TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.
FHWA-RD-73-54

2. Government Accession No.

3. Recipient's Catalog No.
PB 233 172

4. Title and Subtitle
ROAD ROUGHNESS TECHNOLOGY, STATE OF THE ART

5. Report Date
December 1973

6. Performing Organization Code
HRS-12

7. Author(s)
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8. Performing Organization Report No.

9. Performing Organization Name and Address
Protective Systems Group
Structures and Applied Mechanics Division
Offices of Research and Development
Federal Highway Administration

10. Work Unit No.
FCP 21H3-244

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Federal Highway Administration
U. S. Department of Transportation
Washington, D. C. 20590

13. Type of Report and Period Covered
Final report

14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager: Glenn G. Balmer (HRS-12)

16. Abstract

This paper gives an overview of road roughness technology, lists the most prominent equipment used in longitudinal profile evaluations, and discusses uses of the measurements. Several types of roughness measurement equipment are operational for the purpose of measuring riding quality; whereas, development of equipment, data reduction procedures, and meaningful acceptance criteria of roughness for highway safety, for predicting pavement loading from heavy vehicles, and for determining pavement life expectancy have not reached the point where the equipment and procedures are operational for large scale road inventory purposes.

17. Key Words
Road roughness, roughness, highway profiles, profile measurement.

18. Distribution Statement
No restrictions. This document is available through the National Technical Information Service, Springfield, Virginia 22151

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
39

22. Price
3.25-1.45

Form DOT F 1700.7 (8-69)

Form FHWA 121 (Rev. 7-72)

UNITED STATES GOVERNMENT

Memorandum

DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

DATE: May 3, 1974

In reply refer to: HRS-12

SUBJECT: Transmittal of Research Report No. FHWA-RD-73-54, "Road Roughness Technology, State of the Art"

FROM : Director, Office of Research

TO : Regional Federal Highway Administrators
Regions 1, 3-10

This report gives a summary of road roughness technology by discussing measurement systems, methods of analysis, and applications of test results. Roadway safety, riding comfort, pavement impact loads, and serviceability are functions of pavement roughness. Irregularities in the roadway increase the rate of deterioration of the pavement and shorten the service life of the roadway because of environmental effects and traffic.

Information on measurement equipment is tabulated in Table 1 which lists the operating characteristics, limitations, and outputs. Table 2 gives uses of the equipment with consideration of technological developments. An extensive bibliography is available at the end of the paper for those who wish to study particular references on road roughness.

Distributed with this memorandum are sufficient copies of the report to provide a minimum of one copy to each regional office, one copy to each division office, and two copies to each State highway department. Direct distribution is being made to the division offices. Additional copies are available at the National Technical Information Service, Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22151. A small charge will be imposed for each copy ordered from NTIS.

Charles F. Scheffey
Charles F. Scheffey

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I. INTRODUCTION

Road roughness refers to an uneven, impaired, or bumpy roadway. The American Society for Testing and Materials is defining roughness as "The deviations of a pavement surface from a true planar surface with characteristic dimensions greater than 16mm," to distinguish roughness from pavement texture.

Road roughness is important because it affects

(1) the safety of individuals using the highway,
(2) the riding quality of the roadway,
(3) the pavement loading, especially the impact loads from heavy vehicles, and
(4) the remaining service life of the pavement.

The relationship of roughness measurement and analysis to these factors is illustrated in the flow diagram of Figure 1. Loss of control is directly associated with vehicle handling and highway safety, and may result from the condition of the roadway. Pavement roughness, maintenance, and resurfacing influence the serviceability, riding quality, impact loading, and the useful life of the highway. The analysis of impact loading from the dynamic forces of moving vehicles is achieved through mathematical simulation and experimentation on pavements (57, 61). If the roadway characteristics can be measured and analyzed accurately, a systematic program of rehabilitation or reconstruction can be implemented to provide efficient transportation facilities.

Roughness technology may be divided into several aspects, namely, methods of measurement, analysis and interpretation of data, and application of the results. Most of the roughness measurement equipment discussed in this paper relates to the variation in the longitudinal profile of the highway pavement.

Equipment (1,2,3,4,7) to measure pavement profiles varies from a simple 10-foot straight edge to complex electronically instrumented vehicles, and includes rolling straight edges, multiple wheel profilometers, road meters, and roughometers. These devices are used as construction controls, measures of pavement roughness, and means of predicting vehicle response and riding comfort.

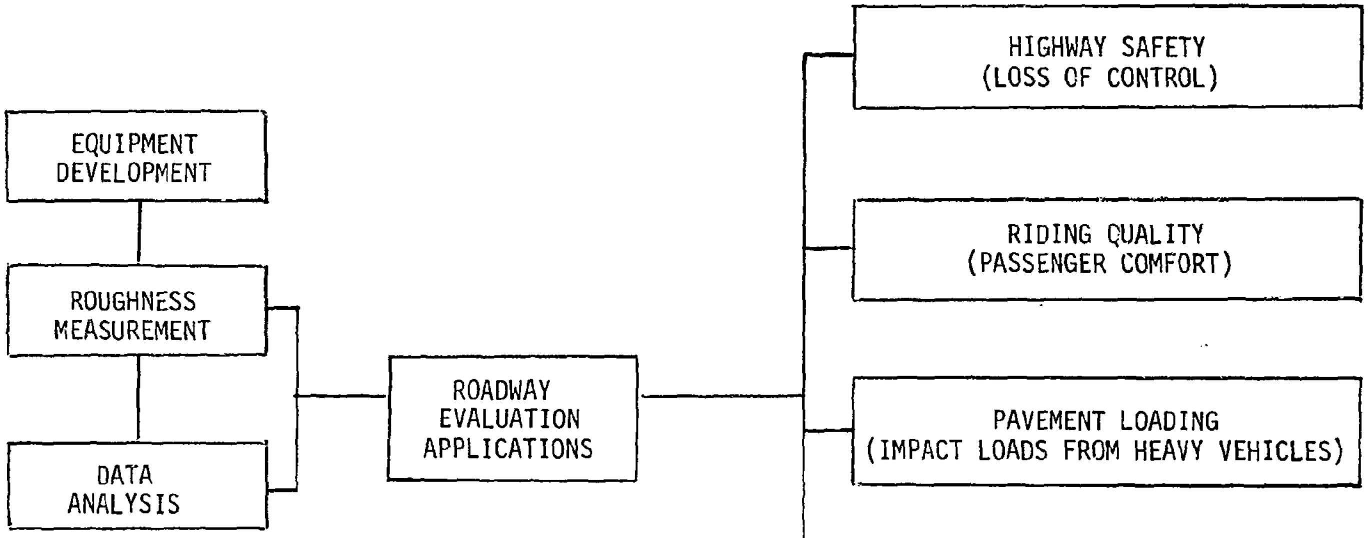


Figure 1. The Uses of Road Roughness Technology.

The data are collected in units convenient to the measuring system and give only comparative values in many cases.

One of the most promising and comprehensive methods (9,11,12,13) of evaluation involves the use of power spectral density analysis. Details of this technique are given in the cited references. Power spectral density analysis gives the frequency (or wavelength) composition of the pavement profile in terms of the associated mean square values of amplitude.

Riding quality and vehicle response depend upon the speed of travel, driver behavior, and vehicle characteristics such as the weight, suspension system, tires, and the type of vehicle as well as upon the roughness of the roadway. The question has been raised as to whether dynamic tire forces can be used as a criterion of pavement condition. Certainly the roughness of the pavement influences the forces transmitted to the tires and the response of the vehicle. Dynamic tire force measurements (11, 15, 16, 61) have been conducted on both passenger cars and trucks.

Applications of roughness technology include safety of the highway (10); pavement design, condition, and serviceability (6, 14, 19, 22, 23, 37, 38); and vehicle performance (17, 18, 21, 24, 61).

II. MEASUREMENT OF PAVEMENT ROUGHNESS

There are a number of devices (1) that have been used or are being developed for appraising highway roughness; the most important of these will be discussed briefly.

A. Straight Edge

The 10-foot straight edge (1) and modifications of it mounted on wheels have been used for many years as pavement construction controls and compliance tools. Further improvements produced multiple wheel profilometers of varying complexity. Most of this equipment is operated statically or at very slow speeds.

B. Multiple Wheel Profilometers

Typical examples of multiple wheel equipment are given in Reference 1, and these have been designated by a variety of names. California has a profilograph that is hand propelled, a version that is power driven, and one that is mounted on a truck. Michigan and Illinois have used this type equipment, and there are several foreign countries that have developed multiple wheel units. The profilogram is a trace recorded from a rolling wheel of the profilograph which represents the profile of the roadway. It is greatly condensed in the longitudinal direction. It is necessary to analyze the trace to determine a profile index. Test Method No. California 526E, "Operation of California Profilograph and Evaluation of Profiles", has been formulated for instructions to field personnel using the test procedure.

C. GMR Road Profilometer

The road profilometer (2, 19, 20, 22, 23, 58, 59, 60, 62) developed by the General Motors Corporation, is a modern system for evaluating pavement surface profiles at traffic speeds. The equipment is instrumented to sense road roughness by spring-loaded road-following wheels mounted below the chassis of a vehicle, to process the measurements (voltage signals) by an analog computer on board, and to record the data on magnetic or a visual analog tape. The tape then can be analyzed and interpreted in a central laboratory at the engineer's convenience. The profilometer is capable of appraising many miles of highway at a rapid rate with a minimum of interference to vehicular traffic; however, the road-following wheel is one of the weaknesses of the system. This wheel leaves the pavement occasionally as it bounces on a rough road, and the wheel deteriorates rapidly from the rigorous wear by the pavement. Both of these irregularities impair the quality of the measurements.

D. Noncontact Profiling System

A noncontact probe (3) to sense road roughness from a moving vehicle is being developed by the Federal Highway Administration. The sensor is an acoustic probe with fixed and variable sound length paths to determine the distance between the instrument and the pavement. It consists of a sound generator and receiver facing the road surface so that the sound transmitted by the generator reaches the receiver after reflection from the road surface. It averages the reflections over a rectangle on the road surface approximating the size of a tire-pavement contact area. The time delay of the sound wave arriving at the receiver is a function of the probe height above the surface. Differences in time delay due to changes in road to probe distances have been validated in the laboratory and the system shows great promise as a measurement technique.

The next increment of research is to install the probe on a highway vehicle and adapt instrumentation to make roadway roughness measurements. The output of the probe is to be combined with the output of an accelerometer through an electronic integrating circuit to correct for the motion of the vehicle, and thus permit the recording of a true roadway amplitude profile. If the research is successful, and we believe it will be, the equipment should provide a fine tool for determining the longitudinal profile of the roadway.

E. CHLOE Profilometer

The CHLOE Profilometer (6, 35, 36, 38) was developed after the AASHO Road Test to measure the slope variance of a pavement. It consists of two essential units, the trailer that carries the transducer mechanism and the electronic computer indicator that accepts information from the transducer, performs a computation on it, and yields the results. The 20-foot trailer is comprised of two 8-inch wheels, 9 inches on center, a roller contact on an upright arm fastened at the pivot point between the wheels, and a printed circuit switch with 29 active segments. The transducer gives a continual measure of the angle between the base connecting the two slope wheels and the reference of the trailer. The slotted disc-photocell combination attached to one of the carriage wheels produces command to sample pulses at 6-inch intervals along the roadway to obtain data on slope variance.

The profilometer measures the slope of the road profile at regular intervals from which the slope variance is computed. The equipment requires calibration and demands the care of a qualified electronics technician occasionally. Tests are conducted between 2 and 5 mph, which necessitates a barricade for redirecting traffic or an escort for protection, and the results are incorporated in Present Serviceability Index (PSI) (6, 36, 37, 38) equations.

A large percentage of the index is obtained from the slope variance; however, cracking, patching, rut depth, and sometimes the texture of the pavement are included in the equations. Separate equations (shown later in the paper) are used for rigid and flexible pavements.

F. BPR Roughometer

The road roughness indicator, a single wheel trailer, developed in the 1930's by the Bureau of Public Roads and now produced commercially (4,5,6,43), has been used by a number of highway departments for many years to evaluate roadway roughness. The equipment, now often referred to as the BPR roughometer, measures the unidirectional vertical movements of the damped, leaf sprung wheel by a mechanical integrator (a ball-clutch mechanism) as the trailer is towed along the roadway. Usually the tests are conducted at 20 mph, and the results are accumulated on mechanical or electronic counters to yield the number of wheel revolutions (distance of travel) and inches of roughness. Testing at this velocity is hazardous especially on modern high speed highways. Another disadvantage of the roughometer is that the measurements do not define the nature of the roughness.

G. Modified Roughometer

Several highway departments (77,78) have modified the roughometer with a cumulative tape recorder, an auxiliary oscillograph, or other equipment. Purdue Research Foundation has significantly changed the measurement system by means of a series of instrumented beams. On a platform above the wheel, four beams with natural frequencies of vibration of 7-1/2, 2, 2/3, and 1/4 cps have been installed on a breadboard prototype. The oscillations of these beams are detected electronically through SR-4 strain gages from the vibrations caused by the wheel traveling over the rough pavement, and the towing vehicle can be instrumented to obtain the test data on a scope, on an analog tape, or on a magnetic tape.

Instrumentation has been completed to measure results from only one beam at a time. A test is conducted with a specific beam at a selected velocity. This yields one data point for the power spectral density graph as shown in Figure 2. (See page 7). To obtain other points, the test is repeated at different velocities with the same beam or with other beams. Instrumentation is to be developed which will measure the results from several beams simultaneously.

The measurement system is protected from disturbance by wind, rain, and other factors by a cover mounted over the equipment during testing. From the tests the amplitudes and

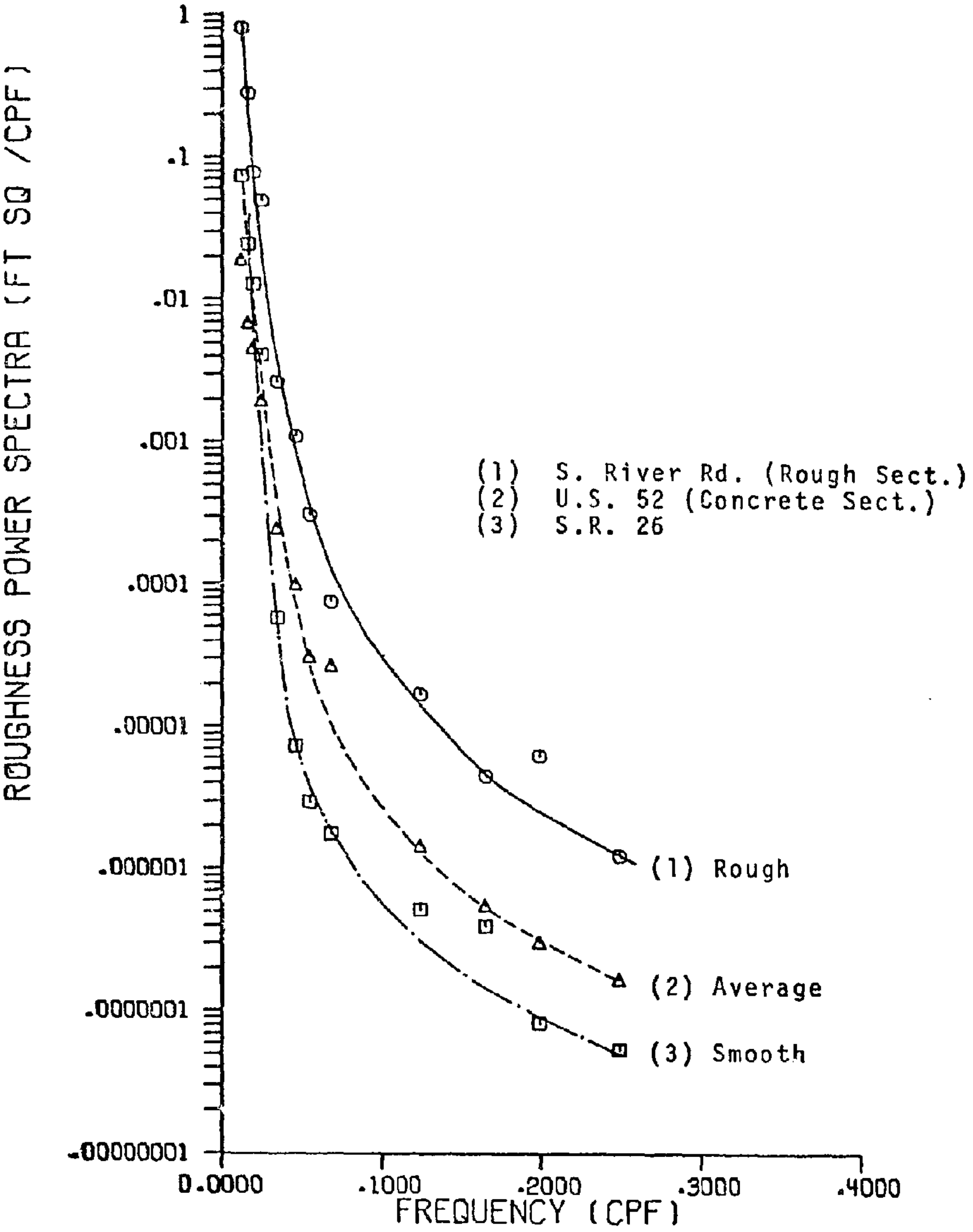


Figure 2. Pavement Roughness Spectra. (From Reference 11.)

wavelengths of the pavement roughness can be determined. Actually the tests measure the amplitude of vibration and the wavelength is calculated from the relationship, $f = \frac{v}{\lambda}$, in which f is the frequency, v is the velocity and λ is the wavelength. With the first three beams, roughness profiles as long as 100 feet in wavelength have been obtained. The longest beam with a natural frequency of 1/4 cps has extended the capability of the system to wavelengths of about 230 feet. Most tests are conducted between velocities of 20 and 40 mph.

Prior to installing the beams on the roughometer, the integrator was removed, the damping cylinders were inactivated, and the axle of the wheel was rigidly fastened to the frame of the roughometer. Even the effect of the deflection of the tire was removed by electrical filtering in order that the vibrations of the beams would represent the true roughness characteristics of the roadway.

Tests have been conducted (11, 12) successfully with the modified roughometer. Further research will improve this system of measurement, and it will then be ready for implementation.

H. <u>Road Meters</u>

Road meters have been built as a low-cost, rapid method of measuring roadway roughness for inventory purposes. Tests can be conducted at 50 mph or greater; therefore, an extensive road network can be evaluated in a few months.

Roughness measurements (25,26,30,31,34,73,74) are obtained from the vertical movement of the instrumented rear axle of an automobile similar to earlier measurements made from the front axle (76); consequently, they are vehicle dependent. Furthermore, they are sensitive to the type of tires, tire pressure, and load; vehicle suspension system and speed of the car; deterioration of the automobile; and other factors that affect vehicle response.

The instrumentation (25, 34) of the test car is relatively simple, and the road meter can be installed in a vehicle with ordinary tools by personnel with mechanical aptitude. The test data may be graphically collected on a strip chart from the excursions of the recording pen or may be accumulated by digital or electronic counters in response to the axle movements.

The tests give comparative values of road roughness, and usually the road meters are correlated (27, 28, 29, 32, 33) with other measurement systems such as the roughometer, CHLOE, or a profilometer to allow interpretation of the data. Correlation checks should be conducted whenever the tires are replaced, whenever there is an extended period of time between tests, and whenever any significant change is made in the test car.

I. Laser Profilograph

The Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico is developing equipment to measure runway profiles by means of a laser profilograph. A horizontal laser beam is transmitted as a reference from a source near one end of a runway. A tracker vehicle some distance from the transmitting source measures the undulations of the pavement as the tracker slowly moves along the runway. Profiles with wavelengths of 400 feet can be measured with precision as it travels 3 to 5 mph.

III. CURRENT EQUIPMENT CAPABILITIES

Information on measurement equipment is summarized in Table 1, and this table gives opportunity for comparison of the attributes and operating characteristics of the equipment.

A. Highway Safety

Table 2 provides subjective ratings for the uses of the measurements. Each piece of equipment listed in the first three columns (the noncontact profiling system, the GMR road profilometer, and the modified BPR roughometer) is capable of measurements which can be analyzed to determine the longitudinal profile characteristics of a roadway for the range of wavelengths which significantly affect tire forces; therefore, each can be applied to highway safety problems as the technology is developed. The influence of pavement roughness on safety has been analyzed for several cases (10,64), and current research is being conducted for other applications. The profilograph yields a description of longitudinal pavement profiles over a limited range of wavelengths. This wavelength limitation makes the profilograph a poor candidate for development for highway safety purposes. Road meters can produce strip chart representations of the relative motion between a vehicle axle and some portion of the sprung mass of the vehicle,

TABLE 1

INFORMATION ON ROAD ROUGHNESS MEASUREMENT EQUIPMENT

EQUIPMENT[a]	DATE OF DEVELOPMENT	STATUS	NORMAL OPERATING SPEED	NO. OF OPERATORS	LIMITATIONS	WHAT DOES IT MEASURE?	DATA OUTPUT	OUTPUT UNITS	DATA ANALYSIS	USE
Noncontact Profiling System	1974	in research	probably 50-70 mph	2	unknown	sound path length change	probably magnetic or analog tape	volts	PSD[b] or AFD	longitudinal profile evaluation
GMR Road Profilometer	1965	operational	40-50 mph	1 or 2	following wheel; cost	vertical movement of following wheel	magnetic or analog tape	voits	PSD or AFD	longitudinal profile evaluation
CHLOE	1961	operational	2-5 mph	2	speed of travel; traffic hazard; wavelength	slope variance	digital computation	$\overset{N}{\Sigma} Y$ ΣY^2	slope variance	pavement evaluation
Modified BPR Roughometer	1967	being improved	20-40 mph	2	speed of travel; traffic hazard	vibration of beams (electronic)	oscilloscope, magnetic or analog tape	volts	PSD or AFD	longitudinal profile evaluation
BPR Roughometer	1940	operational	20 mph	2	speed of travel; traffic hazard; wavelength	vertical displacement of standard wheel	digital count	in/mile	index, rank, or comparison	survey
Road Meter[c]	1966	operational	50 mph	1 or 2	wavelength	vertical displacement of vehicle axle	paper tape or digital count	scaled trace or in/mile	index, rank, comparison, or slope variance	survey
Profilograph[d]	1955	operational	3-5 mph	1 or 2	speed of travel; traffic hazard; wavelength	movement of profilometer wheel	paper tape	scaled trace	index, rank, or comparison	construction control BY survey
Straight Edge	unknown	operational	static	1 or 2	speed of travel; traffic hazard; wavelength	variation from straight line	compliance validation	parts of an inch	compliance	construction control

a - Historical equipment descriptions are given in Reference 1.

b - PSD - Power Spectral Density

AFD - Amplitude-Frequency Distribution

c - Common Types: PCA Road Meter, Mays Ride Meter, Cox Road Meter, Soiltest, Wisconsin Road Meter, Autoflect.

d - Hand pushed, propelled, truck mounted, and other multiple wheel profilometers

TABLE 2

EQUIPMENT MEASUREMENT APPLICATIONS

	Noncontact Profiling System	GMR Road Profilometer	Modified BPR Roughometer	Profilograph	Road Meter	CHLOE	BPR Roughometer	Straight Edge
Highway Safety	NV*	Ø	Ø	NA	NA	NA	NA	NA
Riding Quality	NV	■	Ø	■	■	■	■	0
Pavement Loading**	NV	Ø	Ø	NA	NA	NA	NA	NA
Predicting Pavement Life**	NV	Ø	Ø	0	0	0	0	NA

*Subjective evaluations: NV - not validated, prototype equipment under development; ■ - validated; Ø - applications not fully developed; 0 - of partial use; NA - not applicable.
**Measurements are used in conjunction with simulation studies or other supplemental analyses.

typically the deck behind the rear seat. This relative motion is not the road profile itself. Therefore, this device cannot be used for safety aspects of roughness measurement without accounting for vehicle motion. The CHLOE and the BPR roughometer produce single characteristic outputs which are not directly related to highway safety. The straight edge is used in establishing construction tolerances and of course is not an efficient survey or road inventory tool.

B. Riding Quality

Riding comfort has received early attention from researchers. Because of this, equipment was designed with measurement of road riding quality as a principal objective; hence, most of the equipment listed in Table 2 is capable of accomplishing this purpose quite well.

C. Pavement Loading

One of the chief inputs in the analysis of dynamic loads (11, 57, 61, 65) on roadways is the pavement roughness spectrum. The equipment listed in the first three columns of the table have the capability of providing spectral information; therefore, they are useful for these analyses. The other equipment yields only comparative values of road roughness for the most part.

D. Predicting Pavement Performance

An accurate measurement of road profile is a required input for the purpose of predicting remaining pavement life. Thus, the noncontact profiling system, the GMR road profilometer, and the modified BPR roughometer are candidates for providing this input information into the predictive techniques.

Further discussion of these applications is given in later sections of this paper.

IV. ANALYSIS OF ROAD ROUGHNESS

A. Construction Controls

Tolerances of pavement roughness have been included in construction specifications for several decades. As an example a specification may limit the variation of the surface profile to 1/8 of an inch in 10 feet or to

0.01 foot in 10 feet, and compliance with the regulation can be confirmed by means of a 10-foot straight edge. A rolling straight edge or a profilometer also may be used as a construction control.

Somewhat better specifications have been incorporated in the construction contracts as measurement equipment has become more advanced. Some States specify inches of roughness per mile, for example.

B. Pavement Serviceability-Performance Evaluation

The pavement serviceability-performance concept (37, 38) was conceived during the AASHO Road Test. This concept includes a scale from zero to 5 for present serviceability rating of the pavement.

One method of appraising a roadway is to select a panel to evaluate it. It is a subjective method, and panel members individually appraise the roadway by traveling over it in an automobile at traffic speeds. The members also may inspect the roadway in detail. Definitions of terms and instructions are given to the panel members prior to their appraisal, and the Present Serviceability Rating, PSR, is a mean value obtained from averaging their evaluations. Examples are given in References 37, 38, 39 and others. Experience has shown that ratings above 4.5 are relatively rare and are obtained only for roadways in unusually fine condition. One published paper (39) states, "Primary highways with PSR's of 2.5 or higher and secondary highway pavements with PSR's of 2.0 or higher are acceptable to the traveling public."

C. Present Serviceability Index

In conjunction with the serviceability-performance concept, Present Serviceability Equations were determined for evaluating the roadway. Separate equations are given--one for flexible pavement and one for rigid pavement:

Flexible, $PSI = 5.03 - 1.91 \log (1+\overline{SV}) - 1.38\, \overline{RD}^{2} - 0.01\sqrt{C+P}$

and

Rigid, $PSI = 5.41 - 1.80 \log (1 + \overline{SV}) - 0.09\sqrt{C+P}$, in which

PSI is the Present Serviceability Index,
$\overline{SV}$ is the mean slope variance (6, 37, 38) in the two wheel paths,
RD is the mean rut depth, and
C and P are measures of cracking and patching.

A texture term (6, 45) may be included in the flexible pavement equation which changes it slightly. Other variations in the equations are given in Reference 23.

D. Slope Variance

The variance of the slope, SV, of a longitudinal pavement profile is the mean squared deviation of the slope from its squared mean, and it is computed from the formula (35, 38),

$$SV = 8.46 \left[\frac{\Sigma Y_i^2}{N} - \left(\frac{\Sigma Y_i}{N} \right)^2 \right] - 3.0, \text{ in which}$$

SV is the slope variance,
Y_i is the i^{th} slope measurement, and
N is the total number of measurements.

The CHLOE may be employed as one method for measuring slope variance (35, 37, 38).

E. Roughness Index

The roughness value, inches per mile, obtained from readings by the roughometer has been defined as the Roughness Index. Much data have been collected by using the roughometer, and these data may be interpreted as comparative values of road roughness.

They also may be used to approximate the PSI through the equation (5),

$$PSI = 5.00 - 0.015R - 0.140 \log R, \text{ in which}$$

PSI is the Present Serviceability Index, and
R is the Roughness Index.

Correlation studies (39) have been made between serviceability ratings obtained from the roughometer and from panel evaluations by means of regression analysis, and favorable results were obtained for rigid pavements. Roughometer measurements did not yield quite as good predictions of PSI for flexible pavements. Other comparison results are given in Reference 54.

F. Pavement Rating

The following table has been compiled as a guide for riding quality of newly constructed rural Interstate pavements (40, 41):

TABLE 3

Road Roughness Rating Table
(Newly Constructed Rural Interstate Pavements)

Adjective Rating	Present Serviceability Index	BPR Roughness Index Flexible Pavement Inches Per Mile	BPR Roughness Index Rigid Pavement Inches Per Mile
Outstanding	Above 4.5	Below 54	Below 67
Excellent	4.5 - 4.1	54 - 66	67 - 82
Good	4.1 - 3.7	66 - 82	82 - 100
Fair	3.7 - 3.3	82 - 102	100 - 121
Poor	Below 3.3	Above 102	Above 121

Notice separate columns are given for flexible pavement and for rigid pavement, and the serviceability indices assigned to the adjective ratings are above the values quoted from Reference 39.

The following table along with other considerations has been used by Maryland as a reference when programming resurfacing of roadways (40).

TABLE 4

Guidance for Resurfacing

Highway Classification	BPR Roughness Index for Resurfacing
Interstates	165 - 180
Primary and Secondary	180 - 200
Other Rural	200 - 220

It should be emphasized that the criteria and tables discussed in the previous paragraphs were developed from experience and judgment. Not all State highway departments necessarily adhere to these criteria. In a number of cases, they have developed criteria of their own.

For example, Kentucky (42) has conducted testing with automobiles by determining the vertical accelerations of a passenger. A roughness index is obtained from these measurements, and the pavement age and cumulative traffic influence the results. (See later section of the paper for more detail.)

Idaho (33) adopted the following table to rate pavement roughness from measurements made by the PCA Road Meter:

TABLE 5

Roughness Rating

Adjective Rating	Roughness Count
Very Smooth	0 - 250
Smooth	250-500
Slightly Rough	500 - 1000
Rough	1000 - 2000
Very Rough	Over 2000

Brokaw (25) computed the sum of squares of road-car deviations measured by the PCA Road Meter to compare the measurements with the slope variance obtained with the CHLOE, and test results showed that the equipment can be correlated with satisfactory precision.

NCHRP Report 7 (44) gives various methods of appraising pavement condition and discusses their merits and the equipment employed in conducting the measurements.

G. Power Spectral Density Analysis

The power spectral density analysis of pavement profiles is one of the current evaluations of longitudinal roadway roughness. It may be obtained from tests conducted on the highway by the modified roughometer, the GMR road profilometer (19), or other equipment, including the noncontact probe when it is completed, and can be represented as shown in Figure 2. (See page 7.) Each data point is the mean square amplitude for a frequency band measured during the testing.

Two analytic procedures (11), the Indirect Method and the Fast Fourier Transform Method, are available for determining power spectra.

Information on the calculations required to compute curves of this nature is given in References 9, 11, and 13, and power spectral techniques are discussed in References 7, 12, and 14. A graph of a roughness power spectrum can be plotted with the ordinate as the spectral density in feet squared per cycle per foot and with the abscissa as the frequency (inverse of the wavelength) in cycles per foot. The roughness spectrum shows the extent to which various wavelengths in the pavement profile contribute to the roadway roughness. The area bounded by the curve, the horizontal axis, and any two selected ordinates represents the total mean square value of roughness for wavelengths lying between the two ordinates. The total area under a power spectrum curve gives the total mean square roughness of the pavement in feet squared or other comparable units.

H. Amplitude-Frequency Distribution

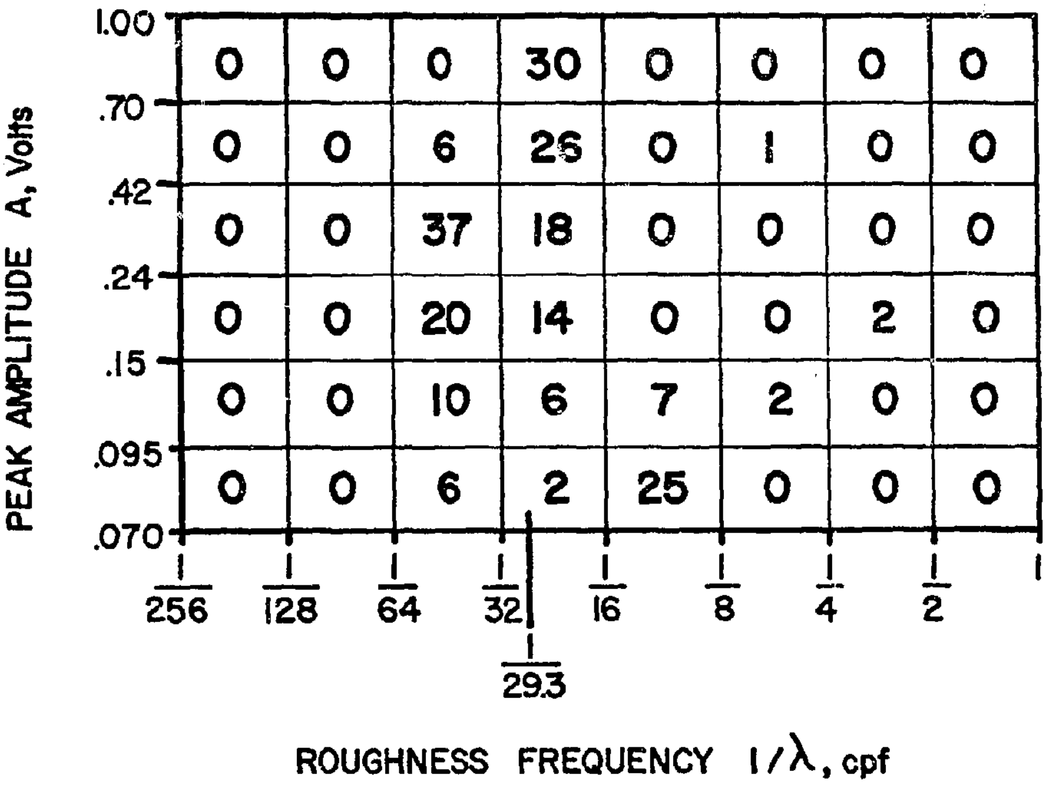
A tabular representation of road roughness, the Amplitude-Frequency Distribution (AFD), (48, 49) has also been developed for summarizing profile data. The tape recorded profile signals obtained from roughness measurements by the GMR profilometer, the modified BPR roughometer, or the noncontact profiling system can be reduced to tabular form by data processing procedure. Each entry in a table (see Figure 3--from Reference 48) gives the equivalent number of cyclic "bumps" of a given height (volts) and wavelength from the measurements. This analysis shows a distribution of the values for a particular frequency band in contrast to the power spectral density analysis which shows only a mean value for each frequency band. The AFD method has not been used as extensively as the power spectral density analysis, but it wi'l become better known as engineers recognize its merits.

I. Harmonic Analysis

Harmonic analysis (58, 75) has also been used in the interpretation and representation of profile data. It is useful for evaluating periodic or repetitive wave patterns.

J. Data Processing

Data processing and analysis techniques have been developed (23, 48, 49, 60, 75, 79) to change information obtained from roughness measurements to a usable form for rapid interpretation. The roughness data may be collected (62) on magnetic tape or visual analog tape and converted to



0	0	0	30	0	0	0	0
0	0	6	26	0	1	0	0
0	0	37	18	0	0	0	0
0	0	20	14	0	0	2	0
0	0	10	6	7	2	0	0
0	0	6	2	25	0	0	0

Figure 3. Amplitude-Frequency Distribution.
(From Reference 48. See Reference 49 for other examples.)

digital print-out by data processing procedures. In some cases the electronic equipment is mounted on-board to provide digital results immediately; whereas, in other instances the data reduction is completed in a central laboratory.

K. Quarter Car Simulator

Longitudinal road profile measurements, recorded on magnetic tape, can be used as inputs to a quarter car simulator (80). The computer is programmed to analyze the roughness data obtained at various speeds, for example, 20, 40, or 60 mph and simulate a roughness index. The simulator is correlated with the BPR Roughometer so as to interpret the data with measurements conducted at 20 mph. It can also be correlated with other test equipment to give readouts of jerk, acceleration, vertical displacement, or tire forces for a vehicle. The quarter car simulator provides a method of analysis of road roughness data.

V. APPLICATIONS OF ROUGHNESS TECHNOLOGY

A. Highway Safety

Highway safety is dependent upon vehicle steering, stability, directional control, braking, and skid resistance, and each of these is significantly influenced by pavement roughness.

The lateral friction force on a tire is a function of normal load, camber, and slip angle as well as of the vehicle speed and the pavement surface characteristics. This force is involved in cornering, passing maneuvers, and vehicle handling. The irregularities of the pavement cause variations in the normal load on the tire as the vehicle travels over the roadway which result in variations in the lateral force. Dynamic tire forces and their influence on vehicle handling characteristics have been investigated by several researchers (10, 11, 12, 16, 17, 64, 71, 72), and the force increases as the normal load increases but at a decreasing rate.

Thus, the loss in normal load on the inside wheels of a vehicle from the tendency to roll due to centrifugal force during cornering or passing causes a decrease in the lateral force. A compensating increase in normal load is produced on the outside wheels, but as the relationship between normal load and lateral force is nonlinear only part of the lateral force loss is recovered by the outside wheels. Therefore, a net loss in lateral force is experienced during cornering.

If the pavement is rough (11, 64) , further loss in the lateral force occurs from the dynamic reactions of the vehicle during cornering. Drivers correct for this effect by increasing the steering angle. The decrease in lateral force due to roughness is especially critical when the driver must complete a passing maneuver quickly to avoid collision with an approaching vehicle.

If the tire bounces leaving the roadway, the friction forces are entirely lost instantaneously. In an extreme case complete loss of control may transpire and the vehicle may leave the roadway, collide with another vehicle, or collide with some other object.

The decrease in friction forces due to road roughness is not restricted to cornering but is similarly experienced on tangents. Rough pavements cause a loss in braking and traction forces because of the variations in the normal load on the tires as the vehicle bounces or tends to pitch and roll from the undulations of the roadway.

The roughness of the road causes vibration of the vehicle and induces pitching and rolling tendencies. Frequencies of the roughness induced excitation near the "tire hop" resonant frequency cause the vehicle dynamic responses to be intensified and "tire hop" or "freeway hop" may result. This has a pronounced bearing on directional control as well as on braking and traction.

The following quotations from a research report illustrates the significance of roughness to highway safety.

"Results show simulated roughness amplitude and frequency to have a strong influence on the average force available for braking: at 0.04 in. and 14 Hz, there was a 30% loss of friction while at 0.71 in. and 6 Hz, a 90 % loss was observed.

"The most important conclusion reached is that friction predictions without road profile consideration can result in gross errors and may be one of the causes for lack of correlation of friction data." (64)

Friction loss also occurs and the braking distance is increased further if the pavement is slick from moisture, ice, snow, or other lubricants. Furthermore the traction varies from wheel to wheel because the lubrication and roughness are not uniform which may result in instability or loss of directional control. This may induce the vehicle to go into a spin.

B. Riding Quality

Even though an accurate roughness analysis of the pavement is obtained, this alone is not sufficient to ascertain the response or the riding comfort of the vehicle. The latter is also a function of the speed, vehicle type, weight, suspension system, seat mounts, spring constants, human sensitivity, and other factors; therefore, the response and riding quality will vary from vehicle to vehicle.

Not only the spectrum of road roughness must be obtained, but the characteristics of the vehicle must be determined to predict vehicle response. One way to investigate the characteristics of a vehicle is to instrument the rear axle housing as described in Reference 11 and operate the vehicle on several roadways with known roughness spectra. The excitation of the sprung and unsprung mass of the car as it travels along the roadways produces a realistic evaluation of the vehicle frequency response characterisitics.

In a similar manner, it is possible to determine the vehicle characteristics from a vibrating platform in a laboratory. Programmed sinusoidal excitations of the platform induce vibrations to the vehicle comparable to those of a roadway.

There are also other techniques (15, 46, 47) for determining the vehicle response such as measurement of the tread displacement or the fluctuation of the tire pressure during travel over rough pavement; however, these approaches are complicated by changes in temperature.

After the vehicle characteristics and the road roughness spectrum have been obtained, these are used to determine the force power spectrum (the vehicle response), and Purdue Research Foundation has determined the dynamic tire forces as one form of vehicle response. This approach is represented mathematically and shown schematically in Reference 11 and elsewhere.

The subjective method of appraising the riding quality of a pavement by panel evaluations was discussed in an earlier section of this paper.

Riding comfort criteria have been expressed in terms of displacement, velocity, or acceleration. Kentucky (42) has quantified this reaction by analysis of jerk. Jerk is defined as the derivative of acceleration with respect to time, and the magnitude may be represented in g's (g-gravitational acceleration) per second. No single parameter is recognized as the appropriate measure of riding quality. It depends upon human sensitivity as well as upon the roughness of the road and the vehicle characteristics.

Comparisons have been made of the relationship between jerk and the road roughness at various speeds. Riding comfort in the Kentucky tests was determined with passenger cars and trucks, and, of course, there was a difference between loaded and unloaded trucks.

Early in the investigations, a triaxial accelerometer (70) was developed to measure the riding quality of a roadway. The accelerometer was hung around the neck and rested on the chest of the observer, and measurements of riding quality were made with the equipment as the passenger traveled over the roadway in a vehicle.

Test results show that both traffic and age influence the riding quality of pavements. Deterioration from traffic is dependent upon the frequency and weight of the vehicles traveling the roadway, particularly heavy trucks, and upon environmental factors. Moisture present in the pavement and in the foundation of the roadway has a significant influence on pavement deterioration and on the development of roughness. Expansion, contraction, warping, and spring break-up from freezing and thawing, temperature changes, and from wetting and drying are some of the principal environmental effects related to roadway change. Additional research is needed to quantify riding comfort accurately.

C. Pavement Loading

Dynamic reactions of heavy vehicles (61) as a result of pavement roughness can double the static loads of the vehicles.

A comprehensive study (57) of the dynamic forces acting on a pavement from moving loads utilizes mathematical simulation and digital computation to predict the magnitude and position of the normal components of dynamic wheel loads. A natural road profile or a simulated roughness consisting of bumps with different sizes and arrangements in each wheel path is used as input to this program. This model provides a tool to investigate the loading reactions of the pavement from the operation of heavy vehicles on a rough roadway.

Studies on fatigue of bridges from heavy loads are presented in References 55 and 56. The heavy loads in these studies produce stresses in the roadway that affect the life of the pavement also.

Airplane dynamic wheel load effects (69) on runways have been investigated by scaled pavements tests, analyses, and correlation between empirical data and analyses.

D. Predicting Pavement Performance

The performance and service of a pavement are related to traffic, environment, and roadway roughness.

Extensive nomographs (66) have been developed with information obtained from the AASHO Road Test for estimating pavement life and serviceability.

Road irregularities cause impact loads from traffic which increase the stress on the pavement. Heavy trucks (57, 61, 65) are especially detrimental in accelerating the deterioration when the pavement is faulted, rough, or cracked.

Research has been conducted on determining cumulative damage and pavement serviceability, and a computer model (50) (VESYS II) is being developed to predict serviceability from parameters associated with pavement condition and traffic.

Environmental cycles of wetting and drying, freezing and thawing, and spring break-up along with pavement loading have a pronounced effect on the life of a roadway.

VI. ADDITIONAL RESEARCH NEEDS

A. Noncontact Profiling System

Research now underway includes the completion of the noncontact profiling system with validation on the roadway. This should provide a useful system for evaluating the longitudinal profile of the roadway at traffic speeds.

Modifications to this system or a new system should be developed to measure the transverse roughness of the roadway from a moving vehicle. Rutting of the pavement will be included in these measurements.

B. Data Reduction Techniques

In addition to the measurement of roughness, the data must be processed, interpreted and applied. There is a need for further research on improvement of data reduction techniques -- better methods of reducing the data to useful form quickly. Additional applications made possible by rapid interpretation will enhance the value of the measurements.

C. Vehicle Handling

Further research should be conducted on vehicle handling, control, response, and riding comfort as related to pavement roughness and highway safety. Measurement techniques should be developed to yield quantified test results. A simulation model should be programmed which can be used to determine the vehicle characteristics of any car traveling the roadways -- from small vehicles to deluxe heavy weight cars. The purpose of this simulation is to obtain information that can be applied with a pavement roughness spectrum to predict the vehicle response, the force power spectrum. Sufficient parameters for each car should be identified to define the vehicle characteristics when employed as inputs to the simulation. These results will then be extended to the riding quality of the roadway or to riding comfort.

Consideration also needs to be given to commercial vehicles such as buses, trucks, and semitrailers. Such research would not only provide information on riding quality of the roadway, but would improve the understanding of the influence of roughness on heavy vehicle response.

The Federal Highway Administration has plans to investigate the effects of pavement grooving and finishing striations on vehicle control, response, and braking. The grooving is to include channels produced in plastic concrete by special built machines with vibrators as well as by saw cuts in hardened pavements.

D. Roughness Criteria

Finally roughness criteria for various roadways are needed. It may be that these criteria will vary for the different classes of roads or they may be based on roughness that can be tolerated for the maximum speed limits of the highway. Corrective action will be required when these criteria are exceeded. These values should be determined from a broad knowledge of roughness technology coupled with experience in the real world.

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