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Special Report 133

PAVEMENT EVALUATION USING ROAD METERS

Highway Research Board

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Proceedings of a workshop held April 18-20, 1972, at Purdue University

Subject Areas

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26 Pavement Performance
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FOREWORD

Many instruments are available for measuring pavement roughness. Some of these instruments are costly and obtain very detailed data. Most require that pavement condition be measured at low speeds, thus demanding that production rates be quite low. For many years, engineers have been searching for a device that gives the required information but is inexpensive to produce and operate.

The road meter, first developed by Max P. Brokaw, is a simple device that essentially measures the relative movement of the rear axle of a passenger car with respect to the frame of the car. This device permits obtaining a large amount of data and can in fact be operated by 1 person in a passenger car, although generally 2 individuals are required.

Because the instrument is new, a need has existed to bring together engineers and researchers who are using the device to discuss the experience of various agencies in obtaining pavement condition data by this technique. Further, it seemed desirable to have an open meeting where the various aspects of the pavement evaluation problem might be discussed.

The primary purposes of this workshop, hence, were threefold. The first purpose was to bring together various individuals who have used the instrument for an open exchange of ideas and of data; a second purpose was to permit anyone in the paving field to learn about the device; a third was to demonstrate the instrument in actual use. Each of the objectives was fulfilled at this workshop. The 2½-day meeting held at Purdue University was attended by practicing engineers, consulting engineers, and researchers from both the United States and Canada. A ½-day session was devoted to demonstration of the road meter and several other devices on pavements in the Lafayette area.

This Special Report consists of the papers that were presented at the meeting. The papers are grouped according to the breakdown of the several sessions of the workshop. The first part deals with general concepts of pavement serviceability ratings and methods of measuring serviceability along with discussions of the development of the road meter. The second part is concerned with the evaluation of the road meter based on U.S. and Canadian studies; the third part deals with correlation of road meter data with data obtained from other types of instruments. The fourth part is concerned with evaluation of several variables that influence road meter output, and the fifth section deals with uses of the road meter for obtaining mass inventories of pavement condition and its use in maintenance studies.

It is expected that the papers contained in this report will stimulate interest in use of the meter and will focus the attention of engineers on appropriate applications of the data obtained with the road meter and on further research that needs to be carried out.

—E. J. Yoder

PART I

CONCEPTS AND DEVELOPMENT OF THE ROAD METER

WORKSHOP SUMMARY

Eldon J. Yoder

This workshop brought together engineers and researchers from the United States and Canada to discuss the development and uses of the road meter. The meeting was divided into 5 distinct phases:

1. Concepts and development of the road meter;
2. Evaluation of the road meter;
3. Correlation of road meter data with information obtained from other instruments;
4. Road meter correlation with rating panels and effects of variables; and
5. Use of the road meter for mass inventories and maintenance studies.

In addition to the formal sessions, a ½-day session was devoted to field inspection of several meters. During the field inspection, the participants were permitted to observe operation of the meters and to ask questions pertinent to their performance.

It is difficult to summarize in several paragraphs the results of a comprehensive session such as this, but several points were brought up from time to time by the participants that suggest needed areas of research. It was agreed by all attendees that the road meter offers a quick and easy tool for obtaining a large number of measurements in a short period of time. It was brought out that its greatest usefulness is probably in mass inventories and in maintenance and priorities planning.

The discussions at several points brought out the need for establishing some type of standards against which road meters of various makes can be calibrated. Perhaps this standard can take the form of a specially instrumented car or a standard pavement section at some central locale to which the various meters could be brought for comparative purposes.

Another point that came up on several occasions was the manner in which correlations between road meter data and serviceability ratings can be made. Some individuals correlate road meter data with information from the CHLOE, roughometer, or some other instrument, and they then rely on established serviceability equations previously set up for these instruments. Other individuals establish their own equations by correlating road meter data with information obtained from rating panels. This latter method is the preferred method.

Throughout the meeting a great deal of discussion was centered on the accuracy of data obtained by the road meter. It was recognized that the shock absorbers on the car, the type of vehicle, the temperature, and many other factors have their effect on the data obtained from the instrument. However, great advances have been made in eliminating much of the variance caused by these factors. The null-seeking device recently developed is a major step in this direction. The null device accounts for shifting of the readings as the test car progresses down the road. This and other refinements in the instrument have increased its accuracy greatly.

There is little question that additional research should be conducted on this method of measuring pavement condition. Nevertheless, it is apparent that a great deal of information is already on hand and that the device can be put into routine use by highway departments in all parts of the world.

OPENING REMARKS

Ralph C. G. Haas

The Canadian experience in measuring road roughness began as early as 1950 for some agencies. In 1958, a special committee on pavement design and evaluation was formed under the auspices of the Canadian Good Roads Association (CGRA), which is now the Roads and Transportation Association of Canada (RTAC). All of the provincial and federal highway or transport agencies were represented on the original committee, which is still the case today. The terms of reference of the special committee in 1958 were basically concerned with developing design and performance evaluation procedures for Canadian conditions.

The special committee began by establishing a large number of inventory sections across the country and periodically measuring a variety of performance and behavior factors. A procedure for measuring present serviceability, called present performance rating (PPR), was developed. This was all going on in parallel with the AASHO Road Test, and a considerable amount of useful information was acquired from the test. In fact, CGRA had a full-time observer at the site at Ottawa, Illinois.

The studies culminated in 1965 with the publication of "A Guide to the Design of Flexible and Rigid Pavements in Canada," but the special committee continued to be very active and embarked on a series of special studies. This subsequent work, and of course much of the previous work, indicated that there was a real need for a comprehensive system of pavement design and management. As a consequence, in 1967 the development of our pavement management system was begun.

A key part of this system was the performance evaluation phase, and a subcommittee on pavement outputs measurements was formed. One of its major initial tasks was to investigate methods for acquiring mass inventory data on pavement serviceability, and of course the PCA and Mays road meters were studied.

The goal is to produce a pavement management guide for Canada that incorporates the best available practices not only in design but also in the planning, construction, and maintenance of pavements. In addition, one of the major parts of the guide will be recommended techniques for performance evaluation.

USES OF SURFACE PROFILE MEASUREMENTS

W. N. Carey, Jr.

The Highway Research Board is listed in the program as a cooperating agency. This means that we support the workshop as being needed and worthwhile but that we do not provide any financial support. I assure you that the Highway Research Board is vitally interested in this workshop, and I believe that this workshop will help to solidify our understanding of what we are trying to do and our knowledge of the instruments that are available to those ends. I am certain that the workshop will make a real contribution toward identification of the directions that need to be followed to make the road meter an accepted and truly valuable tool for pavement evaluation and, more importantly, for pavement design.

I think that each of you is far more knowledgeable than I about the current capabilities of the road meter and other instruments for measuring the surface characteristics of pavements. It would be presumptuous of me to discuss the modern technology in this field, but still I think I have something to say about the reasons behind these activities. I have sensed in recent years a concern for the technology of profile measurements that frequently seems to reflect a lack of concern for the basic issue. I want to bring the basic issue back to your minds.

There are at least 4 fundamental uses of pavement surface profile measurements. First, surface profile measurements can be used as a construction quality-control tool. Limits can be written into specifications, measurements made, and construction contractors required to meet the specifications. I think that this use of profile measurements is highly desirable and that we do not have sufficient knowledge as to how to write specifications such that they truly reflect the surface profile statistics or parameters that we are trying to control. In the beginning, Francis Hveem of California, the great innovator in pavement design and construction, decided that deviation from a planned longitudinal profile of ⅛ in. in 10 ft was the maximum that could be tolerated in a high-speed highway surface. That, of course, is a statistic, and his specifications led to some very fine highways. However, we all know that he was rather lucky because ⅛-in. deviations do not normally occur in a systematic way, and thus he was not faced with periodic aberrations. We now know that ⅛-in. amplitude waves with wavelengths corresponding to wheel-hop frequency can make for a highly unsatisfactory ride. Thus, amplitude alone is not enough. This does not negate the value of profile measurement for quality control. Rather, there is some doubt as to what we should measure and more importantly what we should specify.

The second reason for measurement of surface characteristics of pavements is to locate those points, practically inevitable along any highway, where something has happened that is not what we like to call normal: someplace where the subsurface drainage or subsurface soils were significantly different from those for which the pavement structure was designed. Here, although the structure contained perfectly sound components and although the contractor performed as he was expected to, the pavement in fact broke up or became very unserviceable. Similarly, in this category are those spots where the contractor left cement out of the concrete or the inspection was extraordinarily lax. Early proponents of profile measurement considered this an important function. They thought that they were building pavements that should be perfect and that any aberration was an act of God or bad faith on the part of someone other than the design engineer. Frankly, I think this is a waste of the time and cost of profile measurement. Any good inspector or maintenance man riding over a recently built pavement can pinpoint these areas. Conventional tests on the site can be made to determine the cause of the problem and the action necessary to correct it.

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

The fourth reason for making measurements of longitudinal profile of pavements seems to me the most valid one. It is founded in the concept for defining pavement performance that was developed at the AASHO Road Test 15 years ago. I still believe that the philosophy behind those early developments is valid and important, although in our attempts today to simplify or refine measurement tools we sometimes forget why we want to make the measurements.

I would like to discuss what was behind the development of the pavement serviceability and performance concepts developed at the AASHO Road Test. The fourth reason for making surface profile measurements is to provide an objective measure for determining relations between pavement performance and pavement design factors, including materials, construction practices, conditions of traffic loading, and climate. These things, of course, have been expressed in some detail in the literature and are summarized in the following paragraphs.

Prior to the AASHO Road Test, there was no definition of pavement performance. Designers claimed to be designing for "20 years of service life" or for "working stresses of 50 percent of the tensile strength of concrete," or for "pavement structures of such thickness and quality as to be nonsusceptible to frost action." Nowhere was there expressed an objective measure of how changes in design could influence the condition of the pavement during its life. Nowhere was expressed any concern for the relation between the stress in the concrete and the ultimate performance of the pavement. Central to all this is a fact that still exists today. When a pavement starts to deteriorate in 5 years, it does not fall apart uniformly over its entire mileage. Rather, 100 ft in, say, a mile gets extraordinarily rough or deteriorates. If 100 ft per mile of a section of Interstate highway requires heavy maintenance within 5 years of its construction, the design was not adequate. Be careful, though, not to pass the blame to the designer too quickly. He had no definition of what pavement performance was. There was absolutely no distinction in his instructions between whether the 20-year pavement should be completely shot 20 years from the date of construction or whether it should still be in perfect shape after 20 years (but not in 21 years).

This did not seem to be rational, so we tried to define pavement performance. First, we reasoned that the real purpose of a pavement is to serve traffic, not to reduce stress in the subgrade. As you know, we tried to determine how well pavements in various conditions actually were serving traffic on any particular day by asking drivers of trucks and automobiles for their considered opinions. We simply asked the drivers to rate pavements as to the ability of the pavements to serve high-speed, high-volume, mixed traffic (trucks and passenger cars). Again, as you know, these ratings of particular pavement sections were remarkably consistent and showed little or no bias that depended on the drivers' vehicles. Apparently, there was some characteristic of pavement that was central to the opinions of the drivers who were using it.

Next, we set about to determine objective measurements that could be made and combined in some systematic and mathematical way to predict the central rating of any particular pavement. We measured everything that we felt could conceivably influence the feeling of the drivers as to the serviceability of the road. We did not measure stress or deflection because we knew that the drivers could not sense these things.

As a result of hundreds of trials involving multiple regression analyses, we decided that some measure of longitudinal profile would provide the strongest simple predictor of the users' ratings of serviceability and that the transverse profile also played a significant part. Thus we were able to make a few simple measurements on all pavement sections, apply the formula we had developed, and predict with rather good certainty the opinion of the highway users as to the usefulness for highway transportation or serviceability of a particular pavement on a particular day.

If one could in this manner measure serviceability of the same pavement at intervals over several years, and note the rate and manner of its deterioration under known climatic and loading conditions, one would have for the first time a real measure of pavement performance.

Knowing now how pavements perform, one can begin to compare the relative performance of pavements of different designs, pavements subjected to different traffic density, pavements in different climates, and pavements over different soils. When such comparisons can be made, we have the basic necessary elements for a pavement structural design mechanism.

It is only after these fundamentals have been established that we can begin to look at the relations between stress and deflection, the viscoelastic behavior of components, and other mechanistic parameters and how they relate to pavement performance. In short, I find it of academic interest only to predict stress in an element of pavement structure, under idealized or laboratory conditions, unless a relation can be established between the statistical distribution of such stresses over the life of a pavement and the performance of that pavement measured in some real-life way.

I will summarize the fourth reason for measuring pavement profile in this way. The use of a summary statistic, which to my mind must somehow be related to power spectral density analysis of the pavement surface profiles or derivatives thereof, is the simplest objective tool for the determination of the present serviceability of the pavement. Some study of the changes of present serviceability over time and traffic is the only available basis for objective determination of pavement performance. A knowledge of pavement performance, as related to pavement structure, traffic, and climate, is the strongest foundation for rational design.

That, then, is the reasoning behind the relatively sophisticated measurement of road profile, beyond the simplistic counting of bumps. If one uses this line of reasoning, the specifications for the tools used to measure profile, the reliability required, the requirements for data reduction, and the operational simplicity all become relatively obvious.

I believe that performance rests on serviceability, that serviceability depends primarily on surface profiles or other devices that measure the statistical distribution of surface aberrations, and that effective road meters are truly the basis for pavement evaluation.

PRESENT SERVICEABILITY RATING AND PRESENT SERVICEABILITY INDEX CONCEPTS

Paul Irick

The purpose of this presentation is to review concepts that are associated with the present serviceability rating (PSR) and the present serviceability index (PSI). In his opening remarks, Carey introduced philosophical and practical considerations for these concepts. I shall discuss the concepts from an analytical point of view. There is, of course, much overlap among the philosophical, analytical, and practical aspects of PSR-PSI concepts. I have separated my remarks into topics that start with general considerations in experimental research and then progress through the conceptual and analytical steps that were taken at the AASHO Road Test.

EXPERIMENTAL PAVEMENT RESEARCH

If research by experiment is to be successful, it is necessary to have clear-cut objectives for the experiment and to have a sound experiment design for the experimental units, their treatments, and their observation. It is also necessary to analyze the observations in ways that are consistent with the experiment design and objectives. It is not a simple matter to maintain consistency among objectives, design, and analysis. At the very least, the experiment design should provide an appropriate basis for determining relations that are implied by the objectives and that can be expressed as effects of the design factors on the observed variables.

Road tests are one form of experimental pavement research in which the general objectives are to learn how pavement behavior depends on built-in pavement characteristics and/or external influences such as environmental conditions and loading factors. In these terms the experimental units are test sections. Treatments are those factors that describe how test sections are constructed and subjected to environmental and loading conditions. Pavement behavior is a response, or a combination of responses, of test sections to treatments that have been applied.

In a road test it is possible to define a large number of variables that describe elements of pavement behavior, and for each variable there may be several alternative measurement systems. At the AASHO Road Test many individual elements of behavior were observed and analyzed with respect to the design factors. In addition, it was clearly desirable to define, observe, and analyze pavement performance as a "supervariable" that could represent the overall response of a test section to its treatment.

PAVEMENT PERFORMANCE

It was decided that pavement performance should indicate the amount of traffic carried at an acceptable level of service. When more specifically formulated, pavement performance becomes a "supervariable" for the external behavior of a pavement section and can therefore be analyzed with respect to experiment design factors.

PRESENT SERVICEABILITY

The concept of pavement performance implies that, from the viewpoint of a perceptive user, a pavement provides a particular level of service at any point in time. Thus the concept of pavement performance leads to the concept of present serviceability.

PRESENT SERVICEABILITY RATINGS

If the concept of present serviceability is to be useful for describing pavement performance, then users can presumably discern various levels of serviceability among pavements whose physical conditions cover the full spectrum of interest. The PSR of a pavement is a user's judgment of the level of service that a particular pavement provides at a point in time.

In the AASHO Road Test studies, raters were asked to judge present serviceability in 1 of 5 categories: 4.0 to 5.0, very good; 3.0 to 4.0, good; 2.0 to 3.0, fair; 1.0 to 2.0, poor; or 0.0 to 1.0, very poor.

It was found that the average PSR given by a panel of raters was reproducible within and among various panels. The next question was whether and how PSR was correlated with objective measures of pavement condition.

PRESENT SERVICEABILITY CORRELATES

Candidates for correlation with PSR include only those variables whose variations can be sensed by the present serviceability raters. Thus the list of potential correlates includes surface irregularities and defects that can be measured in terms of longitudinal and transverse profiles, cracking, spalling, faulting, and so forth.

There are also many alternative PSR correlates for longitudinal profiles, ranging from surface elevations and their derivatives to measurement system values for the integrated roughness of a given length of pavement.

PRESENT SERVICEABILITY INDEXES

A PSI was defined to be an algebraic function of PSR correlates. Moreover, the PSI concept incorporated the view that coefficients in the function should be determined through multiple regression analysis of the form $Y = A_0 + A_1 X_1 + A_2 X_2 + \ldots + E$, where Y is an average PSR for a pavement section; X_1, X_2 are PSR correlates; $A_0 + A_1 X_1 + A_2 X_2 + \ldots$ is a PSI determined by the regression analysis; and E is a discrepancy between the PSR and the PSI. In other words, PSR = PSI + E. Multiple regression procedures were used to find the set of correlates $(X_1, X_2, \ldots)$ that minimized the sum of E^2 and that excluded correlates that did not contribute significantly to the goodness of fit provided by those correlates that were included.

PRESENT SERVICEABILITY HISTORIES

A PSI value relates to only one point in time and is not in itself a measure of pavement performance. If PSI values for a particular pavement are plotted against time, however, it becomes possible to see (or to project) the period of time during which the pavement provided (or will provide) acceptable service, regardless of the serviceability level that is selected as being acceptable.

PAVEMENT PERFORMANCE INDEXES

The serviceability-time history of a pavement is necessary but not sufficient for determining pavement performance because the performance concept includes the amount of traffic that has been served.

The major performance index used to analyze AASHO Road Test data was log N_p, where N was the number of axle loads of a given weight that the pavement carried at a serviceability level greater than p.

ANALYSIS OF PERFORMANCE DATA

The biweekly measurement program at the AASHO Road Test produced serviceability data for each test section. From these data a PSI was computed, and a PSI history was thus maintained. At the end of the test, performance indexes were computed (or extrapolated) for p = 2.5 and 1.5.

Finally, the performance index values were analyzed for their relation with pavement design factors and loading factors.

CONCLUDING REMARKS

The main objective of the AASHO Road Test was to determine how pavement performance depends on pavement design factors such as thickness and on loading factors such as axle load and axle spacing. In this presentation we have tried to show how performance was defined and evaluated through the concepts of PSR's and PSI's.

The measurement of surface profile was a dominant element for the implementation of all these concepts. We are therefore pleased to see the continued interest and concern that this workshop shows for the evaluation of surface profiles and pavement serviceability.

HOW YA DOIN?

R. V. LeClerc

How ya doin? We use this expression almost every day as we greet our friends and neighbors, but quite often the full import of the question is not intended nor a detailed answer expected. Somewhat akin to this is the question often asked in social gatherings after the initial greetings—How's your wife? A friend of mine always answers this question with another question, Compared to what? Although our happy imaginations can handle such comparisons of wives, or possibly girl friends, we cannot afford such laxity when it comes to highways.

When the question, How ya doin? is applied to a highway, we should have answers available for the implied question, Compared to what? In the not-too-distant past, the attention of pavement design engineers seemed to be confined in large measure to ways and means of formulating or deriving a rational design, or obtaining representative test methods, correlating test specimen conditions to field control, and attempting to reproduce roadway construction and service environments in laboratory test procedures. Theories of stress distribution, strain limits, layer effects, layer equivalencies, elastic moduli, and linear viscoelastic and resilient moduli were advanced, and sometimes applied, as the basis for roadway design methods. Highway Research Board committees reviewed papers on these methods and provided a format for their presentation to the highway practitioner.

These unfortunate people, pressed for some means of conducting their business, selected a design method that, in their judgment, best suited their highway field conditions as well as their available resources, test facilities, equipment, technical expertise, and departmental interest and policy. Generally, these choices involved compromises, and the compromises produced no great uniformity of design procedures, although each and every practitioner would defend his system as being "best for his conditions" as indicated by "performance." Just what the performance consisted of could not, in many cases, stand close scrutiny as to how it was measured or in what units it was presented. When pressed for more details or a more definitive description, the practitioner's definition of "performance" usually boiled down to a lack of persistent complaints by maintenance personnel or by the traveling public.

Perhaps illustrative of this semi-exclusive concentration on the structural design aspect of pavements are the operations of the Triaxial Institute for Structural Pavement Design. This is a loose-knit group of producers, educators, and highway engineers who have been meeting for some 25 years in informal back-room sessions to discuss their current efforts as related to pavement design. Characteristic of this group is the fact that no agenda is tolerated at the annual 2-day meetings so as not to restrict the mutual exchange of information and full discourse on all subject matter. However, some 12 years ago, after they had confirmed the suitability and propriety of the Hveem stabilometer for evaluating specimens of roadway materials prepared by the Triaxial Institute kneading compactor, it seemed prudent to list by priority the various new elements of design to which their attention might be directed. Nine such items were then listed during a discussion period of 2 days. In search of a tenth item to round out the list, a subject was offered by some attendees who had recently graduated from one of the management courses for state highway personnel. The suggestion was that perhaps it might be well to consider a subject having to do with "control."

In management parlance, control is a means of ascertaining the effectiveness of management techniques. As applied to pavement design, control would be a means of checking the effectiveness of design systems. It was pointed out that our attention had been exclusively devoted to the input for the structural design of pavements and that it was about time that attention was directed to what the output looked like at the conclusion of the design period.

Although this happened about 12 years ago, it was not necessarily unique. Over the years, similar thoughts had been quietly developing from the old-style basic approach of condition survey—mapping surface cracks and other distress. Literature references depict the growing awareness of roadway condition, and thus we find a departure from the early subject of "sufficiency ratings."

The publication that sets the theme for this workshop, or provides a basis for what our present concerns are for pavement condition ratings, is Highway Research Record 40, which was sponsored by an HRB committee chaired by Eldon Yoder. Evidence of his concern in this area is still evident today, some 9 years later. He is still trying to promote what we all are coming to recognize as a very important, if not the most important, element of pavement design—the feedback or control mechanism for measuring performance.

While this groundwork was being carried out, the Canadian Good Roads Association, now the Roads and Transportation Association of Canada, had implemented its own means of checking on the performance of Canadian roadways. Undoubtedly this stemmed from the Association's observation of AASHO Road Test evaluations, and it was apparent that the Association moved quickly to establish this vital part of a pavement management system. In the 1962 International Conference on Structural Design of Asphalt Pavement, the Canadian Good Roads Association paper describes a "present performance rating" based on Benkelman beam deflections. It further described how the present performance data were analyzed and translated into an overall measure of performance for various types of roadways. This gave Canadians a basis for predicting needs and programming rehabilitation.

Some of us in the United States are just now getting around to thinking that this is a good thing—some 10 years later. We now see this element in the various systems approaches to pavement design and pavement management.

What means are used to tell "how we're doin" with respect to roadway design and maintenance? The answer may rest with the activities at accelerated road tests or test tracks where such measurements are, of course, an integral feature.

Maryland Road Test 1 on concrete pavements measured performance by the physical evidence of defects such as extent of structural cracking, observation and identification of pumping, average frequency of first crack, and faulting. Although some measurements of pavement roughness were made with the Bureau of Public Roads (BPR) roughometer, the conclusions of the report are concerned more with performance as measured by structural defects of the roadway slab.

The early California road tests carried out by the Army Engineers at Stockton and by the California Highway Department on flexible pavements measured performance by the rate at which rutting and cracking appeared. On the WASHO test road in Malad City, Idaho, performance of the various structural sections was keyed to the occurrence and frequency of cracking, rutting, and general measurement of the area of distress. Finally, the AASHO Road Test, while measuring structural defects to rate the performance, also brought up the concept of ride—how the defects would affect ride.

We are all familiar, or should be, with the philosophy developed at the AASHO Road Test—roadways were built for people to ride on, and the measurement of how satisfactory the ride was, or is, should be a prime criterion for its performance. Structural defects were not neglected of course at AASHO, but here they were correlated with some measurement of ride. This is not to say that the other test roads ignored measurement of pavement roughness, but the earlier attempts were incidental to the primary purpose of measuring performance by the appearance of structural distress.

The CHLOE profilometer developed at the AASHO Road Test, together with the concept of present serviceability index (PSI), provided a new approach to the matter of rating a pavement's performance in terms of ride while not neglecting the engineer's other concern—structural distress. Although there may be some argument about the relative balance between ride and structural distress that appears in the AASHO serviceability equation, particularly with regard to the elements of distress used in the equation—rutting and cracking—there have been few, if any, proposals advanced that show better correlation with what happened at AASHO.

With the advent of the AASHO test road, we seem to have had an emergence of a new philosophy in rating roadway performance. In the past, the main concern was with the rate at which a pavement would develop structural distress and the extent of this distress. During this time only passing interest was given to the ride or to the roughness of the pavement, and perhaps at legal speeds roughness of the extant pavement was not too great a concern. Even if roughness measurements could be made with profilographs or roughness indicators, there really was no way to translate these readings into an acceptable standard. The work at the AASHO Road Test brought forth the concept of the rating panel and provided a means for establishing standards for road ridability or acceptability to the highway user. As stated before, the test also provided the means for a pavement rating system that considered ride as well as structural distress.

Publication of the AASHO reports and the presentation of the pavement rating concept created a lot of discussion and analysis by highway engineers. It seems that we in the United States devoted considerable time and effort to reanalysis and study and review of this concept to the detriment of its utilization in our own operations. However, as indicated previously, the Canadians were able to readily appreciate the significance of the findings, or at least recognize in them possibilities for implementation in their operations.

The last step in the development of our attempts to gauge performance of pavements seems to have come with the gradual realization that it would be most desirable to establish an inventory of pavement condition for the entire highway and, following the PSI concept, provide for periodic ratings to show performance and possibly to predict time needed for rehabilitation.

With this state of enlightenment came the realization that the tools necessary for rating the pavement must be capable of covering many miles of road in 1 day. Although the CHLOE, with an operational speed of only 3 mph, was satisfactory for the test road with its limited range, there is some doubt that it could be used effectively to rate, say, 7,000 miles of roadway in a time frame considered necessary to meet the requirement for uniform seasonal rating conditions.

This started a whole new series of efforts to develop devices for measuring pavement roughness at near highway speed. At this point, devices for measuring roadway roughness (or smoothness) were brought out of the mothballs and reexamined for their capabilities. The BPR roughometer, which had been around for a long time, and various profilograph devices were studied to determine how they could be converted to greater production.

Concurrent with this were other attempts to develop more sophisticated means of measuring the roadway profile. Typical of these were the University of Michigan and the California Highway Department profilometers that measure the roadway profile on a 30- or 25-ft reference plane. Another example is a General Motors instrument that measures the pavement profile with reference to an inertial platform. None of these vehicles, however, actually simulates the ride experienced by the majority of the highway users—that of a car passenger.

The next attempts then were made to see just what happens in a passenger car. Studies were initiated to measure the response of the vehicle to roadway roughness and the response of the passenger, in terms of human sensibilities, to the vehicle movement thus generated. The disadvantages of subjective ride rating were pointed out. For instance, some ride raters would be influenced by the appearance of a roadway regardless of the ride. Although statistical studies showed that some of these shortcomings could be overcome by utilizing a panel of raters, this idea never caught on too well, and attention then seemed to shift to the desirability of instrumenting a passenger car to achieve objectivity in ride rating.

At Purdue University, the change in tire pressure as related to the ride felt by car passengers was studied. The state of Kentucky instrumented the passenger himself, and thus we find studies on an accelerometer device worn by an individual sitting on the passenger side of the front seat of a sedan. In Washington, the highway department has evaluated the roughness of newly constructed pavements by using a roughometer device that accumulates the vertical excursions of the right front wheel (50-psi tire pressure) as the vehicle traverses the highway at 35 mph.

Although this use of the passenger car as a rating tool seemed to breach the barrier of productivity and allow more miles of road to be rated in a day, there were questions about the precision of the ratings and the actual mechanics of correlating the data to performance.

In retrospect, it seems that the transition from these previous studies to the use of the Brokaw road meter was a rather elementary move. Why not instrument the center of the rear axle and measure its vertical excursions as an indicator of vehicle ride? In this way, all roadway distortions affecting ride could be measured. Also in retrospect, it seems not too unlikely that whatever movement was felt by the passenger would be a consequence of the movement of the rear axle.

Thus evolved the Brokaw, or PCA, road meter. Modifications generated from the original concept have been developed primarily to provide more ready means of accumulating and logging the data. We are going to hear about the Mays meter and the Cox modifications of the road meter to enable this display of data. It appears that we now have the ability to derive some measure of roadway ridability in a manner suitable for periodic inventory of extensive highway systems and at reasonable cost. What appears to remain are attempts to standardize the meters when installed in different vehicles and to provide a means of "calibrating" such vehicles.

Although our efforts at this workshop will be concentrated on theories of roadway ridability, it is well to keep in mind the basic reason for our concern about pavement condition. It perhaps cannot be stated any more clearly than it was by Bill Carey in his preface to the 1963 Symposium on Pavement Condition and Evaluation:

> The most important need for condition surveys of highways is to establish trends of pavement condition with time in order that advance estimates of maintenance needs and costs can be made. Condition surveys are also needed to provide information on the performance of particular materials and construction techniques.

At this same symposium, Al Maner of The Asphalt Institute pointed out that there are 2 objects of condition surveys or evaluations—to determine ridability (how well the pavement rides) and to determine structural adequacy (the ability of the pavement structure to carry its traffic without failure).

If we are going to be able to provide our maintenance and planning engineers with timely estimates of maintenance and reconstruction needs, our evaluation system must be sensitive enough to allow advance programming. In most highway departments, an increasingly large lead time is being required because of all of the paperwork, hearings, impact statements, and approval actions that must be endured and completed. Hopes for future improvement in this area are bleak. Any rating system that we have can measure only the present condition of the roadway, and thus we must rely on trends established by periodic ratings to predict these needs. Therefore, an effective rating system must be sensitive enough to clearly define these trends. Regardless of how precisely we can measure a roadway condition, it will all be for naught if we cannot predict when a roadway will require maintenance. This capability will depend on the rating system.

There are many who believe that poor predictability is one of the dangers of relying solely on ride measurements to define condition and hence performance. As Al Maner indicated, there are 2 considerations—the ride and the structural capacity. Many feel that, although the ride is the most important aspect of roadway performance, we cannot ignore structural considerations and that possibly a measure of this vague property, structural capacity, can be used to temper the ride measurement to the ultimate end of increasing the sensitivity of procedures for determining performance and for predicting future needs. The "ride" situation seems well on its way toward solution. We have an instrument capable of objective measurements and capable of production testing to meet the time requirements for periodic ratings, but as yet we do not have the companion equipment to measure structural capacity with either the precision or the speed to match the ride evaluation.

I would like to include a few thoughts about pavement rating and particularly the means for measuring structural adequacy. Currently, there are several approaches for this; each appears to have its limitations. The cataloging of pavement surface defects is a basic horse-and-buggy approach. It is to a certain extent subjective, and it most certainly does not have a high productivity rating. The only way this could be speeded up would be to travel over the roadway and record the roadway condition on film that could be later analyzed. Several states, Washington included, have photographic vans that cover roadways, taking 35-mm photographs every 50 ft. Although these pictures are good, it would be rather difficult to catalog surface defects from them. However, the scanning angle can certainly be modified to accommodate a better view of the roadway surface and still retain all of the other desirable output features. As a matter of fact, an academic institution in Washington believes photographic techniques can measure not only surface defects but also skid resistance, surface texture, elastic deformation, and surface configuration.

Other engineers are convinced that deflection measurements provide the structural element that is needed in pavement rating. The Benkelman beam is a fine tool for measuring deflection, but it, too, fails on the productivity scale. The state of California tried mechanizing the Benkelman beam with the Grasshopper, but 3 mph is still too slow.

The Dynaflect machine measures response of the pavement surface to vibratory effort, as does the road rater. Although there is some correlation with structural capacity using these devices, they still are slow. They travel quickly between test locations but still have to be stopped and set up before measurements begin.

None of these can match the speed with which ride can be measured, and what is needed is some means of developing this structural aspect of a rating system to match the productivity we have with the ride system.

Washington State University is currently working with what we call the "thumper." It measures the relative response of the pavement to a shock produced by a hammer blow. They tell us that this piece of equipment can be made to operate at speeds of 30 mph, which if successful will move us somewhat closer to the productivity goal. However, the correlation of this response factor to structural capacity will involve much work.

Undoubtedly there are other means being considered for measuring structural adequacy. If they can be properly calibrated or correlated and if they can meet the productivity requirements, we will be in a much better position to meet the prime need for making condition surveys. Probably the best thing that can be done along this line would be to develop instrumentation that could measure structural adequacy and could be incorporated in the skid tester. Highway engineers are going to be measuring skid resistance on a continual basis over the next few years, and skid trailers will probably be operating full time. If at the same time we can evaluate structural capacity, we will save ourselves additional work and time.

The perfect condition evaluation system—one that will provide the pertinent and necessary answers to the design engineer, the maintenance engineer, or the planning engineer when he asks, How ya doin?—will have to meet several challenges.

During the late 1950s, many miles of asphalt concrete roadways were constructed on cement-treated base. Currently, these roadways are exhibiting much evidence of cracking, mostly longitudinal, with some ladder patterns and some general "alligatoring." It is apparent that much more extensive cracking is imminent. We have the general impression that the proper time to resurface such a structural section is 1 year before the appearance of the first crack. This is indeed a difficult condition to predict, and possibly the new pavement management systems being developed and promoted will offer some ready means of assisting in the solution to this problem. The evaluation system and/or the management system is going to have to be very effective to convince some of our maintenance engineers to resurface a roadway that shows no surface evidence of distress.

Another corollary problem that the rating system might be called upon to handle exists on our multilane highways. We have a number of miles of 4-lane divided roadway, the travel lanes of which indicate extreme distress whereas the passing lanes show no such evidence whatsoever. The problem of what to do is perhaps basically a design problem, but the time for that is long past when the distress starts to appear. The rating system must be able to clearly identify and delineate the failure in the travel lane even though the "average" condition, across both lanes, might be tolerable.

A third problem faced by the ideal condition rating system involves the relativity of ride and structural adequacy, i.e., what is true serviceability. On Bainbridge Island in the Puget Sound area, there is a short section of mixed-in-place cement-treated base roadway that exhibits a terrific pattern of block cracking that most people would call advanced structural failure. This condition appeared not too long after the cement-treated base roadway was completed in 1954. Currently, the crack pattern has tripled in intensity. In spite of its appearance, at 60 mph this road produced one of the smoothest rides and has for a number of years. One of these days, the bottom is going to fall out all at once—but when?

Along this same line, there are 2 sections of asphalt concrete pavement in the eastern part of Washington, one of which has transverse cracks from one end to the other. Immediately abutting this is the same type of roadway without a single transverse crack. Both are less than 6 years old. All means of measuring ride show no significant difference between the 2. What should the performance be? Is the serviceability the same? Will one have to be resurfaced before the other? Should design, or construction, or materials be investigated? A perfect rating system should enable us to know.

In Washington, we have a prime example of the need for a closed circuit between rating and rehabilitation. In 1954, we constructed a 4-lane divided highway with a raised sodded median and asphalt concrete over cement-treated base; it was considered the ultimate. Two years later, however, the outside wheel tracks of the outside lane consisted almost completely of advanced ladder cracking. As of today, after many years of makeshift maintenance, we are finally getting around to the reconstruction contract. Any rating system would have noticed this condition, but unless it is coupled closely with rehabilitation programming, the end product suffers.

Undoubtedly there are other anomalies that would serve as challenges to a perfect rating system. It appears though that the equipment needed to implement such a system and clearly rate all of the parameters of pavement performance would be one that measures ride (the PCA road meter or the Mays meter), measures rider response (instrumented driver), evaluates roadway resilience or deflection (California Grasshopper), checks reaction to shock or vibration (a "thumper," Dynaflect, or road rater), measures skid resistance, evaluates appearance, and records all data for future reference.

DEVELOPMENT OF THE ROAD METER: 1965 TO 1972

M. P. Brokaw

The Portland Cement Association (PCA) road meter was developed by the author in April 1965 to provide a rapid, simple, and inexpensive way of measuring road roughness, the principal ingredient of the present serviceability index (PSI) established as a result of the AASHO Road Test (1, 2). With the cooperation of Karl Dunn, tests were made that related PCA road meter output to AASHO slope variance as measured by the Wisconsin CHLOE profilometer.

The road meter was used extensively in Wisconsin and at special sites in the United States during 1966. Based on these experiences, the PCA road meter was announced and described at the 1967 Annual Meeting of the Highway Research Board (3).

As a result of the announcement, several state highway departments constructed meters according to the original version, with numerous variations. Many of these meters were described in individual engineering reports that received limited circulation. The author summarized parts of the reports in a paper given at the 1970 Summer Meeting of the Highway Research Board (4).

Increased use, familiarity, and confidence in the device have resulted in this workshop. The meeting is timely and provides an opportunity for the exchange of ideas and applications and makes these available to others unable to attend.

During the past 7 years, the author has recognized a number of factors that tend to disturb road meter users. These are (a) differences in mechanical and electrical components that control road meter output, (b) differences in road meter output when a meter is used in various automobiles, (c) effects of seasonal and diurnal ambient air temperature on the meter and pavement, (d) differences in road meter output caused by ambient wind velocities during test, and (e) need for a dependable standard for road roughness measurements that is essentially time-stable and is available for calibrating all road meters and profilometers.

The following sections include a discussion of each factor along with recommendations where appropriate and suggestions for additional field evaluation.

DIFFERENCES IN MECHANICAL AND ELECTRICAL COMPONENTS

Road meter output is controlled by the sensitivity of electric digital counters (make and break time) and also by the width of switch segment. Uniformity of these parts should enable interchange of meter data without risk of losing the built-in advantage of mechanical switching and counting and filtration of extraneous electrical impulses.

At present, reliable digital counters with a capacity of 1,500 cpm are available (Hecon, Hengstler). These give consistent results when combined with switch plate segments having a net width of 0.10 in. and with insulated interstices of 0.025 in.

DIFFERENCES RESULTING FROM AUTOMOBILES

Assembly-line automobiles are not alike, even when produced for the same order in a given assembly plant. In general, the differences are not of consequence to highway users. However, road meter outputs can be affected.

Major differences are related to standard versus heavy-duty suspension within cars, coil-spring versus leaf-spring suspension within or among different makes and models, and size and weight of the automobile itself.

Because the choice of road meter vehicle does control road meter output, the author has always recommended standard supension in a coil-spring vehicle of conventional size, e.g., Ford Custom 500. The recommendation is also extended to specification of automatic speed control, built-in air-conditioning, and maximum available size of engine. These specifications provide better control and comfort of road meter crews, reduce the effects of crosswinds on a vehicle with open windows, and increase the front stability of the survey vehicle because of the additional weight of the air-conditioning unit and large engine.

Additional discussion of these factors will take place at this workshop. The important point is that an acceptable vehicle can be calibrated with panel serviceability ratings, a standard profilometer, or a precalibrated vehicle if due care is exercised in the number of tests per site.

DIFFERENCES RESULTING FROM CHANGES IN AMBIENT AIR TEMPERATURE

Changes in ambient air temperature are known to change pavement roughness. Sustained low temperature results in frozen bases and subgrades and causes frost heave and increased pavement roughness. Sustained high temperature can place a pavement structure in compressive restraint, and this can result in increased pavement roughness also. Extremes of high and low temperatures probably change automobile suspension characteristics and thus influence road meter outputs, with low output accompanying low temperatures and high output accompanying high temperatures.

Interaction of these roughness factors tends to impair field research of the effect of ambient air temperature on road meter alone. For example, a test made at low temperature, say 15 F, might result in low meter output because of stiffness in the automobile suspension system. At the same time, it might result in high meter output if the pavement is subjected to frost heave. In this case, the amount of roughness can be very erratic, especially during spring thaws when foundation material can switch from liquid to solid state during a single day and when the changeability can continue for several weeks. Meter output can be attenuated in a different way if the 15 F test is conducted before onset of freezing of base and subgrade when pavements are usually smoothest.

Another example is a test conducted at high air temperature, e.g., at 95 F, when the automobile suspension might be more limber and give high meter outputs. These high outputs can be amplified by real increases in road roughness caused by pavement expansion. Sudden increase in maximum daily temperature is less apt to affect pavement roughness if the pavement is in a relaxed state at the onset of summer rather than in full restraint during midsummer. In the latter case, pavement roughness can increase hourly with an increase in ambient air temperature but recedes rapidly with a lowering of temperature. The rate depends also on the volume of heavy vehicles.

Within the extremes set forth, there is no limit to seasonal and diurnal combinations that are capable of confusing research appraisal of temperature effects on real road roughness and road meter output. Results of a few tests have been reported (3, 4), but these appear inconclusive and suggest the need for additional investigation.

DIFFERENCES RESULTING FROM AMBIENT WIND VELOCITY

Road meter output can be affected by changes in external conditions during a single test. All of the changes tend to shift the initial centering of the roller contactor and zero segment of the switch plate and result in high meter outputs and a low serviceability index. Shifts can be caused by changes in position of car load (especially rear-seat passengers) after a test commences, by rapid acceleration or deceleration of the survey vehicle, and most important by uplift of the automobile body caused by aerodynamics and ambient wind direction and velocity.

Automatic correction for aerodynamic and wind shift could be expected to reduce within-test variability, afford the closest measure of real road roughness, and remove present wind restrictions on meter operation. A device capable of achieving the objectives has been developed by the author and is described in another paper (5).

CALIBRATION OF ROAD METERS AND PROFILOMETERS

Interpretation and extension of AASHO Road Test results and continued application of the methods developed require that mechanical road roughness measuring devices be calibrated to a universal standard. Initial plans envisioned that the standard should be the present serviceability rating (PSR) (the judgment of an observer as to current ability of a pavement to serve the traffic it is meant to serve) and consequently the present serviceability index (PSI) (an estimate of the mean of serviceability ratings made by a panel of judges). Because PSI is the output of a mathematical equation relating serviceability rating and physical measurements of road roughness and road condition, it is apparent that road meters and profilometers must be calibrated in common.

The best procedure would be calibration via PSR's. Unfortunately, PSR's are not a universal standard. Judgments of an individual or panel in a given geographical and political area can be quite different from those in another area. The differences arise from accustomed levels of highway service afforded the local highway user, and these are decided by types of pavement constructed, maintenance practices, timing of resurfacing, and availability of highway funds.

Serviceability ratings are also subject to human vagaries. These result in high intrapanel standard deviations and high standard deviations of mean rating, unless the panel is composed of at least 50 raters. For example, at the AASHO Road Test, the standard deviation of serviceability rating among raters was 0.47 PSR unit. With a 10-rater panel, standard error of mean rating amounts to about 0.15 PSR unit. Once adopted, panel ratings are considered inviolate, yet they probably contribute most to the variability observed in correlations of serviceability rating and road meter output.

The author believes that road meters and profilometers cannot be calibrated in common on a universal basis by panel serviceability ratings. Nevertheless, equipment measurements of attributes ought to be standardized. With a common standard, results of tests can be exchanged universally and without loss of the advantage of subsequent local serviceability ratings. This can be accomplished by cooperative effort with the Federal Highway Administration, or even the Bureau of Standards, to provide a single instrument (such as the AASHO profilometer) that can provide timely bench marks of pavement roughness for calibration with other devices.

SUMMARY

Progressive acceptance of the road meter as a viable instrument for pavement evaluation has been established. Simplicity, economy, and safety of operation are especially attractive to those agencies engaged in mass inventory of highway systems. Future improvements and increased precision are possible. Some of these avenues have been discussed in this paper and in others presented at the workshop.

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PART II

EVALUATION OF THE ROAD METER

EVALUATION OF THE PCA ROAD METER

Patrick C. Hughes

Present serviceability rating (PSR) as employed by the Minnesota Department of Highways is an adaptation of the system developed and used at the AASHO Road Test (1).

Present serviceability is defined as "the ability of a specific section of pavement to serve high-speed, high-volume, mixed (trucks and automobiles) traffic in its existing condition" (2). In general, present serviceability is a function of transverse and longitudinal profile. However, patching, cracking, faulting, and spalling no doubt contribute to some extent.

In evaluating a roadway on the basis of PSR, a numerical rating between 0 and 5 is given each section surveyed with respect to its present serviceability as previously defined. The numerical scale and range of general pavement conditions that the ratings represent are as follows: 4.0 to 5.0, very good; 3.0 to 4.0, good; 2.0 to 3.0, fair; 1.0 to 2.0, poor; and 0.0 to 1.0, very poor.

The individual rater must disregard grade, alignment, right-of-way width, shoulder, ditch condition, and all other factors not directly related to the ridability of the highway. He, in effect, asks himself: "How well would I like to drive over roads just like this section all day long?" He decides what the existing pavement condition is and then refines the corresponding numerical range by rating to one-tenth of a point. As an example, a roadway considered to be "good" and approaching "very good" might be given a rating of 3.8 or 3.9

The true PSR for a section of pavement would be the average of the ratings of all the individual users of that pavement. Obviously, obtaining a true PSR is not practical. The number of raters must be quite small to make the determination of the ridability factor by this method a practical matter. Because 3 raters were needed to conduct the structural rating portion of the surveys to determine a pavement condition rating and because the ridability determinations (PSR) and structural ratings could be made in one general operation, it was decided that the average of 3 raters would have to suffice for PSR determinations.

Investigators at Purdue University (3) determined the number of raters required to rate pavements within various permissible errors of the true rating at the 90 and 95 percent probability levels. Table 1 gives these results at both the 90 and 95 percent probability levels.

With 3 raters, we can expect that 10 percent of the average ratings will be at least 0.8 from the true rating. A deviation from the true rating of this magnitude is definitely unacceptable.

RIDABILITY AS DETERMINED BY RATING PANELS

The determination of PSR, then, in the early stage of this study was accomplished by 3 raters (driver, front-seat passenger, and rear-seat passenger) riding in a car traveling at the posted speed limit of the section of highway in question. Each rater recorded his PSR on a scratch pad for every ½ mile driven for the length of the project. The driver announced "half mile" each time the odometer indicated that ½ mile had been driven since the start of a project or since the last announcement. Each ½ mile

Table 1. Number of raters required to estimate the true rating.

Permissible Error	Number of Raters Required: 95 Percent Probability	90 Percent Probability
0.3	31	21
0.4	17	12
0.5	11	8
0.6	8	5
0.7	6	4
0.8	4	3
0.9	3	2

Table 2. Comparison of district and research ratings.

Rating Number	Type of Pavement	District PSR	Research PSR	Deviation
1	Bituminous	2.3	2.8	-0.5
2	Bituminous	2.9	2.8	+0.1
3	Concrete	3.2	3.4	-0.2
4	Concrete	2.5	1.6	+0.9
5	Bituminous	1.3	2.6	-1.3
6	Bituminous	2.2	3.0	-0.8
7	Concrete	1.7	2.0	-0.3
8	Concrete	2.9	2.7	+0.2
9	Bituminous	2.5	2.8	-0.3
10	Bituminous	1.7	2.4	-0.7
11	Bituminous	2.1	2.3	-0.2
12	Bituminous	2.0	2.7	-0.7
13	Bituminous	2.1	2.5	-0.4
14	Bituminous	1.9	1.9	0.0
15	Bituminous	2.2	2.4	-0.2
16	Bituminous	1.4	2.0	-0.6
17	Bituminous	3.0	2.9	+0.1
18	Bituminous	1.6	2.5	-0.9
19	Bituminous	2.3	2.6	-0.3
20	Bituminous	2.9	2.3	+0.6
21	Bituminous	2.4	2.6	-0.2
22	Concrete	1.5	2.0	-0.5
23	Concrete	2.4	2.5	-0.1
24	Concrete	1.6	2.4	-0.8
25	Bituminous	2.3	2.5	-0.2
26	Bituminous	2.7	3.0	-0.3
27	Concrete	2.5	2.1	+0.4
28	Concrete	2.8	2.4	+0.4
29	Bituminous	2.2	2.5	-0.3
30	Bituminous	3.0	3.1	-0.1
31	Bituminous	2.4	2.6	-0.2
32	Concrete	2.4	2.3	+0.1
33	Bituminous	3.4	3.1	+0.3
34	Bituminous	2.9	2.3	+0.6
35	Concrete	2.7	2.2	+0.5
36	Concrete	2.5	2.2	+0.3
37	Bituminous	2.5	2.9	-0.4
38	Concrete	2.1	2.3	-0.2
39	Concrete	2.4	2.5	-0.1
40	Bituminous	2.1	2.6	-0.5
41	Concrete	2.7	2.6	+0.1
42	Concrete	1.7	2.2	-0.5
43	Bituminous	2.8	3.0	-0.2
44	Bituminous	2.8	2.7	+0.1
45	Concrete	2.7	2.3	+0.4
46	Concrete	2.9	2.3	+0.6

Figure 1. Pavement rating form.

Trunk Highway________ Control Section________ Lane Surveyed________ Date________

Begin Survey ________ End Survey ________ Total Length ________ Weather ________

Raters 1________, 2________, 3________ Unit Type________ Unit Number________

MILE	P.S.R.				JOINTS					CRACKS					PATCHED				SCALE		DISTORTION				NOTES
	Rater 1	Rater 2	Rater 3	AVG.	Total Visible	Spalled	%	Faulted	%	Panels Visible	Number Cracked	%	Faulted	%	100 % Overlay	%	5 Ft Square	%	5 Ft. Square	%	Rater 1	Rater 2	Rater 3	AVG.	
	(1a)	(1b)	(1c)	(1d)	(2)	(3)	(3a)	(4)	(4a)	(5)	(6)	(6a)	(7)	(7a)	(8)	(8a)	(9)	(9a)	(10)	(10a)	(11a)	(11b)	(11c)	(11d)	
							$(\frac{3}{2} \times 100)$		$(\frac{4}{2} \times 100)$			$(\frac{6}{5} \times 100)$		$(\frac{7}{5} \times 100)$		$(\frac{8}{5+8} \times 100)$		$(\frac{9}{5} \times 100)$		$(\frac{10}{5} \times 100)$					

was rated as a separate section of highway, and there was no discussion among the raters until the entire project was completed. Each rater recorded his PSR value on a rating form (Fig. 1, columns 1a, 1b, and 1c), and an average value was derived.

During 1966, 3-man rating teams from each of the 9 construction districts applied this rating system to more than 6,000 miles of inferior and old Minnesota highways. The results of the first year's efforts were used in a resurfacing program.

After the district rating teams were well into their schedule of rating, a team from the research office rated a sample of the roads that had been rated by the district teams. The purpose of this was to check the accuracy and repeatability of the rating system.

From the experience of the research team and information accumulated from district rating teams, it appeared that the system, when applied uniformly, was an accurate indicator of the relative condition of pavements. It was not difficult for one team to rate consistently. Also, it appeared that teams that fully understood the system rated consistently and uniformly. Of the 9 district teams, 4 rated pavements very similarly to the research team. In 2 districts where a member of the research team accompanied the district team for 1 day, the subsequent check rating by the research team disclosed good agreement between ratings. In 4 of the 5 districts where the ratings did not agree well, the discrepancies were, in general, explainable.

Table 2 gives the data collected as a result of the check ratings. It was assumed that the research team's ratings were uniform throughout the state. Therefore, those ratings were subtracted from the districts' ratings to show the difference.

Figure 2 shows a frequency distribution of the deviations in PSR's for the projects. As can be seen, the deviations were distributed in an approximately normal curve. The mean of all the deviations was -0.14. A mean of -0.14 indicates that the district teams tended to rate lower than did the research team. However, this was unduly influenced by one district, which was consistently lower and in which several checks were made. Excluding the values from that district, the mean is -0.04, which would be highly acceptable.

The discouraging aspect of the investigation of the PSR was the range of deviations that occurred. The values ranged from a +0.9 to -1.3 or a total of 2.2. At the outset it was hoped that the system for determining PSR would be accurate to ±0.3. However, it is apparent from the investigation that this was not realized.

There are explanations for some of the discrepancies that occurred, but not all can be explained. One source of deviation was the difference in cars used by the various teams. The car used by the research team was a 1962 2-door Plymouth. Cars used by the districts were a 1966 Ford, three 1965 Plymouths, three 1964 Fords, and two 1962 Plymouths. There was one obvious discrepancy when concrete pavements had faulted joints: This type of roughness was smoothed out by the new cars better than by the old cars.

Another problem that may have affected the PSR was the tendency of some rating teams to "zero in" on one member or on each other. If this was the case, then the PSR lost its validity as an unbiased sample of opinions. Raters probably were not aware of its happening since it can occur almost subconsciously. Practices that encouraged this were rating many projects consecutively without a break, having the driver call out his rating to be recorded by a passenger, or discussion of the project while rating.

Projects that were too long were difficult to rate accurately. There seems to be an "attention span" or maximum length of time during which a raters' attention is directed toward the business of rating. After the attention span is passed, a rater typically reaches the end of a ½-mile section and discovers that he does not remember what the first three-fourths of the ½ mile was like. He then either rates the last 500 ft or gives the section a rating that reflects the ride of the previous ½ mile. Also, in projects that are too long, there may be a definite change in the condition of the road. Projects should have been split up in these situations.

A problem occurred when a rater allowed himself to be affected by the visual condition of the road. As an example, a patch is associated with a bump or rutting with sidesway. A good patch, however, is smooth, and sometimes even severe rutting does not cause sidesway. Seeing a patch and associating it with a bump, a rater may "feel" a bump that in reality is not there.

It would seem that, if the rating system is to be an effective means of determining pavement condition, differences between any 2 rating teams on a given section of pavement should, in general, be within 0.3. To obtain this accuracy using a panel rating system would require more than 20 raters per district (Table 1). This of course is not practical.

It is felt that a considerably higher degree of uniformity of rating on a statewide basis could be attained if only one team rated the entire state. The values obtained could be significantly different from those obtained from the true PSR (Table 1), but the uniformity would be improved to the point that an acceptable relative measure of pavement condition would result. It would, of course, be almost impossible for one team to rate the 6,000 miles of pavement that were surveyed in the first year.

Because it was considered essential that a ridability factor remain a part of the condition rating, a more objective means of determining this factor, such as an electromechanical apparatus, was researched. It was felt that such an alternative method would give a reasonable estimate of true PSR, provide acceptable uniformity throughout the state, be economical, and not require an excessive amount of manpower.

RIDABILITY AS DETERMINED BY THE ROUGHOMETER

One device that was available for measuring ridability was the Minnesota roughometer. This device continuously records on tape the roughness of the pavement. Its operating speed, however, is only 20 mph, and there was only one such device available in the highway department. It would, therefore, be almost impossible to use this device for a program as extensive as that envisioned for the condition rating surveys. To purchase just one additional roughometer would cost in excess of $10,000. The need was for a rapid, inexpensive means for accurately and uniformly measuring pavement ridability.

RIDABILITY AS DETERMINED BY THE ROAD METER

The PCA road meter was evaluated on the basis of its ability to correlate with PSR. In an effort to better approximate true PSR, 6 raters were used in the correlation study. It was recognized that a significant error in PSR might occur when using 6 raters. However, this was all the manpower available at the time, and it was felt that a good indication of the road meter's ability to correlate with PSR would result. The road meter was installed in a 1966, 2-door, full-sized Ford (coil springs) for the evaluation.

A total of 26 sections of bituminous pavement having an estimated PSR range of 1.7 to 4.2 and 17 sections of concrete pavement having an estimated PSR range of 1.4 to 4.0 were rated by using both methods. The length of section varied from 0.5 to 5.0 miles. In most cases, both lanes of the roadway were rated, and each lane was considered to be one section.

The PSR determinations were, in all cases, made prior to use of the road meter to ensure that the road meter results would not influence the raters.

It was previously concluded that any acceptable means for determining riding quality must (a) be capable of giving a reasonable estimate of PSR, (b) provide satisfactory uniformity of rating on a statewide basis, (c) be reproducible, (d) not require excessive manpower, and (e) be economical.

The Road Meter Must Give a Reasonable Estimate of PSR

Figure 3 shows the relation between PSR and road meter summation of counts (Σ-counts) for all 43 projects rated. The curve was drawn by the freehand method. The standard deviation of 0.205 PSR indicates that the road meter is capable of making a reasonable estimate of PSR. It must be realized that PSR as shown in Figure 3 was determined by a 6-man rating team and that 10 percent of these values could be more than 0.5 from the true PSR. It is felt that increasing the number of members on the

Figure 2. Frequency distribution of PSR deviations between district and research raters.

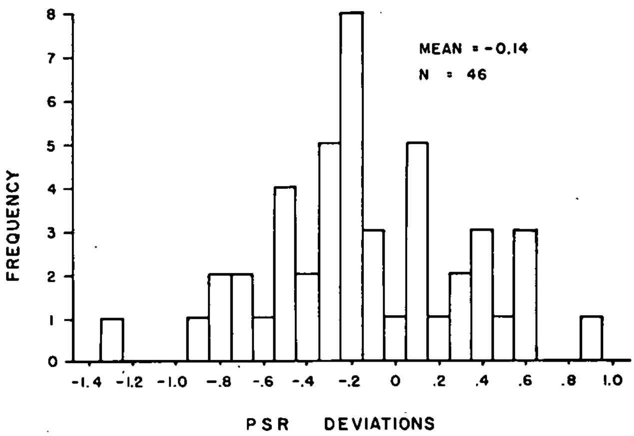


Figure 3. Correlation of PSR and road meter data (concrete and bituminous pavements).

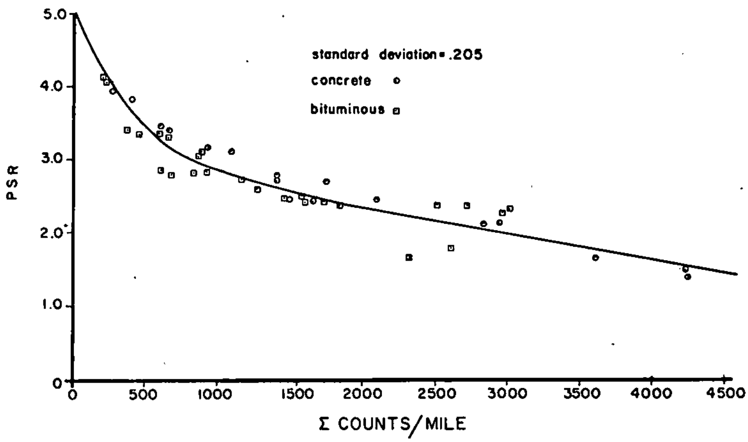


Figure 4. Correlation of PSR and road meter data (bituminous pavements).

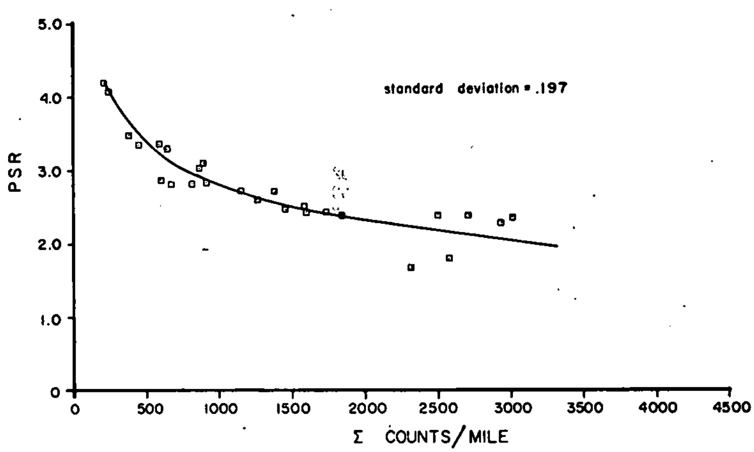


Figure 5. Correlation of PSR and road meter data (concrete pavements).

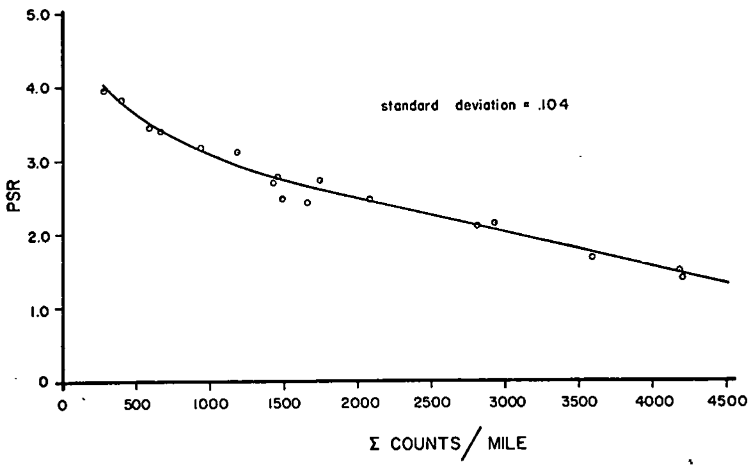


Table 3. Repeatability check of road meter.

Test Section	PSR Maximum	Average	Minimum	Range	Standard Deviation
1	1.50	1.33	1.21	0.29	0.09
2	1.64	1.58	1.54	0.10	0.03
3	3.28	3.20	3.10	0.18	0.04
4	3.38	3.26	3.20	0.18	0.05
5	2.52	2.50	2.48	0.04	0.01
6	2.52	2.50	2.46	0.06	0.02
7	2.79	2.71	2.65	0.14	0.05

Note: Tests made with 1966, 2-door, full-sized Ford (coil springs).

Table 4. Effect of type of tire on PSR as determined by road meter.

Test Section	PSR Standard Tires	Snow Tires	Difference
1	2.95	3.12	+0.17
2	3.15	3.20	+0.05
3	2.20	2.25	+0.05
4	2.40	2.30	-0.10
5	1.14	1.26	+0.12
6	1.40	1.58	+0.18

Note: Tests made with 1968, 4-door, full-sized Plymouth (leaf springs).

Table 5. Effect of vehicle speed on PSR as determined by road meter.

Test Section	Type of Pavement	PSR at 30 mph	Difference[a]	PSR at 45 mph	Difference[b]	PSR at 60 mph
1	Concrete	4.15	+0.05	4.20	-0.19	4.01
2	Concrete	2.55	-0.18	2.37	-0.21	2.16
3	Bituminous	4.22	-0.22	4.00	-0.30	3.70
4	Bituminous	4.05	-0.25	3.80	-0.44	3.36
5	Bituminous	4.50	-0.36	4.14	-0.29	3.85
6	Concrete	3.33	-0.33	3.00	-0.20	2.80
7	Concrete	3.75	-0.64	3.11	-0.58	2.53
8	Bituminous	4.15	-0.45	3.70	-0.23	3.47
9	Bituminous	3.08	-0.67	2.41	-0.27	2.14
10	Bituminous	4.62	-0.38	4.24	-0.34	3.90
11	Concrete	4.70	-0.50	4.20	-0.40	3.80
12	Concrete	3.50	-0.08	3.42	+0.05	3.47
13	Concrete	3.58	-0.26	3.32	-0.14	3.18
14	Bituminous	3.48	-0.16	3.32	-0.30	3.02
15	Bituminous	3.51	-0.16	3.35	-0.32	3.03
16	Bituminous	3.49	-0.28	3.21	-0.23	2.98
17	Concrete	2.31	-0.17	2.14	-0.27	1.87
18	Concrete	2.95	-0.35	2.60	-0.17	2.43
19	Concrete	2.10	-0.12	1.98	-0.17	1.81

Note: Tests made with 1966, 2-door, full-sized Ford (coil springs).

[a]Average difference is -0.30. [b]Average difference is -0.28.

rating team would, in general, tend to decrease the deviation between the road meter and PSR.

Figures 4 and 5 show the correlation between PSR and road meter results for bituminous and concrete pavements respectively. Plotting the results from the 2 types of pavement on separate curves improves the correlation as evidenced by the reduction in standard deviation (σ = 0.197 for bituminous pavements and σ = 0.104 for concrete pavements). Although correlation is improved only slightly for bituminous pavements, a significant improvement is noted for concrete pavements. It would seem, then, that use of 2 separate curves for the 2 types of pavements is advantageous.

The Road Meter Must Give Reproducible Results

Several factors were studied to see which would affect the reproducibility of the road meter output. Such things as tire type and pressure, automobile speed, automobile load, air temperature, wind velocity and direction, automobile type (make and suspension system), and changes in the condition of the automobile due to use were considered.

To check the repeatability of the road meter under the same conditions, we ran the device 5 times on 7 sections of pavement (bituminous and concrete) ranging from 1 to 4 miles in length. Table 3 gives the results of the repeatability check. As indicated, the road meter showed excellent repeatability under the same operating conditions. In fact, the maximum standard deviation found for any of the sections rerun was less than 0.10.

Once it was determined that the road meter results were reproducible under the same operating conditions, it was necessary to find what changes in operating conditions would affect the PSR as determined by the road meter. These were made as follows.

Type of Tire and Tire Pressure—Initial tests on 6 sections of roadway (bituminous and concrete) were made with standard 2-ply tires and winter 4-ply snow tires (all tires inflated to a pressure of 30 psi). The winter tires were only placed on the rear. Table 4 gives the results of the tire check. The data gathered indicate that there is no significant difference between the PSR's obtained with snow tires and those obtained with standard tires.

As for the effect of change in tire pressure, Brokaw (4, p. 8) stated that, for standard tires, tire pressure within the range of 24 to 26 psi had no significant effect on present serviceability index.

Based on the preceding information it was decided that standard tires should be used on the test vehicle. It was decided also that the tires and tire pressure should be kept the same as when the vehicle and road meter were calibrated. The tire pressure should be checked each test day when the tire is cold.

Speed of Automobile—To check the effect of vehicle speed on PSR as determined by the road meter, we ran tests on 19 sections of roadway (10 concrete and 9 bituminous) at 30, 45, and 60 mph. Table 5 gives the PSR's obtained at the different test speeds. Also given are the average differences in PSR's obtained between 30 and 45 mph and between 45 and 60 mph. The results indicate that vehicle speed does significantly affect PSR. The PSR dropped an average of 0.29 per 15-mph increment increase in speed. The variation was not uniform, however, because variation per individual section ranged from +0.05 to -0.67 per 15-mph increment increase in speed. The effect of vehicle speed on Σ-counts was studied by Brokaw (4), who found it to be significant also.

Ideally, the operating speed of the test vehicle should be the same as the posted speed limit because that is the speed that most vehicles travel and is the speed at which ridability is usually judged. However, having an operating speed equal to the posted speed limit is impractical because slow-moving traffic frequently causes a large reduction in speed (over 5 mph). It was decided that an operating speed equal to the posted speed limit minus 5 mph would be used. The allowable variation in operating speed, using the preceding information, was set at ±5 mph.

Load in the Automobile—Because of the short length of time available for evaluating the road meter, only a limited number of tests were made to determine what effect different vehicle loadings (amount of gas in tank, weight of equipment in trunk, and number of occupants in car) would have on PSR as determined by the road meter. Table 6 gives the results of the testing. Although only a limited number of tests were run, it appears that, except for the case of a passenger in the back seat, none of the other types of car loadings had any effect on the PSR. The variation found in test sections 1 through 4 appeared to be within acceptable limits.

Based on the limited information gathered from the vehicle loading tests it was decided that, when testing, no passenger would sit in the back seat, the gas tank would be at least one-quarter full, and there would be no more than 100 lb in the trunk (excluding spare tire and jack). Additional tests should be run to determine the effect of large weights in the back seat or trunk on PSR.

Air Temperature—Tests by Brokaw (4, p. 10) evaluate temperature effects. Low temperatures appear to significantly affect road meter results. This is probably due to changes in the operating characteristics of the shock absorbers and other vehicle components including tires.

After due consideration of this variable, it was decided that the road meter should only be operated at temperatures above 15 F. Also, before beginning the actual testing, the road meter should be turned on and the test vehicle driven several miles to allow all components to warm up and to check out the counters.

Wind Velocity and Direction—Effects of wind were also researched by Brokaw (4, p. 10). He found that the wind did not significantly affect the road meter PSR until it reached a velocity of 15 mph. He found that crosswinds of more than 15 mph were of the most concern because they can result in a change in the static reference position of the rolling contact of the road meter. He also indicated that head winds and tail winds are of less concern than crosswinds, but that no limits have been established. Although no actual data were accumulated on this variable, the results of Brokaw's tests were verified during the evaluation of the other test variables.

Based on Brokaw's findings, it was determined that the road meter should only be operated when the wind velocity is less than 15 mph regardless of the direction.

Type of Automobile—Automobile variability has gained most attention since the road meter came into use in Minnesota. In 1967, tests were run to correlate Σ-counts obtained using the road meter in a 1967 Plymouth with PSR as determined using the road meter in the 1966 Ford. The Plymouth was a full-sized, 2-door vehicle with leaf springs and heavy-duty suspension. Figure 6 shows the relation of Σ-counts and PSR for the 1967 Plymouth for both bituminous and concrete pavements. Based on this limited amount of test data, it was determined that the 1967 Plymouth could not be used as the test vehicle. As indicated in Figure 6, between a PSR of 4.0 and 3.0 there is a difference of less than 300 in the Σ-counts. The road meter probably cannot discriminate between a 4.0 road and a 3.0 road with any accuracy. Likewise, toward the other end of the curve, there is an extremely large range in Σ-counts for a corresponding small range in PSR. Such a relation between PSR and Σ-counts was determined to be unacceptable.

Also in 1967, 10 road meters were built and installed in 1966 Fords (all were 2-door, full-sized vehicles with coil springs). This allowed an evaluation of the variability between identical vehicles. One meter (laboratory) was calibrated with panel ratings. The other 9 meters were then calibrated to a PSR determined using the laboratory meter, and correlation curves were drawn for each of the 10 road meters. Table 7 gives a comparison of the correlation curves at 7 different Σ-counts. Although the car-to-car standard deviations at the various Σ-counts do not show great variation (although the differences might be significant), it is obvious that there is a need for individual calibration of meters even though they are installed in identical automobiles.

During 1968, because it was anticipated that the road meter vehicle (1966 Ford) would be exchanged for a 1968 vehicle (Chevrolet or Plymouth), tests were run to correlate PSR obtained by using the road meter in the 1966 Ford with Σ-counts using the 2 other vehicles. The Chevrolet was a full-sized, 2-door vehicle with coil springs.

Table 6. Effect of various car loadings on PSR.

Test Section	Gas Tank Level	Number of Passengers[a]	Location of Passengers	Weight in Trunk (lb)	PSR
1	Full	1	Front seat	100	1.80
1	Full	1	Front seat	0	1.84
1	3/4	1	Front seat	0	1.84
2	Full	1	Front seat	100	2.40
2	Full	1	Front seat	0	2.43
2	3/4	1	Front seat	0	2.45
3	Full	1	Front seat	100	2.30
3	Full	1	Front seat	0	2.33
3	3/4	1	Front Seat	0	2.42
4	Full	1	Front seat	100	1.82
4	Full	1	Front seat	0	1.82
4	3/4	1	Front seat	0	1.85
5	Full	1	Front seat	0	3.55
5	Full	1	Back seat	0	3.65
6	Full	1	Front seat	0	3.00
6	Full	1	Back seat	0	3.15

Note: Tests made with 1966, 2-door, full-sized Ford (coil springs).

[a]Does not include driver.

Figure 6. Correlation of PSR and road meter data using 1967 Plymouth.

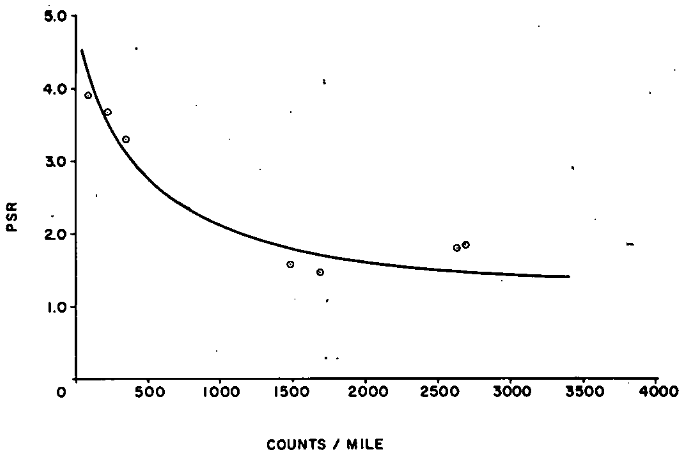


Table 7. Comparison of PSR's (concrete pavements).

Σ-counts[a]	PSR Value by Vehicle[b]										Average	Standard Deviation	Range
	Laboratory	1	2	3	4	5	6	7	8	9			
500	4.30	4.29	4.05	4.47	4.45	4.33	4.48	4.43	4.35	4.25	4.34	0.13	0.43
1,000	3.65	3.65	3.45	3.95	3.90	3.66	3.96	3.92	3.70	3.54	3.74	0.18	0.51
2,000	2.77	2.67	2.61	2.90	2.83	2.65	3.00	3.03	2.70	2.60	2.78	0.16	0.43
3,000	2.20	2.00	1.96	1.98	2.17	2.15	2.21	2.39	2.10	2.07	2.12	0.13	0.43
4,000	1.82	1.54	1.51	1.50	1.75	1.76	1.62	1.90	1.68	1.67	1.68	0.14	0.40
5,000	1.54	1.18	1.17	1.29	1.42	1.45	1.25	1.54	1.36	1.36	1.36	0.13	0.37
6,000	1.26	0.90	0.89	1.08	1.16	1.20	0.95	1.22	1.11	1.11	1.09	0.13	0.37

[a]Same type of counter was used in all vehicles. [b]All vehicles were 1966 Fords with standard suspension and standard shock absorbers.

The Plymouth was a full-sized, 4-door vehicle with leaf springs. Figures 7 and 8 show the relation of PSR and Σ-counts determined by using the road meter in the 1968 Chevrolet. Both figures show an acceptable relation. Figure 9 shows a curve relating PSR and Σ-counts on bituminous roads determined by using the road meter in the 1968 Plymouth. The reason that the 1968 Plymouth was an acceptable test vehicle and not the 1967 Plymouth is not known, but it was probably due to the fact that the 1967 car had heavy-duty suspension.

In 1969, road meters were installed in six 1969 Fords of identical model and suspension system. This again allowed a comparison of PSR's at the same road meter outputs for identical automobiles. The results are given in Table 8. The results again show that there is a need for individual calibration of road meters even though they are installed in identical cars.

Some work has been done to evaluate the effect of standard versus heavy-duty suspension systems on road meter PSR. As mentioned earlier in this report an attempt was made in 1967 to correlate PSR with Σ-counts obtained by using a road meter installed in a 1967 Plymouth having heavy-duty suspension. The test results (Fig. 6) indicated that the Plymouth could not be used as the test vehicle because the slope of the curve in the figure was too steep at the top and too flat at the bottom. The slope of the curve made it difficult to differentiate between roads with PSR's ranging between 4.5 and 3.0 and between 2.0 and 1.0. Additional testing of this type was done in 1970. A comparison was made between a 1969 Ford with heavy-duty suspension and a 1970 Ford with standard suspension. The PSR's obtained with the same Σ-counts for both vehicles are given in Table 9. There is a noticeable difference between the PSR's with the same Σ-counts for both automobiles. However, curves were drawn relating PSR to Σ-counts for both vehicles, and both were determined to be acceptable. The heavy-duty suspension in the 1969 Ford reduced the movement between the rear-axle housing and the vehicle body, especially on smooth roads. As the roads became rougher, the road meter outputs also got closer and in fact equaled each other at a PSR of about 1.5 on bituminous roads and 1.0 on concrete roads.

As a result of all of the testing, it was determined that, to ensure that an acceptable correlation exists between PSR and Σ-counts for any combination of road meter and test vehicle, the combination must be calibrated individually with the laboratory road meter. The laboratory road meter is calibrated to panel PSR each spring. Although heavy-duty suspension apparently can be used in a test vehicle (correlation check must be made), it is recommended that standard suspension be used because it is more responsive to pavement roughness.

Condition of Test Vehicle—Although no testing was done to evaluate the effect of the deterioration in vehicle condition on road meter output, it is reasonable to assume that there is some significant effect.

To avoid any change in road meter output due to deterioration in vehicle condition, the suspension system, shock absorbers, and tires must be maintained in excellent condition. Each spring the shock absorbers should be replaced, the tires should be balanced dynamically and checked for roundness, the front end should be in good alignment, and any vibrations that may interfere with obtaining accurate PSR's must be corrected. New vehicles, the same model for each district and the central laboratory, should be obtained every 3 years.

If repairs are to be made on the test vehicle, the following procedures should be used:

1. Select 2 sections of pavement, one having a high PSR and one having a low PSR.
2. Run the road meter on both sections before and after repairs. The Σ-counts obtained on each section should be an average of a minimum of 2 runs. The values of the runs should be within 0.1 PSR of each other.
3. If the difference in PSR of either pavement is more than 0.2 PSR, return the vehicle and road meter to the central office for recalibration.

In order to make a calibration check of the road meter and test vehicle, a calibration check course consisting of at least 5 sections of pavement should be established within each district. These pavements should be constructed such that little change

Figure 7. Correlation of PSR and Σ-counts using 1968 Chevrolet (concrete pavements).

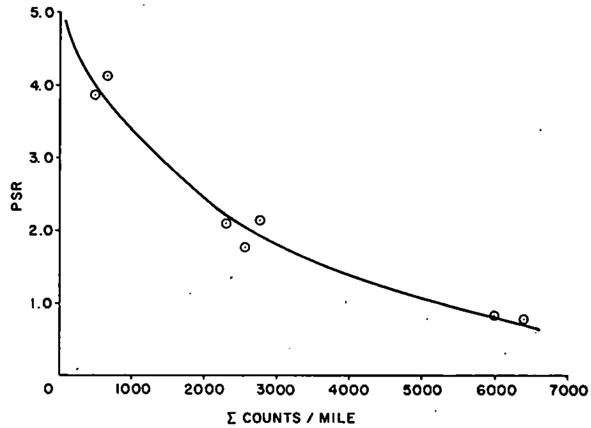


Figure 8. Correlation of PSR and Σ-counts using 1968 Chevrolet (bituminous pavements).

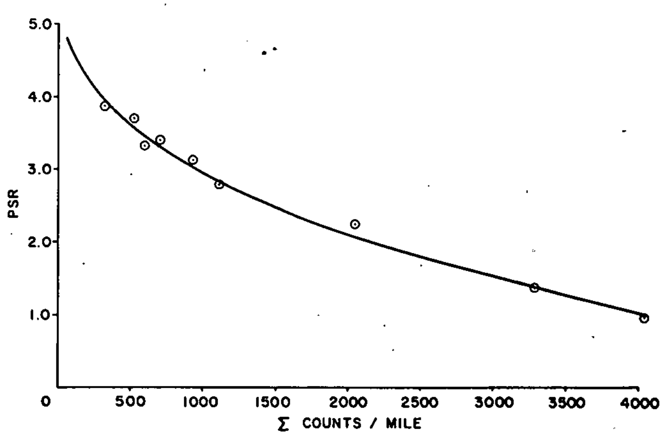
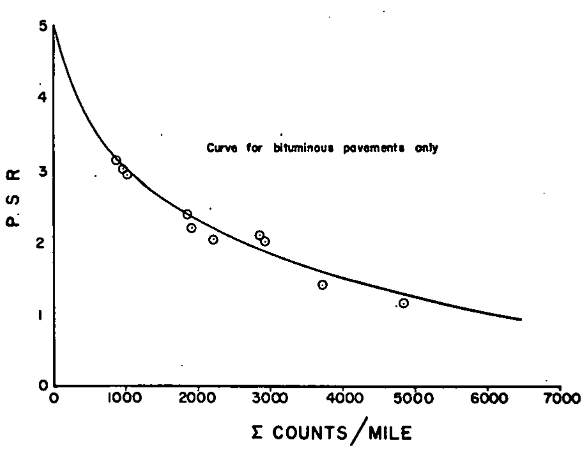


Figure 9. Correlation of PSR and Σ-counts using 1968 Plymouth (bituminous pavements).



in roughness is expected. The course should be run immediately after initial calibration and periodically thereafter to ensure that initial calibration is maintained. The initial calibration should be established from an average of a minimum of 2 runs on each section, provided that the PSR values are within 0.1 unit of each other. If the calibration check rating on at least 2 of the sections is within 0.2 PSR of the initial rating, calibration is acceptable. If the difference in rating of 4 of the sections is more than 0.2 PSR, a check for road meter malfunctions as well as deterioration in test vehicle condition should be made. Both the road meter and the test vehicle should be taken to the central office for recalibration.

The methods previously outlined to keep the road meter within calibration and to ensure reproducible results have worked satisfactorily so far. To cite an example, during the fall of 1968 one construction district ran its road meter over newly completed construction projects that were to be considered for the merit award program. The resulting PSR's were very low, considering the age of the projects. Because the district claimed that its road meter checked closely with its calibration check course, it was felt that there was an error in the testing procedure or something was wrong with the car.

The central office road meter vehicle was sent to the district to drive over the district calibration check course. The results were that the laboratory car indicated PSR's as much as 0.8 higher than the district's car.

In November 1968 a check was made in the metropolitan area with the district equipment. First, the laboratory meter was used in the laboratory vehicle, which was driven on 2 sections of bituminous road that had a significant difference in PSR. The district road meter was then placed in the laboratory car, which was driven over the same 2 sections. The results showed no significant difference (PSR of 0.1) in road meters. Next, the district's car and road meter were run on the same 2 sections of road. This combination showed a significantly lower PSR.

During testing it was observed that the district's car developed a shimmy in the front end at speeds of more than 55 mph. A check of the car repair records showed that this problem had been occurring regularly without any permanent repair having been made. This problem probably explains the reason for a greater difference in PSR at higher speeds. Therefore, a list of suggested repairs was submitted to the district in the hope that they would make the needed corrections for future ratings. The repairs were made before the 1969 rating season, and, although there were no checks made, the problem appeared to have been corrected.

In addition to all of the preceding factors, which were evaluated to determine their effect on road meter output reproducibility, several other variables were at least taken into consideration. These included effects of digital counter sensitivity, spring tension, and pretest adjustments. Although no formal evaluation was made of these variables, they were checked and are covered, as well as all of the other factors, in the operating instructions for the PCA road meter in the Appendix.

The Road Meter Must Provide Satisfactory Uniformity of Rating on a Statewide Basis

It was obvious that, if the mileage rated in 1966 by the panels from each district (6,379 miles) was typical of the mileage to be rated in future years, more than one road meter would be required. Therefore, a total of 10 devices were employed. One was located in each of the 9 construction districts for rating pavements in that district. The remaining road meter was controlled by the office of materials, and, as a master, was used for calibration of the other devices.

In 1967 the master road meter was correlated with PSR on both bituminous and concrete pavements. Twelve raters were used for the PSR determinations to ensure that true PSR would be approached (Table 1). A total of 28 sections of bituminous pavement and 15 sections of concrete pavement were used for this correlation.

A calibration course, consisting of 8 concrete and 7 bituminous pavements, was laid out, and each district road meter was calibrated against the master road meter. It was felt that in this way a high degree of uniformity in PSR would result among districts.

Probably the best indication of the actual uniformity of the rating system is a comparison of the standard errors between the laboratory vehicle and each of the district vehicles. Table 10 gives such a comparison for bituminous and concrete pavements using the data collected in the 1969 calibration of district road meters.

In 1969 the "pooled" standard error and standard deviation of the standard error were 0.17 and 0.07 for bituminous pavements and 0.16 and 0.05 for concrete pavements. This means that there is a 95 percent probability that a single test of PSR determination on a bituminous pavement, using any 1 of the district road meters chosen at random, will be within 0.31 of the PSR determined using the laboratory road meter. Similarly, there is a 95 percent probability that a PSR determination on a concrete pavement will be within 0.26 of the PSR determined using the laboratory road meter.

The standard error between laboratory vehicle and panel PSR was 0.26 and 0.19 for bituminous and concrete pavements respectively. However, if we were to assume that the PSR determined using the laboratory road meter is the true PSR, we can, using the results of Nakamura and Michael (3), determine the number of raters required to get the same uniformity that we expect to get with district road meters. At the 95 percent probability level, we can expect to be within 0.31 and 0.26 of the true PSR on bituminous and concrete pavements respectively (PSR determined using the laboratory road meter). The results of the Purdue study (Table 1) indicate that, at the 95 percent probability level, it would take about 31 raters to be within 0.3 of the true rating. In other words, using a district road meter in 1969 was as good as using a rating panel consisting of 31 people. This degree of uniformity is quite high and results in a much better rating system than the one (3-man panels) used at the outset of this study.

The Road Meter Must Not Require Excessive Manpower

The road meter can be effectively operated by 1 man. It requires no manipulation during operation, and, except for an occasional glance at the counters to see that the device is functioning properly, the operator can devote full time to driving.

The Road Meter Must Be Economical

The cost of building the 10 road meters now in service (one for each construction district and one for the central laboratory) was about $3,760 or $376 per road meter. Materials accounted for approximately $214 per device with labor costing the remaining $162.

Because only 1 man is required to determine PSR with the road meter, the time of 2 men can be saved over the normally used 3-man rating team. In 1966 approximately 6,379 miles of pavement were rated. This averages out to about 700 miles per district. If we assume that each district rating team rated 700 miles of road at an average rating speed of 50 mph and also that each team drove an additional 1,000 miles going to and from the roads to be rated at an average speed of 50 mph, than the man-hours saved per district would be as follows: 1,700 miles/50 mph × 2 men = 68 man-hours. If we use $6 per hour as the average salary (rater's were H.T. III's, CE II's, CE III's, or CE IV's), the savings per district per year would be at least $6 per hour × 68 man-hours = $408. The maintenance costs of the road meter are quite low. If we assume a maintenance cost of $25 per year, the road meter would pay for itself in about 1 year: construction and maintenance costs = $401; annual road meter saving = $408.

CONCLUSION

Based on the results of the evaluation of the PCA road meter, it can be concluded that the road meter is superior to the normal 3-man rating team as a method of determining riding quality. The road meter provides a uniformly accurate determination of PSR at a cost that compares favorably with the rating team method.

Table 8. Comparison of PSR's using 1969 Fords (bituminous pavements).

Σ-counts	PSR Value by Vehicle[a] Laboratory	1	2	3	4	5	Average	Standard Deviation	Range
150	3.75	3.80	3.68	3.78	4.01	3.91	3.82	0.12	0.33
500	3.11	3.13	3.03	3.13	3.30	3.22	3.15	0.09	0.27
1,500	2.52	2.53	2.45	2.55	2.67	2.60	2.55	0.08	0.22
2,500	2.25	2.25	2.18	2.30	2.36	2.31	2.28	0.06	0.18
3,500	2.07	2.07	2.00	2.11	2.17	2.13	2.09	0.06	0.17

[a]All vehicles were 1969 Fords with heavy-duty suspension and heavy-duty shock absorbers.

Table 9. Comparison of PSR's, 1969 and 1970 Fords.

Σ-counts	PSR Value by Vehicle 1[a]	2[b]	3[c]	4[d]
150	4.46	5.0	3.75	5.0
500	3.51	4.49	3.11	4.0
1,500	2.65	3.22	2.52	3.05
2,500	2.25	2.63	2.25	2.63
3,000	1.99	2.24	2.07	2.34

[a]1969 Ford with heavy-duty suspension on concrete pavement.
[b]1970 Ford with standard suspension on concrete pavement.
[c]1969 Ford with heavy-duty suspension on bituminous pavement.
[d]1970 Ford with standard suspension on bituminous pavement.

Table 10. Comparison of standard errors between laboratory vehicle and each district vehicle.

Type of Pavement	PSR Standard Error by District Vehicle[a] 1	2	3	4	5	6	7	8	9	Average	Standard Deviation	Range
Bituminous	0.18	0.10	0.25	0.13	0.16	0.27	0.22	0.11	0.09	0.17	0.07	0.18
Concrete	0.25	0.12	0.20	0.11	0.11	0.12	0.22	0.19	0.13	0.16	0.05	0.12

[a]District vehicles were 1966 Fords with standard suspension except for district 8 vehicle, which was a 1969 Ford with heavy-duty suspension.

Figure 10. Present serviceability rating form.

Trunk Highway ________ Control Section ____________ Lane Surveyed ________ Date ____________

Begin Survey ________________________ End Survey ______________________ Driver ________

Tire Pressure ________ Temperature ________ Ave. Speed ______ Length ________

Counter No.	Counts	Factor	Product	Notes
1		1		
2		2		
3		3		
4		4		
5		5		
6		6		
7		7		
8		8		
9		9		
10		10		
11		11		
Σ =				

Σ/Length = PSR =

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APPENDIX

GUIDELINES FOR USE OF PCA ROAD METER

These instructions have been prepared to ensure uniform and proper use of the PCA road meter for determining pavement ridability by the pavement rating teams in the construction districts. Contained herein is a list of the requirements of the vehicle in which the road meter is mounted, an outline or check list of the procedures for operation, and sections on preventing, recognizing, locating, and correcting malfunctions.

To ensure uniformity of rating by the 9 separate road meters that will be used throughout the state, it is imperative that each operator be completely familiar with and rigidly follow the instructions herein.

Vehicle Requirements

1. The vehicle in which the road meter is mounted must be in excellent condition with standard suspension, shock absorbers, and tires. Each spring the shock absorbers should be replaced (check part numbers to ensure shocks are not heavy-duty type), the tires should be balanced dynamically and checked for roundness, the front end should be in good alignment, and any vibrations that may interfere with obtaining accurate PSR's must be corrected. New vehicles, the same for each district and the office of materials, should be obtained every 3 years. This can be coordinated through the equipment section and the materials section.

2. If so desired, the road meter may be removed from the vehicle when the vehicle is to be used for purposes other than pavement rating.

3. If it is necessary to use the road meter in a vehicle other than the one in which it was calibrated, the road meter and new vehicle must be brought into the central office for calibration. The office of materials will provide a calibration and troubleshooting service.

4. If any repairs are to be made on the vehicle or road meter which may affect results, the procedure listed below should be followed:

   a. Select 2 sections of pavement—one having a relatively high PSR and the other a relatively low PSR.

   b. Use the road meter on both sections both before and after repairs. The number of counts obtained on each section should be an average of a minimum of 2 runs. The values of these runs should be within 0.1 PSR of each other.

   c. Compare the road meter results before and after repairs for each pavement. If the difference in PSR of either pavement is more than 0.2 PSR, the vehicle and road meter should be brought back into the central office for recalibration.

5. The road meter should be used only when the vehicle gas tank is at least one-quarter full.

6. The vehicle should have no more than 100 lb (excluding spare tire and jack) in the back seat or trunk when the road meter is being used.

7. Tire pressure shall be checked and maintained at the same pressure as when the vehicle and road meter were calibrated. Readings shall be made when the tire is cold.

Road Meter Operation

1. Insert the locking pin to hold rolling contact plate to aluminum track. Pull cable chain to attaching bolt on contact plate, taking care that all slack in the cable is removed, and note the "normal fit." Proper hookup is normal fit minus one link. The locking pin must be removed before making proper hookup. Connect the tension spring to the eyebolt.

2. Insert the single plug of the electrical cable into the receptacle on the counter box. Insert the 2 plugs on the other end of the cable into the appropriate receptacles of the switch assembly.

3. Turn on the road meter and drive for several miles to allow all components to warm up and to check counters 1 through 10 with number 11 counter.

4. Prior to rating, stop the car and make sure it is on a relatively level surface that is similar in crown to the pavement to be rated. Put car in parking gear. With the driver and passenger (if there is one) seated where they will be during rating, make use of the vernier dial and the indicator light to move the switch plate until the center segment is directly under the rolling contact. Turn meter off and make sure counters are zeroed. The road meter is now ready for use.

5. Select starting point of section of highway to be rated. Get up to operating speed (5 mph less than posted speed limit) ahead of starting point. At starting point switch road meter on and accurately note odometer reading. Drive the project at 5 mph less (±5 mph) than the posted speed limit. At the end of section being rated, switch road meter off and at the same time accurately note odometer reading. Determine length by taking the difference between beginning and ending odometer readings and record on the rating form.

6. The road meter should be turned off just before railroad crossings and bridge decks and turned on again after passing over the crossing or deck.

7. If at any time the speed of the automobile varies more than 5 mph from the speed limit minus 5 mph, the road meter will be turned off, the odometer reading recorded, and a landmark at the point of termination will be noted. Without zeroing the counters, rating can be resumed when the proper speed can be attained at the point of termination.

8. After the project is rated, stop the car on a relatively level surface that is similar in crown to the pavement just rated. Turn on the road meter. If the rolling contact is not on the center segment (indicator light off), the entire project must be run again. If the meter is still zeroed (indicator light on), proceed to the next step.

9. Record the readings on each counter in the appropriate column on the rating form.

10. Determine Σ-counts by adding the products of the readings on each counter and the appropriate counter number (Fig. 10).

11. Determine and record the PSR using the appropriate curve.

12. If the operator feels there is a large discrepancy between PSR determined from the appropriate curve and what he actually noted while performing the test, the project should be run again. (Example: a new project that should have a PSR of about 4 recording a PSR of 2.5 or 2.9.) If the discrepancy continues after a recheck, the road meter should be checked for a malfunction. If no malfunction is found, call the office of materials.

13. If more than 20 miles is to be driven before rating again, disconnect tension spring, disconnect cable, and insert hold-down pin.

Malfunctions

1. Preventing malfunctions: The following procedures should be observed to ensure a minimum number of malfunctions and erroneous readings.

a. Prior to each rating the road meter should be "warmed up" by operating for several miles.

b. Each day the effective unstressed length of the tension spring should be determined. The spring should be replaced once the unstressed length is more than $4\frac{3}{4}$ in. and must be replaced before the unstressed length reaches 5 in.

c. When connecting the cable to the plate, one must be sure to remove the hold-down pin before connection is made. Any substantial movement of the car body with respect to the axle, while the pin is still in place, may cause the cable to break.

d. The road meter shall not be used if the wind velocity is more than 15 mph or the air temperature is below 15 F.

e. A calibration check course consisting of at least 5 sections of pavement should be established within each district. These pavements should be such that little change in roughness is expected. The course should be run immediately after initial calibration and periodically thereafter to ensure that initial calibration is maintained. The initial calibration should be established from an average of a minimum of 2 runs on each section, provided that the PSR values are within 0.1 of each other. If the calibration check rating on at least 2 of the sections is within 0.2 PSR of the initial rating, calibration is acceptable. If the difference in rating of 4 of the sections is more than 0.2 PSR, the road meter and vehicle should be taken to the central office for recalibration.

2. Recognizing malfunctions: To ensure that results obtained with the road meter are representative of the pavements' ridability, the operator must be able to recognize erroneous readings when and if they occur. In general, the most successful method of determining if a malfunction has occurred is to observe the readings on the counters after a project has been run. The relative number of counts on the various counters should be such that the following conditions are met. Failure to do so indicates a possible malfunction and will result in an erroneous reading.

a. If at least 50 counts have been accumulated on a counter, the total count on that counter should be less than the count on every lower numbered counter.

b. If at least 100 counts have been accumulated on a counter, the count on that counter should be no more than 80 percent of the count on the next lower numbered counter.

c. Regardless of count, no counter should have over 3 counts more than any lower numbered counter.

3. Locating and correcting malfunctions: Once it is recognized that a malfunction exists, it is then necessary to locate the problem so that corrective action can be taken. The following procedure, if followed, will result in locating and correcting most malfunctions. After the operator is satisfied that all connections between the road meter and counters are secure, the electrical power is turned on; while the car is in a static position, the switch plate is moved so that the rolling contact makes contact with each segment. As contact is made, observe if the appropriate counter is activated.

a. If all counters record properly, the meter should be rezeroed and the projects rerun.

b. If one or more counters record properly only when the rolling contact is on one side of the center segment, then the malfunction is in the wiring encapsulated within the sealer alongside the switch plate.

c. If one or more counters fail to function properly, regardless of which side of center the rolling contact is located, then use the rotary switch to switch the number 11 counter to the counter number in question. If the counter numbered 11 does not function when the rolling contact is on the proper segment, the malfunction is in the electrical wiring and can be located by using an electrical continuity tester. If the counter numbered 11 functions properly when switched to the counter number in question, then the counter number in question is defective, and the following procedure should be carried out:

(1) Remove cover of counter box by removing 4 screws on side;

(2) Check to see that electrical connection of counter in question is intact;

(3) If the connection is good, remove the red wire from the terminal, and cut the black wire as far away from the counter as possible;

(4) Send the defective counter to the office of materials for repair; and

(5) Use the number 11 counter as a substitute for the defective counter by using the rotary switch. It is then necessary to operate without a number 11 counter. The counts for the number 11 counter will be estimated to be one-half of the counts on the number 10 counter and will be recorded as such.

d. If 5 or more counters indicate a consistent "skipping" tendency (e.g., 2 or 3 counters each having the same total number of counts), then examine the road meter to be sure that the grid plate contact strips and the switch plate rolling contact are clean. Steel wool or emery cloth can be used for cleaning.

A CANADIAN EVALUATION STUDY OF ROAD METERS

G. H. Argue

Road construction and maintenance activities may be considered as a service provided to the motoring public. The level of service extended is a function of the pavement's characteristics and properties. One variable having considerable influence is the riding quality of the pavement, i. e., the roughness of ride produced by the pavement surface. Methods must be available to measure this property in order to establish the level of service on a quantitative basis and to determine the cost-effectiveness of funds invested in pavement maintenance and rehabilitation.

A number of methods have been developed to measure pavement riding quality or roughness, but the cost and other characteristics of these methods often limit their use to special studies or to the testing of representative sections. A need exists for a low-cost, rapid method that can produce reliable and consistent measurements for the mass inventory of extensive road networks.

The road meter is a promising development toward fulfilling this need. The device is relatively inexpensive, and its speed of operation allows roughness measurements to be taken on several miles of highway in a day. This report concerns a study carried out by the Pavement Management Committee of the Roads and Transportation Association of Canada (RTAC) to investigate the reliability and consistency of road meter measurements.

ROAD METER EVALUATION STUDY

Objectives

The road meter evaluation study made by the Pavement Management Committee of RTAC was carried out during the summer of 1970. Several members of the committee had acquired one or more road meters; these meters often differed from the standard model (1, 2) and from each other. Differences were commonly found in the number of counters installed on the meter, and one agency (3) had made extensive electronic modifications to the basic road meter design. Moreover, these meters were installed in vehicles of various makes and models having substantial differences in suspension characteristics. Consequently, a prime objective of the evaluation study was to compare the measurements of these different meters and to determine the extent to which variations in meter design affected accuracy and reliability of measurements.

A second objective of the evaluation study was to correlate road meter Σ-counts with subjective ratings. Riding comfort index (RCI) is the standard measure of pavement riding quality recommended by RTAC (4, 5), and over the years Canadian agencies have developed considerable data and experience in terms of this measure. It was, therefore, considered that road meters would not receive general acceptance unless RCI's could be predicted with reasonable accuracy from road meter Σ-counts. RCI is similar to the present serviceability rating (PSR) widely used in the United States, except that RCI is established from subjective ratings made on a scale of 0 to 10, whereas PSR is established on a scale of 0 to 5.

A further objective of the study was to investigate the effect of testing speed and to establish whether an optimum testing speed existed that would minimize the error in relating road meter Σ-counts to RCI.

Testing Program

The investigations carried out actually consisted of 4 studies in which several types of road meters were used. The road meter common to all 4 studies was owned by the Canadian Department of Transport. This road meter was used at various airports and was compared with the meters of other agencies.

The first and most extensive of the 4 studies was carried out on 30 road sections in Quebec. Measurements were made on these sections with 4 road meters belonging to the Department of Highways of Quebec, by a road meter owned by the Department of Highways of Ontario, and by the Department of Transport road meter. The 4 Quebec meters tested the sections at 30 and 40 mph, and the Ontario and Transport meters ran measurements at 40 and 50 mph. RCI's of the Quebec test sections were established with a 9-man panel, except for 6 of the sections that were rated by only 3 persons.

A second study was conducted in Manitoba, where road meters of the Department of Transport and the Manitoba Department of Public Works were used on 30 test sections at 50 mph. RCI's were not determined for the Manitoba test sections.

A third study was conducted in Alberta, where the Research Council of Alberta established a set of 38 test sections to calibrate measurements by its road meter in terms of RCI. They conducted road meter measurements on these sections at 30, 40, and 50 mph and established RCI's with a 3-man panel. Twenty-eight of the Alberta test sections were also tested with the Transport road meter at 50 mph.

The fourth study was carried out in British Columbia, where 34 sections were tested by the Transport road meter and were rated by a panel from the Department of Highways of British Columbia. The rating panel consisted of 12 men, each of whom rated the sections on 3 separate occasions while seated in a different place within the test vehicle. The ratings obtained for the British Columbia test sections thus represented the mean opinion of a large-sized panel.

RESULTS OF EVALUATION STUDIES

Variation in Road Meter Measurements

The evaluation studies, involving 8 road meters, demonstrated that different road meters do not necessarily give the same Σ-values. Figure 1 shows the average relations between Σ-counts produced by the Department of Transport road meter and Σ-counts produced by each of the other 7 meters. Some of the other meters gave Σ-counts quite similar to those of the Transport meter, whereas other meters gave Σ-counts that were substantially different. As an extreme example, Figure 2 shows a comparison of the 40-mph measurements on the Quebec test sections by Quebec meters 3 and 4. The Σ-counts produced by Quebec meter 3 were approximately twice those produced by Quebec meter 4. Consequently, it cannot be assumed that 2 different meters will give similar Σ-counts. A comparison of results from 2 different meters requires that a correlation be established between their measurements.

Although measurement may not be numerically similar, the road meter evaluation studies indicated that a good linear correlation existed between any 2 meters. Table 1 gives the results of regression analyses between Σ-counts by the Department of Transport road meter and Σ-counts produced by the other road meters. The coefficient of correlation in these relations is 0.94 or better.

The ability to correlate the measurements of 2 road meters with a good degree of accuracy suggests that details concerning the construction of road meters are not highly significant in achieving consistent measurements. The Ontario and Manitoba meters had 8 counters, the 4 Quebec meters had 11 counters, the Transport meter had 12 counters, and the Alberta meter had the equivalent of 16 counters along with extensive electronic modifications. The Alberta road meter actually has only 8 counters, but the equivalent of 16 counters is produced by an extended switch plate and a double pole

Figure 1. Comparison of Transport road meter with other road meters.

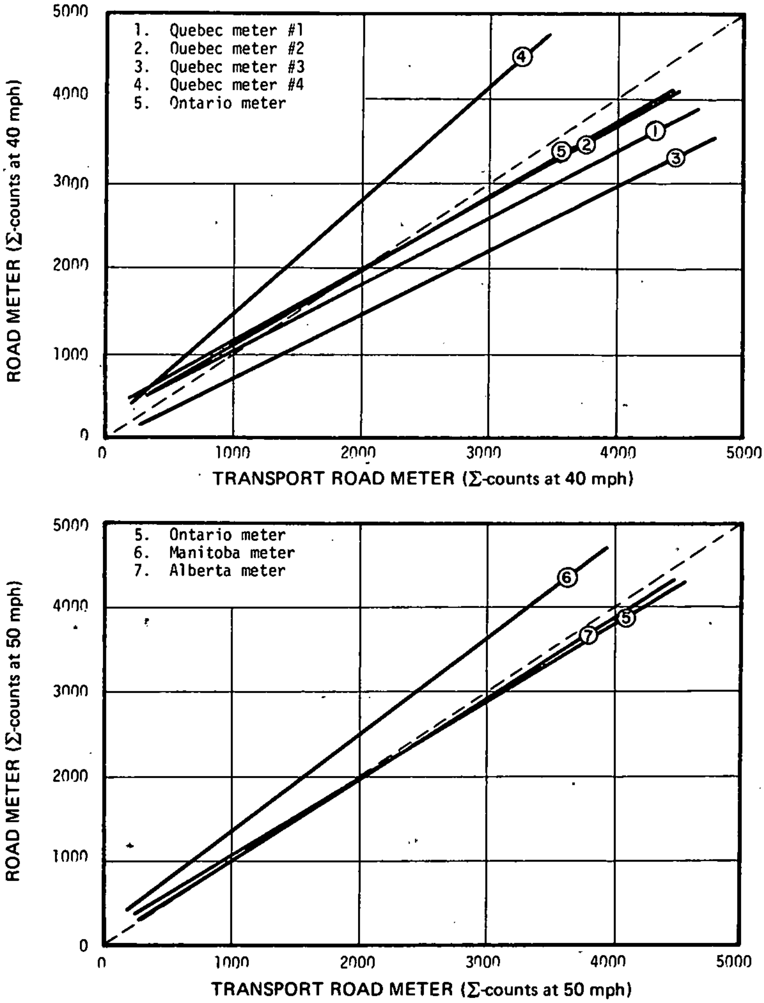
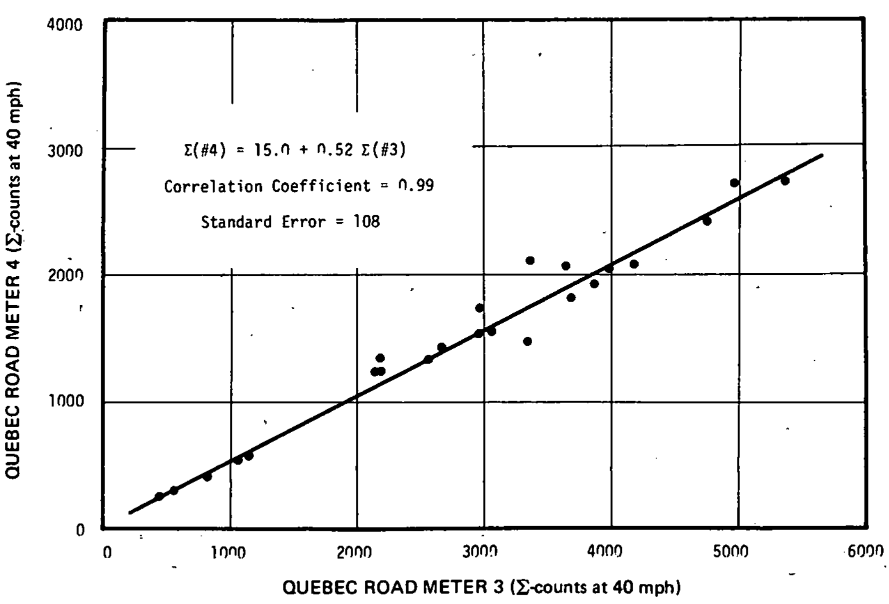


Figure 2. Comparison of Quebec road meters 3 and 4.



switch to change the counters from a low to high range during a second test run. In addition to these construction differences, various types and models of automobiles were employed as test vehicles. Despite all these variations, the coefficients of correlation between Σ-counts by different road meters ranged from 0.94 to 0.98. It would thus appear that the standard 8-counter road meter available from commercial sources is adequate for general use. Additional counters may be desirable for the testing of rougher pavements because they give more information on the larger car-axle movements.

Road Meter Ratings Versus Subjective Ratings

The road meter evaluation studies generated a number of correlations between RCI and road meter Σ-counts measured at various testing speeds. A summary of these correlations is given in Table 2. Figure 3 shows the correlations between RCI and Transport road meter Σ-counts for the Quebec, Alberta, and British Columbia test sections.

The degree with which road meter measurements relate to RCI may be judged from the standard error in predicting RCI from Σ-counts. As given in Table 2, these standard errors were rather high for the Quebec and Alberta test sections, where the ratings were established by panels ranging in size from 3 to 9 men. The magnitude of these standard errors would suggest that road meter measurements do not predict RCI with a high degree of accuracy. With the British Columbia sections, however, where the ratings represent the average opinion of a large-sized panel, the standard error in predicting RCI from Σ- values was 0.39 RCI unit. Although not conclusive, this figure indicates that RCI can be estimated from Σ-counts with reasonable accuracy and that the larger errors associated with the Quebec and Alberta data are possibly due to the smaller size of rating panels.

Another variable that may influence RCI and Σ-counts correlation is panel bias. This effect is noticeable in Figure 3, where the individual regression relations between RCI and Transport road meter Σ-counts are shown separately for the Quebec, Alberta, and British Columbia data. The curves for the Quebec and British Columbia data almost coincide, indicating that these 2 panels rated pavements in much the same manner. The regression curve for the Alberta data indicates that the Alberta panel, on the average, rated pavements 1.0 to 1.5 RCI units more severely than the other 2 panels.

The results illustrate some of the difficulties inherent in establishing accurate and reproducible calibrations for road meter Σ-counts in terms of subjective ratings. To promote accuracy and reproducibility, we must consider carefully the manner in which calibrating tests are carried out. It is suggested that calibrating test sections should be at least ½ mile in length, of uniform roughness throughout the section, and situated on level, tangent alignments. An adequate sample of sections would possibly number 30 or more, with surfaces ranging from smooth to rough. Better correlations with smaller standard errors are likely to result if a large rating panel is employed, and the panel members should be fairly representative of the general population in order to avoid biases.

Road Meter Testing Speed

Road meter measurements are influenced to various degrees by a number of variables. One variable having a significant effect is vehicle test speed, as shown in Figure 4, where Σ-counts measured at 50 mph are compared to values obtained on the same sections by the same vehicle traveling at 40 and 60 mph. One objective of the evaluation trials was to obtain some indication of the best vehicle speed at which to take measurements.

Two factors must be considered in deciding on testing speed. One consideration is safety and a requirement for compatibility with normal traffic speeds. The other factor is the effect that testing speed has on the error in predicting RCI from Σ-counts. The data given in Table 2 indicate a slight trend to smaller standard errors in relating RCI to Σ-counts when the Σ-counts are measured at 40 to 50 mph rather than at 30 mph. No significant difference is apparent in the error for testing speeds of 40 and 50 mph. A road meter testing speed of 50 mph would therefore seem most appropriate for normal highway operations.

Table 1. Average relation between Σ-counts of Transport road meter and other road meters.

Testing Speed (mph)	Type of Meter	A	B	Correlation Coefficient
40	Quebec 1	297	0.776	0.94
	Quebec 2	331	0.815	0.94
	Quebec 3	-30	0.752	0.96
	Quebec 4	114	1.342	0.95
	Ontario	211	0.879	0.95
50	Ontario	185	0.905	0.95
	Manitoba	233	1.137	0.95
	Alberta	25	0.949	0.98

Note: $\Sigma_T = A + B\,\Sigma_X$, where Σ_T = Σ-counts by Transport meter and Σ_X = Σ-counts by other meters.

Table 2. Summary of RCI versus Σ-counts regression analyses.

Test Section	Type of Meter	Testing Speed (mph)	A	B	Standard Error
Quebec	Quebec 1	30	15.8	-3.21	0.83
		40	17.6	-3.63	0.82
	Quebec 2	30	16.8	-3.54	0.82
		40	17.4	-3.61	0.81
	Quebec 3	30	18.2	-3.78	0.49
		40	18.0	-3.62	0.52
	Quebec 4	30	19.1	-4.52	0.78
		40	18.2	-4.02	0.75
	Ontario	40	17.3	-3.57	0.77
		50	18.1	-3.70	0.85
	Transport	40	17.9	-3.76	0.84
		50	19.5	-4.11	0.84
Alberta	Alberta	30	19.4	-4.71	0.96
		40	19.7	-4.68	0.88
		50	21.1	-4.98	0.87
	Transport	50	19.8	-4.63	0.90
British Columbia	Transport	50	19.3	-4.01	0.39

Note: RCI = A + B log (Σ).

Figure 3. Relation between RCI and Transport road meter measurements.

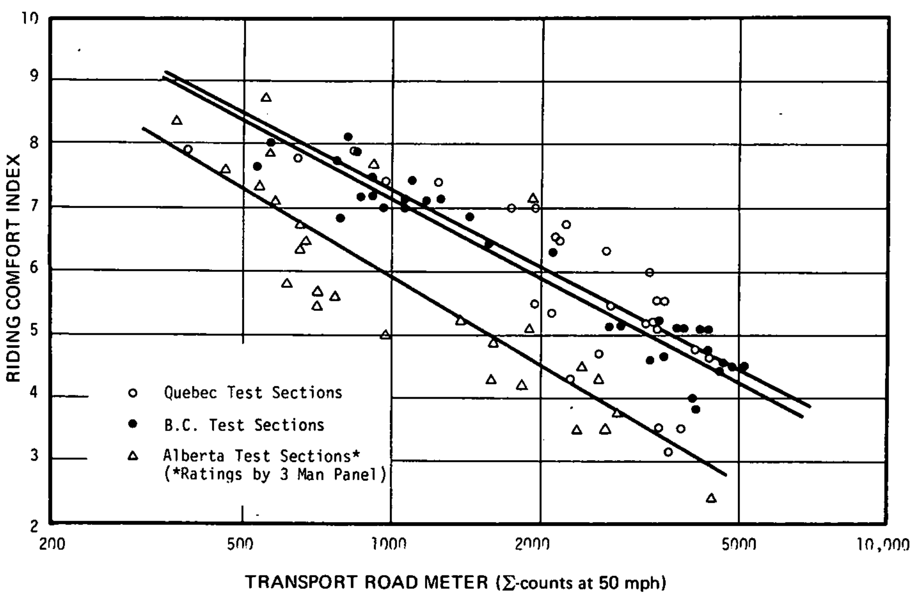


Figure 4. Comparison of road meter measurements at different test speeds.

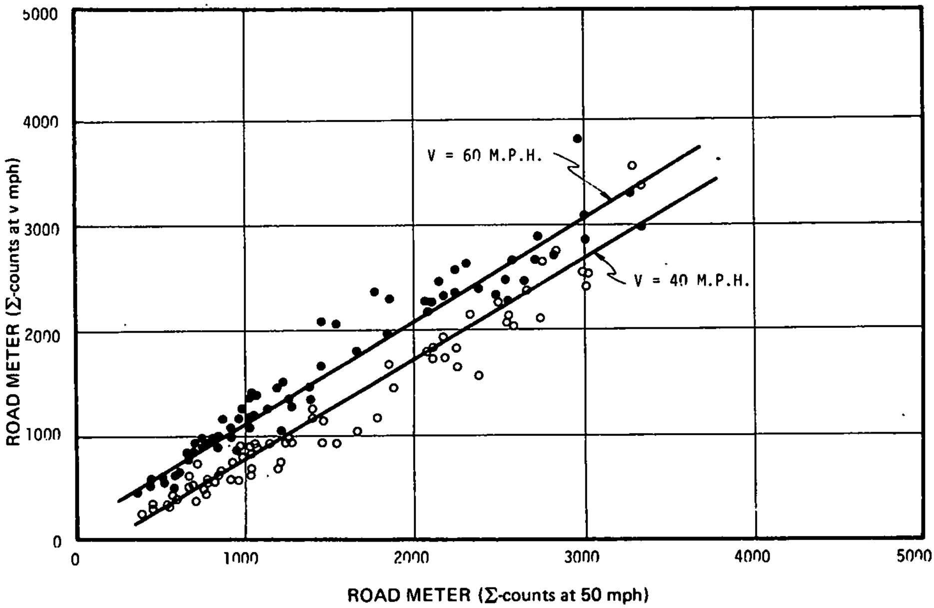
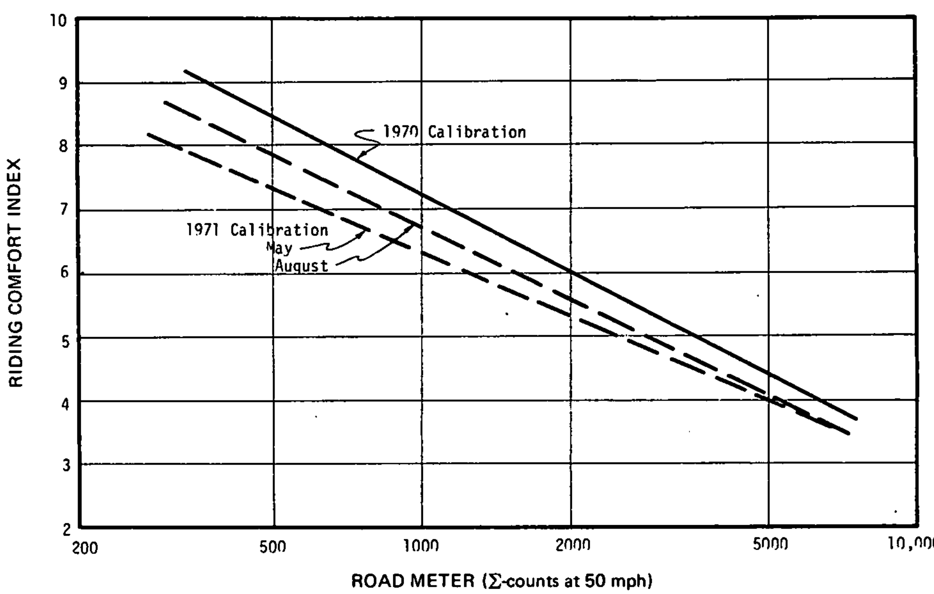


Figure 5. 1970 and 1971 calibrations of Transport road meter.



APPLICATION OF ROAD METER MEASUREMENTS

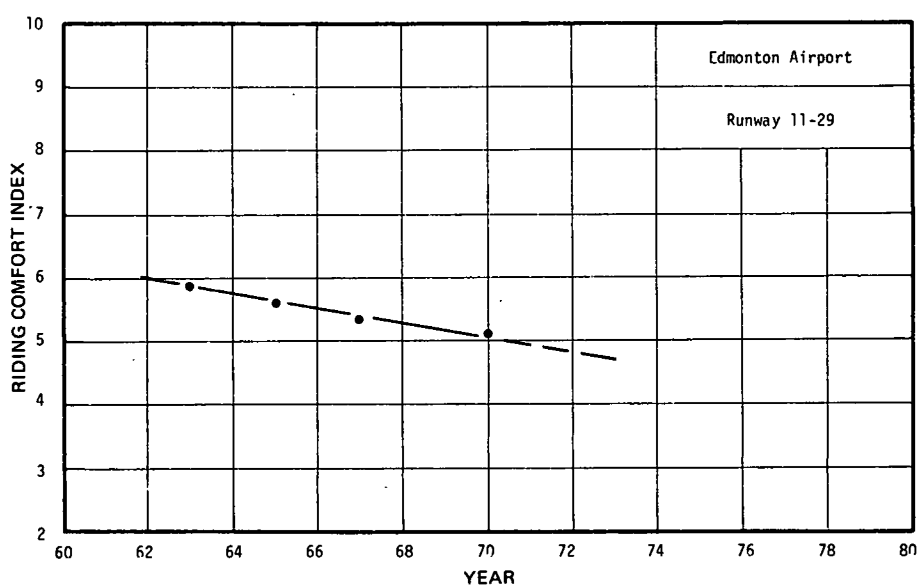
The possible lack of numerical similarity in Σ-counts produced by different meters constitutes one of the main deficiencies of the road meter as a roughness measuring device. Agencies using more than one meter in an inventory program will find it necessary to calibrate the individual meters in terms of a standard meter or some other standard measurement such as RCI. It may also be possible that measurements by a given road meter will change with time because of wear in the meter's components or changes in the suspension system of the test vehicle. To avoid errors of this nature, a set of calibrating test sections should be established so that a meter's calibration can be checked periodically.

An example of change in the measurements by a road meter is shown in Figure 5; the figure shows the calibration curves used for the Department of Transport's meter in 1970 and 1971. Prior to commencing the 1971 testing program, a new set of shocks was installed on the test vehicle. When checking the meter's calibration afterward, it quickly became evident that the new shocks had substantially reduced the Σ-counts produced by the meter. The extent of this change is reflected in the difference between the 1970 and 1971 calibration curves (Fig. 5). The meter's calibration was again checked on completion of the 1971 testing program in which the test vehicle traveled about 12,000 miles. The calibration had again changed to a limited extent.

The evaluation studies have indicated that measurements by a road meter can be relied on to at least classify the roughness, or the riding qualities, of a pavement in the correct order of magnitude. Because of the problems that occur in establishing and maintaining a calibration for the device, it might be questioned whether the road meter in its present state of development will give measurements that can be reproduced with good accuracy over a period of years. The utility of the road meter, therefore, depends on the intended application of its measurements.

An agency, for example, might be interested in conducting a condition survey of its highway network to determine where maintenance and rehabilitation funds could be spent with maximum effect. For a relatively small expenditure, a road meter would provide valuable and significant information in a survey of this nature. Another application of roughness measurements is in the construction of roughness performance charts such as shown in Figure 6. These charts are simply a plot of roughness measurements taken in different years so that one may record the gradual accumulation of roughness in a pavement over its life span. The variation likely to be encountered in

Figure 6. Pavement roughness performance chart.



road meter measurements over a period of years may be of sufficient magnitude to severely limit the usefulness of performance charts.

SUMMARY AND CONCLUSIONS

The following conclusions were derived from the road meter evaluation studies:

1. The assumption cannot be made that 2 road meters will produce measurements of the same numerical value; however, a good linear correlation should exist between these measurements.
2. A reasonable correlation should result between road meter measurements and subjective ratings when these ratings are established by a large, representative panel.
3. Details concerning the construction of road meters and the vehicles in which they are mounted do not seem highly significant in the reliability and consistency of measurements. The standard road meter model with 8 counters is sufficiently accurate for general use although additional counters may be desirable for more detailed information in the testing of rough pavements.
4. Road meter measurements vary with testing speed, and a standard testing speed of 50 mph is appropriate for normal highway applications.
5. Difficulties exist in establishing and maintaining an accurate calibration for a road meter. A set of calibrating test sections is necessary to periodically check the reproducibility of measurements by a meter.

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PART III

CORRELATION OF ROAD METERS WITH OTHER INSTRUMENTS

PCA ROAD METER MEASURING ROAD ROUGHNESS AT 50 MPH

G. J. Chong and W. A. Phang

The roughness of highway pavements is of concern to highway users and to highway engineers. Usually, whenever a highway user travels over a stretch of highway he consciously or unconsciously rates the roughness of the ride and decides whether it is tolerable. Highway maintenance personnel will have done this also to appraise the serviceability of the road and to determine whether the road condition meets current acceptable standards.

There is usually a diversity of opinion on such matters as deciding how rough a road may be, and, because of this, highway engineers now measure road roughness in a quantitative or objective way. Several types of equipment are currently used for this purpose. Two machines have been in use for the past few years in Ontario: the roughometer (developed by the U. S. Bureau of Public Roads) and the profilometer (developed by the British Road Research Laboratory) (1).

The profilometer (Fig. 1) is a road roughness measuring machine that produces a profile of the pavement surface as well as a measurement of roughness. For reproducibility of results, however, it must not be operated at speeds greater than that of a slow walk—about 1 mph.

The roughometer (Fig. 2) produces a roughness measurement by integrating the upward vertical motion of a standard suspension system relative to the frame of a vehicle, as the vehicle travels over the pavement surface at 20 mph. This equipment (a towed trailer) simulates the interaction of a vehicle and the road surface, and, because of its standardized suspension system, the measurements obtained do not vary in the same manner as they would if produced by automobiles designed by different car manufacturers.

When operating the profilometer or the roughometer, traffic must be diverted from the lane being measured. In the case of the roughometer, however, it is only necessary for the trailer to be equipped with warning signs and lights, except in multilane high-volume situations where, for the purposes of traffic control, the trailer must be followed by a properly signed auxiliary vehicle. The roughometer is the more versatile of the 2 machines because of its operating speed (20 mph); it can be used to measure the roughness of municipal roads as easily as the roughness of major highways.

The capabilities of the profilometer, on the other hand, are quite limited because of its very low operating speed. There are few situations where it can be operated without seriously impeding traffic flow. It is extremely useful, however, for measuring the roughness of newly constructed pavement not opened to traffic and where speed-dependent instruments cannot be used (such as on bridge decks). In most traffic situations the profilometer must be followed by a control vehicle to divert traffic from the lane being measured, and flagmen using a 2-way radio must be employed.

Although these 2 instruments have served well in the measuring of road roughness, there has been an increasing need for equipment that will perform satisfactorily at normal traffic speeds. Such an instrument has now been introduced by the Portland

Figure 1. The Ontario Department of Highways profilometer.

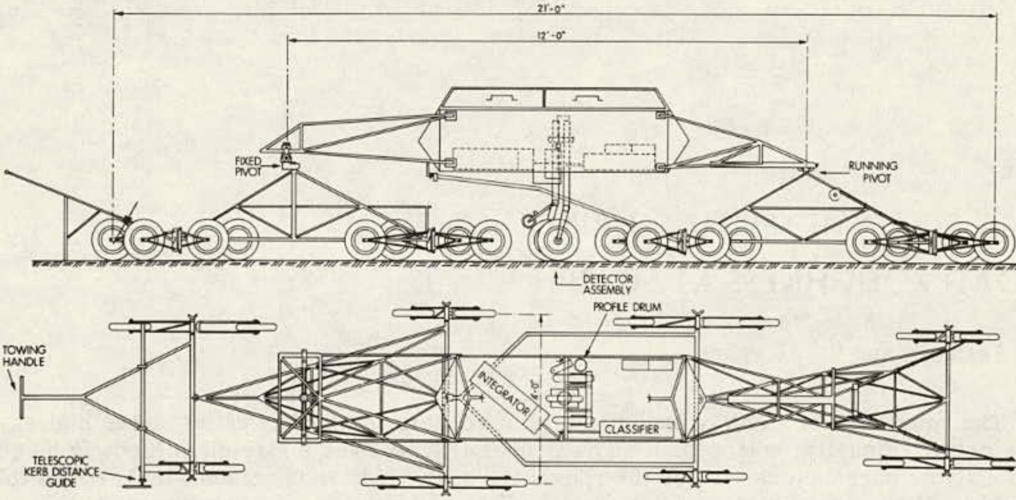


Figure 2. Roughometer trailer.

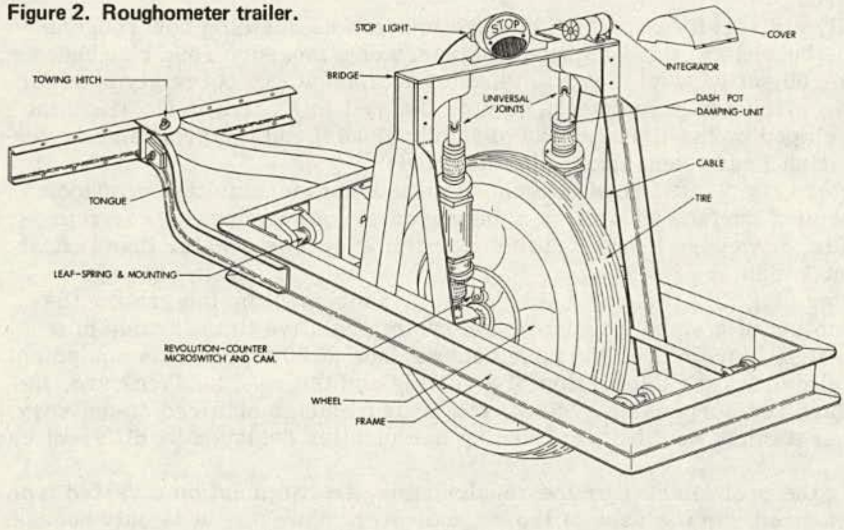
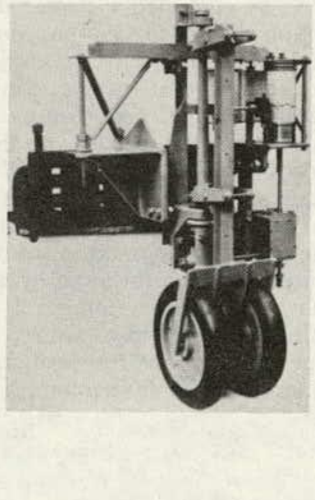


Figure 3. Profilometer recording wheel assembly.



Cement Association in its PCA road meter, which is fitted into an automobile (a normal passenger car) and is capable of measuring road roughness while being driven at 50 mph.

This report describes the PCA road meter and compares measurements obtained from its use with those of the roughometer and the profilometer.

METHOD OF EVALUATION

For evaluation purposes, 50 test sections were selected from both rigid and flexible pavements, and measurements of road roughness were carried out with all 3 measuring instruments.

The various measurements were not carried out on any one section at the same time because of the different speeds of operation but were arranged over a 6-week period during June and July of 1968.

The present performance ratings (PPR's) of the 50 test sections were determined by an individual rater; curves of PPR's were constructed for each instrument and correlation coefficients obtained.

The road meter was used to derive present serviceability indexes (PSI's) for each road section, using correlation data provided by the developers of the equipment. These derived PSI values were compared with the individual PPR values of the test sections, and regression analyses were performed to show how close the correlation was between the derived PSI and the PPR.

ROAD TEST SECTIONS

The test sections of highways were all within reasonable distance of Toronto. Each test section was ½ mile in length and was selected to provide uniform characteristics within its length.

Twenty-five of the sections were rigid pavement on Highway 401, between Highway 27 and Highway 6. The 25 flexible pavement sections were selected from 12 highways within 60 miles of Toronto; all of these pavements had been surfaced with a hot-mix asphalt.

Within each group of rigid and flexible pavement, the sections were chosen to provide a variety of roughnesses over the available range. The boundaries of the test locations were clearly identified by sketch maps and by painting start and finish marks on the sections of pavement concerned. This was done to ensure that the results obtained with the 3 instruments were from the same test sections.

PROFILOMETER

The profilometer is basically a 16-wheeled articulated carriage that supports a detecting and recording device at a constant height above the main level of the road surface. The 16 wheels and their axles support four 4-wheeled bogies that cover a total width of 4 ft and provide a 21-ft long wheel base. The design of the unit is such that only $\frac{1}{16}$ of the vertical movement of any single wheel is transmitted to the mounting of the detector wheels. The tires of the wheels are made of soft rubber and are inflated to a low pressure to ensure that very small irregularities in the road surface are not introduced into the measurement.

The detector assembly is located at the center of the chassis and consists of a detector wheel mounted centrally on a vertical detector shaft positioned in vertical guides (Fig. 3). Two trailing (flanking) wheels, mounted on elbows and pivoted on the detector shaft, ensure that the detector wheel "tracks" the line of travel properly. This results in a compensating forward movement of the profile pen, which keeps the plot of each vertical drop vertical.

The profilometer plots a profile of the road surface in a natural vertical scale and measures the number of bumps of different sizes by means of a classifier. In this unit, electrical counters record bumps of different sizes in intervals of 0.1 in.; other counters are included for each interval of 0.1 in., up to 1.5 in. The roughness value q, in inches per mile, is determined by the sum of all downward vertical motions in each interval (Fig. 4). This q-value automatically disregards any motion less than 0.1 in. and clas-

Figure 4. Profilometer data sheet.

DEPARTMENT OF HIGHWAYS, ONTARIO — SHEET 1 OF 3

PROFILOMETER DATA SHEET

DATE Sept. 7 19 67 HWY. NO. 401 PAVEMENT Concrete LANE WBDL OFFSET 6' off ℄

CONTRACT NO. 58 - 71 LOCATION Highway 27 Interchange to Etobicoke Creek

TIME OF TEST xxxx p.m. AIR TEMP. 25 °F. WEATHER sunny SURFACE CONDITION: Dry, Clean

PROFILE SCALE: 240 INTEGRATOR SCALE: ½ FOOTAGE/INDICATOR CORRECTION FACTOR: 1.005

FOOTAGE INDICATOR 1312 (ft.) CORRECTED TEST CELL LENGTH 1320 (ft.) FOOT-MILE RATIO (f) 4

$(\Delta q)_r = n_r \times \bar{h}_r$ WHERE: N = CUMULATIVE COUNTS; n'_r = NUMBER PER TEST LENGTH; $n_r = n'_r \times f$; $\bar{h}_r = h_r + 0.045$

$f = \frac{5280\ (ft.)}{L\ (ft.)}$ WHERE: L = CORRECTED TEST LENGTH

CELL (1)

h_r	N	n'_r	n_r	$\bar{h}_r$	$(\Delta q)_r$
.1	59	27	108	0.145	15.66
.2	32	18	72	0.245	17.64
.3	14	10	40	0.345	13.80
.4	4	1	4	0.445	1.78
.5	3	1	4	0.545	2.18
.6	2	1	4	0.645	2.58
.7	1	1	4	0.745	2.98
.8				0.845	
.9				0.945	
1.0				1.045	
1.1				1.145	
1.2				1.245	
1.3				1.345	
1.4				1.445	
1.5				1.545	
				TOTAL q =	56.62

Δp = 20.4 INCHES

q = CLASSIFIER INDEX 56.6 INCHES/MILE
p = INTEGRATOR INDEX 81.6 INCHES/MILE

CELL (2)

h_r	N	n'_r	n_r	$\bar{h}_r$	$(\Delta q)_r$
.1	61	31	124	0.145	17.98
.2	30	17	68	0.245	16.66
.3	13	8	32	0.345	11.04
.4	5	3	12	0.445	5.34
.5	2	0	0	0.545	0
.6	2	1	4	0.645	2.58
.7	1	0	0	0.745	0
.8	1	0	0	0.845	0
.9	1	0	0	0.945	0
1.0	1	1	4	1.045	4.18
1.1				1.145	
1.2				1.245	
1.3				1.345	
1.4				1.445	
1.5				1.545	
				TOTAL q =	57.78

Δp = 20.3 INCHES

q = CLASSIFIER INDEX 57.8 INCHES/MILE
p = INTEGRATOR INDEX 81.2 INCHES/MILE

CELL (3)

h_r	N	n'_r	n_r	$\bar{h}_r$	$(\Delta q)_r$
.1	61	36	144	0.145	20.88
.2	25	14	56	0.245	13.72
.3	11	8	32	0.345	11.04
.4	3	3	12	0.445	5.34
.5				0.545	
.6				0.645	
.7				0.745	
.8				0.845	
.9				0.945	
1.0				1.045	
1.1				1.145	
1.2				1.245	
1.3				1.345	
1.4				1.445	
1.5				1.545	
				TOTAL q =	50.98

Δp = 20.4 INCHES

q = CLASSIFIER INDEX 51.0 INCHES/MILE
p = INTEGRATOR INDEX 81.6 INCHES/MILE

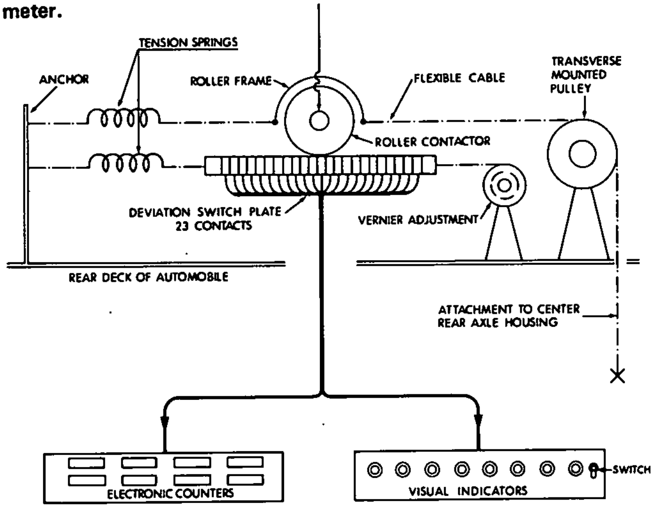
CELL (4)

h_r	N	n'_r	n_r	$\bar{h}_r$	$(\Delta q)_r$
.1	65	30	120	0.145	17.40
.2	35	17	68	0.245	16.66
.3	18	14	56	0.345	19.32
.4	4	1	4	0.445	1.78
.5	3	2	8	0.545	4.36
.6	1	0	0	0.645	0
.7	1	0	0	0.745	0
.8	1	1	4	0.845	3.38
.9				0.945	
1.0				1.045	
1.1				1.145	
1.2				1.245	
1.3				1.345	
1.4				1.445	
1.5				1.545	
				TOTAL q =	62.90

Δp = 22.3 INCHES

q = CLASSIFIER INDEX 62.9 INCHES/MILE
p = INTEGRATOR INDEX 90.4 INCHES/MILE

Figure 5. PCA road meter.



sifies all motion between 0.1 in. and 0.199 in. as 0.1 in.; it does the same for each class interval. There is, therefore, inherent in the q-value, a disregard for small fluctuations that might be caused by surface texture.

ROUGHOMETER

The roughometer is a single-wheeled trailer having a recording wheel located centrally in a frame that represents the top of a suspension system; it is comprised of 2 standard leaf-springs and 2 standard hydraulic dashpot dampers. An integrator capable of moving in both directions (but which is arranged to integrate only in one direction) is coupled to an electric counter that is calibrated to record inches of vertical movement. The integrator that is fixed to the framework attached to the suspension system is connected to the axle of the recording wheel by a steel cable.

The recording system thus measures the inches of vertical movement of the axle relative to the top of the suspension system. A second counter records the revolutions of the recording wheel so that between the 2 counters the roughness of any length of road may be recorded.

The Federal Highway Administration specifies a standard operational speed of 20 mph to ensure that the conditions of the test are exactly repeatable.

PCA ROAD METER

The PCA road meter also measures pavement roughness at the top of the suspension system of a vehicle. It is a simple electromechanical device that is installed in a standard passenger car to measure the number and magnitude of vertical deviations between the body of the automobile and the center of the rear-axle housing (2).

The instrument consists of a nylon-covered flexible steel cable connected to the top center of the rear-axle housing in the carrier vehicle (which should be in good condition and have a mechanically sound suspension system and good tires). The cable is brought vertically through the floor of the car to a package deck just behind the rear seat. At this point the cable is passed over a transverse-mounted pulley and restrained by a tension spring attached to a small post on the package deck, at a point near the right side of the body shell. Consequently, any vertical movement between the rear-axle housing and the package deck is translated into a horizontal movement of the steel cable and a corresponding movement to the recorder.

Halfway between the pulley and the tension spring, a roller type microswitch is attached to the steel cable. The switch, which is mounted on a small rectangular plate (that slides in transverse metal guides), is forced by its own internal compression spring onto a copper switch plate. The switch, therefore, is always in a partially compressed state, and electrical impulses are conducted through the roller and not by the microswitch contacts. A roller-type microswitch is used solely because its physical size and compression spring are well suited to the application, not because of any requirement for the special characteristics of a microswitch.

The switch plate is divided into 23 segments ⅛ in. long so that any transverse roller movements derived through the action of the steel cable are measured in ⅛-in. increments of vertical motion, which are either plus or minus from a reference standing position of the automobile. The transverse reference position of the switch plate can be adjusted beneath the roller to accommodate different static loads in the automobile. This adjustment is accomplished by a separate tension spring attachment and a vernier control.

The 12-volt electrical power of the automobile is applied to the roller and switch-plate circuit. Output is fed to the visual indicators of the road-car deviations and also connected to 8 high-speed electric counters capable of recording electrical impulses having a "make" time of 0.03 sec. The counters sum the impulses received from the segments of the switch plate, according to the magnitude of the impulses relative to the road-car deviations. Individual counters are connected to switch-plate segments, which correspond to road-car deviations of ± ⅛, ¼, ⅜, ½, ⅝, ¾, ⅞, and 1 in. The center segment, which is used for the initial zero reference, has no electrical connection.

Figure 6. Switch assembly in operating position.

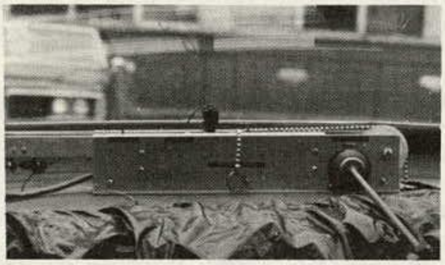


Figure 7. Switch plate and roller contactor.

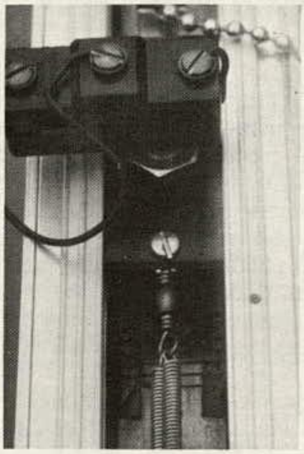


Figure 8. Electrical counters.

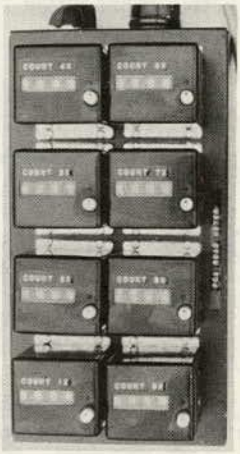


Figure 9. Visual indicators and control switch.

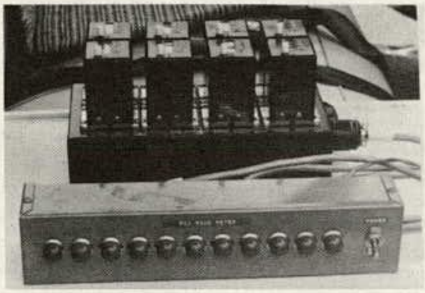


Figure 10. Road meter data sheet.

PCA ROAD METER SURVEY

DATE *May 17* COUNTY ______ ROUTE *401* PROJECT SECTION *10* TYPE *PCC*

FROM *Streetsville Road* TO *Highway 10* LANE *EBDL*

SURVEY BEGINS *2.0 Miles East Streetsville Road* ODOMETER ______

SURVEY ENDS *3.0 Miles East Streetsville Road* ODOMETER ______

TIME ______ TEMPERATURE *60°F* WIND *Light* CLOUDS ______

DATA FOR SECTIONS TESTED

BO: ______ EO: ______

L = *1.0* MILES

1X *360*	= *360*		*360* =	*360*
2X *317*	= *634*		*331* =	*662*
3X *186*	= *558*		*201* =	*603*
4X *78*	= *312*		*79* =	*316*
5X *32*	= *160*		*29* =	*145*
6X *14*	= *84*		*16* =	*96*
7X *4*	= *28*		*6* =	*42*
8X *1*	= *8*			*2224*
SUM	= *2144*		REPEAT ENTRIES	

SUM/L = ______

PSI (RIDE) = *3.16*

C + P = *–*

RUTTING = *–*

FINAL PSI = ______

NOTES : SPEED = *50 MPH*

Figure 5 shows some of the mechanical and electrical details of the road meter, and Figures 6, 7, 8, and 9 show the switch assembly, switch plate and roller contactor, visual indicators and control switches, and the electric counters.

The method of data reduction is straightforward. Each counter accumulates the number of impulses equal to, or greater than, its segment number. For example, a maximum road-car deviation of ½ in. will be recorded twice on the ⅛-, ¼-, and ⅜-in. counters and only once on the ½-in. counter because under most circumstances the roller will move away from the reference point and then return to it for each impulse. Each counter will therefore record the road-car deviation each time the roller passes over the individual segments of the switch plate up to the magnitude of the impulse. However, because the number of counters is limited to 8, the maximum deviation readable is 1 in., and all deviations greater than 1 in. will be recorded on the 1-in. counter and all other counters as the roller passes the segments.

Figure 10 shows a sample of a data record and its reduction. The summation of counts (Σ-counts) is obtained by reading off the number accumulated on each counter and then multiplying these numbers by the factor of 1, 2, 3, 4, 5, 6, 7, and 8. The total is the Σ-counts for a preestablished length of pavement, usually 1 mile. The PSI is derived from the Σ-counts that have been correlated with the CHLOE slope variance. The chart used to obtain these PSI values is shown in Figure 11.

PRESENT PERFORMANCE RATING

The Canadian Good Roads Association's PPR procedure was used to obtain a subjective ridability rating, for each test section, for correlation purposes with the roughness measurements from the instruments.

The PPR is the condition of the pavement at any time as determined by a rater, or a rating panel, who judges the present ability of the pavement to serve comfortably and conveniently, high-speed, high-volume, mixed automobile and truck traffic (1, 3).

The rating form is shown in Figure 12. The rater drives, or is driven, over the pavement section in a passenger vehicle at the assigned speed limit. On completion, the rater decides in which of the 5 categories he will rate the ridability. He then subdivides his rating in a given category by drawing a line upward or downward on the 2-unit scale within the category. The PPR value is then read off from the 0-to-10 rating scale.

The rater also answers the question, Is pavement of acceptable quality? by deciding whether the road ridability (in his opinion) is adequate for the class of traffic being served.

CORRELATION OF THE RESULTS

The results of all the measurements of the 50 test sections obtained with the 3 instruments are given in Tables 1 and 2. The PPR values and the PSI values derived from the PCA road meter measurements are also shown in these tables.

The results for rigid and flexible pavements have been separated because it was found that better correlations could be obtained in this way than from the combined data.

Regression analyses were carried out on all of the data, and the results of these analyses are given in Table 3 and shown in Figures 13 through 26.

The correlation coefficients (Table 3) are all of a high order, which shows that the performance of the instruments and the consistency of the raters' judgment were both good.

SURFACE TREATMENTS

A subsequent series of PPR and road meter evaluations were made in 1970 on 45 half-mile sections of surface-treated roads from the secondary and municipal road networks. The Wisconsin road meter used was installed in a 1970 Ford Sedan. The PPR was carried out in this same vehicle by the rater. The correlation shown in Figure 27 is of high order, and the regression equation is $PPR = 21.7239 - 5.3976 \log \Sigma$.

Correlations were made on the same surface-treated sections for the profilometer and the roughometer. No correlations were found for the PPR and the profilometer and the roughometer.

Table 1. Roughness measurements for flexible pavements.

Section Number	Highway	Profilometer (q)	Roughometer (R)	Subjective Rating (PPR)	Road Meter Σ-counts	Road Meter PSI
1	2	51.1	100.6	6.5	1,752	2.83
2	2	38.8	93.4	7.0	1,070	3.28
3	7	10.1	51.4	8.0	184	4.80
4	7	17.2	57.4	8.3	270	4.46
5	7	29.9	69.4	7.7	892	3.42
6	7	10.9	51.0	7.2	316	4.33
7	7	52.8	88.6	4.5	4,420	2.04
8	7	64.1	104.0	3.0	5,880	1.81
9	8	17.6	56.6	7.8	404	4.10
10	10	19.3	64.6	7.3	526	3.86
11	10	14.4	64.6	8.0	522	3.86
12	24	38.0	80.6	5.8	1,086	3.25
13	24	13.4	59.4	7.0	386	4.14
14	24	10.1	58.0	7.0	282	4.44
15	25	7.9	52.0	7.8	174	4.86
16	25	9.3	50.0	7.7	364	4.20
17	27	45.7	104.6	6.0	1,116	3.22
18	50	68.2	120.6	4.4	2,720	2.47
19	50	69.7	123.0	4.0	2,838	2.42
20	50	35.1	113.0	4.9	1,518	2.97
21	50	51.2	110.0	4.0	2,850	2.44
22	Cty.	52.8	126.6	4.2	3,280	2.32
23	Cty.	89.9	161.4	3.2	3,568	2.22
24	48	12.7	58.0	8.6	470	3.96
25	90	15.9	57.4	7.9	396	4.12

Table 2. Roughness measurements for rigid pavements.

Section Number	Highway	Profilometer (q)	Roughometer (R)	Subjective Rating (PPR)	Road Meter Σ-counts	Road Meter PSI
1	401	55.3	92.0	5.2	1,204	3.65
2	401	43.7	86.0	5.9	942	3.83
3	401	42.0	70.0	6.9	714	4.17
4	401	55.5	90.0	5.8	1,232	3.64
5	401	63.9	102.0	5.2	936	3.83
6	401	52.3	80.0	7.3	538	4.30
7	401	41.4	84.0	7.3	792	3.99
8	401	32.8	86.0	8.0	652	4.15
9	401	24.0	72.0	7.6	546	4.30
10	401	29.5	64.0	7.8	416	4.52
11	401	21.9	58.0	8.3	388	4.58
12	401	29.7	68.0	7.7	472	4.42
13	401	27.2	74.0	8.0	442	4.48
14	401	29.7	70.0	8.0	372	4.60
15	401	25.3	76.0	7.5	492	4.37
16	401	32.6	66.0	7.7	746	4.03
17	401	89.8	100.0	4.3	1,342	3.57
18	401	81.2	100.0	5.0	1,166	3.68
19	401	85.2	98.0	4.4	1,400	3.54
20	401	79.8	102.0	4.1	970	3.83
21	401	103.4	104.0	3.8	1,936	3.28
22	401	73.1	98.0	4.2	1,328	3.59
23	401	13.0	54.0	8.7	308	4.77
24	401	16.2	60.0	8.8	338	4.70
25	401	14.0	58.0	8.5	290	4.81

Table 3. Regression analysis of results.

Type of Pavement	Independent Variable	Dependent Variable	Figure Number	Regression Formula	Correlation Coefficient
Rigid	Profilometer, q	Roughometer, R	13	Log R = 0.3241 log q + 1.3793	0.9313
	Profilometer, q	Road meter, Σ-counts	14	Log Σ = 0.8516 log q + 1.4810	0.9286
	Roughometer, R	Road meter, Σ-counts	15	Log Σ = 2.3890 log R - 1.6907	0.9037
	Profilometer, q	PPR	16	PPR = 16.2037 - 5.9878 log q	0.9341
	Roughometer, R	PPR	17	PPR = 38.1211 - 16.5961 log R	0.9012
	Road meter, Σ-counts	PPR	18	PPR = 25.0720 - 6.4873 log Σ	0.9276
	PPR	PSI (derived from Σ-counts)	19	$PSI_{(D)}$ = 0.2484 PPR + 2.4555	0.9276
Flexible	Profilometer, q	Roughometer, R	20	Log R = 0.4496 log q + 1.2581	0.9566
	Profilometer, q	Road meter, Σ-counts	21	Log Σ = 1.3265 log q + 1.0671	0.9461
	Roughometer, R	Road meter, Σ-counts	22	Log Σ = 2.7160 log R - 2.1929	0.9068
	Profilometer, q	PPR	23	PPR = 12.7288 - 4.5291 log q	0.8519
	Roughometer, R	PPR	24	PPR = 25.2519 - 10.0093 log R	0.8813
	Road meter, Σ-counts	PPR	25	PPR = 16.4401 - 3.4377 log Σ	0.9066
	PPR	PSI (derived from Σ-counts)	26	$PSI_{(D)}$ = 0.4733 PPR + 0.4454	0.9030

Figure 11. Relation of AASHO PSI to road meter Σ-counts.

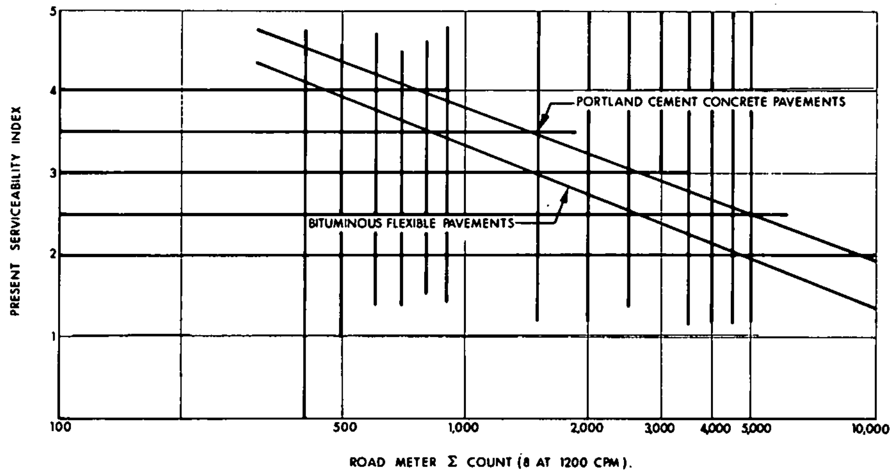


Figure 12. PPR form.

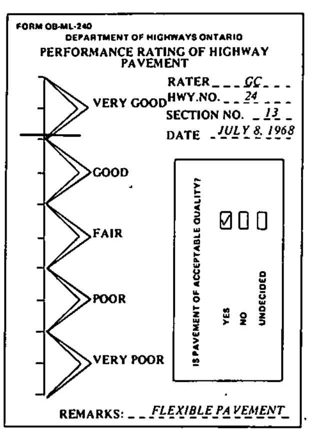


Figure 13. Correlation of profilometer and roughometer for rigid pavements.

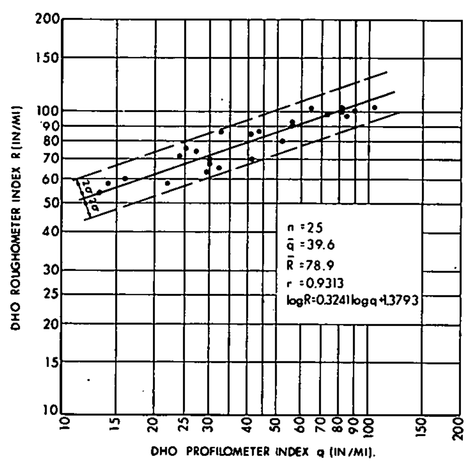


Figure 14. Correlation of profilometer and road meter for rigid pavements.

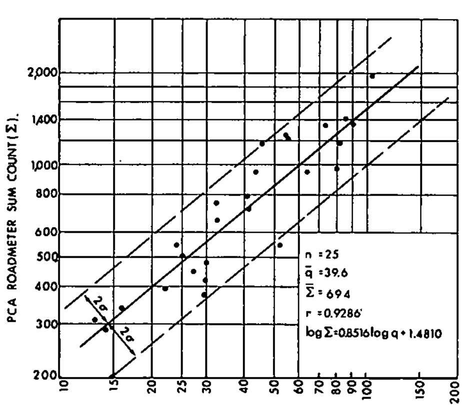


Figure 15. Correlation of roughometer and road meter for concrete pavements.

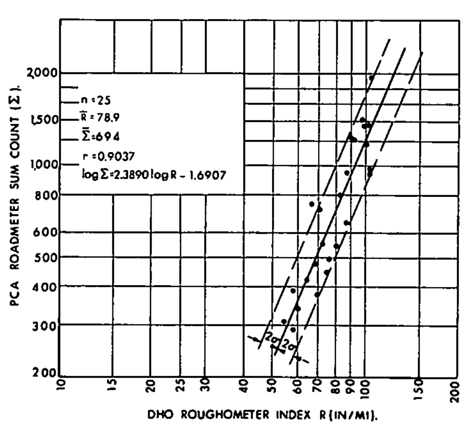


Figure 16. Correlation of profilometer index q and PPR for rigid pavements.

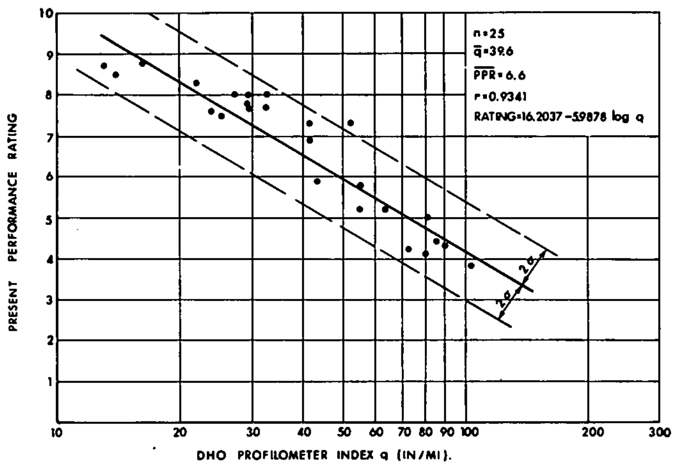


Figure 17. Correlation of roughometer index R and PPR for rigid pavements.

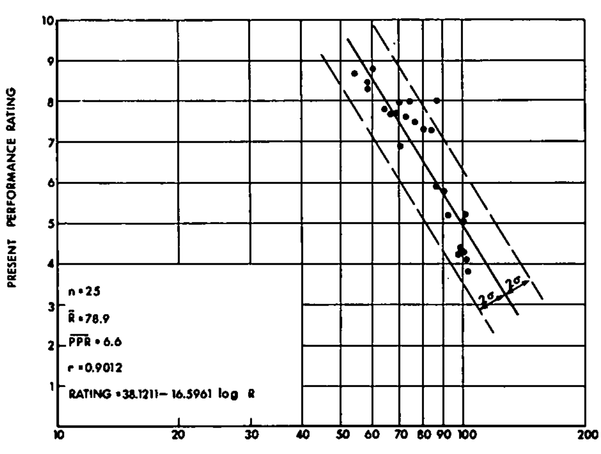


Figure 18. Correlation of road meter Σ-counts and PPR for concrete pavements.

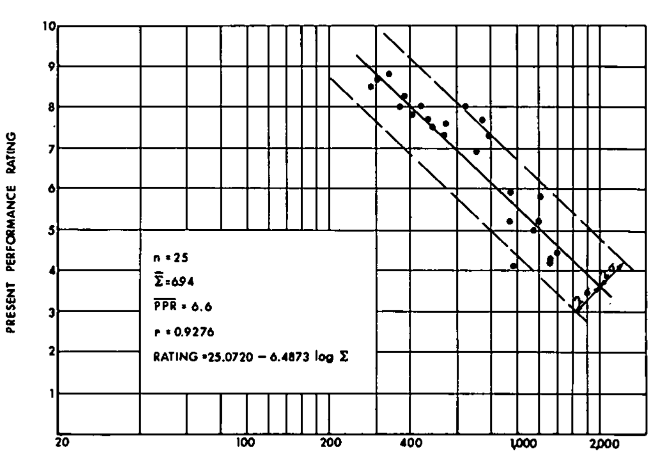


Figure 19. Correlation of PPR and PSI based on road meter Σ-counts for rigid pavements.

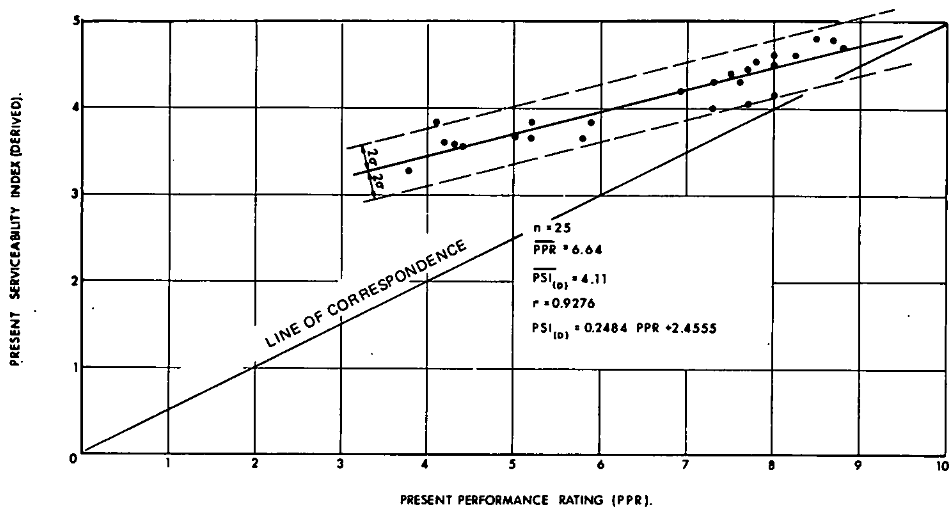


Figure 20. Correlation of profilometer and roughometer for flexible pavements.

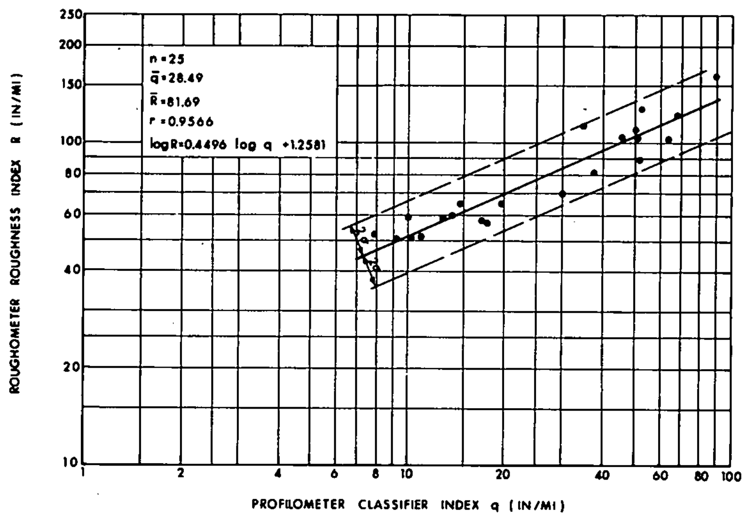


Figure 21. Correlation of profilometer and road meter for flexible pavements.

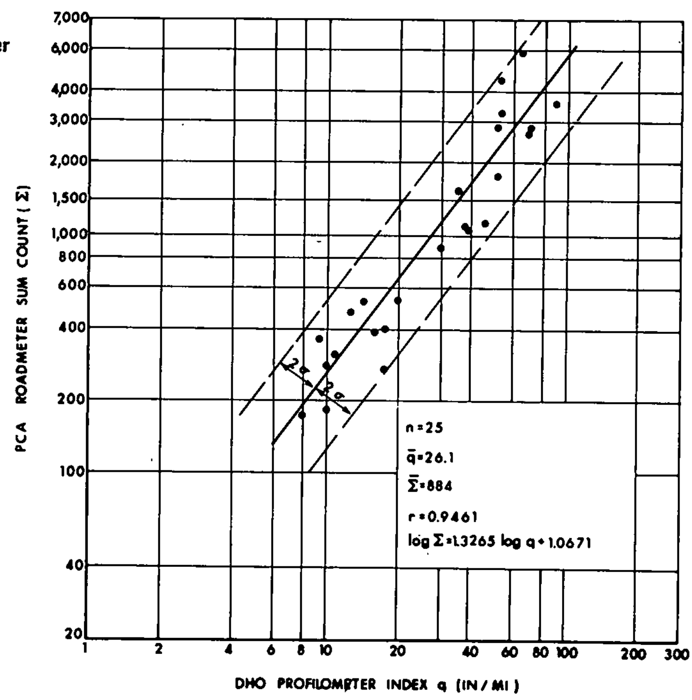


Figure 22. Correlation of roughometer and road meter for flexible pavements.

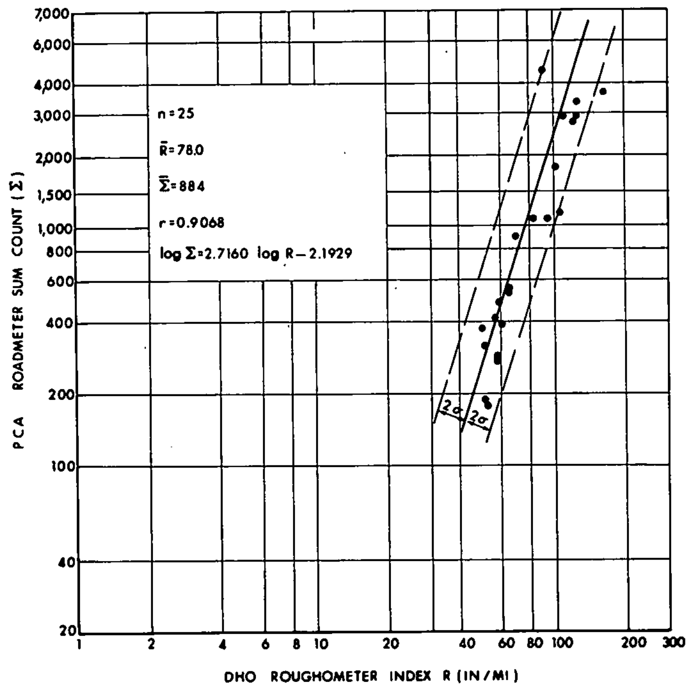


Figure 23. Correlation of profilometer index q and PPR for flexible pavements.

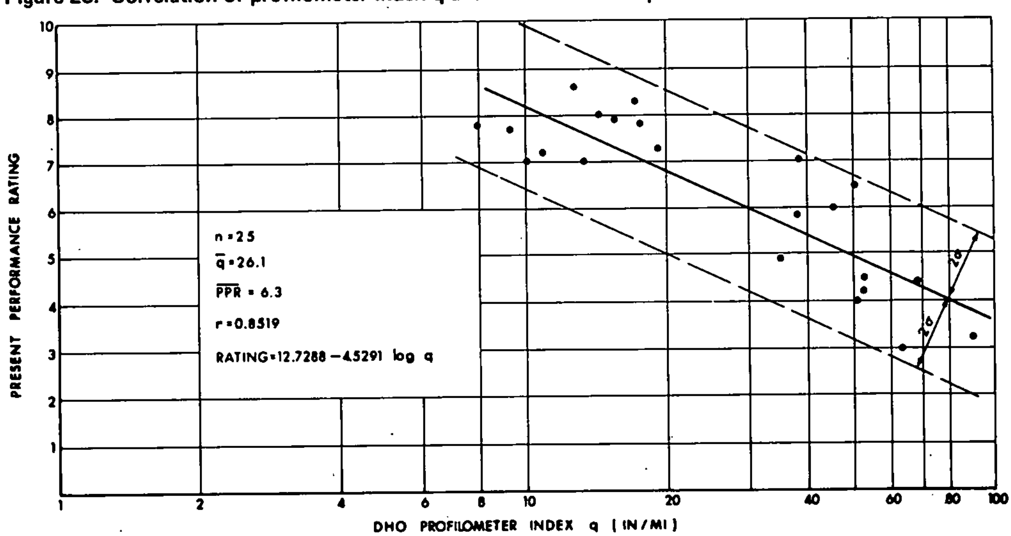


Figure 24. Correlation of roughometer index R and PPR for flexible pavements.

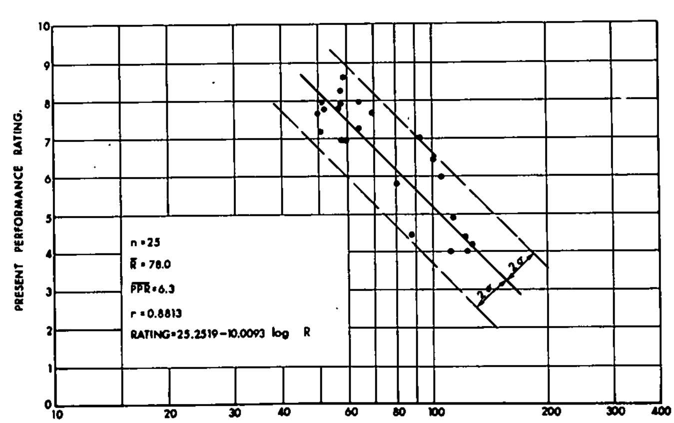


Figure 25. Correlation of road meter Σ-counts and PPR for flexible pavements.

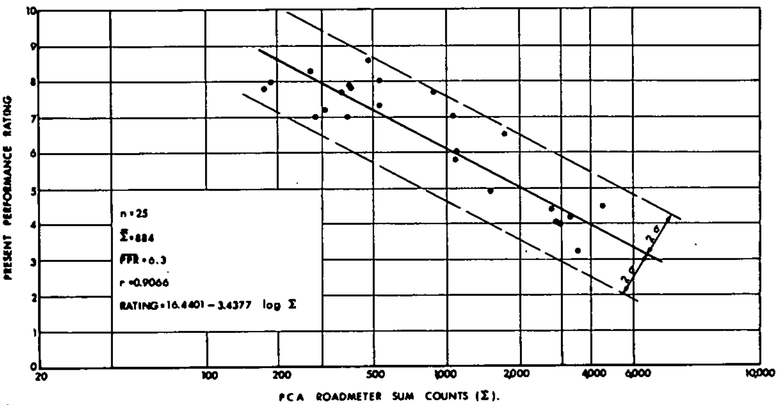


Figure 26. Correlation of PPR and PSI based on road meter Σ-counts for flexible pavements.

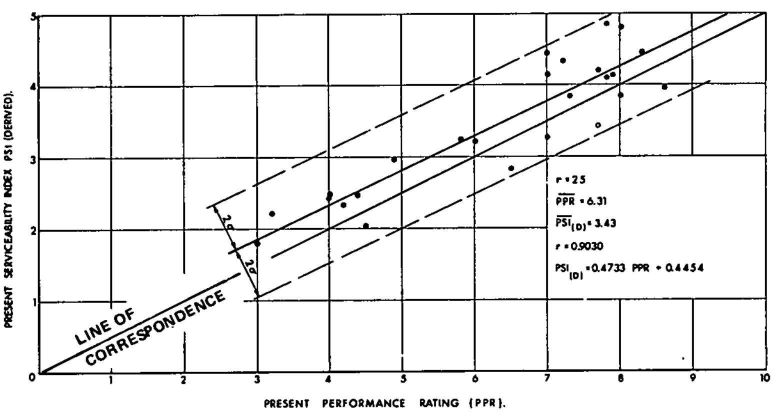
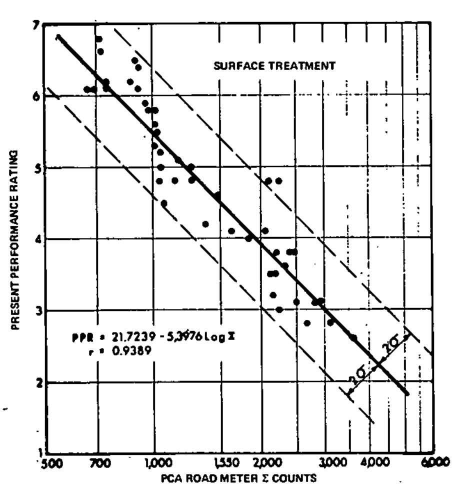


Figure 27. Correlation of PPR and road meter Σ-counts for surface-treated pavements.



IMPORTANT POINTS IN OPERATING THE PCA ROAD METER

The PCA road meter must be maintained in proper order at all times so that good repeatability is ensured. To maintain it in proper condition, the designer suggests a number of important points to observe in its operation in addition to the normal maintenance procedures.

Condition of Automobile

To achieve repeatable sum-count measurements, the automobile in which the road meter is used must be in good mechanical condition, particularly the suspension components. Shock absorbers must be removed every 10,000 miles of operation and inspected for wear along the piston sides; the working action must be compared with new shock absorbers.

Good front- and rear-wheel balance and front-end alignment must be maintained because improper alignment results in uneven tire wear, which will affect meter counts.

Tire pressures must be maintained at 24 to 26 psi (static pressure when cold); if the vehicle is equipped with rear snow tires, they should be kept between 22 and 24 psi.

The gasoline tank must be at least one-quarter full at all times. No extra weight must be carried by the vehicle, nor should the weight be redistributed after calibration.

Operating Speed

The best results are obtained with the road meter when the operating speed is maintained at 48 to 52 mph; if the speed falls below, or exceeds, these limits, correction should be made quickly—but in a manner that will not cause an increased count rate due to sudden acceleration or deceleration.

Special Conditions

The road meter should be switched off just before crossing railroad tracks to avoid damage from sudden jarring of the instrument.

The road meter should be operated only when the air temperature is above 10 F because the characteristics of the automobile's suspension system will likely change at lower temperatures.

To avoid unnecessary jarring, the road meter should be disconnected by removing the steel cable from the roller contactor and carefully sliding the contactor to the "switch stop" position when traveling between projects that are 20 or more miles apart.

Zero Balance

A valid Σ-counts of vertical motion is achieved only when the road meter is properly balanced to produce minimal deviation when the car is stopped on the pavement. Changes in crossfall, superelevations, and even pavement rutting affect the zero position of the vernier while the car is in motion; consequently the results obtained are an average of plus or minus variations from the actual zero position on any point in the test section.

It is advisable to check the road meter operation periodically on a known stretch of roadway whose roughness does not change extremely through seasonal or normal deterioration of the roadbed. An independent means of assessing the road meter's performance with the profilometer or roughometer is also advisable. It is suggested that long, exposed concrete bridge decks offer the best areas for this periodic check.

CONCLUSIONS

This comparative study of the 3 roughness measuring instruments has resulted in the important finding that little difference exists among the 3 instruments in predicting serviceability of a pavement. Therefore, the choice of instrument to use on any particular project depends on the nature of the data desired, instrument and operating costs, ease of data reduction, and efficiency of operation.

Of similar importance is the finding that the PCA road meter has a number of advantages over the other 2 instruments, which makes it more desirable for certain types of roughness measuring applications such as mass inventory of the road roughness of existing highway systems and seasonal serviceability surveys. The instrument is advantageous in many respects. Because of its simplicity, initial costs are low; the instrument can be manufactured and installed at a cost of less than $1,000, and the only other equipment required is a standard passenger car. No special outfitting of the carrier automobile, other than the mounting of the unit, is necessary. The data obtained are immediately usable because no calculations are involved. PSI's are derived directly from a prepared chart by using only the total sum counts obtained for each pavement section. Its efficiency is good because of the high operating speed (50 mph) at which it can be used. An additional benefit from the high operating speed is the relative safety with which the test vehicle can merge with normal traffic flow.

However, if large-scale use of the PCA road meter is envisaged because of these advantages, it is essential that the test vehicle be kept in good operating condition at all times and the specified standard speed be adhered to. It is also important to make frequent check runs on standard pavement sections and to use an independent method of rating the standard pavement section with a profilometer or roughometer.

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ROAD METER CORRELATIONS: IOWA STATE HIGHWAY COMMISSION

Vernon J. Marks

In April of 1967, Phil Brua of the Portland Cement Association (PCA) demonstrated the use of the PCA road meter to the Iowa State Highway Commission. The apparatus showed real promise for road inventory, so a unit was constructed and by July was installed in a 1967 Chevelle station wagon (because it was the only passenger vehicle with coil-type rear springs available). This unit was functional, but it was believed that a standard-sized automobile with coil-type rear springs would yield better results. The purchasing department obtained a poorly equipped 1967 Ford Custom with very weak suspension. This vehicle was unsatisfactory as a road meter vehicle. In the spring of 1968, 3 units were mounted in fully equipped 1968 Ford Customs with very good results.

It was apparent from the beginning that the road meters would have to be correlated against a more stable and exacting standard to make the values meaningful from one agency to another. The 3 identical Fords, all having identical road meter units, exhibited enough variation in count to prove the need for individual correlation of each car.

We have used some rating panels in Iowa but have not been completely satisfied with these. The BPR roughometer and the CHLOE profilometer were available and were considered. The CHLOE profilometer was selected as a standard because, if it is operated on roadways having uniform surface textures, it yields very accurate and repeatable results. It also is not dependent on a suspension system, and if the electrical calibration checks out it yields reliable results. Because it checks a line profile, its repeatability varies with the transverse undulations of the various roadways but is generally very good.

The correlation test sections should be carefully selected. Sections should have uniform ridability with no extreme profile in or just prior to the test section. Surface texture of all test sections used for the correlation must be uniform because open textures will yield erroneous CHLOE results. In early correlations, both asphaltic concrete and portland cement concrete sections were used. A greater surface variation and a winter change were soon evident in the asphaltic concrete sections. This did not seem to be true on portland cement concrete, which had a relatively uniform burlap drag finish; therefore, all correlation sections were selected on portland cement roadways. One case has been enountered where dogs had played on the slab prior to hardening of the portland cement, and the uniform texture was destroyed. One-half mile long correlation sections have served satisfactorily. They are short enough for the CHLOE (3 mph) and long enough for the road meter (50 mph). The sections should include a wide range of present serviceability ratings. We have a range of 2.7 to 4.6. A greater range is available, but we choose to limit our sections to relatively new, more stable sections, thus making it difficult to find roads below 2.7. Usually these are quite old, very broken, and not as uniform as desired.

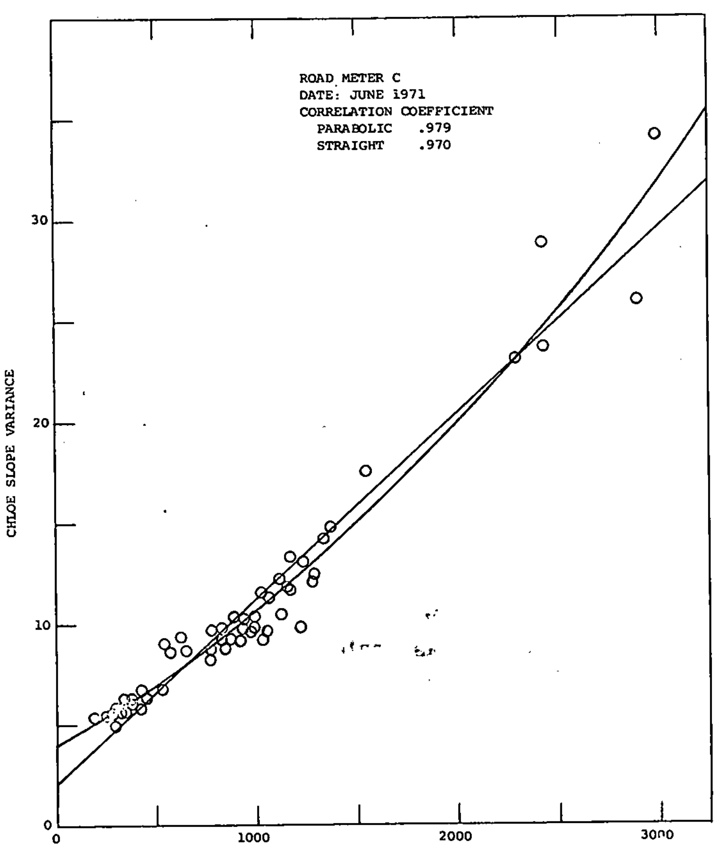
In the actual correlation operation, the CHLOE is operated in both the inside and outside wheelpaths. The reason for this is that the road meter is influenced by both wheelpaths, and from experience there is no definite relation between the CHLOE slope variance of the inside and the outside. The values obtained are averaged to determine the CHLOE slope variance of a section.

The CHLOE slope variance and the road meter summation of counts are determined for all correlation sections (we currently have 54). In 1968, we assumed a straight-line relation between CHLOE slope variance and summation of count. The data, however, continually exhibited a certain amount of curvature (Fig. 1). This curvature varies with the vehicle, and in general we have decided that stiffer suspensions yield straighter correlation lines and that softer suspensions yield more curvature. There are many factors that influence this, however. The data are submitted to the data processing center by way of a computer terminal, and a parabolic fit is determined by the method of least squares. If a straight line is the best fit, the X^2 term will be zero, and a linear relation will result. In all cases the correlation coefficient has been better for the parabolic fit than for a linear fit.

We determine a correlation annually in May and then make weekly checks on 6 convenient correlation sections to verify the original correlation. The resulting correlation equation is combined with both the flexible and rigid equations as determined at the AASHO Road Test, and the result is plotted on a semilogarithmic graph.

An inventory of Iowa's 10,000 miles of primary highway including a cracking and patching survey has been conducted and stored on magnetic tape in the data processing center to be used in the determination of maintenance and construction priorities.

Figure 1. Relation between CHLOE slope variance and road meter summation of counts.



METHOD FOR MEASURING SERVICEABILITY INDEX WITH THE MAYS ROAD METER

Roger S. Walker and W. Ronald Hudson

The age-old problem of providing an objective tool for determining when a pavement has failed has yet to be solved completely. However, the development of the pavement serviceability performance concept by Carey and Irick (1) during the AASHO Road Test standardized a performance measurement procedure through which efforts toward solving this problem might better be directed. A high-speed road roughness measuring capability has been developed for the Texas Highway Department using this concept at the Center for Highway Research, where the surface dynamics profilometer (SDP) (2, 3, 4) is used for obtaining objective road profile measurements. Serviceability index (SI) is then computed from the power spectral estimates of these data. Use of the SDP for obtaining SI has several advantages, one being an internal calibration facility that ensures proper operation of the measuring equipment. It has proved to be an excellent device for obtaining accurate road profile information over selected bandwidths. However, there are some factors that limit its usefulness in obtaining routine SI measurements throughout the state. Among these are high equipment investment, operating cost, and the lack of an immediate SI measurement. (Technology is now such that an immediate SI for any given run can be obtained by the use of a small digital computer installed in the vehicle.) Because of the need for such routine SI information, a more economical device was sought. The availability, low cost, and favorable initial evaluations of the Mays road meter (MRM) by other agencies made this device an attractive candidate for providing such information needs. However, MRM roughness measurements are dependent on all factors that affect the vehicle's suspension system, and, because these factors vary from vehicle to vehicle, standard roughness measurement units are needed. For this reason, studies were directed toward correlating this device with the SDP-SI measurements. By using the SDP-SI measurements as a standard, a general set of calibration, operational, and control procedures were then developed for all MRM devices purchased by the Texas Highway Department. These procedures provide a means of measuring roughness in standard roughness units for all MRM devices, thus allowing 2 separate instruments, installed in separate vehicles, to get the same roughness readings for the same road section. Five MRM devices have been calibrated and are currently being used in accordance with these procedures. Following is a brief discussion of these procedures.

MAYS ROAD METER CALIBRATION, OPERATION, AND CONTROL

The procedures developed are divided into 3 areas: calibration, operation, and control. Calibration involves obtaining the necessary tables for converting MRM roughness readings in inches per mile to SI values. The operational procedures provide a standard method for measuring roughness. The control procedures provide a method of ensuring that the MRM is functioning properly. No measuring device ever gives exactly the same measurement each time it is used; that is, there are measurement errors. For the MRM device using SI, these errors can be divided into 3 types: actual

MRM measurement errors (equipment errors), errors due to the lack of nonhomogeneous roughness characteristics of roads, and model or regression errors between the actual and predicted SI measurements. The Rainhart meter (Mays road meter) seems to exhibit very insignificant errors of the first type, as compared to those of the second type, and the MRM-SI model development in the calibration procedures ensures that those of the third type are never statistically significant in relation to those of the first 2 types.

Calibration

MRM calibration consists of running 25 quarter-mile pavement sections of various roughness classes in accordance with the following specifications:

1. MRM vehicle—The MRM device must be calibrated in the vehicle in which the device is to operate. Physical characteristics that affect vehicle body motion, such as excess weight and vehicle shocks, should likewise be the same during calibration as in operations.
2. Calibration runs—Each ¼-mile section is run 5 times at 50 mph. (Vehicle speed was set at 50 mph because this was the speed used in developing the original SI models for the SDP.) The calibration procedure is performed on a typical day; that is, when no extreme weather conditions exist. Because the MRM provides a measurement of vehicle body movement, conditions that might affect this movement should be avoided.

The general calibration procedure is used to obtain a representative sample of roughness readings to derive an equation of the form

$$SI = 5e^{\left(\frac{\ln M}{\beta}\right)^5}$$

where

M = the MRM roughness reading, in inches per mile, and
β = the MRM instrument coefficient.

This equation was obtained by linearly regressing the MRM readings onto the SI values and then solving for SI. From this equation, an MRM-SI conversion table is generated that can easily be used during measurement operations for obtaining SI. Figure 1 shows a typical plot of this equation for one of the MRM devices calibrated (β = 5.697).

Operation

The MRM operations section is divided into 2 parts. The first part explains how SI readings are obtained from the MRM roughness record. Following this, the tentative operating procedures that should be followed for obtaining an accurate record are described.

SI Computation—The MRM device provides as output 6-in.-wide strip chart paper that contains 3 channels of information (Fig. 2). The purpose of each of these 3 channels is as follows:

1. Distance event channel (upper channel record in Fig. 2)—Distance traveled by the MRM vehicle is indicated by alternate up and down ⅛-in. pen movements (pen movements in the same directions occur every 0.1 mile). This event marker is driven by the speedometer drive cable of the vehicle. Because the strip chart paper drive is a function of the vehicle body movement, the distance between successive distance marks is proportional to the cumulative vehicle body movement and hence can be scaled to inches of body movement per unit distance traveled.
2. Roughness signature—The strip chart paper movement is proportional to the vehicle body movement. Vehicle body movement also drives a second pen (center channel record in Fig. 2) across the chart, depending on the direction and magnitude of the up or down vehicle body movements with respect to the differential. Thus, this record or channel is used to indicate the pattern of vehicle body movements.

Figure 1. Typical equation plot of MRM device.

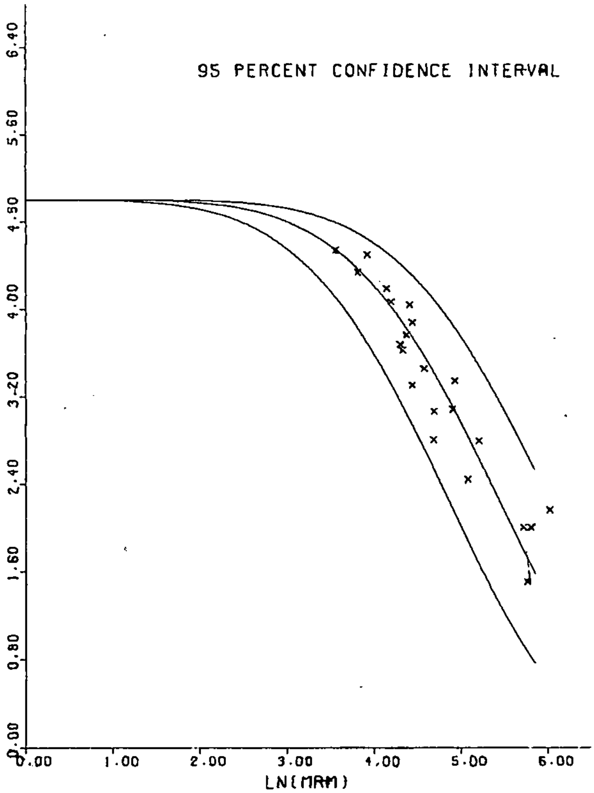


Figure 2. MRM output chart.

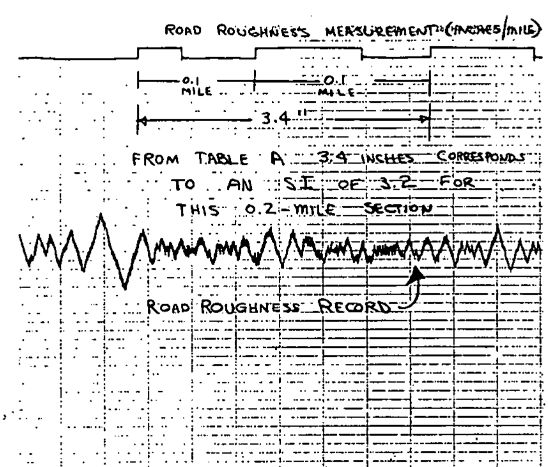


Table 1. MRM-SDP serviceability index correlations.

Mays Meter (in./0.2 mile)	Serviceability Index	Mays Meter (in./0.2 mile)	Serviceability Index
21.5	0.50	4.5	2.80
19.4	0.60	4.2	2.90
17.6	0.70	3.9	3.00
16.1	0.80	3.7	3.10
14.8	0.90	3.5	3.20
13.7	1.00	3.2	3.30
12.7	1.10	3.0	3.40
11.9	1.20	2.8	3.50
11.1	1.30	2.6	3.60
10.4	1.40	2.4	3.70
9.7	1.50	2.2	3.80
9.1	1.60	2.1	3.90
8.6	1.70	1.9	4.00
8.1	1.80	1.7	4.10
7.6	1.90	1.5	4.20
7.2	2.00	1.4	4.30
6.8	2.10	1.2	4.40
6.4	2.20	1.1	4.50
6.0	2.30	0.9	4.60
5.7	2.40	0.7	4.70
5.3	2.50	0.6	4.80
5.0	2.60	0.4	4.90
4.7	2.70	0.0	5.00

3. General event marker—The third channel (lower channel record in Fig. 2) provides an up or down pen displacement when a manual event marker located on the floorboard is depressed, thus providing a means of marking specific events of interest by the driver. For the Rainhart device, the operator may also mark specific events or write notes with pencil or pen directly on the chart paper.

The MRM-SI measurements are then made as follows:

1. The MRM device is activated and the roughness record for a desired road section obtained. Figure 2 shows a typical example of one such 0.2-mile section.
2. The roughness measurement in terms of SI is obtained by first measuring the length of paper (in inches) between 0.2-mile marks on the distance event channel (as shown in Fig. 2) and then using Table 1 to relate this measurement to SI. As shown in the figure, the length of paper between the 0.2-mile event markers was 3.4 in. (or 3.4 × 6.4 = 21.8 in. of body movement per 0.2 mile) of strip chart movement. Table 1 gives the relations between body movement and SI in terms of SI intervals of 0.5; for example, 3.4 in. of body movement corresponds to an SI of 3.2. Because of the accuracies involved, the SI readings need not be read beyond one decimal place, and the nearest distance interval value can be used for obtaining the appropriate SI.

Operating Procedures—The operating procedures briefly described are recommended for MRM operators to ensure accurate SI readings. Variations from these procedures, such as having a load of cement in the trunk, can significantly affect or bias the SI measurement:

1. SI measurements should be made only under normal driving conditions, especially with regard to weather. For instance, measurements should not be made during heavy rain, snow, extremely cold weather, or under gusty wind conditions.
2. Two operators are recommended, one for driving the vehicle and the second for operating the MRM. The average weights should be approximately those (e.g., ±50 lb) of the operators during MRM calibrations. The vehicle driver typically provides mileage information to the MRM operator and operates the event marker channel. The MRM operator monitors the roughness record, ensuring proper operation, and makes any necessary event marks or comments on the strip chart during operations.
3. Minimum section length has been established as 0.2 mile. This is the minimum length that can be measured without introducing excessive errors due to nonhomogeneity of roadway profiles. Note that this length of measurement can be obtained by repeating runs on shorter segments and summing the paper output; that is, a 0.1-mile section can be run twice and the total length resulting from both runs used as the roughness distance.

Control

Accurate SI measurements will depend on proper usage and operation of the MRM. Proper operation of the equipment can be ensured by development of a set of quality control procedures in which MRM results are continually monitored. Control procedures provide a means of detecting MRM out-of-calibration conditions and involve the use of replication runs or measurements over known test or control sections. The mean and range SI values from these are compared with control values. The general procedures developed provide a means for selecting MRM control sections, establishing control charts, and maintaining MRM control operations:

1. Selecting MRM control sections—A set of twenty 0.2-mile control sections is initially selected, convenient to the MRM base of operations. These sections are selected so as to provide a representative sample of smooth-to-rough sections for the area or district in which the MRM is to operate.
2. Establishing control charts—Two control charts are used for monitoring MRM measurement validity, one for checking the measurement mean (or average) from repeated SI measurements and the second for checking the variations from the mean of the replication measurements. The control limits for 2 control charts are established from initial measurements of the 20 control sections.

3. Maintaining MRM control operations—As previously indicated, MRM control is provided by comparing the mean and range values from periodic test runs with the control limits. When the values fall outside the limits, an out-of-calibration condition would be suspected.

SUMMARY

A set of calibration, operational, and control procedures has been developed for the MRM in order to provide a means of obtaining standard roughness measurements for Texas highways in terms of SI. These procedures involve correlating the MRM roughness readings in inches per mile to SI as measured by the SDP. Because of the SDP measurement characteristics, SI values computed from road profile data obtained with this instrument provide an accurate measurement standard.

Several MRM devices have been calibrated according to these procedures and are currently in use. Initial uses of this procedure for obtaining SI are quite promising, and, by providing standard roughness measurements for roads throughout Texas, invaluable information for aiding in solving the problems of pavement failure can be obtained.

ACKNOWLEDGMENT

The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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CORRELATIONS OF WISCONSIN ROAD METERS

K. H. Dunn and R. O. Schultz

The first Wisconsin road meter was purchased by the Wisconsin Division of Highways in September 1968 to supplement the use of the CHLOE profilometer as a means of evaluating pavement serviceability. It was evident by this time that the CHLOE was not suited for the continued use necessary for a full evaluation program. Because the present serviceability index (PSI) rating system had been adopted for pavement evaluation and because the CHLOE profilometer was the original instrument involved in this system, it was decided to correlate the output of the road meter to the output of the profilometer. This eliminated the need for a panel rating program and provided a relatively time-stable rating standard.

ORIGINAL CORRELATION

In the original correlation, the summation of the squared deviations of the road meter was related to the slope variance output of the CHLOE. The correlation was accomplished by operating both instruments over selected pavement sections to obtain raw data. The profilometer was run in the outer wheelpath in at least three 0.1-mile long sections within a selected 1-mile section of pavement. The slope variance values obtained from these 3 runs were averaged, and this average was compared to the average of several summations of counts obtained by the road meter traversing the entire 1-mile long section.

The pavements were divided into 2 types, rigid and flexible, and the test sections were selected primarily on the basis of their level of ridability, with the objective of yielding a broad distribution of values for comparative purposes. However, this particular objective was not satisfactorily achieved because there was a considerable grouping of points rather than a good distribution among all values.

The odometers of vehicles were used to lay out the sections and to situate them near prominent landmarks. Before the completion of this original correlation, it was evident that this method of location left much to be desired because of variances from one odometer to another and interpretation of the readings.

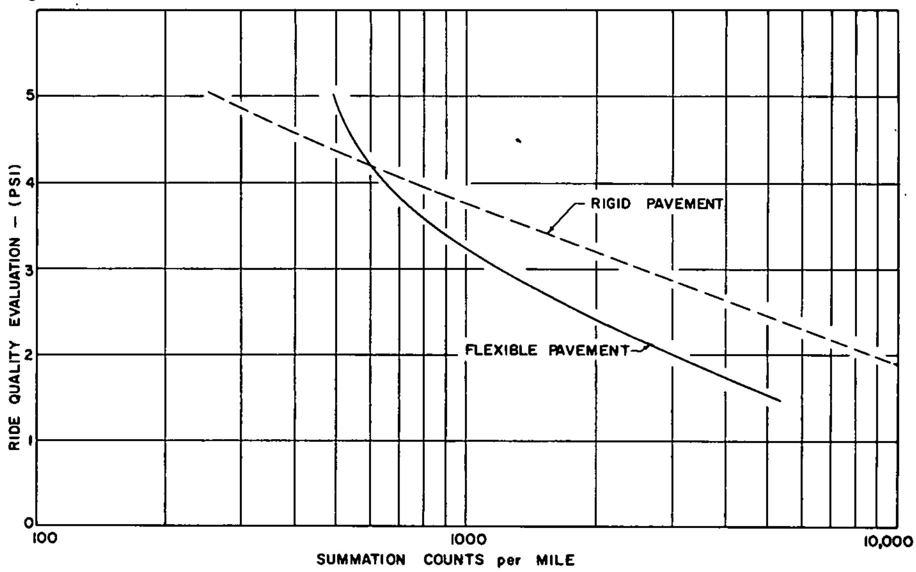
The end result of this first correlation is shown in Figure 1. Note that both correlation lines are curves. This is due to the fact that the correlation was based on a linear relation between the summation of counts and the CHLOE slope variance rather than on a linear relation between summation of counts and PSI. These curves have been used since 1969.

1971 CORRELATION

By the summer of 1971, the 1968 Ford that housed the road meter had traveled about 85,000 miles, so an order was placed for a new automobile, which was delivered in the fall of 1971. Several drastic changes were incorporated in the 1971 road meter, so a new correlation was required. In addition to the new automobile, changes were made to the meter, including faster counters and an automatic nulling device.

Profiting from experience with the initial correlation, we tried to obtain data points for the full scale of the PSI (2.0 to 5.0) for the new correlation. This required careful

Figure 1. Wisconsin road meter conversion chart.



screening of test sections by conducting preliminary testing with the CHLOE profilometer. Information previously obtained using the CHLOE and the 1968 road meter was used in selecting sections of pavement for correlation, but new sections were included. The test sections were located from highway network data information (HNDI) reference markers and prominent landmarks. These HNDI markers are part of a system that has been recently instituted in Wisconsin. The markers are located along state trunk highways at structures, town roads, and property lines and are generally located one per mile. They provide a convenient and permanent reference and a means to identify locations in the computer program.

The pavement types were divided into 4 categories rather than the 2 used for the original correlation. The 4 types were rigid, flexible, flexible overlay over a rigid pavement, and a flexible mat over a portland cement concrete stabilized base course. This was done to determine if the type of pavement might influence the relation between the outputs of the road meter and the CHLOE. Wind direction, velocity, and temperature were recorded to document the conditions existing during the correlation surveys.

The test sections were 2,530 ft in length; the road meter surveyed the total length, and the CHLOE surveyed two 1,000-ft lengths plus one 500-ft length. Fifteen-foot gaps were provided between these 3 lengths so that the limitation of the numerical accumulations of the CHLOE computer would not be exceeded on rough pavements. The test sections were located primarily on tangent lengths of pavements and included cut and fill cross sections.

A typical survey consisted of operating the CHLOE profilometer in the outer wheelpath of the travel lane of each test section in each direction followed immediately by a run with the road meter. These runs were repeated in each direction of each test section to obtain replicate sampling. The data obtained will eventually be entered into a 5-step computer program that should produce a calibration curve relating the output of the road meter to the CHLOE output, a conversion chart relating road meter output directly to PSI, and information concerning the variability of the 2 instruments. The computer program had not been started at the time of the preparation of this paper, so it is not possible to present results of the correlation; however, it is believed that the results will provide a reliable basis for relating road meter output to PSI values for pavements.

PART IV

EFFECT OF VARIABLES ON ROAD METER OUTPUT

ROAD METER OUTPUT AND ITS CORRELATION WITH PANEL RATINGS IN SASKATCHEWAN

M. F. Clark

The history of attempting to obtain a systematic measure of the performance of highway pavements began in Saskatchewan in the early 1950s. These early studies were carried out in cooperation with the Canadian Good Roads Association, now renamed the Roads and Transportation Association of Canada (RTAC).

These early ratings of performance were carried out by panels of experts who rated the present performance rating (PPR) on a scale of 0 to 10 (1). The term PPR has lately been renamed riding comfort index (RCI) in Canadian terminology. This method of rating is very similar to that reported by Carey and Irick (2) for determining a present serviceability rating (PSR) and that estimated by using physical measures and a mathematical formula to obtain the present serviceability index (PSI). The major difference is that of scale.

In 1965 the Saskatchewan Department of Highways and Transportation purchased a British Road Research Laboratory profilometer, which is described in detail by Culley (3). One major drawback of this unit is that it operates at speeds of 3 mph or less and requires a substantial crew. This unit measures surface smoothness as related to a 12.5-ft traveling datum. Although riding quality is indirectly related to surface smoothness, it is vehicle response or even passenger response to surface irregularities that governs riding quality.

Because a systems approach to highway management requires a large inventory on pavement performance, the PCA road meter was chosen as the most promising unit based on RTAC evaluations (4, 5, 6, 7). As a result of these reports, the Department purchased a unit in the spring of 1971. Recently RTAC has suggested that this type of road meter be referred to as a car road meter (CRM).

CRM DESCRIPTION

The CRM sensing and recording units were purchased from Soiltest, Inc., and follow the general principles as detailed by Brokaw (8). The main difference is that the Saskatchewan unit has 2 recording consoles that can be operated independently of each other. This allows consecutive sections to be tested without having to stop to record data and zero counters between each test section. The recording consoles are mounted above the transmission hump ahead of the front seat. Between the 2 consoles is a toggle switch that controls their operation. A switching plate is mounted on the deck behind the rear seat and is vertically connected to the center of the differential housing. Figure 1 shows the unit.

Distances are recorded by an A-I-Fab Gemini odometer that registers each $^1/_{100}$ mile. For purposes of this study, the section lengths were also accurately measured by survey instruments.

The vehicle in which the CRM is mounted is a 1970 Chevrolet Biscayne sedan with 350-cu in. V-8 motor, F40 heavy-duty suspension, 119-in. wheelbase, 216-in. overall

Figure 1. Car road meter.

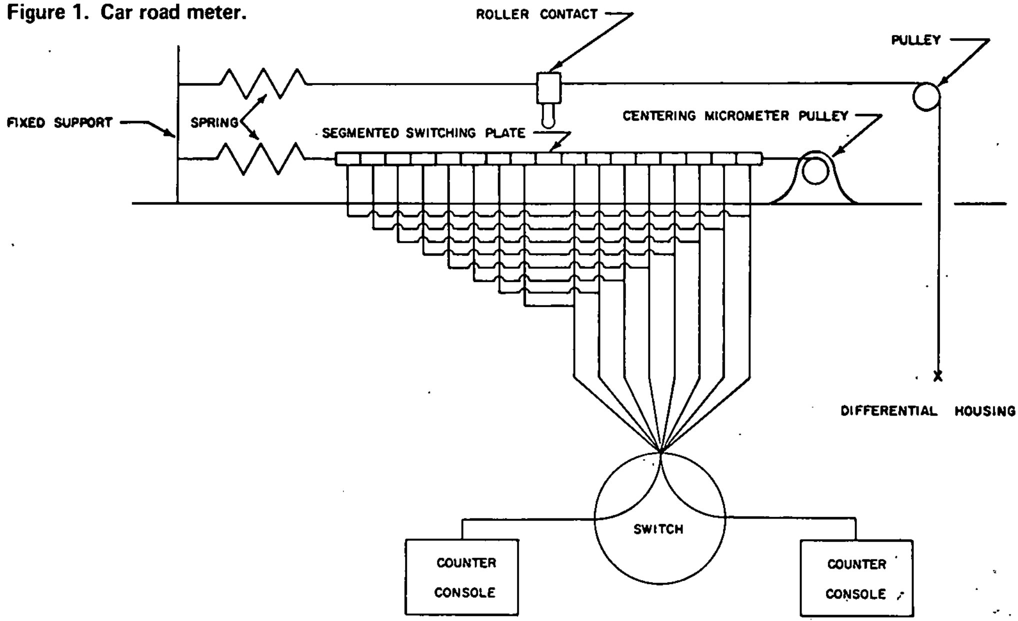


Table 1. RCI rating summary for CRM correlation studies.

Control Section	From Mile	To Mile	Panel 1 Rating Avg.	Panel 1 Rating S.D.	Panel 2 Rating Avg.	Panel 2 Rating S.D.	Panel 3 Rating Avg.	Panel 3 Rating S.D.	Panel 4 Rating Avg.	Panel 4 Rating S.D.	All Panels Combined Avg.	All Panels Combined S.D.
1-10	2.000	3.014	6.65	0.52	8.12	0.05	7.59	0.29	7.14	0.54	7.38	0.67
6-04	7.400	8.401	5.62	0.62	–	–	7.09	0.29	5.97	0.83	6.23	0.87
6-04	7.140	8.140	–	–	6.17	0.26	–	–	–	–	6.17	0.26
6-04	0.100	1.081	5.47	0.75	6.42	0.63	6.77	0.20	6.00	0.82	6.16	0.77
6-03	22.700	23.693	5.25	0.80	5.77	0.05	6.64	0.31	5.72	0.53	5.84	0.69
6-03	23.700	24.696	4.70	0.93	4.37	0.49	5.85	0.97	5.07	0.93	4.99	0.96
39-06	1.100	2.096	6.90	1.60	8.05	0.36	8.27	0.40	7.90	0.46	7.78	0.96
39-06	17.000	17.986	6.80	0.63	6.70	0.40	7.20	0.47	6.95	0.44	6.91	0.49

Table 2. Effect of vehicle speed on road meter Σ- counts.

Control Section	From Mile	To Mile	Vehicle Speed (mph)	Run Number (Σ-counts per mile) 1	2	3	4	5	Avg.	S.D.
39-6	1.100	2.096	50	239.96	252.01	238.96	260.04	227.91	243.77	12.46
39-6	17.000	17.986	50	419.87	402.63	412.78	464.50	518.26	443.60	47.96
6-3	22.700	23.693	50	818.73	754.28	732.13	798.59	850.96	790.93	48.04
6-3	23.700	24.696	50	1,276.10	1,266.06	1,263.05	1,252.01	1,176.71	1,246.79	40.12
6-4	0.100	1.081	50	691.13	622.83	644.24	608.56	645.26	642.40	31.27
6-4	7.400	8.401	50	604.39	600.40	566.43	562.44	534.47	573.62	29.03
1-10	2.000	3.014	50	472.39	539.45	493.10	466.47	530.57	500.38	33.25
39-6	1.100	2.096	40	172.69	184.74	144.58	143.57	167.67	162.64	18.05
39-6	17.000	17.986	40	327.59	315.42	337.73	354.97	344.83	336.09	15.28
6-3	22.700	23.693	40	627.39	592.15	638.47	598.19	591.14	609.46	21.93
6-3	23.700	24.696	40	1,024.10	1,026.10	1,005.02	996.99	988.96	1,008.23	16.44
6-4	0.100	1.081	40	622.83	638.12	590.21	620.80	635.07	621.40	18.97
6-4	7.400	8.401	40	520.48	498.50	526.47	520.48	518.48	516.87	10.68
1-10	2.000	3.014	40	302.76	293.89	296.84	285.01	305.72	296.84	8.09
39-6	1.100	2.096	60	357.43	385.54	381.53	396.59	378.51	379.91	14.31
39-6	17.000	17.986	60	465.52	495.94	510.14	515.21	518.26	501.01	21.60
6-3	22.700	23.693	60	928.50	979.86	973.82	1,012.08	988.92	976.63	30.58
6-3	23.700	24.696	60	1,251.00	1,310.24	1,285.14	1,360.44	1,327.31	1,306.82	41.54
6-4	0.100	1.081	60	888.89	839.96	888.89	915.39	832.82	873.18	35.38
6-4	7.400	8.401	60	764.24	700.30	734.27	809.19	730.27	747.64	41.48
1-10	2.000	3.014	60	555.23	524.66	530.57	645.96	527.61	556.80	51.29

Note: In all tests, there were 2 vehicle occupants, tire pressure of 27 psi, and one-half (plus) full gas tank.

length, and 20.75-imperial gal gas tank capacity. The tires are G78-15 Goodyear Custom Powercushion Polyglass belted tires and are subjected to periodic wheel balancing and alignment.

For the initial correlation and study the unit had 10,000 miles on the odometer and 34,000 miles during the study of temperature effects.

OUTLINE OF TEST PROGRAM

The test program consisted of (a) determining the RCI for several sections of highway in the Regina area; (b) following this, and within the same week, making replicate runs with the CRM under so-called standard conditions; and (c) then repeating the CRM runs with these conditions varied.

DESCRIPTION OF TEST SECTIONS

Seven sections of highway located within a 50-mile radius of the city of Regina were chosen as being representative of the range of riding quality existent over the major portion of the paved highway system. All sections had an asphaltic concrete surface course, and the ride within each section was considered uniform. Each section length was determined to $\frac{1}{1,000}$ mile, and the beginning and end points were marked on the pavement.

The 3 sections given in Table 1 as 1-10 and 39-06 are old pavements having a history of very slow change in RCI, and all had been overlaid in 1970. The sections noted as 6-04 are older pavements whose performance history has also shown a very slow rate of change. The sections shown as 6-03 are constructed on a lacustrine clay soil with swelling properties that result in a rapid loss in pavement performance. Sections 6-03 therefore represent pavements of low performance.

DETERMINATION OF RCI

The RCI was determined for each section by using a large panel of 16 people, with the exception of section 6-04, mile 7.400 to mile 8.401, which was evaluated by a 12-man panel. The panel was subdivided into groups of 4, each group traveling in a different automobile. These automobiles were similar to the unit previously described as carrying the CRM.

The panelists were senior members of the Department who travel extensively on the highway system. No effort was made to select the panel on a statistical basis because it was felt that the panel size was sufficient to nullify any errors.

Table 1 summarizes the data from the panels. The data are analyzed by subgroups as well as for the overall group. In the correlation studies, the average of the 16-member (12-member in 1 instance) panel was used as the true value of the RCI; thus each point on the forthcoming figures represents 16 RCI values.

CRM STANDARD OPERATING CONDITIONS

Prior to carrying out the correlation and variable effects study, certain arbitrary conditions of CRM operation were assigned. These conditions are the "standard" conditions referred to further in this paper.

A vehicle speed of 50 mph was chosen as the standard operating speed. At speeds above this, traffic conflicts make it difficult to maintain constant speed. At lower speeds, the CRM unit tended to act as a traffic obstruction.

The standard load was chosen as 2 people plus the gas tank more than one-half full plus one spare tire in the trunk. The choice of gas tank level was strictly arbitrary. The choice of 2 people was based on unit efficiency.

The mass inventory was set up such that the RCI was to be determined on 2-mile sections of highway. This meant that, at 50 mph, a 2-min, 24-sec time interval existed during a specific test. As previously mentioned, the CRM unit is equipped with 2 independent counter consoles activated by a toggle switch. Thus, the passenger has time to record the data and clear a console in 2 min, 23 sec. By switching consoles back and forth, he can make a continuous series of tests.

Table 3. Effect of vehicle speed and number of occupants on road meter Σ-counts.

Control Section	From Mile	To Mile	Vehicle Speed (mph)	Number of Vehicle Occupants	Run Number (Σ-counts per mile) 1	2	3	4	5	Avg.	S.D.
39-6	1.100	2.096	65	2	418.68	400.60	414.66	387.55	335.34	391.36	33.63
39-6	17.000	17.986	65	2	556.80	619.68	618.66	628.80	589.25	602.63	29.62
6-3	22.700	23.693	65	2	1,127.90	1,133.90	1,113.80	1,092.70	970.80	1,087.82	67.32
6-3	23.700	24.696	65	2	1,318.27	1,455.82	1,433.78	1,411.65	1,391.57	1,402.21	52.77
6-4	0.100	1.081	65	2	817.53	792.05	949.03	830.79	815.49	840.97	62.00
6-4	7.400	8.401	65	2	675.32	737.26	765.23	723.28	783.22	736.85	41.60
1-10	2.000	3.014	65	2	656.81	748.52	662.72	714.99	687.38	694.08	38.13
39-6	1.100	2.096	50	1	273.09	292.17	296.19	299.20	330.32	298.18	20.63
39-6	17.000	17.986	50	1	462.48	441.18	443.21	495.94	454.36	459.42	22.15
6-3	22.700	23.693	50	1	782.48	894.26	780.46	767.37	813.70	807.65	51.31
6-3	23.700	24.696	50	1	1,133.53	1,133.53	1,172.69	1,177.71	1,233.94	1,170.28	41.29
6-4	0.100	1.081	50	1	668.71	642.20	693.17	627.93	749.24	676.24	47.85
6-4	7.400	8.401	50	1	566.43	565.43	567.43	585.41	600.40	577.01	15.44
1-10	2.000	3.014	50	1	463.51	409.27	431.95	395.46	421.10	424.25	25.80
39-6	1.100	2.096	50	3	247.99	232.93	261.04	273.09	241.97	251.40	15.85
39-6	17.000	17.986	50	3	381.34	375.25	449.29	504.06	521.30	446.24	67.52
6-3	22.700	23.693	50	3	901.31	833.84	900.30	915.41	981.87	906.54	52.68
6-3	23.700	24.696	50	3	1,015.06	1,096.39	1,158.63	1,163.65	1,124.50	1,111.65	60.50
6-4	0.100	1.081	50	3	781.86	664.63	697.25	735.98	730.89	722.11	44.04
6-4	7.400	8.401	50	3	586.41	737.26	680.32	614.39	664.34	656.53	58.81
1-10	2.000	3.014	50	3	481.26	483.24	509.86	500.99	502.96	495.65	12.69

Note: In all tests, tire pressure was 27 psi and gas tank was one-half (plus) full.

Table 4. Effect of vehicle speed, tire pressure, and gas tank level on road meter Σ-counts.

Control Section	From Mile	To Mile	Tire Pressure (psi)	Gas Tank Level	Run Number (Σ-counts per mile) 1	2	3	4	5	Avg.	S.D.
39-6	1.100	2.096	22	Plus ½	264.06	285.14	272.09	259.04	270.08	270.07	9.86
39-6	17.000	17.986	22	Plus ½	488.84	484.79	488.84	432.05	447.26	468.35	26.79
6-3	22.700	23.693	22	Plus ½	905.34	789.53	871.10	830.82	769.39	833.22	56.17
6-3	23.700	24.696	22	Plus ½	1,185.74	1,176.71	1,152.61	1,143.57	1,208.84	1,173.49	26.18
6-4	0.100	1.081	22	Plus ½	725.79	771.66	745.16	656.47	760.45	731.90	45.54
6-4	7.400	8.401	22	Plus ½	548.45	617.38	676.32	753.25	595.40	638.15	79.06
1-10	2.000	3.014	22	Plus ½	496.06	492.11	441.81	500.99	464.50	479.08	25.19
39-6	1.100	2.096	32	Plus ½	325.30	340.36	349.39	353.41	321.29	337.94	14.26
39-6	17.000	17.986	32	Plus ½	553.75	607.51	494.93	569.98	640.97	573.42	55.41
6-3	22.700	23.693	32	Plus ½	932.53	1,020.14	1,128.90	1,077.54	916.42	1,015.10	91.43
6-3	23.700	24.696	32	Plus ½	1,245.98	1,279.12	1,255.02	1,371.49	1,335.34	1,297.39	54.09
6-4	0.100	1.081	32	Plus ½	767.58	854.23	821.61	824.67	819.57	817.53	31.27
6-4	7.400	8.401	32	Plus ½	733.27	768.23	832.17	763.24	857.14	790.80	51.69
1-10	2.000	3.014	32	Plus ½	490.14	500.99	528.60	530.57	491.12	508.28	19.90
39-6	1.100	2.096	27	Below ¼	349.40	332.33	313.25	361.45	341.37	339.55	18.18
39-6	17.000	17.986	27	Below ¼	527.38	501.01	583.16	453.35	523.33	517.64	46.98
6-3	22.700	23.693	27	Below ¼	941.59	873.11	988.92	1,019.13	927.49	950.04	56.53
6-3	23.700	24.696	27	Below ¼	1,287.15	1,278.11	1,317.27	1,247.99	1,266.06	1,279.32	25.79
6-4	0.100	1.081	27	Below ¼	780.84	757.39	722.73	797.15	766.57	764.93	27.97
6-4	7.400	8.401	27	Below ¼	638.36	636.36	691.31	716.28	614.39	659.33	42.57
1-10	2.000	3.014	27	Below ¼	476.33	449.70	463.51	431.95	490.14	462.32	22.64
1-10[a]	2.000	3.014	27	Plus ½	416.17	394.48	562.14	701.18	858.97	586.58	196.13
39-6[b]	17.00	17.986	27	Plus ½	430.02	478.70	433.06	441.18	458.42	448.27	20.26

Note: In all tests, there were 2 vehicle occupants, and vehicle speed was 50 mph.

[a]Head wind of 23 mph gusting to 35 mph. [b]Road surface had free water with tire splashing continuously during tests and continuous rainfall during tests.

Table 5. Effect of temperature on CRM.

Control Section	From Mile	To Mile	Σ-counts[a] at +35 F	RCI[b]	RCI[c]	Σ-counts[d] at -33 F
39-6	1.100	2.096	306	7.58	7.99	182
39-6	17.00	17.986	495	6.72	6.92	314
6-3	22.700	23.693	1,595	4.63	5.89	1,558
6-3	23.700	24.696	2,382	3.92	5.07	2,128
6-4	0.100	1.081	738	6.01	6.26	–
6-4	7.400	8.401	637	6.27	6.46	–
1-10	2.00	3.014	533	6.59	6.70	–

Note: The CRM values are averages of 5 individual runs.

[a]Taken on 3/14/72.
[b]Estimated from Figure 3.
[c]Estimated from Tables 2 through 4.
[d]Taken on 3/1/72.

The standard tire pressure was arbitrarily set at 27-psi cold-inflation pressure. This was constant in all 4 tires and was 2 psi above normal operating pressure for this type of tire. This pressure was chosen to minimize the probability of reductions in tire life due to blowouts.

The maximum wind velocity during testing was chosen at 10 mph because the literature (8) indicated that, up to 15 mph, wind velocity had a negligible effect on CRM output.

During testing, the road surface had to be dry, that is, free from water or snow. Temperature restrictions were arbitrarily placed at +32 F ambient temperature or higher because the literature (8) indicated that little effect was noted when temperatures were above +10 F.

DETERMINATION OF CRM VALUES

In determining CRM values, each section was tested 5 times under given sets of conditions. These values are given in Tables 2 through 5. In all correlation work, the average of the 5 readings was used.

Although Brokaw (8) has suggested that data from the CRM unit be reduced to the sum of the squares [$\Sigma(D^2)$] of road-car deviations, Canadian practice (4, 5, 6, 7), has been to reduce the data as the summation of the extended counter readings (Σ-counts) per mile. These 2 methods of reduction are related as follows:

$$64\ \Sigma(D^2) = \Sigma\text{-counts}$$

This formula holds true where the segmented switching plate is divided in ⅛-in. increments.

CRM-RCI CORRELATION

Figure 2 summarizes correlation curves as reported by some Canadian agencies (4, 5, 6, 7). The data from Alberta and Ontario agree very closely, whereas the Quebec curve is somewhat steeper. The Saskatchewan curve tends to have an intermediate slope falling between the Ontario-Alberta slope and the Quebec slope.

Figure 3 shows the actual correlation of the Saskatchewan curve. In this correlation, the range of RCI values is limited to 4.99 to 7.78. This limited range is justified because, for the major portion of highways, only limited extrapolation is required to estimate RCI values outside this range. One area where difficulty might arise is in evaluating new construction, where the high intercept would indicate RCI values in excess of 10. This may indicate that a more complex relation exists than the equation would indicate for the narrow range studied. Thus, at 50 mph the relation is

$$\text{RCI} = 17.815 - 4.116 \log_{10} \Sigma\text{-counts}$$

where correlation coefficient = 0.946 and standard error = 0.338.

The correlation coefficient appears to be equal to or higher than that found by others and indicates that the CRM operating at high speeds will adequately estimate RCI.

EFFECT OF CRM UNIT SPEED ON ESTIMATING RCI

The effect of vehicle speed on the output of the CRM was assessed at 40, 50, 60, and 65 mph. All other controllable variables previously listed were held constant at the prestated values.

Figure 4 compares the summation of the counts at 50 mph with those at the other speeds. The analysis indicates that the slope of the curves tends to become steeper as vehicle speed increases.

Figure 5 shows a correlation of RCI and Σ-counts for the various speeds. In all instances the correlation is high; however, at 40 mph it is exceptional at 0.977. Generally, the repeatability, as given in Table 2, is also better at 40 mph. This higher degree of correlation is in line with that reported by Tessier (7).

Figure 2. Summary of correlation curves.

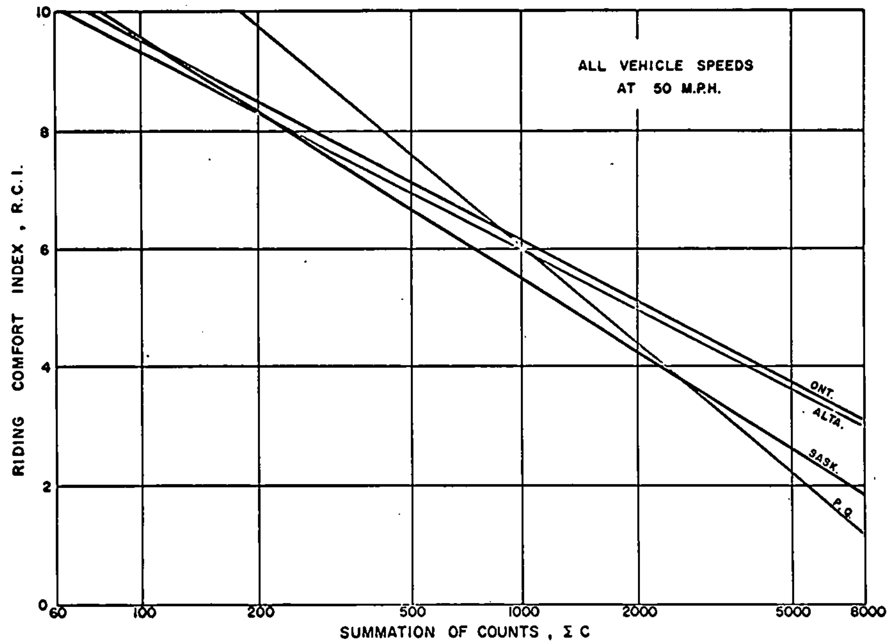
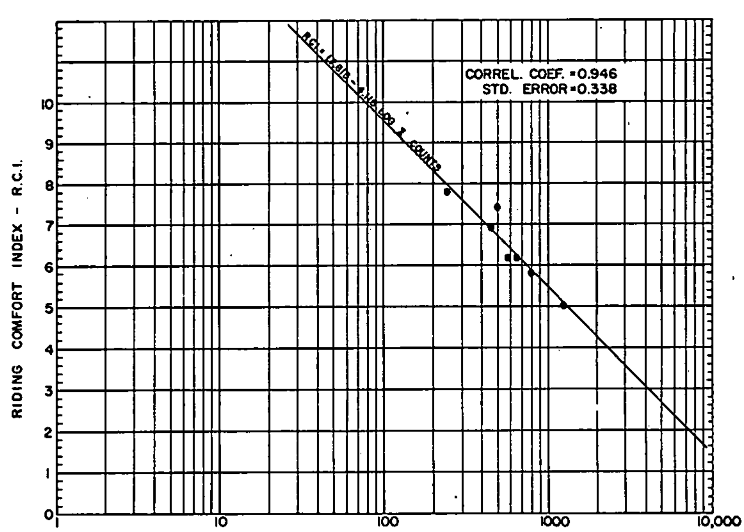


Figure 3. Correlation of CRM and RCI at test speed of 50 mph.



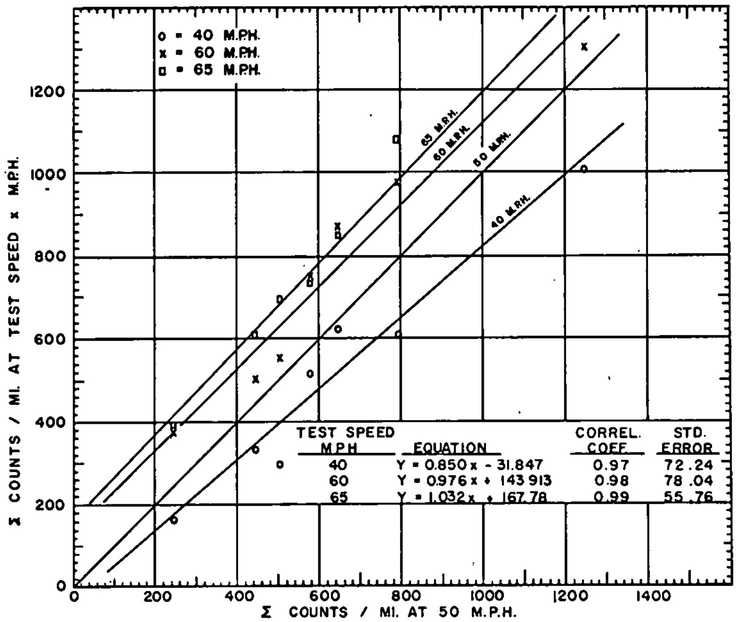


Figure 4. Effect of vehicle speed on rating value.

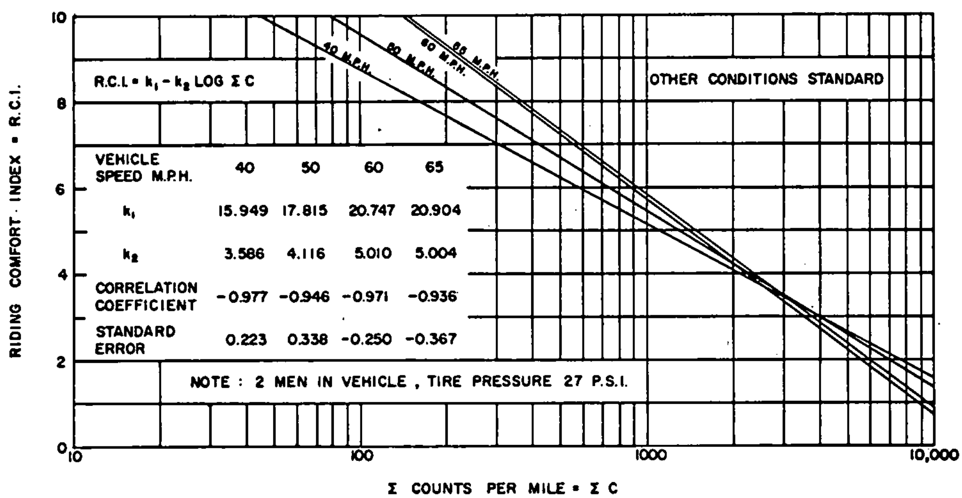


Figure 5. Effect of vehicle speed on CRM for estimating RCI.

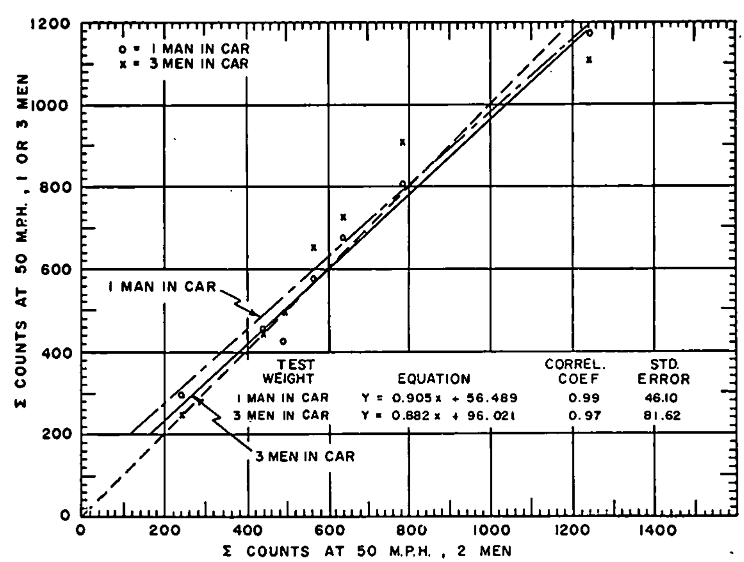


Figure 6. Effect of number of vehicle occupants on rating values.

It is also interesting to note that the curves for various speeds tend to cross at RCI values of 3 to 4 or Σ-counts values of 2,000 to 4,000. This could indicate that at higher speeds the vehicle tends to float over some of the rough areas of pavement; the extrapolated curves intersecting an RCI of 2 indicate that the higher the speed, the less is the movement between vehicle axle and car body.

EFFECT OF VEHICLE LOAD ON CRM UNIT OUTPUT

Two effects of vehicle load were studied: one was the effect of the number of people in the car, and the other was the effect of gas tank level.

The effect of the number of people was assessed using 1, 2, and 3 men in the vehicle. When 3 people were in the vehicle, the third person rode in the rear seat behind the driver. Figure 6 compares the Σ-counts with 2 men in the vehicle versus 1 and 3 men in the vehicle. The curve for 1 and 3 men is flatter than for 2 men.

Figure 7 compares the effect of a full gas tank versus a gas tank less than one-quarter full. The 2 curves are almost parallel with a decrease in gas load indicating a similar increase in car body-axle deviations at all levels of roughness studied.

The total effects of change in the vehicle live load are shown in Figure 8. Although the correlation coefficient is high in all instances, it would appear that better correlation is achieved by a decrease in live load. The correlation coefficient of 0.989 found with less than one-quarter tank of gas and all other variables standard is the highest correlation attained in this study.

EFFECT OF VARIATION IN TIRE PRESSURE ON CRM UNIT

To determine the effect of tire pressure, we made replicate tests in which the tire pressure was varied by ±5 psi from the standard of 27 psi. In all instances, the tire pressure was measured when the tires were cold.

Figure 9 indicates that, for a decrease of 5 psi, smoother pavements showed an increase in Σ-counts, whereas rougher pavements showed a slight decrease in Σ-counts. On the other hand, an increase in tire pressure of 5 psi showed a somewhat constant increase in Σ-counts of approximately 130 units over the entire range tested. Figure 10 shows the effect of change in tire pressure on estimating RCI. Here again, all correlation coefficients are high, with the correlation coefficient of -0.985 for 32-psi tire pressure almost the same as the coefficient determined with the gas tank less than one-quarter full.

EFFECT OF TEMPERATURE ON CRM UNIT

Brokaw (8) indicates that temperature does not affect the CRM until temperatures fall below +10 to +15 F. At the maximum stipulated wind speed, the wind chill could be far lower than this level. Therefore, it was desirable to determine the effect of equivalent extremely low temperatures.

On March 1, 1972, a sharp drop in temperature occurred to -33 F. This allowed testing of 4 of the test sections, the results of which are given in Table 5. Each value is the average of 5 runs. On March 14, 1972, the temperature rose to +35 F, at which time all 7 test sections were tested with 5 replicate runs, the average of which is given in Table 5.

To estimate the RCI of March 14 when the temperature was +35 F, the following mathematical model was used:

$$\text{RCI} = 17.815 - 4.116 \log \Sigma\text{-counts}$$

Utilizing the calculated RCI values of March 14 as being the actual values of March 1, we correlated RCI and Σ-counts at -33 F.

Figure 11 shows that the summation of counts at low temperatures is less than the summation of counts at high temperatures over the range of roughness tested. This probably results from stiffening of the vehicle suspension caused by increased viscosity of the lubricants at suspension points and in the shock absorber. The effect of tempera-

Figure 7. Effect of gas tank level on rating values.

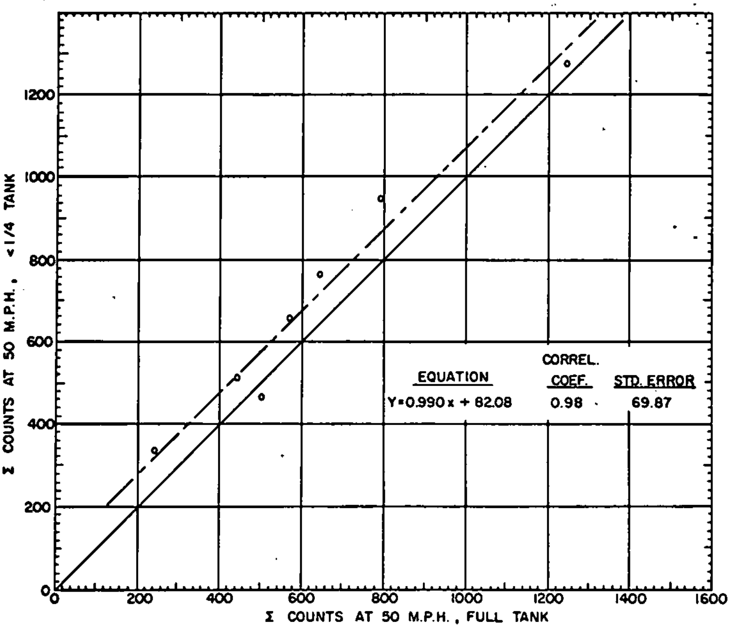


Figure 8. Effect of number of vehicle occupants and gas tank level on CRM output.

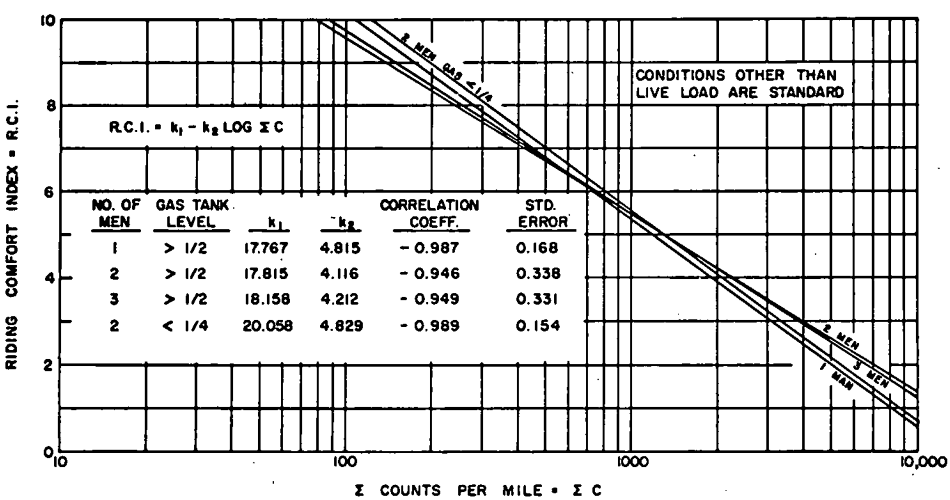


Figure 9. Effect of tire pressure on rating values.

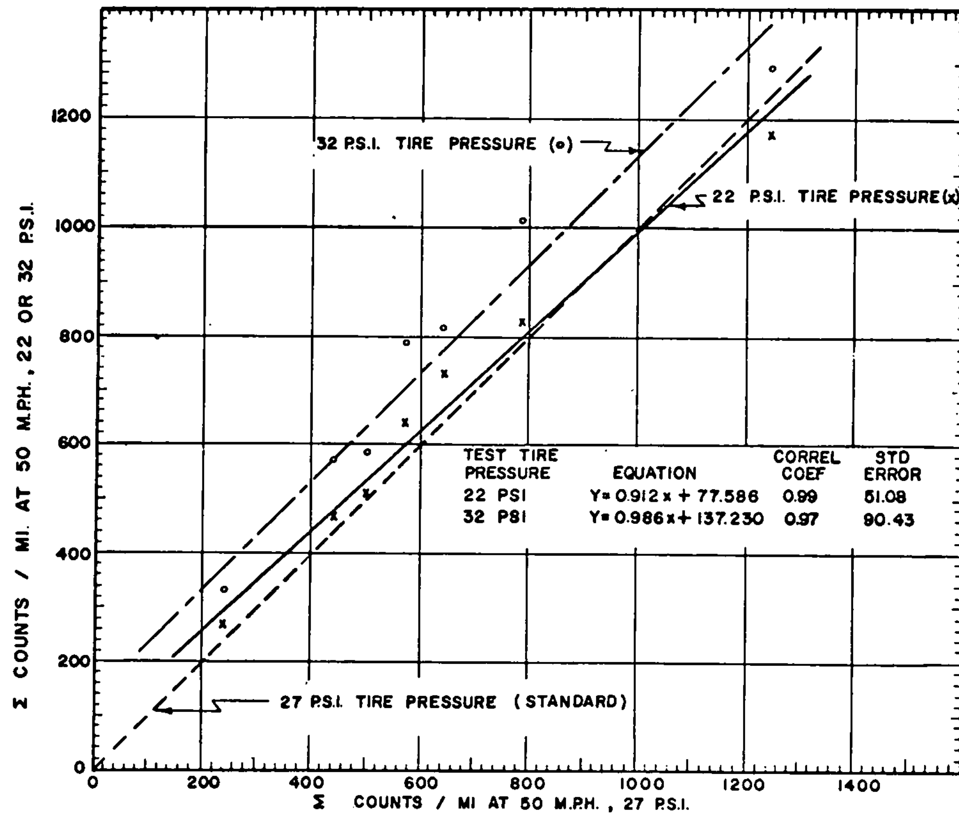
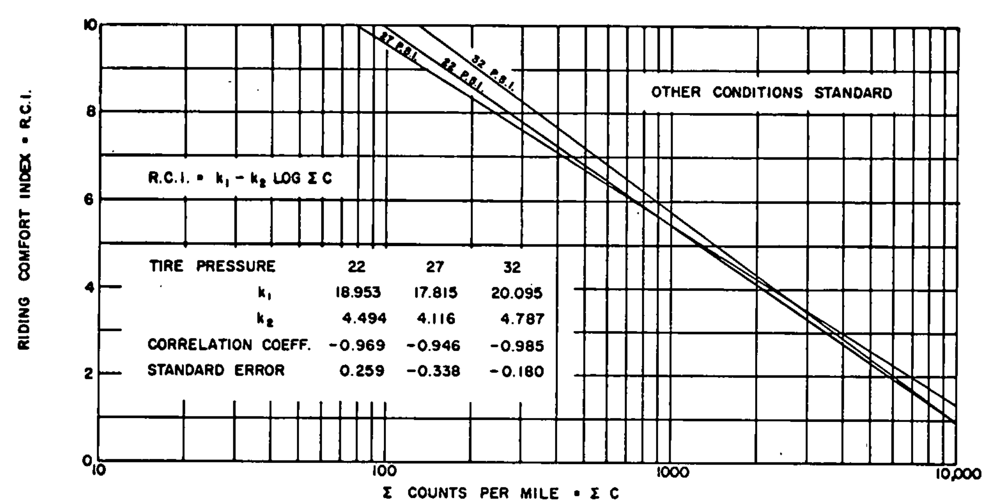


Figure 10. Effect of tire pressure on CRM for estimating RCI.



ture on tires is either negligible or counteracted by suspension dampening because there is less total travel between vehicle axle and the vehicle body at low temperatures.

Figure 12 shows the correlation between RCI at +35 F and -33 F. The correlation coefficients here must be ignored because they are not correlations between panel rating and CRM but between RCI's estimated by the CRM unit at +35 F and the CRM output at -33 F.

REPEATABILITY AND CORRELATION

All CRM tests in this study were replicated 5 times. The results of each run, with the exception of the temperature effect series, are given in Table 2 as are the average and the standard deviation calculated for each of the 5 test series. Generally, there appears to be an increase in standard deviation with an increase in the summation of counts (Fig. 13). Correlation coefficients of these curves are low but give an indication of what repeatability may be expected under varying conditions.

The best repeatability under most ranges of roughness occurred with the standard conditions and at a speed of 40 mph. Figure 13 shows that, at this speed, one may expect one standard deviation to vary between 13 and 25 for a Σ-counts range of 85 to 2,300 respectively. Figure 5 shows that these variations would result in an RCI change of 0.2 for a very smooth roadway and have no effect on a rough roadway.

Under standard conditions, including a speed of 50 mph, Figure 13 shows a standard deviation varying from 25 to 70 for a Σ-counts range of 140 to 2,300 respectively. Figure 5 shows that one standard deviation of the Σ-counts on a smooth roadway would result in an RCI change of approximately 0.3, whereas a change of one standard deviation on a rough roadway will result in a change in RCI of approximately 0.1. In the preceding 2 paragraphs smooth and rough roadways were considered to be roadways having RCI's of 9 and 4 respectively.

Table 6 summarizes the various correlation coefficients when relating RCI determined by panel to Σ-counts per mile for the various conditions of this study and for those reported by other agencies (6, 7, 9). The constants k_1 and k_2 for the mathematical model RCI = k_1 - k_2 log Σ-counts are also noted.

Although all correlation coefficients studied here are relatively high, the correlations for the variables of 40 mph, 60 mph, 1-man unit, gas tank less than one-quarter full, or tire pressure of 32 psi are exceptionally high. However, it is noted that repeatability with high tire pressures is rather poor and at 40 mph is very good, whereas the other variables tend to group in between (Fig. 13). Tessier (7) has also reported better correlation coefficients at speeds of 30 to 40 mph than at 50 mph.

The correlation coefficients may be higher than those noted in the literature because of the technique of averaging the large panel group and CRM runs. Also, the number of sections studied and the range are limited.

DATA RECORDING SYSTEM

The CRM data are reduced by computer to an equivalent RCI value, and the total data are stored on magnetic tape. Figure 14 shows a typical computer output sheet for a section of roadway, with all data shown being stored. The program uses PPR rather than RCI. The formula used to calculate the RCI (PPR) is shown and may be replaced by other formulas if, for example, a speed other than 50 mph is used in the CRM testing.

CONCLUSIONS

This study indicated that the variables considered each had an effect on the ability of the CRM to predict the RCI and that each variable should be controlled. This is most crucial when testing pavements that have high RCI values.

Assessments of pavements having a high RCI, as in new construction, appear to be more accurate when a vehicle speed of 40 mph is used.

When assessing pavements having a relatively high RCI, and where accuracy is important, one should perform replicate tests.

Figure 11. Effect of temperature on CRM output.

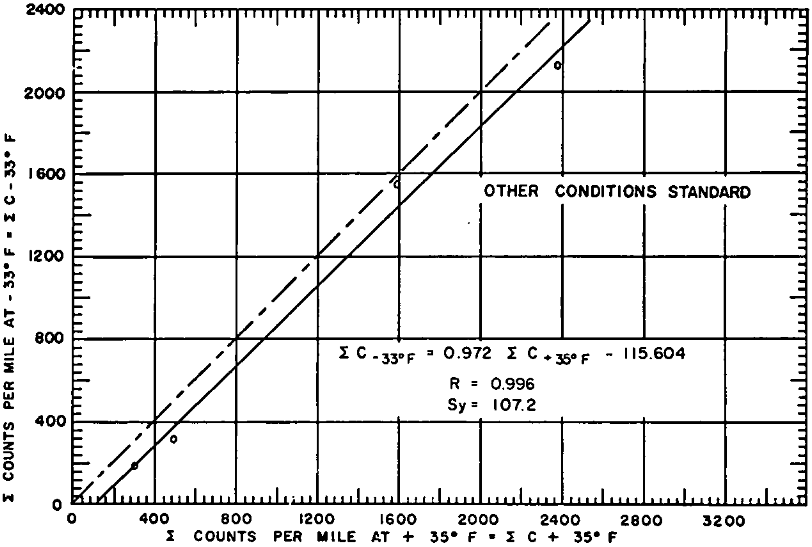


Figure 12. Effect of temperature on CRM for estimating RCI.

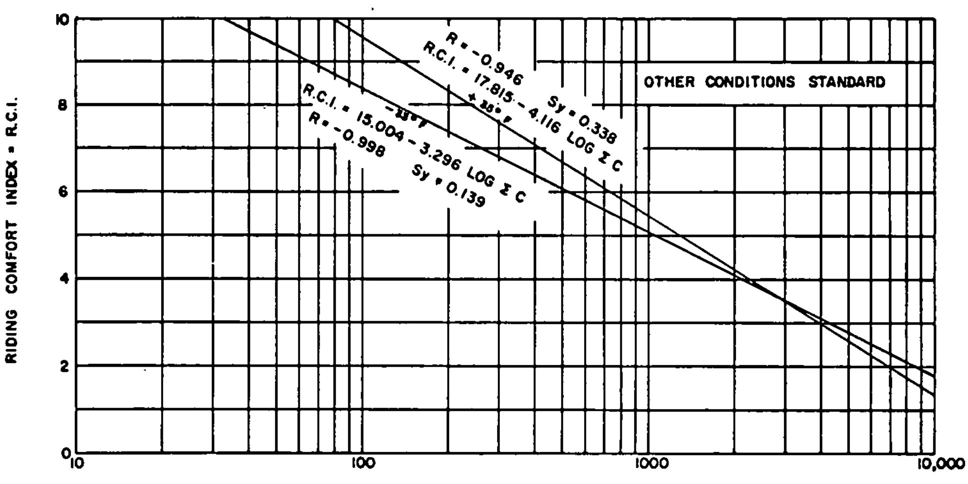


Table 6. Summary of RCI-CRM correlations.

Characteristic	Speed (mph)				Number of Occupants		Gas Tank	Tire Pressure (psi)		Temperature	Agency[c]		
	40	50[a]	60	65	1	3	<¼ full	22	32	-33 F[b]	Ontario	Alberta	Quebec
k_1	15.949	17.815	20.747	20.904	19.767	18.158	20.058	18.953	20.095	15.004	16.440	16.03	22.280
k_2	3.586	4.116	5.010	5.004	4.815	4.212	4.829	4.494	4.787	3.296	3.438	3.35	5.437
Correlation coefficient	-0.977	-0.946	-0.971	-0.936	-0.987	-0.949	-0.989	-0.969	-0.985	-0.998	-0.907	-0.843	-0.779
Standard error	0.223	0.338	0.250	0.367	0.168	0.331	0.154	0.259	0.180	0.139	–	–	–

Note: RCI = k_1 - k_2 log Σ-counts.

[a]Standard test conditions.

[b]Correlation by estimating RCI using mathematical model for standard test conditions for tests made 13 days prior at T = +35 F.

[c]Data taken from references 6, 7, and 9; all runs at 50 mph and other variables not constant.

Figure 13. Standard deviation versus Σ-counts.

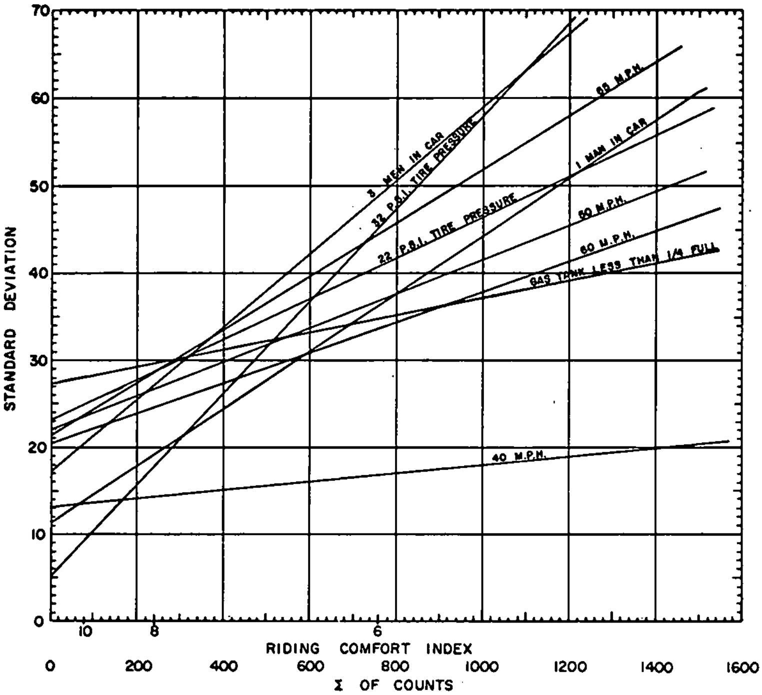
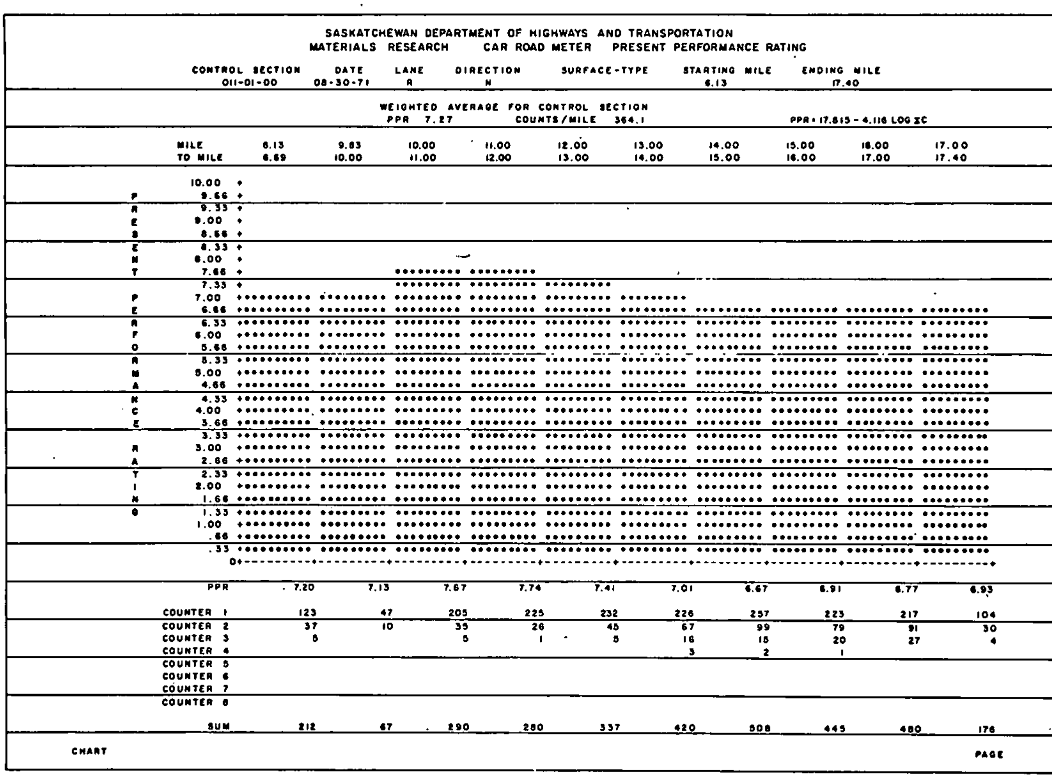


Figure 14. Computerized data sheet.



SASKATCHEWAN DEPARTMENT OF HIGHWAYS AND TRANSPORTATION
MATERIALS RESEARCH CAR ROAD METER PRESENT PERFORMANCE RATING

CONTROL SECTION	DATE	LANE	DIRECTION	SURFACE-TYPE	STARTING MILE	ENDING MILE
011-01-00	08-30-71	R	N		6.13	17.40

WEIGHTED AVERAGE FOR CONTROL SECTION
PPR 7.27 COUNTS/MILE 364.1 PPR = 17.615 − 4.116 LOG ΣC

MILE	6.13	9.83	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00
TO MILE	6.69	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	17.40
PPR	7.20	7.13	7.67	7.74	7.41	7.01	6.67	6.91	6.77	6.93
COUNTER 1	123	47	205	225	232	226	257	223	217	104
COUNTER 2	37	10	35	26	45	67	99	79	91	30
COUNTER 3	5		5	1	5	16	15	20	27	4
COUNTER 4						3	2	1		
COUNTER 5										
COUNTER 6										
COUNTER 7										
COUNTER 8										
SUM	212	67	290	280	337	420	508	445	480	176

CHART PAGE

Although the standard deviation of the CRM output increased with decreasing RCI, its sensitivity for predicting RCI increased because of the logarithmic relation.

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TEMPERATURE AND VEHICLE SUSPENSION EFFECTS

K. H. Dunn and R. O. Schultz

The first winter survey conducted with a road meter in Wisconsin occurred during the winter of 1968-1969. This survey was conducted over the entire rural Interstate system in Wisconsin. Following this original survey, the entire system was surveyed in the summer of 1969, winter of 1969-1970, summer of 1970, and winter of 1970-1971.

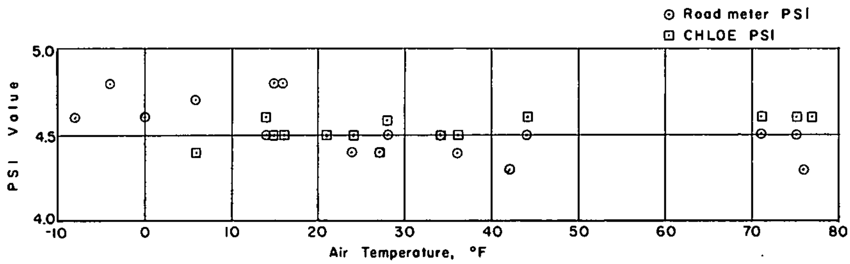
It was noted in these early surveys that winter present serviceability index (PSI) values typically were higher than summer values; however, because the differences were slight and inconsistent, they were viewed as reflecting normal variation that is caused by repeated use of the instrument and effects such as wind velocity and direction. However, by the summer of 1971, when 3 comparisons between winter and summer surveys were available, it was evident that the winter values were generally slightly higher than the summer values for those pavements that had relatively good longitudinal profiles (3.5 to 4.5 PSI). This was contrary to what would normally be expected; that is, pavements normally are expected to be slightly rougher in the winter. There were many pavements, however, that became significantly rougher during the winter months, and the road meter values did reflect this increased roughness. Thus, it was suspected that the road meter was being affected by low temperatures during winter surveys, but the effect was not sufficient to override extreme roughness.

In an attempt to evaluate the influence of temperature on the road meter, a study was initiated in the fall of 1971 to conduct continuing surveys through the fall, winter, and spring. Because temperature could also be expected to influence the pavement (and therefore ride quality), the CHLOE profilometer was used throughout the evaluation. It was our opinion that the CHLOE would not be influenced mechanically or electronically by low temperatures, so any change in slope variance (or PSI) would be due to change in the pavement profile. Thus, a comparison of changes in road meter values and CHLOE values with variations of air temperature at the time of testing should provide an indication of the influence of temperature on the road meter.

The pavement selected for the continuing surveys was a 2-lane portland cement concrete pavement near Madison. The pavement is a 9-in. jointed concrete slab, 24 ft wide (with joints at about 80 ft cc), on 9 in. of gravel base and 9 in. of granular subbase. The 1970 average 2-way daily traffic was 2,645 vehicles. This particular section of pavement had been used for numerous tests with a road meter, so considerable information on its general performance was available.

The comparison was started in December 1971, and the resultant values are shown in Figure 1. The values shown are averages for 2 tests conducted by each instrument in the northbound lane of the test pavement. Note that the values obtained with the CHLOE profilometer have remained relatively constant at 4.5 PSI, with occasional deviations above or below this value but well within the range of accuracy of the CHLOE. In contrast, the road meter results were consistently above 4.5 PSI when the air temperatures were below 20 F (down to -10 F) but fell to values generally below 4.5 when temperatures were above 20 F. Note also that the values obtained when air temperatures were between 70 and 80 F were about the same as those obtained between 30 and 50 F. As a means of checking the road meter values, the road meter was used to also

Figure 1. Relation between temperature and output of road meter versus CHLOE profilometer.



survey the southbound lane. The values were very similar to those shown for the northbound lane.

It is apparent from the results obtained that the road meter is affected by extremely low temperatures, perhaps because of a stiffened vehicle suspension system. In view of this limitation of the road meter, several alternatives are being considered for future observation, including (a) suspension of operations when air temperatures are below 25 F or (b) determining if a correction factor could be applied if operations were continued during cold weather.

DEVELOPMENT OF AN AUTOMATIC ELECTROMECHANICAL NULL-SEEKING DEVICE FOR THE PCA ROAD METER

M. P. Brokaw

Success of the original PCA road meter has been largely due to the unique road meter switch plate that allows simplification of statistical calculation of the summation of squared road-car deviations [$\Sigma(D^2)$]. The idea, equipment, and procedures involved in the development of the road meter are given elsewhere (1).

The paper disclosed that the number and magnitude of road-car deviations are distributed in a plus-minus array so that $\Sigma(D)$ is practically zero or so small that $\Sigma(D^2)$ can be calculated with minimum effort and complication. However, the method depends on ability to maintain initial static null reference between roller contactor and null segment of the switch plate after the test begins and the road meter car is in a dynamic state.

During the test, the original static null can be changed by a number of events. These are (a) error in the initial adjustment itself, (b) change in position and weight of car load, (c) excessive braking or acceleration, and, most important, (d) lifting of the car body (deviation datum) by aerodynamic forces created by car speed and ambient wind velocity and direction relative to car travel.

Any or all of these changes can take place during a single test. Each change or condition results in recordings of digital counter data peculiar to the existing condition. Therefore, the composite data are a combination of groups of high-frequency road roughness recordings, each separated in the switch plate by extraneous movement or translation not associated with pavement roughness. Use of composite data, no matter how measured and recorded, will result in a $\Sigma(D^2)$ statistic that is always greater than $\Sigma(D^2)$ attributable to road roughness alone.

A solution to the problem is to have a mechanism attached to the road meter that is capable of sensing extraneous inputs that change static null, correct for these in amount and direction, and thus ensure digital counter recordings that are a result of road roughness alone. This paper presents a discussion of the problem and describes an inexpensive device capable of accomplishing the solution.

PRACTICAL EFFECT OF NULL SHIFT DURING TEST

Shifting of the road roughness spectrum can be caused by a number of events during a single test. Some, such as passenger movement, may be of short duration, and others may be of long duration and varied as in the case of ambient wind velocity and direction relative to car travel.

To illustrate the effects of null shift, we have constructed a hypothetical example (Table 1). Counter recordings are listed for a 1-mile section of road, where these recordings represent true road-car deviations without extraneous effect. On a hypothetical rerun of the 1-mile section, ½ mile was accomplished without extraneous effect. The remaining ½ mile, included in the single test, was affected by high side wind so that null adjustment was shifted ²⁄₈ in.

Table 1. Hypothetical example of effect of null shift during test.

	Perfect Null		Null Shift ($^2/_8$ in.)	Composite*		
Road-Car Deviation ($^1/_8$ in.)	Counter Recording (1 mile)	Counter Recording ($^1/_2$ mile)	Counter Recording ($^1/_2$ mile)	Counter Recording (1 mile)	Shift Deviation Base	Σ-counts
-4	0	0	0	0	-5	0
-3	6	3	0	3	-4	12
-2	42	21	0	21	-3	63
-1	152	76	3	79	-2	158
0	232	116	21	137	-1	137
+1	152	76	76	152	0	0
+2	42	21	116	137	+1	137
+3	6	3	76	79	+2	158
+4	0	0	21	21	+3	63
+5	0	0	3	3	+4	12
Σ-counts per mile	508	508	1,276	892	-	740
PSI	4.30	4.30	3.44	3.75	-	3.93

*The data in this column are derived from the preceding 2 columns.

Figure 1. Diagram of electrical equipment for automatic null adjustment of PCA road meter.

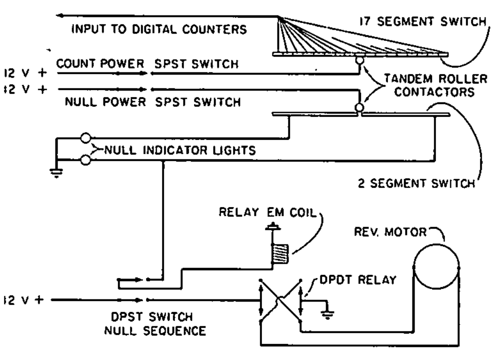


Figure 2. Connections between reversible motor and switch plate.

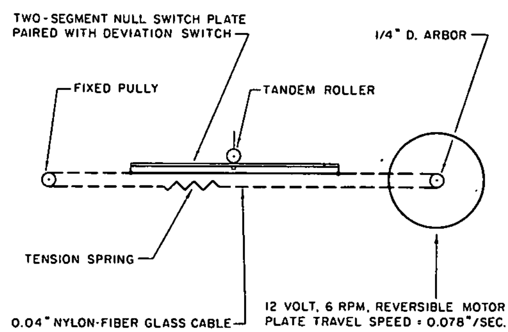


Table 2. Effectiveness of automatic null-seeking device attached to PCA road meter.

Road-Car Deviation ($^1/_8$ in.)	Static Null (southerly wind, 10 mph) Count Record	Automatic Null (westerly wind, 28 mph) Count Record	Static Null (westerly wind, 28 mph) Count Record
1	532	409	332
2	270	280	328
3	79	92	211
4	20	26	98
5	4	4	31
6	1	0	8
7	0	0	3
Σ-counts	1,415	1,458	2,237
PSI	3.36	3.33	2.98

According to Table 1, the full mile has a true PSI of 4.30 when measured without extraneous effect. The first ½ mile, measured in the rerun without extraneous effect, also shows a PSI of 4.30. The second ½ mile, run with extraneous effect amounting to null-shift of ²⁄₈ in., shows a PSI of 3.44. Composite 1-mile data for the rerun give a PSI of 3.75. In each case computations have been made on the assumption that the road meter remained in perfect static null.

Had the operator known that a shift had taken place, he might view the data from digital counters and conclude that the frequency curve was symmetrical but shifted +⅛ in. He might then shift the measurement scale by ⅛ in. and compute Σ-counts. PSI then comes out at 3.93, still less than the true value without extraneous influence.

SOLUTION OF THE NULL-SHIFT PROBLEM

Road-car deviation inputs to digital counters in a PCA road meter are very rapid. On the average, time for a complete plus or minus deviation should not exceed about 0.3 sec and could be as short as 0.025 sec at the maximum capacity of the counter itself. Therefore, the duration of a single plus or minus excursion of the roller contactor from the null switch plate segment is very limited; and when perfectly nulled, the contactor will spend about as much time on one side as the other during a lengthy test.

If an extraneous influence is introduced and continued during a test, the contactor will move off null, but it will still maintain the centrally oriented rapid movements induced by road roughness input. Then the contactor will spend more time on one side of static null than the other. Correction of the off-null position can be achieved by a time-sensing device that makes automatic correction by shifting the switch plate to a new position that will tend to equalize plus and minus excursion times.

Within-test adjustment of the switch plate can be done mechanically by use of a reversible motor actuated by a separate roller contactor and 2-segment switch plate exactly paired with the roughness deviation plate. Pairing means that the division in the 2-segment plate is exactly adjacent to the center of the null segment of the deviation plate and that the motor roller contactor is exactly adjacent to the deviation roller where both operate in unison according to relative road-car movement.

The general position of deviation and motor switches, roller contactors, and electrical requirements is shown in Figure 1. Figure 2 shows the connections between reversible motor and combined switch plate.

Figure 1 shows that the position of the contactor on the 2-segment switch plate will activate a DPDT relay that will decide the direction of rotation of the motor and direction of travel of the combined switch plate. By selection of proper polarity in wiring, the relay will direct plate movement always toward a perfect null.

It is obvious that very fast correctional movement of the switch plate might override roller movements related to roughness alone. However, motor rotation is geared down, and by use of the indicated motor speed and reduction arbor, plate travel has been reduced to only 0.078 in. per sec. If a plus or minus deviation requires 0.3 sec for completion, the maximum attenuation possible is only 0.023 in.

In spite of the slow plate movement, the very rapid reversals of direction will quickly compensate for extraneous effects creating a faulty null. The predominant movement of the plate will be automatically controlled by the relative time that the motor roller contactor spends on one side or the other of its own 2-segment switch plate. Experience has shown that these corrections for extraneous influence will be made in 2 or 3 sec and that perfect null will be achieved. If extraneous conditions change, corrections are automatically applied.

USE OF THE AUTOMATIC NULL DEVICE

The automatic null device was developed by the author in early 1971. It has been in use in numerous road and airport surveys, and tests have been conducted to verify its effectiveness. One example is given in Table 2, where tests in a single site were influenced by high wind velocity. In this case, the survey car was operated southbound into a tolerable 10-mph head wind, and a PSI of 3.36 was recorded. On the following day, wind had increased to 28 mph, and direction was at right angle to car movement. With static null, wind effects reduced PSI to 2.98, and count recordings were questionable because of the unlikely array displayed by counters 1, 2, and 3. Immediate rerun with the automatic null in operation gave results that correspond to those of the previous day.

Other observations indicate that within-test variability will be reduced substantially, probably in the order of 50 percent. The Wisconsin Division of Highways has reported great improvement in repeatability, reduction in downtime due to wind restrictions, and increased safety in the operation of road meter vehicles because static null adjustment is not required.

CONCLUSION

Development of the automatic, null-seeking device should increase the reliability of the PCA road meter, improve efficiency and safety, and reduce mass inventory costs.

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EVALUATION OF THE CAR ROAD METER BY USING THE K-COEFFICIENT

Benjamin G. Fortin

The car road meter designed from Brokaw's concept is a practical and simple instrument that is quite useful in measuring the condition of the road surface through the response of a car as felt by the driver. This apparatus is fast and easy to operate and has a good reliability; therefore, a large network of roads can be covered during the summer season. The riding comfort index (RCI) can be measured safely because the operational speed of the road meter is close to the legal speed.

RIDING COMFORT INDEX

The RCI measured by a road meter is the sum of products of counters' readings by their location (or numerical order). RCI is expressed by the following equation:

$$\Sigma = (e/L)(C_1 + 2C_2 + 3C_3 + \ldots nC_n)$$

where

Σ = riding comfort index,
e = correction factor for the car speedometer,
L = length of the section in miles, and
C_1, C_2, C_3 = readings of the counter 1, 2, 3, n.

RCI is given as a value per mile at a given speed, normally 40 mph. In Quebec, the calibration of mounted apparatus is done by comparison to a standard car and meter maintained only for this purpose. This seems to be the normal procedure adopted by all users in Canada and the United States.

K-COEFFICIENT

The development of the K-coefficient resulted from a search to find a way to use RCI in a modified or simplified way. Previously, to compare RCI values to those obtained by using the present performance rating (PPR), which involves a panel of observers, we had to transform their values into logarithms. The same was true when comparing RCI values at different speeds for a given vehicle or among vehicles. Furthermore, the province of Quebec is currently evaluating the provincial road network, and values from the road meter were not readily compatible with results from the Benkelman beam. Therefore, by transforming the RCI equation, we came up with a new way of using data from the road meter. As stated previously, the RCI equation is as follows:

$$RCI = (C/L)(C_1 + 2C_2 + 3C_3 + \ldots nC_n)$$

The factor multiplying the counter's value is determined by the location of pairs of segments equidistant about the center. This factor is a multiple of 118 in. and directly proportional to the amplitudes of oscillations.

We can therefore say that

$$RCI = K(d_1C_1 + d_2C_2 + d_3C_3 + \ldots d_nC_n) = K\,\Sigma dC$$

where

d = equal distance from center,
C = reading on counter, and
dC = moment of any segment.

However, if we take out the sum of moments from the preceding equation and set it against a resulting moment such as $\Sigma dC = D\Sigma C$, we can get a resulting moment arm D whose value will be $D = (\Sigma dC/\Sigma C)$. The equation of K-coefficient as used in calculation is $K = (\Sigma C/\Sigma dC)$; therefore, we can state that K-coefficient is the reciprocal of the resulting moment arm D.

ROAD METER VARIATIONS

Figures 1 through 3 were plotted from data collected using different road meters installed in the automobiles listed below:

Road Meter	Type of Automobile	Type of Suspension
4	1969 Ford	Heavy-duty, leaf
7	1967 Oldsmobile	Regular, coil
11	1971 Ford	Regular, coil
12	1971 Ford	Regular, coil

The test sections were selected for their wide continuous variation in roughness. However, no data were kept as to the geometric design of the sections, temperature variation during runs, weather, and so forth. Only tire pressure was maintained as recommended by the manufacturers. Each vehicle made double runs at 3 different speeds (30, 40, and 50 mph) on all test sections.

Figures 1 and 2 show the interrelation of values at different speeds for road meters 4 and 7; Figure 3 shows the relation of values at 40 mph for these 2 road meters (Table 1).

K-COEFFICIENT VERSUS RCI

For a given strip of road, the RCI will be expressed as a value per mile, whereas K, being inversely proportional to the average amplitude of roughness, is independent of length.

The K-coefficient is a fraction that normally will range from 0.2 to 1.0, and for practical purposes, the value is multiplied by 100. On the other hand, the values of RCI will start near 100 and increase up to and above 10,000, depending on the counters used.

Unless the surface of the road is relatively good, no correlation should be expected from the K-coefficient and RCI because RCI is determined by the sum of moments, whereas K is the arm of a resulting moment (Fig. 4).

RCI values will be quite dependable for roads with good surfaces but will become erratic as road surfaces get rougher and bumpier. The K-coefficient on the other hand is quite trustworthy for the surface conditions on most roads.

When the surface of the road is rough, the contact on central segments is very short, and counters will skip count. This undesirable condition will be detrimental to RCI values but will work in favor of the K-coefficient. Under adverse conditions, RCI values will be completely false, whereas K will exhibit a valid value (Fig. 5).

ADVANTAGES OF THE K-COEFFICIENT

The K-coefficient can be used advantageously in evaluating and interpreting data collected from the road meter.

Figure 1. Road meter 4 data.

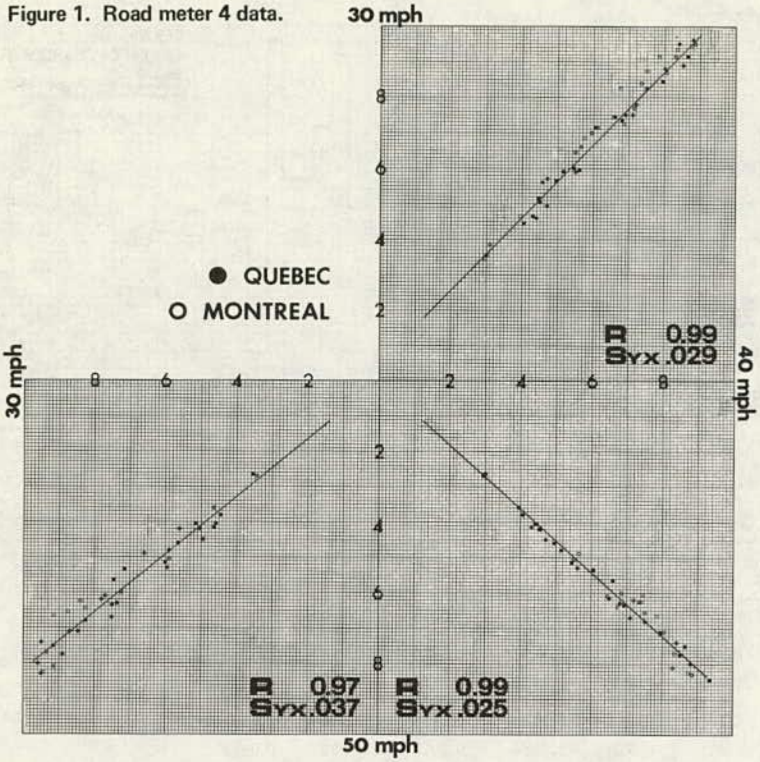


Figure 2. Road meter 7 data.

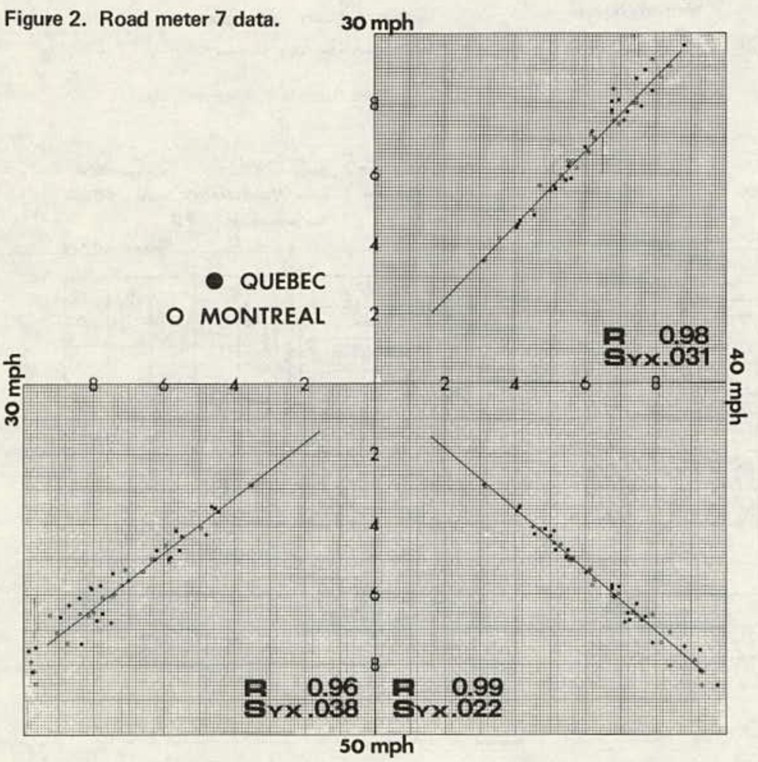


Figure 3. Comparison of road meters 4 and 7.

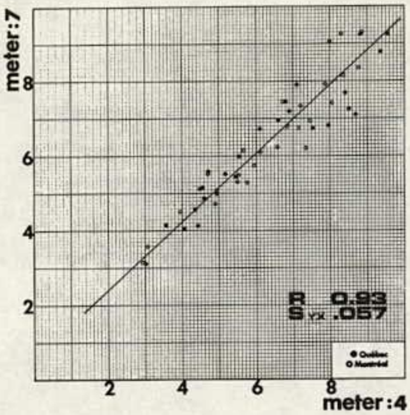


Figure 4. Comparison of RCI and K-coefficient.

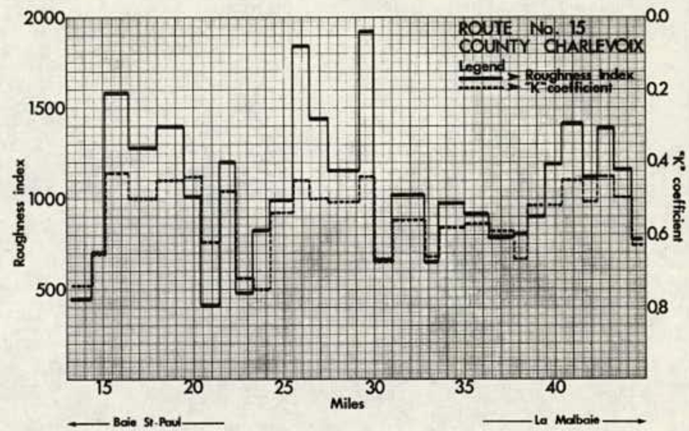
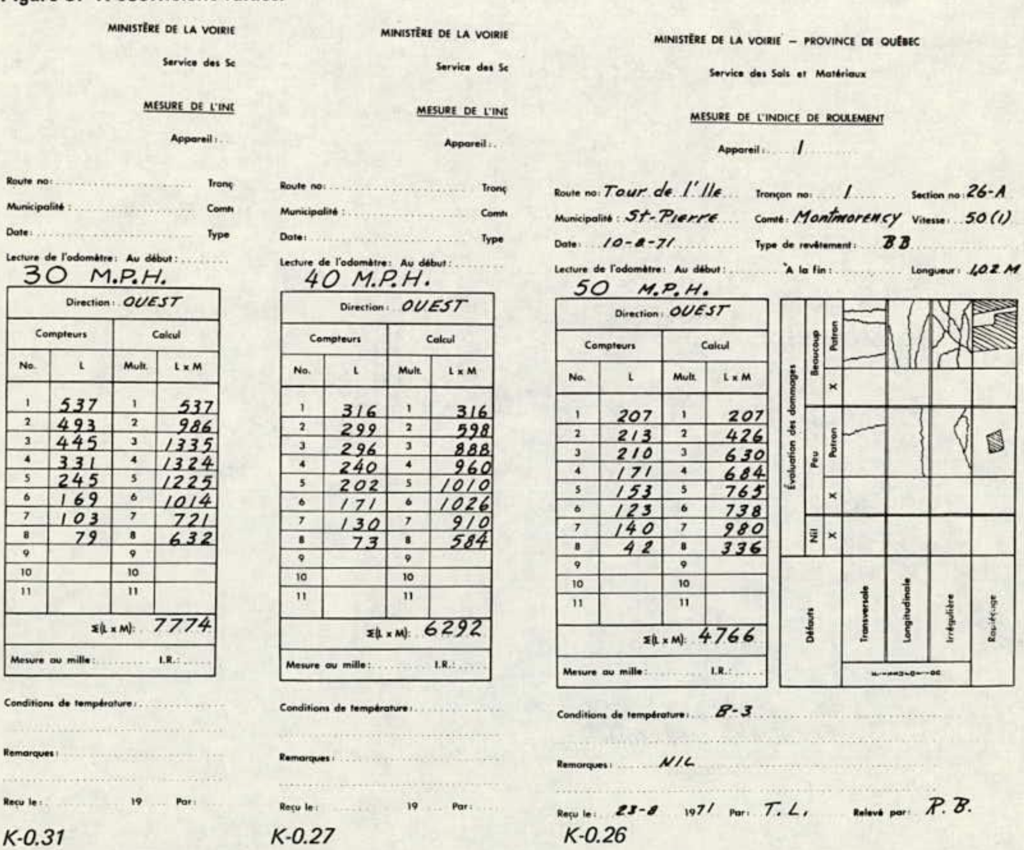


Table 1. Linear regressions.

Figure Number	Meter	Speed (mph)	$\overline{X}$	$\overline{Y}$	a	b	R	Syx
1	4	30 to 40	0.701	0.628	0.9610	0.0475	0.986	0.0289
		40 to 50	0.650	0.588	0.8839	0.0138	0.986	0.0254
		30 to 50	0.708	0.580	0.8152	0.0026	0.971	0.0365
2	7	30 to 40	0.695	0.628	0.9414	0.0281	0.983	0.0305
		40 to 50	0.656	0.580	0.8723	0.0081	0.988	0.0222
		30 to 50	0.706	0.564	0.7793	0.0139	0.960	0.0381
3	4 versus 7	40	0.635	0.642	0.8554	0.0923	0.932	0.0572

Figure 5. K-coefficient values.



K-0.31 K-0.27 K-0.26

A road meter, when installed in a vehicle, can be calibrated by making a series of runs at different speeds on several road sections chosen for their varied surface roughnesses. Then linear regressions can be calculated from the data collected.

From available calibration data on file, sets of graphs were plotted for each vehicle at various speeds and then among vehicles for a given speed for this study. We note the following:

1. The values can be plotted on regular arithmetic graph paper;
2. The values can be evaluated by use of linear regression;
3. Interrelation of values for a given vehicle at various speeds can be expressed (a) for any 2 speeds, as a linear regression of the first degree, such as $y = b + ax$, and (b) for the 3 speeds, as a linear regression in space, such as $z = aX + bY + C$;
4. At a given speed, the values from the different vehicles compared in pairs give a linear regression of the first degree; and
5. The coefficient of correlation in all cases is well above 0.90.

The value of the K-coefficient is effectively illustrated. The K-coefficient gets the best out of RCI in interpreting graphic data. Any error during calibration runs will stand out on the graph. To illustrate common errors, we shall assume the following:

1. The apparatus was not set at zero, or was operated improperly for a certain run (say, at 30 mph) but operated normally at other speeds. The points will be way off on the 30- to 40-mph and 30- to 50-mph graphs, but within normal tolerance on the 40- to 50-mph graph.
2. The apparatus became defective somewhere during the test. The points would be off the usual regression line and would have a tendency to form another linear regression on the graph so long as the fault remained more or less constant.

This behavior of the K-coefficient could be advantageously used in evaluating operators, detecting a sluggish or faulty apparatus, or carrying out trials to determine effects from temperature, wind, and so forth.

LIMITATIONS OF THE K-COEFFICIENT

The K coefficient has several weaknesses that one has to consider before using it as a tool in evaluating data from road meters. For example, when a road's surface is excellent, only counter 1 will have a value, and regardless of this value we always get the maximum value (100) for K. We are therefore unable to identify the degree of excellence of the road.

As stated previously, K is independent of the distance measured. This could be disadvantageous because K does not take into account the frequency of bumps; it is affected only by the amplitudes and distributions of the bumps.

To illustrate, suppose the readings on counters 1, 2, and 3 are as follows for a 1-mile survey:

C_1:	240 × 1 = 240	120 × 1 = 120	60 × 1 = 60
C_2:	120 × 2 = 240	60 × 2 = 120	30 × 2 = 60
C_3:	60 × 3 = 180	30 × 3 = 90	15 × 3 = 45
	420 660	210 330	105 165
	K = 63.6	K = 63.6	K = 63.6

Finally, when using the K-coefficient to evaluate road roughness, it is important to closely observe the counters' readings. The value of K is quite reliable to describe the roughness of a given section of road, but if this road section is not homogeneous and is composed of 1 or 2 bumps or potholes, the value of K will be adversely affected.

CONCLUSIONS

The information presented is believed sufficient to support the following statements:

1. Very good linear regressions can be obtained from each vehicle at different

speeds. Therefore, by adopting a specific speed as standard, all values obtained at other speeds can be converted to those obtained at the standard speed.

2. By using a given speed common to all vehicles, values of K can be compared among vehicles.

3. Errors during calibration can be easily detected and the type of fault identified.

4. By giving a vehicle's operator the result of calibrations, either in the form of graphs or tables, he can check the vehicle when in doubt or do periodic calibration runs with the apparatus anytime and anywhere. This will prevent the accumulation of false values during inventory operations.

Finally, the K-coefficient is not intended to replace any current method of evaluation, but rather to serve as another tool in investigating pavement conditions and behavior. Although the K-coefficient is quite useful in its present state, improvements and modifications can be expected from its continued use.

PART V

USE OF ROAD METERS FOR INVENTORIES AND MAINTENANCE STUDIES

PHOTOGRAPHIC INVENTORY

R. M. Hearst

Each summer for the past 5 years the British Columbia Department of Highways has been making a photographic inventory of the highway system. Total coverage is approximately 6,000 miles per year, which includes about 5,000 miles of major roads repeated each year in alternate directions and a gradually expanding coverage of secondary roads.

PHOTOGRAPHIC OPERATIONS

A 16-mm custom modified camera is set in an instrument package mounted through the roof of a van. The 10-mm (53-deg field of view) lens is pointed straight ahead and very slightly down to give good coverage of the road. The upper one-fifth of the picture frame (full width) shows the instruments through mirrors. These include date, time, and location information; odometer (with manual reset); ball bank indicator; 2 roughness meters, one for each frame interval and another for 1,000-ft sections; altimeter (reading to 10-ft elevation); speedometer; and various indicator lights.

A driver-operator loads the film, resets initial information, and controls the picture interval. Photography is automatic, with odometer drive actuation and electronic controls of interval, aperture, and flash lighting. After standard mail processing, the Kodachrome II film is edited and indexed for retrieval (5 min) and projection on a flickerless analyst projector with continuously variable speeds, forward and reverse.

ROUGHNESS METERS

The roughness meters display the amount of differential movement between the rear axle and the van body according to the following formula:

$$\text{Reading} = \log \left\{ \frac{5{,}280}{\text{interval in feet}} \left[\Sigma \text{ absolute } (f_i \; n_i)_i = 1, \; 8 \right] \right\}$$

where i is the sensor number 1, 2, . . . 8 for axle movement sensors set ⅛ in. apart and covering ±1 in.; f_i is 1, 2, . . . 8 for i = 1, 2, . . . 8; and n_i is the number of counts recorded for sensor i since last reset.

The reading represents the accumulated movement, factored by the amount of movement, adjusted to an equivalent reading per mile and the logarithm taken to compress the scale.

There are 2 roughness meters. The left meter shows the reading for the individual picture interval; the right meter covers a fixed interval of 1,000 ft (changed to 1 mile in 1972) and is valid only immediately prior to reset when the appropriate indicator light is on. The roughness recording equipment includes the following:

1. Cable attached to the rear axle at centerline, which follows axle movements and transfers them through pulleys to an indicator head on the vehicle floor;
2. Light source and fiber optic pickups for zero position at ⅛-in. intervals for ±1-in. movement, and overrun, to sense indicator head movement;

3. Transistorized circuitry that applies appropriate multiplier factors, splits pulses into 2 paths, applies appropriate distance interval divisor factor, and accumulates charge through a logarithm simulating capacitor to read out meters;
4. Meter discharge circuit;
5. Zero adjustment control; and
6. Overrun (more than ±1 in.) indicator light circuit.

All of the photographic instrumentation was built for the Department by the British Columbia Research Council.

ROUGHNESS METER USE

In 1971 the film inventory was reviewed, and all 1,000-ft sections with roughness reading ≥ 3.2 (≈ 1,580) were recorded for consideration for the current paving program.

Some 1971 roughness readings have been compared with 1969 present performance ratings, and a reasonable correlation was noted. Further work is, however, necessary.

PHOTOGRAPHIC INVENTORY USE

The photographic inventory is a valuable tool. It is used by the planning branch as the principal road inventory record. It is also used as a source of data for the computer inventory system, but data extraction is limited to basic information (e.g., mileages and landmarks) and data considered essential to daily operations of other branches and officials.

The advantages of the film record are as follows:

1. Everything within the field of view of the camera lens is recorded objectively and nonselectively. (The record is complete.)
2. One 400-ft reel stores records for 250 miles of road. (The record is compact.)
3. Viewing of film generally conveys better impressions than written descriptions of road sites (or even drawings or maps).
4. Detailed data can be extracted at any later date for specific purposes as necessary. For example, detailed frame-by-frame roughness readings can be retrieved for detailed study of pavement sections as required. (The film record is permanent.)
5. The film record costs approximately $2 per mile, when equipment is amortized over 5 years.
6. The film is available on short notice and is particularly valuable in British Columbia, a large area.

Although the film records do not substitute for detailed on-site study and measurement, the photographic inventory is a very efficient information collection and storage system, and the simple operation in use in British Columbia is an excellent communication medium.

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USE OF CAR ROAD METERS IN A ROAD MASS INVENTORY

Gerard Tessier

One of the most important instruments in any pavement management system is the road mass inventory, which can be divided into 3 subsystems: structural, traffic, and safety characteristics. This paper explains the part played by car road meters in the collection of data on the structural characteristics of road surfaces and provides some idea of the planning and control of the collection of data across Quebec; it also indicates the limitations of the device and comments on the results.

One of the major difficulties encountered in roughness studies is the calibration of car road meters. The data compiled are gathered and put in graphic form by the computer (road diagram) and sent to the road engineers. These data are used simultaneously with those on deflection and those compiled through condition surveys to prepare a list of structural priorities. The roughness criteria will be assessed and corrected if the need arises. A table gives a global picture of the road network from the point of view of roughness and serves as a planning tool. A graph shows the theoretical relation between the roughness coefficient K_r and the riding comfort index (RCI). This paper clearly shows the use made of car road meters in a structural mass inventory of a vast road network.

The purposes of a road mass inventory are to obtain an overall picture of all classes of roads, from the viewpoints of structure, traffic, and safety; to keep track of the condition of the roads over a period of time; to establish the network's priorities with a view to short-term and long-term programming of maintenance and reconstruction; to rationalize a budget for bituminous overlay; to guide the road engineers in repairing and rebuilding roads in their regions; and to provide a tool for planning within the pavement management system.

Road mass inventories, then, are of immense importance to highway department engineers and should be made on as many Quebec roads as possible. Also, the most important data can be collected in areas such as pavements, bases and subbases, road geometry, and traffic. In order that they be more useful, these data must form an integral part of a management system; they will be stocked in a data bank for reference and study purposes and processed by computer.

IMPORTANCE OF ROAD MASS INVENTORY

The pavement management system emphasizes the role played by the road mass inventory. The proposed management system outline (Fig. 1) shows the main elements of such a system and stresses the use of the inventory in deciding on priorities. The data gathered during the inventory on the actual state of the highways allow verification of performance standards and establishment of criteria for good roads. Performance standards may possibly lead to correction of design standards. All the data from any road mass inventory are compiled in a road data bank, and the results of the research are used as guidelines in making decisions following the preparation of a list of urgent sections covering the entire numbered road network. The numbers that appear above each pattern refer to the patterns for the global system shown in Figure 2. Essentially, the management system shown here is that designed by Haas (1), with a

Figure 1. Pavement management system.

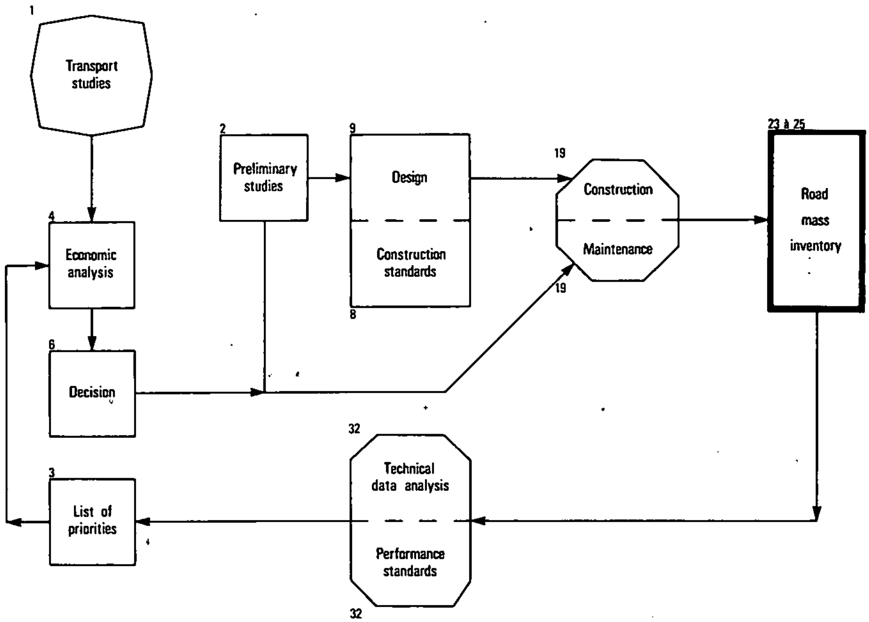
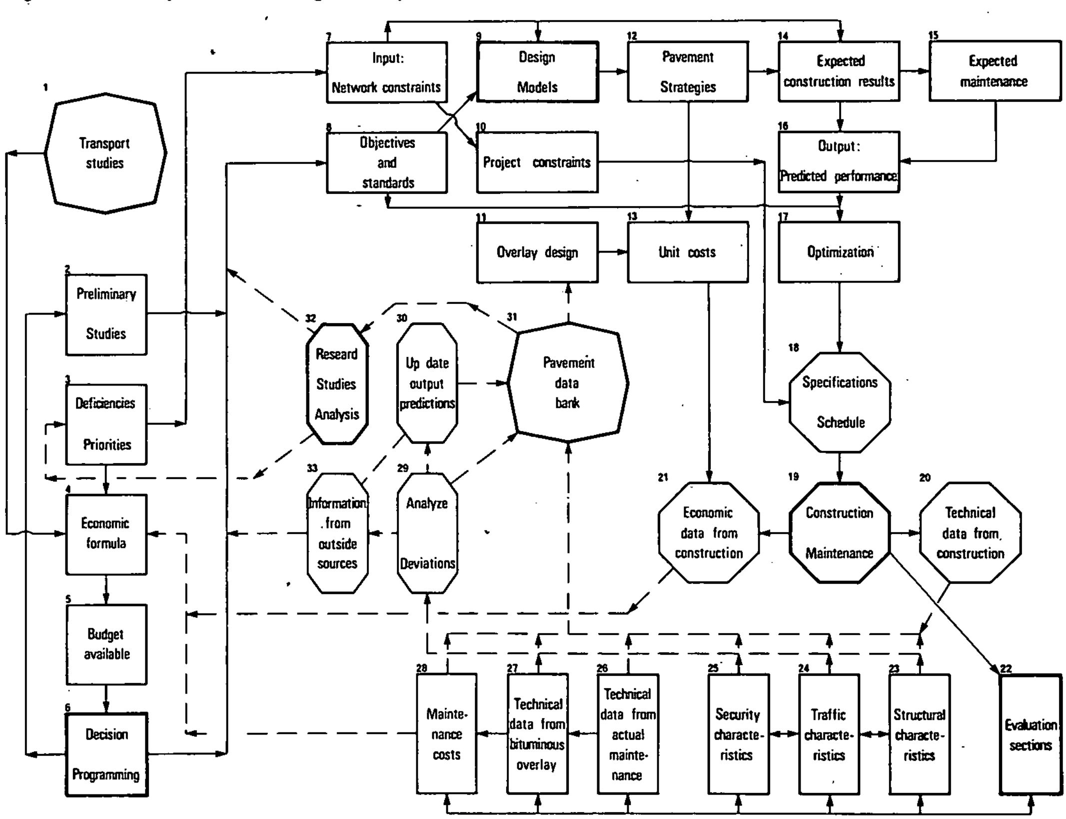


Figure 2. Global pavement management system.



few changes, especially in the part that deals with road mass inventory. Other pavement management systems have been put forth (2, 3).

It will be seen that the system outlined here (Fig. 2) only gives the titles of the principal activities within the pattern of the system. Each activity will eventually be developed accordingly and explained, but that is not the object of this paper. In order to clarify the system, we have divided it into 5 sections or activity groups: planning (1 to 6), design (7 to 17), construction (18 to 21), mass inventory (22 to 28), and research (29 to 33). Each group has its own pattern (model) for making the system easier to understand. The broadest patterns represent the key activities within the system. Attention is drawn to the size of the road mass inventory shown in patterns 22 and 28, which feed the data bank. Figure 3 shows the role played by the data bank, indicating total input (bottom) and total output (top). In this way a good idea can be had of all the data that will be processed and how the decision will be made once a list of deficiencies and priorities has been drawn up through research, with account being taken of the economic analysis and budgets allowed or available.

IMPORTANCE OF ROUGHNESS DATA IN A ROAD MASS INVENTORY

Having established the importance of inventories within a global pavement management system, our next step is to determine the means of compiling the necessary data in a road mass inventory. In order that the data may be better prepared, the results better analyzed, and a global list of priorities better drawn up for the road network, the inventory has been divided into 3 subsystems, structural, traffic, and safety characteristics, which are shown respectively in patterns 23, 24, and 25 (Fig. 2). Each subsystem will build up its own list of priorities, taking account of structural, traffic, and safety deficiencies. The global list of priorities will constitute an integration or mixture of 3 lists (structural, capacity, and security) given by the 3 subsystems within the road mass inventory. Once a list of priorities has been drawn up for the whole road network, programs will be decided on and drawn up based on economic analysis and budgetary constraints.

The list of structural priorities will be established by the structural characteristics subsystem. The main characteristics to be used as basic data in any structural analysis of roads are deflection, roughness, cracking, patching, and drainage. Through a multiple regression analysis it will be possible to establish the relative value of each variable considered important in preparing a list of structural priorities: deflection ($x + 2\sigma$), roughness coefficient K_r, cracking index, patching index, and drainage index. Other data on the background of the road and its surface, traffic, and maintenance will be used in the analysis. Activity 23, structural characteristics, consists of gathering data on roughness, deflection, condition survey, and drainage. Roughness data constitute one of the principal components of the "structural characteristics" activity. Roughness becomes one of the guidelines used in drawing up a list of structural priorities. Once the importance of each of these variables has been established, it will be relatively easy to make a list of structural priorities, using an appropriate point system.

Until now, we have placed the characteristic of roughness within one of the 3 subsystems of the road mass inventory, which itself is part of the global network of pavement management systems. We hope soon to be able to demonstrate its importance in relation to the other variables analyzed within the structural characteristics subsystem.

CALCULATION OF ROUGHNESS

Roughness was assessed quantitatively; it was surveyed on the road network within the road mass inventory in the following manner. We used a car road meter, a device that measures roughness over many miles but within a relatively short time. Three of these meters were used to measure the roughness of 10,500 miles of Quebec roads in 2 years (1970 and 1971). We intend to complete the collection of data on the roughness of Quebec's entire numbered road system in 1972, a total distance of 12,500 miles. For mass inventory needs, the roads have been divided into large sections, sections, and subsections. Identification can be illustrated by the following example: 0155, road; 02, large section; 060, section; and 01, subsection.

Figure 3. System data bank.

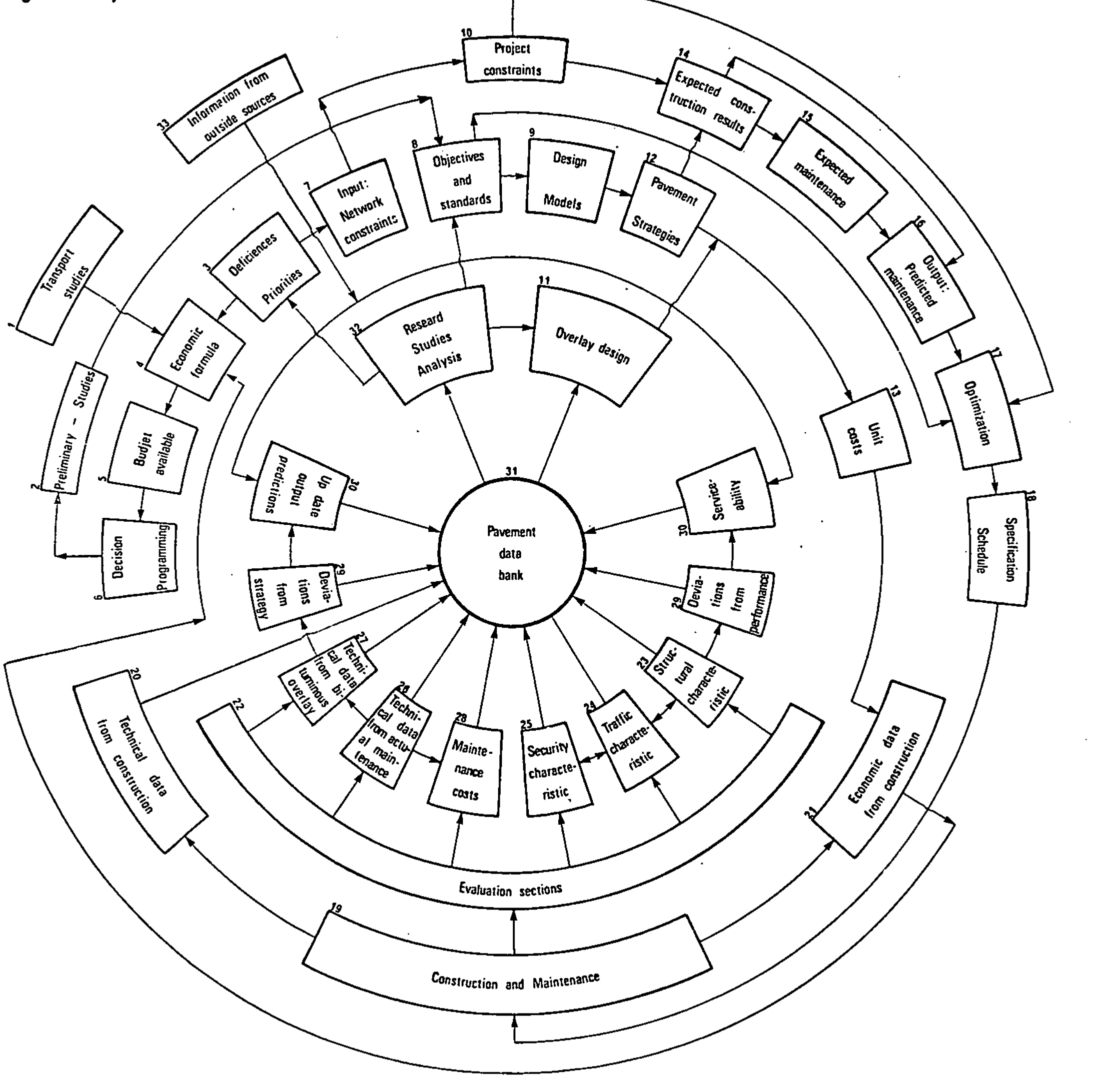


Figure 4. Correlation of index q and road meter Σ-counts.

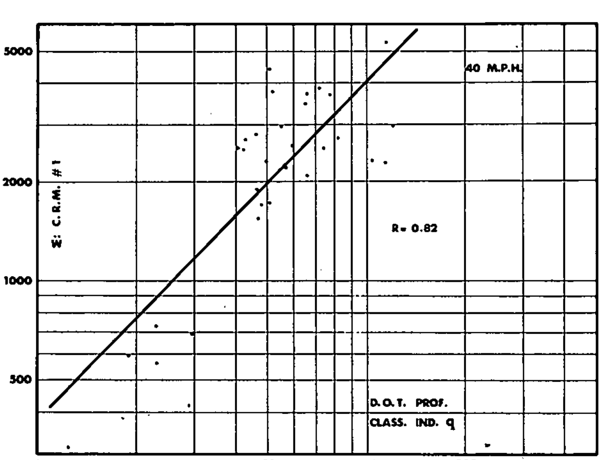
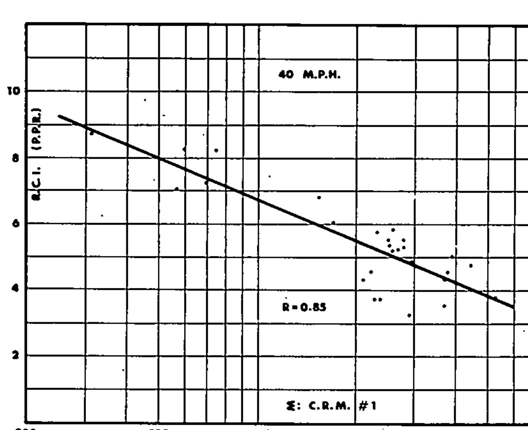


Figure 5. Correlation of RCI and road meter Σ-counts.



In order to ensure the shortest possible run and proper control of the results of the inventory, we divided the province of Quebec into 10 circuits in which deflection and roughness data were collected. Each car road meter (3 in 1970 and 2 in 1971) was given a number of circuits that were completed individually. Knowing the speed of each day's operation, we were able to control the surveys and check the car road meters any time during the week. Weekly reports were submitted by the teams involved.

SELECTION OF A STANDARD CAR ROAD METER

Calibration of the machines was one of our major problems. It was necessary to make sure that the value given by one meter for one section could be compared to another value given by a second machine for another section of the road, i. e., that the sections were comparable from the point of view of roughness. First, we calibrated all car road meters with the British profilometer used by the Department of Transport in Ottawa. The results of this calibration are discussed in a report prepared by Argue (4). Figure 4 shows the correlation obtained between the classifier index q and the summation of counts (Σ-counts) given by car road meter 1 for 1 mile. The coefficient of correlation R is 0.82. The average reading error on both sides of the calculated straight line is in the order of 33 percent. This correlation is not satisfactory. The correlation between Σ-counts of the other car road meters used and q is about the same.

A calibration was made between the car road meters and the RCI. Figure 5 shows the correlation between the Σ-counts for car road meter 1 and the RCI established by a 3-man panel for the same sections analyzed by the British profilometer. The coefficient of correlation was 0.85, and the average reading error on both sides of the calculated straight line was about 10 percent. The correlation shows a slight improvement over that in the preceding figure. The correlation between Σ-counts of the other meters and the RCI established by the same 3-man panel is about the same. If another, or a larger, panel had been used, the correlation might have been quite different because the appraisal of the RCI varies with the panelists. A correlation between Σ-counts and RCI for the same meter varies according to the members of the panel or panels at the time.

Calibrations were later established among the Σ-counts of the different car road meters used for the calibration and also among the roughness coefficients of these instruments. The roughness coefficient is defined in Fortin's paper (5). Figure 6 shows the correlation between the Σ-counts for car road meters 1 and 2 respectively at an operating speed of 40 mph. The coefficient of correlation is 0.97, and the average reading error on both sides of the calculated straight line is about 11 percent. The correlation for the other meters is similar ($R > 0.95$). It is more satisfactory for an operating speed of 40 mph than for 30 mph.

Sections of roads change with time, as do the machines used; they deteriorate. Vehicles also change, and this makes the interpretation of roughness data among sections and years extremely difficult. Because the correlation between Σ-counts or between roughness coefficients of car road meters is satisfactory, we chose a road meter that would be used only to calibrate the other road meters used in our study of roughness. This was merely a partial solution because after some years the standard road meter itself will also change. It is essential that a time-stable mechanical device for calibrating road meters be developed.

The standard meter will be satisfactory for calibrating the road meters that we will use on Quebec roads during the next 2 years. Calibration was established between all the road meters used and the standard road meter in 1971, and this will be done again in 1972 and 1973. Correlation coefficients have been highly satisfactory (> 0.95). A line of correlation is thus established between each road meter and the standard apparatus for a speed of 40 mph. Another correlation is established for each machine between the speeds of 30 and 40 mph. For each section studied, then, we have the K_r or Σ-counts expressed in relation to the standard road meter, for an operating speed of 40 mph. In order to follow the development of the standard road meter over a period of time and to ensure its flexibility, we selected checking sections on concrete pavement that was likely to remain practically unchanged over the next few years and on which riding conditions remained very good (varied as little as possible). Figure 7 shows

Figure 6. Correlation of Σ-counts for road meters 1 and 2.

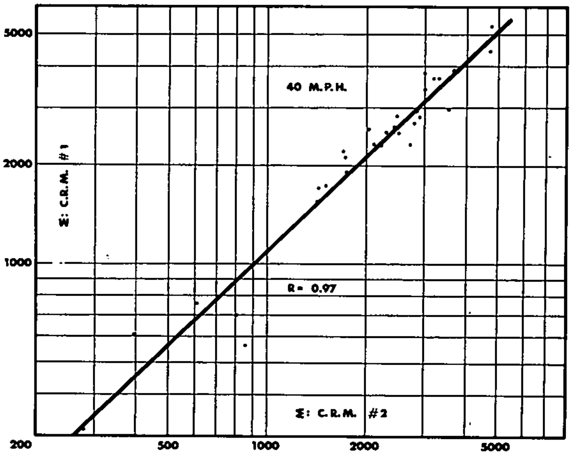


Figure 7. Road meter performance.

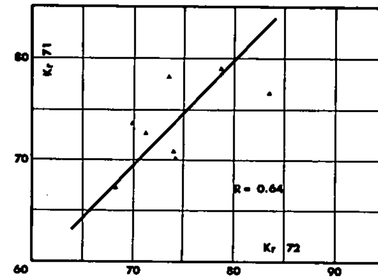


Figure 8. Theoretical relation between RCI and K_r.

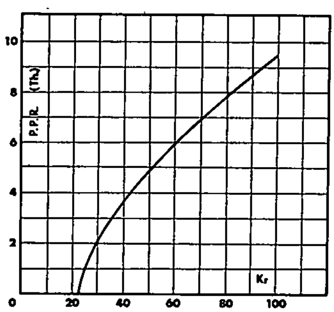
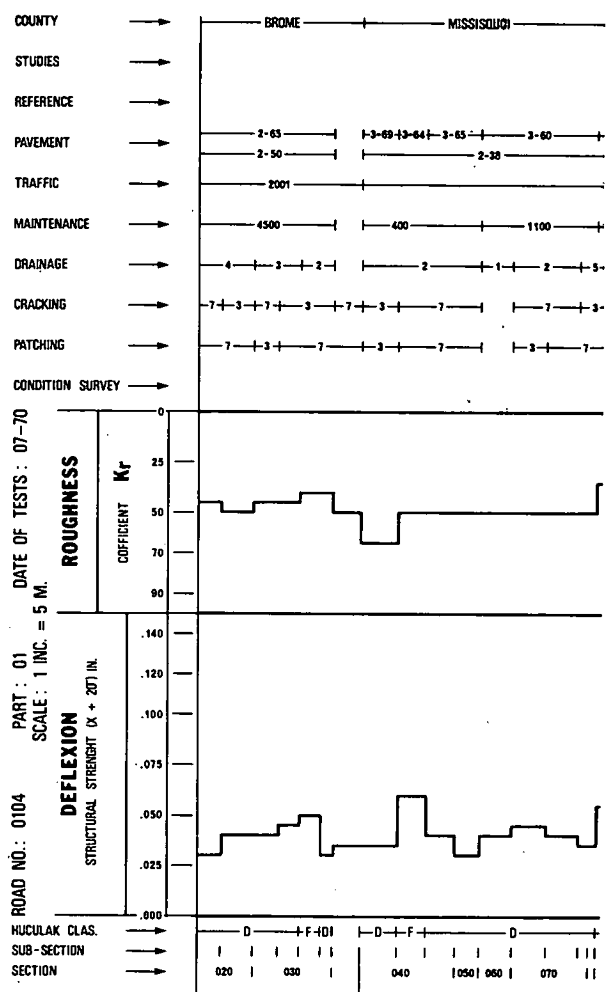


Figure 9. Road diagram.



the standard road meter's performance since 1971. Although these sections are few, there is a marked trend toward a 45-deg line, which shows that road meter readings in 1972 were substantially the same as for 1971. With more points, the line of correlation would be more precise.

K_r-COEFFICIENT IN TERMS OF RCI

In order to demonstrate the similarity between the RCI concept and the value of K_r, a theoretical relation has been established according to the following criteria (Fig. 8):

1. On ideal pavement, RCI = 10;
2. If only one meter is used, K_r = 100;
3. Pavement would be ideal if no reading was recorded;
4. When K_r = 100, it cannot be said that RCI = 10;
5. RCI can always be fixed at 9.5 when K_r = 100;
6. If all the meters record the same reading, K_r = 22, and the road is in very bad condition with an RCI of 0.0; and
7. If each meter (2 through 8) gives half the reading of the preceding one, K_r = 51, and the surface is passable with an RCI of 5.0.

In this way the curve shown in Figure 8 has been drawn, which represents a theoretical relation between K_r and RCI.

ROAD DIAGRAM

Figure 9 is an example of a road diagram that condenses the principal data for the pavement. In addition to the diagram, an overall table will be given for the road network, and a summary of data will be provided for each road in each county in Quebec. These tables will be sent to the planning staff and the road engineers. The road diagram and the tables will be prepared on request once a year and will help the engineers in planning their road maintenance work for the coming year.

SUMMARY

With the help of multiple regression, indications will be used for each of the following indexes: deflection, roughness, drainage, patching, and cracking. The combined indications for each road section that is inventoried will be used in drawing up a list of structural priorities for the entire road network, with criteria given and verified for each variable. Mathematical equations will be used to define the indexes of deflection and roughness in relation to the others. This process will be computer-operated and will also be of help to us in refining our criteria for performance and design.

The initial process should be completed within the next few years, taking account of the following points: improvement of measuring devices, time-stable calibration system, establishment of roughness data survey within a continuing road mass inventory, refinement of data processing, roughness criteria as a guide to road maintenance and as a means for checking pavement condition, a flexible system for adding and assessing other possible data, and constant circulation of information from the data bank with information feedback from the road engineers.

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USE OF THE PCA ROAD METER IN THE WASHINGTON PAVEMENT CONDITION SURVEY SYSTEM

R. V. LeClerc, T. R. Marshall, and K. W. Anderson

In 1965 Washington State developed a new system for evaluating the condition of pavements for use in programming future reconstruction or rehabilitation. Basically, the method involves the cataloging of the extent and severity of pavement distresses and an evaluation of the ridability of the pavement. Each of the 4 statewide surveys that have been performed to date have been by teams that were trained in the elements of the system and then were "calibrated" to achieve a uniformity of ratings.

Although this method has served to provide comparative rankings of pavements that were generally accepted by all concerned, it was believed that more accurate ratings would result if the subjective "seat-of-the-pants" ride rating could be supported by a more objective method of pavement smoothness evaluation. A possible answer to this problem was presented by the introduction of the PCA road meter (1).

The PCA road meter, developed by Brokaw, is basically an electrical-mechanical instrument for measuring a vehicle's reaction to the roadway while traversing the pavement at speeds up to 65 mph. The element of measurement is the vertical deviation of the rear axle from the body of the vehicle as the rear wheel and axle assembly is activated by pavement roughness. In the development of this apparatus, it was calibrated against the CHLOE profilometer, which was used in determining the present serviceability of pavement test sections in the AASHO Road Test. This calibration provided a means for converting the road meter results to a present serviceability index (PSI) for any pavement tested.

In 1968 a road meter was lent to the Materials Laboratory for familiarization and evaluation. The instrument was installed in a 1968 Ford Custom sedan. As experience was gained with the characteristics of the instrument, its potential in our pavement condition rating system was recognized, and the decision was made to purchase a PCA road meter for inventory use. However, the original manufacturer of the instrument had ceased production, but it was soon learned that a California manufacturer was working on a modified version of the PCA road meter.

THE MODIFIED PCA ROAD METER

In our use of the original road meter, we recognized several shortcomings in the instrument's performance with regard to inventory work. To overcome these deficiencies, we discussed several improvements with the California manufacturer, which were included in the specifications for the instrument that was ordered. The modifications by which more efficient use of the road meter would be obtained included the following:

1. Dual sets of counters—In the Washington Pavement Condition Rating System (WPCRS), pavement segments that range in length from 0.1 to 1 mile are rated. With one bank of counters, it would be necessary to stop at the end of each segment, record the results from the counters, reset them, and either back up sufficiently to reach the next rating section at test speed or rate alternate test sections and make duplicate

passes over the pavement. Dual sets of counters eliminated the need for this duplication.

2. Accurate odometers coupled to the counters—Because the derived readings from the road meter are counts per mile, the accuracy of the results are improved by the use of electrical odometers reading to 0.01 mile, which are connected through one switch to each bank of counters.

3. Automatic remote zeroing—The original version of the PCA road meter required that the test vehicle be stopped on the level and out of gear when the meter was zeroed. The zero point shifts on the contact plate with any change in the load distribution in the test vehicle. One consistent cause of shifting during testing is the amount of gas in the gas tank. With automatic remote zeroing through a small servomotor, it is possible to zero the instrument while the vehicle is in motion by observing the indicator lights on the counter console.

4. Multiple readout capability—With the dual banks of counters, switching arrangements were provided to permit counting on either bank alone, both banks simultaneously, or the accumulation of all counts to one side of zero on one bank and all counts to the opposite side of zero on the other bank. This last capability was included to see if different causes of pavement roughness could be distinguished by the type of reaction imparted to the test vehicle.

The manufacturer of the instrument also had made several modifications to the original PCA road meter, which he had been including in instruments made for other purchasers. The most significant of these were in the translator contact assembly and the linkage between the axle housing and the translator.

The translator assembly was moved into the trunk of the test vehicle and mounted vertically. The contact plates were made for easy replacement when the contact ribbons become worn enough to cause a significant change in contact spacing.

The connecting linkage was made from a solid rod as compared to the chain used on the original model. This resulted in a much more positive response by the instrument to any roadway roughness; i.e., reaction time of the chain-spring arrangement on the original meter permitted a certain amount of relaxation on any sudden axle movement, which the solid connection does not allow.

CALIBRATION OF MODIFIED ROAD METER

The modified PCA road meter was received from the manufacturer in August 1970 and installed in the same 1968 Ford Custom sedan as used for the original road meter.

The first study with the new meter was an attempt to correlate test results between the old and new meters by testing a number of miles of roadway that had been tested with the old meter. This soon revealed that the characteristics of the 2 instruments were sufficiently different that direct correlation was not practical. Efforts were then concentrated on familiarization and evaluation of the new meter.

The road meter is affected by many variables, of which only 3 have significant influence on test results for discussion in this report. They are wind velocity, vehicle speed, and vehicle suspension changes.

Initial calibration experiments with the new road meter pointed out the need for alterations to the vehicle's suspension to eliminate excessive vibration and sidesway. The situation was remedied by the installation of new heavy-duty shock absorbers on all 4 wheels and a complete front-end alignment that included wheel balancing. Steel-belted radial tires were also installed for improved uniformity. A number of measurements were repeated on sections that had previously been measured prior to suspension modifications. The results are shown in Figure 1. The scatter of results and correspondingly low coefficient of correlation are indicative of the influence of the running gear on the vehicle. The measurements were made on both asphalt concrete (AC) and portland cement concrete (PCC) pavements having a range of roughness characteristics.

The next variable investigated was the effect of wind. A number of sections of roadway were repeatedly measured with the road meter under different wind conditions and the results compared. Three sections of road were chosen as test sites: 2 on Interstate 5 and 1 on a county road in the Olympia area. The Interstate sections were essentially north-south routes having less than average roughness, and the county road section was essentially an east-west route having more than average roughness. Wind measurements were made prior to each run with a hand-held floating-ball-type wind gauge. Wind conditions varied from zero wind to a steady 10- to 12-mph wind with gusts to 25 mph. It was concluded from the results that a steady wind has little effect on the count rate, but that a gusty wind increases the count rate in proportion to the number and magnitude of the gusts. Isolation of the exact count-rate increase with wind speed was not attempted because of the time and variables involved in such a study, but it may be sufficient to recommend that road meter measurements be ceased when the test vehicle is perceptively rocked back and forth by the wind during testing.

The remaining variable examined was vehicle speed. A series of readings was taken at 30, 40, and 50 mph on the same mile sections of road, and the average count rates for each mile at each speed were compared. The route included various pavement types and varied roughness. The results indicate a general decrease in counts as the speed of the test decreased. A greater count decrease was noted in going from 50 mph to 40 mph than from 40 mph to 30 mph. The equation for the relation between counts per mile at 50 mph and counts per mile at 40 mph is $C_{50} = 1.15\ C_{40} + 36$, where C_{50} is the count at 50 mph and C_{40} is the count at 40 mph. A similar equation written for 30 mph is $C_{50} = 1.17\ C_{30} + 75$, where C_{30} is the count at 30 mph and C_{50} is the count at 50 mph. These equations appear to be valid regardless of pavement type or roughness.

In summary, the following conclusions can be stated based on our research:

1. A change in the suspension of the test vehicle can have a large effect on the count rate of the road meter;
2. The counts per mile of any particular section of roadway decrease in a linear function as the speed of the test vehicle decreases; and
3. The counts per mile of a particular section of roadway will be influenced by wind gusts that strike the vehicle during the test, and testing should not be attempted under conditions of gusty or strong winds.

COMPARISON OF ROAD METER AND SUBJECTIVE RIDE RATINGS

In the development of the original PCA road meter, the instrument was calibrated against the CHLOE profilometer (6, 10, 14), and therefrom a relation between count and present serviceability was developed. To go back a little further, the CHLOE-present serviceability relation was developed by comparing the subjective evaluations by a panel of raters with the results obtained with the CHLOE profilometer on the same sections of pavement.

As stated previously, an integral part of the WPCRS is the subjective ride rating. During the 1971 WPCRS survey, all pavement smoothness evaluations were made both by subjective ride ratings and with the modified road meter. These dual ratings furnished an excellent sample for comparison and analysis and, in effect, provided a basis for standardization quite similar to that used to calibrate the original PCA road meter.

In our analysis, 10,082 individual ratings were reviewed; from these it was decided that, with the large number of observations, good representation could be obtained for the AC pavements by including only the rated segments of 1 mile in length. Because of the fewer number of observations available, the rated segments of PCC pavements of ½ mile or more in length were included. As any rated section is shortened, the accuracy of rating is subject to a higher percentage error, both in the subjective ride rating and the road meter count.

After evaluating the road meter for effects from wind, speed, and vehicle suspension system, we repeatedly traversed a number of sections of pavement to determine the variations within the instrument. Typical results are given in Table 1. These were run over a period of time after the test vehicle characteristics were stabilized with new heavy-duty shock absorbers, radial tires, wheel balancing, and so forth.

Figure 1. Comparison of old and new shock absorbers.

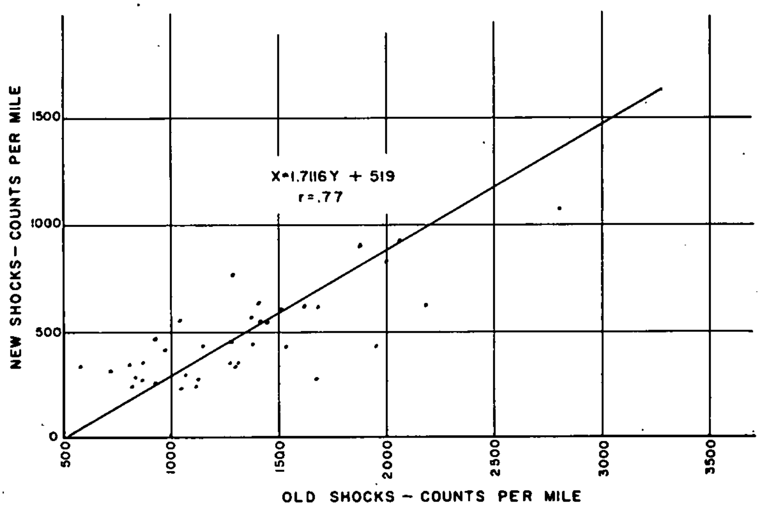

Table 1. Road meter evaluation.

Test Location	Number of Observations	Road Meter Count (average)	Standard Deviation	Coefficient of Variation (percent)
1	10	219	60	27
2	10	272	90	33
3	10	320	93	29
4	10	333	88	26
5	5	1,630	161	10
6	5	815	129	16
7	5	1,207	156	13
8	4	721	48	7
9	16	2,612	275	10
10	16	2,909	283	10
11	16	2,710	298	11
12	16	2,632	257	10
13	16	275	69	25
14	16	294	101	34
15	15	270	72	27
16	16	224	50	22

Table 2. Analysis of bituminous pavements.

Ride Rating	Number of Observations	Road Meter Count			Standard Deviation	Coefficient of Variation (percent)
		Average	Low	High		
1	0	–	–	–	–	–
2	132	427	115	1,133	181	42
3	241	574	179	1,508	235	42
4	663	760	165	2,194	332	44
5	1,081	1,299	253	4,262	590	45
6	410	1,850	361	5,087	918	50
7	208	2,576	544	5,518	1,140	44
8	19	4,187	2,739	6,601	1,158	28
9	0	–	–	–	–	–

A direct comparison of ride ratings with road meter counts was used to develop a well-defined logarithmic curve from the overall averages, but rather wide ranges of values were noted with resultant high standard deviations. The results of these comparisons are given in Table 2 for the AC pavements and Table 3 for the PCC pavements.

In comparing the results given in Tables 1, 2, and 3, it is necessary to establish the road meter as the standard for measuring the ridability of a pavement. The analysis shows this to be reasonable in that the standard deviations for the road meter itself are much lower than the standard deviations developed from the comparisons of subjective ride ratings with road meter counts during the 1971 WPCRS. This is shown in Figure 2.

Another factor that supports this approach is revealed when subjective ride ratings are evaluated on a day-to-day basis and when long stretches of apparently equal roadway are rated. This appears to be related to what might be labeled the psychology of the rater's task in that a level of rating is established in his mind for a particular section of roadway, and little or no change in ride rating is made until triggered by a very obvious change such as pavement type. Repetitious testing by the road meter on some of these sections has shown that there is often a measurable difference in the mile-by-mile smoothness of the section that is sufficiently significant to have an effect on the ride score.

The comparisons between ride rating and road meter values were reviewed to determine the possible effect of functional class of highway on the level of ratings. It should be mentioned that, within the parameters for length of rating sections included in this analysis, there were no ride ratings at the 0, 1, or 9 levels. There were very few ratings of 2 and 8, which would tend to make these results somewhat suspect, but the ratings were not out of line with the other data and therefore were included. In effect, then, the potential scale of 10 was reduced to 7. In ratings 2 through 7, the ride ratings with the lowest average road meter count were on the Interstate System. There were no ratings of 8 on the Interstate System. Conversely, the ride ratings with the highest average road meter counts were found on the lowest functional class system. This could indicate that the rating teams are influenced by the functional class of highway being rated, i.e., being more critical in their ride ratings of the higher class highways.

A similar analysis was made to see if a variation pattern could be developed among rating teams. There were basically four 2-man teams involved in the 1971 survey with very little shift of personnel. In comparing the 4 teams, it was possible to develop 25 relations, with all 4 teams involved in 15, 3 teams involved in 4, and 2 teams involved in 6. Of the 25 relations, the ride ratings of team 1 had the lowest average road meter count in all 15 relations, and the remaining comparisons of lowest count with ride ratings were distributed among teams 2, 3, and 4 in the ratio of 3, 5, and 2 respectively. The highest road meter count per ride rating was noted 12 times for team 4, 8 times for team 2, 3 times for team 3, and twice for team 1. These relations do indicate a pattern of variation among rating teams. Although in most instances the variations are within the standard deviation for the rating being compared, such variation does indicate that the subjective ride rating should be replaced by the road meter.

DEVELOPMENT OF FORMULAS

From these background data were developed the means of incorporating the road meter results into the WPCRS with 2 principal objectives in mind. First, the transfer should be done with the highest degree of continuity possible; i.e., the new overall pavement ratings resulting from the use of the road meter should be capable of comparison with previous readings with minimum departure in the normal point drop from the past biennial ratings of the individual pavements. Second, the scale or formula developed should result in an expanded rating scale using the full range of the relative ride rating from 0 through 9.

As can be seen, these 2 objectives are somewhat opposed and can only be resolved by compromise. In reviewing the overall rating results, such a compromise can be

Table 3. Analysis of PCC pavements.

Ride Rating	Number of Observations	Road Meter Count Average	Road Meter Count Low	Road Meter Count High	Standard Deviation	Coefficient of Variation (percent)
1	0	–	–	–	–	–
2	0	–	–	–	–	–
3	31	618	315	1,083	224	36
4	129	693	209	1,615	287	41
5	143	1,025	350	3,924	552	54
6	43	1,549	538	2,678	627	41
7	18	3,532	1,432	8,090	1,738	49
8	1	3,692	–	–	–	–
9	0	–	–	–	–	–

Figure 2. Standard deviation versus road meter count.

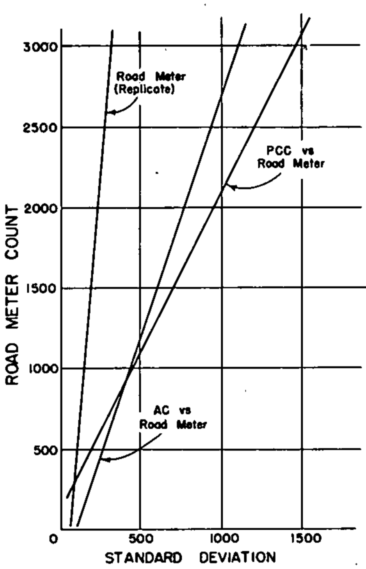

Figure 3. Relation of ride rating scores and road meter counts.

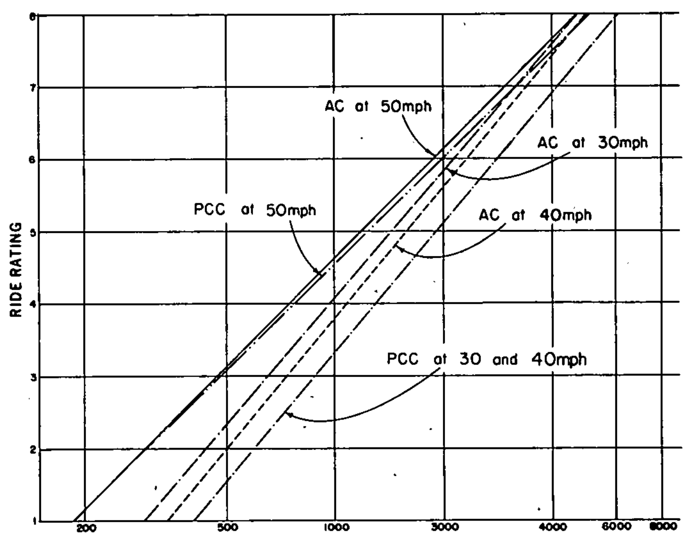

Table 4. Conversion of road meter counts to ride rating scores.

Type of Pavement	Test Speed (mph)	Common Logarithm A	Common Logarithm B	Natural Logarithm A	Natural Logarithm B
Bituminous	50	2.0833	0.1983	4.7970	0.4567
Bituminous	40	2.3717	0.1663	5.4609	0.3830
Bituminous	30	2.3008	0.1714	5.2978	0.3947
PCC	50	2.0648	0.2061	4.7543	0.4746
PCC	30 and 40	2.4373	0.1689	5.6120	0.3889

Note: $R_s = \frac{\log(RM) - A}{B}$, where R_s = ride score, RM = road meter counts per mile, and A and B = constants related to pavement type and test speed.

effected that will have little influence on a large percentage of the state's highway mileage and that will accommodate the variations inherent in the present method.

The ride-rating-versus-road-meter-count relation is of a logarithmic nature. By regression analysis, a series of formulas was developed for both bituminous and PCC pavements at the 3 test speeds used in the road meter inventory. Curves were plotted from these formulas, and, by applying the full range of road meter counts obtained in the survey, the formulas were modified such that the potential for using the full range of ride scores was introduced.

This procedure produced rational curves for all combinations of pavement types and test speeds except for PCC pavements tested at 30 mph. There were only 43 observations for this combination, and they were centralized in only 4 ride ratings, 4 through 7. These data are insufficient for a meaningful analysis, and, because such a small percentage of pavements is involved, it is recommended that the curve developed from PCC pavements tested at 40 mph also be used for 30 mph.

The formulas for the various combinations are given in Table 4. Expressions are given in both common and natural logarithms. The curves that were developed are shown in Figure 3. The ride score (R_s) as determined by these equations is comparable to the ride as scored by the rating teams and enters into the formula for calculating the final rating in the same manner; i.e., $R_R = \sqrt{G_R \times G_D}$, R_R = final rating, G_R = ride rating = $100 - 10 \times R_s$, and G_D = defect rating.

CONCLUSIONS AND RECOMMENDATIONS

Experience with the PCA road meter, both the original model and the modified version, has confirmed the value of this instrument in providing an objective measure of the smoothness, or ridability, of a pavement. Comparisons of results of subjective evaluations with road meter testing show the coefficients of variation with the road meter to be significantly lower.

From attempts at comparing results obtained by the original version with those by the modified model of the PCA road meter, it is concluded that there are response characteristics for each instrument that make straight-line correlation questionable at best. Rather than attempting a correlation of the modified version with a CHLOE profilometer to provide a relation between meter count and present serviceability index on a scale from 1 to 5, we correlated the results of a statewide survey using the road meter with subjective ride ratings by teams of trained raters as determined during the course of a normal condition survey. The results thus obtained were used to develop formulas that could be used for integrating road meter results into the pavement condition rating system. These formulas will also expand the ride rating portion of the system to include a wider range of values than previously obtained by the subjective ride ratings.

It is recommended that the subjective ride ratings in the present method for evaluating pavements be replaced by the use of the modified PCA road meter. It is recognized that our experience to date is based on one instrument in one vehicle and that, undoubtedly, when it becomes necessary to change vehicles, a correlation study will be required. This may result in a modification of formulas, but the improved accuracy of ratings more than compensates for this possibility.

In the operation of road meters, testing should not be done during periods of strong or gusty wind. Careful attention must be given to wheel balance, tire pressure, and suspension system. Whenever a change is made in one or more of these areas, the instrument should be recalibrated against established standards. When more than one road meter becomes available, one instrument can be established as standard. Also, selected sections of roadway can be established as temporary standards, but it must be remembered that roughness in roadway sections will increase with time and, in some cases, will change daily, or even hourly, with varying weather conditions.

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PART VI

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