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16. Abstract

This report focuses on the development of a methodology for determining an end-result smoothness specification for use on newly constructed flexible and rigid pavements. Details of the experimental study and data analysis undertaken to define acceptance levels using several criteria are presented, along with necessary guidelines that can be used for the training of personnel involved in the implementation of the smoothness specifications. Finally, the report correlates profile index with other roughness indices.

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by

Dimitrios G. Goulias
Terry Dossey
W. Ronald Hudson

Research Report 1167-2F

Research Project 3-8-88/1-1167

Development of Smoothness Specifications for Rigid and Flexible Pavements

conducted for the

Texas Department of Transportation

in cooperation with the

U.S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

October 1992

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES

W. R. Hudson, P. E. (Texas No. 16821)
Study Supervisor

PREFACE

This is the second and final 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 Department of Transportation (TxDOT). Specifically, this report documents the development of a methodology to determine pavement smoothness specifications for both rigid and flexible pavements in Texas. This report extends the findings of the first project report (1167-1), which developed the form of smoothness specification and the most appropriate instrument for use with that specification.

We would like to thank the Texas Department of Transportation, who sponsored this project, and the many staff members who assisted the authors. Also, we are grateful for the expertise provided by Mr. Rob Harrison of CTR, who developed the smoothness specifications presented in the first report of the project and assisted in preparing this report.

Dimitrios G. Goulias
Terry Dossey
W. Ronald Hudson

LIST OF REPORTS

Report 1167-1, "The Development of Smoothness Specifications for Rigid and Flexible Pavements in Texas," by Rob Harrison and Carl B. Bertrand, describes the development of the draft 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.

Report 1167-2F, "End-Result Smoothness Specifications for Flexible and Rigid Pavements in Texas," by Dimitrios G. Goulias, Terry Dossey, and W. Ronald Hudson, describes a methodology for determining the smoothness specifications used in assuring the pavement quality of both rigid and flexible pavements in Texas. In addition, it provides guidelines for the training of TxDOT personnel charged with (1) operating the California-type profilographs and (2) implementing the specifications. Finally, the report correlates the profile index (PI) obtained from the California profilograph with IRI and other roughness indices.

ABSTRACT

This report focuses on the development of a methodology for determining an end-result smoothness specification for use on newly constructed flexible and rigid pavements. Details of the experimental study and data analysis undertaken to define acceptance levels using several criteria are presented, along with necessary guidelines that can be used for the training of personnel involved in the implementation of the smoothness specifications. Finally, the report correlates profile index with other roughness indices.

KEY WORDS: End-result specifications, smoothness specifications, profile index (PI), roughness indices, profilograph, training.

SUMMARY

This report presents a smoothness specification to be used for segments of main travel lanes of newly constructed flexible and rigid pavements in Texas. Establishing a schedule of bonus and penalty payments based on end-result smoothness is expected to assure quality, while at the same time allowing the contractor to choose the equipment and methods to produce the required end product. Additional specifications were examined for segments located on other roadway components, such as shoulders, bridge approaches, and exit ramps. Preliminary suggestions are made for acceptance levels on these segments.

A survey was first undertaken to determine which states are currently using smoothness specifications and what instruments and procedures are being employed. Findings from this part of the study identified the California-type profilograph—specifically the McCracken profilograph—as the instrument of choice. Factorial experiments involving both flexible and rigid pavements from a number of roadway components were performed to evaluate the variability associated with each instrument, and to determine if the performance of the Ames profilograph was significantly different from that of the McCracken.

In the next phase of the study, the draft smoothness specification was evaluated by examining the distribution of the profile index (PI) from newly constructed pavements across the state. Separate distributions were obtained for each of the various roadway components to determine possible adjustments to the specification categories. Finally, field testing using the Face Dipstick and McCracken profilograph was performed to develop models correlating PI to such other roughness indices as IRI and RMSVA.

Findings from the study indicate that the McCracken and Ames profilographs do not significantly differ in terms of roughness evaluation. Guidelines for the assembly, calibration, and field testing of the profilographs have been included as an appendix. An examination of the PI for newly completed sections indicates that (1) bonus payments for flexible pavements may not be needed (as the large majority of these pavements are built with low initial PI), and (2) separate schedules of payment should be established for rigid pavements laid with continuous paving operations (as against stop-and-go paving operations, which are inherently less likely to produce smooth pavements). Finally, preliminary roughness test results pertaining to shoulders, ramps, and other roadway components are presented, along with recommendations for establishing future acceptance levels in the field.

IMPLEMENTATION STATEMENT

The guidelines developed in this study can be used for continued implementation of end-result specifications in Texas, which will provide such potential benefits as lower bidding prices, improved quality of the end product, and lower labor and overhead costs (since the agency's involvement would be limited solely to acceptance testing). Because of the close interaction between the research team and TxDOT, implementation of the study is already underway. This implementation includes input on current specifications being tested, and the decision to allow Ames profilograph results as valid measurements. Any final specification must come after extensive field testing and modification based on agency policy. The analysis of the Ames profilograph indicates that it may be used interchangeably with the McCracken device, provided that operators are sufficiently trained. Models developed relating profile index to other roughness indicators may be used for comparison purposes.

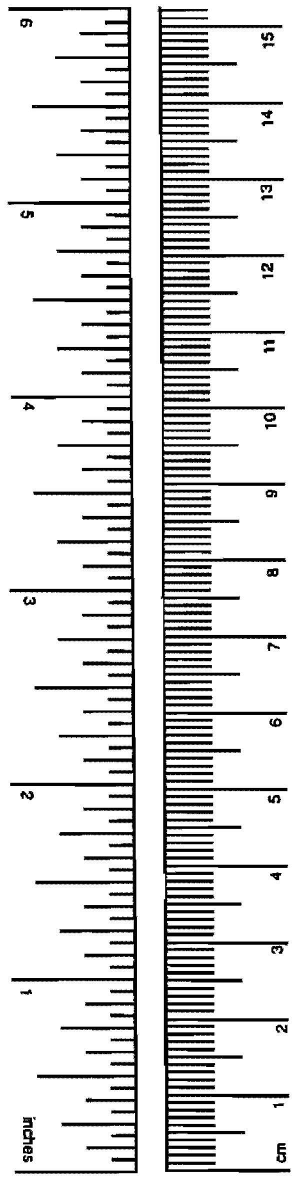
METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	0.3048	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0328	meters cubed	m^3
yd^3	cubic yards	0.0765	meters cubed	m^3

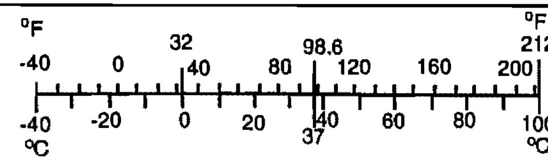
NOTE: Volumes greater than 1,000 L shall be shown in m^3.

Symbol	When You Know	Multiply by	To Find	Symbol
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.20	square yards	yd^2
km^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1,000 kg)	1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

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CHAPTER 1. INTRODUCTION

BACKGROUND

Pavement structures have for many years been constructed using "method" type specifications. This type of specification is analogous to a cookbook or recipe in that it directs the contractor to combine specified materials in definite proportions using approved equipment (Refs 1, 2). Thus, if the contractor adheres to the methods prescribed by the agency, and if such operations are accepted by the inspector, then the contractor is awarded full payment.

There have been cases, however, where the agency's step-by-step procedure has failed to produce an end product of the desired quality (Ref 3). Moreover, while some specifications stipulate that the contractor or producer is responsible for the final result, such stipulations are not usually legally enforceable, since material and method requirements will have been met by the contractor under the inspection of the agency's representatives.

In their attempts to avoid the controversial reasoning behind method specifications—and in order to obtain end products of the desired level of quality—highway agencies developed end-result construction specifications (ERS), which allow the contractor to choose the equipment and methods to produce the required end product. With an ERS, production quality control is the contractor's responsibility, while the agency accepts or rejects the end product through acceptance testing. Thus, with an ERS the contractor is solely responsible for achieving the desired level of quality for the product.

End-result specifications are generally considered by both contractors and highway agencies to be the most desirable type of specification (Refs 4-6) for two reasons: (1) they provide certain economic benefits, and (2) they ensure the proper allocation of responsibility for product quality control. Additionally in their favor, these specifications have been used for assuring pavement smoothness for some time (Ref 5). Yet many states are still uncertain about which type of specification is best for their particular requirements. Thus, in 1984, AASHTO conducted a survey of smoothness specifications with the objective of recommending a draft smoothness specification for state use (Ref 7).

In Texas, the Department of Transportation undertook to develop a new end-result smoothness specification for newly constructed flexible and rigid pavements—a specification that would replace the current Texas acceptance specification that uses the 10-foot straightedge (Ref 8) as the roughness measuring instrument. This specification was felt to have several disadvantages: (1) it cannot report any rate of repetition for deviations over some longitudinal or transverse distance; (2) it is not sensitive to ride quality or to associated pavement profile characteristics experienced by road users; (3) it contains no measure of roughness wavelength or recurrence interval; and (4) it cannot provide criteria for either pavement acceptance or contractor penalty/bonus payments.

OBJECTIVES

The objectives of this research are: (1) to define a methodology for developing a rational end-result smoothness specification for flexible and rigid pavement in Texas; (2) to define guidelines for the training of personnel charged with the implementation of end-result smoothness specifications; and (3) to define correlations of roughness indexes with the output of the instrument selected for use with the end-result smoothness specification.

RESEARCH APPROACH

The methodology used for defining and implementing a rational end-result specification is presented with the development of the smoothness specification for flexible and rigid pavements. Then, through the analysis of data collected on newly constructed rigid and flexible pavements, the specification's acceptable limits and proposed bonus/penalty payment schedules for variation from the specifications, including the variability of components involved in the evaluation of the end product quality, were defined. Finally, this report provides guidelines for the training of personnel involved in the implementation of the smoothness specifications.

The level of pavement roughness, an aspect of pavement quality, can be described with various roughness statistics. For this reason, the output (profile index in inches/mile) of the instrument (California-type profilograph) used with these proposed smoothness specifications was correlated with roughness indexes commonly used by different engineers (such as IRI in inches/mile or RMSVA's of different wavelengths) for comparative purposes.

ORGANIZATION OF THE REPORT

The first chapter of the report has presented background, the objectives of the research, and the research approach. Chapter 2 surveys current state practice with respect to smoothness specifications and focuses particularly on the components of the draft end-result smoothness specifications for newly constructed rigid and flexible pavements in Texas, as well as on the research approach used for defining the final version (and implementation) of the specification.

Chapter 3 describes the collection of data on both rigid and flexible pavements, with particular focus on the factors producing variability. Chapter 4 then presents the analysis of that collected data. In Chapter 5, the draft smoothness specification for main travel lanes is evaluated against the results of the data analysis.

Chapter 6 then examines the possibility of defining and using for other components of the roadway a specification similar to that used in main lanes. Chapter 7 presents the correlation of a profilograph's output with other roughness indices, while Chapter 8 summarizes the major conclusions of the research and presents several recommendations.

CHAPTER 2. IMPLEMENTATION OF DRAFT SMOOTHNESS SPECIFICATIONS

INTRODUCTION

The smoothness quality of newly constructed asphalt and portland cement concrete pavement has a direct influence on pavement performance and user cost. Thus, many highway agencies, once they perceived a decline in this initial pavement smoothness nationwide, began focusing on end-product (end-result) specifications as a way of assuring quality performance. The Center for Transportation Research (CTR) of The University of Texas at Austin, under the sponsorship of TxDOT, undertook to evaluate an end-product smoothness specification and its requisite roughness measuring device.

In documenting the initial development of the draft end-result smoothness specification, this chapter presents a brief history of the application of pavement smoothness specifications in the U.S., along with a CTR survey of states operating with smoothness specifications. The chapter concludes with a discussion of the implementation of the CTR-defined draft smoothness specification.

BACKGROUND AND STATE PRACTICE

State smoothness specifications have been customarily based on measurements made with a 10-foot straightedge (Ref 9, 10), allowing a plus or minus 1/16-inch deviation in any 10-foot length. The problem has been that such specifications do not provide criteria that relate quality of work to contractor's compensation. Furthermore, while the straightedge detects some fluctuation in vertical profile from the straightedge data, the specifications based on its measurement cannot report any rate of repetition for such deviations over a longitudinal distance. There are other problems as well: The straightedge is not sensitive to either ride quality or to associated pavement profile characteristics experienced by road users; it contains no measure of roughness wavelength or recurrence interval; and finally, it cannot provide measurable criteria for either pavement acceptance or contractor penalty/bonus payments.

California became one of the first states to address these problems when, in the early 1960's, it began to apply longitudinal roughness to construction quality control. Such measurements were made possible through the development of an offset pavement profile measuring instrument that was manually operated and multi-wheeled. The device, known as the California profilograph, records the pavement surface profile on a paper roll from which a profile index (PI), in units of inches per mile, can be interpreted. In the 1960's California changed its acceptance specifications to include profilograph output, but up until the 1980's few other states followed this example.

AASHTO Survey

In 1987, AASHTO conducted a survey to identify those states using smoothness specifications; the purpose of the survey was, first, to document state experience with such specifications, and, second, to develop a unified set of recommendations. The results, based on 39 responding states (Ref 11), show that 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 specification that evaluates individual excessive deformations on the profile surface. The survey data, presented in the first report of this study (Ref 12), indicate that over 70 percent of the responding states used both a ride and a bump specification, 20 percent used a bump specification only, while 8 percent used no smoothness specifications whatsoever. Bump deviations were almost always controlled using a tape measure and a 10-foot straightedge, and the instrument of choice was most often the California-type profilograph (around 70 percent of the responding states reported using this instrument).

While the survey identified the profilograph as the basic smoothness instrument used in specification enforcement, it also found that equipment provision was equally shared between contractors and highway departments (42 percent each), and 16 percent of respondents stated that both groups supplied devices for cross-checking. Moreover, under the acceptance range of the smoothness specification, the contractor's daily output is broken down into lane lengths, usually 1/10th of a mile (528 feet), and smoothness measurements are taken for quality acceptance purposes. Finally, the survey revealed that only a third of the responding states used bonus provisions for high-quality work. Following the survey, AASHTO published its recommended guide specifications (Ref 9).

CTR Survey

The Center for Transportation Research of The University of Texas at Austin undertook a follow-up survey as part of a research project for TxDOT (Ref 9). In evaluating different state specifications, CTR staff concluded that the most commonly used instrument is the 10- or 12-foot straightedge, followed by the rolling straightedge, and then the profilograph. When a rolling straightedge or profilograph is used, the instrument is operated either (1) along the centerline of the travel lane, (2) in one wheelpath, or (3) in both wheelpaths of a travel lane. In general, when a profilograph is used in the specifications, a variety of acceptance levels is also used.

The telephone survey conducted by CTR staff concluded that engineers in nine states using smoothness specifications confirm the effectiveness of the California-type profilograph. The majority of the contacted states have had about 10 years' experience with smoothness specifications, thus making the data especially pertinent to the TxDOT decision. Both contractors and state highway staff confirm that the California-type profilograph has an extremely beneficial effect in improving quality control, and that its adoption in state specifications has consequently resulted in higher ride-quality standards. Details on the results of this survey are given in the first report of this study.

Selection of Profiling Instrument

The choice of roughness instruments was based on the roughness instruments available to TxDOT. These included static instruments (such as the rod-and-level survey and the Face Dipstick), Class I instruments (according to the FHWA classification; see Refs 13, 14), the K. J. Law Surface Dynamics profilometer, a laser-based instrument (CLASS II), response-type road roughness measurement systems (or RTRRMS, which include the Maysmeter, ARAN, and Walker SI-ometer considered as Class III[A] instruments), and finally, moving datum profilers (such as the straightedge, Ridedas, and profilographs, Class III[B]).

The final instrument selection was based on the results of the acceptance matrix, which in turn was based on criteria established by project staff (Ref 12). Several selection criteria were chosen to identify an appropriate instrument to go with the specifications. 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 were important criteria in the decision process. The acceptance matrix for the selection of the roughness instrument to be used with the specification is presented in Table 2.1. (The final instrument selection was based on the results of this acceptance matrix.) Thus this analysis shows that the profilograph is the instrument of choice for use with the specifications.

Finally, a comparative evaluation of two types of California profilographs demonstrated that the McCracken California-type profilograph is the best overall; however, it was further recommended that an acceptance testing matrix be developed in Texas for the Ames or any other profilograph whose manufacturer would like their instrument considered for adoption in Texas. The Ames device met these criteria.

NEXT OBJECTIVES

Having selected a smoothness device to be used with the specifications, and having developed the draft end-result smoothness specification that could be applied to the testing and acceptance of newly constructed flexible and rigid pavements, the next objectives of the study (treated in detail in subsequent chapters of this report) were to conduct several analyses for evaluating:

1. the components of variability involved in roughness measurements;
2. the rationality of the acceptance categories of the draft specifications for main lanes of newly constructed flexible and rigid pavements from data collected through different paving projects throughout Texas;
3. the applicability of such specifications for other components of roadway, such as shoulders and exit ramps;
4. guidelines for the training of personnel involved with the implementation of end-result smoothness specifications; and, finally,

Table 2.1 Instrument evaluation matrix decisions (Ref 12)

Class	Instrument	Accuracy	Operator Expertise	Price	Distance Event Marking	Speed of Survey	Ability to Follow Paver	Verification and Ease	TOTAL
I	Rod & level	4	2	3	4	0	1	4	18
	Dipstick	4	3	2	4	1	2	3	19
II	SDHPT prof.	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 prof.	2	4	2	4	2	4	3	21
	Ridedas	2	2	4	3	0	2	3	16

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

5. correlations of the output of the selected roughness device with other roughness indexes for comparative purposes.

IMPLEMENTATION OF DRAFT SPECIFICATIONS

Using the initial CTR study, and after meeting with the TxDOT specification committee, CTR researchers defined the draft smoothness specifications for flexible and rigid pavements. The specifications apply to contracts where design speed exceeds 40 miles per hour on the travel lane (thus eliminating city streets, frontage roads, shoulders and freeway ramps). According to this draft specification, the California profilograph should be used for obtaining the profile index (in inches per mile) of the two wheelpaths. The final index is then the average of both wheelpaths on each travel lane. The CTR draft smoothness specification presented in Report 1167-1 has recently been revised by TxDOT. The latest version of the specification, Item 585 (Ref 15), is presented in Appendix B. The new bonus/penalty payment schedule is shown in Table 2.2, with the acceptance categories of the revised specification shown in Figure 2.1. With this revised specification, identification of the high points (bumps greater than 0.3 inches) is made from the profilogram of the segments and through the use of a bump template, as described in Appendix A.

This draft specification has been implemented by TxDOT in several paving projects in Texas, with some of the results of this implementation discussed in the following chapters. This specification was then examined in this study with data collected across Texas.

Table 2.2 Profile Pay Adjustment Schedule for CTR draft Smoothness Specification (Ref 12)

Profile Index (Inches Per Mile, per Each 0.1-Mile Section)	Bonus or Deduction (Percent of Unit Bid Price)
3.0 or less	+ 5
3.1 thrugh 5.0	+3
5.1 thrugh 7.0	+1
7.1 thrugh 10.0	+0
10.1 thrugh 11.0	-2
11.1 thrugh 12.0	-4
12.1 thrugh 13.0	-6
13.1 thrugh 14.0	-8
14.1 thrugh 15.0	-10
Over 15.0	Corrective work required

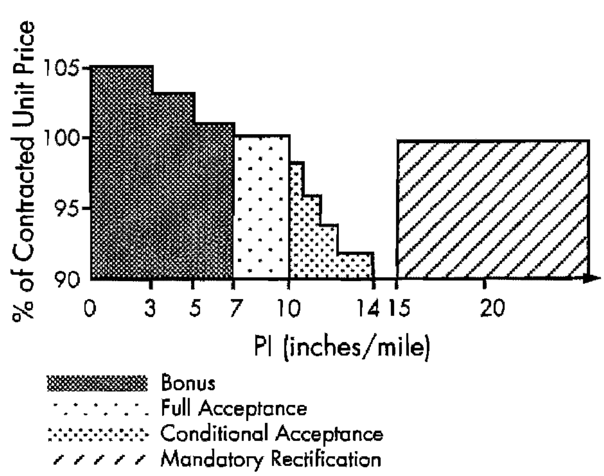


Figure 2.1 CTR draft smoothness specification (Ref 12)

CHAPTER 3. EXPERIMENTAL STUDY

INTRODUCTION

Following the development of the draft end-result smoothness specification, further research was conducted to examine: (1) the factors producing variability in roughness measurements; (2) the variability associated with these factors; and (3) the acceptance limits of the draft specification for main travel lanes and other roadway components.

This chapter focuses on such factors as the type of roughness equipment, the operators, and, finally, the interpreters of equipment output. The location of the roadway segment is also considered for testing the applicability of the specifications on roadway components other than main travel lanes. Roughness level, measured in PI (inches/mile), is included in the factors examined (since variability in roughness measurements might be related to the level of roughness of the segments).

Field measurements were conducted to evaluate the significance of the variability introduced by these factors into roughness evaluation. These measurements were collected based on factorial experiments with cells identifying different combinations of the above factors. Factorial experiments, defined for both flexible and rigid pavements, are also discussed in this chapter (again, because variability related to the previously mentioned factors might be different for these types of pavements). Data collection factorials were used to analyze the effects of various factors on roughness measurements.

SIGNIFICANCE OF VARIABILITY

The factors producing variability during the testing of a product's quality should be carefully examined. Specifically, the variability related to these factors should be quantified for defining (or modifying) the specifications more precisely.

In the case of smoothness specifications for main travel lanes, the overall variability from testing (defined as the sum of the variance of factors such as instrument, operator, and interpreter or reader) should be evaluated. If the overall variability is relatively low, discrete specification acceptance categories might not be necessary. Instead, a continuous curve that reduces the difference between payments in contiguous categories might be sufficient to account for such variation. An example of such an approach is given in Figure 3.1.

On the other hand, when the overall variability is significantly large, the introduction of gaps between the different acceptance categories of the specifications might be introduced.

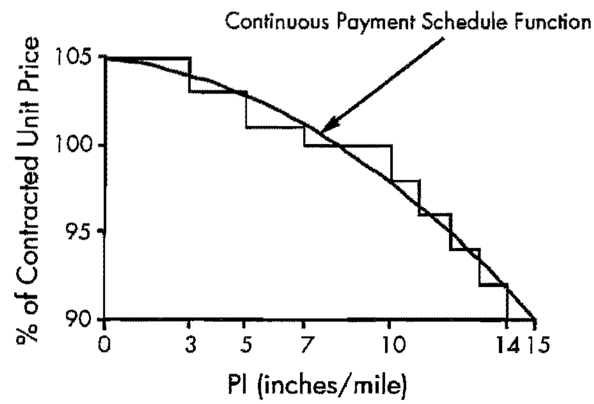


Figure 3.1 *Continuous payment schedule function for the specifications*

FACTORS PRODUCING VARIABILITY IN ROUGHNESS MEASUREMENTS

Several factors may influence the roughness measurement. For end-result smoothness specifications, this variability may be related to roughness instrumentation, the instrument's operator, or to the interpretation of the instrument's output (reader variability).

Ames and McCracken Profilographs

The McCracken profilograph was accepted as the approved instrument for use with the draft specifications (Ref 15). Thus, variability in roughness evaluation between this instrument and other California-type profilographs should be considered before approving any other California-type profilograph for use with the specifications.

This study also evaluated the Ames profilograph. A description of the Ames and McCracken profilographs is included in Appendix A (Refs 16, 17, and 18). Thus, two profilographs were considered in the factorial experiments for flexible and rigid pavements.

The analysis conducted in this study for comparing the Ames and McCracken profilographs may be used whenever it is desired to approve other brands of California profilographs for use with the specifications.

Operator and Reader Variability

California profilographs are manually operated, pushed along the wheelpaths of the sections according to the guidelines described in Appendix A (Ref 19). Operator variability was considered, since not all the operators are able to follow exactly the wheelpaths of the segments profiled. In studying operator variability, two different operators were used.

Once the segments were profiled, the output of the instruments (profilograms) were interpreted according to the profilogram evaluation technique presented in Appendix A (Ref 16 and 19). Because different interpreters might evaluate profilograms differently, the study used two readers and compared their interpretations.

PAVEMENT TYPE AND ROADWAY COMPONENTS

End-result specifications are based on the historical performance of the construction industry. Accordingly, the rationality of the acceptance categories of the draft specifications should be compared with the historical achievement of pavement roughness by different contractors. Because different materials and construction techniques are used for building asphalt and portland cement concrete pavements, factorial experiments for these two types of pavements were developed.

The draft specifications defined in the initial study (ref 12) are applicable for main travel lanes. However, for this study it was considered important to evaluate the applicability of such specifications on other components of the roadway. Thus, the location of segments on roadways (i.e., segments located on main travel lanes, shoulders, ramps, and on main lanes in the vicinity of bridge approaches) was considered when defining the factorials for pavement type. This multi-component approach mirrored that used by Iowa DOT staff, who developed a range of smoothness specifications for different infrastructure elements. In addition, we thought it important to study the applicability of the specifications for patched sections of main travel lanes.

FACTORIAL EXPERIMENT FOR ACP

Once the factors to be included in the experiments were defined, the factorials for both rigid and flexible pavements were obtained. In defining the factorial for asphalt concrete pavements, the following factors and corresponding levels were considered:

Factor	Level
Profilograph type	McCracken and Ames profilographs
Operator	Operator A and B
Reader	Reader A and B
Segment's location	Main travel lane, shoulder, ramp, main travel lane in the vicinity of bridge approach and patched sections
PI level	Low (PI≤10), High (PI>10)

The sampling design obtained for asphalt concrete pavements is reported in Figure 3.2. Based on this factorial, several paving projects around Texas were tested to obtain measurements with the characteristics of the cells of the factorial. The data collected, along with the analyses, are reported in subsequent chapters.

FACTORIAL EXPERIMENT FOR PCCP

A factorial for portland cement concrete pavements was next defined, and the following factors were considered for this sampling design (factorial):

Factor	Level
Profilograph type	McCracken and Ames profilographs
Operator	Operator A and B
Reader	Reader A and B
Segment's location	Main travel lane, shoulder, ramp, main travel lane in the vicinity of bridge approach and patched sections
PI level	Low (PI≤10), High (PI>10)

With the factorial for portland cement concrete pavements defined (Figure 3.3), several paving projects around Texas were tested according to the factorial design. These data are reported in later chapters.

Location	PI Level*	McCracken				Ames			
	Operator	A		B		A		B	
	Reader	1	2	1	2	1	2	1	2
Main Lanes	Low								
	High								
Shoulder	Low								
	High								
Access Ramps	Low								
	High								
Bridge Approach	Low								
	High								
Patched Sections	Low								
	High								

*Factor Midpoints:
PI Level 10 inches/mile

Figure 3.2 Sampling design for asphalt concrete pavement

Location	PI Level*	McCracken				Ames			
	Operator	A		B		A		B	
	Reader	1	2	1	2	1	2	1	2
Main Lanes	Low								
	High								
Shoulder	Low								
	High								
Access Ramps	Low								
	High								
Bridge Approach	Low								
	High								
Patched Sections	Low								
	High								

*Factor Midpoints:
PI Level 10 inches/mile

Figure 3.3 Sampling design for portland cement concrete pavement

CHAPTER 4. ROUGHNESS MEASUREMENTS AND DATA ANALYSIS

INTRODUCTION

Using both the Ames and McCracken profilographs on rigid and flexible pavements, the study team collected roughness measurements from paving projects across Texas. The measurements were collected in accordance with the factorial experiments of asphalt concrete pavements and portland cement concrete pavements defined in Chapter 3.

Several analyses using the collected data were undertaken to: (1) evaluate the significance of different levels of the factors, profilograph type, operator, and interpreter (as defined in Chapter 3) that might produce variability in roughness evaluation; (2) quantify the variability introduced by the two levels of such factors; and (3) quantify the repeatability of the profilographs, taking into account both operator variability (i.e., the ability of an operator to follow the wheelpath each time) and a reader's inherent variability (i.e., the difference in the evaluation of the same profilogram by a single operator).

Simple comparisons between the McCracken and Ames profilographs were first conducted; then, the significance of the factor levels in producing variability on roughness measurements was examined using an analysis of variance (ANOVA) method, which is described below. These methods test whether the different levels of each factor have a significant effect in roughness evaluation. The variability is then quantified for these significant effects.

Several factors can produce variability in roughness measurements made with the California-type profilograph. For example, there is a certain amount of variability inherent in the equipment (repeatability). In addition, more or less variability can result from the ability of the individual operators to follow precisely the wheelpath located 3 feet from each edge of the lane. Variability might also be introduced by the inability of the reader or interpreter to evaluate the same profilogram in the same way. To determine the extent of such effects, repeated roughness measurements were taken on both pavement types and with segments of different roughness levels.

Because the training of personnel operating the California-type profilograph is important for minimizing variability in roughness evaluation, this chapter also discusses issues related to the training of TxDOT personnel. Finally, this chapter reports the experience gained in our field testing of the Ames and McCracken profilographs (so as to alert profilograph field operators of the factors and conditions that might produce excessive variability in roughness measurements).

PRELIMINARY COMPARISON OF CALIFORNIA-TYPE PROFILOGRAPHS

A preliminary comparison of the Ames and McCracken profilographs was conducted based on data collected on a new flexible pavement on U.S. 67 in Rankin and on a section of rigid pavement on the U.S. 183 and MoPac intersection in north Austin.

In comparing these instruments, the study team evaluated data from 76 segments of the flexible pavement on U.S. 67 and from 14 segments of the rigid pavement on U.S. 183. The profilograms collected were interpreted by one reader according to Texas Test Method Tex-1000-S. The wheelpath profile index (PI), and the average PI for each segment (obtained by averaging the two wheelpath PI's of the segment) were then calculated.

The wheelpath and average PI values of the McCracken versus the Ames were plotted in Figures 4.1 and 4.2, respectively, for the data obtained from the flexible pavement. As shown in these figures, the data scatter presents some variability along the 45° line. While this scatter is wider for the wheelpath values (Figure 4.1), the averaging process of the wheelpaths eliminates some of the variability (Figure 4.2).

The same conclusions can be drawn by observing the plots of the wheelpath and average PI

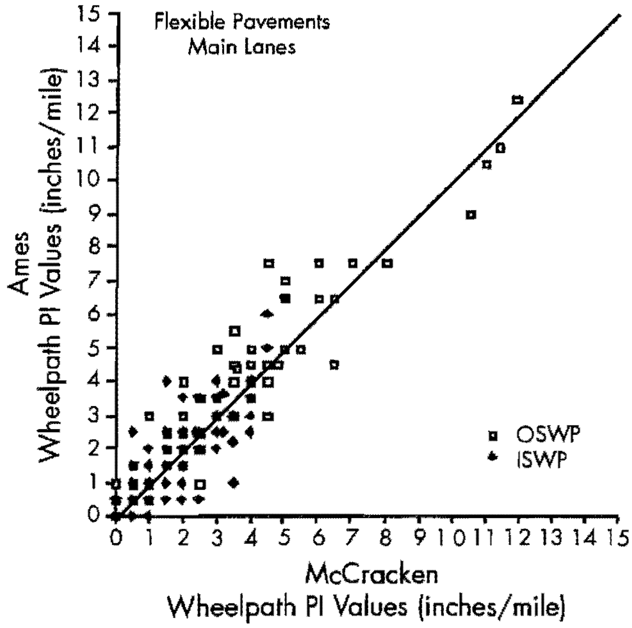


Figure 4.1 ***Comparison of Ames and McCracken profilographs for flexible pavements using wheelpath PI values***

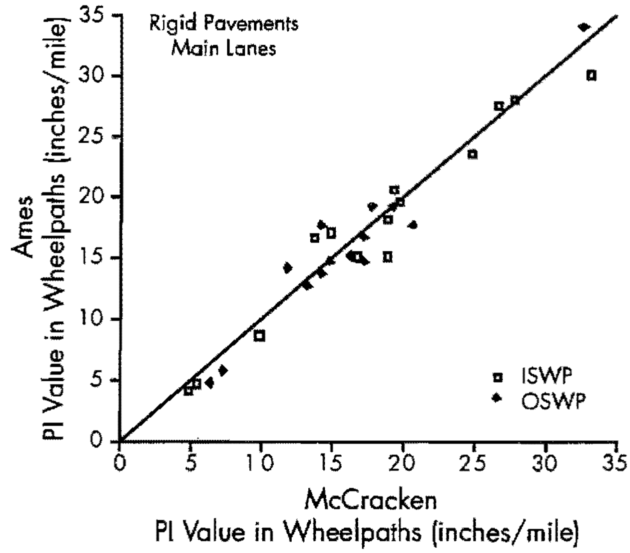


Figure 4.3 ***Comparison of Ames and McCracken profilographs for rigid pavements using wheelpath PI values***

values of the McCracken versus the Ames for the data obtained from the rigid pavement (reported in Figures 4.3 and 4.4).

The average and wheelpath values of the McCracken vs. the Ames, using the data obtained from both pavement types, are plotted in Figures 4.5 and 4.6. In these figures, data from the flexible pavement are located in the lower range of PI, while most of the data of the rigid pavement are located in the higher range of PI (PI>10 inches/mile). The wheelpath plot in Figure 4.5 shows that a constant variability exists over the entire PI range independent of the PI level. This variability decreases when the average PI values are considered. For the wheelpath values, all the observations fall within a band of ±3.5 inches/mile from the 45° line, while for the average PI values, the observations fall within a band of ±2.0 inches/mile.

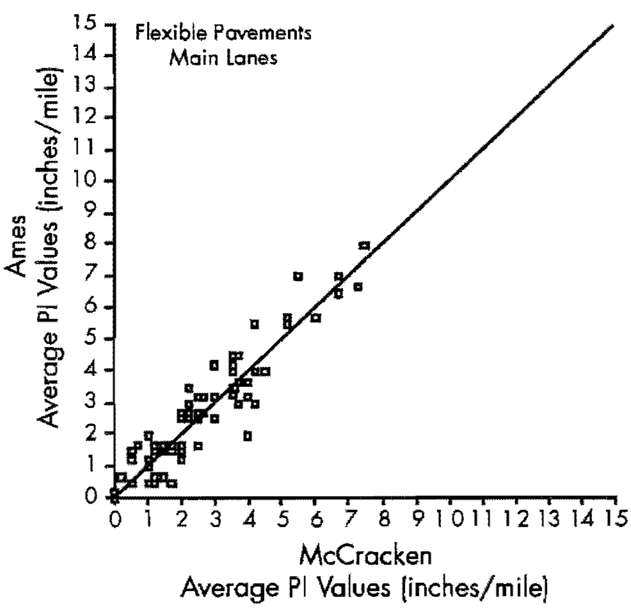


Figure 4.2 ***Comparison of Ames and McCracken profilographs for flexible pavements using average PI values***

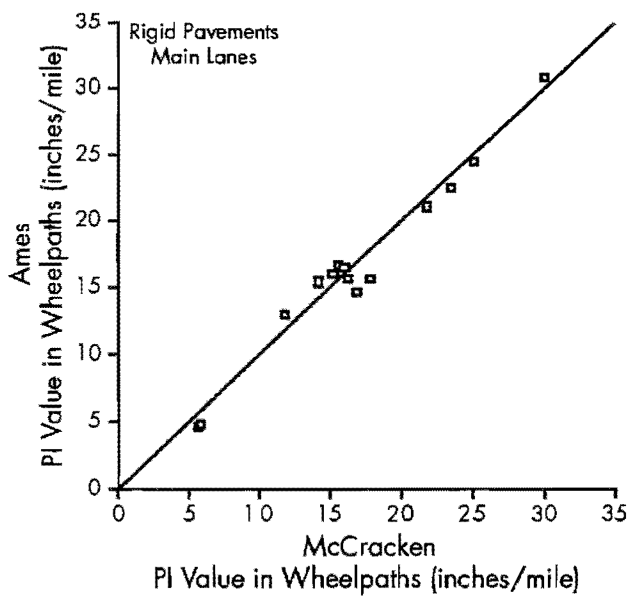


Figure 4.4 ***Comparison of Ames and McCracken profilographs for rigid pavements using average PI values***

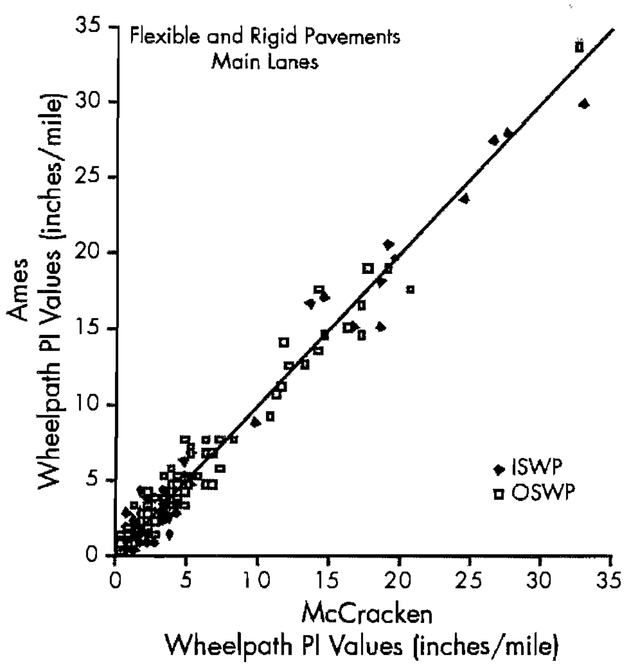


Figure 4.5 Comparison of Ames and McCracken profilographs for flexible pavements using wheelpath PI values

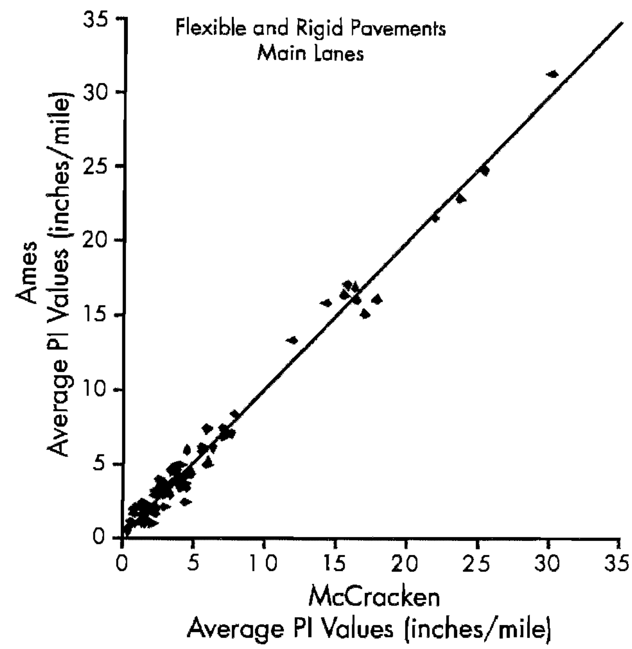


Figure 4.6 Comparison of Ames and McCracken profilographs for flexible pavements using average PI values

Using these data, we next conducted statistical analyses using the wheelpath PI of the segments. To determine if the instruments were equal, we used the students t-test (see Ref 21), which compared the data collected with both profilographs. The results are shown in Table 4.1.

As seen in the above table, the instruments are equivalent for both pavement types, based on the data collected.

The same statistical analysis was conducted using the average PI values of the segments, since the specifications use the average PI value; again the two instruments are equivalent for both pavement types. The results of the test are reported in Table 4.2.

As was noticed in the plots of the average and wheelpath PI values, the averaging process eliminates some variability. As expected, the standard deviations based on the average values are lower than the ones calculated from the wheelpath values.

Table 4.1 Preliminary comparison of Ames and McCracken profilographs based on wheelpath pi values

Pavement Type	Profilograph	Variable	n*	Profile Index: Mean	Profile Index: St Dev	Student T-Test: Equal Instruments	Student T-Test: Probability of Acceptance
Flexible	McCracken	Wheelpath	152	2.6	2.2	Yes	0.69
	Ames	Wheelpath	152	2.7	2.3		
Rigid	McCracken	Wheelpath	28	16.8	7.3	Yes	0.93
	Ames	Wheelpath	28	16.6	7.5		

*n = sample size

Table 4.2 Preliminary comparison of Ames and McCracken profilograph based on average pi values

Pavement Type	Profilograph	Variable	n*	Profile Index Mean	Profile Index St Dev	Student T-Test Equal Instruments	Student T-Test Probability of Acceptance
Flexible	McCracken	Average PI	76	2.6	1.7	Yes	0.71
	Ames	Average PI	76	2.7	1.8		
Rigid	McCracken	Average PI	14	16.8	6.8	Yes	0.72
	Ames	Average PI	14	15.8	6.9		

*n = sample size

FACTORIAL APPROACH AND ANALYSIS OF VARIANCE

Factorial analysis and ANOVA were used to evaluate the effect of the various factors on measured segment roughness. In the factorial approach method, all the possible combinations (treatments) that can be formed by combining the levels of the different factors are compared. This analysis considered the following main factors: the type of California profilograph (Ames and McCracken), operator (A or B), and reader (A or B). Based on these three main factors of two levels each, a 23 factorial experiment was defined. Thus, all the possible combinations (8 total) between the levels of these factors are defined and used in examining the significance of the factors at each level. The eight combinations are shown in Table 4.3.

Table 4.3 Factor combinations for the 2^3 factorial experiment

Operator	Reader	Profilograph: Ames	Profilograph: McCracken
A	A		
	B		
B	A		
	B		

FACTORIAL ANALYSIS FOR FLEXIBLE PAVEMENTS

Factorial Analysis for Flexible Pavements with Wheelpath PI Values

The significance of profilograph type, operators, and readers in evaluating the roughness of flexible pavements was investigated with the factorial approach described above. Measurements on several segments of flexible pavement located on Parmer Lane in Austin were conducted so as to produce eight factor combinations of operator, reader, and instrument at two levels each. The data and the analysis are reported in the following tables. Table 4.4 presents the wheelpath PI values, along with the evaluation of the factor combination totals. Yates' algorithm (Ref 20) was used for evaluating the sum of squares and the F-ratio for the factors effect total, given in Table 4.5.

As can be seen in Table 4.5, only the profilograph-operator (P-O) interaction is significant ($p = 0.02$). Thus, we examined the two-way P-O interaction. Table 4.6 shows the overall significance of the model; Table 4.7 presents the mean values of the roughness measurements with both levels of profilograph type and operator.

As can be seen from the above table, there is no difference in roughness evaluation from operator to operator when the McCracken profilograph is used. On the other hand, there is some difference in roughness evaluation (0.3 inch/mile) between operators using the Ames profilograph. Also, some difference in roughness evaluation is obtained when the same operator is using two different profilographs, ranging from 0.1 to 0.2 inch/mile. Both operators in the experiment were equally skilled; thus, it is believed that the differences observed might be related to the ability of the operators to use the location marker of the Ames in following the wheelpath. The marker is located in the front of the profilograph, making it more difficult to position the recording wheel exactly on the wheelpath. The McCracken marker is near the recording wheel, permitting more precise control.

Table 4.4 Roughness measurements on flexible pavements

Segment-Wheelpath	McC-O1-R1	A-O1-R1	McC-O1-R2	McC-O2-R1	A-O1-R2	A-O2-R1	McC-O2-R2	A-O2-R2	Mean
1-os	2.0	2.5	2.0	1.5	2.0	1.0	2.0	1.0	1.75
1-is	2.5	4.0	2.5	3.5	4.0	2.5	3.5	2.5	3.13
2-os	1.5	1.0	1.5	1.5	1.0	0.5	1.5	0.0	1.06
2-is	2.0	2.5	2.0	2.5	2.5	2.0	1.5	2.0	2.13
3-os	3.5	2.5	3.5	3.5	3.0	2.5	3.0	3.0	3.06
3-is	0.5	1.0	0.0	0.5	1.0	0.0	1.0	0.0	0.50
4-os	3.0	4.0	3.0	3.0	3.0	2.5	2.5	2.5	2.94
4-is	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.0	0.56
5-os	0.5	0.0	0.5	0.5	1.0	0.5	0.5	0.5	0.50
5-is	0.5	0.5	0.0	0.0	0.0	0.5	0.0	0.5	0.25
6-os	5.0	5.0	4.5	3.5	5.5	4.5	4.0	4.5	4.56
6-is	1.0	1.0	1.0	1.0	0.5	1.0	1.0	0.0	0.81
7-os	2.5	3.0	2.0	3.0	3.0	4.5	2.5	4.0	3.06
7-is	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
8-os	4.0	4.0	4.0	5.0	5.5	4.5	4.0	5.5	4.56
8-is	1.5	1.5	2.0	1.5	1.5	0.5	1.5	0.5	1.31
Factor combination totals	30.5	33.0	29.0	31.0	34.0	27.5	29.0	27.5	30.19

Note: McC = McCracken profilograph, A = Ames profilograph, O = Operator, R = Reader,
os = outside wheelpath, is = inside wheelpath, p = profilograph, r = reader, o = operator

Table 4.5 Factorial analysis for flexible pavements using wheelpath pi values

Factor Combinations	F-Ratio	p-Value
Profilometer	0.40	>0.25
Reader	2.35	0.18
Operator	0.66	>0.25
Profilometer-Reader	0.99	>0.25
Profilometer-Operator	5.09	0.02*
Reader-Operator	0.07	>0.25
Profilometer-Operator-Reader	0.99	>0.25

* Significant at 95% confidence level

Table 4.7 Mean values for p-o interaction (wheelpath pi values)

	Profilograph		
Operator	McCracken	Ames	Difference
A	1.8	2.0	0.2
B	1.8	1.7	0.1
Difference	0.0	0.3	

Table 4.6 Analysis of variance for flexible pavement data using wheelpath pi values

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio	p-Value
Replicants	15	270.39	18.03	1.51	>0.1
Factor comb.	7	2.53	0.36		
Residuals (error)	105	25.19	0.24		
Total	127	298.11			

Factorial Analysis for Flexible Pavements with Average PI Values

Since the profilograph-operator interaction was significant (for wheelpath PI values), and since the specification's acceptance limits are based on the average of the two wheelpath values of a segment, it was important to examine whether the differences in roughness evaluation noted in Table 4.7 would differ when the average values of the segment are considered. Accordingly, the factorial approach was next applied to the average PI values of the segments. The results of the analysis, reported in Tables 4.8 and 4.9, support the conclusions drawn from the wheelpath value analysis.

Table 4.8 Factorial analysis for flexible pavements using average pi values

Factor Combinations	F-Ratio	p-Value
Profilometer	0.45	>0.25
Reader	2.64	0.20
Operator	0.74	>0.25
Profilometer-Reader	1.10	>0.25
Profilometer-Operator	5.70	0.02*
Reader-Operator	0.08	>0.25
Profilometer-Operator-Reader	1.10	>0.25

* Significant at 95% confidence level

different operators. On the other hand, there is some difference in roughness evaluation (0.1 inch/mile) between operators using the Ames profilograph. The difference was considerably smaller this time because the average PI values were used. Again, some difference in roughness evaluation was obtained when the same operator is using two different profilographs. This difference, having the same magnitude whether wheelpath or average PI values are considered, ranged from 0.1 to 0.2 inch/mile, depending on the operator.

The analyses conducted here were based on data obtained from the main travel lanes of newly constructed flexible pavements. As shown in Table 4.4, these segments are at low-roughness levels (PI≤10 inches/mile). During field testing, no segments with high PI level were observed for this type of pavement.

In summary, regardless of whether the wheelpath or average PI values of the segments were considered, no difference was found in the significance of factors in roughness evaluation.

FACTORIAL ANALYSIS FOR RIGID PAVEMENTS

As for flexible pavements, the influence of profilograph type, operator, and reader in evaluating the roughness of rigid pavements was examined using the factorial approach. For newly constructed portland cement concrete, pavement segments on main travel lanes with low and high PI levels were observed. In this analysis, measurements of several segments of a rigid pavement located on U.S. 183 in Austin were conducted so as to produce the eight factor combinations listed in Table 4.3. The analyses conducted are presented below.

Table 4.9 Analysis of variance for flexible pavement using average pi values

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio	p-Value
Replicants	7	36.61	5.23		
Factor comb.	7	1.26	0.18	1.69	>0.1
Residuals (error)	49	5.24	0.11		
Total	64	43.12			

As shown previously, the profilograph-operator interaction was significant (p = 0.02) for the case of the wheelpath values; thus, the same interaction was examined using average PI values (Table 4.10).

Table 4.10 Mean values for P-O interaction using average pi values

	Profilograph		
Operator	McCracken	Ames	Increase
A	1.8	2.0	0.2
B	1.8	1.9	-0.1
Increase	0.0	-0.1	

As can be seen in Table 4.10, there is no difference in roughness evaluation from the operation of the McCracken profilograph by the two

Factorial Analysis for Rigid Pavements with High PI Level

The wheelpath data for segments with high PI level were collected on U.S. 183 in Austin and are reported in Table 4.11. A factorial analysis was conducted with these data using Yates' algorithm and ANOVA. The results are presented in Tables 4.12 and 4.13.

As shown in Table 4.12, none of the main effects or the interactions between factors were found to be significant. Thus, for rigid pavements with high PI levels, profilograph, reader, and operator have no significant influence on segment roughness evaluation. This is demonstrated by the high p-values for all main factors and interactions.

Table 4.12 factorial analysis for rigid pavements (high pi level)

Factor Combinations	F-Ratio	p-Value
Profilometer	0.90	>0.25
Reader	0.03	>0.25
Operator	0.38	>0.25
Profilometer-Reader	0.70	>0.25
Profilometer-Operator	0.15	>0.25
Reader-Operator	0.15	>0.25
Profilometer-Operator-Reader	0.53	>0.25

Table 4.11 Roughness measurements on rigid pavements (high pi level)

Segment-Wheelpath	McC-O1-R1	A-O1-R1	McC-O1-R2	McC-O2-R1	A-O1-R2	A-O2-R1	McC-O2-R2	A-O2-R2	Mean
1-os	11.5	14.0	11.5	13.0	13.0	12.5	14.0	13.0	12.8
1-is	19.5	19.5	20.5	19.0	19.5	20.5	19.0	21.0	19.8
2-os	17.0	16.5	17.5	17.0	16.0	14.5	17.5	15.0	16.4
2-is	18.5	15.0	19.5	16.5	15.0	15.0	17.0	15.5	16.5
3-os	16.0	15.0	16.5	14.5	15.0	14.5	15.5	14.0	15.1
3-is	14.5	17.0	14.0	13.5	16.5	16.5	13.0	16.5	15.2
Factor combination totals	97.0	97.0	99.5	93.5	95.0	93.5	96.0	95.0	95.8

Note: McC = McCracken profilograph, A = Ames profilograph, O = Operator, R = Reader,
os = outside wheelpath, is = inside wheelpath, p = profilograph, r = reader, o = operator

Table 4.13 Analysis of variance for rigid pavements (high pi level)

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio	p-Value
Replicants	5	212.05	42.41		
Factor comb.	7	4.74	0.68	0.41	>0.25
Residuals (error)	35	58.41	1.67		
Total	47	275.20			

Table 4.14 Roughness measurements on rigid pavements (low pi level)

Segment-Wheelpath	McC-O1-R1	A-O1-R1	McC-O1-R2	McC-O2-R1	A-O1-R2	A-O2-R1	McC-O2-R2	A-O2-R2	Mean
1-os	6.0	4.5	6.5	7.0	4.5	5.5	7.5	5.5	5.88
1-is	5.0	4.5	5.0	4.5	4.5	4.0	4.5	4.0	4.50
Factor combination totals	11.0	9.0	11.5	11.5	9.0	9.5	12.0	9.5	10.4

Note: McC = McCracken profilograph, A = Ames profilograph, O = Operator, R = Reader,
os = outside wheelpath, is = inside wheelpath, p = profilograph, r = reader, o = operator

Factorial Analysis for Rigid Pavements with Low PI Level

The same analysis was conducted using segments with low PI level from the same rigid pavement. The wheelpath values of these measurements are reported in Table 4.14. The results from the factorial analysis and the analysis of variance are presented in Tables 4.15 and 4.16.

Table 4.15 Factorial analysis of data for rigid pavements (low pi level)

Factor Combinations	F-Ratio	p-Value
Profilometer	1.78	0.20
Reader	4.00	0.09
Operator	0.11	>0.25
Profilometer-Reader	1.00	>0.25
Profilometer-Operator	0.00	>0.25
Reader-Operator	0.00	>0.25
Profilometer-Operator-Reader	2.78	>0.25

Table 4.15 shows that none of the main factors or interactions were found to be significant at the 95 percent confidence level ($p \leq 0.05$). Thus, for segments on rigid pavements with low PI level, profilograph type, reader, and operator had no influence on roughness evaluation.

CONCLUSIONS

Based on the data and the results of the analysis, it can be concluded that for rigid pavements, profilograph type, operator, and reader have no significant influence on roughness evaluation. This finding supports the preliminary analysis conducted by the project team (Ref 23).

For flexible pavements, none of the main factors had any influence on roughness measurements. However, the interaction of profilograph type and operator may introduce some variability. Among operators using the Ames profilograph, an average difference in roughness evaluation of 0.3 inch/mile was observed over all sections, while for the McCracken profilograph no difference was found. The magnitude of this difference is considerably decreased to 0.1 inch/mile when only the average values of the segments are considered. When the same operator used a different type of profilograph, some variance was introduced. This variability, ranging from 0.1 to 0.2 inch/mile, differs from operator to operator. Operator training and certification appear to be significant.

EVALUATION OF PROFILOGRAPH, OPERATOR, AND READER VARIABILITY

The study next conducted investigations of profilograph repeatability, variability inherent to an individual operator (the ability of the operator to follow the wheelpath of a segment), and variability of reader interpretation.

Profilograph and Operator Variability for Flexible Pavements

Profilograph repeatability (variability within instrument) and variability introduced by the operator (variability within operator) were evaluated for flexible pavements through repeated wheelpath runs. Each set of the repeated runs on a segment were conducted by the same operator, and the resulting profilogram was interpreted by the same reader.

The data collected and the corresponding statistics (average of the repeated runs on each segment, standard deviation, coefficient of variance, and the 95-percent confidence intervals) are presented in Table 4.17 for the wheelpath values and in Table 4.18 for the average PI of each segment.

From the wheelpath analysis on a newly constructed pavement located on MoPac Highway in Austin, the variability related to the Ames and McCracken profilographs was found to be identical for segments having a wheelpath PI in the range $0.0 \leq PI \leq 0.2$ (average of the six runs). Such variability is expected to be, 95 percent of the time, between 0.0 to 0.6 inch/mile (see Table 4.17). For segments that had a wheelpath PI in the interval 6.8 to 10.3 inches/mile, the variability related to the McCracken profilograph is expected to be between 0.8 to 2.2 inches/mile 95 percent of the time. Measurements using the Ames profilograph on these last segments were not possible, since the Ames was not yet available

Table 4.16 Analysis of variance for rigid pavements (low pi level)

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-Ratio	p-Value
Replicants	1	7.56	7.56		
Factor comb.	7	5.44	0.78	1.38	>0.25
Residuals (error)	7	3.94	0.56		
Total	15	16.94			

Table 4.17 Analysis of repeated runs on flexible pavements using wheelpath pi values

Segment	Location	Wheel-path	Profilograph	Repeated Run 1	2	3	4	5	6	Mean	Stand. Dev.	CV	Confid. Int. (95%)
1	MoPac	os	McCracken	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0±0.0
1	MoPac	is	McCracken	0.0	0.0	0.0	0.5	0.5	0.0	0.2	0.6	346.4	0.2±0.6
2	MoPac	os	McCracken	7.0	6.0	6.5	8.0	6.5		6.8	1.5	22.3	6.8±1.7
3	MoPac	is	McCracken	6.0	7.0	6.5	9.0	7.0		7.1	2.3	32.1	7.1±2.6
2	MoPac	is	McCracken	8.0	8.5	8.0	7.0	8.0		7.9	1.1	13.9	7.9±1.2
3	MoPac	os	McCracken	10.0	10.0	10.0	11.0	10.5		10.3	0.9	8.7	10.3±1.0
1	MoPac	os	Ames	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0±0.0
1	MoPac	is	Ames	0.0	0.0	0.0	0.5	0.0	0.0	0.2	0.6	346.4	0.2±0.6

Note: os = outside, is = inside, Stand. Dev. = standard deviation, Confid. Int. = confidence interval, CV = coefficient of variation.

Table 4.18 Analysis of repeated runs on flexible pavements using average pi values

Segment	Location	Profilograph	Repeated Run 1	2	3	4	5	6	Mean	Stand. Dev.	CV	Confid. Int.
1	MoPac	McCracken	0.0	0.2	0.0	0.0	0.2	0.0	0.1	0.2	346.4	0.1±0.2
2	MoPac	McCracken	7.5	7.2	7.2	7.5	7.2		7.3	0.3	4.5	7.3±0.4
3	MoPac	McCracken	8.0	8.5	8.2	10.0	8.7		8.7	1.6	18.1	8.7±1.8
1	MoPac	Ames	0.0	0.0	0.0	0.2	0.0	0.2	0.1	0.2	346.4	0.1±0.2

Note: Stand. Dev. = standard deviation, Confid. Int. = confidence interval, CV = coefficient of variation.

for the study. However, from comparison of the data and from the analysis of the measurements in the previous segments, it is believed that the two profilographs have similar repeatability.

Since the smoothness specifications are based on average PI values, analyses using these values were conducted as well. The analysis of the average PI for each segment is shown in Table 4.18. As expected, the averaging of the two wheelpaths reduces variability. For the segments with a mean PI of the repeated runs equal to 0.1, the variability for both profilographs was reduced to 0.2 inch/mile (with 95 percent confidence). The variability of the McCracken profilograph for segments having PI in the range of 7.3 to 8.7 inches/mile is expected to range from 0.4 to 1.6 inches/mile, according to the 95 percent confidence intervals (Table 4.18).

Profilograph and Operator Repeatability for Rigid Pavements

As with flexible pavements, repeated runs on newly constructed rigid pavements were conducted to evaluate the repeatability of both profilographs, as well as to determine any variability introduced by the operator. The wheelpath values for these segments, along with the statistics, are reported in Table 4.19. Table 4.20 presents the values and the statistics using the average PI values for the segments.

From the analysis on the wheelpath values for segments having low roughness levels (PI≤10 inches/mile), the variability in roughness evaluation is expected (95 percent of the time) to measure between 0.6 to 1.0 inches/mile for the Ames profilograph, and between 0.8 to 1.4 inches/mile for the McCracken. From the segments with high wheelpath PI level, the variability range for the McCracken is expected to be within 1.0 to 2.0 inches/mile, and between 1.0 to 1.6 inches/mile for the Ames (Table 4.19).

Analyzing the average PI values of the segments resulted in reduced variability owing to profilograph and operator. For segments having low average PI, the variability associated with the McCracken and the Ames profilographs is 0.7 and 0.5 inch/mile, respectively. For high average PI, the McCracken had an expected variability of 0.8 inch/mile; variability for the Ames is expected to be 1.1 inches/mile (with 95 percent confidence).

INTERPRETER VARIABILITY

Interpreter or reader variability (i.e., variability inherent in interpreting differently a profilogram by the same reader) was examined using profilograms from both the Ames and the McCracken profilographs on both types of pavement. The data for this analysis were obtained from repeated evaluations of the profilograms of high and low PI level using the same reader or interpreter. The data and statistics are presented in Tables 4.21 and 4.22 for flexible pavements, and in Tables 4.23 and 4.24 for rigid pavements.

As shown in Table 4.21, there is no variability for very smooth segments on flexible pavements (wheelpath PI equal to 0 inch/mile). For segments in the low PI level (PI≤10) but having a wheelpath value other than 0, the interpreter's inherent variability ranged from 0 to 0.4 inch/mile for the profilograms of the McCracken, and from 0 to 0.6 inch/mile for the Ames. When average PI values are considered, variability is reduced to a maximum of 0.2 inch/mile for the McCracken and to 0.3 inch/mile for the Ames.

From the analysis of rigid pavements profilograms, it was observed that segments having low wheelpath PI (PI≤10 inches/mile) demonstrated interpretation variability of 0.4 to 0.7 inch/mile for the McCracken and 0.5 to 1.0 for the Ames. For segments having high PI levels, variability ranged from 1.2 to 1.4 inches/mile for the McCracken and from 0.8 to 1.3 for the Ames.

The analysis of average PI values shows that interpreter variability is reduced by the averaging process. In fact, for segments having low PI, interpreter variability decreases to 0.4 inch/mile for the McCracken, and to 0.6 inch/mile for the Ames. For segments having high average PI, variability in interpretation was 0.2 inch/mile for the McCracken and 0.6 inch/mile for the Ames.

In conclusion, averaging the wheelpath PI values of a segment reduced the variability introduced by profilograph repeatability and operator variability. The same was observed for the reader variability. These components of variability are used in the following chapter to define the final version of the smoothness specification.

CONCLUSIONS AND METHODOLOGY FOR COMPARING CALIFORNIA-TYPE PROFILOGRAPHS

Based on the results of the analysis presented in this chapter it was concluded that: 1) There is no significant difference in roughness evaluation whether the Ames or McCracken profilographs are used; and 2) The variability in roughness evaluation for flexible pavements is related to the variance resulting from operator-profilograph interaction, profilograph-operator repeatability, and interpreter variability. For rigid pavements, this overall variability is associated with profilograph-

Table 4.19 Analysis of repeated runs on rigid pavements using wheelpath pi values

Segment	Location	Wheel-path	Profilograph	Repeated Run 1	2	3	4	5	6	Mean	Stand. Dev.	CV	Confid. Int. (95%)
1	US 183	os	McCracken	5.0	4.5	6.5	6.0	5.5	5.5	5.5	1.6	28.7	5.5±1.6
1	US 183	is	McCracken	6.0	7.0	6.0	6.5	6.0	6.0	6.3	0.9	15.0	6.3±0.9
2	US 183	os	McCracken	11.5	13.0	13.0	14.5	14.0	13.5	13.3	2.3	17.5	13.2±2.3
2	US 183	is	McCracken	20.5	19.0	20.0	19.5	19.5	19.5	19.7	1.2	5.9	19.7±1.2
1	US 183	is	Ames	4.5	4.0	4.5	5.0	4.5	4.5	4.5	0.7	15.7	4.5±0.7
1	US 183	os	Ames	4.5	5.5	6.0	5.5	5.5	5.5	5.4	1.1	20.3	5.4±1.1
2	US 183	os	Ames	14.0	13.0	12.0	12.0	13.0	31.0	12.8	1.7	13.1	12.8±1.7
2	US 183	is	Ames	19.5	19.0	18.5	19.5	19.5	20.0	19.3	1.2	6.0	19.2±1.2

Note: os = outside, is = inside, Stand. Dev. = standard deviation, Confid. Int. = confidence interval, CV = coefficient of variation.

Table 4.20 Analysis of repeated runs on rigid pavements using average pi values

Segment	Location	Profilograph	Repeated Run 1	2	3	4	5	6	Mean	Stand. Dev.	CV	Confid. Int. (95%)
1	US 183	McCracken	5.5	5.7	5.2	4.7	5.0	5.0	5.2	0.8	15.8	5.2±0.8
3	US 183	McCracken	16.0	16.0	16.5	17.0	16.7	16.5	16.5	0.9	5.4	16.5±0.9
1	US 183	Ames	4.5	4.7	5.2	4.7	5.0	5.0	4.9	0.6	11.9	4.9±0.6
2	US 183	Ames	16.7	16.5	15.2	15.7	16.2	16.0	16.2	1.2	7.6	16.1±1.2

Note: Stand. Dev. = standard deviation, Confid. Int. = confidence interval, CV = coefficient of variation.

Table 4.21 Inherent variability of interpreter for flexible pavements (wheelpath pi values)

Location	Wheel-path	Profilograph	Reading 1	2	3	4	5	6	Mean	Stand. Dev.	CV	Confid. Int. (95%)
MoPac	os	McCracken	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0±0.0
MoPac	is	McCracken	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0±0.0
US 67	os	McCracken	8.0	8.0	8.5	8.0	8.0	8.0	8.1	0.5	5.6	8.1±0.5
US 67	is	McCracken	4.0	4.0	4.0	4.0	4.0	4.0	4.0	0.0	0.0	4.0±0.0
MoPac	os	Ames	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0±0.0
MoPac	is	Ames	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0±0.0
US 67	os	Ames	7.5	8.0	8.0	7.5	8.0	8.0	7.8	0.6	7.4	7.8±0.6
US 67	is	Ames	4.0	4.0	4.0	4.0	4.0	4.0	4.0	0.0	0.0	4.0±0.0

Note: os = outside, is = inside, Stand. Dev. = standard deviation, Confid. Int. = confidence interval, CV = coefficient of variation.

Table 4.22 Inherent variability of interpreter for flexible pavements (average pi values)

Segment	Location	Profilograph	Reading 1	2	3	4	5	6	Mean	Stand. Dev.	CV	Confid. Int. 95%
1	MoPac	McCracken	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0±0.0
2	US 67	McCracken	6.0	6.0	6.2	6.0	6.0	6.0	6.0	0.2	3.0	6.0±0.2
1	MoPac	Ames	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0±0.0
2	US 67	Ames	5.7	6.0	6.0	5.7	6.0	6.0	5.9	0.3	5.9	5.9±0.3

Note: Stand. Dev. = standard deviation, Confid. Int. = confidence interval, CV = coefficient of variation.

Table 4.23 Inherent variability of interpreter for rigid pavements (wheelpath pi values)

Segment	Location	Wheel-path	Profilograph	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5	Reading 6	Mean	Stand. Dev.	CV	Confid. Int. (95%)
1	US 183	is	McCracken	5.0	4.5	5.0	5.0	5.0	5.0	4.9	0.5	9.3	4.9±0.5
1	US 183	os	McCracken	6.0	5.5	5.5	5.5	5.0	5.0	5.4	0.8	15.5	5.4±0.8
2	US 183	os	McCracken	11.5	12.0	12.5	12.5	11.0	11.5	11.8	1.4	11.4	11.8±1.4
2	US 183	is	McCracken	20.5	20.0	20.0	19.5	21.0	19.0	20.0	1.6	7.9	20.0±1.6
1	US 183	is	Ames	4.5	5.0	5.0	4.5	4.5	4.5	4.7	0.6	12.4	4.7±0.6
1	US 183	os	Ames	4.5	5.5	6.0	5.5	5.5	5.5	5.4	1.1	20.3	5.4±1.1
2	US 183	os	Ames	14.0	12.0	12.5	12.5	13.0	13.0	12.8	1.5	11.9	12.8±1.5
2	US 183	is	Ames	19.5	20.0	19.5	19.0	19.0	19.0	19.3	0.9	4.7	19.3±0.9

Note: os = outside, is = inside, Stand. Dev. = standard deviation, Confid. Int. = confidence interval, CV = coefficient of variation.

Table 4.24 Inherent variability of interpreter for rigid pavements (average pi values)

Segment	Location	Profilograph	Reading 1	Reading 2	Reading 3	Reading 4	Reading 5	Reading 6	Mean	Stand. Dev.	CV	Confid. Int. (95%)
1	US 183	McCracken	5.5	5.0	5.2	5.2	5.0	5.0	5.2	0.4	8.6	5.2±0.4
2	US 183	McCracken	16.0	16.0	16.2	16.0	16.0	16.2	16.1	0.2	1.4	16.1±0.2
1	US 183	Ames	4.5	5.2	5.5	5.0	5.0	5.0	5.0	0.7	14.5	5.0±0.7
2	US 183	Ames	16.7	16.0	16.0	15.7	16.0	16.0	16.1	0.7	4.6	16.1±0.7

Note: Stand. Dev. = standard deviation, Confid. Int. = confidence interval, CV = coefficient of variation.

operator repeatability and interpreter variability. These results are considered in a later chapter for defining the acceptance categories of the specifications.

TxDOT may be solicited by other manufacturers of California profilographs to examine and compare their instruments for possible use in Texas. The methodology followed in this chapter, and used to compare the Ames and McCracken profilographs, may also be used for other purposes. The methodology is as follows:

(1) Identify flexible and rigid pavement sections 528 feet (0.1 mile) long with high and low roughness levels (i.e., PI>10in/mi and PI≤10 in/mi).
(2) Conduct testing for evaluating the eight combinations identified in Table 4.3 and examine (via ANOVA) the significance of profilograph, operator, and reader according to the method presented in this chapter. In this study up to 16 replicates (i.e., 16 different pavement sections) for each of the eight combinations were considered. At least 3 replicates should be used for future evaluations.
(3) Examine profilograph, operator, and reader repeatability. Six replicates were considered sufficient for this analysis. Profilograph and operator repeatability was examined by repeatedly profiling the same segment with the same operator and profilograph. Reader repeatability was examined by having the same reader examine the same profilogram several times. This type of analysis should be done at both high and low roughness level and for both pavement types.

TRAINING OF PERSONNEL OPERATING THE CALIFORNIA PROFILOGRAPH

Training personnel to operate the California-type profilographs properly is important for assuring the effectiveness of the specifications. When profilograph operators have been well trained, variability in roughness measurements and in the evaluation of the profilograms will be minimized. The Texas DOT is currently conducting courses for the training of TxDOT personnel who are involved both with the operation of the profilographs and with the implementation of the specifications. Important guidelines for the assembly, calibration, and field testing of the profilographs were defined in the subject project and presented to the Department in the form of a manual (Appendix A).

FIELD EXPERIENCE WITH THE CALIFORNIA-TYPE PROFILOGRAPHS

The two California-type profilographs tested extensively during this study collected profiles on both rigid and flexible pavements. Tables 4.25 and 4.26 provide information regarding the location of the paving projects, the equipment used at each site, and the date of testing. As shown in the tables, the field testing on some paving projects was conducted over two or more days because of the volume of data collected.

The following comments, based on experience gained during the field testing, are presented in order to alert profilograph field operators to conditions that might lead to excessive variability in roughness measurements. At various times during the field testing it was often observed that a small offset in the longitudinal calibration is amplified when test sections of four or more segments (of 0.1 mile) are profiled together; therefore, it is important to mark the stations on the profilograms periodically. This procedure will also allow more precise location of bumps and joints.

The manufacturer suggests a maximum speed of 3 m.p.h. (walking speed). However, when pavement surfaces of high roughness (PI >10 inches/mile) are profiled, much noise (scatter around the trace profile) is produced. In such cases, reading the profilogram becomes difficult; it is then necessary to outline the trace with a pencil before reading the profilogram.

However, no false readings resulting from high speed were observed during the field tests, unless the testing speed exceeded the maximum speed suggested by the manufacturer. False readings are encountered when sudden corrections in the travel direction of the profilograph are conducted. Only smooth, gradual corrections toward the trace of the wheelpath should be performed.

Finally, for the McCracken profilograph, excessive paper slack in the paper drum, or incorrect placement of the paper roll in the paper spool knobs, produces an offset in longitudinal scale. Every time a new paper roll is positioned in the paper drum, the paper slack and the positioning of the paper in the paper spool knobs should be checked. Because the graph box of the Ames profilograph is fed with computer paper, it is easier to position the paper in that instrument's paper feeder.

Table 4.25 Field testing on flexible pavements

Location	Equipment	Date	Segment Location
IH-35	Ames, McCracken	5/20/91	Ramps Bridge approaches
MoPac, Austin	Face Dipstick	1/29/91	Main lanes
MoPac, Austin	Ames, McCracken	1/28/91	Main lanes, exit ramp
MoPac, Austin	Ames, McCracken	12/17/90	Main lanes, shoulders
MoPacC, Austin	Ames, McCracken	12/13/90	Main lanes
US 67, Rankin	Ames, McCracken	10/10/90	Main lanes
US 67, Rankin	Ames, McCracken	10/9/90	Main lanes
US 67, Rankin	Ames, McCracken	10/8/90	Main lanes
Parmer Lane, Austin	Ames, McCracken	9/7/90	Main lanes, shoulders
Parmer Lane, Austin	Ames, McCracken	9/5/90	Main lanes, shoulders
Parmer Lane, Austin	Ames, McCracken	8/20/90	Main lanes, shoulders
IH-35, Round Rock	Ames, McCracken	8/2/90	Main lanes, Bridge approach Patched segments
IH-35, Round Rock	Ames, McCracken	8/1/90	Main lanes, Bridge approach
US 281-San Antonio	McCracken	3/23/90	Main lanes
MoPac, Austin	McCracken	12/11/89	Main lanes
US 281, Wichita Falls	McCracken	11/14/89	Main lanes, Bridge approach Seal-coated
BRC, Austin	McCracken	8/17/89	Main lanes

Table 4.26 Field testing on rigid pavements

Location	Equipment	Date	Segment Location
US 27, Lubbock	Ames, McCracken Face Dipstick	5/14/91 1/15/91	Main Lanes, shoulders Bridge approach, Exit ramps
US 175, Kaufman County	Ames, McCracken	2/5/91	Main lanes
US 75, Plano County	Ames, McCracken	2/6/91 6/18/91 6/20/91	Main lanes, shoulders Bridge approach, Main lanes
SH 190	Ames, McCracken	2/6/91	Main lanes
US 183, Austin	Face Dipstick	12/19/90	Main lanes
US 183, Austin	Face Dipstick	12/18/90	Main lanes
US 183, Austin	Ames, McCracken	11/16/90	Main lanes
US 183, Austin	Ames, McCracken	10/19/90	Main lanes
US 183, Austin	Ames, McCracken	07/14/90	Main lanes Exit ramp, Shoulder
US 71, La Grange	Ames, McCracken	07/19/90	Main lanes, Exit ramp, Shoulders
US 183, Austin	McCracken	12/14/89	Main lanes
US 71, La Grange	McCracken	08/17/89	Main lanes

CHAPTER 5. EVALUATION OF DRAFT SMOOTHNESS SPECIFICATIONS

INTRODUCTION

This chapter documents our testing of the revised CTR draft smoothness specifications (discussed in Chapter 2), using data from the main travel lanes of asphalt concrete (AC) and portland cement concrete (PCC) pavements collected from various paving projects across Texas.

Smoothness acceptance within this specification is based on the average profile index (PI) of the segments obtained by averaging the two wheelpath PI values for each segment. The first part of this chapter examines the distribution of the average PI values for segments of AC and PCC pavements. Distributions are examined for individual PI values and also in terms of the specification's acceptance, bonus, and penalty categories.

Based on the distribution of average profile index for the surveyed segments, and on the evaluation of the variability related to profilograph type, operator, and reader presented in Chapter 4, the limits of the acceptance categories of the draft specifications were tested. The results are presented in the last part of this chapter, along with suggestions for defining the final version of the smoothness specification for AC and PCC pavements.

Bonus/penalty pay schedules should be legally defensible. Several methods were proposed by various research teams for defining pay schedules. In the methodology defined herein the influence on user and pavement maintenance costs from a non-compliance of the as-built pavement with the specification roughness acceptable level was examined and used for defining pay schedules. This approach was used in other studies for the development of pay schedules for specifications of both rigid and flexible pavements. Details on this analysis are reported as well.

PROFILE INDEX DISTRIBUTION FOR ASPHALT CONCRETE PAVEMENTS (ACP)

All data used in this analysis were gathered with the McCracken profilograph, since it was originally the only profilograph approved for use with the smoothness specifications. Because the factorial analysis demonstrated no significant effect of the main factors (profilograph type, operator, and reader) on the evaluation of segment roughness, these distributions can be considered valid for any measurements collected with any other factor combination. Even though the profilograph-operator interaction was significant for flexible pavements, it had only a minor influence in evaluating segment roughness (Table 4.10) and was considered of no practical significance to this analysis.

The distribution of individual PI values was obtained from 120 segments on the main travel lanes of various newly constructed flexible pavements across the state, as shown in Figure 5.1. Figure 5.2 shows how this distribution would fall into the draft specification categories. All of the segments had an average PI value below 10 inches/mile, with most falling between 0 and 3 inches/mile. When the distribution was examined in terms of the draft specification, 67.5 percent of the 120 segments had a PI in the highest bonus category, 26.7 percent fell into the remaining bonus categories, 5.8 percent qualified for acceptance without bonus or penalty, and none fell into the penalty category. The characteristics of this distribution are used later for identifying possible improvements to the draft specifications.

PROFILE INDEX DISTRIBUTION FOR PORTLAND CEMENT CONCRETE PAVEMENTS (PCCP)

As for asphalt concrete pavements, the distribution of the average profile index on individual PI values and in the specification categories was examined for segments of portland cement concrete pavements. The average PI value of 82 segments on main travel lanes from various newly constructed rigid pavements around Texas profiled with the McCracken profilograph was used for obtaining these distributions.

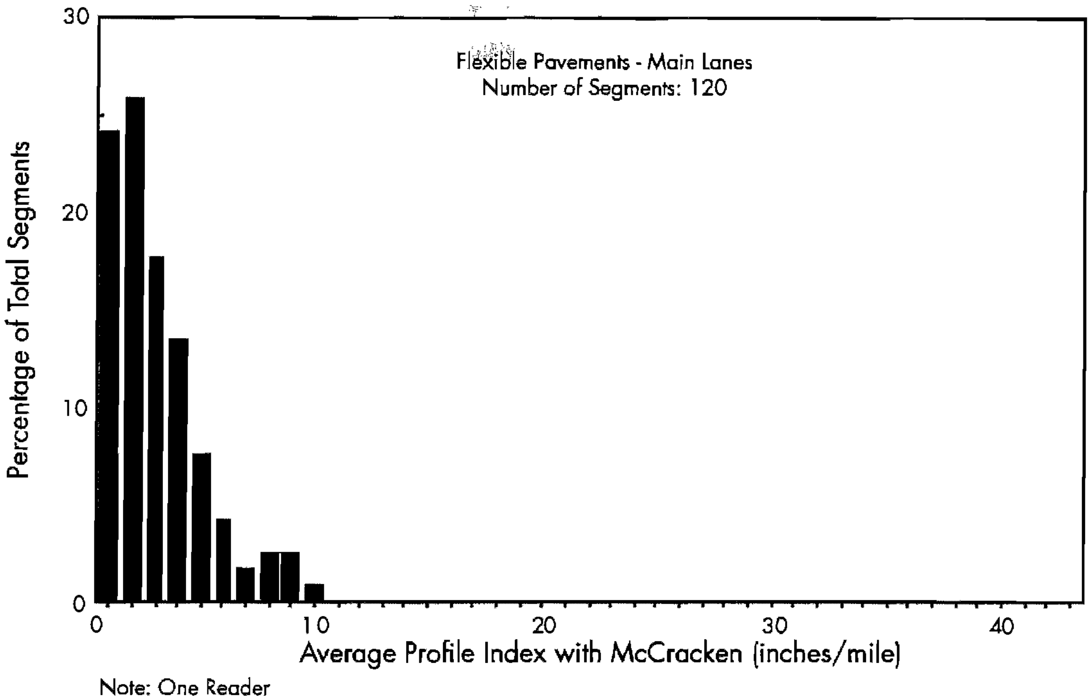


Figure 5.1 Distribution of average PI for segments of asphalt concrete pavement

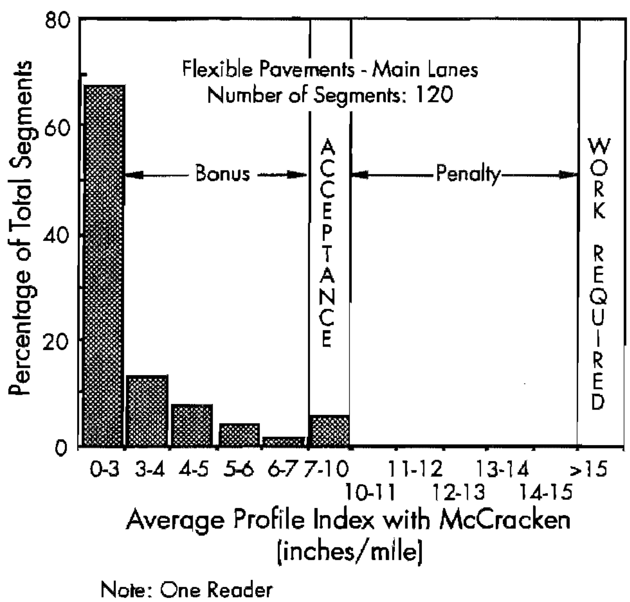


Figure 5.2 Distribution of average PI on specification categories for asphalt concrete pavement segments

The distribution of the average PI values was widely spread, from 0 inch/mile to 43 inches/mile (Figure 5.3); in addition, there were two spikes, one located near 3 inches/mile and the other at 34 inches/mile. This type of distribution is typical when data from two different populations are combined (Ref 20). The distribution across the specification categories also exhibits this effect (Figure 5.4); again, there are two spikes with 17.1 percent of the segments in the lower spike (0≤PI≤3), and 45.2 percent of the segments in the upper, unacceptable category (PI≥15 inches/mile).

By examining the data and the characteristics of the pavement projects surveyed, we attempted to identify the two populations causing the spikes. It was found that in paving projects having frequent shutdown in paving operations (stop-and-go paving operations, defined as paving less than a 1-mile section at a time), a smooth surface profile was difficult to achieve because of the frequent adjustments required by the laydown equipment. Conversely, for paving projects that did not have frequent shutdown of the laying operations (i.e., continuous paving operations), a smooth pavement surface was frequently achieved. Based on these conclusions, the data from "stop-and-go" paving projects (51 segments) and from "continuous" paving operations (31 segments) were examined separately.

Profile Index Distribution for Continuous Paving Operations

First, the distribution of average profile index of segments collected on rigid pavements built with continuous paving operations was examined.

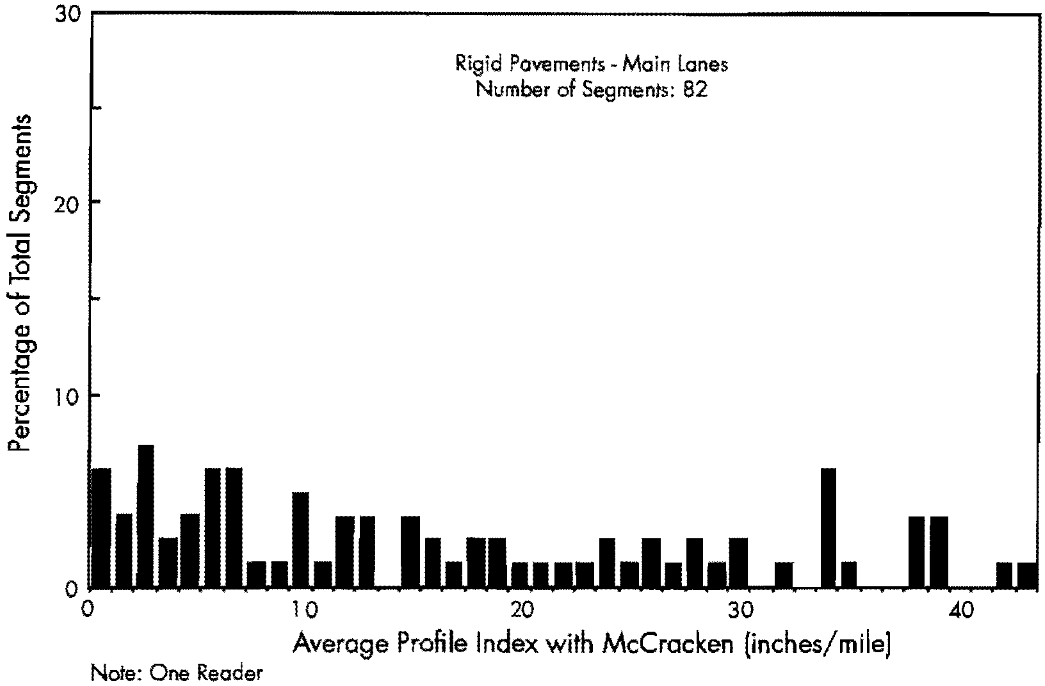


Figure 5.3 Distribution of average PI for portland cement concrete pavement segments

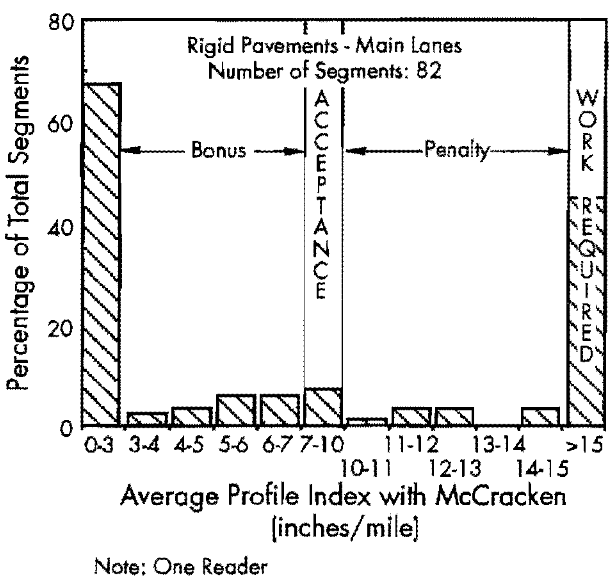


Figure 5.4 Distribution of average PI on specification categories for portland cement concrete pavement segments

Most of the segment PI values were located in the low PI range (PI≤10), as shown in Figure 5.5. Grouped into the specification categories (Figure 5.6), 80.7 percent of the segments fell in the bonus categories, 12.9 percent qualified for acceptance at 100 percent contract price, and 6.4 percent were in the penalty region. Nearly half of the segments had an average PI in the highest bonus category (0≤PI≤3).

Profile Index Distribution for Stop-and-Go Paving Operations

Next, the distribution of average PI on rigid pavement segments built with stop-and-go paving operations was examined. Almost all of the segments built with stop-and-go paving operations had average PI values in the upper range (PI≥10) and were widely distributed (Figure 5.7). With regard to the specification acceptance categories, only 7.9 percent were in the bonus categories, 3.9 percent were acceptable, 15.7 percent were acceptable with penalty, and the great majority, 72.5 percent, fell into the mandatory correction category (Figure 5.8). These results confirm that it is much more difficult to obtain a smooth ride when frequent shutdowns in paving operations are required.

Table 5.1 summarizes the bonus and penalty distributions for both types of pavement.

IMPROVEMENTS TO THE REVISED CTR DRAFT SMOOTHNESS SPECIFICATIONS FOR MAIN LANES

Considering the results of the (1) factorial analysis, (2) the examination of variability

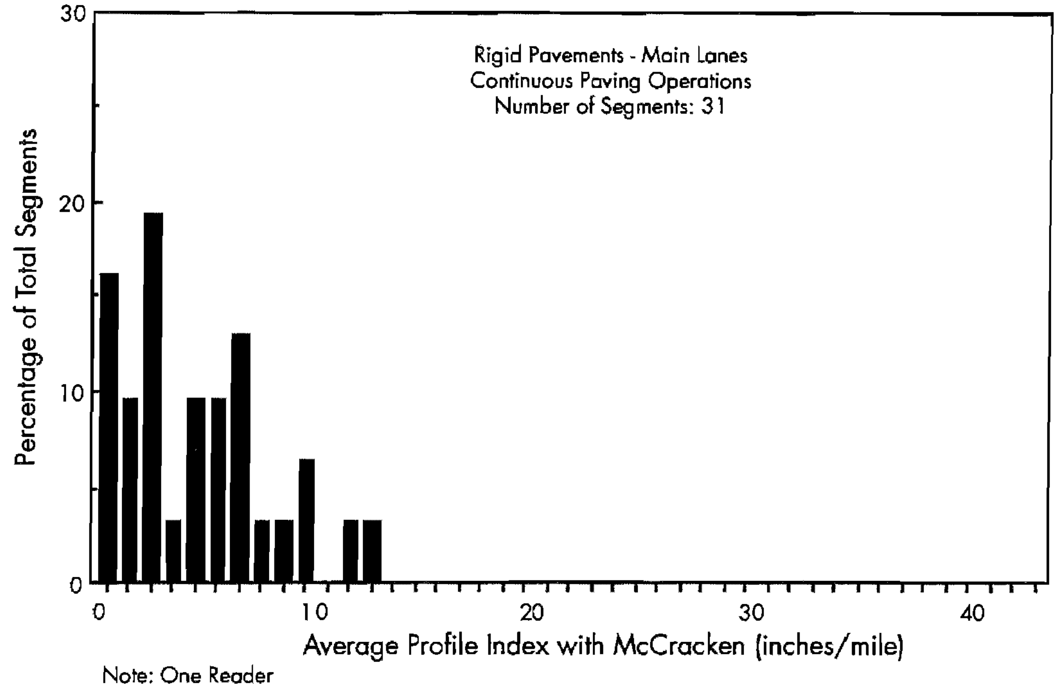


Figure 5.5 **Distribution of average PI for portland cement concrete pavement segments built with continuous paving operations**

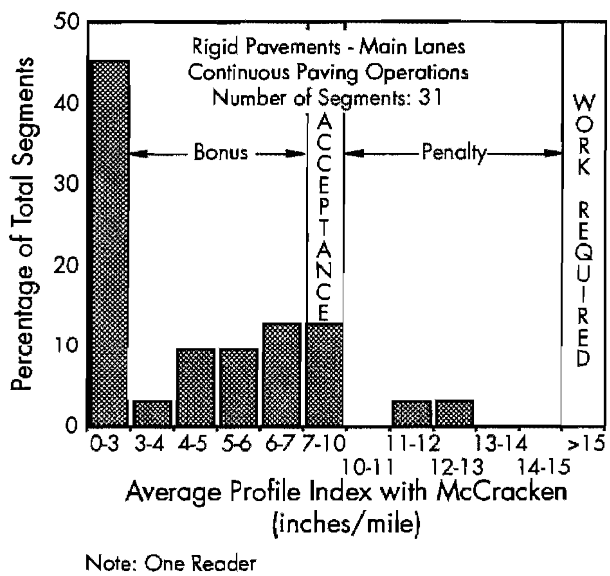


Figure 5.6 **Distribution of average PI on specification categories for portland cement concrete pavement segments built with continuous paving operations**

inherent to profilographs, operator, and interpreter, and (3) the distribution of the segments' average PI value on the specification acceptance categories and bonus/penalty payment schedule categories, the draft smoothness specifications for both pavement types were examined to identify possible improvements.

Comparing the field data collected on rigid and flexible pavements with the draft specification limits provides a measure of the rationality of the specification categories. The first step in this analysis is to determine the percent of segments falling within the acceptable limits of the specification. If the collected data are normally distributed, the rationality of the specification can be assessed by checking if 99.7 percent of the observed values fall within the upper and lower acceptable limits (i.e., the acceptance limits lie at plus and minus three times the standard deviation from the mean, Refs 24 and 25). According to the properties of a normal distribution, 99.7 percent of the test values must fall between ±3 standard deviations (s) of the mean, 95 percent of the values will fall between ±2 s, and 68.1 percent of the values fall within ±1 s. In the case of the smoothness specification, the upper acceptance limit is 0 inch/mile, while the lower is 15 inches/mile. Once the rationality of these limits has been examined, acceptance categories for rigid and flexible main lane segments can be defined based on detailed examination of their average PI distribution. Also, once the specification acceptance limits have been defined (and modified if necessary), the uncertainty

Table 5.1 Percent of segments in bonus and penalty specification categories

PI level	0<PI≤3 (%)	3<PI≤4 (%)	4<PI≤5 (%)	5<PI≤6 (%)	6<PI≤7 (%)	7<PI≤10 (%)	10<PI≤11 (%)	11<PI≤12 (%)	12<PI≤13 (%)	13<PI≤14 (%)	14<PI≤15 (%)	15<PI (%)
Bonus/ Penalty	105	104	103	102	101	100	98	96	94	92	90	Corrective work Required
Flexible pavements	67.5	13.4	7.5	4.2	1.6	5.8	0	0	0	0	0	0
Rigid pavements	17.1	2.4	3.6	6.1	6.1	7.3	1.2	3.6	3.6	0	3.6	45.2
Rigid "stop-and-go"	0	2.0	0	3.9	2.0	3.9	2.0	3.9	3.9	0	5.9	72.5
Rigid "continuous"	45.2	3.2	9.7	9.7	12.9	12.9	0	3.2	3.2	0	0	0

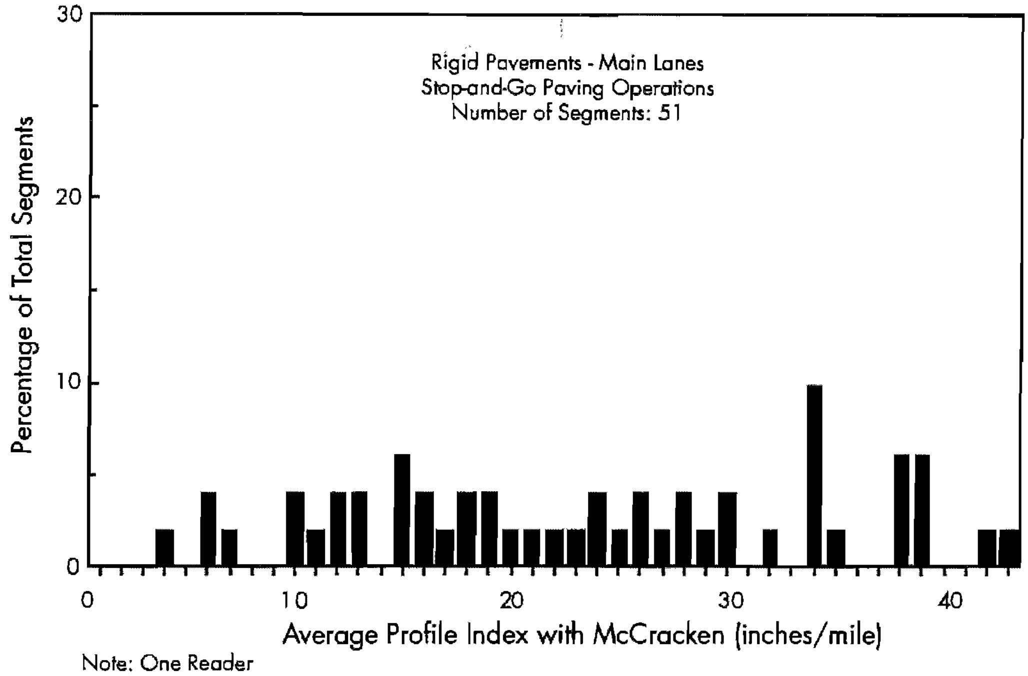


Figure 5.7 **Distribution of average PI for portland cement concrete pavement segments built with stop-and-go paving operations**

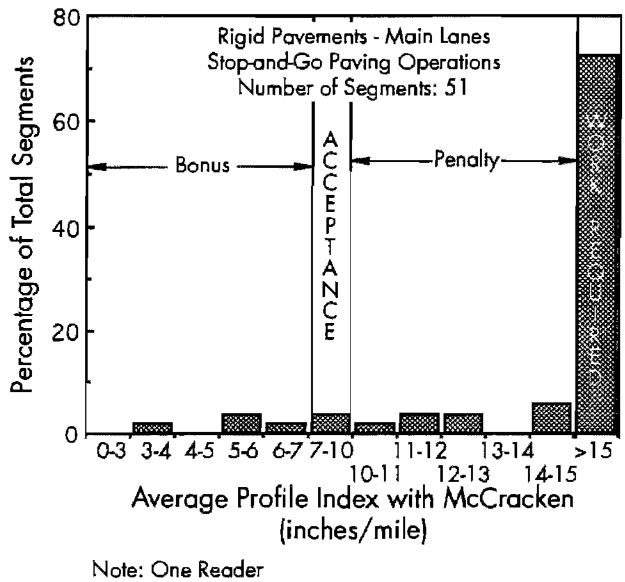


Figure 5.8 **Distribution of average PI on specification categories for portland cement concrete pavement segments built with stop-and-go paving operations**

inherent in roughness measurements should be considered for defining gaps between the specification categories.

From the examination of the average PI of portland cement concrete pavement segments, we determined that pavements built with stop-and-go and continuous paving operations have two distinct distributions. Thus, a specification should be defined for each of these cases.

Flexible Pavements

The overall variability to the roughness evaluation of a segment (introduced because of profilograph-operator interaction, repeatability of profilograph, and operator and reader inherent variability) should be considered for the segments in which PI falls close to the lower acceptance limit, since the contractor may argue for the precise evaluation of the segments' PI. Such variability is obtained as the square root of the sum of the variances for the factors profilograph-operator interaction, repeatability of profilograph, and operator and reader inherent variability. For flexible pavements, the overall variability in terms of standard deviations is equal to:

$$\sqrt{(0.1^2 + 1.6^2 + 0.2^2)} = \sqrt{(2.61)} = 1.6 \text{ inches/mile} \quad (5.1)$$

With this variability, it is impossible to use a continuous function for payment schedules. In addition, particular attention should be given to segments having a PI that falls within 1.6 inches/mile of the specification acceptable boundaries.

From the data collected on the flexible pavement, the mean and the standard deviation of the segments were equal to 2.7 and 2.1 inches/mile respectively. The normality test on these data showed that the data are almost normally distributed ($p = 0.041$, Kolmogorov-Smirnov). In the Kolmogorov-Smirnov test, small p values indicate increasing doubt that the data come from a normal distribution; distributions with p value greater than or equal to 0.05 are generally accepted as normal (Ref 20). The segments' PI are within the upper and lower 3 standard deviation limit, since all the segments fall in the low level of roughness $PI \leq 10$. Thus, a smooth ride can be easily achieved for flexible pavements and there is no need for the Department to pay a bonus for the majority of the contracts. However, a bonus category should still be included in the specification to provide incentives for superior product quality.

With the mean of the segments' PI equal at 2.7 inches/mile, and with a standard deviation of 2.1 inches/mile, the interval of ±2 s is equal to $0.0 \leq PI \leq 6.9$. In order to provide a bonus category and a gap in-between bonus and full acceptance category, the upper boundary of the interval ±1s is set as the upper limit for the full acceptance category. The specifications defined in this study, once implemented, should be further refined with the collection of additional data from paving projects throughout Texas. Because the averaging of the two wheelpath values introduces some approximation in the average PI value of a segment, it is acceptable at this stage to round to the nearest half point the boundaries of the specification intervals.

Consequently, the full acceptance interval is defined as the interval $2.0 < PI \leq 5.0$ since the intervals $0.0 \leq PI \leq 1.0$ and $1.0 < PI \leq 2.0$ are included as a bonus and a gap between the bonus and the full acceptance category. The first conditional acceptance category is identified from the interval $5.0 < PI \leq 7.0$ (where PI = 7.0 is the boundary ±2 s). Finally the gap $7.0 < PI \leq 9.0$ between acceptance and non-acceptance category is introduced. The specification identified by these intervals is then:

Specification Category	PI range
"Bonus"	$0.0 \leq PI \leq 1.0$
	$1.0 < PI \leq 2.0$
"Full Acceptance"	$2.0 < PI \leq 5.0$
"Conditional Acceptance"	$5.0 < PI \leq 7.0$
	$7.0 < PI \leq 9.0$
"Mandatory Rectification"	$PI > 9.0$

The distribution of the segments PI in this specification is shown in Figure 5.9.

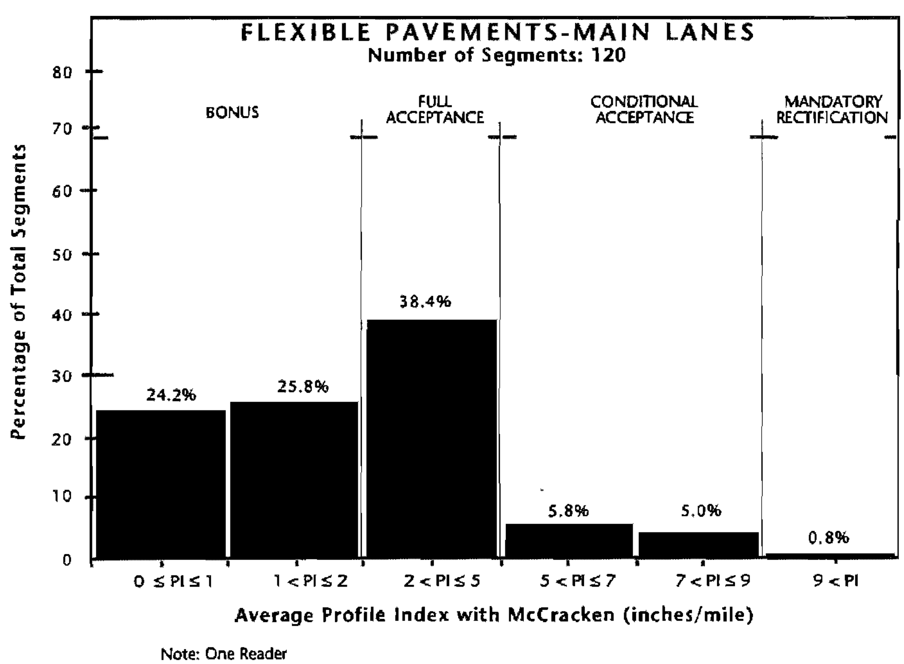


Figure 5.9 Modified draft smoothness specification for flexible pavements

Rigid Pavements

For rigid pavements built with "continuous" paving operations, the overall variability in terms of standard deviation is equal to:

$\sqrt{(0.7^2+0.4^2)} = \sqrt{(0.65)} = 0.8$ inches/mile (5.2)

The mean and the standard deviation for the segments of this type of pavement are equal to 4.6 inches/mile and 3.3 inches/mile, respectively. The normality test on these data showed that the data are normally distributed ($p = 0.211$, Kolmogorov-Smirnov).

The interval of ±2 s is then equal to $0.0 \le PI \le 11.0$. With the same criteria followed for defining the specification for flexible pavement, the bonus, $0.0 \le PI \le 1.0$ and $1.0 < PI \le 2.0$, and the full acceptance categories, $2.0 < PI \le 8.0$ were defined. Then the gap $8.0 < PI \le 9.0$ between full and conditional acceptance is introduced. Then the boundary ±2 s identifies the conditional acceptance category, $9.0 < PI \le 11.0$, and finally the gap, $11.0 < PI \le 12.0$, between acceptance and non-acceptance categories is included. The specification identified is then:

Specification Category	PI range
"Bonus"	$0.0 \le PI \le 1.0$
	$1.0 < PI \le 2.0$
"Full Acceptance"	$2.0 < PI \le 8.0$
"Conditional Acceptance"	$8.0 < PI \le 9.0$
	$9.0 < PI \le 11.0$
	$11.0 < PI \le 12.0$
"Mandatory Rectification"	$PI > 12.0$

The distribution of the segment PI in this specification is shown in Figure 5.10.

The data collected on rigid pavements built with "stop-and-go" paving operations were collected from paving projects in urban and elevated highways. No specification is proposed because the data do not reflect the achievable level of the industry for this type of pavement.

BONUS/PENALTY PAY SCHEDULES

As mentioned in Chapter 5, the payment schedules of end-result smoothness specifications are usually set arbitrarily. It was also mentioned that a payment schedule should be defined according to the economic consequences from the

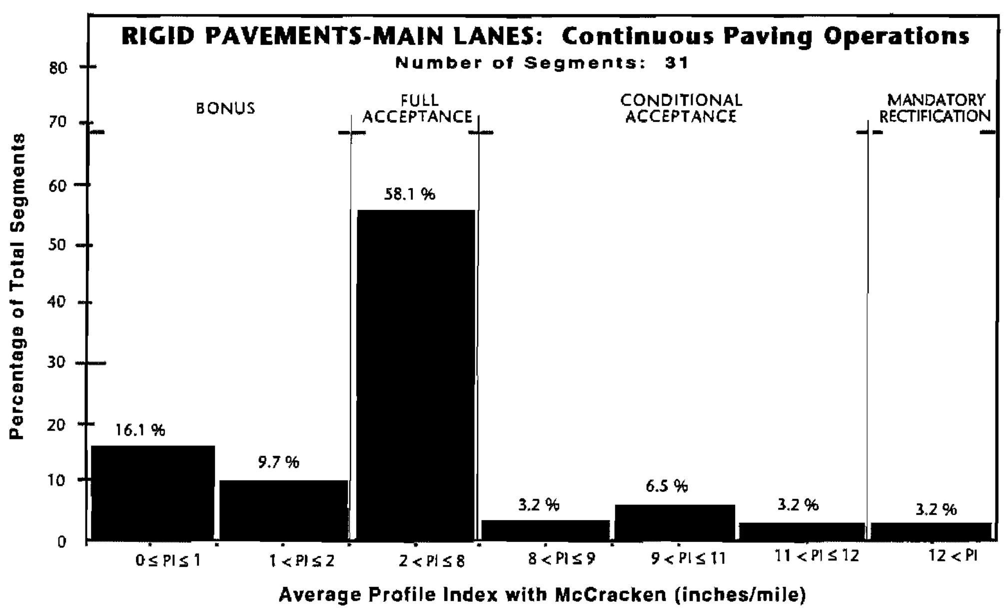


Figure 5.10 Modified draft smoothness specification for rigid pavements built with continuous paving operations

difference between the roughness of the as-constructed pavement and the target (i.e., design) pavement. A contractor's responsibility to conform to specification should be limited to the performance period, since each additional performance period is a function of how well a specific contractor conforms to the specification in that period. The initial design period is usually in the range of 10 to 15 years since one or more overlays are often scheduled in the design period of a pavement. To accommodate these variances, the design period for the objectives of this study was set at 15 years.

The effects on pavement maintenance and user costs are based on the difference in pavement smoothness of the as-constructed and the target pavement. The initial pavement roughness of the target pavement should be set. Since the full acceptance category represents the achievable levels by the industry and the desired product quality by the agency, the initial design roughness for the target pavement was selected as the midpoint of this interval. This value represents the roughness quality that is achievable by most contractors. For evaluating the payment to be assigned to the "Bonus" and "Conditional Acceptance" specification categories, the middle PI value of each category was considered in determining the effects on user costs and pavement maintenance cost.

Equations have been developed for evaluating pavement maintenance and user costs. Most of the models developed for the determination of user costs require assumptions on several factors, such as geometric design characteristics of the roadway, vehicle characteristics, fuel price, pavement condition, and others. User costs associated with these factors are outside the scope of this study. However, pavement maintenance cost has been related to traffic characteristics, pavement age, and other factors (Ref 26). One way to determine maintenance cost for a specific region would be to use historical data on maintenance of existing roads of different condition, age, traffic, and pavement type, among other factors. Since such information is not usually available, simplified equations had to be used in this study.

From the results of a 1982 FHWA study (Ref 27), vehicle operating costs for year y (VOC_y ($/sy)) were related to pavement condition, in terms of PSIy for year y, and load applications W_y (ESAL) with simplifying assumptions for traffic distribution, vehicle loading, operating speed, etc. Annual routine maintenance cost RMC_y ($/sy) was correlated to PSI_y for year y. These equations are:

$$RMC_y \text{ (\$/sy)} = m\ (5 - PSI_y)\ 2/6.25 \qquad (5.3)$$

where: RMC_y is the routine maintenance cost in year y; m is the routine maintenance cost when PSI is equal to 2.5, and for both pavement types m is equal to 0.5 $/sy (Refs 27 and 28); PSI_y is the serviceability index for year y; and

$$VOC_y \text{ (\$/sy)} = q\ (0.00203\ W_y)(1.397 - 0.088\ PSI_y) \qquad (5.4)$$

where: VOC_y is the vehicle operating cost for year y; and q is the percentage of the total predicted VOC that is to be considered in determining the contractor's penalty or rewards since VOC may have a large effect on contractor payment. This percentage was set equal to 10 percent in the development of performance related specifications (Ref 27). However, this parameter will be chosen based on the effects that VOC has on contractor's payment from the analysis of this study.

Since these equations are based on PSI, the Profile Index from the California profilograph must be correlated to PSI. Walker and Lin defined such correlations from newly constructed and in-service flexible and rigid pavement located in Texas (Refs 29 and 30). The equations that correlate PSI with PI from the California profilograph and the 0.2" blanking band are reported in Table 5.2.

Table 5.2 Correlation of psi and pi for flexible and rigid pavements (Refs 29 and 30)

Pavement Type	Correlation	Standard Error	R^2
Flexible	$PSI = 4.71 - 0.05\ PI$	0.11	0.89
Rigid	$PSI = 4.81 - 0.30\sqrt{PI}$	0.27	0.85

Finally, in order to predict PSI over the performance period, the 1986 AASHTO design equations were used. These equations were used for designing the target pavement and then solved for PSI_y so as to predict PSI for each year of the design period. Traffic, environmental, and material design inputs, representing average conditions for the region where the specification is going to be implemented, should then be assumed. These values are presented in the following sections.

Once the PSI of the as-constructed and the target pavement are obtained for each year, maintenance and user cost are calculated as described previously. The difference in maintenance and user cost for the as-constructed and the target pavement can then be discounted in terms of present worth. The discount rate to be used with the present worth method is usually set to 3 percent. Once the differences in costs in terms of present worth are obtained, the cumulative present worth can be calculated from their sum over the performance period. This value is then discounted or added to the unit bid price for evaluating the penalty or bonus payment.

Effect of RMC and VOC on Pay Schedules

In order to define the pay schedules of the specification, the difference in pavement maintenance and user cost during the design period of the as-constructed and the target pavement was calculated.

For flexible pavements, the initial roughness for the design pavement was equal to PI = 3.5, corresponding to a PSI of 4.5. The input values for the design equation are presented in Table 5.3. The required layer thicknesses for this design were then obtained equal to 6, 8, 14 inches for the surface, base and subbase layers. Based on the in-place cost of materials (Refs 31), the bid price was equal to 25.6 $/sy.

The next step was to use the design equation for predicting the Present Serviceability Index (PSI) over the performance period for the as-constructed and the target pavement. The results of this analysis are presented in Table 5.4. As can be seen in this table, the influence of various percentage of VOC on the reward was examined. A higher percentage VOC gives a higher reward for the "Bonus" category. At the same time, the penalty becomes higher for the "Conditional Acceptance" categories. Finally, when 10 or 15 percent of the VOC is considered, the incentives/penalties are low.

The same analysis was conducted for portland cement concrete pavements built with continuous paving operations. The input values for the design equation are presented in Table 5.5. The required slab thickness was 10. The in-place material price, and thus the bid price for both cases, was equal to 30.0 $/sy (Ref 31).

The results of these analyses are presented in Table 5.6. Again, as for the flexible pavement specification, when a higher percent of VOC is considered in the analysis, a higher reward is given for the "Bonus" category, but at the same time the penalty becomes higher for the "Conditional Acceptance" categories.

Table 5.3 Input data for evaluating the payment schedule of flexible pavement specification

Input Variable	Value
Serviceablity and Reliablity	
Initial PSI for Target Pavement	4.5
Final PSI	2.5
Reliability	90%
Standard Deviation	0.49
Traffic Factors	
Daily ESAL $_{18}$ in Design Lane	1,200
Traffic Growth Factor	3%
Material and Construction Factors	
Subgrade Resilient Modulus	5,000 psi
Structural Coefficient for Asphalt Material	0.44
Structural Coefficient for Base Material	0.14
Structural Coefficient Subbase Material	0.11
Drainage Coefficients for Base and Subbase	1.0
Economic and Cost Factors	
Discount Rate	5%
Cost of Asphalt Material (in place)	1.8 ($/sy)
Cost of Base Material (in place)	0.8 ($/sy)
Cost of Subbase Material (in place)	0.6 ($/sy)

Table 5.4 Influence of pavement maintenance and vehicle operating cost on specification pay schedule for flexible pavements

		Percent of Unit Bid Price for		
Specification Category	PI Range	RMC[a] + 10% VOC[b] (%)	RMC + 15% VOC (%)	RMC + 20% VOC (%)
"Bonus"	0.0 ≤ PI ≤ 1.0	101.0	101.5	102.0
	1.0 < PI ≤ 2.0	100.7	101.0	101.5
"Full Acceptance"	2.0 < PI ≤ 5.0	100.0	100.0	100.0
"Conditional Acceptance"	5.0 < PI ≤ 7.0	99.0	98.5	98.0
	7.0 < PI ≤ 9.0	98.0	97.5	97.0
"Mandatory Rectification"	PI ≥ 9.0	–	–	–

[a] RMC = Routine Maintenance Cost
[b] VOC = Vehicle Operating Cost

Table 5.6 Influence of pavement maintenance and vehicle operating cost on the specification pay schedule for rigid pavements built with "continuous" paving operations

Specification Category	PI Range	Percent of Unit Bid Price for RMC[a] + 10% VOC[b] (%)	RMC + 15% VOC (%)	RMC + 20% VOC (%)
"Bonus"	0.0 ≤ PI ≤ 1.0	101.0	101.5	102.0
	1.0 < PI ≤ 2.0	100.7	101.0	101.5
"Full Acceptance"	2.0 < PI ≤ 8.0	100.0	100.0	100.0
"Conditional Acceptance"	8.0 < PI ≤ 9.0	98.5	98.0	97.0
	9.0 < PI ≤ 11.0	98.3	97.4	96.5
	11.0 < PI ≤ 12.0	97.7	96.6	95.5
"Mandatory Rectification"	PI > 12.0	–	–	–

[a] RMC = Routine Maintenance Cost
[b] VOC = Vehicle Operating Cost

Table 5.5 Input data for evaluating the payment schedule of rigid pavement specifications

Input Variable	Value
Serviceablity and Reliablity	
Initial PSI for Target Pavement	4.2
Final PSI	2.5
Reliability	90%
Standard Deviation	0.39
Traffic Factors	
Daily ESAL $_{18}$ in Design Lane	1,200
Traffic Growth Factor	3%
Material and Other Factors	
Modulus of Subgrade Reaction	60 pci
Elastic Modulus of Concrete	4.1×10^6 psi
Modulus of Rupture for Concrete	690 psi
Load Transfer Coefficient	3.2
Drainage Coefficient	1.0
Economic and Cost Factors	
Discount Rate	5%
Cost of Concrete for 10- or 11-inch slab (in place)	30.0 ($/sy)

Proposed Specifications and Recommendations

From the influence of the VOC on the incentives and penalties in the specifications for flexible pavements it was observed that a 10 or 15 percent level of VOC produces low incentives and rewards for defective or high-quality product, respectively. Thus, the pay schedules based on 20 percent VOC and RMC are recommended. The proposed specifications are presented in Tables 5.7 and 5.8.

Table 5.7 Smoothness specifications for main lanes of newly constructed flexible pavements

Specification Category	PI range	Percent of Unit Bid Price
"Bonus"	0.0 ≤ PI ≤ 1.0	102.0
	1.0 < PI ≤ 2.0	101.5
"Full Acceptance"	2.0 < PI ≤ 5.0	100.0
"Conditional Acceptance"	5.0 < PI ≤ 7.0	98.0
	7.0 < PI ≤ 9.0	97.0
"Mandatory Rectification"	PI > 9.0	–

Table 5.8 Smoothness specifications for main lanes of newly constructed rigid pavements

PI (inches/mile)	Percentage of Unit Contract Price
0.0≤PI≤11.5	100
11.5<PI≤13.0	99
PI>13.0	Corrective work required

The payment schedules defined herein are based on several assumptions of traffic, material properties and cost, etc. It is expected that the payment schedules defined from this study might be only slightly modified from a change in the values of these variables. For example, when a higher level of traffic is considered, the difference in user and maintenance cost between the target and the as-constructed pavement might increase, but on the other hand the bid contract unit price will also increase because of an increase in thickness during design. In the same way, an increase of the design period will produce an increase in the difference of user and maintenance cost between the target and the as-constructed pavement and, at the same time, an increase in bid price due to the additional design thickness required. The influence of these variables on the payment schedules could be further examined through a sensitivity analysis study.

The effect of an overlay thickness on cost required to keep an as-constructed pavement above a PSI of 2.5 at the end of the performance period was not considered, since, in the most extreme case, this thickness was equal to 0.5 inch, producing no significant variation in the unit price cost.

Another alternative is to define variable payment schedules with the equations presented in this study so that any change in traffic, materials, and environmental factors can be taken into account for a specific project. However, this approach will define a complex specification for highway personnel and will create additional complexity in the bidding process.

CHAPTER 6. EVALUATING RIDING QUALITY OF OTHER ROADWAY COMPONENTS

INTRODUCTION

The revised CTR draft smoothness specifications defined for main lanes were also tested with data from shoulders, ramps, and bridge approaches. Although too few pavement segments were available to support a definitive specification, this material has been included as an example of how the methodology presented in the previous chapter can be applied to other roadway components.

Data from rigid and flexible pavements were collected using both profilographs. For this analysis, however, the McCracken profilograph was used, since no difference in roughness evaluation was found between the two devices (Chapter 4) and because the Ames device had not yet been approved by TxDOT at the time the data were collected.

The distribution of the average PI values for segments on bridge approaches and ramps for both pavement types were examined and are presented in this chapter. For the segments on shoulders, the PI down the middle of the shoulder was used.

From the examination of the profile index distribution of segments on shoulders, bridge approaches, and ramps, the limits of the specification categories were tested. Modifications to the specification were then identified using the same methodology applied for the specifications of newly constructed main travel lanes. The specifications proposed herein have limited validity since limited data were used. Thus, the methodology followed herein should be used with data from several paving projects across Texas.

Once the specification categories were defined, the payment schedule had to be set. For these types of roadway components, the application of the methodology used for newly constructed main travel lanes (i.e., defining pay schedules based on the effects on user and maintenance costs due to the departure from the specified design quality level), was not possible, since for roadway components such as exit ramps and shoulders, the level of traffic is significantly lower than main travel lanes and is usually unknown. In addition, the use of such methodology for evaluating payment schedules becomes more complex since additional assumptions are required for variables related to the design and construction of these roadway components. Thus, for roadway components other than main travel lanes, bonus and penalty rewards were defined arbitrarily for these types of specifications by several states.

As mentioned in the examination of specifications for newly constructed main travel lanes, a continuous pay function was not possible because of the relatively big variability in roughness evaluation.

PROFILE INDEX DISTRIBUTION AND DRAFT SPECIFICATIONS FOR SHOULDERS

The distribution of the profile index for segments located on shoulders of flexible and rigid pavements was examined separately; a proposed specification is presented for each type of pavement.

Flexible Pavements

The distribution of the segment profile index is presented in Figure 6.1; the distribution in terms of the specification categories is presented as Figure 6.2. Data from 16 segments on shoulders of newly constructed flexible pavements in Texas were used for obtaining these distributions. Most of the segments had a PI value below 10 inches/mile, and many had a PI of less than or equal to 3 inches/mile.

Approximately 62.5 percent of the segments on shoulders had a PI in the highest bonus category, 68.7 percent qualified for some bonus, 25 percent were acceptable without bonus, and 6.2 percent fell in the penalty region (Figure 6.2). Overall, 93.8 percent of the segments on shoulders of flexible pavements had a PI in the acceptable categories, meriting a bonus or full payment (PI≤10).

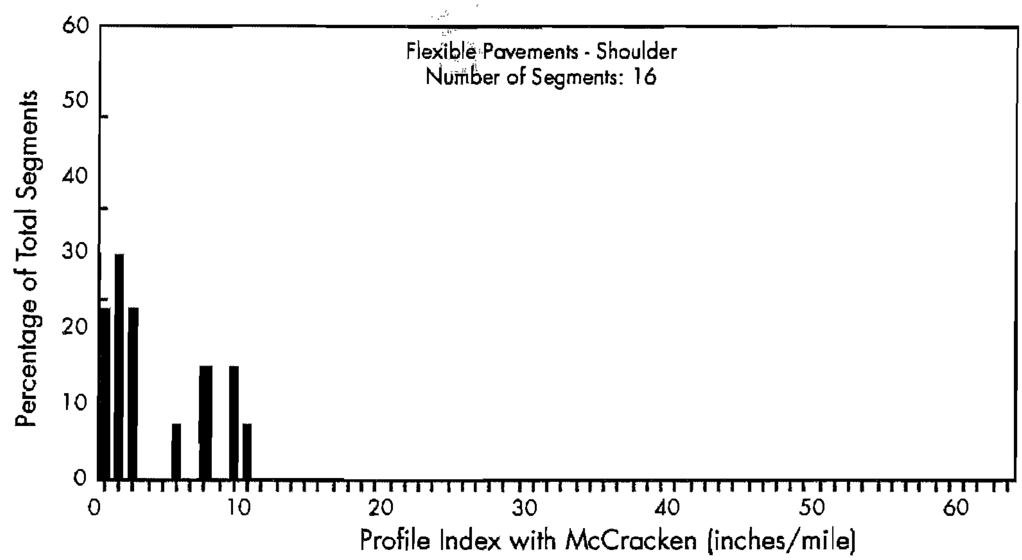


Figure 6.1 *Distribution of PI for segments on shoulders of asphalt concrete pavements*

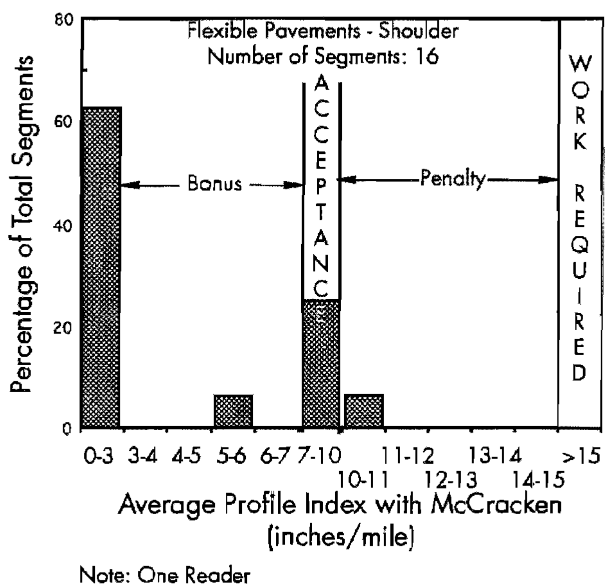


Figure 6.2 *Distribution of PI on acceptance categories for asphalt concrete shoulder segments*

The mean and standard deviations for the shoulder segments were 4.3 inches/mile and 3.6 inches/mile, respectively. A normality test on the data determined that the data are normally distributed (Kolmogorov-Smirnov, p=0.148), which indicates that acceptance limits could be set according to the mean and standard deviation. All PI values fell within two standard deviations of the mean (0,11.5); to account for the uncertainty in roughness evaluation, the interval 11.5 to 13.0 should be defined as the conditional acceptable category. Since 62.5 percent of the segments on shoulders have a PI≤3 inches/mile, the definition of a bonus category would not be cost-effective. With 100 percent of the contract unit price assigned to the acceptance category, a lower contract price (perhaps 99) could be assigned to segments having 11.0<PI≤13.0, so that uncertainty related to roughness evaluation is shared by the Department and the contractor. This possible smoothness specification for flexible pavement shoulders is presented in Table 6.1.

Table 6.1 *Smoothness specification for flexible pavement shoulders*

PI (inches/mile)	Percentage of Unit Contract Price
0.0≤PI≤11.5	100
11.5<PI≤13.0	99
PI>13.0	Corrective work required

Rigid Shoulders

The distributions of rigid pavement shoulder PI as individual values and in terms of the specification categories are presented in Figures 6.3 and 6.4, respectively. As was the case for main travel lanes on rigid pavements, the segments seem to have been sampled from two distinct populations (Figure 6.3). If these populations were not separated, it would be impossible to develop a reasonable specification, based on the large difference in roughness (Figure 6.4). Accordingly, the 24 shoulder segments were subdivided for further analysis into (1) the 15 segments built with continuous paving operations, and (2) the 9 segments built with stop-and-go paving operations.

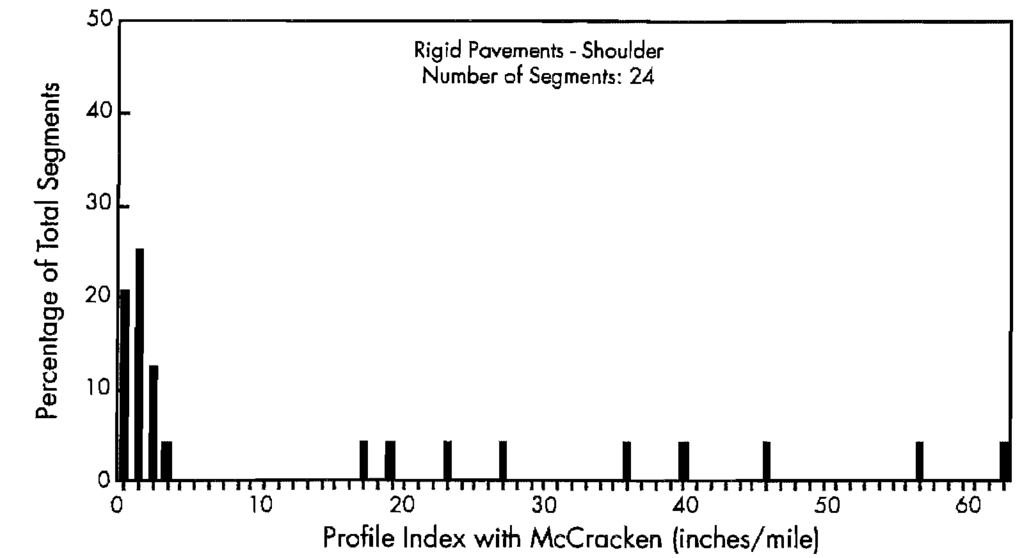
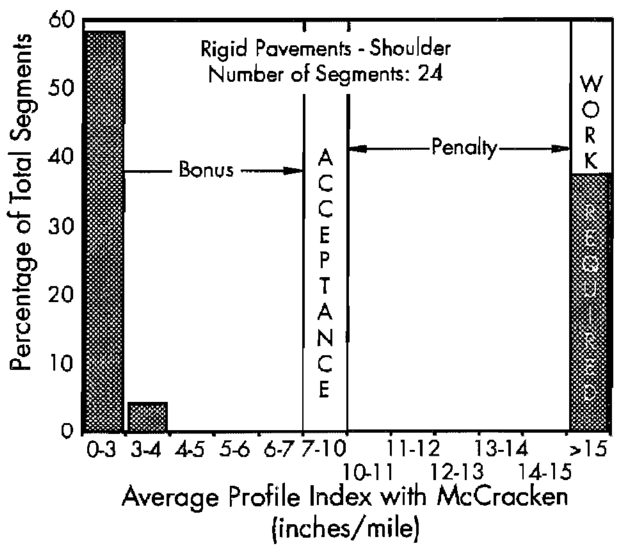


Figure 6.3 ***Distribution of PI for segments on shoulders of portland cement concrete pavements***



Note: One Reader

Figure 6.4 ***Distribution of PI on specification categories for portland cement concrete shoulder segments***

Shoulders Built with Continuous Paving Operations

The distribution of PI for rigid shoulders built with continuous paving operations is presented in Figures 6.5 and 6.6. All segments had a PI less than 4 inches/mile, which placed them in the bonus category of the specification. A normality test showed the data to be normally distributed, with a mean of 1.58 and a standard deviation of 1.02 inches/mile. All data from rigid pavement shoulders built with continuous paving operations fell within 3 standard deviations of the mean (0.0, 4.64). Because of the mean's proximity to the lower level of PI ($PI \leq 1$), it is impossible to define a bonus category. Defining the acceptance category as the mean PI ± 2 standard deviations results in payment of 100 percent unit price for PI values in the interval 0 to 3.5. As with flexible pavement shoulders, measurement uncertainty (1.3 inches/mile) can be shared between the agency and contractor by defining a lower (99 percent) payment category for PI values between 3.5 and 5.0. This possible specification is presented in Table 6.2.

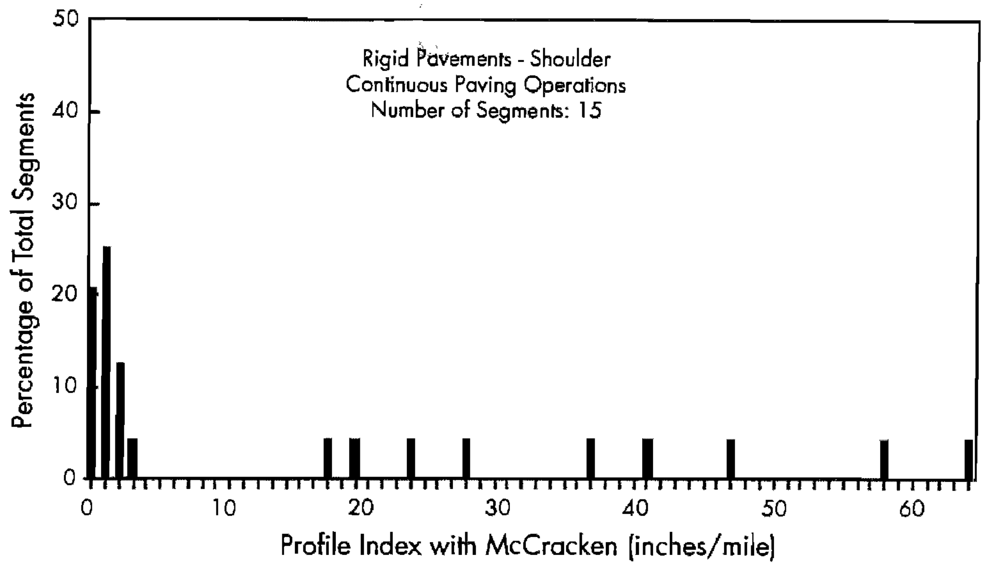


Figure 6.5 ***Distribution of PI for portland cement concrete pavement shoulders built with continuous paving operations***

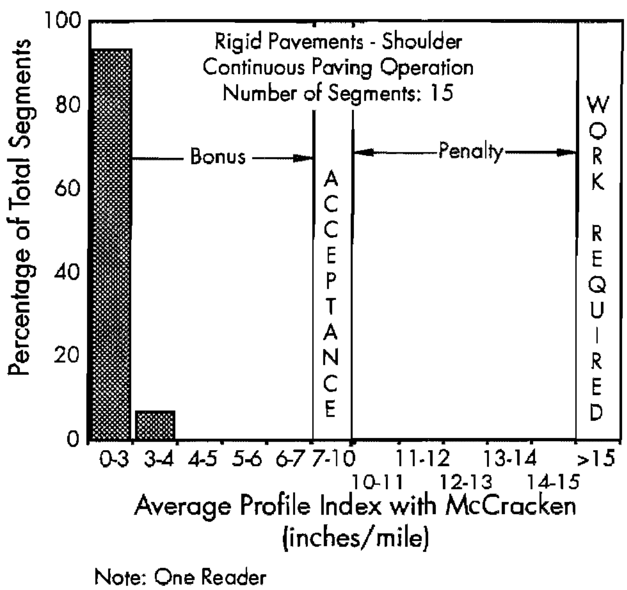


Figure 6.6 ***Distribution of PI on specification categories for segments on shoulders of portland cement concrete pavements built with continuous paving operations***

Table 6.2 ***Smoothness specification for shoulders of rigid pavements built with continuous paving operations***

PI (inches/mile)	Percentage of Unit Contract Price
0.0≤PI≤3.5	100
3.5<PI≤5.0	99
5.0<PI	Corrective work required

Shoulders Built with Stop-and-Go Paving Operations

The distribution of PI for shoulders built with stop-and-go paving operations on rigid pavements is presented in Figure 6.7. The PI values for these segments are spread out in the higher region; all of the segments had a PI in the non-acceptable region of the specification (Figure 6.8). The data were normally distributed, with a mean of 37.2 inches/mile and a standard deviation of 16.5 inches/mile. All of the data from shoulders on rigid pavements built with stop-and-go paving operations fell within two standard deviations of the mean (4.28, 70.16). The highest PI value for these segments was 64 inches/mile and the lowest PI value was 18 inches/mile.

If the same procedure used for continuous paving was used to define stop-and-go paving categories, the 100 percent payment category would be defined as the interval 17 < PI ≤ 64. To account for measurement variability (1.3 inches/mile), the 99 percent payment category would be assigned to the interval 64 < PI ≤ 66. The bonus category would be defined as 0 ≤ PI < 16 with 102 percent of contract unit price and the interval 16 < PI ≤ 17 with 101 percent of contract unit price to account for the overall variability in roughness evaluation. This possible specification is presented in Table 6.3; however, because of the very small number of segments available (9), more study is needed to determine a specification for this type of pavement.

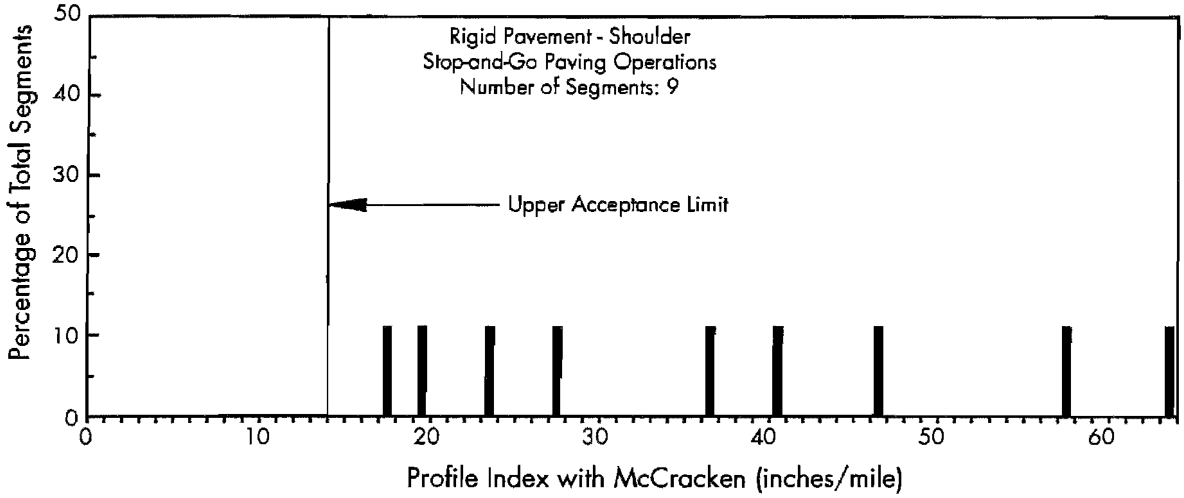


Figure 6.7 ***Distribution of PI for segments of portland cement concrete shoulders built with stop-and-go paving operations***

Table 6.3 ***Smoothness specification for shoulders of rigid pavements built with stop-and-go paving operations***

PI (inches/mile)	Percentage of Unit Contract Price
0.0≤PI≤16.0	102
16.0<PI≤17.0	101
17.0<PI≤64.0	100
64.0<PI≤66.0	99
66.0<PI	Corrective work required

PROFILE INDEX DISTRIBUTION AND DRAFT SPECIFICATIONS FOR RAMPS

The distributions of profile index for segments located on ramps of flexible and rigid pavements were examined separately. A proposed specification is presented for each type of pavement.

Flexible Pavement Ramps

The distribution of PI values for flexible pavement ramps is presented in Figure 6.8. Only eight segments were available for the study—too few to warrant a reliable specification recommendation. However, for consistency, the same procedure used for the other pavement types can be followed here. Since the data were found to be normal (p=0.202), having a mean of 9.5 inches/mile and a standard deviation of 10.6 inches/mile, and since the sample mean is less than one standard deviation from 0 inch/mile, no bonus category

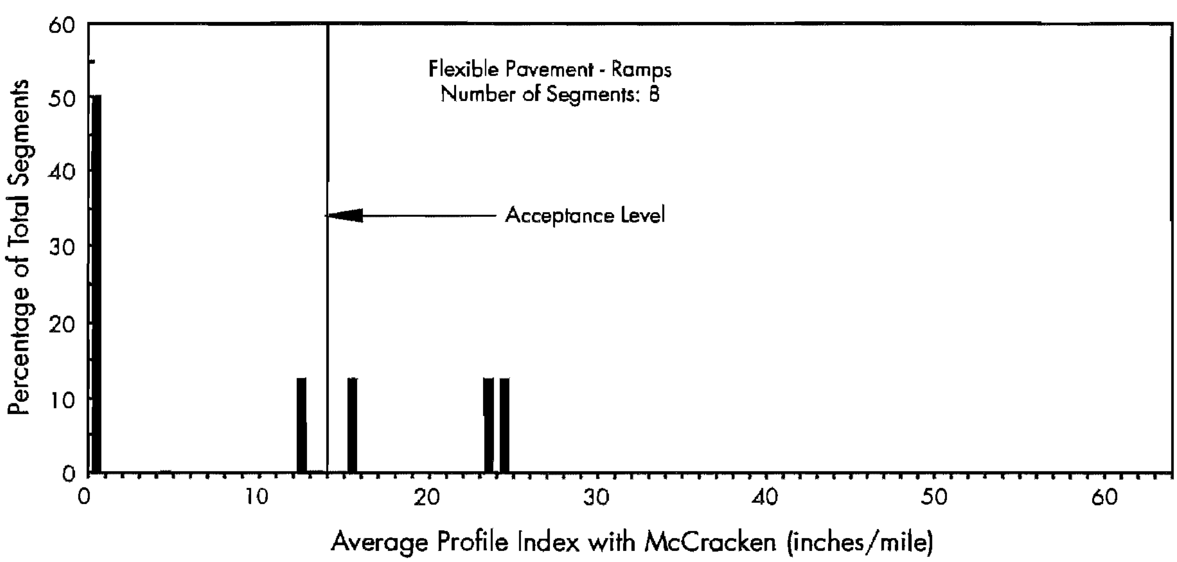


Figure 6.8 ***Distribution of PI for segments on asphalt concrete pavement ramps***

can be defined; however, an acceptance category of two standard deviations about the mean (0≤PI≤25) can be specified. As before, a reduced payment category to account for measurement uncertainty is included (Table 6.4).

Table 6.4 Smoothness specification for flexible pavement ramps

PI (inches/mile)	Percentage of Unit Contract Price
0.0≤PI≤25.0	100
25.0<PI≤27.0	99
27.0>PI	Corrective work required

Rigid Pavement Ramps

The distribution of PI values for ramps on rigid pavements is presented in Figures 6.9 and 6.10. Again, it appears that the data collected are part of two different populations, as was observed for main travel lanes and shoulders of rigid pavements. Because of the wide roughness range, it would be impractical to set a single specification for the combined population. Instead, the 14 segments on ramps were subdivided for further analysis into (1) the 8 segments built with continuous paving operations, and (2) the 6 segments built with stop-and-go paving operations.

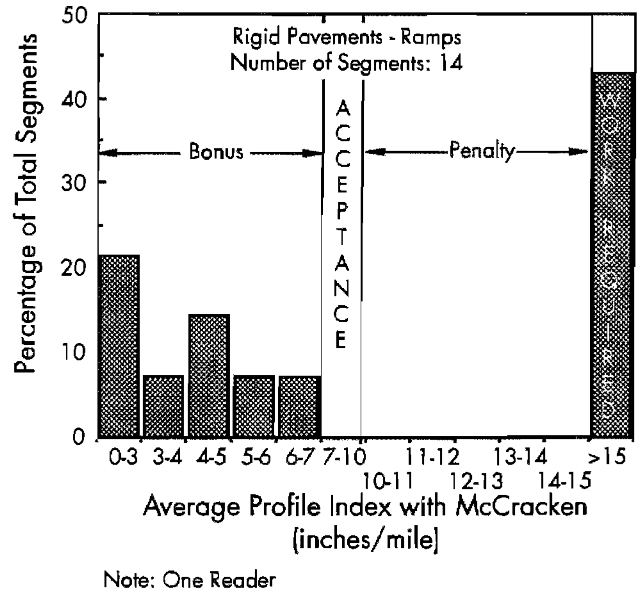


Figure 6.10 Distribution of PI on specification categories for segments of portland cement concrete pavement ramps

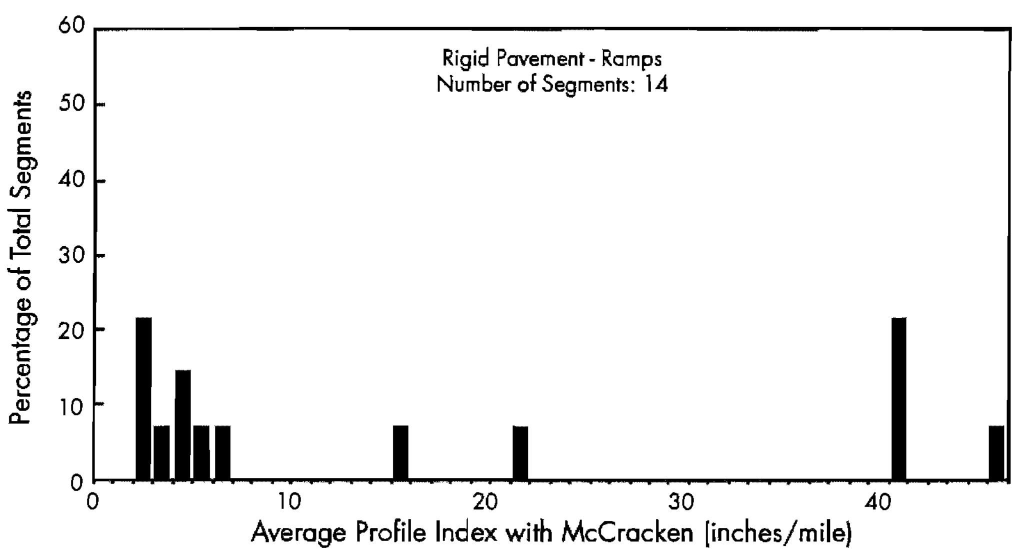


Figure 6.9 Distribution of PI for portland cement concrete ramp segments

Ramps Built with Continuous Paving Operations

The distribution of PI values for ramps built with continuous paving operations on rigid pavements is presented in Figures 6.11 and 6.12. All of the segments fell into the bonus area, with more than a third in the uppermost bonus category. The data were normally distributed ($p = 0.316$), with a mean of 4.12 and a standard deviation of 1.67 inches/mile. All of the data were within two standard deviations of the mean (0.78, 7.46). The acceptable category for 100 percent of the contract unit price could be set as the interval $2 < PI \leq 7$. To account for the variability in roughness evaluation, the intervals $0 \leq PI < 2$ and $7 < PI \leq 8.5$ are considered with 101 and 99 percent of contract unit price payments. A possible specification is presented in Table 6.5.

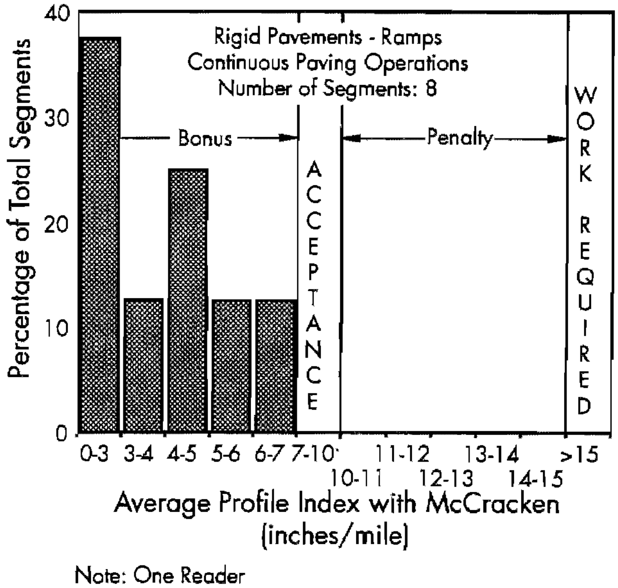


Figure 6.12 Distribution of PI on specification categories for portland cement concrete ramps built with continuous paving operations

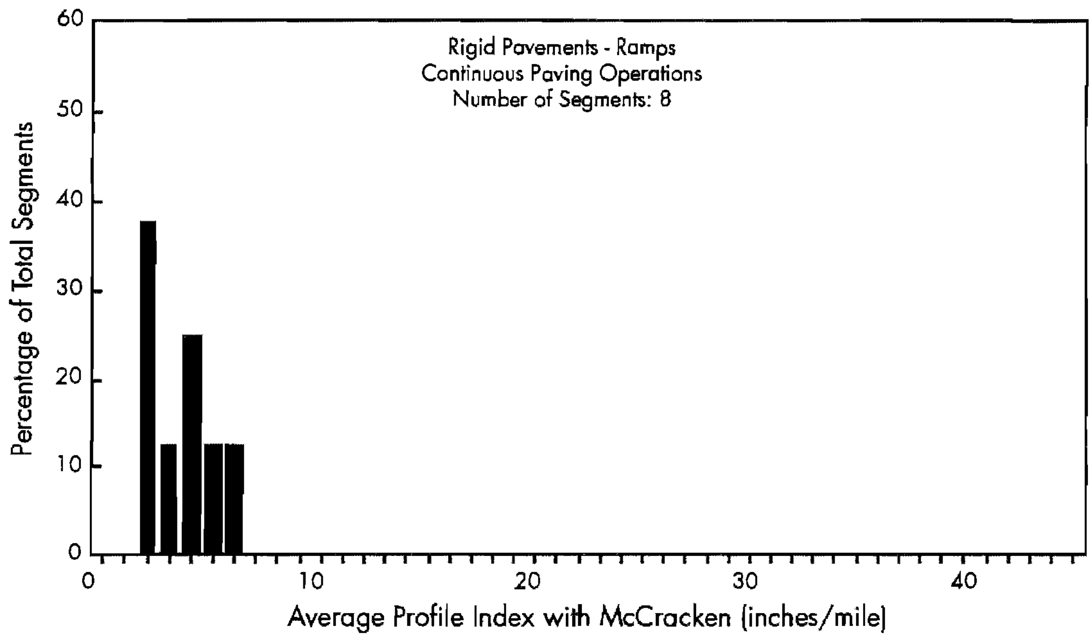


Figure 6.11 Distribution of PI for segments on ramps of portland cement concrete pavements built with continuous paving operations

Table 6.5 Smoothness specification for rigid pavement ramps built with continuous paving operations

PI (inches/mile)	Percentage of Unit Contract Price
0.0≤PI≤2.0	101
2.0<PI≤7.0	100
7.0<PI≤8.5	99
8.5<PI	Corrective work required

Ramps Built with Stop-and-Go Paving Operations

The distribution of PI values for rigid pavement ramps built with continuous paving operations is presented in Figure 6.13. Only six segments were available for the study—again, too few to warrant a reliable specification recommendation. All fell within the mandatory correction category. Again, for consistency, the same procedure used for the other pavement types can be followed. The data were found to be normal ($p = 0.189$), with a mean of 33.9 inches/mile and a standard deviation of 12.5 inches/mile. If all the segments were deemed acceptable (they are within two standard deviations of the mean), the interval ($15 \le PI \le 46$) can be specified for the 100 percent acceptance level. To account for the variability in roughness evaluation (1.3 inches/mile), the categories of $14.0 < PI \le 15$ and $46 < PI \le 47.5$ are considered as 101 and 99 percent of contract unit price, respectively. The bonus category is defined as $0.0 \le PI \le 14.0$, with 102 percent of contract unit price. Thus, a possible specification for ramps on rigid pavements built with stop-and-go paving operations is presented in Table 6.6.

Table 6.6 Smoothness specification for ramps of rigid pavements built with stop-and-go paving operations

PI (inches/mile)	Percentage of Unit Contract Price
0.0≤PI≤14.0	102
14.0<PI≤15.0	101
15.0<PI≤46.0	100
46.0<PI≤47.5	99
47.5<PI	Corrective work required

PROFILE INDEX DISTRIBUTION AND DRAFT SPECIFICATIONS FOR BRIDGE APPROACHES

The distributions of profile index for segments located on ramps of flexible and rigid pavements were examined separately. A possible specification is presented for each type of pavement.

Flexible Pavements

The distribution of profile index is presented in Figure 6.14. Only eight segments were available for the study, a limitation which made it difficult to develop a meaningful specification. Of the segments surveyed, 87.5 percent had a PI in the non-acceptable category of the draft specification for main lanes.

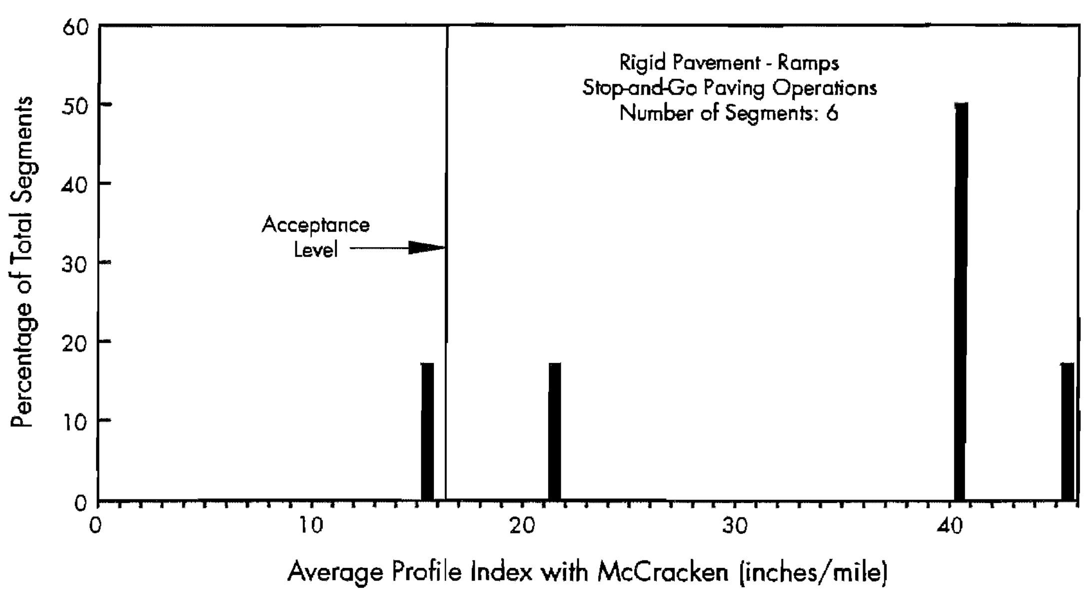


Figure 6.13 Distribution of PI for ramp segments of portland cement concrete pavements built with stop-and-go paving operations

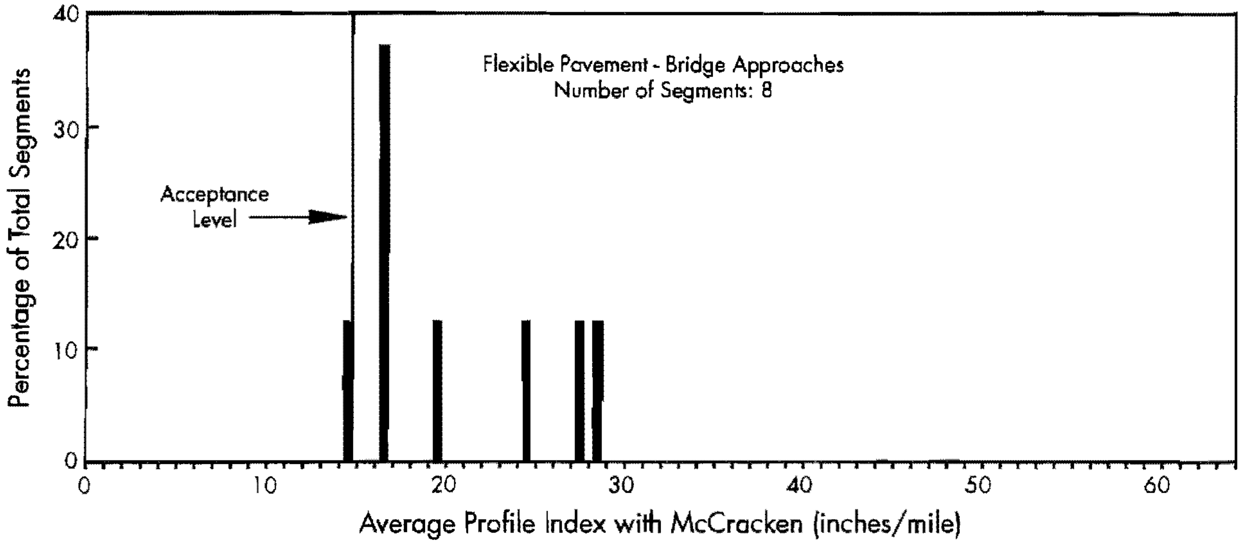


Figure 6.14 Distribution of PI for segments on asphalt concrete bridge approaches

The mean and the standard deviations were equal to 20.5 inches/mile and 5.4 inches/mile, respectively. The normality test on these data showed that the data are normally distributed (Shapiro-Wilk, $p = 0.232$). All of the PI values fell within a two-standard-deviation interval about the mean (9.8, 31.3). Since no segments had an average PI lower than 14 inches/mile or higher than 29 inches/mile, the acceptable category with 100 percent of the contract unit price can be set equal to $14 < PI \leq 29$. To account for variability in roughness evaluation, the intervals $12 < PI \leq 14$ and $29 < PI \leq 31$ with 101 and 99 percent of contract unit price are introduced. The bonus category is then defined from the interval $0 < PI \leq 12$, with the bonus equal to 102 percent of the contract unit price. This possible specification for bridge approaches of flexible pavements is presented in Table 6.7.

Rigid Pavements—Bridge Approaches

The bridge approach segments on rigid pavement are always built with short paving operations, since the bridge deck and the main travel lanes far from the bridge deck are always built separately. Thus, all 17 segments in the study were built with stop-and-go paving operations.

As can be seen from Figure 6.15, all the segments surveyed had a PI greater than 24 inches/mile (the maximum PI value was 56 inches/mile), falling into the non-acceptable category of the specification defined for main lanes (Figure 5.10). The data were normally distributed ($p = 0.214$), with sample mean and standard deviation equal to 34.8 and 9.6 inches/mile, respectively.

Table 6.7 Smoothness specification for bridge approaches of flexible pavements

PI (inches/mile)	Percentage of Unit Contract Price
$0.0 \leq PI \leq 12.0$	102
$12.0 < PI \leq 14.0$	101
$14.0 < PI \leq 29.0$	100
$29.0 < PI \leq 31.0$	99
$31.0 < PI$	Corrective work required

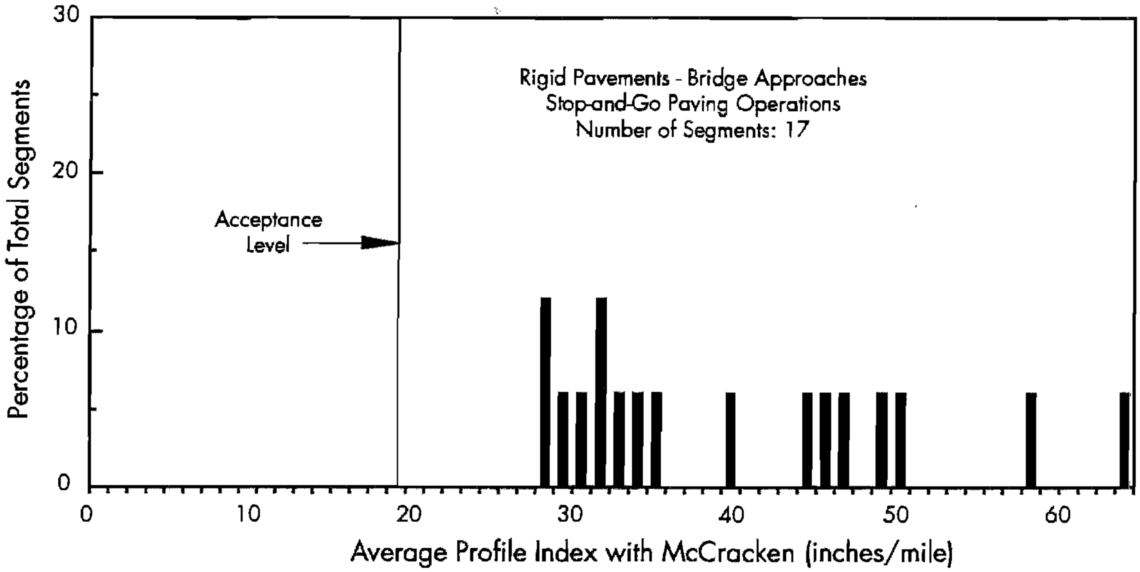


Figure 6.15 Distribution of PI for segments on portland cement concrete bridge approaches

All of the data from bridge approaches of rigid pavements fall within three standard deviations of the mean (6.1, 63.5). Since none of the segments observed had an average PI value lower than 24.0 inches/mile and higher than 56.0 inches/mile, the acceptable category for 100 percent of the contract unit price can be set for the interval 24 < PI ≤ 56. To account for variability in roughness evaluation, the intervals 22.5 ≤ PI < 24.0 and 56 < PI ≤ 57.5 are established at 101 and 99 percent of contract unit price payment, respectively. The bonus category of 102 percent of contract unit price is then defined as the interval 0 < PI ≤ 23. Thus, a possible specification for bridge approaches on rigid pavements is presented in Table 6.8.

Table 6.8 Smoothness specification for bridge approaches of rigid pavements

PI (inches/mile)	Percentage of Unit Contract Price
0.0≤PI≤23.0	102
23.0<PI≤24.0	101
24.0<PI≤56.0	100
56.0<PI≤57.5	99
57.5<PI	Corrective work required

CHAPTER 7. CORRELATION OF PROFILOGRAPH OUTPUT WITH ROUGHNESS INDEXES

INTRODUCTION

The California-type profilograph—the instrument used by TxDOT to evaluate roughness for the new end-result specification—produces an output profilogram that is converted to a profile index (PI) in inches per mile. If this device is to be physically meaningful, PI should be related to the output of other roughness devices used for evaluating the roughness of newly constructed pavements or for periodic evaluation of pavements.

One way to compare PI to the output of other roughness devices is to conduct an experiment in which measurements are taken on the same set of pavement sections using several roughness devices; such an experiment was impractical for this study.

However, the output of many roughness instruments have been related to such roughness statistics as the International Roughness Index (IRI) and the root mean square vertical acceleration (RMSVA) of different base wavelengths (Refs 13 and 14). Thus, it is possible to compare PI with the output of any other roughness device by comparing PI to IRI and RMSVA from such devices.

This chapter describes the field testing undertaken to obtain roughness measurements used to compare PI with IRI and RMSVA. Both the Face Dipstick, a Class I roughness instrument according to the FHWA classification (Ref 32), and the McCracken profilograph were used to collect data on sections of both flexible and rigid pavements. Using the data collected with these instruments, PI was related to the IRI and RMSVA at different base wavelengths. The resulting correlations, analyzed in detail in this chapter, represent a standard reference for converting PI values to IRI and RMSVA.

FIELD TESTING AND EVALUATION OF ROUGHNESS INDEXES

Roughness measurements were collected using both a manual-type Face Dipstick (see Figure 7.1) and the McCracken profilograph on 18 different segments of flexible and rigid pavements. Roughness measurements with the McCracken profilo-graph were made according to the description presented in Chapter 3. On each 528-foot-long segment, both instruments were used to measure both the right and the left wheelpaths, which were located 3 feet from each side of the edge of the lane. Since the objective of the study was to correlate PI over a wide range of roughness, both newly constructed and in-service pavements were included in the field testing. Detailed information on the segments included in this study are presented in Table 7.1.

The Face Dipstick measures the change in elevation at 1-foot horizontal intervals as it is walked down a wheelpath. The individual elevation readings are displayed and reported to the nearest 0.001 inch. In each segment, both the start-and-stop location and the wheelpath location were marked for the operator to follow.

The profilograms obtained with the McCracken profilograph were evaluated according to the interpretation method described in Appendix A, obtaining a PI value for each wheelpath of each segment. The readings obtained with the Face Dipstick for each wheelpath of a segment were entered into files using software commercially available from the Face Dipstick Company. The same software was used to calculate the IRI for each wheelpath in each segment. The International Roughness Index, defined in the International Road Roughness Experiment (Ref 14), is calculated as the sum of the rectified slope (RS) evaluated from the measurements obtained along the length of the segment using the following equation:

$$IRI = \left(1/\left(n-1\right)\right)\sum_{i=2}^{n} RS_i \qquad (7.1)$$

where

n = number of data points in each wheelpath.

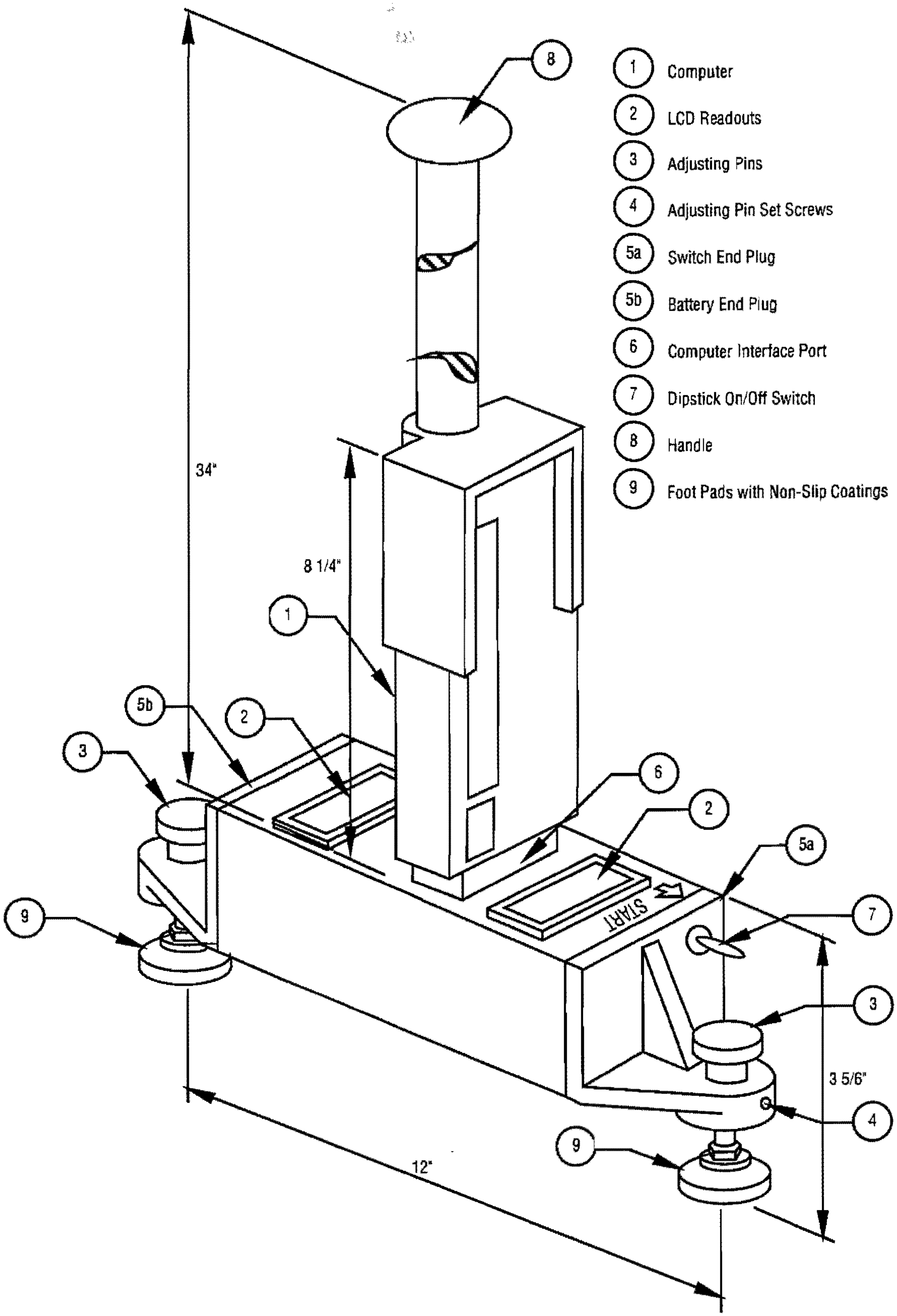


Figure 7.1 Auto-read version of the Face Dipstick (Ref 12)

Table 7.1 Characteristics of segments profiled

Segments	Wheelpath	Pavement Type	New or In - Service
ATS01-1	Left	Flexible	In-Service
ATS01-1	Right	Flexible	In-Service
ATS01-2	Left	Flexible	In-Service
ATS01-2	Right	Flexible	In-Service
ATS04-1	Left	Flexible	In-Service
ATS04-1	Right	Flexible	In-Service
ATS04-2	Left	Flexible	In-Service
ATS04-2	Right	Flexible	In-Service
ATS31-1	Left	Flexible	In-Service
ATS31-1	Right	Flexible	In-Service
ATS31-2	Left	Flexible	In-Service
ATS31-2	Right	Flexible	In-Service
ATS36-1	Left	Flexible	In-Service
ATS36-1	Right	Flexible	In-Service
ATS36-2	Left	Flexible	In-Service
ATS36-2	Right	Flexible	In-Service
ATS42-1	Left	Flexible	In-Service
ATS42-1	Right	Flexible	In-Service
ATS42-2	Left	Flexible	In-Service
ATS42-2	Right	Flexible	In-Service
ATS43-1	Left	Flexible	In-Service
ATS43-1	Right	Flexible	In-Service
ATS43-2	Left	Flexible	In-Service
ATS43-2	Right	Flexible	In-Service
MoPac 1	Left	Flexible	New
MoPac 1	Right	Flexible	New
MoPac 2	Left	Flexible	New
MoPac 2	Right	Flexible	New
US 183-1	Left	Rigid	New
US 183-1	Right	Rigid	New
US 183-2	Left	Rigid	New
US 183-2	Right	Rigid	New
Lubbock-1	Left	Rigid	New
Lubbock-1	Right	Rigid	New
Lubbock-2	Left	Rigid	New
Lubbock-2	Right	Rigid	New

ATS = Austin Testing Section

The root-mean-square vertical acceleration for base wavelength B was evaluated through the sum of the second derivative on points of the road profile equally spaced at distance B, as shown in Figure 7.2.

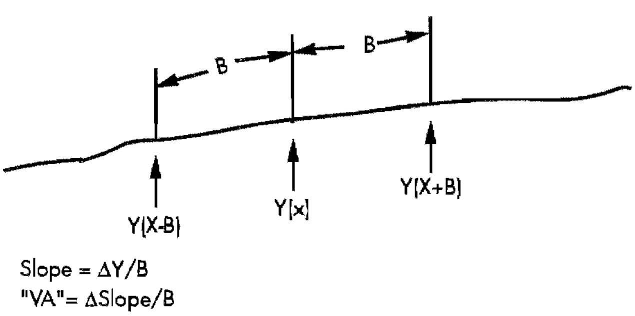


Figure 7.2 Calculation of RMSVA

A program for calculating the RMSVA's of different base wavelengths was developed according to Equations 7.2 and 7.3 (Refs 34 and 35) below.

$$(S_b)_i = ((Y_{i+k} - Y_i)/ks) - ((Y_i - Y_{i-k})/ks) \quad (7.2)$$
$$(S_b)_i = ((Y_{i+k} - 2Y_i - Y_{i-k})/ks^2)$$

where

$(S_b)_i$ = second derivative of Y at point i with respect to the base length distance, b,

b = base length = ks,

k = an arbitrary integer used to define b as a multiple of s (sampling interval), and

s = data sampling interval, i.e., the horizontal distance between adjacent elevation points at which the profile data were taken;

and

$$VA_b = c\left[\sum_{i=k+1}^{n-k}(Sb)_i^2 / n - 2k\right]1/2 \quad (7.3)$$

where

VA_b = root mean square vertical acceleration corresponding to the base length, b,
n = total number of elevation points, and
c = a constant required for unit conversion from a frequency domain acceleration to a spatial acceleration.

The 18 segments included in the study produced 36 data points, one measurement from each wheelpath. These data are reported in Table 7.2.

CORRELATION OF PROFILE INDEX WITH IRI

Several models were fitted to the PI and IRI data. Using the profile index as the dependent variable (Y = PI) and IRI as the independent variable (X = IRI), linear and polynomial models of second degree with and without constant term (b_o) were tested. The following shows the form of these models:

MODEL

Linear without constant term:

$$Y = b_1 * X \quad (7.4)$$

Linear with constant term:

$$Y = b_o + b_1 * X \quad (7.5)$$

Polynomial without constant term:

$$Y = b_1 * X + b_2 * X^2 \quad (7.6)$$

Polynomial with constant term:

$$Y = b_o + b_1 * X + b_2 * X^2 \quad (7.7)$$

From the analysis conducted, regression models with the constant term were able to explain the variability of the observed data. In fact, as shown in Figure 7.3, when PI obtains values close to or equal to 0 the corresponding IRI is in the range of 70 to 80 inches/mile. On the other hand, the coefficient for the second degree term of the polynomial model with a constant term was not significant. Thus the best model is presented in Table 7.3.

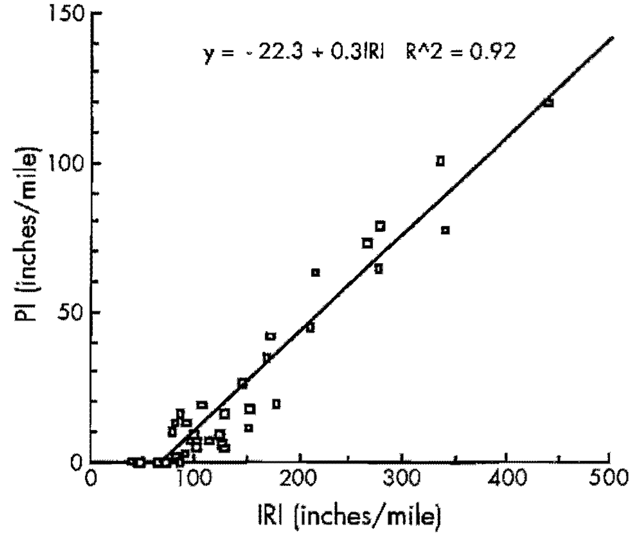


Figure 7.3 Relationship of PI and IRI for flexible and rigid pavements

CORRELATION OF PI WITH RMSVA

Two types of correlations between PI and RMSVA were examined. The first type represents correlations of PI with individual RMSVA of different wavelength. Models with and without the constant term (b_o), having the form of Equations 7.4, 7.5, 7.6, and 7.7, were analyzed. The models with polynomial form of second degree were included in the analysis since in most cases a plot of PI and RMSVA had a typical trend, such as the relationship shown in Figure 7.4.

In the second case, models relating PI with more than one RMSVA—each of a different base wavelength—at a time were examined. The results of these analyses follow.

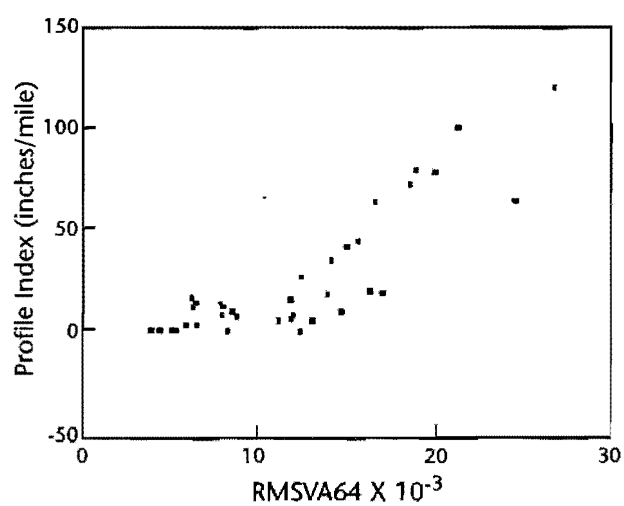


Figure 7.4 Plot of PI versus RMSVA64

Table 7.2 Roughness indexes for surveyed segments

Segments	Wheelpath	IRI	$RMSVA_2$	$RMSVA_4$	$RMSVA_8$	$RMSVA_{16}$	$RMSVA_{32}$	$RMSVA_{64}$	$RMSVA_{128}$	PI
ATS01-1	Left	276.8	14.144	4.298	1.075	0.347	0.069	0.019	0.005	79.0
ATS01-1	Right	338.7	15.010	5.354	1.116	0.364	0.075	0.020	0.005	78.0
ATS01-2	Left	171.8	12.343	3.238	0.877	0.210	0.056	0.015	0.004	42.0
ATS01-2	Right	168.6	12.400	3.301	0.864	0.199	0.053	0.014	0.004	35.0
ATS04-1	Left	214.8	11.700	3.413	0.954	0.238	0.059	0.017	0.004	63.5
ATS04-1	Right	265.4	14.580	4.469	0.985	0.278	0.069	0.018	0.004	73.0
ATS04-2	Left	334.4	17.323	5.204	1.303	0.341	0.078	0.021	0.005	101.0
ATS04-2	Right	438.5	20.786	6.869	1.488	0.388	0.097	0.027	0.006	120.0
ATS31-1	Left	144.9	12.722	3.112	0.766	0.208	0.052	0.012	0.003	26.5
ATS31-1	Right	210.1	12.481	3.449	0.914	0.258	0.062	0.016	0.004	45.0
ATS31-2	Left	151.6	13.018	3.339	0.841	0.208	0.053	0.014	0.003	18.0
ATS31-2	Right	275.1	20.954	6.014	1.395	0.382	0.097	0.024	0.006	64.5
ATS36-1	Left	94.7	10.921	2.818	0.735	0.165	0.046	0.012	0.003	7.5
ATS36-1	Right	177.9	18.821	4.620	1.035	0.294	0.070	0.016	0.003	20.0
ATS36-2	Left	99.9	11.386	2.549	0.643	0.169	0.043	0.011	0.003	5.5
ATS36-2	Right	128.1	12.100	2.935	0.683	0.184	0.046	0.012	0.003	16.0
ATS42-1	Left	84.8	5.429	1.408	0.351	0.100	0.024	0.006	0.001	16.0
ATS42-1	Right	92.3	7.057	1.727	0.469	0.112	0.030	0.008	0.002	13.5
ATS42-2	Left	123.6	12.427	3.121	0.826	0.197	0.056	0.015	0.004	9.5
ATS42-2	Right	98.6	7.621	1.845	0.460	0.115	0.030	0.009	0.002	9.5
ATS43-1	Left	111.7	7.269	1.943	0.525	0.120	0.032	0.008	0.002	7.5
ATS43-1	Right	80.1	5.244	1.422	0.367	0.097	0.025	0.006	0.002	13.0
ATS43-2	Left	99.8	8.265	2.108	0.536	0.132	0.036	0.009	0.002	7.0
ATS43-2	Right	78.6	5.467	1.366	0.371	0.092	0.023	0.006	0.002	10.5
MoPac 1	Left	71.0	12.332	2.976	0.759	0.198	0.051	0.012	0.002	0.0
MoPac 1	Right	39.7	3.603	0.925	0.245	0.058	0.016	0.004	0.001	0.5
MoPac 2	Left	46.5	4.673	1.198	0.282	0.068	0.020	0.005	0.002	0.0
MoPac 2	Right	42.5	3.732	0.935	0.249	0.057	0.015	0.004	0.001	0.0
US 183-1	Left	127.6	7.918	2.445	0.627	0.162	0.046	0.013	0.003	5.0
US 183-1	Right	123.8	10.427	2.919	0.685	0.183	0.043	0.012	0.003	6.0
US 183-2	Left	105.7	8.559	2.290	0.680	0.183	0.056	0.017	0.005	19.5
US 183-2	Right	150.5	7.676	1.950	0.505	0.128	0.033	0.008	0.002	11.5
Lubbock-1	Left	89.6	6.976	1.723	0.433	0.101	0.029	0.007	0.002	3.0
Lubbock-1	Right	81.7	5.074	1.350	0.384	0.087	0.023	0.006	0.001	2.5
Lubbock-2	Left	84.1	8.012	2.176	0.452	0.131	0.032	0.008	0.002	0.0
Lubbock-2	Right	64.0	4.752	1.254	0.308	0.078	0.020	0.005	0.001	0.0

Table 7.3 Regression model for PI and IRI

Model	t-Statistic	F-Model	R^2	Plot of Residuals vs IRI
PI=22.3 + 0.3* IRI	Constant -8.2 IRI 20.9	437	0.92	No Pattern

Note: n = 36

Simple linear regression models and polynomial of second degree, with and without the constant term b_0, were examined for correlating PI and individual RMSVA of base wavelengths 2, 4, 8, 16, 32, 64, and 128 feet. The coefficients for the second degree terms of the polynomial models were insignificant. In addition, the plots of the residuals against the independent variable for these models exhibited a definite trend: the residuals increased as the value of the independent variable increased (an example of this pattern is shown in Figure 7.5). Such a trend indicates that the assumption of constant variance for the errors (residuals) does not hold for all cases in the data. Thus a transformation of the dependent variable (PI) is necessary for stabilizing the variance. The square root of the dependent variable PI was then selected as a transformation for defining new models. For the models having a polynomial form, the coefficients of the second degree terms were still insignificant; therefore, simple linear regression models were defined. The coefficients of the constant term for the linear models relating PI with RMSVA having base wavelengths of 2, 4, and 16 feet were not significant. Thus, for these base wavelengths the linear models with the intercept of the model forced through the origin are the best relationships of RMSVA and PI (see Table 7.4). For the remaining wavelengths, the models with the constant term represent the best relationships of PI with RMSVAs since the coefficients for these models are significant and the models have higher coefficient of determination.

The normality test for the residuals of these models shows that the assumption of normal distribution for the residuals holds. Finally, most of these models are able to explain more than 70 percent ($R^2 \geq 70$) of the variability of the observed points. Figure 7.6 shows the model between the square root of PI and RMSVA with length 64 with the data.

In addition to the square root transformation, a logarithmic transformation of PI was conducted. The models obtained, when compared with the models obtained from the square root transformation of PI, did not bring any improvement into the PI and RMSVA relationships, i.e., models with lower coefficient of determination (R^2).

In order to obtain the second type of relationship between PI and RMSVA, multiple regression should be used. However, the models from multiple regression will be meaningless if the independent variables RMSVAi are correlated. Thus, the correlation matrix between the independent variables was examined. This matrix is shown in Table 7.5. As can be seen from this table, the independent variables are highly correlated. Thus, when multiple regression was used, none of the models was able to explain properly the data observed.

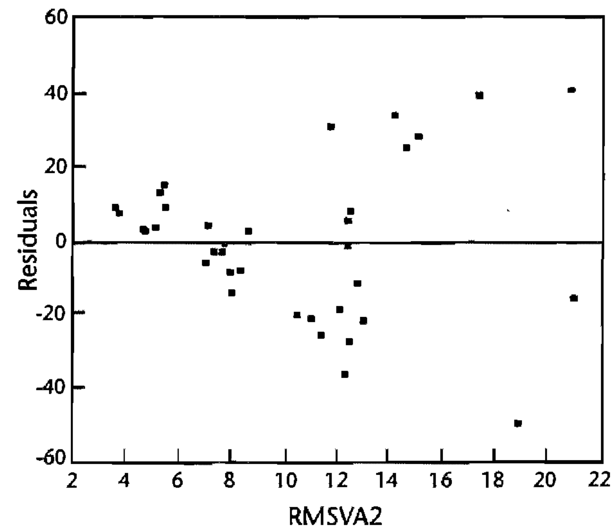


Figure 7.5 Residual plot for linear model of PI with $RMSVA_2$ and a constant term

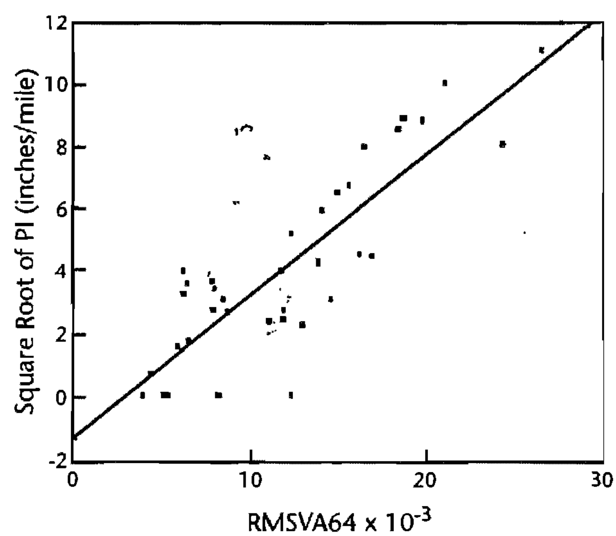


Figure 7.6 Relationship of square root of PI and RMSVA with base length 64

Table 7.4 Regression models for pi with individual RMSVA

Model	t-Statistic	F-Model	R^2	Plot of Residuals vs RMSVA
$\sqrt{PI}$= 0.4 $RMSVA_2$	$RMSVA_2$ 13.8	44	0.56	No Pattern
$\sqrt{PI}$= 1.5 $RMSVA_4$	$RMSVA_4$ 16.7	74	0.68	No Pattern
$\sqrt{PI}$= -1.48 + 7.98 $RMSVA_8$	Constant -2.3 $RMSVA_8$ 9.7	95	0.73	No Pattern
$\sqrt{PI}$= 23.3 $RMSVA_{16}$	$RMSVA_{16}$ 17.9	88	0.72	No Pattern
$\sqrt{PI}$= -1.3 + 117.9 $RMSVA_{32}$	Constant -2.0 $RMSVA_{32}$ 8.9	80	0.73	No Pattern
$\sqrt{PI}$ = -1.3 + 449.8 $RMSVA_{64}$	Constant -2.1 $RMSVA_{64}$ 9.6	92	0.73	No Pattern
$\sqrt{PI}$= -1.2 + 1771.8 $RMSVA_{128}$	Constant -2.0 $RMSVA_{128}$ 9.6	92	0.73	No Pattern

Note: n = 36

Table 7.5 Correlation matrix for RMSVA's

	RMSVA2	RMSVA4	RMSVA8	RMSVA16	RMSVA32	RMSVA64	RMSVA128
RMSVA2	1.000	0.970	0.969	0.950	0.964	0.931	0.880
RMSVA4	0.970	1.000	0.983	0.980	0.978	0.962	0.918
RMSVA8	0.969	0.983	1.000	0.980	0.989	0.979	0.940
RMSVA16	0.950	0.980	0.980	1.000	0.979	0.968	0.932
RMSVA32	0.964	0.978	0.989	0.979	1.000	0.991	0.959
RMSVA64	0.931	0.962	0.979	0.968	0.991	1.000	0.978
RMSVA128	0.880	0.918	0.940	0.932	0.959	0.978	1.000

CHAPTER 8. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

Throughout the United States and Europe there is now broad agreement among highway engineers and planners that newly constructed pavements should be smooth, and that such smoothness favorably affects user acceptance, comfort, reduced vehicle operating costs, and enhanced pavement performance. This study recommends that unacceptable levels of smoothness can be discouraged by employing end-product smoothness specifications that reward quality work and penalize poor work. A smoothness specification, based initially on the AASHTO work, is recommended for main travel lanes of newly constructed flexible and rigid Texas pavements; along with this, other potential specifications for key infrastructural elements are included. Although the scope of the research did not permit the precise specifications for penalty and acceptance throughout Texas, the study did investigate and does recommend a methodology for subsequent use in determining exact levels. The research also compared different instruments for enforcing the end-product specification; guidelines for the training of personnel charged with operating profilographs and implementing the draft specifications are also recommended. Finally, correlations of the output of profilographs with IRI and other roughness indexes were defined.

CONCLUSIONS

This study identified the following key elements:

(1) End-product smoothness specifications have been shown to be extremely effective in improving the quality of pavement riding profiles, both within the continental U.S. and throughout many European countries. Moreover, such specifications have met with widespread contractor approval, since they tend to limit the success of inferior contractors in bidding contracts. Initially, project staff were concerned about the possibility of litigation between contractor and state departments; at this point, however, the issue does not appear to be of major concern in states where end-roughness specifications have been used for a number of years. For example, staff from the Iowa Department of Transportation assured the project team that few problems with penalties result when incentives have been suitably structured, and that in their state there have been no cases of complex litigation associated with the use of end-smoothness specifications. Rather, the quality of the main highways, in terms of riding profile, has significantly improved according to that department's long-term pavement performance studies.

(2) The study showed that the devices preferred by both contractors and state officials for enforcing these specifications—California-type profilographs—were effective, even though their design and operation are now considered obsolete. Typically, the equipment is heavy, labor-intensive, mechanical, and requires considerable operator input; nonetheless, the equipment provides a series of adequate measurements useful in enforcing the specifications. In comparing the various types of profilographs, the study team concluded that the instrument would be substantially improved if it were lighter and if its current mechanical systems could be converted to electronic operations. However, experience of other states with automated profilographs showed that particular attention should be given to the filters used when collecting the data (Ref. 37).

(3) The study suggests a methodology for determining PI acceptability and penalty values that differs from that suggested by the AASHTO specifications. In the AASHTO specifications, there are trigger values beyond which vehicle excitation, passenger discomfort, increased operating costs, and poorer pavement performance result. In the draft

AASHTO specification, this trigger was set at 15 PI units per mile. This required that research be conducted to determine what these triggers are. This study adopted a different methodology. A sample of flexible and rigid operations was collected and a detailed analysis was carried out on the distribution of PI values; this then provided median values (for potential use as an acceptance value) and gave suggested values for bonus and penalty features. Obviously, this approach needs further research; it would be necessary to conduct a random sample of construction sites throughout Texas in order to determine the exact distribution of PI values across flexible and rigid operations so that general conclusions can be drawn concerning the values to be chosen for an end-roughness specification. The values recommended in this report are illustrative only, and do not constitute recommendations by the staff. However, they are valuable in describing how the various values for different elements of a specification would be determined for widespread adoption in Texas.

(4) Analysis of the data collected for main lanes showed that none of the main factors—profilograph type (Ames or McCracken), operator, and reader—had a significant effect in smoothness evaluation for flexible or rigid pavements. The interaction of operator-profilograph was significant only for flexible pavements. Profilograph repeatability (variability within instrument) and variability introduced by the operator and reader (variability within operator and reader) were evaluated on both flexible and rigid pavements. It was found that the overall variability of the roughness evaluation of a segment was 1.6 inches/mile for flexible pavements and 0.8 inches/mile for rigid pavements.

(5) Using the data, the study team identified possible modifications to the revised CTR smoothness specification for main travel lanes of both rigid and flexible pavements. The analysis of a segment PI distribution suggests that two different specifications should be defined for rigid pavements: one for segments built with continuous paving operations, and another for segments built with stop-and-go paving operations (frequent shutoff of paving equipment).

(6) Draft specifications for segments located on shoulders, bridge approaches, and ramps were presented based on the distribution of segment PI on these roadway components. In addition, a proposed specification for seal-coated segments of flexible pavement was defined. In most cases, the amount of data available for roadway components other than main lanes was very limited; for example, the seal-coated segments studied were all taken from a single paving project. Because of this limitation, the bonus/penalty schedules presented in Chapter 6 should be considered as a case study only, demonstrating how the specification for main lanes may need to be altered for other roadway components.

(7) Correlations of the California profilograph profile index with IRI and RMSVA of different base wavelengths were defined. Linear and polynomial models were examined to obtain the best fit of the observed values. The best model relating PI with IRI was a simple linear model having a constant term. PI was also correlated to RMSVA of different base lengths using multiple regression models. The best correlations of PI with a single RMSVA were obtained with linear models including a constant term. The best model obtained with multiple regression also includes a constant term and correlates PI with RMSVA of base lengths of 2, 4, and 8 feet.

(8) Training guidelines for personnel involved with the operation of the California profilographs are defined and presented (Appendix A). Because the California-type profilographs built by various companies present some differences (in assembly, operation, and calibration), guidelines regarding these matters are also presented.

RECOMMENDATIONS

Profilographs

A major finding of the study was that the McCracken and Ames profilographs yield roughness evaluations so similar that they may be used interchangeably. Operation of the two devices, which differs only slightly, can be facilitated by training conducted according to the manual presented in Appendix A.

An analysis of the collected data shows that the California profilographs experience repeatability problems, a conclusion confirmed by other researchers (Ref 30). Repeatability of these instruments is directly influenced by the ability of the operator to follow the wheelpath of the segments. Thus, the training level (e.g., number of hours trained) of the operators becomes important; to provide improved precision in roughness evaluation, it will therefore be necessary to define the optimal training level of the operators, and to further monitor the reduction in variability of roughness evaluation as the experience of the operators increases.

Improvements to the profilographs are also required. Because profiling segments on grade or long paving projects demands a significant physical effort on the part of the operator, a motorized version of the profilograph would represent a major improvement. With such an instrument, the operator would be able to concentrate on driving the profilograph as close to the wheelpath as possible. (Position markers should also be placed as close to the recording wheel as possible to enable the operator to follow the wheelpath precisely.)

Another possible area of profilograph improvement is automation. Considering the sophistication of some of the other profiling instruments in use today, the purely mechanical strip chart and interpreter system used by the profilograph seems anachronistic by comparison. If, instead of the strip chart, a microcomputer-based data collection system could be employed, it should be possible to automate the interpretation process, eliminating even the slight variance between chart readers and greatly simplifying the entire procedure.

Roughness Specifications

The revised draft smoothness specifications for main lanes presented in Chapter 2 can be used as a starting point for an end-product smoothness specification for Texas. Analysis of the roughness distribution of newly constructed flexible pavements (Chapter 5) suggests that it may not be necessary to provide bonus incentives, since smoothness is readily achieved for this type of pavement. One such suggested revision is included in Chapter 5.

For rigid pavements, separate specifications for pavements built with stop-and-go paving operations are needed, as these pavements cannot be built smoothly as readily as those produced by continuous paving operations. Bonus and penalty incentives are clearly needed for these pavements if low roughness is desired (a lower acceptance specification may also be necessary).

The specifications suggested for shoulders, ramps, and bridge approaches were based on a limited number of segments. Additional study will be required for improving and justifying the specification. As a case in point, the smoothness specification defined for seal-coated segments of flexible pavements was based on data collected on segments of just one paving project. These specifications should be further examined with additional data, preferably collected from a more diverse array of paving projects.

The analysis presented in Chapters 5 and 6 can best be used as an initial estimate of what percentage of paving projects will fall in each category of a proposed smoothness specification for each type of pavement and roadway component. Using the means and standard deviations calculated from the sample segments, the estimated cost or benefit of any bonus or penalty can be calculated with reasonable confidence. Any final specification for these pavements must be based on a number of additional factors (e.g., agency policy, contractor incentive, and cost/benefit analysis) and should be modified as needed after implementation.

Correlation Models

The models presented in Chapter 7 may be used to compare roughness measurements from various instruments. Many such devices measure roughness in terms of International Roughness Index (IRI), profile index (PI), or root mean square vertical acceleration (RMSVA). The models presented in the chapter constitute a standard reference for comparison between these types of instruments.

FUTURE IMPROVEMENTS

The study has been able to identify a series of future studies that would enhance adoption of an end-product specification in Texas.

(1) A random sample of flexible and rigid sites needs to be developed; from this, a determination needs to be made regarding the distribution of PI values in order to identify potential acceptance bonus, acceptance, penalty, and corrected work categories.

(2) Discussions must be held with contractors to establish potential incentive levels for incorporation into a specification. Although the initial work in this study showed that many paving operations are capable of high-quality work without bonus incentives being offered, there is still strong evidence in the literature and in other states that the existence of a bonus is extremely important in ensuring high-quality profiles. In addition to the incentive to produce a high-quality pavement, a substantial incentive element can be very useful in terms of bidding strategy. Good, well-organized companies capable of providing high-quality work are able to discount the expectation of bonuses into their bidding process, and thus the contract prices need not be dramatically higher because there is

an incentive. But more importantly, the lesser-skilled companies that in many cases have been responsible for inferior pavements (for example, the first half of the La Grange bypass) are excluded from the likelihood of success, since they cannot bid into their price the probability of achieving bonus payments. This is a very interesting area that merits further investigation on the part of future TxDOT researchers.

(3) Once a random sample of Texas paving operations has been conducted and the distribution of PI values has been determined, the draft specification can be applied (as shown in this report) and the percentage of segments earning bonuses and penalties can be determined. It may well be that the total amount of bonuses paid turns out to be a very small part of the aggregate pavings contracts let annually in Texas. This is an important issue for TxDOT policymakers. Those responsible for determining whether product specifications should be applied need to know the magnitude of the financial payments in terms of their total contracting budgets. This element could be handled in the way described, using some of the work developed in this study.

(4) Finally, new instrumentation needs to be developed to replace the existing machinery. This study has identified characteristics that need to be incorporated into new instrumentation—characteristics which in themselves represent a fruitful area of research for TxDOT. Specific areas for profilograph improvement include automation, mechanization, and operator training (as detailed in the recommendation section).

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APPENDIX A

TRAINING MANUAL FOR TXDOT PERSONNEL OPERATING CALIFORNIA-TYPE PROFILOGRAPHS

PREFACE

This manual, to be used for the training of TxDOT personnel operating California-type profilographs, was developed by The University of Texas at Austin, Center for Transportation Research (CTR), under research contract 3-8-88-1167 with TxDOT. The manual was developed by Mr. Dimitrios G. Goulias and Dr. Germán Claros of The University of Texas at Austin, Center of Transportation Research (CTR), with guidance and support from Dr. W. R. Hudson of The University of Texas at Austin. The purpose of the manual is to provide a document for the uniform training of TxDOT personnel operating California-type profilographs.

INTRODUCTION

The primary purpose of this manual is to provide a document for the uniform training of Texas Department of Transportation personnel operating California-type profilographs. Training courses are regarded as mandatory for the successful implementation of the Texas end-result smoothness specifications (Ref 1) using the California-type profilograph.

The following basic modules are included in this manual:

I. Description of California-type profilographs
II. Calibration of profilographs
III. Testing of pavement sections
IV. Trace reduction
V. Monitoring of contractors' measurement
VI. Reporting procedures
VII. Bonus or penalty payments

Components and assembly of the McCracken and Ames profilographs are described in detail in Supplements A and B, respectively. Information regarding profilograph certification is included In Supplement C.

TABLE OF CONTENTS

I. DESCRIPTION OF THE CALIFORNIA PROFILOGRAPHS

Introduction

The California-type profilograph is used for measuring longitudinal pavement roughness. This type of profilograph is a manually operated, multiwheeled instrument having a 25-foot span. It records the pavement surface profile on a paper roll from which a profile index (PI), in units of inches per mile, can be interpreted. While there are several manufacturers of California-type profilographs, the McCracken is currently the only instrument approved for use with the specifications in Texas, although the Ames profilograph is also under consideration. A description of these two California profilographs is presented below. Details on components and assembly, along with the operation, are described in Supplement A for the McCracken profilograph, while the same information for the Ames profilograph is reported in Supplement B.

Description of the McCracken Profilograph

The profilograph is essentially a 25-foot-long truss with a support at each multiwheeled end and a recording wheel positioned at midpoint (See Figure A.1). It is constructed of sections that are easily assembled to facilitate moving and storage. A recorder for plotting a continuous profilogram (trace) of the pavement traversed is located atop the frame at midpoint directly above the recording wheel. The recorder produces the trace to a scale of 1 inch equals 25 feet longitudinally and 1 inch to 1 inch vertically. The profilogram is indicative of the vertical movement of the recording wheel. The recorder is equipped with an integrator and counter for recording the roughness (or vertical deviations) in inches. The integrator records downward or upward movements of the recording wheel. These movements are equal to the vertical deviations called roughness. The integrator is geared to provide the counter mechanism with the roughness.

Description of Ames Profilograph

The Ames profilograph has a 25-foot-long truss with support at each of its multiwheeled ends. The recording wheel, positioned at midpoint (see Figure A.2), is made of rubber. A bicycle wheel is located at the left rear end for measuring the longitudinal distance. This profilograph is composed of light sections easily assembled by one person.

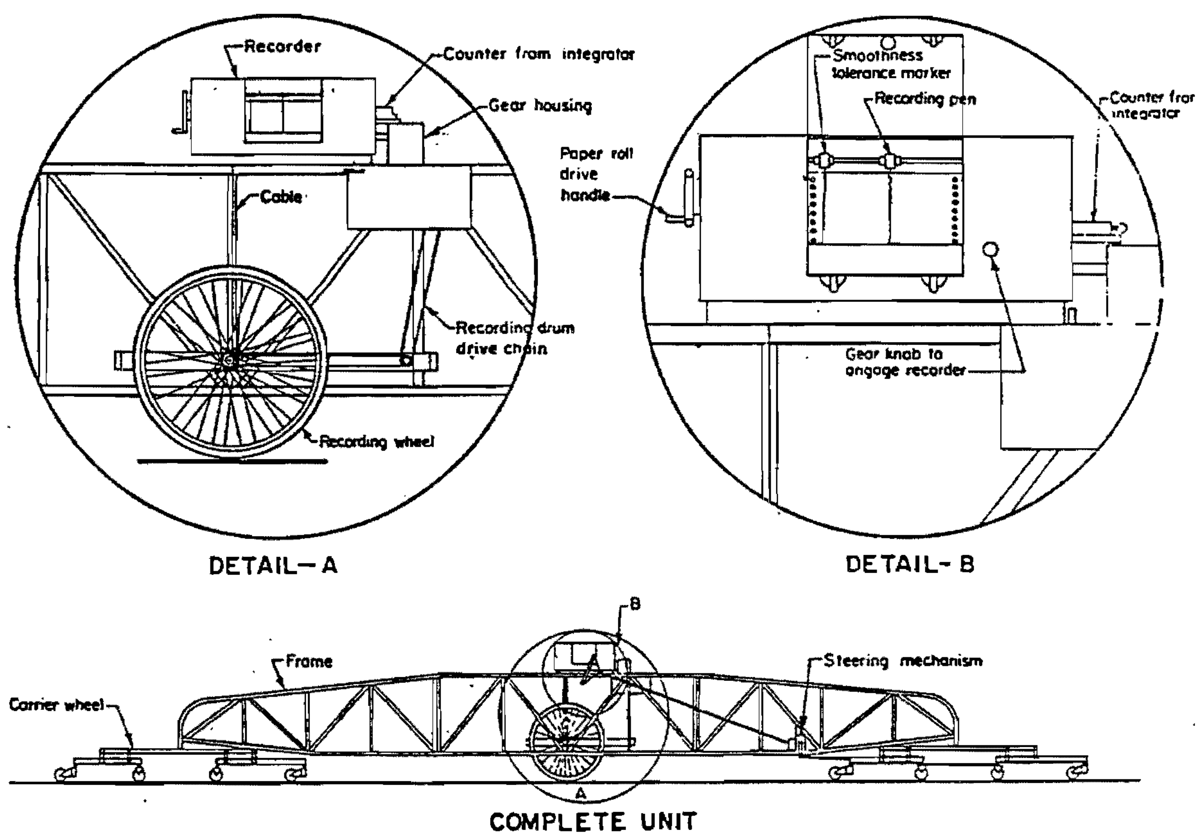

Figure A.1 McCracken Profilograph (Ref 2)

A recorder for plotting a continuous profilogram of the pavement is located at the right rear end. The recorder produces the trace to a scale of 1 inch equals 25 feet longitudinally and 1 inch to 1 inch vertically.

The three frame-beams of the Ames profilograph create an articulated beam when connected. The recording wheel then records the vertical movement of the articulated beam in the location of the recording wheel. Such vertical movement is then transmitted to the recording box through the articulated beam connected with a cable to the recorder.

II. CALIBRATION OF PROFILOGRAPHS

Before field testing with the California-type profilographs, both vertical and longitudinal calibration should be performed. The first step for calibrating the profilographs is to set the bicycle tire pressure equal to 25 psi.

Longitudinal Calibration

The longitudinal calibration consists of pushing the profilograph over a premeasured distance (500 feet) and determining whether the length of the chart is equal to 20 inches, since the chart scale factor is equal to 25 (500/25 = 20). In case the length of the chart is not 20 inches, then adjustment of the profilograph should be made until the length of 500 feet is measured accurately to within 1 foot or in scale ± 4/10 inch.

Adjustments to the McCracken profilograph are made through changes in the gear ratio of the chart drive mechanism.

For the Ames profilograph, longitudinal calibration is accomplished by varying air pressure in the bicycle tire. If the trace is too short, then lower the air pressure in the tire by approximately 2 psi increments until the correct measurement is achieved. Start the calibration process with the factory-determined air pressure of 25 psi.

Vertical Calibration

For vertical calibration, the profilographs should be stationary. Using pre-measured calibration plates (measured to the nearest 0.01 inch), pull or slide the plate(s) under the recording wheel of the Ames or McCracken Profilograph. Measure the vertical trace line from the baseline to the peak and return. (NOTE: The trace line must return to the baseline.) Tolerance will be ±0.01 inch.

III. TESTING OF PAVEMENT SECTIONS

Prior to recording the road profile, the roadway shall be cleaned of all equipment, covers, mud, debris, and other loose material. Position the profilograph near the pavement section to be tested and follow the instructions given below:

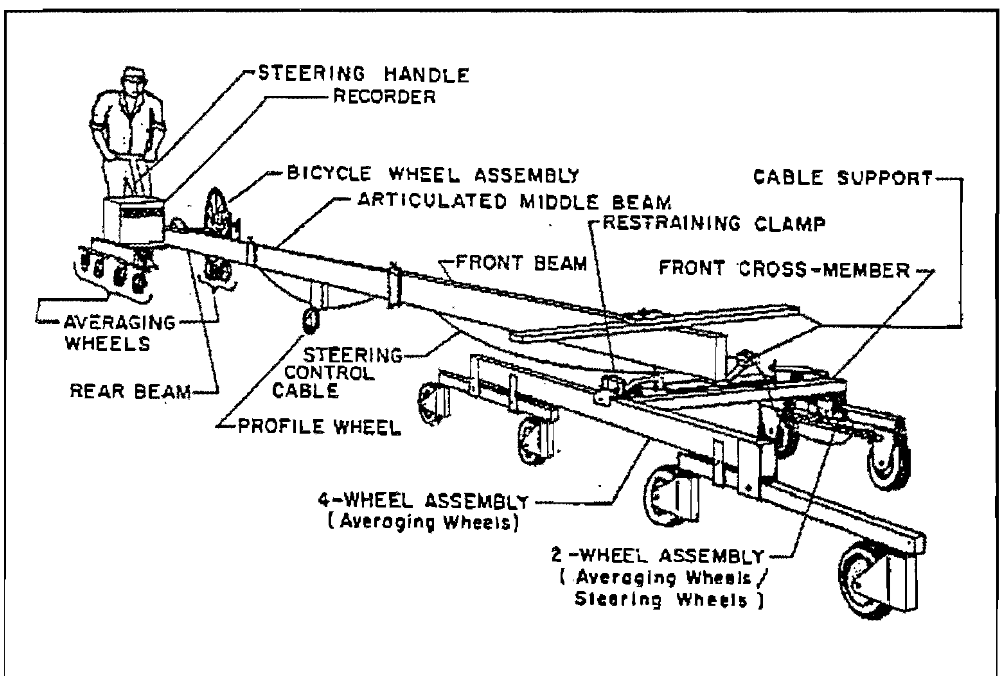

Figure A.2 Ames Profilograph (Ref 3)

1. Lift the paper drive wheel (bicycle wheel for the Ames profilograph and recording wheel for the McCracken) to take slackness out of the paper and turn the wheel to check that the paper is feeding properly. To define termini of the section to be tested, pull the recording cable. Push the profilograph until the profile wheel is at the beginning of the test section, then lower the paper drive wheel.
2. Record on the profile paper the project number, date of test, location of test (including lane and wheelpath), and the beginning station number.
3. The profilograph is normally tested along each wheelpath or in a line about 3 feet from the edge of the pavement or lane lines. Testing should not be conducted on pavement segments less than 50 feet, horizontal curves with a centerline radius of curvature less than 1,000 feet, or on the transition of such curves.
4. Note stationing should be written on the profilogram at least every 1000 feet and preferably every 500 feet. Closer station references of every 100 feet or every 200 feet are highly desirable where possible for locating bumps (Ref 4).
5. Completely label both ends of the profilograph roll and note the stationing and roll number at each end of the roll. Fill out a report form in pencil or pen and place the report around the trace roll with a rubber band. This report insures that the person reducing the trace and reporting the results will have all the information necessary. Profile traces will become part of the permanent project records.
6. The 25-foot profilograph should be used only on new construction for which the contractor is responsible (see Figure A.3). In addition, the profile will terminate 50 feet from each bridge approach joint.
7. Acceleration and deceleration tapers are omitted from 25-foot profilograph testing. The end of an entrance ramp is located by the point where the ramp is full lane width. The end of an exit ramp is also located by the point where the ramp is full lane width. The 25-foot profilograph is completely on the ramp at these termini points (see Figure A.4).
8. On shoulders, testing should be performed as closely to the centerline as possible.

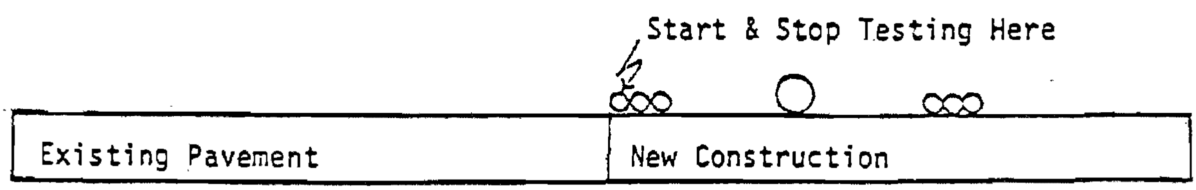

Figure A.3 Start and stop of profile evaluation (Ref 5)

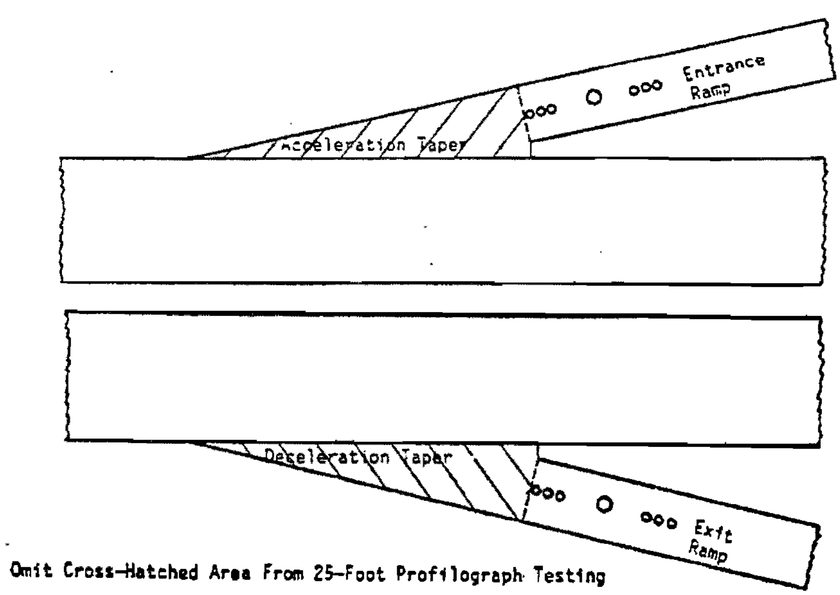

Figure A.4 Profile evaluation of exit ramps (Ref 3)

IV. TRACE REDUCTION

Equipment for Trace Reduction

A plastic scale (blanking band) is used to evaluate the profilogram (Ref 6). This scale is 21.125 inches long, representing the length of a 528-foot-long pavement segment (on a scale of 1 inch equals 25 feet). Two-tenths of an inch in the center of the plastic scale are blanked, with subdivisions above and below this blanked area located one-tenth of an inch apart (see Figure A.5).

For evaluating the bumps or high points on the profile trace, a 0.4-inch bump template is needed. This template is shown in Figure A.6. In addition to the plastic scale and the bump template, a scale ruler and a calculator are needed.

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 (Figure A.5). 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 (Figure A.6). 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 inch that do not extend longitudinally for at least 0.08 inch are not counted (Figure A.5).

For profiles containing bridge approaches or construction joints, 50 feet from both sides of the joint and the bridge deck—as well as the bridge deck itself—should be excluded from the profile evaluation. The above length of the profile excluded from the evaluation will be tested for determination of high points.

Calculations for Main Lanes and Exit Ramps

The profile index (PI) is calculated as "inches per mile in excess of the 0.2-inch blanking band" (Ref 7). 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.

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 (Ref 8). 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.

Segment length (mi.)	Count (tenths in.) Left Wheel Path	Right Wheel Path
0.1	8.9	6.7

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

Calculations for Shoulders

The profile index (PI) for the shoulders of each segment is obtained from the calculation of the trace obtained from the middle of the shoulder. Thus, there is no wheelpath-averaging process for segments on shoulders.

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 (mi.)	Count (tenths in.)
	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 = 29.5/3 = 9.8 in./mi.

Calculation of Partial Segments

There will sometimes be situations that require one to calculate 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 length of the partial segment and the ratio of the full and partial segment length. Second, determine the total vertical deviation count from the partial segment's profilogram. Then calculate the PI value in inches/mile by multiplying the calculated count in inches by the previously mentioned ratio. The following example illustrates the calculation process for partial segments.

Partial Segment length (ft)	Ratio of Full and Partial Segment length	Counts (tenths in.)
450 ft	528/450 = 1.17	6.5 x 1.70 = 7.6
PI (for partial segment) = 7.6 in./mi.		

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

Determination of High Points (Bumps)

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 baselines do not have to be horizontal. In no case shall this baseline be greater than 25 feet long or 1 inch on the template. Longer bumps shall be evaluated using a 25-foot baseline or 1 inch on the template, and this line's location is approximately horizontal (Figure A.7). With the template in place as described, a sharp pencil is used to mark a line 0.3 inch from the baseline, depending on the application. Any part of the peak projecting above this mark represents a bump above the 0.3-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. Check for high points by examining the bridge deck and the areas located 50 feet from both sides of construction joints.

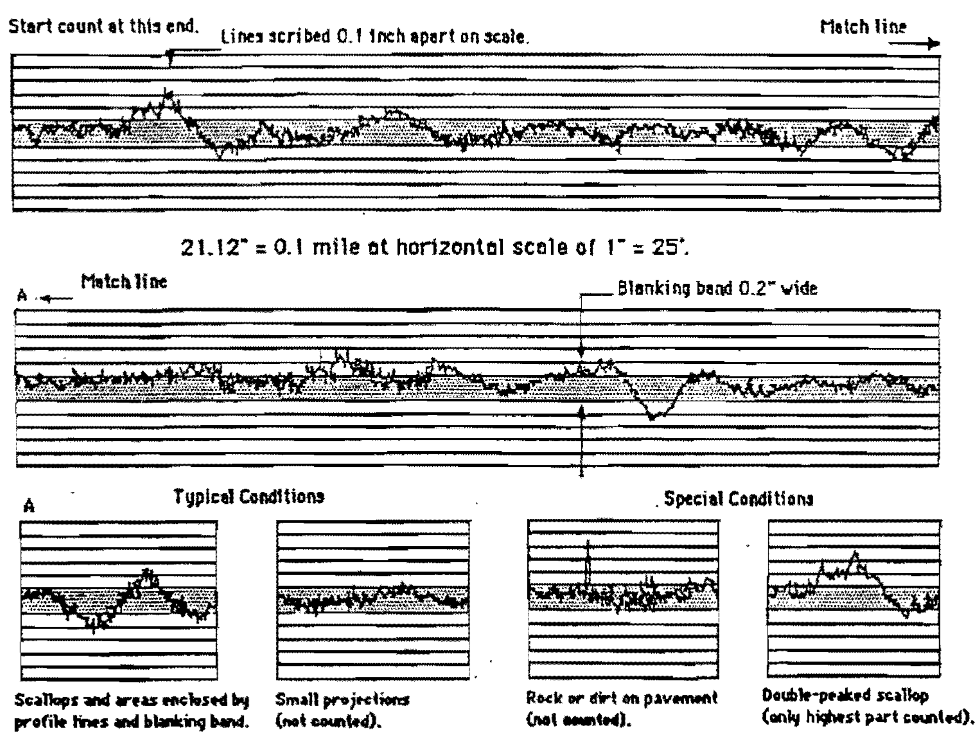

Figure A.5 Profilogram evaluation (Ref 9)

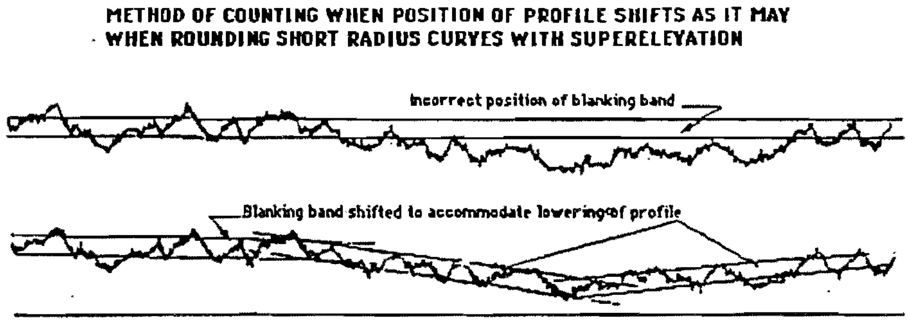

Figure A.6 *Profilogram evaluation for short radius curves with superelevation (Ref 9)*

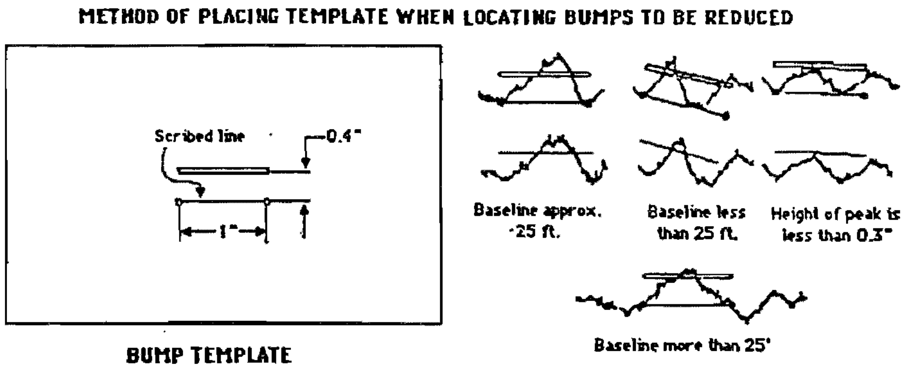

Figure A.7 *Methods for counting and placing bump template (Ref 9)*

V. MONITORING OF CONTRACTORS' MEASUREMENTS

Department inspectors will check constructor measurements during calibration of the profilographs. The certification of the profilograph from the Department will be required before the profilograph is used for testing. Operation of the profilograph by a certified California profilograph operator is desired. The Department inspectors should periodically check the operation of the profilograph during testing of the completed project to ensure that testing guidelines are followed by the contractor's operator.

VI. REPORTING PROCEDURES

The engineer shall receive each profilogram and a report showing the project and control numbers, as well as the exact location of the profilograms. Information regarding the certification of the profilograph should also be given. 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, wheel-path, 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.

An example of a completed report form is shown in Figure A.8. Always start with a full 0.10-mile segment and align both directions or lanes on the form. Entitle the first report "Preliminary" even if no pavement corrections are required.

VII. BONUS OR PENALTY PAYMENTS

The daily average profile index defined previously is used for determining the quality of paving operations. When the daily average profile index exceeds 15 inches per mile 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.

Payments are based on the profile index per each 0.1-mile section according to the schedule on the right.

Not more than 100 percent of the unit bid price will be paid for pavement sections that were originally constructed with a Profile Index greater than 10 inches per mile. A running total of this bonus or deduction will be determined for each day's production.

PROFILE PAY ADJUSTMENT SCHEDULE (REF 1)

Profile Index Inches per mile, per each 0.1-mile section	Bonus or Deduction Percent of Unit Bid Price
3.0 or less	+5
3.1 thru 4.0	+4
4.1 thru 5.0	+3
5.1 thru 6.0	+2
6.1 thru 7.0	+1
7.1 thru 10.0	+0
10.1 thru 11.0	-2
11.1 thru 12.0	-4
12.1 thru 13.0	-6
13.1 thru 14.0	-8
14.1 thru 15.0	-10
Over 15.0	Corrective work required

PAVEMENT TEST REPORT
25-FOOT CALIFORNIA PROFILOGRAPH

For Information Only ☐ Preliminary ☐ Intermediate ☐ Final ☐

Lab No. ______ Route No. ______ Project No. ______
Date Reported ______ Date Paved ______ County ______
Tested at: Middle ☐ Wheel Track ☐ Contractor ______
Tested by ______ Date ______
Trace Reduced by ______ Date ______

Primary Schedule A ☐
Primary Schedule B ☐
Secondary ☐
Municipal ☐
Other ☐

PCC Slip Form ☐
PCC Fixed Form ☐
PCC Bonded Overlay ☐
PCC Unbounded Overlay ☐
PCC Patches ☐

ACC Paving ☐
ACC Resurfacing ☐
ACC Patches ☐

Roadway Type: 2-Lane ☐ 4-Lane ☐ Ramp ☐ Other ______

N.B. ☐ E.B. ☐ S.B. ☐ W.B. ☐

Inside Lane ☐ Outside Lane ☐ Centerline ☐

	ISWP		OSWP		AVERAGE
Location (Station)	**Length (Miles)**	**Profile Index (Inches/Mile)**	**Length (Miles)**	**Profile Index (Inches/Mile)**	**Profile Index (Inches/Mile)**
122+45	0.10	3.00	0.10	7.00	5.00
127+73	0.10	14.00	0.10	15.00	14.50
133+01	0.10	12.00	0.10	6.00	9.00
138.29	0.10	11.00	0.10	4.50	7.75
143.57	0.10	1.00	0.10	1.50	1.25
	0.50		0.50		37.50

Daily Average Profile Index = 37.5/10 x 1.00/0.50 = 7.5 inches/mile

This is to certify that all testing and trace reduction herein described have been performed according to applicable contract specifications and requirements.

Station None ← **0.4" Bump Locations** → None **Station**

Signature: ______

Figure A.8 Reporting form for PI calculations (Ref 5)

REFERENCES

1. Texas Department of Transportation, Office of Materials, "Ride Quality for Pavement Surfaces," Item 585, revised February 26, 1991.

2. McCracken Corporation, "Operation of McCracken Profilograph," Sioux City, Iowa, (n.d.).

3. Louisiana Department of Transportation, "Handbook for California-Type Profilograph," Draft, 1991.

4. Utah Department of Transportation, "Procedure for Operating and Evaluating Results from a 25-foot Profilograph," Test Procedure 8-995, April 1983.

5. Iowa Department of Transportation, Office of Materials, "Method of Test for Determining Pavement Profiles with the 25-foot Profilograph," Instructional Memorandum, Matls. I.M. 341, January 1987.

6. Texas Department of Transportation, Materials and Tests Division, "Operation of the California Profilograph and Evaluation of Profiles," Test Method TEX1000 S, Draft, 1991.

7. Kansas Department of Transportation, "Method of Test for Determining Pavement Profile with the 25-foot Profilograph," 80P-232, Special Provision to the Standard Specifications, Edition of 1980 - Portland Cement Concrete Pavement Smoothness.

8. California Department of Transportation, "Operation of California Profilograph and Evaluation of Profiles," California Test 523, 1978.

9. Harrison, R., and C. Bertrand, "The Development of Smoothness Specifications for Rigid and Flexible Pavements in Texas," Report 1167-1, Center for Transportation Research, The University of Texas at Austin, January 1991.

SUPPLEMENT A. ASSEMBLY AND OPERATION OF MCCRACKEN PROFILOGRAPH

Assembly of the McCracken profilograph requires the following components:

- three frame sections (Figure SA.1)
- a steering wheel assembly (Figure SA.2)
- a six-caster front wheel assembly (Figure SA.3)
- a six-caster rear wheel assembly (Figure SA.3)
- a graph recorder (Figure SA.4)
- a location marker

STEP 2. STEERING CONNECTION

1. Insert steering universal connection into steering tube (Figure SA.2).
2. Swing steering support into frame connection.
3. Slide support through both frame brackets.
4. Align holes and insert cross pin.

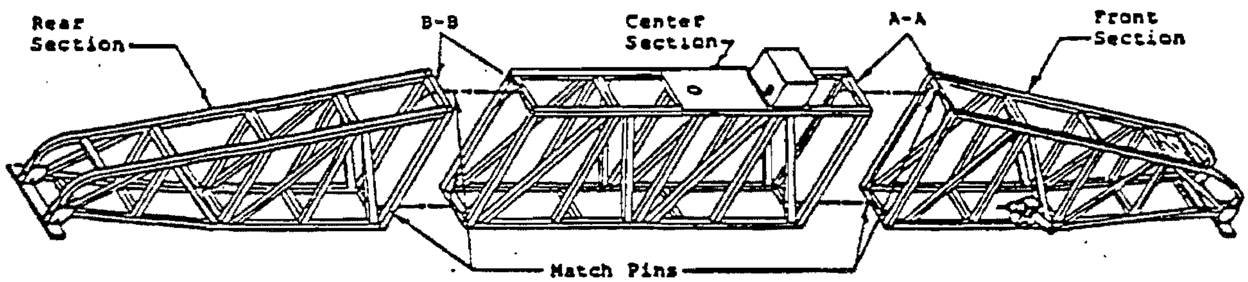

Figure SA.1 Frame sections of McCracken profilograph (Ref 2)

Assembly of the McCracken profilograph requires a two-man crew. Assembly should proceed according to the following steps:

STEP 1. JOIN FRAME SECTIONS

1. Place frame sections on floor as shown in Figure SA.1.
2. Arrange sections according to letter match markings (e.g., A-A and B-B); see Figure SA.1.
3. Align match pins and slide sections together.
4. Secure the clamps installed in the frame at each joint.

STEP 3. FRONT AND REAR WHEEL ASSEMBLY

1. There are two (2) six-caster wheel assemblies: a front assembly and a rear assembly.
2. Separate the parts according to the letter marking each piece.
3. Position the "F" parts as shown in Figure SA.3.
4. Slide the connecting plate into the mating retainer clips and secure with the clamp provided.
5. Repeat procedures #3 and #4 with the "R" parts.

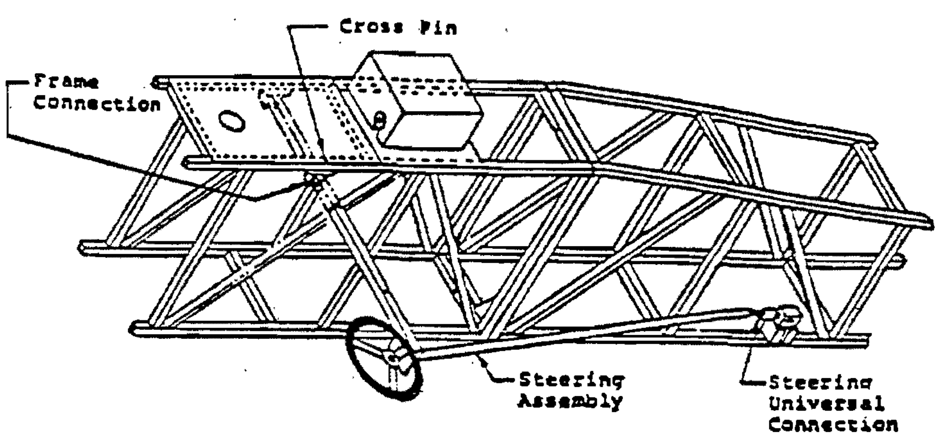

Figure SA.2 Steering connection of McCracken profilograph (Ref 2)

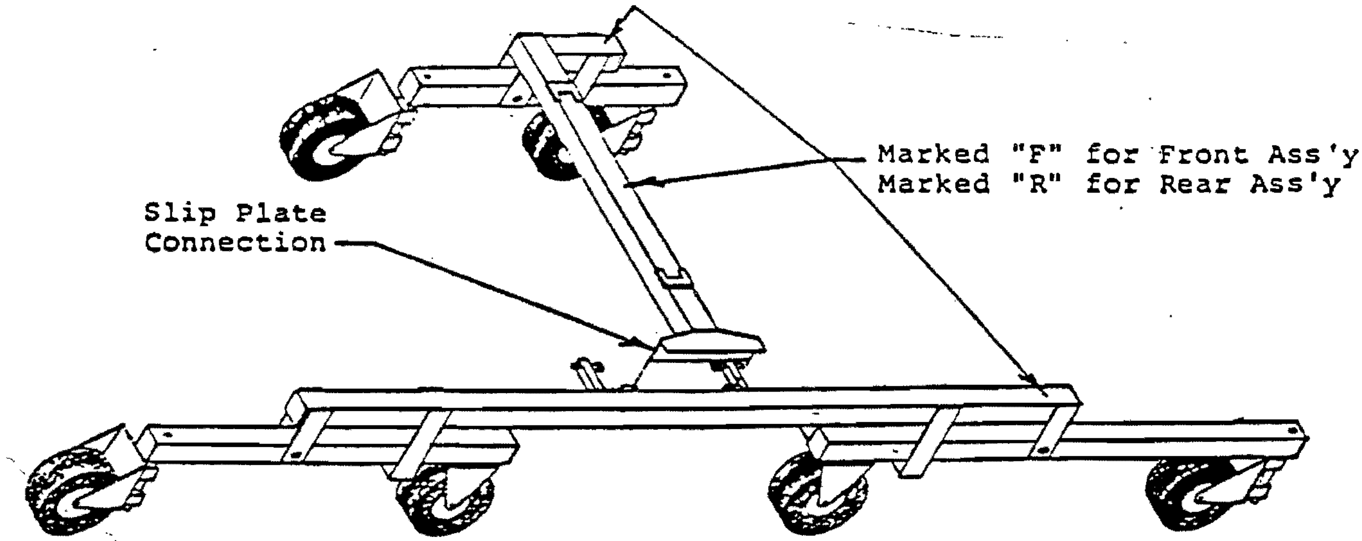

Figure SA.3 Front and rear wheel assembly of McCracken profilograph (Ref 2)

STEP 4. FINAL ASSEMBLY (FIGURE SA.4)

1. Position front and rear wheel assemblies close to the front and near part of the frame.
2. Lift front of frame and set the hinged flat into the nesting area provided on the top of the front wheel frame.
3. Secure connection with clamps.
4. Lift back of frame and set the hinged flat into the nesting area provided on top of the rear wheel frame.
5. Remove the tie rod end of the steering wheel from its transport position and secure it on the steering caster bolt.
6. Set the graph recorder box on the frame with the crank handle toward the rear. Loosen the box clamp bolt located under the top plate on the frame. Coordinating the clamp bolt, the frame pin and the drive gear teeth, slide the graph box in place and tighten the clamp bolt to secure.
7. Connect the cable snap under the graph box to the yoke cable on the profile wheel.
8. Slide the location marker rod into frame brackets and secure with cross pin. Insert marker wire at the desired width distance.

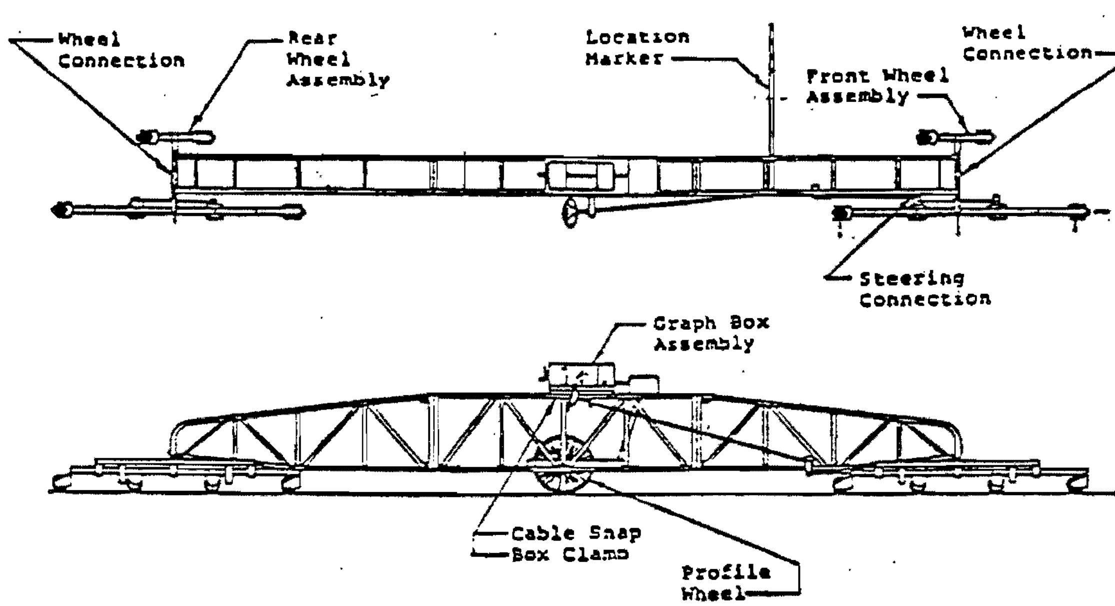

Figure SA.4 Final assembly of McCracken profilograph (Ref 2)

STEP 5. CONTROLS ON THE GRAPH RECORDER ASSEMBLY

The graph recorder, shown in Figure SA.5 below, requires no additional assembly and is ready for service when it is set in place on the frame and connected. (Refer to Step 4, Item #6.)

graph assembly cover, the cross marks can be noted with specific reference information, including location, distance, or direction. The distance recorded on the graph paper is 1:300 the surface traveled by the profile wheel, i.e., a graph length 1 inch long represents 3,000 inches (25 feet) traveled by the profile wheel.

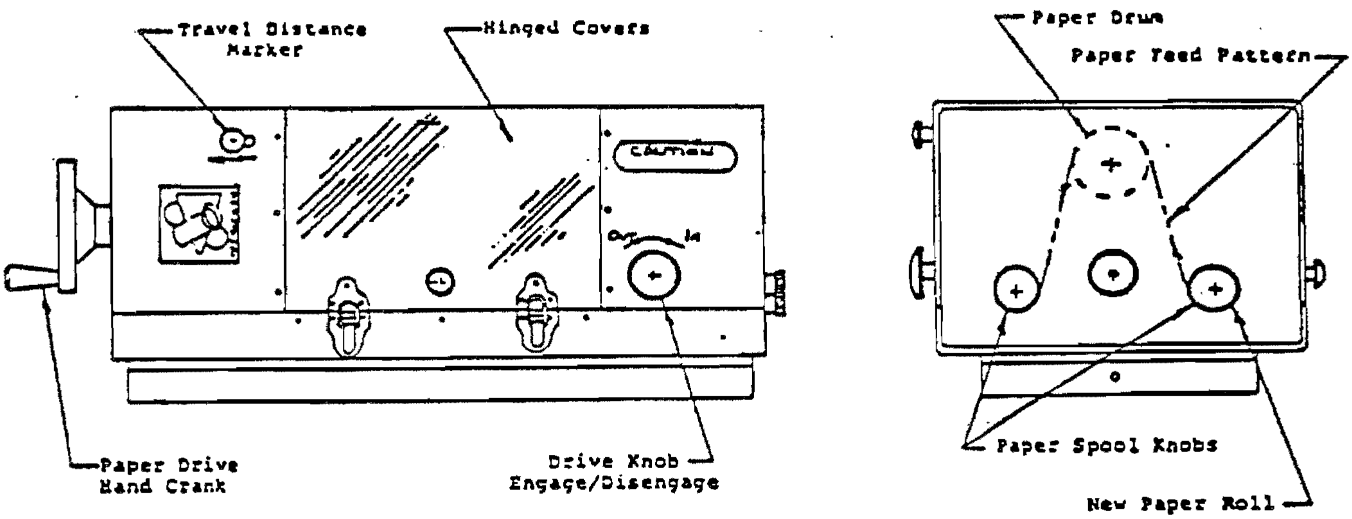

Figure SA.5 The graph recorder assembly (Ref 2)

The following describes the graph recorder assembly controls:

1. *Drive Knob - Engage/Disengage:* Turning this knob clockwise connects gearing that transmits the profile wheel rotation to the graph recorder assembly. Turning this knob counterclockwise disconnects the profile wheel drive and allows the paper drum to rotate freely by turning the paper drive hand crank.
2. *Paper Drive Hand Crack:* This is used for feeding paper manually, usually during loading or removal of graph paper. Make sure to disengage drive knob before turning paper drive hand crank.
3. *Paper Spool Knobs:* The paper spool knobs assist in loading and removing the graph paper rolls. They are also used to remove manually the excessive paper slack that may occur during paper loading. Note the position of the new paper roll and the feed direction pattern in Figure SA.5. (Use paper roll #5701.)
4. *Travel Distance Marker:* The marking device uses a pen to record a baseline on the left side of the graph paper. When the marker knob is moved from side to side, a "cross" mark is made on the graph paper. This cross mark can be used to indicate the beginning or end of an examined area. By opening the This calibration is preset and locked at the factory.
5. *Profile Marker Pen:* Located in the center/right of the graph assembly is the profile marker pen. It is mechanically attached to the profile wheel by a cable connection. As the profile wheel raises, the marker moves right; as the wheel lowers, the marker moves left. Movement ratio is 1:1, i.e., as the wheel raises 1/2 inch, the marker moves right 1/2 inch. This linkage therefore makes possible the recording of surface changes on the graph paper as the profile wheel travels over the surface contour.
6. *Marker Pens:* Both the travel distance marker and the profile marker use standard ballpoint pen refills. The refills will require bending for case clearance. Several spare refills are recommended and the pressurized type is best for use in cold weather.
7. *Maintenance:* The graph recorder is constructed mostly from aluminum material; however, there are steel components used where aluminum was impractical. Inspect the sprockets, chains, gears, and shafts. Components with rust should be cleaned and protected with a light coat of oil. Inspect the set screws and tighten those which have become loose. Daily dirt removal by compressed air is recommended.

The profile wheel is preassembled and installed in the center frame from the factory. Air pressure is to be maintained at 25 psi for consistent graph recording (check daily). A 24 inch x 1.75 inch Schwinn wheel with tire and tube is used. The tire surface has been ground to insure roundness. Tire surface irregularities that develop through wear can be removed by regrinding. Replacement tires will require the rounding process and calibration.

Once the McCracken profilograph is assembled and calibrated, testing may start. Only one person is needed to operate the McCracken profilograph. Once the gear knob of the recorder box is engaged, the recording pen is lowered onto the paper and the recording wheel is lowered onto the pavement surface; use the steering wheel to turn the profilograph right or left. In order to follow the wheelpath, use the location marker (Figure SA.4). The outer edge of the location marker should follow the lane edge. The distance between the outer edge of the location marker and the center line of the profilograph should be set equal to the distance of the wheelpath from the edge of the pavement (usually 3 feet for 12-foot-wide lanes). When finished profiling, lift recording pen and recording wheel and move the profilograph to the next wheelpath of the segment or to the section that needs to be profiled next. Follow the same procedure as described above.

SUPPLEMENT B. ASSEMBLY AND OPERATION OF AMES PROFILOGRAPH

The components used for the assembly of the Ames profilograph include:

- three frame sections
- a steering handle
- a steering cable
- a bicycle wheel
- a six-caster front wheel assembly (Figure SB.1)
- a six-caster rear wheel assembly (Figure SB.1)
- a recording box
- a front cross-member
- a location marker

The Ames profilograph can be assembled by one person, since its components are lightweight. The following steps should be followed for assembling the profilograph.

STEP 1. FRONT AND REAR WHEEL ASSEMBLY

1. There are two (2) six-caster wheel assemblies: a front assembly and a rear assembly.
2. Separate the parts according to the letter marked on each piece.
3. Position the "F" parts as shown in Figure SB.1.
4. Slide the connecting plate into the mating retainer clips and secure with the clamp installed in the wheel assembly.
5. Place the small restraining clamps over the join points near the middle of each four-wheel assembly.
6. Repeat procedures #3 and #4 with the "R" parts.

STEP 2. CONNECT WHEEL ASSEMBLIES WITH FRONT AND REAR FRAME BEAMS

1. Position the front and back assemblies about 25 feet apart, with the four-wheel assemblies positioned on the right side. (Front assembly has the steering wheels.)
2. Connect front beam to the front cross-member and the back beam to the back cross-member (Figure SB.2).

STEP 3. JOIN FRAME-BEAMS

1. Place the stabilizer support just behind the hinge bars of the articulated beam. Straddle the forward end while facing forward and connect the rear of the front beam starting with the bottom clamp first, then the top clamp (Figure SB.3).
2. Straddle the rear end of the articulated beam facing rearward. Raise the rear end until the enclosed lever arm is fully depressed. Align the articulated beam with the back beam and then clamp the bottom clamp, making sure the enclosed lever arm in the back beam is on top of the front lever arm. Clamp the top clamp. The stabilizer support may now be removed. Never try to force the clamps. Only moderate pressure is required to secure the clamps.

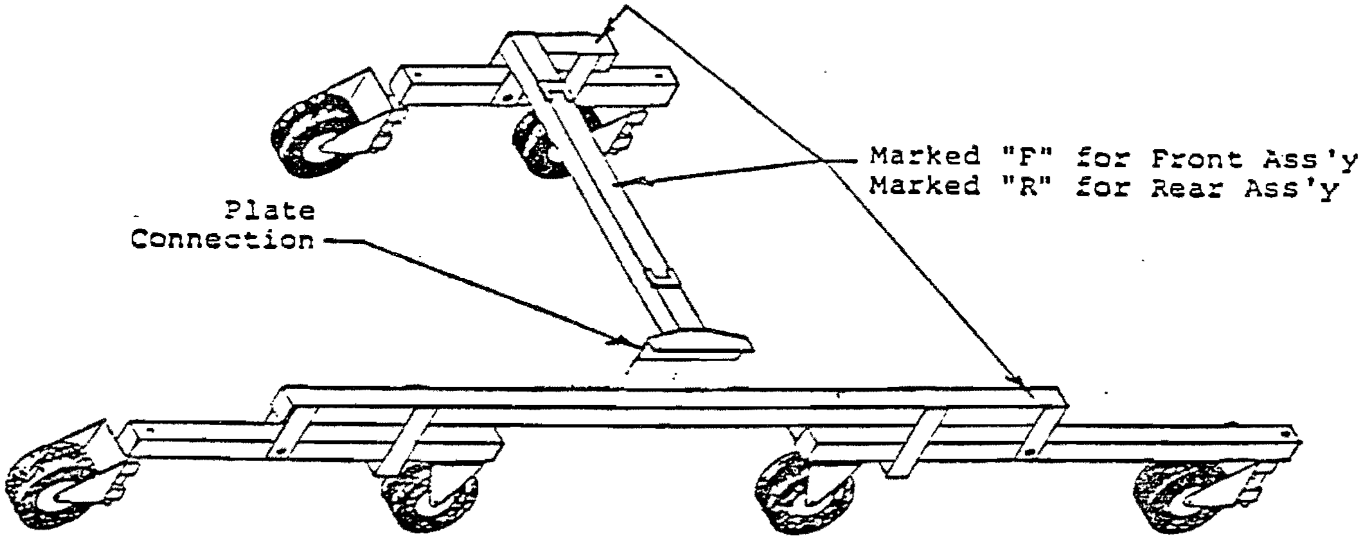

Figure SB.1 Front and rear wheel assembly of Ames profilograph

STEP 4. STEERING CONNECTION

1. Connect the rear steer-cable block. Slide the pointer-holder over the front of the front beam. Pull the cable from the front until the square block on the cable rests in the notch on the pointer-holder. Then connect the front cable block by applying a twist to the cable at the forward end of the front beam to relieve pressure on the block while it slides down into its receptor. The cable can be supported by the two hooks placed at points along the articulated beam.
2. Slide the steering handle onto the steering hub; insert the cotter pins at the clevises.

STEP 5. FINAL ASSEMBLY (FIGURE SB.3)

1. Place the recording box at the rear of the back beam on the right side. Attach the spring from the front of the box to the tab on the side of the back beam.
2. Pull the cable connector down from the side of the recorder box with one hand. Place the other hand on top of the connector to hook

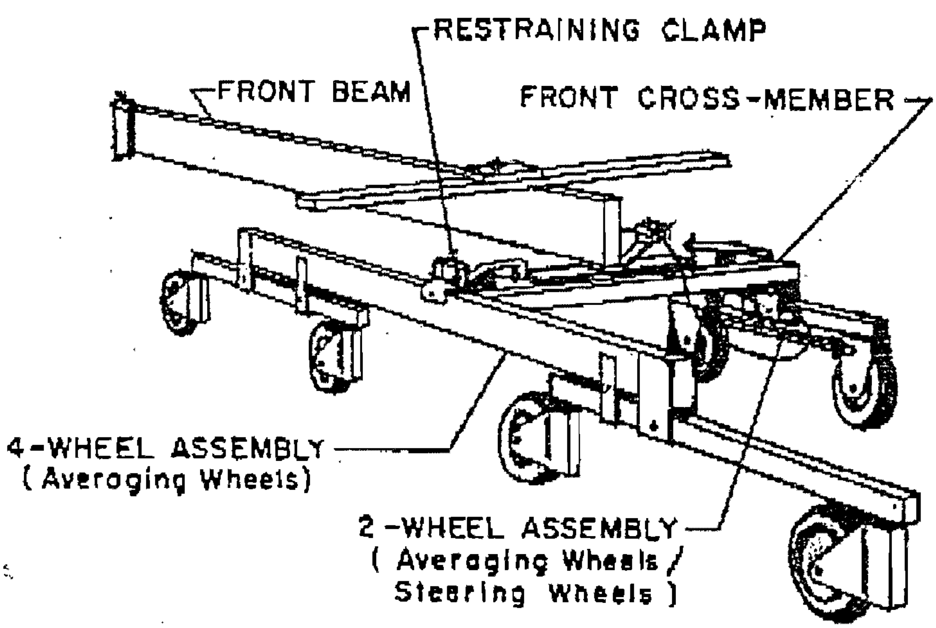

Figure SB.2 Wheel assembly and frame-beam connection

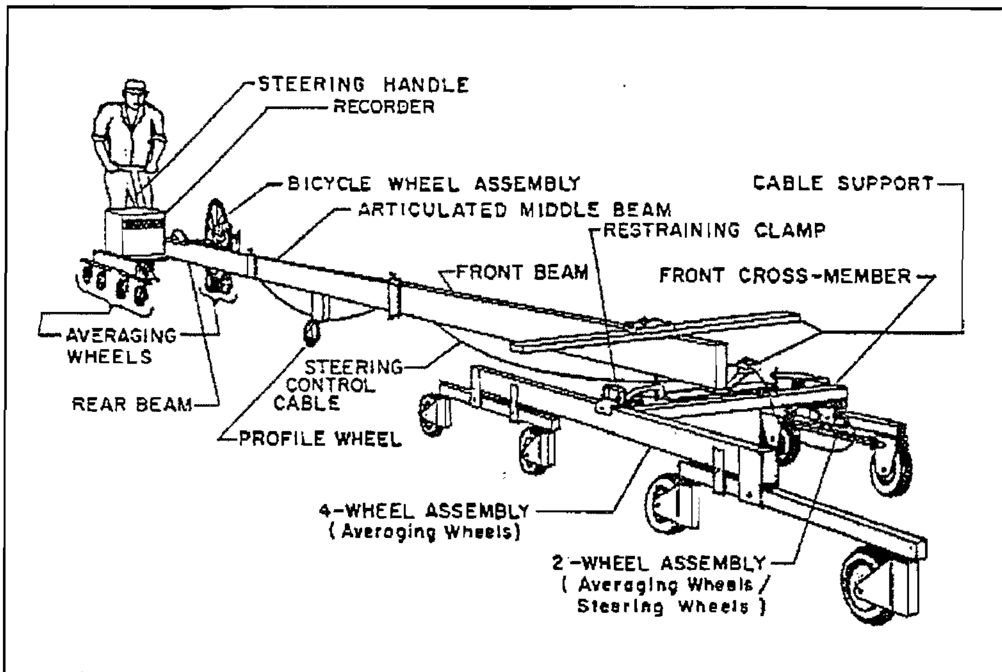

Figure SB.3 Assembled Ames profilograph (Ref 3)

the cable stop (emerges from the top of the back beam) onto it.

3. Attach the bicycle-wheel assembly over the end of the back cross-member, but do not fully depress the hold-down clamp.
4. Connect the 1/4-inch drive shaft to the paper drive extension (at side of recording box); then twist the drive shaft, while depressing the bicycle wheel hold-down clamp, to engage the socket with the hex-head bolt at the 45-tooth sprocket. The clamp that secures the left side of the back beam must be loosened to accommodate the placement of the bicycle wheel assembly; fully depress it after the 1/4-inch drive shaft has been connected.
5. During disassembly, reverse the procedure, being careful to use both hands when disengaging the recording cable connectors.

STEP 6. CONTROLS ON THE RECORDER BOX

1. Loading Paper: Raise the moveable flaps at both sides of the paper drive mechanism inside the recorder box. Lift the ball-point pen so that the tip rests squarely on top of the 1/8-in.-diameter transverse rod. The pen can be adjusted by loosening the thumbscrew. Slip the paper (ordinary computer paper) under the 1/8-inch rod from the back of the box and then engage the paper with the drive strips; lower the flaps to secure the paper in place. Raise the bicycle wheel by grasping the rear of the wheel frame. Spin the wheel tightly with the free hand in a forward direction to remove slack at the connections and chains before beginning the trace.
2. Recording Pen: Lower the pen onto the paper by pulling the 1/8-inch rod rearward with the index finger. The pen will drop onto the paper. (To raise the pen, simply lift the pen until the point rests on the rod.) To start the trace, an event mark can be made by pulling the cable connector outward from the box. (For pen replacement, specify Paper-Mate Power Point refill, fine-point pen.)

The Ames profilograph is operated by one person. The steering handle is used to turn the profilograph right or left. Once the profilograph is located on the segment to be profiled, the bicycle wheel is lowered onto the surface of the pavement and the recording pen onto the paper. The outer edge of the location marker should follow the lane edge during operation. The distance between the outer edge of the marker and the center line of the profilograph should be set equal to the distance of the wheelpath from the edge of the pavement. When profiling is completed, lift recording pen and bicycle wheel.

SUPPLEMENT C. REQUIREMENTS FOR PROFILOGRAPH CERTIFICATION

All contractor-owned California-type profilographs satisfying the construction characteristics defined in Texas Test Method 1000-S must be certified at the beginning of each construction season by the Department. Certification includes vertical and longitudinal calibration on a pavement section maintained by the Department. Dimensions of the profilograph should be checked and should conform to manufacturers' dimensions. Any maintenance and repair required to bring equipment into conformance with manufacturers' guidelines should be made by the contractor at the contractor's expense.

Reports and tests from a decertified profilograph will not be recognized until (1) the contractor makes corrections to the equipment, and (2) the profilograph is recertified through the calibration procedure described above.

Each certified 25-foot profilograph test report must also include the signature of the person performing the test and the following certification statement: "This is to certify that all testing and trace reduction herein described has been performed according to applicable contract specifications and requirements."

APPENDIX B. ITEM 585 RIDE QUALITY FOR PAVEMENT SURFACES

ITEM 585 RIDE QUALITY FOR PAVEMENT SURFACES

(Revised 2-26-91)

585.1 Description

This Item shall govern the evaluation of ride quality on pavement surfaces.

585.2 General

The finished surface of the pavement shall be smooth and true to the established line, grade, and cross section. Surface Test Type A shall be used on all pavement surfaces, including intermediate layers. When shown on the plans, Surface Test Type B shall apply longitudinally along the finished riding surface of all travel lanes, including service roads, unless specific areas are excluded or other areas are designated for Surface Test Type B. The transverse slope of the riding surface will be tested in accordance with Surface Test Type A.

585.3 Testing Procedures

The surface finish shall be tested and corrected, when necessary, to a smoothness as described herein.

(1) *Surface Test Type A.* The surface or layer shall 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 shall not exceed 1/8 inch between any two (2) contacts, when measured longitudinally or transversely.

(2) *Surface Test Type B.* The surface shall be tested using a profilograph in accordance with the requirements shown in Test Method Tex-1000-S. Unless otherwise shown on the plans, a profilograph meeting the requirements of Test Method Tex-1000-S shall be furnished and maintained by the Contractor. The equipment shall be calibrated by the Engineer in accordance with Test Method Tex-1000-S prior to its use on the project. Unless otherwise shown on the plans, the Contractor shall propel the profilograph under the direction of the Engineer. The results of the profilograph test will be evaluated by the Engineer in accordance with Test Method Tex-1000-S.

(a) *Scope.* Testing will be limited to those pavement surfaces having a construction length of 0.1 mile or more. Pavement with horizontal curves having a centerline radius of curvature less than 1,000 feet (including the super-elevation transition to such curves) will not be profiled. Pavement within 15 feet of a transverse joint separating the pavement from a bridge structure or from an existing pavement structure that was not placed by this project will not be subjected to this test. These areas shall be evaluated using the 10-foot straightedge as outlined above under Surface Test Type A.

(b) *Pavement Profiles.* Pavement profiles will commence 15 feet into the previous day's placement and will be taken along both of the approximate wheelpaths of each travel lane or as directed by the Engineer. The profile location will normally lie 3 feet from and parallel to the approximate location of the pavement lane lines. The profile index used for evaluating each 0.1-mile section of each travel lane to determine its bonus or deduction shall be the average of these two (2) profiles. The profilograph may be used to define the limits of an out-of-tolerance surface variation.

(c) *Initial Paving Operation.* During 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 possible without damaging the pavement surface. The purpose of this testing is to aid the Contractor and the Engineer in evaluating the paving methods and equipment. The length of this initial paving operation shall not exceed 0.2 mile, unless otherwise approved by the

Engineer. When the paving methods and paving equipment produce a profile index of 10 inches per mile or less, the Contractor may proceed with the paving operation.

When this initial paving profile index exceeds 10 inches per mile, the Contractor shall make corrections in the paving operation as approved by the Engineer, and another 0.2-mile section may be paved.

(d) *Daily Average Profile Index.* A day's paving is defined as a minimum of 0.1 mile of pavement placed in a single day. When less than 0.1 mile is paved, the day's production will be grouped with the subsequent day's production. Profiles of each day's paving shall be run as soon as practical, but not later than the next working day, unless otherwise approved by the Engineer.

A Daily Average Profile Index will be determined for each day's paving. The Daily Average Profile Index is a roughness value obtained by averaging the profile indices of all 0.1-mile sections of pavement placed during each day's paving. When the Daily Average Profile Index exceeds 15 inches per mile 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. When paving operations are suspended as a result of the Daily Average Profile Index exceeding 15 inches per mile, subsequent paving operations will be in accordance with Section 585.3.(2)(c).

585.4 Pavement Evaluation and Corrections

(1) *Surface Test Type A.* All irregularities exceeding the specified tolerance shall be corrected as approved by the Engineer and at the Contractor's expense. Following correction, the area shall be retested to verify compliance with the specification.

(2) *Surface Test Type B.* After the pavement surface has been tested, all areas having deviations in excess of 0.3 inches in 25 feet or less shall be corrected. Following correction, the area shall be retested to verify compliance with this specification.

After correction of all individual deviations, any 0.1-mile section having an initial profile index of 15 inches per mile or more shall be corrected to reduce the profile index to 10 inches per mile or less. On those 0.1-mile pavement sections where corrections are necessary, the corrected pavement section shall be re-profiled to verify that corrections have produced a profile index of 10 inches per mile or less.

When the profile index exceeds 10 inches per mile on any 0.1-mile section but does not exceed 15 inches per mile, the Contractor may elect to accept a contract unit price adjustment on that 0.1-mile section in lieu of reducing the profile index. All corrective work is to be done at the Contractor's expense.

(a) *Portland Cement Concrete Pavement*

All corrections shall be made using equipment approved by the Engineer or by removing and replacing the pavement. The use of bush hammers or other impact devices will not be permitted.

The Contractor shall demonstrate that any proposed corrective work will produce results satisfactory to the Engineer.

When corrections are completed, the Contractor shall re-establish a transverse texture pattern by grooving the concrete to meet the surface finishing specifications. This work will be at the Contractor's expense. All corrective work shall be completed prior to determinations of pavement thickness.

(b) *Asphaltic Concrete Pavement*

The Contractor shall demonstrate that any proposed corrective work will produce results satisfactory to the Engineer.

585.5 Pay Adjustment

The pay adjustment for ride quality will be determined as follows:

(1) *Surface Test Type A.* No pay adjustment will be made when Surface Test Type A is used.

(2) *Surface Test Type B.* Pay adjustments will be made in accordance with the following schedule:

PROFILE PAY ADJUSTMENT SCHEDULE (REF 1)

Profile Index Inches per mile, per each 0.1-mile section	Bonus or Deduction Percent of Unit Bid Price
3.0 or less	+5
3.1 thru 4.0	+4
4.1 thru 5.0	+3
5.1 thru 6.0	+2
6.1 thru 7.0	+1
7.1 thru 10.0	+0
10.1 thru 11.0	-2
11.1 thru 12.0	-4
12.1 thru 13.0	-6
13.1 thru 14.0	-8
14.1 thru 15.0	-10
Over 15.0	Corrective work required

Not more than 100 percent of the unit bid price will be paid for pavement sections that were originally constructed with a profile index greater than 10 inches per mile.

(a) The bonus or deduction for asphaltic concrete pavement will be based on the unit bid price of asphaltic mixture for each type of mixture used, and on the plan rates shown for each of the various layers of different types of mixture constructed under the same bid item as the surface course or its alternates. A total bonus or deduction will be calculated in dollars and cents for each 0.1-mile-long section of the lane represented by the profilogram. A running total of this bonus or deduction will be determined for each day's production.

(b) The bonus or deduction for portland cement concrete pavement will be based on the unit bid price and the plan depth shown. A total bonus or deduction will be calculated in dollars and cents for each 0.1-mile-long section of the lane represented by the profilogram. A running total of this bonus or deduction will be determined for each day's production.

585.6 Measurement and Payment

The work performed, materials furnished, and all labor, tools, equipment and incidentals necessary to complete the work under this Item will not be measured or paid for directly, but will be considered subsidiary to the various bid items of the contract.

The bonus or deduction adjustment as described under "Pay Adjustment" will be made under the item in which the pavement was constructed.