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16. Abstract

The Texas Department of Transportation (TxDOT) is implementing smoothness specifications based on profilograph testing as part of its construction quality control/quality assurance (QC/QA) program. To improve upon the existing test method, TxDOT sponsored a research project with the Texas Transportation Institute (TTI) to develop a smoothness specification for asphalt concrete overlays based on the current generation of profiling equipment which offer better accuracy and repeatability than the profilograph. To develop this specification, researchers evaluated the relationship between pavement profile and predicted overlay life assuming reflection cracking as the primary failure mechanism. This relationship is evaluated in two steps. First, the effect of surface profile on predicted dynamic loads is determined by vehicle simulation. Then, the effect of dynamic load variability on predicted pavement life is analyzed. This work led to the development of a relationship between the predicted change in pavement life associated with the placement of the overlay, dynamic load variability, and the fracture parameter, *n*, of the asphalt overlay mixture. Using this relationship, the study developed two categories of evaluation procedures that are applicable for the range of overlay thicknesses and treatments generally used in Texas. Test methods falling under Group A evaluate the contractor's performance based on the change in profile before and after the overlay. These methods are intended for thin overlays (< 63 mm) where no surface preparations are planned or where only spot level-ups are specified. Under these conditions and where a reasonable doubt exists that smoothness requirements based on final profile may be achieved, the Group A test methods can be used as options in lieu of dropping the smoothness specification or using the straightedge to check the surface smoothness on these projects. Test methods falling under Group B evaluate the contractor's performance based on the final surface profile. This report documents the development work conducted during the study.

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DEVELOPMENT OF A PROFILE-BASED SMOOTHNESS SPECIFICATION FOR ASPHALT CONCRETE OVERLAYS

by

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Report 1378-S
Project Number 0-1378
Research Project Title: Development of Ride Quality Specifications Criteria for ACP Overlays

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IMPLEMENTATION RECOMMENDATIONS

The Texas Department of Transportation (TxDOT) sponsored a research project to develop a smoothness specification for asphalt concrete overlays based on pavement profile. Different methods for evaluating the acceptability of overlay smoothness are proposed. These fall into two major categories, designated herein as Group A and Group B. The two test methods in Group A, referred to herein as Surface Tests A1 and A2, evaluate the contractor's performance based on the change in profile before and after the overlay. This category is primarily applicable for evaluating the smoothness of thin overlays (< 63 mm) where no surface preparations are planned or where only spot level-ups are specified. Under these conditions and where a reasonable doubt exists that the smoothness requirements based on final profile may be achieved, these test methods can be used as options in lieu of dropping the smoothness specification or using the straightedge to check the surface smoothness on these projects. The three test methods in Group B, designated herein as Surface Tests B1, B2, and B3, evaluate the contractor's work based on the final profile. Group B test methods are applicable on projects where the overlay thickness is more than 64 mm or where surface preparations such as milling to grade or in-place recycling are used to correct or remove existing surface distress. Surface Test B3 in this group uses the null blanking band profile index determined on the final surface to evaluate the smoothness achieved by the contractor. This method was developed to facilitate the transition from the current profilograph specification to the profile-based methodology proposed in this report. In making the change to a profile-based overlay smoothness specification, the following recommendations are offered for consideration:

1. Pilot implementation of the proposed specification may begin with Surface Tests A2, B2, and B3. Surface Tests A2 and B2 are based on the International Roughness Index (IRI) while Surface Test B3 is based on the null blanking band profile index, PI_0. Of these methods, Surface Test B3 is the logical choice to implement in the interim because of the availability of profilographs and experience

with its use in the state. However, to introduce contractors and TxDOT engineers to the profile-based test methods developed in this study, projects should be selected in which profile measurements will be collected with the profilograph and TxDOT's profilers. The objective is to develop an understanding of the statistics, IRI and PI_0, among contractors and TxDOT engineers and to help them learn to perceive roughness in terms of these statistics;

2. Inertial profilers are available that provide not only IRIs but also profile indices by profilograph simulation. This option of simulating the profilograph response to the measured profile should be considered during the interim. The flexibility afforded by this option carries the potential for smoothing the conversion to a profile-based specification of the form proposed in this study;
3. Implementation of a profile-based smoothness specification will require the construction and maintenance of a test facility for evaluating surface profilers to ensure that the equipment for evaluating surface smoothness are accurate, repeatable, and reliable;
4. The charts prepared for evaluating the acceptability of overlay smoothness are based on a fracture parameter, *n*, of 3.6. This value was determined from creep compliance data generated from frequency sweep tests, using a relationship between the fracture parameter, *n*, and the slope of the creep curve, *m*, developed by Lytton et al. (1993). This relationship is given by Eq. (3) in Chapter III. Researchers recognize that very limited test data based on the shear mode of crack propagation are available on the fracture parameter, *n*. Thus, estimates were generated using Eq. (3) with creep compliance data taken from frequency sweep tests conducted by Lytton et al. (1993). The value of 3.6 used in developing the charts corresponds to the average of the estimates determined by researchers. In the absence of test data to characterize the *n*-value for a particular overlay mix, the author proposes that the charts presented in Chapter VII be used for evaluating the change in pavement life because of the overlay. For the long-term, researchers recommend that TxDOT support the development of a data base of *n*-values

characterizing the asphalt concrete overlay mixtures commonly placed in Texas. The department should evaluate the need to tie surface smoothness requirements with asphalt mixture requirements for construction quality control and acceptance;

5. The methodology presented in this report permits TxDOT to establish different criteria for evaluating overlay smoothness depending on the functional classification of a given highway. While the charts presented correspond to a confidence level of 95 percent, charts at other confidence levels may be developed should TxDOT decide to consider the level of highway use in evaluating the acceptability of surface smoothness on resurfacing projects;
6. The pavement damage indices, Δ and λ, for evaluating smoothness are based on reflection crack growth, identified from previous research as the primary distress mechanism for asphalt concrete overlays. It is recognized that, for other pavements, other distress mechanisms such as fatigue cracking or permanent deformation may govern. For these pavements, new damage-based criteria for evaluating surface smoothness would have to be developed;
7. The pay adjustment schedules in the proposed specification should be evaluated during the pilot implementation to identify any changes that are necessary and to modify the schedules accordingly so that they more closely reflect the value attached by TxDOT to the quality of the contractor's work based on the criteria used in the new specification;
8. Implementation of Surface Tests A1 and B1 will benefit from the development of a computer program that is specifically tailored to these test methods. A number of simulation programs for predicting vehicle response to measured profiles are available with which to develop a computer program for implementing a specification of the form given by Surface Tests A1 and B1. This program will make it easier for TxDOT engineers to use Surface Test A1 or B1 on overlay projects and can be developed as part of efforts to convert from the current specification to the profile-based specification developed in this study. While this

computer program is under development, the other surface test methods proposed herein may be used;

9. It is noted that Surface Tests A1 and A2 are specifically intended as options for evaluating surface smoothness on projects where the overlay is thin and no surface preparations are planned or only spot level-ups are to be applied. Under these conditions and where a reasonable doubt exists that the smoothness requirements based on final profile are achievable, these methods are offered for use in lieu of the alternative of dropping the smoothness specification or of using the straightedge to check the overlay smoothness on these projects. For other cases, Surface Tests B1, B2, or B3 are expected to be applicable;
10. Implementation of the proposed smoothness specifications based on surface profile will also benefit from the development of graphical routines that will plot the measured profiles or simulated vehicle dynamic loads, along with the IRIs or pavement damage indices determined from the surface profiles or load profiles, respectively. One good point about the profilograph is that it produces a profilogram which shows the rough spots on a given section that contractors and engineers readily understand. In this way, the method is not perceived to be a black box. Similar graphical routines should be developed to facilitate the conversion to a profile-based smoothness specification.

In summary, the proposed smoothness specifications represent a significant improvement over the existing ride specification, in the author's opinion. Under the proposed specifications, surface profiles will be measured using devices that offer greater accuracy compared to the profilographs currently used. Of equal or greater significance is the fact that surface profiles are evaluated based on the predicted change in pavement life associated with the overlay. This development showed the importance, not only of building smoother pavements, but also of designing, manufacturing, and encouraging the use of trucks with improved dynamic performance and of designing and producing bituminous overlay mixtures that offer greater crack resistance. From the recommendations offered, it is obvious that work remains to be done in order to move forward on the road to implementing a profile-based smoothness specification for asphalt concrete overlays. In the opinion of the author, this research has laid the groundwork on which further development and implementation can proceed. What is important is to move forward, realizing that implementation is a phased process and that further developments along the way will be necessary to move the process from the existing plateau to a higher one. In the author's opinion, TxDOT need not wait until a fully-developed profile-based smoothness specification is achieved before it begins the conversion. This process can begin, at the very least, with efforts to implement, in the interim, a smoothness specification of the form given by Surface Test B3, followed by near-term efforts to implement specifications based on Surface Tests A2 and B2. For the long-term, the author recommends additional development efforts that would lead to the implementation of smoothness specifications of the forms given by Surface Tests A1 and B1.

As a final recommendation, TxDOT should support development efforts for a database of pavement profiles collected from construction projects and from the periodic surveys done to maintain the Pavement Management Information System (PMIS) database. This is feasible with today's computer technology, which steadily undergoes improvements in processing capability, storage media, and affordability. Limits of construction projects do not normally coincide with limits of the PMIS sections. In addition, the limits of PMIS sections, as well as the method of rating ride quality, may change over the years. By having the profiles, a consistent historical record of a pavement's ride quality can be maintained, which in time can be used to establish the benefits, in terms of pavement life, of better initial surface smoothness. In the author's opinion, this database is extremely important. Without it, it will be difficult to evaluate the effectiveness of smoothness specifications in terms of enhancing ride quality, improving pavement performance, and reducing life-cycle costs. In the author's opinion, TxDOT needs to be in a position to make this evaluation in the future to show the public that it is achieving its mission of providing highways that allow the safe and comfortable movement of people and goods.

DISCLAIMER

The contents of this report reflect the views of the author who is responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT), or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineer in charge of the project was Dr. Emmanuel G. Fernando, P.E. # 69614.

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The work reported herein was conducted as part of a research study sponsored by the Texas Department of Transportation and the Federal Highway Administration. The support, guidance, and cooperation of the project director, Mr. Ken Fults, are gratefully acknowledged. Mr. Carl Bertrand of TxDOT's Pavements Section provided valuable advice in the evaluation of relationships between profile indices from the profilograph and IRIs computed from measured profiles. Mr. Paul Krugler, of the Materials and Tests Division, reviewed the data from the district overlay projects. A sincere note of appreciation is also extended to the following individuals who participated in this research:

1. Mr. Robert Light of the Pavements Section conducted the profile measurements on the district overlay projects using TxDOT's Surface Profiler.
2. Mr. Mark Simmons of TTI was responsible for the profilograph measurements on the district projects.
3. Mr. Jeff Woodall assisted in the evaluation of relationships between profile indices and IRIs.
4. Mr. Umesh Bachu assisted in preliminary development work on the profile-based smoothness specification.

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SUMMARY

In pursuit of its goal of providing smooth pavements, TxDOT sponsored a research project with TTI to develop a smoothness specification for asphalt concrete overlays based on pavement profile. To achieve this objective, researchers initially evaluated the applicability of the new flexible pavement profilograph specification for asphalt concrete overlays. Through a field study of district overlay projects, data were obtained that gave evidence of the applicability of the existing specification in the evaluation of ride quality of overlaid pavements, provided that existing surface distresses are corrected or removed by surface preparation. This study also showed thin overlays as the primary resurfacing treatment used by the districts. Consequently, in developing the smoothness specification for asphalt concrete overlays, researchers developed test methods based on the improvement in surface smoothness before and after the overlay.

To develop the specification, researchers evaluated the relationship between pavement profile and predicted overlay life assuming reflection cracking as the primary failure mechanism. This work led to the development of a relationship between the predicted change in pavement life associated with the placement of the overlay, dynamic load variability, and the fracture parameter, *n*, of the asphalt overlay mixture. Using this relationship, researchers developed two categories of evaluation procedures, designated as Group A and Group B, which are applicable for the range of asphalt concrete overlay thicknesses and treatments generally used in Texas. The two test methods in Group A, referred to herein as Surface Tests A1 and A2, evaluate the quality of the overlay smoothness based on the change in profile before and after the overlay. This category is primarily applicable for evaluating the smoothness of thin overlays (< 63 mm) where no surface preparations are planned or where only spot level-ups are specified. Under these conditions and where there is reasonable doubt that smoothness requirements based on the final profile may not be achieved, these test methods are offered for use as alternatives to dropping the smoothness specification or using the straightedge to check the surface smoothness on these projects. The three test methods in Group B, designated herein as Surface Tests B1, B2, and B3, evaluate the quality of the overlay smoothness based on the final surface profile. Group B test methods are applicable on

projects where the overlay thickness is more than 64 mm or where surface preparations such as milling to grade or in-place recycling are used to correct or remove existing surface distress. Surface Test B3 in this group is intended as a provisional test method and uses the null blanking band profile index determined on the final surface to evaluate the smoothness achieved by the contractor. This method was developed to facilitate the transition from the current profilograph specification to the profile-based methodology proposed in this report.

The test methods proposed were evaluated using profile data collected from the district overlay projects. The results were found to be generally consistent between the different test methods developed in this study. Recommendations for continued development and implementation of a profile-based smoothness specification are provided in this report.

CHAPTER I
INTRODUCTION

"Highways are for the comfort and convenience of the traveling public."

Attributed to the late Texas state highway engineer, Mr. D. C. Greer, the preceding statement echoes the prevailing sentiment that highways are built to serve the traveling public. As taxpayers, the public demands roadways that are built and maintained within "acceptable" levels of serviceability, which is largely based on user perception of pavement riding comfort and safety. While riding comfort may be largely subjective, there exist certain roadway characteristics that are measurable and strongly correlated to user perception of ride quality. Foremost among these is pavement roughness or road profile. Indeed, a smooth road profile has become a standard measure of pavement quality. Smooth roads are associated with lower road user costs, favorable user perceptions of quality and acceptability, long pavement service lives, and lower life-cycle costs.

Given that the basic function of highways is to provide for the safe and comfortable transport of people and commodities, the implementation of specifications on pavement ride quality will help states provide highways that serve this purpose over their design lives. In pursuit of this objective, the Texas Department of Transportation (TxDOT) has implemented end-result smoothness specifications in its construction quality control/quality assurance (QC/QA) program. Smoothness specifications developed for newly constructed flexible and rigid pavements (Harrison and Bertrand, 1991; Goulias et al., 1992) saw statewide implementation beginning with the 1995 fiscal year. These existing specifications are based on the profilograph which is widely used by state highway agencies for QC/QA of surface smoothness on paving projects. Most tests are presently conducted with automated California-type profilographs (Figure 1) in which the equipment is pushed over a prescribed wheelpath. A profile of the surface is obtained from recorded vertical displacements of the

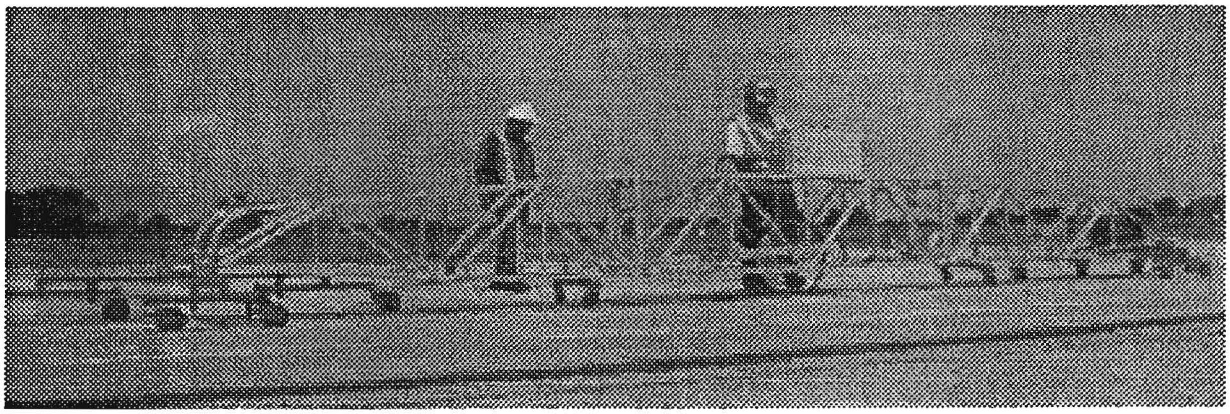

Figure 1. Picture of an Automated Profilograph

measuring wheel relative to a 7.6 m reference plane established by 12 support wheels. As an instrument for measuring surface profile, the profilograph is relatively inexpensive, simple to operate and maintain, and provides a trace of the surface that users can easily understand. However, there have always been concerns about the accuracy of the measured profiles. Francis Hveem, in comparing profilograph traces with rod and level data, noted that the "*agreement appeared to be sufficiently close for all practical purposes but unanswered questions always persisted as to the exact shape of the bumps in the pavement,*" (Scofield, 1993). Field tests conducted by TTI researchers showed that false depressions are introduced in the profilograph trace as the measuring wheel approaches, goes over, and leaves a given bump. Further, Kulakowski and Wambold (1989) have determined that the frequency response of the instrument is uniform only within the narrow range of wavelengths between 1.2 to 2.1 m. Outside this range, the frequency response oscillates, and profile components are either attenuated or amplified. In Texas, a number of districts have also raised questions about the sensitivity of the profilograph to short wavelengths or high frequency ripples. These concerns raise the need for more accurate measurements of surface profile for the purpose of building pavements that offer excellent ride quality, lower road user costs, and longer service lives.

In pursuit of its goal of providing smooth pavements, TxDOT initiated a research project with the Texas Transportation Institute (TTI) to develop a smoothness specification for asphalt concrete overlays based on the current generation of pavement profilers that offer greater accuracy in profile measurement relative to the profilographs presently used in construction projects. There are a number of benefits that this change will bring:

1. It will allow the department to implement a smoothness specification that is sensitive to the range of frequencies of importance to ride quality;
2. The improved accuracy in profile measurement permits the evaluation of relationships between pavement roughness and vehicle dynamic loads, and the consequent effects thereof on predicted pavement life. Thus, the smoothness specification can be tied not only to user perception of riding comfort but also to predicted pavement performance; and
3. The development of a smoothness specification based on pavement profile permits highway agencies to implement a consistent measure of pavement smoothness throughout the life-cycle of a given roadway. With the present TxDOT specification, new or resurfaced pavements are accepted based on the profile index from a profilograph. However, once the pavement is put into service, its smoothness over time is monitored using the Present Serviceability Index (PSI) computed from pavement profile. Additionally, if the pavement is included in the Highway Performance Monitoring System (HPMS) database, the department is required to report the International Roughness Index (IRI) from the measured profile. This situation exists in many other highway agencies. Having a profile-based smoothness specification will allow TxDOT to tie the as-built smoothness to the rest of the performance history on a given segment and thus achieve consistency in the historical serviceability data which is important for pavement management.

STUDY OBJECTIVES

The development of a profile-based smoothness specification was carried out in Project 0-1378, "Development of Ride Quality Specifications Criteria for ACP Overlays." As the study title suggests, the main objective was to develop a profile-based smoothness specification for asphalt concrete (AC) overlays which represents the majority of paving projects in the state. In pursuit of this development, researchers accomplished the following objectives:

1. Evaluate the applicability of the existing new flexible pavement smoothness specification for asphalt concrete overlays;
2. Test a number of profile measuring devices to establish the availability of equipment for implementing a new profile-based smoothness specification;
3. Evaluate relationships between the profile index from the profilograph and profile-based smoothness statistics;
4. Develop methods for evaluating the acceptability of asphalt concrete overlay smoothness that are based on measured profile;
5. Compare the proposed methods for evaluating surface smoothness with the existing profilograph specification;
6. Provide a transition from the existing smoothness specification to a profile-based smoothness specification for asphalt concrete overlays; and
7. Lay the groundwork for continued development and implementation of profile-based smoothness specifications in Texas.

SCOPE OF REPORT

The development work conducted during the study is documented in this report. Chapter I gives the impetus for conducting this study and presents the research objectives. To provide a smoothness specification for the short-term, an early task conducted was a field study of overlay projects around the state to evaluate the applicability of the new flexible pavement smoothness specification for asphalt concrete overlays. The findings from this task are reported in Chapter II. This work resulted in guidelines formulated by TxDOT for implementing the profilograph-based smoothness specification on overlay construction projects. Because of the importance placed on relating the smoothness specification to predicted pavement life, researchers formulated a methodology that allows the evaluation of the effects of pavement profile on expected pavement performance. The appendix presents the formulation of this methodology which is based on predicting the vehicle dynamic loads from measured pavement profiles. This methodology is further developed in Chapter III to establish a procedure for acceptance testing of asphalt concrete overlay smoothness based on the change in surface smoothness before and after the overlay. This procedure is evaluated in Chapter IV using field measurements obtained from the field study of overlay projects reported in Chapter II. To accomplish this task, vehicle simulations were conducted to predict the dynamic load variability on the overlay test sections. The coefficients of variation of predicted dynamic loads for the standard 80 kN single axle were used in evaluating the acceptability of the overlay smoothness on the sections surveyed in the district projects. From this work, researchers were able to verify that the proposed methodology produces reasonable and consistent results. To develop an alternative test method based on the International Roughness Index (IRI), the relationship between dynamic load variability and IRI was evaluated in Chapter V. This led to the development of a test method based on the IRI to evaluate the change in predicted pavement life due to the change in surface smoothness before and after the overlay. Relationships between the profile index and IRI were also determined which led to the development of a provisional profilograph specification based on the null blanking band. Consistent with the existing specification, this alternative method uses the measurements made after the overlay to evaluate the acceptability of the overlay smoothness. This development is documented in Chapter VI which also presents two other methods for acceptance testing of overlay smoothness using the profiles measured after the overlay. In one method, the predicted dynamic load variability from vehicle simulation is used to evaluate overlay smoothness. In the other, the IRI is used. Chapter VII summarizes the different methods proposed for evaluating the acceptability of asphalt concrete overlay smoothness. In this chapter, methods are presented for evaluating overlay smoothness based on the change in profile before and after the overlay, or from the difference between the as-built and target surface smoothness. Finally, Chapter VIII offers recommendations for converting to a profile-based smoothness specification to evaluate the acceptability of overlay smoothness. In addition, recommendations for the continued development and implementation of profile-based smoothness specifications are offered.

It is noted that an evaluation of available surface profilers was also conducted to establish the availability of equipment for implementing a profile-based smoothness specification. This study showed that devices are available for collecting accurate and repeatable profile data and revealed a wide variety of profilers for implementing profile-based smoothness specifications. The types of surface profilers range from automated devices that provide unfiltered or true profiles, lightweight inertial profilers mounted on tractors or golf carts, automated portable profiling equipment that may be mounted on any conventional vehicle, and the traditional van-mounted inertial profilers. The interested reader is referred to the companion report by Fernando and Leong (1997) for information on the findings from this profile equipment evaluation. The present report documents the development of methods for evaluating the acceptability of overlay smoothness based on measured profile.

CHAPTER II
APPLICABILITY OF NEW FLEXIBLE PAVEMENT SMOOTHNESS SPECIFICATION FOR ASPHALT CONCRETE OVERLAYS

While the development of a profile-based smoothness specification is the main goal of this research project, a short-term objective was to address the question of adapting the existing profilograph-based smoothness specification for overlay construction work. In pursuit of this objective, TTI researchers evaluated the applicability of the present new flexible pavement smoothness specification for quality control and quality assurance of pavement rideability on overlay construction projects. Prior to this study, there was very limited experience within the state to establish the improvement in ride quality that may be expected from placement of asphalt overlays, particularly the thin overlays (38 to 51 mm) that are generally constructed in Texas. To collect data with which to determine whether the existing specification can be implemented for overlay construction work, TTI, with the assistance of TxDOT, monitored a number of overlay projects during the 1994 calendar year. All of the projects involved thin asphalt concrete overlays. Profilograph measurements were made on the different projects prior to any required surface preparation, after surface preparation, and after placement of the asphalt overlay. The evaluation conducted and the results thereof are documented in this chapter and in Fernando (1997).

FIELD TEST PROGRAM

Table 1 shows the test matrix established for the field data collection effort. Initially, the researchers considered overlay thickness as a study variable. However, from communications with the different districts within TxDOT, it was found that single overlay thicknesses are generally between 38 and 51 mm within the state. Consequently, this variable was not included in the final test matrix. The actual project plan thicknesses are shown in Table 2.

Table 1. Field Test Matrix

Initial Ride Quality	Surface Preparation	Profile Measurements		
		Before Surface Preparation	After Surface Preparation	After Overlay
Rough	None	X		X
	Mill	X	X	X
	Level-Up	X	X	X
	Other	X	As Applicable	X
Moderate	None	X		X
	Mill	X	X	X
	Level-Up	X	X	X
	Other	X	As Applicable	X
Smooth	None	X		X
	Mill	X	X	X
	Level-Up	X	X	X
	Other	X	As Applicable	X

Table 2. List of District Overlay Projects

Project	QC/QA ?	Highway	Location of Test Sections	Date of Overlay	Overlay Thickness (mm)	Surface Preparation	Location of Test Sections
Atlanta	No	US 59	Northbound, outside lane	October 1994	51	Milling	2.9 to 3.9 km north of intersection of US 59 and FM 3129
Carthage	Yes	US 79	Southbound, inside lane	June 1994	51	Milling	Reference marker (RM) 295 to RM 297
Dallas	No	IH 35	Southbound, inside lane	November 1994	51	Multiple Treatments	5.8 to 6.9 km south of intersection of Parkerville Road and IH 35
Odessa CMHB[a] overlay	Yes	IH 20	Eastbound, outside lane	June 1994	42	Level-up	RM 111.058 to RM 111.758
Odessa CRM[b] overlay	No	IH 20	Eastbound, outside lane	August 1994	45	Seal Cracks	RM 120.460 to RM 121.760
San Angelo	Yes	US 87	Northbound, inside lane	September 1994	51	Level-up	0.6 to 1.6 km north of intersection of US 87 and FM 1223
San Antonio	Yes	FM 2790	Southbound lane of 2-lane highway	August 1994	38	None	1.9 to 3.4 km south of intersection of Loop 410 and FM 2790

[a] CMHB - Coarse Matrix High Binder

[b] CRM - Crumb Rubber Modified

With assistance from TxDOT, researchers identified a number of projects for monitoring in the field study. Table 2 presents the different projects. It is noted that, on three of the seven projects, the existing QC/QA smoothness specification for flexible pavements was not enforced. This was because current TxDOT policy excludes application of the smoothness pay adjustment schedule on projects which do not include a total construction thickness greater than 63 mm, or where the construction is not preceded by milling, or in-place recycling operations. An exception to this policy was made for the San Antonio project.

For each project identified in Table 2, a number of 0.16 km test segments were established, of initial ride quality ranging from smooth to rough. Profilometer measurements made on the projects before construction were used to identify and select test segments for monitoring in the field study. The minimum number of test segments established on any given project was six. For each segment, the surface profile was measured using the California-type profilograph and TxDOT's profilometer. Two to four replicate measurements were made on each test segment before construction, after surface preparation, and after the overlay.

FIELD STUDY RESULTS

To establish the initial pavement condition on each project, researchers obtained pavement condition survey information from TxDOT's Pavement Management Information System (PMIS) database. The available distress data on the projects prior to construction are summarized in Table 3. It is observed from this table that the Atlanta and Carthage projects showed significant distress before construction, as indicated by the low distress scores. The PMIS distress score ranges from 0 to 100 with 0 being an extremely distressed pavement and 100 indicating a pavement with no surface distress. The Atlanta and Carthage projects are heavy truck routes that showed significant rutting, patching, and failures along the project lengths prior to construction. Both of these projects were milled before the overlay, with mill depths ranging from 38 to 50 mm.

Figure 2 presents the profile indices (PIs) determined from the profilograph measurements made on the Atlanta project before milling, after milling, and after the overlay. In determining the PIs, a blanking band width of 5 mm was used following the procedure

Table 3. Initial Distress Conditions on Overlay Projects from TxDOT PMIS Database

Project	Beginning Reference Marker	Ending Reference Marker	Distress Score
Atlanta	223.0	223.5	20
	223.5	224.0	58
Carthage	295.0	295.5	44
	295.5	296.0	40
	296.0	296.5	44
	296.5	297.0	49
Dallas	408.4	409.0	98
	409.0	409.5	47
Odessa (CMHB)[a]	111.0	111.5	100
	111.5	112.0	100
Odessa (CRM)[b]	120.0	120.5	99
	120.5	121.0	100
	121.0	121.5	69
San Angelo	476.0	476.5	100
	476.5	477.0	100

[a] CMHB - Coarse Matrix High Binder

[b] CRM - Crumb Rubber Modified

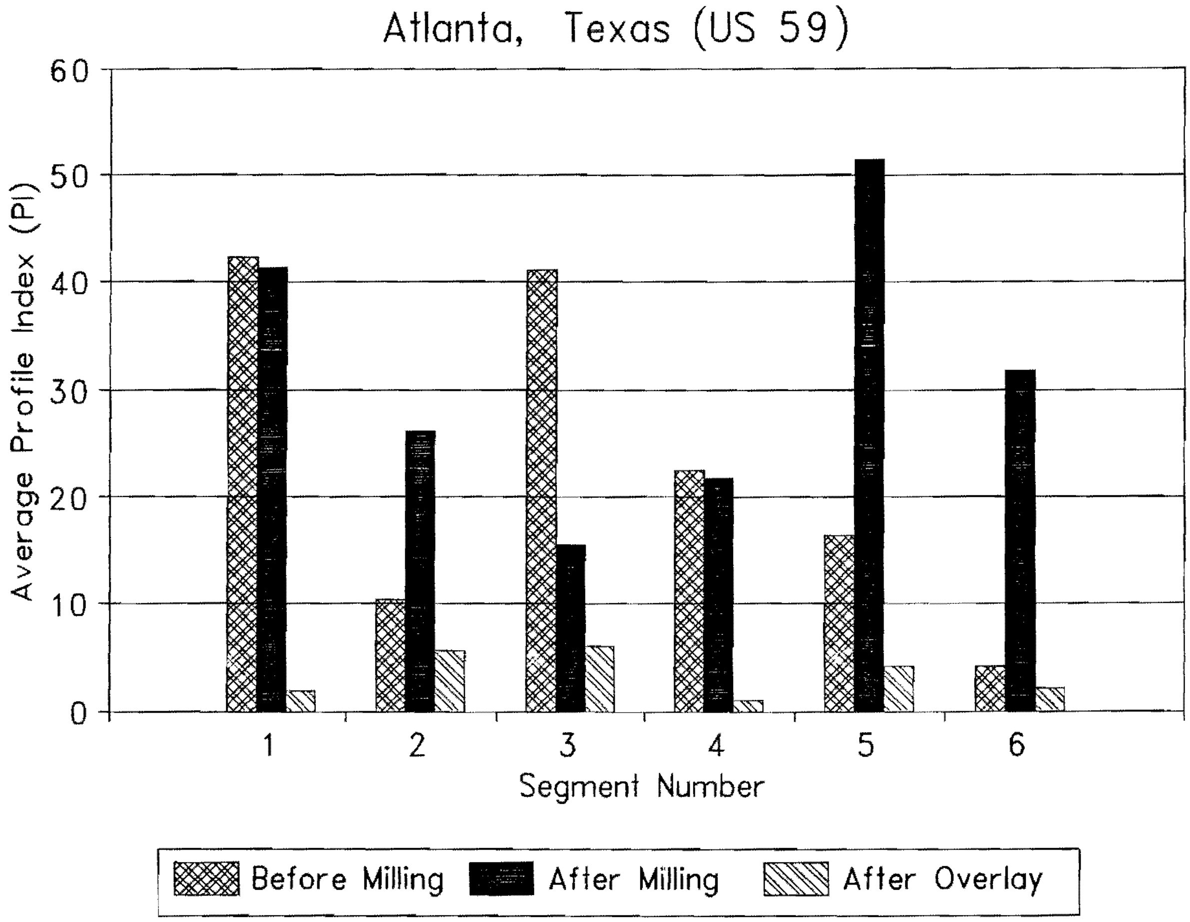

Figure 2. Measured Profile Indices on Atlanta Test Sections

established by TxDOT for interpreting profilograph data given in Test Method Tex-1000-S (1994). The profile index is used as a measure of surface smoothness in the current QC/QA specifications. It is calculated by summing the vertical deviations in excess of the 5 mm blanking band from the profilograph trace obtained during testing. The vertical deviations are summed for each wheelpath, the totals are averaged, and the mean is divided by the segment length to get the section profile index. The higher the sum of the vertical deviations, the higher the profile index, and the rougher the surface. In addition, a bump template is used with the profilograph trace to detect bumps in excess of 8 mm over a 7.6 m base length.

Figure 2 shows that on three of the six Atlanta test segments, the PIs increased after milling, indicating that the surface became rougher. This increase in roughness may have been due to the increased movement of the measuring wheel because of the grooves created by milling. During the measurements, the profilograph wheel tended to bounce as the profilograph was pushed along a given test segment. As a result, the increase in roughness readings after milling may be artificial, that is, caused by the broad profile plot created by continuous spikes. In the opinion of the researchers, milling was essential on the Atlanta and Carthage projects to take out the unevenness in the road profile due to surface distresses and thus achieve a flat and level surface prior to the overlay. Otherwise, it would not have been possible to reduce the profile indices to acceptable levels with just the thin overlay that was placed.

Another project monitored was the overlay along a stretch of Farm-to-Market (FM) 2790 in San Antonio in which a 38 mm overlay was placed on the existing surface without any surface preparation. This project is worth particular attention because it was the only overlay project with no surface preparation where the contractor was motivated by bonus and penalty specification provisions. Figure 3 shows the measured profile indices on the test sections established for this project before and after the overlay. Again, the test sections covered a range in initial riding quality, from a minimum Profile Index (PI) of 11 to a maximum PI of 45. No condition survey data were available on the San Antonio project from the TxDOT PMIS data base. However, a visual survey conducted prior to construction indicated bleeding of the asphalt and washboarding in several places. There were also some short, shallow depressions. However, no surface cracking, failures, or patching were observed.

The profilograph data shown in Figure 3 indicate that very significant reductions in surface roughness were achieved with just the placement of a thin (38 mm) overlay. In segment 5, for instance, Figure 3 shows that the PI was reduced from 45 to about 7. In segment 9, the PI went from 11 to approximately 0. These reductions were achieved without any surface preparation. However, the existing San Antonio pavement exhibited minimal distress compared with the overlaid Atlanta and Carthage pavements. Although washboarding and some short, shallow depressions were observed prior to construction in San Antonio, they were not of significant concern to the contractor, who was confident that the smoothness requirements could be achieved.

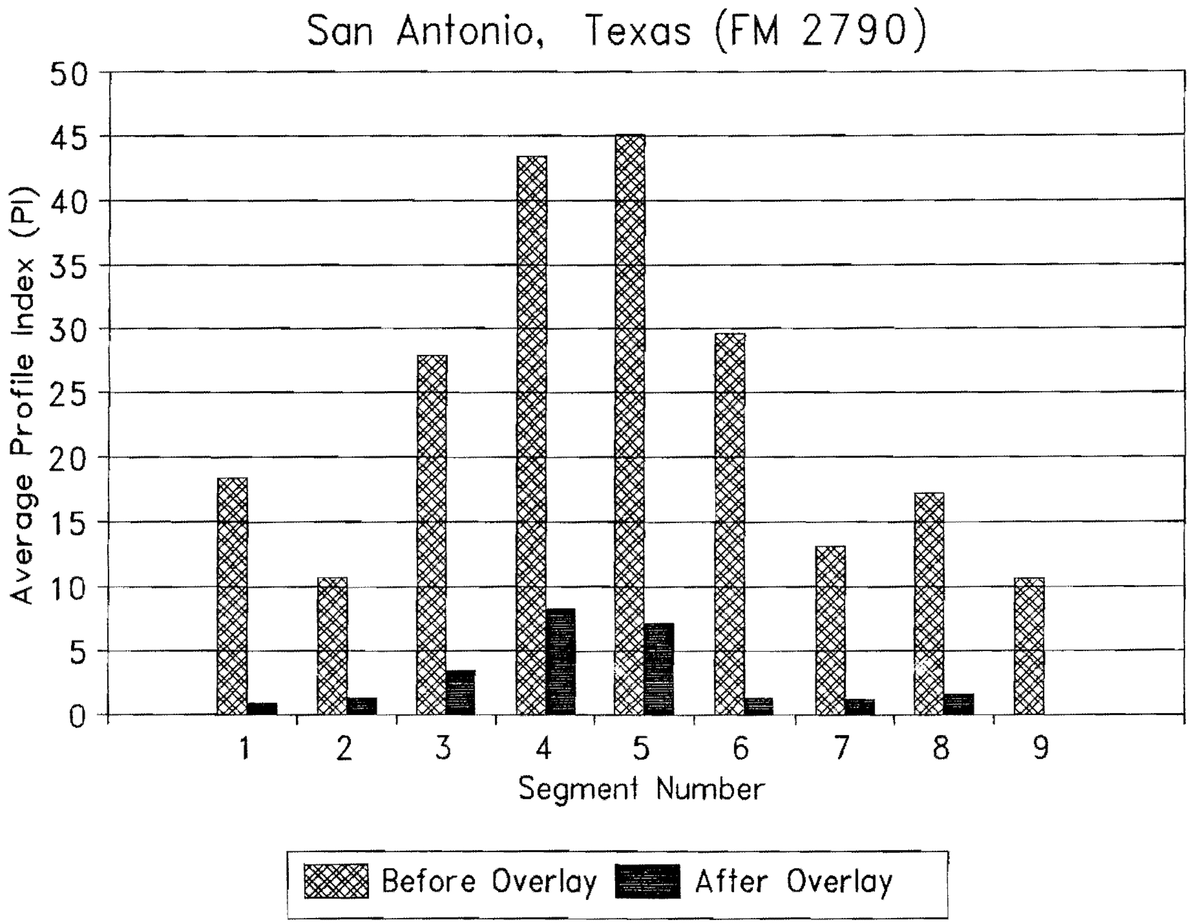

Figure 3. Measured Profile Indices on San Antonio Test Sections

A third project was the overlay job done along a stretch of US 87 in San Angelo. The PMIS data available on the test segments established for this project indicated that no distresses were observed prior to construction. This is reflected in the perfect distress scores of 100 from the PMIS database (Table 3). The area engineer noted, however, slight rutting in several places along the project but determined it was not a problem for the test sections established. However, the test sections did cover a wide range of initial riding quality, from a minimum PI of 8 to a maximum PI of 38 (Figure 4).

A level-up was applied on the entire width of the travel lanes of the San Angelo project. The thickness of the level-up was 19 mm, on average, and the level-up mix was the same as the overlay mix, a 9.5 mm maximum aggregate size mixture (TxDOT Type D mix).

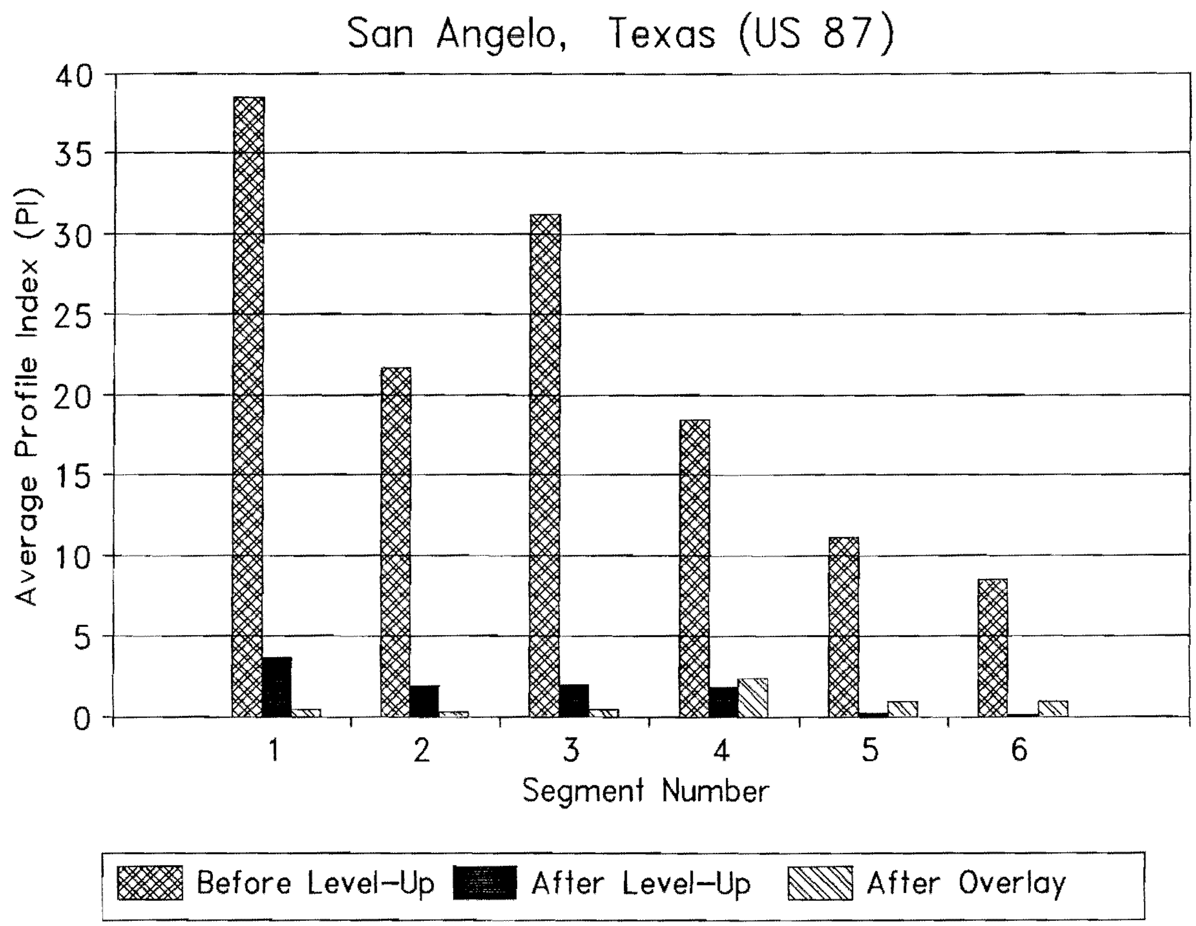

Figure 4. Measured Profile Indices on San Angelo Test Sections

Figure 4 shows that substantial reductions in surface roughness were already achieved after placement of the level-up course. In fact, if the same profile indices were measured after the overlay, the contractor would merit bonus payments based on the pay adjustment schedule in the TxDOT QC/QA smoothness specification shown in Table 4. It should be noted, however, that the existing pavement on the San Angelo project showed minimal to no surface distress throughout the length of the project. Thus, the results suggest that the smoothness specification is achievable for thin lifts where the pavement exhibits very little surface distress and where the primary deficiency is less than desired ride quality.

Figure 4 also shows that, on three of the six test segments profiled, the measured PI values after the overlay are slightly higher than the corresponding PI values after the level-up.

Table 4. Pay Adjustment Schedule for Ride Quality on Flexible Pavements

Profile Index Per 0.16 km Segment	Pay Adjustment[a]	
	Posted Speed > 68 kph	Posted Speed ≤ 68 kph
2.0 or less	+ $90	+ $90
2.1 through 3.0	+ $70	+ $70
3.1 through 4.0	+ $50	+ $50
4.1 through 5.0	+ $35	+ $35
5.1 through 6.0	$0	+ $20
6.1 through 9.0	- $35	$0
9.1 through 11.0	- $50	- $20
11.1 through 12.0	- $70	- $50
12.1 through 13.0	- $105	- $105
13.1 through 14.0	- $140	- $140
14.1 through 15.0	- $175	- $175
Over 15.0	Corrective work required	

[a] These pay adjustment values will apply, for each 0.16 km segment tested, unless other pay adjustment values are shown on the plans. No bonus will be paid for pavement sections which were originally constructed with a pay deduction. There will be no pay adjustments for the sections where the contractor took corrective action.

Although the differences are small, this observation is relevant when the payment schedule in a smoothness specification is based on a reduction in surface roughness after an overlay, expressed as a percentage of the original roughness. For portions of a project which are initially smooth, negative reductions in surface roughness may be obtained after placement of the overlay even though the smoothness of the overlay is acceptable. A provision should thus be included in the smoothness specification to address these situations in a manner that is equitable to both the agency and the contractor. For example, a provision may be written to use the smoothness of the final surface as the basis for paying the contractor under these situations.

The two overlay projects in Odessa were both on the eastbound lanes of IH-20. On one project, a Type F Coarse Matrix High Binder (CMHB-F) overlay was placed between Reference Markers (RMs) 103.174 to 111.758. On the other project, a Crumb Rubber Modified (CRM) mixture was used. This CRM project was done between RMs 111.758 to 122.0. Seven 0.16 km test segments were monitored on the CMHB project that are located between RMs 111.058 to 111.758. The most recent PMIS data available on these test segments before construction show perfect distress scores of 100, as reported in Table 3. Communications with the Odessa District established that the primary deficiency on the test segments was roughness due to segregation of the asphalt mix during placement, specifically in test segments 4, 5, and 6. This observation is evident in the average Profile Indices (PIs) measured on the test segments before construction (Figure 5). Note that segments 4, 5, and 6 were the roughest of the 7 test segments monitored on the Odessa CMHB project. The other test segments had acceptable PIs of less than 5 before construction.

A CMHB level-up course was placed on the entire surface of test segments 4, 5, and 6. Due to the tackiness of the mix used for the level-up course, it was not possible to measure the smoothness after level-up before the overlay was placed. An attempt at testing the level-up course resulted in asphalt/aggregate material sticking to the measuring wheel of the California-type profilograph. Further, electronic grade control could not be used during placement of the overlay because of the tackiness of the CMHB-F mixture. However, based on the measured PIs after the overlay shown in Figure 5, the contractor did a good job of satisfying the smoothness specification. All of the PIs after overlay are acceptable. According to the area engineer, the contractor maintained an ample supply of material at the job site so that delays in laydown were minimized. In addition, truck drivers were careful not to bump the laydown machine during construction. This, coupled with the good effort to maintain a continuous operation, was key to achieving the smoothness specification on the Odessa CMHB project, according to the area engineer.

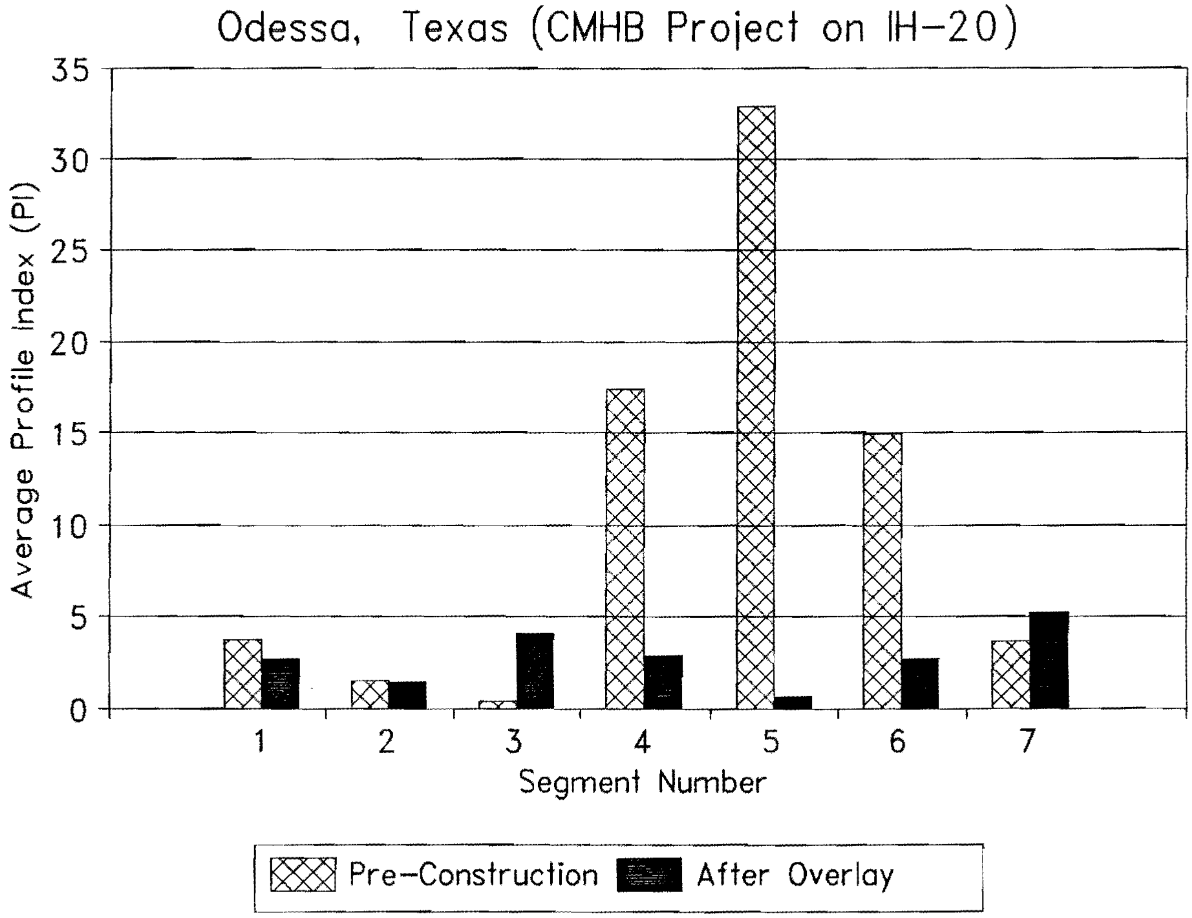

Figure 5. Measured Profile Indices on Odessa CMHB Test Sections

The contractor on the CMHB project also did the CRM overlay. This project was significantly rougher, according to the area engineer. The test segments established on the CRM project confirmed this as the PIs measured before construction (Figure 6) were generally higher than the PIs measured before construction on the CMHB project (Figure 5). The average PI before construction on the CRM project was 16.6 compared to the corresponding average of 10.6 for the CMHB project. The nine test segments monitored on the CRM project are between RMs 120.46 to 121.56. Based on the PMIS data shown in Table 3, the interval between segments 5 and 9 had significant distress prior to construction as inferred from the reported distress score of 69. According to the area engineer, the existing asphalt layer had extensive surface cracking. The cracks appeared within a month of

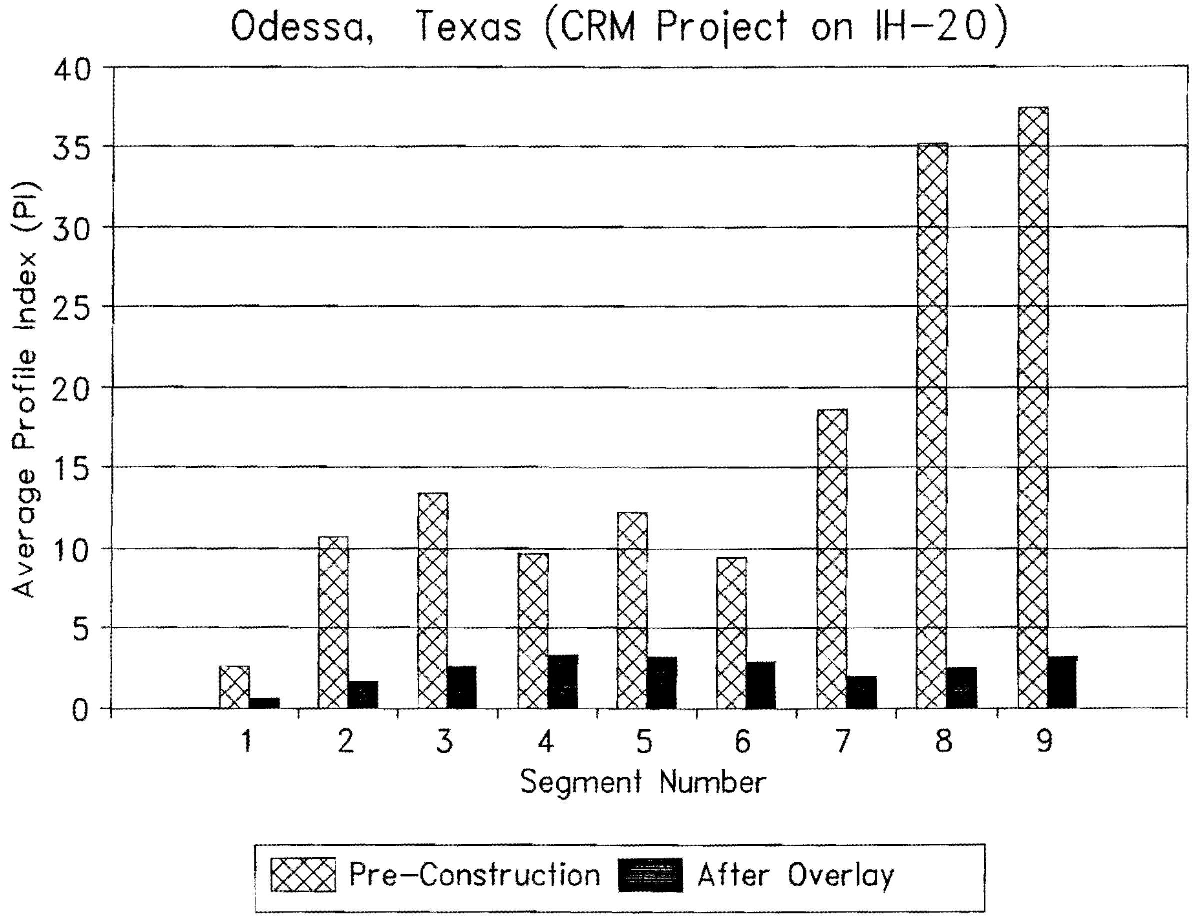

Figure 6. Measured Profile Indices on Odessa CRM Test Sections

placement of the existing asphalt layer which was also an overlay. For this project, a CRM mixture had been selected with the hope that it would perform better than the previous overlay which was a conventional asphalt mix. No milling or patching was done on the CRM project. However, the surface cracks were sealed prior to overlaying. Figure 6 shows the PIs measured after the overlay. As may be observed, all of the PIs measured after overlay are acceptable and would have resulted in bonus payments to the contractor had the QC/QA smoothness specification been enforced.

The final project monitored was the overlay in Dallas where the existing pavement was jointed concrete. Based on the PMIS data in Table 3, the reported distress score of 47 between RMs 409.0 to 409.5 may be taken to indicate that portions of the project exhibited significant distress. The PIs measured before construction (Figure 7) indicate that the six test segments monitored on this project were rough. Communications with the Dallas District established that the following treatments were scheduled before the overlay:

1. Repair of spalled joints and broken slabs;
2. Application of rubber type membrane with woven fabric over the joints;
3. Seal coat application over the entire project length; and
4. Application of a 25 mm level-up.

The PIs measured on the test sections after overlay are shown in Figure 7. All test sections exhibited acceptable PIs after the overlay. There was also a significant reduction in surface roughness after the level-up. This reduction can probably be attributed not only to the level-up but also to the repair of spalled joints and broken slabs and the seal coat application.

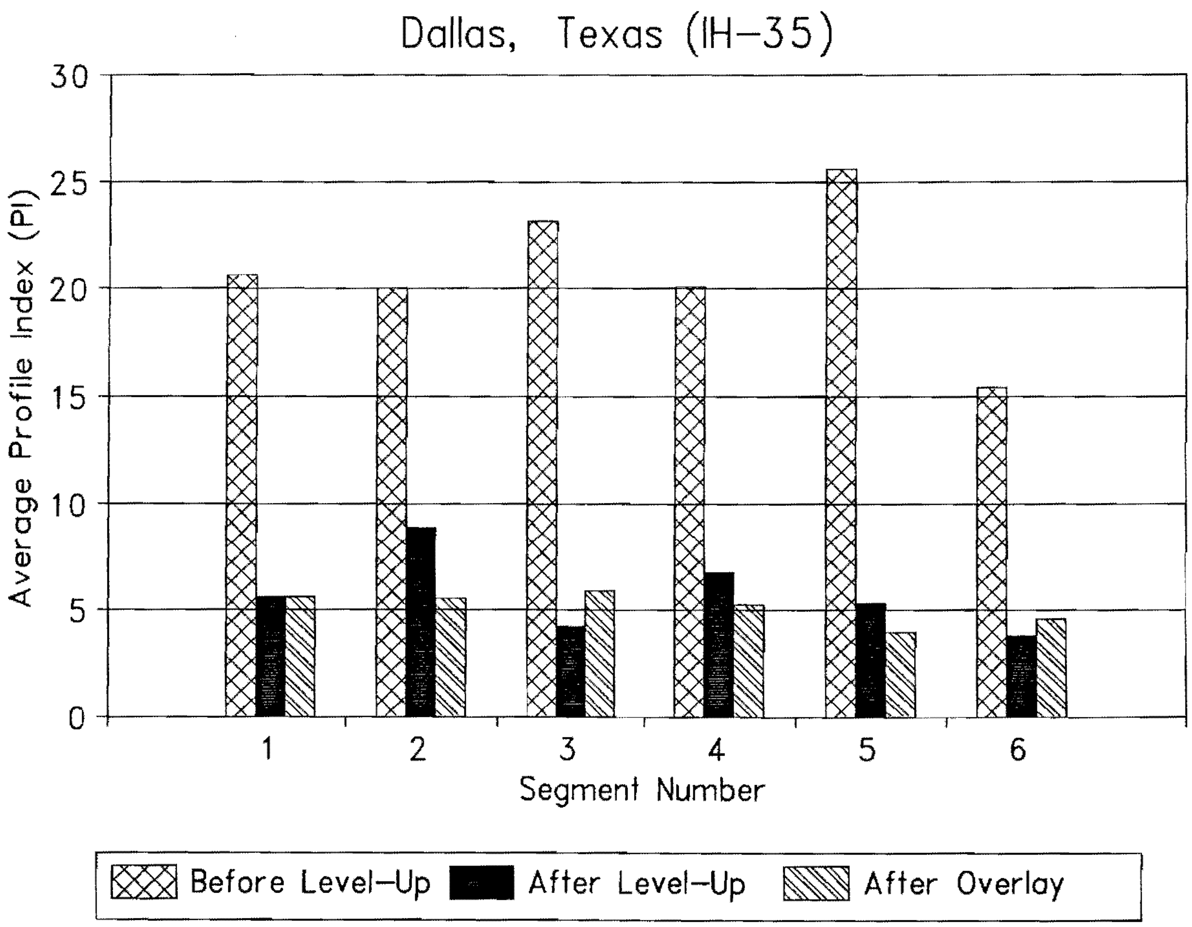

Figure 7. Measured Profile Indices on Dallas Test Sections

However, because no roughness measurements are available after each treatment, no conclusive evidence can be offered other than the fact that the roughness after level-up was substantially lower than the roughness prior to construction. It is also more likely that these treatments were done not so much to prepare a smoother surface for placement of the overlay but to retard the growth of reflection cracks in the overlay mix. Repairing broken slabs will minimize, if not eliminate, the likelihood of broken concrete moving under traffic loading, and the seal coat functions as a stress-absorbing interlayer. Thus, initial ride quality is important, but so is adequate pavement design.

REVIEW OF SMOOTHNESS SPECIFICATION

Table 4 shows the pay adjustment schedule of the QC/QA smoothness specification for flexible pavements that was applicable on those projects where the smoothness specification was included. This specification is reviewed herein against the field data collected during the district surveys.

Figure 8 compares the PI values before surface preparation with the corresponding PI values after the overlay for all test segments profiled in the seven district projects monitored in this study. The type of surface preparation applied on the different segments are also indicated in the figure. Two horizontal lines extending across the width of the chart demarcate the bonus and penalty regions for highways where the posted speed is above 68 kph. The limits shown are applicable for all projects with the exception of FM 2790 in San Antonio, where the posted highway speed is under 68 kph. The small interval between PIs five and six in the chart denote the region within which payment to the contractor is the bid price, i.e., with no bonus or penalty.

Although only a limited number of projects have been evaluated, Figure 8 suggests that the QC/QA smoothness specification for newly constructed flexible pavements may be implemented with success on projects involving asphalt concrete overlays 38 to 63 mm thick. However, the need for appropriate surface preparation or treatments must be considered by the highway engineer. Surface preparation before the overlay may be necessary to correct existing surface distresses to enable the contractor to provide an overlaid pavement with the

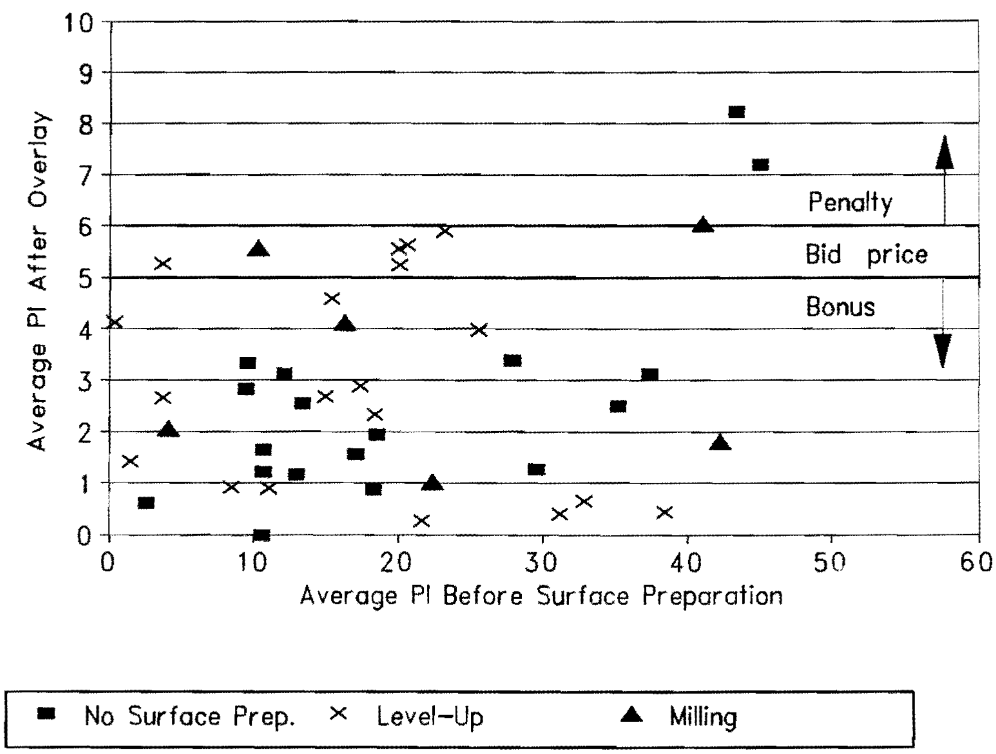

Figure 8. Comparison of PIs After Overlay with PIs Before Surface Preparation

desired level of smoothness. Additionally, surface preparation may be necessary to control the occurrence of other distresses in the overlay, primarily, reflection cracks.

Almost all of the data points in Figure 8 fall within the bonus region. The two points denoted by squares that fall within the penalty region of the chart are test segments from the San Antonio project (Sections 4 and 5 in Figure 3). As noted previously, the bonus, bid price, and penalty regions demarcated in Figure 8 are applicable for projects where the posted highway speed is above 68 kph. For the San Antonio project, the posted highway speed is under 68 kph. Thus, these segments are not actually in a penalty region as shown in Table 4 because the measured PIs after overlay are between 6 and 9. These segments were the roughest segments monitored on the San Antonio project. Even so, acceptable roughness levels were achieved after placement of the 38 mm overlay. In the opinion of the researchers, these test sections might have qualified for a bonus had some form of surface preparation (e.g., milling or level-up) been performed to correct the washboarding observed on these test sections before the overlay.

In addition to the California-type profilograph, measurements of surface roughness on the overlay projects were made using TxDOT's Profilometer. This device allows profile measurements on both wheelpaths to be made at highway speed and provides more accurate profiles than those obtained from a profilograph. The data collected were used to evaluate the ride quality achieved on the overlay projects. One ride quality statistic determined from the measured profiles is the Present Serviceability Index (PSI). This index goes on a 0 to 5 scale, with 0 representing a pavement with an extremely rough ride, and 5 representing a pavement with a very smooth ride. Figure 9 compares the PSI values before surface preparation with the corresponding values after the overlay. The calculated PSIs after overlay are all above 4 indicating that acceptable levels of ride quality were achieved on the overlay projects and confirming what the profilograph data showed.

SUMMARY

The results from the field study were presented by TTI researchers in a meeting between TxDOT and industry representatives from the Texas Association of General Contractors and the Texas Hot Mix Asphalt Pavement Association. Based on the findings presented, there was general agreement that the existing smoothness specification for new flexible pavements is also applicable for overlay projects when the overlay design thickness is between 38 and 63 mm. However, for overlays this thin, appropriate guidelines are needed to establish when surface preparation is required.

TTI researchers suggested using the PMIS data to identify pavement conditions where overlays less than 63 mm thick may be inappropriate for achieving the smoothness

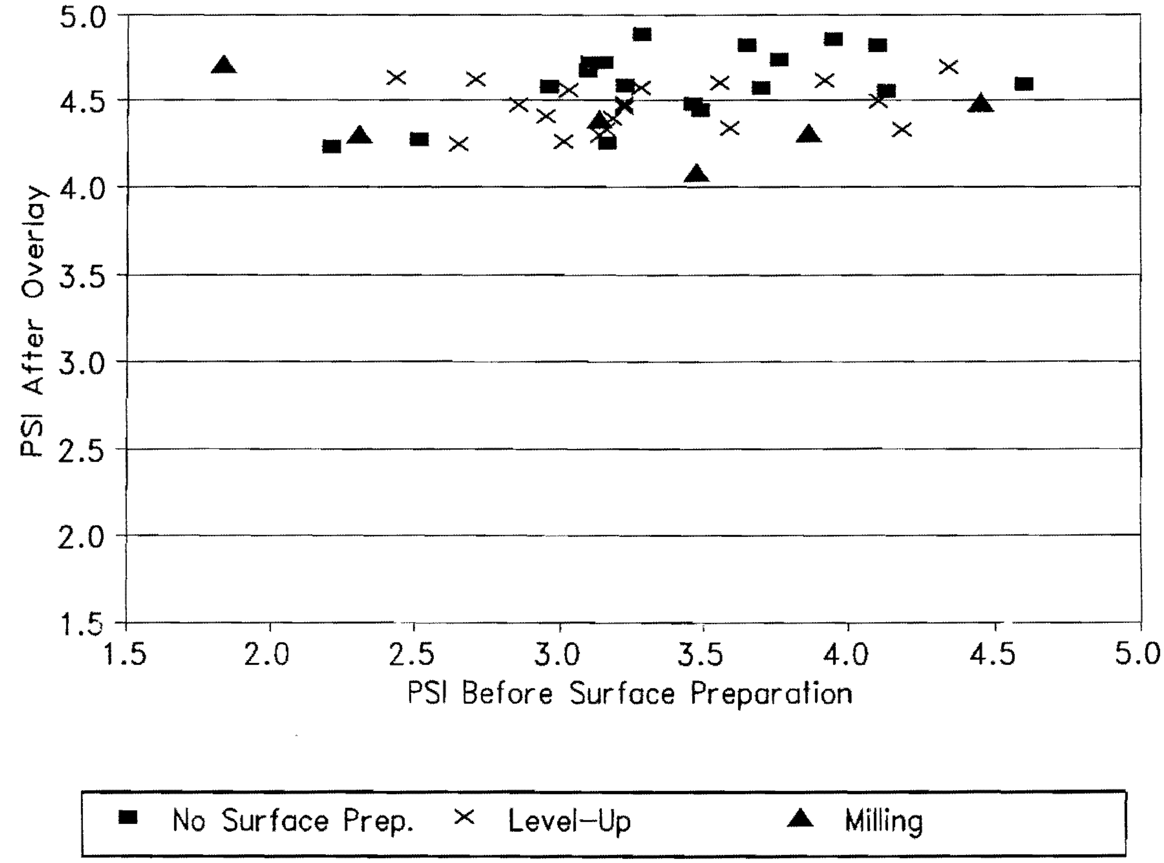

Figure 9. Comparison of PSIs After Overlay with PSIs Before Surface Preparation

specification without some type of surface preparation. These conditions may be defined in terms of limiting values of pavement distresses, such as:

1. segments with ruts deeper than 13 mm that cover more than 20 percent of the surface area;
2. segments with more than one failure per kilometer; or
3. segments with more than 50 percent of the surface area patched.

The preliminary evaluation of PMIS data should then be verified by a field inspection to confirm which segments within the project limits will require some form of surface preparation. Alternatively, the district may consider dropping the existing smoothness specification for problem segments if no surface preparation is planned.

It is noted that TxDOT and researchers considered an alternative acceptance schedule based on the improvement in ride quality from the overlay. Researchers are of the opinion that this is a more appropriate approach for evaluating the ride quality of overlaid surfaces, particularly in view of the thin overlays that are predominantly used in rehabilitation projects around the state. However, because of the necessity to measure the profile indices before and after the overlay, this acceptance schedule is more difficult to implement than one based solely on the final measured smoothness. For this reason, and in view of the results from the field study which showed that the existing smoothness specification can be achieved on overlay projects, the decision was made, at least for the short-term, to use the profile index measured after the overlay for acceptance testing. This requires, however, that districts exercise judgment in using the smoothness specification on thin overlays, particularly when no surface preparations are planned. The need for and the type of surface preparation should be based primarily on the engineer's diagnosis of what is wrong with a given pavement. Decisions made should be driven by this assessment, and not by the practical concern of allowing smoothness requirements to be met. Surface preparation must be a means to cure the problems identified. Otherwise, the potential benefit of longer service life because of a smoother pavement may not be realized.

CHAPTER III

ACCEPTABILITY OF ASPHALT CONCRETE OVERLAY SMOOTHNESS BASED ON SURFACE PROFILE

INTRODUCTION

A relevant question to ask when developing and implementing smoothness specifications is, "What do we get from smoother pavements?" In addition to providing a smooth and comfortable ride, what is the benefit of smoother pavements in terms of pavement service life? Surely if engineers in the highway department and in pavement research are to provide roads that make cost-effective use of taxpayers' money, surface smoothness criteria should be tied not only to riding quality but to pavement life as well. To establish this connection, researchers developed a methodology for relating surface smoothness to predicted pavement life through a two-step process:

1. First, the effect of surface profile on vehicle dynamic loads is evaluated; and
2. Second, the effect of vehicle dynamic loads on pavement service life is determined.

The effect of surface profile on vehicle dynamic loads is illustrated in Figures 10 to 12. In these figures, researchers predicted the vehicle response to measured surface profiles using a vehicle simulation model. Figure 10 shows the predicted variation in dynamic axle loads on a smooth pavement. In this report, this is referred to as the dynamic load profile, analogous to a surface or road profile which shows the variation in elevation with distance along a given segment. Figure 11 illustrates the predicted dynamic load profile for a medium-smooth pavement while Figure 12 shows the load profile for a rough pavement. It is observed from Figures 10 to 12 that the variability in predicted dynamic axle loads increases with an increase in surface roughness. The dynamic axle loads fluctuate about the static axle load which corresponds to the mean of the predicted dynamic loadings. In the figures given, the static axle load is 80 kN applied on a single axle. In the limit, if the surface profile is perfectly flat, the predicted dynamic loads would be a constant, equal to the static axle load, and the load

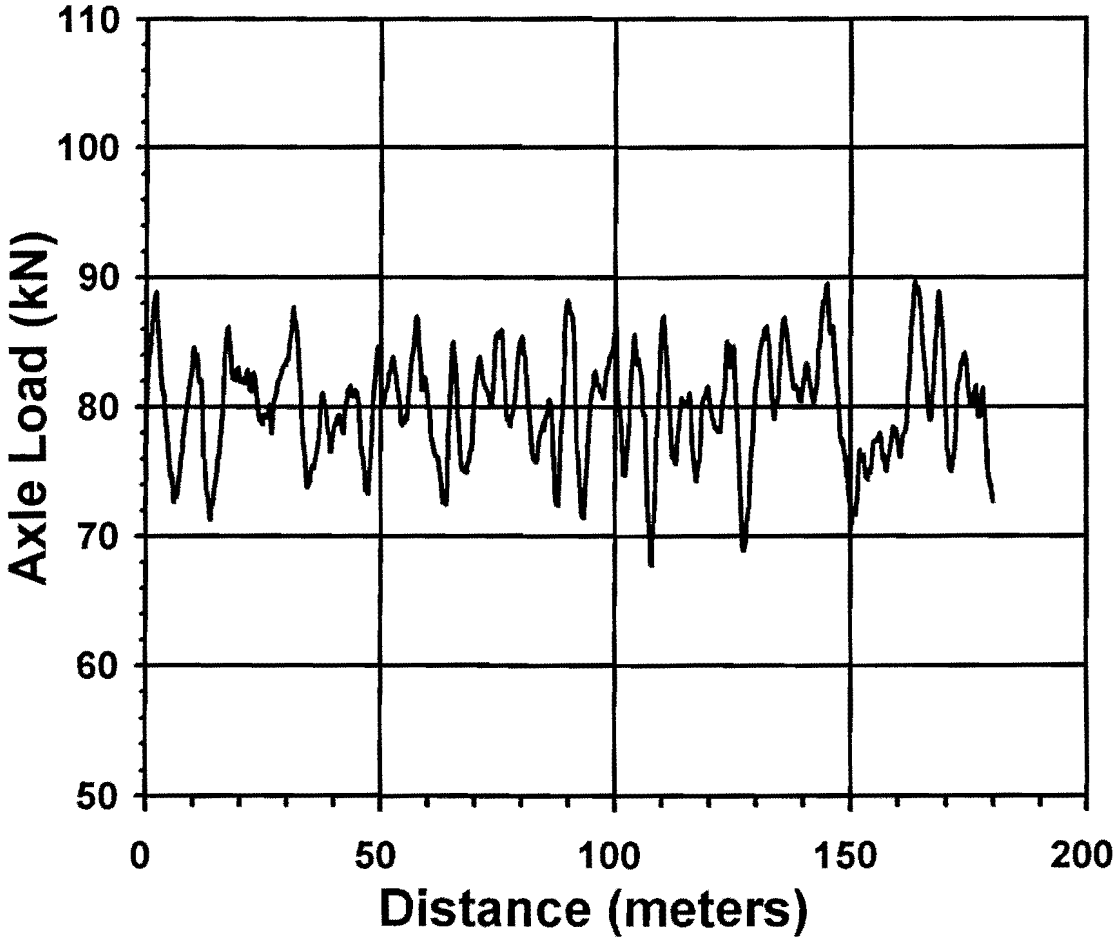

Figure 10. Predicted Dynamic Loads on a Smooth Pavement

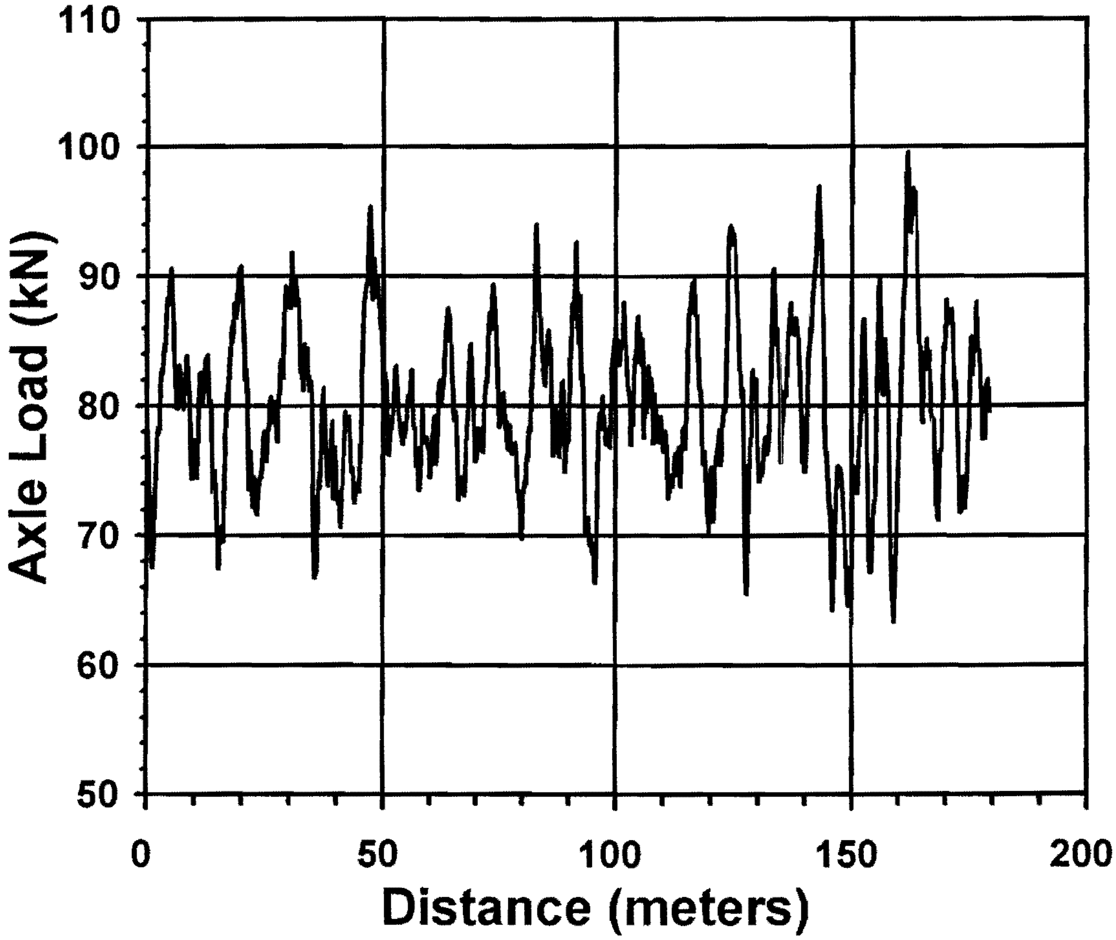

Figure 11. Predicted Dynamic Loads on a Medium-Smooth Pavement

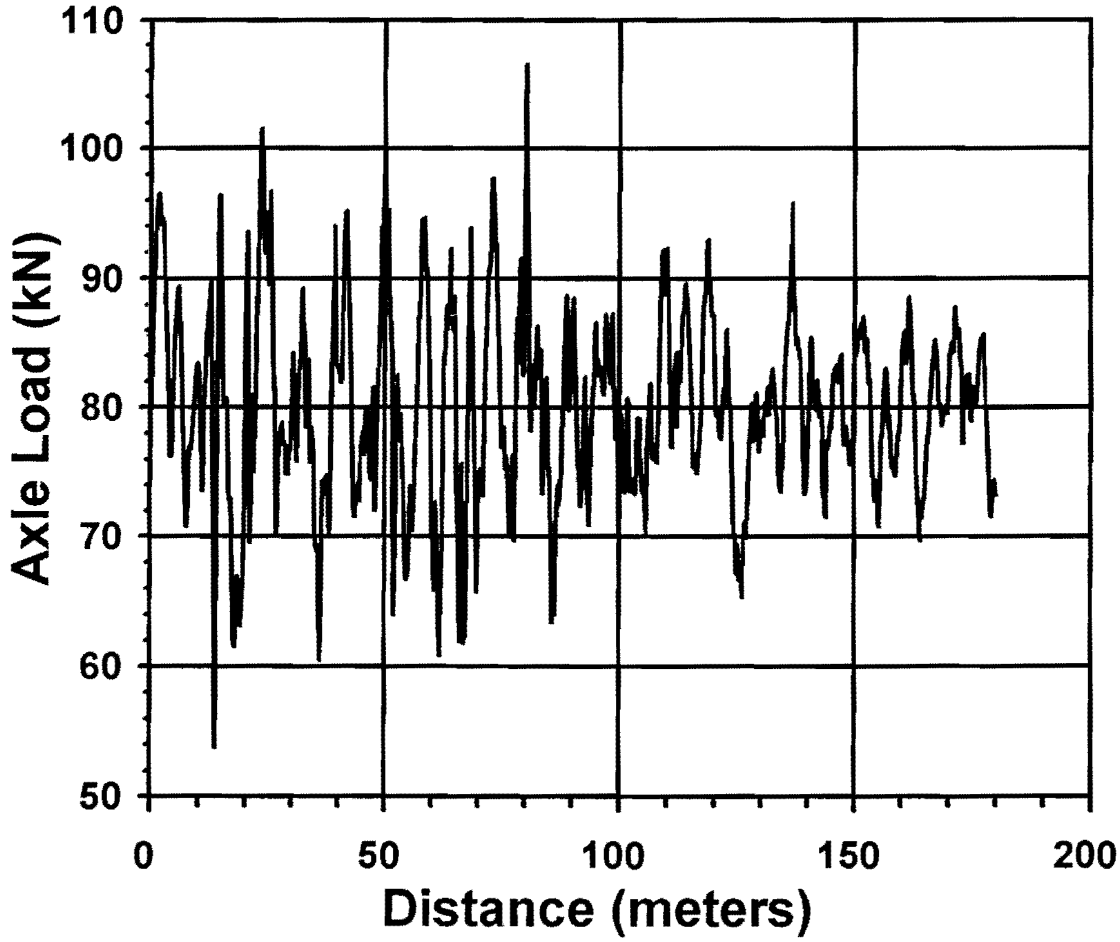

Figure 12. Predicted Dynamic Loads on a Rough Section

profile would plot as a horizontal line. In this case, there will be no variability in the predicted axle loads. Because pavement response is directly tied to axle load magnitudes, it is logical to expect that dynamic axle load variations will lead to differences in predicted pavement performance. In this study, researchers related the variability in applied surface loads to pavement performance to establish a methodology for evaluating the effect of surface profile on pavement life. An index for evaluating the acceptability of overlay smoothness was developed that is related to the predicted performance of the overlay based on reflection crack growth. This index estimates the predicted change in overlay service life due to departures from the target profile, established in the design stage, and the as-built profile. The development of this damage index, Δ, is presented in the appendix of this report. It is defined by the equation:

$$\Delta = \left[\frac{1 + zCV_0}{1 + zCV_1} \right]^n - 1 \qquad (1)$$

where,

CV_0	=	coefficient of variation of the applied dynamic wheel loads associated with the target profile;
CV_1	=	coefficient of variation of the applied dynamic wheel loads associated with the as-built profile;
z	=	the number of standard deviations corresponding to a given percentile of the predicted dynamic load distribution; and
n	=	the exponent of the Paris-Erdogan crack growth law given by Eq. (A1) in the appendix.

The reader is referred to the appendix for the derivation of Eq. (1). This equation provides a rational method for evaluating the quality of the finished surface on the basis of the expected performance of the overlaid pavement. In practice, the coefficient of variation in Eq. (1) is determined by vehicle simulation using the measured profile. Note that, Δ, is related not only to the surface profile but to vehicle suspension and geometric characteristics, which all affect the variability in the applied dynamic wheel loads. The benefit of reducing this variability on predicted pavement life is readily apparent from Eq. (1). If $CV_1 < CV_0$, the predicted change is positive, indicating an increase in pavement life with a smoother surface. Note that the reduction in wheel load variability is achieved not only by building smoother pavements but also by designing, manufacturing, and encouraging the use of trucks with improved dynamic performance. Equation (1) also shows that the effect of surface profile on predicted pavement life is tied to the fracture parameter, *n*, of the bituminous overlay mix. The higher this parameter, the faster the crack propagation through the overlay material under repeated traffic loading. Consequently, the design and production of the mix is also important to building overlays that last their design lives.

FACTORS AFFECTING THE PAVEMENT DAMAGE INDEX, Δ

To develop the procedure for acceptance testing of overlay smoothness, it is important to establish the range in the coefficient of variation (*CV*) of predicted dynamic loads and in the fracture parameter, *n*, of the Paris and Erdogan equation. Sweatman (1983) reported test results from a field experiment conducted in Australia in which dynamic loads were measured for different suspensions types, pavement roughness, and vehicle speed. The objective of the experiment was to identify axle group suspensions that produce severe dynamic pavement loads. Figure 13 shows the axle suspensions that were evaluated in the study. A statistic, called the dynamic load coefficient (DLC), was used to characterize the dynamic loading for each suspension type. Sweatman (1983) defined this statistic as the standard deviation of the measured dynamic loads divided by the mean axle group load. It is thus equivalent to a coefficient of variation. Figure 14 summarizes the dynamic load coefficients determined from the field measurements. It is seen that the DLCs increase with increase in pavement roughness and vehicle speed. Sweatman also observed a strong interactive effect between these variables, noting that the effect of speed is accentuated at higher roughness values and vice versa. From analyses of the test data, he found that dynamic loading was strongly related to the interaction term, $VR^{0.5}$, where V is the vehicle speed in kph, and R is the surface roughness in counts per kilometer measured with the Mays Meter. This finding is used later in this report to establish an equation for estimating the coefficient of variation of predicted

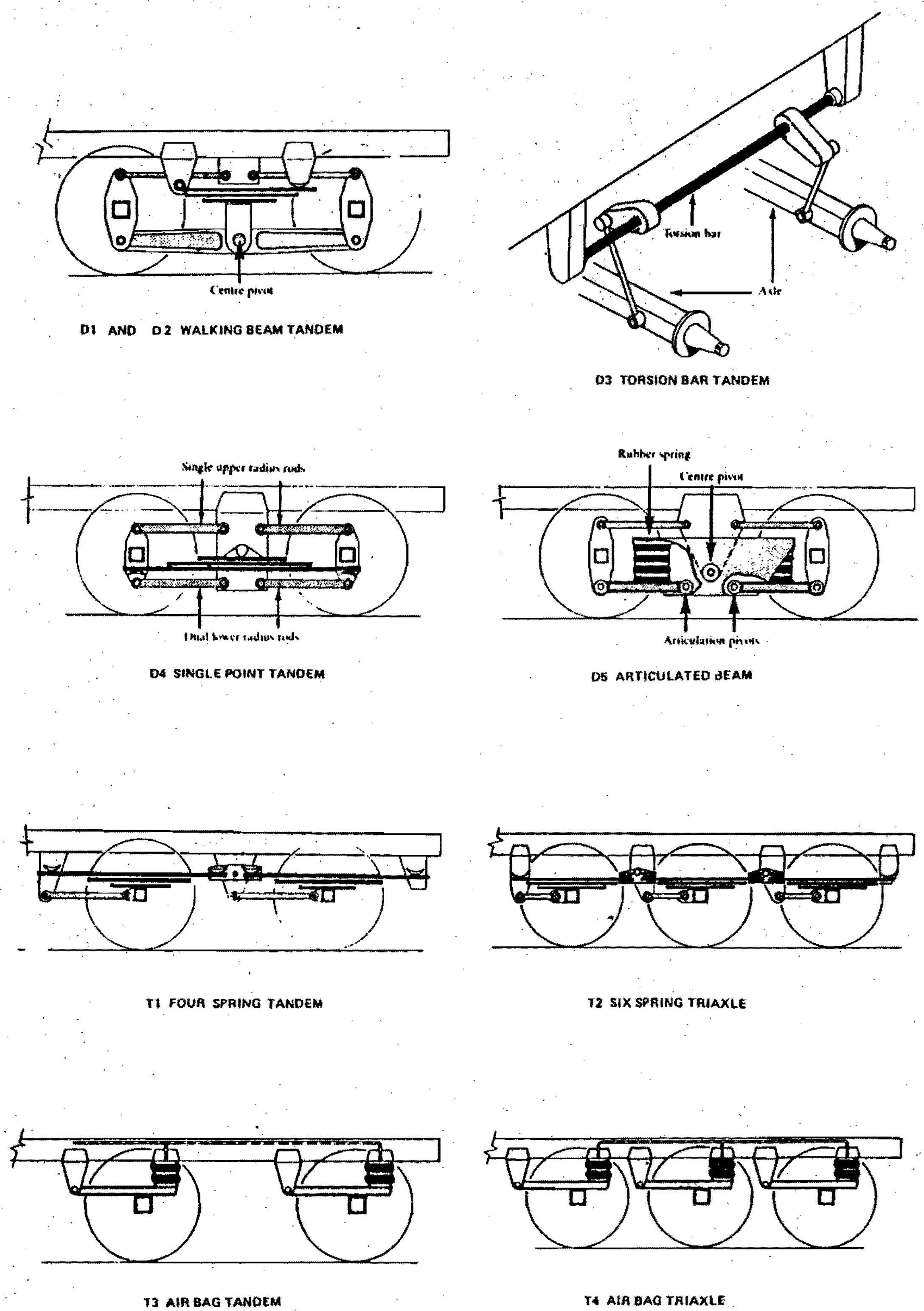

Figure 13. Suspension Types Investigated by Sweatman (1983)

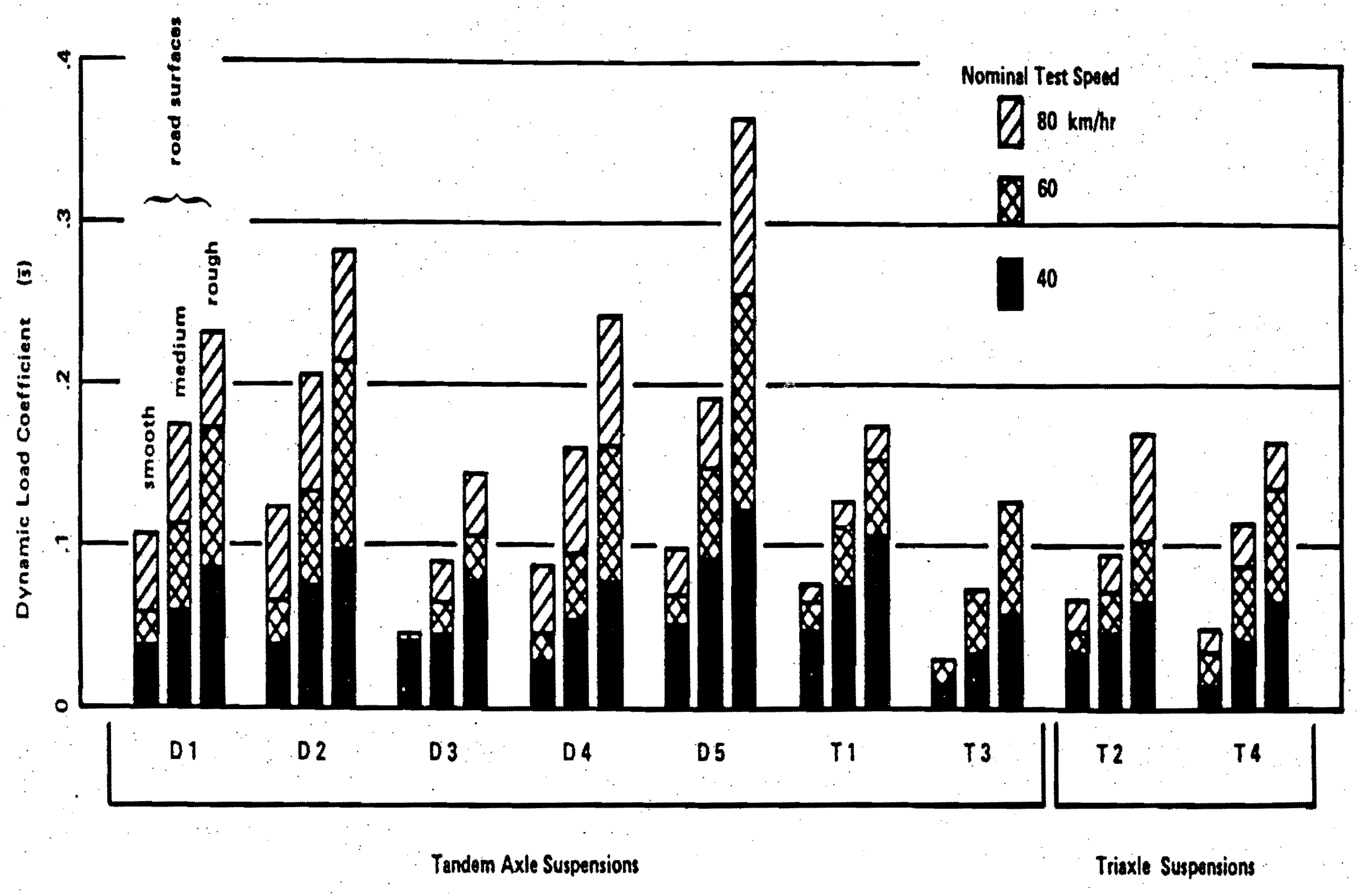

Figure 14. Dynamic Load Coefficient as Affected by Speed and Road Roughness for Various Suspensions (Sweatman, 1983)

dynamic loads. Sweatman proposed using the DLC as a criterion for distinguishing between different suspensions in terms of their dynamic loading characteristics. Specifically, he proposed a DLC criterion of 20 percent or less under roughness and speed conditions given by $VR^{0.5} = 850$ to identify vehicles that generate severe dynamic pavement loading. He also noted the importance of limiting pavement roughness to reduce vehicle dynamic loads.

In addition to the variability of the applied wheel loads, the fracture parameter, *n*, affects the damage index, Δ. For a given level of roughness, the higher *n* is, the larger will be the predicted reduction or increase in pavement life, depending on whether the as-built pavement is rougher or smoother than the target. Because Eq. (1) is based on the shear mode of crack propagation, the parameter, *n*, must also be determined accordingly. Unfortunately, most of the data reported in the literature is based on the opening mode of crack propagation, and thus are not compatible with Eq. (1). However, Lytton et al. (1993) derived a relationship between the shear-based fracture parameter, *n*, and the slope, *m*, of the creep compliance curve based on calibration with field pavement performance data. The relationship determined is of the form:

$$n = g_0 + \frac{g_1}{m} \tag{2}$$

where g_0 and g_1 are calibration coefficients determined for different environmental zones. Because these coefficients vary slightly between climatic zones, researchers used the coefficients determined using the performance data on all the calibration sections to get estimates of the fracture parameter, *n*, required in this study. Consequently, *n* is estimated using the relation:

$$n = -2. + \frac{1.97}{m} \tag{3}$$

Figure 15 shows the distribution of the slopes of the creep curve, *m*, determined from laboratory frequency sweep tests conducted on core specimens taken from the calibration

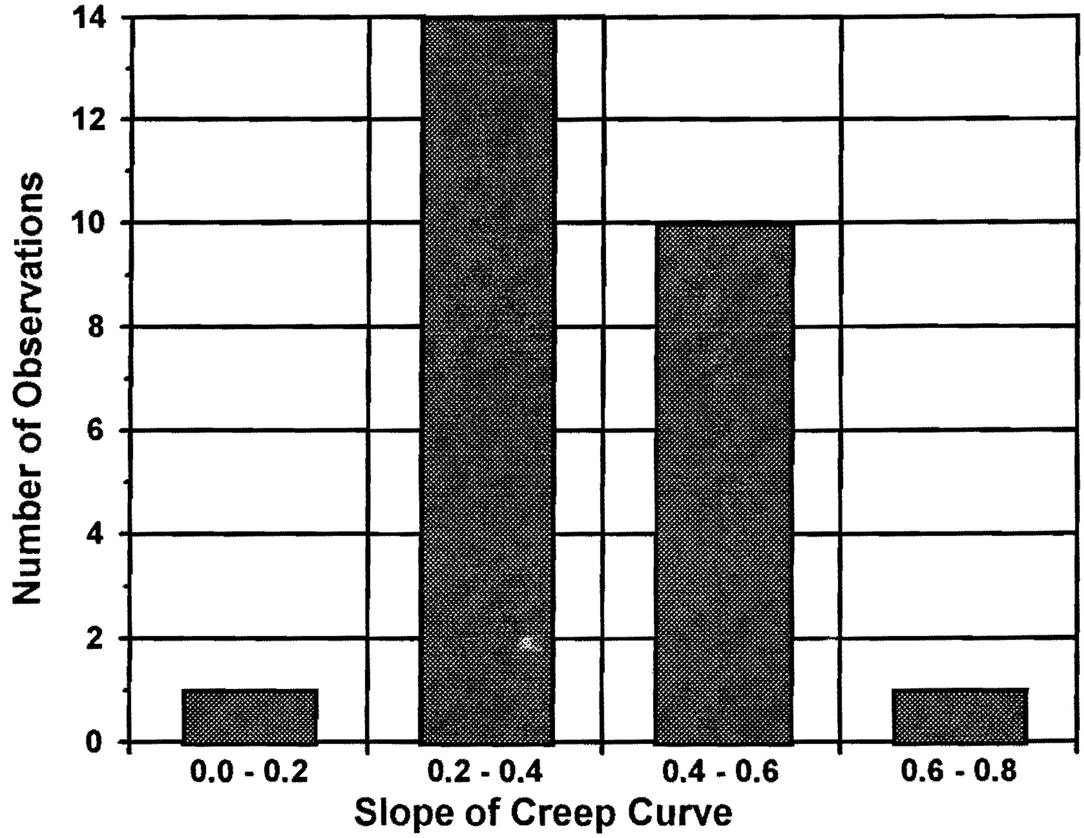

Figure 15. Distribution of the Slopes of the Creep Curve from Frequency Sweep Tests Conducted by Lytton et al. (1993)

sections of the study reported by Lytton et al. (1993). It is observed that most of the measured slopes fall within the range of 0.2 to 0.6. From the reported data, the average slope was computed to be 0.39. Researchers used the values of the slope, *m*, in Eq. (3) to establish the range of the fracture parameter, *n*, based on the shear mode of crack propagation. Figure 16 shows the distribution of the estimated values of *n* for the 25 core specimens on which frequency sweep tests were conducted. It is observed that the majority of the predictions fall within the range of 2 to 4 with an average value of 3.6. These results, as well as those reported in the study by Sweatman, are used in the next section to evaluate the effect of

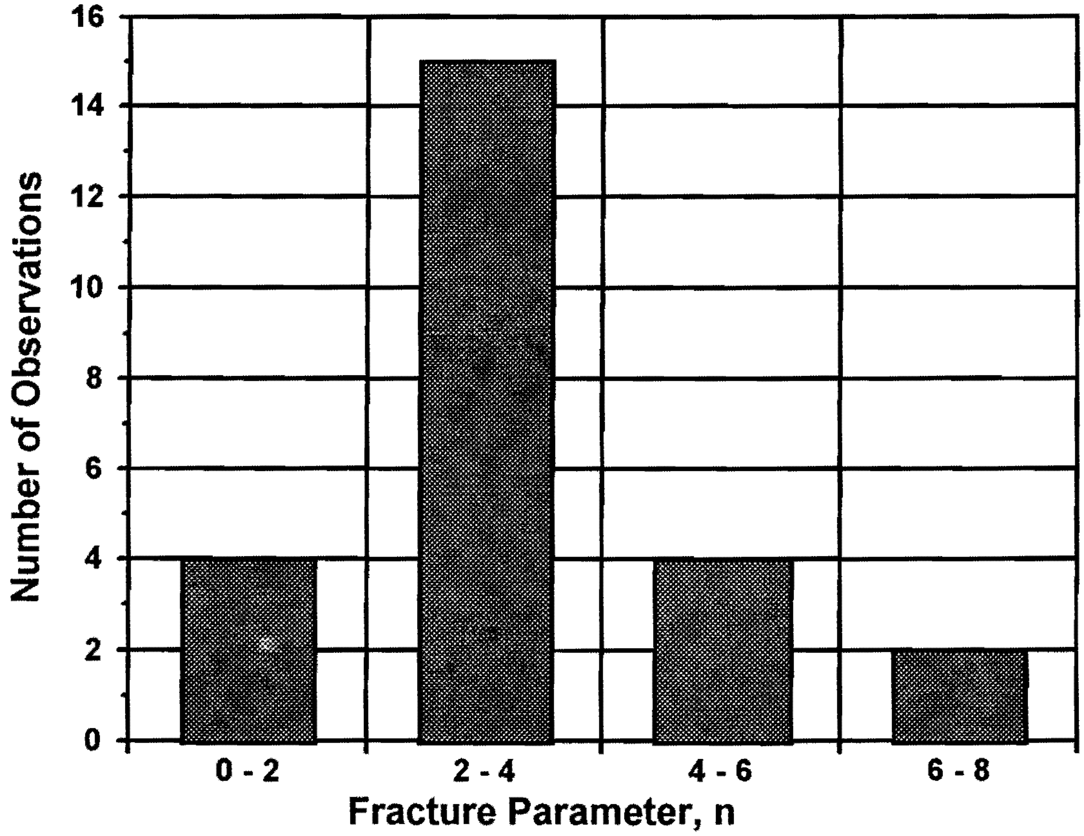

Figure 16. Distribution of Fracture Parameter, *n*, Estimated from Slopes of Creep Curve

surface profile on the damage index, Δ, and to propose a procedure for acceptance testing of asphalt concrete overlay smoothness.

EVALUATING THE EFFECT OF SURFACE PROFILE ON PREDICTED PAVEMENT LIFE

Consider the case where $CV_0 = 0$ in Eq. (1) corresponding to the assumption of a perfectly smooth target profile where the wheel loads are all at the static value used in pavement design. In this instance, the equation reduces to the form:

$$\Delta = \frac{1}{(1 + zCV_1)^n} - 1 \tag{4}$$

From Figure 14, the coefficient of variation for smooth pavements is observed to vary from close to 0 to about 10 percent, for the different suspensions evaluated by Sweatman (1983). Assuming that this range is representative of the dynamic load variability expected of new or overlaid pavements, Δ may be determined for different confidence levels and n values from Eq. (4). Figure 17 shows curves of Δ determined at confidence levels varying from 95 to 80 percent using the average n value of 3.6 obtained from the study by Lytton et al. (1993). As expected, the higher the dynamic load variability, the bigger the predicted reduction in pavement life (relative to the target), as indicated by the negative values of Δ. Figure 17 also shows that the higher the confidence level, the smoother the pavement required to maintain Δ to a prescribed value. In practice, the confidence level may be tied to the expected use of a given roadway. Primary roads, for example, that carry high traffic volumes and heavy trucks would most likely have to be evaluated at a higher confidence level because of the greater life-cycle costs to be incurred if the road should fail prematurely.

Figure 18 shows the effect of the fracture parameter, n, on the predicted change in pavement life. A 95 percent confidence level was used to generate the curves shown in the figure. As expected, the greater the value of n, the more the predicted reduction in pavement life for a given level of dynamic load variability or surface roughness. Figure 18 indicates that, in addition to pavement smoothness, the design and production of crack-resistant asphalt mixtures is equally important towards building a pavement that will provide the required service life.

The curves shown in Figures 17 and 18 illustrate a basis for evaluating the quality of surface smoothness of asphalt concrete overlays based on the damage index, Δ. This approach will require evaluation of dynamic load variability associated with the as-built surface profile. A method for accomplishing this is by simulation of the vehicle response to the measured profile. While computer programs are available to simulate vehicle dynamic loads, this approach will require establishing a standard vehicle and modifying an existing

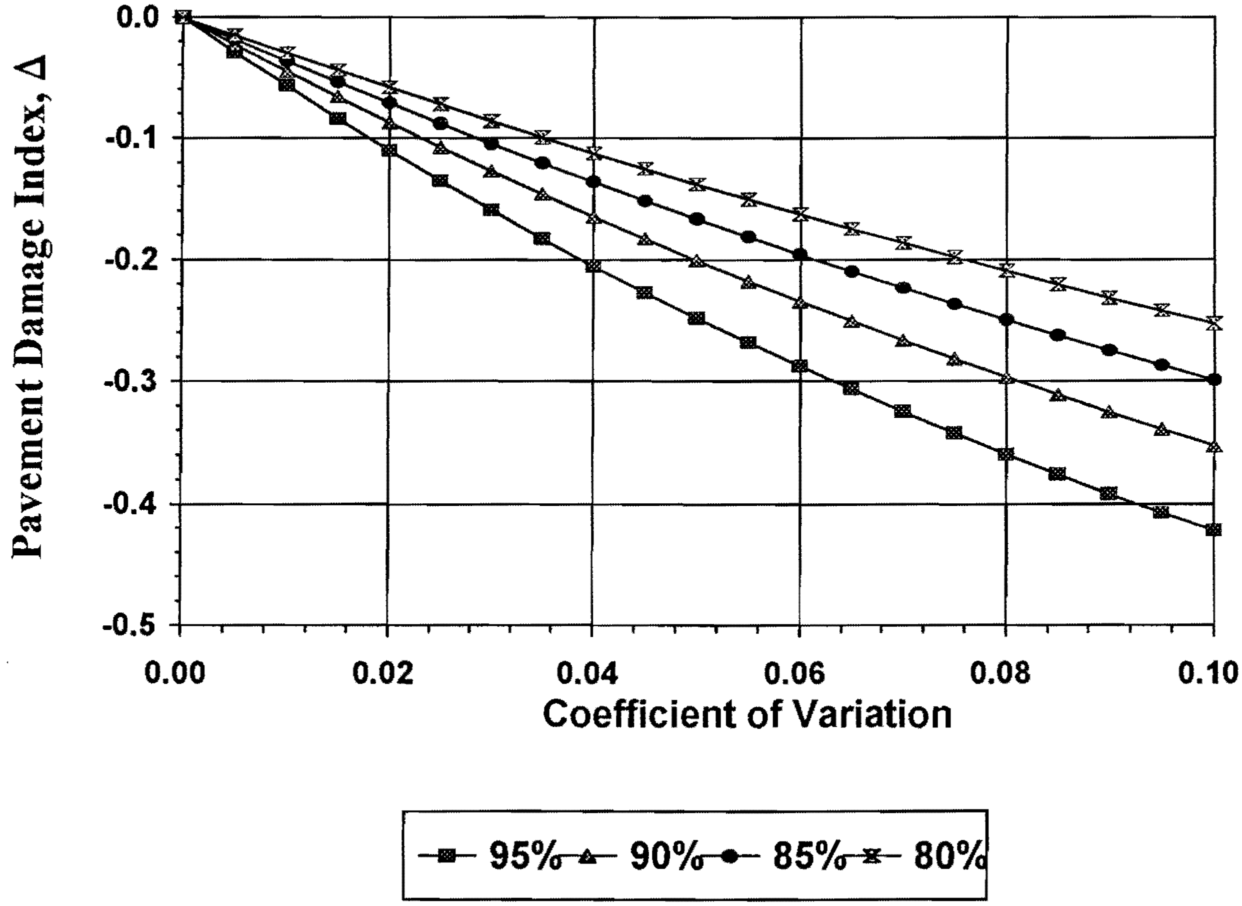

Figure 17. Values of Δ for Different Levels of Dynamic Load Variability and Confidence Levels (CV_0=0 and n=3.6)

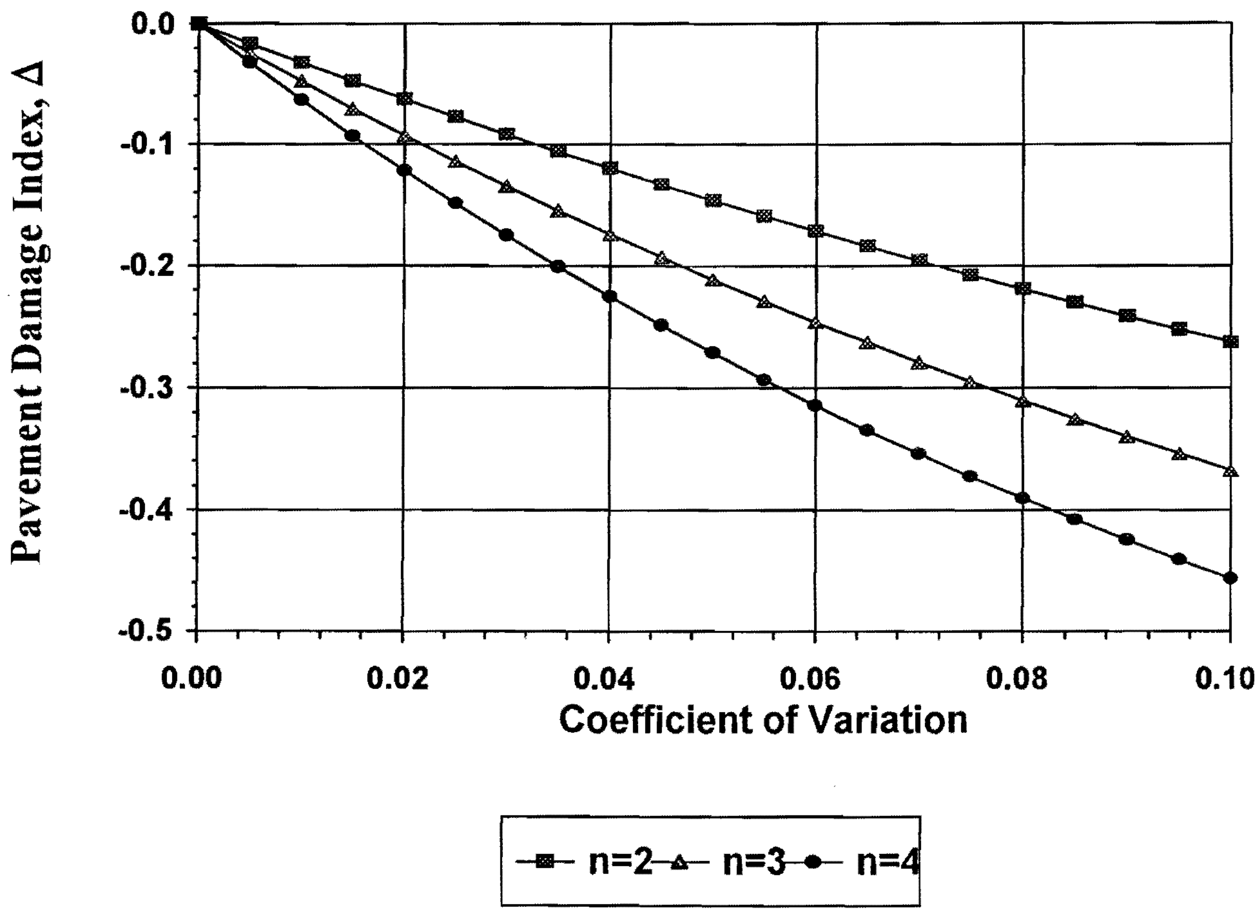

Figure 18. Relationships Between Δ and Dynamic Load Variability for Different *n* Values (Confidence Level of 95 Percent and CV_0=0)

program into a form that is directly applicable for QC/QA of pavement smoothness on overlay projects. In connection with this, Project 0-1862 entitled, "Synthesis Study of Current Truck Configurations Used in Texas," is expected to yield truck data that will be useful in establishing a "standard vehicle" for evaluating the quality of surface smoothness based on predicted performance. This TxDOT study is scheduled to begin in the 1999 fiscal year. In the interim, researchers developed an equation to estimate the coefficient of variability of predicted dynamic loads based on data generated from vehicle simulations. The development of this equation is discussed in a subsequent chapter.

EVALUATING THE ACCEPTABILITY OF ASPHALT CONCRETE OVERLAY BASED ON CHANGE IN SURFACE SMOOTHNESS

Figures 17 and 18 illustrate a basis for evaluating the acceptability of asphalt concrete overlay smoothness using the as-built profile. Since the smoothness that may be achieved depends not only on the construction procedures used but also on the existing pavement condition, the overlay design thickness, and any surface preparations planned prior to the overlay, a smoothness specification based solely on the as-built profile will primarily be applicable in the following cases:

1. on projects where the overlay thickness is more than 63 mm, or where the overlay is accompanied by milling or recycling;
2. on new flexible pavement construction projects; and
3. on projects where the overlay design thickness is between 38 to 63 mm provided that surface preparations are done to reduce or remove uneveness in the existing profile due to existing distresses.

Most overlays constructed in the state generally range in thickness from 38 to 63 mm. In many applications where overlays this thin are placed without surface preparation, it may not be applicable to use a smoothness specification based solely on the as-built profile. For these cases, it may be necessary to use a specification based on the difference between the surface smoothness before and after the overlay. An approach for developing this smoothness specification is presented in the following.

Let CV_b equal the coefficient of variation of predicted dynamic loads associated with the surface profile before construction. If it is assumed that the surface smoothness remains unchanged after the overlay, Δ, may be evaluated from Eq. (4) as follows:

$$\Delta_b = \frac{1}{(1 + zCV_b)^n} - 1 \tag{5}$$

Consequently, for any value of CV after the overlay, the acceptability of the surface smoothness may be determined as the difference in Δs based on the predicted dynamic load variability associated with the as-built profile, and the corresponding quantity determined on the basis of the profile measured before construction. This is expressed in equation form as follows:

$$\lambda = \Delta - \Delta_b = \frac{1}{(1 + zCV_1)^n} - \frac{1}{(1 + zCV_b)^n} \tag{6}$$

where, λ, is the predicted normalized change in pavement life based on the change in profile before and after the overlay, and the other variables are as defined previously. Figure 19 shows values of λ corresponding to different levels of roughness before and after the overlay. The curves were drawn assuming $n = 3.6$ and a 95 percent confidence level. Note that the smoother the pavement, the lower will be the predicted dynamic load variability as expressed by the coefficient of variation, CV. Consequently, if the surface smoothness is better after the overlay, $CV_l < CV_b$ and λ from Eq. (6) is positive, indicating an improvement over the initial condition. Conversely, if the surface smoothness is worse after the overlay, $CV_l > CV_b$ and λ is negative, indicating a reduction in predicted service life. Finally, if the surface smoothness remains unchanged after the overlay, $CV_l = CV_b$ and no change in pavement life is predicted, i.e., λ=0. Note that all of these trends are observed in Figure 19.

In practice, there is usually a tolerance band around λ = 0 to take care of slight differences between the predicted coefficients of variation before and after the overlay. For example, if the estimated CV before the overlay is 1 percent and the corresponding quantity

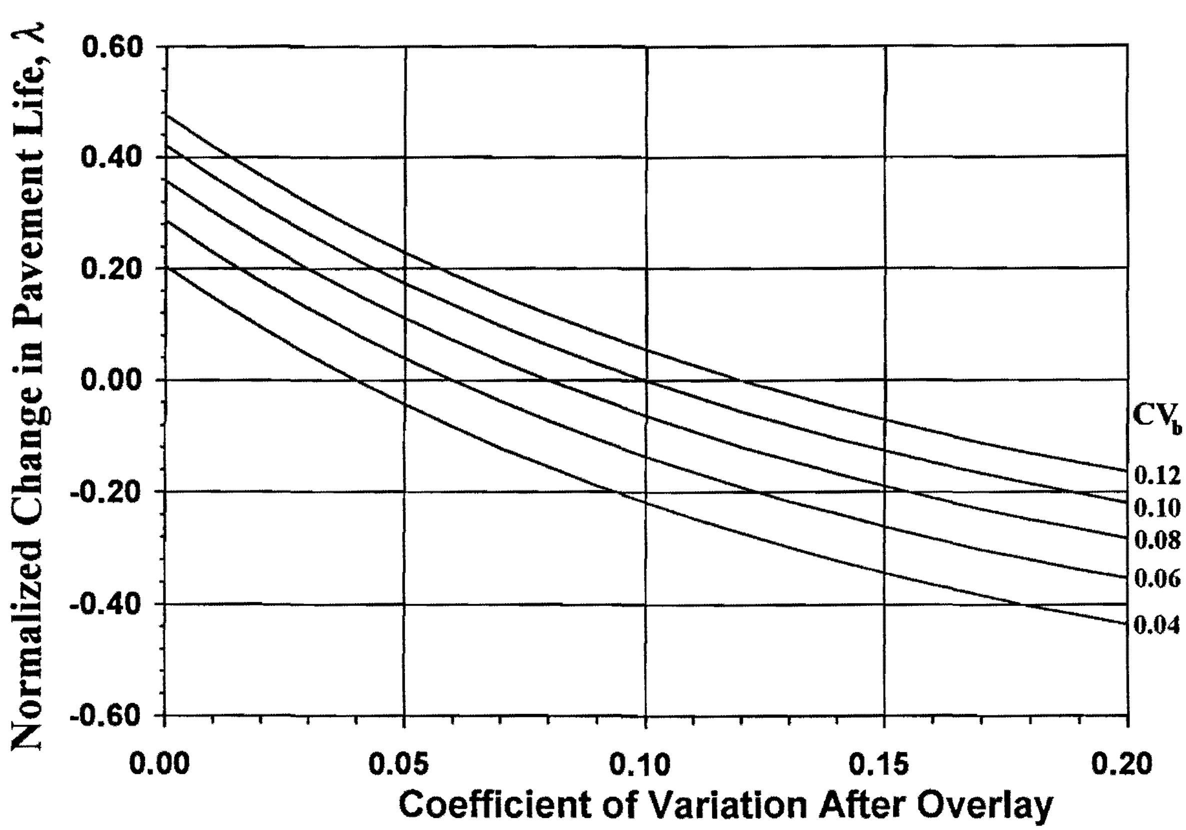

Figure 19. Predicted Normalized Change in Pavement Life Based on Change in Smoothness Before and After the Overlay (n=3.6 and Confidence Level of 95 Percent)

after the overlay is 2 percent, the predicted change in pavement life corresponding to this difference may not be significant enough to warrant a reduction in payment to the contractor. This tolerance band may be defined in terms of the range in λ within which payment to the contractor is the bid price. Denoting the prescribed tolerance as, ϵ, incentives and disincentives may thus be established based on, λ, as follows:

1. If $|\lambda| \leq \epsilon$, then payment to the contractor is the bid price;
2. If $|\lambda| > \epsilon$ and $\lambda > 0$, then the contractor is paid a bonus; and
3. If $|\lambda| > \epsilon$ and $\lambda < 0$, then the contractor is assessed a penalty.

An application of the proposed procedure is presented in the next chapter to illustrate its use. This is accomplised using profile data collected from the district overlay projects discussed in Chapter II. The results from this analysis are used later to propose a profile-based smoothness specification for asphalt concrete overlays.

CHAPTER IV

APPLICATION OF PROPOSED PROCEDURE TO EVALUATE QUALITY OF BITUMINOUS OVERLAY SMOOTHNESS

In the previous chapter, researchers proposed a procedure to evaluate the quality of asphalt concrete overlay smoothness based on the predicted change in pavement life associated with the change in surface smoothness from the overlay. This chapter presents an application of the evaluation procedure using profile data collected from the district overlay projects with TxDOT's Surface Profiler. This device has been shown to provide accurate and repeatable profiles based on the evaluation conducted by Fernando and Leong (1997). The procedure developed requires the prediction of dynamic load variability to establish the acceptability of asphalt concrete overlay smoothness. For the purpose of illustrating the procedure to evaluate the acceptability of surface smoothness, researchers simulated the response of the standard 80 kN single axle to measured profiles. In this way, the predicted normalized change in pavement life is evaluated in terms of equivalent 80 kN single axle load applications consistent with the way pavement life is quantified by TxDOT for pavement design.

A two-axle planar model consisting of a system of masses, springs, viscous dampers, and frictional dampers was used in the simulations. The 80 kN single axle was assumed to have leaf spring suspensions and dual bias-ply tires at each end, inflated to 552 kPa tire pressure. Simulation parameters, given in Table 5, are mostly based on data compiled by Fancher et al. (1986). The wheelbase and axle suspension parameters represent the mid-range of the reported values. The tire spring rate for the selected tire type and tire pressure was estimated from an equation developed by Fernando et al. (1991) using tire load-deflection curves predicted using Tielking's (1984) tire model.

Dynamic axle loads were determined using the surface profiles measured on the test sections monitored by researchers in the district overlay projects. Since surface profiles were measured on both wheelpaths of a given test section before and after the overlay, the change

Table 5. Model Parameters Used in Simulations

Parameter	Axle	Level	Unit
Frictional damping	Front	2.22	kN/side
	Rear	4.67	kN/side
Viscous damping	Front	5.25	kN-sec/m/side
	Rear	—	—
Suspension spring rate	Front	175	kN/m/side
	Rear	1050	kN/m/side
Wheelbase	—	5	m
Tire spring rate	—	973	kN/m/tire
Speed	—	97	kph
Axle load	Front	35.56	kN
	Rear	80	kN

in dynamic load variability was predicted for each overlaid section. For this purpose, the simulations were conducted using the Phase 4 computer program described by MacAdam et al. (1980). Since this program models vehicle roll in addition to pitch and yaw motions, the coefficient of variation (CV) of predicted dynamic loads was determined for each wheelpath. The average of the wheelpath CVs for the 80 kN single axle was then used to evaluate the quality of overlay surface smoothness for each test section.

COMPARISON OF PROPOSED PROCEDURE WITH PROFILOGRAPH SPECIFICATION

As noted in Chapter II, TxDOT considered an alternative acceptance schedule based on improvement in ride quality from the overlay. However, because of the low operational speed under which profilograph measurements are made, and in view of the results from the field study, the decision was made, at least for the short-term, to use the profile index measured after the overlay for acceptance testing. This alternative specification is reviewed herein as part of evaluating the proposed profile-based procedure for assessment of overlay surface smoothness.

Table 6 shows the payment schedule based on improvement in ride quality that was previously considered by TxDOT. Under this alternative specification, two payment schedules are used. The profile index measured after the overlay is also compared against the payment schedule shown in Table 7, and the schedule resulting in the higher incentive or lower penalty is applied. This scheme thus addresses situations where the smoothness after the overlay is acceptable but is slightly less than the smoothness measured before the overlay. Cases like these may arise on portions of a given project which are initially smooth, as was observed on the San Angelo and Odessa CMHB projects discussed in Chapter II. It is noted that the payment schedule shown in Table 7 differs from the schedule shown in Table 4. The tighter limits in Table 7 were established after the field study of district overlay projects was conducted.

Under the alternative profilograph specification given in Tables 6 and 7, assessment of the overlay smoothness on the test sections monitored during the field study yields the results given in Table 8. Note that data on the Carthage test sections are not included in the table since no profilograph measurements before the overlay are available. The results given in Table 8 show that, for each test section, the surface smoothness after placement of the overlay passes the alternative profilograph specification. On all but three sections where payment is the bid price, bonuses of varying amounts would have been paid to the contractor, with the sum of the bonuses for all sections amounting to $2910.

From the vehicle simulations the coefficients of variation for all wheelpaths profiled were predicted, both before and after the overlay. The averages of the wheelpath CVs determined for the 80 kN single axle are given in Table 9. The average coefficients of variation before and after the overlay were used in Eq. (6) to predict the normalized change in pavement life, λ, due to the overlay. Table 9 shows the values of λ computed for the different test sections. These values were determined using a value of 3.6 for the fracture parameter, n, and a 95 percent confidence level. It is observed that, in all but three test sections, λ, is positive indicating an improvement over the initial surface smoothness.

Table 6. Pay Adjustment Schedule Based on Percent Improvement in Ride Quality

Percent Improvement to Existing Profile Index (per 0.16 km Segment)	Pay Adjustment[a]	
	Posted Speed > 72 kph	Posted Speed ≤ 72 kph
91% or more	+ $90	+ $90
81% through 90%	+ $70	+ $70
71% through 80%	+ $50	+ $50
61% through 70%	+ $35	+ $35
51% through 60%	$0	+ $20
46% through 50%	- $35	$0
40% through 45%	- $50	- $20
36% through 39%	- $70	- $50
30% through 35%	- $105	- $105
25% through 29%	- $140	- $140
Less than 25%	Corrective work required	

[a] The new profile index will be compared to the pay adjustment schedule given in Table 7 and the higher incentive or lower penalty will be applied.

Table 7. Updated Pay Adjustment Schedule Based on Final Profile Index

Profile Index per 0.16 km Segment	Pay Adjustment[a]	
	Posted Speed > 72 kph	Posted Speed ≤ 72 kph
1.5 or less	+ $90	+ $90
1.6 through 2.0	+ $70	+ $70
2.1 through 3.0	+ $50	+ $50
3.1 through 4.0	+ $35	+ $35
4.1 through 6.0	$0	+ $20
6.1 through 8.0	- $35	$0
8.1 through 9.0	- $50	- $20
9.1 through 10.0	- $70	- $50
10.1 through 11.0	- $105	- $105
11.1 through 12.0	- $140	- $140
Over 12.0	Corrective work required	

[a] These pay adjustment values will apply, for each 0.16 km segment tested, unless other pay adjustment values are shown on the plans. No bonus will be paid for pavement sections which were originally constructed with a pay deduction. There will be no pay adjustments for the sections where the contractor took corrective action.

Table 8. Assessment of Surface Smoothness on District Overlay Projects Using Alternative Profilograph Specification

Project	Section	Avg. PI Before Any Surface Preparation	Avg. PI After the Overlay	Percent Improvement	Bonus or Penalty ($)[a]		
					from Table 6	from Table 7	Payment for Section
Atlanta	1	42.3	1.8	96	90	70	90
	2	10.3	5.6	46	-35	0	0
	3	41.1	6.0	85	70	0	70
	4	22.5	1.0	95	90	90	90
	5	16.4	4.1	75	50	0	50
	6	4.2	2.1	50	-35	50	50
Odessa CRM	1	2.6	0.6	76	50	90	90
	2	10.7	1.7	85	70	70	70
	3	13.4	2.6	81	70	50	70
	4	9.6	3.3	65	35	35	35
	5	12.2	3.1	74	50	35	50
	6	9.4	2.8	70	35	50	50
	7	18.6	1.9	90	70	70	70
	8	35.2	2.5	93	90	50	90
	9	37.4	3.1	92	90	35	90
San Angelo	1	38.4	0.5	99	90	90	90
	2	21.6	0.3	99	90	90	90
	3	31.2	0.4	99	90	90	90
	4	18.5	2.3	87	70	50	70
	5	11.1	0.9	92	90	90	90
	6	8.4	0.9	89	70	90	90
San Antonio	1	18.4	0.9	95	90	90	90
	2	10.7	1.2	88	70	90	90
	3	27.9	3.4	88	70	35	70
	4	43.3	8.2	81	70	-20	70
	5	45.1	7.2	84	70	0	70
	6	29.6	1.3	96	90	90	90
	7	13.0	1.2	91	90	90	90
	8	17.1	1.6	91	90	70	90
	9	10.6	0.0	100	90	90	90

Table 8. Assessment of Surface Smoothness on District Overlay Projects Using Alternative Profilograph Specification (continued)

Project	Section	Avg. PI Before Any Surface Preparation	Avg. PI After the Overlay	Percent Improvement	Bonus or Penalty ($)[a]		
					from Table 6	from Table 7	Payment for Section
Dallas	1	20.7	5.6	73	50	0	50
	2	20.0	5.6	72	50	0	50
	3	23.2	5.9	75	50	0	50
	4	20.1	5.2	74	50	0	50
	5	25.6	4.0	85	70	35	70
	6	15.4	4.6	70	35	0	35
Odessa CMHB	1	3.8	2.7	29	-140	50	50
	2	1.5	1.4	3	Correct	90	90
	3	0.4	4.1	-1001	Correct	0	0
	4	17.4	2.9	83	70	50	70
	5	32.9	0.7	98	90	90	90
	6	14.9	2.7	82	70	50	70
	7	3.7	5.3	-42	Correct	0	0

[a] The higher bonus or lower penalty from the schedules given in Tables 6 and 7 is used.

Table 9. Assessment of Surface Smoothness on District Overlay Projects Using Proposed Profile-Based Methodology

Project	Section	Average Coefficient of Variation (percent)		Predicted Normalized Change in Pavement Life, λ
		Before Any Surface Preparation	After the Overlay	
Atlanta	1	10.19	4.54	0.20
	2	6.24	5.30	0.04
	3	11.99	3.02	0.32
	4	7.28	4.46	0.11
	5	6.74	4.52	0.09
	6	4.89	4.07	0.04
Odessa CRM	1	4.70	3.48	0.05
	2	3.96	3.56	0.02
	3	7.39	3.09	0.17
	4	5.76	4.33	0.06
	5	9.25	5.25	0.14
	6	8.27	3.77	0.17
	7	5.90	4.10	0.07
	8	7.23	3.75	0.14
	9	6.57	3.97	0.11
San Angelo	1	8.74	4.03	0.18
	2	5.21	4.02	0.05
	3	6.73	4.17	0.10
	4	11.68	3.63	0.28
	5	9.37	4.26	0.19
	6	13.67	4.17	0.31
San Antonio	1	6.93	2.61	0.18
	2	5.00	3.16	0.08
	3	8.42	3.34	0.20
	4	11.63	4.44	0.24
	5	10.90	4.42	0.22
	6	8.74	3.40	0.21
	7	6.05	2.64	0.15
	8	5.41	3.02	0.10
	9	5.60	2.93	0.12

Table 9. Assessment of Surface Smoothness on District Overlay Projects Using Proposed Profile-Based Methodology (continued)

Project	Section	Average Coefficient of Variation (percent)		Predicted Normalized Change in Pavement Life, λ
		Before Any Surface Preparation	After the Overlay	
Dallas	1	7.74	3.89	0.15
	2	9.19	4.48	0.17
	3	6.61	5.23	0.05
	4	9.28	4.53	0.17
	5	9.06	4.23	0.18
	6	8.74	4.72	0.15
Odessa CMHB	1	4.30	4.33	-0.001
	2	3.64	4.08	-0.02
	3	6.02	4.39	0.07
	4	8.69	3.86	0.18
	5	6.64	4.20	0.10
	6	4.45	4.50	-0.001
	7	9.58	5.23	0.15

There are three test sections belonging to the Odessa CMHB project where the predicted coefficients of variation before the overlay are slightly less than the corresponding statistics after the overlay. For these sections, negative values of λ were determined as shown in Table 9. The magnitudes of these λs are rather small, ranging from 0.1 to 2 percent. For practical purposes, the overlay smoothness of the test sections may be considered acceptable. As noted in Chapter III, the proposed methodology allows the specification of a tolerance band to take care of slight differences between the predicted coefficients of variation before and after the overlay. Based on the results presented in Table 9, a tolerance band within a ±5 percent range appears to be appropriate.

Figure 20 shows the approach for determining pay adjustments in the proposed methodology to evaluate overlay smoothness based on surface profile. In this methodology, the damage-based index, λ, is used in lieu of the profile index from the profilograph. The notations in the figure are defined as follows:

1. ΔP is the pay adjustment for a given test interval on which profile measurements are made to establish the acceptability of the surface smoothness;
2. λ_m is the upper limit of λ at which the maximum monetary incentive, ΔP_m, is reached. For values of λ greater than λ_m, the monetary incentive is ΔP_m;
3. ϵ_0 and ϵ_m define, respectively, the lower and upper limits of the tolerance band within which the pay adjustment is zero;
4. The base incentive is denoted as, b_m, while the base penalty is b_0; and
3. λ_0 is the lower limit of λ at which the maximum penalty, ΔP_0, is reached. For values of λ less than λ_0, corrective work at the contractor's expense will be required.

Following Figure 20, the pay adjustments are determined as shown in Table 10. The approach presented provides flexibility in determining pay adjustments through the specification of the constants, ΔP_m, λ_m, b_m, ϵ_m, ϵ_0, b_0, ΔP_0, and λ_0 that define the payment schedule. These constants may be specified such that the resulting pay adjustments reflect, as closely as desired, the value attached by TxDOT to the contractor's work. To illustrate the proposed approach, assume that the constants are defined as follows:

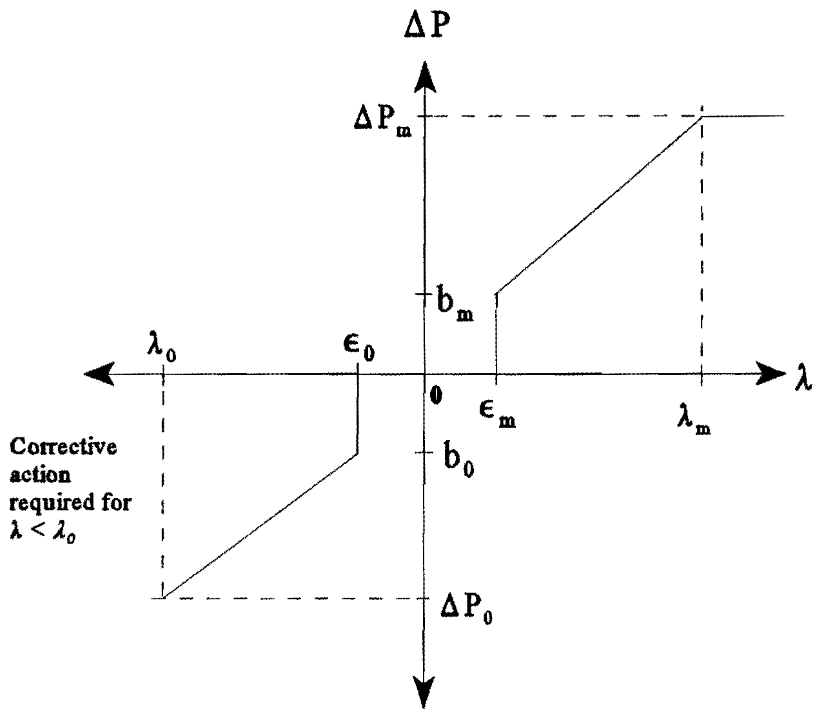

Figure 20. Illustration of Proposed Approach to Determine Pay Adjustments Based on λ

Table 10. Calculation of Pay Adjustments to Evaluate Overlay Smoothness Based on λ

Range of λ	Pay Adjustment[a]
$\lambda < \lambda_0$	Corrective work at contractor's expense
$\lambda_0 \le \lambda < \epsilon_0$	$b_0 + \frac{\Delta P_0 - b_0}{\lambda_0 - \epsilon_0} (\lambda - \epsilon_0)$
$\epsilon_0 \le \lambda \le \epsilon_m$	0
$\epsilon_m < \lambda \le \lambda_m$	$b_m + \frac{\Delta P_m - b_m}{\lambda_m - \epsilon_m} (\lambda - \epsilon_m)$
$\lambda > \lambda_m$	ΔP_m

[a] Pay adjustments are rounded off to the nearest dollar.

1. Maximum monetary incentive, ΔP_m, of $90 (same as profilograph specification);
2. λ_m of 35 percent;
3. Base incentive, b_m, of $35 (the starting bonus in the profilograph specification);
4. Lower (ϵ_0) and upper (ϵ_m) limits of −3 and +3 percent respectively on the tolerance band;
5. Base penalty, b_0, of −$35 (the starting penalty in the profilograph specification);
6. Threshold for corrective work (λ_0) of −10 percent; and
7. Maximum penalty, ΔP_0, of −$140 (same as profilograph specification).

If the above constants are used in determining the pay adjustments for the test sections surveyed in the district overlay projects, the results given in Table 11 are obtained. Note that the monetary incentives determined using the proposed procedure are generally lower than those from the profilograph specification, with the incentives totaling $2139 compared to $2910 for the profilograph specification. However, the criteria used are different so that the results are not directly comparable, although the proposed procedure has a more rational and concrete basis, in the opinion of researchers. Because of the difference noted, applying the same maximum and base incentives used in the profilograph specification may not be entirely appropriate. Consequently, there is a need to evaluate the constants of the pay function shown in Figure 20 so that the pay adjustments reflect the value attached by TxDOT to the contractor's work based on the variable, λ, and not the profile index. This can be done as part of efforts to implement the proposed procedure. To illustrate, if the pay adjustments are determined using a maximum incentive of $140 (equal in magnitude to the maximum penalty assessed in the current profilograph specification), the results given in Table 12 are obtained. Note that in this instance, the incentives determined are more comparable to those obtained from the profilograph specification. The total incentives amount to $2850 compared to $2910 for the profilograph specification.

The results given in Table 12 are illustrated graphically in Figure 21. Each radius of the circle represents a test section. For each radius, the average coefficients of variation before and after the overlay are plotted as dots and squares, respectively. The position of a point along a given radius denotes the value of the average CV for the point. The average CV

Table 11. Sample Illustration of Determining Pay Adjustments in the Proposed Procedure for Evaluating Overlay Smoothness

Project	Section	Average Coefficient of Variation (percent)		Predicted Normalized Change in Pavement Life, λ	Pay Adjustment (US$)
		Before Any Surface Preparation	After the Overlay		
Atlanta	1	10.19	4.54	0.20	64
	2	6.24	5.30	0.04	36
	3	11.99	3.02	0.32	84
	4	7.28	4.46	0.11	49
	5	6.74	4.52	0.09	45
	6	4.89	4.07	0.04	36
Odessa CRM	1	4.70	3.48	0.05	39
	2	3.96	3.56	0.02	0
	3	7.39	3.09	0.17	60
	4	5.76	4.33	0.06	40
	5	9.25	5.25	0.14	54
	6	8.27	3.77	0.17	60
	7	5.90	4.10	0.07	43
	8	7.23	3.75	0.14	54
	9	6.57	3.97	0.11	48
San Angelo	1	8.74	4.03	0.18	60
	2	5.21	4.02	0.05	38
	3	6.73	4.17	0.10	47
	4	11.68	3.63	0.28	78
	5	9.37	4.26	0.19	62
	6	13.67	4.17	0.31	82
San Antonio	1	6.93	2.61	0.18	61
	2	5.00	3.16	0.08	44
	3	8.42	3.34	0.20	64
	4	11.63	4.44	0.24	72
	5	10.90	4.42	0.22	68
	6	8.74	3.40	0.21	65
	7	6.05	2.64	0.15	55
	8	5.41	3.02	0.10	48
	9	5.60	2.93	0.12	50

Table 11. Sample Illustration of Determining Pay Adjustments in the Proposed Procedure for Evaluating Overlay Smoothness (continued)

Project	Section	Average Coefficient of Variation (percent)		Predicted Normalized Change in Pavement Life, λ	Pay Adjustment (US$)
		Before Any Surface Preparation	After the Overlay		
Dallas	1	7.74	3.89	0.15	56
	2	9.19	4.48	0.17	59
	3	6.61	5.23	0.05	39
	4	9.28	4.53	0.17	59
	5	9.06	4.23	0.18	60
	6	8.74	4.72	0.15	55
Odessa CMHB	1	4.30	4.33	-0.001	0
	2	3.64	4.08	-0.02	0
	3	6.02	4.39	0.07	41
	4	8.69	3.86	0.18	61
	5	6.64	4.20	0.10	47
	6	4.45	4.50	-0.001	0
	7	9.58	5.23	0.15	56

Table 12. Pay Adjustments Determined Using a Maximum Incentive of $140

Project	Section	Average Coefficient of Variation (percent)		Predicted Normalized Change in Pavement Life, λ	Pay Adjustment (US$)
		Before Any Surface Preparation	After the Overlay		
Atlanta	1	10.19	4.54	0.20	90
	2	6.24	5.30	0.04	37
	3	11.99	3.02	0.32	129
	4	7.28	4.46	0.11	61
	5	6.74	4.52	0.09	54
	6	4.89	4.07	0.04	37
Odessa CRM	1	4.70	3.48	0.05	43
	2	3.96	3.56	0.02	0
	3	7.39	3.09	0.17	83
	4	5.76	4.33	0.06	45
	5	9.25	5.25	0.14	72
	6	8.27	3.77	0.17	82
	7	5.90	4.10	0.07	49
	8	7.23	3.75	0.14	71
	9	6.57	3.97	0.11	60
San Angelo	1	8.74	4.03	0.18	83
	2	5.21	4.02	0.05	42
	3	6.73	4.17	0.10	59
	4	11.68	3.63	0.28	117
	5	9.37	4.26	0.19	87
	6	13.67	4.17	0.31	126
San Antonio	1	6.93	2.61	0.18	85
	2	5.00	3.16	0.08	52
	3	8.42	3.34	0.20	90
	4	11.63	4.44	0.24	105
	5	10.90	4.42	0.22	99
	6	8.74	3.40	0.21	93
	7	6.05	2.64	0.15	73
	8	5.41	3.02	0.10	59
	9	5.60	2.93	0.12	63

Table 12. Pay Adjustments Determined Using a Maximum Incentive of $140 (continued)

Project	Section	Average Coefficient of Variation (percent)		Predicted Normalized Change in Pavement Life, λ	Pay Adjustment (US$)
		Before Any Surface Preparation	After the Overlay		
Dallas	1	7.74	3.89	0.15	75
	2	9.19	4.48	0.17	82
	3	6.61	5.23	0.05	43
	4	9.28	4.53	0.17	82
	5	9.06	4.23	0.18	84
	6	8.74	4.72	0.15	74
Odessa CMHB	1	4.30	4.33	-0.001	0
	2	3.64	4.08	-0.02	0
	3	6.02	4.39	0.07	47
	4	8.69	3.86	0.18	85
	5	6.64	4.20	0.10	57
	6	4.45	4.50	-0.001	0
	7	9.58	5.23	0.15	75

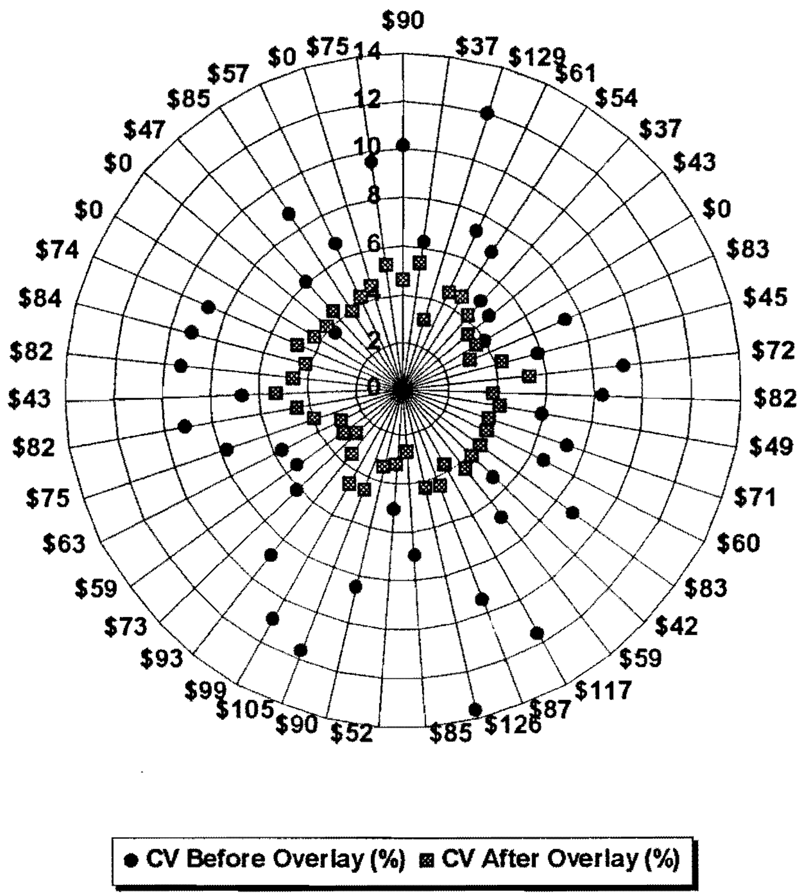

Figure 21. Results from Evaluation of Overlay Smoothness Based on Change in Predicted Dynamic Load Variability After the Overlay

is 0 percent at the center and increases radially outward up to a value of 14 percent at the outside perimeter. Along this perimeter, the pay adjustments for the different sections are given. As an example, the radius corresponding to twelve o'clock in Figure 21 represents the first test section of the Atlanta project. From the figure, the average CV before the overlay is about 10 percent. After the overlay, the predicted dynamic load variability is reduced to about 4.5 percent resulting in a pay adjustment of $90 based on the damage index, λ. Note from the figure that the predicted coefficients of variation after the overlay are below 6 percent for all test sections indicating that good levels of smoothness were achieved. Note also that the pay adjustments depend on the change in smoothness after the overlay so that a lower coefficient of variation will not necessarily result in a higher bonus. While the sections evaluated showed good levels of smoothness after the overlay, this observation indicates a possible need to specify a maximum allowable level of roughness in a specification that is based on the change in smoothness after the overlay.

It should be noted that differences in opinion exist on whether a smoothness specification for overlays should be based on the change in profile brought about by the overlay or solely on the final surface profile. From the road user's perspective, the final surface is what matters. However, it is one thing to require pavement smoothness, and another to have construction specifications for an overlay project that allow the contractor to achieve the smoothness requirements. This, of course, is the job of the pavement engineer. In view of the thin overlays that are generally placed in the state, there is an understandable concern among contractors regarding the applicability of smoothness requirements, particularly on projects involving thin overlays where no surface preparations are planned. While there is evidence from the field study that smoothness requirements can also be met on these projects, the data are rather limited and apply only to thin overlays of pavements that show minimal distress or where the primary deficiency is less than desired riding quality. In the author's opinion, if no surface preparations are planned on projects involving thin overlays, it would be appropriate to use a specification based on the change in surface smoothness, particularly if the engineer is uncertain that the alternative specification based on final profile is applicable. Having this option would provide a motivation to the contractor to achieve the best smoothness that can be realized under the given conditions and is a better alternative, in the author's opinion, to dropping the smoothness specification on these projects or using the straightedge to check the final smoothness. For these reasons, a specification based on the change in surface profile is among one of the methods considered in this study for evaluating overlay smoothness. A smoothness specification of this form is proposed later for TxDOT's consideration.

CHAPTER V

RELATIONSHIP BETWEEN DYNAMIC LOAD VARIABILITY AND RIDE QUALITY

The methodology presented requires the prediction of dynamic load variability to establish the acceptability of asphalt concrete overlay smoothness. In this study, the dynamic load variability is evaluated by simulating the response of the standard 80 kN single axle to the measured profile, using the two-axle planar model referred to in the previous chapter. To provide an alternative to vehicle simulation and facilitate the interim implementation of the proposed procedure, this research evaluated the relationship between dynamic load variability and pavement ride quality as measured by the International Roughness Index (IRI). The development of this relationship is presented in this chapter.

ESTIMATING THE COEFFICIENT OF VARIATION OF PREDICTED DYNAMIC LOADS FROM IRI

To evaluate the relationship between dynamic load variability and IRI, a data base of surface profiles was initially assembled that covered the range of pavement roughness shown in Table 13. Each profile given in the table was used to simulate the response of the standard 80 kN single axle at speeds of 48, 64, 80, 97, and 113 kph over a simulation distance of 161 m. The coefficients of variation (CV) of the predicted dynamic loads for this standard axle were then computed and used in a regression analysis to determine the relationship between dynamic load variability, IRI, and vehicle speed. In addition, results from vehicle simulations using profiles from the test sections surveyed in the district overlay projects were combined with the simulation results on the profiles shown in Table 13 to evaluate the relationship between dynamic load variability and ride quality. The form of the regression relationship was selected on the basis of Sweatman's (1983) finding that the CV is highly correlated with the interaction between roughness and vehicle speed. This finding was corroborated by the

Table 13. Profile Data Used to Evaluate Relationship Between Dynamic Load Variability, IRI, and Vehicle Speed

Data File	RWP IRI (mm/m)	LWP IRI (mm/m)	Present Serviceability Index	Average IRI (mm/m)
PSI2-00.DAT	3.55	3.63	2.00	3.590
PSI2-19.DAT	3.44	3.41	2.19	3.425
PSI2-38.DAT	3.77	2.64	2.38	3.205
PSI2-58.DAT	2.72	3.00	2.58	2.860
PSI2-80.DAT	2.41	2.37	2.80	2.390
PSI3-02.DAT	2.24	2.27	3.02	2.255
PSI3-19.DAT	2.16	1.94	3.19	2.050
PSI3-41.DAT	1.86	1.97	3.41	1.915
PSI3-60.DAT	1.68	1.66	3.60	1.670
PSI3-79.DAT	1.62	1.45	3.79	1.535
PSI4-00.DAT	1.31	1.37	4.00	1.340
PSI4-12.DAT	1.17	1.31	4.12	1.240
PSI4-31.DAT	1.18	1.01	4.31	1.095
PSI4-52.DAT	0.89	0.84	4.52	0.865
PSI4-72.DAT	0.78	0.80	4.72	0.790
PSI4-91.DAT	0.64	0.69	4.91	0.665

results of the regression analysis which led to the following equation for predicting dynamic load variability:

$$CV = 0.04123(V \times IRI) \tag{7}$$

where,

CV = average of the coefficients of variation of the predicted dynamic loads for the inner and outer wheelpaths, in percent;

V = vehicle speed in kph; and

IRI = average of the IRIs determined for both wheelpaths, in mm/m.

Figure 22 compares the coefficients of variation computed from the above equation with the corresponding values determined from the vehicle simulations. Note the good

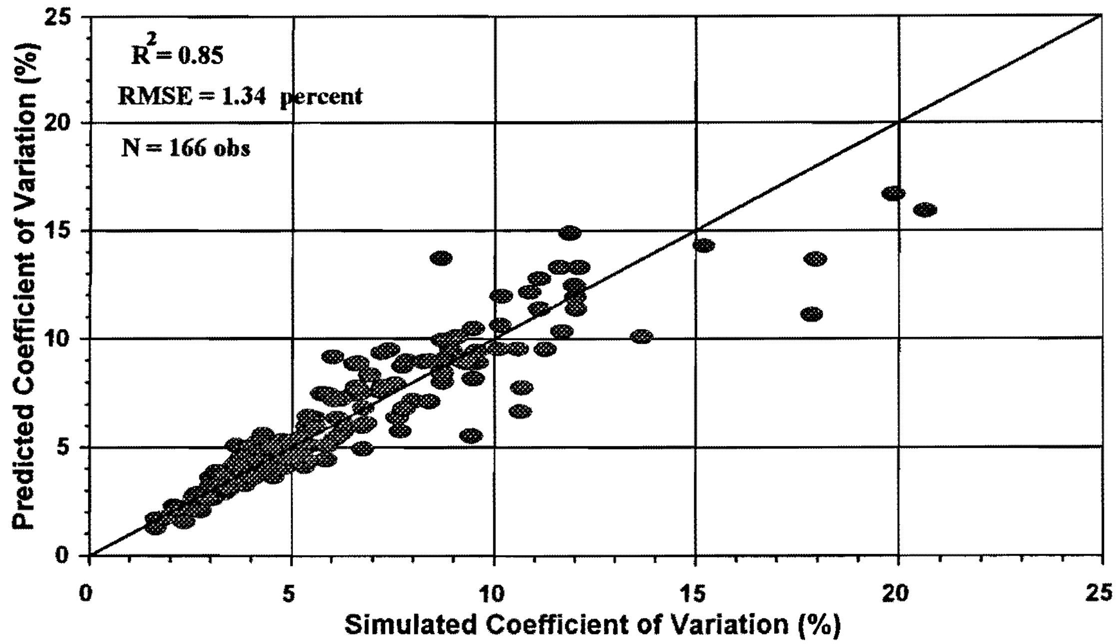

Figure 22. Comparison of Predicted Coefficients of Variation with Values Determined from Vehicle Simulations

agreement between the predicted and simulated values as indicated by the coefficient of determination, R^2, of 85 percent and a root-mean-square error (RMSE) of 1.34 percent. This strong relationship between CV, IRI, and vehicle speed is consistent with the findings from the field study conducted by Sweatman (1983). As noted in Chapter III, Sweatman found, from analysis of field measurements, that dynamic loading is strongly correlated to the interaction term, $VR^{0.5}$. This and other forms of the interaction between vehicle speed and roughness were evaluated in the regression analysis of the simulation data. The best relationship, in terms of the agreement between the simulated and predicted data, was obtained using the simple product of the vehicle speed and IRI as the predictor variable, as given in Eq. (7). This equation is applied in the next section to evaluate the surface smoothness on the test sections monitored in the district overlay projects. In this way, researchers verified that reasonable results are also obtained when the above relationship is used, in lieu of vehicle simulation, to evaluate the acceptability of asphalt concrete overlay smoothness based on measured profile.

APPLICATION OF EQUATION FOR PREDICTING DYNAMIC LOAD VARIABILITY IN THE EVALUATION OF OVERLAY SMOOTHNESS

Table 14 shows the CVs predicted using the IRIs from the profiles measured in the field study of district overlay projects. The CVs determined were used with Eq. (6) to predict the normalized change in pavement life, λ, due to the overlay. This index is used in the methodology developed to evaluate the quality of the overlay smoothness based on predicted pavement life. The λs determined using the predicted CVs from Eq. (7) are compared with the corresponding values from the vehicle simulation in Figure 23. There is a noticeable scatter of the data points about the line of equality that is attributed to the error associated with the regression relationship between CV, IRI, and vehicle speed. However, the agreement between the λs computed from the IRIs and those from vehicle simulations is reasonable. The coefficient of determination, R^2, between the λs plotted in the figure is 70 percent with an average absolute error of 3.58 percent. These results indicate the accuracy that may be expected when Eq. (7) is used to estimate the coefficient of variation of predicted dynamic loads to evaluate the quality of overlay surface smoothness. Considering the fairly good correlation shown in Figure 23, the results of evaluations using the regression relationship should generally be consistent with those obtained using vehicle simulations to predict the dynamic load variability. Table 15 shows the pay adjustments based on the λs predicted from the IRIs. These were determined using the same pay function used in Chapter IV to evaluate the smoothness of the test sections in the district overlay projects based on the dynamic load variability associated with the measured profiles. The pay adjustments from this evaluation are also presented in Table 15. It is observed that the pay adjustments are generally consistent between the two methods. The sum of the pay adjustments for the sections evaluated as well as the average of the adjustments are given at the bottom of Table 15 and are observed to be comparable between the two methods.

Table 14. Predicted CVs and λs Based on IRIs Determined from District Overlay Projects

Project	Section	IRI (mm/m)		Predicted CV (percent)		Predicted Normalized Change in Pavement Life, λ (percent)
		Before Any Surface Preparation	After Overlay	Before Any Surface Preparation	After Overlay	
Atlanta	1	3.005	1.200	11.97	4.78	23.79
	2	1.815	1.310	7.23	5.22	7.62
	3	3.125	0.910	12.45	3.62	30.04
	4	1.965	1.225	7.83	4.88	11.07
	5	1.505	1.160	5.99	4.62	5.54
	6	1.130	1.065	4.50	4.24	1.11
Odessa CRM	1	1.265	0.880	5.04	3.51	6.65
	2	1.125	1.020	4.48	4.06	1.81
	3	2.380	0.905	9.48	3.60	21.92
	4	1.880	1.070	7.49	4.26	12.53
	5	2.300	1.375	9.16	5.48	12.97
	6	2.245	0.995	8.94	3.96	18.65
	7	1.875	1.080	7.47	4.30	12.29
	8	2.350	1.125	9.36	4.48	17.70
	9	2.225	1.265	8.86	5.04	13.81
San Angelo	1	2.015	0.980	8.03	3.90	15.94
	2	1.360	1.005	5.42	4.00	5.94
	3	1.895	0.960	7.55	3.82	14.67
	4	2.595	1.065	10.34	4.24	21.62
	5	2.230	1.115	8.88	4.44	16.38
	6	2.535	1.315	10.10	5.24	16.75
San Antonio	1	2.095	0.665	8.34	2.65	22.83
	2	1.335	0.975	5.32	3.88	6.07
	3	2.260	0.800	9.00	3.19	22.37
	4	3.335	1.175	13.28	4.68	27.48
	5	3.050	1.280	12.15	5.10	22.93
	6	2.110	0.790	8.40	3.15	20.65
	7	1.805	0.715	7.19	2.85	17.93
	8	1.615	0.815	6.43	3.25	13.30
	9	1.485	0.665	5.91	2.65	14.18

Table 14. Predicted CVs and λs Based on IRIs Determined from District Overlay Projects (continued)

Project	Section	IRI (mm/m)		Predicted CV (percent)		Predicted Normalized Change in Pavement Life, λ (percent)
		Before Any Surface Preparation	After Overlay	Before Any Surface Preparation	After Overlay	
Dallas	1	2.195	1.150	8.74	4.58	15.34
	2	2.260	1.205	9.00	4.80	15.24
	3	1.955	1.245	7.79	4.96	10.61
	4	2.240	1.150	8.92	4.58	15.91
	5	2.535	1.220	10.10	4.86	18.31
	6	2.495	1.210	9.94	4.82	18.00
Odessa CMHB	1	1.405	1.090	5.60	4.34	5.18
	2	1.280	0.910	5.10	3.62	6.35
	3	2.305	1.030	9.18	4.10	18.78
	4	3.440	1.055	13.70	4.20	30.51
	5	2.230	1.095	8.88	4.36	16.72
	6	1.305	1.260	5.20	5.02	0.73
	7	2.370	1.165	9.44	4.64	17.26

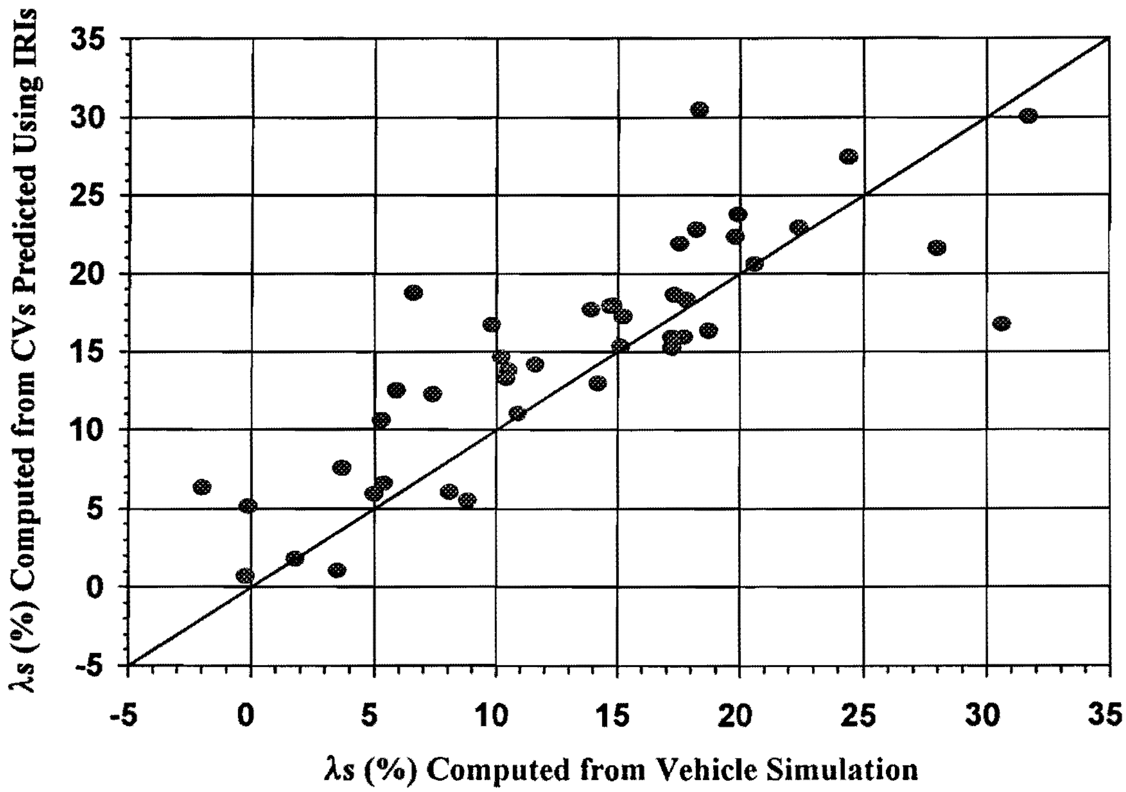

Figure 23. Comparison of λs Computed by Vehicle Simulation with λs Based on IRIs

Table 15. Comparison of Pay Adjustments Determined Using λs from Vehicle Simulations with λs Predicted from IRIs

Project	Section	Pay Adjustment ($ per 161 m Segment per Lane)	
		Based on CVs Determined by Vehicle Simulation	Based on CVs Predicted from IRIs
Atlanta	1	64	71
	2	36	43
	3	84	81
	4	49	49
	5	45	39
	6	36	0
Odessa CRM	1	39	41
	2	0	0
	3	60	68
	4	40	51
	5	54	52
	6	60	62
	7	43	51
	8	54	60
	9	48	54
San Angelo	1	60	57
	2	38	40
	3	47	55
	4	78	67
	5	62	58
	6	82	59

Table 15. Comparison of Pay Adjustments Determined Using λs from Vehicle Simulations with λs Predicted from IRIs (continued)

Project	Section	Pay Adjustment ($ per 161 m Segment per Lane)	
		Based on CVs Determined by Vehicle Simulation	Based on CVs Predicted from IRIs
San Antonio	1	61	69
	2	44	40
	3	64	68
	4	72	77
	5	68	69
	6	65	65
	7	55	61
	8	48	53
	9	50	54
Dallas	1	56	56
	2	59	56
	3	39	48
	4	59	57
	5	60	61
	6	55	61
Odessa CMHB	1	0	39
	2	0	41
	3	41	62
	4	61	82
	5	47	59
	6	0	0
	7	56	60
Total		2139	2296
Average		50	53

CHAPTER VI
DEVELOPMENT OF AN ALTERNATIVE PROFILOGRAPH SMOOTHNESS SPECIFICATION

The existing profilograph smoothness specification has been implemented in Texas over the past four years. As such, it is a procedure that TxDOT engineers and paving contractors have become accustomed to and gained experience in since its initial implementation. To provide a transition from the current specification to the profile-based methodology developed in this study, efforts were made to evaluate the relationship between the profile index (PI) determined from the profilograph, and the International Roughness Index (IRI) determined from pavement profile. The objective was to determine whether a suitable relationship can be found that can ease the conversion from the existing specification to the profile-based procedure presented in the previous chapters. These efforts led to the development of an alternative profilograph specification that uses the null or zero blanking band PI determined on the final surface, to evaluate the quality of the overlay smoothness. The evaluation of the relationship between PI and IRI, and the subsequent development of the provisional profilograph specification, are documented in this chapter.

PROFILOGRAPH SIMULATION

To evaluate the relationship between PI and IRI, researchers simulated the response of the profilograph to surface profile. While it is recognized that field measurements of IRI and PI are available to perform this evaluation, the differences between wheelpaths tracked will introduce errors that will tend to mask the true relationship between these two indices. By determining these statistics from the same surface profile, this source of variability is eliminated, and a better evaluation of the relationship between IRI and PI may be achieved. Thus, researchers conducted profilograph simulations to predict the profile index from measured surface profiles. For this purpose, the kinematic model derived by Kulakowski and Wambold (1989) was initially evaluated. To accomplish this, researchers wrote a simulation program of the kinematic model and used it with measured profiles to get the profilograph response in the form of simulated profilograms. These were subsequently compared with corresponding traces obtained with a manual profilograph to evaluate the accuracy of the simulated data. In addition, researchers compared profile indices determined from measured and simulated traces.

Three test sections, ranging in smoothness, from smooth, medium-smooth, to rough, were used in the evaluation of the profilograph model. Two of the test sections are located at the end of Runway 35L inside the Texas A&M Riverside Campus, and the other is on the southbound, outside lane of SH 47, a new highway opened to traffic in August 1996. These test sections were used in the profile equipment evaluation reported by Fernando and Leong (1997). Researchers used test data from that evaluation to verify the kinematic model for simulating the profilograph response to measured profile. For this purpose, surface profiles were measured along designated wheelpaths which were delineated with paint stripes to guide the measurements on the test sections.

To predict the profilograph response, rod and level data were input to the simulation program. Rod and level measurements were taken at 152.4 mm intervals along a prescribed wheelpath using a digital level that provided a resolution of 0.03 mm. Both filtered and unfiltered rod and level data were used. The unfiltered rod and level data represent the true surface profile along the test wheelpaths. The data were also filtered using a third-order Butterworth filter that removed wavelengths 33 m and longer resulting in filtered profiles that were also input to the simulation program. The simulated profilograph traces were subsequently compared with corresponding profilograms taken with the manual McCracken profilograph. The comparisons showed that the simulated profilograms match the measured profilograms quite favorably as illustrated in Figures 24 and 25. The simulated profilograms in the figures are based on filtered rod and level data. It is observed that the simulated traces consistently follow the measured traces on the wheelpaths tested.

To further evaluate the profilograph model, the simulated and measured profilograms were processed using ProScan to determine profile indices. ProScan is a computerized, automatic profile reduction system that scans profilograms obtained with a manual

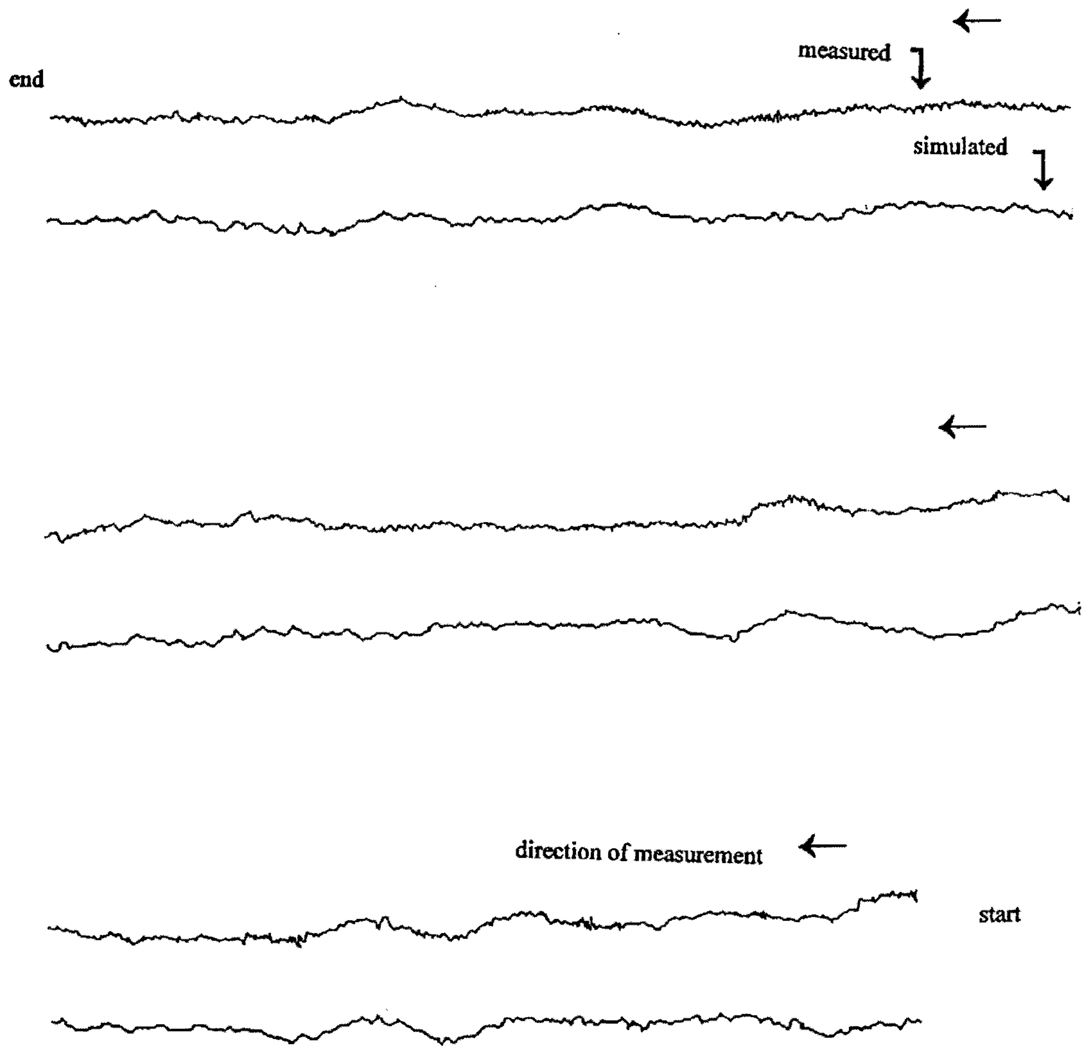

Figure 24. Comparison of Measured and Simulated Profilograms on a Smooth Section (SH 47, Southbound Outside Lane, Left Wheelpath)

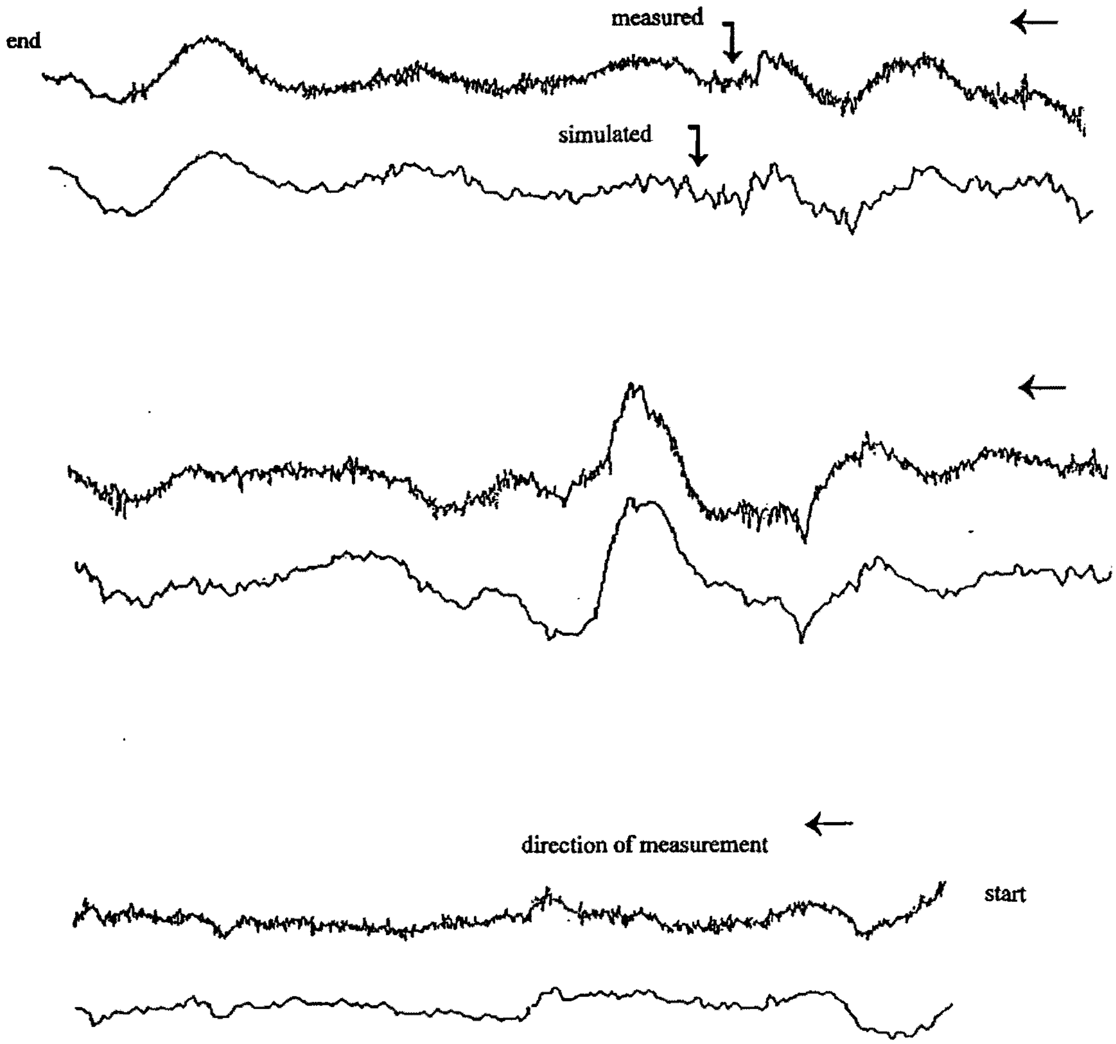

Figure 25. Comparison of Measured and Simulated Profilograms on a Rough Section (Annex 1, Left Wheelpath)

profilograph and determines the profile indices of the scanned segments. The system was evaluated by Fernando and Carmona (1994) who found that it provides profile indices consistent with those determined manually and are more repeatable. The simulated and measured PIs of the test sections were compared to establish the agreement between corresponding indices determined from field measurements and from profilograph simulations.

Table 16 summarizes the PIs determined. It is noted that the simulated PIs are higher than the measured PIs. However, the differences are considered to be minor. In terms of the existing profilograph smoothness specification, for example, the PIs determined on all sections merit the same pay adjustment. In view of the good agreement between measured and simulated profilograms, and between measured and simulated PIs, researchers used the kinematic model developed by Kulakowski and Wambold (1989) to evaluate the relationship between the profile index and IRI in this study.

RELATIONSHIPS BETWEEN PI AND IRI

The profilograph model evaluated previously provides a way of relating any profile-based statistic to the profile index. To evaluate the relationship between PI and IRI, profile data compiled during the field study of district overlay projects were analyzed. Specifically, profile data taken with TxDOT's Surface Profiler (SP) on 48 overlaid test sections were used with the profilograph simulation program to predict the profilograph response to the input profiles. The simulated profilograms were subsequently used with ProScan to determine profile indices for the overlaid pavements using a segment length of 161 m, and blanking bands of 5 and 0 mm. Table 17 shows the average PIs determined on the test sections as well as the average IRIs computed from the measured profiles.

In determining the average PIs shown in Table 17, the profilograph response to the input wheelpath profile was simulated. Thus, a simulated profile index was determined for each wheelpath, and the mean of the right and left wheelpath PIs was computed to get the section PI corresponding to a given run of TxDOT's Surface Profiler. This procedure was repeated for two more repeat runs so that three section PIs were determined for a given overlaid segment and blanking band. The average of the section PIs was then computed and

Table 16. Measured and Simulated PIs from Evaluation of Profilograph Model

Profile Method	Section	Profilograph PI (5 mm Blanking Band)			
		Pass 1	Pass 2	Pass 3	Average
Manual McCracken (measured)	Annex 1	24.2	25.4	24.8	24.8
	Annex 2	16.1	16.2	16.0	16.1
	SH 47A	0.0	0.0	0.0	0.0
Rod & Level Filtered (simulated)	Annex 1	26.9	26.1	25.8	26.3
	Annex 2	17.8	17.6	17.2	17.5
	SH 47A	0.4	0.0	0.0	0.1
Rod & Level Unfiltered (simulated)	Annex 1	25.3	26.8	25.5	25.9
	Annex 2	18.2	18.2	17.6	18.0
	SH 47A	1.4	0.8	0.5	0.9

Table 17. Simulated PIs and Measured IRIs from Evaluation of Surface Profiler Data Collected on District Overlay Projects

Project	Section	Average Section PI		Average Section IRI (mm/m)
		5 mm Blanking Band	Null Blanking Band	
Atlanta	1	5.55	27.70	1.218
	2	8.68	31.47	1.350
	3	0.65	16.38	0.879
	4	3.08	23.47	1.172
	5	6.27	22.28	1.178
	6	2.60	19.67	1.048
Odessa (CMHB)	1	3.47	24.92	1.135
	2	1.50	20.83	0.914
	3	4.25	23.93	1.043
	4	1.98	20.95	1.040
	5	2.23	20.72	1.048
	6	3.97	30.05	1.246
	7	5.42	27.37	1.109
Dallas	1	2.65	26.97	1.132
	2	4.28	28.02	1.199
	3	5.30	28.97	1.249
	4	4.92	26.40	1.151
	5	2.67	26.27	1.214
	6	6.90	27.45	1.231

Table 17. Simulated PIs and Measured IRIs from Evaluation of Surface Profiler Data Collected on District Overlay Projects (continued)

Project	Section	Average Section PI		Average Section IRI (mm/m)
		5 mm Blanking Band	Null Blanking Band	
San Angelo	1	3.40	21.03	0.989
	2	2.38	21.68	0.995
	3	3.17	19.15	0.929
	4	1.75	18.95	0.980
	5	3.57	24.50	1.138
	6	3.90	24.52	1.251
Odessa (CRM)	1	1.78	18.80	0.874
	2	1.43	19.38	1.035
	3	1.20	17.40	0.901
	4	4.88	25.05	1.075
	5	8.77	29.70	1.375
	6	2.32	21.15	1.006
	7	2.63	23.38	1.080
	8	2.95	21.88	1.116
	9	1.63	23.48	1.252
San Antonio	1	2.30	15.22	0.698
	2	1.50	17.57	0.995
	3	2.97	15.13	0.839
	4	7.72	24.62	1.193
	5	5.73	22.53	1.243
	6	2.05	16.35	0.804
	7	0.82	13.75	0.705
	8	1.53	14.03	0.791
	9	0.67	13.10	0.691

Table 17. Simulated PIs and Measured IRIs from Evaluation of Surface Profiler Data Collected on District Overlay Projects (continued)

Project	Section	Average Section PI		Average Section IRI (mm/m)
		5 mm Blanking Band	Null Blanking Band	
Carthage	1	0.55	15.02	0.824
	2	0.65	15.88	0.835
	3	0.63	17.80	0.862
	4	1.35	16.58	0.863
	5	0.85	15.93	0.794

reported in Table 17. Likewise, the IRI statistics given in Table 17 are averages of corresponding section IRIs, where the section IRI is calculated as the mean of the left and right wheelpath IRIs determined for a given run of the Surface Profiler.

The relationship between IRI and PI determined using the 5 mm blanking band is shown in Figure 26. The data cover the range in pavement smoothness expected of asphalt concrete overlays. Because of the noticeable curvature in the relationship between IRI and PI, a hyperbolic model of the form:

$$IRI = \frac{\beta_0 + \beta_1 \cdot PI}{1 + \beta_2 \cdot PI} \qquad (8)$$

was fitted to the test data. In the above equation, PI refers to the average profile index for a given section determined using the simulated profilogram. The coefficients, β_0, β_1, and β_2 were found from nonlinear regression as 0.695, 0.352, and 0.217, respectively. The relationship determined is shown by the solid line in Figure 26. To quantify the scatter of the test data about the fitted line, the root-mean-square error (RMSE) associated with the predicted IRIs was determined and was found to be equal to 0.110 mm/m.

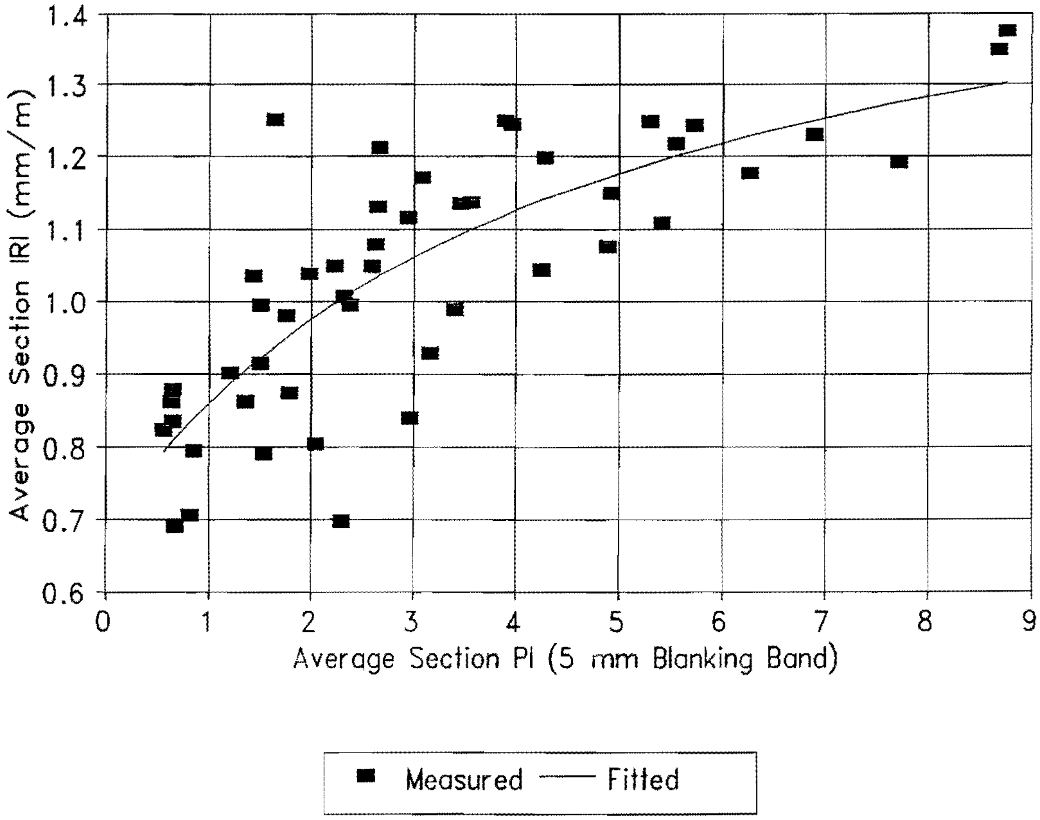

Figure 26. Relationship Between IRI and Profile Index Based on 5 mm Blanking Band

The relationship between IRI and the null blanking band PI is shown in Figure 27. Note that a stronger and more linear relationship is observed between these two statistics as indicated by the fitted line to the test data. Using linear regression, researchers determined the equation of the fitted line as:

$$IRI = 0.305 + 0.034 PI_0 \tag{9}$$

where, PI_0, refers to the null blanking band PI. The above relationship has a coefficient of determination, R^2, of 85.3 percent and an RMSE of 0.069 mm/m. From these results, it is clear that IRI has a stronger relationship with the the null blanking band PI.

It is noted that Eq. (9) has a non-zero intercept. Since PI_0 and IRI are theoretically zero for a perfectly flat surface, attempts were made to determine a regression relationship

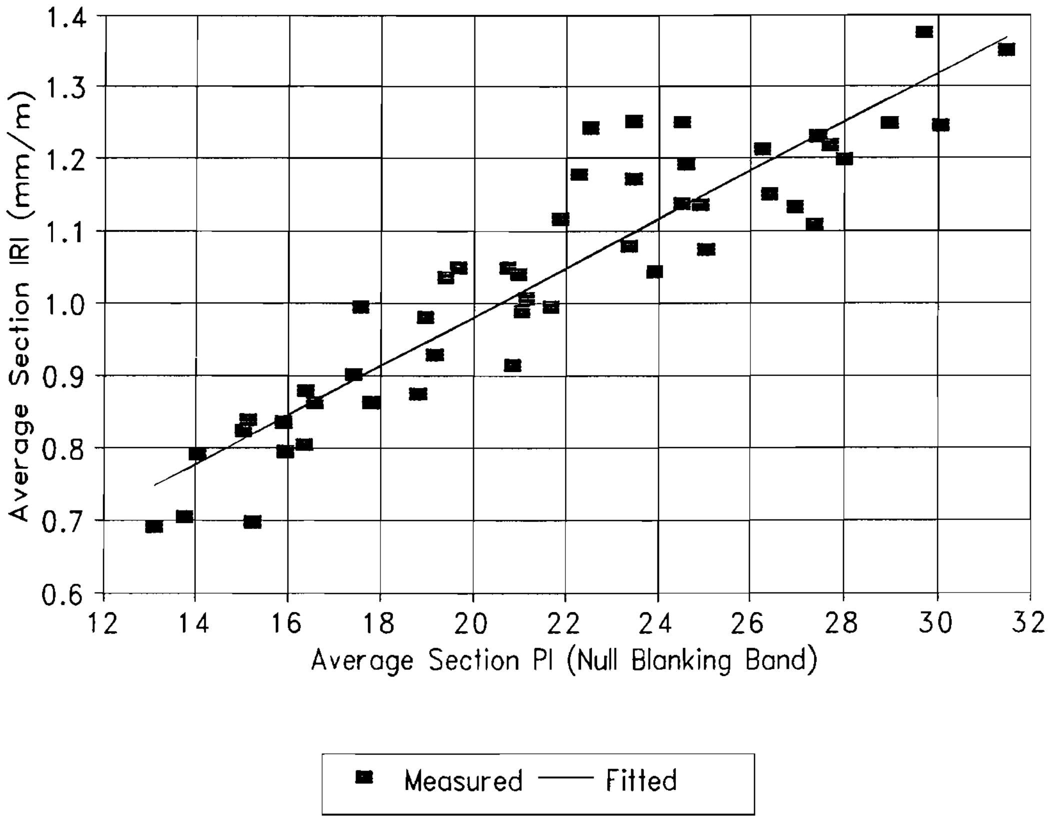

Figure 27. Relationship Between IRI and Null Blanking Band PI

that satisfies this boundary condition. Researchers first tried a linear regression equation with the intercept term forced to zero and obtained the relationship:

$$IRI = 0.047\, PI_0 \tag{10}$$

However, the above equation did not fit the data as well as the previous equation. The coefficient of determination, R^2, dropped from 85.3 percent to 71.2 percent, and the RMSE increased from 0.069 to 0.096 mm/m. Consequently, researchers tried the hyperbolic model given by Eq. (8) with the parameter, β_0, set to zero. Through nonlinear regression analysis, the following relationship between IRI and PI_0 was determined:

$$IRI = \frac{0.07013 \cdot PI_0}{1 + 0.02073 \cdot PI_0} \tag{11}$$

The root-mean-square error of the above relationship is 0.066 mm/m which is comparable to the RMSE of 0.069 for Eq. (9). Figure 28 compares the three different relationships between IRI and PI_0. Note that the hyperbolic equation fits the measured data quite well and predicts an IRI of zero for a PI_0 of zero. In view of these results, researchers recommend the application of the hyperbolic equation for predicting IRI from the null blanking band PI. In addition, since this profile index relates better with the IRI than the corresponding index determined using the 5 mm blanking band, researchers selected PI_0 as the basis for developing a provisional profilograph specification that can be used to bridge over to the profile-based specification developed in this study. This provisional profilograph specification is presented in the following section.

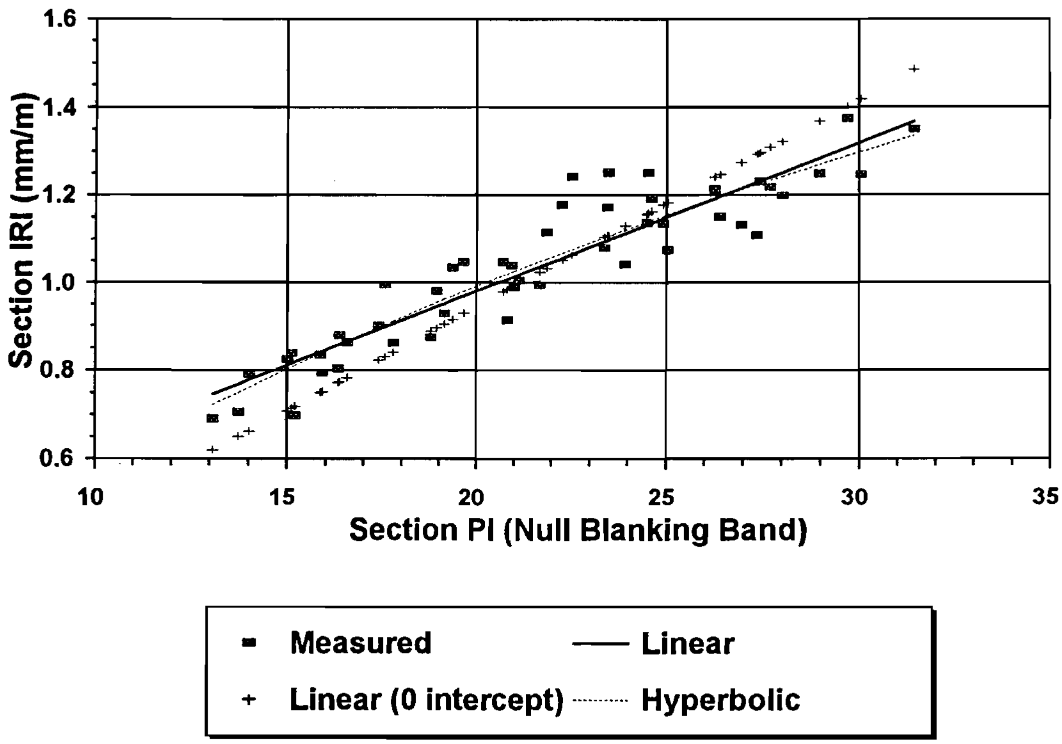

Figure 28. Comparison of Different Relationships Between IRI and PI_0

DEVELOPMENT OF THE PROVISIONAL PROFILOGRAPH SPECIFICATION

If the relationship between IRI and PI_0 given by Eq. (11) is substituted into the relationship between pavement roughness and dynamic load variability (Eq. 7), the following equation relating CV to PI_0 is obtained:

$$CV = 0.04123\,V\left(\frac{0.07013 \cdot PI_0}{1 + 0.02073 \cdot PI_0}\right) \tag{12}$$

Figure 29 illustrates the above relationship assuming a vehicle speed of 97 kph. By predicting the dynamic load variability associated with the as-built profile, the change in pavement life due to departures from the target smoothness may be estimated using Eq. (1) in Chapter III. Thus, Eq. (12) provides a way of evaluating the measured PI_0 after the overlay on the basis of predicted pavement life. Note that in this development, the contractor's work is evaluated based on the final surface smoothness measured with the profilograph, in line with the current smoothness specification.

From the evaluation of the dynamic load variability associated with the measured surface profiles on the district overlay projects, the average coefficient of variation (CV) of predicted dynamic loads after the overlay is found to be 4 percent with a 95 percent confidence interval ranging from 3 to 5 percent. Note that these statistics are for the standard 80 kN single axle defined in Chapter IV. If the average coefficient of variation of 4 percent is used to evaluate the final surface smoothness, the predicted change in pavement life, Δ, due to departures from this target, may be determined as a function of PI_0 from Eqs. (1) and (12). This relationship between Δ and PI_0 is shown in Figure 30 which provides a basis for evaluating the final surface smoothness in the revised profilograph smoothness specification. Specifically, the author proposes that pay adjustments based on the final profile index of the overlay surface be determined following the same procedure illustrated in Figure 20 except that the index, Δ, is used in lieu of λ. Note that, Δ, is determined based on the difference between the as-built and target profiles, whereas, λ, is based on the improvement in the surface profile due to the overlay, i.e, the difference between the before and after overlay smoothness.

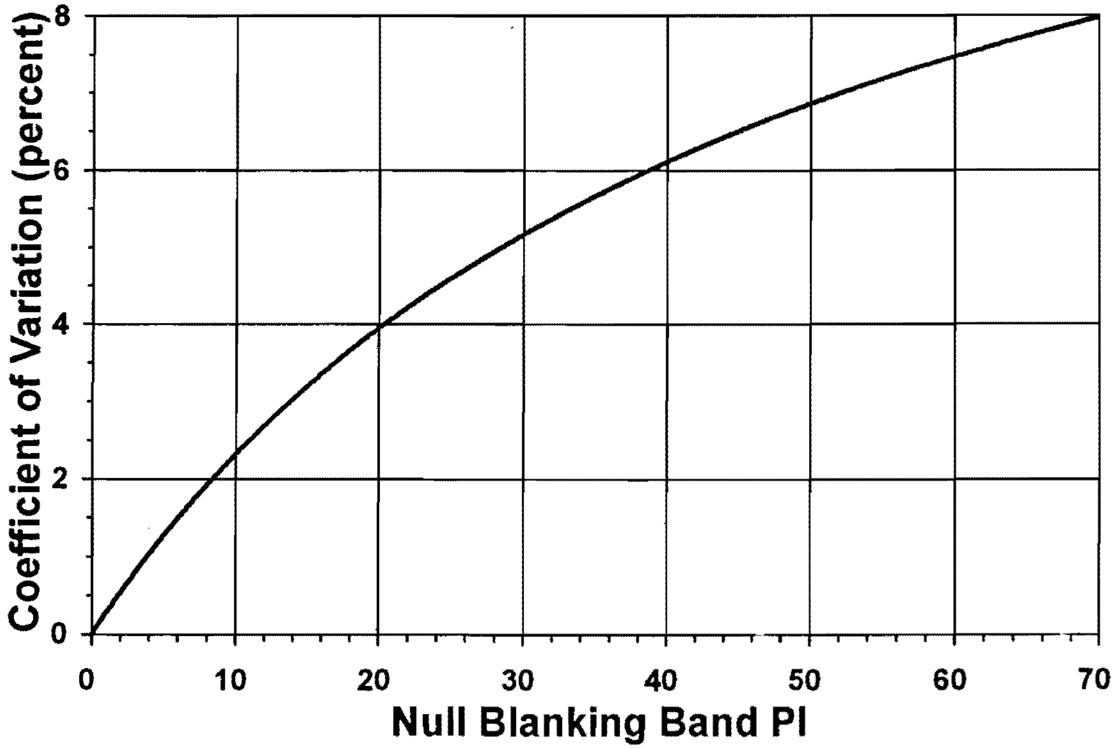

Figure 29. Relationship Between Coefficient of Variation of Predicted Dynamic Loads on Overlaid Surface and Null Blanking Band PI

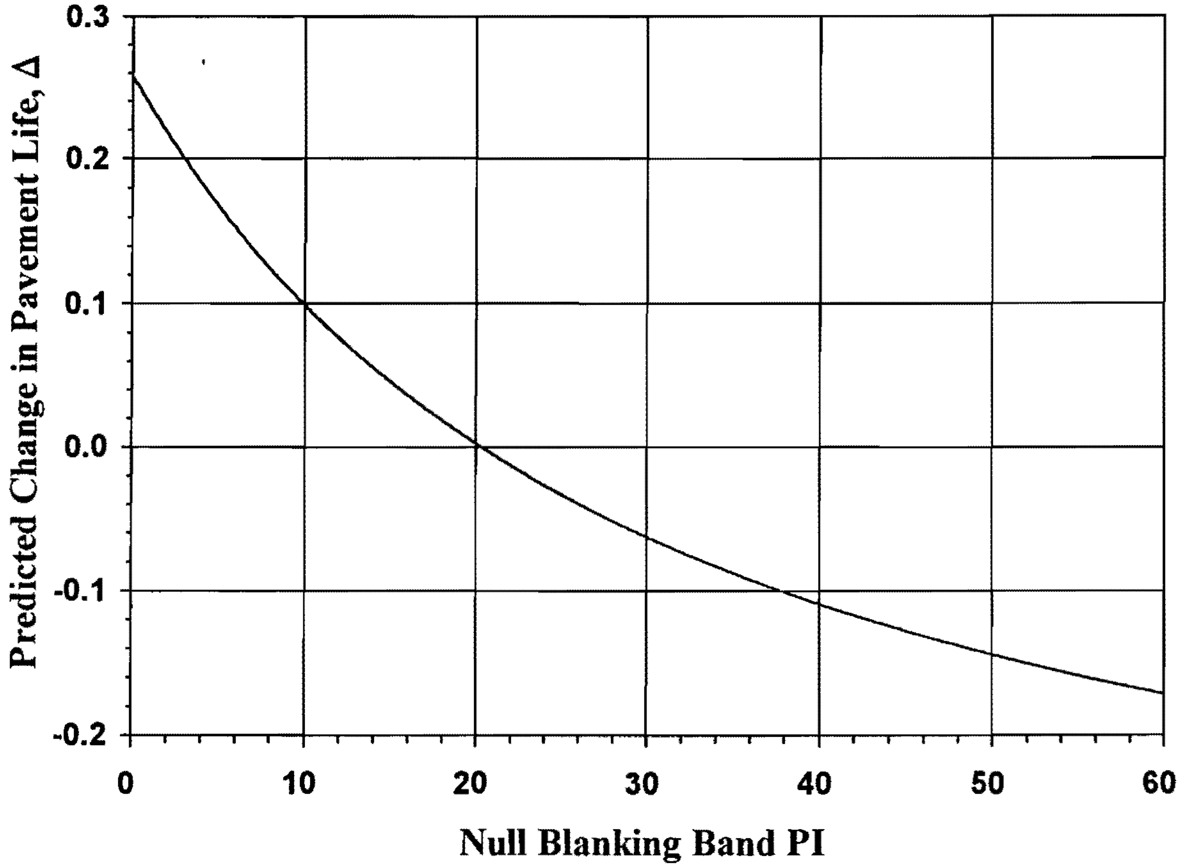

Figure 30. Predicted Change in Pavement Life Due to Departures from Target Smoothness of the Final Overlay (Paris n of 3.6 and 95 Percent Confidence Level Used)

To illustrate the proposed approach for evaluating surface smoothness using PI_0, suppose that the following constants of the pay function are used for acceptance testing:

1. Maximum monetary incentive, ΔP_m, of $90;
2. Δ_m of 15 percent, defined as the value of Δ at which the maximum monetary incentive is reached;
3. Base incentive, b_m, of $35;
4. Lower (ϵ_0) and upper (ϵ_m) limits of −3 and +3 percent, respectively, on the tolerance band within which the pay adjustment is zero;
5. Base penalty, b_0, of −$35;

6. Threshold for corrective work (Δ_0) of - 10 percent; and

7. Maximum penalty, ΔP_0, of - \$140.

If the above constants are used, the payment schedule illustrated in Figure 31 is obtained. Thus, for a given PI_0, the predicted change in pavement life, Δ, corresponding to the difference between the as-built and target profiles, is determined from Figure 30. This value of Δ is then entered in Figure 31 to determine the pay adjustment for the tested segment. The relationships shown are combined in Figure 32 to determine the pay adjustment from PI_0 directly.

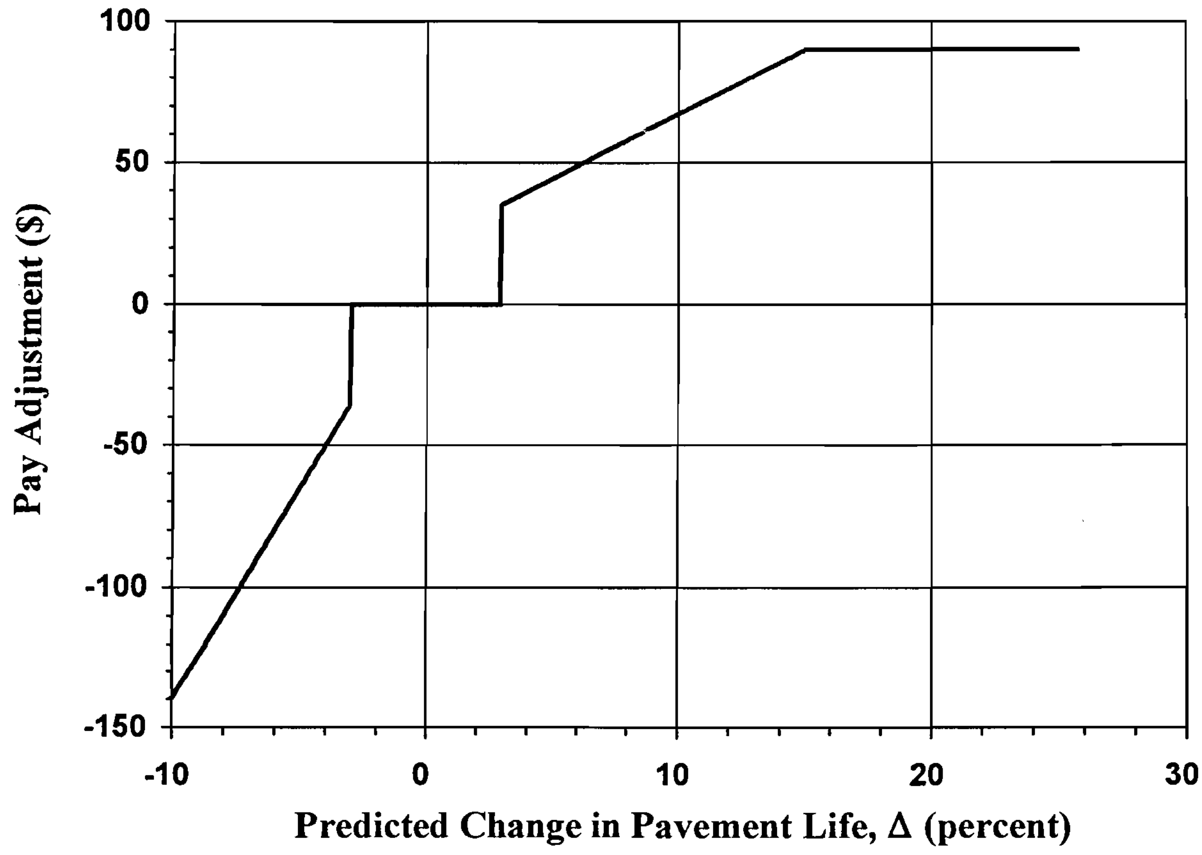

Figure 31. Illustration of Pay Adjustment Schedule Based on Δ

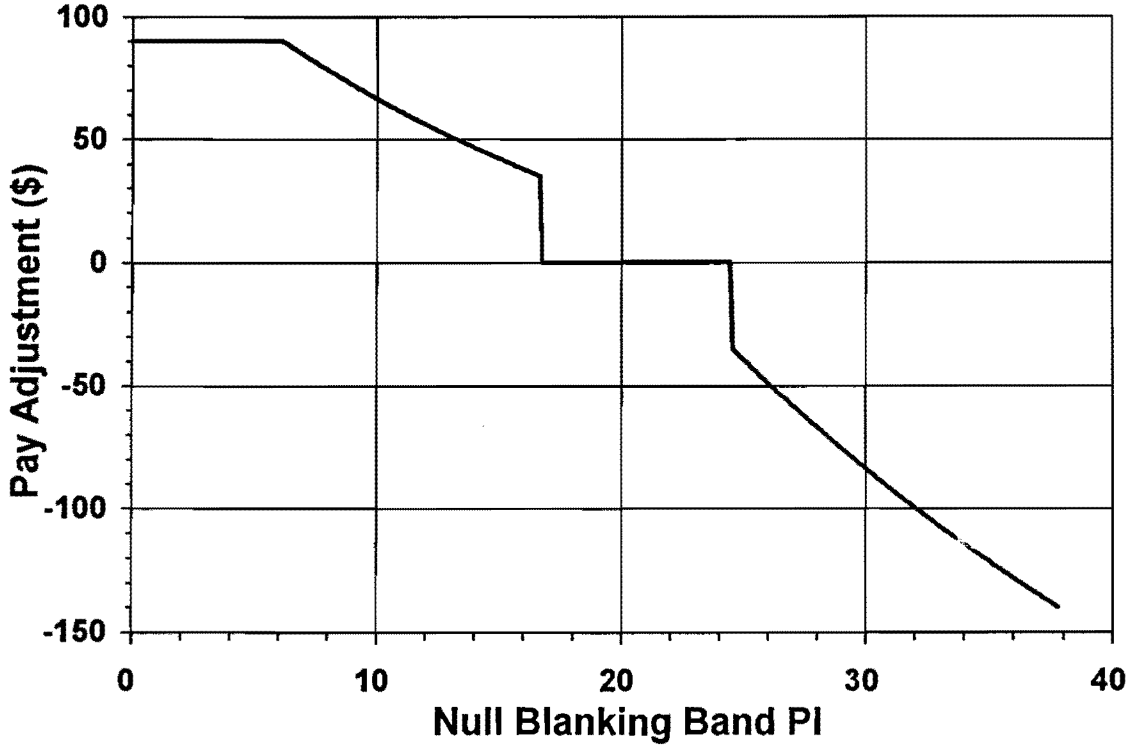

Figure 32. Pay Adjustment Schedule Based on Null Blanking Band PI

The following observations are noted from the figure:

1. The maximum monetary incentive is reached at a PI_0 of 6.2, corresponding to a +15 percent change in predicted pavement life due to the difference between the target and as-built surface profiles;
2. The pay adjustment is zero for values of PI_0 between 16.7 to 24.6; and
3. The maximum penalty of − \$140 is reached at $PI_0 = 37.9$. At higher values, the contractor is required to take corrective measures.

It is of interest to use the approach presented to evaluate the smoothness of the test sections surveyed in the district overlay projects. If the null blanking band PIs for the overlaid sections are used with the proposed schedule shown in Figure 32, the results in Table 18 are obtained. Note that the PI_0s given in Table 18 were determined by profilograph simulation using the profiles measured with TxDOT's Surface Profiler on the final overlay surface.

Table 18 shows that significantly less bonuses are paid the contractors under the proposed profilograph specification that uses the null blanking band profile index. Under the existing specification, 36 of the 48 sections merit bonuses compared to 11 if the null blanking band PI is used. In addition, only one section is assessed a penalty under the existing specification compared to 12 under the revised profilograph specification.

The profiles of the overlaid sections were also evaluated using the profilograph specification implemented by the Kansas Department of Transportation (KDOT) which uses the null blanking band. Table 19 shows the pay adjustment schedule for evaluating flexible pavement surface smoothness under this specification. In KDOT, bonuses are paid when the average profile index for a 161 m section is 10 or less, according to the schedule given in Table 19. For null blanking band PIs between 10 to 40, no adjustments are made. However, when the PI_0 is more than 30, the contractor is required to perform corrections to reduce the profile index to 30 or less. An exception is made for ramps, acceleration, and deceleration lanes. For these pavements, corrective work is required when the initial average profile index is greater than 40. In these cases, the contractor must correct the surface to produce an index of 40 or less. After corrections, the contractor is paid the price adjustment that corresponds to the initial average profile index of the corrected surface, according to the schedule given in Table 19. Corrective methods accepted by KDOT include:

1. Diamond grinding or use of other profiling devices;
2. Removal and replacement of the entire pavement thickness;
3. Milling off the surface and application of the specified surface course; and
4. Overlaying (not patching) with the specified surface course.

Other methods that will provide the desired results may also be used. However, for all cases, the method selected by the contractor is subject to the approval of the KDOT engineer, and corrections are made at the contractor's expense.

Table 18. Comparison of Pay Adjustments Based on Existing Profilograph Specification with Pay Adjustments Based on Null Blanking Band PIs

Project	Section	Average PI After Overlay		Pay Adjustment[a] ($ per 161 m Section per Lane)		
		5 mm Blanking Band	Null Blanking Band	Existing (5 mm Blanking Band)[b]	Proposed (Null Blanking Band)[c]	KDOT Specification
Atlanta	1	1.81	27.70	70	-57	0
	2	5.58	31.47	0	-88	Correct
	3	6.04	16.38	0	38	0
	4	1.03	23.47	90	0	0
	5	4.11	22.28	0	0	0
	6	2.06	19.67	50	0	0
Odessa CRM	1	0.62	18.80	90	0	0
	2	1.65	19.38	70	0	0
	3	2.57	17.40	50	0	0
	4	3.34	25.05	35	-36	0
	5	3.13	29.70	35	-73	0
	6	2.83	21.15	50	0	0
	7	1.94	23.38	70	0	0
	8	2.51	21.88	50	0	0
	9	3.13	23.48	35	0	0
San Angelo	1	0.45	21.03	90	0	0
	2	0.25	21.68	90	0	0
	3	0.41	19.15	90	0	0
	4	2.33	18.95	50	0	0
	5	0.90	24.50	90	0	0
	6	0.93	24.52	90	0	0
San Antonio	1	0.88	15.22	90	44	0
	2	1.24	17.57	90	0	0
	3	3.39	15.13	35	45	0
	4	8.23	24.62	-20	0	0
	5	7.18	22.53	0	0	0
	6	1.28	16.35	90	38	0
	7	1.17	13.75	90	51	0
	8	1.57	14.03	70	50	0
	9	0.00	13.10	90	55	0

Table 18. Comparison of Pay Adjustments Based on Existing Profilograph Specification with Pay Adjustments Based on Null Blanking Band PIs (continued)

Project	Section	Average PI After Overlay		Pay Adjustment[a] ($ per 161 m Section per Lane)		
		5 mm Blanking Band	Null Blanking Band	Existing (5 mm Blanking Band)[b]	Proposed (Null Blanking Band)[c]	KDOT Specification
Dallas	1	5.64	26.97	0	-51	0
	2	5.55	28.02	0	-59	0
	3	5.90	28.97	0	-67	0
	4	5.23	26.40	0	-46	0
	5	3.97	26.27	35	-46	0
	6	4.58	27.45	0	-55	0
Odessa CMHB	1	2.66	24.92	50	0	0
	2	1.42	20.83	90	0	0
	3	4.13	23.93	0	0	0
	4	2.89	20.95	50	0	0
	5	0.65	20.72	90	0	0
	6	2.69	30.05	50	-76	0
	7	5.25	27.37	0	-54	0
Carthage	1	1.28	15.02	90	45	0
	2	0.53	15.88	90	41	0
	3	0.00	17.80	90	0	0
	4	2.78	16.58	50	37	0
	5	0.15	15.93	90	41	0

[a] Pay adjustments are rounded off to the nearest dollar.
[b] Determined using Table 7.
[c] Determined using Figure 32.

Table 19. Pay Adjustment Schedule Used by KDOT to Evaluate Flexible Pavement Smoothness Based on Null Blanking Band PI

Average Profile Index, PI_0	Price Adjustment (US$ per 161 m section per lane)
7.0 or less	+152
7.1 to 10.0	+76
10.1 to 30.0	0
30.1 to 40.0	0[a]
40.1 or more	-203[a]

[a] Correct to 30 or less except for ramps, acceleration, and deceleration lanes which shall be corrected to 40 or less.

Table 18 shows that no bonuses will be paid if the KDOT specification is used to evaluate the smoothness of the overlaid sections surveyed in the district projects. In one case (Section 2 of the Atlanta project), the contractor will be required to perform corrections to reduce the profile index to 30 or less. These results may appear to be very conservative at first. However, it is noted that the payment schedules are based on two different indices. Determining PIs using a 5 mm blanking band may mask certain components of roughness that are otherwise picked up if no blanking band is used. Viewed from this perspective, and from the finding that it correlates much better with the IRI, the null blanking band PI is probably a better indicator of pavement smoothness than the profile index determined using a 5 mm blanking band. Indeed, certain districts have expressed concerns that bonuses are being paid for surfaces that ride "rough."

Table 18 also indicates that the alternative profilograph specification proposed in this chapter gives results that are about as conservative (relative to the existing TxDOT specification), as those obtained using the KDOT specification. Compared to the proposed profilograph specification, it is noted that the KDOT specification has a narrower interval ($0 \leq PI_0 \leq 10$) within which bonuses are paid, and a wider interval ($10 < PI_0 \leq 30$) within which neither pay adjustments nor corrective measures are required. From Figure 30, a PI_0 of 10 corresponds to a Δ of 10 percent, while a PI_0 of 30 corresponds to a Δ of approximately −6 percent. This explains, for the most part, the differences in the pay adjustments determined from the two procedures. In the proposed specification, the interval within which the pay adjustment is zero is based on a symmetric tolerance band of ±3 percent. In the KDOT specification, a higher requirement is prescribed before bonuses are paid, and relatively less tolerance is given before penalties or corrective measures are assessed. Thus, no bonuses are determined using the KDOT specification. However, because of the greater tolerance given for profiles that are rougher than the target (−6 versus −3 percent in the suggested specification), only one section is assessed a penalty (in the form of corrective work), compared to 12 sections under the proposed specification where monetary disincentives are assessed.

Of course, the proposed approach for determining pay adjustments (illustrated in Figure 20), allows the limits on the tolerance band to be different in magnitude. Indeed, the tolerance band corresponding to the KDOT specification may be used which will lead to the same pay adjustments between the two methods. The only exception is Section 2 of the Atlanta project which will require corrective work by the contractor under the KDOT specification versus assessment of a monetary disincentive under the alternative profilograph specification evaluated in this chapter.

EVALUATING SURFACE SMOOTHNESS USING STATISTICS DETERMINED FROM PROFILES MEASURED AFTER THE OVERLAY

In lieu of the null blanking band profile index, the procedure presented may also be used with the IRI or the coefficient of variation (CV) of predicted dynamic loads to evaluate the quality of overlay smoothness. Figures 33 and 34 show the relationships between Δ and IRI, and between Δ and CV, respectively. Figure 33 is based on a vehicle speed of 97 kph. Both figures assume a fracture parameter, n, of 3.6, a 95 percent confidence level, and a target CV of 4 percent, corresponding to the average predicted dynamic variability on the overlaid sections of the district projects. These figures may be used to evaluate the quality of the overlay smoothness on the test sections surveyed in these projects. To illustrate the effect

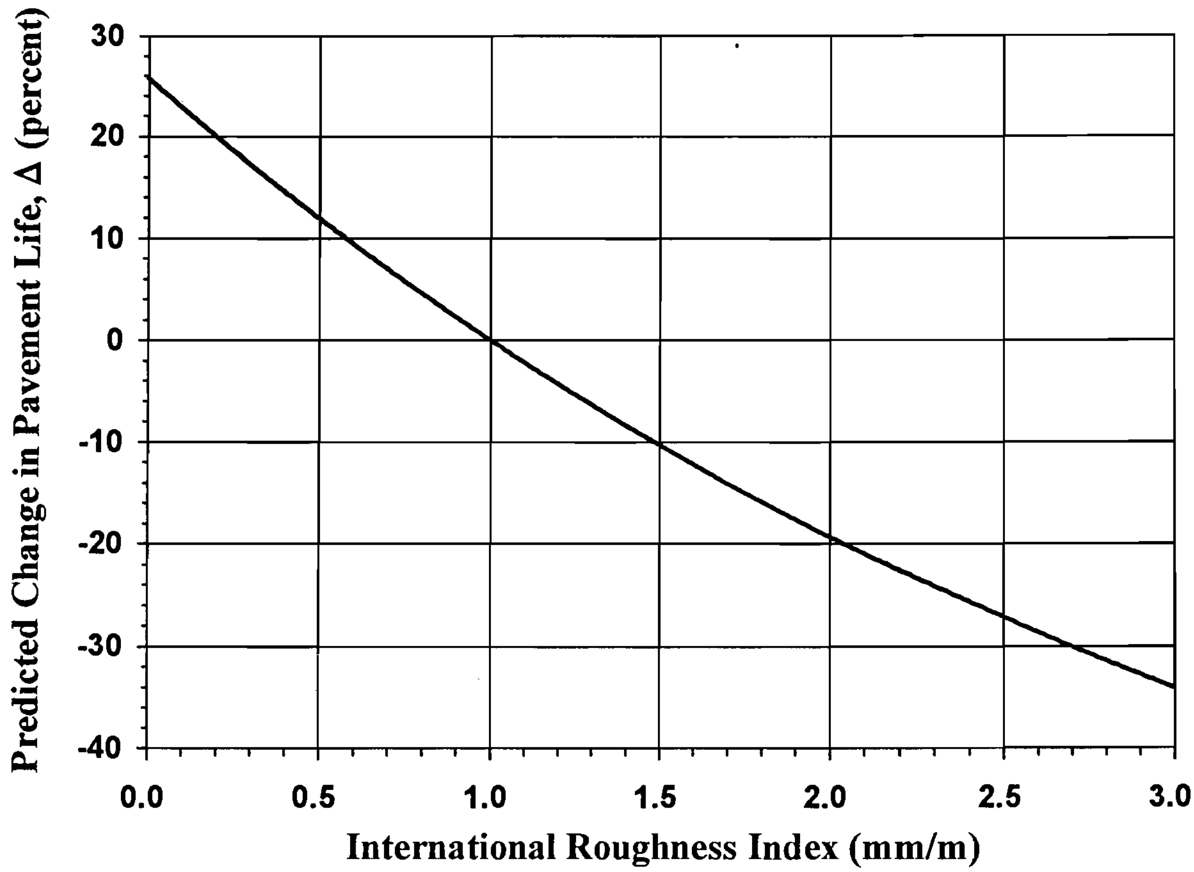

Figure 33. Relationship Between IRI and Damage Index, Δ

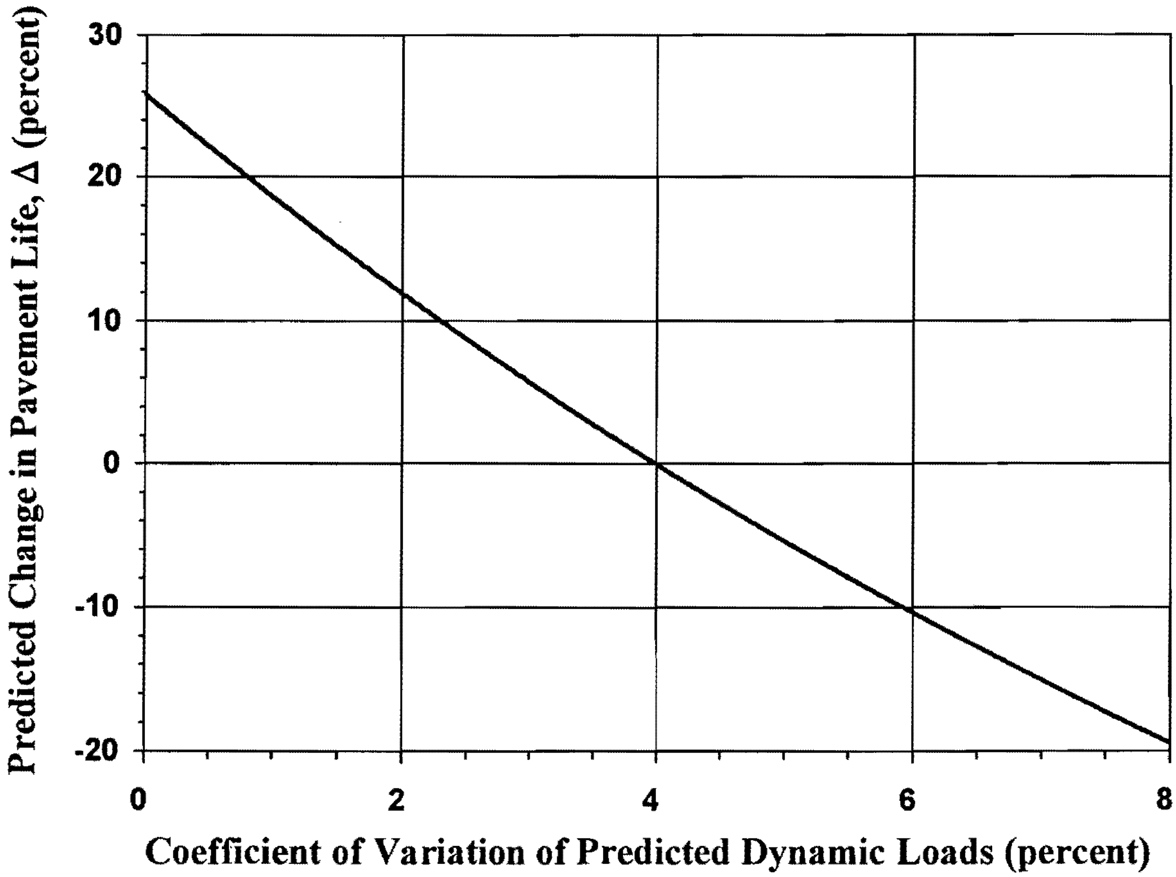

Figure 34. Relationship Between CV and Damage Index, Δ

of the tolerance band, the evaluation is conducted using a band of ±6 percent in lieu of ±3 percent. As noted previously, the KDOT specification corresponds to a tolerance band on Δ of −6 to +10 percent. The band selected has the same lower limit as the KDOT specification, but has a +6 percent upper limit to be symmetric about Δ=0. Figure 35 shows the pay adjustment schedule based on the selected tolerance band. In determining this figure, the other constants of the pay function were kept the same as in the previous evaluation.

Figure 33 or 34 may be used to predict the change in pavement life, Δ, given the IRI or CV determined from the profile measured after the overlay. Figure 35 is then used with the value of Δ to evaluate the acceptability of the final surface smoothness. If these charts are used to evaluate the smoothness of the overlaid test sections in the district projects, the results in Table 20 are obtained. All methods predict significantly less bonuses as compared to the pay adjustments determined using the current profilograph specification based on the 5 mm blanking band. Because of the greater tolerance, there are more segments where zero pay adjustments are determined using the statistics, PI_0, IRI, and CV than were determined previously with a ±3 percent tolerance band on Δ. There are a few segments where bonuses or penalties are predicted. For these segments, it is observed that differences in the pay adjustments exist between the three methods. Since Δ is theoretically related to the coefficient of variation of dynamic axle loads, the pay adjustments determined using this statistic are considered to be the most accurate among the three methods investigated. Where pay adjustments are determined, the differences may be attributed to errors in predicting the coefficient of variation from IRI or PI_0 using Eq. (7) or (12). However, using the pay adjustment schedule given in Figure 35, the results from all three methods are generally comparable.

In developing the smoothness specification, TxDOT must consider the importance of having a payment schedule that is defensible and equitable to both the agency and the contractor, in addition to reflecting the value attached by the department to the work received. In the author's opinion, the profilograph smoothness specification evaluated in this chapter is a suitable starting point towards the goal of improving the ride quality of asphalt concrete overlays and the eventual conversion to a profile-based smoothness specification. It is

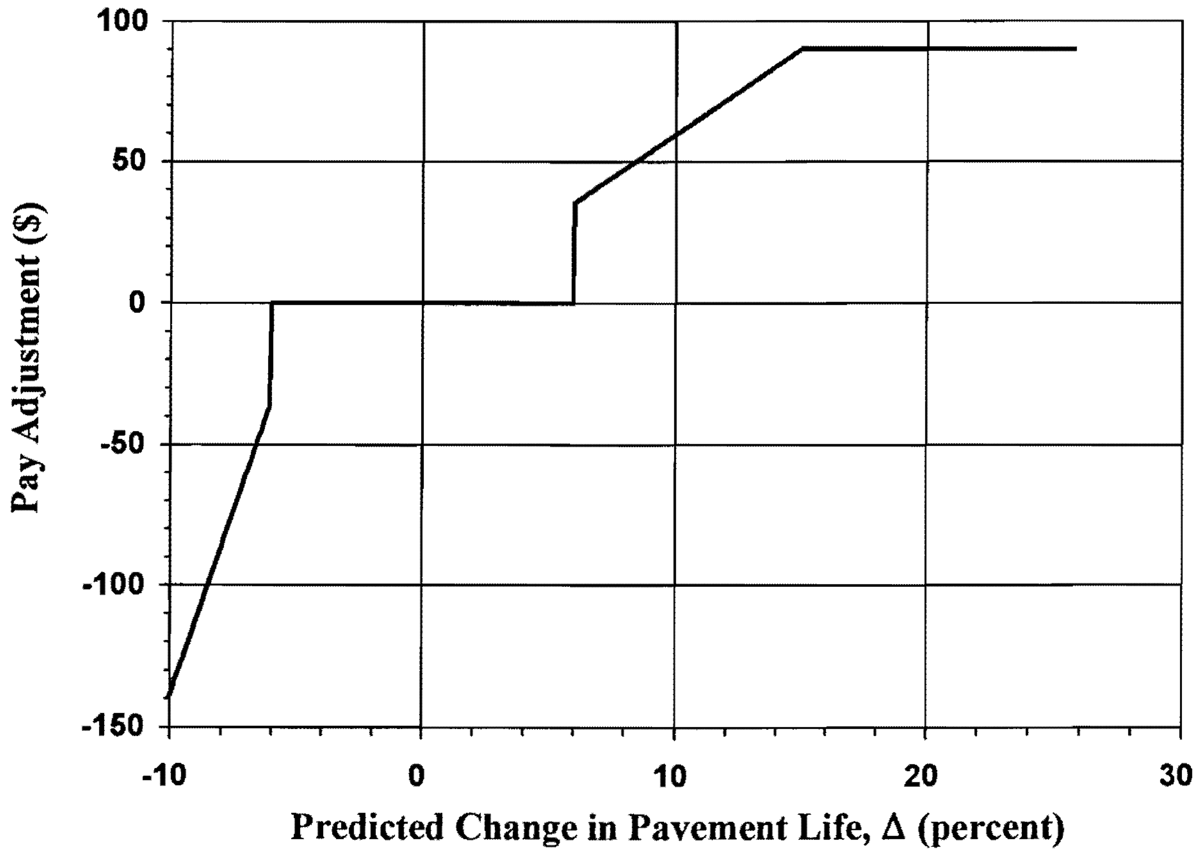

Figure 35. Pay Adjustment Schedule Based on a Tolerance Band of ±6 Percent on Δ

Table 20. Comparison of Pay Adjustments Determined from Various Methods

Project	Section	After Overlay[a]			Pay Adjustment ($)[b]			
		PI_0	IRI (mm/m)	CV[c] (percent)	PI_0	IRI (mm/m)	CV (percent)	KDOT
Atlanta	1	27.70	1.218	4.540	0	0	0	0
	2	31.47	1.350	5.300	-61	-69	-59	Correct
	3	16.38	0.879	3.020	0	0	0	0
	4	23.47	1.172	4.460	0	0	0	0
	5	22.28	1.178	4.515	0	0	0	0
	6	19.67	1.048	4.070	0	0	0	0
Odessa CRM	1	18.80	0.874	3.475	0	0	0	0
	2	19.38	1.035	3.555	0	0	0	0
	3	17.40	0.901	3.090	0	0	0	0
	4	25.05	1.075	4.325	0	0	0	0
	5	29.70	1.375	5.245	-37	-82	-51	0
	6	21.15	1.006	3.770	0	0	0	0
	7	23.38	1.080	4.100	0	0	0	0
	8	21.88	1.116	3.745	0	0	0	0
	9	23.48	1.252	3.965	0	0	0	0
San Angelo	1	21.03	0.989	4.030	0	0	0	0
	2	21.68	0.995	4.020	0	0	0	0
	3	19.15	0.929	4.165	0	0	0	0
	4	18.95	0.980	3.630	0	0	0	0
	5	24.50	1.138	4.260	0	0	0	0
	6	24.52	1.251	4.165	0	0	0	0

Table 20. Comparison of Pay Adjustments Determined from Various Methods (continued)

Project	Section	After Overlay[a]			Pay Adjustment ($)[b]			
		PI_0	IRI (mm/m)	CV[c] (percent)	PI_0	IRI (mm/m)	CV (percent)	KDOT
San Antonio	1	15.22	0.698	2.605	0	42	48	0
	2	17.57	0.995	3.160	0	0	0	0
	3	15.13	0.839	3.340	0	0	0	0
	4	24.62	1.193	4.435	0	0	0	0
	5	22.53	1.243	4.420	0	0	0	0
	6	16.35	0.804	3.395	0	0	0	0
	7	13.75	0.705	2.640	0	41	47	0
	8	14.03	0.791	3.020	0	0	0	0
	9	13.10	0.691	2.925	38	43	36	0
Dallas	1	26.97	1.132	3.885	0	0	0	0
	2	28.02	1.199	4.475	0	0	0	0
	3	28.97	1.249	5.225	0	0	-49	0
	4	26.40	1.151	4.525	0	0	0	0
	5	26.27	1.214	4.230	0	0	0	0
	6	27.45	1.231	4.715	0	0	0	0
Odessa CMHB	1	24.92	1.135	4.325	0	0	0	0
	2	20.83	0.914	4.080	0	0	0	0
	3	23.93	1.043	4.385	0	0	0	0
	4	20.95	1.040	3.860	0	0	0	0
	5	20.72	1.048	4.195	0	0	0	0
	6	30.05	1.246	4.500	-42	0	0	0
	7	27.37	1.109	5.230	0	0	-49	0

Table 20. Comparison of Pay Adjustments Determined from Various Methods (continued)

Project	Section	After Overlay[a]			Pay Adjustment ($)[b]			
		PI_0	IRI (mm/m)	CV[c] (percent)	PI_0	IRI (mm/m)	CV (percent)	KDOT
Carthage	1	15.02	0.824	2.890	0	0	38	0
	2	15.88	0.835	3.480	0	0	0	0
	3	17.80	0.862	2.890	0	0	38	0
	4	16.58	0.863	3.780	0	0	0	0
	5	15.93	0.794	3.085	0	0	0	0

[a] All statistics were computed for a section length of 161 m and are averages of corresponding left and right wheelpath statistics.
[b] Pay adjustment per 161 m segment per lane.
[c] CV determined using a simulation speed of 97 kph.

realized that the constants of the pay function used in the alternative profilograph specification may undergo changes as experience is gained through implementation of the proposed procedure. However, since the evaluation of pavement smoothness is tied to the predicted change in pavement life, a firm basis is provided for TxDOT to establish an acceptance schedule that is rational, defensible, and equitable to all concerned.

CHAPTER VII

PROPOSED FORMS OF A SMOOTHNESS SPECIFICATION FOR ASPHALT CONCRETE OVERLAYS

INTRODUCTION

Different forms of a smoothness specification for asphalt concrete overlays are proposed for TxDOT's consideration. The purpose is to present alternative methods for evaluating the acceptability of overlay smoothness and thus identify choices available to the Department from which decisions can be made regarding the implementation of a profile-based smoothness specification in Texas. It is recognized that further work may be required before the proposed methods based on profile can be implemented. To provide a transition from the existing profilograph-based specification, a provisional method is presented that uses the null blanking band profile index measured on the final surface. It is recognized that time will be needed to make the conversion from the profilograph to the more accurate surface profilers. Thus, it is important to provide an option, in the interim, that will allow the surface smoothness to be evaluated using available equipment. For this purpose, a profilograph specification based on the null blanking band PI (in lieu of the 5 mm blanking band) is proposed. The remaining methods will require the use of surface profilers that provide more accurate profiles than can be collected with existing profilographs. In connection with this, Fernando and Leong (1997) evaluated a number of profilers to establish the availability of equipment for implementing a new profile-based smoothness specification in Texas. The experience with this evaluation revealed a greater variety in the profilers available, ranging from automated devices that provide unfiltered or true profiles, lightweight inertial profilers mounted on tractors or golf carts, automated portable profiling equipment that may be mounted on any conventional vehicle, and the traditional van-mounted inertial profilers. To ensure that accurate, precise, uniform, and comparable profile measurements are obtained during construction, Fernando and Leong (1997) recommended the construction of a test facility for evaluating pavement profilers and offered applicable guidelines for conducting the equipment evaluation. With this test facility, a mechanism is provided by which TxDOT engineers and contractors can verify that the profilers in use are giving accurate, precise, uniform, and comparable measurements for construction quality control and assurance. The interested reader is referred to the report by Fernando and Leong (1997) for specific recommendations and guidelines relating to the evaluation of pavement profilers. Given that accurate profilers are available, the present report is primarily concerned with developing a procedure to evaluate the acceptability of surface smoothness on asphalt concrete overlay projects using the profile data determined from these devices.

PROPOSED METHODS FOR EVALUATING OVERLAY SMOOTHNESS

Five surface test methods are proposed for evaluating the smoothness of asphalt concrete overlays. These methods are classified into two groups as follows:

1. Methods that use the measured profiles before and after the overlay to establish the quality of the contractor's work; and
2. Methods that require only the profile after the overlay to evaluate the acceptability of the finished surface.

The two surface test methods belonging to the first group are primarily intended to be used with inertial profilers that permit the collection of profiles at highway speed. In this way, the profiles prior to construction may be obtained without the need for traffic control and lane closures. The methods are specifically applicable on projects where the overlay is thin (i.e., less than 63 mm), and no surface preparations are planned, or only spot level-ups are specified. Under these conditions where a reasonable doubt exists that the smoothness requirements based on final profile are achievable, the first group of methods are offered for use in lieu of the alternatives of dropping the smoothness specification or using the straightedge to check the overlay smoothness on these projects.

The second group of test methods is primarily applicable on projects where the overlay thickness is greater than 64 mm, and/or where surface preparations are planned to remove or correct existing surface distress. Examples of these are milling to grade, and level-ups applied over the entire lane width. Belonging to this group are two test methods that are based on surface profilers, and one that is based on the profilograph. This latter method is intended as a provisional specification that can be used by TxDOT to smooth the transition from the current profilograph specification to one which uses surface profilers for evaluating the acceptability of asphalt concrete overlay smoothness.

In the proposed methods, profile measurements are collected in both wheelpaths and the acceptability of the surface smoothness is evaluated per 161 m segment per lane, consistent with the current specification. For tests where the acceptability of the overlay smoothness is based on the improvement gained from the overlay, the damage index, λ, is used to evaluate the contractor's work. For the other category, the evaluation is based on the damage index, Δ, which estimates the difference in predicted pavement life due to departures from the target smoothness.

Group A Evaluation Methods

These procedures require the use of surface profilers to evaluate contractor performance relative to the overlay smoothness achieved from construction. In this group, surface profiles are collected on both wheelpaths of a given project, before and after the overlay. From the profile data, the acceptability of pavement smoothness is evaluated based on the damage index, λ, evaluated using one of the following two test methods.

Surface Test A1

Surface Test A1 requires the prediction of dynamic loads for the standard 80 kN single axle. This is accomplished by vehicle simulation using the planar model described in Chapter IV. The author proposes that vehicle simulations be conducted at a speed of 97 kph, corresponding to the truck speed limit in Texas. From the simulation results, the coefficient of variation (CV) of predicted dynamic loads is evaluated for each wheelpath at 161 m intervals. The coefficients of variation are then averaged to get the dynamic load variability per 161 m segment per lane. These calculations are done on both profiles measured before and after the overlay. The average CVs are then used in one of the charts presented in Figures 36 to 39 to evaluate the damage index, λ, corresponding to the predicted change in pavement

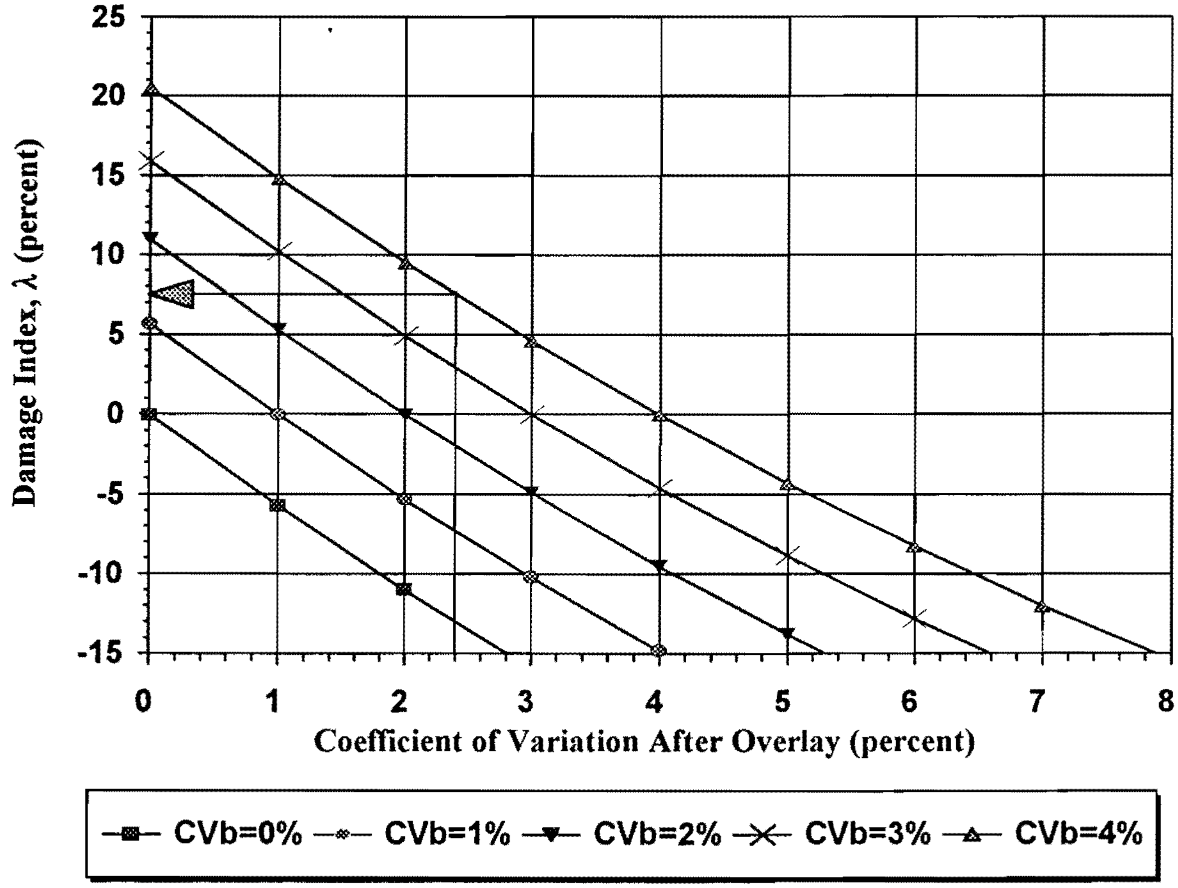

Figure 36. Chart to Evaluate Surface Smoothness Using Group A Test Methods for Coefficients of Variation Before the Overlay Between 0 and 4 Percent

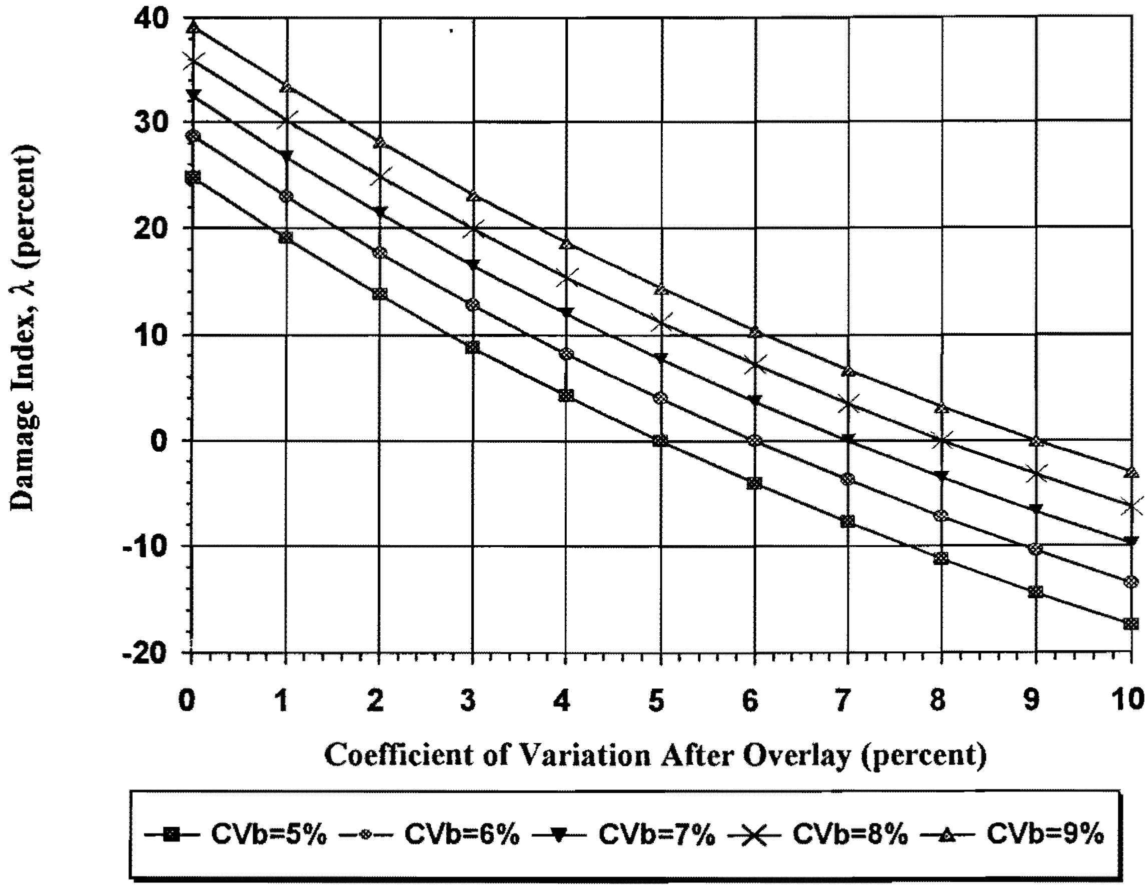

Figure 37. Chart to Evaluate Surface Smoothness Using Group A Test Methods for Coefficients of Variation Before the Overlay Between 5 and 9 Percent

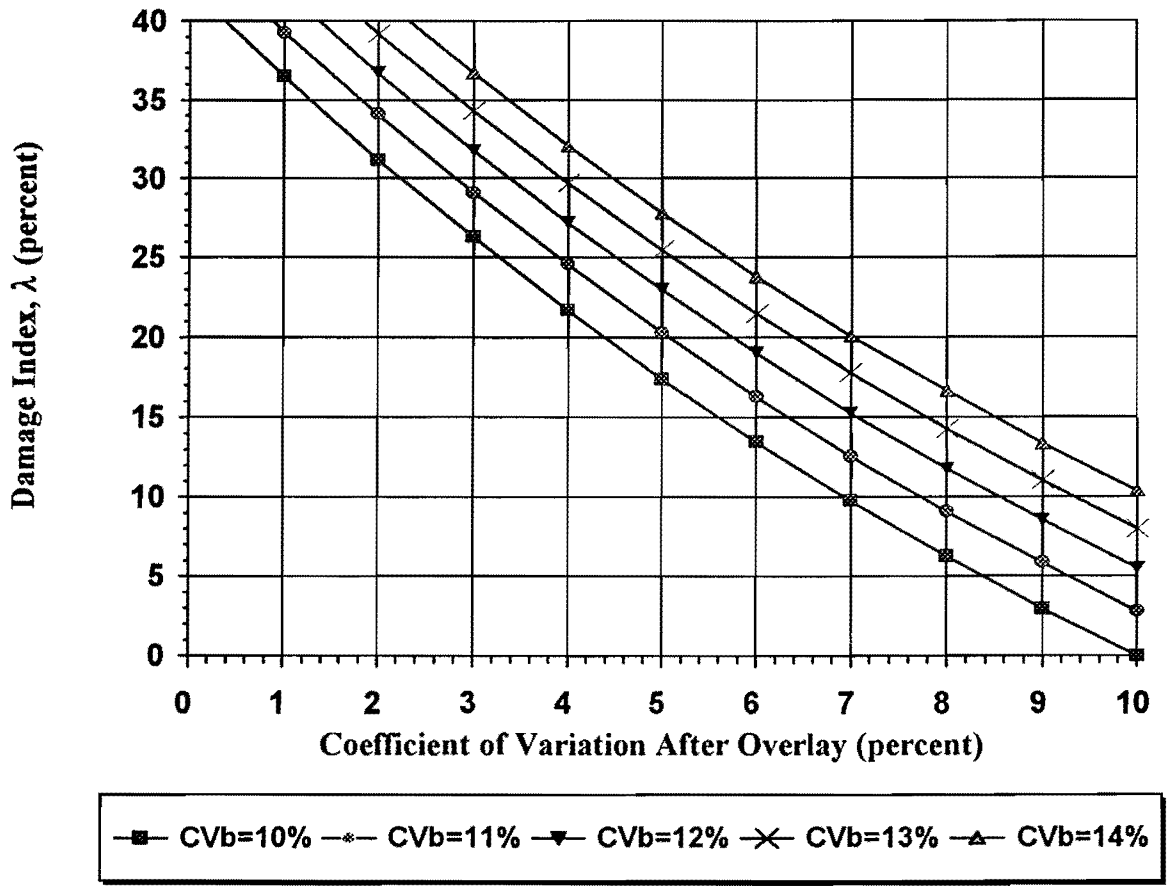

Figure 38. Chart to Evaluate Surface Smoothness Using Group A Test Methods for Coefficients of Variation Before the Overlay Between 10 and 14 Percent

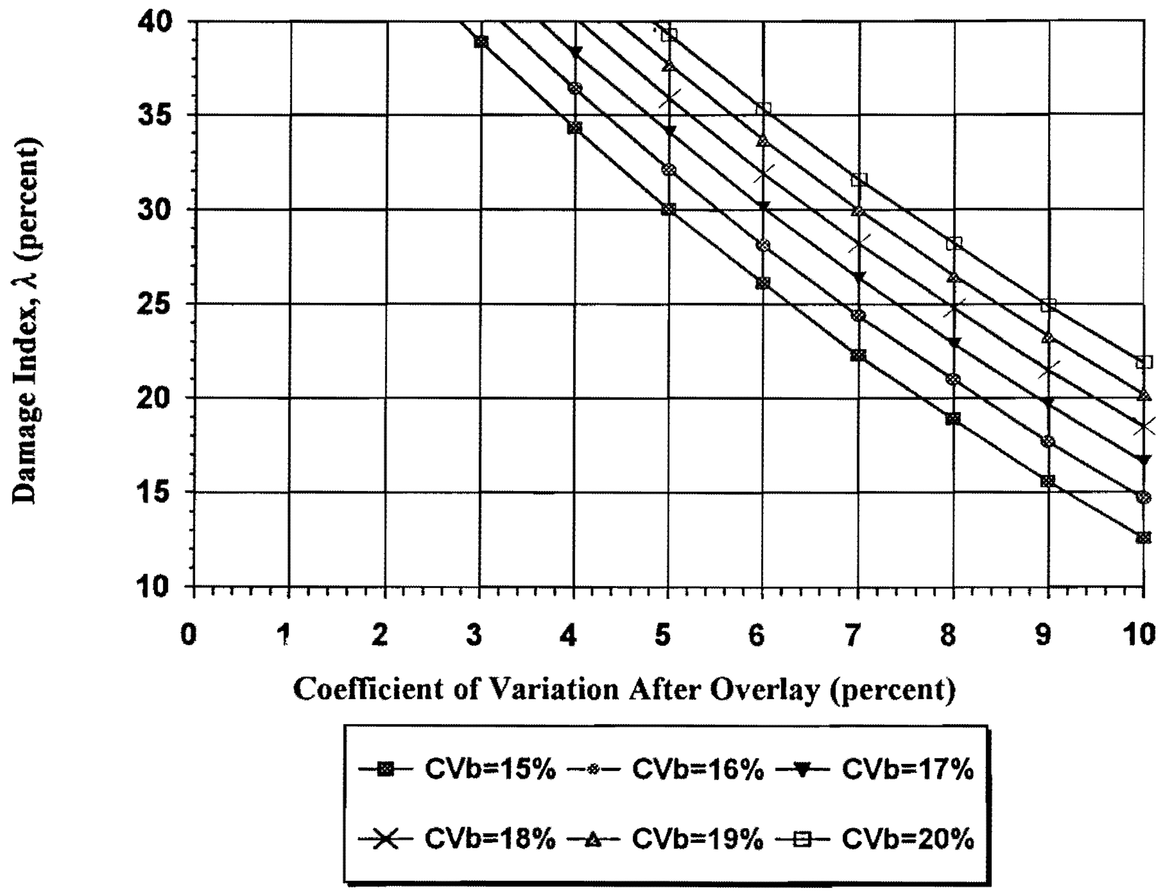

Figure 39. Chart to Evaluate Surface Smoothness Using Group A Test Methods for Coefficients of Variation Before the Overlay Between 15 and 20 Percent

life due to the change in surface smoothness as a result of the overlay. Figure 36 illustrates an example application of the charts. From the point on the abscissa corresponding to the average coefficient of variation, CV_1, after the overlay, the engineer proceeds vertically until the curve corresponding to the predicted coefficient of variation, CV_b, before the overlay is reached. The engineer then proceeds horizontally to the left and reads off the index, λ, which determines how much the contractor gets paid in the proposed procedure. This payment schedule is presented shortly.

It is noted that a number of computer programs are available for simulating the response of vehicles to measured profiles (Al-Rashid, Lee, and Dawkins, 1972; MacAdam et al., 1980; Fernando et al., 1991). While any of the available programs may be used to accomplish the simulations required in this test method, further work is needed to take one of the existing programs and develop a computerized procedure that is specifically tailored for this method of surface smoothness evaluation. This program, which will make it easier for TxDOT engineers to use Surface Test A1 on overlay projects, can be developed as part of efforts to convert from the current specification to the profile-based specification developed in this study. While this computerized procedure is under development, other surface test methods described herein may be used.

Surface Test A2

Surface Test A2 is based on the same principles underlying Surface Test A1. However, the coefficient of variation, CV, of predicted dynamic loads is estimated from the IRI computed on each measured wheelpath. Given the IRI, the statistic, CV, is estimated using Figure 40. Note from the figure that CV is about four times the IRI at a vehicle speed of 97 kph. The CVs estimated for each wheelpath are averaged to evaluate, λ, using one of the charts presented in Figures 36 to 39. This parameter is then used to evaluate pay adjustments for the overlaid segments using the payment schedule presented in the following.

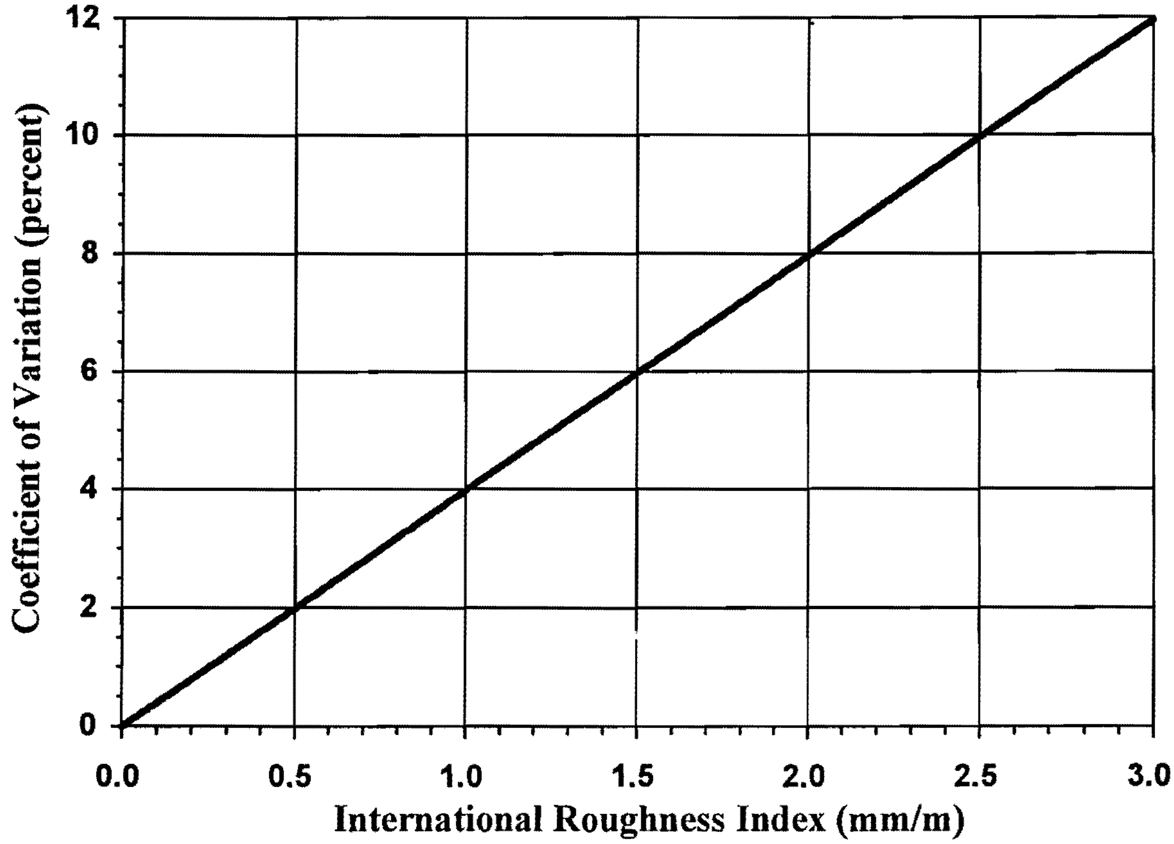

Figure 40. Chart to Estimate the Coefficient of Variation of Predicted Dynamic Loads Using IRI for a Vehicle Speed of 97 kph

Payment Schedule for Group A Evaluation Methods

Given the value of λ from Surface Test A1 or A2, the pay adjustment for a particular segment is determined using Figure 41. The following observations are noted from the figure:

1. No pay adjustments are made for values of λ within the range of ±6 percent;
2. Above 6 percent, bonuses are paid beginning at a base value of $35 and increasing linearly until the maximum monetary incentive of $90 is reached at a value of λ equal to 25 percent. For larger values of λ, the monetary incentive is $90; and
3. For values of λ smaller than −6 percent, penalties are assessed beginning at a base value of −$35 and increasing linearly until the maximum penalty of −$140 is

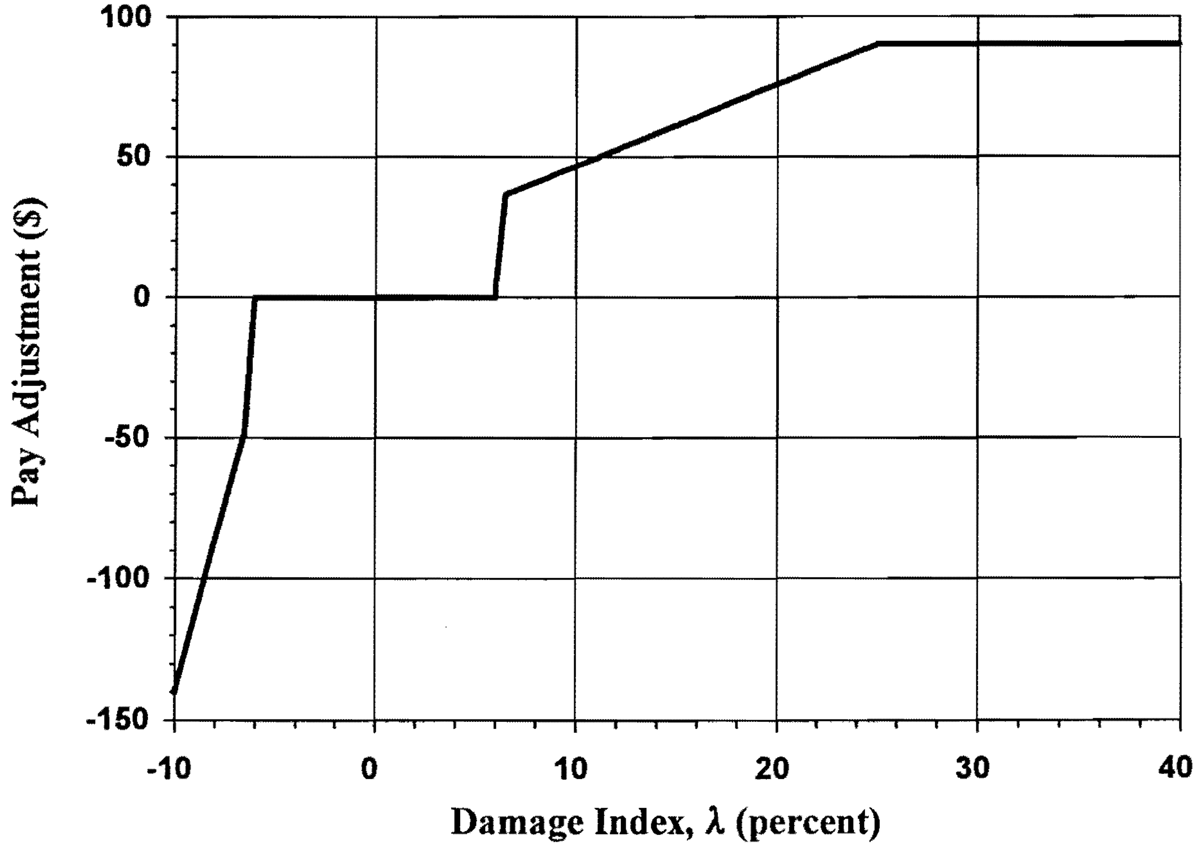

Figure 41. Proposed Pay Adjustment Schedule for Group A Test Methods

reached at a λ of − 10 percent. At lower values of λ, corrective work to be done at the contractor's expense, is required.

It is recognized that the proposed pay schedule will likely undergo changes as the test methods get implemented within the districts. However, based on the evaluation presented in Chapter IV using data from the district overlay projects, the proposed schedule is a suitable starting point, in the author's opinion, toward implementing a profile-based smoothness specification in the state.

There is a question of whether a maximum tolerable level of roughness should be specified in the pay adjustment schedule. Since the acceptability of the overlay smoothness is evaluated on the basis of the change in surface profile before and after the overlay, it appears that a permissible roughness criterion is necessary to prevent surfaces that are unduly rough from being accepted even though an improvement is gained in surface smoothness. However, since the Group A test methods are primarily intended for thin overlays where no surface preparations are planned, or where only spot level-ups are specified, the engineer must assess whether a permissible roughness criterion is achievable on a given project. Results from the field study of district overlay projects indicate that acceptable levels of smoothness can be achieved on thin overlays even without surface preparation, provided that the existing pavement exhibits minimal distress and where the primary deficiency is less than desired ride quality. For these cases, a maximum tolerable dynamic load variability of 8 percent under Surface Test A1, or a maximum allowable IRI of two mm/m under Surface Test A2 are recommended. Under these situations, if the final overlay smoothness exceeds the permissible level, corrective work at the contractor's expense will be required. For other cases where a permissibie roughness criterion may not be realistic, the engineer should consider including surface preparations in the construction plans or using only the change in surface smoothness before and after the overlay as the basis for evaluating the finished pavement.

Group B Evaluation Methods

Test methods belonging to this group are primarily applicable on projects where the overlay thickness is greater than 64 mm, and/or where surface preparations are planned to remove or correct existing surface distress. In contrast to the previous test methods discussed, the procedures falling under this category use only the wheelpath profiles measured after the overlay to evaluate the acceptability of the surface smoothness. This evaluation is done on the basis of the predicted change in pavement life, Δ, due to departures from the target smoothness. Note that this is different from the parameter, λ, which is based on the change in surface smoothness before and after the overlay. However, just like the Group A methods, the effect of surface smoothness on pavement life is evaluated by predicting the effect of surface smoothness on vehicle dynamic load variability. There are three test methods falling under Group B which are described briefly in the following paragraphs.

Surface Test B1

Similar to Surface Test A1, this method requires the prediction of dynamic loads for the standard 80 kN single axle. This simulation is conducted using the wheelpath profiles measured on the overlay surface as input. From the simulation results, the coefficient of variation (CV) of predicted dynamic loads is evaluated for each wheelpath at 161 m intervals. The coefficients of variation are then averaged to get the dynamic load variability per 161 m segment per lane. This average is then used in Figure 42 to evaluate the damage index, Δ.

In the proposed test method, a target coefficient of variation of 4 percent is assumed, corresponding to the average predicted dynamic load variability of overlaid segments monitored in the field study. The index, Δ, determined from the measured profile is used to evaluate the acceptability of the overlay smoothness using the schedule shown in Figure 43. This figure is used to evaluate pay adjustments under the Group B test methods. The proposed schedule has the following characteristics:

1. No pay adjustments are made for values of Δ within the range of ±6 percent;
2. Above 6 percent, bonuses are paid beginning at a base value of $35 and increasing linearly until the maximum monetary incentive of $90 is reached at a value of Δ equal to 15 percent. For larger values of Δ, the monetary incentive is $90; and
3. For values of Δ smaller than -6 percent, penalties are assessed beginning at a base value of -$35 and increasing linearly until the maximum penalty of -$140 is reached at Δ equal to -10 percent. At lower values of Δ, corrective work is required of the contractor. This threshold of -10 percent corresponds to a predicted coefficient of variation of approximately 6 percent from Figure 42, or an IRI of 1.5 mm/m based on the relationship shown in Figure 40.

Surface Test B2

In this test method, the IRI computed from the measured wheelpath profile is used to estimate the coefficient of variation of vehicle dynamic loads. This is accomplished using the relationship between dynamic load variability and IRI given in Figure 40. The coefficient of

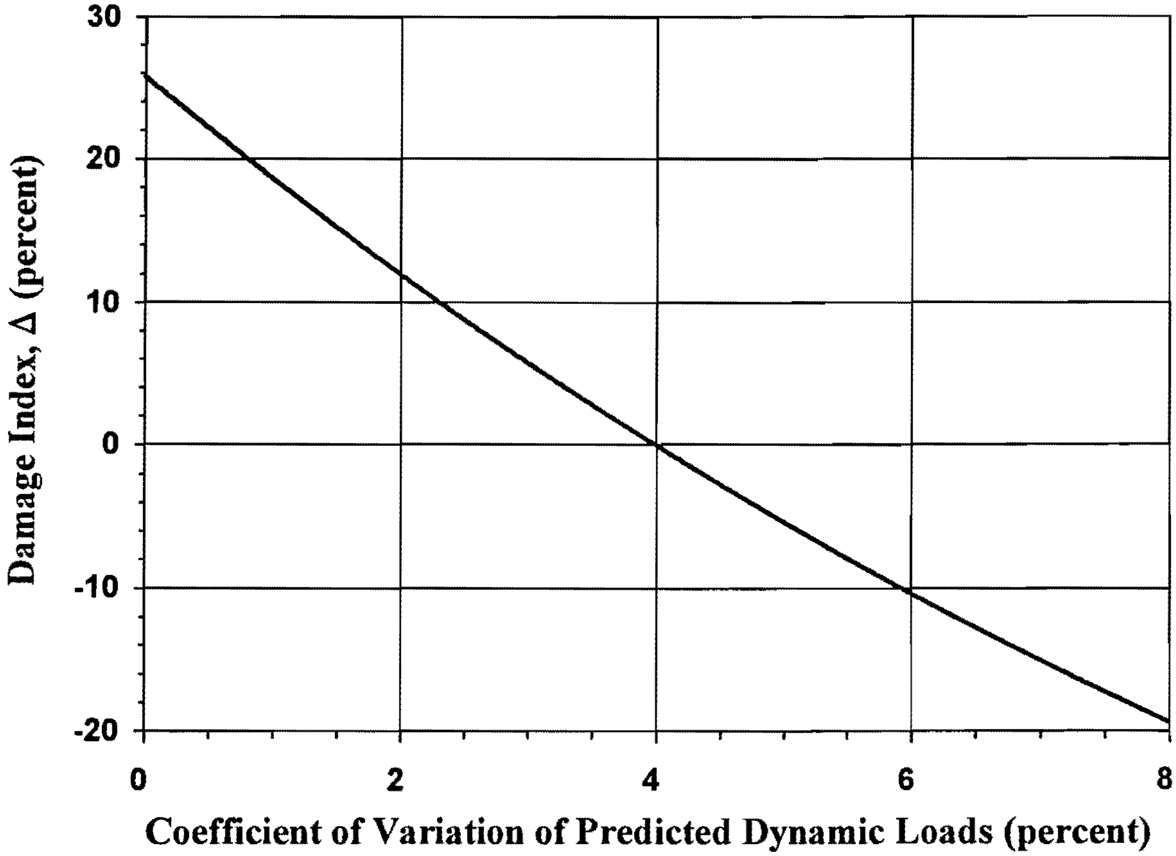

Figure 42. Relationship Between CV and Predicted Change in Pavement Life, Δ

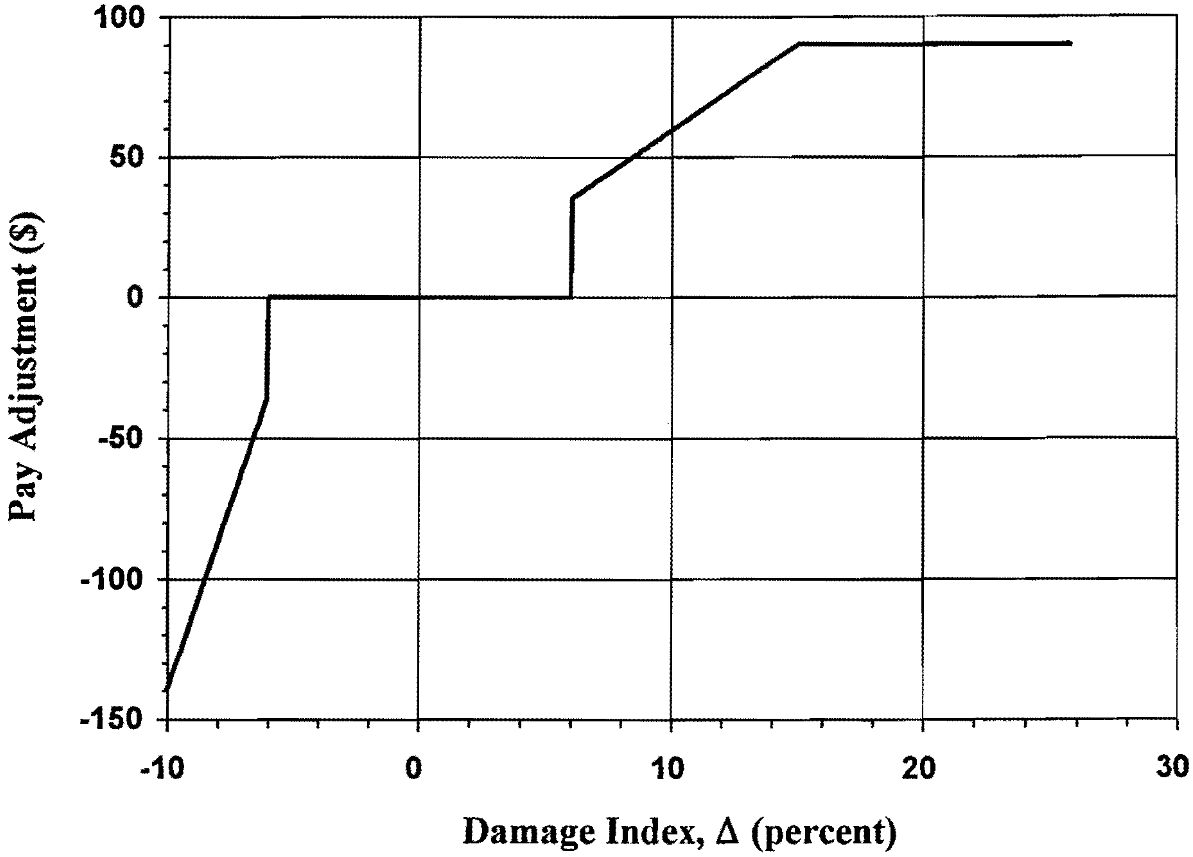

Figure 43. Pay Adjustment Schedule Based on a Tolerance Band of ±6 Percent on Δ

variation is predicted for each wheelpath and the average of the wheelpath statistics is used in Figure 42 to evaluate Δ. Pay adjustments are then determined using Figure 43.

Surface Test B3

This test method was developed to facilitate the transition from the current profilograph specification to the profile-based smoothness specification developed from this research. Under Surface Test B3, the coefficient of variation of predicted dynamic loads is estimated using the null blanking band profile index from the profilograph. This is accomplished in a stepwise manner, as follows:

1. The IRI is estimated from the null blanking band PI from Figure 44; and

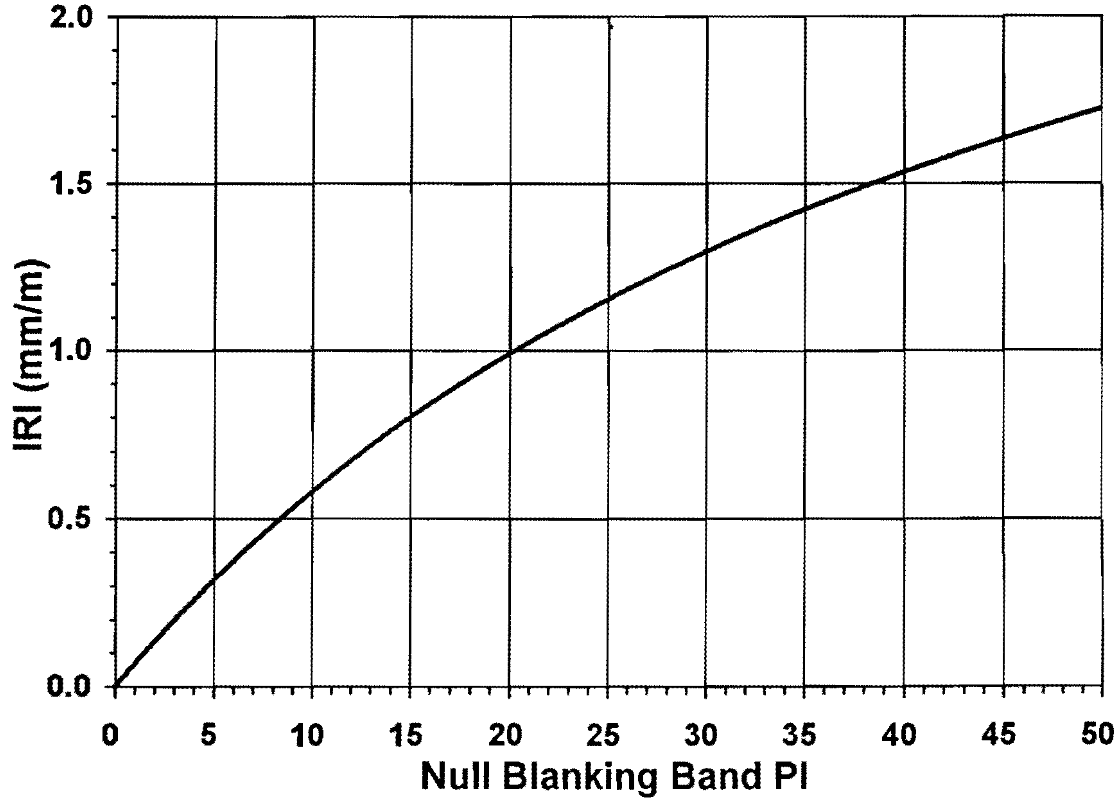

Figure 44. Chart to Estimate IRI from the Null Blanking Band Profile Index (PI)

2. The predicted IRI is then used in Figure 40 to estimate the dynamic load variability associated with the measured profile.

The above steps are done for each wheelpath tested. The average of the wheelpath coefficients of variation is computed to determine the damage index, Δ, which is used in Figure 43 to get the pay adjustment for a given segment. It is noted that under Surface Test B3, corrective work will be required if the null blanking band profile index reaches 38, corresponding to a value of Δ equal to − 10 percent.

CHAPTER VIII
SUMMARY AND RECOMMENDATIONS

This research aimed to develop a profile-based smoothness specification for bituminous overlays. Toward this goal, researchers initially evaluated the applicability of the new flexible pavement profilograph specification for asphalt concrete overlays. Through a field study of district overlay projects, data were obtained that gave evidence of the applicability of the existing specification in the evaluation of ride quality of overlaid pavements, provided that existing surface distresses are corrected or removed by surface preparation. This study also showed thin overlays as the primary resurfacing treatment used by the districts. Consequently, in developing the smoothness specification for asphalt concrete overlays, researchers developed test methods based on the improvement in surface smoothness before and after the overlay.

The specification developed in this study permits TxDOT to evaluate the quality of the overlay smoothness based on the predicted change in pavement life associated with the overlay. From theoretical considerations, researchers related overlay life, based on reflection cracking, to the fracture characteristics of the overlay mix, and the variability in vehicle dynamic loading due to unevenness in the surface profile. The methodology developed allows TxDOT to tie surface smoothness requirements with mixture design requirements should this be a direction the department may wish to explore in the future. Different methods for evaluating surface smoothness were proposed including a provisional test method based on the null blanking band profile index, PI_0. This required the development of relationships between the null blanking band PI and IRI, and between IRI and the coefficient of variation of predicted dynamic loads. From this work, the null blanking band PI was found to correlate better with the IRI, compared to the profile index based on the 5 mm blanking band presently used by TxDOT. Since the 5 mm blanking band may mask certain components of roughness, and in view of the higher correlation of PI_0 with IRI, researchers developed an interim test method based on the null blanking band profile index to facilitate the conversion from the existing specification to the profile-based specification developed in this study. In making the change to a profile-based overlay smoothness specification, the following recommendations are offered for consideration:

1. Pilot implementation of the proposed specification may begin with Surface Tests A2, B2, and B3. Of these methods, Surface Test B3 is the logical choice to implement in the interim because of the availability of profilographs and experience with its use in the state. However, to introduce contractors and TxDOT engineers to the profile-based test methods developed in this study, projects should be selected in which profile measurements will be collected with the profilograph and TxDOT's profilers. The objective is to develop an understanding of the statistics, IRI and PI_0, among contractors and TxDOT engineers and to help them learn to perceive roughness in terms of these statistics;
2. Inertial profilers are available that provide not only IRIs but also profile indices by profilograph simulation. This option of simulating the profilograph response to the measured profile should be considered during the interim implementation of the profile-based smoothness specification. The flexibility afforded by this option carries the potential for smoothing the conversion to the profile-based specification developed in this study;
3. Implementation of a profile-based smoothness specification will require the construction and maintenance of a test facility for evaluating surface profilers to ensure that the equipment for evaluating surface smoothness are accurate, repeatable, and reliable;
4. The charts prepared for evaluating the acceptability of overlay smoothness are based on a fracture parameter, n, of 3.6. This value was determined from creep compliance data generated from frequency sweep tests, using a relationship between the fracture parameter, n, and the slope of the creep curve, m, developed by Lytton et al. (1993). This relationship is given by Eq. (3) in Chapter III. Researchers recognize that very limited test data based on the shear mode of crack propagation are available on the fracture parameter, n. Thus, estimates were

generated using Eq. (3) with creep compliance data taken from frequency sweep tests conducted by Lytton et al. (1993). The value of 3.6 used in developing the charts corresponds to the average of the estimates determined by researchers. In the absence of test data to characterize the *n*-value for a particular overlay mix, the author proposes that the charts presented in Chapter VII be used for evaluating the change in pavement life because of the overlay. For the long-term, researchers recommend that TxDOT support the development of a database of *n*-values characterizing the asphalt concrete overlay mixtures commonly placed in Texas. The department should evaluate the need to tie surface smoothness requirements with asphalt mixture requirements for construction quality control and acceptance;

5. The methodology presented in this report permits TxDOT to establish different criteria for evaluating overlay smoothness depending on the functional classification of a given highway. While the charts presented correspond to a confidence level of 95 percent, charts at other confidence levels may be developed should TxDOT decide to consider the level of highway use in evaluating the acceptability of surface smoothness on resurfacing projects;
6. The pavement damage indices, Δ and λ, for evaluating surface smoothness are based on reflection crack growth, identified from previous research as the primary distress mechanism for asphalt concrete overlays. It is recognized that, for other pavements, other distress mechanisms such as fatigue cracking or permanent deformation may govern. For these pavements, new damage-based criteria for evaluating surface smoothness would have to be developed;
7. The pay adjustment schedules in the proposed specification should be evaluated during the pilot implementation to identify any changes that are necessary and to modify the schedules accordingly so that they more closely reflect the value attached by TxDOT to the quality of the contractor's work based on the criteria used in the new specification;
8. Implementation of Surface Tests A1 and B1 will benefit from the development of a computer program that is specifically tailored to these test methods. A number of

simulation programs for predicting vehicle response to measured profiles are available with which to develop a computer program for implementing a specification of the form given by Surface Tests A1 and B1. This program will make it easier for TxDOT engineers to use Surface Test A1 or B1 on overlay projects and can be developed as part of efforts to convert from the current specification to the profile-based specification investigated in this study. While this computer program is under development, the other surface test methods proposed herein may be used;

9. It is noted that Surface Tests A1 and A2 are specifically intended as options for evaluating surface smoothness on projects where the overlay is thin and no surface preparations are planned or only spot level-ups are to be applied. Under these conditions and where a reasonable doubt exists that the smoothness requirements based on final profile are achievable, these methods are offered for use in lieu of the alternative of dropping the smoothness specification or of using the straightedge to check the overlay smoothness on these projects. For other cases, Surface Tests B1, B2, or B3 are expected to be applicable;
10. Implementation of the proposed smoothness specifications based on surface profile will also benefit from the development of graphical routines that will plot the measured profiles or simulated vehicle dynamic loads, along with the IRIs or pavement damage indices determined from the surface profiles or load profiles, respectively. One good point about the profilograph is that it produces a profilogram which shows the rough spots on a given section that contractors and engineers readily understand. In this way, the method is not perceived to be a black box. Similar graphical routines should be developed to facilitate the conversion to a profile-based smoothness specification.

In summary, the proposed smoothness specifications represent a significant improvement over the existing ride specification, in the author's opinion. Under the proposed specifications, surface profiles will be measured using devices that offer greater accuracy compared to the profilographs currently used. Of equal or greater significance is the fact that surface profiles are evaluated based on the predicted change in pavement life associated with the overlay. This development showed the importance, not only of building smoother pavements, but also of designing, manufacturing, and encouraging the use of trucks with improved dynamic performance and of designing and producing bituminous overlay mixtures that offer greater crack resistance. From the recommendations offered, it is obvious that work remains to be done in order to move forward on the road to implementing a profile-based smoothness specification for asphalt concrete overlays. In the opinion of the author, this research has laid the groundwork on which further development and implementation can proceed. What is important is to move forward, realizing that implementation is a phased process and that further developments along the way will be necessary to move the process from the existing plateau to a higher one. In the author's opinion, TxDOT need not wait until a fully-developed profile-based smoothness specification is achieved before it begins the conversion. This process can begin, at the very least, with efforts to implement, in the interim, a smoothness specification of the form given by Surface Test B3, followed by near-term efforts to implement specifications based on Surface Tests A2 and B2. For the long-term, the author recommends additional development efforts that would lead to the implementation of smoothness specifications of the forms given by Surface Tests A1 and B1.

As a final recommendation, TxDOT should support development efforts for a database of pavement profiles collected from construction projects and from the periodic surveys done to maintain the PMIS database. This is feasible with today's computer technology, which steadily undergoes improvements in processing capability, storage media, and affordability. Limits of construction projects do not normally coincide with limits of the PMIS sections. In addition, the limits of PMIS sections, as well as the method of rating ride quality, may change over the years. By having the profiles, a consistent historical record of a pavement's ride quality can be maintained, which in time can be used to establish the benefits, in terms of pavement life, of better initial surface smoothness. In the author's opinion, this database is extremely important. Without it, it will be difficult to evaluate the effectiveness of smoothness specifications in terms of enhancing ride quality, improving pavement performance, and reducing life-cycle costs. In the author's opinion, TxDOT needs to be in a position to make this evaluation in the future to show the public that it is achieving its mission of providing highways that allow the safe and comfortable movement of people and goods.

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APPENDIX

METHODOLOGY FOR RELATING SURFACE PROFILE TO PREDICTED SERVICE LIFE OF ASPHALT CONCRETE OVERLAYS

DEVELOPMENT OF DISTRESS IN ASPHALT CONCRETE OVERLAYS

Asphalt concrete overlays are commonly used in rehabilitating both flexible and rigid pavements. In order to establish a smoothness specification that is tied to the predicted performance of asphalt concrete overlays, researchers first identified the mechanisms that control the development of distress in bituminous overlays. Jayawickrama et al. (1987) studied the failure mechanisms that govern the service life of overlays and concluded that reflection cracking is often the primary cause of deterioration in this method of pavement rehabilitation. The mechanisms which are generally recognized as causing reflection cracking are the horizontal and vertical movements of the original pavement layers attributed to temperature changes and traffic loading. Because of these movements, cracks and joints in the original pavement, are reflected up through the overlay. Once reflection cracks appear on the surface, other forms of distress, such as raveling and spalling often occur at the cracks. In addition, water intrusion through the cracks may result in loss of bond between the overlay and the original pavement, or in a weakening of the support provided by the underlying base and subgrade layers. Thus, the service life of the overlay is largely dependent on retarding the growth of reflection cracks.

Because this study is concerned with the effects of surface smoothness on predicted pavement life, focus is placed on the load-associated mechanism of reflection crack growth. After all, Figures 10 to 12 in Chapter III show that surface profile affects the vehicle dynamic loads applied to the pavement. Consequently, it will influence to some extent, the propagation of reflection cracks through the asphalt concrete overlay. This is not to imply that the temperature-associated mechanism of reflection crack growth is unimportant. On the contrary, it is. However, this mechanism is best considered through a material specification on the bituminous overlay as it is primarily related to the coefficient of thermal expansion based on the study by Jayawickrama et al. (1987).

Figure A1 illustrates the load-associated mechanism of reflection cracking. Under a moving wheel load, the crack tip experiences three pulses of high stress concentrations. As the load approaches the crack, the shear stress at the crack tip reaches a maximum value at point A. This is followed by a maximum bending stress (of magnitude denoted by point B)

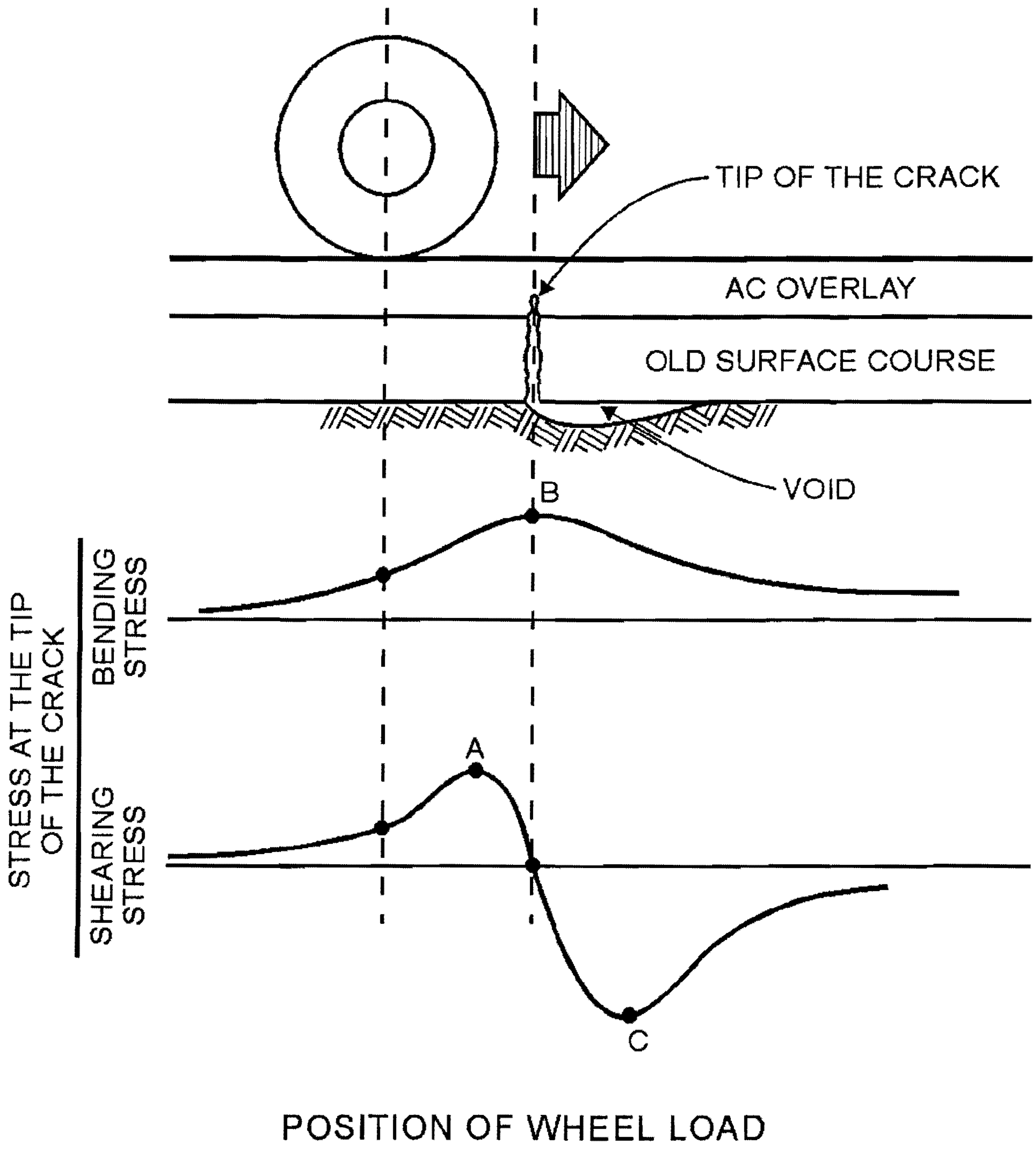

Figure A1. Stresses Induced at the Crack Tip Due to a Moving Wheel Load (Jayawickrama et al., 1987) that occurs when the wheel is directly over the crack. Finally, as the load passes the crack, a shear stress (point C) is induced at the crack tip which is equal in magnitude to the first stress amplitude (point A) but opposite in sign. Thus, each time a wheel passes over a crack in the old pavement, the overlay is subjected to shear and bending stresses that induce the crack to propagate up to the surface. This propagation may be modeled using the Paris and Erdogan (1963) equation given by:

$$\frac{dc}{dN} = A(\Delta K)^n \tag{A1}$$

where,

c	=	crack length;
N	=	cumulative load cycles;
dc/dN	=	rate of change in crack length with number of load repetitions;
ΔK	=	change in stress intensity factor at the crack tip; and
A, n	=	fracture parameters of the asphalt concrete overlay.

Through finite element analyses, Jayawickrama (1985) evaluated stress-intensity factors for different crack tip positions and levels of aggregate interlock. The results from these calculations are presented in Figure A2 where the stress intensity factors for both bending and shear stresses are shown in non-dimensionalized form. Two observations are made from these figures:

1. For the same crack length, the lower the degree of aggregate interlock, the higher the rate of crack propagation due to a higher stress intensity factor; and
2. The failure mechanism due to bending is effective only up to a certain c/d ratio where, d, is the pavement thickness. Beyond a c/d ratio of about 0.25, the bending stress intensity factor starts to diminish. This implies that the shear mechanism is primarily responsible for propagating the crack through the overlay.

The results shown in Figure A2 have also been verified by Lytton et al. (1993). Because of the predominant effect of shear in propagating reflection cracks through the surface layer, researchers evaluated the relationship between surface profile and pavement life

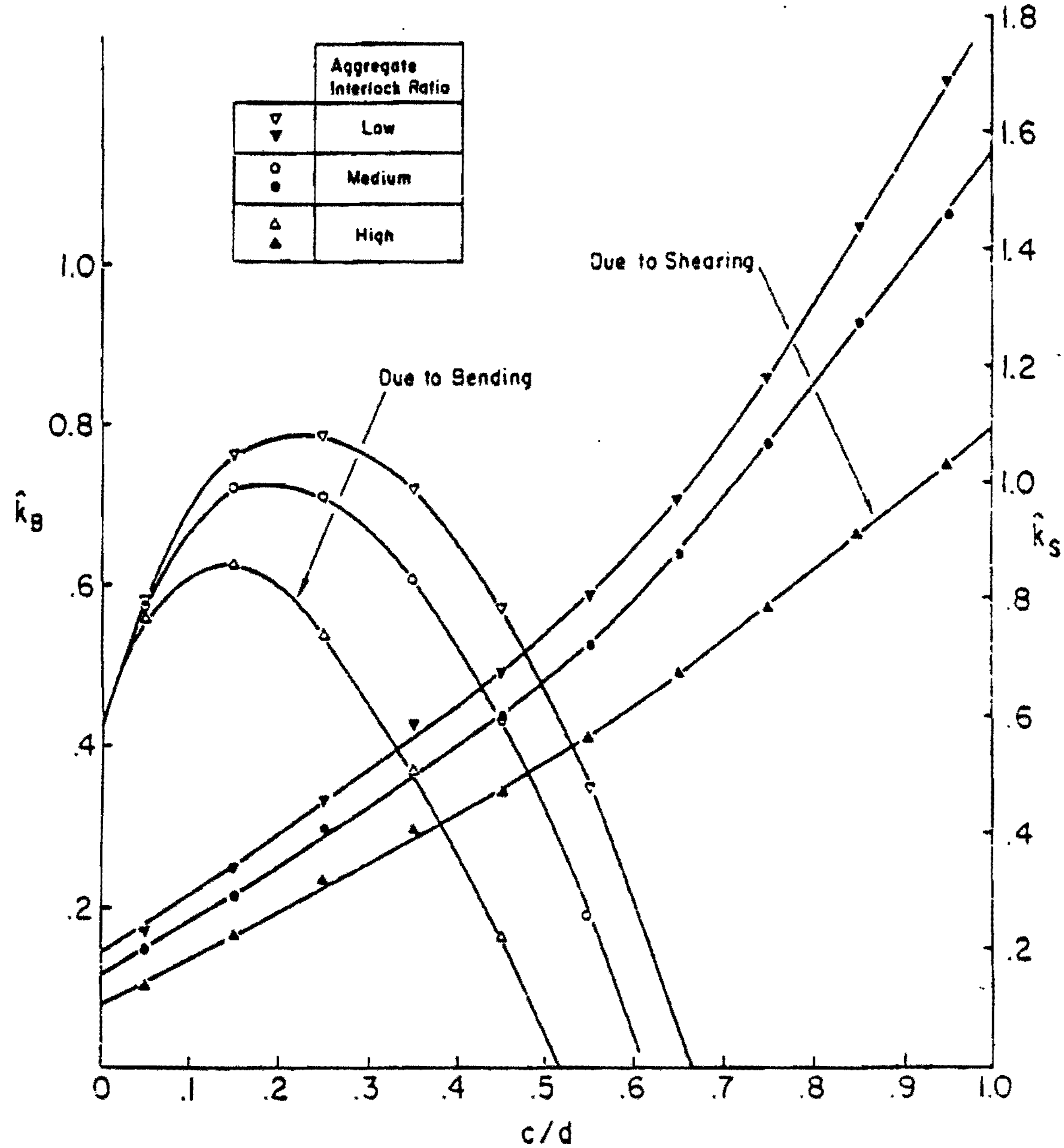

Figure A2. Non-dimensionalized Stress Intensity Factors Due to Bending and Shear (Jayawickrama, 1985) on the basis of this load-associated distress mechanism. However, it is noted that while bending appears to have only a minor effect in propagating the crack, it may be quite important in initiating one.

Integrating the Paris and Erdogan equation leads to the following expression for, N_p, the number of load cycles to propagate a crack to the surface:

$$N_p = \int_{c_0}^{d} \frac{dc}{A\ \Delta K^n} \tag{A2}$$

where,

c_0 = initial crack length; and

d = pavement thickness.

Using the beam-on-elastic foundation theory, Jayawickrama et al. (1987) derived a relationship for the shear stress intensity factor that reflected the influence of layer stiffnesses, layer thicknesses, wheel load, and subgrade support on crack propagation. This relationship is of the form:

$$K_{II} = K_{so}\ \hat{K}_s \tag{A3}$$

where, K_{II}, is the stress intensity factor associated with the shear mode of crack propagation, and the other terms are defined as follows:

$$K_{so} = \frac{q}{4\ \beta\sqrt{d}} \left[1 + e^{-\beta a} (\sin\beta a - \cos\beta a)\right] \tag{A4}$$

$$\hat{K}_s = f(c/d) = \mathit{function\ of\ crack\ geometry} \tag{A5}$$

q = applied surface pressure

a = width of the loaded area

β = ratio of subgrade support to the flexural stiffness of the upper layers

Substituting Eqs. (A4) and (A5) into Eq. (A2), the service life based on the shear mode of crack propagation is predicted from the following relation:

$$N_p = \frac{1}{AK_{so}^{\ n}} \int_{c_o}^{d} \frac{dc}{\left(\hat{K}_s\right)^n} = \frac{1}{AK_{so}^{\ n}} I_s \tag{A6}$$

Note that, from Eq. (A5), $\hat{K}_s$, is only a function of the crack geometry. Thus, the integral in Eq. (A6) is also a function of crack geometry, and is denoted for convenience as, I_s. The above relationship is used in the next section to develop a relationship for evaluating the effects of surface smoothness on the predicted service life of asphalt concrete overlays.

RELATIONSHIP BETWEEN SURFACE SMOOTHNESS AND PREDICTED PAVEMENT LIFE

As illustrated in Figures 10 to 12 of Chapter III, the surface profile has a significant effect on the dynamic loads applied to the pavement. Because the stress intensity at the crack tip is a function of the applied surface pressure as evident from Eq. (A4), the surface profile will influence the rate of crack propagation and consequently, the predicted service life. To develop a smoothness specification that is tied to predicted performance, consider the two pavements illustrated in Figure A3. In the first case, a smooth overlay is built over the existing pavement while in the second case, a rough overlay is constructed. Note that the underlying pavement is the same for both scenarios as would be true for a given resurfacing project. Because this study is concerned with pavement smoothness, only the effect of differences in surface profile is considered. Thus, it is assumed that the pavements illustrated in Figure A3 are alike and uniform in every respect except for the surface profile. Researchers then evaluated the effect, on predicted pavement life, of differences between the target and as-

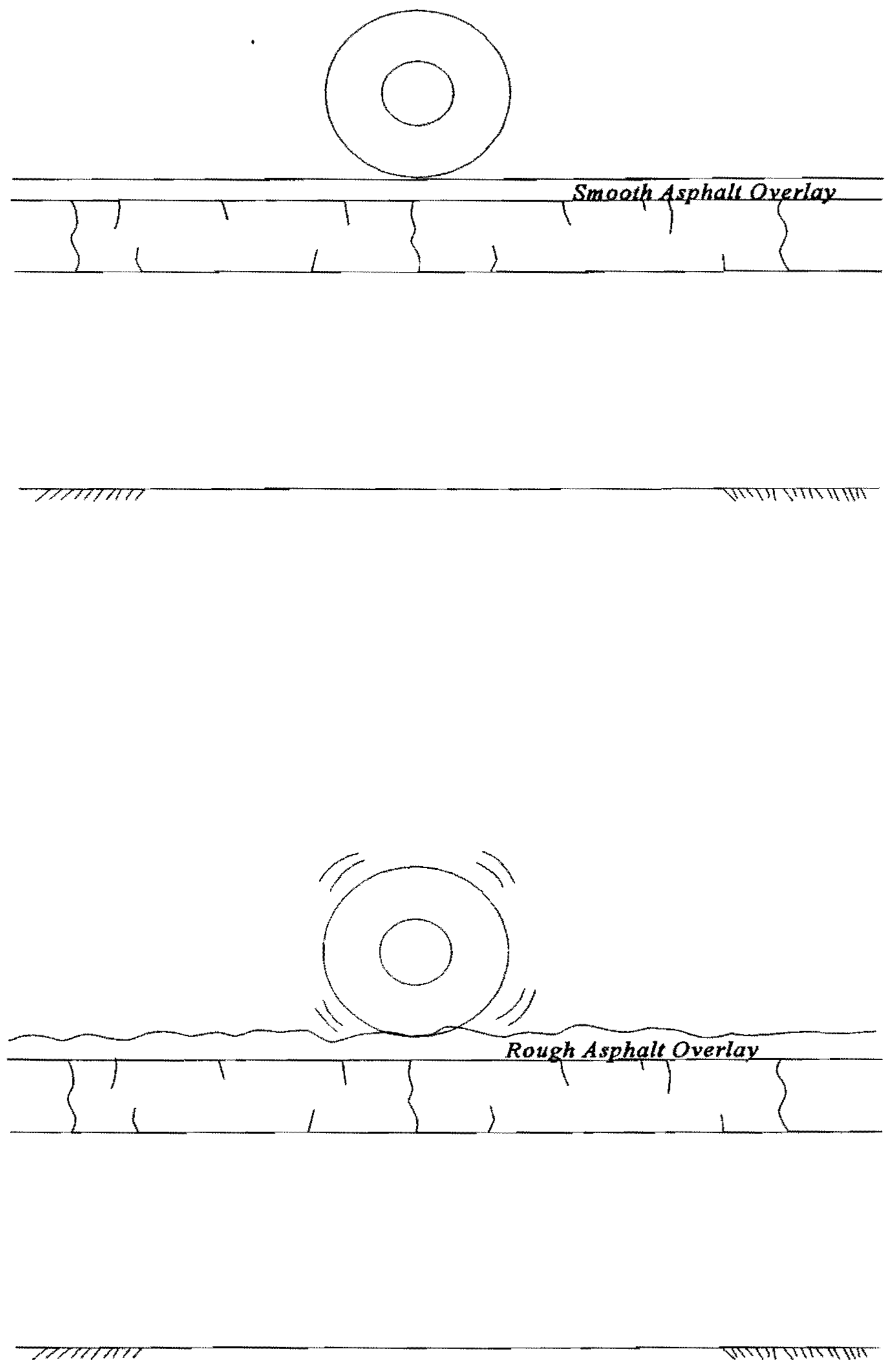

Figure A3. Illustration of Approach Used to Evaluate Overlay Smoothness Based on Predicted Service Life built profiles of asphalt concrete overlays. The former is defined herein as the pavement established in the design stage, i.e., according to the design plans, while the latter is the pavement obtained from construction.

The service life for any pavement may be evaluated using Eq. (A6). If N_{p1} is defined as the predicted service life for the as-built pavement, and N_{p0}, is the corresponding prediction for the target, then, from Eq. (A6):

$$N_{p1} = \frac{1}{A\left(K_{so}\right)_1^n} I_s \tag{A7}$$

$$N_{p0} = \frac{1}{A\left(K_{so}\right)_0^n} I_s \tag{A8}$$

where,

$(K_{so})_1$ = $f(q_1)$, is a function of the tire contact pressures associated with the as-built pavement;

$(K_{so})_0$ = $f(q_0)$, is a function of the tire contact pressures associated with the target pavement; and

A, n = fracture parameters characterizing the asphalt concrete overlay.

Equations (A7) and (A8) may be used to evaluate the change in the predicted service life of the overlay because of deviations from the target profile. Note that the difference between the two equations will vary with design parameters, such as the overlay thickness, the stiffness of the asphalt concrete layers, the layer thicknesses and moduli of the supporting layers, and the general condition of the underlying pavement. To isolate the effect of surface profile, the methodology proposed herein is based on evaluating the change in predicted pavement life normalized with respect to the design life. This approach has the added benefit of providing a criterion for evaluating the acceptability of the as-built profile. Thus:

$$\Delta = \frac{N_{p1} - N_{p0}}{N_{p0}} \tag{A9}$$

where, Δ, is the normalized change in predicted pavement life associated with differences between the as-built and target profiles. Using Eqs. (A4), (A7), and (A8), Δ may be further simplified to the following form:

$$\Delta = \left[\frac{(K_{so})_0}{(K_{so})_1}\right]^n - 1 = \left(\frac{q_0}{q_1}\right)^n - 1 \tag{A10}$$

where,

q_0 = $f(P_0)$, is a function of the predicted dynamic loads for the target; and

q_1 = $f(P_1)$, is a function of the predicted dynamic loads for the as-built pavement.

Note that Eq. (A10) represents a distribution due to the variation in the predicted dynamic loads brought about by unevenness in the surface profile. The distributions of q_0 and q_1 are illustrated in Figure A4. For a given wheel, the loads applied on the pavement will vary from the mean or static value. On a smooth overlay, the variability will be less as illustrated in the tighter distribution for q_0. In contrast, a rough overlay will induce more variability and a wider spread in the distribution of the applied dynamic loads, q_1, in Figure A4. At locations where the profile induces loads greater than the static value used in design, the overlay will deteriorate at a faster rate because of higher induced stresses at the tips of existing cracks in the original surface. For the purpose of evaluating the change in predicted pavement life due to deviations from the target profile, the dynamic load corresponding to a given percentile of the load distribution is used to characterize the magnitude of impact loading. Specifically, q_0 and q_1 in Eq. (A10) are evaluated as follows:

$$q_0 = q_{st} + z\sigma_0 \tag{A11}$$

$$q_1 = q_{st} + z\sigma_1 \tag{A12}$$

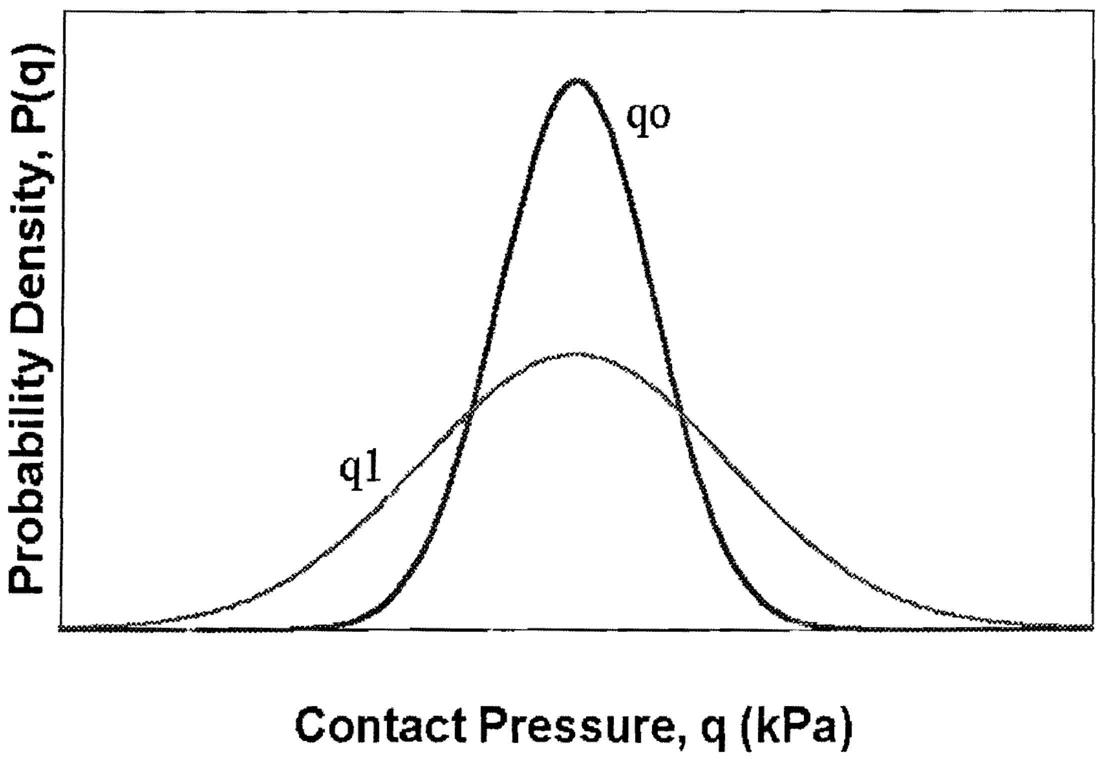

Figure A4. Illustration of the Dynamic Load Distributions for Smooth (q_0) and Rough (q_1) Surfaces

where,

q_{st} = contact pressure corresponding to the static wheel load;

σ_0 = standard deviation of the dynamic loads associated with the target profile;

σ_1 = standard deviation of the dynamic loads associated with the as-built surface; and

z = the number of standard deviations corresponding to a given percentile of the dynamic load distribution.

The above approach is used because of the spatial repeatability of vehicle dynamic loads which has been reported in the literature (Papagiannakis et al., 1990; Cole and Cebon, 1992). Experiments with instrumented vehicles have revealed repeated patterns in heavy vehicle dynamic loading which show that loads higher than static tend to recur at specific points along the pavement. This indicates that pavement failure is likely to be determined by peak dynamic forces rather than by average or root-mean-square values. Consequently, researchers evaluated the effect of surface profile on predicted pavement life on the basis of the prescribed percentile of the dynamic load distribution as given in Eqs. (A11) and (A12).

Assuming a normal distribution of the dynamic loads, Table A1 shows values of z corresponding to different percentiles or confidence levels. For a given z, the table shows the percent of dynamic loads that are smaller than the calculated q_0 or q_1 from Eq. (A11) or (A12), respectively. Note that the calculated impact load is the same as the static load at the fiftieth percentile which corresponds to the mean of the dynamic load distribution. Since the concern is with loads generated that are greater than the static value assumed in design, higher percentiles or confidence levels are used to evaluate the severity of impact loading because of differences in pavement profiles. Substituting Eqs. (A11) and (A12) into Eq. (A10), the following expression is obtained for evaluating the change in predicted pavement life due to differences between the as-built and target profiles:

$$\Delta = \left[\frac{q_{st} + z\sigma_0}{q_{st} + z\sigma_1}\right]^n - 1 \qquad \text{(A13)}$$

Since the standard deviation is the same as the coefficient of variation multiplied by the mean, Eq. (A13) may be re-written as:

$$\Delta = \left[\frac{1 + zCV_0}{1 + zCV_1}\right]^n - 1 \qquad \text{(A14)}$$

Note that $\Delta = 0$ when $CV_0 = CV_1$, i.e., the as-built and target profiles are the same. However, if the as-built surface is rougher than the target, i.e., $CV_1 > CV_0$, Δ is negative indicating a reduction in predicted pavement life because of the higher impact loading.

Table A1. Values of z Corresponding to Different Percentiles or Confidence Levels

z Value	Percentile or Confidence Level (Percent)
2.327	99
1.645	95
1.282	90
1.037	85
0.842	80
0.675	75
0.524	70
0.253	60
0.000	50

Conversely, if the as-built surface is smoother than the target ($CV_1 < CV_0$), Δ is positive indicating an increase over the design life. Note that the predicted change also varies with the confidence level and the fracture parameter, n, of the asphalt concrete overlay. In practice, different confidence levels may be used to evaluate the acceptability of the overlay profile for various highway functional classes. The relationship determined also shows that the effect of surface profile on predicted pavement life is tied to the fracture parameter, n, of the particular overlay mix. The higher this parameter, the faster the crack propagation through the overlay material under repeated traffic loading. Thus, Eq. (A14) also implies that, aside from surface smoothness, the design and production of the overlay mix is also important to building overlays that last their design lives. Equation (A14) is used in this study as an index for evaluating the acceptability of asphalt concrete overlay smoothness.