to remain in contact with the road surface (even at relatively high constant speed of up to 144 km/h or 72 km/h for normal tests),
2. An inertial pendulum used as the measurement reference, and
3. A measuring wheel-carrier arm that rotates around the same axis as that of the pendulum.

The center of mass of the inertial pendulum is located at the center of percussion of the trailer relative to the towing point, which allows measurements of the profile to be made by considering the angular displacement of the wheel carrier-arm and the pendulum. This is achieved with a satisfactory mechanical decoupling from the towing vehicle. A transducer transforms the angular displacement into a magnetic tape-recorded electric signal. This information is later available for computation. The transfer function of the APL equipment is flat over the frequency range of 0.4-20 Hz (response between +5 and -5 percent of the mean). The two-track version permits the study of average longitudinal evenness as well as average rolling movements. However, because each trailer has its own reference, there is no assurance that the roll component is correct. A common transverse sensor between the two independent trailers would be required to ensure a correct measurement relative to the same reference.

Another apparatus, the profile analyser from the Technical University of Berlin (24), works on a similar principle; the apparatus involves a reference base of pendulum type and a bogie used as a sensor wheel. The signal corresponds to the gradient between the bogie truck and the reference base. This gradient can be translated by an analog or digital computer into amplitude of differences in level or acceleration. The transfer function is flat between 3 and 25 Hz, but the testing speed is low, about 20 km/h.

Figure 6. Dynamic profile analyzer, French design APL.

Figure 7. Components of APL.

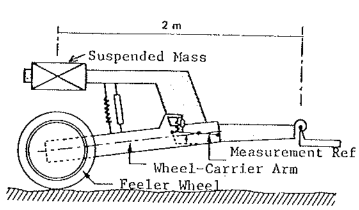


Figure 8. Theoretical differences among GMR profilometer, APL, CHLOE, rolling straightedges, and BPR roughometer.

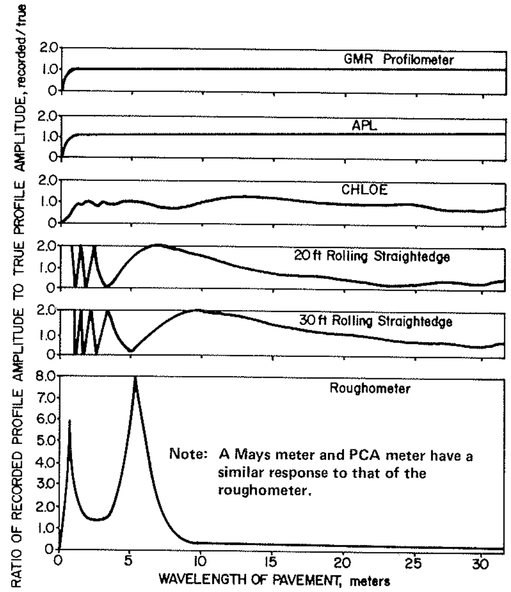
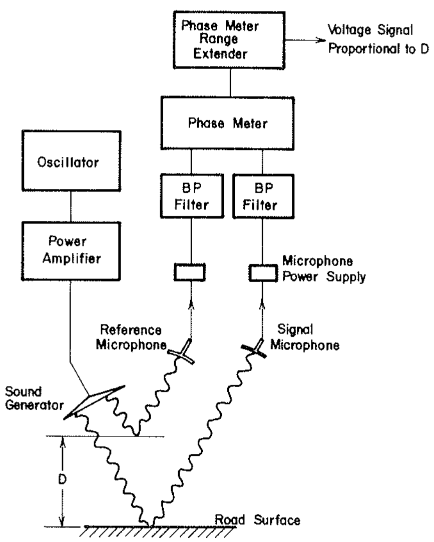


Figure 9. Block diagram of acoustic probe signal conditioning equipment.



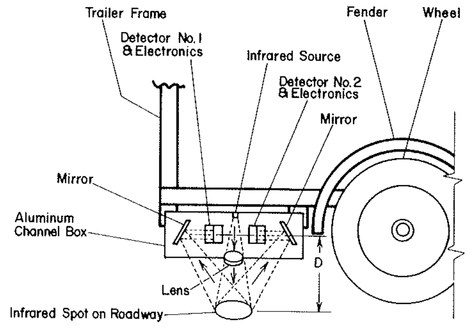
Darlington (25) has analyzed the response of several profiling devices by means of Bode plots. These have been reproduced in Figure 8 (24,25) with the addition of the APL. These plots show that, of the road roughness measurement systems in use today, only the GMR profilometer and the APL can record the true road profile.

Research Equipment Under Development

The main limitation of the GMR system has been the road-following wheels (26,27). Because the GMR is a mechanical dynamic system, frequency response, and thus profiling speed, is generally limited to 65 km/h (40 mph). To remedy this weakness in the GMR, several noncontact probes have been developed to replace the road-following wheels.

To date, many types of noncontact probes have been proposed that use various radiation frequencies

Figure 10. Electro-optical height sensor as installed on trailer to measure height D.



(acoustic, infrared, white light, laser, and microwave). FHWA is currently investigating two of these, the acoustic and the infrared (see Figures 9 and 10). The acoustic probe is still in a development state (28,29). At present, two projects are under way, one to provide on-board data reduction equipment and the other to provide a rugged version of the probe for everyday road use. The infrared system is now in the evaluation stage. It appears that it will provide a much less expensive probe than the acoustic probe. Further evaluation and development are scheduled. The infrared sensor was developed as a part of a study by the Southwest Research Institute to devise a measuring system for hydroplaning potential. Twelve sensors, mounted transversely on the trailer, measure profile in the longitudinal direction. Each sensor has two differential detectors that produce two voltages proportional to the light intensity received by each half of the detector. The light intensity changes with distance and also with changes in reflectivity within the light spot. The output of one of the detectors is reversed, which has the effect of cancelling the signals for changes in reflectivity but reinforcing them for height changes.

The system also measures acceleration, together with pitch, roll, and yaw rates, to give the motion of the reference frame of the 12 sensors and thus correct the relative measurements in order to produce the 12 road profiles. Processing provides a 1-ft grid from which longitudinal and transverse profile data are available.

A noncontact probe based on white light is being developed by K.J. Law Engineers, Inc., a manufacturer of the GMR-type profilometer. In this approach the noncontact probe (Figure 11) will take the place of the road-following wheel assembly on the profilometer systems now manufactured by that company. The noncontact probe is based on the measurement of the angle at which an incandescent spot, projected vertically down from the vehicle on the pavement, is viewed by the system. A change in the vehicle-to-pavement distance causes a change in the viewing angle that is related to a change in vehicle displacement. A prototype system based on this concept has been built and demonstrated. The displacement measuring resolution of the prototype system has been found to be better than 0.25 mm, which compares favorably with the road-following wheel system it is designed to replace. This noncontact probe has several advantages. The radiated spot or footprint is visible to the human eye, and the shape and size of the footprint can be tailored to the application.

The British Transportation and Road Research Laboratory (1,2,30) is also working on a noncontact sensor (see Figures 12 and 13). This system focuses a laser beam to a 0.282-mm diameter spot and records

Figure 11. GMR profilometer with a noncontact displacement transducer.

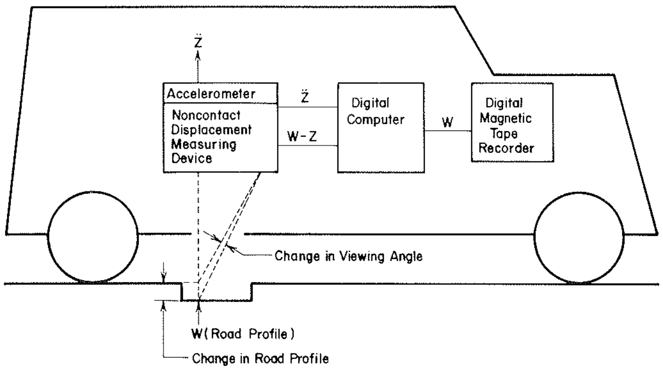
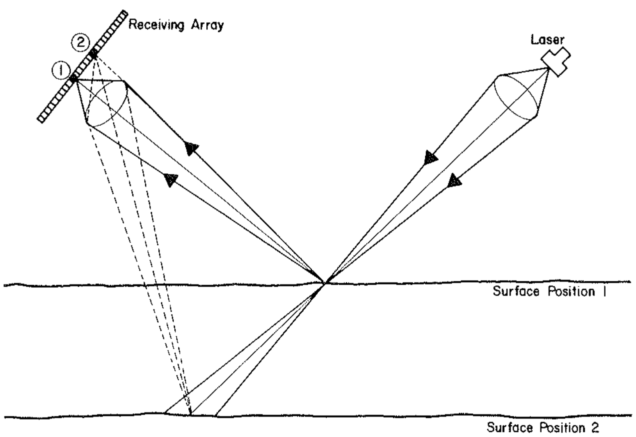


Figure 12. Principle of contactless sensor.



the position of the reflected light spot on a linear array of photocells. The system is claimed to be capable of measuring profile roughness at speeds from 5 to 80 km/h (2). Four noncontact sensors are mounted in line, and the reference is established by computation. Thus, no accelerometer or double integration is required.

Calibration of Devices for Measuring Road Roughness

The time instability in devices for measuring road roughness must be accounted for by calibration procedures that convert their present performance to an established standard performance.

Profilometers, for which dynamic effects are negligible, can be calibrated statically. This can be done directly on surfaces for which the absolute profile has been obtained. In the GMR-type profilometer, the complete system can be calibrated by bouncing the profilometer vehicle in a stationary position. In this mode (Figure 5) the output of the system (W) should be close to zero because there is no change in the road profile. In the early GMR-type profilometers, the quality of system performance was an operator judgment. In the new digital West Virginia profilometer, a computer program guides the operator through the calibration procedures and makes the judgment about the quality of the system's performance.

Calibration of response-type devices for measuring road roughness is a more difficult task. Calibration of response-type devices was addressed in a recent NCHRP project (17) in which the time instability of the response-type devices was evaluated

Figure 13. Construction of prototype profilometer, without polyurethane foam lagging and cover.

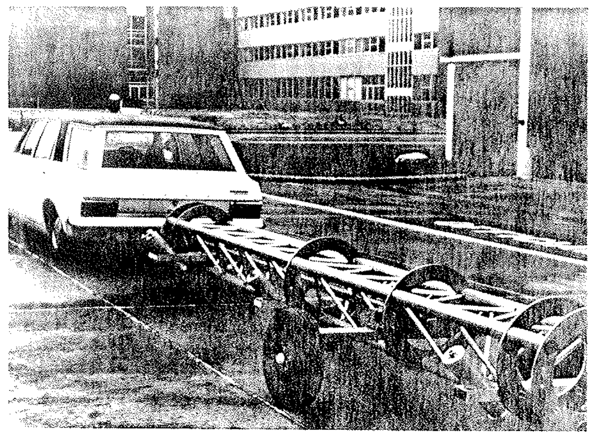
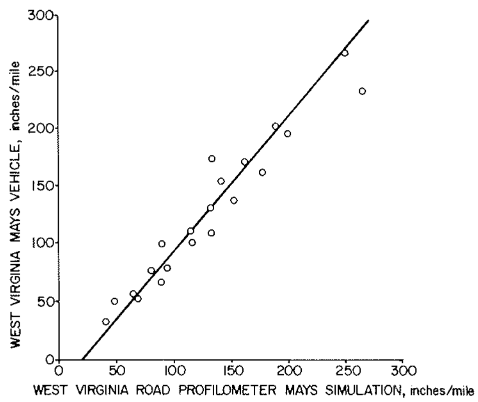


Figure 14. Calibration of West Virginia Mays meter.



and standard calibration procedures were developed. Two procedures were proposed--the primary procedure involves the use of a GMR-type profilometer and the secondary procedure involves the use of a specially designed set of artificial road bumps. In the GMR profilometer approach, the profilometer was used to measure a road profile that was then used as an input to a simulation of a response-type device. The output of the simulation is then the output that would be expected from a response-type device driven on that road profile. Since the output of a response-type device is also a function of road roughness, the same procedure must be done for a range of road roughnesses. A Mays meter calibration capability has been programmed into the West Virginia digital profilometer system, including the simulation of West Virginia's Mays meter vehicle. The resulting calibration for the West Virginia Mays meter vehicle is shown in Figure 14.

The proposed secondary calibration procedure involves driving over a foreshortened set of specially designed artificial bumps at low vehicle speed. The theory is that the system output at the lower speed can be used to calibrate the system output at the normal 80-km/h operating speed. It is also observed that more work needs to be done on this approach.

ROAD ROUGHNESS EVALUATION

Measuring the profile of a road is a preliminary step in evaluating its performance as a riding surface for vehicles and in judging its surface geometry. In recent years the trend in road profilometer design has been toward instruments capable of sensing undulations in the road surface with wavelengths as long as 100 m, and doing this accurately at highway speeds.

Because visual evaluation of the recorded road profile is difficult, the major problem in application is extracting useful roughness data. The methods selected for the reduction of road profile data depend on the ultimate uses for which the roughness measurements are intended and on the inherent limitations of the equipment. Some potential uses of road profile data include the following:

Use	Data
Construction	Specification of surface profile limits in new road construction, evaluation of costs to improve road
Maintenance	Prediction of loss of serviceability in existing roads, establishment of maintenance and replacement criteria
Vehicle behavior	Correlation with vibrational response and fatigue damage in vehicles, development of passenger comfort criteria, evaluation of roughness effects on vehicle steering and braking

Some of these applications require highly sophisticated data processing, which would lead to an entirely mathematical representation of the profile record, for example, of its power spectral density (PSD). Other applications may require only an averaging or summing to establish a single roughness criterion, such as the BPR roughness index. However, departments that have profiling equipment are able, in effect, to bring the road surface into the laboratory and to seek the most useful data-processing method.

Measured records are recognized as random signals of finite duration; as such, they can be viewed and described in terms of three basic domains: space (or time), amplitude, and frequency. The description of the space domain is the unprocessed signal-versus-space (or time). All descriptions of amplitude domain reduce the measured signal to a single number or table of values; this procedure is mathematically equivalent to computing an amplitude probability distribution for the signal. Frequency domain representations of signals are generally considered to contain the most information.

The most commonly used method, the present serviceability index (PSI)(31), is of the amplitude domain type. The equations are determined from subjective evaluations, with one relation for flexible pavement and one for rigid pavement. Both equations are developed to use either the mean slope variance (32) or the roughness index (33) as the required input value to make the PSI calculation. The slope variance is the mean squared deviation of the slope from its mean square, and the roughness value is a reading of inches of displacement per mile of travel.

There are three frequency domain representations used in the analysis of road roughness data: harmonic analysis, PSD, and amplitude-frequency distribution. Harmonic analysis is a representation that assumes that the road roughness data are periodic. This analysis method reduces a complex road roughness wave form to a harmonic series of sinusoidal wave forms that, in effect, are the amplitude contributions of the various harmonics in the road roughness data being analyzed. The computed amplitudes of the various sinusoidal wave forms can be shown graphically as a function of spatial wave length, Figure 3. Representation of harmonic analysis is useful in isolating periodic spatial wave lengths in a road surface that, when driven over at a certain vehicle speed, can produce time domain frequencies that cause poor ride quality.

The PSD representation assumes that the road roughness data are random. PSD shows the extent that spatial wave lengths within a bandwidth contribute to road roughness. A PSD estimate is obtained by accumulating the squared amplitude within a bandwidth over the length of pavement processed, dividing by the pavement length to obtain mean variance over that pavement length, and then dividing by the bandwidth to obtain an average for that bandwidth. A graph of roughness power spectrum can be plotted with the spectral density in meters squared per cycle per meter as the ordinate and the spatial frequency (inverse of the wavelength) in cycles per meter as the abscissa. The area bounded by the curve, the horizontal axis, and any two selected abscissas represent the total mean square value of roughness for wavelengths that lie between the two ordinates. The total area under a power spectrum curve gives the total mean square roughness of the pavement in meters squared or other comparable units. Several researchers, including Hutchinson (34), Quinn (35), as well as the Michigan Department of Transportation, advocate the use of the PSD. In 1965, Vogel (36) reported on the wavelengths and amplitudes of road surfaces. He stated that, if the PSD of road surfaces are plotted on log-log plots, one obtains straight lines that have a slope at a certain angle. Furthermore, parallel shifting of these lines occurs for different road amplitudes that have similar distributions and change in slope shows different distributions.

Amplitude-frequency distribution (AFD) (37,38) is an effective method for combining the information contained in both the PSD and the amplitude representations. The complete array of numbers of the AFD identifies the random signal as a combined amplitude and frequency distribution (AFD) and includes not only continuous or periodic makeup but also singularities in the input.

From the preceding discussion, we can see that response-type equipment, if properly tuned and calibrated, is useful to highway departments for surveying at low cost. However, the profiling methods provide the more detailed information that is needed for research. In fact, the response data are still available and can be predicted with a quarter-car simulation. With the development of new profiling methods, further analysis can be made available from profiles. Although there is a reluctance to use new technology because of the costs involved (new equipment and trained personnel), new methods are being developed to make available more information contained in the profiles. Although there are many useful analysis methods already developed, many methods, like some of those developed by the University of Texas, have yet to be implemented, and others, like those developed by Michigan, are implemented but relatively unknown.

With the development of the digital GMR-type profilometer, processing of road profile data can be performed as the road profile is being measured, or afterwards, by retrieving data stored on digital magnetic tape. Several computer programs for this purpose have been implemented on the West Virginia digital profilometer by the K.J. Law Company, manufacturer of that system. Two of the programs involve the simulation of low-speed inspection devices (BPR roughometer and moving straight edge) to produce the output of these devices without the devices being used. In this approach, road profile can be measured at safe normal traffic speed and the output of the slow-speed inspection device computed as required. This approach also allows the retirement of old, difficult-to-maintain inspection equipment without losing continuity with historic inspection procedures. A third computer program involves the simulation of the Mays meter on response-type device calibration. The Mays meter model used in the simulation was developed in the NCHRP project (17) and is the first implementation of the calibration procedure recommended in this project. A fourth program implemented for West Virginia involves a bituminous fill program developed by Michigan. In this program, the measured road profile is input to a simulation of a bituminous paving machine. The outputs of the program are a graphical representation of the repaved surface and the amount of material required to perform the repaving.

On the other hand, the data of response-type measurement systems cannot be reduced to the absolute roughness profile. Nevertheless, these systems, if properly tuned and calibrated, are useful for surveying a highway system at relatively low cost and with a minimum of data processing. The profiling method could obviously replace response-type measurements but, until the cost of procurement and operation of the two becomes competitive, response-type measurements will be used for the bulk of road survey operations.

Two roughness analysis methods used in Europe have been reported by the Permanent Association of Road Congresses (24). One of the methods, which is now traditionally used in Europe, is the determination of the spectral density of the variations in amplitude level. This method, which is very accurate and carried out by means of a specialized analog computer, is effective for research. The minimum length of a section studied with this method is about 3 km.

The other method is the analysis of the average variance of differences in level from the mean classified for various bands of wavelength. By breaking down the whole scale of the results obtained into 10 bands of wavelength of increasing geometry, a scale of values has been set up that allows simple comparison of results of measurements carried out on various roads. This more primitive but more directly accessible method is well adapted to systematic measurements. The lengths of the sections studied need to be at least 200 m.

STANDARDIZATION OF ROAD ROUGHNESS MEASUREMENTS

Road roughness measurements have been used for many years in construction control and, with the introduction of the roadmeters, surveys for PSI ratings have become widespread. Standardization of the various measurement methods would be helpful to all current users and particularly to potential users who must select equipment and train operators.

The committee on traveled surface characteristics of the American Society for Testing and Materials (ASTM) has recently organized a third subgroup on roughness. The group is now made up of three subcommittees: (a) on methods for measuring profile and roughness, (b) on measurement and control of roughness in construction and rehabilitation of pavements, and (c) on methodology for analyzing pavement roughness. The groups' principal assignment is to standardize the accepted and widely used measurement methods and to serve as a forum for the exchange of information. Candidate measurement methods for standardization include the high-speed profiling devices and the associated data processing methods, the roadmeters, PSI calculations, and the various devices used specifically in construction control.

FUTURE OF ROAD ROUGHNESS MEASUREMENTS

From the above discussion, it is apparent that both measurement methods, profiling and response-type, are useful in meeting the needs of highway departments. The profiling method provides detailed information on the roughness profile, which may be needed for research or experimental projects. This roughness profile can be processed in various ways and can be used in principle to predict the output of any response-type measurement system if its mechanical properties are known. This capability is used by several states to calibrate response-type measurement systems.

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Abridgment

Overview of Road Meter Operation in Measuring Pavement Roughness, with Suggested Improvements

M. SAYERS AND T.D. GILLESPIE

Road meter systems that measure vehicle response to pavement roughness have limited accuracy, but more importantly, cannot be calibrated validly for use on all types of roads without access to a General Motors Research Laboratory-type profilometer. Even with good practice on the part of the users that eliminates the obvious effects of varied tire pressure, cargo weight, faulty components, and the like, limitations inherent to the road meter system remain. These limitations are due to the unique dynamic properties of each vehicle, the nonlinearities inherent to the vehicles and road meter instruments, and nonuniformities of the tire and wheel assemblies. This paper explores various improvements to road meters that will reduce the required calibration effort. The major source of nonlinearities in the vehicle-road meter systems are due to the road meter instruments and can be eliminated by the use of an equivalent electronic meter based on a linear transducer. With linear meters, it becomes possible to measure and correct for vehicle motions caused by tire and wheel nonuniformities. This can be done in the laboratory on a smooth drum roller or by special processing of on-road measurements keyed to wheel rotation as detected by an inductive pickup. However, even then, reference road-type surfaces are still required for calibration to scale the vehicle dynamic response. Only by the addition of accelerometers is it possible to compensate for vehicle dynamic response by simpler means of calibration. With this level of instrumentation, the road profile can be roughly determined and the road meter system has become a crude profilometer.

Road meter systems have become increasingly popular for quantifying pavement serviceability due to their relatively low cost and simple operation. These systems consist of a conventional automobile or special trailer, together with a road meter [such as