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16. Abstract

Because both the highway agency and the traveling public desire a smooth pavement surface, there exists a need to ensure smoothness and ride quality. Indeed, a smooth road profile has become a standard measure of pavement quality. Smoothly constructed roads are associated with minimal vehicular wear (and therefore cost), user perceptions of quality and acceptability, and, finally, long pavement surface lives.

In 1987 the Texas State Department of Highways and Public Transportation (SDHPT) commissioned the Center for Transportation Research (CTR) to develop smoothness specifications for both flexible and rigid pavements. These standards were to be of the "end-use" variety; that is, the standards, applied after the contractor had completed paving a section, would be used to compare the as-built profile with that smoothness desired by the highway agency, using a designated instrument and measurement unit. Deviations from the acceptable profile range would result in either monetary rewards to the contractor for high-quality work exceeding standards, or corrections/penalties for work falling below standard. In 1984 AASHTO began conducting a survey into state smoothness specifications with the objective of recommending a draft smoothness specification for state use. This specification, reported in 1987, was to be evaluated as part of the CTR 1167 study.

This report, then, details the initial work on pavement smoothness criteria, including in particular the issues related to financial incentives and the instrumentation used for measuring profiles on newly laid rigid pavements.

17. Key Words
smoothness specifications, Profile Index (PI), financial incentive/penalty schemes, dynamic loads and drainage, profile components of roughness

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THE DEVELOPMENT OF SMOOTHNESS SPECIFICATIONS FOR RIGID AND FLEXIBLE PAVEMENTS IN TEXAS

by

Robert Harrison
Carl Bertrand

Research Report Number 1167-1

Research Project 3-8-88/1-1167

Develop Smoothness Specification for Rigid and Flexible Pavements

conducted for

Texas State Department of Highways and Public Transportation

in cooperation with the

U.S. Department of Transportation
Federal Highway Administration

by the

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Bureau of Engineering Research
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W. Ronald Hudson, P.E. (Texas No. 16821)

Research Supervisor

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PREFACE

This is the first report for Research Project 1167, "The Development of Smoothness Specifications for Rigid and Flexible Pavements in Texas." This research project was conducted by the Center for Transportation Research (CTR), The University of Texas at Austin, as part of the Cooperative Highway Research Program sponsored by the Texas State Department of Highways and Public Transportation. Specifically, this report describes the development of a pavement smoothness specification for use on both rigid and flexible pavements in Texas. And because compliance with such a specification would be determined by a designated instrument and measurement unit, this report, in addition, evaluates a host of pavement roughness profile measuring instruments.

Many individuals have provided valuable assistance in the completion of this report. In particular, the authors gratefully acknowledge the technical assistance provided by James M. Sassin of the Texas State Department of Highways and Public Transportation, who served as Technical Coordinator for this project. We also would like to thank the Center for Transportation Research staff members who assisted in various ways.

Robert Harrison
Carl B. Bertrand

LIST OF REPORTS

Research Report 1167-1, "The Development of Smoothness Specifications for Rigid and Flexible Pavements in Texas," by Robert Harrison and Carl Bertrand, describes the development of a pavement smoothness specification for use on both rigid and flexible pavements in Texas. In addition, it provides an evaluation of the measuring instrument most appropriate for use with such specifications. January 1991.

ABSTRACT

Because both the highway agency and the traveling public desire a smooth pavement surface, there exists a need to ensure smoothness and ride quality. Indeed, a smooth road profile has become a standard measure of pavement quality. Smoothly constructed roads are associated with minimal vehicular wear (and therefore cost), user perceptions of quality and acceptability, and, finally, long pavement service lives.

In the early years of highway paving operations, smoothness—and thus ride quality—was dependent upon motivated and experienced construction crews, most of whom used a straightedge to locate individual pavement deformities. As vehicle speeds increased, and as the Interstate program gathered pace, it became increasingly clear that these early methods were inadequate for ensuring smoothness and ride quality, and that some other, more rigorous measure of smoothness (as a measure of pavement quality) would be necessary. Efforts made in the late 1950's—the most important of which was the AASHO Road Test—continued to make progress toward a smoothness specification, but such efforts were ultimately limited in that they were merely subjective assessments and, hence, inappropriate for highway agency use.

In 1987 the Texas State Department of Highways and Public Transportation (SDHPT) commissioned the Center for Transportation Research (CTR), The University of Texas at Austin, to develop smoothness specifications for both flexible and rigid pavements. These standards were to be of the "end-use" variety; that is, the standards, applied after the contractor had completed paving a section, would be used to compare the as-built profile with that smoothness desired by the highway agency, using a designated instrument and measurement unit. Deviations from the acceptable profile range would result either in monetary rewards to the contractor for high-quality work exceeding standards or in corrections/penalties for work falling below standard. In 1984 AASHTO began conducting a survey into state smoothness specifications with the objective of recommending a draft smoothness specification for state use. This specification, reported in 1987, was to be evaluated as part of the CTR 1167 study.

This report, then, details the initial work on pavement smoothness criteria, including in particular the issues related to financial incentives and the instrumentation used for measuring profiles on newly-laid rigid pavements.

KEY WORDS: smoothness specifications, profile index (PI), financial incentive/penalty schemes, dynamic loads and drainage, profile components of roughness, profilograph

SUMMARY

This report describes the development of smoothness criteria for use on flexible and rigid pavements in Texas. Issues related to financial incentives are also discussed, especially with respect to the 1987 AASHTO recommended draft specification. In addition, this report presents an evaluation of those smoothness profile instruments that were determined to have potential for use with end-use specifications.

The report recommends that preliminary ride-quality specifications be based on the California-type profilograph, and that financial incentives and penalties be included as a way of encouraging high-quality work from contractors.

IMPLEMENTATION STATEMENT

End-use specifications, when accepted by the construction profession, would provide considerable benefits to such agencies as the Texas Department of Highways and Public Transportation. First, the responsibility for quality work in the production phase would pass to the contractor and not to state highway officials. Second, having such responsibility would result in a stronger commitment to quality on the part of the contractor, since it is the contractor who is in charge of the entire process and, where bonuses are awarded, stands to benefit financially. Finally, the implementation of end-use specifications would have benefits in terms of highway agency staffing levels, particularly as they relate to staff working on the site. For example, transferring manpower workloads to the contractor could reduce highway staffing requirements.

Thus, incentive and penalty end-use roughness specifications provide both the contractor and state highway agency with a mechanism for ensuring smoother pavements. They reward quality work, penalize faulty work, and are capable of evaluating quantitatively the ride quality of a pavement.

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CHAPTER 1. INTRODUCTION

BACKGROUND

In the pursuit of quality highway infrastructures, both the agency owning the highway and the users traveling over it desire a smooth pavement surface. Indeed, a smooth road profile has become a standard measure of pavement quality. Smoothly-constructed roads are associated with minimal vehicular wear (and therefore cost), user perceptions of quality and acceptability, and, finally, long pavement service lives.

In the early years of highway paving operations, smoothness—and thus ride quality—was dependent upon (1) motivated construction crews who closely followed paving equipment guidelines, (2) experienced state engineers making subjective judgments, and (3) the use of a straightedge to locate individual pavement deformities. As vehicle speeds increased, and as the Interstate program gathered pace, it became increasingly clear that these early methods were inadequate for ensuring smoothness and ride quality, and that some other, more rigorous measure of smoothness (as a measure of pavement quality) would be necessary.

In the late 1950's, subjective panel assessments provided the basis for determining the relationship of performance standards to ride quality. One such panel assessment, formalized as the Present Serviceability Index (PSI), was developed at the AASHO Road Test (Ref 1) and consisted of a five-point scale quantifying the subjective ratings of both ride quality and pavement condition, as determined by a panel of experienced highway users. Yet for reasons of speed, cost, and consistency, panel ratings were determined to be inappropriate for highway agency use (even though in the case of PSI they were found to correlate very highly with pavement roughness). Consequently, direct measures of pavement roughness have become the preferred basis for evaluating performance standards.

In 1987 the Texas State Department of Highways and Public Transportation (SDHPT) commissioned the Center for Transportation Research (CTR), The University of Texas at Austin, to develop smoothness specifications for both flexible and rigid pavements. These standards were to be of the "end-use" variety; that is, the standards—applied after the contractor had completed paving a section—would be used to compare the as-built profile with that smoothness desired by the highway agency, using a designated instrument and measurement unit. Deviations from the acceptable profile range would result either in monetary rewards to the contractor for high-quality work exceeding standards or in corrections/penalties for work falling below standard. The CTR study was considered appropriate in view of a reported decline in the PSI values of newly-constructed and overlaid sections in Texas (Ref 2), where values were found to be near the 50th percentile value of 2.9 PSI reported in the original PSI acceptability tests. (Texas has not been unique in this respect: lower PSI values for newly constructed pavements have been reported by a number of states which have already incorporated more detailed end-use specifications in an attempt to raise pavement ride quality.) In 1984 AASHTO began conducting a survey into state smoothness specifications with the objective of recommending a draft smoothness specification for state use. This specification, reported in 1987 (Ref 3), was to be evaluated as part of the CTR 1167 study.

The current Texas end-use acceptance specification is based on the use of the 10-foot straightedge (Ref 4) as the roughness measuring instrument, allowing a plus or minus 1/16-inch deviation from any 10-foot length of pavement measured with the straightedge. There are serious drawbacks to using this specification. First, while it detects some fluctuation in vertical profile from the straightedge data (bumps), it cannot report any rate of repetition for such deviations over some longitudinal or transverse distance. Second, it is not sensitive to ride quality or to associated pavement profile characteristics experienced by road users. Third, it contains no measure of roughness wavelength or recurrence interval. Finally, it cannot provide criteria for either pavement acceptance or contractor penalty/bonus payments. CTR research was therefore directed toward developing an improved specification based on a pavement roughness measuring device that was robust, portable, easy to operate, inexpensive, and economical to maintain.

STUDY OBJECTIVES

The central objectives of the three-year Project 1167 study were, first, to select a smoothness device and, second, to develop an improved end-use profile specification that could be applied to the testing and acceptance of newly-constructed or overlaid flexible and rigid pavements. Criteria used in the selection of the specification included consideration of its ease of implementation and administration statewide, with particular preference given to a structure that would not prompt legal action on the part of contractors. In addition, the new specification was to be responsive both to the objective components of longitudinal pavement roughness and to the subjective considerations of ride quality. The new smoothness specification, moreover, would need to provide incentives for contractors to build pavements of higher quality. In one possible incentive plan, for example, completed work rated toward the smoother end of the roughness scale adopted in the new specification could entitle a contractor to some type of bonus reward, while work assessed to be in the rougher end could make the contractor either liable for penalty payments or responsible for timely corrective actions.

DEFINITIONS

Smoothness and Roughness: Smoothness and roughness are different values of a scalar function describing a variety of absolute surface profiles, including the different wavelengths and amplitudes of which they are composed; these profiles vary somewhat with the type of surface (Ref 5). It is the interaction of these profile elements with vehicle suspension and tire responses which gives rise to user perceptions of discomfort and vehicular changes. As a consequence, the impact on vehicle responses of such profile characteristics as elevations, slopes, and accelerations has received much attention in the development of a measurement for roughness (Ref 6), currently defined by the American Society for Testing and Materials (ASTM) as "the deviations of a surface from a true planar surface having characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads and drainage" (Ref 5).

Dynamic Loads and Drainage: While vehicle dynamics and ride quality are associated with user acceptance, dynamic loads and drainage are factors determining service life. A user is adversely affected by any undesirable combination of surface profile, vehicle design characteristics, and travel speed. Increases in dynamic loadings by vehicles on the pavement surface accelerate its structural deterioration and shorten its service life. Highways should therefore be constructed to high standards of smoothness and structural strength (while meeting acceptable drainage and skid resistance specifications), since such characteristics are associated with good riding qualities and long service life. Standards imposed during, or immediately after, construction are one way of achieving such desirable objectives.

Profile Components of Roughness: There are three profile components comprising roughness—transverse, longitudinal, and vertical variations. While all impart vertical acceleration and yaw (in varying degrees, based on the combination of vehicle characteristics and speed), previous studies have established that longitudinal roughness is the major contributor to undesirable vehicle behavior (Ref 8). Consequently, it is this profile element which forms the current focus of standards for newly-constructed pavements.

SCOPE

This report, then, while detailing both the initial work on smoothness criteria and the issues related to financial incentives, primarily discusses the instrumentation used for measuring profiles on newly-laid rigid and flexible pavements.

Chapter 2 gives a brief history of the application of pavement smoothness specifications in the U. S. As this chapter reports, California was, in the early 1960's, the first state to develop end-use specifications built around dedicated instrumentation. As further reported, the move to apply more stringent end-use pavement quality controls in other states was slow in coming, but by the early 1980's there was broad national recognition that such standards were highly desirable. With this new interest came a need to address such issues as type, tightness and range of the specification, the instrument and measurement units chosen to report the profile, and the linking of financial incentives and penalties to such standards.

Chapter 3 identifies the components of a smoothness specification. Results of the 1987 AASHTO survey on rideability and state specifications are given, together with details of the recommended draft specification.

Chapter 4 reports the findings from (1) the first study literature review; (2) two technical surveys on related pavement profile quality issues; and (3) interviews with state engineers, contractors, and industry specialists. The set of pavement smoothness specifications developed by state highway engineers in Iowa is examined in particular.

Chapter 5 presents a range of smoothness profile instruments that have potential for use with end-use specifications. Because one of the objectives of Study 1167 is to designate an instrument for measuring pavement smoothness (including a related set of measurement units), each instrument is described and accompanied by illustrations. In this chapter, the results of the comparative testing and evaluation of the selected instruments tested at various pavement sites are presented; the attractiveness of each device as the controlling smoothness instrument is discussed and the choice narrowed (by use of a ranking procedure) to determine subsequent experimental testing and evaluation.

Chapter 6 assesses the performance of the California-type profilograph on rigid and flexible pavement sections. It suggests that, at this moment, ride specifications should be based on this particular profilograph, since it is an established device widely understood by contractors and state highway engineers, and because it has led to significant improvements in pavement ride quality.

Chapter 7 details and recommends preliminary ride quality specifications based on the California-type profilograph, with financial incentives and penalties included as a way of encouraging a high standard of work from contracting staff. The need to develop a variety of smoothness categories within an overall specification, based on the technical challenges and difficulties of building certain elements of the highway infrastructure, is also discussed. Finally, this chapter suggests directions for future research in the development of specifications for both flexible and rigid pavements.

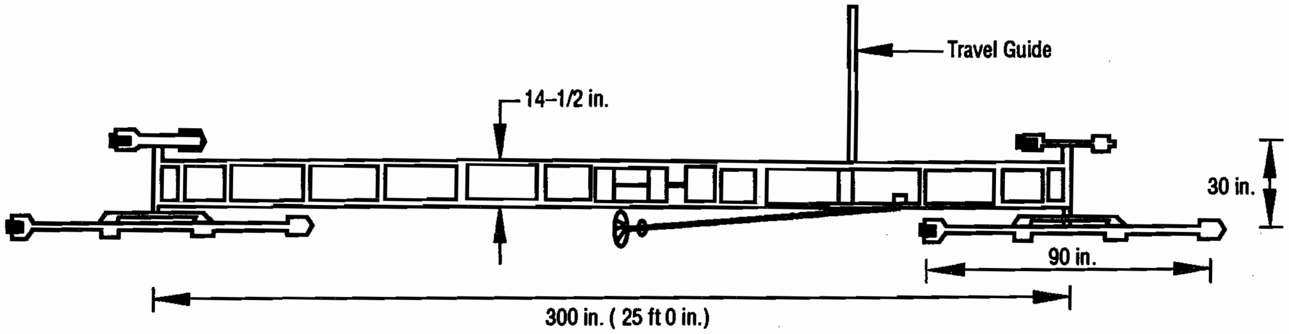
CHAPTER 2. DEVELOPMENT OF PAVEMENT SMOOTHNESS SPECIFICATIONS

INTRODUCTION

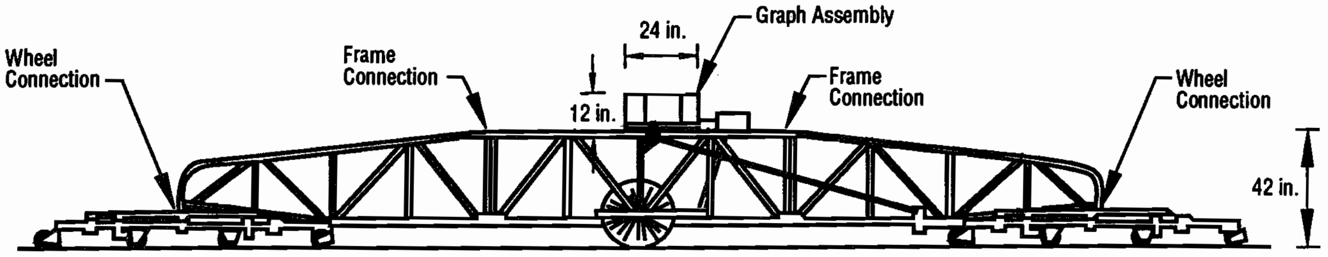
Although equipment for the measurement of pavement surface roughness has been available for almost sixty years (Ref 9), only since the late 1950's has such equipment been the subject of widespread interest—a consequence of both the AASHO road test and the funding of the Interstate highway program. The "serviceability-performance" evaluation system (Ref 10), reported in 1960 by AASHO road test researchers Carey and Irick, has, in particular, generated interest among engineers and planners. In developing this evaluation system, highway test sections were first profiled using the AASHO profilometer, a multi-wheeled, manually-operated device generating slope variance as a roughness measure; these same test sections were then rated subjectively by panels of highway users, with a regression then established between these two measures. The result was the present serviceability index—PSI—which is still used today. But because PSI panel values are both expensive and inconvenient to establish, considerable effort has since been made to relate PSI scores to the output of mechanical and non-contact devices that could be used to monitor pavement performance over highway networks.

The research emphasis on recording pavement serviceability as a way of monitoring and managing networks underscored the need to develop devices capable of generating numerical values for application at the project level. At the same time, the Interstate program, in calling for the rapid development of a national network of durable, high-quality pavements, in the late 1950's attracted the attention of state highway engineers responsible for maintaining quality control standards. Thus, the possibility of using, during construction, an instrument more effective and precise than the 10-foot straightedge (typically used to check pavement surfaces) generated industry-wide interest.

California became one of the first states to address this issue when in the early 1960's it began to apply longitudinal roughness to construction quality controls. Such measurements were made possible through the development (by one of its state highway engineers, Francis Hveem) of a manually-operated, multi-wheeled, vertically-traveling, offset measuring instrument for pavement profile determination (Fig 2.1). The device, known as the California profilograph, records the pavement surface profile on a paper roll from which a



Top View



Side Elevation

Fig 2.1. California profilograph.

Profile Index (PI), in units of inches per mile, can be interpreted. Previously, a straightedge (usually 10 feet) was employed to check surface roughness behind the paver; corrections were required wherever deviations exceeded some specified depth, for example 1/8 inch. In the 1960's California changed its acceptance specifications to include its profilograph, but up until the 1980's few other states followed this example. Such reluctance was due partly to the feeling that existing specifications were adequate, and partly to the fact that all measuring instruments—including the profilograph—exhibited certain inherent problems. For example, some monitoring and calibration profile devices, because they were required to be either mounted inside, or pulled by vehicles, were consequently too heavy to operate on newly-placed concrete pavements during the initial curing stages. In addition, the dynamic operation of such devices sometimes made it difficult to locate pavement surface defects accurately, where corrective action was required.

Yet highway officials continued to be concerned about pavement quality control, and they therefore moved to change their construction acceptance specifications. The California profilograph was invariably adopted as the control device, despite reported repeatability problems (Ref 12) associated with its difficulty in isolating the effect of long wavelengths in the pavement profile. Financial inducements, discussed below, have also been used more frequently by highway officials to elicit the desired quality from the contractor.

FINANCIAL INCENTIVES AND PENALTY SCHEMES

The provision of penalty or bonus systems, either separately or in combination, has been incorporated in a number of other highway acceptance standards—for example, pavement thickness. Proponents of incentive schemes believe that contractors will ensure that their product meets or exceeds control standards if there exists the potential for sufficient financial rewards. Furthermore, when contracts are being let, well-managed contractors will take some or all of the bonus into account when developing their bids, in effect discounting the bonus elements into the base price. Such considerations, proponents believe, may have the desirable effect of restricting the success of cut-price contractors on highway work, resulting in benefits that exceed a simple assurance of surface profile quality.

Incentive schemes should be guided by three "E's" —equity, enforcement, and effectiveness—so that standards are perceived to be fair, enforceable by highway engineers, and capable of providing the desired effect. It has been suggested (Ref 13) that incentive schedules should retain payments at the time of construction to cover the extra future cost forecast as a result of substandard work. CTR staff, however, believe that such a feature would not meet the equity criterion, since forecasting the timing and extent of the deficiency would be extremely difficult and contentious, particularly with respect to determining withholding values. Therefore, even at this stage in the study, it seemed appropriate to concentrate on practices that would deal with deficiency issues as they arose within the contract period, rather than deferring them to some future date after the work was completed.

The financial elements of bonus, acceptance, and penalty clauses need to be structured as simply as possible, on the assumption that complexity obscures effectiveness. But obtaining such structural simplicity becomes problematic when a stepped, rather than a continuous, incentive scheme is adopted. Moreover, stepped schemes raise the issue of fairness with respect to both the breaks between steps and the ability of the chosen measuring device to position a profile accurately within the stepped categories. Taking a hypothetical bonus section as an example, is it equitable that a PI profile in the 5- to 7-inch range gets a 1 percent bonus, while a PI profile in the 0- to 3-inch range gets 5 percent? Is it five times better, or is the bonus allocated in an arbitrary rather than a scientific manner?

The basis for computing the values, particularly as they relate to the financial consequences of both good and poor-quality work, represents another major problem with pay rewards. This problem can be illustrated by considering the example of rewards for meeting consolidation standards in concrete pavement construction work. The effect of consolidation on compressive strength can be determined by first estimating flexural strength and then inputting this value into the AASHTO design guide equation (Ref 14), which predicts equivalent single axle loads as a function of several parameters, including this variable. As we know, the effect of consolidation on pavement service life can be dramatic. A 1987 FHWA report (Ref 15) shows that for straight-line traffic growth and for a 600-psi (4.1-MPa) flexural strength at 100 percent consolidation, predicted service life falls from a designed 20-year life to 10.4 years at 95 percent consolidation and to 5.4 years at 90 percent consolidation. The financial ramifications of these data cannot be directly reflected in penalty clauses, since the costs associated with such truncated service lives overwhelm construction costs, particularly if user costs, in addition to agency costs, are considered. On even a lightly-trafficked highway, the cost savings realized through the prolongation of service life by only a few years dwarf the bonus payments contemplated by even the most generous incentive scheme.

SUMMARY

Because the calculation of direct benefits or costs does not seem to be the appropriate benchmark for bonus or penalty payments, some other means for determining levels has to be developed. It may be appropriate to identify here those specific issues within each acceptance category, namely:

(1) an inducement level to assure high-quality work;
(2) a nominal acceptance range that reflects adequate ride quality and service life;
(3) an adjusted payment schedule for acceptance at a slightly deficient standard; and
(4) a level where ride quality would be unacceptable and service life reduced.

Project 1167 staff attempted to establish the acceptable range and then determine the level beyond which ride quality becomes unacceptable. Bonus limits could then be established and a continuous function fitted through the stepped categories shown in Fig 2.2. Such functions could take various forms. One method would be to fit two non-linear relationships through the bonus and conditional acceptance stages while retaining the linear acceptance category. Such an arrangement, however, is rather cumbersome to implement and somewhat inequitable. If it is desirable to obtain higher levels of smoothness, then a continuous function throughout the entire range of acceptable values might represent a more reasonable arrangement. Based on Fig 2.2, a contractor would receive a financial incentive for all changes in smoothness over the range of non-mandatory values. Further statistical modifications (to be considered at a later stage of the study) could be devised to incorporate the variability of the chosen measurement device.

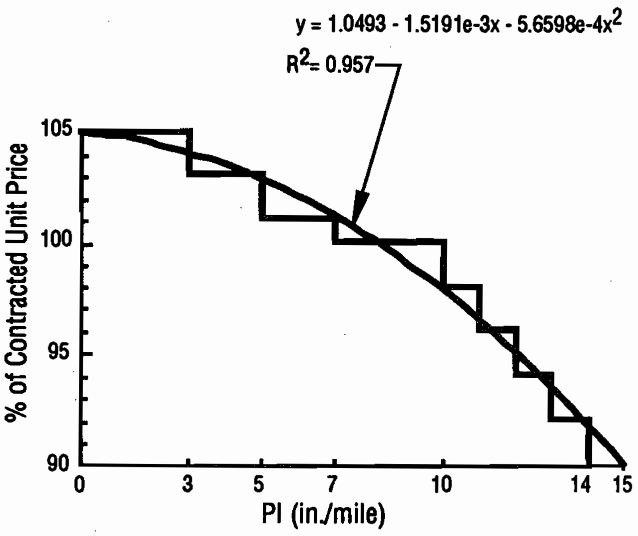


Fig 2.2. Continuous function fitted through bonus and acceptance PI ratings.

Having determined the need for a smoothness specification and its constituent elements, study staff undertook to evaluate current state practices. The next chapter, then, begins this evaluation process with a review of the various AASHTO surveys carried out in this area since 1980. In particular, the survey findings—including the characteristics of the first 1167 rigid smoothness specification—are discussed.

CHAPTER 3. AASHTO RIDEABILITY SURVEY AND DRAFT 1167 STUDY SPECIFICATIONS

BACKGROUND

By the early 1980's, there was a consensus of support among state highway engineers for the adoption of standardized pavement quality smoothness specifications. As a consequence, AASHTO in 1984 conducted a survey for the purpose of identifying those states using smoothness controls, documenting their experience, and developing a unified set of recommendations. The results, based on thirty-nine responding states (Ref 16) and summarized in Table 3.1, provide insight into the current status of pavement ride quality specifications.

First of all, there are two main components in such a specification: (1) a ride element that evaluates the quality of the continuous longitudinal profile (typically from the wheelpath) and (2) a bump element that evaluates individual spot deformations (such as a dip) on the profile surface. The survey data, detailed in Fig 3.1, indicate that over 70 percent of the responding states used both a ride and a bump specification; 20 percent used a bump-only specification, while 8 percent used no smoothness specifications whatsoever. Bump deviations were almost always controlled using a tape measure and a 10-foot straightedge.

Responses regarding designated smoothness devices used to enforce state specifications are presented in Fig 3.2. The instrument of choice, as illustrated in the figure, appears to be the California-type profilograph, with around 70 percent of the responding states reporting using this instrument. (The California device relates to the Hveem design in that it incorporates wheelbase dimensions and specific wheel configurations. The majority of such devices are currently supplied by the McCracken Company, although other companies manufacture a California-type instrument.) Around 14 percent of the states reported using Rainhart devices (these instruments are manually-propelled, possess a rolling straightedge design, produce a profile trace based on single wheel deviations, and record these traces on paper output). Finally, 17 percent of the responding states reported using other devices, including Maysmeters and profilometers (though because of the profilometer's cost and weight, it is highly unlikely that any state uses that instrument as a smoothness acceptance device).

According to this survey, then, the profilograph appears to be the basic smoothness instrument used in

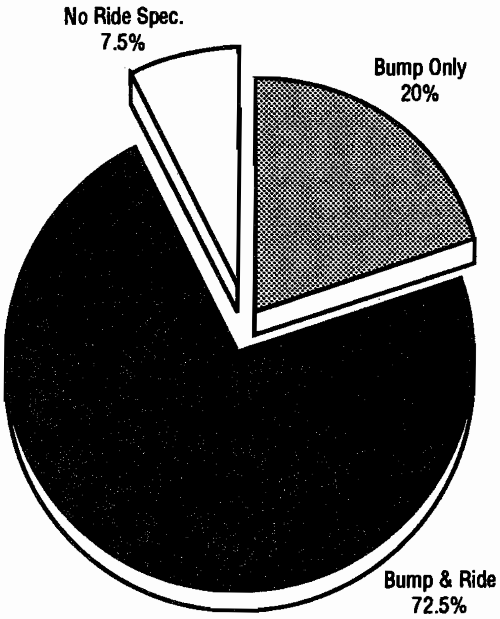


Fig 3.1. Percentage of states currently using bump or ride specification.

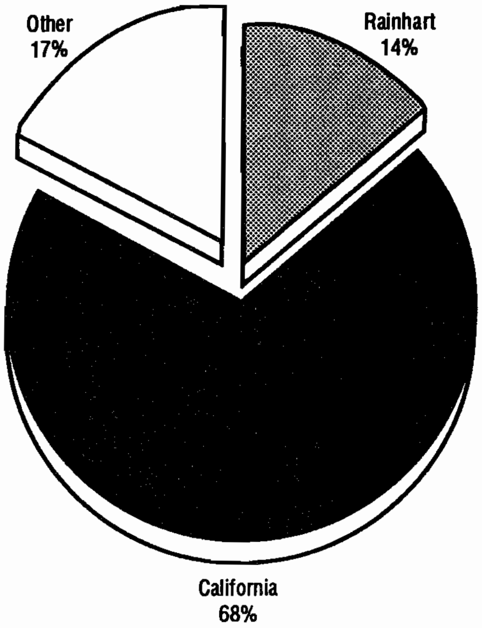


Fig 3.2. Type of pavement monitoring equipment.

TABLE 3.1 SUMMARY OF RESULTS OF THE 1987 AASHTO RIDEABILITY SURVEY

			Application Limitations				Monitoring Equipment							
State	Presently Use Ride Specification (?)	Presently Use Bump Specification (?)	AC Pavement Ride	Bump	PCC Pavement Ride	Bump	AC Pavement Ride	Bump	PCC Pavement Ride	Bump	Provides Equipment	Data Reduction	Monetary Incentives	Monetary Disincentives
Alabama	Yes	Yes	NA	No Limit	No Limit	NA	NA	10 ft edge	Rain 12"/mi	NA	Sha & Contr	Sha	NR	NR
Alaska	No	Yes	NA	No Limit	NA	NA	NA	10 ft edge	NA	NA	Sha	Sha	NR	NR
Arizona	Yes	Yes	NA	No Limit	No Limit	NA	NA	10 ft edge	Calf 7'/mi	NA	Sha	Sha	Yes	Yes
Arkansas	Yes	Yes	NA	NA	No Limit	No limit	NA	NR	Rain 12"/mi	Rainhart	Sha	Sha	No	No
California	Yes	Yes	Over 55	No Limit	Interstate	No limit	Calf. 7'/mi	Calf 3/16 10	Calf 7"/mi	Calf 3/16 25	Sha	Sha	No	No
Colorado	Yes	Yes	NA	No Limit	Urban Inter	NA	NA	10 ft edge	Calf 7"/mi	NA	Contractor	Sha	Yes	Yes
Connecticut	Yes	Yes	NA	No Limit	Over 40 mph	No limit	NA	10 ft edge	Calf 12"/mi	10 ft edge	Contractor	Sha	Yes	Yes
Delaware	No	Yes	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	Nr	Nr
Florida	No	Yes	NA	No Limit	NA	No limit	NA	15 ft edge	NA	10 ft edge	Sha & Contr	Sha	NR	Nr
Hawaii	Yes	Yes	NA	No Limit	Rural Inter	No limit	NA	10 ft edge	Calf 7"/mi	10 ft edge	Sha	Sha	No	No
Idaho	Yes	Yes	Rural Inter	Rural Inter	Rural Inter	Rural Inter	Calf. 7'/mi	Edge	Calf 7"/mi	Straightedge	Contractor	Sha	No	No
Illinois	Yes	Yes	NA	No Limit	Over 40 mph	No limit	NA	10 ft edge	Calf 15"/mi	16 ft edge	Sha & Contr	Sha	No	No
Indiana	Yes	Yes	No limits	No Limit	No Limit	No limit	Calf. 12"/mi	16 ft edge	Calf 15"/mi	16 ft edge	Sha & Contr	Sha	No	Yes
Iowa	Yes	Yes	Over 45	No Limit	Over 45 mph	No limit	Calf. 15"/mi	Calf 1/2 25	Calf 15"/mi	Calf 1/2 25	Contractor	Contractor	Yes	Yes
Kansas	Yes	Yes	NA	No Limit	Rural Inter	No limit	NA	10 ft edge	Calf 12"/mi	Calf 4/10 25	Contractor	Contractor	Yes	Yes
Kentucky	Yes	Yes	Over 45 mph	No Limit	Over 45 mph	No limit	Mays PSI 3.6	10 ft edge	Rain 12"/mi	10 ft edge	Sha	Sha	No	Yes
Louisiana	No	Yes	NA	No Limit	NA	No limit	NA	10 ft edge	NA	10 ft edge	Contractor	Sha	No	Yes
Maine	No	Yes	NA	No Limit	NA	NA	NA	16 ft edge	NA	NA	Contractor	Sha	NR	NR
Maryland	No	Yes	NA	No Limit	NA	No limit	NA	10 ft edge	NA	5 ft edge	Contractor	Sha	No	No
Michigan	Yes	Yes	NA	No Limit	Over 45 mph	No limit	NA	10 ft edge	Profilometer	10 ft edge	Sha & Contr	Sha	Yes	Yes
Minnesota	Yes	Yes	NA	No Limit	No Limit	No limit	NA	10 ft edge	BPR Rough	10 ft edge	Sha	Sha	Yes	Yes
Mississippi	Yes	Yes	NA	No Limit	No Limit	No limit	NA	10 ft edge	Calf 7"/mi	Calf 3/10 25	Sha	Sha	No	No
Missouri	No	Yes	NA	No Limit	NA	No limit	NA	10 ft edge	NA	10 ft edge	Sha	NR	Nr	NR
Montana	Yes	Yes	NA	No Limit	No Limit	NA	NA	10 ft edge	Calf 10"/mi	NA	Contractor	Sha	Yes	Yes
Nebraska	Yes	Yes	NA	NA	Rural Inter	No limit	NA	NA	Calf 12"/mi	10 ft edge	Sha	Sha	No	Yes
Nevada	Yes	Yes	NA	No Limit	No Limit	No limit	NA	12 ft edge	Calf 7"/mi	Calf 3/10 25	Sha	Sha	No	No
New Jersey	No	No	NA	No Limit	NA	No limit	NA	10 ft edge	NA	10 ft edge	Contractor	Sha	No	Yes
New Mexico	No	Yes	NA	NR	NR	NR	NR	NR	NR	NR	NR	Sha	NR	Nr
N. Carolina	Yes	Yes	NA	No Limit	No Limit	No limit	NA	10 ft edge	Rain 7"/mi	Rain 3/10 25	Contractor	Sha	No	No
Ohio	Yes	Yes	NA	No Limit	Interstate	No limit	NA	10 ft edge	Calf 12"/mi	Calf 1/2 25	Contractor	Sha	No	Yes
Oklahoma	No	No	NA	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Oregon	Yes	Yes	NA	No Limit	No Limit	NA	NA	12 ft edge	Calf 7"/mi	NA	Contractor	Contractor	No	Yes
Pennsylvania	Yes	Yes	Interstate	No Limit	Interstate	No limit	NA	10 ft edge	Calf 15"/mi	Calf 3/10 25	Sha	Sha	No	Yes
S. Carolina	Yes	Yes	Interstate	No Limit	Over 50 mph	No limit	Mays 40"/mi	10 ft edge	Mays 70"/mi	10 ft edge	Sha	Sha	No	No
S. Dakota	Yes	Yes	NA	No Limit	Over 40 mph	No limit	NA	10 ft edge	Calf 10"/mi	Calf 3/10 25	Contractor	Sha	Yes	Yes
Tennessee	Yes	Yes	Over 50 mph	No Limit	Over 50 mph	No limit	Mays 40"/mi	12 T Edge	Mays 40"/mi	12 ft edge	Sha	Sha	No	Yes
Utah	Yes	Yes	NA	No Limit	Over 40 mph	No limit	NA	Calf 3/10 2	Calf 7"/mi	Calf 3/10 25	Contractor	Contrator	Yes	Yes
Vermont	No	No	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Washington	Yes	Yes	NA	No Limit	No Limit	No limit	NA	10 ft edge	Calf 7"/mi	Calf 3/10 25	Sha	Sha	No	Yes
W. Virginia	Yes	Yes	NA	No Limit	No Limit	NA	NA	10 ft edge	Law Profil	NA	Sha & Contr	Sha	No	Yes

specification enforcement and, consequently, deserves special attention in the research scope and planning.

Profilographs, though relatively inexpensive compared with much pavement instrumentation (they typically list for around $14,000 with trailer), can have short lives as a result of wear on the job, accidents, and transit damage. The provision of smoothness instruments is therefore of concern to any state agency contemplating adopting end-product specifications. The AASHTO survey, as shown in Fig 3.3, found that equipment provision was equally shared between contractors and highway departments (42 percent each), with 16 percent of respondents stating that both supplied devices, presumably for cross-checking and other corroborative purposes.

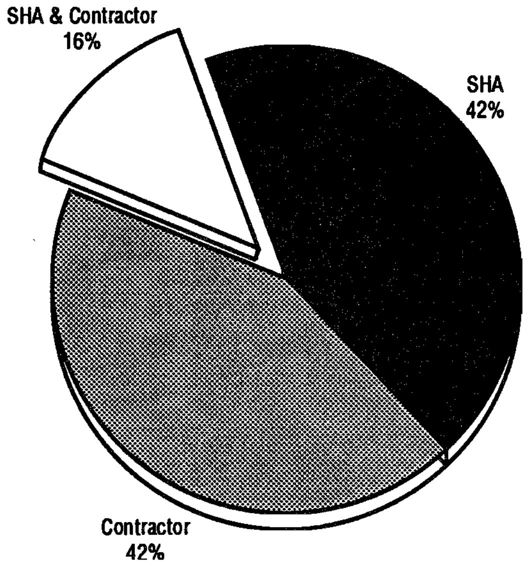


Fig 3.3. Equipment provider.

The central feature of a smoothness specification is the acceptance range, representing as it does the target level of profile quality acceptable to the highway department and, hence, the basis for determining final contract payment. Typically, the contractor's daily output is broken down into lane lengths (for example, one-tenth of a mile), and smoothness measurements are taken for quality acceptance purposes. A breakdown of the lower boundary of the acceptance range for profilographs is presented in Fig 3.4, where it can be seen that almost half of the respondents report using 7 PI inches per mile over a range of 7 to 15 PI inches per mile. The provision of penalties for poor work and bonuses for high-quality work is then built into the acceptance range, if these are considered desirable. The AASHTO survey shows, in Fig 3.5, that only a third of the responding states used bonus provisions for high-quality work. This reflects, in part, the opinion of some highway engineers that bonuses are difficult to control and can cause problems between highway staff and contracting personnel. Figure 3.6 demonstrates that penalty provisions, on the other hand, are commonly employed in smoothness specifications. This is presumably to provide the highway agency with recourse to fiscal compensation when receiving work of poor quality. In assessing profile numbers, state officials, because of the sensitivity of this issue, were generally responsible for smoothness data interpretation.

A two-part end-use specification that related to acceptance and rejection profile ranges would represent the simplest formulation; a more complicated arrangement would incorporate an intermediate smoothness range between acceptance and rejection levels where corrective work would not be required as long as the contractor accepted a monetary penalty (for example, receiving only 90 percent of the unit price for the work). Since construction correction is not mandatory, this range is sometimes referred to as a *conditional* acceptance segment. Finally, where high smoothness levels are being achieved, a bonus may be offered based on the unit price for the job.

Thus, a comprehensive specification would comprise bonus, acceptance, conditional acceptance, and mandatory rectification. The set of guide specifications recommended by the AASHTO construction committee subgroup task force is, in fact, of this type; the specifications are reproduced in Appendix B. As illustrated in Fig 3.7, the specifications include the essential components of acceptance and rejection boundaries incorporated into optional bonus and improvement schemes based on a PI

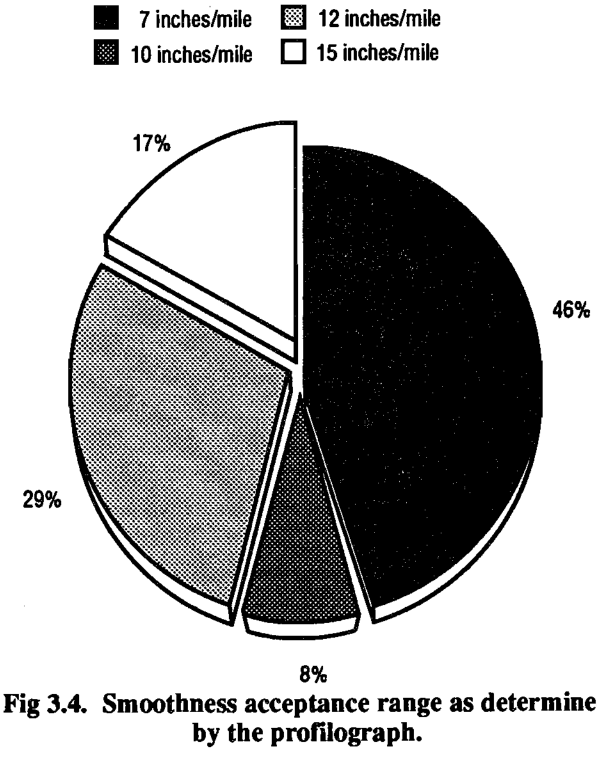


Fig 3.4. Smoothness acceptance range as determined by the profilograph.

scale measured by a California-type profilograph. Currently, the ranges are tentative and lack corroborative data to support the precise cut-off values between categories in general and within the conditional acceptance range of PI values in particular.

Table 3.2 provides details of the draft criteria based on Profile Index values. As can be seen, the table gives ranges of PI values in inches per mile; indicates whether this range is acceptable or needs rectification to meet the desired smoothness standards; and, finally, provides a financial adjustment factor for each range. For example, the 0- to 3-inch range is acceptable with no rectification, and a bonus of 5 percent of unit price is paid. If the profile lies within the 7- to 10-inch range, the contractor is paid full unit price, since the work meets the acceptable specification (again, no rectification is required and no bonus payment is paid). Profiles in the range of greater than 10 inches but less than 15 inches per mile require that the contractor make a choice: the work can either be handed over to the highway agency and a penalty assessed (see final column of Table 3.1 for details), or it can be brought back into the 7- to 10-inch acceptance range (for example, by grinding), at which time full contract unit price will be paid. These choices constitute financial trade-offs for the contractor and will be examined in later work on CTR Project 1167. Finally, section profiles with a PI greater than 15 inches per mile would require mandatory rectification to less than 10 inches, at which time full unit price will be paid.

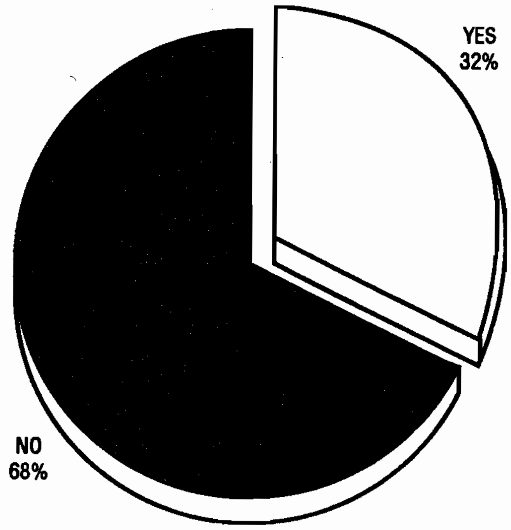


Fig 3.5. Monetary incentives.

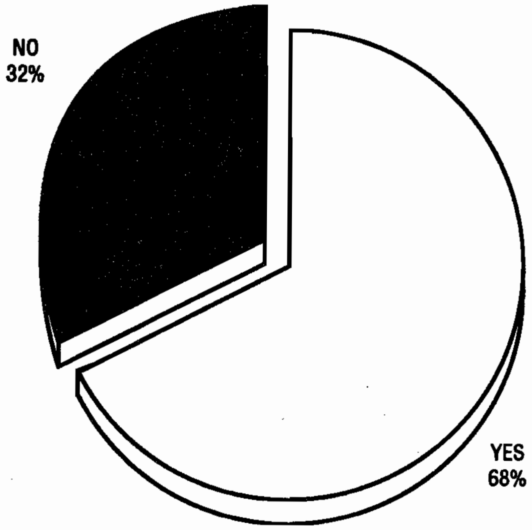


Fig 3.6. Monetary penalties.

TABLE 3.2 SYSTEM OF ROUGHNESS BONUSES AND PENALTIES

Profile Deviation in./mile	Profile Acceptable	Rectification Required	Adjusted Unit Price Multiplier
0 – 3	Yes	No	1.05
> 3 – 5	Yes	No	1.03
> 5 – 7	Yes	No	1.01
> 7 – 10	Yes	No	1.00
> 10 – 15	No	Yes	1.00
> 10 – 11	Yes	No[1]	.98
> 11 – 12	Yes	No[1]	.96
> 12 – 13	Yes	No[1]	.94
> 13 – 14	Yes	No[1]	.92
> 14 – 15	Yes	No[1]	.90
> 15	No	Yes, to 10 or Less	1.00

[1] Contractor chooses between no rectification and adjusted unit price penalty or rectification back to 10 inches or less for full unit price.

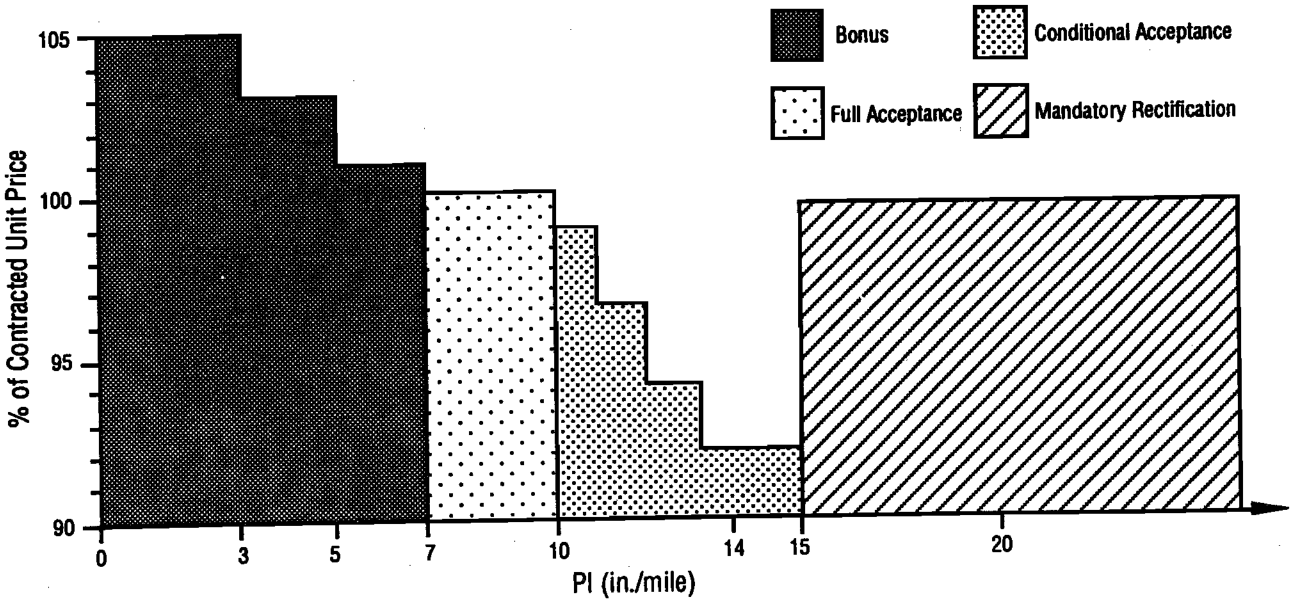


Fig 3.7. Set of guide specifications recommended by AASHTO.

DRAFT 1167 STUDY SPECIFICATIONS

Following a number of internal meetings, project staff met with the Texas SDHPT specification committee, who recommended testing a smoothness specification characterized by the key elements listed below.

(1) The specifications should apply to contracts where design speed exceeds 40 miles per hour on the travel lane (thus eliminating city streets, frontage roads, and freeway ramps). This recommendation is meant to control the CTR evaluation more closely and to restrict the focus of smoothness controls to those sections of highway where roughness was likely to influence perceptions of user serviceability. Frontage road smoothness, for example, was not considered critical to user ride quality, since smoothness on such roads is affected by combinations of slower speeds, intersections, and property-access driveways.

(2) The control instrument should give a measure of longitudinal roughness in Profile Index units of inches per mile. The final index should be an average of both wheelpaths on each travel lane of the contract.

(3) A decision was made to incorporate a bonus for high-quality work, an acceptance band for full contract price, and some system of penalties for poor work. The bonus scheme was to apply to one-tenth-mile (528-foot) sections of the contract. This element is discussed in more detail in later sections.

(4) The recommended instrument was a California-type profilograph, though other instruments capable of providing acceptable profile data were not excluded from the evaluation tests. While equipment would be provided by the contractor, the Texas SDHPT would be permitted to compare and check the performance of the instrumentation against that of similar state equipment. A calibration system and operator's guide would be required and, in the case of the California-type profilograph, would be based on existing documentation.

(5) The 10-foot straightedge was to be retained for smoothness control on ramps and on access and transfer points, with bump control along the main travel lanes. Other equipment capable of performing these functions would be evaluated.

(6) The basic procedure would be tested by CTR, with such a test including both focused work in key areas and comprehensive work involving, at later stages of the project, a major engineering contract.

In order to gain further insight into state specifications presently in force (and apparently performing well), a literature and telephone survey, incorporating the information reported by the AASHTO rideability survey, was next conducted. Selected findings from this exercise are reported in the following chapter.

CHAPTER 4. LITERATURE REVIEW AND TELEPHONE SURVEYS

This chapter comprises three sections. The first reports some of the results of a general review of literature on pavement smoothness. The second section details several states' flexible smoothness specifications, focusing particularly on Iowa's flexible and rigid specifications. The final section synthesizes related issues and includes telephone surveys of personnel and pavement specialists working in related state and trade organizations.

LITERATURE REVIEW

To acquaint CTR Project 1167 study staff with the concepts, characteristics, and features of a smoothness specification, a literature survey was conducted using data from a variety of sources, including state highway authorities. The first group of reviewed documents related to the operation of paving equipment and to the importance of material quality, mix consistency, and well-motivated staff. For example, smoothness on slipform paving equipment (Refs 17, 18, and 19) was found to be affected by such variables as subgrade preparation, a uniform head of uniform quality concrete, paver speed, correct vibration, and fluid movement of the paver and its general maintenance. High technology in the form of non-contact sensor monitoring (Ref 20) of profile traces has also been employed to control paving equipment operation. Moreover, there are references in the literature (e.g., Ref 21) of flexible pavement construction that emphasize that the technology to ensure a smooth surface already exists. The key drawbacks, though, as far as the construction industry is concerned, involve the profitability of the work and the belief that quality problems grow as profit margins narrow. Thus, the documents within this literature category suggested that experienced contractors can provide a smooth surface on main travel lanes as long as they are not constrained by time and financial pressures.

The literature regarding surface profiles was next reviewed. Because the primary purpose in evaluating pavement smoothness is to monitor longitudinal pavement profiles (typically in the lane wheelpaths), this literature category specifically focused on the variety of surface profiles, including evaluations of their wavelength characteristics, measurement equipment, and how they relate to pavement performance. Given that roughness and smoothness are simply different locations on the same scale, a profile (defined as a summation of the variations in the surface profile at some given wavelength) does the best job of characterizing smoothness (Ref 5). In terms of highway construction, profiles are limited to wavelengths of between 0.1 and 500 feet, and for the purposes of both ride quality and service life it would be useful to have a multi-dimensional measure capturing the various profile features. However, because no such measure has been developed, uni-dimensional measures are used both for the purposes of creating end-use specifications and monitoring pavement performance. Yet choosing particular wavelengths can cause problems; for example, straightedge devices miss wavelengths longer than the span and can, moreover, distort wavelengths that are the harmonic of its span. In Darlington's (Ref 22) test that plots response ratios of various devices as a function of wavelength, the profilograph showed an erratic response, particularly in the 0- to 30-foot wavelengths. The BPR type Roughometer yielded reasonable results only over the 4- to 14-foot wavelengths, and Maysmeters seem to have responses similar to the Roughometer (Ref 23). The responses of the Chloe and Law profilometers are far better over the range of profile wavelengths and relate to previous work done at CTR using Maysmeters calibrated with the SDHPT Law profilometer (Refs 24, 25).

The issue of wavelengths is critical in Study 1167, given that the only available devices for measuring end-use specifications have a fixed wavelength. Shorter wavelengths impart shock to user vehicles and, even worse, can induce in trucks dynamic suspension responses highly damaging to pavement serviceability (Ref 26). Longer wavelengths, on the other hand, can cause vehicle ride qualities to fall, affecting the user's perception of pavement quality (independent of the pavement strength and serviceability). It would seem that the latter would be important in overlay paving, where the new surface takes on some of the characteristics of the highway being overlaid. In such a case, longer deformations would tend to be built into the final profile irrespective of contractor, paving operations, or material qualities. Yet because Study 1167 is addressing new construction, the issue is not directly pertinent, though from the perspective of the Texas SDHPT it deserves future attention.

In the final literature category, equipment used in determining profile characteristics, including devices that collect data for long-term pavement monitoring (as opposed to end-use specifications), was reviewed. As this survey revealed, a significant development in recent years has been the smoothness seminar tests sponsored by the Colorado Department of Highways and the FHWA (Ref 27). In these tests, all available U.S. pavement roughness and profile measuring devices were compared so as to provide: (1) an understanding of pavement monitoring theory that included profile features, theory of sensing devices, data storage, and data processing; and (2) an overview of how such data fit planning, pavement management, and design. A variety of equipment, including Law profilometers, the Texas SDHPT-modified profilometer, ARAN, Maysmeters, Face Dipstick, and the McCracken and Ames profilographs, was assembled for testing, with the performances of the various instruments compared over a series of test sections (some of which had been rod-and-leveled). The results were inconclusive: While other literature sources suggest significant differences should exist, all instruments showed fairly good correlation in these Colorado tests. Nonetheless, the exercise was useful in bringing together the profile measurement and analysis elements of pavement smoothness. In addition, there emerged in these tests a recognition that only two instruments—the Face Dipstick and the profilograph—could be used for both rigid and flexible end-use specifications. But because the Dipstick, introduced in 1988, is still rather new to highway contractors, the 30-year-old profilograph is acknowledged as the more widely understood instrument. Therefore, as a start, it would seem that the profilograph is the logical instrument with which to measure a smoothness specification for both rigid and flexible pavements.

STATE SPECIFICATIONS

Copies of several state specifications were closely evaluated and are summarized in this chapter. While eight specifications were relatively simple in structure,

TABLE 4.1 DETAILS OF FLEXIBLE SMOOTHNESS ACCEPTANCE SPECIFICATIONS AND PENALTIES

Organization	Acceptance	Length	Position	Instrument	Passes
Texas Special HMAC Specs	Linear % < 1/8 in.	Day's Output	1 path, 1 lane entire length	10 ft Straightedge	One
Corps of Engineers[1]	Int < 1/4 in. Top < 1/8 in.	Not Given	Not Given	12 ft Straightedge	Not Given
Arizona	Int < 1/4 in. Top < 1/8 in.	All	Center Line	10 ft Straightedge	Not Given
Florida	Top < 3/16 in.	All	Center Line	15 ft Rolling Straightedge	One
	Non-travel lane < 3/8 in.	All	Not Given	15 ft Straightedge	Not Given
West Virginia	Int < 1/4 in.	All	All	10 ft Straightedge	Not Given
	Top < 3/16 in.	Ditto	Ditto	Ditto	Ditto
Oregon	S lift[2] < 0.02 ft = 0.24 in.	All	Center Line	12 ft Straightedge	One
	M lift[3] < 0.015 ft = 0.18 in.	500 ft[4]	Each Path, Each Lane	12 ft Rolling Straightedge	One
Maryland	THC[5] PI < 10 in. PI 10-13 penalty	528 ft	Not Given	Profilograph	Not Given
	MLC[6] PI < 7 in. PI 7-10 penalty	528 ft	Ditto	Ditto	Ditto
	CC[7] PI < 12 in. PI 12-15 penalty	528 ft	Ditto	Ditto	Ditto

Notes: 1. Airport Runways and Taxiways
2. Single Lift
3. Multiple Lift
4. Testing strip, if profile does not meet spec then entire mile to be tested
5. THC - Tangent Alignment and Pavement of Horizontal Curves, Single Lift
6. MLC - Tangent Alignment and Pavement of Horizontal Curves, Multiple Lift
7. CC - Curve Construction

Source: 1161 Project File

Iowa's was exceptional in its complexity. Accordingly, the latter will be treated as a special case.

Details of the longitudinal profile smoothness specifications from seven states and from the Corps of Engineers are summarized in Table 4.1. First, the most commonly used instrument is the 10- or 12-foot straightedge, followed by the rolling straightedge and then the profilograph. Where the straightedge is employed, the usual acceptance tolerance is 1/4 inch per 10- or 12-foot paved section. Where multiple lifts are specified, two acceptance tolerances may be given—for example, 1/4 inch for the intermediate layer and 3/16 inch or 1/8 inch for the top layer. Where a rolling straightedge or profilograph is specified, the instrument is used either (1) along the centerline of the travel lane, (2) in one wheelpath, or (3) in both wheelpaths of a travel lane. In some cases, the measurement is sampled out of the day's output, while in other instances all work is measured. In general, where a profilograph is used in the specifications, a variety of acceptance levels is also used. In Maryland's specifications, for example, less than 10 PI inches per mile is acceptable for single lift work on tangents, less than 7 PI inches per mile is acceptable for multiple lifts, and less than 12 PI inches is acceptable for curve construction. The evidence from our survey suggests that the profilograph device stimulates the development of specifications that relate to different categories of pavement construction, and in fact this accords with experience gained on rigid pavement specifications — namely, that use of the profilograph permits a more sophisticated specification to be developed, despite misgivings regarding the response of the device. Study 1167 must determine whether other instruments should be used in conjunction with the profilograph to provide that degree of accuracy required for penalty and bonus determination. Apparently, many states are employing the profilograph device alone and to good effect. Further work examining this issue in more detail is clearly warranted.

IOWA SPECIFICATIONS

BACKGROUND

Work on profile testing in Iowa began in 1981. By 1984, Iowa officials had formulated a state-required specification for smoothness which, today, represents the most comprehensive yet collected by the 1167 staff. Since 1985, then, contractors in Iowa have been providing certified results.

The newly revised 1988 specification for Iowa (Ref 28) covers three types of roadway categories, three penalty schedules, and three bonus categories. Specifically, highway lanes and sections are first classified according to their design speed—one category for those below 45 mph, and one for those above 45 mph—with significantly greater tolerances allowed at lower travel speeds.

Table 4.2, providing a breakdown of these categories, shows the degree of specialization within the specification. There are, for example, four different subcategories within the speed categories. Three of the subcategories—termed A, B, and C—relate to greater tolerance ranges and different penalty and bonus schedules. The fourth—termed ABI—covers the specific issue of tying a new lane into an existing one as part of roadway widening. Here, the acceptance level is set by averaging the target level for the category into which the newly constructed lane will fit with the actual profile of the existing lane to be tied into the new construction. Presumably, this recognizes the problem of imparting roughness characteristics (frequently undesirable) from the existing roadway into which the new lane is being tied.

TABLE 4.2 IOWA FLEXIBLE SMOOTHNESS SPECIFICATIONS CATEGORIES

Road Type	Speed	
	45 or Less	45 or More
Mainline, curbed	B	A
Mainline, not curbed	A	A
Ramps, Loops	B	B[1]
Side Streets (over 500 ft)	B	A
Grade Separations[2]	B	A
Bridge Decks	C	C
Major Widening (added lane)	ABI[3]	ABI[3]

Notes: 1. High speed ramps will be A, if designated on plans
2. Including municipal and secondary roads
3. ABI = (PI + X)/2 where PI is taken at adjacent edgeline of existing lane, and X = 12 if Schedule A, and 30 if Schedule B.

Source: Iowa Department of Transportation, State Specification SS-1070, 1988.

In all cases, profile data are provided solely by California-type profilographs (manufactured by both the McCracken and the Ames companies, with each having the usual base length of 28 feet), approximately forty of which were operating in Iowa in 1989. Again, contractors working in that region have been supplying profilograph output data to state engineers for acceptance, penalty, and reward purposes since 1985.

EXCLUSIONS

The draft 1987 AASHTO specification proposed for modification and testing by project staff for rigid pavements is presently applied only to those main travel lanes where speeds exceed 40 mph. The Iowa specifications are much more comprehensive, with smoothness evaluated on all primary and Interstate final mainline pavements (through lanes, climbing lanes, and tapers to parallel lanes), bridge decks, interchange ramps, and loops.

While each specific work contract designates those areas/sections to be evaluated, the following items are, however, excluded from the Iowa specification: acceleration and deceleration lanes; less than full lane pavement widening; crossovers; shoulders; side streets under 500 feet in length; and sections of any type less than 50 feet in length. Single-lift HMAC overlays 2 inches or less are also excluded unless the existing surface has been corrected by milling, a leveling course, or some other means. Also excluded are county secondary, farm-to-market, municipal, or federal-aid urban system paving. Finally, bridge decks less than 100 feet in length, and deck overlays (including approaches) less than 100 feet are also not tested with the profilograph. All excluded surfaces will be evaluated by the state engineer by means of a "surface checker" (a modified straightedge designed by the Iowa Highway Authority).

SMOOTHNESS CRITERIA

Highway features are first categorized into the A, B, or C schedules. To obtain full unit payment, the contractor must produce a section with a longitudinal profile that does not exceed 12 PI inches for A, 30 PI inches for B, and 15 or 30 PI inches on C for Interstate bridge overlays and other bridge projects, respectively. Table 4.2 details the various highway sections, the travel speed, and the smoothness schedule to be applied (unless otherwise specified in the job contract). In addition, where full-width lanes are being added to the existing pavement, an average base index (ABI) is calculated to set the acceptance standard. This ABI index is a simple average of the existing travel-lane smoothness and the acceptance standard for the new lane which it would have if it were being newly constructed or overlayed. In other words, if it were a schedule A job there would be a 12-inch acceptance cut-off, and if the existing highway has a PI of 16 inches, the resulting ABI would be PI 14 inches for acceptance. In addition to acceptance ranges, there are in the schedules both penalty and bonus clauses, which will be described later in this report.

MEASUREMENT

(A) *Pavement smoothness.* First, the pavement surface is divided into continuous placement sections. Sections terminate at a day's work joint, bridge deck, or when the laid surface merges with another surface of a different smoothness standard. Sections longer than 778 feet are broken down into 528-foot segment lengths. A segment is one travel lane and the testing takes place at the centerline of each travel lane in both directions.

(B) *Bridge deck and approach smoothness.* Bridge deck work is not broken down into segments unless it exceeds 500 feet or is specified for evaluation in the job plans. Where such bridge deck work is to be measured, the profilograph is operated in each wheelpath, while bridge approach sections longer than 50 feet are tested at the centerline.

(C) The contractor furnishes the test results (in the form of profilograms) to state officials certified by a trained individual. State engineers may order the testing of the entire job if the profilogram results are inaccurate. The submittal includes the identification of areas (sections) qualifying for both penalty and bonus awards. The contractor is responsible for the provision and cost of certifying the smoothness, including any traffic control needs.

(D) PI units are calculated in 0.1-inch deviations from a 0.2-inch blanking band. Bumps are separately identified as vertical deviations exceeding 0.5 inch for a 25-foot span.

SURFACE CORRECTIONS

(A) Bumps greater than 0.5 inch in a 25-foot span will be corrected, and where a straightedge ("surface checker") is employed instead of a profilograph, any deviations of 1/8 inch or more over 10 feet will also be corrected. On HMAC pavements, corrections cannot be carried out without prior permission of the engineer.

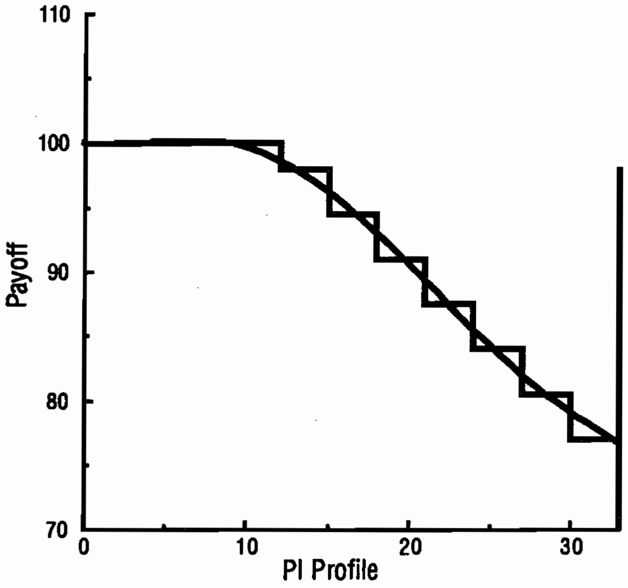
(B) *Interstate* pavement acceptance cut-off is PI 12 inches per mile (correction required after 33 inches for *Schedule A* and 60 inches for *Schedule B*). For pavement lane widening, corrections are required after ABI exceeds the targeted ABI + PI 12 inches. The state engineer works with the contractor to determine the best method of correction, and after rectification, the profile is re-determined and recorded as the final profile for payment.

SCHEDULES OF PAYMENT—PENALTIES

This is a crucial element of the specifications, first, because penalty amounts overwhelm any potential bonus payments, and, second, contractors may challenge penalty awards. Only the final course of HMAC will be tested for smoothness, *although the corresponding price adjustments will apply to the full paving depth.* In addition, there is a dollar penalty associated with each bump not corrected back to under 0.5 inch per 25 feet.

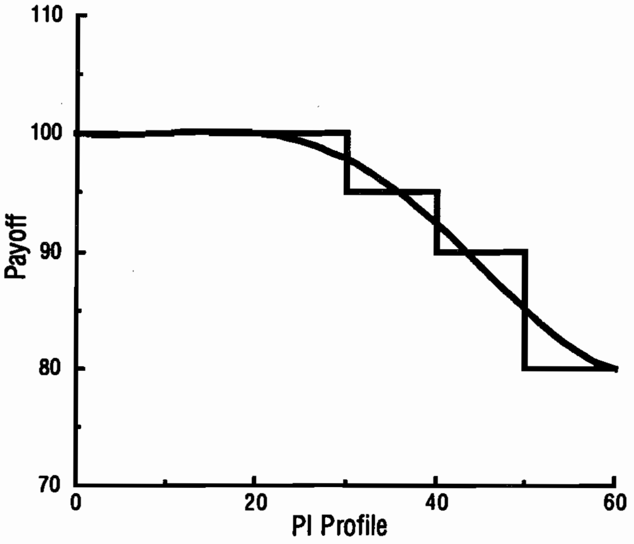
(A) *Pavement smoothness penalties.* Where schedule A is implemented, the penalties are assessed in accordance with the stepped function shown in Fig 4.1 (Iowa Specs A) below. Instead of the stepped function, an alternative method would be to calculate a continuous function—in this case a polynomial—which would avoid the sometimes awkward fall in payment associated with extremely small changes in PI values. Such adjustments are unrealistic and inequitable. Where smoothness is to be evaluated under schedule B, payments for final profiles are made from the schedule given in Fig 4.2 (Iowa Spec B).

Again, a continuous function is fitted to give an alternative payment method that avoids sharp price falls.



y = 100.00 - 0.22645x + 0.10143x^2 - 1.1427e-2x^3 + 3.6030e-4x^4 - 3.6504e-6x^5
R^2 = 0.972

Fig 4.1. Iowa specifications A.



y = 100.04 - 8.8578e-2x + 1.3316e-2x^2 - 4.2993e-4x^3 - 2.1790e-6x^4 + 7.5150e-8x^5
R^2 = 0.887

Fig 4.2. Iowa specifications B.

(B) *Bridge decks and added lanes.* These categories also have payment schedules, the first dropping to a 70 percent payment when PI values exceed the range 50-60, and the latter falling to 85 percent of unit price when the PI value falls over the range ABI + 8 to ABI + 12. Neither the evidence as to why these adjustments should apply, nor the economic/financial reasons for the calculation of their size and differentials, is given.

SCHEDULES OF PAYMENT—BONUSES

These schedules apply to interstate and primary projects only, unless otherwise specified. Sections qualifying for bonus payments must be initially constructed to the profile standard (no corrections receive bonus payments). Bonus payments are fairly straightforward.

(A) *Interstate projects.* Where a section pavement smoothness exceeds 2.0 inches per mile, a bonus of 4 percent in the contract price will be made.

(B) *Non-Interstate projects.*

  (1) *Single lift.* Bonus payments are made where PI values are less than 4.0 inches per mile when constructed on soil or raw subgrade, or less than 3.0 inches when constructed on a base or subbase. A 2 percent payment is paid.

  (2) *Multi-lift.* Bonuses are due when smoothness reaches 2.0 inches per mile for multi-lift pavements on a pad line of paved, stabilized, or granular shoulders. When placing equipment operates on a pad line of other materials, the incentive index is 4.0 inches per mile. In both cases, a 2 percent contract unit price bonus is paid.

(C) *Bridge decks and bridge deck overlays.* For each traffic lane, a PI value of 10 inches per mile for new construction, and 2.0 inches per mile for overlays, will qualify the job for bonus payments. The incentive payment is 5 percent of the contract price (square or cubic yard) of the travel lane placement width.

Finally, as noted before, there is no evidence offered as to the scale, structure, and impact of the bonus payments. Because it was determined that this merited further investigation, Iowa DOT staff, contractors, and associations (such as the National Asphalt Pavement Association) were contacted.

DISCUSSIONS WITH SPECIALISTS

TELEPHONE SURVEY

Research staff for Project 1167 conducted a telephone survey of engineers in nine states using smoothness specifications, with the responses tending to confirm the effectiveness of the California-type profilograph. The majority of the contacted states have had about 10 years of experience with smoothness specifications, thus making the data especially pertinent to the Texas SDHPT decision. The results, summarized in Table 4.3, show a strong consensus in the majority of responses, although the topic of bonus and penalty clauses emerged as an issue of some dispute (this was to be expected, given the sensitive nature of the issue). Equally important in this survey was the very positive opinion expressed by both contractors and state highway staff regarding the impact of the specifications. Such positive expressions, again, tend to confirm that the device has had an extremely beneficial effect in improving quality controls; moreover, as our survey indicated, its adoption in state specifications has consequently resulted in higher ride quality standards.

IOWA DOT SMOOTHNESS SPECIFICATIONS

The specification engineer at the Iowa DOT provided much useful information regarding the development and implementation of the Iowa smoothness specifications. Such information was particularly important insofar as there is virtually no documentation regarding the development of the specifications (why certain acceptance levels were used, why different ranges of PI values were chosen, and how effective the whole process has been in terms of raising pavement riding quality).

The telephone discussion provided interesting supplemental data as well. First, on most category A jobs, HMAC end-profiles now generally fit a 4- to 7-inch PI range, close enough to induce contractors to attempt a bonus level. Rigid pavements are in the 8- to 9-inch PI range, which would meet the draft Texas SDHPT acceptance range (7 to 10 PI inches). Both surface types have benefited from bonus payments, with each receiving about $100,000 last year. Incentives are viewed as critical features of the flexible specification, much more important than penalties. Apparently, many contractors are able to get within the acceptance ranges easily, electing subsequently to go for the bonus as an additional financial reward.

The different category smoothness specifications were not determined through scientific study and investigation. Rather, considerable common sense, pragmatism, and on-the-job evaluations determined the roughness ranges for the various categories. And as it turns out, few 528-foot sections are ever at the high end of the roughness scale, where penalties can be severe (see Fig 4.1). Such evidence would normally argue for an adjustment of the scale back down to some lower PI level, but the existence of the high roughness portion of the scale does permit a section with particular technical problems to be approved if the contractor cannot correct the profile back to higher smoothness standards. An apparently attractive feature, this may permit more flexibility in dealing with contractors.

There are no problems regarding profilograph performance that currently concern project staff. They stated that interpretation of the profilogram for pavement purposes is within ±2 inches for a PI of 20 inches/mile, but said that contractors had not yet begun debate regarding cut-off points in the specification. The contractor is responsible for the provision and operation (including traffic control) of the profilograph, as well as the production of the profilograms. This is done through state-certified profilograph operators who are on the contractor's payroll. Iowa DOT has had four training courses for such personnel, with 45 trainees presently enrolled in the current course. The state certification takes 6 hours, and re-certification is required at regular intervals. Because falsified profile data are occasionally submitted, state officials check about 10 percent of the contractors' output. This checking exercise, we were told, has been effective in deterring contractors from attempting such falsifications. Clearly, the pioneering work of the Iowa DOT with respect to its implementation of smoothness specifications merits further consideration in the 1167 study.

NATIONAL ASPHALT PAVEMENT ASSOCIATION (NAPA) OF MARYLAND

Project staff next contacted the Maryland NAPA Director of Engineering, who stated that the Maryland state specification, drafted late in 1988, had not yet been adopted, and that the NAPA would continue to resist its adoption as long as it retained the severe acceptance penalties. As the director related, it was felt that either a specification should be written to permit contractors to become accustomed to the new standards (that is, avoid high acceptance levels like PI 6 inches), or an interim specification should be adopted prior to the final specification. NAPA members were disappointed that Maryland had chosen not to incorporate bonus awards, particularly since they seemed to be so effective in Iowa.

In addition, NAPA members were concerned about the performance of the profilograph, particularly its ability to meet the sometimes stringent specification requirements. According to these members, the use of a higher-resolution profile device, in conjunction with the profilograph, might be a better solution. In principle, NAPA objects to quality-assurance guides being associated with inadequate measurement devices.

Finally, the Maryland NAPA Director of Engineering expressed his view that there should be no difference between portland cement and asphalt concrete smoothness criteria; they should, in his judgment, be identical.

AMERICAN CONCRETE PAVING ASSOCIATION GUIDE

The American Concrete Paving Association (ACPA) has developed a rideability guide specification which, although based on the California-type profilograph, can

TABLE 4.3 CTR TELEPHONE SURVEY RESULTS

Parameters	Arkansas	California	Georgia	Illinois	Iowa	Kansas	Louisiana	Utah	Wisconsin
Year specification was initiated	78-79	1960	1978	1977	1980	1987	Not yet	1983	1984
Initiated on all projects (A), few (F)	A	F in 1958	Yes	>40 mph	F	Yes	Unknown	All	All
Type of measuring device	Rainhart Prof.	Calif Prof.	Mays RM	Calf. Prof.	Calf. Prof.	Calf. Prof.	Calif. Prof.	Calf. Prof.	Calf. Prof.
Straightedge	Yes	Yes		16					Yes
Maximum roughness */mi	28 spec. "15"	7	65	15	12	15.1	8	7	12
Cost bonus for smoothness	No	No	No	No	Yes	4% for 4 */mi	No	n/a	
Cost reduction for roughness	No	No	No	No	Yes	Yes	Yes	n/a	
Require corrective work	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Length for required corrective work	25 feet	n/a	1/4 mile sect.	See Cal 526-D	50 feet		4000 sy	0.1 mile	0.1
Length for payment		n/a							
Contractor furnishes device	No	No	No	Yes	Yes	Yes	n/a	Yes	No
State checks with same device	Yes		Yes	Yes	Yes		n/a	n/a	Yes
Manual describing test procedures	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Use Calf. manual
Number of profiles per lane	1	n/a	1	2	2	2	2	1	2
Location of profile in lane	Centerline	n/a		3' from edge	Wheel tracks	3' from edge	Wheel path	n/a	3' from edge
Equipment use training (state)	Exper. crew	Yes	Yes	Workshop	n/a	n/a	n/a	n/a	Workshop
Equip. use training (contractor)	No	No		No	n/a	n/a	n/a	n/a	No
Calibrate Equipment	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	n/a
How	By owners book		Test sections		See instruct.	See state spec.	Manufact. rec.	See state spec.	
How often				Annually	Annually		n/a		
Spec. results in smoother ride	Unkown	Yes	Yes	Yes	Yes	Too soon	Too soon	Yes	Yes
Opinion of contractors	Good	Good	Good	Good	Good	Good	Too soon	Good	Good
Opinion of state DOT	Good	Good	Good	Good	Good	Good	Too soon	Good	Good
Recommended changes in specification	Yes	Yes	No	No	Yes	No	Too soon	No	No
What changes	Lower index	Different PI for Low speeds			10 */mile				
Total PC construction with spec.	30-40 miles	many	100 jobs	2-3 mill. sq. yd.	2 mill. sq. yd.	40 miles	5 miles	3 mill. sq. yd.	2 mill. sq. yd.

presumably be interpreted to include other types of profilographs. The ACPA specification is based on a profile index taken from a ride table of different indexes for different road classifications. This is similar to the use of multiple classes in the Iowa specification, though simpler in structure. It does indicate that rigid pavement contractors are now willing to employ smoothness instruments and that, again, the profilograph seems to be the best device with which to write a current specification.

SUMMARY AND CONCLUSIONS

A number of states are employing flexible end-product specifications to good effect. And the literature survey shows—in terms of both technical characteristics and applicability—a wide range of specification categories. Iowa's smoothness specifications are particularly impressive and merit further investigation; in particular, the 8-year evolution of those specifications supports the recommendation (see Chapter 3) that Texas develop an initial smoothness specification for main travel lanes having traffic exceeding 40 mph. Thereafter, specifications for other elements of the infrastructure—bridge decks, bridge approaches, ramps, frontage roads, etc.—can be determined (as they were in Iowa).

To evaluate smoothness criteria thoroughly for inclusion in end-use specifications, a range of smoothness, or roughness, measurement units needs to be examined. It should be stated that although the California-type profilograph is the most widely used device, it was not mandated for Study 1167. Instead, project objectives required CTR staff to select an instrument from the full range of devices and measurement units available for evaluation. The next chapter describes in detail the range of equipment identified for such an evaluation.

CHAPTER 5. INSTRUMENT EVALUATION

BACKGROUND

A number of selection criteria were chosen to identify an appropriate instrument for monitoring an end-roughness specification for pavement construction. While the accuracy and the repeatability of the reported roughness data were important considerations, they were not the principal criteria used in the ultimate decision. The cost of the instrument, ease of use, the technical expertise needed to maintain and operate the instrument, and whether or not trouble spots could be accurately located on the pavement surface—all were of paramount importance in the decision-making process.

ACCURACY AND REPEATABILITY

Accuracy and repeatability determinations were initially formulated by the World Bank (Ref 29) and subsequently adopted and classified by the Federal Highway Administration (FHWA, see Ref 30). Table 5.1 (Ref 31), a representation of this FHWA classification scheme, shows that roughness evaluation instrumentation is divided into three main classes—Class I, Class II, and Class III—with each class defined on the basis of the spacing between individual readings, the maximum error, and the percentage of bias associated with the operation of the instrument. There is a Class IV category, but because it is based on the subjective assessment of a panel, it is not therefore acceptable for FHWA reporting purposes. Table 5.1 also provides examples of instruments associated with each of the classes.

COST

The cost criterion required that the instrument be commercially available and not prohibitively expensive. Irrespective of whether the SDHPT or the contractor is responsible for instrument purchase, maintenance, and operation, the cost must be reasonable. In terms of value, an individual instrument was determined to be of good quality if the instrument was sturdy enough to be used for a number of years on a number of paving projects.

If the SDHPT is required to provide the instrument, a minimum of one instrument per district would be necessary (although districts having large urban centers would need two or three of the selected instruments). On the other hand, requiring the contractor to provide the instrument necessitates that the initial capital expenditure for the device be as nominal as possible so that the final bid price is not adversely affected.

EASE OF OPERATION

Ease of operation, another criterion in the selection of the appropriate instrument, included a consideration of the technical background necessary for instrument operation. If the operation, calibration, and maintenance of the instrument proved too complicated, then each instrument would require a dedicated technician. Such a requirement would increase the operational cost of the device and would, in addition, present logistical problems associated with scheduling, which again would increase the operational cost of the instrument.

The delivery speed of the roughness data was another concern. Although the Class I instruments specified in Table 5.1 provide the highest resolution of the raw elevations of the pavement surface, they are manual surveying techniques, and as such they would have difficulty maintaining pace with the paving operation. Since it is considered desirable to work with the contractor to provide quality daily paving output, it is essential that the instrument of choice be capable of maintaining an adequate pace. The monitoring of the daily paving output also requires an instrument which is relatively lightweight. The weight of vehicle-mounted instruments, as well as the curing time associated with newly-laid pavements, limits the immediate access of these vehicle-mounted devices for monitoring daily output.

Finally, the output of the chosen instrument should be relatively easy to understand and should provide a statistical indication of the overall roughness of the monitored pavement. While instruments that provide only a single roughness statistic per distance traveled can give an indication of the average surface roughness, they cannot indicate locations of trouble areas (bumps) on a particular pavement section.

INITIAL INSTRUMENT EVALUATION

The initial considerations for the final decision of the instrument of choice were based on the roughness instrumentation available from the Texas SDHPT's Maintenance and Operations Division, D-18. The majority of available instruments are used for network-level pavement roughness evaluation and reporting purposes. As such, they are high-speed, vehicle-mounted instruments that produce only a single roughness statistic for a given length of pavement (most are incapable of providing pavement profile information from a particular location on the pavement's surface).

In addition to the existing equipment, three new instruments—the Face Technologies' Dipstick, the Ridedas (developed and produced by the Road and Traffic Authority in New South Wales, Australia), and the McCracken profilograph—were purchased and evaluated. A literature survey was also conducted to determine whether suitable alternative instruments were available for consideration. The results of this study's evaluation of each instrument is presented below.

TABLE 5.1 FHWA CLASSIFICATION SCHEME FOR ROUGHNESS EVALUATION INSTRUMENTATION

Class	Method	Maximum Error	Measurement Interval	Example Instruments	Comments
I Precision Profiles	Manual Absolute elevation relative to true horizontal	1.5% Bias 19 inch/mile	Less than or equal to 1 foot	Rod & Level Dipstick TRRL Beam	Data collected manually and processes to give roughness statistic; very accurate but laborious and slow
II Direct Profiling Measurement	Electronically measured elevation profile from artificial "horizontal" datum	5% Bias 44 inch/mile	Less than or equal to 2 ft	K.J. Law Profilometer G.M. Profilometer Texas Profilometer French APL	Data collected from moving vehicle; differ in reference used and method of sensing; not absolute profile because of lack of low frequency response; can be utilized for calibration
III A RTRRMS	Measure dynamic response of a mechanical device to roadway surface	10% Bias; 32-63 inch/mile	Continuous over test section length	Mays Ride Meters ARAN BPR Roughmeter Dynatest 5000 RDM Cox Roadmeter	Most common instruments; (1) measure of axle-body movements usually summed to give cumulative "bumps" per unit distance, or (2) measure of accelerations of axle or body via accelerometers; data collected at highway speeds; requires calibration
III B Moving Datum Profiles	Measure deviation of profile relative to a datum moved along road surface	Blanking bands used to filter out construction techniques such as tining	Continuous over test section length	Rolling Straightedge Sliding Straightedge Profilographs	Insensitive to wavelengths equal to instrument baselength; profilograph averages end reference points; signal gain highly tuned and variable (ideal is uniform gain)
IV	Subjective estimates made by observer(s) using a descriptive scale				Not suitable for collecting roughness data for HPMS

BACKGROUND

The instruments to be evaluated were first divided into the classification system used by the FHWA (Ref 30) and based on World Bank reports (Refs 29, 30). As stated in the previous section, the classification of a particular instrument is determined by (1) the report interval between readings, (2) the allowable percent of bias associated with the instrument's operation, and (3) the maximum error in the roughness determination. Additionally, each instrument was evaluated using those criteria (cost and operational characteristics) presented earlier.

CLASS I INSTRUMENTS

Class I includes the most accurate and repeatable of all available roughness instruments. But because they are static devices (they are manually propelled down the pavement surface), they are slow. The two instruments evaluated for this classification were the rod-and-level survey and both the auto-read and the manual-read versions of the Face Dipstick (the TRRL Beam, the third example of a Class I instrument, was unavailable for evaluation). The cost of both of these instruments was judged reasonable in terms of their initial costs and their ability to function properly over an extended period of time. Instrument output is in the form of raw elevation data obtained from the surface being profiled.

ROD AND LEVEL

Rod-and-level survey techniques have been used for many years to collect elevation data for all types of construction, including pavement construction. The interval between elevation readings can be as short as the width of the survey rod, or as long as the line of sight. In a Class I instrument, the maximum distance between readings has to be equal to, or less than, 1 foot. The resolution of this method of profiling is 0.01 foot, although a competent survey crew can estimate elevations to the nearest 0.001 foot.

The very high accuracy of the rod-and-level technique results from referencing each individual elevation to the setup of the level (that is, the elevations are a series of independent readings). Only when the level changes locations is the reference of concern. The relative elevation from one level location to the next is verified by closing the loop, which involves taking additional elevation shots from the end of a survey run back to the beginning.

The data from rod-and-level surveys can be converted to any of the various roughness statistics that require individual elevation data as input. Other roughness statistics can be computed by regression analysis from the elevation-calculated statistics. Most of the roughness statistics calculated from the elevation data require units in inches, meaning that the rod-and-level data must be multiplied by a factor of 12 for conversion from feet to inches. This requirement tends to magnify any errors in the reported rod-and-level elevation data.

The considerable time and manpower needed to conduct a rod-and-level survey represents the greatest drawback to using this technique for end-roughness specification determination. The procedure requires, first of all, both a rod person and a person to read and record the elevation data; then each wheelpath must be located within the travel lane and laid out using a steel tape at 1-foot (or less) intervals so that the maximum reporting interval can be achieved—a requirement that results in very long setup times. In our evaluation, the time necessary for conducting a rod-and-level survey at 1-foot spacing on both wheelpaths on a 0.2-mile test section was approximately 10 hours. For these reasons, the rod and level was effectively eliminated from further consideration as the instrument of choice for end-roughness specifications.

FACE DIPSTICK

The Face Dipstick, manufactured and marketed by the Face Technologies Company of Norfolk, Virginia, was initially developed to measure the flatness of superflat floors. The original instrument was a manually-read device that employed an inclinometer to determine the elevation change between its two feet. The manufacturers, seeing a potential market in the pavement industry, designed an electronic interface to computerize and electronically store the Dipstick's elevation readings (Fig 5.1). In the following evaluation, the manually-read Dipstick will be referred to as the manual-read configuration, while the computerized Dipstick will be referred to as the auto-read configuration. The auto-read Dipstick can be used in the manual-read mode by removing the computer and manually recording the displayed elevations. The cost of the manually-read Dipstick is approximately $10,000 (1990 prices).

The Dipstick meets the Class I criteria because the feet (and therefore the elevation readings) are spaced 1 foot apart, with the individual readings reported to the nearest 0.001 inch. The calibration of the Dipstick is easily checked by leveling one foot relative to the other and checking the displayed elevation using a gauge block. If the Dipstick fails the calibration check it must be returned to the manufacturer for adjustment.

In operation, the Dipstick is "walked" down a wheelpath, with any change in elevation from one location to the next displayed and recorded. A pavement section must be laid out with a start and a stop location, as well as a wheelpath location marked for the operator to follow. The accuracy of the individual readings is related to the reference elevation: If the position of the rear foot is changed before a reading is taken, the reference elevation will be lost, since the reference elevation is determined by the rear foot's location relative to the front foot's height. Consequently, a "closure error"

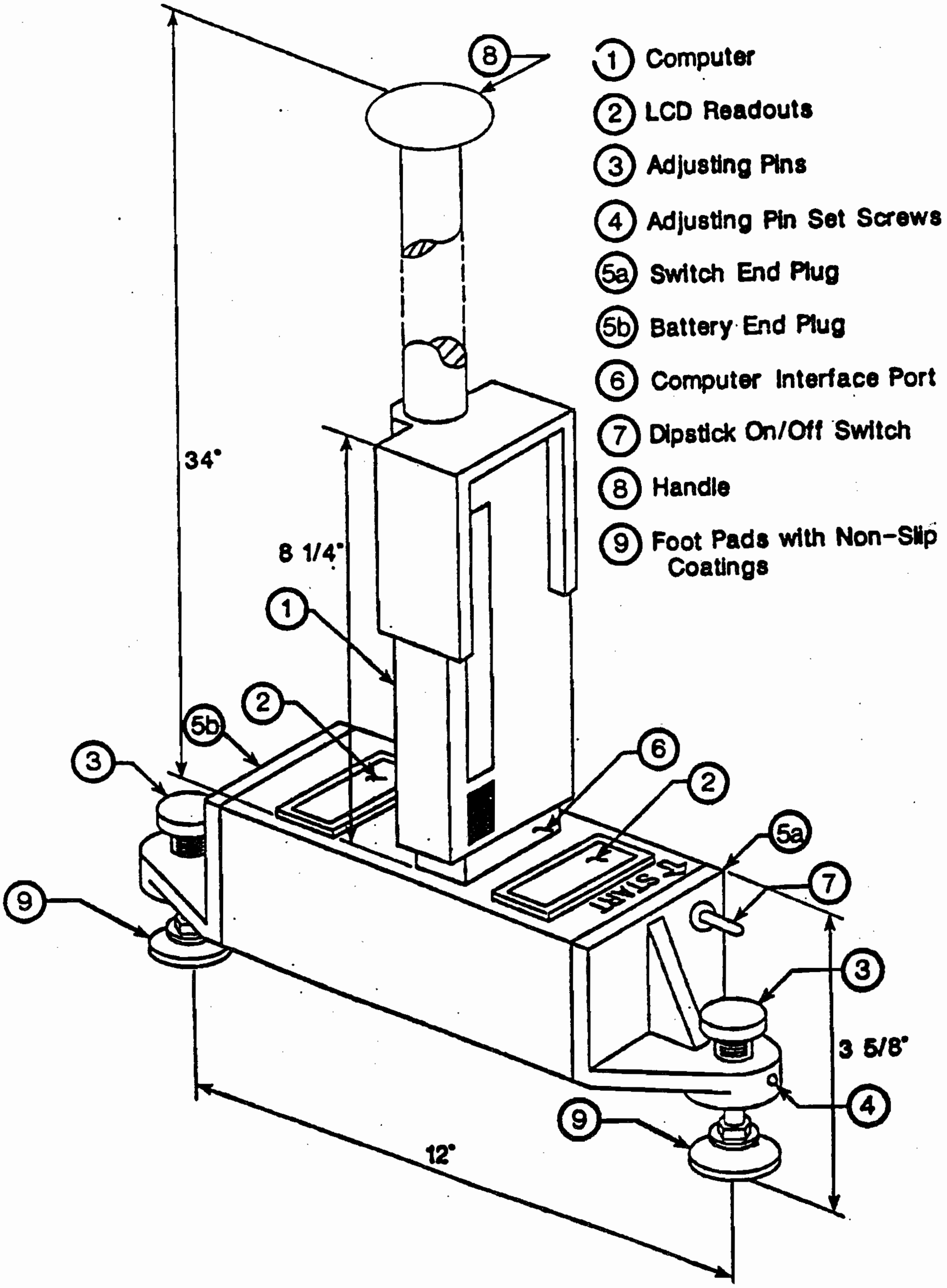


Fig 5.1. Auto-read version of the Dipstick.

for a survey section should be determined by rerunning the survey section without removing the Dipstick from the surface, thereby maintaining the reference for a forward and a reverse run (Ref 33). Obviously, this increases both the data acquisition time and the expense of operating the instrument.

The auto-read Dipstick was thoroughly evaluated and, based on its poor repeatability, determined to be unacceptable as a roughness calibration or end-roughness specification device (Ref 34). Furthermore, the interface hardware and the quality control of the inclinometers used in the Dipstick make the instrument susceptible to false readings (or no readings) after the Dipstick has been moved to a new location on the pavement. The operator is therefore never certain that the acquired data are accurate. On the other hand, while the manual-read version is accurate and much faster than the rod-and-level surveying technique, its use should be limited to the calibration of other roughness instrumentation or to the evaluation of very short, newly-constructed pavement sections (e.g., bridge decks and ramps).

CLASS II INSTRUMENTS

The Class II modified K. J. Law Surface Dynamics profilometer (see Fig 5.2) owned by the Texas SDHPT is a laser-based instrument (as distinct from the newest K. J. Law profilometer, which uses incandescent lighting, and the South Dakota profilometer, which uses ultrasonic sensors). In the SDHPT version, two lasers are mounted on each side of the vehicle to determine the relative elevation changes for each wheelpath, reporting the elevations at 6-inch intervals.

Profilometer operation is basically the same for all units. Accelerometers mounted to the axle and body of the housing vehicle are used to monitor the vehicle motion as it travels over the pavement surface. The output of the accelerometers indicates the vehicle's response to the profile of the surface, which is then subtracted from the elevation sensor's output to give an indication of the true surface profile. Several hardware and software filters are employed on the profilometer systems to reduce the effect of different speeds of operation, to omit the longer wavelengths (usually 200 to 300 feet) associated with the pavement design slope, and to eliminate nonexistent spikes (short wavelengths) from the captured data sets. These techniques vary from one manufacturer to another.

Because both wheelpaths of a pavement section can be surveyed at the same time, the profilometer's speed of operation is an attractive feature. The instrument is also comparatively accurate, providing data that—because they can be reported at fixed intervals—give the user a relative location on the pavement surface. The start and stop location can vary because the operator inside the vehicle must start the acquisition system while the vehicle is moving at a constant speed (consequently, the data can be skewed longitudinally). The same roughness statistics available for the Class I surveying techniques can be computed for the Class II devices.

Fig 5.2. Texas SDHPT-modified Surface Dynamics profilometer.

There are, however, three main drawbacks to the selection of the Class II profilometer as the instrument of choice for end-roughness specifications:

(1) The weight of the instrument: Profilometers are mounted on relatively heavy vehicles and therefore cannot be used immediately after the paving operation. (This is especially true for rigid pavements; on flexible pavements, the profilometer could be used after the pavement has cured and after the final rolling is completed.)

(2) The technical expertise needed to maintain and operate the instrument: These systems represent the latest in the instrumentation and computer technology necessary to collect surface roughness data. The technical training required to maintain, calibrate, and operate these systems is considerable.

(3) The high initial and operational costs of these systems: The initial cost of a profilometer is approximately $250,000 (the South Dakota profilometer is supposed to be priced under $50,000 when it becomes commercially available; however, the accuracy and repeatable of this particular profiling technique has yet to be independently verified). Presently, the Texas SDHPT has only one profilometer for the entire state, and only one technician dedicated to the operation and maintenance of that instrument. It is common practice in the U. S. to require that the contractor be responsible for providing and maintaining the instrument in most end-roughness specifications. Yet if the profilometer in its current configuration were specified for Texas, the contract price for paving operations would most certainly reflect the instrument purchase price and maintenance costs. Thus, the initial expenditure and maintenance costs associated with the profilometer tend to preclude its use as an end-roughness device for pavement construction. The certification of calibration could also be a problem, since the output of the profilometer can be influenced by its software, and since dynamic calibration procedures have not yet been established.

CLASS III AND III(A) INSTRUMENTS

The instruments categorized as Class III include all of the response-type road roughness measurement systems (RTRRMS) and moving datum profilers. Like the first two categories, the Class III designation is based on the maximum error and measurement interval associated with the collection of roughness data.

Class III(A) RTRRM devices, the most commonly used roughness instruments in the world (Ref 35), employ a variety of techniques to produce the final roughness output. In one version, the instrument measures the total displacement of the axle-body movements as the housing vehicle travels down the pavement surface to be monitored; the total number of displacements (bumps) are then summed over the length of the pavement section to produce the roughness output. Another technique uses accelerometers mounted on the axle or the body of the housing vehicle or a towed trailer; the acceleration data are collected and analyzed to produce a variety of roughness statistics reported over the length of the pavement section.

The majority of the Class III(A) roughness instruments have similar limitations. They are, for example, speed-dependent and therefore must be calibrated (with the output reported in terms of the speed of operation). In addition, their outputs do not give the user any indication as to the location of trouble spots on the pavement surface. Most of the instruments produce a roughness statistic based on the average response of the vehicle or trailer to both wheelpaths in a travel lane. This condition is not altogether undesirable: One of the main functions of an end-roughness specification is to produce pavements that users (the driving public) enjoy using, and user perception is based on the vehicle's response to both wheelpaths.

In addition to the above categories, CTR has added a Class III(B) category that includes a variety of instruments that measure pavement surface roughness based on the displacement measured between the two end points of the instrument. Some of these Class III(B) instruments are rolled along the surface to be monitored, while others are either glided over or placed on designated surface locations. The following discussion focuses on the RTRRM and Class III(B) instruments made available to CTR for this research effort, with the particular instruments cited below representing a spectrum of the current technology for Class III(A) and III(B) roughness instruments.

MAYSMETERS

The Maysmeter, a device towed from a trailer or mounted in a vehicle (see Fig 5.3), is one of the most popular RTRRM instruments in use today, having been used very successfully for network-level roughness determinations. While some manufacturers have computerized the output of the Maysmeter to produce a total number of bumps per unit distance traveled, many models still produce a graphical output from which the total number of bumps per unit distance must be counted. The output is speed-dependent and represents the vehicle's response to the pavement roughness in both wheelpaths.

There are some disadvantages: Its response must be calibrated against Class I or Class II profiling techniques using multiple runs on several calibration sites with fixed distances. And, as mentioned earlier, these instruments are too heavy to be used immediately after new pavement has been laid. Moreover, because the outputs of the Maysmeter-type instruments are susceptible to changes in the suspension systems, the calibration of their outputs should be checked frequently

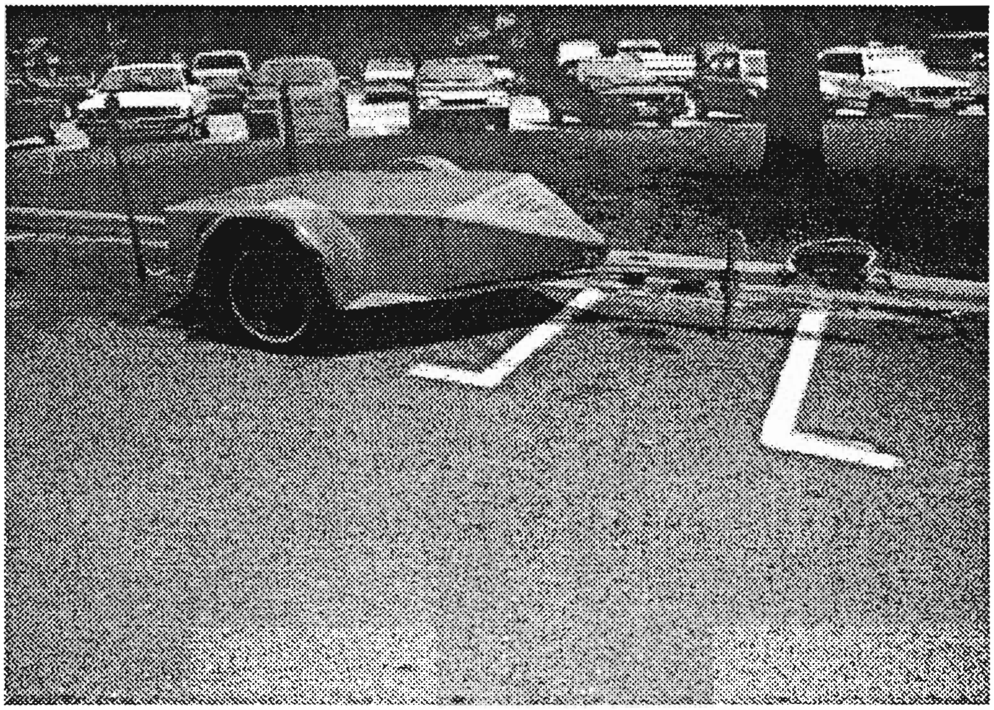


Fig 5.3. Trailer-mounted Maysmeter.

Fig 5.4. Texas SDHPT ARAN unit.

for changes resulting from normal suspension wear. The Maysmeters are also more sensitive to short wavelengths than to the longer wavelengths of pavement roughness (Ref 36). Finally, while the present cost of a Maysmeter trailer itself is roughly $10,000, a vehicle must be purchased to tow the trailer, thus bringing the total cost to approximately $20,000 to $25,000.

ARAN UNIT

The SDHPT's Automatic Road Analyzer (ARAN) unit, shown in Fig 5.4, is capable of collecting pavement distress data via video cameras at highway speeds. In addition, the unit, housed in a large dual rear tire van, can collect data on rut, gyro, and roughness. The initial cost of this unit ($350,000), its additional maintenance costs, its weight, and the technical expertise necessary to operate and maintain the ARAN, all represent drawbacks to its use for end-roughness determinations.

The roughness subsystem of the ARAN is an RTRRM instrument with accelerometers mounted on both the axle and the body. Several roughness statistics are calculated and reported by the ARAN, including Root Mean Square of Vertical Acceleration (RMSVA), Mean Absolute Slope (MAS), and Texture. These statistics represent the calculations for the long and short wavelengths of the evaluated pavement. Additionally, an estimated IRI can be collected by turning on both accelerometers and turning off the other subsystem instrumentation. The roughness response and the output statistics of the ARAN depend on its speed of operation, as selected by the operator (Ref 37).

WALKER SIOMETER

The Walker Roughness Device (SIometer) is an RTRRM roughness measurement system developed for the SDHPT in the early 1970's by Dr. Roger Walker of The University of Texas at Arlington (Ref 38). Figure 5.5 shows the Dodge Diplomat-mounted SIometer.

Developed as a cost-effective alternative to the Maysmeter, the Walker SIometer employs an accelerometer mounted above the rear axle in the trunk of a passenger vehicle. In operation, a statistical modeling procedure first characterizes the housing vehicle's dynamic responses to the pavement section's roughness condition. Once the vehicle responses have been characterized, the instrument is said to be "calibrated." The SIometer then utilizes the accelerometer information to produce a Serviceability Index (SI) over a given distance (Ref 39).

The Texas SIometers are presently mounted in two types of passenger vehicles: a Chevrolet Celebrity and a Dodge Diplomat, with both vehicle-types considered too heavy to be placed on newly-constructed or overlayed pavements immediately. And while the technical expertise necessary to operate and calibrate the SIometer is less than that required by such instruments as the profilometer or the ARAN, this instrument does require of its operators more computer literacy than does the Maysmeter.

The cost of the SIometer alone is approximately $20,000. With the cost of the vehicle, the total figure rises to between $30,000 and $35,000.

Fig 5.5. Dodge Diplomat-mounted SIometer.

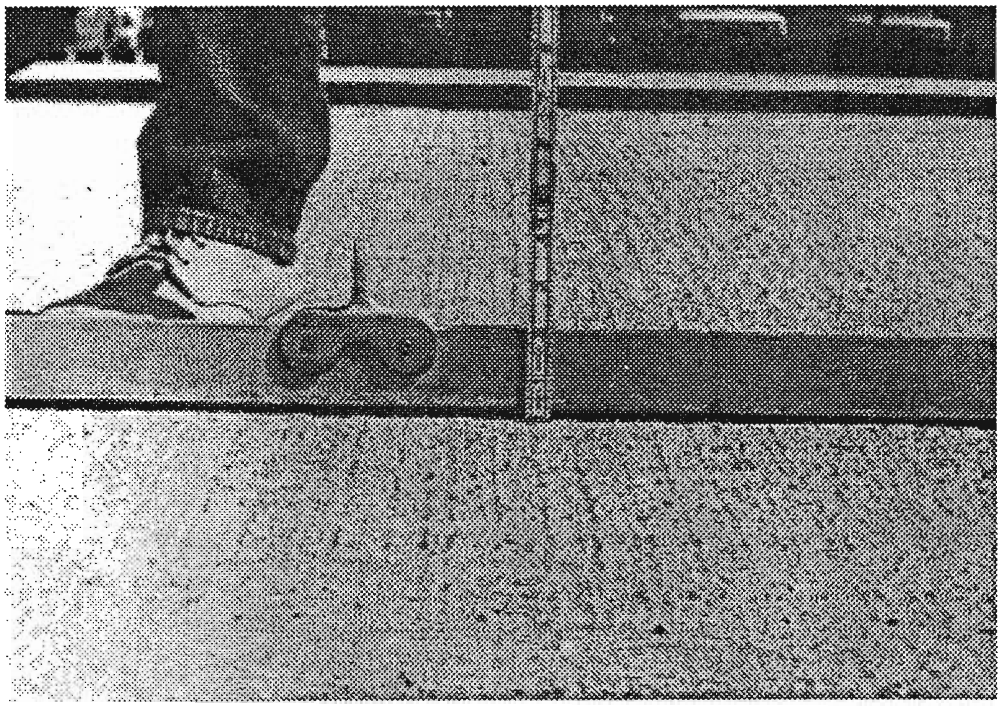


Fig 5.6. Commonly-used 10-foot straightedge.

CLASS III(B) INSTRUMENTS

This category was added to the World Bank classification scheme as previously stated. Although the maximum error and bias associated with the operation of the instruments contained in Class III can be considered the same, the principle behind the operation of the Class III(B) instruments is entirely different than that of the RTRRM's.

STRAIGHTEDGE

The instruments in Class III(B), which can be either stationary or rolling straightedges, measure deviations in the pavement surface between the two end points. Relatively inexpensive and requiring varying degrees of technical expertise to operate, these instruments are capable of following a paver as long as the surface has cured to the point where a man's weight can be supported. Because they are able to measure the wheelpaths independently, they therefore do not indicate a vehicle response to the surface roughness. The statistics associated with the individual instruments vary from the deviation of individual readings in length units, to reading and interpreting graphical profiles.

Several states, including Texas, presently have pavement roughness standards based on the 10-foot straightedge, an example of which is shown in Fig 5.6. In using this device, the state highway agency measures the deviation along the straightedge placed at any location or orientation on a pavement's surface. If the measured deviation is greater than the maximum allowable deviation, say 1/16 inch in 10 feet, then the contractor must correct the surface at the appropriate location. Because this process is very slow, its application should be limited to those pavement design features for which the procedure could be cost effective.

RIDEDAS

The Ridedas, developed in Australia, represents a variant of the straightedge technique. As illustrated in Fig 5.7, this instrument is a 1-meter straightedge with a dial gauge and plunger mounted on the centerline of a bar. The output of the dial gauge is stored in a computer carried by the operator. The pavement section is laid-out in 1-meter increments down both wheelpaths in a travel lane, an arrangement that permits the Ridedas operator to place the feet down without missing a location. The cost of the instrument is approximately $3,000 (U. S.), including the computer. The layout and evaluation of pavement roughness utilizing the Ridedas is too slow to follow a flexible paver, but it is light enough to evaluate green concrete.

CTR staff purchased a Ridedas for this evaluation effort, the initial plan being to incorporate the Ridedas on some pavement design features where the 10-foot straightedge is presently employed as the quality-control device.

There were two main concerns regarding the Ridedas. The first was its metric output (the dial gauge and the beam length are based on millimeters and meters, respectively). The second concern was the Epson computer used to read and record the pavement roughness

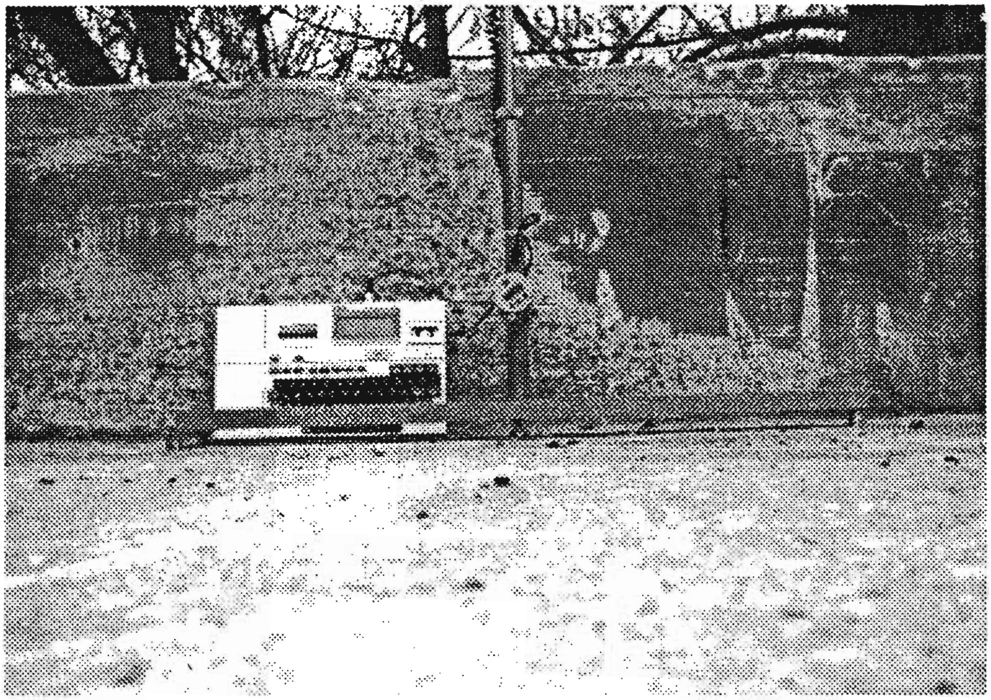


Fig 5.7. Ridedas 1-meter profiling instrument.

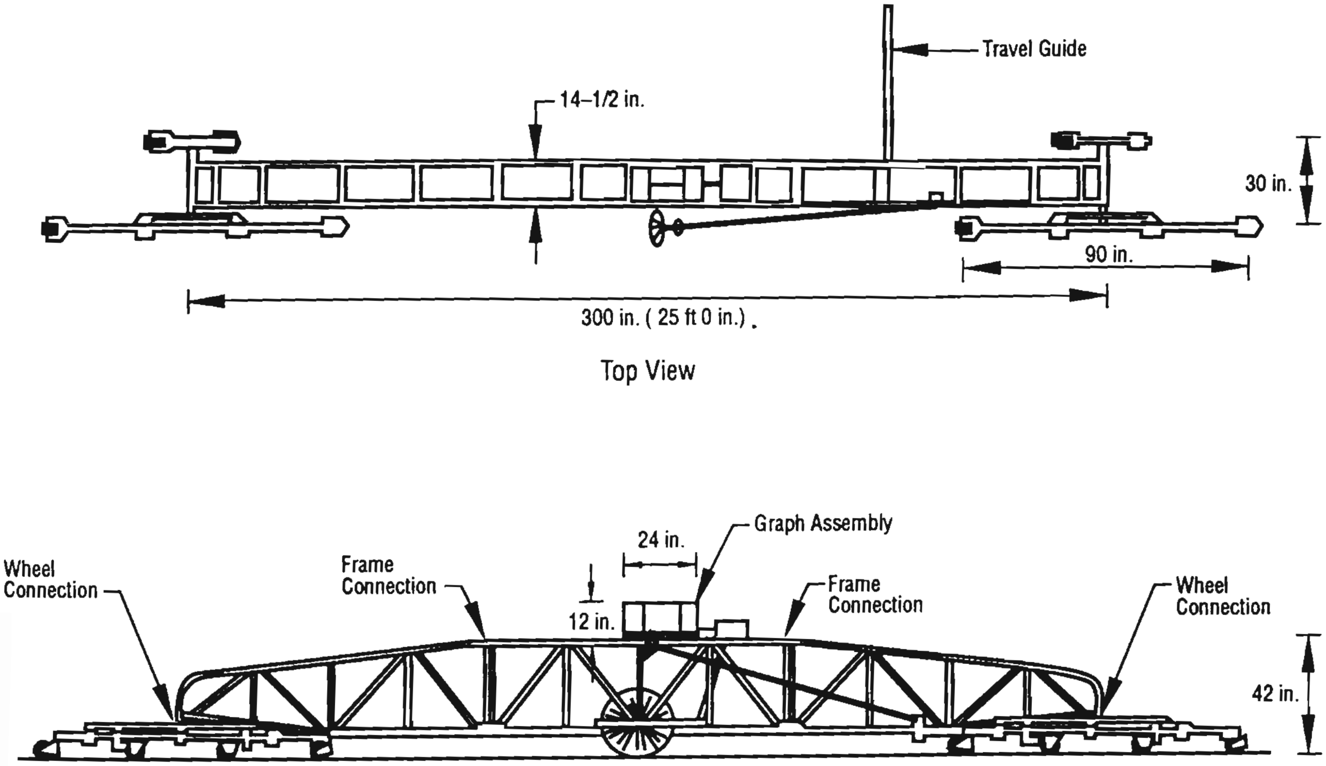


Fig 5.8. The McCracken profilograph.

data: The mini-cassette tapes this computer uses to store the acquisition program, collect the roughness data, and calculate the roughness statistic are not widely available. And efforts to interface the instrument with a Zenith laptop computer proved unsuccessful (these problems were compounded by the manufacturer's refusal to provide for our trouble-shooting purposes the source code of the program). Nevertheless, while CTR staff had limited success using the Ridedas instrument with the Zenith laptop in the field, it is believed that a concerted effort in this area could produce successful results.

The calibration of the dial gauge is based on obtaining a zero reading and a reference reading while reading and checking the range of the maximum and minimum readings. A desktop or some other flat surface (difficult to obtain in the field) is needed to check and adjust, if necessary, the zero reading. In the calibration process, the bar is lifted from the surface to allow the plunger to extend fully. The output of the dial gauge is then read and adjusted for +8.00 mm, the maximum displacement. Next, the plunger is fully retracted so that it is against the body of the bar. The output of the dial gauge is again read and adjusted for -8.00 mm for the minimum displacement. The actual readings collected from the pavement surface are recorded as plus or minus magnitudes relative to the calibration reference. During a survey run, any readings outside of the +/- 8.00 mm range are recorded as out-of-range values.

The maximum number of readings that can be collected with the present software during a survey run is 100 (each wheelpath must be marked and run separately), and the profile statistic used is called the Profile Factor (PF). In operation, the software calculates and reports the mean and standard deviation for the readings, the reading number, the chainage, the individual readings, as well as how many standard deviations each reading is from the mean. The PF for both wheelpaths in a travel lane is calculated by averaging the standard deviations from the wheelpaths. The quality control indication of pavement smoothness is based on this averaged Profile Factor.

PROFILOGRAPHS

There are several types of profilographs—or rolling straightedges—on the market today, all of them operating on basically the same principle. As previously mentioned, a number of states are already using these instruments for acceptance testing of newly constructed pavements. Figure 5.8 shows a diagram of the McCracken California-type profilograph.

In operation, these instruments are manually propelled down the wheelpath of a travel lane at approximately 2 mph. (Some manufacturers have mounted electric motors or gasoline engines on the instrument's truss to make them self-propelled.) The wheelpaths can be either marked or located using extension bars mounted on the instrument's main truss.

The basic cost of the manual version of this instrument type is between $9,000 and $14,000, depending on the manufacturer. Some of these instruments can be "broken down" and transported in trailers to job sites, while others must be towed. All, however, are light enough to be placed on the pavement behind the paver.

Most profilographs produce a purely mechanical graphical tracing of the pavement profile between the two end points of the instrument. By event-marking the construction stationing and by knowing the paper-to-distance-traveled ratio, a record of the location of surface deviations can be produced. The outputs respond to limited roughness wavelengths, with the maximum limit depending on the distance between the two end points. Recently, some manufacturers have digitized the mechanical response of these instruments in an attempt to standardize the output.

The only technical expertise required for the operation of these devices is an ability to interpret the resulting profilograms. The calibrations for the vertical displacements can be accomplished by offsetting the profile wheel with blocks of known heights and measuring the profilograph's response on the resulting profilograms. Most of the profilographs have to be sent back to the manufacturer if the vertical displacement is out of calibration. The longitudinal or distance calibration check is accomplished by rolling the instrument a known distance and measuring the length of the output to determine if the output is within the manufacturer's stated tolerance. Some types of profilographs have adjustments for the longitudinal calibration, while others are set by the inflation pressure and by the diameter of the profiling wheel.

The output statistic is calculated by overlaying a clear index scale containing a blanking band on top of the profilogram. The blanking band, which varies in width depending on the instrument manufacturer, blanks out the very short wavelengths (or microtexture) of the pavement surface so that they are not counted in the roughness statistic. Deviations outside the band are counted and summed over a known length of pavement. A Profile Index (PI) is then computed and reported in units of inches of deviation per mile of pavement.

FINAL INSTRUMENT SELECTION

An acceptance matrix, illustrated in Table 5.2, was devised to help determine the appropriate instrument for evaluating the roughness of newly-constructed rigid and flexible pavements in Texas. As seen in that table, the scale ranges from the poorest rating (quantified by a zero) to the highest rating (quantified by a four). Categorized according to the World Bank classification scheme, the instruments evaluated within this matrix are listed down the left-hand side of the matrix; across the top of the matrix are the criteria used for the evaluation of each instrument. Total scores, represented in the final column, are obtained by summing across the table for each instrument.

The results of this evaluation show that presently there is no single perfect instrument for quantifying the surface roughness of pavements. But based on the criteria established by the CTR researchers, the profilograph would be the instrument of choice for collecting pavement roughness data for use in determining end-roughness specifications. And although the interpretation of the resulting profilograms are somewhat subjective, procedures can be devised to help insure that different operators interpret similarly the same profilogram.

The following chapter identifies and describes the profilograph recommended for use with proposed end-roughness specifications in Texas. Results of CTR staff testing for operator bias and instrument-to-instrument variations are also presented, including recommended procedures for profilograph calibration, operation, and data reduction.

TABLE 5.2 INSTRUMENT EVALUATION MATRIX DECISIONS (CRITERIA)

Class	Instrument	Accuracy	Operator Expertise	Price	Distance Event Marking	Speed of Survey	Ability to Follow Paver	Verification & Ease	Total
I	Rod & Level	4	2	3	4	0	1	4	18
	Dipstick	4	3	2	4	1	2	3	19
II	SDHPT Profilometer	3	0	0	3	4	0	2	12
III	Maysmeter	2	2	1	0	4	0	0	9
	ARAN	2	0	0	1	4	0	0	7
	SIometer	2	3	1	0	4	0	1	11
	California Profilometer	2	4	2	4	2	4	3	21
	Ridedas	2	2	4	3	0	3	3	17

Scale = 0 to 4
0 – Does not meet criteria
1 – Slightly meets criteria
2 – Meets criteria
3 – Slightly exceeds criteria
4 – Exceeds criteria

CHAPTER 6. PROFILOGRAPH EVALUATION

BACKGROUND

Although there are several manufacturers of instruments fitting into the Class III(B) category, the results of several surveys conducted by ASTM and AASHTO indicate that, within that category, the California-type profilograph is the most widely used instrument employed in measuring the rideability of pavements for acceptance testing (Ref 40). The straightedge, on the other hand, is the most widely accepted device for measuring the bump specification for new pavements (although some states also use the profilograph for bump determination). The results of the evaluation matrix presented in the preceding chapter are consistent with survey results and, accordingly, tend to support the selection of the California-type profilograph as the instrument to be adopted in Texas for monitoring end-roughness specifications.

PROFILOGRAPH SIMILARITIES

While there are several types and manufacturers of California-type profilographs, all of these various instruments operate on basically the same principle. As shown in Fig 5.8, the general layout of a California-type instrument (in this case, the McCracken profilograph) includes a series of supporting wheels mounted to the front and rear of the main truss. The wheelpaths that the supporting wheels follow are offset so that the wheels are not influenced by the same deviation (macrotexture) on the pavement surface. A profiling wheel is mounted in the center of the main truss and is used to measure the vertical deviations of the pavement being evaluated. With respect to output, each type of profilograph has some mechanical device for driving the chart paper feed in some ratio to the actual distance traveled (usually 1 inch of paper travel equals 25 feet of profilograph travel over the pavement surface, although the Rainhart allows the user to select a 1-inch equivalency of either 10 or 25 feet of travel). The resulting graphical representation of the surface profile, called a profilogram, has until recently been subjectively interpreted by an operator using an index scale containing a blanking band, with the results reported in inches of deviation per mile of pavement. The roughness statistic thus produced is termed the Profile Index (PI).

PROFILOGRAPH DIFFERENCES

At this point in our comparison the similarities end and the differences begin. In particular, we note that, among the various instruments, the superstructures, which determine the overall weight and length of the individual

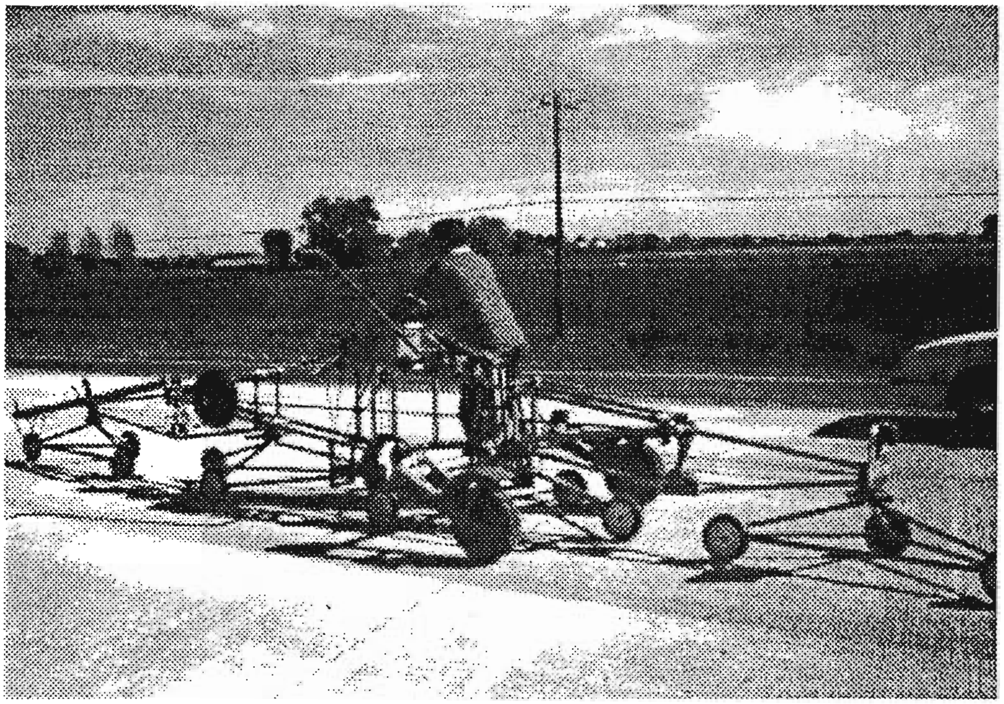


Fig 6.1. Rainhart profilograph.

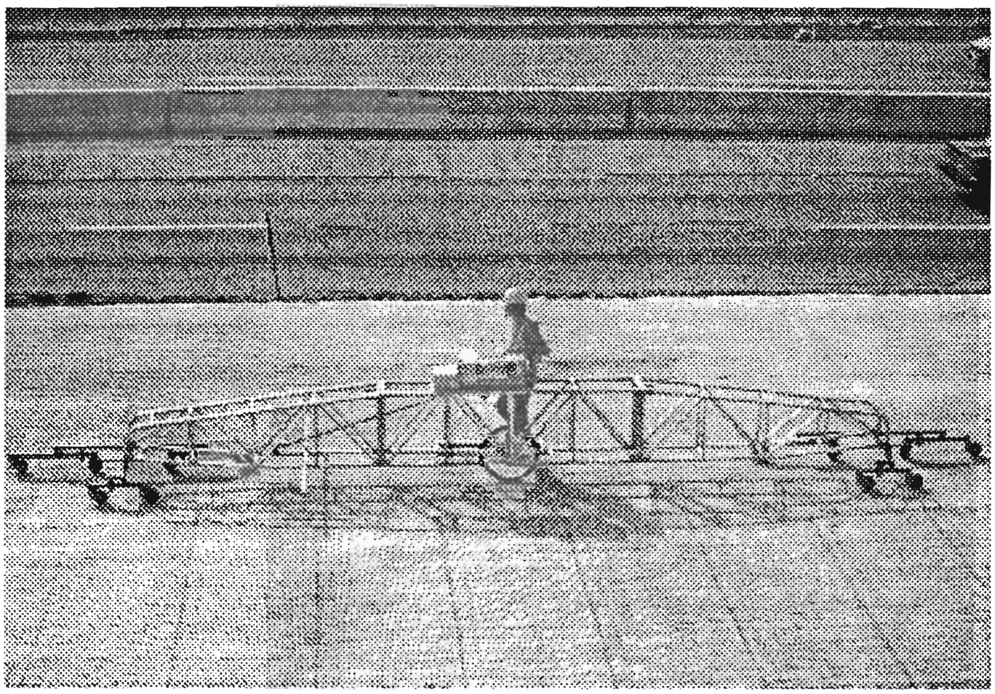


Fig 6.2. McCracken profilograph evaluating a pavement section in Austin.

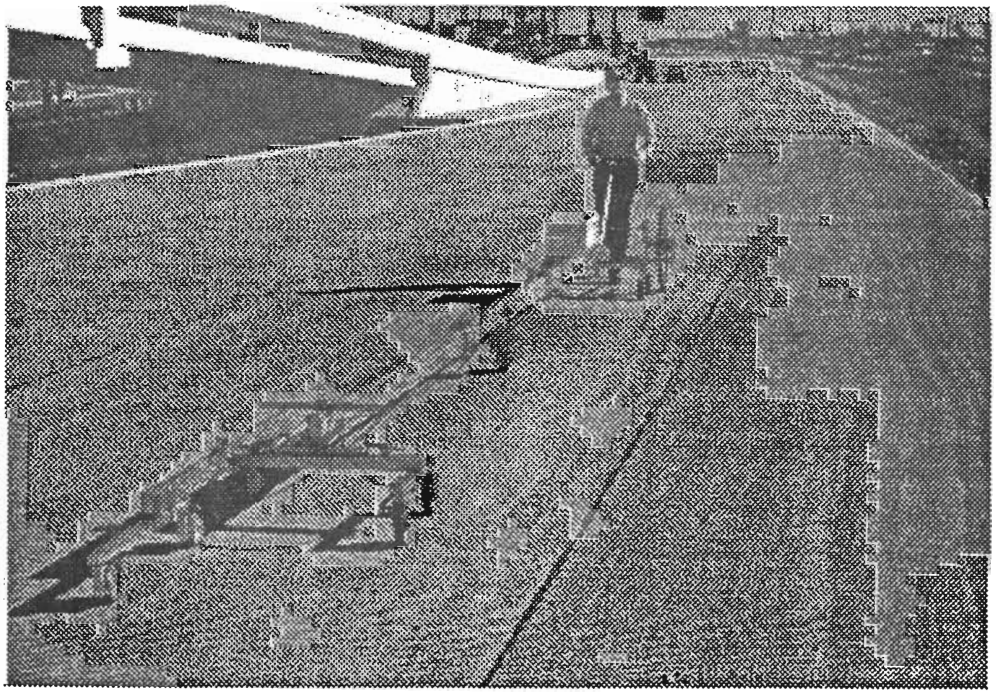


Fig 6.3. Ames profilograph evaluating a pavement section in Austin.

profilograph, are designed and constructed differently—with sometimes unfavorable results. For example, the Rainhart incorporates a three-piece superstructure that can pivot but cannot be disconnected, thus requiring that it be transported in one piece. And its overall length of approximately 26 feet, 10 inches (including the supporting wheels) makes this instrument particularly unattractive. Figure 6.1 shows the Rainhart profilograph being pushed down a roadway.

The McCracken profilograph, on the other hand, employs a main truss that can be broken down into three sections and trailered to the job site (Fig 6.2 shows the McCracken profilograph evaluating a section of newly-constructed rigid pavement in Austin, Texas).

The Ames Profilograph, a relatively new instrument developed in Ames, Iowa, has been specifically designed as a lightweight version of such heavier instruments as the McCracken machine (Fig 6.3 shows the Ames Profilograph being used to evaluate a pavement section in Austin, Texas). This device, consisting of a single beam spanning 25 feet, can be broken down into two sections for transport; its supporting wheel design is similar to that of the McCracken. The construction is indeed lightweight, and for that reason may cause some concern as to the durability of the instrument, given the rigors of the work site.

The Rainhart instrument is distinguished in that it allows the chart paper to be fed in both directions. This bidirectional paper feeding saves paper, since both wheelpaths in a single travel lane can be recorded on a single profilogram. It also means that the profilograph itself does not have to be turned around for the reverse run; the operator simply switches the direction of the paper feed and pushes the profilograph in the opposite direction. In contrast, the McCracken and Ames machines offer only one direction of paper feed and therefore must either be turned around or pushed back to the starting location to run the second wheelpath in a travel lane. In addition, the Rainhart and the McCracken both require special graph paper for the proper operation of their tractor paper feed mechanisms. The Ames profilograph requires ordinary tractor feed computer paper.

In all of the profilographs, the mechanism used to detect vertical pavement deviations consists of a sensing wheel mounted in the middle of the main truss. In the case of the Rainhart and the McCracken, the vertical sensing wheel is also used to monitor the horizontal (longitudinal) distance traveled.

With respect to calibration, all three profilograph types must be sent back to the factory if the vertical calibration is out of adjustment. As to distance calibration, the McCracken instrument can be independently adjusted. For the Rainhart, there is a 5-foot circumference sensing wheel that drives the chart recorder; if the circumference of this wheel changes, the distance calibration will be lost and the wheel must be replaced. The Ames profilograph, on the other hand, uses a separate wheel to drive the chart recorder. The distance calibration for this device is controlled by the tire inflation pressure and, therefore, its circumference. The manufacturer specifies the proper inflation pressure for each individual distance tire and the profilograph to which it is mounted. If the tire's diameter changes (thereby changing the longitudinal calibration), then the tire must be re-calibrated. This process could be very time consuming, since the profilograph must be pushed at least 500 feet and the profilogram checked for proper distance calibration; the tire inflation pressure must be changed and the process repeated until the reported distance is within calibration limits.

Whereas the Rainhart's profile trace is usually reduced using a 0.1-inch blanking band, and both the Ames and the McCracken use a 0.2-inch blank band for reducing their traces, the outputs of the Rainhart and the McCracken profilographs have been compared using both the 0.1-inch and 0.2-inch blanking bands (Ref 41). The outputs of the two instruments were evaluated on the same pavement sections constructed of new and old rigid pavements, with the corresponding profilograms of each instrument reduced using both 0.1-inch and 0.2-inch blanking bands. The results showed that the highest correlation with the least standard error occurred when the profilogram of the Rainhart read with the 0.1-inch blanking band was compared with the McCracken's output read with the 0.2-inch blanking band. The same tests were conducted for the Rainhart and the McCracken profilographs on asphalt pavements and concrete pavements with asphaltic overlays (Ref 42). The general correlation results for the asphalt pavements were the same as stated above for the concrete pavements. The difference is that the instrument-to-instrument correlations were not as good as were observed on the concrete pavements, and the standard errors were generally greater.

For quality control on asphalt pavements, the output of the Ames profilograph has been compared with that of the McCracken in a recent study designed to compare a profilograph's response to pavement roughness with that of the 10-foot rolling straightedge (Ref 43). The comparison between profilographs was based, first, on the initial cost of each type of profilograph (the McCracken Profilograph cost approximately $13,000; the Ames is listed at around $9,000), and, second, on profilograms obtained from different sections of pavements. According to the study, the traces from the profilograms of only two sections of pavement were sufficient to conclude that the McCracken and the Ames have essentially the same response. The output of the $12,000 Rainhart instrument was not compared with the Ames in this study.

Previous research (Refs 40 and 42) has demonstrated that the various profilograph designs respond differently to different wavelengths of pavement roughness. The flexibility of the box beam design of the main truss of the Ames profilograph—and the fact that pushing the instrument at too high a travel speed causes excess chatter in the resulting profilograms—indicates that there may be differences in the output that have not been thoroughly evaluated.

FINAL PROFILOGRAPH SELECTION

The selection of a particular profilograph to recommend for use in Texas was based on the preceding comparisons.

The lower initial cost, reduced weight, and ease of handling of the Ames make that instrument a very attractive alternative to the more commonly used McCracken profilograph. But because the Ames is a relatively new instrument, and because a literature review failed to indicate extensive comparisons of it with other profilograph types, it is recommended that the Ames not be specified for use in Texas at this time. However, it is further recommended that an acceptance testing matrix be developed in Texas for the Ames profilograph, or for any other profilograph manufacturer who would like their instrument used in Texas.

The Rainhart profilograph is harder to steer and difficult to transport (it cannot be broken down into sections), and is therefore less attractive than the McCracken version.

Consequently, the fact that most states that use a profilograph to monitor end-roughness specifications use a McCracken California-type instrument (and have reported good success) makes an excellent case for specifying a California-type profilograph for use in Texas. Contractors using the McCracken unit have reported that the instrument is very sturdy and that they are familiar with its operation. These considerations lead the researchers to recommend that the McCracken California-type profilograph be purchased for further testing and for the development of a state end-roughness specification.

PROFILOGRAPH TESTING

In testing the operation of the profilograph, CTR was interested in (1) confirming what had been published earlier (Refs 40, 41, 42, and 43), and (2) implementing any needed changes in Texas Test Method Tex 1000-S, which was written several years ago by the Texas SDHPT (Ref 44). Issues addressed in the CTR evaluation included concerns regarding the presence of interpretation bias when reading the profilograms, the repeatability of the same profilograph using multiple runs on the same pavement, and any variations detected while running the instrument with and against traffic flow. All of these tests were performed with the McCracken California-type profilograph.

REPEATABILITY AND INTERPRETATION ERROR

Research staff at CTR used two 1,000-foot sections of a newly-constructed, rigid multilane high-speed facility of Texas 71 around La Grange, Texas, for this part of the evaluation. These sections had not yet been open to traffic and, consequently, provided the researchers with an opportunity to work unrestricted by traffic control requirements. The Texas 71 facility consisted of a 10-foot shoulder and two 12-foot travel lanes. The shoulder and the outside travel lane were laid with one pass of the paver, and the inside travel lane was tied into the outside lane on the second pass of the paving operation. One of the selected sections was relatively flat, with a +1.26 percent grade. The second section contained a superelevated curve, a bridge deck with a +1.00 percent grade, and ended on the bridge beyond the expansion joint. The first test section was designated as LG-1, while the second section containing the bridge was designated as LG-2.

Both wheelpaths in each travel lane of each test section were profiled by the same profilograph operator using the same instrument. In addition, both wheelpaths in each lane were laid out with string line and marked with painted dots so that repeat runs could be made on the same locations on the pavement surface. All runs on LG-1 were made traveling in the direction of traffic flow, while the LG-2 sections were run against the flow of traffic. The wheelpaths in both sections were designated using the same nomenclature; that is, the outside wheelpath in the outside lane was designated WP1, the inside wheelpath of the outside lane was designated WP2, the outside wheelpath of the inside lane was designated WP3, and finally, the inside wheelpath of the inside lane was designated WP4. The distance and vertical calibration of the profilograph were checked before any runs were made. A total of six repeat runs were made on each wheelpath of each test section.

Following these runs, the profilograms were brought back from the field for interpretation by a profilograph operator familiar with the Texas Test Method Tex 1000-S. (This test method describes how the profilograms will be read and the vertical deviations counted.) Two other persons—one who had read profilograms before, and another who had never seen a profilogram—were asked to evaluate the profilograms from the two test sections. Both were instructed to read the sections of Texas Test Method Tex-1000-S describing profilogram interpretation and PI statistic calculation; following this, any questions they had regarding the methodology would be answered. They were then to read the profilograms and calculate the resulting PI values. The resulting PI values calculated from the three interpreters for all runs are shown in Tables 6.1 through 6.3. The comparison of the statistics calculated by the three interpreters are presented in Table 6.4. The coefficient of variance calculated for each wheelpath in both test sections gives an indication of the repeatability of the instrument. The higher the coefficient of variance, the less repeatable the instrument's response and/or the higher the operator bias. Since all three interpreters were reading the same profilograms, it could be assumed that the least variance value for an individual wheelpath determined by the three interpreters is a reasonable estimate of the true coefficient of variance of the profilograph used for this testing. The coefficient of variance would then range from 4.52 to 9.36. This coefficient of variance range is well within that reported by Kulakowski and Wombold (Ref 40).

A one-way analysis of variance test was conducted on the above data to compare the PI values obtained by the three operators. The average PI for each wheelpath for each interpreter and the associated standard deviations were used in the statistical calculations. Additionally, an F statistic was computed for each wheelpath using a pooled standard deviation, with the probability (P) then calculated. The results of these calculations and the

TABLE 6.1 PI VALUES FOR LA GRANGE TEST SITES FROM INTERPRETER #1

Run	Section LG-1				Section LG-2			
Number	WP1	WP2	WP3	WP4	WP1	WP2	WP3	WP4
1	27.78	24.64	21.12	11.88	23.08	15.05	30.45	11.55
2	25.52	30.80	19.36	9.66	19.06	16.10	27.65	10.50
3	31.68	29.04	21.12	9.68	21.70	15.40	27.30	10.50
4	29.48	28.16	19.36	8.80	19.60	17.85	26.26	10.15
5	29.92	28.60	16.72	11.00	20.30	19.25	30.45	10.85
6	29.48	22.44	18.04	11.00	20.65	16.45	29.45	10.50
Average	28.97	27.28	19.29	10.34	20.73	16.68	28.59	10.68

TABLE 6.2 PI VALUES FOR LA GRANGE TEST SITES FROM INTERPRETER #2

Run	Section LG-1				Section LG-2			
Number	WP1	WP2	WP3	WP4	WP1	WP2	WP3	WP4
1	30.36	27.72	23.76	11.00	24.13	15.39	30.77	11.54
2	28.18	30.36	20.68	8.36	19.58	17.13	27.62	11.89
3	36.52	27.72	22.44	11.44	19.58	16.43	29.37	12.24
4	29.04	32.56	20.24	11.44	20.63	17.13	25.18	10.49
5	29.92	27.28	18.92	11.44	20.28	18.18	30.77	11.89
6	32.56	35.20	17.60	11.44	18.18	17.83	30.77	11.19
Average	31.10	30.14	20.61	10.85	20.40	17.02	29.08	11.54

TABLE 6.3 PI VALUES FOR LA GRANGE TEST SITES FROM INTERPRETER #3

Run	Section LG-1				Section LG-2			
Number	WP1	WP2	WP3	WP4	WP1	WP2	WP3	WP4
1	29.04	29.04	20.68	10.12	22.73	18.53	29.72	11.54
2	27.28	28.60	19.36	10.56	18.18	12.13	25.88	9.79
3	30.80	28.16	20.68	8.80	20.63	16.43	25.88	10.14
4	32.12	26.84	18.92	10.12	20.28	17.48	25.53	10.49
5	32.56	26.84	17.16	9.24	20.28	16.78	27.97	10.49
6	30.80	30.80	17.60	11.44	21.33	18.88	27.97	11.20
Average	30.43	28.38	19.07	10.05	20.57	16.71	27.16	10.61

TABLE 6.4 COMPARISON OF SUMMARY STATISTICS FROM LA GRANGE TEST SITES FOR THE THREE INTERPRETERS

Run	Section LG-1				Section LG-2			
Number	WP1	WP2	WP3	WP4	WP1	WP2	WP3	WP4
#1								
Average PI	28.97	27.28	19.29	10.34	20.73	16.68	28.59	10.68
CV*	7.25	11.41	8.94	11.04	7.06	9.54	6.18	4.52
#2								
Average PI	31.10	30.14	20.61	10.85	20.40	17.02	29.08	11.54
CV*	9.77	10.64	10.92	11.37	9.87	5.90	7.84	5.43
#3								
Average PI	30.43	28.38	19.07	10.05	20.57	16.71	27.16	10.61
CV*	6.49	5.26	7.81	9.36	7.25	14.58	6.12	6.16

*Coefficient of Variance (percent)

TABLE 6.5 RESULTS OF THE ONE-WAY ANALYSIS OF VARIANCE TEST COMPARING THE PI VALUES OBTAINED BY THE THREE INTERPRETERS

Section	WP	Int.	Mean	Std Dev	Pooled SD	F	P
LG-1	1	1	28.97	2.102			
		2	31.10	3.040	2.420	1.21	.327
		3	30.43	1.976			
	2	1	27.28	3.111			
		2	30.14	3.206	2.719	1.69	.218
		3	28.38	1.492			
	3	1	19.29	1.725			
		2	20.61	2.251	1.849	1.22	.324
		3	19.07	1.490			
	4	1	10.34	1.141			
		2	10.85	1.234	1.112	0.81	.463
		3	10.05	0.940			
LG-2	1	1	20.73	1.464			
		2	20.40	2.013	1.675	0.06	.942
		3	20.57	1.492			
	2	1	16.68	1.591			
		2	17.02	1.003	1.777	0.07	.937
		3	16.71	2.436			
	3	1	28.59	1.768			
		2	29.08	2.280	1.922	1.62	.231
		3	27.16	1.661			
	4	1	10.68	0.482			
		2	11.54	0.626	0.592	4.62	.027
		3	10.61	0.653			

Note: Int. is the interpreter. Pooled SD is the Pooled Standard Deviation.

TABLE 6.6 THE 95 PERCENT CONFIDENCE INTERVALS FOR THE THREE INTERPRETERS BASED ON THE POOLED STANDARD DEVIATION

Section	WP	Int.	C.I.	L.B.	U.B.
LG-1	1	1	28.97±2.54	26.43	31.51
		2	31.10±2.54	28.56	33.64
		3	30.43±2.54	27.89	32.97
	2	1	27.28±2.85	24.43	30.13
		2	30.14±2.85	27.29	32.99
		3	28.38±2.85	25.53	31.23
	3	1	19.29±1.94	17.35	21.23
		2	20.61±1.94	18.67	22.55
		3	19.07±1.94	17.13	21.01
	4	1	10.34±1.17	9.17	11.51
		2	10.85±1.17	9.68	12.02
		3	10.05±1.17	8.88	11.22
LG-2	1	1	20.73±1.76	18.97	22.49
		2	20.40±1.76	18.64	22.16
		3	20.57±1.76	18.81	22.33
	2	1	16.68±1.86	14.82	18.54
		2	17.02±1.86	15.16	18.88
		3	16.71±1.86	14.85	18.57
	3	1	28.59±2.02	26.57	30.61
		2	29.08±2.02	27.06	31.10
		3	27.16±2.02	25.14	29.18
	4	1	10.68±0.62	10.06	11.30
		2	11.54±0.62	10.92	12.16
		3	10.61±0.62	9.99	11.23

Note: Int. is the Interpreter
C.I. is the 95% Confidence Interval
L.B. is the Lower Bound
U.B. is the Upper Bound

variance test are shown in Table 6.5. The 95 percent confidence intervals were computed for each wheelpath and each interpreter using the pooled standard deviations. The results are presented in Table 6.6.

A review of Tables 6.5 and 6.6 indicates that only one (LG-2, wheelpath 4) out of the eight wheelpaths used for this evaluation yielded PI values that could be assumed with 95 percent confidence to be significantly different for the three interpreters. Figure 6.4 shows the plotted values of the 95 percent confidence intervals for the three interpreters on this section. As can be seen, interpreter No. 2 obtained higher PI values than the other two interpreters for this wheelpath, while the variance between runs was relatively low.

FORWARD VERSUS REVERSE RUNS

The forward (or with the direction of traffic) flow versus the reverse (or against the traffic) variability was next studied. This aspect of the performance of the profilograph was considered important because it should not be necessary to push the instrument in the same direction on every survey run, especially for flexible paving operations (which can have lengthy daily outputs). The efficient use of both manpower and equipment would require reverse runs to be made during the evaluation of the paving operation.

A section of newly-constructed flexible pavement at the MoPac and US 183 intersection was used for this evaluation. This facility contained three travel lanes in each direction, of which only the inside and middle lanes in the northbound direction were used. The paving had not been completed at the time of this evaluation, with only the second of three lifts in place. A test section of 0.1 mile was laid out and the wheelpaths marked for repeat runs. A total of six repeat runs in each wheelpath of each travel lane—both with traffic and against traffic flow—were taken. Table 6.7 shows the resulting data obtained after the profilograms were interpreted by a single person. It should be noted that the PI values for this test section are much lower, thus indicating a smoother pavement than the Texas 71 rigid pavement sections used earlier. The results, seen in Table 6.7, are also consistent with the results obtained from the rigid pavement sections around La Grange.

The PI values from the two wheelpaths in each travel lane were averaged to obtain a single PI for each travel lane. This technique is consistent with the procedure used for obtaining the PI value by which contractor payment would be determined (in accordance with Test Method Tex-1000-S). This was done for both with-traffic and against-traffic data sets, with the results shown in Table 6.8. As can be seen by comparing the means, the standard deviations, and the coefficients of variance presented in Tables 6.7 and 6.8, the process of averaging the individual wheelpath PIs reduces both instrument and interpretative variability.

Additionally, the 95 percent confidence intervals were calculated using the mean value and the standard deviation presented in Table 6.7, with the data presented

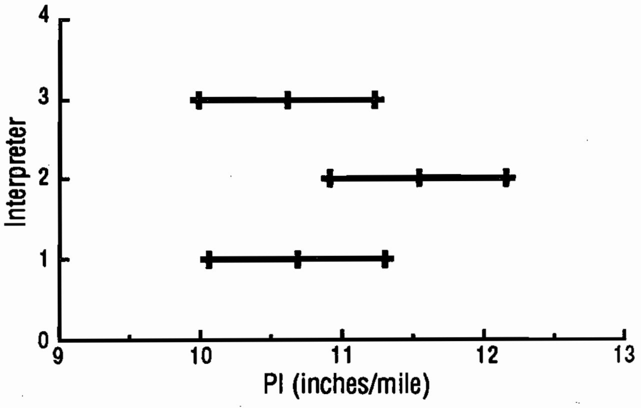


Fig 6.4. Confidence interval of section LG-2, wheelpath 4.

TABLE 6.7 SUMMARY OF PROFILE INDICES, MEANS, STANDARD DEVIATIONS, AND COEFFICIENTS OF VARIATION

	Middle Lane				Inner Lane			
	Inner WP		Outer WP		Inner WP		Outer WP	
	WT[1]	AT[2]	WT	AT	WT	AT	WT	AT
	10.0	12.5	9.5	11.0	10.0	10.0	9.5	10.5
	11.5	10.5	9.5	10.5	12.0	12.0	10.0	10.0
	11.5	9.0	9.5	10.5	12.0	12.5	11.5	10.0
	11.5	9.0	9.5	10.5	13.5	13.5	9.0	11.0
	12.0	11.5	11.0	9.0	12.5	13.5	11.0	9.0
	11.5	10.0	9.0	10.0	12.5	11.5	8.5	8.0
Mean	11.08	10.58	9.67	10.17	12.92	12.50	9.83	9.75
Std. Dev.	0.861	1.242	0.683	0.683	1.158	0.837	1.211	1.084
COV[3]	0.0777	0.1174	0.0706	0.0672	0.0896	0.0670	0.1232	0.1112

[1] With Traffic (Northbound)
[2] Against Traffic (Southbound)
[3] COV stands for Coefficient of Variation COV = Std. Dev./Mean

TABLE 6.8 SUMMARY OF PROFILE INDICES, MEANS, STANDARD DEVIATIONS, AND COEFFICIENTS OF VARIATION CALCULATED FOR EACH TRAVEL LANE

	Middle Lane		Inner Lane	
	WT[1]	AT[2]	WT	AT
	9.75	11.75	9.75	10.25
	10.50	10.50	11.00	11.00
	10.50	9.75	11.75	11.25
	10.50	9.75	11.25	12.25
	11.50	10.25	11.75	10.75
	10.25	10.00	10.50	10.25
Mean	10.50	10.33	11.00	10.96
Std. Dev.	0.570	0.753	0.774	0.749
COV[3]	0.0543	0.0729	0.0704	0.0683

[1] With Traffic (Northbound)
[2] Against Traffic (Southbound)
[3] COV stands for Coefficient of Variation
COV = Std. Dev./Mean

TABLE 6.9 95 PERCENT CONFIDENCE INTERVALS FOR EACH WHEELPATH FOR BOTH DIRECTIONS

Lane	WP	Direction	Mean	Std. Dev.	LB[1]	UB[2]
Middle	Inner	With Traffic	11.08	0.861	10.18	11.99
Middle	Inner	Against Traffic	10.58	1.242	9.28	11.89
Middle	Outer	With Traffic	9.67	0.683	8.95	10.38
Middle	Outer	Against Traffic	10.17	0.683	9.45	10.88
Inner	Inner	With Traffic	12.92	1.158	11.70	14.13
Inner	Inner	Against Traffic	12.50	0.837	11.62	13.38
Inner	Outer	With Traffic	9.83	1.211	8.56	11.10
Inner	Outer	Against Traffic	9.75	1.084	8.61	10.89

[1] Lower Bound of Confidence Interval
[2] Upper Bound of Confidence Interval

in Table 6.9. This analysis has thus shown that the data collected with the traffic and that collected against the traffic flow are the same, with 95 percent confidence.

WAVELENGTH RESPONSE

The profilograph's response to different roughness wavelengths within a pavement has been researched and is referenced in this text (Refs 40 and 41). The different types of profilographs have slightly different response characteristics, but all have the same response patterns. They are all bounded by an upper limit; that is, they can respond to a maximum wavelength based on the distance between the two ends of the individual instrument. The shorter wavelengths are either slightly attenuated, slightly amplified, or have a unity gain. The frequency at which the unity gain occurs means that the response of the individual profilograph is passed through the system without being attenuated or amplified. All roughness monitoring equipment have individual response characteristics, and some, like RTRRM systems, are speed-dependent. While Class I and II roughness devices are able to see longer wavelengths of surface roughness and can respond more uniformly to all wavelengths, some are limited on the short-wavelength end of the spectrum.

MODIFICATION OF PROFILOGRAM INTERPRETATION PROCEDURES

The procedure used for the interpretation of the profilograms was established in Texas by Texas Test Method Tex 1000-S. The initial evaluation of the profilograph and the resulting profilograms were conducted using this procedure. In an attempt to reduce the subjectivity of the profilogram interpretation (and hence reduce any variation in the interpretation of the same profilogram), Texas Test Method Tex 1000-S was modified to include other areas of concern (such as calibration procedures). This discussion, however, concentrates on the interpretation for the calculation of the PI value from the profilograms.

The latest (third) revision of the Test Method, attached as Appendix A, incorporates comments and recommendations made by several individuals within different divisions of the Texas SDHPT.

The two major changes concerning the interpretation of the profilograms involve (1) the placement and marking of the index scale containing the blanking band, and (2) the counting of the magnitude of the scallops which extend above or below the blanking band. Interpretation differences can occur because of the individual placement of the index scale and the blanking band on a single profilogram. (These differences could occur even if the same interpreter reads the same profilogram.) The placement of the index scale is according to the interpreter's judgment and is determined by finding the index scale position which yields the least profile deviations above and below the blanking band. For each individual profile trace there exists a "best" position; that is, that position which gives the least deviations and therefore the lowest PI value. For pavement sections which contain slope changes, the index scale must be repositioned to follow the changes in slope. Examples of these conditions are contained in Appendix A.

The modification requires that the index scale's position be marked once the interpreter finds this "best" blanking band location. The marking procedure, which includes marking the ends (distance) of the index scale as well as its horizontal edges, allows the same interpreter (or even a different interpreter) to position and reposition the index scale in the same location during repeat measurements.

The counting of the magnitude of the individual scallops is still a matter for the profilogram interpreter to resolve. For this, the original and the modified test methods provide the interpreter with guidelines for determining whether an individual scallop should be counted, based on the extent (height and length) to which the scallop protrudes above or below the blanking band. For example, short and narrow "spikes," which could be caused by road debris or tining, would not be counted in the roughness calculation. The bands on the

TABLE 6.10 SECOND INTERPRETATION OF TEST SECTION LG-2, WHEELPATH 4, SEGMENT 1

	Run Number							Standard
Interpreter	1	2	3	4	5	6	Mean	Deviation
1	13	13	13	13	14.5	14	13.4	0.7
2	13	12.5	13	13	14	13.5	13.2	0.4

TABLE 6.11 SECOND INTERPRETATION OF TEST SECTION LG-2, WHEELPATH 4, SEGMENT 2

	Run Number							Standard
Interpreter	1	2	3	4	5	6	Mean	Deviation
1	5	6	5.5	5.5	7	8	6.2	1.1
2	5	6	5.5	5.5	7	8	6.2	1.1

index scale used for counting the magnitude of a scallop are spaced 0.1 inch apart. The interpreter is instructed to read the profile trace to the nearest 0.05 inch, or half the distance between adjacent index bands. Such an interpretation, however, can cause variations between interpreters, or even between repeat calculations with the same interpreter.

The modification to the test method calls for the interpreter to outline the profile trace in a different color before placing the index scale on the profilogram. This procedure removes many of the spikes associated with pavement texture or surface debris, which should not be counted when reducing the profiles. It also allows the interpreter to judge less subjectively the magnitude and the extent of the remaining roughness (which should be counted for the PI calculation).

Some of the original La Grange Texas 71 profilograms were reread to evaluate the effectiveness of the modifications to the Test Method. The results, presented in Table 6.5 and Fig 6.4, indicate that the statistical difference between the three interpreters on the test section designated LG 2, wheelpath 4, could be considered significant. Therefore, the six profilograms from this test section were re-evaluated by two new interpreters using the modified test method.

First, the 1,000-foot test section was divided into a standard 0.1-mile (528-foot) segment plus a partial segment as specified in the modified test method. The PI values for the two segments on all six profilograph runs were calculated by the new interpreters. Tables 6.10 and 6.11 show the PI values, the means, and the standard deviations which were calculated for the two segments by each of the interpreters. It should be noted that by breaking the 1,000 feet into a segment and a partial segment, the PI values changed. The modified Test Method 1000-S specifies that the pavement length be divided into segments of 528 feet (0.1 mile). These segments are to be evaluated and reported individually so as to ensure the consistency of the profilogram interpretation.

In Fig 6.4, the 95 percent confidence intervals of the three original interpreters were plotted. Two of the three interpreters read the profilograms with virtually the same results, while interpreter No. 2 reported significantly different results. Figures 6.5 and 6.6 represent the 95 percent confidence intervals of the two new interpreters for the full and the partial segment, respectively. As can be seen in Figs 6.5 and 6.6, the modified test method seems to have reduced the differences in PI calculation between the different interpreters.

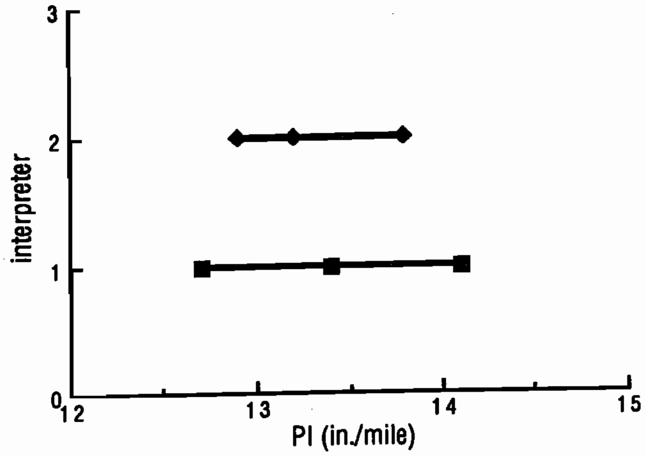


Fig 6.5. Confidence intervals of re-evaluation of section LG-2, wheelpath 4, segment 1.

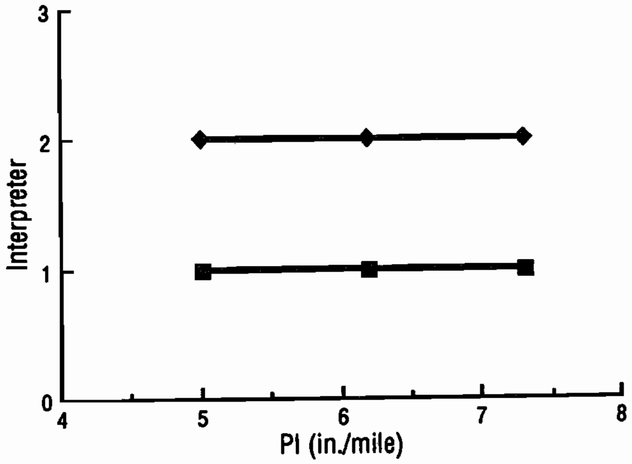


Fig 6.6. Confidence intervals of re-evaluation of section LG-2, wheelpath 4, segment 2.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

Project staff identified a significant body of literature pertaining to the problem of smooth pavement construction. In general, the literature confirmed the opinion of many state highway staff that newly-constructed pavement smoothness levels declined during the last two decades in the absence of corrective actions by state highway agencies. Furthermore, where actions were taken, the most effective were those that enhanced pavement quality through end-use specifications. A particularly important study identified in the literature was the 1984 AASHTO survey on pavement smoothness, which showed that a majority of states did not employ a comprehensive set of specifications designed to provide for smoother pavements. The results of this survey, in turn, prompted in 1987 a general AASHTO recommendation that such states begin employing end-use specifications for pavement construction, with incentives provided for high-quality work.

The first stage of this 1167 study evaluated the basic specification format recommended by AASHTO on rigid pavements, considering in particular its structure, recommended instrumentation, its effectiveness, and the implications for incorporating it into the Texas SDHPT highway specifications. These will now be considered.

CONCLUSIONS

GENERAL ISSUES

Study staff found that there was a nation-wide concern regarding deteriorating new-pavement construction smoothness standards. This main issue was divided into three constituent issues:

(1) construction procedures, practices, and manpower issues;
(2) truncated pavement service lives; and
(3) highway-user perceptions of quality.

The first group covers prescriptive actions related to construction activities. These actions typically address the performance of the equipment (e.g., setting up the slipform paver), the quality of the materials used, and challenges in managing and motivating personnel. The literature reported sets of well-defined rules covering a range of construction issues which, if followed, result in high-quality work. Yet critical though these are, they are not the focus of this study. Rather, they are a result of developing smoothness specifications which successfully induce contractors to follow procedures to meet the desired specification.

The second issue relates to the decrease in the service life of pavements. Service lives are now generally calculated from highway inventory data using a recognized surface roughness unit (e.g., the Present Serviceability Index). Where they are in routines that fit within a pavement management system (PMS), they show that building a rougher pavement accelerates the time to a minimum point on the roughness curve where maintenance or rehabilitation actions are triggered. The impacts in terms of life-cycle costs from these early rehabilitation and maintenance activities can be very considerable and can, moreover, translate into increased agency expenditures. In addition, there are considerable user-delay and congestion costs associated with such activities, all of which further support the need for more smoothly constructed pavements.

The third issue of concern relates motorists' perceptions of comfort and safety to the roughness of the pavement. In times of fiscal constraint and agency cut-backs, it is important to convince motorists that spending substantial amounts of money in pavement construction is a cost-effective exercise. Motorists, in general, directly equate roughness with quality; for example, a pavement having a high level of roughness built into its surface during construction is considered by motorists to be inferior to one having a lower roughness level.

Ideally, a pavement surface should provide a comfortable ride and have a long service life. And evidence of such pavements would suggest that the state highway department is following an appropriate and timely policy in attempting to build pavements to a much higher degree of measurable pavement smoothness. The surveys undertaken in this study, augmented by the literature review, show that a growing number of states are now employing end-use roughness specifications to improve pavement surface quality. Conversely, fewer states (Texas included) are using exclusively a bump specification, an extremely simple structure that does not induce contractors to produce high-quality work.

END-USE SPECIFICATIONS

Study staff noted a distinct decline in the use of prescriptive specifications in construction work. In such schemes, the contractor follows a sequence of actions resulting in a desired effect. An end-use specification, on the other hand, is much simpler. While the agency tests the quality and quantity of materials used in the specification to insure against fraud, the responsibility for the condition of the final product reverts back to the contractor. In the case of pavement smoothness, the contractor is informed that a certain level of smoothness is acceptable to the agency. In the event such an acceptable level is not achieved, the contractor would be required to either correct the surface to an acceptable level or be liable for financial penalties.

A basic end-use specification typically has two components: (1) a range defining acceptable values, and (2) a range within which the contractor must either correct deficiencies or be financially penalized. This basic specification can be expanded to include an incentive or bonus element; that is, a system by which the contractor is rewarded for high-quality work exceeding the acceptable specification. In these more sophisticated end-use specifications there are ranges which relate to bonus elements, acceptability, corrections and penalties.

End-use specifications, once accepted by the construction profession, would provide considerable benefits to such agencies as the Texas State Department of Highways and Public Transportation. First, the responsibility for quality work in the production phase would pass to the contractor and not to state highway officials. Second, it would result in a stronger commitment to quality on the part of the contractor, since it is the contractor who is in charge of the entire process and, where bonuses are awarded, stands to benefit financially. Finally, it has benefits in terms of highway agency staffing levels, particularly as they relate to staff working on the site. Manpower workloads could be transferred to contractor staff, thus reducing the numbers of highway staff.

States such as Iowa that have successfully employed end-use specifications report a number of desirable highway program impacts. First, and most importantly, there has been a rise in end-product pavement smoothness. End-use specifications have produced in Iowa, for example, reports of higher quality roads in terms of smoothness. Second, the benefits in terms of the financial incentives paid by states do not compare with the greater benefits to the agency and motorists in terms of smoother pavements. Typically bonuses do not exceed 5 percent of unit costs—a small percentage of the total life-cycle discounted costs. Third, the specifications make it more difficult for poor-quality construction companies to get pavement work. In the early 1980's, economic downturns in a number of construction sectors encouraged companies inexperienced in highway work to bid for contracts. Though it is difficult to measure, it is likely to have contributed to the trend of rougher pavement sections being built during the last decade. Where a contract is bid with an end-use bonus specification, the experienced company can bid part of the bonus into the contract price, as was noted in a recent job in La Grange, Texas. This then gives the experienced company a competitive edge over the less-experienced company, and is an extremely desirable feature in terms of contracting highway work.

To summarize, incentive and penalty end-use roughness specifications provide both the contractor and state highway agency with a mechanism for ensuring smoother pavements; they reward quality work, penalize faulty work, and evaluate the ride quality of a pavement in a quantitative form.

ROUGHNESS SPECIFICATION

Study staff took the recommended AASHTO specification and used it to develop a rigid pavement end-product specification. This particular stage of the research focused on evaluating a range of potential instrumentation that might be used with such a specification. This instrumentation included the Californian-type profilograph, which is presently the most commonly employed instrument on pavement contracts.

The specification was designed with four profile smoothness ranges: (1) bonus, (2) acceptance, (3) conditional acceptance, and (4) mandatory rectification. This first draft was applied to main travel lanes where design speeds exceeded 40 miles per hour. This was done both to constrain the boundaries of the study and to focus on those highway lanes most sensitive (in terms of agency cost and motorist impacts) to higher levels of pavement roughness.

The evaluation scores for the various instruments tested in this study are given in Fig 7.1. Based on the results of this early research effort, the California-type profilograph was confirmed as the instrument of choice for determining the ride quality of newly-constructed pavements. This device in most cases is the McCracken profilograph, but there are other California-type profilographs (e.g., the Ames unit) that deserve future testing.

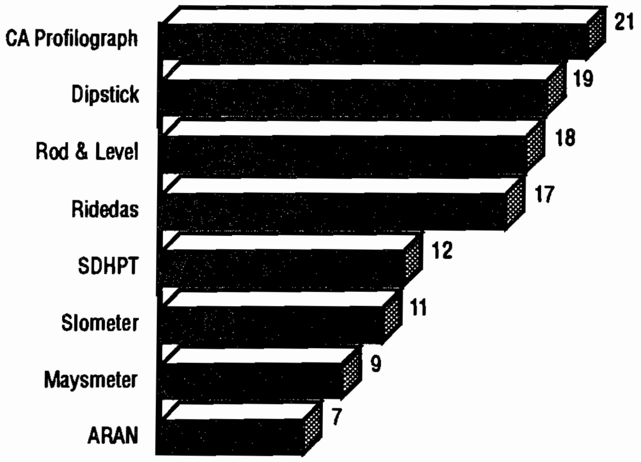


Fig 7.1. Instrument evaluation totals.

Forward and reverse runs on the same wheelpath on the pavement lane surface using the McCracken profilograph were not found to vary significantly. Furthermore, where profilographs were used on rigid pavement jobs, clear benefits in pavement quality were noted by state engineers and measured by project staff. Finally, the study staff modified Texas Test Method Tex-1000-S covering profilograph operation and profilogram interpretation. The modification appears to have reduced the subjectivity associated with interpreting profilograms (interpretation has at times been a problem with this instrument). It is believed that this will enable the profilograph output to be interpreted similarly by a number of people—for example, contracting and state highway staff.

RECOMMENDATIONS

Early study results have shown distinct and measurable benefits following the implementation of end-use roughness specifications containing bonus clauses. Staff are now proceeding to develop a rigid and flexible end-roughness specification for testing on a variety of bids throughout the state. It would seem that the best policy is to evaluate thoroughly the specification prior to its formal inclusion into the state specification handbook. There are a number of issues to be addressed technically, and both contractors and highway agency staff need to be reassured that end-use roughness specifications are appropriate improvements in pavement construction procedures. The thrust of the research will continue to be on main travel lanes. Data from other infrastructure features (e.g., exit ramps, bridge approaches, shoulders, and multi-layered flexible pavement surfaces) must also be collected and evaluated so that recommendations can be made regarding the possibility of incorporating additional infrastructural end-use categories into a recommended specification.

The Californian-type profilograph should be used initially for the development of Texas rigid and flexible draft specifications. Furthermore, at this time it seems appropriate to have the same range of roughness acceptability for both pavement types. However, the bonus paid may well vary to reflect the inherent difficulties in attaining very smooth rigid pavement profiles on rigid contracts. When the Texas specifications are finalized, any instrument that meets these California-type profilograph standards could be accepted. For example, an automated version of the California-type profilograph could be evaluated, since such a feature will dramatically reduce the manpower associated with the instrument's operation and subsequent calculation of the roughness statistic. In addition, it is possible that this automated feature may reduce operator bias introduced while data are being collected and interpreted.

The Ames California-type profilograph, made available after the study was already underway, seems to be a cost-effective alternative to the McCracken instrument. It is recommended that the study obtain one of the devices (currently performing very well on contracts with the Iowa specification) for comparison with the McCracken instrument. Such a comparison in the field might lead to a methodology that includes a whole range of profilographs that might be used in the final Texas specification. (Shortcomings and limitations of the instrumentation considered in the development of the Texas specifications will be addressed in the final report of Project 1167.)

At least one flexible and one rigid paving contract should be bid and let with the draft end-use roughness specifications. This arrangement would allow project staff to monitor the work and revise, where necessary, the draft specification. Other roadway design features could be monitored and evaluated at the same time for eventual incorporation into the specification.

Finally, a state certification class should be instituted and offered at least once a year for both contractor staff who operate profilographs on state contracts, and highway agency involved with enforcing the specifications. These classes would cover the instrument's operation, data produced, and interpretation of profilograms, and would ensure that all involved in the monitoring of pavement roughness are following a consistent set of procedures. With this certification process in place, the Texas SDHPT agency would be provided a knowledgeable contracting and highway staff whose competent efforts could improve the paving operations and, thus, the ride quality of Texas highways.

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APPENDIX A. PROPOSED REVISIONS TO TEXAS TEST METHOD TEX-1000-S (REV-3) BASED ON MODIFICATIONS RECEIVED FROM SDHPT, D-9

SCOPE

This test method describes the procedure for the operation, calibration, and maintenance of a California-type profilograph. It also describes procedures for evaluating the profilograph-generated profilogram, as well as the method for determining the profile index.

APPARATUS

1. DESCRIPTION OF APPARATUS

The California-type profilograph consists of a 25-foot-long frame supported by an arrangement of twelve support wheels. Each end of the frame is supported by two sets of wheel assemblies with six wheels each. The wheels are arranged in a manner such that each wheel shares approximately an equal load, and no two wheels track the same path. The profile is recorded by the vertical movement of a wheel attached to the frame at midpoint, and is in reference to the mean elevation of the points of contact with the pavement surface established by the support wheels. The profilogram is recorded on a scale of 1 inch equal to 25 feet longitudinally and 1 inch equal to 1 inch (full-scale) vertically. It may be powered manually or by the use of a propulsion unit attached to the center assembly. The results are recorded on a profilogram (a trace of the pavement profile recorded on graph paper) for permanent storage and later evaluation.

2. PROFILE INDEX SCALE

The profile index scale shall be a clear plastic scale 1.70 inches wide by 21.12 inches long, representing a scaled pavement length of 528 feet (0.1 mile). The center of the scale shall be a marked or opaque band 0.2 inches wide that extends the length of the scale. On both sides of this band are scribed lines 0.1 inch apart that are parallel to the center line of the opaque band. These lines shall serve as a scale to measure deviations of the profilogram above and below the blanking band.

3. BUMP TEMPLATE

The bump template shall be a rectangular clear plastic guide with a scribed line 1 inch long, and a parallel slot or template edge that is spaced 0.3, 0.4, or 0.5 inches from the scribed line, depending on the application. There should be a small hole of pencil-point size at both ends of the scribed line. If used, the slot should be wide enough to accept a sharp pencil point. The 1-inch-long scribed line represents a scaled distance of 25 feet on the profilogram.

4. CALIBRATION STANDARDS

A. The longitudinal or horizontal calibration standard should be a straight, smooth, relatively clean paved surface. The test section should be of a known length (at least 500 feet).

B. The suggested vertical deflection standards should be of flat durable material of accurate thickness, approximately 3 inches by 6 inches. Suggested standard sets should include thicknesses of 0.10, 0.20, 0.40, and 0.80 inch (an additional 0.40 inch may be substituted for the 0.80 inch). The thickness should be accurate to ±0.01 inch.

5. TOOLS AND EQUIPMENT

The following is a basic list of equipment that is recommended when field testing with the profilograph.

(1) Tire inflation pressure gauge
(2) Bicycle tire pump
(3) Profile chart recorder paper
(4) Pencils
(5) Pens or pen refills
(6) Calibration gauge blocks
(7) 100-foot steel tape or roll-a-tape
(8) Tool box with assorted hand tools for adjustments to profilograph
(9) Engineering scale marked in tenths of an inch
(10) Calculator
(11) Marking paint
(12) Masking tape

CALIBRATION

1. FREQUENCY OF CALIBRATION

Calibration of the profilograph shall be performed prior to use after storage or transportation and shall be performed daily during use. Additional calibrations should be made when results are questionable. The results of all calibrations should be maintained in a logbook to provide a history of each profilograph and the resulting calibration. The profile wheel should be inspected for wear and cracks and should be changed when the wheel is worn or cracked. To determine if the profile wheel is out of round, a test setup for measuring the roundness of the profile wheel is required.

2. *DISTANCE CALIBRATION*

Longitudinal or horizontal calibration shall be performed by operating the profilograph over a measured test section of at least 500 feet. The scale factor is determined by dividing the length of this test section in feet by the length of chart paper in inches. This factor shall be 1 inch = 25 feet ± 0.2 percent. If the graph length does not meet specifications, the profilograph should be adjusted for proper calibration according to the manufacturer's recommended procedures.

3. *VERTICAL CALIBRATION*

Vertical calibration shall be checked by using the Calibration Gauge Blocks in thicknesses of 0.10, 0.20, 0.40, and 0.80 inch. Vertical calibration is performed on a level and flat area. The recorder pen is zeroed and the profile wheel shall be elevated and a calibration block placed under the wheel. This block must be firmly on the ground or pavement and shall not rock or tilt. The wheel shall be lowered onto the block and the recorder pen deflection marked. The longitudinal position of the profile wheel should be maintained as the calibration blocks are stacked and unstacked from their position under the wheel. The profilogram should be marked as each block is placed under the profile wheel. When unstacking the gauge blocks, the profilogram trace must return to the zero displacement or starting position. The scale of this measurement should be 1-to-1 (1 inch of thickness equal to 1 inch of recorder pen movement). Adjustments shall be made according to the manufacturer's instructions or returned to the manufacturer for calibration if recorded vertical deviations exceed ± 0.02 inch of the gauge block thickness.

PROCEDURE

Prior to recording the road profile, the roadway shall be cleaned of all equipment, covers, mud, debris, and other loose material.

When recording a profile, the profilograph shall be pushed or propelled at a speed no greater than a normal walk (about 3 mph). A speed greater than 3 mph will produce a profilogram that will contain excessive "spikes" and will be difficult to evaluate. After the assembly and calibration check, and immediately prior to taking each profile, the recorder pen and all counters, if present, are set to zero. When taking the profile, frequent reference marks shall be placed on the profilogram with the operator reference pen or event marker, in order to identify pavement locations when analyzing the profilogram. A reference mark shall be made at each 100-foot construction station marker, at the beginning and end of grades, on curves with super elevation, and on bridges. The start-and-stop location should be written on the profilogram for reference. Operation of each profilograph shall be in accordance with the manufacturer's instructions. Profilograms shall be taken on longitudinal or horizontal lines as required by the specifications. These lines are normally parallel to and 3 feet from each edge of the pavement travel lane that is 12 feet or less in width. These lines represent the individual wheelpaths of each travel lane. Pavement travel lanes wider than 12 feet will normally have profilograms taken 3 feet from and parallel to the approximate locations of the lane markings. Additional profiles may be needed to define areas of out-of-tolerance variations. When the profilograph is moved and is not being used to take a profilogram, the profile wheel shall be in the up position to prevent damage. The operator shall place the profile wheel on the pavement at least 30 feet before the beginning of the section to be profiled. This allows the operator to observe the profile recorder for correct operation before the beginning of the section of pavement to be profiled is reached.

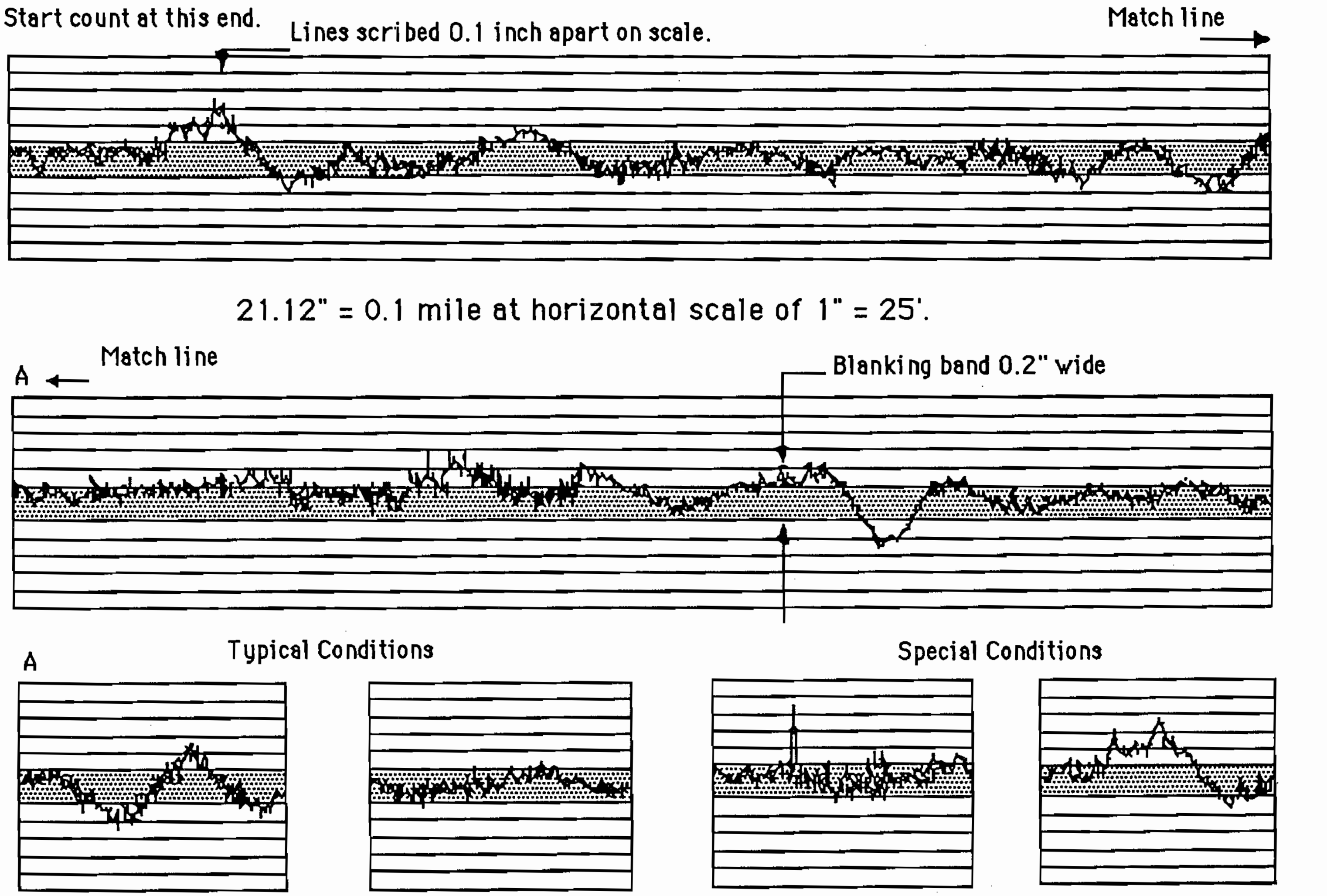
EVALUATION

1. *PROFILOGRAM EVALUATION*

The profilogram is evaluated in segments, each 0.1 mile in length. A pen of a contrasting color should be used to outline the trace through the middle of the spikes. Outlining the trace removes spikes that may be counted and aids in a more uniform trace reduction. The clear plastic profile index scale is placed over the recorder chart profile such that the blanking band (opaque region) blanks or covers as much of the profile as possible. The scallops (pen traces projecting beyond the blanking band) should be evenly distributed above and below the blanking band (Fig A.1). The profilogram evaluator should mark the placement of the blanking band by placing a solid line at each end and a dashed line above and below the blanking band position. The recorded profile may drift or move from the usual horizontal position, particularly when the profilograph is used on superelevated curves. When this occurs, break the profile into short subsections and reposition the blanking band on each section before counting the scallops (Fig A.2). Starting at the left end of the trace, measure and total the height of all scallops that protrude above and below the blanking band. Measure each scallop to the nearest 0.05 inch. Short deviations of less than 0.03 inches that do not extend longitudinally for at least 0.08 inches are not counted (Fig A.1).

2. *CALCULATIONS*

The Profile Index (PI) is calculated as "inches per mile in excess of the 0.2-inch blanking band." The example below shows this calculation. Note that the profilogram's deviation values are in tenths of an inch. By counting the deviations in whole numbers and adding the deviations for a tenth-of-a-mile segment, the unit for each segment PI will be in inches per mile.



Scallops and areas enclosed by profile lines and blanking band.

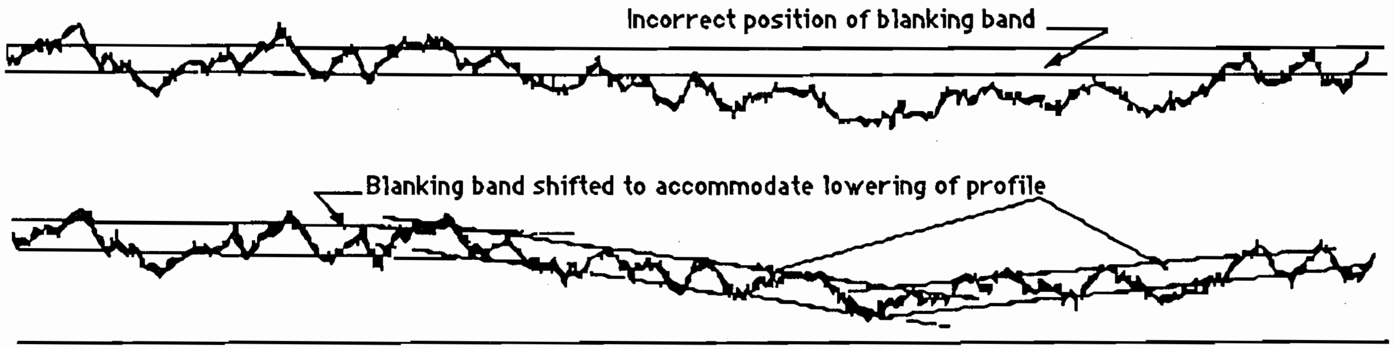
Small projections (not counted).

Rock or dirt on pavement (not counted).

Double-peaked scallop (only highest part counted).

Fig A.1. Profilogram evaluation.

METHOD OF COUNTING WHEN POSITION OF PROFILE SHIFTS AS IT MAY WHEN ROUNDING SHORT RADIUS CURVES WITH SUPERELEVATION



METHOD OF PLACING TEMPLATE WHEN LOCATING BUMPS TO BE REDUCED

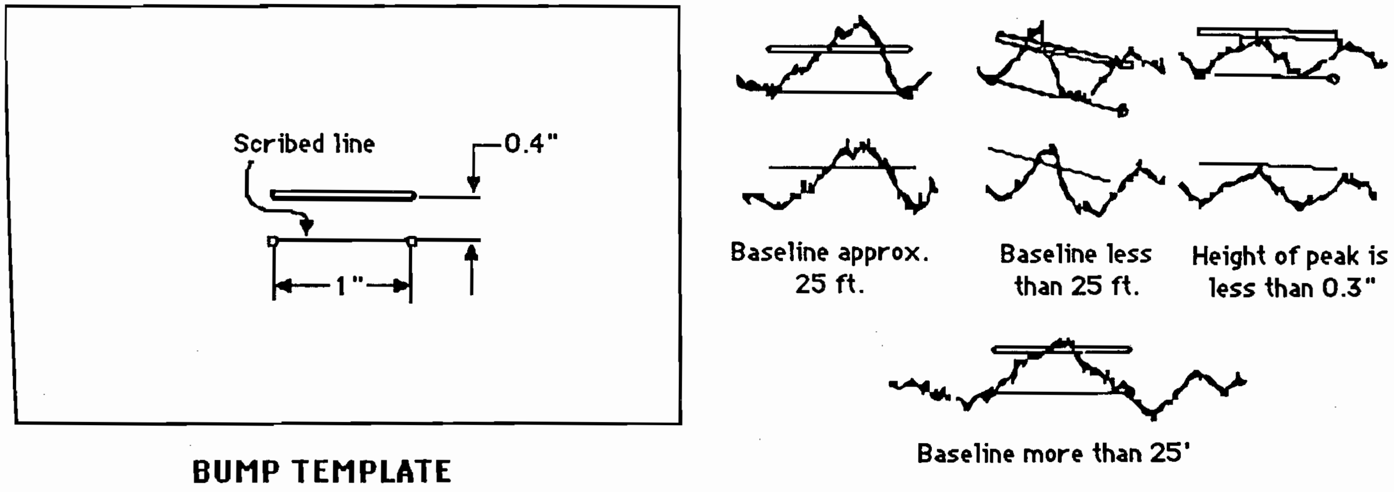


Fig A.2. Methods for counting and placing template.

3. PROFILE INDEX

The Profile Index (PI) for each segment is calculated by averaging the individual Profile Indexes from each wheelpath of a travel lane contained in a segment. Note that the profilogram's vertical deviation values are in tenths of an inch per segment, which is equivalent to the Profile Index in inches per mile.

	Count in tenths of an inch	
Segment Length (miles)	**Left Wheel Path**	**Right Wheel Path**
0.1	8.9	6.7

Profile Index (segment) = (8.9 + 6.7) /2 = 7.8 in./mile

4. DAILY AVERAGE PROFILE INDEX

The Daily Average Profile Index is obtained by averaging all Profile Indexes made on the pavement placed during a given day, except for segments less than 0.1 mile in length. These partial segments will be added to the next day's paving output. The example below illustrates the calculation of the Daily Average Profile Index for a day's paving output.

Segment Length (miles)	**Count in tenths of an inch**
0.1 1st segment	7.8
0.1 2nd segment	9.3
0.1 3rd segment	12.4
Length = 0.3 miles	29.5

Daily Average Profile Index =
(29.5 Counts in Tenths/10) x
(1 mile/0.3 miles) = 9.8 in./mi.

5. CALCULATION OF PARTIAL SEGMENTS

Situations may occur which require the calculation of the PI value for paving lengths less than the 0.1-mile segment length. In these cases, the following procedure will be used. First, determine the decimal value in miles for the partial segment. Second, determine the total vertical deviation count from the partial segment's profilogram and divide by a factor of 10 to give the number of counts in inches/mile. Then calculate the PI value in inch/mile by dividing the calculated count in inches by the decimal part of a mile. The following example illustrates the calculation process for partial segments.

Partial Segment Length (ft)	**Partial Segment Length (miles)**	**Count in tenths of an inch**
450	450/5,280 = 0.085	**6.5/10 = 0.65**

PI (for partial segment) = (0.65/0.085) = 7.6 in./mi

Note: This process can be applied to the calculation of the Daily Average Profile Index when the total of the segment lengths is in units other than tenths of a mile.

6. DETERMINATION OF HIGH POINTS

The bump template shall be used to evaluate peaks or high points on the profile trace. This template is placed so that the two holes at each end of the 1-inch scribed line lie on the profilogram trace at the base of each prominent peak or high point. If the base of the bump is less than 25 feet long, the scribed line shall be across the low points. Note that these base lines do not have to be horizontal. In no case shall this base line be greater than 25 feet long or 1 inch on the template. Longer bumps shall be evaluated using a 25-foot base line or 1 inch on the template, with this line located approximately horizontal (Fig A.2). With the template in place as described, a sharp pencil is used to mark a line either 0.3, 0.4, or 0.5 inches from the base line, depending on the application. Any part of the peak projecting above this mark represents a bump above the 0.3-, 0.4-, or 0.5-inch limit. This bump may be located on the pavement using the operator's reference marks placed on the profilogram. These bumps shall be marked on the profilogram and noted in the final report summary.

REPORTING

The engineer shall receive each profilogram and a report showing the project and control numbers, as well as the exact location of the profilograms. The date, the name of the operator, and the name of the evaluator of the profilogram shall be listed on each profilogram. The direction of travel, wheelpath, travel lane, and the start-and-stop construction station identification shall also be included with each profilogram. Additionally, the profilogram shall contain information regarding which event marks represent bridges and grades identified by the profilograph operator. The profilograms shall be evaluated and marked according to the Profilogram Evaluation Section included in the test method.

APPENDIX B. AASHTO DRAFT FLEXIBLE AND RIGID END-USE SPECIFICATIONS, 1987 (REF 3)

401.03 ASPHALT CONCRETE

Surface Test: Method #1 – The surface will be tested with a 10-foot straightedge at locations selected by the engineer. The variation of the surface from the testing edge of the straightedge between any two contacts, longitudinal or transverse, with the surface shall not exceed 1 inch (3/18 to 1/8 inch suggested). Irregularities exceeding the specified tolerance shall be corrected by and at the expense of the contractor by removing the defective work and replacing it with new material, by an overlay (not patching), or by grinding/cold milling as directed by the engineer. Following correction, the area shall be retested to verify compliance with the specified tolerances.

Profilograph Surface Test: Method #2 – The smoothness of the pavement will be determined by using a profilograph over each designated lane. The surface of mainline pavement where the design speed will be 40 miles per hour (mph) or higher will be tested and shall be corrected by the contractor to a smoothness as follows.

If the final surface course is a friction course or other special-purpose pavement layer, this specification, including corrective actions and pay adjustments, shall be applied to the pavement layer placed prior to the final surface course. The contractor shall place the final surface course so the profile index of the final surface course is less than or equal to the profile index of the preceding pavement layer.

Equipment – The profile index will be determined using a California-type profilograph furnished and operated by the Department. The profilogram is recorded on a scale of 2 inches, or full-scale, vertically. Motive power may be manual or by a propulsion unit attached to the assembly. The profilograph will be moved longitudinally along the pavement at a speed no greater than 3 mph to minimize bounce. The results of the profilograph tests will be evaluated as outlined in California Test 526.

Surface Test – The contractor shall furnish paving equipment and employ methods that produce a riding surface having a profile index of 10 inches per mile or less, except as provided for in subsequent paragraphs. Initial profiles up to 15 inches per mile may be accepted with applicable price adjustments. The profile will terminate 15 feet from each bridge approach pavement or existing pavement that is joined by the new pavement.

Pavement profiles will be taken 3 feet from and parallel to each edge of pavement for pavement placed at a width of 12 feet or less. When pavement is placed at a width greater than 12 feet, the profile will be taken 3 feet from and parallel to each edge and from the approximate location of each planned lane marking. Additional profiles may be taken only to define the limits of an out-of-tolerance surface variation.

During the initial paving operations, either when starting up or after a long shut-down period, the pavement surface will be tested with the profilograph as soon as the final rolling has been completed. Initial testing will be used by the contractor and the engineer to evaluate the paving methods and equipment.

If the initial pavement smoothness, paving methods, and paving equipment are acceptable to the engineer, the contractor may proceed with the paving operation. After initial testing, profiles of each day's paving will be run prior to continuing paving operations or prior to opening the pavement to public traffic.

A daily average profile index will be determined for each day's paving. A day's paving is defined as a minimum of 0.1 mile of full-width pavement placed in a day. If less than 0.1 mile is paved, the day's production will be grouped with the next day's production. If an average profile index of 15 inches per mile is exceeded in any daily paving operation, the paving operation will be suspended and will not be allowed to resume until the contractor takes corrective action. In the event that paving operations are suspended as a result of the average profile index exceeding 15 inches per mile, subsequent paving operations will be tested in accordance with the initial testing procedures.

For determining pavement sections where corrective work or pay adjustments will be necessary, the pavement will be evaluated in 0.1-mile sections using the profilogram. Within each 0.1-mile section, all areas represented by high points having deviations in excess of 0.4 inches in 25 feet or less shall be corrected by the contractor. After correcting individual deviations in excess of 0.4 inches in 25 feet, corrective action shall be made to reduce the profile index to 10 inches per mile or less.

In addition, any 0.1-mile section having an initial profile index in excess of 15 inches per mile shall be corrected to reduce the profile index to 10 inches per mile or less.

On those sections where corrections are made, the pavement will be tested to verify that corrections have produced a profile index of 10 inches per mile or less.

Corrective actions shall be made at the contractor's expense. All corrective work shall be completed prior to determining the pavement thickness. Corrections made by cold milling, by diamond grinding, by overlaying, or by removing and replacing shall be as directed by the engineer in accordance with the following:

(1) *Cold Milling/Grinding.* Cold milling/grinding shall be performed by the contractor until the required surface tolerances are achieved. Cold milling/grinding shall be performed so that a uniform cross-section is produced. All milled areas shall be neat and of uniform surface appearance.

(2) *Overlaying.* Asphaltic concrete pavement overlays shall meet all the requirements specified in the contract. The overlay lift shall extend the full width of the underlying pavement surface and have a finished compacted thickness sufficient to correct the roughness and produce a final surface meeting specified surface tolerances.

If the overlay does not meet the longitudinal smoothness requirement, a second overlay will not be allowed. The repairs to an overlay not meeting smoothness requirements shall be made by the contractor as directed by the engineer.

(3) *Removing and Replacing.* Corrections made by removal shall be replaced by asphalt concrete pavement materials meeting the requirements specified in the contract.

Price Adjustments – When the profile index does not exceed 10 inches per mile per 0.1-mile section, payment will be made at the contract unit price for the completed surface course. When the profile index exceeds 10 inches per mile per 0.1-mile section but does not exceed 15 inches per mile per 0.1-mile section, the contractor may elect to accept a contract unit price adjustment in lieu of reducing the profile index. Contract unit price adjustments will be made in accordance with the following schedule:

Profile Index Inches per Mile per 0.1-mile Section	**Contract Unit Price Adjustment % of Pavement Unit Bid Price**
Less than 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

This unit bid price adjustment will apply to the total theoretical tonnage representing the total thickness of the asphaltic pavement structure of the 0.1-mile-long section for the lane width represented by the profilogram.

The above price adjustment schedule will apply to pavement sections where corrective work has been completed.

Pay Adjustments with Incentives: Method #3 – When the profile index is greater than 7 inches per mile but does not exceed 10 inches per mile per 0.1-mile section, pavement will be made at the contract unit price for the completed surface course. When the profile index exceeds 10 inches per mile per 1.0-mile section but does not exceed 15 inches per mile per 0.1-mile section, the contractor may elect to accept a contract unit price adjustment in lieu of reducing the profile index. When the profile index is less than or equal to 7 inches per mile, the contractor will receive an incentive payment.

Contract unit price adjustments will be made in accordance with the following schedule:

Profile Index Inches per Mile per 0.1-mile Section	**Contract Unit Price Adjustment % of Pavement 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
Over 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 adjustment for incentives will be based only on the initial measured profile index, prior to any corrective work. The price adjustment schedule for 100 percent pay or pay reductions applies to pavement sections where corrective work has been completed.

This unit bid price adjustment will apply to the total theoretical tonnage representing the total thickness of the asphaltic pavement structure of the 0.1-mile-long section for the lane width represented by the profilogram.

501.03 PORTLAND CEMENT CONCRETE

Surface Test: Method #1 – The surface will be tested using a 10-foot straightedge at locations selected by the engineer. The variation of the surface from the testing edge of the straightedge between any two contacts, longitudinal or transverse, with the surface, shall not exceed 3/16 inch. Irregularities exceeding the specified tolerances shall be corrected by and at the expense of the contractor with an approved profiling device or by other means as directed by the engineer. Following correction, the area will be retested to verify compliance with the specified tolerances.

Profilograph Surface Test: Method #2 – The smoothness of the pavement will be determined by using a profilograph over each designated lane. The surface finish of mainline pavement where the design speed will be 40 miles per hour (mph) or higher shall be tested and corrected to a smoothness as follows.

Equipment – The profile index will be determined using a California-type profilograph furnished and operated by the Department. The profilogram is recorded on a scale of 1 inch, or full-scale, vertically. Motive power may be manual or by a propulsion unit attached to the assembly. The profilograph will be moved longitudinally along the pavement at a speed no greater than 3 mph to minimize bounce. The results of the profilograph tests will be evaluated as outlined in California Test 526.

Surface Test – The contractor shall furnish paving equipment and employ methods that produce a riding surface having a profile index of 10 inches per mile or less, except as provided for in subsequent paragraphs. Initial profiles up to 15 inches per mile may be accepted with applicable price adjustments. The profile will terminate 15 feet from each bridge approach pavement or existing pavement that is joined by the new pavement.

Pavement profiles will be taken 3 feet from and parallel to each edge of pavement for pavement placed at a 12-foot width or less. When pavement is placed at a width greater than 12 feet, the profile will be taken 3 feet from and parallel to each edge and from the approximate location of each planned longitudinal joint. Additional profiles may be taken only to define the limits of an out-of-tolerance surface variation.

During the initial paving operations, either when starting up or after a long shut-down period, the pavement surface will be tested with the profilograph as soon as the concrete has cured sufficiently to allow testing. Membrane curing damaged during the testing operation shall be repaired by the contractor as directed by the engineer. Initial testing will be used to aid the contractor and the engineer in evaluating the paving methods and equipment.

If the initial pavement smoothness, paving methods, and paving equipment are acceptable to the engineer, the contractor may proceed with the paving operation. After initial testing, profiles of each day's paving will be run prior to continuing paving operations.

A daily average profile index will be determined for each day's paving. A day's paving is defined as a minimum of 0.1 mile of full-width pavement placed in a day. If less than 0.1 mile is paved, the day's production will be grouped with the next day's production. If an average profile index of 15 inches per mile is exceeded in any daily paving operation, the paving operation will be suspended and will not be allowed to resume until corrective action is taken by the contractor. In the event that paving operations are suspended as a result of the average profile index exceeding 15 inches per mile, subsequent paving operations will be tested in accordance with the initial testing procedures.

For determining pavement sections where corrective work or pay adjustments will be necessary, the pavement will be evaluated in 0.1-mile sections using the profilogram. Within each 0.1-mile section, all areas represented by high points having deviations in excess of 0.4 inches in 25 feet or less shall be corrected by the contractor.

After correcting individual deviations in excess of 0.4 inches in 25 feet, corrective action shall be made to reduce the average profile index to 10 inches per mile or less. Any 0.1-mile section having an initial profile index in excess of 15 inches per mile shall be corrected to reduce the profile index to 10 inches per mile or less.

On those sections where corrections are made, the pavement will be tested to verify that corrections have produced a profile index of 10 inches per mile or less.

Corrections shall be made using an approved profiling device or by removing and replacing the pavement as directed by the engineer. Bush hammers or other impact devices will not be permitted. Corrective work shall be done at the contractor's expense.

Where surface corrections are made, the contractor shall re-establish the surface texture to a uniform texture equal in roughness to the surrounding uncorrected pavement. This work shall be at the contractor's expense.

Corrective work shall be completed prior to determining pavement thickness.

Price Adjustments – When the profile index does not exceed 10 inches per mile per 0.1-mile section, payment will made at the contract unit price for the completed pavement. When the profile index exceeds 10 inches per mile per 0.1-mile section but does not exceed 15 inches per mile per 0.1-mile section, the contractor may elect to accept a contract unit price adjustment in lieu of reducing the profile indexes. Contract unit price adjustments will be made in accordance with the following schedule:

Profile Index Inches per Mile per 0.1-mile Section	Contract Unit Price Adjustment % of Pavement Unit Bid Price
Less than 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

The unit bid adjusted price will be computed using the planned thickness of portland cement concrete pavement. This unit bid adjusted price will apply to the total area of the 0.1-mile section for the lane width represented by the profilogram.

The above price adjustment schedule will apply to pavement sections where corrective work has been completed.

Pay Adjustments with Incentives: Method #3 – When the profile index is greater than 7 inches per mile but does not exceed 10 inches per mile per 0.1-mile section, payment will be made at the contract price for the completed pavement. When the profile index exceeds 10 inches per mile per 0.1-mile section but does not exceed 15 inches per mile per 0.1-mile section, the contractor may elect to accept a contract unit adjusted price in lieu of reducing the profile index. When the profile index is less than or equal to 7 inches per mile, the contractor is entitled to an incentive payment. Contract unit price adjustments will be made in accordance with the following schedule in those cases where the contractor is entitled to incentive payments or elects to accept contract unit price adjustments in lieu of reducing the profile index.

Pay adjustments for incentive will be based only on the initial measured profile index, prior to any corrective work. The price adjustment schedule for 100 percent pay or pay reductions apply to pavement sections where corrective work has been completed.

Profile Index Inches per Mile per 0.1-mile Section	**Contract Unit Price Adjustment % of Pavement 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
Over 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

The unit bid adjusted price will be computed using the planned thickness of portland cement concrete pavement. This bid will apply adjusted price to the total area of the 0.1-mile section for the lane width represented by the profilogram.