NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE 167

MEASUREMENTS, SPECIFICATIONS, AND ACHIEVEMENT OF SMOOTHNESS FOR PAVEMENT CONSTRUCTION

TRANSPORTATION RESEARCH BOARD
National Research Council

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. NOVEMBER 1990

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP SYNTHESIS 167

Project 20-5 FY 1987 (Topic 19-12)
ISSN 0547-5570
ISBN 0-309-04915-6
Library of Congress Catalog Card No. 90-71380

Price $8.00

Subject Areas
Pavement Design and Performance
Construction

Mode
Highway Transportation

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration of the U.S. Department of Transportation.

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Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to construction engineers, pavement designers, contractors, and others interested in construction of new highway pavements with smooth surfaces. Information is provided on the various devices and specifications that are being used to obtain smooth pavements.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

The public rates a pavement primarily on its smooth-riding characteristics and highway agencies recognize that constructing smooth pavements results in fewer problems later and lower annual maintenance costs. This report of the Transportation Research Board describes the devices and specifications that highway agencies use to ensure that newly constructed pavements will provide a smooth ride.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

ACKNOWLEDGMENTS

This synthesis was completed by the Transportation Research Board under the supervision of Robert E. Skinner, Jr., Director for Special Projects. The Principal Investigator responsible for conduct of the synthesis was Herbert A. Pennock, Special Projects Engineer. This synthesis was edited by Judith Klein.

Special appreciation is expressed to James H. Woodstrom, Carmichael, California, who was responsible for the collection of the data and the preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of David O. Cox, Highway Engineer, Construction and Maintenance Division, Federal Highway Administration; Alfred Donofrio, Chief, Materials and Research, Delaware Department of Transportation; Rudolph R. Hegmon, Research Mechanical Engineer, Office of Engineering and Highway Operations Research and Development, Federal Highway Administration; William D. O. Paterson, Senior Highway Engineer, Transportation Division, Policy Planning and Research Office, World Bank; Rolands L. Rizenbergs, Pavement Management Engineer, Kentucky Transportation Cabinet, Department of Highways, Division of Specialized Programs; James C. Wambold, Director, Vehicle/Surface Interaction and Safety and Professor of Mechanical Engineering, Pennsylvania Transportation Institute, Pennsylvania State University; and John C. Wasley, Highway Engineer, Office of Implementation, Federal Highway Administration.

George W. Ring, Engineer of Design, Transportation Research Board, assisted the NCHRP Project 20-5 Staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

MEASUREMENTS, SPECIFICATIONS, AND ACHIEVEMENT OF SMOOTHNESS FOR PAVEMENT CONSTRUCTION

SUMMARY

The concern about the smoothness of highway surfaces precedes the development of motorized vehicles. In the early days, the simple straightedge was used as the sole indicator of smoothness. But even before the turn of the century, efforts were directed at developing improved devices for smoothness evaluation. From 1900 to near midcentury, numerous devices of increasing complexity were invented. These were primarily mechanical devices with elaborate multi-wheeled support systems. Advances in several technological fields have now been applied to smoothness-measuring equipment, resulting in the incorporation of electrical circuitry, electronics, ultrasonics, lasers, and computerization.

Although the early devices were primarily of concern to the practicing engineer, the advent of test road construction brought the research engineer onto the scene. Many devices were developed in connection with specific research efforts. The automotive industry became interested because of the effect that certain types of pavement had on motor vehicles. In recent years highway managers have recognized that the public rates a highway primarily on its riding characteristic. Thus it is necessary to program an increasing amount of highway funds to address the issue of pavement smoothness on a system-wide basis.

As a consequence, several smoothness-measuring devices have been developed and are in current use. The fundamentals of operation, cost, and appropriateness to address a specific need vary considerably. Certain devices are far better suited than others to the purpose of controlling the smoothness of newly constructed pavements. Therefore, it is important for those concerned with obtaining smoothness in construction to be aware of the equipment best suited for that purpose and the relation of that equipment to the entire spectrum of smoothness-measuring devices.

Smoothness-measuring equipment currently used in new pavement construction includes straightedges (static and rolling), profilographs, response-type road-roughness-measuring systems, and inertial profilometers. All agencies use a straightedge—a few as the sole approach to smoothness control, but most as an adjunct to other equipment. The type of instrument receiving increased application is the profilograph, either the California or Rainhart type. These devices are similar in that they portray graphically certain characteristics of pavement smoothness, are relatively simple mechanical devices, can be used on new concrete pavement surfaces soon after construction, are low-cost/low-maintenance devices, and provide information that is readily acceptable by specifying agencies and the construction industry. Profilographs provide an analog trace to which specification tolerances are applied. The traces can be used to locate specific pavement features in the field. The primary disadvantages with this type of instrument are the slow speed of operation (3 mph) and the time required for evaluating the profiles, although the latter item has been addressed by computerized models that are now available. Other disadvantages include the exaggeration and suppression of parts of the surface wavelength spectrum, the occasional

exclusion by the blanking band of surface irregularities that may be of importance, and a mediocre correlation to other reference roughness standards.

Other devices being used in evaluating smoothness of new construction, including response-type road-roughness-measuring systems and inertial profilometers, are used considerably less often than profilographs for a variety of reasons. They are not able to be used on concrete pavements for a considerable time after paving (i.e., until the concrete gains sufficient strength), they don't allow ready identification or location of pavement surface aberrations, and, in some cases, they are very costly items. However, they can operate at high speeds; thus a considerable amount of data can be obtained at a lower cost. Also, the smoothness statistic is achieved with little or no manual processing. High-speed equipment has its greatest application in entire highway system assessment, research applications, and for calibration purposes.

Numerous research efforts as well as symposia and workshops have been directed toward providing information on the use of smoothness-measuring equipment. Although there are vast differences in equipment types and their ultimate application, the relationships of several smoothness indexes have been compared and are reasonably well defined.

A survey of practices in use in the United States and Canada revealed that there is a wide diversity in the use of smoothness specifications and equipment. However, emphasis on smoothness by specifying agencies, together with strong support from the construction industry, has led to the attainment of increasingly smoother pavements.

CHAPTER ONE

INTRODUCTION

Highway engineers are concerned about many facets of quality with relation to the facilities for which they are responsible.

These facilities should provide economy in construction and service, be durable, provide for safe movement of traffic, and provide a smooth, comfortable ride for the user. Numerous approaches have been developed for evaluating pavement smoothness, some in connection with research efforts on test roads, some for pavement management systems, and some for defining standards of new construction. It has become evident that a smoothness-measuring device suitable for one purpose is not necessarily appropriate for another. The evolution of equipment and methods for evaluating construction smoothness has thus taken many forms that are being used with varying degrees of success, in the view of the highway engineer and the construction industry.

Levels of smoothness being achieved on new construction are known to vary widely among state agencies. This is attributed to the variety of construction equipment being used, differences in contractor effectiveness, and the range of specifications used by the various states. The construction industry, which usually operates on a regional basis, finds frustration in having to deal with the numerous approaches, all of which, presumably, are designed to achieve the same end.

The primary purpose of this synthesis is to review current practices being used to address the subject of pavement smoothness in new construction with respect to: (a) methods and equipment for measurement, (b) costs and operating principles of such equipment, (c) advantages and disadvantages of each type, (d) construction specifications, (e) effectiveness in complying with specifications, and (f) levels of smoothness being achieved.

HISTORICAL REVIEW

In 1960 Hveem (*1*) presented some interesting historical information on early devices for recording and evaluating pavement roughness. According to Hveem, the first device for measuring road roughness was invented before 1900 and was called a "Viagraph":

> It is said to be the invention of a J. Brown, an engineer of Belfast, Ireland, and is described as being "a straight-edge, twelve feet long and nine inches wide, applied continuously to the road surface, along which it is drawn." This early Viagraph contained "an apparatus for recording on paper a profile of the road surface tested, and the sum of unevenness is indicated by a numerical index. . . ." Brown goes on to discuss the gravel and macadam-type road surfaces that were characteristic of his time (in the years prior to 1900) and concluded that steam rollers offer a distinct advantage in producing a regular and smooth surface. He shows some "autograph records" of macadamized surfaces and states that ". . .a standard of fitness or smoothness of 15-ft of unevenness, or variation from a plane, per mile of road might be safely adopted."

Brown's device furnished information somewhat similar to profilograph units of today—except that he measured "roughness" in feet instead of inches per mile.

Other devices described by Hveem (*1*) include:

- A profilometer used on the Bates test road in Illinois in 1922. This was an impressive instrument consisting of a frame supported by 32 bicycle wheels mounted in tandem, the overall length of which was about 50 ft. This model was reportedly not too successful and was quite unwieldy and difficult to handle.
- A device developed by the state of New York in the 1920s and referred to as the "Via-Log." This device was mounted in an automobile and it provided an analog recording of the differential movements of the front axle with reference to the frame of the car. Modifications of this device were used in California for many years and by other states and agencies.
- A device mounted on a trailer developed by the Bureau of Public Roads in 1941:

> In principle, this device is similar to those mounted in an automobile except that carefully selected springs, means for damping, and the weight of the unit could be standardized and thus produce an instrument that is not subject to the variations such as exist between automobiles of different size and make.

The device was widely used by several states and other agencies.

- Another device referred to as a "Viagraph," designed by the Los Angeles County Road Department and reported on in 1939. It was a rolling straightedge 10 ft long with a profile wheel at the midpoint. The three-wheeled unit had an elaborate recording mechanism operated from the profile wheel that indicated deviations from the datum established by the front and rear supporting wheels.
- A profiling device produced by the Illinois Division of Highways and referred to as the "Mailander Wave Measurer." This was a 16-wheel unit that established a datum plane from which deviations were measured.
- A device described as:

> A large unit equipped with marking devices [that would] delineate by a series of stripes all of the depressions or low spots on an old pavement. These markings serve as a guide to the repair crews . . .to cover the markings and hence improve the riding quality by leveling the surface.

This device was developed in France by the Central Laboratory of Bridges and Roads.

- A 16-wheel unit developed by the British Road Research Laboratory. This was quite similar in principle to the Mailander unit from Illinois.
- A "profilometer" developed for the AASHO test road in the 1950s. This unit embodied a new principle of measurement and consisted essentially of a trailer that is towed over the pavement by an instrument van at a speed of approximately 5 mph. Two wheels located only 9 in. apart determine the slope of the pavement with respect to a datum established by a rather long tongue of the trailer. Slope was continuously recorded for analyzing at a later date. This unit was a forerunner of the CHLOE Profilometer, which operates on the same principle.

From his investigation and research, Hveem ultimately developed what has come to be known as the "California"-type profilograph, which will be discussed in some detail later in this synthesis.

The above provides evidence of the broad interest in evaluating pavement smoothness that existed before 1960. Since that time interest has broadened considerably, fueled in part by the construction of the Interstate Highway System, but even more so by the technological advances in instrumentation, electronics, lasers, and computers. More recently, the growing implementation of pavement management systems has focused attention on the need for high-speed profiling technology to be applied routinely to entire highway systems, although these devices are not usually used for construction control.

In the early years, the profile measurements were primarily of interest to the researcher and the construction engineer. The researcher needed a tool to measure the surface changes that occurred on test roads and in many instances on experimental pavements on the existing highway system. The construction engineer shared these interests but was more concerned with developing tests and specifications to assist in building a smoother highway. They worked together to address questions regarding the effects on pavement smoothness of new construction practices and new construction equipment. Typical questions were: What levels of smoothness could be obtained? What types of equipment and construction practices affected smoothness? Could smoother AC pavements result if layered construction was required? What is the effect of the use of vibratory compactors on smoothness, of higher or lower temperatures, and of varying laydown procedures? How did the smoothness of slipformed concrete pavements compare with that of the side-form methods?

As events progressed, the new applications for profiling instruments, together with a burgeoning technology, resulted in a certain amount of cross-application of available equipment. The best or most appropriate equipment was not always being used for the proper purpose. This is certainly understandable in view of the complexities and the costs involved in replacing existing equipment in times of rapid technological advances. As experience was gained, optimization of equipment was realized for specific applications. This synthesis will focus on the application of pavement-smoothness-measuring equipment in current use in highway construction.

BENEFITS OF SMOOTHER PAVEMENTS

Smooth pavements are important to highway users and contractors, as well as to the engineers, planners, and managers of highway systems. The first significant quantification that ride quality, as affected by road roughness, was a major aspect of highway performance was outlined by Carey and Irick (*2*) in road tests developed by the American Association of State Highway Officials (AASHO). They pointed out four fundamental uses of pavement-roughness measurements:

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

Wambold et al. (*3*) expanded this list to include:

- Specification of surface profile limits and rideability of new road construction.
- Evaluation of costs to improve the road.
- Prediction of loss of rideability in existing roads.
- Establishment of maintenance and replacement criteria.
- Correlation with vibrational response and fatigue damage in vehicles.
- Development of passenger comfort criteria.
- Evaluation of roughness effects on vehicle steering and braking.

Janoff et al. (*4*) point out that a number of authors have reported on the effect of road roughness on safety, vehicle behavior, vehicle braking, vehicle steering, vehicle ride, and fuel economy. The consensus appears to be that as the roughness increases, safety, vehicle behavior, fuel economy, etc. all decrease.

Zaniewski and Butler (*5*) reported on use-related depreciation expense from surface roughness changes based on a Brazilian study. In comparing adjustment factors for a serviceability index of 4.5 versus 3.5, a benefit in the form of reduction of user operating costs of 2 percent and 6 percent is indicated for passenger cars and trucks, respectively.

The 1986 "AASHTO Guide for Design of Pavement Structures" emphasizes the importance of pavement smoothness as indicated by the following (*6*):

> Because roughness is such an important consideration for the design of pavements, the change in roughness will control the life cycle of pavements. In this regard, the quality of construction will influence performance and the life cycle of the designed pavement. The initial pavement smoothness is an important design consideration. For example, the life cycle of a pavement initially constructed with a smoothness or PSI of 4.5 will have a significantly longer life cycle than one constructed to a PSI of 4.0. Thus, quality control in the construction of a pavement can have a beneficial impact on performance (life cycle).

Janoff (*7*) studied pavement performance data from Arizona and Pennsylvania. He found that there was a significant decrease in roughness after eight years if initial smoothness was increased. There was also decreased cracking after eight years. Maintenance data showed significant reductions in average annual maintenance costs for pavements that were smoother initially.

CHAPTER TWO

MEASURING EQUIPMENT, OPERATING PRINCIPLES, EVALUATION PROCEDURES, CALIBRATION, AND COST

Modern interest in road-roughness measurements is exemplified by the extensive literature that is available on the subject. Gatherings of representatives of agencies concerned with this subject have been held to determine and compare some of the performance characteristics of equipment in current use. These include the 1982 International Road Roughness Experiment held in Brazil (*8*), the Ann Arbor Road Profilometer Meeting, reported by Sayers and Gillespie (*9*), the Fort Collins Pavement Profile Measurement Seminar, reported by Donnelly et al. (*10*), and various symposia and workshops sponsored by the American Society for Testing and Materials (ASTM) and industry associations.

The International Road Roughness Experiment compared 11 major methods, including manual and dynamic profilometric devices, response-type devices, and subjective rating, on 49 test sites comprising asphalt, surface treatment, and unpaved roads. It was found that the differences between methods depended on their response characteristics, and that all could be compared when related to the absolute longitudinal profile of the wheeltrack. This led to the definition of the International Roughness Index (IRI) as a standard for calibration of all types of method, defined by a mathematical quarter-car simulation of the absolute profile (*11*). The IRI has recently been adopted by the Federal Highway Administration (FHWA) as a standard for reporting roughness, and it appears in ASTM standard E 1364 and others currently under preparation.

At the Ann Arbor meeting 12 profilometers of different types were operated over 27 test sites. In addition, manual rod and level profiles were taken on 10 of the sites. The profilometers used were all considered "high-tech" equipment in that most of them incorporated noncontact measuring systems, operated at highway speeds, and used computers for accumulating profile data. These types of instruments have received limited application in control of construction smoothness at the present time.

The Fort Collins seminar brought together a wider variety of pavement-smoothness-measuring devices, with a total of 20 being demonstrated. They ranged from the relatively simple, slow-moving profilographs capable of charting a longitudinal profile, to high-speed measuring equipment. The following devices were represented in this seminar:

- Calibration and Construction Control
  - Profilograph (Rainhart)
  - Profilograph (McCracken)
  - E.W. Face Dipstick
  - Ames Profilograph
- Response-Type Systems
  - Mays Ridemeter (one-car and two-trailer based)
  - Cox Roadmeter
  - B&K Accelerometer
- Accelerometer-Based Systems
  - Portable Universal Roughness Device (PURD)
  - Dynatest 5000 Roughness Distress Meter
  - Self-Calibrating Roughness Unit
  - Automatic Road Analyzer (ARAN)
- Noncontact Profile-Measuring Systems
  - K.J. Law M8300 Roughness Surveyor
  - Laser Road Surface Tester
  - K.J. Law 690 Digital Noncontact Profilometer
  - Pro Rut System
  - South Dakota Profilometer
  - Surface Dynamics Profilometer

This chapter discusses pavement-roughness-measuring equipment used in the United States, including the basic types as well as variations that have evolved in certain models. The discussion will include roughness-measuring equipment for the evaluation of newly constructed pavement surfacing that has either received widespread use or in which there is significant interest.

STRAIGHTEDGE

The principle of the straightedge is used in a variety of construction applications. At one time it was undoubtedly the only available tool to evaluate pavement smoothness. Its use remains nearly universal to this day, usually as a supplement to the more sophisticated forms of measurement but occasionally as the sole specified method of smoothness control. In addition to its application in the longitudinal direction, it is commonly used in evaluating evenness in the direction transverse to the highway alignment.

The straightedge is usually 8 to 16 ft long and is made of wood or metal. A wire or string stretched taut from the ends of a bow-shaped form is sometimes used. When it is placed on a pavement surface, variations in distance from the bottom of the straightedge to the pavement surface are readily observed and measurements of these variations can be made. Tolerances in the form of specification limits can thus be used to interpret smoothness.

This tool is very labor intensive for large projects; thus most applications are limited to the evaluation of localized areas. Considerable effort is required for the operator to make accurate evaluations of the pavement surface because work frequently must must be done in a kneeling position and fairly precise measurements must be made at the pavement surface. Although the straightedge is useful in defining local surface aberrations, accuracy diminishes as the wavelength of the bump increases beyond about one-half the length of the straightedge.

The primary advantages of the straightedge are its simplicity and low cost, less than $100.

ROLLING STRAIGHTEDGE

A rolling straightedge is merely a straightedge with a wheel (or wheels) under each end. Located at its midpoint is a third wheel, which also rides on the pavement surface. This wheel is linked to some form of indicator that shows deviation from the plane of the rolling straightedge. The indicator may show high or low spots by an arrow on the unit itself or such points may be indicated on the pavement surface by chalk marks or spray paint.

These devices have proved to be somewhat impractical for general use because of the slow speed of operation and their inability to provide adequate definition of pavement roughness.

PROFILOGRAPHS

Numerous models of profilographs have been used since about 1900. They consist of a rigid beam or frame with a system of support wheels that serve to establish a datum from which deviations can be evaluated. They are somewhat more sophisticated than the rolling straightedge because they create an analog record of surface deviations. A "profile" wheel is located at the midpoint of the unit and is attached to a strip chart recorder in order that variations in the vertical movement of the profile wheel from the established datum can be recorded. Two models have evolved and are being used widely at this time. These are the Rainhart Profilograph, sold by the Rainhart Co. of Austin, Texas, and the California Profilograph, developed by the California Department of Transportation (Caltrans).

There are several similarities between the Rainhart and California profilographs. The overall length of the Rainhart is 24 ft 9 in., compared with 25 ft for the beam portion of the California model. They both produce an analog trace to a true vertical scale and a horizontal scale of 1 in. = 25 ft. In addition, the Rainhart can produce a horizontal scale of 1 in. = 10 ft, if desired.

The recorders of both units are driven by linkage to the profile wheel. Thus, its diameter affects the accuracy of the horizontal scale of the profile trace. The calibration of either unit involves checking the horizontal scale by operating it over a known distance of several hundred feet and by checking the vertical movement of the recording pen by placing blocks of known thickness under the profile wheel.

The profile produced by both units is evaluated in a similar manner, using a plastic template with a blanking band and determining smoothness in terms of a "profile index" in inches per mile. The blanking band serves to define a tolerance that is built in to the evaluation process. It "blanks" out minor aberrations on the analog trace that is obtained so that excursions above and below this zone can be counted in arriving at an evaluation of smoothness. With the Rainhart unit a 0.1-in.-wide blanking band is normally used, whereas on the California profile a 0.2-in. band is used.

Both the Rainhart and California profilographs have the appealing feature of being able to be used on concrete pavement surfaces a few hours after placement. Profiling with these units is normally done on the day following placement, thus providing vital information to both contractor and agency at the earliest opportunity.

The operating principles of profilographs are straightforward and are readily understood by field personnel. The strip charts provide a means for precise location of pavement surface irregularities in the field and a permanent record as well.

The main disadvantage in the use of profilographs is the slow speed (3 mph) at which they operate and the time required in evaluating the chart to determine the profile index. Also, on rare occasions, certain pavement surface features can occur that are essentially blanked out by the "tolerance zone" provided by the blanking band. These are usually cyclic features that can be associated with some aspect of construction. At times these aberrations may have an adverse effect on the natural harmonics of certain vehicles using the road.

Detailed descriptions for operating profilographs and evaluating the profiles are given in the test procedures of individual user agencies and in ASTM Designation E 1274, "Standard Test Methods for Measuring Pavement Roughness Using a Profilograph."

Rainhart Profilograph

The Rainhart Profilograph was developed by the Rainhart Co. in conjunction with the Texas Highway Department (*12, 13*) in 1967.

Their studies served to establish the parameters under which the device was designed and constructed. These include:

- Twelve averaging wheels

> The results of the study of the number of wheels indicate 12 wheels are better than eight, up to a wave length of approximately 10 feet. . . .At wave lengths over 10 feet, very little difference in (optimum) values was noted.

- 24.75-ft length

> An approximate length of 25 to 30 feet was decided on because the studies showed that the roughness of interest would not be sensed by a shorter instrument. Cost and (in)convenience of a longer machine could not be justified with diminishing returns.

- Averaging wheels spaced 27 in. apart

> The study of the wheel positions indicates the value (to be optimum) for the even wheel spacing with the exception of one large deviation which is indicated at various wave lengths depending upon the profilograph length. . . .The longitudinal spacing of 2′-3″ was selected because this spacing was not a multiple of standard construction joints. . . .Any fully transverse but short bump is averaged in only one wheel at a time.

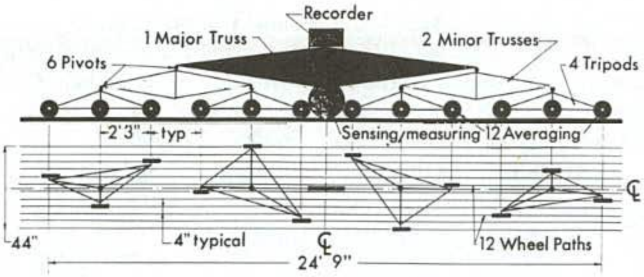

FIGURE 1 Rainhart Model 860 Profilograph.

The 12 wheels are arranged in four groups of three as shown in Figure 1. Each of the 12 wheels has its own longitudinal path, spaced at 4-in. intervals. The apex of each tripod is attached with a ball joint to the ends of two minor trusses. The two minor truss centers are pivoted on the ends of a major truss, which supports a recorder at its center. The datum thus established is influenced by 12 points on the pavement surface that are located within an area 24 ft 9 in. long by 44 in. wide. All surface deviations, whether bumps or dips, therefore become part of the datum from which profile wheel measurements are made.

The Rainhart Profilograph is a fully assembled unit that does not break down for transport to and from the job site. The recorder can be removed, but the rest of the unit remains intact. It is equipped with a trailer hitch for towing and also possesses two wheels (not shown in Figure 1) that are used for transport. The transport wheels are raised or lowered with respect to the truss system for the profiling or transporting mode. Upon arrival at the job site the unit can be disconnected from the towing vehicle and positioned in place on the pavement, ready for operation in about 5 min. It is propelled manually. Current cost is under $12,000.

California Profilograph

California's first profilograph was developed in the 1940s. It was a multiple-wheel unit on a 10-ft frame. The frame could be broken down for ready transportation in a pickup or the trunk of a sedan. After considerable application and study with the 10-ft model, it was concluded that an improved profilograph should have a longer frame, and a 25-ft length was arbitrarily selected.

The 25-ft dimension applies to the straightedge or beam length of the profilograph. Early models had an articulated wheel system that was 7 ft long and centered under each end point of the beam. The overall length of the unit was thus about 32 ft (Figure 2). Each wheel system consisted of a total of six wheels, four on

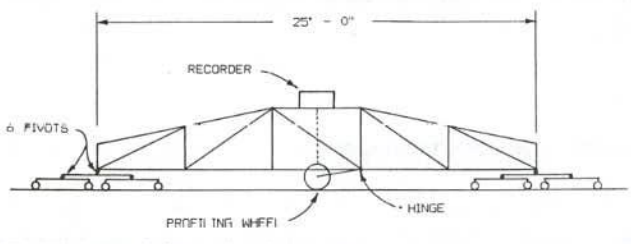

FIGURE 2 Schematic of California Profilograph with multiple-axle carriage wheel assembly.

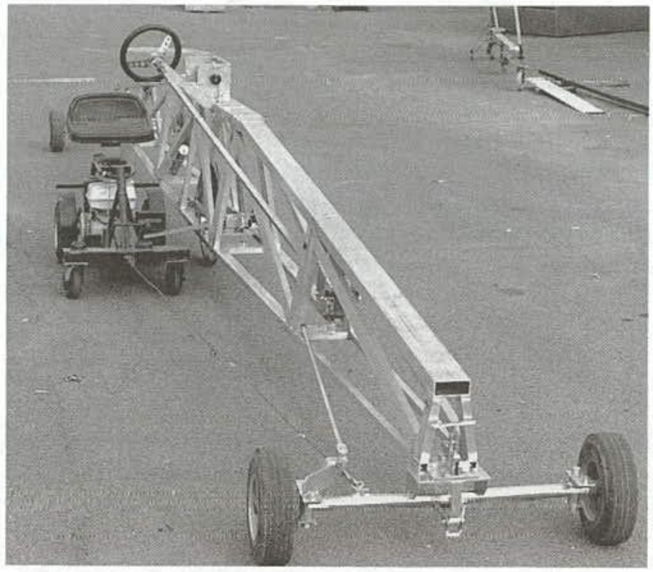

FIGURE 3 California Profilograph with single-axle carriage wheel assembly in current use by Caltrans.

the right side and two, serving somewhat as outriggers, on the left. In 1983 the need for the complex wheel support system was reexamined by California engineers, and a simplified wheel system with a single axle and two wheels was substituted. A comparison of profiles made with the two types of wheel assemblies showed only subtle differences in profile features and no difference in profile index; thus, the decision was made to convert to the new wheel system. All units in current use by the state of California are four-wheel models, such as the ones shown in Figures 3 and 4. Impetus for the change was recognition that the original wheel assembly design had proved to be a significant

FIGURE 4 Front-wheel assembly of profilograph in current use by Caltrans.

part of the total cost of the unit and was also vulnerable to rough usage that sometimes occurs on construction projects. Units in use by agencies other than California are, at the present time, predominantly of the early 12-wheel design configuration.

Although the basic parameters of the California Profilograph appear to be quite straightforward, a variety of materials and designs have been used in the creation of devices to achieve the completed product. Frames have been constructed of plywood, aluminum, and steel, and have comprised either three or five sections, except in a some rare instances when a one-piece 25-ft-long beam has served the purpose. Also, several innovative approaches have been used in the design of recorders. All of the devices that have been used by the state of California have been built by its own personnel at its laboratory shops. However, some unique designs have been developed by others. The current units that are available commercially will be discussed in some detail in the following sections.

The California Profilograph is normally viewed as a take-down unit, with the components being transported in a pickup or utility van. Upon arrival at the job site the components are laid out on the pavement surface and assembled using quick-connect features and toggles. Assembly time runs about 10 min. Propulsion can be provided either manually or, on some models, by a small motorized unit that attaches to the profilograph.

A voluminous amount of profilograph information was accumulated in the late 1950s. Items included: (a) the general levels of smoothness being obtained on various projects, (b) progressive loss of smoothness with time, (c) effects of various construction practices and equipment, and (d) curling and step-off characteristics of concrete pavements as affected by time, temperature, and other factors. It became apparent that if profiles could be evaluated and assigned some numerical values, smoothness specifications could be written around the use of this instrument. In 1957, the "profile index" concept was developed and, shortly thereafter, a method of assessment of maximum tolerances to be accepted for individual bumps. The instrument was first used as a specification control tool for concrete pavement construction in 1958 and first appeared in California Standard Specifications in January 1960.

Cox Model

James Cox and Sons, Inc. of Colfax, California, began manufacturing profilographs in 1973. The basic parameters of the California type were adhered to, but numerous innovations in design and construction were developed by Cox. In the mid 1980s electronics were incorporated into the recorder, resulting in the current version, which is marketed as Model CS 8200. According to the manufacturer (*14*):

> The CS 8200 is a micro computer based profile measuring device designed to measure roadway profiles and reduce profile data in accordance with test method California 526, 1978. The CS 8200 reduces the measured profile data and generates graphic reports containing the measured profile annotated with stationing, excursion information, and documentation points. Profilograms may be reduced to obtain profile index or high points or may do both simultaneously.

Figure 5 shows a sample of the annotated profilograph printout. The 0.2-in.-wide null or blanking band is centered upon a best fit line through all the points within the section being reduced (normally 528 ft). Also, the individual high points are located in accordance with preprogrammed parameters.

Figure 6 indicates the printout formats available with the CS 8200. The header report lists all the control and calibration parameters. The profile index report can be written at the end of each measurement segment, if desired. A summary report contains all of the data accumulated for a complete pass at a section of pavement.

The cost of the computerized Cox and Sons, Inc. Model CS 8200 is just under $24,000.

McCracken Model

The McCracken Concrete Pipe Machinery Co. of Sioux City, Iowa, is one of the current commercial manufacturers of the California Profilograph. It is constructed using a three-piece aluminum frame and complies with the guidelines stated in California Test Method No. 526. The current selling price is approximately $12,500 FOB the point of manufacture.

Ames Model

The Ames Model (Figure 7) is manufactured by Ames Profilograph of Ames, Iowa. It is designed to produce the same profile trace as other California units that have been mentioned, but it is considerably different in basic construction. The wheel assemblies are similar to those of other models in that an articulated system consisting of a total of six wheels is used to support each end of the device. Also, a profile wheel is located at the midpoint of its 25-ft length. Rather than being a truss type of framework with a recorder located directly over the profile wheel, the frame for the Ames device is a 2-in.-×-6-in. aluminum box beam. The recorder is located at the rear end of the unit, and a leverage system located inside of the box beam transmits vertical movements of the profile wheel back to the recorder. A larger-diameter wheel to provide power to drive the strip chart is located opposite the recorder. The operator propels this lightweight unit manually with a full view of the recorder and with linkage that can steer the forward wheels some 25 ft away.

The FHWA, Central Direct Federal Division conducted a study (*15*) in 1987 in which the Ames Profilograph was compared with two units of the more conventional design. These units were owned by the states of Arizona and California and had been manufactured by McCracken Concrete Pipe Machinery Co. and Caltrans, respectively. The traces produced by the Ames device were found to be "virtually identical to those produced by the two state profilographs."

The current cost of the Ames Profilograph is under $8000.

California Bridge Profilograph

This device (Figure 8) was developed by Caltrans in 1977. It is 12 ft long, operates on the same principle as the larger model, and is applied on bridge decks and bridge approach slabs. The profile trace is to a true vertical scale and 1 in. = 15 ft longitudi-

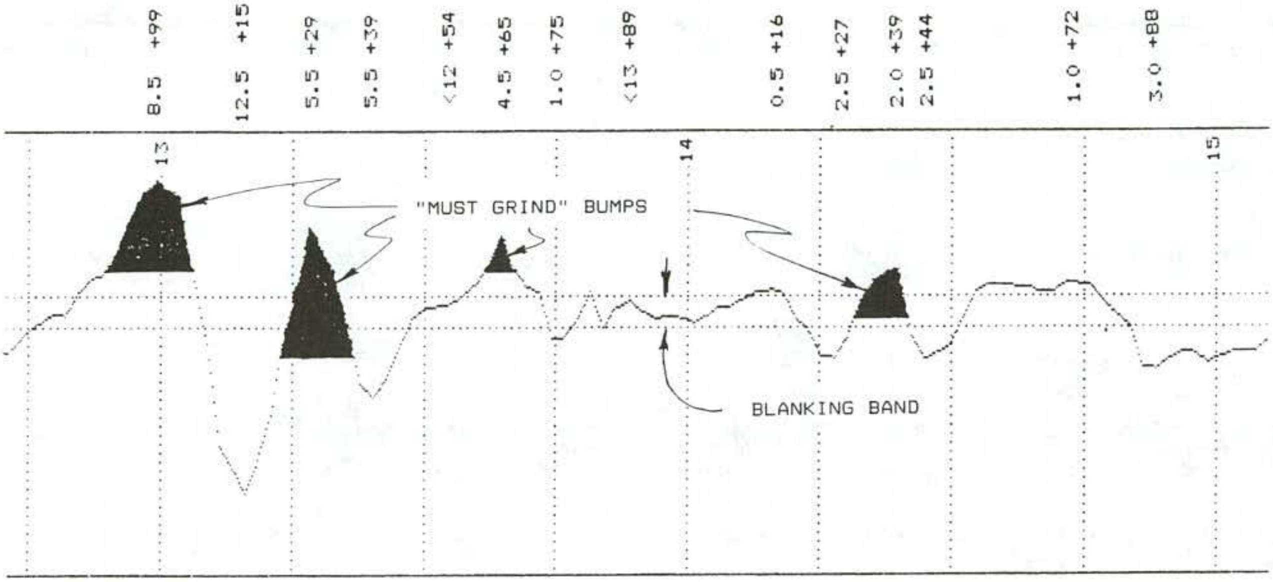

FIGURE 5 Annotated profilogram from Cox Model CS 8200.

HEADER REPORT

```
****************************************
10:23 03/21/84

DISTRICT  ROUTE    PAVEMENT   PASS
87654321 12345678 65433456      2

FACTORS
  100000    23453      528    2.0
     .20      .05       25    .30
    .100
****************************************
```

SECTION PROFILE INDEX REPORT

```
1494+34      1499+62    528     14.5
```

PROFILE INDEX SUMMARY REPORT

```
  FROM       TO        DIST    COUNTS
1494+34    1499+62     528      14.5
1499+62    1504+90     528      10.0
1504+90    1510+18     528       9.5
1510+18    1515+46     411      11.5
                       ----     ----
PI = 12.0              1995     45.5
```

FIGURE 6 Printout formats available with the Cox Model CS 8200.

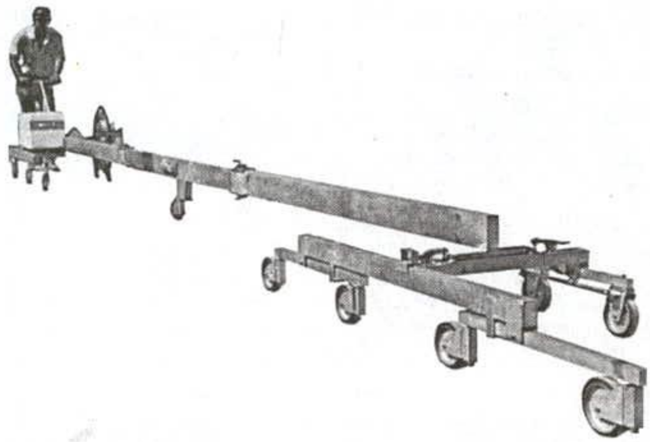

FIGURE 7 The Ames Model California-type profilograph.

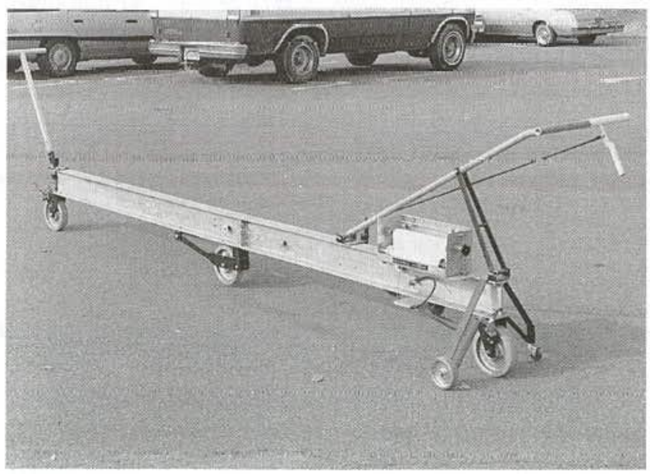

FIGURE 8 California Bridge Profilograph.

nally. Evaluation involves the use of a clear plastic template 1.70 in. wide by 6.66 in. long to represent 100 ft of bridge deck. A 0.15-in.-wide blanking band is used with parallel lines scribed 0.1 in. apart. Each 0.1 in. of distance between the blanking band and the profile is referred to as a "count," and the statistic to be determined is in terms of counts per 100 ft.

MANUAL PROFILING SYSTEMS

Rod and Level

Measurements using a surveyor's rod and level are sometimes used to evaluate pavement surface characteristics. The method is covered by ASTM E 1364, "Test Methods for Measuring Road Roughness by Static Level Methods." Because of the high cost of accumulating data, the application of this technique is limited to evaluating special conditions, such as assessing surface drainage problems and the severity of distortion in an existing pavement prior to designing an overlay.

Rod and level measurements are also used to obtain accurate profiles of control sections of certain highways. This is done so that the control section can serve as a standard on which calibration of various types of high-speed roughness-measuring equipment can be conducted.

E.W. Face Dipstick Road Profiler

The Dipstick Road Profiler is a hand-held instrument that is operated over the pavement surface. It stands on two pins spaced at 250 mm (9.8 in.), which rest on the pavement surface. Two digital displays are provided, one at each end of the instrument. Each liquid crystal display shows the elevation difference between its pin relative to the other pin when positioned on the road surface. To make a calibration survey, the operator simply "walks" the unit down the premarked wheel path by alternately pivoting the instrument about each leg. The difference in elevation between equidistant points is recorded sequentially. A signal light alerts the operator when the unit's computer has captured the reading (about 4 sec per reading), and then the operator pivots the machine to the next point. The displayed readings are reportedly accurate to within 0.002 in. "True" pavement profiles are generated, and, according to the manufacturer, the system has two principal applications: obtaining profiles for the calibration of high-speed road meters and tolerance control on projects having limited daily production. This type of equipment has seen considerable use in evaluating the smoothness of concrete floor slab construction and has been used for the calibration of road-roughness devices. Its use for general smoothness control in highway construction is impractical because of the slow pace of measurement—about 0.2 mph.

RESPONSE-TYPE ROAD-ROUGHNESS-MEASURING SYSTEMS (RTRRMS)

With response-type equipment, road roughness is evaluated by measuring the dynamic response of a mechanical device traveling over a pavement surface at a given speed. Either an automobile or a standardized trailer may be used for this purpose, with measurements taken of the vertical movements of the rear axle of the automobile or the axle of the trailer with respect to the vehicle frame. The primary use of RTRRMS is for data collection on highway networks for pavement management purposes, although limited use is directed at controlling smoothness of new-pavement construction. The primary advantages of RTRRMS are:

- Initial and operating costs are low. Data are collected at high speeds (usually 50 mph); thus a considerable length of pavement can be evaluated in a relatively short period of time.
- Reasonably accurate and reproducible roughness data can be collected if the device is properly calibrated and maintained.

The limitations of RTRRMS are as follows:

- The characteristics of the mechanical system and the speed of travel affect measurements.
- Response-type road-roughness-measuring systems measure a dynamic effect of roughness but do not define pavement profile features.
- They must frequently be calibrated, through a range of operating speeds, against sections of known profile ranging from very smooth to rough, to provide accurate, repeatable data. The costs of calibration can be quite high.
- The vehicles in which RTRRMS are installed contribute to many sources of potential variation, including rear suspension damping, tire nonuniformities, vehicle weight changes, and windage effects.
- Because of variations of the different mechanical systems, comparability of data among users is difficult.

Numerous pieces of response-type equipment have been developed; however, only the more widely used types and those that have been used in pavement-smoothness specifications will be discussed herein. Applicable operational and equipment requirements are described in ASTM Designations E 1082, "Standard Test Method for Measurement of Vehicle Response to Traveled Surface Roughness," and E 1215, "Standard Specifications for Trailers Used for Measuring Vehicle Response to Road Roughness."

Bureau of Public Roads (BPR) Roughometer

This device was first introduced in 1925 and was recognized as being the best "high-speed" smoothness device available at that time (Figure 9). It consists of a single-wheeled trailer that

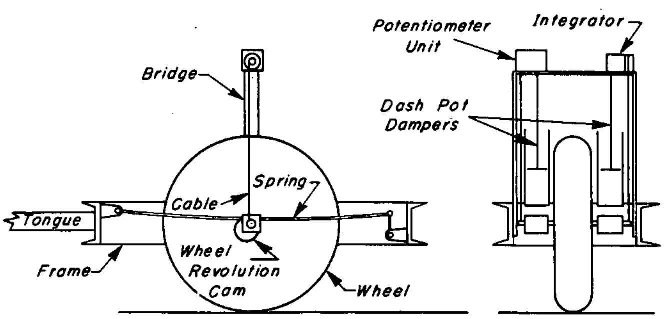

FIGURE 9 Schematic diagram of the essential elements of the Bureau of Public Roads Road Roughness Indicator.

is towed by a car or a light truck. According to Ahlborn and Moyer (*16*):

> as the. . .[unit] is towed over a given section of road, the irregularities in the road surface transmitted through the tire to the axle of the wheel are measured in terms of the vertical movements of the axle [with respect to the frame of the trailer]. . . .Roughness tests [were] standardized at a speed of 20 mph and the measurements [were] recorded by an observer for each half mile section and/or at the end of each test section.

Many equipment modifications were made in an attempt to increase the operating speed of the Roughometer. Replacing the electromechanical recorder with an electronic one overcame many of the instrumentation problems; however, the basic operational characteristics of the unit were altered at higher speeds, and the appeal of the device gradually declined.

Portland Cement Association (PCA) Roadmeter

This road meter was developed by Brokaw of PCA in 1965 (*17*) "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." The device measures the number and the amplitude of vertical deviations between the body of a "standard" automobile and the center of the rear-axle housing. The deviations are recorded in $\frac{1}{8}$-in. increments up to a maximum excursion of $\pm 1\frac{1}{2}$ in. from the neutral or null position. Readings are taken at 50 mph. A schematic showing the operating principles of a PCA Road Meter is shown in Figure 10. As the roller contact is driven in either direction it passes over contact points generating counts in both the outward and return movement. For example, a $\frac{1}{2}$-in. bump would be recorded once at the $\frac{4}{8}$-in. increment and twice each at $\frac{3}{8}$, $\frac{2}{8}$, and $\frac{1}{8}$ in. All the $\frac{1}{8}$-in. units are extended and totaled, resulting in a ride statistic in terms of counts per mile.

Portland Cement Association Road Meters have been used primarily in connection with pavement-rating systems and to a very limited degree as a part of smoothness specifications.

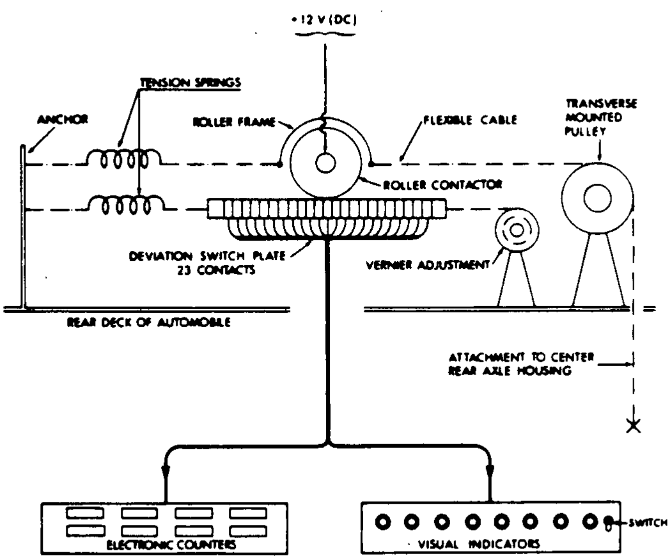

FIGURE 10 Schematic diagram of the PCA Road Meter.

Mays Ride Meter

The Mays Ride Meter was developed by an employee of the Texas Highway Department. Like the PCA Road Meter, the Mays meter is driven by movement of the rear-axle housing with respect to the body of the vehicle. The unit can be mounted in either a standard sedan or a trailer and can be operated at highway speeds. Usually, 50 mph is selected as the standard operating speed.

When car mounted, the rear-axle movements are transmitted to a recorder located in the front compartment of the vehicle. The recorder generates a strip chart that indicates the length of pavement covered and axle/body excursions at one-half the actual vertical distance traveled. Using the total inches of vertical movement and the length traveled, Mays roughness is expressed in terms of inches per mile. Figures 11 and 12 show the Mays roughness-sensing equipment and recorder. The strip chart is driven by two stepper motors. The chart is driven at a fixed scale for smooth pavements and an additional $\frac{1}{64}$ in. for each $\frac{1}{10}$ in. of vertical axle travel. Rougher pavements thus produce a greater length of chart, allowing a larger scale for portrayal of rough areas. The length of chart produced for a given length of pavement is thus in itself an indicator of roughness. The cost of the basic instrument, not installed, is just under $3000.

Computerized equipment has recently become available to record Mays roughness data. International Cybernetics Corp. offers a system that consists of a compact portable computer and printer, a distance sensor interface, Mays transmitter interface, and necessary appurtenances and software to record distance, Mays count, and inventory data for about $13,000.

Calibration of Response-Type Meters

A comprehensive analysis of RTRRMS by Gillespie et al. (*18*), directed primarily at the PCA and Mays meters, identifies many sources of measurement variation. The road meter instruments exhibit error caused by hysteresis and quantization effects. The vehicles in which the meters are installed contribute variation by rear suspension damping (shock absorber strength), tire pressure variations, tire/wheel nonconformities, vehicle weight changes, and wind effects.

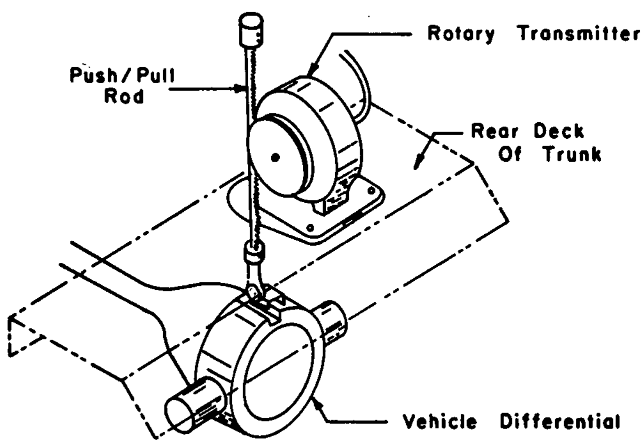

FIGURE 11 Mays roughness-sensing equipment.

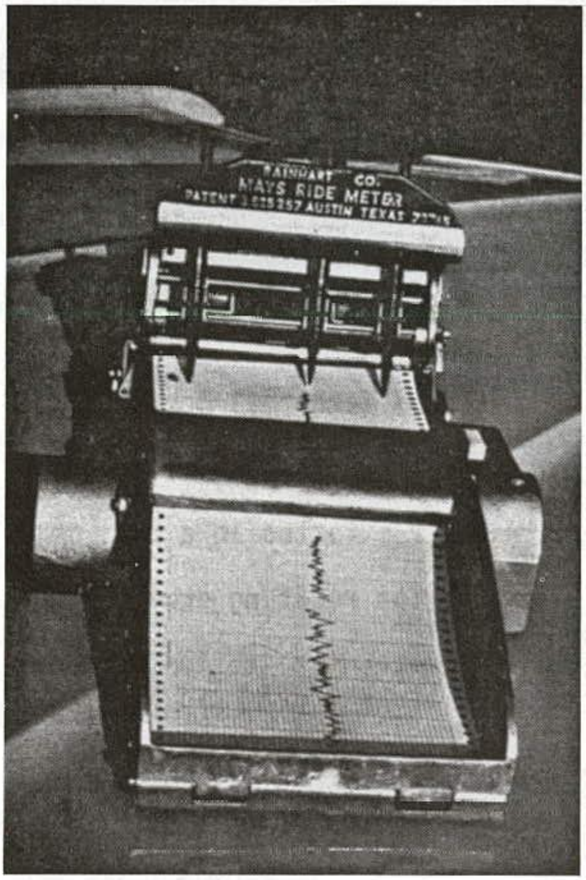

FIGURE 12 Mays recorder.

Calibration of RTRRMS involves some complex issues. Among these are: (a) To what standard is the calibration to be made (some other roughness statistic such as Present Serviceability Index)? (b) Will the calibration procedure assure that the full spectrum of pavement roughness is being covered? (c) How frequently must the calibration be made to compensate for changes in vehicle characteristics? (d) What travel speed should be used for calibration?

Several approaches to calibration were evaluated in the Gillespie study (*18*), including local reference roads, a central calibration site, hydraulic road simulator, drum rollers, artificial surfaces, and high-speed profilometers. Ultimately, the combination of a series of local road sections and the measurement of the absolute longitudinal profiles on those sections has proved to be the most reliable and transferable method of calibration. Pioneered by Hudson and others in Texas and Brazil, the method was standardized in the guidelines resulting from the International Road Roughness Experiment (*11*), and is the basis of the ASTM standard under preparation.

INERTIAL PROFILOMETERS

Underlying the efforts that have been invested in the development of the various pieces of road-roughness-measuring equipment, rating systems, indexes, etc., there has existed a recognition of the need for a high-speed profiling system that would yield a "true" portrayal of pavement surface characteristic. Such devices have come to be known as "inertial profilometers" or "inertial road profiling systems." In practice, the range and resolution of such systems are limited to a minor degree, but within the wavelength and amplitude limitations of the system, a profile measurement may be called "absolute" in that it does not require comparison to any other system but requires only the calibration of its own sensors and associated electronics, together with proper functioning of its computer hardware and software. Inertial profilometers thus develop information that can be evaluated according to specific needs. This may be as a calibration standard for other systems or for the development of a variety of smoothness statistics.

Modern inertial road profiling systems require four basic subsystems:

- Accelerometers for determination of the height of the vehicle relative to an inertial reference frame (the vehicle or trailer).
- Height sensors for measurement of the instantaneous riding height of the vehicle relative to a location on the road below the sensor.
- Distance or speed sensor for measurement of the position of the vehicle along the length of the road (odometer).
- Computer hardware and software for computation of road profiles from the above sensor inputs.

Inertial systems are rarely used as an evaluation tool for new construction because of their high cost and inability to provide readings on newly placed concrete pavements. These devices and their operation are described in ASTM Designation E 950, "Standard Test Method for Measuring the Longitudinal Profile of Vehicular Surface with an Inertial Profilometer."

General Motors Corporation Research Laboratories (GMR) Profilometer

An inertial profilometer was developed in the early 1960s at GMR (*19, 20*). It was originally developed for the purpose of measuring, recording, and bringing a replica of a pavement surface profile into the laboratory for use in computerized vehicle-suspension simulations. The development of the inertial profilometer was made possible by the availability of high-quality force balance accelerometers used in the aerospace industry for inertial guidance, as well as high-quality analog computer components, including the integrators used in profile computation.

The equipment was mounted in a panel truck and could be operated at 40 mph. It had the ability to record pavement features covering a broad range of wavelengths. Early use on California highways identified the adverse harmonics developed in certain vehicles traveling on concrete pavement having a 15-ft joint spacing. Research findings led to the construction of staggered panel lengths of 12 ft, 13 ft, 19 ft, and 18 ft, then repeated.

Interest in the GMR profilometer grew among several transportation agencies, and the General Motors Corporation was requested to make the inertial profilometer technology available to the transportation community. K.J. Law Engineers, Inc. was granted a license to manufacture and sell inertial profilometer equipment under a General Motors patent. A cooperative effort between GMR and the Michigan Department of Transportation furthered the evaluation of the device for highways application.

The Law Inertial Profilometers

The first commercial profilometer built by K.J. Law Engineers, Inc. was manufactured in 1966 for the Texas Highway Department and operated by the Center for Highway Research at the University of Texas (*21*). By 1976, two more states and the country of Brazil, under a World Bank-sponsored research project, had acquired Law Profilometers. These units were all manufactured using essentially the same state-of-the-art technology as the GMR Profilometer. Availability of new technology, recognition of earlier weaknesses that should be corrected, and a growing national interest in pavement-roughness problems led to the development of the Model 690 Surface Dynamics Profilometer in 1979. Improvements have continued, resulting in the current Model 690 DNC (digital noncontact). It measures and computes the longitudinal profile of the pavement through the creation of an inertial reference by using accelerometers placed on the body of the measuring vehicle. Relative displacement between the accelerometers and the pavement surface is measured with a noncontact light beam-measuring system mounted with the accelerometers on the vehicle body. The profile is computed in each wheel path as a function of the distance traveled. Operation requires a driver and a system operator.

Numerous software programs are available from K.J. Law to obtain simulated roughness-measurement output of several RTRRMS. Roughness indexes include root mean square accelerations (RMSA), BPR Roughometer, Mays meter, PCA meter, Cox meter, IRI, and others. The simulators can thus be used to calibrate RTRRMS, or the generated roughness index values can be used as the reported roughness statistic (*22*).

The cost of the K.J. Law Model 690 DNC Inertial Profilometer is in excess of $250,000 and will vary somewhat, depending on certain optional features and on computer programs that may be selected.

PRORUT—FHWA System

In 1983 the FHWA contracted with the University of Michigan Transportation Research Institute to design and construct a profiling and rut depth-measuring system. The objectives of the project were to: (a) assess the capabilities that are needed to measure profile and rut depth at highway speeds, (b) develop a design tailored to minimize life-cycle costs of the system, (c) build the system for delivery to FHWA, and (d) validate the system. A system that uses the IBM PC microcomputer was designed. With the exception of a signal conditioning unit, the system is constructed from commercial components. The software controls the measurement of road profile and rut depth, the viewing of the data, and daily checks of the hardware integrity. A prototype, currently known as the PRORUT system, was built and delivered to the FHWA.

A road-profiling meeting was organized to determine performance limits of the profiling capabilities of the PRORUT and 10 other profilometers.

The development of the PRORUT, with a description of its components and features, is provided by Gillespie, et al. (*23*). An estimate of hardware costs, using 1984 prices, is about $55,000.

Other Profilometer Systems

Carmichael (*22*) describes several types of state-of-the-art roughness and data-collection equipment that are available and have proved to be technically sound and suitable for large-scale data collection. These include:

- K.J. Law Model 690 Digital Noncontact Profilometer, previously described.
- French Longitudinal Profile Analyzer (APL), which was developed by the French Road Research Laboratory in 1968. It is a contact-type profilometer consisting of a single-wheel trailer unit pulled by a towing vehicle at constant speed. It has been used primarily for project-level construction control and acceptance roughness measurements.
- South Dakota Profiling System, which was developed by South Dakota DOT; now available commercially from International Cybernetics. Several states have shown interest in this unit, and some are reportedly building similar systems using technical information supplied by South Dakota DOT; at least 15 states were expected to have one in operation by the end of 1990. The device is mounted on the front of a van-type vehicle and measures pavement profile and rut depth.
- The Automatic Road Analyzer (ARAN). Measurements include ride/roughness, rut depth, grade, cross slope, radius of curvature, surface condition or distress, and video logging. The ARAN requires a two- or three-worker crew for operation.
- The Portable Universal Roughness Device (PURD), which can be either van- or trailer-mounted. It measures roughness or ride using axle-mounted accelerometers and rut depth by acoustic displacement transducers.
- The Swedish Laser Road Tester. This is a road-surveying system developed by the Swedish National Road Administration. The equipment has the capability to measure ride or roughness, rut depth, cracking, and macrotexture. The equipment is not sold, but engineering services are available through a U.S. firm that is the marketing representative for the device in the United States.
- The Law Model 8300A Pavement Roughness Surveyor. This is also a noncontact pavement-roughness-measuring system. This device uses an ultrasonic probe and an accelerometer to measure roadway roughness. The output of Model 8300A is RMSA roughness and any one of several RTRRMS simulations. Unlike the Model 690 DNC Profilometer, the measured profile data are not retained by the Model 8300 system and cannot be retrieved by the user. The cost for the K.J. Law 8300A Roughness Surveyor is approximately $50,000, exclusive of the vehicle.
- The Dynatest 5000 Roughness and Distress Meter (RDM). This device is used for roughness inventory and pavement-distress surveys.

CHAPTER THREE

CONSTRUCTION SMOOTHNESS SPECIFICATIONS AND CORRECTIVE ACTIONS

In early pavement construction, straightedges were used more to monitor and control the actual spreading and compaction operations during placement than to provide an acceptance standard for the final surface. Because paving progress was relatively slow, the straightedge could be applied immediately behind the paver and corrective measurements could be taken while the portland cement concrete (PCC) was still plastic or the asphaltic mix was still soft enough to be manipulated. The straightedge remains a valuable control instrument to the contractor, enabling bumps to be located during paving operations in time for corrections to be made.

Under present specifications, straightedge requirements are used for a variety of applications, including the following:

- On production paving, as a catchall smoothness requirement for surface aberrations that may not be identified specifically by the primary smoothness-evaluating system.
- In the transverse direction, where straightedge testing is the most practical approach.
- In low-production areas (compared with main line pavement), such as bridge decks, bridge approach slabs, replacement slabs, patches, and where new pavement is matched to existing pavement.
- In special situations, especially in dealing with critical surface drainage problems.

All highway smoothness specifications incorporate a limit on surface deviations from a straightedge in some form. The lengths of the devices and the tolerances vary considerably, however.

Approaches at correcting those areas that exceed smoothness tolerances were greatly enhanced by the development of pavement-grinding equipment in the 1950s. This work resulted in the use of abrasive saw blades with embedded diamond grit mounted on a mandrel to form a cutting head of from 2 to 6 ft in width. Such equipment has proved to be very effective in eliminating irregularities from pavement surfaces. The initial profilograph specification that appeared in the 1960 California Standard Specifications relied on the use of diamond-grinding equipment to correct pavement surfaces that did not comply with allowable tolerances. The specifications required that each 0.1-mile section of pavement that did not comply with a profile index of 7 in. per mile or the individual bump limitation of 0.3 in. in 25 ft be ground using diamond abrasive cutting heads until the surface conformed to those requirements. Corrective action, of course, was done at the expense of the contractor. Thus, an incentive was established to comply with the smoothness specifications, because the corrective grinding was a rather costly treatment.

Smoothness specifications written for the use of profilographs (Rainhart and California) are in wide use at the present time, with more than 30 states using them. There is little uniformity in the smoothness levels that are being specified, however. For example, on PCC pavement, where these instruments are most widely used, about one-third of the states have a smoothness limit of 7 in. per mile, the remainder being higher (i.e., 10, 12, or 15 in. per mile.)

In addition to profile index requirements, states that use profilographs specify a tolerance on individual bumps. The initial tolerance developed by the state of California was for a maximum bump of 0.3 in. in a distance of 25 ft. This is the most commonly used limit for individual bumps at the present time; however, some states specify 0.4 in. and others 0.5 in. in 25 ft. Similarly, Rainhart profilograph users specify either 0.2-in. or 0.3-in. bumps in a 25-ft length.

It should be understood that smoothness levels as discussed herein are applicable to highways constructed to high-speed design standards, unless otherwise indicated. On facilities developed to lower standards (i.e., with short radius horizontal curves, abrupt vertical curves, controls set by intersecting streets, driveways, and existing pavement surfaces, etc.), more liberal smoothness specifications are appropriate.

Of the states using profilographs, about one-half (14 states) require that a specific limit of smoothness be met, whereas the remainder of the states are using a variable scale with pay adjustments, depending on the degree of smoothness achieved. The adjustments are referred to as incentive/disincentive clauses and have grown in popularity in recent years. These specifications have taken slightly different formats and are illustrated in the current AASHTO smoothness specifications as follows (*24*): When the profile index is greater than 7 in. per mile but does not exceed 10 in. per mile per 0.1-mile section, payment will be made at the contract unit price for the completed pavement. When the profile index exceeds 10 in. per mile per 0.1-mile section but does not exceed 15 in. per mile per 0.1-mile section, the contractor may elect to accept a reduced unit price in lieu of correcting the profile index. When the profile index is less than or equal to 7 in. per mile, the contractor is entitled to an incentive payment. Contract unit price adjustments will be made in accordance with the following schedule:

Profile Index In. per mile per 0.1-mile section	Price Adjustment (Percent of payment unit bid price)
3 or less	105
Over 3 to 4	104
Over 4 to 5	103
Over 5 to 6	102
Over 6 to 7	101
Ovr 7 to 10	100
Over 10 to 11	98
Over 11 to 12	96
Over 12 to 13	94
Over 13 to 14	92
Over 14 to 15	90
Over 15	Corrective work required

Pay adjustments for incentives are only based on the initial measured profile index, before any corrective work. The price adjustment schedule for 100 percent pay or pay reductions applies both before and after corrective work has been completed.

Straightedge and profilograph specifications relate to measurements of pavement surface features. This is in contrast to specifications that are written around the use of response-type equipment. In the latter, it is not the pavement feature that is addressed but rather the effect that the pavement feature has on the RTRRMS (ride quality). Generally, the direct measure of pavement surface features is preferred by the construction industry and by most agencies in developing specifications.

Achieving smoothly constructed pavements is an involved process requiring the combined efforts of specifying agencies and the construction industry. Specifications must be appropriate for the facility and must be attainable through the use of effective construction processes and equipment; smoothness measurements must be reproducible and must be obtained as early as possible; evaluation of smoothness should be understood by both parties; and defects (bumps) need to be corrected in a manner that lends itself to ready evaluation and correction.

Specifying agencies have not proceeded in a unified manner with respect to the types of equipment and the specifications used to evaluate smoothness. Attempts have been made at standardization, and considerable progress has been made in recent years. However, agencies still tend to remain somewhat independent in developing and applying their own approaches to pavement smoothness. The paving industry, however, often finds it necessary to provide services to several agencies and has experienced considerable frustration at times in dealing with a plethora of requirements.

Among industry groups, the American Concrete Pavement Association (ACPA) has been an active advocate of the use of the profilograph approach to acceptance testing. The *ACPA Rideability Guide Specifications* state, "The smoothness of the pavement will be determined by using a California profilograph over each designated lane. The surface of mainline pavement shall be tested and corrected if necessary to a smoothness as described herein. . . ."

The ACPA encourages its contractor members to acquire profilographs to monitor their own operations, and most of the major pavers have done so. It acknowledges that smooth pavements are necessary in marketing its product to the motoring public. Having a smoothness evaluation in a matter of hours after paving enables the paving crew to assess their effort and fine-tune their operation as needed. As stated by Capper, a paving superintendent (*25*), "A well maintained profilograph is an excellent tool for evaluating the ride quality characteristics of each paving operation." A similar viewpoint is expressed by Jensen (*26*):

> The Irving F. Jensen Company believes that the construction of high quality and smooth riding pavements is absolutely essential to the growth of the portland cement concrete paving industry. We are striving to provide the top quality in our market. We also believe that the profilograph specification has had a profound effect on our pavement smoothness and on the quality of our completed paving. . . .

The Asphalt Institute and the National Asphalt Pavement Association (NAPA) have been less active in promoting profilograph smoothness specifications. Their current published smoothness criteria center on the use of a 10-ft straightedge test. However, among the Asphalt Institute engineers, it is generally believed that:

- Some measure of rideability should be included in acceptance criteria for pavement construction.
- Smoothness requirements should be the same for asphalt and portland cement concrete pavement.
- Specification limits should be reasonably stringent and correlate to rideability.
- Specification limits should usually be less strict for overlay work than for new construction. Commonly specified limits for the California Profilograph are 5 to 7 in. per mile for new construction and 10 to 12 in. per mile for overlays. As an alternative, on overlays a level of smoothness "improvement" could be specified.

The American Association of State Highway and Transportation Officials (AASHTO) has become increasingly concerned with the smoothness of pavements, both new and old, in the last decade. The primary means by which the traveling public evaluates the quality of both newly constructed and rehabilitated pavement is its rideability. This awareness, along with the increased emphasis on pavement management, has caused a heightened interest in rideability specifications and measurements.

In 1981, the AASHTO Highway Subcommittee on Construction developed a rideability questionnaire that was sent to each of the member states to establish a compilation on the use of rideability specifications. The data were updated in 1984 and 1987. The data from the original questionnaire were used by AASHTO in developing the 1988 Guide Specifications for Highway Construction. In brief, the Guide Specifications call for the California-type equipment and specification to be used on both asphalt and concrete pavement construction.

The ASTM has also become more involved in road roughness. Committee E 17 on Pavement Management Technologies (formerly called Traveled Surface Characteristics) is currently organized with the following subcommittees dealing with the subject of pavement roughness:

- Subcommittee E 17.31, Methods for Measuring Profile and Roughness,
- Subcommittee E 17.32, Measurement and Control of Roughness in Construction and Rehabilitation, and
- Subcommittee E 17.33, Methodology for Analyzing Pavement Roughness.

In addition to the standards mentioned in Chapter 2, standards are nearing finalization on the use of profilographs, the calibration of response-type road-roughness meters, and the computation of roughness indexes.

There is little doubt that the emphasis that agencies, trade associations, and industry representatives have placed on the construction of smoother pavements has had a positive effect. The trend for specifying agencies to tighten smoothness requirements continues. Based on surveys in recent years, four separate agencies report reducing profile index requirements as follows: (a) 28 to 12, (b) 15 to 12, (c) 10 to 7, and (d) 7 to 5 (in. per mile). At least four additional agencies anticipate reducing smoothness levels in the future. It is also evident that the specified smoothness requirements are being complied with essentially, necessitating a minimum of corrective grinding or disincentive assessments against the bid prices for the paving material.

CHAPTER FOUR

RELATIONSHIP BETWEEN VARIOUS ROUGHNESS INDEXES

During the AASHO Road Test, the concept of pavement serviceability was developed and defined as the ability of a pavement to serve the traveling public. Ever since the road test, the most commonly used measure of serviceability has been the present serviceability index (PSI). Data from nearly all of the available pavement-smoothness-measuring equipment have, at one time or another, been analyzed for their relationship to the serviceability concept, either PSI or present serviceability rating (PSR), which are established by panels of road users. Until relatively recently, most of the studies involving relationships to PSI ratings included equipment primarily suited for system-wide condition evaluation. In recent years, equipment designed primarily for construction smoothness evaluation has been included in correlation studies. Also, as an outgrowth of the 1982 International Road Roughness Experiment (*8*), an IRI was developed.

A discussion of the relationship between the various roughness indexes necessarily incorporates a collection of somewhat diverse research efforts that provide information on various groupings of measuring equipment. Hudson et al. (*27*) describe the results of field testing and comparing the Surface Dynamics 690D Profilometer, the K.J. Law Model 8300 Roughness Surveyor, the Mays meter, the California Profilograph, and the Rainhart Profilograph. Comments are provided on each of the instruments included in the study, in addition to comments on other available pieces of smoothness-measuring equipment.

Hudson et al. expressed concern about the California Profilograph with respect to its operation on a pavement surface with a sine wave configuration having some given amplitude and a wavelength coinciding with one-half the length of the profilograph (i.e., 12.5 ft). (A similar concern would apply at some even divisor of the 12.5-ft dimension.) In this situation, the front, rear, and profile wheels would all be moving parallel to one another, upward or downward in unison, resulting in a straight line being displayed on the profile printout (see Figure 13). Theoretically

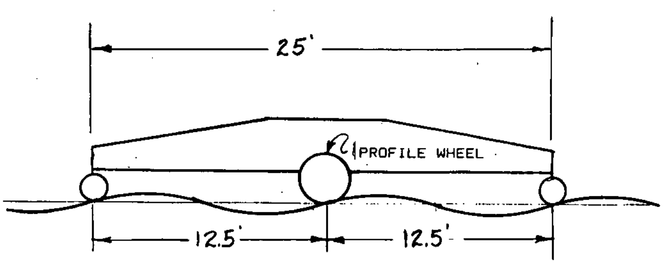

FIGURE 13 Possible effect of operating California-type profilograph over pavement having sine wave undulations one-half the length of the instrument. Profile wheel indicates no variance from datum established by end wheels.

this situation could occur, but whether it ever has, or to what degree it may have occurred, is unknown. In practice, surface irregularities are rarely repetitive anomalies occurring in sine wave form, but rather they are singular events often traceable to the malfunction of some aspect of the construction operation. On concrete paving projects, factors such as encountering a dry batch of concrete, slippage of the paver track, and stoppages in production are typical events resulting in a singular deviation from the controlled smoothness. In any case, none of the states that use the California-type profilograph has reported or otherwise indicated any concern about this potential phenomenon as being a problem, nor has the segment of the industry that has actively advocated its use.

Roughness data were collected from pavement sections near Austin, Texas, that ranged from smooth to very rough. The profilographs were tested on 12 selected sections, three from each of four roughness groups. The roughness groups cover the following ranges of serviceability index (SI): 5 to 4, 4 to 3, 3 to 2, and 2 to 0. Roughness in terms of profile index (using the California method) for the roughest test sections exceeded 120 in. per mile. The appropriateness of choosing pavements with that degree of roughness for a study that is directed at evaluating the surface characteristics of new construction is open to question.

Hudson et al. concluded that the California Profilograph "is satisfactory if used for construction smoothness control in untrafficked areas. The significant limitation of the profilograph is the laborious, time consuming, and subjective data analysis." The matter of "subjective" analysis does not receive elaboration in the report. Also, raw data obtained from measurements on the test sections are not given. Examination of data in which profile index is plotted against the Law 690D Profilometer index shows that a fairly wide range of values of profile index was obtained for repeat runs on the test sections (Figure 14).

Hudson et al. ranked the 690D Profilometer and the Mays meter as being "very good" and "good" respectively. Data on the Rainhart Profilograph were not provided; however, a comment was made that "it is judged to be approximately equal in precision to the California Profilograph."

In a study sponsored by the Texas State Department of Highways and Public Transportation, Walker and Lin (*28*) examined instruments that were considered appropriate for construction specifications. The main objective of their project was to determine the relationship between measurements obtained from the Rainhart and California profilographs and the relationship of those data to PSI.

To conduct the study, in addition to the devices mentioned above, the Surface Dynamics Profilometer (SDP) and the Walker

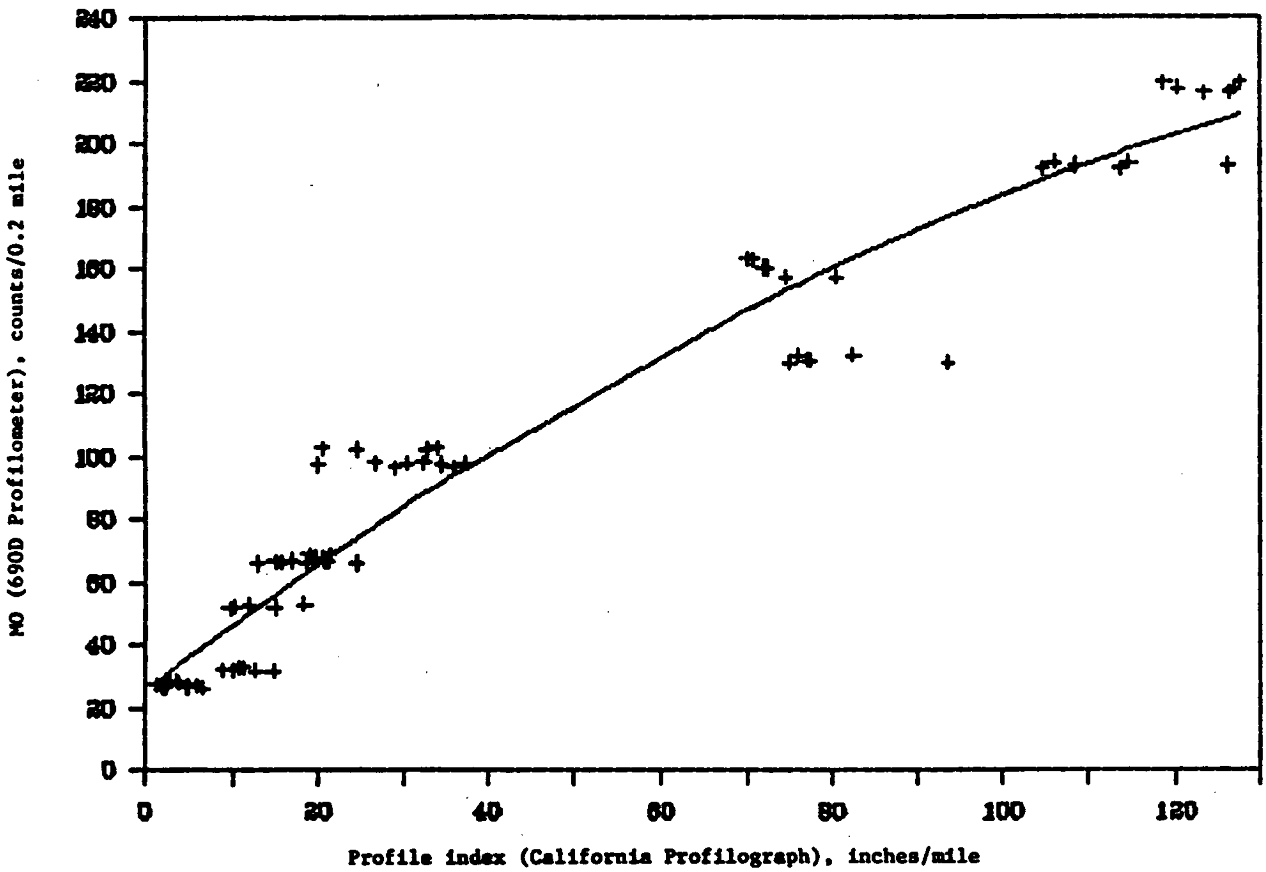

FIGURE 14 MO (690D Profilometer) index versus profile index (California Profilograph) relationship.

Self-Calibrating Roughness Device (WRD) were used. The WRD consists of an accelerometer mounted vertically in the trunk of a vehicle, a control module containing microprocessors to accomplish real-time computing, and an optional computer for data storage. It is a compact, simple device and can be installed and operated in virtually any vehicle.

A total of 41 rigid pavement sections, each 0.2 mile in length, were used in the study. Each of the devices was operated over all 41 sites. The profile indexes of the Rainhart and California profilographs were computed using both a 0.1-in. and 0.2-in. blanking band. The PSIs of the sections were computed using both the SDP and the WRD. Mathematical models of the two profilographs were developed and applied to the SDP data.

The research indicated that a high correlation exists between the Rainhart and California profilographs. The best correlation found between the two devices occurred when using a 0.1-in. blanking band for the Rainhart device and a 0.2-in. blanking band for the California unit (Figure 15). Those happen to be the blanking bandwidths most commonly used for the two devices.

A fair correlation was found between PSI obtained from the SDP and the profile index obtained from the two profilographs (Figures 16 and 17). Also, fair correlation was found between PSI and the slope variance statistic provided by the WRD.

The concluding paragraph in the "Summary and Conclusions" of the Walker and Lin report presents a practical assessment of profiling equipment as applied to new construction. It reads as follows (*28*):

Although the SDP is a good device for obtaining accurate road profiles, its equipment investment and operating cost are high and using it for construction sites all over the state is a difficult task and not economically practical. As noted, the Rainhart and/or California Profilograph are currently being used for providing the necessary measurements and may be the best device for such measurements. The profilograph is less expensive than most currently used roughness measuring devices, is easy to understand, has a low operations cost, and requires no special skills from the operator. However, the frequency response of these two devices to road profile are such that the effects of some roughness frequencies can be under estimated, and others over estimated. Thus although such devices may be best, particularly for new construction, their limitations must be clearly understood.

In contrast to the good correlation between the Rainhart and California profilographs shown by Walker, a review of the data obtained at the Fort Collins Pavement Profile Measurement Seminar indicates that this is not always the case. The following data were obtained on the five test sites where the two instruments were operated:

	Profilograph	
Test Site	California (McCracken)	Rainhart
1	13.2	2.8
3	23.8	7.3
5	91.4	20.8
6	41.1	64.8
7	83.2	49.2

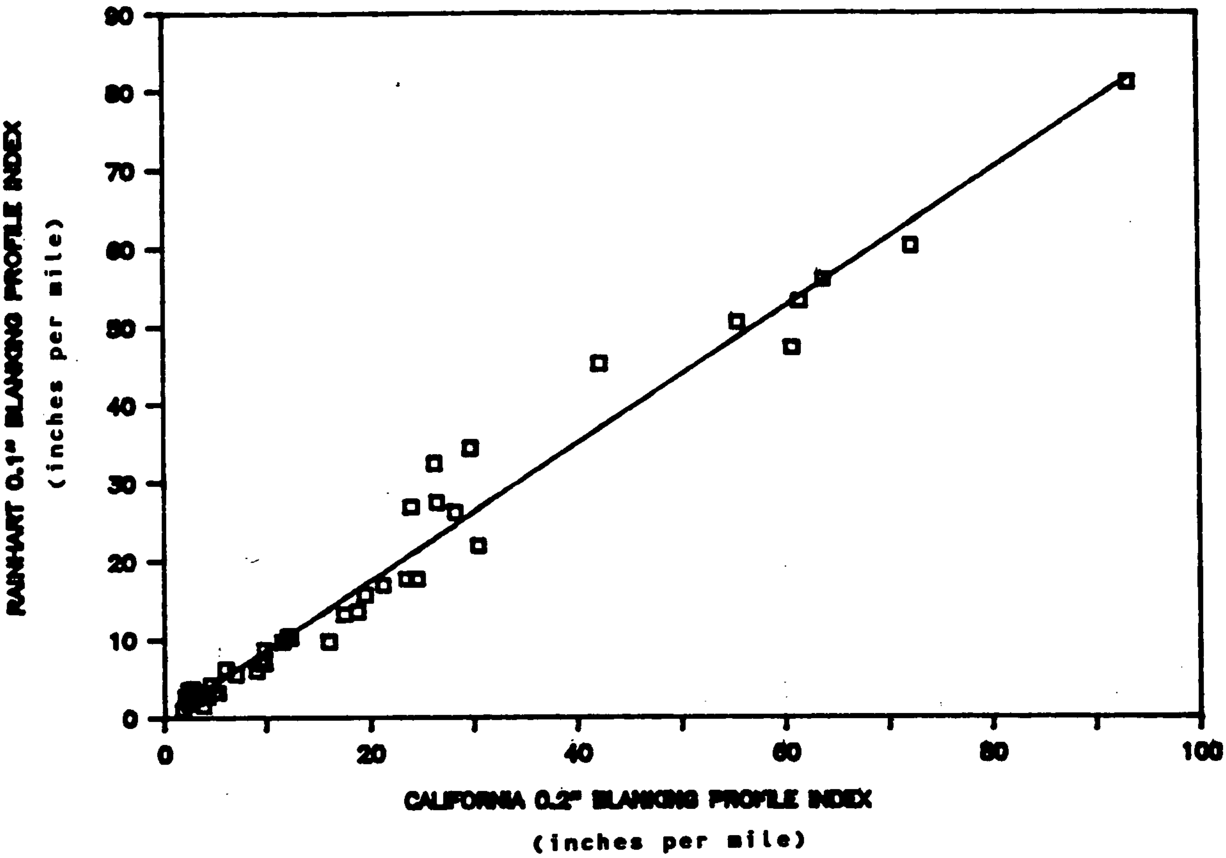

FIGURE 15 Rainhart 0.1-in. versus California 0.2-in. blanking band profile indexes.

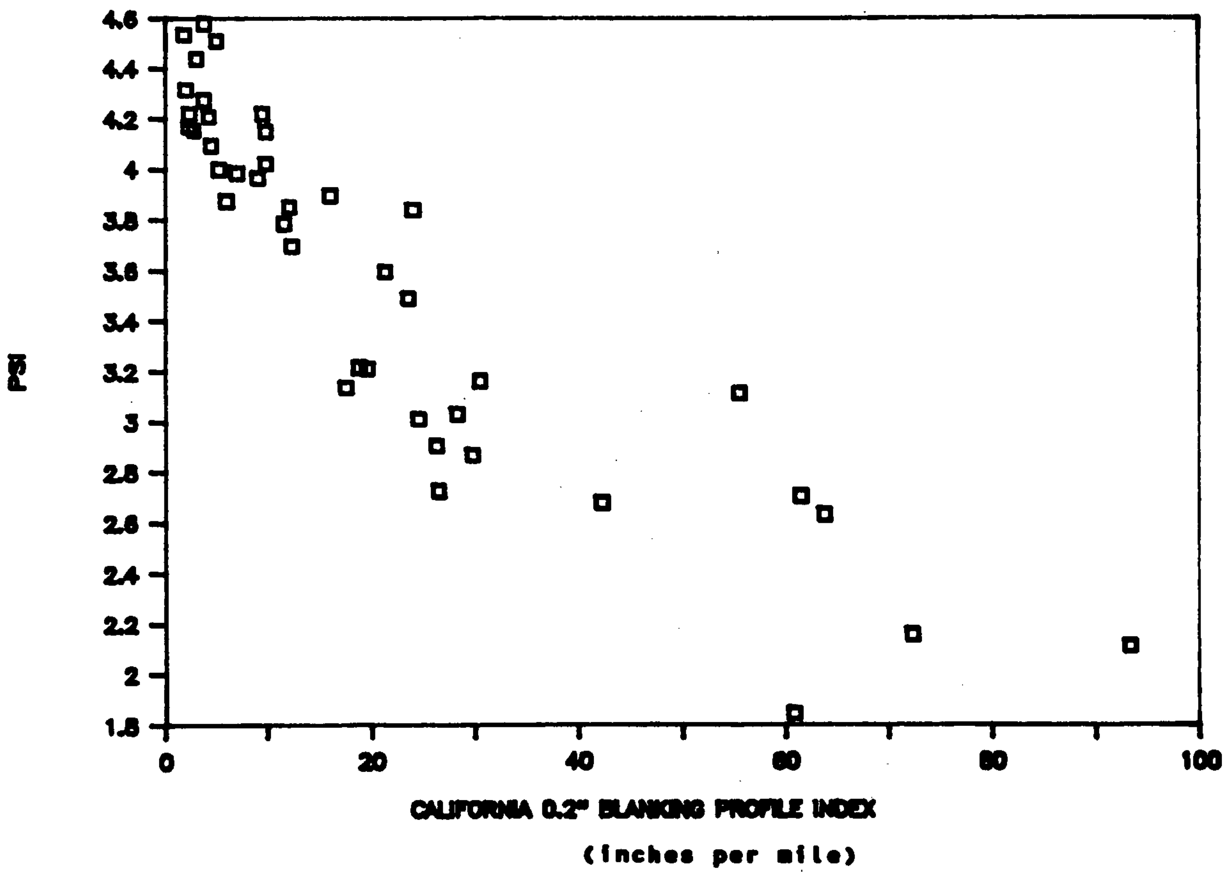

FIGURE 16 PSI versus California 0.2-in. blanking band profile index.

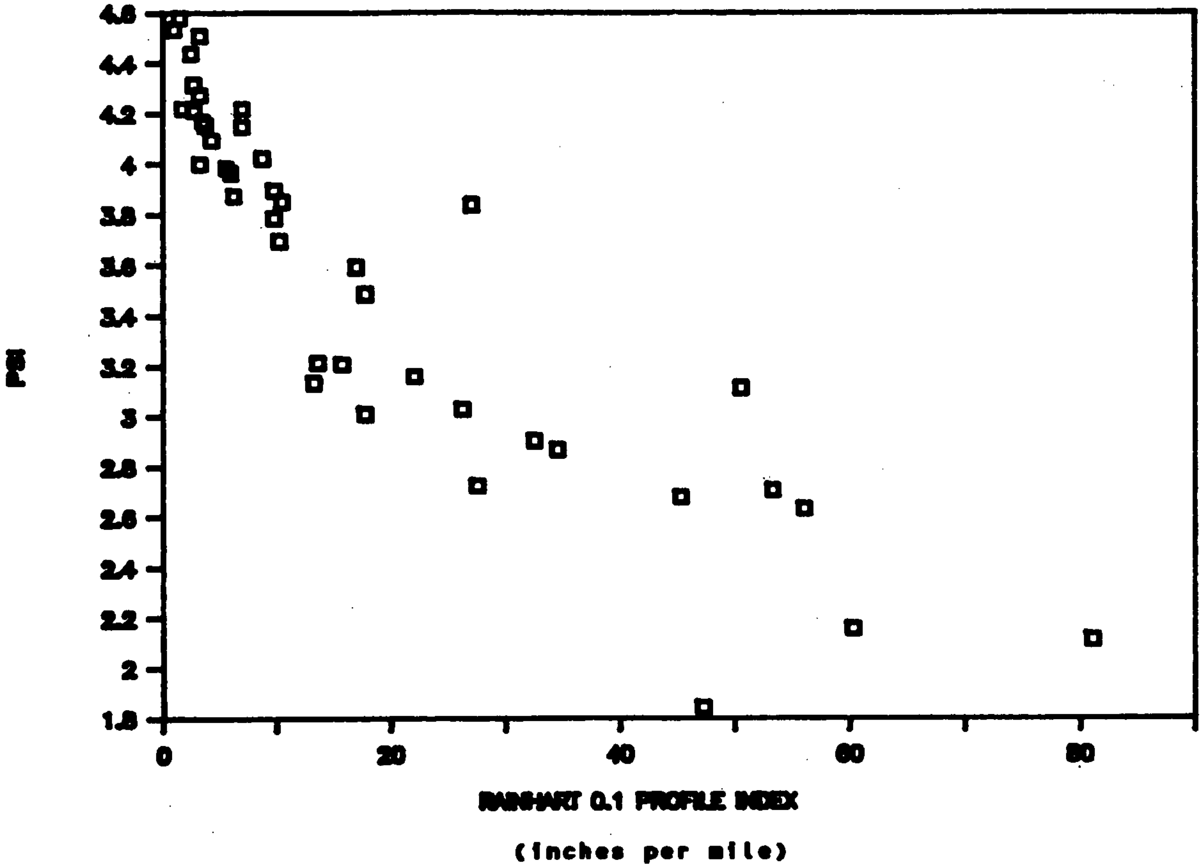

FIGURE 17 PSI versus 0.1-in. blanking band profile index.

Temple and Cumbaa (*29*) describe:

> the techniques and relationships developed to design a Serviceability Index (SI)-based measurement system for acceptance of jointed concrete pavement construction in Louisiana. Pavement roughness statistics obtained from Mays Ride Meter equipment, a Surface Dynamics Profilometer, and a Chloe Profilometer were regressed to establish an AASHO Road Test-based SI measurement system for concrete pavements with 20-foot joint spacings. . . .A 1986 panel rating of 25 concrete pavements confirmed the validity of the model. Field testing of 50 newly constructed concrete pavement test sections provided a relationship between the model and profile statistics from rolling profilograph equipment and a 10-ft rolling straightedge. The research resulted in the development of a rational method of providing specification limits for profilograph equipment that relate to pavement rideability. Specification limits in terms of profile statistics are provided to indicate the quality of paving necessary to construct a jointed concrete pavement with a Serviceability Index of 4.5.

Kulakowski and Wambold (*30*) reviewed current information for FHWA concerning the methods and equipment for measuring the roughness of new pavements. They reported on a full-scale testing program that investigated the basic roughness characteristics of new pavements, represented by power spectral density functions, that were then used to generate average profile data. Road-roughness-measuring devices, including the California, Rainhart, and Ames profilographs, a high-speed profilometer, and a Mays meter, were evaluated on the basis of frequency response, precision, repeatability, reliability, and ease of operation. Researchers examined aspects of correlation between the profilographs and other roughness-measuring devices. Computer simulation of a profilograph, in which the effect of varied design parameters on profilograph performance was investigated, yielded the formulation of an optimal profilograph design as a general optimization problem.

Kulakowski and Wambold's evaluations led to the following recommendations (*30*):

> (1) An RTRRM device should be used to evaluate new pavement only if no other equipment is available, and then its frequency response must be determined at the speed it is used and time-consuming computer corrections are required.
>
> (2) Profiling vehicles are the only type of equipment of those investigated in this study that have satisfactory frequency response and resolution.
>
> (3) Profilographs have a varying response to wavelength. Some wavelengths are measured correctly, some hardly at all, and others are amplified. The 12-wheel California profilograph gives a poor measurement at 10-to 15-ft wavelengths and then amplifies those in the 20- to 50-ft range by as much as two times. The Rainhart profilograph has a better frequency response in the range of 1- to 20-ft wavelengths, nominally a one to one relation on the average. However, it attenuates wavelengths between 9 and 13 ft. Above 30-ft wavelengths, it attenuates the amplitude by at least 2, producing less than half of the actual amplitude in the road.

The report discussed problems of correlation as affected by the use of the blanking band and alluded to the potential effects of surface features that are removed from any form of evaluation. As stated in the summary:

> It was established that a 7-IPMca (Inches Per Mile, California) acceptance value is the most commonly used, but there is a desire to lower this value to 5 IPMca. These amplitude requirements are needed over a range of wavelengths from 1.6 to 32 ft. The use of profilographs to measure the roughness of new pavements where the acceptance criterion is below 7 in/mi is unacceptable unless the data acquisition is changed and the blanking is eliminated from the data processing procedure. If the height and distance are recorded so that these measurements can be used as input to a quarter-car model, the International Roughness Index could be calculated and used as the acceptance criterion. However, this would still not account for the variable frequency response of the particular profilograph.

It is pertinent to further mention the IRI, as work on its development has served as a focal point for much of the interest in profiling systems and equipment in the 1980s. With the extensive array of instruments on the market, correlation and transferability of measures from the various instruments and their correlation to a common scale were needed. This need was addressed in the International Road Roughness Experiment (IRRE) (*8, 10, 31, 32*) in Brazil in 1982. The IRI was a product of this experiment, which was conducted by research teams from Brazil, France, England, Belgium, and the United States. It involved the controlled measurement of road roughness for a number of roads under a variety of conditions by a variety of instruments and methods. The roughness scale selected as the IRI was the one that best satisfied the criteria of being time stable, transportable, and relevant, while also being readily measurable by all practitioners. Although the IRI will undoubtedly realize increased application in surveying the roughness of road networks, its application in specifications for pavement smoothness on high-speed highways is not foreseen at this time.

CHAPTER FIVE

SURVEY RESULTS AND TRENDS

A questionnaire dealing with many aspects of construction smoothness specifications, measuring equipment, and various practices and opinions was sent to all state governments in the United States and to the Canadian provinces. A copy of the questionnaire is attached as Appendix A. Responses were received from 37 states and three provinces and are tabulated in Appendix B. It can readily be seen that a wide range of practices exist with respect to evaluating pavement smoothness. All agencies use a simple straightedge in their smoothness control, but most use it as an adjunct to more sophisticated specifications and equipment. (Of the three responding Canadian provinces, none used equipment other than a straightedge.) The length of straightedge and the allowable tolerances vary considerably. After the straightedge, the profilograph is the most widely used device, with a total of 30 states responding affirmatively as to its use. Of those 30 states, 25 use the California type and 6 use the Rainhart. (One state currently has one profilograph of each type.) In reviewing the 1987 AASHTO survey, it was found that three states that did not respond to the current survey reported using the profilograph. Thus, it is likely that at least 33 states currently use a profilograph.

Six states report using a Mays meter, but only four of those states use it on new asphalt concrete or PCC construction. The Law 690 is used on PCC construction in two states. The BPR Roughometer and the PURD also were each used by a single state.

A trend toward the use of profilograph equipment is very evident when comparing the results of the present survey with earlier surveys conducted by AASHTO. This is shown in the following summary:

Number of states using profilograph equipment	Year
12	1981
18	1984
25	1987
33	1989

For the states using profilographs, 19 provide their own and 19 require the contractor to provide it on all or at least some projects. Data reduction is done totally by agency forces in 25 cases, but four agencies require the contractor to do the data reduction with periodic checks by the agency. General acceptance of the use of profilograph testing equipment and specifications is good on both the contractor and agency side.

For the agencies using a profilograph, 14 indicated that they do not use incentive or disincentive clauses relating to pavement smoothness, and 16 indicated that they do use them. Two agencies had used them at one time but no longer do so. Of the 16 agencies using incentive/disincentive specifications, 5 report bonuses up to 5 percent of the bid price, 1 up to 4 percent, and 1 up to 2 percent. Four agencies have formulas of varying complexity in calculating final pay adjustments.

Of the agencies using a Mays meter, three do not use incentive/disincentive clauses and three do. Of the three that do, one uses a formula for calculating pay adjustments, and the other two do not use incentives but have a penalty schedule for disincentives for achieving low smoothness levels.

Levels in smoothness specification limits are gradually being lowered. Profile index values have recently been reduced by four states, and no responding state currently uses a limit greater than 15 in. per mile for new construction. Five states indicate that they plan to reduce their tolerances in the future. Smoothness tolerances are being achieved in the field without any particular difficulty when good construction practices are followed.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

The subject of pavement smoothness, including its definition, methods of measuring it, and how to specify it, has received considerable attention since the turn of the century. These efforts have resulted in ingenious measuring devices and creative specifications, both of which have been effective in achieving smoother pavements. This could not have been achieved, however, without the cooperation and effort of specifying agencies, the construction industry, and the manufacturers of construction and paving equipment. The joint effort that has been displayed is commendable, because real progress has been realized and indications are that this trend will continue.

There are two facets of pavement smoothness that are of interest to the highway engineer: smoothness in new construction and the evaluation of performance of entire highway systems. Measuring equipment suitable for one of these facets has been found to be something less than totally satisfactory for the other. The most commonly used equipment for construction control is the profilograph. This instrument provides a graphic representation of pavement surface features that can be associated with specific points on the pavement. This relationship is suitable as a basis for preparing appropriate specifications, for associating surface features with paving operations, and for giving guidance in taking necessary corrective measures. Those responsible for pavement construction need this type of information to assess their practices and to guide pavement-smoothness grinding operations, when necessary. In some cases in which agencies use a "ride score" type of smoothness specification, paving contractors find it necessary to provide and operate their own profilograph to allow the necessary detailed analysis of surface characteristics. The use of high-speed, vehicle-mounted equipment, although capable of providing an adequate smoothness measure, is therefore undesirable for application on new construction.

It is recommended that research be directed at further evaluation of the trace or profile produced by the profilograph. Although the blanking band used in the evaluation of profiles serves to provide a reasonable tolerance upon which the roughness parameter is based, there are rare occasions in which the blanking band either totally or partially obliterates surface characteristics that result in an adverse ride. Such surface characteristics are generally repetitive, have a low amplitude and have a wavelength of from 3 ft to possibly 12 ft. They are believed to be created by certain cyclic construction operations that may or may not be apparent during construction. Appropriate evaluation of this sort of phenomenon should result in an evaluation procedure and a specification that would serve as an adjunct to the current conventional parameters. Merely reducing the profile index requirement to something less than the widely used base value of 7 in. per mile would not address this condition.

With respect to the evaluation of pavement smoothness on a system-wide basis, the widespread adoption of the IRI as a reference and calibration standard is being encouraged worldwide to improve the reliability of exchanging information related to road roughness. The IRI would then be a common denominator, in some cases existing in parallel with a local index or series of profile statistics.

REFERENCES

1. Hveem, F.N., "Devices for Recording and Evaluating Pavement Roughness," in *Highway Research Board Bulletin 264: Road Roughness and Skidding Measurements: 1960*, Highway Research Board, National Research Council, Washington, D.C. (1960) pp. 1–26.
2. Carey, W.N. and P.E. Irick, "The Pavement Serviceability-Performance Concept," in *Highway Research Board Bulletin 250: Pavement Performance Concepts*, Highway Research Board, National Research Council, Washington, D.C. (1960) pp. 40–58.
3. Wambold, J.C., L.E. DeFrain, R.R. Hegmon, K. McGhee, J. Reichert, and E.B. Spangler, "The State of the Art of Measurement and Analysis of Road Roughness," in *Transportation Research Record 836: Pavement Roughness and Skid Properties*, Transportation Research Board, National Research Council, Washington, D.C. (1980) pp. 21–29.
4. Janoff, M.S., J.B. Nick, P.S. Davit, and G.F. Hayhoe, *NCHRP Report 275: Pavement Roughness and Rideability*, Transportation Research Board, National Research Council, Washington, D.C. (September 1985) 69 pp.
5. Zaniewski, J.P. and B.C. Butler, " Vehicle Operationg Costs Related to Operating Mode, Road Design, and Pavement Condition," ASTM STP 884 (1985).
6. "AASHTO Guide for Design of Pavement Structures," American Association of State Highway and Transportation Officials, Washington, D.C. (1986).
7. Janoff, M.S., "The Relationship Between Initial Pavement Smoothness and Long-Term Pavement Performance," paper presented to Committee A2B07 at the 69th Annual Meeting of the Transportation Research Board, Washington, D.C. (January 1990).
8. Sayers, M., T.D. Gillespie, and C.A.V. Queiroz, "The International Road Roughness Experiment: Establishing Correlation and a Calibration Standard for Measurements," Technical Paper 45, World Bank, Washington D.C. (January 1986).
9. Sayers, M.W. and T.D. Gillespie, "The Ann Arbor Profilometer Meeting," Report No. FHWA/RD-86/100, University of Michigan Transportation Research Institute (1986).
10. Donnelly, D.E., W. Hutter, and J.P. Kiljan, *Volume I: Data Seminar Overview. Demonstration Project No. 72—Automated Pavement Data Collection Equipment*, Report No. FHWA DP-88-072-003, *Proceedings*, Pavement Profile Measurement Seminar, Fort Collins, Colo., Colorado Department of Highways (1988).
11. Sayers, M., T.D. Gillespie, and W.D.O. Paterson, "Guidelines for Conducting and Calibrating Road Roughness Measurements," Technical Paper 46, World Bank, Washington, D.C. (January 1986).
12. Hankins, K.D., "Construction Control Profilograph Principles," Research Report 49-1, Texas Highway Department (June 1967).
13. Hart, L.E., "Using the Rainhart Profilograph," paper presented at the 67th Annual Meeting of the Transportation Research Board, Washington, D.C. (January 1988).
14. James Cox and Sons, Inc., "Preliminary Specifications-Profilograph" (1988).
15. Miller, A.S. and C.E. Watson, "Pavement Rideability Study," Central Direct Federal Division, Federal Highway Administration, Denver, Colo. (1987).
16. Ahlborn, G. and R.A. Moyer, "New Developments in BPR Roughness Indicator and Tests on California Pavements," in *Highway Research Board Bulletin 139: Road Roughness and Slipperiness: Some Factors and Test Methods*, Highway Research Board, National Research Council, Washington, D.C. (1956) pp. 1–28.
17. Brokaw, M.P., "Development of the Road Meter: 1965 to 1972," in *Highway Research Board Special Report 133: Pavement Evaluation Using Road Meters*, Highway Research Board, National Research Council, Washington, D.C. (1973) pp. 17–19.
18. Gillespie, T.D., M.W. Sayers, and L. Segel, *NCHRP Report 228: Calibration of Response-Type Road Roughness Measuring Systems*, Transportation Research Board, National Research Council, Washington, D.C. (December 1980) 81 pp.
19. Spangler, E.B. and W.J. Kelly, "GMR Road Profilometer—A Method for Measuring Road Profile," in *Highway Research Record No. 121: Pavement Design and Evaluation: 3 Reports*, Highway Research Board, National Research Council, Washington, D.C. (1966) pp. 27–54.
20. Spangler, E.B., "Inertial Profilometer Uses in the Pavement Management Process," in *Transportation Research Record 893: Distress Measurement and Interaction of Vehicles with Pavement Surfaces*, Transportation Research Board, National Research Council, Washington, D.C. (1982) pp. 20–21.
21. Hudson, W.R., "High-Speed Road Profile Equipment Evaluation," in *Highway Research Record No. 189: Design, Performance, and Surface Properties of Pavement: 9 Reports*, Highway Research Board, National Research Council, Washington, D.C. (1967) pp. 150–163.
22. Carmichael, R.W., "State-of-the-Practice of Roughness and Profile Measuring Technology," paper presented at the Second North American Conference on Managing Pavements, Toronto, Ontario, Canada (November 1987) pp. 3.259–3.272.
23. Gillespie, T.D., M.W. Sayers, and M.R. Hagan, "Methodology for Road Roughness Profiling and Rut Depth Measurement," Report No. 86-54, University of Michigan Research Institute for Federal Highway Administration, Report No. FHWA/RD-87-042 (December 1987).
24. "Guide Specifications for Highway Construction," American Association of State Highway and Transportation Officials, Washington, D.C. (1988) 283 pp.
25. Capper, M., "Keys to Pavement Smoothness: A Paving Superintendent's Viewpoint," paper presented at the American Concrete Pavement Association National Ride Workshop, Kansas City, Mo. (1987).
26. Jensen, C.C., "Pavement Smoothness," paper presented at the American Concrete Pavement Association National Ride Workshop, Kansas City, Mo. (1987).

27. Hudson, W.R., W. Uddin, and G. Elkins, "Smoothness Acceptance Testing and Specifications for Flexible Pavements," paper presented at the Second North American Conference on Managing Pavements, Toronto, Ontario, Canada (November 1987) pp. 3.331–3.362.
28. Walker, R.S. and H.T. Lin, "Profilograph Correlation Study with Present Serviceability Index (PSI)," Report No. 569-1F, FHWA-DP-88-072-002, Texas State Department of Highways and Public Transportation, Austin, Tex. (March 1988).
29. Temple, W.H. and S.L. Cumbaa, "Serviceability Index Base for Acceptance of Jointed Concrete Pavements," in *Transportation Research Record 1196: Pavement Evaluation and Rehabilitation*, Transportation Research Board, National Research Council, Washington, D.C. (1988) pp. 251–256.
30. Kulakowski, B.T. and J.C. Wambold, "Development of Procedures for the Calibration of Profilographs," Pennsylvania Transportation Institute, Report No. FHWA-RD-89-110 (August 1989).
31. Paterson, W.D.O., "International Roughness Index: Relation to Other Measures of Roughness and Riding Quality," in *Transportation Research Record 1084: Pavement Roughness and Skid Resistance*, Transportation Research Board, National Research Council, Washington, D.C. (1986) pp. 49–59.
32. Sayers, M.W., T.D. Gillespie, and C.A.V. Queiroz, "The International Road Roughness Experiment: A Basis for Establishing a Standard Scale for Road Roughness Measurements," in *Transportation Research Record 1084: Pavement Roughness and Skid Resistance*, Transportation Research Board, National Research Council, Washington, D.C. (1986) pp. 76–85.

APPENDIX A

SURVEY OF PAVEMENT-SMOOTHNESS SPECIFICATIONS AND TESTING EQUIPMENT

The purpose of this survey is to gather information on the various types of specifications and testing equipment in current use for acceptance testing with respect to the smoothness of new pavement construction as well as the smoothness of various treatments being used to restore good riding qualities to older pavements. It is hoped to establish the relative capabilities and effectiveness of the strategies and also to determine general trends that may be taking place. Your cooperation in answering the questions and in providing the supplemental information requested will be appreciated by specifying agencies and the construction industry, who have a common interest in this subject.

1. Please indicate, by placing an "x" in the blanks provided, the types of equipment that are utilized by your agency for the various categories of construction on "mainline" pavements.

	New Construction			Overlays			Profile Correction by Milling or Grinding	
	AC	PCC	Bridge Decks	AC over AC or PCC	Thick PCC over AC or PCC	Thin PCC over PCC	AC	PCC
a. Straightedge								
b. Profilograph								
California Type								
Rainhart								
c. Mays meter								
d. PCA Roadmeter								
e. Law Profilometer 960								
f. Law Surveyor 8300								
g. BPR Roughometer								
h. Other (Describe)								

NOTE: The following example is shown to aid in answering Question 2:

	AC	PCC	Bridge Decks	AC over AC or PCC	Thick PCC over AC or PCC	Thin PCC over PCC	AC	PCC
a. Straightedge	x 1	x 2		x 1	x 2	x 2	x 1	x 2
b. Profilograph California Type		x 3			x 3			x 4

(1) .01' from lower edge of 12' straight edge
(2) .02' " " " " " " "
(3) 7 inches per mile
(4) 10 " " "
(5)
(6)

2. Describe the acceptance limits that your agency typically uses for the types of pavement shown in Question 1. Do this by adding code numbers after the x's given in #1 and providing appropriate explanations as indicated in the example shown above.

(1) ____
(2) ____
(3) ____
(4) ____
(5) ____
(6) ____

3. For the devices listed in Question 1 (other than a straight-edge) please describe smoothness acceptance limits that your agency uses on other than "mainline" pavements and/or on short radius curves. ____

4. If a "blanking band" or some other form of test tolerance is used, please define: ____

5. If you have a tolerance limit for individual bumps, please describe. ____

6. Please provide comments on the following items with respect to the equipment you are currently using.

a. Equipment type ____

b .Manufactured by ____

c. Durability of equipment/Ruggedness ____

d. Repeatability of results ____

e. Approximate cost ____

f. Operator training required ____

7. a. How is acceptance testing equipment calibrated? ____

b. How often? ____

8. a. Once the smoothness-measuring device arrives at the project site, what steps are necessary to prepare it for operation? ____

b. How long a time period is involved? ____

9. What is the operating speed of the unit? ____

10. At what point in time is the pavement surface typically evaluated? Same day ____ Next day ____ End of paving ____ Other ____

11. How much pavement, in terms of lane miles, is evaluated in a typical work day? ____

12. How much time is required to analyze the data? ____

13. a. Who provides the testing equipment?
Agency ____ Consultant ____ Contractor ____
b. Who provides the data reduction?
Agency ____ Consultant ____ Contractor ____

14. If agency owned, how many devices do you currently have available for use? ____

15. Is the equipment relatively maintenance free? ____

16. Are repairs normally the type that can be accomplished in the field or a small machine shop or does the equipment need to be taken to a specialist? ____

17. What are the primary performance problems associated with its use? ____

18. a. Is the rideability/smoothness specification used by your agency considered to be totally successful in achieving the desired results? ____
b. If yes, to what do you attribute the reason? ____
c. If no, to what do you attribute the reason? ____

19. What is the primary reason(s) that this particular device was selected by your agency? ____

20. What are its principal advantages?________________________

21. What are its principal disadvantages?________________________

22. How long has your agency been using the device that you are currently using for acceptance testing?________________________

23. a. How is your smoothness-testing approach generally accepted by the industry?________________________

b. By your field personnel?________________________

24. What operations are involved in locating the high points that need to be addressed in the profile correction?________________________

25. If your agency has made any major changes in smoothness specifications in the last 3 years please describe. From________

To________________________

26. If you contemplate any changes in the foreseeable future, in specifications or equipment what direction are these likely to take? From________________________

To________________________

27. In this question we are attempting to establish the approximate levels of smoothness that are being achieved on the construction of mainline pavements with both asphalt and concrete surfaces. To do this we ask that you take the smoothness level that your agency uses, divide it into three approximately equal categories, and indicate the proportion of new pavement construction that falls in each category. Include a category for pavement that falls outside the acceptance limit, even though that category may be ultimately corrected by pavement grinding. As an example, if a Profile Index of 7" per mile is specified, the categories could be 0-2; 2-5; 5-7; and >7. The corresponding percentages could be 50; 30; 18; and 2. With this in mind, please fill in the following table:

Asphalt pavement Acceptance limit________________

Lower 1/3	Range____to____	Percentage______
Mid 1/3	Range____to____	Percentage______
Upper 1/3	Range____to____	Percentage______
Exceeds limit		Percentage______

Concrete pavement Acceptance limit________________

Lower 1/3	Range____to____	Percentage______
Mid 1/3	Range____to____	Percentage______
Upper 1/3	Range____to____	Percentage______
Exceeds limit		Percentage______

28. a. Do you employ monetary incentives and/or disincentives as part of the pavement-smoothness specification?________________

b. What are they?________________________

29. How were the incentive/disincentive levels arrived at? (Research study, engineering judgment, panel, other.)__________

30. What percentages of completed pavements employing these clauses have involved a. a net monetary incentive?____________ and b. a net monetary disincentive?________________ c. remedial action by the contractor?________________

Possibly there are questions where there was not adequate space to provide a complete answer. If so, you are invited to furnish supplemental information at your discretion.

Also, we would appreciate your providing the following types of information:

1. A copy of the smoothness specifications currently being used by your agency for the various types of construction.

2. A copy of each research report or special study, including memo reports that have been prepared by your agency that express findings and concern for the subject.

3. Photographs of the equipment if they are conveniently available.

4. The following information on the rater: (Optional)

Name________________________
Title________________________
Agency________________________
Address________________________
________________________Zip________
Phone________________________

APPENDIX B

TABULATION OF RESPONSES TO SURVEY QUESTIONS

Question 1. Types of equipment in current use-number of agencies using.

	New Construction			Overlays			Profile Correction by Milling or Grinding		Total Number of Agencies Using Device
	AC	PCC	Bridge Decks	AC over AC or PCC	Thick PCC over AC or PCC	Thin PCC over PCC	AC	PCC	
a. Straightedge									
Stationary	33	22	25	29	10	7	11	8	33
Rolling	5	3	5	3	-	-	1	2	5
b. Profilograph									
California Type	7	22	2	5	11	2	4	15	25*
Rainhart	1	4	2	-	1	1	-	3	6
c. Mays meter	3	3	-	2	1	-	2	4	6
d. PCA Roadmeter	-	0	-	-	-	-	-	-	-
e. Law Profilometer	-	2	-	-	-	-	-	1	2
f. Law Surveyor 8300	-	-	-	-	-	-	-	1	1
g. BPR Roughometer	-	-	-	-	-	-	-	1	-
h. Other (Describe)	-	-	-	-	-	-	-	-	-

* A review of the 1987 AASHTO survey indicates that three of the states that did not respond to this survey had indicated using the California profilograph. Thus, a more accurate estimate of the number of states currently using that instrument is 28.

Question 2(a). Summary of the acceptance limits associated with use of straightedges.

STATIONARY STRAIGHTEDGES

	NEW			OVERLAY			REPROFILE	
10-long	ACP	PCCP	BR. DECK	ACP/ACP	THICK PCCP	THIN PCCP	ACP	PCCP
1/16"			1	1	1	1		
1/8"	8	10	14	8	5	4	4	4
3/16"	9	2	2	7			2	
1/4"	6	4	5	4	1		1	2
0.02'	1	1		1				
12'-Long								
0.01'	1		1	1				
0.015'	1			1			1	
0.02'	1	2	1	1	1	1	1	1
15'-Long								
1/4"		1			1	1	1	
16'-Long								
1/4"	4	1		4	1			1
3-Meters								
3mm	1	1	1	1				
6mm	1			1			1	

ROLLING STRAIGHTEDGES

	NEW			OVERLAY			REPROFILE	
	ACP	PCCP	BR. DECK	ACP/ACP	THICK PCCP	THIN PCCP	ACP	PCCP
10'-Long								
1/8"	2	1	3	1				1
3/16"		1	1					
0.01'	1	1	1	1				
0.02'								1
15'-Long								
3/16"	2			1			1	

Question 2(b). Summary of the acceptance limits associated with the use of the California and Rainhart profilographs.

	NEW			OVERLAY			REPROFILE	
	ACP	PCCP	BR. DECK	ACP/ACP	THICK PCCP	THIN PCCP	ACP	PCCP
California								
7"/mile	2	10		2	6	1		3
10"/mile	1	4			1		2	3
12"/mile	3	6	1	3	4	1	1	6
15"/mile		2						2
30"/mile			1					
Project Specific	1						1	1
Rainhart								
3"/mile								1
5"/mile	1							
7"/mile		1						1
12"/mile		3	1		1	1		1
15"/mile			1					

PROFILOGRAPHS-BUMP GRINDING

	States
California	
Blanking band-0.2"	25
Bump grinding template	
0.3"/25'	16
0.4"/25'	4
0.5"/25'	5
Rainhart	
Blanking band-0.1"	4
Blanking band-0.2"	2
Bump grinding template	
0.2"/25'	1
0.3"/25'	5

Question 2(c,e,f,g). Summary of acceptance limits using the equipment listed.

	New Construction AC	New Construction PCC	New Construction Bridge Decks	Overlays AC over AC or PCC	Overlays Thick PCC over AC or PCC	Overlays Thin PCC over PCC	Profile Correction by Milling or Grinding AC	Profile Correction by Milling or Grinding PCC
Mays Meter 35 in/mi	2	1		1				
45 in/mi							1	
50 in/mi								1
55 in/mi								1
65 in/mi		1			1			1
70 in/mi							1	
100 in/mi		1						
3.6 R.I.	1			1				
78 W								1
Law 690 100 in/mi		2						
Law 8300 85 in/mi								1
BPR 80 in/mi								1

Question 3.

Of the 31 agencies using a profilograph, 11 report using a higher acceptance limit on short radius curves than on main line alignment.

Question 4.

All 25 agencies using the California profilograph report using a 0.2" blanking band. Of the 6 agencies using the Rainhart, 4 use a 0.1" blanking band and 2 use a 0.2" blanking band.

Question 5.

Tolerance limits for individual bumps for agencies using profilographs are as follows:

	No. of States
California profilograph	
0.3" in 25'	16
0.4" in 25'	4
0.5" in 25'	5
Rainhart profilograph	
0.2" in 25'	1
0.3" in 25'	5

Question 6.

Information was not provided on all pieces of equipment by agencies using more than one type. A tabulation of pertinent information follows with the first number indicating the number of agencies reporting on that item.

Type of Equipment	Manuf. by
5 - Rainhart	5 - Rainhart Co.
25 - California	13 - McCracken
	5 - Ames
	1 - Soil test
	8 - Cox
	9 - Macbeth
6 - Mays	6 - Rainhart Co.
1 - Wisconsin	1 - Agency
3 - Law	3 - K. J. Law

All agencies reported "good" or "very good" with respect to the durability and repeatability of the chosen equipment except two which reported both "fair" for the California profilograph. Cost data varied considerably because of date purchased. Current costs are discussed in the report.

All agencies agreed that some training was necessary in the use of smoothness-testing equipment. With the profilograph, either California or Rainhart, 22 agencies indicated that this could be done in 4 hours or less, while 5 indicated that from 6 hours to 2 days was required. The users of the Mays meters and Law equipment indicated that training was more involved and that up to two weeks may be required.

Question 7a.

Profilograph users check to see if the equipment is in calibration by using blocks of known thickness for checking the vertical scale and by running the unit over known distances for checking the horizontal scale.

Question 7b.

The stated frequency of checking the calibration is as follows:

Frequency	No. of Agencies
Daily	4
At beginning of project	9
As needed	4
Monthly	1
Twice a year	2
Once a year	4

Calibration of the Mays meter is reportedly done as often as once every two weeks and as seldom as once a year. Standard pavements or "control sections" are usually used in calibration.

The one user of the Law 690 reports that its calibration is checked once a year over a standard test section of pavement.

Question 8a.

For the Rainhart, the road wheels are retracted and the recorder is positioned. The California unit normally consists of several components that need to be assembled at the site. This includes three to five units comprising the frame, wheel assemblies, steering components, and the recorder.

Question 8b.

Set up and assembly time for profilographs varies as follows: Less than 15 minutes, (4); 15-30 minutes, (7); 30-60 minutes, (4); 60-90 minutes, (5) greater than 90 minutes, (3).

Question 9.

Operating speed of profilograph units is reported to be: 3 mph, (26); 2 mph, (2) and 5 mph (1). The Mays and Law units are operated at 50 mph or at traffic speeds.

Question 10.

Profilographs are normally operated as soon as possible. This could be the same day as construction for AC pavements, for pavement grinding or milling, and occasionally for PCC pavements. Twenty-nine agencies reported operating profilograph equipment "as soon as possible" or on the day following construction. Mays and Law equipment is normally operated at the end of paving.

Question 11.

Thirteen agencies indicated that profiling up to 3 lane miles was a typical day's effort, while 6 agencies indicated that from 3 to 8 lane miles were covered. For the Law and Mays equipment from 10 to 40 miles per day was considered typical.

Question 12.

Most agencies find that they spend about 2 hours in evaluating profilograms. However, users of the Cox computerized California profilograph and users of the Mays meters and Law equipment have their analysis available instantaneously.

Question 13.

Nineteen agencies provide profilograph testing equipment for smoothness evaluation. Nineteen agencies require the contractor to provide profilograph equipment. Twenty-five agencies do the data reduction regardless of whether the profilographs were obtained by the contractor or with their own forces. Four agencies require the contractor to do the data reduction with periodic checks by the agency.

States using smoothness-testing equipment other than the profilograph type own and operate the equipment themselves. In at least one state, contractors operate profilograph equipment to precisely locate and evaluate surface irregularities in order that they can effectively complete the necessary corrective grinding.

Question 14.

For agencies using profilographs, the number of units in their possession is as follows:

No. of units	No. of agencies
0	6
1-5	18
6-10	3
10-15	2
15-20	1

For Mays meters

0	1
2 or 3	4
9	1

The agencies using Law equipment or the BPR Roughometer each have a single unit.

Question 15.

Most agencies indicate that their equipment is relatively maintenance free as tabulated below

Type	Total Users	Maint. Free Yes	Maint. Free No	Don't Know or No Comment	Somewhat
California	25	19	3	3	
Rainhart	6	4		1	1
Mays	6	3	1	2	
Law 690	2	2			
Law 8300	1	2			

Question 16.

Repairs to all equipment are usually of a minor nature and can be taken care of in the field or a small machine shop. Exceptions to this are the computerized profilographs and the Law equipment that occasionally need the attention of a specialist.

Question 17.

The primary performance problems reported are as follows:

Type	Recorder Problems	Poor Reproducibility	Slow Speed	Calibration	Averaging Wheels
California	4	1	6		
Rainhart	3				2
Mays		1		2	
Law 690					
Law 8300					

Question 18.

The degree of success being achieved by the rideability/smoothness specification in use by an agency is indicated in the following tabulation:

Equip. Type	Yes	Good Spec.	Good Test	No.	Contractor Problems	Need Better Spec.	Not Know
California	13	13	12	4	3	3	3
Rainhart	5	3	3				1
Mays	4	3	3				
Law 690							
Law 8300							

Question 19.

The primary reasons for the selection of a given piece of equipment by an agency are shown in the following table, which shows the number of agencies using the given reasons:

Equipment Type					
Calif. Prof.	Rainhart Prof.	Mays Meter	Law 690	Law 8300	Reasons for Selection
11	2	1			Experience of other users
7		3			Ease of operation, simplicity
5	2	3			Low cost of equipment
5					Early application on new pavement
2					Provide a permanent record
2	2				Repeatability
2					Low Maintenance
1					Research and Development
1	2	2			Availability at time of purchase
1					AASHTO recommended specification
1					ACPA recommended specification
1					Administrative decision
			1		Ability to measure ride
1					Computer feature saves time
			1		Immediately useable data

Question 20.

The principal advantages of a piece of equipment are shown in the following table, which indicates the number of agencies using the stated advantage:

Equipment Type					
Calif. Prof.	Rainhart Prof.	Mays Meter	Law 690	Law 8300	Principal Advantage
11	3	1			Ease of operation, simplicity
9					Repeatability
6					Early application on new pavement
5					Define and locate pavement features
3					Provide complete coverage
2					Low cost
2					Not known
1					Computer provides instant results
			1		Ability to measure ride
			1		Absolute accuracy

Question 21.

The principal disadvantages of a piece of equipment are shown in the following table, which indicates the number of agencies stating the disadvantage.

Equipment Type: Calif. Prof.	Rainhart Prof.	Mays Meter	Law 690	Law 8300	Disadvantage
9					Slow speed of operation
5					Data reduction is time consuming
2					Assembly/disassembly time
2					Not known at this time
1					Difficult to turn
1					Computer breakdowns
	2				Variance in evaluation
					Recorder problems
		3			Calibration problems
			2		High cost

Question 22.

The length of time that agencies have had equipment in use is as follows:

Equipment Type: Calif. Prof.	Rainhart Prof.	Mays Meter	Law 690	Law 8300	Time period - Years
3	1				0-1
9	1		1		1-5
2	3	3			5-10
1		1	1		10-15
3	1	1			15-20
7					>20

Question 23.

The reported degree of acceptance as indicated below:

Equipment Type: Calif. Prof.	Rainhart Prof.	Mays Meter	Law 690	Law 8300	Degree of Acceptance
					By Industry:
3					Not Known
14	3	4			Good to Very Good
5					Fair ("OK")
			2		Mixed Feelings
					By Agency forces
3			2		Not Known
14	3	4			Good to Very Good
3					Fair ("OK")

Question 24.

The varied scope of the responses indicate that the question was not clearly stated and, therefore, no tabulation can be provided.

Question 25.

Changes in smoothness specifications in the last three years include the following:

Equipment Type: Calif. Prof.	Rainhart Prof.	Mays Meter	Law 690	Law 8300	Changes
17	2	4	1	1	None
2	1				To profilograph + straightedge
		1			PI 28" to 12"/mi.
1					PI 15" to 12"/mi.
1					PI 10" to 7"/mi.
	1				PI 7" to 5"/mi.
1					Penalty if above 7"/mi
1					Started PI spec. on AC
1					Relaxed regiments on curves.

Question 26.

Anticipated future changes include the following:

Equipment Type					
Calif. Prof.	Rainhart Prof.	Mays Meter	Law 690	Law 8300	Changes
16	4	4	2		None
1					Reduce PI from 15" to 12"/mi.
2					Reduce PI from 12" to 10"/mi.
1					Reduce PI from 10" to 7"/mi.
1					Reduce must grind limit from 0.5" to 0.3"
1					Increase penalty adjustments
		1			Go from Mays to Law Type equip.
1					Use Law Type w/penalty clause
1		1			Use So. Dakota type profilometer
2					Add PI on AC pavements
1					Add PI on local type roads

Question 27.

A tabulation of the approximate levels of smoothness being achieved by profilograph users in various categories of smoothness is as follows:

	AC			PCC														
("/mi.)	7	12		5	7					10		12						
L 1/3	10	10	45	35	10	30	20	20	60	20	10	10	30	15	3	3	60	10
M 1/3	50	40	40	30	20	50	68	75	30	50	75	30	40	40	17	45	27	25
V 1/3	19	45	14	30	60	19	10	5	8	20	14	50	25	40	70	47	9	45
X	1	5	1	5	10	1	2	0	2	10	1	10	5	5	10	5	4	20

("/mi.)	15		28
L 1/3	75	70	10
M 1/3	15	20	30
V 1/3	10	8	50
X		2	10

Where L, M, & U indicate Lower, Middle and Upper 1/3 of spec. range & X = exceeds spec. limit.

Question 28.

For the agencies using a profilograph 14 indicated that they do not use incentive or disincentive clauses relating to pavement smoothness and 16 indicated that they do use them. Two agencies had used them at one time but no longer do so. Of the 16 agencies using incentive/disincentive specifications, 5 report bonuses up to 5% of the bid price, 1 up to 4%, and 1 up to 2%. Four agencies have formulas of varying complexity in calculating final pay adjustments.

Twelve states report the use of a penalty schedule, and of these 12, 6 have an incentive or bonus clause and 6 have a disincentive or penalty clause only.

Of the agencies using a Mays meter, three do not use incentive/disincentive clauses and three do. Of the three that do, one uses a formula for calculating pay adjustments, and the other two do not use incentives but have a penalty schedule for disincentives for achieving low smoothness levels.

Question 29.

For the agencies that use incentives and/or disincentives, the reported manner by which the levels were selected is as follows:

a.	Engineering judgment	15 agencies
b.	Communication with other agencies	6 agencies
c.	AASHTO Guide Specifications	2 agencies
d.	ACPA Guide Specifications	2 agencies

Question 30.

Individual percentages of pavements being affected by the incentive/disincentive specifications as indicated by individual agencies are as follows:

a. Net monetary incentive payment:
0, 0, 0, 3, 3, 15, 30, 70, 100, 100, 100 (%)

b. Net disincentive - penalty:
0, 0, 2, 5, 5, 5, 5, 10, 15, 70, 100 (%)

c. Remedial action required:
2, 3, 5, 5, 30, 30, 95, 100, 100, 100 (%)
(There is apparently misinterpretation on this part of the question.)

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The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Samuel O. Thier is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Frank Press and Dr. Robert M. White are chairman and vice chairman, respectively, of the National Research Council.

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