Measurement of Road Roughness in Australia

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After the introduction of vehicle-based systems of road roughness measurement in the United States, a survey was made of such systems in Australia. The qualities sought were simplicity, trouble-free operation, and ability to predict the present serviceability rating of pavements (as determined by a panel of drivers). Two systems were selected for field trials: the PCA road meter and the Mays road meter. An apparatus was then developed that combines features of both meters. This apparatus and its operation are described in this paper. Development of improved methods of displaying, recording, and storing data as well as a method of obtaining a continuous trace of body-axle displacement is also described. Current use of roughness data in Australia and possible future applications are discussed. An area of concern common to all systems that are based on the measurement of body-axle displacement is the establishment of a standard against which vehicles can be periodically checked. Efforts made in Australia to overcome this problem are described.

To determine the extent to which individual sections of a road network are fulfilling their functions and to determine those sections of the network that need improvement, a method of quantitative assessment of condition is required. Carey and Irick (1), in the design stage of the AASHO Road Test, developed the concept of the condition of a section of road as its "ability to serve the needs of the user." Condition defined in this manner depends predominantly on the quality of the ride experienced by the road user. The changing performance of a road is then reflected by change of condition with time and traffic.

The term present serviceability rating (PSR) was introduced to quantify this measure of condition. To determine the PSR of a section of road, a panel of drivers representative of the driving population travel over the section. Each driver is asked to rate the section on a scale from 0 (very poor) to 5 (excellent). The mean of the panel's ratings is the PSR of the section.

Because of the time and expense involved in conducting such a rating exercise over substantial lengths of a road network, considerable effort has been expended in developing instruments capable of measuring characteristics of the road that can be correlated with PSR. The estimate of PSR from such a measure is called the present serviceability index (PSI). Several types of instruments are currently being used by highway organizations throughout the world. Australian experience in this field is described in this paper.

DEVELOPMENT OF ROUGHNESS MEASURING DEVICES

The first instrument developed to quantify a road surface profile was the CHLOE profilometer (2). This instrument, which was developed in association with the AASHO Road Test, measures the surface slope for each 150 mm (6 in) of travel by means of two rigid wheels in contact with the road surface. A computer calculates the variance of the slopes. The system is based in a long trailer and operates at a travel speed of 8 km/h (5 mph). Because of the slow travel speed and the effect on the results of coarse surface texture (sprayed seals), the instrument has been little used in Australia. However, the Australian Road Research Board (ARRB) possesses an instrument for research purposes (3).

Another device developed was the U.S. Bureau of Public Roads (BPR) roughometer—a single-wheel trailer towed in a wheel path (usually the outer) and capable of a travel speed of 32 km/h (20 mph). The roughometer sums displacements in one direction between trailer wheel and frame, expressing roughness in (U.S. customary) terms of inches of displacement per mile traveled (2).

General Motors (GM) developed a considerably more elaborate and expensive device—the GM road profilometer (4)—a vehicle-based system capable of determining road profile. The acceleration of a solid wheel in contact with the road surface is measured relative to an inertial reference. Double integration of this acceleration with respect to time produces the required profile. The vehicle is capable of operation at 80 km/h (50 mph).

Because of the advantages of a vehicle-based system that operates at highway speed and the cost and complexity of the GM profilometer, other, simpler systems were soon developed. The two most widely used are the Mays road meter (5) and the Portland Cement Association (PCA) road meter (6).

Output of the Mays meter is in the form of a graph of individual displacement between vehicle body and axle versus total body-axle displacement. Thus, the roughness of a section of road is determined by measuring the length of the graph generated by the section. The PCA meter also measures body-axle displacement in a vehicle. The amplitude of each individual displacement is measured to the nearest 3.1 mm (0.125 in) by means of a roller traversing a plate segmented in 3.1-mm intervals; the roller is attached to the vehicle axle, and the plate is attached to the vehicle body. A common configuration uses a plate composed of 23 segments. The segments are electrical conductors, and those equidistant from the central segment are connected together. Associated with each pair of segments is a digital counter (total of 11 counters). When the roller contacts a segment, an electrical connection is made and the count on the corresponding counter is increased by 1.

Before fieldwork begins, the plate is adjusted to bring the central segment in contact with the roller (the vehicle is stationary on level ground). Testing is conducted at 80 km/h (50 mph). The PCA value of a section is determined from the counts by means of the following formula:

$$\text{PCA value} = [(1 \times \text{counter } 1) + (2 \times \text{counter } 2) + \ldots + (N \times \text{counter } n)] \times (1/8) \div \text{distance} \quad (1)$$

where distance is derived in miles. This value is related to the time-based variance of the axle-body displacements. Scala (3) has reported early Australian experience with this device.

AUSTRALIAN DEVELOPMENTS

The development of roughness meters was followed with considerable interest by road authorities in Australia, and in 1969 the National Association of Australian State Road Authorities (NAASRA) and ARRB established a joint subcommittee to report on currently available systems with a view to adopting a system for use in Australia.

The subcommittee was also asked to make recommendations on any modifications it considered desirable. Because a considerable portion of the Australian road network is in sparsely populated areas, emphasis was placed on reliability and simplicity of operation in addition to ability to predict PSR.

A detailed investigation of the PCA meter was carried out and reported by Scala (3). Two major difficulties were experienced: The zero position of the meter (and thus the roughness value) changed with grade and with fuel use, and it was found that the shortest interval of distance in which counter readings could be continuously recorded was approximately 0.8 km (0.5 mile). However, for maintenance and reconstruction programming applications, it was considered desirable to monitor roughness in intervals as short as 0.2 km (0.12 mile). Maintaining satisfactory electrical contact between roller and plate segments, particularly in dusty conditions, was also a problem. In the case of the Mays meter, the main objection centered on the office work involved in measuring up to 1000 strips of paper for each day's field testing.

To overcome these difficulties a device was developed (with the guidance of the subcommittee) that translated the axle-body displacement into rotation of a shaft. Clutches were incorporated to allow one-way-only rotation of the shaft (corresponding to downward displacement of the axle relative to the body), and a mechanical revolution counter similar to a vehicle odometer was attached to the shaft. By means of this system, the degree of roughness of a section of road is obtained by subtracting the reading of the revolution counter at the start of the section from the reading at the end of the section. This difference divided by the section length in kilometers gives a roughness value in counts per kilometer. Details of the meter, designated the NAASRA roughness meter, are given in a technical manual that contains full operating instructions (7).

The meter is mounted in a "station sedan" (i.e., station wagon), directly over the differential. A thin steel cable, attached to the housing of the differential, passes through the vehicle floor and is attached to a length of bicycle chain. The latter passes over a sprocket to a tension spring attached to the vehicle body (Figure 1). The sprocket is attached to a shaft by a sprag clutch, which allows rotation of the shaft in only one direction. A second sprag clutch is incorporated between shaft and meter housing to eliminate backlash. A speedometer type of flexible drive connects the shaft to the counter, which is located in the glove compartment of the vehicle. An accurate mechanical odometer is also housed in the glove compartment adjacent to the roughness counter (Figure 2).

After successful preliminary trials, a detailed study was conducted to determine the effect on roughness count of vehicle type, test speed, ballast, tire type and pressure, road surface texture, and vehicle driver (8).

Correlation of NAASRA Meter With PSR

Studies were carried out in four of the six Australian states to determine the correlation of the NAASRA roughness meter with PSR. Panels consisting of approximately 15 highway engineers were selected. Each panel member rated approximately 30 rural and 30 urban sections. Each section was approximately 0.8 km (0.5 mile) long and of uniform roughness. Sections differed in roughness over a smooth to rough range and encompassed a representative range of pavement widths and types. Rural sections were traversed at 80 km/h (50 mph) and urban sections at 50 km/h (30 mph).

In rating a section, a panel member was required to assign a number between 0 (very poor) and 5 (excellent) to the section. The PSR of the section was the mean rating for the sections. NAASRA roughness values (counts per kilometer) for each section were taken as the mean of four runs. Figures 3 and 4 (8) show typical results obtained. On the basis of these studies, it was concluded that the correlation of the NAASRA roughness meter with PSR was comparable to that of other systems based on the measurement of body-axle displacement. Further details are given elsewhere (8).

Tolerability Rating of Pavements

During the PSR rating of pavements outlined above, additional information was sought from each panel member.

Figure 1. NAASRA roughness meter fitted in vehicle.

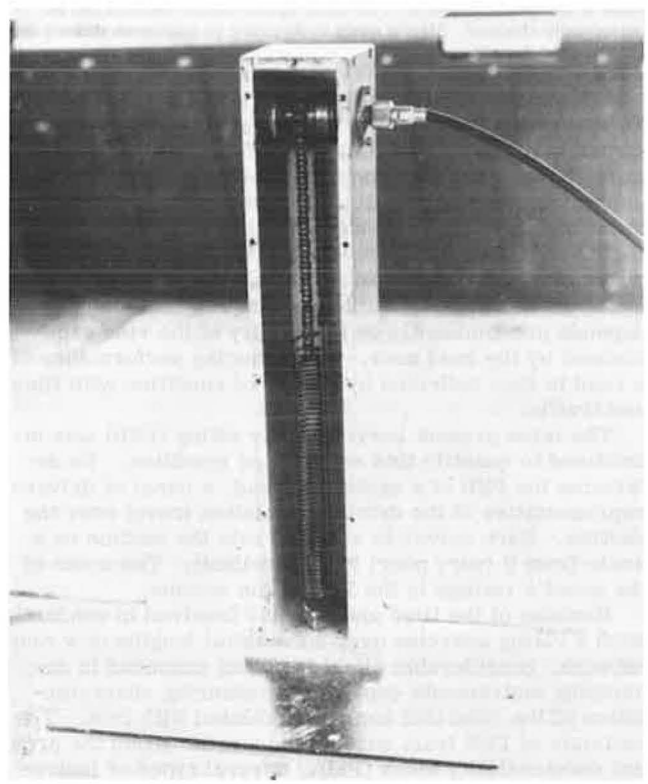


Figure 2. Roughness counter and odometer in glove compartment of vehicle.

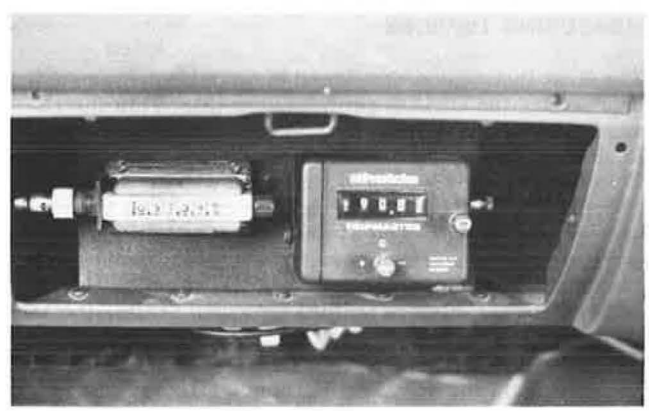


Figure 3. PSR versus NAASRA roughness values at 80 km/h (50 mph).

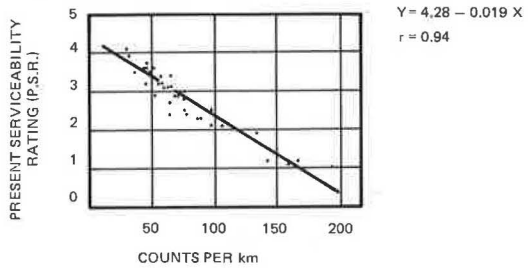
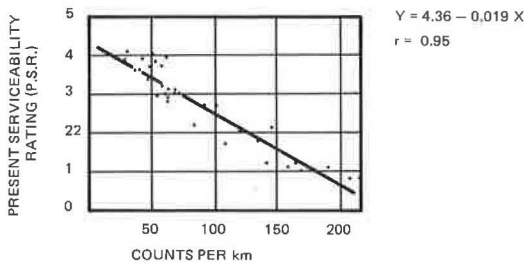


Figure 4. PSR versus NAASRA roughness values at 50 km/h (30 mph).



After the panel members traversed each rural section, they were asked the following questions:

1. Assuming that you have to drive at 80 km/h (50 mph) for 320 km (200 miles) on a highway, is the pavement of acceptable quality?
2. Assuming that you have to drive at 80 km/h (50 mph) for 80 km (50 miles) on a main road, is the pavement of acceptable quality?

After the panel members traversed each urban section, the following question was posed:

3. Assuming that you are on an urban arterial that has a 60-km/h (35-mph) speed limit and you have to drive 32 km (20 miles) in heavy traffic, is the pavement of acceptable quality?

The purpose of this exercise was to determine the maximum NAASRA roughness value (or minimum PSI) for each class of road that could be considered a tolerable limit. Responses to the questions were analyzed, and 50th percentile values (i.e., NAASRA roughness values considered acceptable by 50 percent of the rating panels) were determined. These values were adopted by the NAASRA subcommittee as tentative maximum tolerability limits (1 km = 0.62 mile):

Class of Road	NAASRA Roughness (counts per kilometer)
Highways	110
Main roads	150
Urban arterials and subarterials	175

Roughness Data

Recording and Storage

After the NAASRA roughness meter was accepted by the state road authorities, the device gained rapid acceptance as a routine road survey tool. During this phase it became apparent that, because of the large quantities of data being generated, more sophisticated methods of data collection and analysis were needed. A fully automated system was developed and constructed by ARRB in 1971 and 1972. In this system, the desired distance interval for roughness measurement (0.1, 0.2, 0.5, or 1.0 km) may be preset. Travel time, roughness, and distance from the starting point are automatically recorded for each interval on computer-compatible punched paper tape. This information can also be recorded at any mid-interval position by use of a manual keyboard that consists of 16 alphabet characters. During operation, a record of the alphabet character and the time, roughness, and distance information are placed on the punched tape by the pressing of a key.

A coding system is used that associates each alphabet character with a road feature of special interest. Thus, by use of a suitable computer program for processing the data, roughness associated with special road features such as railway level crossings, stock grids, bridges, culverts, and construction zones can be isolated. This feature can also be used to indicate a change in pavement surfacing or test speed. A printer is supplied with the equipment so that data can be assessed on the spot. Figure 5 shows a schematic diagram of the system, which has been used in Australia for routine survey work for approximately 4 years (7).

A prototype that performs the same function but incorporates improved electronic circuitry and cassette tape recording is currently undergoing field evaluation. This unit is considerably smaller in size and requires significantly less power to operate.

Two additional recording systems have also been developed that, in sophistication, fall somewhere between the standard NAASRA roughness meter and the fully automated system. The first of these has the ability to "hold" on a digital display the roughness reading for the preceding distance interval. The additional time afforded the operator to record the roughness value considerably reduces operator fatigue. The unit is compact [approximately 75 × 100 × 125 mm (3 × 4 × 5 in)] and is mounted under the glove compartment of the vehicle. The second system has capabilities similar to those of the fully automated version except that output data are available only in a printed (not computer-compatible) form. This unit is also compact and is located in front of the operator.

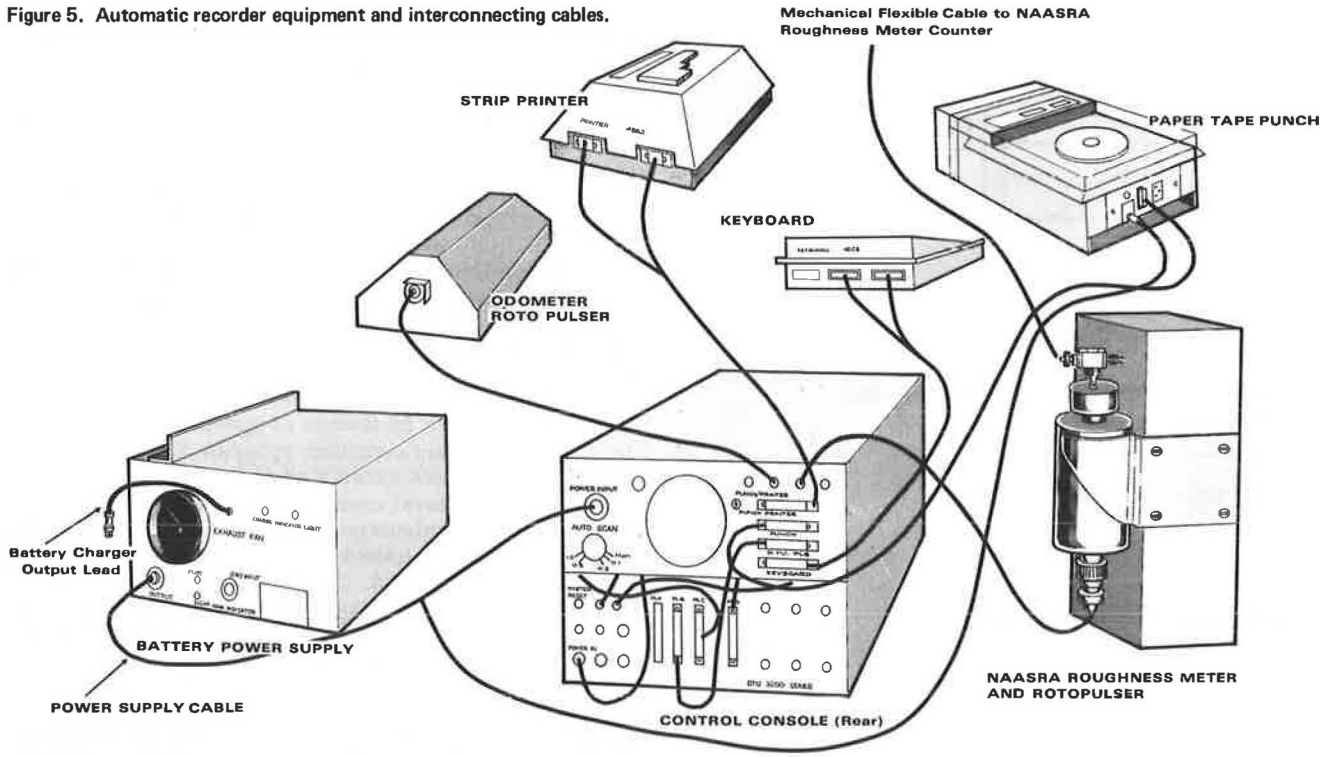
Continuous Trace Recording

A disadvantage associated with the methods of recording road roughness outlined above is that a single roughness value is assigned to each distance interval. However, the roughness for an interval may be attributable mainly to one or two isolated bumps or a short, very rough subsection (e.g., transverse construction joints and bridge expansion joints or uneven settlement of embankments and isolated pavement failures). To enable distinctions of this nature to be made, ARRB has developed equipment that continuously records the body-axle displacement of a vehicle.

Two types of devices are currently in use. Installation of both systems is simple and rapid (9).

The first system uses a paper drive assembly and heated pens from a commercially available (Watanabe Mini-Writer model 711) chart recorder (Figure 6). The pen that records displacement is directly attached to the chain of the roughness meter; the recorder trace is thus direct reading (with a 1:1 displacement scale). A second pen is used to provide event marks on the trace. The paper trace is driven by means of a mechanical cable

Figure 5. Automatic recorder equipment and interconnecting cables.



linked to the vehicle speedometer cable. This produces a record of body-axle displacement versus distance traveled. Controls for pen temperatures and the event marker are housed in a small box that is carried on the front seat between the driver and the operator of the device. The recorder does not affect the operation of the roughness meter and thus may be used as an adjunct to routine testing. The device is installed in a few minutes and has proved to be trouble free in operation.

A second system was developed to allow direct entering of comments and items such as section identification on the trace during testing. A displacement transducer is mounted so that its central core is attached to the roughness meter chain and its body is attached to the meter frame (Figure 7). Output voltage is fed to a conventional chart recorder. The recorder gain is adjusted to give direct-reading body-axle displacements. Again, the paper trace is driven by a mechanized cable. The

Figure 6. Direct link recorder.

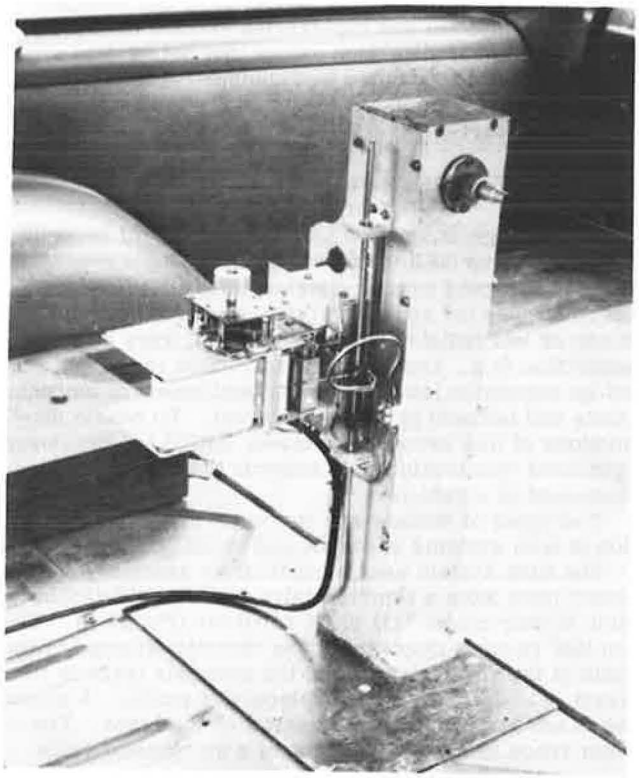
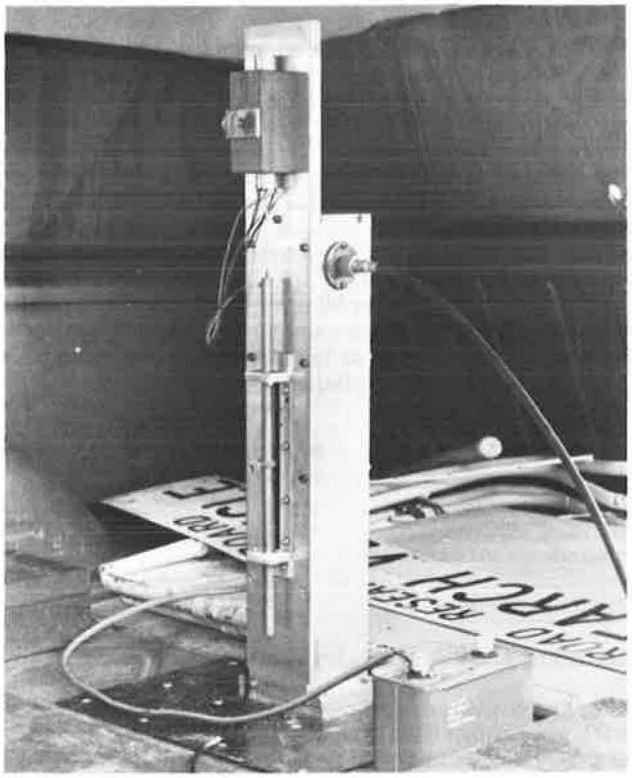


Figure 7. Remote recording apparatus.



recorder can be comfortably carried on the operator's lap, and comments can be directly recorded on the trace.

Current Use

In Australia, roughness data are currently collected at two levels. Each state road authority collects data for the entire road system under its control. These data, categorized according to road class, are used by the state to support its application for financial assistance from the federal government. They are also used within the road authority as input for long-range rehabilitation programming and, in the short term, to assist in assigning priorities in maintenance and overlay programs. Such data were used in a recent major study that assessed the overall economic impact of changes in current restrictions on road vehicles (such as limits on axle load, gross weight, and size). Roughness data and pavement age were used to determine performance relations for each class of road. By use of the "fourth power law" derived from AASHO Road Test results (i.e., the destructive effect of an axle is proportional to the fourth power of the axle load), estimates could be made of the additional expenditures that would be required to maintain the road system in its current condition if it were subjected to increased axle loads (10).

The second major use of roughness data is at the operating, or district, level. To determine specific remedial measures on a section of road to be upgraded, roughness levels are usually determined at 0.2-km (0.1-mile) intervals. This detailed information helps the engineer to locate possible problem areas—such as poor drainage and embankment consolidation—that require attention before overlaying. The continuous trace recorder is also put to considerable use at this level.

Future Applications

It is anticipated that roughness data will increasingly be used in Australia during roadwork construction. A continuous trace of roughness on each successive pavement layer during construction would help in rapidly indicating those areas that require further work. It is also felt that, as the concept of rideability becomes more widely accepted as a criterion of pavement condition, current longitudinal profile requirements based on deviation from a straight edge will be supplanted by maximum acceptable roughness levels.

Roughness data collected from periodic surveys of the entire road system will make possible a continued refinement of estimates of pavement performance, providing information required for the development of pavement management systems and maintenance management subsystems.

ESTABLISHMENT AND MAINTENANCE OF A ROUGHNESS STANDARD

The response to a road profile of a vehicle-based system of roughness measurement depends on, among other things, the response characteristics of tires, springs, and shock absorbers. As vehicles age, these characteristics change, and so does the roughness value determined for a fixed road profile. If meaningful comparisons are to be made between roughness data obtained at different times, a standard is required against which vehicles can be periodically calibrated. Australian studies directed toward establishing a standard started with the selection of standard sections of road, which were chosen on the basis of uniformity of roughness within a section and a range of roughnesses between sections. Other requirements were light traffic (low rate of deterioration with time) and assurances from the controlling authorities that no rehabilitation or major maintenance work on the sections was projected. In addition, an ARRB roughness vehicle was designated as a standard vehicle; its use was restricted to the establishment of correlations with other roughness vehicles.

The limitations of this approach soon became apparent. When the roughness levels of the standard sections recorded by the standard vehicle varied with time, it was impossible to determine what proportion of this change was attributable to changes in road profile and what proportion to changes in vehicle response. After considering the problem, the NAASRA subcommittee recommended that ARRB develop a secondary standard system based on a two-wheel trailer. It was considered that a trailer-based system would offer the following advantages:

1. When the trailer was required to travel interstate for calibration of state road authority vehicles, wear on suspension components would be minimized by transporting the trailer on a flatbed truck.
2. When the trailer was not in use, it could be conveniently stored so that there was no load on its wheels and spring sag was reduced.
3. Fewer components affect the response characteristics of a two-wheel system than affect a four-wheel system. This point was considered relevant because an attempt would be made to determine the response characteristic of each major component.
4. The use of two standards (the trailer and the ARRB vehicle) in conjunction with standard sections of road would overcome the problem presented in item 3. If, on a given standard section of road, both trailer and vehicle responses changed but the relation between trailer response and vehicle response remained unchanged, one could attribute the change in response to a change in section roughness. However, if the response of only one standard changed or if both changed by different amounts, laboratory checking of the suspension components of the trailer should enable the extent of the changes to be determined and the necessary corrections to be made.

Following the recommendations of the subcommittee, ARRB constructed a trailer by using the rear suspension of a station wagon (11, 12). The use of adjustable shock absorbers makes it possible to obtain trailer roughness values that are in close agreement with vehicle roughness values. After establishing this relation, ARRB intends to determine the static load deflection characteristics of the springs and the load displacement characteristics of the shock absorbers under repeated sinusoidal displacements of fixed amplitude and frequency. Tests will be conducted at 1, 2, 5, 10, and 20 Hz.

It is expected that use of the trailer response system will help to achieve a more permanent standard of roughness measurement.

CONCLUSIONS

As a result of the development by ARRB and the acceptance by NAASRA of a simple, vehicle-based device for the measurement of road roughness, roughness values are now used as routine inputs into rehabilitation programming and maintenance scheduling in Australia. Recording systems of varying complexity have been developed to expedite data manipulation. A long-term program is currently being undertaken that, it is believed, will

allow meaningful comparison of roughness values measured at different times.

ACKNOWLEDGMENTS

The work reported in this paper was carried out by ARRB under the guidance of a joint ARRB-NAASRA committee. The committee's assistance is gratefully acknowledged. Special acknowledgment is made to A. J. Scala of ARRB, who has been directly involved in all phases of the work.

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Publication of this paper sponsored by Committee on Pavement Condition Evaluation.

Use of Road Rater Deflections in Pavement Evaluation

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There is a need to predict the future performance of pavements by using deflections measured at any time so that deflection data can be used to determine the strategy for pavement maintenance. The road rater is a relatively new instrument for evaluating pavement performance. This paper presents some basic principles of road rater operation, its method of measuring pavement response, and criteria for evaluating the future performance of flexible pavements that contain bituminous concrete base courses. The response of experimental pavements to 80-kN (18 000-lb) axle loads and road rater loading is analyzed and is related to the actual performance of the experimental pavements. A model 400 road rater was operated at a frequency of 25 Hz. The BISAR computer program was used to obtain spring pavement temperature and subgrade moisture condition. Critical responses analyzed include maximum vertical compressive strain at the top of the subgrade, maximum tensile strain at the bottom of the base course, and maximum surface deflection. Based on the results of the analysis, equations are developed that interrelate various pavement responses and permit the calculation of critical responses to 80-kN axle loads from the road rater deflection basin. A permissible ratio of surface curvature index to maximum deflection is also established based on the fatigue property determined in the laboratory. This value may be used to evaluate pavements for rehabilitation purposes.

Predicting pavement performance is an essential step in the development of maintenance programs to extend the service life of a pavement beyond its original design life. Warrants for overlays are currently based mainly on the functional performance of a pavement, which is essentially a measure of riding comfort. The design of overlays, however, is based on surface deflection data, which primarily measure the structural performance of the pavement. There is thus a need to predict the future performance of pavements by using deflections measured at any time so that deflection data can be used to determine the strategy for pavement maintenance.

Various types of instruments are available for measuring the deflections of a pavement surface under load. The Benkelman beam was developed during the WASHO Road Test in 1952. The underlying principles of operation for this instrument are relatively simple and have been well defined (1, 2). One disadvantage of the Benkelman beam test is the limited rate of progress that can be achieved in the routine evaluation of roads. This has prompted the development of mechanized versions of the instrument that are aimed at providing a much greater rate of progress. The most common of these instruments are the traveling deflectometer developed by the California Division of Highways (3) and the Lacroix de-