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EVALUATION OF INDOT CONSTRUCTION SMOOTHNESS SPECIFICATIONS

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16. Abstract

Currently, Indiana Department of Transportation (INDOT) is using the California Profilograph as the standard measuring device in its smoothness specifications. The output derived from the profilograph is called Profile Index (PI). PI represents the total accumulated deviations of the profilograph output traces beyond a tolerance zone (blanking band). At present, INDOT is using 0.2-inch blanking band to evaluate the profile traces, which has raised some concerns because some small unpleasant surface irregularities are covered by the blanking band.

The major objective of this study was to develop a rational method for interpreting profilograph traces using 0.0-inch blanking band (zero tolerance) method and to establish corresponding pavement smoothness specifications. The secondary objective was to develop/adopt an automated system for the pavement profile analysis from printed profilograph traces.

The study was divided into two parts. In the first part (synthesis study), a literature review was conducted to obtain information of smoothness specifications, smoothness measuring devices, and indices. Profilograph traces from several completed paving projects were analyzed using 0.2-inch and 0.0-inch blanking bands to develop manual reduction procedure for the 0.0-inch blanking band Profile Index. In the second part of the project, new $PI_{0.0}$ construction smoothness specifications were developed by converting current $PI_{0.2}$ smoothness specifications to the new $PI_{0.0}$ specifications using developed conversion models. The converted $PI_{0.0}$ specifications were then compared with the current Kansas DOT (KDOT) and other $PI_{0.0}$ specifications.

A partial verification of the converted $PI_{0.0}$ specification was done by calculating pay factors for several recently completed paving projects measured using California profilograph. Measurement results were reduced manually and automatically by the Proscan system, which includes scanner and analysis program to reduce printed traces. It has been developed by Kansas State University and currently KDOT is using it in their construction QA procedures. The Proscan system showed excellent repeatability, and it saved considerable amount of time compared to the manual trace reduction. It is therefore recommended that INDOT uses Proscan system in their constitution QA operations. The converted $PI_{0.0}$ specifications were also modified to comply with the Proscan reduction results.

17. Key Words
Smoothness specification, zero blanking band, California Profilograph, Proscan, 0.2" blanking band.

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1 INTRODUCTION

1.1 Background

Smoothness/roughness of new pavements is controlled by quality control measurements performed during construction. Smoothness measurements are carried out by contractors using various types of equipment from simple to very sophisticated models. The magnitudes of the profile irregularities and their distribution over the measured distance are used to describe the pavement smoothness. In general, the contractor may get bonuses depending on the level of smoothness exceeding the minimum requirement. If the smoothness of the pavement is less than the minimum acceptable smoothness, the contractor has to grind the identified irregularities to meet the criteria or pay penalties. The smoothness specification is usually applied for both asphalt and concrete pavements.

Indiana Department of Transportation (INDOT) is currently using the California Profilograph as the standard measurement tool in its construction smoothness specifications. The California Profilograph is a multi-wheeled rolling straightedge, which measures the vertical deviations from a moving fixed-length reference plane. The output from the test is a profilogram or profilograph trace, which indicates the smoothness of a newly paved surface. The profilogram is interpreted manually using plastic templates for computing profile index (blanking band template) and for individual irregularities (bump template). The Profile Index (PI) is computed using 0.2-inch blanking band method (hereafter abbreviated as 0.2” bb), which means that deviations smaller than 0.2 inches are not counted when computing the Profile Index.

Inertial profilers have been used from the 60’s to measured road profile, but mostly for pavement management purposes. In recent years a new generation of inertial profilers called “lightweight profilers” has been developed. These devices have the potential of providing nearly instantaneous smoothness measurements through the automated processing of the road profile trace. However, based on the study conducted by Mondal, Hand, and Ward (2000), the measurements using lightweight profilers do not have good reproducibility, so far. Also, the performance of the lightweight profilers could be affected by extreme geometric conditions such as significant dynamics to the profiler caused by bumps. Therefore, they recommended that INDOT should keep its current construction smoothness specification using California Profilograph until further refinement of the lightweight profiler technology. However, they recommended changing the current construction smoothness specification of PI obtained using 0.2” bb to a PI obtained using 0.0-inch blanking band (hereafter abbreviated as 0.0”bb). The 0.0” bb takes in account all deviations in the profilogram trace. They also recommended that the smoothness specification should be developed based on the pay factor adjustments and through interaction with industry in the process. The modified specification should then be evaluated on a trial basis on several projects in the coming construction season. The study also proposed a blanking band PI construction smoothness specification for lightweight profilers discussed later in the report.

1.2 Problem Statement

The Indiana DOT is currently using a manual method to analyze the profilograph traces measured by the contractor. The manual method is using 0.2" bb in assessing the smoothness of the asphalt cement concrete (HMA) and Portland cement concrete (PCC) pavements. This means that the vertical deviations smaller than 0.2 inches are not counted when computing the Profile Index. This has raised some concerns because in some instances the riding quality of a new pavement has turned out to be poor even though the smoothness criterion has been met (Hancock, Hossain, & Parcells, 2000). Therefore, there is a need to move towards 0.0" bb to better assess the riding quality of the newly constructed pavements. In this way all irregularities of the paved surface can be counted.

Currently, INDOT does not have a procedure to analyze the profilograph traces using the 0.0" bb. Research is needed to study the variability of manual profilograph trace processing with 0.2" and 0.0"bb and to develop a procedure and smoothness specification for the 0.0" bb method.

Studies have shown that the major variability of manual interpretation of profilograph traces is due to the difference between the operators and repeated trace reductions (Devore, Hossain, & Parcells, 1995). In addition, the manual interpretation of profilograph traces is a very labor intensive and time-consuming process. Hence, there is also a need to develop/adopt an automated system for the interpretation of profilograph traces.

1.3 Objective of the Study

The major objective of the research is to develop a rational method of interpreting profilograph traces using 0.0" bb and to establish a corresponding pavement smoothness specification. The secondary objective is to develop/adopt an automated system for pavement profile analysis from profilograph traces.

1.4 Scope and Limitations

The study is divided into two parts. In the first part (synthesis study) a literature review is conducted to gather information about the smoothness measuring techniques, indices and methods to develop/establish smoothness specifications. Also, existing profilograph profiles provided by INDOT are analyzed to develop a manual 0.0" bb procedure. The PI values obtained using this new procedure and INDOT current 0.2" bb methods are then compared to analyze the repeatability and reproducibility of both methods.

The main task in part two is to develop a quality control/quality assurance construction smoothness specification for HMA and PCC pavements in Indiana using the 0.0" bb procedure to analyze the profilograph trace. Research also includes validation of the developed specification, and to study ways to automate the process of analyzing profilograph traces to improve repeatability and reduce analysis time.

2 LITERATURE REVIEW

2.1 Background

In general, road roughness is caused by 1) construction techniques that allow some deviation from the design profile, 2) repeated loads that cause pavement distortion by plastic deformation in one or more of the pavement components, 3) frost heave and volume changes due to shrinkage and swell of the subgrade, and 4) non-uniform initial compaction, (Yoder and Hampton, 1958). According to Hudson (1981), the purpose for road roughness/smoothness measurements are to:

- maintain construction quality control;
- locate abnormal changes in the highway, such as drainage, subsurface problems, or extreme construction deficiencies;
- establish a statewide basis for allocation of road maintenance resources; and
- evaluate pavement serviceability-performance life histories for evaluation of alternate designs.

To maintain construction quality control, many states are using Quality Control/Quality Assurance (QC/QA) smoothness specifications in which contractors' pay is proportional with the quality delivered. The contractor is getting bonuses depending on the level of smoothness exceeding the minimum requirement. If the smoothness of the pavement is less than the minimum acceptable smoothness, the contractor has to grind the identified irregularities to meet the criteria. This type of specification demands the contractor strive for the highest quality to ensure full payment and even a bonus. This also demands a good smoothness-measuring device that could generate a precise smoothness index to reveal all the surface irregularities.

Pavement roughness can be described by the magnitude of longitudinal profile irregularities and their distribution over the measurement distance. The profile consists of random multi-frequency waves of varying wavelengths and amplitudes. Different wavelengths will have different effects on ride quality depending upon vehicle characteristics and driving speed. The American Society of Testing and Materials (ASTM), ASTM E 867 (1998) defines roughness as: “the deviations of a pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads, and drainage, for example, longitudinal profile, transverse profile and cross slope.”

2.2 Roughness Indices

Smoothness/roughness measuring systems can be divided into two main categories: response-type and profile type measuring systems. Road profile measuring equipment can produce either “true” road profile or “relative” road profile. Roughness indices based on true profile are independent of the type of measurement equipment, while indices based on relative profile are tied to the equipment type used to measure the road profile.

Response-type road roughness measuring (RTRRM) systems measure the dynamic response of a mechanical device such as a vehicle traveling over a pavement surface at a given speed. The response type system produces only one index, which is tied to the measurement vehicle. Also, measurements are not repeatable even when the same vehicle is used due to change in the vehicle's characteristics over time (Sayers and Karamihas, 1998).

Devices that produce a series of numbers related to a true road profile are called profilers. They work by combining a reference elevation, a height relative to the reference, and a longitudinal distance. A true road profile allows computations of different smoothness indices. However, the measuring devises that are measuring relative road profile instead of true profile, like California profilograph, can produce only one index tied to the measured profile.

Roughness indices can be divided into three categories: 1) subjective rating indices; 2) mechanical filter based indices; and 3) profile based indices. Profile based indices are generally obtained by either a) simulating the response of an RTRRM system as it travels the profile or b) by filtering and weighing waveband spectra that make up the road profile. The profile in both methods is filtered with a band-pass filter, transformed to a positive value, and averaged over the length of the profile. Most roughness indices use either the average rectified slope/velocity (average of positive values) (ARS/ARV) or root means squared (RMS) elevation/slope/acceleration (square root of the squared values) methods to obtain the summation index, (Smith et al., 1997).

Subjective Rating Indices:

A most used subjective rating index is the Present Serviceability Rating (PSR) index that was derived from the AASHO road test results using a rating panel to evaluate the smoothness of test roads (Huang, 1993).

Mechanical Filter-based Indices:

Two of the most important mechanical systems for evaluating roughness are those based on response type road smoothness and rolling straightedge systems. The Mays Ride Meter is one of the most popular response type road roughness measuring (RTRRM) devices. Such devices measure the cumulative vertical displacement between the axle and the vehicle body. The smoothness index, Mays Ride Number (MRN), is calculated by dividing the cumulative average displacement by the travel distance. The Profile Index (PI) derived from profilograph's profile is also a mechanical filter-based index, mechanical filter being a rolling straightedge filter. Another mechanical filter based statistic is the Slope Variance (SV). This index is generated from a CHLOE Profilometer. For the mechanical filter based indices such as MRN and PI, filters are applied by their own geometry. In other words, they respond to only a small range of roadway profile wavelengths, amplifying and attenuating the wavelengths that they measure according to the inertial properties of each mechanical device (Smith et al., 1997).

Profile-base Indices:

A road profile consists of different wavelengths varying from a few inches to hundreds of feet. The purpose of profile filtering is to include only the wavelength of interest. A "moving average filtering" can be used to filter the profile to obtain desired wavelengths. The profile is smoothened at each point by averaging the elevation over a selected base-width. Low pass filter removes short wavelengths (high frequencies) from the profile and the high pass filter filters removes the long wavelengths (low frequencies).

For instance, to remove waves shorter than 1 ft (0.3 m), a 1-ft (0.3 m) base-width is selected (Shahin, 1994). Other filters that can be used are four-pole Butterworth filter and quarter-car filter, which are band-pass filters (high-pass then low-pass with a moving average) that attenuate short and long wavelengths.

Waveband analysis is used to reduce a road profile to several indices, each quantifying roughness over a given range of waveband (range of wavelengths). A Fourier transform can be used to change the profile from a function of distance to a function of wave number. This type of analysis is called power spectral analysis (PSD) (Shahin, 1994; Sayers and Karamihas, 1998).

The most known profile-based mechanical system simulation index is the International Roughness Index (IRI). For IRI, the profile is filtered with a moving average (low-pass filter) with a 9.84 in (250-mm) base length, which attenuates short wavelengths. Then the profile is further filtered with a "Golden Car" quarter-car filter to obtain reference average rectified slope ($RARS_{80}$) at a traveling speed of 50 mph (80 km/h) to simulate the RTRRM system response (Smith et al., 1997). ASTM E 1926 (1998) "*Standard Practice for Computing International Roughness Index of Roads for Longitudinal Profile Measurements*" standardizes the IRI calculations.

Another system simulation index is called Ride Number (RN). Ride Number is a profile index intended to relate rideability on a scale of 0 to 5 similar to the Pavement Serviceability Index (PSI). Thus, the Ride Number is an estimate of a Mean Panel Rating (MPR). Ride Number is a result of a NCHRP research (NCHRP Report 275 by Janoff et al. (1985) in the 1980's and FHWA pooled fund study in 1995 (Smith et al., 1997; Sayers and

Karamihas, 1998). Ride Number is computed from summary statistics called PI (profile index). PI is obtained using PDS analysis of two longitudinal profiles. Thus, Ride Number is an exponential nonlinear transform of PI according to the Equation (1):

$$RN = 5e^{-160(PI)} \tag{1}$$

For the RN, the profile is filtered with a moving average (low-pass filter) with a 250-mm base length, which attenuates short wavelengths. Then the profile is further filtered with a band-pass filter, which is similar to the quarter-car simulation and the filtered profile is then calculated as RN (Sayers and Karamihas, 1998).

ASTM E 1489 (1998) "*Standard Practice for Computing Ride Number of Roads from Longitudinal Profile Measurements Made by an Inertial Profile Measuring Devise*" gives a standard method for computing RN and PI.

The profile-based indices computed by filtering and weighing the waveband spectra include, among others, Michigan DOT Ride Quality Index (RQI), the Janoff's s Ride Number (RN_{Janoff}), and the Spangler Ride Number ($RN_{Spangler}$) (Smith et al., 1997).

Table 1 summarizes indices that have been developed/used over the years, (see also Table 5 in Section 2.3), and Table 2 shows correlations between some roughness indices developed by various researchers and gathered by Smith et al. (1997). The column "Filtering" in the Table 1 lists some of the filters used to filter profiles to compute the roughness index. "Bandwidth" indicates the waveband width of the road profile that is employed to compute the roughness index. For instance, the IRI is addressing only wavelengths longer than 3 ft (0.9 m), while the blanking band Profile Index is addressing also shorter wavelengths of 1 ft (0.3 m).

Table 1. Summary of Various Roughness Indices (based on Smith et al., 1997).

Index Type	Index	Abbr.	Filtering	Bandwidth ft	Rating
Subjective Rating	Present Serviceability Rating	PSR	N/A	N/A	-
	Present Serviceability Index	PSI	N/A	N/A	-
Mechanical Filter Based	Mays Ride Number	MRN	By own geometry	-	3
	Profile Index from Profilograph	PI	Rolling straightedge	1.0 to 75	1
	Slope Variance	SV	N/A		7
True Profile Based - Mechanical System Simulation	International Roughness Index	IRI	Quarter-car with Golden Car parameters	3.0 to 80	1
	Sayer's Ride Number	RN	Quarter-car	1.7 to 36	2
	Sayers's Profile Index from Profiler	PI	Band-Pass		-
	Telescoped Rolling Straightedge	TRS	Straightedge	2-30	7
True Profile Based - Filtered and Weighted	Michigan DOT Ride Quality Index	RQI	3rh order band-pass	2-50	2
	Janoff Ride Number	RN_{Janoff}	Band-pass	1.6-8	2
	Spangler/Kelley Ride Number	$RN_{Spangler}$	Band-pass	-	5
	Quarter Car Index-RMSVA	QI_r	Quarter car model	3.3 and 7.6	6
	Mays Meter RMSVA Output Function	MO	Band-pass	4-16	4

Table 2. Correlation Between Roughness Indices (Smith et al., 1997).

	MRN, in/mi	PI, in/mi	SV, $(in/mi)^2$	IRI, in/mi or m/km
PSI	SI = 5.26 - 0.0124MRM R^2=0.91 *(Uddin, Hudson, and Elkins 1990)*	SIV = -0.03PI_{cal} + 4.06 R^2=0.87 *(Scofield 1993)* PSI = -0.03881$PI_{cal0.1}$ + 4.629 R^2=0.74 PSI = -0.04762$PI_{cal0.1}$ + 4.443 R^2=0.71 for square root PI R^2 = 0.86 for both *(Walker and Lin 1988)* SI = 4.06 - 0.0256PI_{cal} R^2=0.87 *(Uddin, Hudson, and Elkins 1990)*	SI_{pcc} = 5.41 - 1.80log(1 + SV) SI_{ac} = 5.03 - 1.91log(1 + SV) *(Temple and Cumbaa 1988)*	IRI_m = 5.5$\log_e$(5.0/PSI) *(Paterson 1987a)* IRI = 577.42 - 222.17SI + 25.664SI^2 R^2=0.997 *(Bertrand, Harrison, and McCullough 1990)*
PSR	PSR = 4.00 - 0.0078MRN R^2=0.56 *(Spangler and Kelly 1987)*	–	–	$PSR_t = 5e^{(-0.0041IRI)}$ R^2=0.73 *(Al-Omari and Darter 1992)*
MRN	–	PI_{cal} = 0.44MRM - 20.3 R^2=0.94 *(Scofield 1993)* PI_{cal} = 0.466MRM - 41.4 R^2=0.77 *(Scofield 1993)* PI_{cal} = 0.168MRM - 5.8 R^2=0.57 *(Scofield 1993);* MRN = 43.3 + 5.7PI R^2=0.95 *(Kalevela, Kombe, and Scofield 1994)*	Poor	MRN = 0.44996 + 0.74515(IRI) if MRN≤87.7: MRN = -4.42259 + 1.12847(IRI) for MRN>87.7; *(Carmichael, Moser, and Hudson 1992)* IRI = 61.426 + 0.83577MRN R^2=0.997 *(Bertrand, Harrison, and McCullough 1990)*
PI	–	–	–	IRI = 52.9 + 6.0(PI) R^2=0.93 IRI = 73.7 + 2.83(PI) R^2=0.92 *(Kombe and Kaleva 1992)* $PI_{a,p}$ = -22.3 + 0.3IRI R^2=0.92 *(Goulias, Dossey, and Hudson 1992)* IRI = 19.22 + 3.38ARS - 0.0096ARS^2 *(Ksaibati and Kercher 1990)* IRI = 36.4 + 3.11PI R^2=0.56 (PI=5-7 in/mi) *(Kulakowski and Wambold 1989)*
SV	–	Poor	–	–
IRI	–	R^2=0.94	–	–
RN_{Sayers}	–	–	–	–
RQI	–	–	–	–
RN_{Janoff}	RN = f(MRM_{AC})	–	–	–
$RN_{Spangler}$	–	–	–	–
QI_r	R^2=0.91	–	–	IRI_m = (QI_r + 10)/14 *(Sayers, Gillespie, and Queiroz 1986)*
MO	R^2=0.87	R^2=0.95	–	R^2=0.99

The rating shown in Table 1 refers to the study conducted by Smith et al. (1997) where they rated different roughness indices as candidates for initial pavement smoothness index based on the following criteria: 1) correlation with rider response with HMA pavements; 2) correlation with rider response with PCC pavements; 3) correlation with other roughness statistics; and 4) information availability. The top scoring indices were IRI and PI statistics from profilograph. The other good indices were RN developed by Sayers (RN_{Sayers}), the Michigan DOT RQI, and RN developed by Janoff (RN_{Janoff}). Thus, the study recommended retaining the PI values as the initial pavement smoothness index for current specifications, while reducing the blanking band to 0.1 and 0.0 in (2.5 and 0.0mm). A new technology can be used to improve the data collection, repeatability and correlation with other smoothness indices because the blanking band PI statistics can be computed using inertial based high-speed and lightweight profilers.

A more detailed description of the IRI and blanking band PI are presented in the following sections.

2.2.1 International Roughness Index

International Roughness Index (IRI) is a scale of roughness based on the response of a generic motor vehicle to the roughness of a pavement surface. IRI is obtained by simulating the response of an RTRRM system as it travels the road profile. The response properties of an automobile are simulated by a relatively simple dynamic model commonly known as the Quarter-car model. At each wheel position the vehicle behaves as a sprung mass resting on a suspension system with stiffness and damping, which in return is attached to the unsprung mass of the wheel, brake, and suspension components, shown in Figure 1. The wheel contacts the road through a tire which acts like a spring. Pavement surface profiles provide input to the car, which flex the tire, stroke the suspension and cause the sprung and unsprung masses to vibrate in the vertical direction. This simulated suspension motion response is accumulated and divided by the distance traveled to give an index with units of slope (in/mile, m/km) (Shahin, 1994).

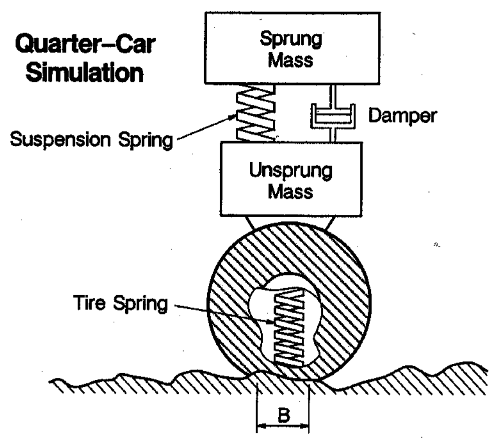

Figure 1. Quarter-Car Model Simulation.

2.2.2 Profile Index from California Profilograph

The profilogram from California profilograph can be interpreted manually or using automated data reduction systems. The Profile Index (PI) is computed using a blanking band ranging from 0.2 to 0.0 inches to “smooth” the profile.

Surveys among State Highway Agencies (SHA) conducted by Smith et al. 1997 indicated that manual method using 0.2” bb with visual judgment of positioning the blanking band for profile evaluation was the most used method, see Table 3. For states that were using computerized profiling devises, SHAs were largely split between using Butterworth (third-order) and Cox (first-order) filters and settings. Other filtering methods were Chebyshev (third-order), moving average, recursive (second-order) and combined Cox and moving average filters.

Table 3. SHA Survey Results (Smith et al., 1997).

Response	New HMA	New PCC or PCC Overlay	HMA Overlay
Blanking band limit for profilographs			
0.1 inch	1	3	1
0.2 inch	19	32	18
Other	2	2	2
Total number of agencies responding		37	21
Methods used for positioning the blanking band			
Alignment of previous section	5		
Visual Judgment	16		
Computer selected best-fit	9		
Other	8		
Total number of agencies responding	38		
Accuracy to which scallops on profilograph traces are rounded			
0.01 inch	3		
0.05 inch	29		
Other	3		
Total number of agencies responding	35		

Smith et al. (1997) reported that, according to the study done by the Pennsylvania Transportation Institute, the use of blanking band evaluating new pavement's profilograph traces lead to unacceptable results for pavements that had PI values less than 7 in/mile (110 mm/km). They concluded that profile traces should be evaluated without the blanking band to achieve better results. The study also showed that correlations improved significantly in linear regression between PI and IRI when the blanking band was reduced to 0.1 and 0.0 in (2.5 and 0.0 mm).

Due to the problems of evaluating pavements that exhibited short sine wave oscillation of about 8 ft (2.4 m) spacing with 0.2 in (5.1 mm) amplitude, Kansas DOT eliminated the blanking band-width from their construction smoothness specification. The problems were related to the blanking band masking the actual roughness of the road profile. Since this change, smoother pavements have been constructed in Kansas (Hancock and Hossain, 2000).

2.2.2.1 Manual Interpretation of Profilograph Trace

Manual interpretation of profilogram involves using plastic templates for computing profile index (blanking band template) and for finding individual irregularities (bump template). INDOT has a Test Method "*The Proper Use of the Profilograph and the Interpretation of Profilograms*", ITM No. 901-93T, which is presented in Appendix A. The following paragraphs give a short description of the method.

Based on INDOT's Test Method ITM No. 901-93T, the Profile Index is determined using a plastic scale 1.70 inches (43 mm) wide and 21.12 inches (536 mm) long. The Profile Index represents a pavement length of 0.1 mile (0.16 km) at a scale of 1:300. Near the center of the scale is the blanking band 0.2 inch (5 mm) wide extending the entire length of 21.12 inches (536 mm). The blanking band is placed on the profile to cover the traces as much as possible. On either side of this band are scribed lines 0.1 inch (2.5 mm) apart, parallel to the blanking band. These lines serve as a convenient scale to measure scallops. The placement of a plastic template is done based on engineering judgment and consequent sections are not aligned. The bump template is used to identify locations of bumps. The PI is determined by dividing the counts (inches of roughness) by the section length in miles.

The PI is computed for each 0.1 mile of finished pavement. With each 0.1 mile section, all areas representing high points (bumps), with deviation in excess of 0.3 inches (8 mm) in a based length of 25.0 ft. (7.5 m) (which is the length of the California profilograph beam) or less, shall be corrected by the contractor regardless of the PI value. Profile Index has a dimension of length per length (in/mile or m/km). Figure 2 shows an example of the profilograph trace covered with a 0.2 inch blanking band template, and Figure 3 shows an example of various alternatives to count the deviations from the profilogram for blanking band length of 21.1 in (0.1 miles at road).

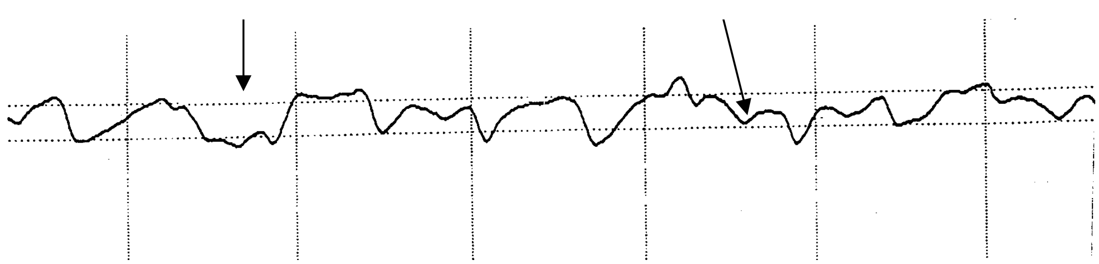

Figure 2. Example of the Profilograph Trace Covered with 0.2 inch Blanking Band Template.

Based on the INDOT test method, the profile should be broken into shorter sections and the location of the template repositioned to round radius curves with superelevations.

Figure 4 shows a method of counting the deviations when positioning of the blanking band is shifted.

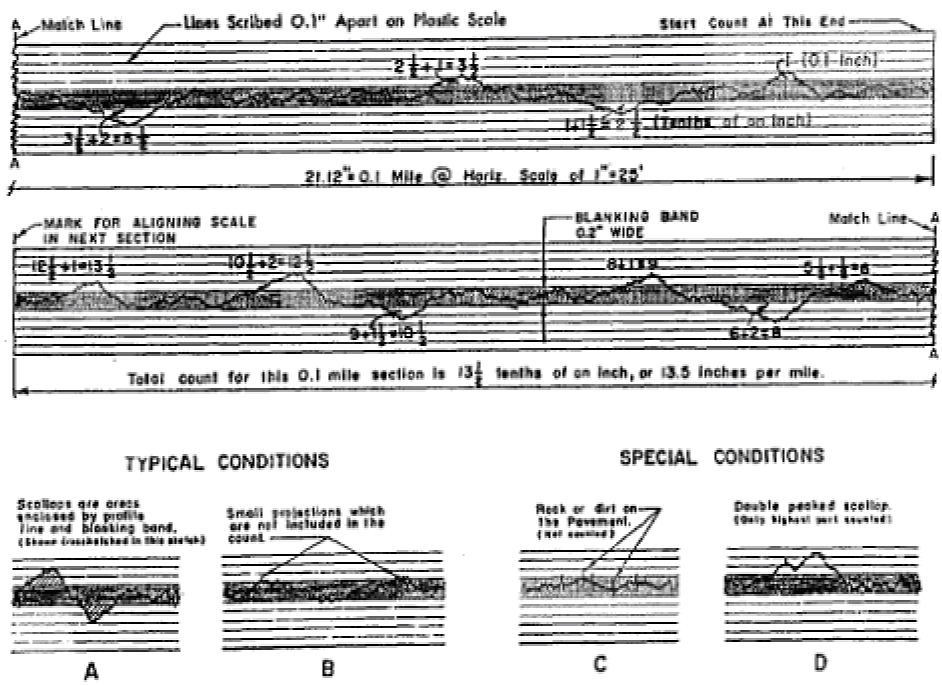

Figure 3. INDOT Test Method to Obtain PI from Profilogram (ITM No. 901-93T).

Kansas DOT Test Method KT-46 describes how to manually reduce profilograph traces using 0.0” bb method. The procedure deviates from the 0.2” bb method in a way that the first step is to trace the profilogram through the middle of any spikes using a ballpoint pen. This removes small deviations and spikes and smoothes the trace for easier reduction and analysis. Then, a dashed reference line is centered on the profile trace and deviations from the reference line and trace are counted. A detailed description of the Kansas method is given in Appendix B.

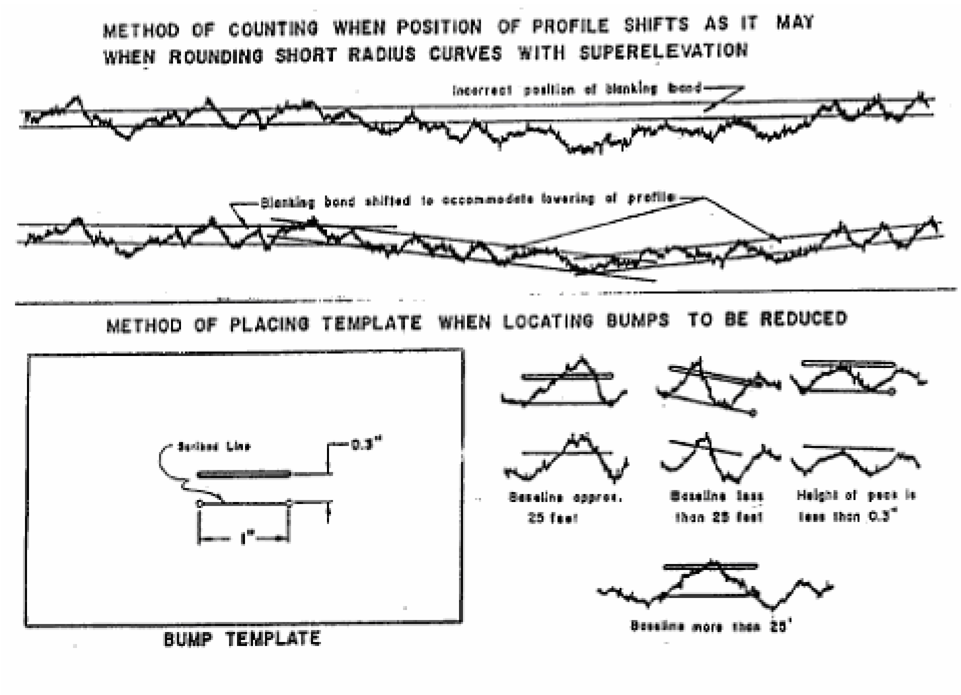

Figure 4. INDOT Test Method to Obtain PI from Profilogram with Superelevations, (ITM No. 901-93T).

2.2.2.2 Automated Interpretation of Profilograph Traces

There are three different categories of automated methods to produce blanking band Profile Index: 1) software and filtering used in the automated California, Reinhart, and Ames type profilographs; 2) signal processing in the inertial profilers and lightweight profilers that produce the real road profile but are trying to mimic the road profile produced by California type profilographs; and 3) software and analysis systems developed to scan and analyze printed profiles produced by various measuring devices. Based on literature, Kansas DOT and Louisiana DOT are two states that have developed their own automated analysis system independent of equipment manufacturers.

As the survey data in Table 3 shows, different equipment manufacturers are using different filtering and analyzing techniques to obtain the blanking band profile index. A method of standardizing the profilograph analysis techniques is in development by ASTM by title of "*Measuring Pavement Roughness Using a Profilograph*" (personal contact, Briggs, 2002).

Automated Pavement Profile Analysis Software: APPARE

APPARE, Automated Pavement Profile Analysis and Roughness Evaluation, is a PC based software system developed by Professor Jim J. Zhu of Electrical and Computer Engineering at Louisiana State University (Zhu and Nayar, 1993). It analyzes the statistical properties of road pavement profiles and reports their roughness indices. APPARE software can process both profilograms and digitized road profiles from other profiling devices. The basic functionality of APPARE includes: 1) a photo scanning a profilogram to create an image data file for digitization of the trace; 2) trace reduction to create digitized data of the pavement profile; and 3) roughness analysis and evaluation using blanking band Profile Index, IRI, etc. (Zhu, Zhu, Smailus, and Martinez, 1996).

To automate the profile trace reduction procedure, the first step is to convert the graphical profilogram into a numerical format for computer processing. In APPARE, this process is achieved through a three-step procedure: 1) scanning the profilogram; 2) editing the scanned image; and 3) extracting the digitized profile trace from the scanned image.

For scanning the profilogram, window based interface software, TWAIN, and a MicroTek PageWiz scanner are used. A maximum of 210 in (6 m) of profilogram at 300 dpi (dot per inch) resolutions can be used for this device.

For editing the scanned image, a Graphical Editor is used. The editor displays the scanned profile image and provides the user with a cursor for selecting the start and end points, an eraser for removing spurious data points, and annotating tools for writing notes on the margins of a scanned profile image. With this editor, the user could determine where the trace should actually start and end in the process of automated trace reduction procedure.

For Louisianan DOT's manual trace reduction, the profile trace is "outlined" by drawing a line through the vertical midpoint of the trace. In APPARE, this procedure is performed on the scanned image to obtain the digitized vector image, that is, a single-valued function described by x-y coordinates of the profile trace (Figure 5). The midpoint extraction is using a moving slope threshold based on the assumption that the slope of the road from one data point to the next cannot exceed a certain bound. This threshold is set to ± 45 degrees in APPARE. Once the threshold is determined, the midpoint at the current location is found within the upper and lower slope limits projected from the previous data points. For the start point, where no previous data point is available, the slope limits are projected from a fabricated previous point at the same elevation of the start point. To deal with the problem of missing data points, a cubic polynomial extrapolation algorithm is used to estimate the missing point using the previous four data points (Zhu and Nayar, 1993).

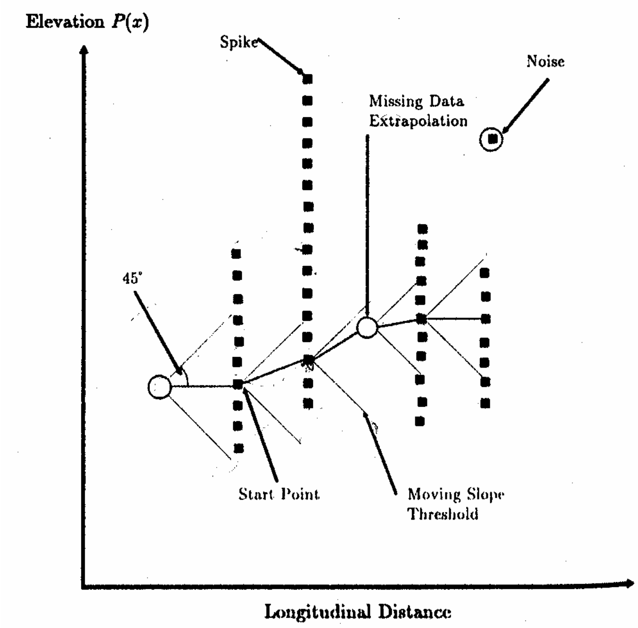

Figure 5. Outlining the trace (Zhu and Nayar, 1993).

The implementation of computing the Profile Index follows closely to the procedures adopted by the Louisiana DOT for manual PI evaluation for the California Profilograph. The algorithm accumulates the counts of excursions beyond the 0.2" bb in increments of 0.05 in (1.25 mm) and divides the total counts by the total distance over which the profile is taken. APPARE applies a digital high pass filter to remove the distortion caused by superelevations.

A Power Spectral Density (PSD) function of a profile trace contains important information about the roughness and other pavement features. Although it is known that the kinematics of the profilograph alters the PSD of the pavement roughness profile, Zhu et al. (1996) developed the compensating filter. This filter is used when computing IRI from the distorted profile. Based on trials, a equation of

$$IRI_L = 0.75\ IRI_p - 60.98 \qquad (2)$$

$R^2 = 0.94$ is implemented in the APPARE, where the IRI_L is IRI value measured by the profilometer and IRI_P is the IRI evaluated from the profilograph traces.

The cost of the system is unknown and the personal contact to Louisiana DOT revealed that the developed system was never fully implemented by the DOT (M. Rasoulian, Louisiana DOT) due to the changes in technology in both scanner equipment and computer operating software. Figure 6 shows a portable APARRE Field Kit Prototype (APARRE 1997).

Figure 6. Portable APPARE Field Kit Prototype (APPARE, 1997).

<u>Electronic Profilogram Evaluation: Proscan</u>

The algorithm of the automated method developed by Devore et al. 1995 follows the Kansas Test Method KT-461 "*Determination of Pavement Profile with the 7.62 m (25-ft) Profilograph*". In general, the profilogram is scanned to digitize its tracing. An image enhancement program is then used to prepare the image for analysis. After the enhancement, filtering is applied to the digitized traces to reduce the noise of the traces and to mimic the process of an operator drawing the outline on the trace. A linear regression analysis is then performed to establish the location of a floating centerline, i.e. a zero blanking band, along the outline of the trace. The PI is computed based on the deviation from the outline (trace) to the centerline (zero blanking band). A further description of this system is presented in the following sections. Bumps were located based on any specified deviation from a 1 in (25.4 mm) reference moving baseline. The program allows incorporating the blanking band of any value between 0 to 0.4 inches into the calculations (Devore et al., 1995).

During the scanning process, a section to be scanned is marked by drawing a 1 in (25.4 mm) or longer line across the two ends of the section. The scanner can measure the distance covered so that the PI values can be calculated for any length. If multiple segments exist between the two marks, the system automatically measures each segment (0.1 mile or 0.16 km) and calculates the PI value for each segment as well as the entire section. The scanning process takes about 22-sec/0.1 mile (0.16 km). A ScanMan model 32 scanner along with a customized scanning program that can scan unlimited lengths of trace was used in the development work for the system. The scanner is operated in a 200-dpi mode.

Several filters were tested for this system in order to reduce the noise of the traces due to the vibration during the recording process. In addition, the filtering also helps to simulate the process of an operator drawing the outline on the trace. Various Butterworth and Chebyshev low-pass filters with different frequencies and a simple two-sided moving average filter were tested. Kansas DOT personnel picked the one that worked the best and the moving average filter was selected as the default into the system. The judging was performed by looking at plots of the various filtered signal overlaid on the original traces using a light table. A least-square error analysis was done to fit a straight line to the traces on the 0.1-mile segment.

Devore et al. (1995) compared the system they called KSCAN with the Cox and Sons automated profilograph results with 19 sections of 0.1-mile length (0.16 km) asphalt segments. The results reduced from KSCAN were also compared to the manual reduction results obtained from 14 experienced operators. The results showed that the worst difference between the manual and KSCAN results, 1.08 in/mile (17 mm/km), could easily satisfy the KT-46I requirement of the maximum allowable variation, which was 2 in/mile (32 mm/km). Besides, the PI value computed by the KSCAN for a given segment varied less than ± 3 percent from scan to scan, and five for more successive segments showed totals that rarely differed by more than ± 1 percent.

This system, shown in Figure 7, is currently being marketed under the name Proscan, cost is approximately $7500. The cost includes the software, paper transport unit and the scanner.

When compared with the APPARE system developed by Zhu and Nayar (1993), both of these two systems are trying to simulate the manual reduction process. They deviate by using different algorithms to "outline" the trace. Devore and Hossain claimed that the KSCAN has a better correlation between the automated and the manual reduction results than the APPARE does (R^2 = 0.91) in the discussion of a TRB paper published by Zhu et al. (1996). However, Zhu et al. (1996) explained that the lower correlation is because of the effect of a larger sample size, 229 sections of 0.2 mile pavement, taken to perform the statistical analysis.

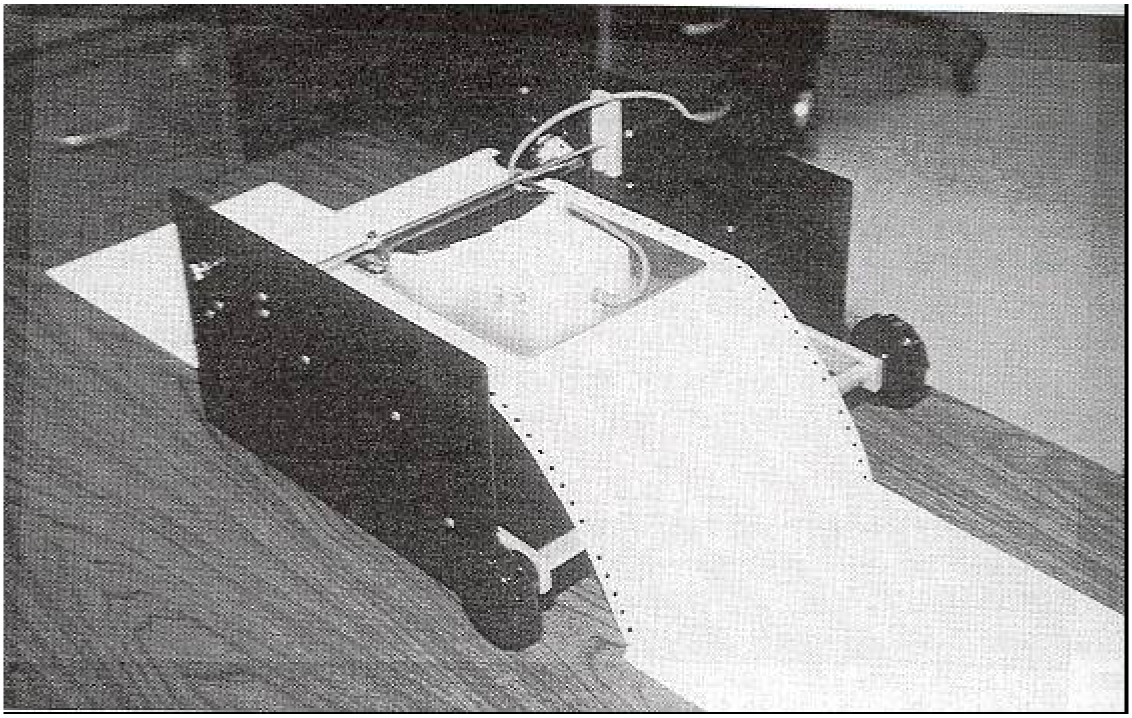

Figure 7. Proscan (Smith et al., 1997).

2.3 Pavement Roughness Measuring Equipment

ASTM defines the road profile measuring systems by class in the ASTM E 950 (1994) standard "*Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference*". The classes present different levels of sampling interval, vertical measurement resolution and precision intending to indicate the accuracy of a profiler. The most stringent requirements are given for the Class 1 equipment. Another classification is given by the World Bank, which classifies the equipment by different methods of obtaining road profile. The Class I includes all manual measuring techniques such as rod and level. Class II includes direct profile measuring equipment and non-contact devises.

Table 4 summarizes various road measuring devices and indices that have been used for pavement smoothness measuring purposes. It also shows which devices are measuring the true road profile and which devices are measuring relative road profile.

Table 4. Various Road Profile Measuring Equipment and Indices.

Devise	Meas'ing Speed	Meas'd Profile	Index (see Table 1)	Note
Straightedge - String line	Walking	Relative	Max variation from reference	Slow
Rolling Straightedge	Walking	Relative	Max variation from reference	Slow
Rod and Level (surveying)	Walking	True	IRI, RN, PI	Slow
Walking Profiler	Walking	True	IRI, RN, PI	Slow, can be used for young concrete
Rolling Dipstick	Walking	True	IRI, RN, PI	Slow, most accurate
California Profilograph	2-3 mph	Relative	PI*	Most widely used
Rainhart Profilograph	2-3 mph	Relative	PI*	
COLES Profilograph	2-3 mph	Relative	SV	AASHO Road Test
Mays Meter RTRRM	20-60 mph	Relative	MRN	Index affected by vehicle dynamics
Full-Size Inertial Profilers	50-60 mph	True	IRI, RN, PI	Fast, cannot be used for young concrete
Lightweight Inertial Profilers	5-15 mph	True	IRI, RN, PI	Fast, can be used for young concrete

* Blanking Band Profile Index.

The American Concrete Pavement Association (ACPA) has been collecting data since 1998 from surveys of all State Highway Departments. Table 5 shows all the different measuring equipment used in the United States for PCC pavements according to a summary from ACPA database (2000). The non-contact profiler refers to a full size high-speed profiling system that could generate a true profile of pavement surface characteristics. Table 5 also shows survey data collected by Smith et al. (1997). This survey included 50 SHAs, 3 Federal Land Agencies, 6 asphalt-paving contractors, and 9 concrete paving contractors. The most popular smoothness measuring equipment is still the California profilograph, as Table 5 shows. A short description of California profilograph and Inertial Profilers are presented later in the report.

Table 5. Distribution of Smoothness Measuring Devises and Indices in the U.S. (Smith et al., 1997; ACPA, 2000)

Measuring Device	Smith et al. 1997, HMA pavements	Smith et al. 1997, PCC Pavements	ACPA, 2000, PCC Pavements
California Profilograph	28	44	70.5
Ames Profilograph	12	10	-
Rainhart Profilograph	1	10	7.8
10-ft straightedge	41	30	5.9
Rolling Straightedge	4	1	-
Mays Meter	10	1	2
Non-contact profilers	3	3	2
LISA (lightweight profiler)	1	1	-
None	-	-	11.8

California Profilograph

INDOT currently uses the California Profilograph as the standard measurement tool in its construction smoothness specifications. The California Profilograph has been the most widely used roughness-measuring device for construction pavement smoothness specifications in the United States. The development of this device can be traced back to the period from 1930-1950 (Hveem, 1960). The current models of the California Profilograph consist of a single axle and two wheels at each end of a 25 ft (7.6 m) long beam. A profile wheel is located at the mid-point and is linked to a recorder that provides a paper strip chart showing change in the distance between the pavement at the point of the profile wheel and the datum established by the carrying wheels. The strip chart produces the deviations on a true vertical scale and on a 1:300 horizontal scale, (Scofield, et al., 1992). The profile produced by the California Profilograph is evaluated using a plastic template with a blanking band and determining smoothness in terms of profile index.

There are a variety of California Profilograph manufacturers such as James Cox & Sons, Paveset and Ames Engineering. A schematic picture of California type profilograph is shown in Figure 8.

Inertial Profilers

Inertial profiler technology became available in the 1960's. Inertial Profilers measure the longitudinal profile using accelerometers located in the body of the measuring vehicle to create an inertial reference. As a result, they yield a true longitudinal profile of the road surface, which can be filtered (to remove longer built-in vertical curves) and analyzed by computing several available smoothness indices (Rufino, et al., 2001).

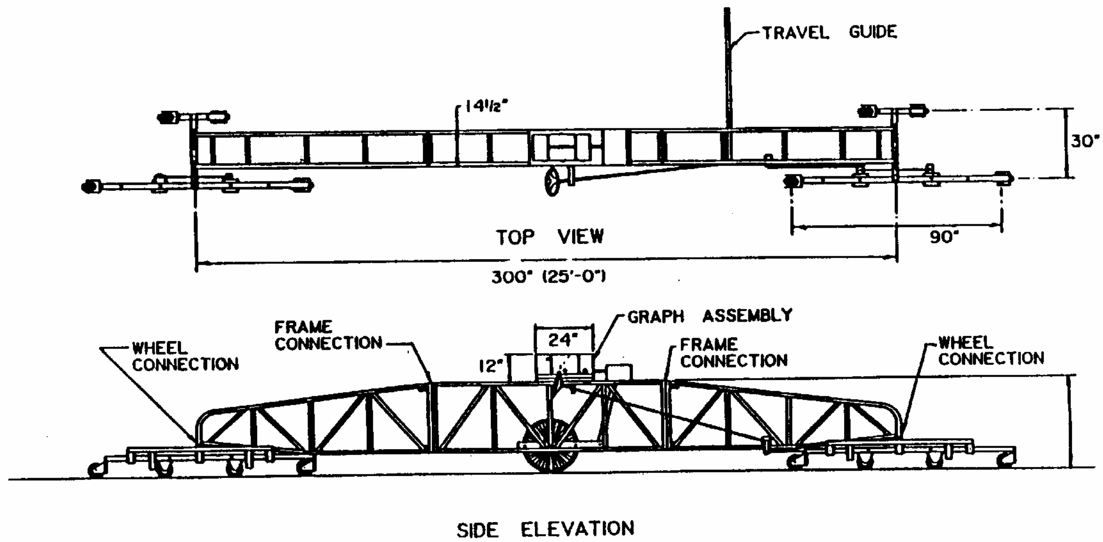

Figure 8.Schematic of California Type Profilograph.

The most popular profilers in the U.S. have been the South Dakota Profiling System (ICC MDR Profiling System) and the FHWA PRORUT. K.J. Law has several models including 690 DNC Profilometer, T6600 Inertial Profilometer and T6500 Road Surveyor. Other systems include, among others ARAN, Dynatest Profiling System, Swedish IMS Laser RST Profiler, Danish Road Institute Profilograph, and INDOT Rip Van (Smith et al., 1995; Mondal et al., 2000).

New generations of inertial profilers called "Lightweight Profilers" have been developed in recent years for quality control/quality assurance purposes, see Figure 9. The advantage is that they can be used immediately after hot mix asphalt construction and much sooner for Portland cement concrete pavements than full size profilers because they are lighter (Modal et al., 2000). Vendors for the device include Ames Engineering Corporation selling a Lightweight Inertial Surface Analyzer (LISA) developed by Materials and

Technology Division of Michigan DOT, K.J. Law with T6400 mounted on a Kawasaki Mule, Surface Systems and Instruments (SSI) Laser mounted on a Club Car, International Cybernetics Corporation's (ICC) Laser mounted on a ATV, Surfan Engineers ROSAN, Trigg Industries International Corporated, and Pathway Services Incorporated's PathRunner LITE mounted on a golf cart.

Figure 9. Lightweight Non-contact Profiler.

2.4 Smoothness Specifications

A 1990 NCHRP study indicated that of the 36 states reporting, 80% exercised smoothness criteria on a new pavement construction (Woodstrom, 1990). According to ACPA database (ACPA, 2000), about 60% of the states in the US have an incentive, disincentive or both programs for PCC pavements. Based on the ACPA database, the use of different blanking bands for PCC pavements are distributed as follows: 0.3" bb 2.8%, 0.2" bb 72.2%, 0.1” bb 13.9%, and 0.0”bb 11.1%. The states using 0.0” bb were Kansas, Missouri, Pennsylvania and South Dakota.

2.4.1 Summary of INDOT Construction Smoothness Specification

The following text has been excerpted word for word from INDOT’s “*1999 Contract Standard Specification Book*” using Sections 401 and 501 dealing with Quality Control/Quality Assurance smoothness specifications.

2.4.1.1 Hot Mix Asphalt (HMA) Pavement

<u>Section 401.18 Pavement Smoothness</u>

The pavement smoothness will be accepted by means of a profilograph, a 4.9 m (16 ft) long straightedge, or a 3 m (10 ft) long straightedge.

The profilograph shall be used on all full width pavement lanes of 75 m (250 ft) or longer, where the HMA to be placed is 180 kg/m2 (330 lb/sq yd) or greater, and having a design speed of greater than 70 km/h (45 mph), unless otherwise specified.

If a pay item, Profilograph, is included in the contract, the Contractor shall furnish, calibrate, and operate an approved profilograph in accordance with ITM 901. The profilogram produced shall become the property of the Department. The profilograph shall remain the property of the Contractor. When a profilograph is not included as a pay item, the Department will furnish, calibrate, and operate the profilograph.

The 4.9 m (16 ft) long straightedge shall be used on all full width pavement lanes shorter than 75 m (250 ft), tapers, within 15 m (50 ft) of bridge ends, and within 15 m (50 ft) of an existing pavement which is being joined. It shall be used on resurface overlays of less than 180 kg/m^2 (330 lb/sq yd).

The 3 m (10 ft) long straightedge shall be used for transverse slopes, approaches, and crossovers.

Pavement smoothness requirements will not apply to single course overlay work unless it is preceded by milling. All wavelike irregularities and abrupt changes in profile of single course nonmilled surface caused by paving operations shall be corrected.

Each finished course of base and intermediate shall be subject to approval. The pavement smoothness shall be checked on the surface course and a new course placed immediately below the surface course at the locations as designated in ITM 901.

Pavement smoothness variations shall be corrected to comply with the smoothness requirements in Table 6. If grinding of the intermediate course is used for pavement smoothness corrections, the grinding shall not precede the surface placement by more than 30 calendar days if open to traffic.

When the profilograph is being used on a surface course, in addition to the requirements for the profile index, all areas having a high point deviation in excess of 8 mm (0.3 in.) shall be corrected. Courses underlying the surface course that are exposed by corrective actions shall be milled to 25 mm (1 in.) and replaced with surface materials. Verifying profilograph measurements will be taken only in the 0.16 km (0.1 mi) length where corrections have been performed to reduce the profile index.

Table 6. HMA Pavement Smoothness Tolerance.

PAVEMENT SURFACE TOLERANCES	
Testing Method	Specified Tolerance
Profilograph Design speeds greater than 70 km/h (45 mph) Design speeds 70 km/h (45 mph) or less	 30 mm/0.16 km (1.2 in./0.1 mi) profile index or less 41 mm/0.16 km (1.6 in./0.1 mi) profile index or less
4.9 m (16 ft) Straightedge All pavements	 6 mm (1/4 in.) or less
3 m (10 ft) Straightedge Base & Intermediates Surface	 6 mm (1/4 in.) or less 3 mm (1/8 in.) or less

When the profilograph is being used on an intermediate course, all areas having a high point deviation in excess of 8 mm (0.3 in.) shall be corrected. When the 4.9 m (16 ft) or 3.0 m (10 ft) straightedge is being used on an intermediate course, all areas having a high point deviation in excess of 6 mm (0.2 in.) shall be corrected.

Section 401.19 Adjustment Points

When test results for mixture properties, density, and smoothness exceed the allowable tolerances, adjustment points will be assessed. The adjustment points will be used to calculate a quality assurance adjustment quantity (q) for the lot.

The quality assurance adjustment points (Table 7) for smoothness will be calculated in accordance with 401.19(c). When the pavement smoothness is tested with a profilograph, payment will be based on the profile index in accordance with the following table. Quality assurance adjustments for smoothness will apply to the planned typical section including the aggregate base, and the HMA base, intermediate, and surface courses.

The quality assurance adjustment for each section will include the total area of each 0.16 km (0.1 mi) long section represented by the profile index calculated by the following formula:

$$q_s = \frac{P}{100} \sum_{i=1}^{N} A \, x \, \frac{S}{T} \, x \, U \qquad (3)$$

where:

q_s = quality assurance adjustment for smoothness for one section
P = adjustment points, Table 7
N = number of layers
A = area of the section, m^2 (Syd)
S = spread rate for material, kg/m^2 (lb/syd)
T = conversion factor: 1000 kg/Mg (2000 lb/ton)
U = unit price for the material, \$/Mg (\$/Ton)

The quality assurance adjustment for smoothness, QS, for the contract will be the total of the quality assurance adjustments for smoothness, q_s, on each section.

In May 2002, INDOT changed the smoothness specifications for the HMA pavements. The new pay adjustments are listed in Table 8. The new specification has also bonus range in addition to penalty range compared to the old specification.

Table 7. Adjustments for Smoothness HMA Pavements.

ADJUSTMENT FOR SMOOTHNESS			
Design Speed Greater Than 70 km/h (45 mph)		Design Speed Less Than Or Equal to 70 km/h (45 mph)	
Final Profile Index mm per 0.16 km (in./0.1 mi)	Adjustment Points	Final Profile Index mm per 0.16 km (in./0.1 mi)	Adjustment Points
0 to 30 mm (0.0 to 1.2)	None	0 to 41 mm (0.0 to 1.6)	None
over 30 to 33 mm (over 1.2 to 1.3)	2.0	over 41 to 46 mm (over 1.6 to 1.8)	2.0
over 33 to 36 mm (over 1.3 to 1.4)	4.0	over 46 to 51 mm (over 1.8 to 2.0)	4.0
over 36 to 38 mm (over 1.4 to 1.5)	8.0	over 51 to 56 mm (over 2.0 to 2.2)	8.0
All pavement with a profile index greater than 38 mm (1.5) shall be corrected.		All pavement with a profile index greater than 56 mm (2.2) shall be corrected.	

Table 8. Pay Factors for New HMA Smoothness Specification.

ADJUSTMENT FOR SMOOTHNESS	
Design Speed Greater Than 70 km/hr (45 mph)	
Profile Index mm per 0.16 km (in./0.1 mi.)	Pay Factor
Over 0 to 5 mm (0.0 to 0.2)	1.05
Over 5 to 10 mm (0.2 to 0.4)	1.04
Over 10 to 20 mm (0.4 to 0.8)	1.02
Over 20 to 25 mm (0.8 to 1.0)	1.00
Over 25 to 28 mm (1.0 to 1.1)	0.96
Over 28 to 30 mm (1.1 to 1.2)	0.92
All pavement with a profile index greater than 30 mm (1.2) shall be corrected	

2.4.1.2 Portland Cement Concrete Pavement (PCCP)

Section 501.25 Pavement Smoothness

The pavement smoothness will be measured by means of a profilograph, a 4.9 m (16 ft) long straightedge, or a 3 m (10 ft) long straightedge.

The profilograph shall be used on all full-width pavement lanes of 75 m (250 ft) or longer and having a design speed greater than 70 km/h (45 mph), unless otherwise specified.

If a pay item, profilograph, PCCP, is included in the contract, the Contractor shall furnish, calibrate, and operate an approved profilograph in accordance with ITM 901. The profilogram produced shall become the property of the Department. The profilograph shall remain the property of the Contractor. When a profilograph is not included as a pay item, the Department will furnish, calibrate, and operate the profilograph.

The 4.9 m (16 ft) long straightedge shall be used on all full-width pavement lanes shorter than 75 m (250 ft), tapers, within 15 m (50 ft) of bridge ends, within 15 m (50 ft) of an existing pavement which is being joined, ramps, or having a design speed of 70 km/h (45 mph) or less, unless otherwise specified.

The 3 m (10 ft) long straightedge shall be used for transverse slopes, approaches, and crossovers.

As soon as the PCCP has cured sufficiently, the smoothness may be checked. Profile testing shall be completed prior to opening the pavement to traffic. The Department may direct that the pavement profile be tested within 24 h following placement. When profile testing is consistently outside pavement surface tolerances the paving operation shall be discontinued until an amended QCP is submitted. An initial profile index will be determined from the profilogram of this profile. The initial profile index for areas requiring replacement will be adjusted to include the results of a profilogram of all replaced areas.

Pavement smoothness variations outside specified tolerances shall be corrected by grinding with a groove type cutter or by replacement. Grinding will not be permitted until the PCCP is 10 days old or until the test indicates a modulus of rupture of 3800 kPa (550 psi) or greater. The grinding of the pavement to correct the profile shall be accomplished in either the longitudinal or the transverse direction. The PCCP texture after grinding shall be uniform. If the grinding operation reduces the tining grooves to a depth of less than 1.5 mm (1/16 in.) and the longitudinal length of the removal area exceeds 4.5 m (15 ft), or two or more areas are within 9.0 m (30 ft) of each other, the PCCP shall be retextured in accordance with 504.03.

Pavement smoothness variations shall be corrected to be in accordance with the smoothness requirements in Table 9.

Table 9. PCC Pavement Surface Tolerances.

PAVEMENT SURFACE TOLERANCES	
Testing Method	Specified Tolerance
Profilograph Design speeds greater than 70 km/h (45 mph) Design speeds 70 km/h (45 mph) or less	 30 mm/0.16 km (1.2 in./0.1 mi) profile index or less 40 mm/0.16 km (1.6 in./0.1 mi) profile index or less
4.9 m (16 ft) Straightedge All pavements	 6 mm (1/4 in.) or less
3 m (10 ft) Straightedge	3 mm (1/8 in.) or less

When the profilograph is being used, in addition to the requirements for the profile index, all areas having a high point deviation in excess of 8 mm (0.3 in.) shall be corrected. Verifying profilograph measurements will be taken only in the 0.16 km (0.1 mi) length where corrections have been performed.

501.28 Adjustment Points.

When the PCCP test results for flexural strength, air content, smoothness, and thickness exceed the allowable tolerances, adjustment points will be assessed. The adjustment points will be used to calculate a quality assurance adjustment quantity (q) for the lot.

The adjustment for flexural strength, air content, thickness and smoothness will be calculated as follows:

$$q = L \; x \, U \; x \, \frac{P}{100} \tag{4}$$

where:

q = quality assurance adjustment quantity
L = lot quantity
U = unit price for QC/QA-PCCP, \$/m2 (\$/yd2)
P = adjustment points

The quality assurance adjustment points for smoothness, QS, will be calculated in accordance with 501.28(d). When test results for smoothness exceed the minimum requirements, adjustments will be based on the initial profile index for each lane in accordance with the following:

Initial Profile Index, mm/0.16 km (in./0.1 mile)	Adjustment Points
0.0 to less than 13 (0.5)	3
13 (0.5) to less than 18 (0.7)	2
18 (0.7) to less than 23 (0.9)	1
23 (0.9) and above	0

A 0.16 km (0.1 mile) section will not be eligible for adjustments if that section or an adjacent 0.16 km (0.1mile) section requires corrective action to meet smoothness requirements.

As equation 4 shows the adjustment points are percent values of the unit price, thus 3 adjustment points will give 3% bonus as the pay factor is 103, etc.

2.4.2 Summary of Other Construction Smoothness Specifications

A study conducted by Ksaibati, Staigle, & Adkins (1995) showed that, for both PCC and HMA pavements, the average specification acceptance limit was 7 in/mile (110 mm/km). Figure 10 shows the maximum acceptance limits for both PCC and HMA pavements. The HMA pavements have slightly tighter acceptance limits than the PCC pavements. The acceptance limits that are less or equal to 12 inch/mile (190 mm/km) in Figure 10 are obtained by using 0.2” bb method and values above 12 in/mile are from Kansas DOT’s specification which use 0.0” bb method.

As a summary, Tables 10 to 14 present the smoothness specifications, pay factors and limits for different states using California Profilograph with 0.0” bb or Lightweight profiler to measure road roughness.

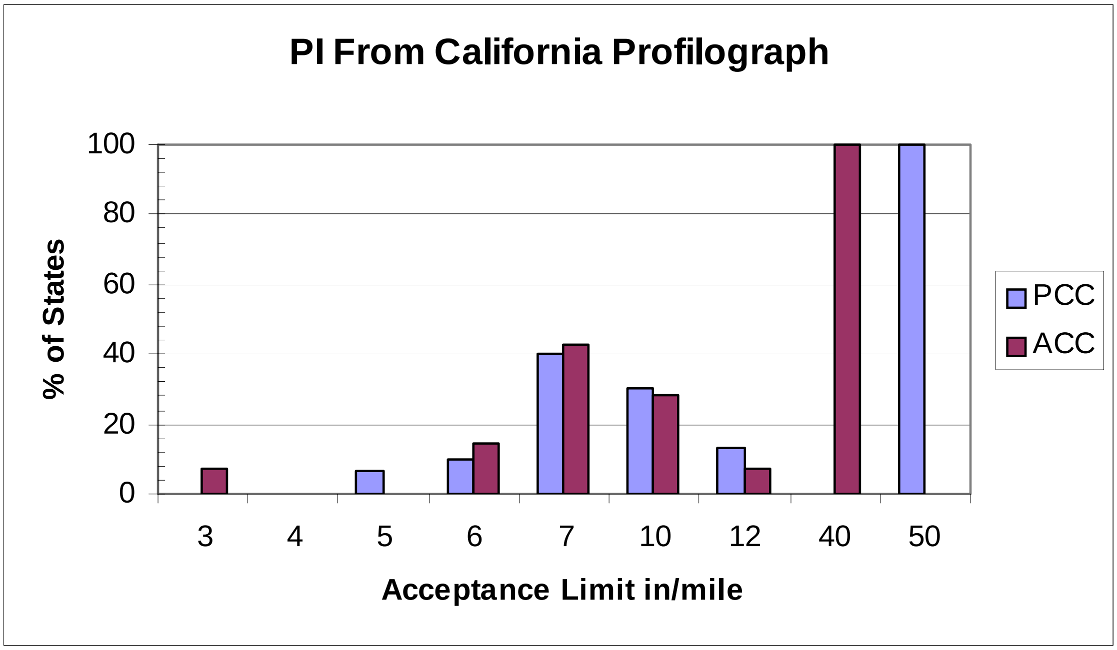

Figure 10. Maximum Acceptance Limit (Ksaibati et al., 1995).

Table 10. Smoothness Specifications - Pay Factors and Limits for Missouri DOT.

Missouri DOT

Device	**Reduction Method**	**Must Grind Height**
California Profilograph (0.0"bb)	Not Specified	0.4inch

AC Pavement

Segment Profile Index, Inches Per Mile (mm/km)		**Percent of**
> 45mph(70km/h)	< 45mph(70km/h)	**Contract Price**
10.0 (158) or less		107
10.1 - 15.0 (159 - 237)	15.0 (237) or less	105
15.1 - 18.0 (238 - 284)	15.1 - 25.0 (238 - 395)	103
18.1 - 25.0 (285 - 395)	25.1 - 45.0 (396 - 711)	100
25.1 - 35.0 (396 - 553)	45.1 - 55.0 (712 - 869)	97*
35.1 - 45.0 (555 - 711)	55.1 - 65.0 (870 - 1026)	95*
45.1 (712) or greater	65.1 (1027) or greater	93*

* Correct to 25in (395mm) or less

PCC Pavement

Segment Profile Index, Inches Per Mile (mm/km)		**Percent of**
> 45mph(70km/h)	< 45mph(70km/h)	**Contract Price**
10.0 (158) or less		107
10.1 - 15.0 (159 - 237)	15.0 (237) or less	105
15.1 - 18.0 (238 - 284)	15.1 - 25.0 (238 - 395)	103
18.1 - 25.0 (285 - 395)	25.1 - 45.0 (396 - 711)	100
25.1 - 35.0 (396 - 553)	45.1 - 55.0 (712 - 869)	97*
35.1 - 45.0 (555 - 711)	55.1 - 65.0 (870 - 1026)	95*
45.1 (712) or greater	65.1 (1027) or greater	93*

* Correct to 25in (395mm) or less

Reference: Missouri Standard Specification for Highway Construction, 2002.

Table 11. Smoothness Specifications - Pay Factors and Limits for Kansas DOT.

Kansas DOT

Device	**Reduction Method**	**Must Grind Height**
California Profilograph (0.0"bb)	Automated (ProScan)	0.3inch

AC Pavement

Segment Profile Index, Inches Per Mile (mm/km)	**Contract Price Adjustment Per 0.1 mile section per lane**
> 45mph (70km/h)	
7.0 (110) or less	$ 152 ($100)
7.1 - 10.0 (111 -160)	$76 ($50)
10.0 - 30.0 (161 - 475)	0
30.1 - 40.0 (476 - 630)	0*
40.1 (631) or greater	(-$203) (-$120)*

* Correct to 30in (475mm) or less

PCC Pavement

Segment Profile Index, Inches Per Mile (mm/km)		**Contract Price Adjustment Per 0.1 mile section per lane**
> 45mph (70km/h)	< 45mph (70km/h)	
6.0 (95) or less		$ 1200 ($760)
6.1 - 10.0 (95 -160)	15.0 (240) or less	$1000 ($630)
10.1 - 15.0 (161 - 240)		$ 750 ($470)
	15.1 - 25.0 (241 -400)	$500 ($310)
15.1 - 18.0 (241 - 285)		$ 370 ($240)
18.1 - 30.0 (286 - 475)	25.1 - 45.0 (401 -710)	0
30.1 - 40.0 (476 - 630)	45.1 - 65.0 (711 - 1025)	0*
40.1 (631) or greater	65.1 (1126) or greater	(-$750) (-$470)*

* Correct to 25in (400mm) or less

Reference: Parcells, W. (2001). "Control of Pavement Trueness in Kansas" Eleventh Interim Report, Kansas DOT.

Table 12. Smoothness Specifications - Pay Factors and Limits for Minnesota DOT.

Minnesota DOT

Device	**Reduction Method**	**Must Grind Height**
California Profilograph or Lightweight Profiler (0.0"bb)	Automated	0.4inch

AC Pavement

Segment Profile Index, Inches Per Mile (mm/km)	**Contract Price Adjustment Per 0.1 mile (0.1 km) section per lane**
11.2 (176.9) or less	300 ($190)
11.3 - 12.4 (177.0 -195.2)	200($130)
12.5 - 13.6 (195.3 - 213.5)	100($70)
13.7 - 17.3 (213.6 - 272.8)	$0.00
17.4 - 19.9 (272.9 - 314.1)	(-$100)*(-$70)*
20.0 - 22.4 (315.7 - 353.6)	(-$300)*(-$130)*
22.5 - 24.9 (355.2 - 393.1)	(-$200)*(-$190)*
25.0 (394.7) or greater	Corrective Action

* Correct to 25in (394.7mm) or less

PCC is using 0.2"bb

Reference: Gallivan, L. (2002) Personal Contact, FHWA.

Table 13. Smoothness Specifications - Pay Factors and Limits for Pennsylvania DOT.

Pennsylvania DOT

Device	**Reduction Method**	**Must Grind Height**
California Profilograph (0.0"bb)	Not Specified	0.4inch

AC Pavement

Segment Profile Index, Inches Per Mile	**Contract Price Adjustment Per 0.1 mile section per lane**
10 or less	$300.00
10.1 - 15.0	$150.00
15.1 -20.0	$75.00
20.1 - 25.0	$0.00
25.1 - 36.0	(-$150)
36.1 or more	Correct to 25"/mile or less

PCC Pavement

A full lot is defined as a single lane of pavement which is 12 ft or greater in width and having a length of 528 ft.

Lots will be specific to an individual lane or ramp and are seperated into twoo categories based on whether they are measured with high speed (Type 1) or with other equipment (Type 2).

The lot payment is determined by the following fomula: **Lot Payment = (Contrat Price per Lot) [(Pp-100)/100}**
where Pp = Characteristic Percentage for Surface Tolerance.

Table 14. Smoothness Specifications - Pay Factors and Limits for Wisconsin DOT.

Wisconsin DOT

Device	**Reduction Method**	**Must Grind Height**
California Profilograph or Lightweight Profiler (0.0"bb)	Automated	0.4inch

AC Pavement

Segment Profile Index, Inches Per Mile (mm/km)	**Contract Price Adjustment Per 0.1 mile section per lane**
10.0 (158) or less	$125.00
10.1-20.0 (159 -316)	$0.00
20.1 (317) or greater	(-$200)

PCC Pavement

Segment Profile Index, Inches Per Mile (mm/km)	**Contract Price Adjustment Per 0.1 mile section per lane**
19.0 (300) or less	$585.00
19.1-25.3 (300 - 400)	$350.00
25.4-44.4 (401 -700)	$0.00
44.5-50.7 (701 -800)	(-$230)
50.8 (801) or greater	(-$937)

Reference: Gallivan, L. (2002) Personal Contact, FHWA.

2.4.3 Smoothness Specification Development Methods

Rufino et al. (2001) obtained correlation between IRI and Profilograph PI established by the Long Term Pavement Performance (LTPP) database and then converted other DOT's PI specification limits into IRI using this correlation curve to develop the PCC bridge specification for Illinois DOT. Another reported study is the Kansas DOT's 0.0" bb specification development for PCC and HMA pavements. The development of the smoothness specification for 0.0" bb for Missouri DOT was established by the engineering judgment without performing any calibration measurements (McDaniel, personal contact, 2002). Engineers used their practical knowledge and field experience of the old specification to select the new specification limits they thought were reasonable.

The following paragraphs reported methods that some agencies have used to develop their contract smoothness specifications. Some of the specifications such as Kansas DOT's have been developed using the 0.0" bb band trace reduction method and some of them are using the lightweight profiler and IRI to measure pavement smoothness. Information has been collected from literature and by surveying (personal contact) several state highway agencies and their practices.

2.4.3.1 Indiana DOT Method

Mondal et al. (2000) developed the pavement smoothness specification for Indiana DOT for lightweight profilers. The study conducted several field tests and the profile traces were evaluated using IRI and PI evaluated using automated 0.2 and 0.0 inch blanking band methods provided by the equipment vendors. The data generated from the field test was then compared to the smoothness specifications developed by other states and a specification for lightweight profilers was proposed for INDOT. The study does not describe in detail how the proposed specification was developed. The proposed specification was then verified using field test data generated in Indiana. Researchers claimed that the incentive/disincentive payment based on this process appeared to be reasonable for the sites considered. Table 15 shows the proposed specification for the PCC pavements and Table 16 for the HMA pavements.

Table 15. Proposed PCC Pavement Specification (Mondal et al., 2001).

Profile Index (PI) with 0.0" blanking band (inches/mile) per 0.1 mile section per lane	Profile Index (PI)with 0.0" blanking band (inches/mile) per 0.1 mile section per lane	Contract Unit Price Adjustment per 0.1 mile section per lane
(for traffic speed >45miles/hr)	(for traffic speed <=45 miles/hr)	Percent of pavement unit bid price
<=6	<=15.0	105%
6.1-10.0		104%
10.1-15	15.1-20.0	103%
15.1-20	20.1-25.0	102%
20.1-25.0	25.1-30.0	101%
25.1-30.0	30.1-40.0	0.0
30.1-36.0	40.1-45.0	0.0*
>36.0**	>45.0**	Subject to correction*
* Correct to 25inches/mile	*Correct to 40 inches/mile	
**Must be corrected before any payment is received		

Table 16. Proposed HMA Pavement Specification (Mondal et al., 2001).

International Roughness Index (IRI) per 0.1 mile section per lane	Contract Unit Price Adjustment per 0.1 mile section per lane
(inches/mile)	Percent of pavement unit bid price
<=45.0	105%
45.1-50.0	104%
50.1-55.0	103%
55.1-60.0	102%
60.1-65.0	101%
65.1-70.0	100%
70.1-80.0	98%
80.1-90.0	96%
90.1-100.0	92%
>100	*Subject to Corrective Action
* Correct to at least 100 inches/mile to be eligible for payment	

2.4.3.2 Kansas DOT Method

Kansas DOT developed the new specification with 0.0 inch blanking band by collecting pavement smoothness data generated by the California Profilograph from several construction projects (Parcells, personal contact, 2002). The traces were first evaluated using the 0.2-inch blanking band. The same traces were then evaluated using the 0.0-inch blanking band and results were plotted on a histogram graph showing the number of sections for each 0.1 inch road section versus inch per mile increment of PI values, see Figures 11 and 12. Figure 11 shows the histogram of PI values obtained using 0.2" bb. Figure 11 also shows the limits for full pay range and for penalty and bonus range.

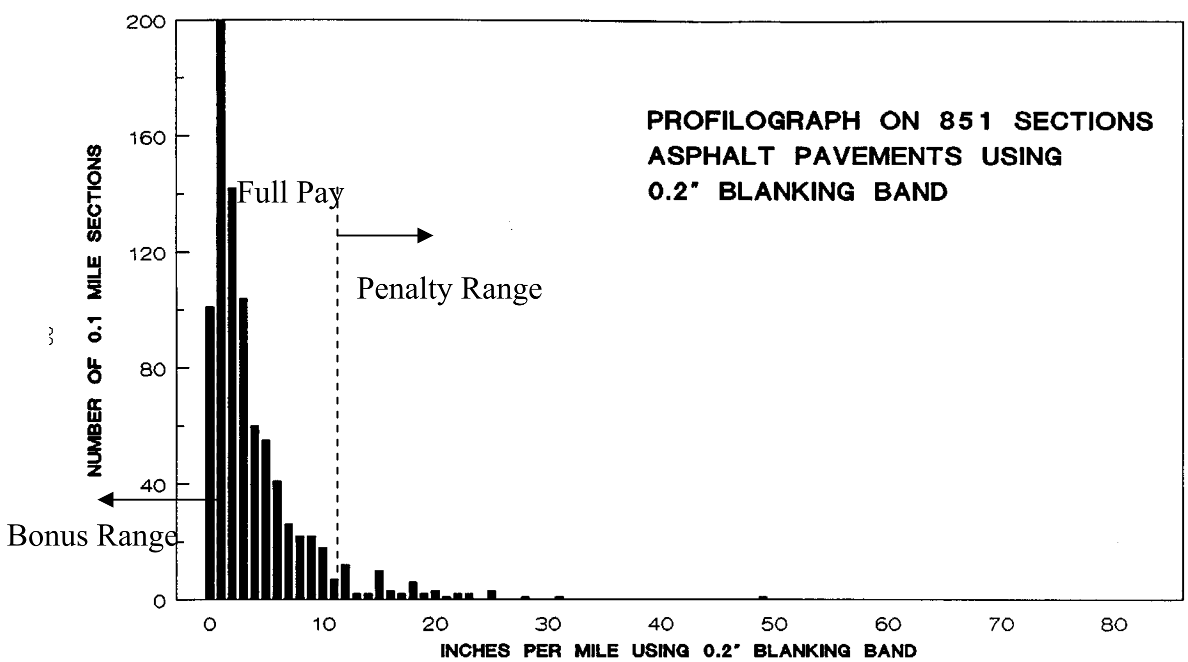

Figure 11. Distribution of $PI_{0.2}$ (Hossain et al., 1995).

Figure 12 shows the development of $PI_{0.0}$ limits. The distribution curve of $PI_{0.0}$ results was first plotted and the percentage range of full pay, bonus, and penalty was selected based on deflecting points on the histogram.

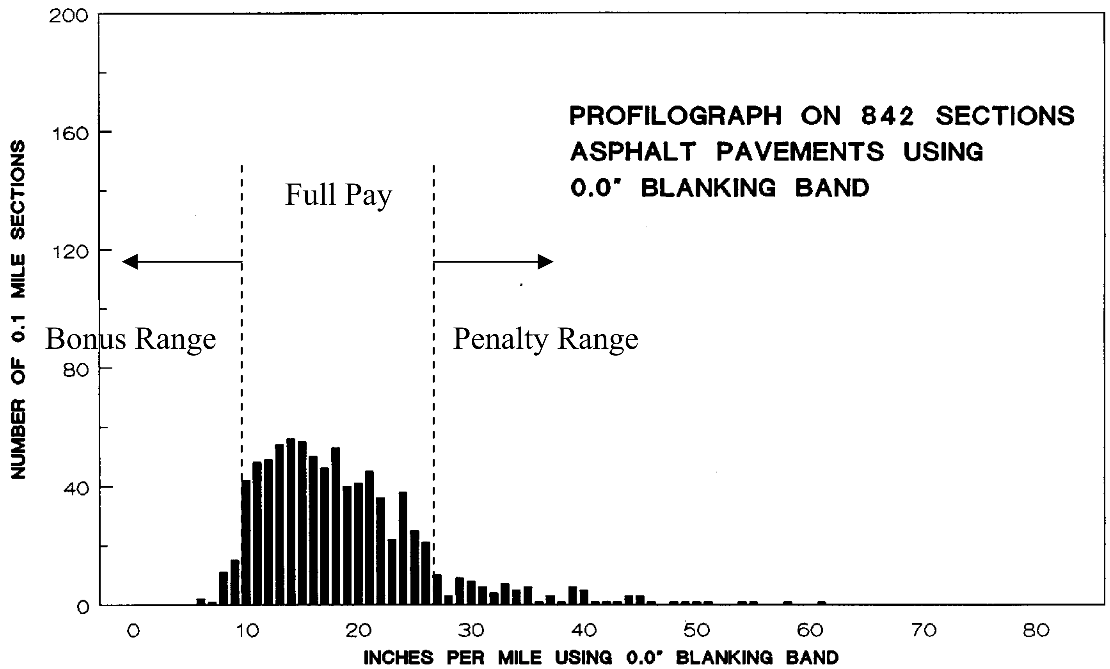

Figure 12. Distribution of $PI_{0.0}$ (Hossain et al., 1995).

2.4.3.3 Illinois DOT Method

Rufino et al. (2001) developed the bridge smoothness specification for Illinois DOT using lightweight profilometer. They first established correlation between IRI and blanking band Profile Index obtained based on the LTPP database, and then converted other DOT's PI specification limits into IRI values using this correlation curve. The converted IRI limits were specified for the bridge specification of Illinois DOT based on the experience of the authors. The IRI and PI values of 20 bridges were measured using lightweight profilers to calibrate the specified smoothness limits. Figure 13 and 14 show use of the correlation between $PI_{0.2}$ and IRI and PI with $PI_{0.0}$ and IRI to convert Kansas specification limits in to IRI. The result showed that the Kansas PI limits for full payment, 30 to 50 in/mi, corresponds to IRI of 93 to 137 in/mi. The maximum incentive for the converted IRI was 70 in/mi when PI was 20 in/mi, and the contractor has to grind back to 35 in/mi of PI, which corresponds to an IRI of 104 in/mi.

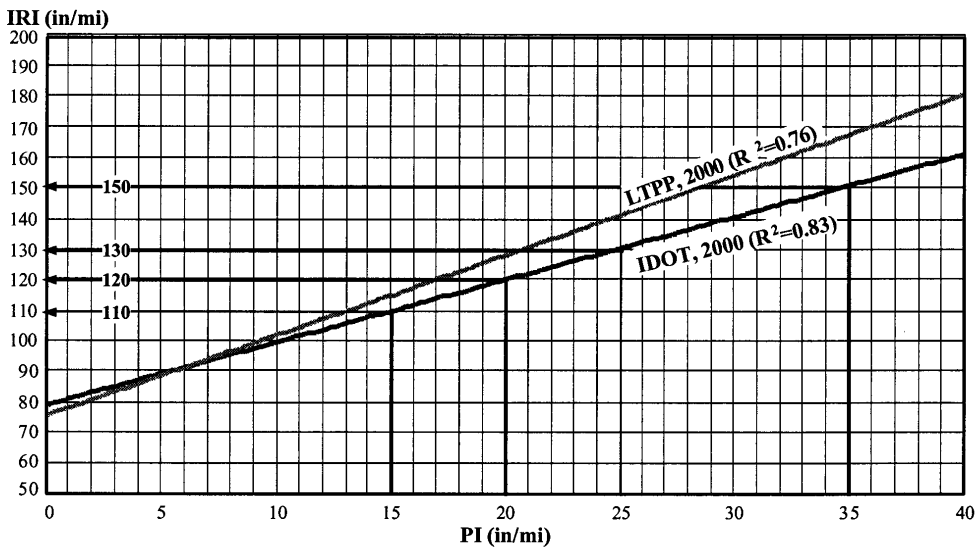

Figure 13. Correlation between $PI_{0.2}$ and IRI (Rufino et al., 2001).

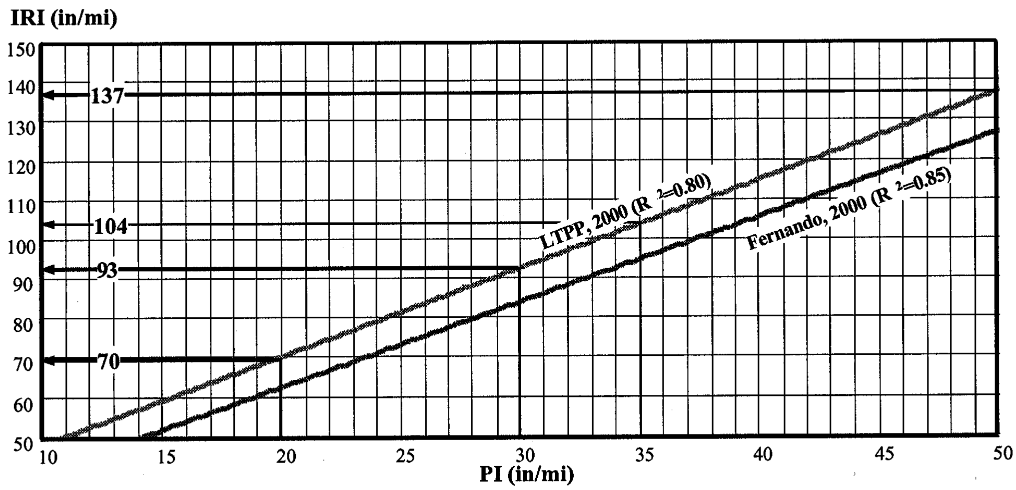

Figure 14. Correlation between $PI_{0.0}$ and IRI (Rufino et al., 2001).

2.4.3.4 Wisconsin DOT Method

Currently Wisconsin DOT is in the process of changing from using the 0.2" bb to the 0.0" bb to evaluate the California Profilograph traces (Hall, personal contact, 2002). For its latest HMA specification, Wisconsin DOT used an empirical approach to establish the incentive/disincentive target values. The DOT piloted projects to gather what they felt was a typical set of projects. Then a histogram of the resulting data was examined for the pilot 0.1-mile sections. They picked break points that had approximately the same number of sections in the penalty range as for the 0.2-inch blanking band specification. For the bonus, they estimated the location of the left inflection point of the resulting distribution. They used the value for the worst allowable ride from the concrete specification point for corrective action.

In the future Wisconsin DOT would like to take a statistically based approach to establish the incentive/disincentive pay ranges. As more data is collected, they would like to offer incentive payment for rides better than one standard deviation below the mean, full pay for rides within one standard deviation from the mean, and disincentive for rides worse than one standard deviation above the mean. Additionally, Wisconsin DOT intends to develop a maximum acceptable ride level. Rides over that level will be assessed the maximum disincentive and must be corrected to a ride one standard deviation above the mean or better.

2.4.3.5 Minnesota DOT Method

Currently Minnesota DOT is implementing the 0.0-inch blanking band requirement on a pilot project basis starting this year (personal contact, Garrity, 2002). Only those projects which have three or more lifts (1.5" minimum lift thickness) will be evaluated with the 0.0” bb. Because the 0.0” bb specification is a pilot provision, penalties will not be assessed. The 25-ft California Profilograph or the Lightweight Profiler with an onboard computer with software for automatic data reduction is required in the specification.

The PI limits for the 0.0” bb were developed from 0.2” bb data. About 700 sections of 0.1-mile profile traces were analyzed under both the 0.0-inch and the 0.2-inch blanking band. Values reduced from the 0.2” bb were plotted on the x-axis and the corresponding 0.0” bb values were plotted on the y-axis, Figures 15 and 16. Using these plots, the 0.0” bb was established by applying the same number of values for both limits. For instance, corrective action is required with 0.2” bb values greater than 10 in/mile, and a vertical line was drawn at 0.2” bb index value as shown in Figure 15. The numbers of values to the right of this line were counted. The same approximate numbers of values above the corresponding zero blanking band value was counted. As a result, a horizontal line above the zero blanking band value of 25 in/mile gave about the same number of corrective actions as 10 in/mile. Other PI limits were developed using the same approach.

According to Garrity (2002), the developed zero blanking band specification is used in the pilot projects and the specification criteria will continue to be refined as more data became available.

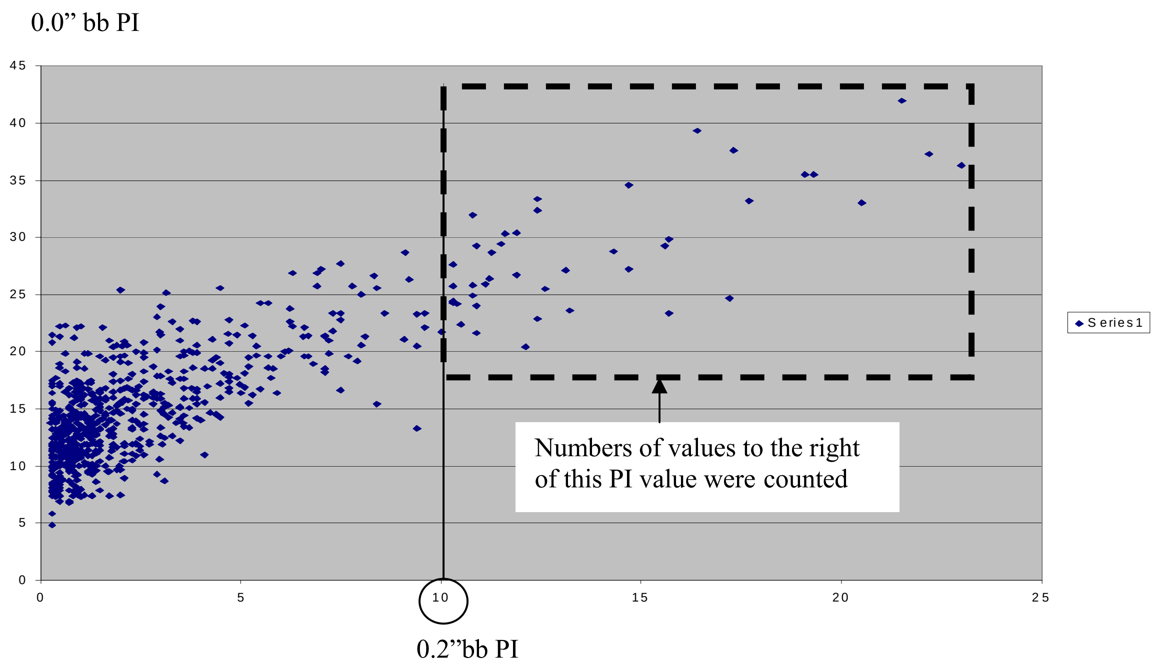

Figure 15. Schematic Plot of Minnesota Method, Step A.

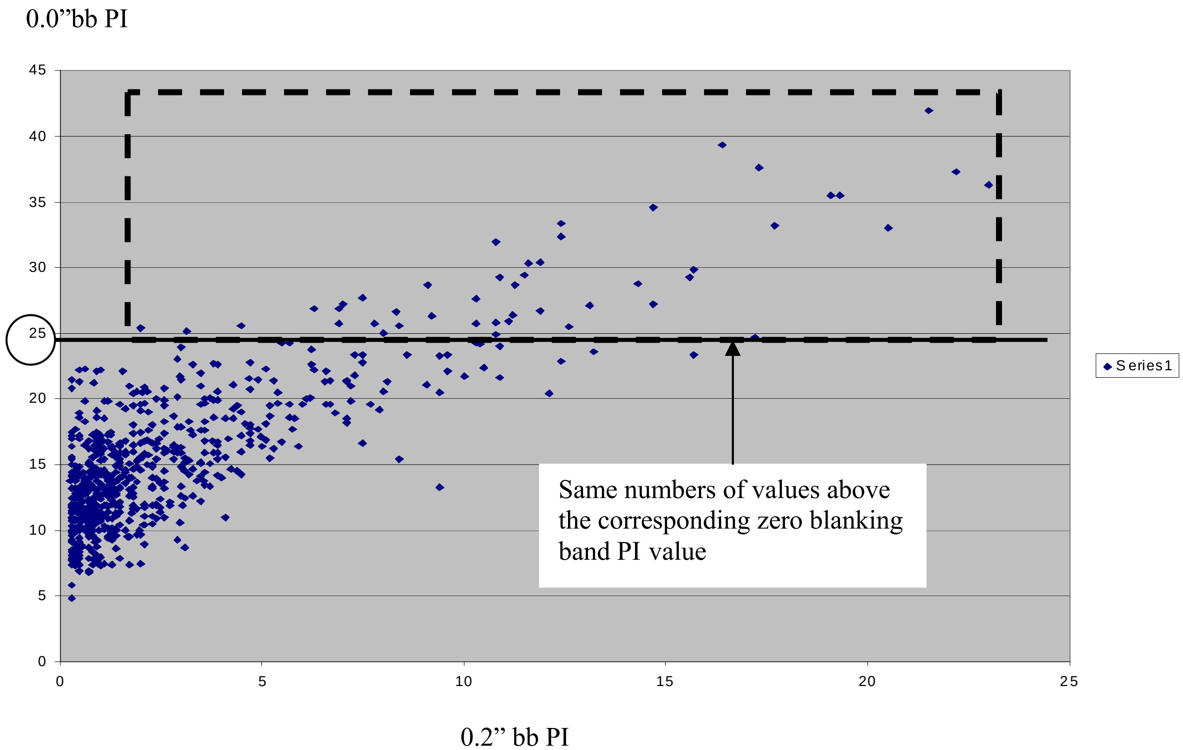

Figure 16. Schematic Plot of Minnesota Method, Step B.

2.4.4 National Development Efforts

The survey of frequent public highway users throughout the country conducted by the Federal Highway Administration (FHWA) in 1996 and in 2001 showed that the road condition was the top priority for what highway users were looking for on their roadways. Many state highway agencies (SHAs) also have identified pavement smoothness as a key issue. Therefore, being aware of the importance of the pavement smoothness as well as the increasing need for SHAs to purchase and upgrade profiling equipment to provide network level and project specific smoothness information, a pooled fund is being developed by the FHWA Expert Task Group (ETG) on smoothness to provide agencies with information and first hand experience to address issues and concerns related to profiler operation, equipment, and procedures.

This pooled fund project is expected to provide direction and funding that will unify the strategies, address implementation efforts, and promote practices that improve accuracy and repeatability of the equipment and promote the knowledge and understanding of profile equipment and measurements. To achieve the purposes, several study tasks are to be accomplished in the near future as follows:

1) Deliver Profiler Acquisition Specifications, Maintenance Guidelines and Analysis Software: As many SHAs begin implementing the use of inertial profilers for pavement management and construction management practices for the delivery of smooth pavements to the traveling public, the issues of equipment acquisition, maintenance and the use and understanding of acquired data will need to be addressed. This product will assist SHA personnel in making knowledgeable decisions to optimize their profiling needs and to identify needed funding.

2) Profiler Calibration - Implement Standardized Procedures to Calibrate Equipment: Variations in profile data hinder construction activities by making it difficult to establish clear measurement standards. The objective of this task is to deploy the type of facilities that are needed to ensure the accuracy of profilers.

3) Profiler Calibration Equipment: The objective of this task is to build a portable calibration center that can be transported to any location for assisting with calibration of inertial profile equipment.

4) Software for Profile Bump Identification for Construction Specifications: This effort aids the development of construction ride specifications and evenness that needs to be maintained, especially at approaches to weigh-in-motion sites, bridge approaches, etc.

2.5 Smoothness Specification vs. Roughness Development

The 1986 AASHTO Guide for Design of Pavement Structure (1986) emphasizes the need for initial pavement smoothness as an important design consideration. Janoff (1990) studied pavement performance data from Pennsylvania and Arizona. He found that there was a significant decrease in roughness after eight years if the initial smoothness was increased. A recently completed National Cooperative Highway Research Program (NCHRP) project indicated that smooth pavements last longer and are more cost-effective (Smith, et al., 1997). This study conducted several analyses regarding the effect of initial pavement smoothness and of pavement smoothness specifications on the future smoothness of the pavement and on pavement life. In this study, a wide range of data sources was used to evaluate the effect of initial smoothness on future pavement smoothness. Data from State Highway Agencies (SHAs), AASHO road test, and the LTPP GPS program were evaluated. The results showed that the effect of initial pavement smoothness was stronger for new pavement construction than for overlay pavement construction, suggesting that the performance for overlay is governed more by other factors such as reflection cracking. Besides, additional pavement life can be obtained by achieving higher levels of initial smoothness. A sensitivity analysis was also conducted to show the percentage change in life versus percentage change in roughness. The study suggested that a 25% increase in initial pavement smoothness yields 9% increase in pavement service life. In terms of the profile index, that is an approximate increase in smoothness from 7 to 5 in/mi for PCC and 5 to 3.5 in/mi for AC pavement could yield at least a 9% increase in life. The analysis also suggested that an approximate increase in smoothness from PI of 7 to 3.5 in/mi for PCC and 5 to 2.5 in/mi for AC pavement could yield at least a 15% increase in pavement life. Mcghee (1999) also indicated that the pavement service life is directly affected by pavement smoothness, with smoother pavements providing longer service lives and ultimately saving taxpayer's money.

However, a recent research conducted by Hossain, Boyer, & Parcells (2002) has shown that the as-constructed smoothness tends to wear out in about 3-5 years. After that the newly constructed smoothness does not affect future roughness development. Therefore, with the improving ability of evaluating the pavement smoothness, concerns have been raised regarding the effectiveness of the "ultra-high" initial pavement smoothness and the justification of the incentive/disincentive based on smoothness specifications.

This study conducted by Hossain et al. (2002) tried to identify the factors responsible for rapid roughness progression on 21 PCC projects built in Kansas after 1992. Data elements were selected based on three groups: inventory, construction, and climate and are shown in the Table 17. Using annually collected IRI data by South Dakota Profilometers, an exponential regression curve was fitted to the mean annual IRI, and the rate of roughness progression was determined from the slope of this curve. A multiple linear regression analysis was then applied to find the relationships between the rate of roughness progression and the independent variables specified in Table 17.

The following models were derived in this study: 1) model for the rate of roughness progression with as-constructed smoothness as dependent variables; 2) models for the increasing rate of roughness progression with the concrete strength as the independent variable; 3) models for the increasing rate of roughness progression without the concrete strength as the independent variable; 4) models for the decreasing rate of roughness progression with the concrete strength as the independent variable; and 5) models for the decreasing rate of roughness progression without the concrete strength as the independent variable. A sensitivity analysis and independent correlation analysis were performed to find out how and which independent variables had the greatest impact on the rate of roughness progression.

Based on the analysis results, the following conclusions were drawn by the authors:

- The concrete modulus of rupture, subgrade material, number of wet days, and initial IRI significantly affect the rate of roughness progression.
- Concrete flexural strength has a very significant effect on roughness progression. Higher flexural strength tends to maintain the as-constructed smoothness longer.
- Permeable subbase tends to decrease the rate of roughness progression.
- Pavements with high initial IRI tend to become smoother as traffic passes over it due to smoothening of minor surface irregularities and stabilization of the subgrade moisture.

Table 17. Variables Used in Kansas Study (Hossain et al., 2002).

INVENTORY	CONSTRUCTION	CLIMATE
County code	Construction date	Annual precipitation*
Route no.	Drainage type*	Wet days/year*
Project no.	JRCP or JPCP	Mean annual Temperature*
Begin milepost	Concrete Comp. Strength*	Minimum average Temp.*
End milepost	Concrete unit weight*	Maximum average Temp.*
Project length*	Concrete M.O.R*	Days below 0C*
AADT	Water-cement ratio*	Days above 32 C*
DHV	% Air *	Freeze-thaw cycles/year*
Directional distribution	% Fine Aggregate*	
Percent trucks*	% Coarse Aggregate*	
Speed limit*	% Cement*	
ESAL/day*	% Water*	
Annual IRI *	Transverse joint spacing*	
	Width of outside shoulder*	
	Subbase thickness*	
	Subbase stabilization*	
	Subgrade treatment*	
	Permeable subbase*	
	Subgrade depth*	
	Subgrade plasticity index*	
	Subgrade liquid limit*	
	Subgrade % pass #4*	
	Subgrade % pass #200*	
	Dowels (y/n)*	
	Dowel Spacing*	
	PI*	

*Independent variables in statistical analysis

- The as-constructed smoothness tends to wear out in about 3 to 5 years. After that the as-constructed smoothness does not influence future roughness progression. Also, as-constructed PI and initial IRI are not correlated.

2.6 Cost Effectiveness of Smoothness Specifications

As discussed before, SHAs implement smoothness specifications in order to produce higher quality on the pavements. However, the literature review indicated that these specifications are mostly based on the engineering judgment or followed the AASHTO or other agency's specifications. The extent of how the incentive/disincentive payment can really reflect the cost effectiveness is still unknown.

Smith et al. (1997) conducted a study trying to evaluate the cost effectiveness of initial smoothness levels and of several current pavement smoothness specifications. The evaluation procedure is based on the Life Cycle Cost Analysis (LCCA) technique. The LCC considered in this section includes initial construction costs, future maintenance and rehabilitation costs, saving value by benefits, and the user cost. In this study, LCC was expressed as the present-worth (PW) cost and was calculated using the following equation:

$$PW = \text{Cashflow} / [(1+I)^n] \quad (5)$$

Where:

I = Discount Rate.

n = Number of years over which costs are to be discounted.

This study assumed there is an optimum cost-effectiveness level between initial smoothness and total life-cycle cost, as shown in Figure 17.

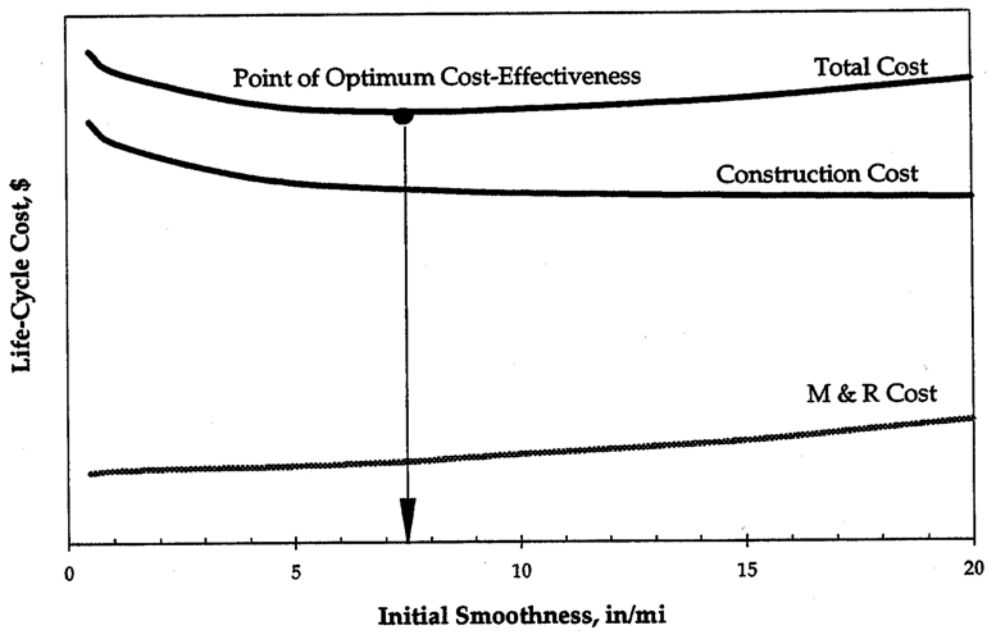

Figure 17. Relationship Between Initial Pavement Smoothness and Total Life-cycle Cost (Smith et al, 1997).

In the analysis, the construction cost also includes the costs which contractors need to pay to achieve the additional smoothness level.

The following formula was used in this study to calculate the pay factor:

$$PF_{ac} = [BP_{ad} + (LCC_{ad} - LCC_{ac})]/BP_{ad} \tag{6}$$

Where,

PF_{ac} = Pay factor for as-constructed smoothness level.

BP_{ad} = Bid price corresponding to as-designed smoothness level, $.

LCC_{ad} = PW life-cycle cost of maintenance and rehabilitation corresponding to as-designed smoothness level, $.

LCC_{ac} = PW life-cycle cost of maintenance and rehabilitation corresponding to as-constructed smoothness level, $.

Based on the analyses results using the concepts and equations above, seven of nine concrete pavement families showed the optimum cost-effectiveness range as being between 0 and 5.5 in/mi. Four out of five asphalt pavement families showed the optimum cost-effectiveness range as being between 0 and 3.5 in/mi. The inclusion of user costs in the LCCA has a deep effect on the determination of the most cost-effective smoothness level. The addition of user costs to total life-costs resulted in 0 in/mi as being the most cost effective smoothness level.

3 MANUAL PROFILOGRAPH TRACE REDUCTION RESULTS

In this section, Profilograph traces obtained from INDOT were analyzed manually using both 0.2 and 0.0 in. blanking band. The trace reduction procedures, statistical analysis of traces reduction result, and conclusions were presented in the following sections.

The database obtained from INDOT included about 230 profilograph measurements sections (0.1 in.) from various PCC pavements and one HMA pavement. Table 18 describes the dataset in terms of length of the measured road section and type of surface. Appendix C shows the manually reduced PI values by INDOT for these sections.

Table 18. Description of Obtained Profilograph Traces.

Contract	Road	Surface	Station Number	Length (mile)
R-23900	I-465	PCC	044+0.00-046+0.00	2.02
R-23901	I-465	PCC	051+0.27-052+0.40	1.11
R-23804	U-24	PCC	107+0.51-111+0.58	4.07
R-23496	U-24	PCC	096+0.00-099+0.00	3.00
R-23719	U-24	PCC	104+0.76-107+0.00	2.23
R-24290	U-24	PCC	102+0.81-104+0.76	1.96
R-23925	I-74	AC	015+0.68-025+0.30	9.58

3.1 Profilograph Traces Reduction Using 0.2-inch Blanking Band

Profilograph traces were evaluated using 0.2-inch blanking band. The purpose of this process was to ensure the interpreter is familiar with the standard trace reduction procedure and can reduce the traces without mistakes. Statistic analysis was performed to evaluate whether this purpose was achieved.

The data reduction procedure used followed the current INDOT Profilograph traces reduction standard procedures ITM No. 901-93T.

3.1.1 Data Analysis

Twenty 0.1 mile long sections were randomly selected from the data given in Appendix C for the analysis using 0.2" bb. A statistical analysis for the repeatability of the trace reduction was also performed. Each section had five trials and the hypothesis was that the mean of the Profile Index reduced from each five trials is equal to the PI value measured by INDOT. A t-test was performed using $\alpha = 0.05$.

Figure 18 shows an example of the trace reduction for the HMA pavement. The measured profile was relatively flat and smooth. For the randomly selected sections, the blanking band was placed directly to the 0.1 mile long profile section, as Figure 18 shows, and there was no need to divide the section into smaller sections for superelevations. This made the trace reduction relatively easy to perform and reduced deviations as statistical data in Table 19 shows. Only two sites deviated between the INDOT and Purdue reductions. Also, roughness values were small and standard deviation for the repeated reductions was very small.

The results of the statistical analysis for the PCC sections showed that in 19 of 20 measured sections there were no statistically significant differences between INDOT and Purdue values, as Table 20 shows. Possible deviations are most likely to do with differences of placing the blanking band as well as the different judgment of measuring

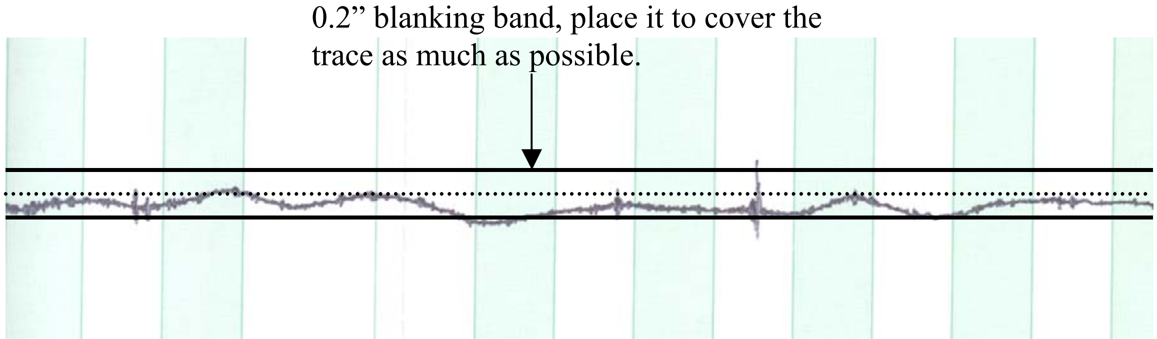

Figure 18. Example for Reduction of HMA Pavement Profile using 0.2” bb.

Figure 19 shows an example of the trace reduction for the PCC pavement. Again, the profile is flat but now the trace is noisier compared to the HMA pavement trace.

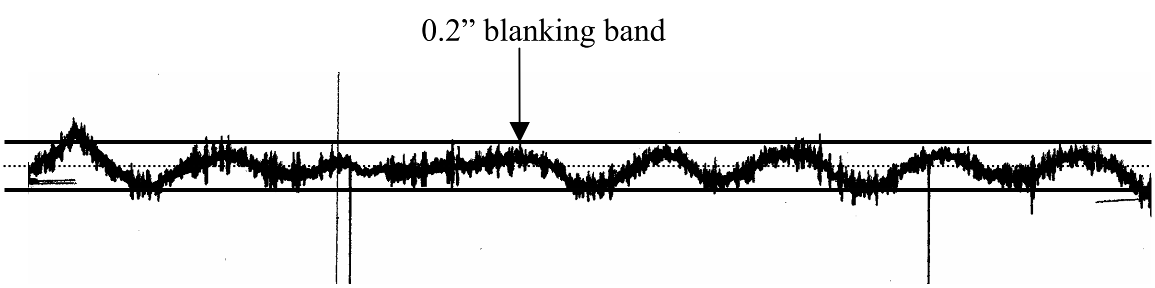

Figure 19. Example of the Reduction of PCC Pavement Profile using 0.2” bb.

each scallop to the nearest 0.05 inch. For the PCC pavements, most of the deviations were covered by the blanking band, which made it easier to measure the deviations. Also, for one of the projects, Project R-23719, an outline of the trace was drawn to the trace by an INDOT engineer, which made it easier to read the trace and also increased the repeatability of the results.

Table 19. Analysis Results for HMA Pavements.

		Profilograph Profile Index with 0.2" Blanking Band										
Project	Site	INDOT	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average	St.Dev.	T	Critical	Diff.
R-2325	10+472-10+630	0.10	0.15	0.15	0.15	0.10	0.10	0.13	0.03	2.45	-2.78	No
	10+948-11+106	0.10	0.15	0.15	0.15	0.10	0.10	0.13	0.03	2.45	2.78	No
	11+742-11+900	0.20	0.25	0.20	0.20	0.20	0.20	0.21	0.02	1.00	2.78	No
	11+900-12+058	0.10	0.05	0.05	0.10	0.10	0.10	0.08	0.03	-1.63	2.78	No
	12+848-13+006	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-2.78	No
	13+478-13+636	0.20	0.10	0.15	0.15	0.15	0.15	0.14	0.02	-6.00	-2.78	Yes
	14+590-14+748	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.78	No
	14+906-15+064	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	-2.78	No
	16+494-16+652	0.10	0.15	0.10	0.15	0.10	0.10	0.12	0.03	1.63	2.78	Yes
	17+446-17+604	0.20	0.25	0.25	0.20	0.20	0.20	0.22	0.03	1.63	2.78	No
	17+452-17+294	0.25	0.25	0.20	0.20	0.20	0.20	0.21	0.02	-4.00	2.78	Yes
	17+294-17+136	0.07	0.10	0.05	0.05	0.05	0.05	0.06	0.02	-1.00	-2.78	No
	16+030-15+872	0.05	0.00	0.00	0.05	0.05	0.05	0.03	0.03	-1.63	-2.78	No
	14+916-14+758	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-2.78	No
	14+440-14+282	0.05	0.10	0.05	0.05	0.05	0.05	0.06	0.02	1.00	-2.78	No
	14+124-13+968	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.78	No
	13+330-13+172	0.10	0.15	0.10	0.15	0.10	0.10	0.12	0.03	1.63	-2.78	No
	12+696-12+538	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-2.78	No
	11+424-11+266	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	2.78	No
	10+476-10+318	0.10	0.15	0.10	0.10	0.10	0.10	0.11	0.02	1.00	-2.78	No

Table 20. Analysis Results for PCC Pavements.

		Profilograph Profile Index with 0.2" Blanking Band										
Project	Site	INDOT	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average	St.Dev.	T	Critical	Diff.
R-23901	WBML(19+410-19+251)	0.20	0.15	0.20	0.15	0.20	0.20	0.18	0.03	-1.63	-2.78	No
	WBML(17+675-17+514)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.78	No
	WBML(16+549-16+388)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.00	0.00	2.78	No
	WBRL(19+417-19+256)	0.20	0.20	0.25	0.25	0.25	0.20	0.23	0.03	2.45	2.78	No
	WBRL(16+549-16+388)	0.10	0.10	0.05	0.05	0.10	0.10	0.08	0.03	-1.63	-2.78	No
R-24290	WBPL(477+26-482+54)	0.20	0.15	0.20	0.20	0.20	0.20	0.19	0.02	-1.00	-2.78	No
	WBDL(482+54-487+82)	0.40	0.40	0.40	0.45	0.40	0.40	0.41	0.02	1.00	2.78	No
	WBDL(524+78-530+06)	0.25	0.20	0.20	0.25	0.25	0.25	0.23	0.03	-1.63	-2.78	No
	WBDL(535+34-540+62)	0.10	0.10	0.15	0.15	0.15	0.15	0.14	0.02	4.00	2.78	Yes
	EBDL(487+82-493+10)	0.15	0.20	0.15	0.15	0.15	0.15	0.16	0.02	1.00	2.78	No
	EBPL(487+82-493+10)	0.20	0.25	0.25	0.20	0.20	0.25	0.23	0.03	2.45	2.78	No
	EBPL(493+10-498+38)	0.05	0.05	0.00	0.00	0.00	0.05	0.02	0.03	-2.45	-2.78	No
	EBPL(514+22-519+50)	0.05	0.00	0.05	0.05	0.05	0.05	0.04	0.02	-1.00	-2.78	No
R-23719	EBPL(701+00-696+00)	5.50	5.00	5.50	5.50	5.50	5.00	5.30	0.27	-1.63	-2.78	No
	EBPL(664+00-659+00)	9.00	8.50	8.50	9.00	9.00	9.00	8.80	0.27	-1.63	-2.78	No
	EBPL(591+50-595+50)	6.00	5.50	6.00	6.50	6.00	6.00	6.00	0.35	0.00	2.78	No
	EBDL(695+00-690+00)	0.50	0.00	0.50	0.50	0.50	0.50	0.40	0.22	-1.00	-2.78	No
	EBDL(690+00-685+00)	6.00	5.50	5.50	6.00	6.00	6.00	5.80	0.27	-1.63	-2.78	No
	EBDL(664+00-659+00)	2.50	2.50	2.50	2.50	2.50	2.50	2.50	0.00	0.00	2.78	No
	EBDL(580+00-575+00)	4.00	3.50	4.00	4.00	4.00	4.00	3.90	0.22	-1.00	-2.78	No

3.2 Trace Reduction Procedure Using 0.0-inch Blanking Band

The same road sections analyzed using 0.2-inch blanking band were analyzed again using 0.0-inch blanking band by two different interpreters, A and B. Both interpreters were Purdue University students. A statistical analysis was performed to evaluate the repeatability and the reproducibility of method used.

3.2.1 Description of Trace Reduction Procedure

The data reduction procedure used followed the current INDOT Profilograph traces reduction standard procedure ITM No. 901-93T with slight modifications. In general, the 0.0" bb procedure used was very similar to the 0.2" bb method. The biggest difference was how the zero blanking band i.e., "dashed" center reference line was placed to the profile trying to center the profile trace as much as possible with the purpose of making scallops above and below the blanking band approximately balanced. The Appendix D describes the detailed manual reduction procedures.

3.2.2 Data Analysis

The selection of these twenty sections was generated randomly and the profilograms were reduced using the zero blanking band following the trace reduction procedure presented in the previous section. The generated results were then used to perform the within-operator repeatability and the between-operators reproducibility by the following methods. Figure 20 shows an example of positioning the centerline to the HMA pavement profile, and Figure 21 shows PCC pavement.

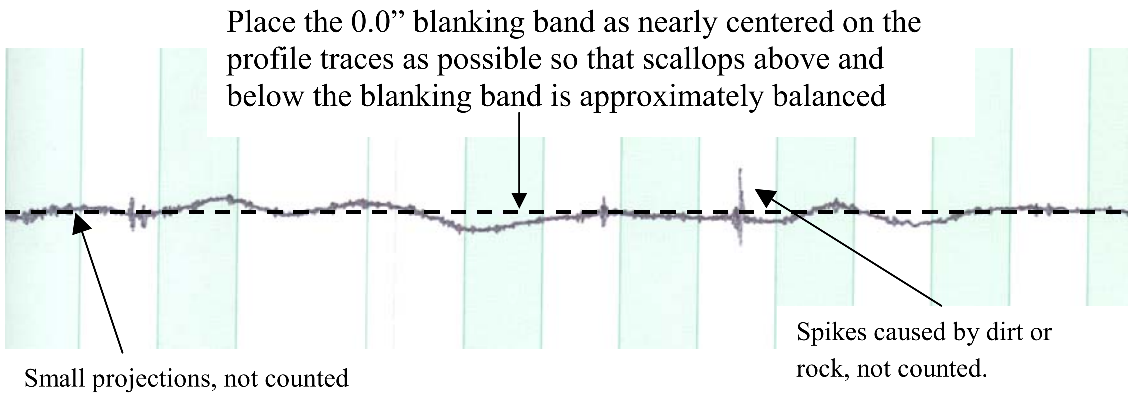

Figure 20. Example for Reduction of HMA Pavement Profile using 0.0” bb.

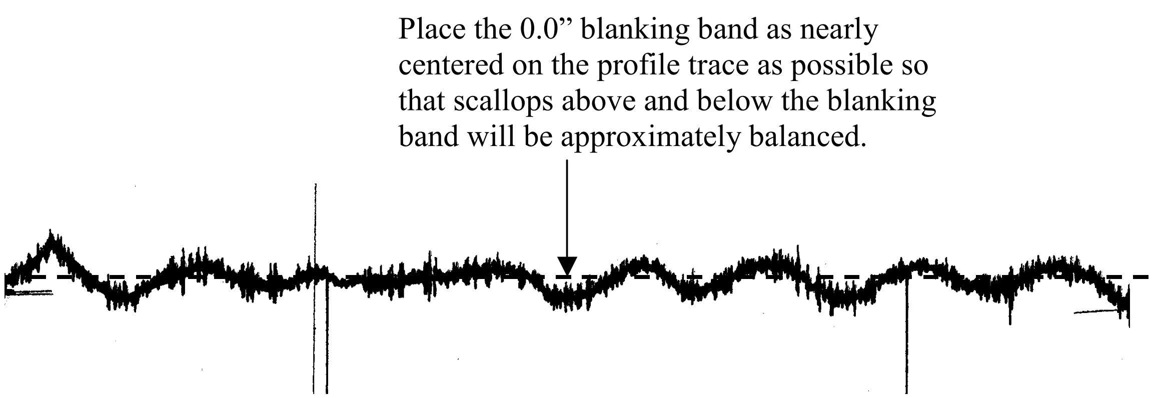

Figure 21. Example for Reduction of PCC Pavement Profile using 0.0” bb.

Same sections as for the 0.2” bb method were selected to perform the analysis. Repeatability statistical analysis included average, standard deviation (STDV) and coefficient of variance (CV%). Tables 21 and 22 show the analysis results for the two interpreters A and B for the HMA pavements, and Tables 23 and 24 for the PCC pavements. The statistic analysis results of the repeatability are good with relatively low standard deviation and coefficient of variance.

Table 21. Repeatability of the Interpreter A for $PI_{0.0}$, HMA.

Project	Site	Profilograph Profile Index with 0.0" Blanking Band										
		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average	STDV	CV%	Average (last 4)	STDV (last 4)	CV % (last 4)
R-23925	1	10.0	10.5	10.0	10.0	10.0	10.1	0.22	2.2	10.1	0.25	2.5
	2	9.0	10.0	9.0	9.5	9.0	9.3	0.45	4.8	9.4	0.48	5.1
	3	11.5	12.5	12.5	13.0	12.5	12.4	0.55	4.4	12.6	0.25	2.0
	4	11.5	13.0	13.0	12.5	13.0	12.6	0.65	5.2	12.9	0.25	1.9
	5	6.0	6.5	7.0	7.0	7.0	6.7	0.45	6.7	6.9	0.25	3.6
	6	9.0	10.0	11.5	11.0	11.0	10.5	1.00	9.5	10.9	0.63	5.8
	7	6.0	6.5	5.5	6.0	5.5	5.9	0.42	7.1	5.9	0.48	8.1
	8	7.0	8.5	8.0	8.5	8.5	8.1	0.65	8.0	8.4	0.25	3.0
	9	10.0	11.5	12.0	12.5	12.0	11.6	0.96	8.3	12.0	0.41	3.4
	10	14.0	14.0	14.5	14.5	14.0	14.2	0.27	1.9	14.3	0.29	2.0
	11	10.5	9.5	9.0	9.5	10.0	9.7	0.57	5.9	9.5	0.41	4.3
	12	9.5	11.5	10.0	11.0	10.5	10.5	0.79	7.5	10.8	0.65	6.0
	13	8.0	8.5	8.5	8.5	8.0	8.3	0.27	3.3	8.4	0.25	3.0
	14	7.0	6.0	6.5	7.0	7.0	6.7	0.45	6.7	6.6	0.48	7.2
	15	10.5	9.5	9.5	10.0	9.5	9.8	0.45	4.6	9.6	0.25	2.6
	16	7.5	8.5	7.5	8.0	8.0	7.9	0.42	5.3	8.0	0.41	5.1
	17	12.0	11.0	10.5	11.0	10.5	11.0	0.61	5.6	10.8	0.29	2.7
	18	7.5	9.0	9.0	9.5	9.0	8.8	0.76	8.6	9.1	0.25	2.7
	19	6.0	7.0	5.5	7.0	6.5	6.4	0.65	10.2	6.5	0.71	10.9
	20	15.0	14.0	13.5	14.5	14.0	14.2	0.57	4.0	14.0	0.41	2.9

Table 22. Repeatability of the Interpreter B for $PI_{0.0,}$ HMA.

Project	Site	Profilograph Profile Index with 0.0" Blanking Band										
		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average	STDV	CV%	Average (last 4)	STDV (last 4)	CV % (last 4)
R-23925	1	8.0	11.5	9.5	10.0	9.0	9.6	1.29	13.5	10.0	1.08	10.8
	2	7.5	6.0	6.5	7.0	5.5	6.5	0.79	12.2	6.3	0.65	10.3
	3	9.5	12.0	10.0	11.5	11.0	10.8	1.04	9.6	11.1	0.85	7.7
	4	10.0	10.0	11.5	12.0	10.0	10.7	0.97	9.1	10.9	1.03	9.5
	5	5.5	6.5	7.0	6.0	5.5	6.1	0.65	10.7	6.3	0.65	10.3
	6	8.0	8.0	9.0	9.5	10.0	8.9	0.89	10.0	9.1	0.85	9.4
	7	4.0	4.5	5.0	4.5	4.5	4.5	0.35	7.9	4.6	0.25	5.4
	8	6.5	6.5	7.0	7.5	6.0	6.7	0.57	8.5	6.8	0.65	9.6
	9	8.5	10.0	10.5	11.0	9.5	9.9	0.96	9.7	10.3	0.65	6.3
	10	13.0	13.0	13.5	12.5	13.5	13.1	0.42	3.2	13.1	0.48	3.6
	11	11.5	10.5	10.0	9.0	9.5	10.1	0.96	9.5	9.8	0.65	6.6
	12	9.5	7.0	8.5	9.0	9.5	8.7	1.04	11.9	8.5	1.08	12.7
	13	8.5	8.5	7.0	7.5	9.0	8.1	0.82	10.1	8.0	0.91	11.4
	14	5.5	5.0	4.5	5.0	6.5	5.3	0.76	14.3	5.3	0.87	16.5
	15	7.5	8.0	8.5	7.0	8.0	7.8	0.57	7.3	7.9	0.63	8.0
	16	8.0	6.0	7.0	7.5	6.5	7.0	0.79	11.3	6.8	0.65	9.6
	17	9.5	8.0	8.5	10.0	9.5	9.1	0.82	9.0	9.0	0.91	10.1
	18	9.0	8.0	8.5	8.0	7.5	8.2	0.57	7.0	8.0	0.41	5.1
	19	6.0	5.0	5.5	6.0	5.5	5.6	0.42	7.5	5.5	0.41	7.4
	20	11.5	12.0	11.0	10.5	12.5	11.5	0.79	6.9	11.5	0.91	7.9

Table 23. Repeatability of the Interpreter A for $PI_{0.0,}$ PCCP.

Project	Site	Profilograph Profile Index with 0.0" Blanking Band										
		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average	STDV	CV%	Average (last 4)	STDV (last 4)	CV % (last 4)
R-23901	1	16.5	19.5	17.0	17.5	18.0	17.7	1.15	6.5	18.0	1.08	6.0
	2	10.0	12.0	11.5	11.0	12.5	11.4	0.96	8.4	11.8	0.65	5.5
	3	12.0	16.5	15.0	15.5	16.0	15.0	1.77	11.8	15.8	0.65	4.1
	4	25.0	28.5	24.0	25.5	24.5	25.5	1.77	6.9	25.6	2.02	7.9
	5	12.0	15.0	12.0	13.5	12.5	13.0	1.27	9.8	13.3	1.32	10.0
R-24290	6	23.0	24.0	22.5	21.5	22.0	22.6	0.96	4.3	22.5	1.08	4.8
	7	19.0	20.0	16.5	17.0	17.5	18.0	1.46	8.1	17.8	1.55	8.8
	8	22.0	24.0	23.0	25.5	24.5	23.8	1.35	5.7	24.3	1.04	4.3
	9	22.5	25.5	23.5	24.0	24.5	24.0	1.12	4.7	24.4	0.85	3.5
	10	18.5	20.0	18.5	17.0	17.5	18.3	1.15	6.3	18.3	1.32	7.2
	11	19.0	21.0	22.5	22.0	23.0	21.5	1.58	7.4	22.1	0.85	3.9
	12	19.0	21.0	16.0	16.5	17.0	17.9	2.07	11.6	17.6	2.29	13.0
	13	13.5	12.5	11.0	13.0	11.5	12.3	1.04	8.4	12.0	0.91	7.6
R-23719	14	32.0	31.5	32.5	31.0	31.5	31.7	0.57	1.8	31.6	0.63	2.0
	15	37.5	39.0	38.0	38.5	39.0	38.4	0.65	1.7	38.6	0.48	1.2
	16	39.0	42.0	43.0	44.0	42.5	42.1	1.88	4.5	42.9	0.85	2.0
	17	17.5	18.0	19.0	20.0	19.5	18.8	1.04	5.5	19.1	0.85	4.5
	18	27.0	26.0	26.5	26.5	27.5	26.7	0.57	2.1	26.6	0.63	2.4
	19	32.5	31.5	31.0	32.5	31.5	31.8	0.67	2.1	31.6	0.63	2.0
	20	26.0	28.0	29.5	28.5	29.0	28.2	1.35	4.8	28.8	0.65	2.2

Table 24. Repeatability of the Interpreter B for $PI_{0.0,}$ PCCP.

Project	Site	Profilograph Profile Index with 0.0" Blanking Band										
		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Average	STDV	CV%	Average (last 4)	STDV (last 4)	CV % (last 4)
R-23901	1	20.5	17.5	17.0	17.5	17.0	17.9	1.47	8.2	17.3	0.29	1.7
	2	10.0	11.0	10.0	10.0	9.5	10.1	0.55	5.4	10.1	0.63	6.2
	3	14.0	12.0	12.0	13.0	14.0	13.0	1.00	7.7	12.8	0.96	7.5
	4	22.0	21.5	22.0	22.5	22.0	22.0	0.35	1.6	22.0	0.41	1.9
	5	14.0	14.5	14.0	14.5	15.0	14.4	0.42	2.9	14.5	0.41	2.8
R-24290	6	21.5	21.0	20.5	20.5	21.0	20.9	0.42	2.0	20.8	0.29	1.4
	7	16.0	19.0	15.5	16.5	17.0	16.8	1.35	8.0	17.0	1.47	8.7
	8	26.5	27.0	25.5	26.5	20.5	25.2	2.68	10.6	24.9	2.98	12.0
	9	20.5	22.5	23.5	22.5	21.5	22.1	1.14	5.2	22.5	0.82	3.6
	10	16.5	15.5	15.0	17.5	15.5	16.0	1.00	6.3	15.9	1.11	7.0
	11	20.0	19.0	19.0	18.5	19.5	19.2	0.57	3.0	19.0	0.41	2.1
	12	16.5	15.5	16.0	17.0	18.5	16.7	1.15	6.9	16.8	1.32	7.9
	13	11.0	13.0	12.0	11.5	11.5	11.8	0.76	6.4	12.0	0.71	5.9
R-23719	14	30.0	29.5	29.0	28.0	28.5	29.0	0.79	2.7	28.8	0.65	2.2
	15	37.0	39.5	38.5	40.0	38.0	38.6	1.19	3.1	39.0	0.91	2.3
	16	31.0	36.0	34.0	33.0	31.5	33.1	2.01	6.1	33.6	1.89	5.6
	17	22.5	23.5	21.5	22.0	23.0	22.5	0.79	3.5	22.5	0.91	4.1
	18	31.0	29.5	28.5	30.0	28.0	29.4	1.19	4.1	29.0	0.91	3.1
	19	27.5	27.5	26.0	26.5	25.5	26.6	0.89	3.4	26.4	0.85	3.2

The trace reduction was performed in consecutive hours by both interpreters, which may have enhanced the measuring consistency.

Tables 21 to 24 show that the average, standard deviation, and the coefficient of variance for the trials 2, 3, 4, and 5 for both interpreters were better than that of the all five trails. This suggests the interpreter is “trained’ during the process. Therefore, better trace reduction results may be achieved by repeating the reduction process.

3.2.2.1 Reproducibility Analysis

A t-test was performed to analyze the reproducibility of the measurements from two different interpreters. The null hypothesis was that there is no statistic difference between the mean values of the measurements at 5% significance level. Analysis results are shown in Table 25. The reproducibility of the $PI_{0.0}$ value was fair. Sixty percent of the reduction results obtained from interpreter A and B were statistically different. The reason for this can be considered to be caused by a) different interpretation of the trace deviations; and b) differences of positioning the zero blanking band to the profile between interpreters.

3.2.2.2 Correlation Between $PI_{0.2}$ and $PI_{0.0}$ Values

The correlation between PI values using 0.2” and 0.0” blanking band was poor. Correlation coefficient for the HMA pavement for interpreter A and B was $R^2 = 0.44$ and 0.53, respectively, as shown in Figures 22 and 23. This indicates that a 0.2” bb reduction makes pavements look smoother than they are, as expected.

Figure 24 and 25 show the correlation of 0.2" bb and 0.0" bb for the PCC pavement sections. The correlation coefficients for the interpreter A and B were $R^2 = 0.53$ and 0.63, respectively. The slightly better correlation for the PCC pavements is most likely due to the fact that the measured profile was rougher and the amount of same irregularities counted in 0.2" and 0.0" bb methods were higher than that of HMA pavements.

Table 25. t-test for Two Interpreters.

	HMA			PCC		
Site	t Statistic	t Critical	Stat. Difference	t Statistic	t- Critical	Stat. Difference
1	0.85	2.31	No	-0.24	2.31	No
2	6.89	2.31	Yes	2.63	2.45	Yes
3	3.05	2.31	Yes	2.2	2.45	No
4	3.62	2.31	Yes	4.34	2.78	Yes
5	1.69	2.31	No	-2.33	2.57	No
6	2.67	2.31	Yes	3.62	2.57	Yes
7	5.72	2.31	Yes	1.35	2.31	No
8	3.61	2.31	Yes	-1.04	2.45	No
9	2.79	2.31	Yes	2.66	2.31	Yes
10	4.92	2.31	Yes	3.37	2.31	Yes
11	-0.8	2.31	No	3.06	2.57	Yes
12	3.09	2.31	Yes	1.13	2.45	No
13	0.52	2.31	No	0.87	2.36	No
14	3.56	2.31	Yes	6.19	2.36	Yes
15	6.17	2.31	Yes	-0.33	2.45	No
16	2.25	2.31	Yes	7.3	2.31	Yes
17	4.15	2.31	Yes	-6.35	2.36	Yes
18	1.41	2.31	No	-4.56	2.45	Yes
19	2.31	2.31	Yes	10.4	2.36	Yes
20	6.19	2.31	Yes	3.29	2.31	Yes

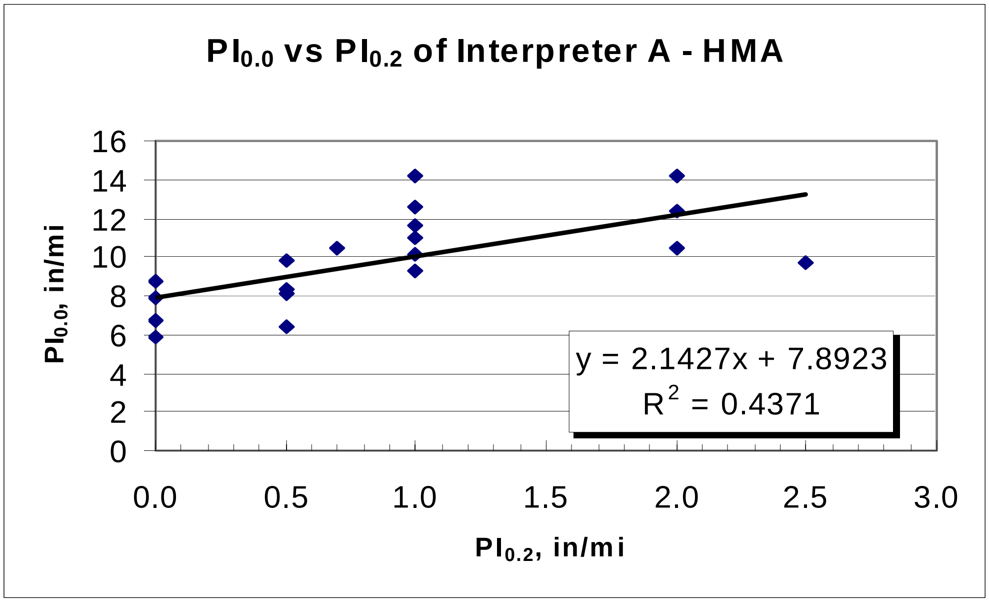

Figure 22. Correlation Between $PI_{0.2}$ and $PI_{0.0}$ for HMA, Case A.

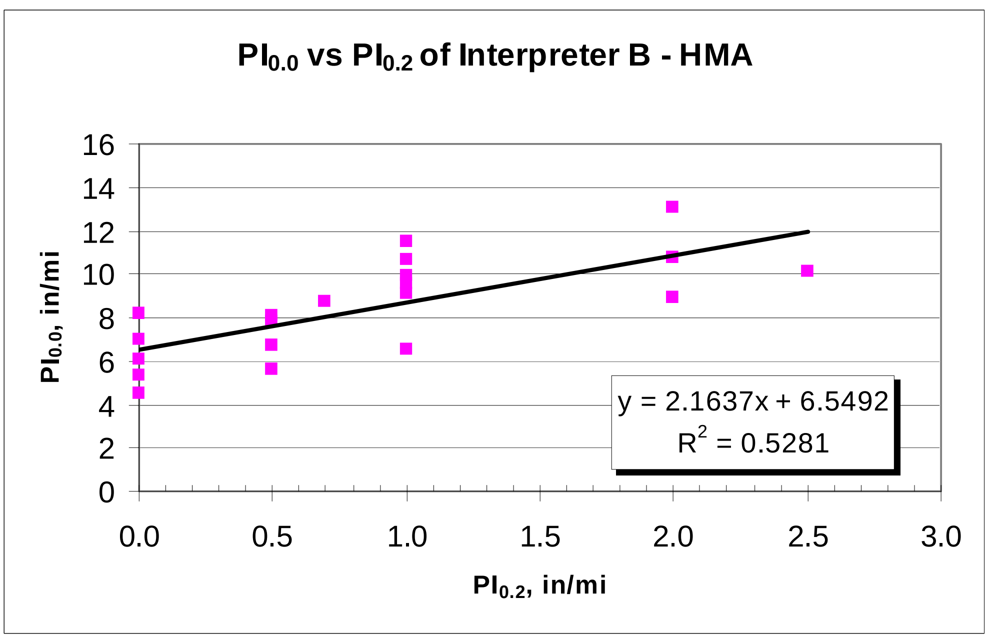

Figure 23. Correlation Between $PI_{0.2}$ and $PI_{0.0}$ for HMA, Case B.

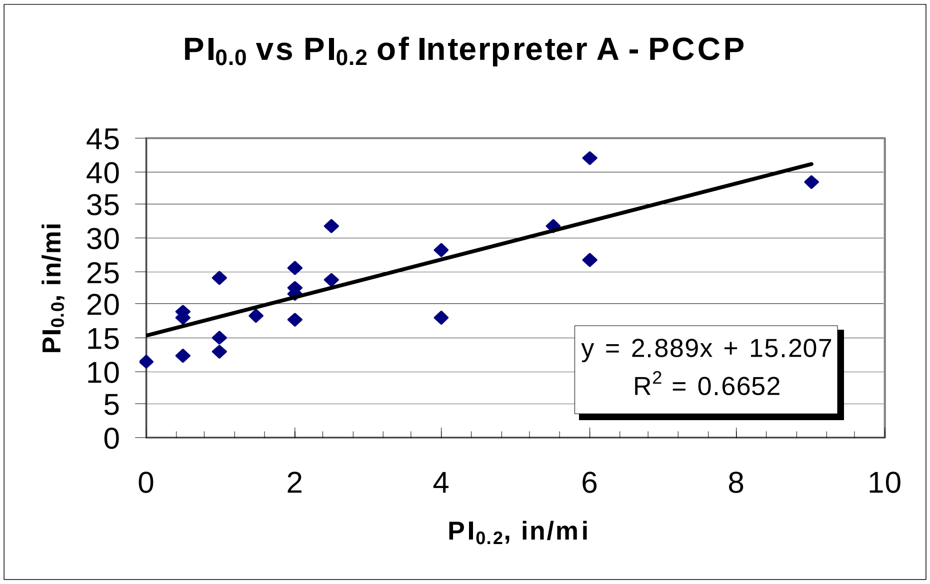

Figure 24. Correlation Between $PI_{0.2}$ and $PI_{0.0}$ for PCC, Case A.

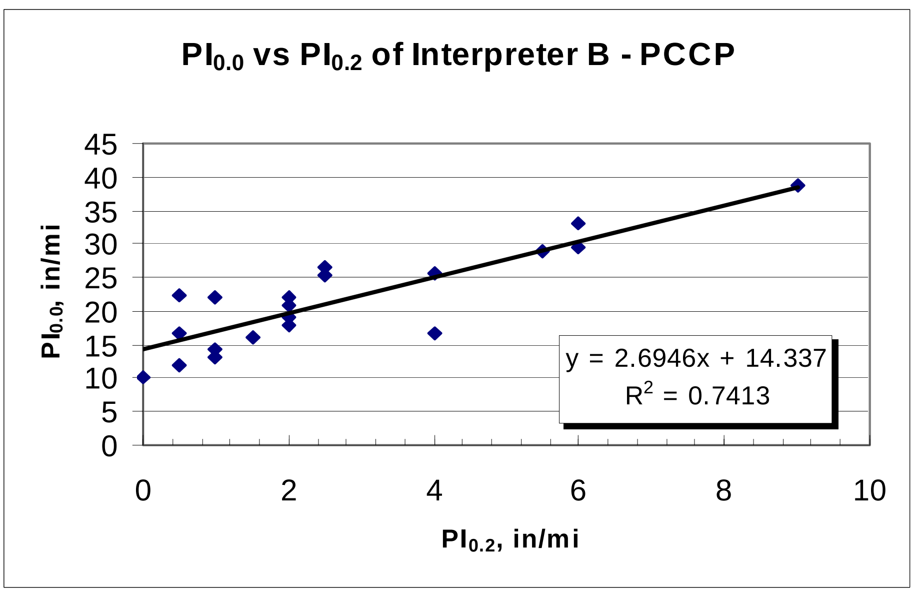

Figure 25. Correlation Between $PI_{0.2}$ and $PI_{0.0}$ for PCC, Case B.

Figures 26 and 27 compare the two Purdue interpreters used in the trace reduction. Correlation for both HMA and PCC pavements between the two interpreters A and B is 0.89. However, interpreter A systematically computed up to 2 in/mile higher roughness values for HMA pavements and up to 5 in/mile for PCC pavements.

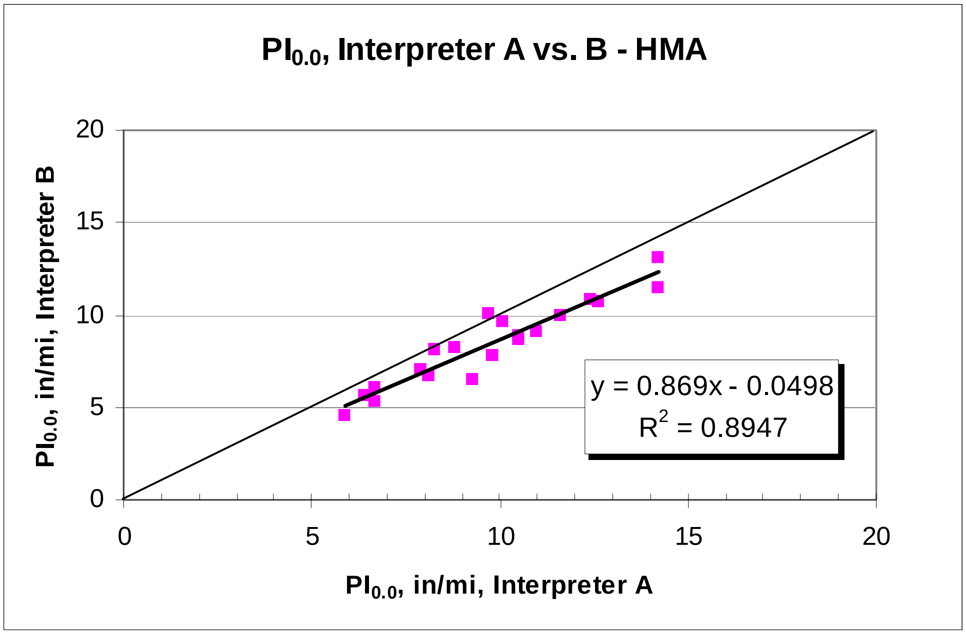

Figure 26. Comparison Between Interpreter A and B, HMA Pavement.

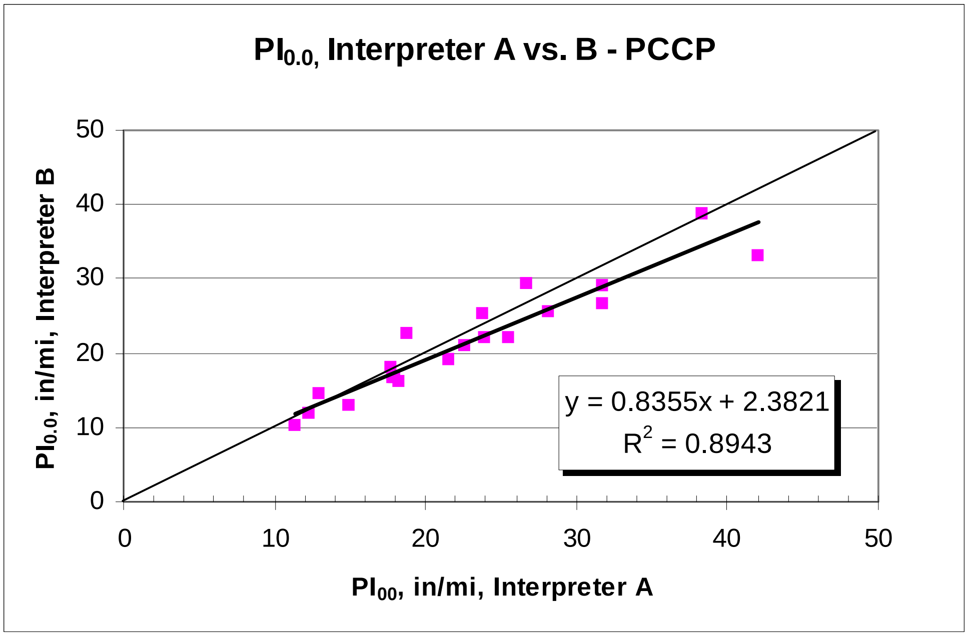

Figure 27. Comparison Between Interpreter A and B, PCC Pavement.

4 RECOMMENDATIONS FOR PHASE II OF THE STUDY

Based on the literature review in Chapter 2 and profile data reduction analysis in Chapter 3 that formed Phase I of the study, the following recommendations were made for continuation of the study in Phase II.

Task 2: Development of Modified Construction Smoothness Specification

The objective of the task is to develop a modified smoothness specification to incorporate 0.0 inch blanking band to reduce profilograph traces. The objective will be achieved by performing the following subtasks:

1. Analyze all available 0.0” blanking band specifications of various SHA’s for acceptance limits and amount of incentives/disincentives.
2. Use data given in Mondal et al. (2001) research report and compute correlation between automated 0.2” and 0.0” blanking band data and IRI values. Using established correlations, transfer the current INDOT 0.2” blanking band specification to the 0.0” blanking band. Use LTPP database correlation between blanking band indices and IRI to convert INDOT specification.
3. Analyze INDOT profile data presented in Chapter 3 using Kansas DOT’s Proscan device and analysis software.
4. Based on all data, construct provisional construction smoothness specification for manual and automated trace reduction using 0.0” blanking band method.
5. Construct ITM Test Method for manual 0.0” blanking band trace analysis.
6. Compare proposed specification to the specifications used by other SHAs.

Task 3: Validation of Modified Specification

The objective of the task is to verify the proposed specification using several projects in the coming construction season. The objective will be achieved by performing the following subtasks:

1. Select several construction projects with HMA and PCC pavements and measure roughness using California profilograph and INDOT Rip Van. Analyze data using 0.2 and 0.0” blanking band procedures and IRI.
2. Assess penalties and/or bonuses the measured smoothness would produce based on the developed new specification and current specification.
3. Adjust acceptance limits in the proposed specification if needed

Task 4: Automated Trace Processing

The objective of the task is to develop/adopt an automated system to reduce profilograph traces. The objective will be achieved by performing the following subtasks:

1. Based on the experience of using Proscan system developed by Kansas DOT, recommend a method to automatically reduce the traces using 0.0” blanking band either by adopting Kansas method or some other method.
2. When the new ASTM standard is established for the profilograph trace reduction, initiate a pooled fund study among all states using 0.0” blanking band to develop software to analyze the traces according to the new standard.

5 COMPARISON OF AUTOMATED AND MANUAL TRACE REDUCTIONS

Chapter 3 presented manual trace reduction results of the California Profilograph data supplied by INDOT. A part of this same dataset was analyzed automatically using Proscan system (described in Section 2.2.2.2 in Chapter 2) developed by Kansas State University and Kansas DOT. Analysis work was done in June 2002 at the Bureau of Materials and Research in Kansas DOT using their Proscan system with the help of Pavement Surface Research Engineer William H. Parcells.

5.1 Comparison Between Automated and Manual $PI_{0.0}$

The first step in the automated Proscan analysis was to digitize the Profilograph traces by continuously feeding them into the scanner. It took 30 seconds to scan one 0.1 mile section and compute the PI, which is much faster than the manual reduction of 2 minutes per section. Analysis was done using both 0.2” and 0.0” blanking band options and analysis resolution was selected to be 0.05”. Analysis for the HMA pavements included INDOT Project 23925 in I-74, which had 36 0.1-mile sections in the east bound driving lane, and 47 sections in the west bound driving lane. This same project was analyzed manually by randomly selecting dataset of twenty 0.1-mile sections (see Chapter 3). The manual reductions were performed by two different interpreters A and B at Purdue University. Also, 0.2” blanking band manual reductions done by INDOT were compared to the automated analysis. Similarly, 15 PCCP sections of INDOT Project R-24290 in U-24 were analyzed by the Proscan. Because the automatically analyzed PCCP sections did not match to the sections analyzed in Chapter 3, the manual analysis of these 15 PCCP sections was done by the Purdue interpreter A separately.

Table 26 and Figures 28 and 29 show the Profile Index (PI) analysis results for 17 HMA pavement sections that were analyzed in both ways. The analysis results indicate a good agreement between the Proscan and manual reductions. For the interpreter A, the smallest and largest differences were 0.2 in/mi and 2.20 in/mi, respectively, with an average absolute difference of 1.00 in/mi. The Kansas specification, KT-46I, requires that for a given test track, the automated and manual PI values may not vary more than 2 in/mi (Devore, et al., 1995), which 94% of the measured sections met. For the interpreter B, the smallest and largest differences were 0.1 in/mi and 3.40 in/mi, respectively, with an average absolute difference of 1.18 in/mi. Now, 82% of the sections met the Kansas KT-46I requirements.

The analysis results for the PCC pavements also indicated good agreement between the Proscan reductions and the manual reductions with the correlation coefficient R^2 being 0.94. Tabulated results are shown in Table 27. The smallest difference was 0.5 in/mi, and the largest difference was 3.4 in/mi with an average absolute difference of 1.19 in/mi. Then, 93% of the sections met the requirement of KT-46I. Figure 30 shows the correlation between the reduction results for these 15 PCC pavement sections.

The PCC profiles were rougher than the HMA pavement profiles that make it easier to count all irregularities, and this may result in improving the correlation between manual and automated reductions for the PCC pavements. Also, the smoother HMA pavement profile makes it more difficult to place the floating centerline or the 0.0” blanking band manually. Therefore, deviations from the centerline are more difficult to count, which may cause a poorer correlation between computer reduction results and manual reduction results for the HMA pavements.

Table 26. Comparison Between Manual and Proscan $PI_{0.0}$ (in/mi), HMA.

Site R-23925 Milepost	Manual, A	Manual, B	Proscan	Difference, A	Difference, B
11+900-12+058	12.60	10.70	10.40	2.20	0.30
12+848-13+006	6.70	6.10	7.50	-0.80	-1.40
13+478-13+636	10.50	8.90	12.00	-1.50	-3.10
14+590-14+748	5.90	4.50	5.50	0.40	-1.00
14+906-15+064	8.10	6.70	7.50	0.60	-0.80
16+494-16+652	11.60	9.90	12.50	-0.90	-2.60
17+446-17+604	14.20	13.10	14.00	0.20	-0.90
17+452-17+294	9.70	10.10	10.50	-0.80	-0.40
17+294-17+136	10.50	8.70	9.50	1.00	-0.80
16+030-15+872	8.30	8.10	7.00	1.30	1.10
14+916-14+758	6.70	5.30	6.00	0.70	-0.70
14+440-14+282	9.80	7.80	8.50	1.30	-0.70
14+124-13+968	7.90	7.00	6.50	1.40	0.50
13+330-13+172	11.00	9.10	12.50	-1.50	-3.40
12+696-12+538	8.80	8.20	8.00	0.80	0.20
11+424-11+266	6.40	5.60	5.50	0.90	0.10
10+476-10+318	14.20	11.50	13.50	0.70	-2.00
Average	**9.58**	**8.31**	**9.23**	**0.35**	**-0.92**
SD	**2.59**	**2.32**	**2.87**	**1.08**	**1.26**
CV (%)	**27**	**28**	**31**	**-**	**-**

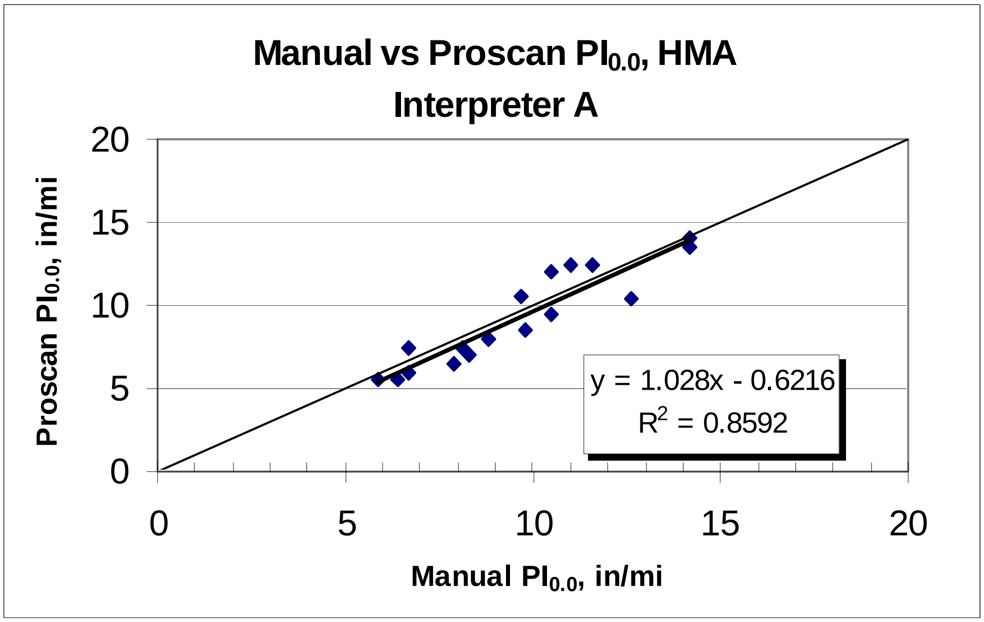

Figure 28. Manual vs. Proscan $PI_{0.0}$, HMA, Interpreter A.

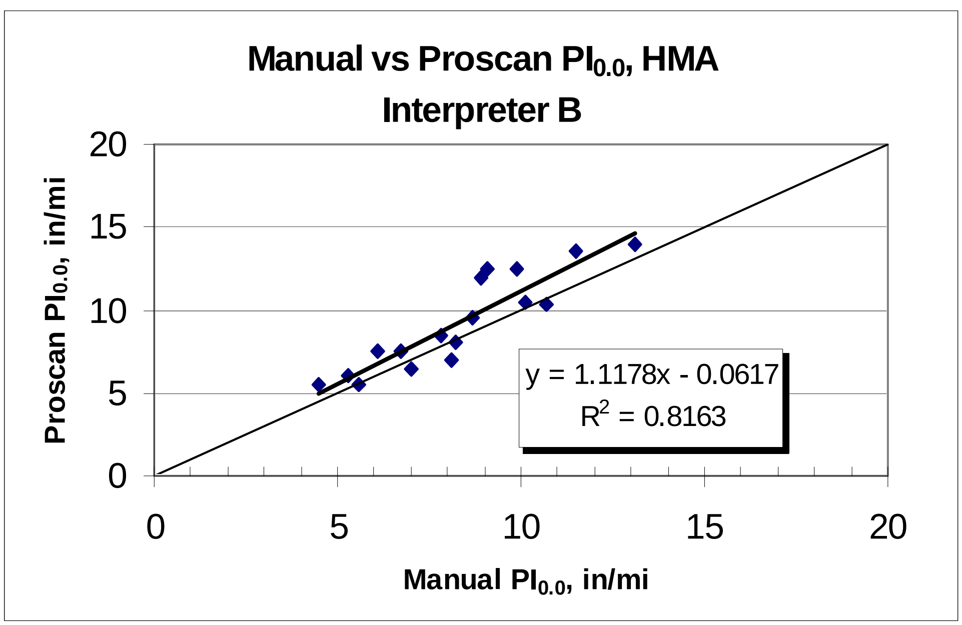

Figure 29. Manual vs. Proscan $PI_{0.0}$, HMA, Interpreter B.

Table 27. Comparison Between Manual and Proscan $PI_{0.0}$ (in/mi), PCC.

Site	Manual, A	Proscan	Difference, A
488+98-493+10	21.50	19.50	2.00
490+10-498+38	17.90	14.50	3.40
498+38-503+66	16.00	14.00	2.00
503+66-508+94	16.50	15.00	1.50
508+94-514+22	10.50	11.00	-0.50
514+22-519+50	12.30	13.00	-0.70
482+54-487+82	18.00	19.00	-1.00
477+26-482+54	22.50	23.50	-1.00
471+98-477+26	22.50	21.00	1.50
466+70-471+98	30.50	31.00	-0.50
540+62-545+90	24.00	23.50	0.50
535+34-540+62	24.00	23.50	0.50
530+06-535+34	22.50	23.50	-1.00
524+78-530+06	23.80	24.50	-0.70
519+50-524+78	14.00	15.00	-1.00
Average	**19.77**	**19.43**	**0.33**
SD	**5.34**	**5.57**	**1.42**
CV (%)	**27**	**28**	**-**

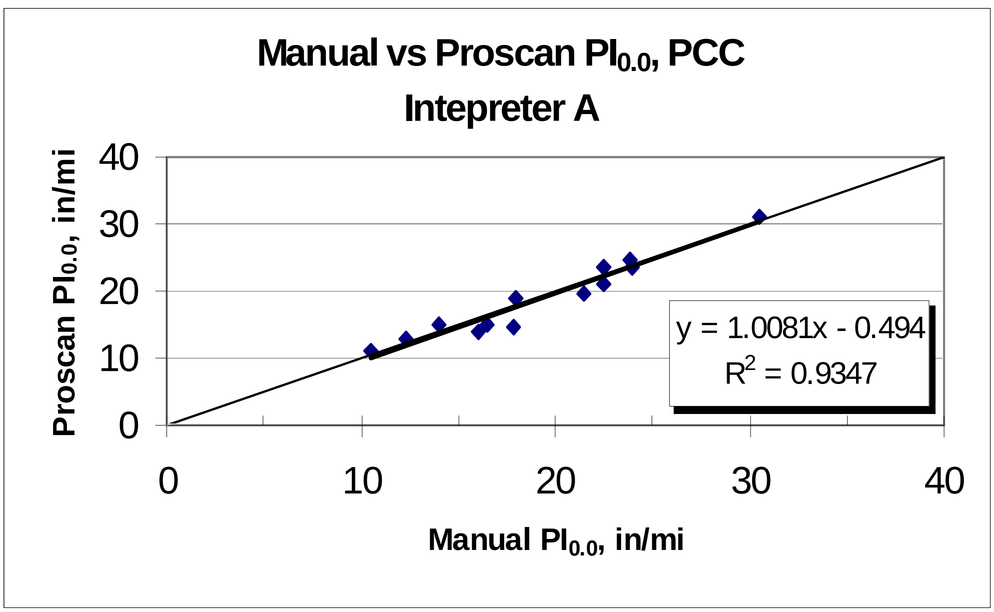

Figure 30. Manual vs. Proscan $PI_{0.0}$, PCC.

5.2 Comparison Between Automated and Manual $PI_{0.2}$

The Proscan analysis of the 0.2” blanking band trace reduction was compared to the manual analysis done by INDOT. In this case, there were 83 sections (I-74) for the HMA pavements and 15 sections (U-24) for PCC pavements that could be compared. The results showed poor correlation between the INDOT reductions and Proscan reductions with R^2 of 0.41 for the HMA and 0.05 for the PCC pavements, as shown in Figures 31 and 32. In both figures many data points are overlapping each other.

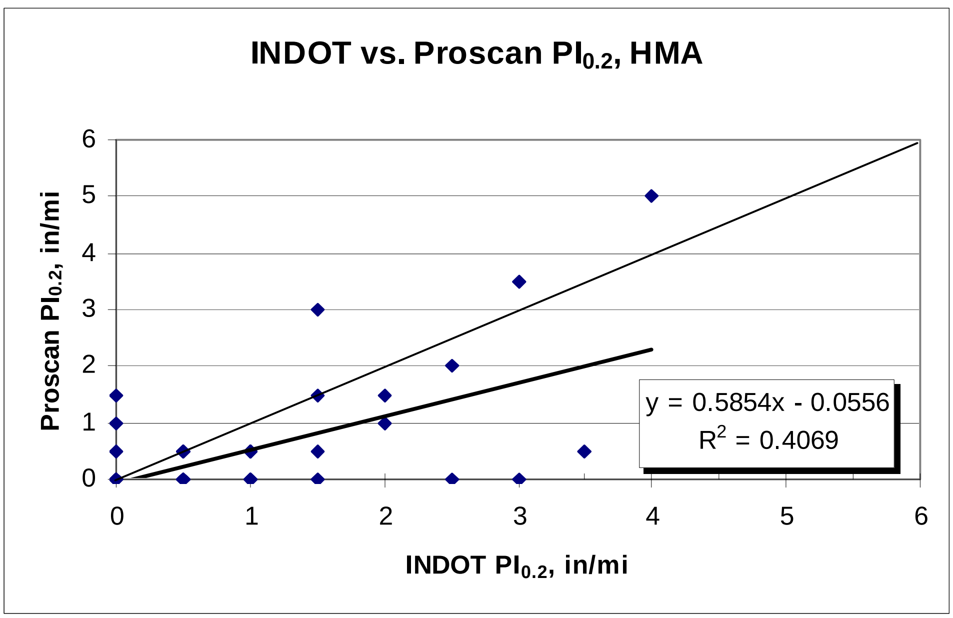

Figure 31. Manual vs. Proscan $PI_{0.2}$, HMA.

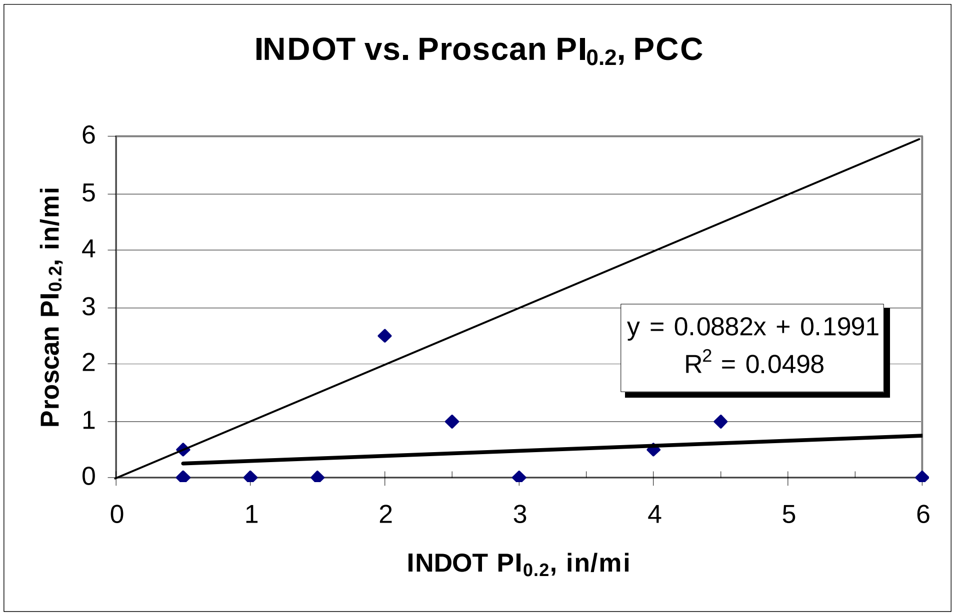

Figure 32. Manual vs. Proscan $PI_{0.2}$, PCC.

This analysis indicates that, in comparison with the 0.0" blanking band method, the correlations between manual and automated trace reduction results were poorer when the 0.2" blanking band method was applied. The poorer correlations may result from the following reasons:

1. In the Kansas DOT's procedure, which is used by the Proscan system, the trace is outlined by drawing a line through the middle of the spikes in the profilogram. When the outline has been drawn, the 0.2"blanking band is placed over the trace and deviations beyond the blanking band are then counted. Thus, some spikes that exceed the 0.2" limit may not be counted because their outline is covered within the blanking band. This method deviates from the method INDOT is using. The INDOT method

does not require to outline the trace hence it is likely that some spikes, which are left out using the Kansas method, are counted when the INDOT method is used. As a result, the INDOT $PI_{0.2}$ values are greater than the Proscan $PI_{0.2}$ values, as Figures 31 and 32 suggest.

2. The INDOT reduction procedures require the interpreter to “place the plastic scale over the profile in such a way as to blank out as much of the profile as possible”. This procedure is very subjective and the placement of the blanking band may cause differences for the reduction results due to the human error. On the other hand, the Proscan is placing the blanking band using the regression method, which is not affected by the subjective blanking band alignment.

6 ZERO BLANKING BAND SPECIFICATION DEVELOPMENT

6.1 Introduction

The development of the smoothness specification for the 0.0” blanking band was performed by converting the existing 0.2” blanking band specification to the 0.0” blanking band specification. The converted new specification was then compared to the existing 0.0” blanking band specifications used by other SHAs. The analysis used some assumptions and interpretations of the collected specification data, which may cause some inaccuracies to the comparisons. The “current” INDOT 0.2”-bb specification for the HMA pavements refers to the new INDOT specification introduced for the spring 2002 construction season.

Kansas DOT (KDOT) adopted the $PI_{0.0}$ smoothness specification about ten years ago. They have adjusted their specification over the years and are quite satisfied with their current specification (personal contact with Parcells (2002)). Therefore, the KDOT 0.0” and 0.2” blanking band PI specifications are used as reference to assess the current and proposed INDOT specifications. The other DOTs such as Minnesota and Wisconsin have just started to use the $PI_{0.0}$ smoothness specification in their pilot projects.

6.2 Comparison of $PI_{0.0}$ Smoothness Specifications of Several SHA’s

Some of the smoothness specifications introduced in Chapter 2 have dollar based incentives and disincentives, and some of the specifications are using percent of unit bid price. The conversions from dollar-based incentive and disincentive payments to the percent of contract unit bid price for the HMA and PCC pavements are based on the studies by Hossain, et al. (1995) and Hancock, et al. (2000), respectively. Therefore, $2,532 and

$15,000 were used as construction costs for each 0.1-mile HMA and PCC pavement sections, respectively. In Minnesota DOT's specifications, the highest incentive payment is limited to 10% of the unit bid price. Thus, the highest incentive for the specification was taken 110% and the calculations for the other payments were adjusted proportionally.

Figure 33 compares the HMA pavement smoothness specifications of five DOTs. The KDOT specifications have a much wider range for the full payment than the other states (10 to 40 in/mi with correction back to 30 in/mi when PI exceeds 30 in/mi). Also, KDOT specification is stricter for the bonus payments but more lenient for the penalty payments than the other specifications. However, KDOT applies a severe penalty, 92% of unit bid price, when the PI exceeds 40 in/mi.

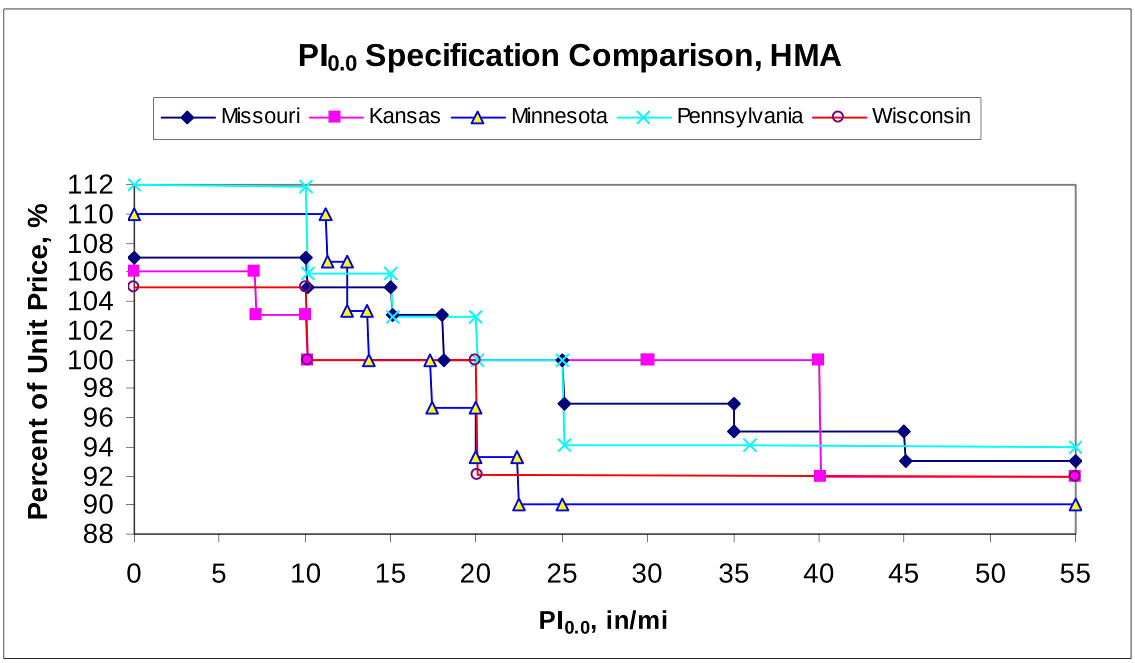

Figure 33. $PI_{0.0}$ Specifications Comparison, HMA.

Figure 34 shows the specification comparisons for the PCC pavements. Again, KDOT has a much wider range for the full payment (10 to 40 in/mi with correction back to 25 in/mi when exceeds 30 in/mi), and a more severe penalty, 92% of unit bid price, when the PI exceeds 40 in/mi. However, KDOT is willing to pay more bonuses for the PCC pavments when compared to the HMA pavements. This may suggest that, from KDOT's experience, smooth PCC pavement is harder to achieve compared to the HMA pavement and KDOT tries to encourage the PCC contractors to improve the smoothness of PCC pavements.

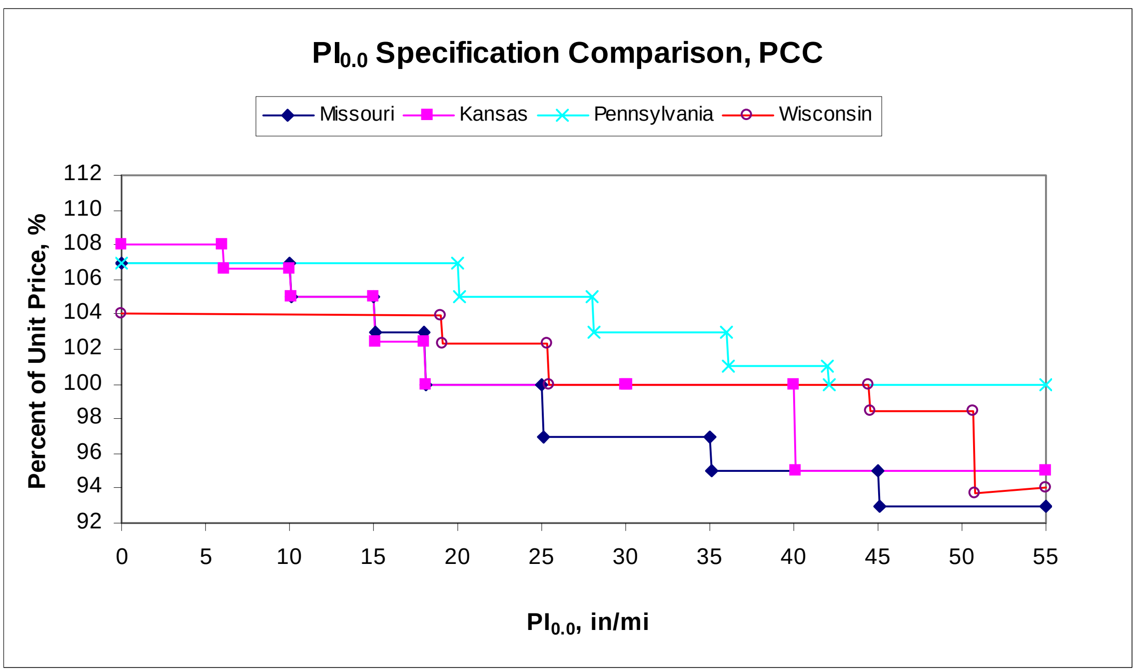

Figure 34. $PI_{0.0}$ Specifications Comparison, PCC.

6.3 Comparison between KDOT and INDOT Specifications

Figure 35 compares Kansas DOT's $PI_{0.0}$ specifications for the HMA and PCC pavements. Stricter limits are applied to the HMA pavements than PCC pavements, as noticed earlier. The KDOT is also willing to pay more bonuses for the PCC pavements than for the HMA pavements. Figure 36 compares Kansas DOT's $PI_{0.2}$ specifications and shows a similar trend in the policy.

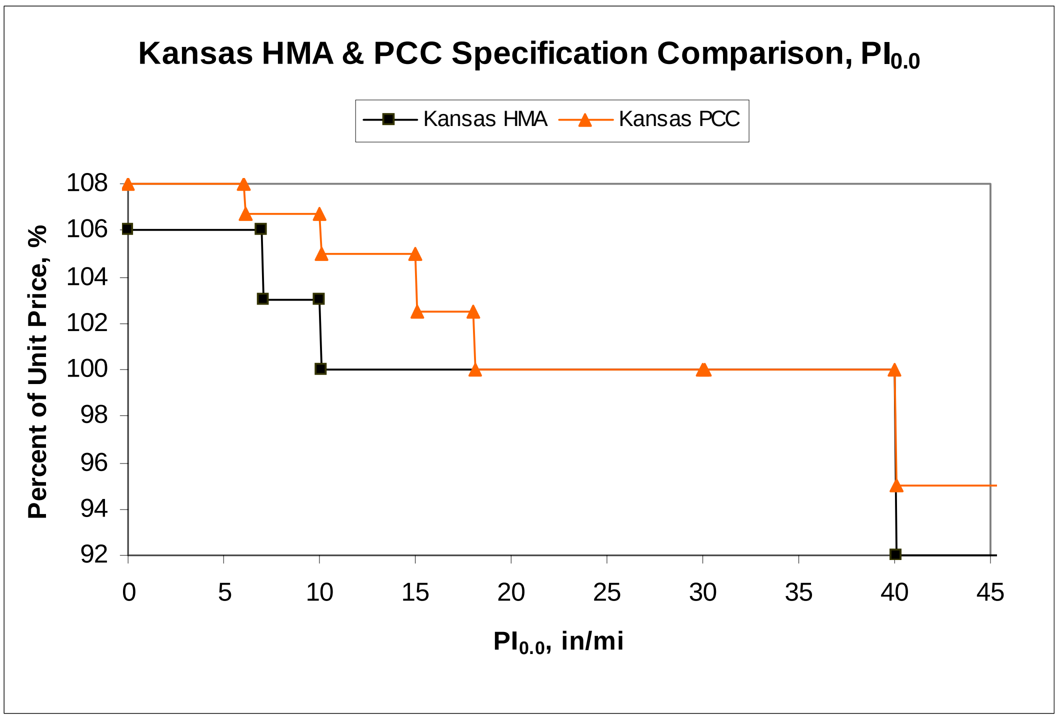

Figure 35. Kansas HMA and PCCP $PI_{0.0}$ Specification Comparison.

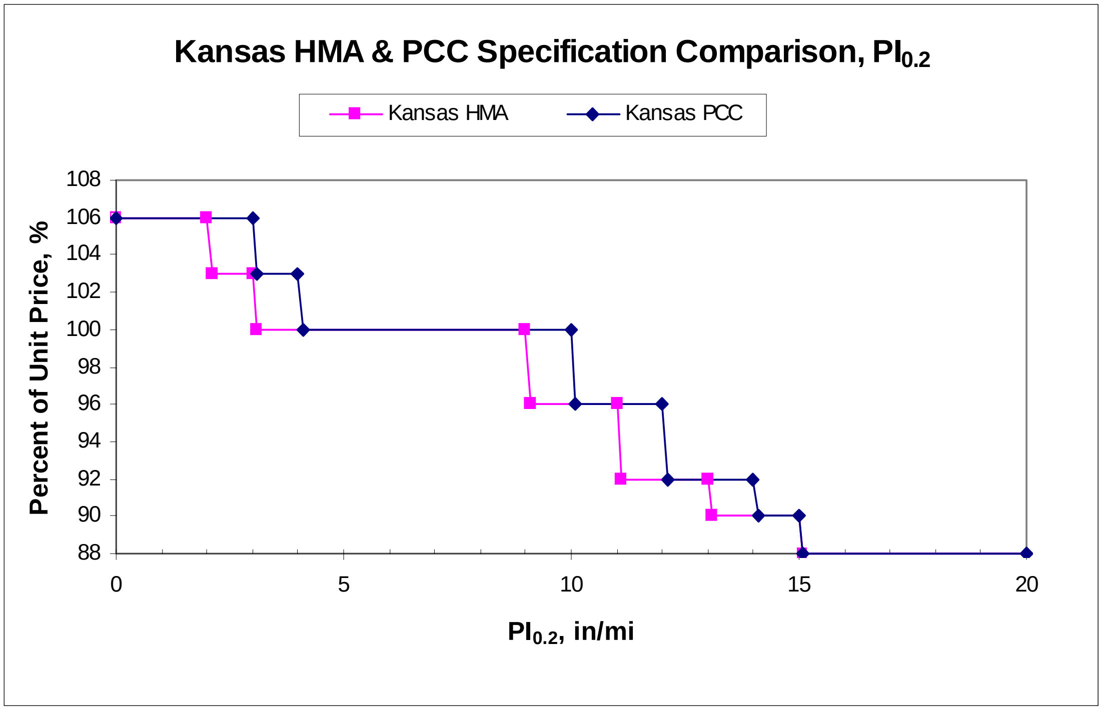

Figure 36. Kansas HMA and PCCP $PI_{0.2}$ Specification Comparison.

Figure 37 shows comparison of the INDOT 0.2"-bb specifications for the HMA and PCC pavements. Based on the analysis, INDOT is willing to pay more bonuses for the HMA pavements at certain instances: For a PI value lower than 4 in/mi, up to 105% of unit price will be paid to the HMA pavements but only 103% will be paid for the PCC pavements. However, INDOT does not apply penalties to the rough PCC pavements, but contractors need to correct sections that exceed 12 in/mi, which is similar to KDOT specifications.

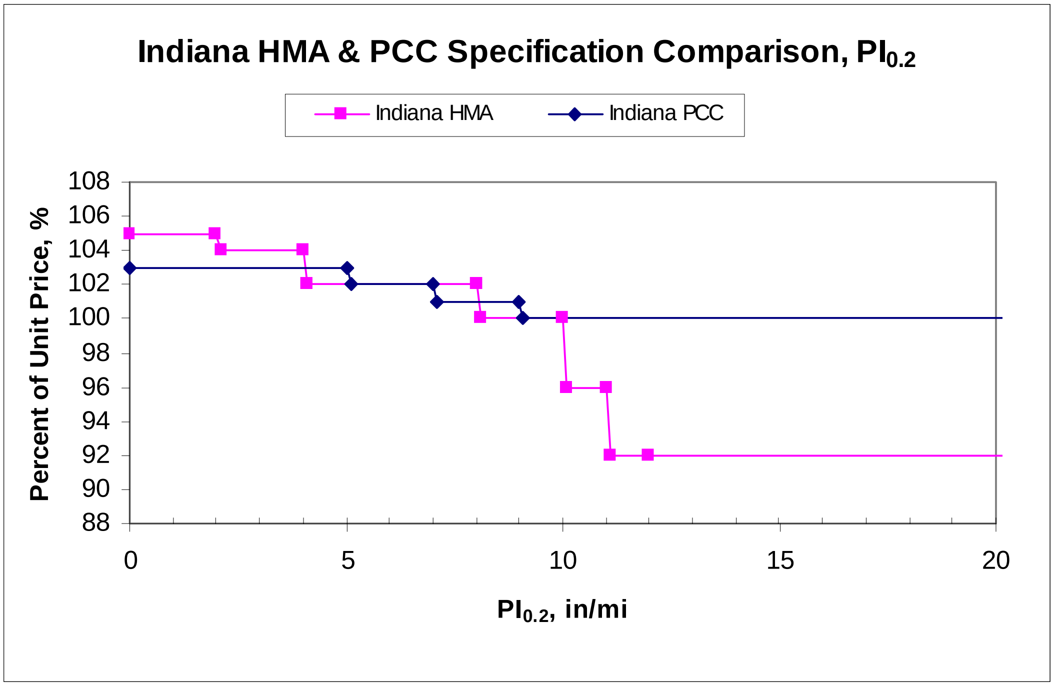

Figure 37. Indiana HMA and PCCP $PI_{0.2}$ Specification Comparison.

Figures 38 and 39 compare the $PI_{0.2}$ specifications between INDOT and KDOT for HMA and PCC pavements. The current INDOT specifications seem to be more lenient for the "average" and very rough pavements compared to the specifications which were used in Kansas about ten years ago. However, as the comparison of the manual and Proscan analysis of Proifilograph traces indicated the differences in the analysis procedures between these two states may explain some of the differences in the computed PI values. Based on a very limited dataset, the INDOT trace reduction procedure tends to produce higher PI values than the KDOT procedure. Therefore, the actual applied smoothness policies may be closer than the figures indicate.

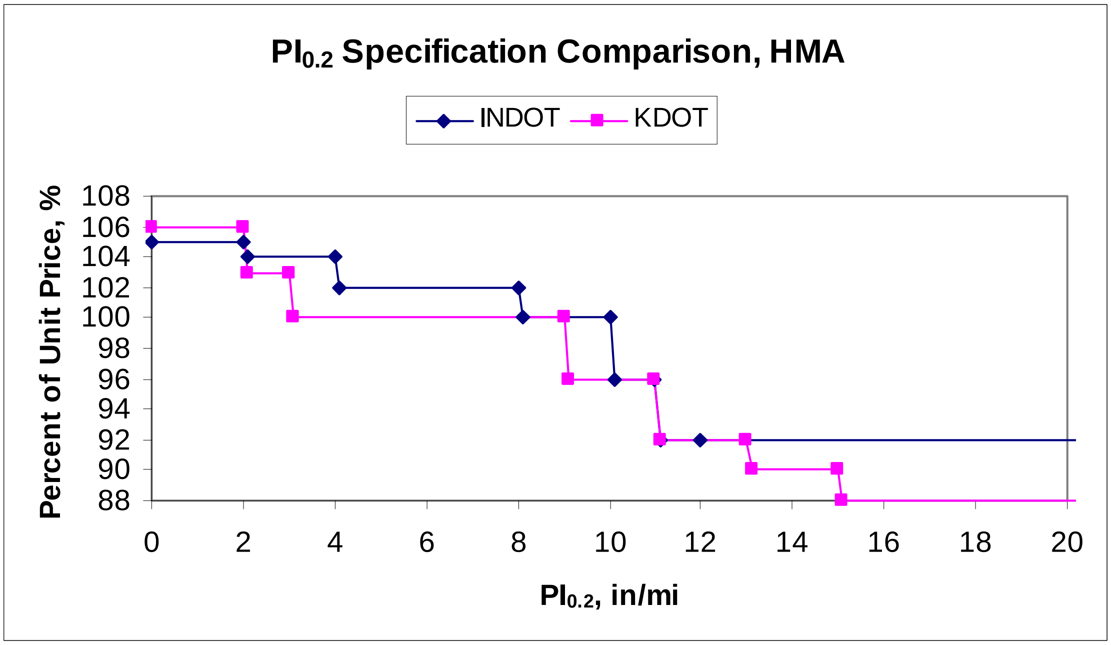

Figure 38. $PI_{0.2}$ Specification Comparison Between KDOT and INDOT, HMA.

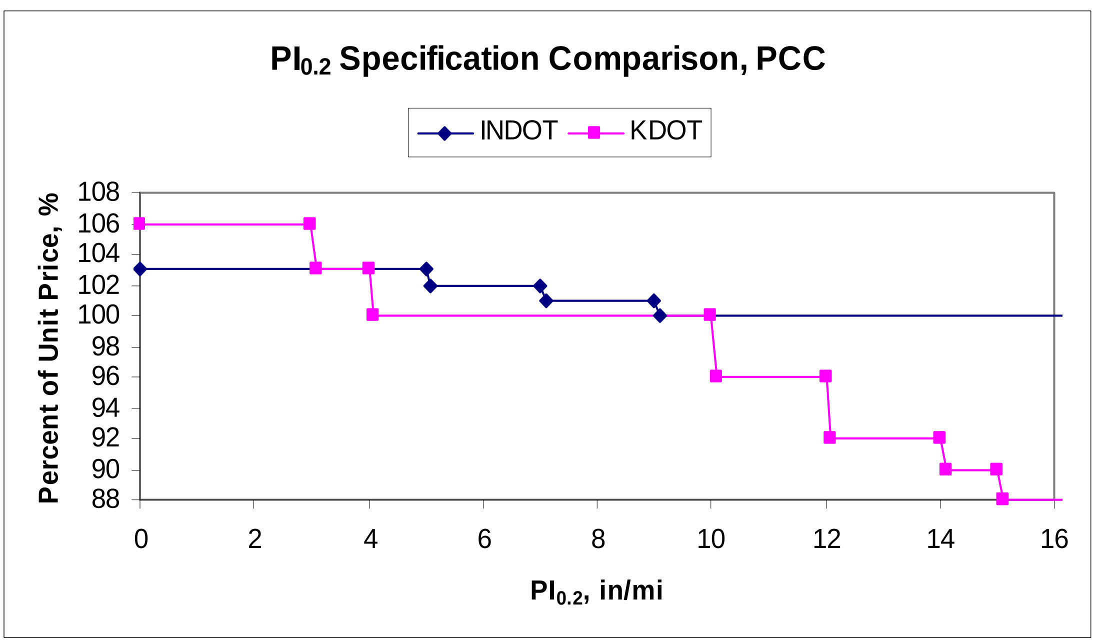

Figure 39. $PI_{0.2}$ Specification Comparison Between KDOT and INDOT, PCC.

6.4 Adopted Conversion Models

The smoothness specification conversions from the 0.2” blanking band to the 0.0” blanking band have been done by using different conversion models described in Chapter 2. These models were used because there was not enough data to do statistical conversions.

Tables 28 and 29 list the conversion equations used in the analysis. The smoothness data presented in the study by Mondal et al. (2000) was analyzed and the conversion equations between $PI_{0.2}$, $PI_{0.0}$, and IRI were established for both the HMA (Equations C-1-C-3) and PCC pavements (Equations C-7-C-9). The measured IRI test data have been obtained using the INDOT Rip Van. Also, conversion equations of $PI_{0.2}$ - $PI_{0.0}$ (Equations C-1 for HMA and C-10 for PCC) developed in Chapter 3 using the study data were used in the analysis. The conversion equations developed by Hoerner et al. (2000) using LTPP smoothness data (Equations C-4 and C-5) were only used for the PCC pavements. Tables 28 and 29 also show the goodness of fit of the data and data range used to develop the relationships. The large data range usually gave better correlations between variables. However, the good correlation does not indicate that the model is better because with a narrow range of smoothness data the correlation should not be good if the 0.0” blanking band is a better roughness index than the 0.2” blanking band.

Table 28. Conversion Equations for the HMA Pavements.

Eq.	Conversion Equations (HMA)	R^2	Reference	Data Range (in/mi)
C-1	$IRI = 2.855\ PI_{0.2} + 43.661$	0.95	Mondal et al. (2000)	1-56 ($PI_{0.2}$)
C-2	$IRI = 2.440\ PI_{0.0} + 20.564$	0.89	Mondal et al. (2000)	5-69 ($PI_{0.0}$)
C-3	$PI_{0.0”} = 1.083\ PI_{0.2} + 11.515$	0.91	Mondal et al. (2000)	5-69 ($PI_{0.0}$)
C-4	$PI_{0.0”} = 2.763\ PI_{0.2} + 7.084$	0.55	Study Data	5.5-13.5 ($PI_{0.0}$)

Table 29. Conversion Equations for the PCC Pavements.

Eq.	Conversion Equations (PCC)	R^2	Reference	Data Range (in/mi)
C-5	$IRI = 2.625\ PI_{0.2} + 75.541$	0.76	Hoerner et al. (2000)	0-112 ($PI_{0.2}$)
C-6	$IRI = 2.233\ PI_{0.0} + 25.557$	0.80	Hoerner et al. (2000)	10.24-147.2 ($PI_{0.0}$)
C-7	$IRI = 2.094\ PI_{0.2} + 57.781$	0.91	Mondal et al. (2000)	0-49 ($PI_{0.2}$)
C-8	$IRI = 1.535\ PI_{0.0} + 31.923$	0.88	Mondal et al. (2000)	11-84 ($PI_{0.0}$)
C-9	$PI_{0.0"} = 1.344\ PI_{0.2} + 17.112$	0.99	Mondal et al. (2000)	11-84 ($PI_{0.0}$)
C-10	$PI_{0.0"} = 1.976\ PI_{0.2} + 15.680$	0.39	Study Data	11-24.5 ($PI_{0.0}$)

6.5 Conversion Models vs. Kansas Specifications

Figures 40 and 41 show the developed conversions using the equations presented in Tables 28 and 29. The applicability of conversions was judged by comparing them to the conversion curve of the KDOT $PI_{0.2}$ versus $PI_{0.0}$ specification. This conversion curve was developed by correlating the pay factors of the 0.0" and 0.2" blanking band scales to obtain the "actual" bonus/penalty relation between the two specifications. Thus, the relationship of the KDOT conversion is not based on the correlation of measured data.

For the HMA pavements, the $PI_{0.0}$ conversion obtained from the study data equation is closest to the Kansas conversion. The other conversion models seem to underpredict the $PI_{0.0}$ values significantly at roughness levels above 15 in/mi. For the PCC pavements, the slope of the study data seems to follow the Kansas conversion curve the best. Again, the other conversion models seem to underpredict the $PI_{0.0}$ values above 35 in/mi. Therefore, conversion equations derived from the study data were selected for both pavement types to convert the current Indiana $PI_{0.2"}$ specifications into a new $PI_{0.0}$ specification.

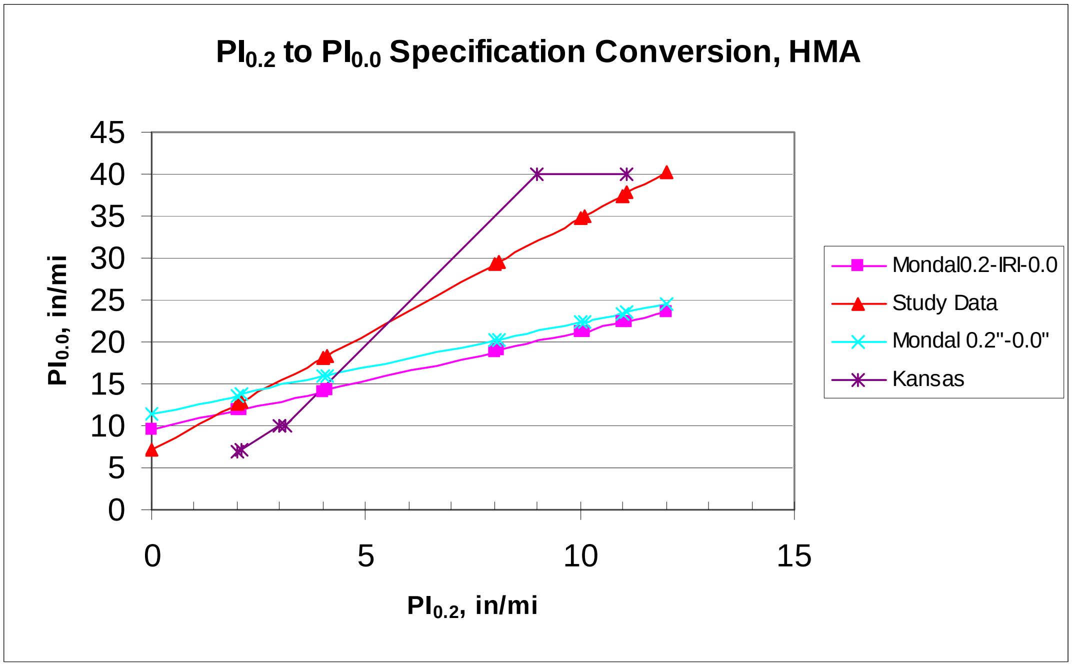

Figure 40. $PI_{0.2}$ to $PI_{0.0}$ Specification Conversion, HMA.

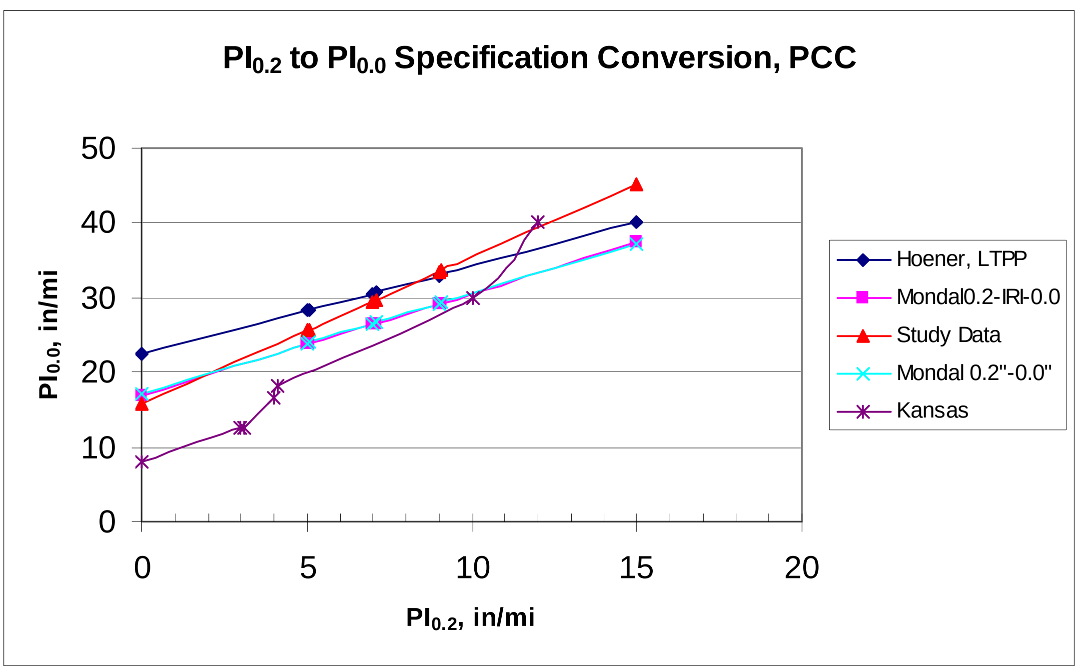

Figure 41. $PI_{0.2}$ to $PI_{0.0}$ Specification Conversion, PCC.

Figures 42 and 43 show the upper and lower 95% confidence interval (CI) limits for the conversion models based on the CI limits for the intercept of the regression model. Thus, figures do not present confidence interval for a line as whole, but a variation of the regression line as a function of the intercept. For the PCC pavements, the closest match to the KDOT conversion models is the lower 95% confidence limit curve. For the HMA pavements, the KDOT conversion data is crossing both confidence limits. It also crosses the 99.9% confidence interval curves of INDOT data at 18 and 30 in/mi in the 0.0”-bb scale. This pattern indicates that the actual measured correlation needs to be adjusted to develop conversion that agrees with the riding comfort, because fundamentally the data should not correlate at low roughness levels.

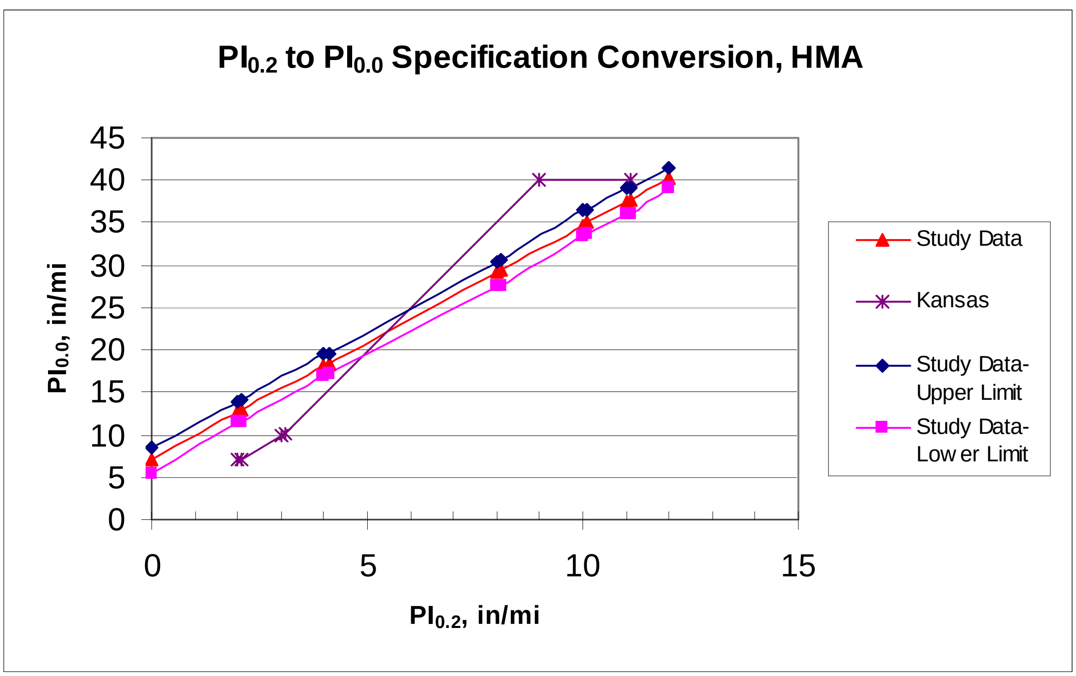

Figure 42. $PI_{0.2}$ to $PI_{0.0}$ Specification Conversion, HMA. (Kansas, Study Data, Study Data with 95% Confidence Interval)

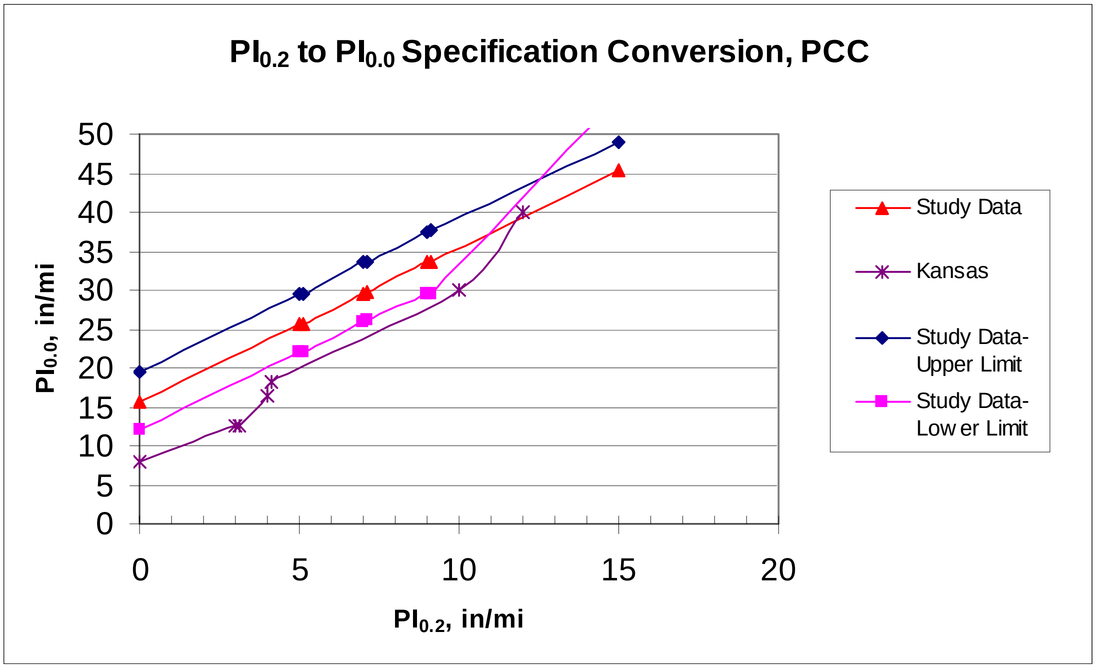

Figure 43. $PI_{0.2}$ to $PI_{0.0}$ Specification Conversion, PCC. (Kansas, Study Data, Study Data with 95% Confidence Interval)

6.6 Comparison of Converted INDOT Specification to Other Specifications

The conversion equations obtained from the study data as well as its 95% CI for the intercept were chosen to convert the current Indiana $PI_{0.2}$ specifications into the $PI_{0.2}$ limits. The developed conversion was compared to the KDOT and other specifications. Figure 44 shows the comparison with the KDOT specification for the HMA pavements. The upper CI limit in the "penalty range" and lower CI limit in the bonus range are closest to the KDOT conversion. The compliance of the lower CI limit at bonus range indicates that KDOT is trying to minimize its risk to pay too many bonuses. The compliance of the upper CI limit indicates that KDOT is trying to minimize the risk of penalizing the contractor of an acceptable work. This means that the KDOT may be taking more risk of accepting poorer quality pavements with full pay than paying bonuses for marginally smooth pavements.

Figure 45 indicates that the lower CI limits are closer to the KDOT limits than the upper CI limits for the PCC pavements. This shows that KDOT is trying even more to minimize the risk of paying too many bonuses for marginally smooth PCC pavements. Also, the risk of penalizing a contractor for acceptable work is lower than that for the HMA pavements. In general, the differences in the smoothness policies between INDOT and KDOT are showing in the two ends of penalty and bonus ranges where the specifications deviate the most.

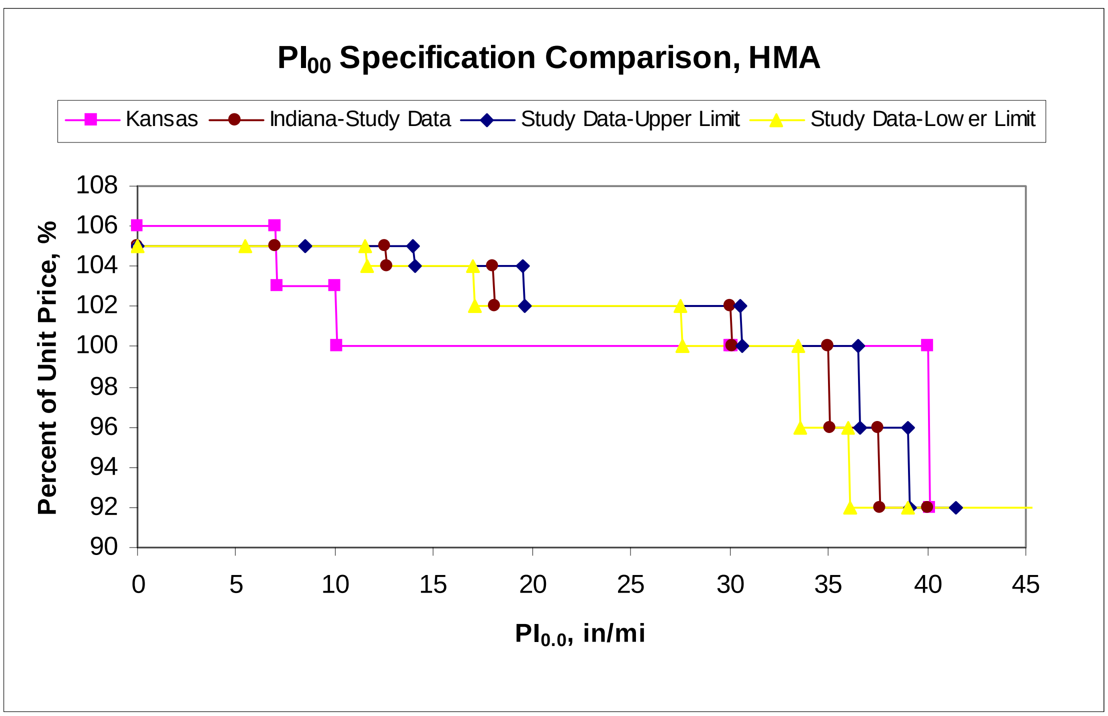

Figure 44. KDOT vs. INDOT $PI_{0.0}$ Specification, HMA.

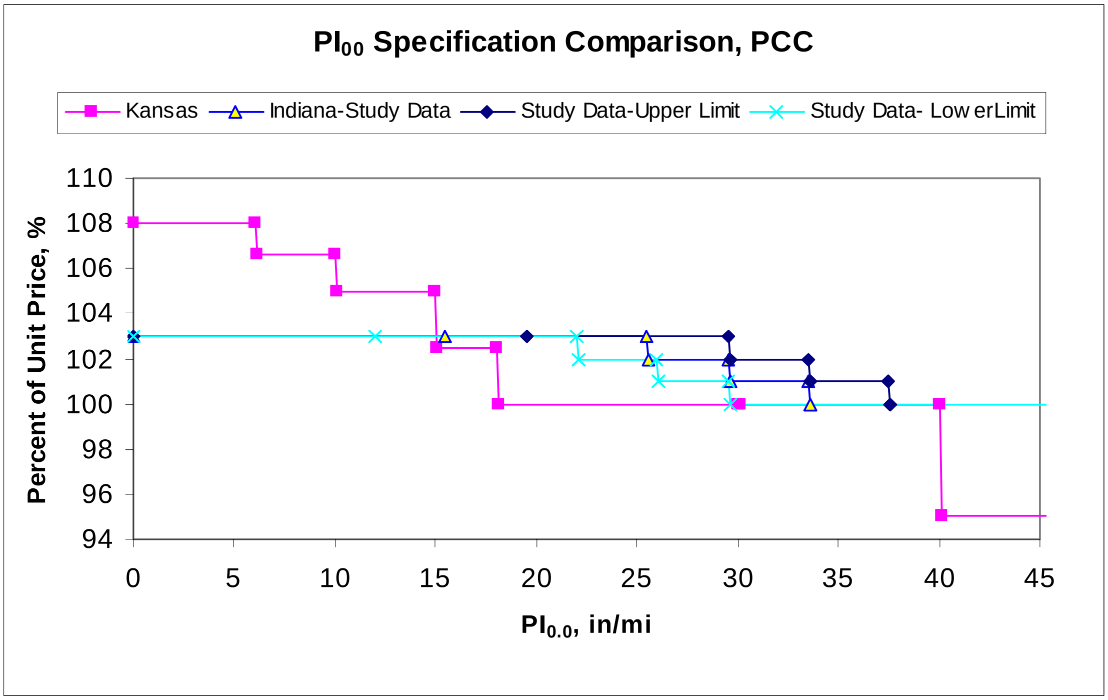

Figure 45. KDOT vs. INDOT $PI_{0.0}$ Specification, PCC.

Based on the above analysis, it was decided to select both the lower and upper 95% CI curves to form the converted 0.0" blanking band smoothness specification. The lower CI was used in the "bonus range" and the upper CI was used in the "penalty range". This also increased the full pay range for the specification to follow the KDOT model of minimizing risk of paying too many bonuses for marginally smooth pavements and penalizing a contractor for an acceptable work.

Figures 46 and 47 compare the KDOT and the converted INDOT $PI_{0.0}$ specifications for the HMA and PCC pavements. The converted INDOT specification is more lenient than the KDOT specification in the bonus side for the average smooth pavements and is slightly stricter at the penalty side for the HMA pavements. For the PCC pavements, the converted

INDOT specification is more lenient, except for very smooth pavements (PI smaller than 10 in/mi).

Figures 48 and 49 compare the INDOT $PI_{0.0}$ specifications to the other specifications. Overall, the INDOT specification for the HMA pavements seems to be more lenient on the bonus side for the average smooth pavements compared to the other specifications. Although the bonus cut off value is the lowest compared to the other specifications, this policy may end up having INDOT pay more bonuses if the smoothness data is assumed to follow the normal distribution. Also, the penalty range seems to be on the lenient side compared to the other specifications. The converted specification for the PCC pavements seems to be more in agreement with the other specifications.

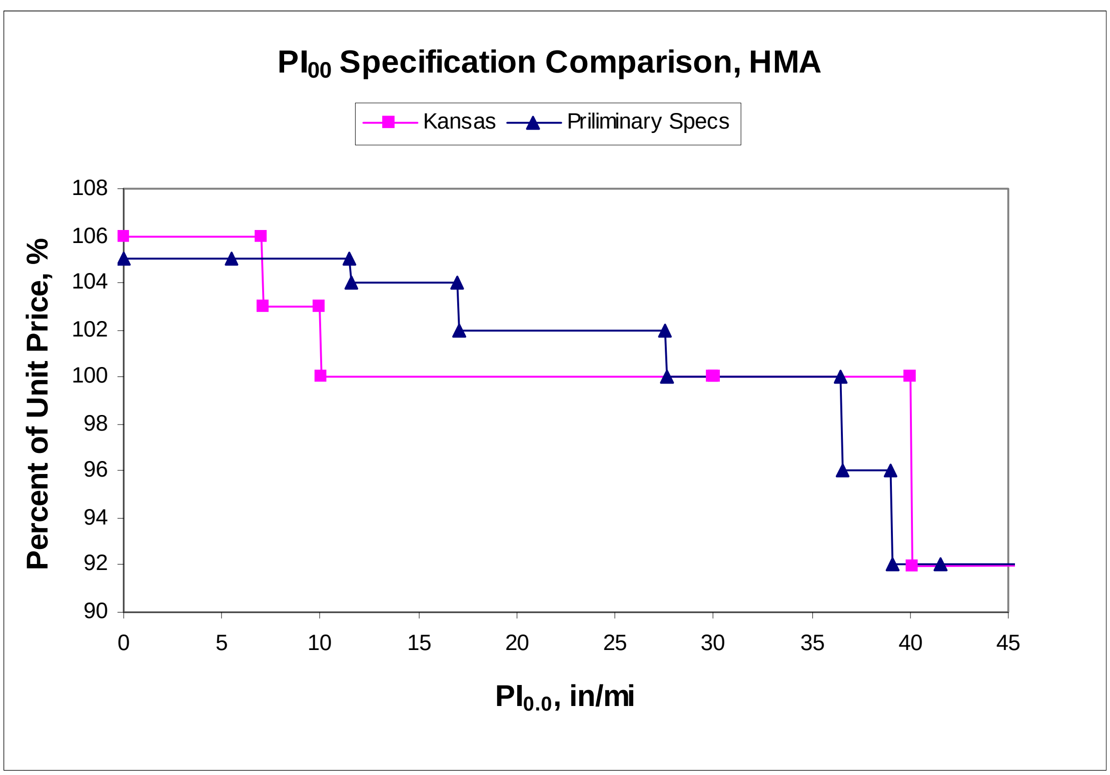

Figure 46. Comparison Between KDOT and Converted INDOT $PI_{0.0}$ Specification, HMA.

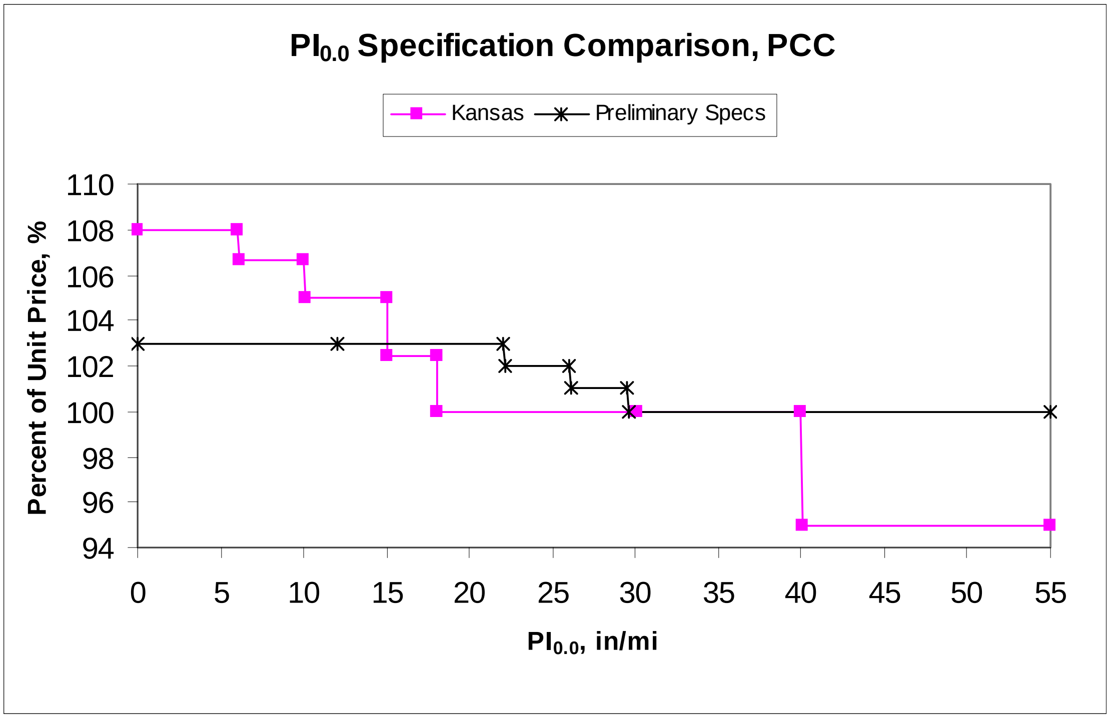

Figure 47. Comparison Between KDOT and Converted INDOT $PI_{0.0}$ Specification, PCC.

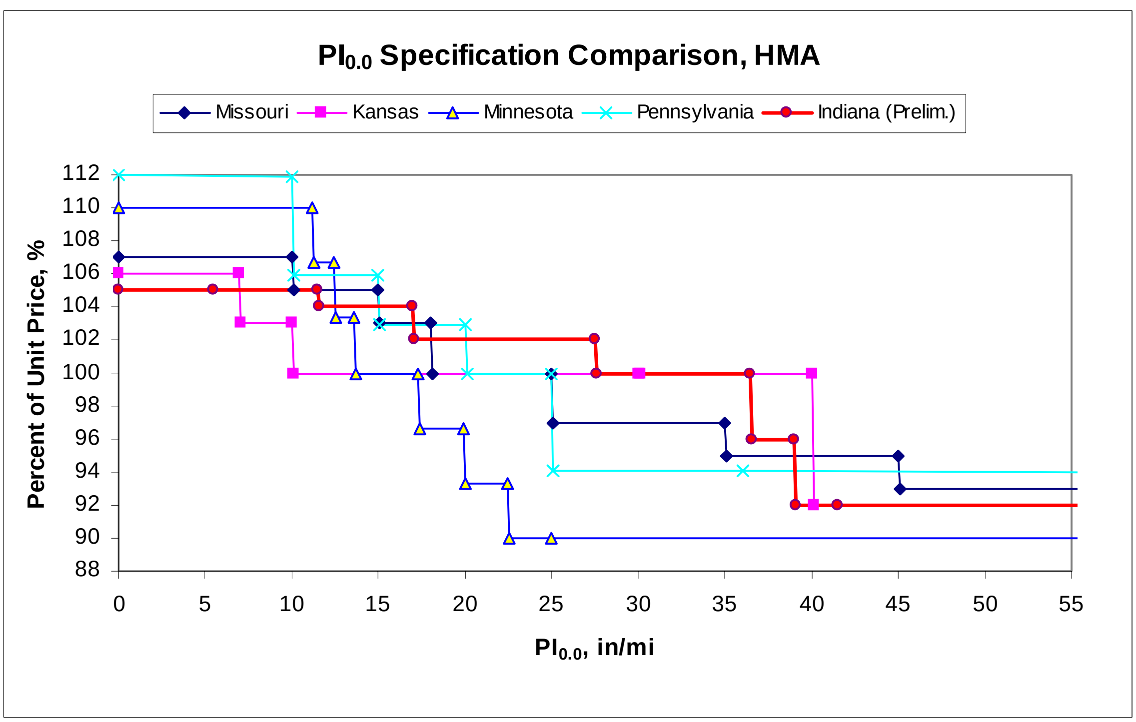

Figure 48. Comparison of INDOT and Other $PI_{0.0}$ Specifications, HMA.

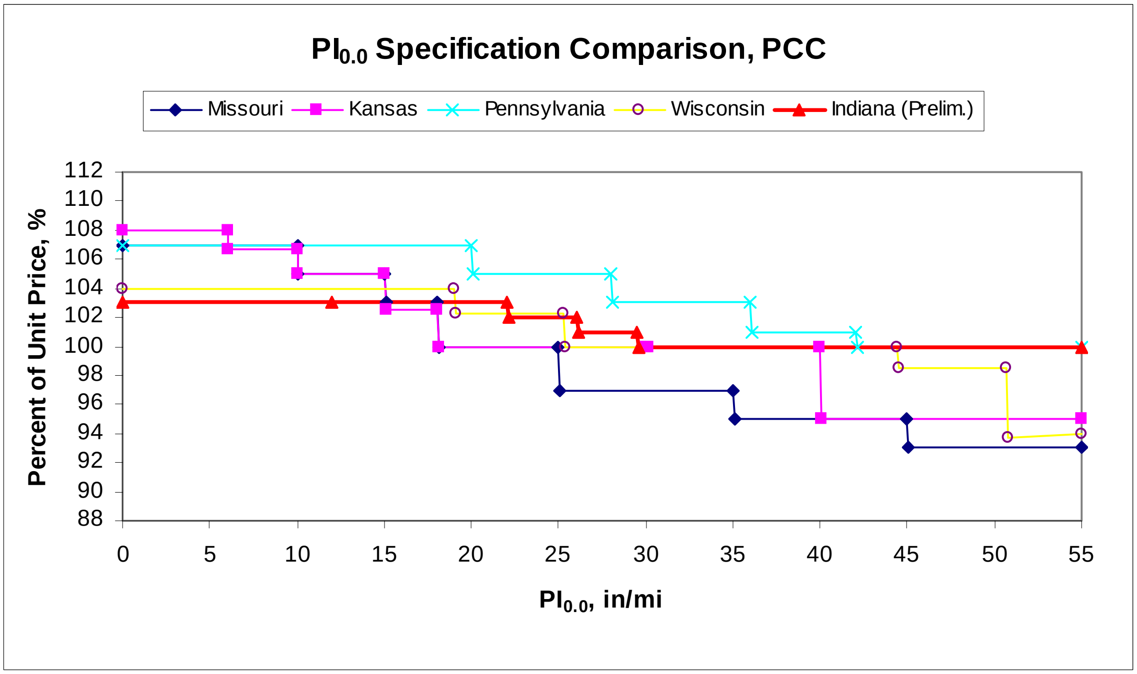

Figure 49. Comparison of INDOT and Other $PI_{0.0}$ Specifications, PCC.

Figure 49 also shows how the converted PCC specification compares to the specification that was developed by Mondal et al. (2002). They used lightweight profilographs to measure and calculate the 0.0" blanking band PI values. The specification they were proposing is more lenient for paying high bonuses when the PI value is less than 10 in/mi, but is tougher for applying penalties in the PI range of 15 to 30 in/mi compared to the current proposed specification. Again, if the smoothness data follows the normal distribution the Mondal et al. specification may end up paying fewer bonuses for the same smoothness level.

6.7 Smoothness Specification Benefits

According to the study from Smith et al. (1997), an increase in smoothness ($PI_{0.2}$) from 7 to 5 in/mi for the PCC and 5 to 3.5 in/mi for the HMA pavements could yield at least a 9% increase in pavement life. The study also suggested that an approximate increase in smoothness from $PI_{0.2}$ of 7 to 3.5 in/mi for the PCC and 5 to 2.5 in/mi for the HMA pavements could yield at least a 15% increase in pavement life. Tables 30 and 31 compare the current bonus policies between INDOT and KDOT in these two specific PI ranges.

For the HMA pavements, the results show that no bonuses are paid to achieve from 5 to 3.5 in/mi (9% pavement life increase) smoothness increase in Kansas, but in Indiana contractors are paid bonuses to achieve this smoothness and, thus, increase in pavement life. The same observations apply to the 15% increase in pavement life as the smoothness increases from 5 to 2.5 in/mi. Similar results can also be observed in the PCC pavement specifications.

Table 30. Bonus Policy Between INDOT and KDOT in Two Specific PI Ranges, HMA.

$PI_{0.2}$	5-3.5 in/mi		5-2.5 in/mi	
DOT	IN	KS	IN	KS
Bonus Increase	102 to104%	100 to100%	102 to104%	100 to103%
Life Increase	9%	9%	15%	15%

Table 31. Bonus Policy Between INDOT and KDOT in Two Specific PI Ranges, PCC

$PI_{0.2}$	7-5 in/mi		7-3.5 in/mi	
DOT	IN	KS	IN	KS
Bonus Increase	102 to103%	100 to100%	102 to103%	100 to103%
Life Increase	9%	9%	15%	15%

6.8 Converted $PI_{0.0}$ Smoothness Specification

Based on the analysis in the previous sections, Table 32 shows the converted smoothness specification for the HMA pavements, and Table 33 shows the converted smoothness specification for the PCC pavements. These specifications have been developed by converting INDOT $PI_{0.2}$ smoothness specification to the $PI_{0.0}$ smoothness specification using conversion equations developed with a very limited data set provided by INDOT. The converted specifications do not include any policy changes for the INDOT smoothness evaluation. However, based on the comparisons of the converted specifications to other specifications, some policy changes can be formulated. Also, when more $PI_{0.0}$ smoothness data becomes available the need for adjusting the specifications can be assessed. The bump specification will be the same for both the $PI_{0.0}$ and $PI_{0.2}$ blanking band smoothness specifications.

Table 32. Converted $PI_{0.0}$ Smoothness Specification for the HMA Pavements.

$PI_{0.0}$, in/0.1mile	$PI_{0.0}$, mm/0.16km	% of Unit Price
0.00-1.15	0.0-29.0	105
1.16-1.70	29.1-42.5	104
1.71-2.75	42.6-69.0	102
2.76-3.65	69.1-91.5	100
3.66-3.90	91.6-97.5	96
≥3.91	≥ 97.6	92 /correct back to 3.65 in/0.1mi (91.5 mm/0.16km)

Table 33. Converted $PI_{0.0}$ Smoothness Specification for the PCC Pavements.

$PI_{0.0}$, in/mile	$PI_{0.0}$, mm/0.16km	% of Unit Price
0.00-2.20	0.0-55.0	103
2.21-2.60	55.1-65.0	102
2.61-2.99	65.1-72.5	101
3.00	72.6-97.5	100
≥3.01	≥ 97.6	Correct back to 3.0 in/0.1mi (97.5 mm/0.16km)

7 ZERO BLANKING BAND SPECIFICATION VERIFICATION

Pavement smoothness of several recently completed paving projects was measured for the verification. The converted $PI_{0.0}$ as well as the current $PI_{0.2}$ smoothness specifications was applied to the measurement results and further modifications of the specification was also recommended based on the pay factor analysis.

7.1 Field Testing

Two smoothness measuring devices, California Profilograph and Ames Lightweight Profiler, were used to perform the field testing. The California Profilograph is currently used as the standard measurement tool in the INDOT smoothness specification. The lightweight profiler could provide nearly instantaneous smoothness measurement and calculate Profile Index and IRI. These two indices generated by the lightweight profiler were used to provide the comparative analysis with PI reduced from the Profilograph traces.

The field measurements were done November 20, 2002 in the test sites in US 52, SR 18, US 231. The test site in SR 71 was measured in the next day. Table 34 gives information about geometric and general pavement conditions at each test site. All measurements were made in the right wheel path. Test data is shown in Appendix E.

Table 34. Selected Sites for Smoothness Verification Measurements.

Pavement Type	Route	Location	Geometric Condition	Pavement Condition	Speed Limit
HMA	US 52	South Bound Driving Lane, (19+00-22+00)	No grade, Continuous curve	Approximately 4 months old, No visual distress	55 mph
HMA	SR 18	East Bound Driving Lane, (29+62-33+02)	No grade, Continuous curve	Approximately 2 months old, No visual distress	55 mph
HMA	SR 71	East Bound Driving Lane, (220+63-415+99)	Significant uphill and downhill grade, Curve through last 500ft.	Approximately 2 months old, No visual distress	55 mph
PCCP	US 231	North Bound Driving Lane, (285+00-332+52)	No grade, Continuous curve	Approximately 16 months old *, No visual distress	45 mph

* Profilograph measurement was done right after the paving construction by the contractor. LISA measurement was performed in this field testing.

California Profilograph

A California Profilograph manufactured by Ames Engineering, shown in Figure 50, was used in this field testing. It is a manual device owned and operated by INDOT. The system consists of a total of 6 wheels used to support each end of the device. The 25 ft beam portion is a 2 in by 6 in aluminum box channel. A profile wheel is located at its midpoint and a non-contact transducer system transmits movement of the profile wheel to a recorder located at the rear end of the unit. It provides strip chart output at the end of the measurement and shows the profilogram trace. The Profilograph was tested and certified by the INDOT Division of Material and Tests prior to its use on this project. A rolling wheel was used for distance measurement so that every 100 feet can be identified and marked on the profilogram.

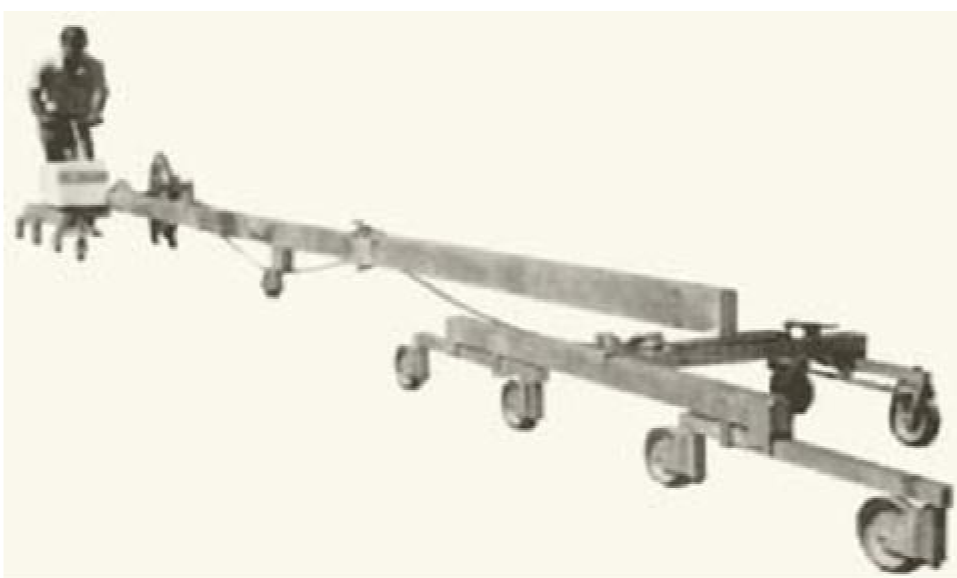

Figure 50. California Profilograph.

Ames Lightweight Profiler (LISA)

A Lightweight Internal Surface Analyzer (LISA) manufactured by Ames Engineering Inc., Figure 51, was also used to measure the road profile. The LISA was provided by Rieth Riley construction company and the measurement was conducted by its personnel. The instrument uses a John Deere four-wheel Gator vehicle to move the laser over the pavement surface and uses an accelerometer and vertical distance sensor to measure the profile. The wavelengths it measures are from 1.8 to 120 feet and the operating speed is from 8 to 12 miles per hour. The output from the LISA can display the profile and automatically locate any bumps and dips and pinpoint their location on the pavement. Several different indices such as IRI, PI with 0.0" or 0.2" blanking band, Ride Number (RN), and Ride Quality Index (RQI) can be calculated using the same data.

Figure 51. Ames Lightweight Profiler (LISA) (Ames Engineering Inc.).

7.2 Profilograph Data Analysis Results

In this section, Profilograph traces were reduced manually using both 0.0” and 0.2” blanking band for each project. The proposed INDOT $PI_{0.0}$ smoothness specification and current $PI_{0.2}$ specification as well as KDOT smoothness specification were then applied to the reduction results to make pay factor comparisons.

7.2.1 Correlation between $PI_{0.2}$ and $PI_{0.0}$ Reduction Results

Analysis included 94 0.1-mile HMA sections with 26 sections in SR 52, 31 sections in SR 18, 37 sections in SR 71, and 9 PPC in US 231. Table 35 summarizes the reduction results for these 4 projects.

The correlation between PI values reduced by 0.2” and 0.0” blanking band was poor for the HMA projects. Correlation coefficient (R^2) was 0.29, 0.09, and 0.45 for SR 52, SR 18, and SR 71 respectively, and 0.23 for the total of 94 sections, as shown in Figures 52 to 55. This shows that the 0.2” blanking band method indeed covers the small irregularities that are detected by the 0.0” blanking band.

Figure 56 shows the correlation between 0.2” and 0.0” bb reduction results for the PCC pavement. The correlation coefficient was $R^2 = 0.82$. The measured PCCP profile was rougher (with average $PI_{0.0}$ of 32.94 and $PI_{0.2}$ of 10.20) that the HMA profiles, which increases the possibility of obtaining similar PI values.

Table 35. Summary of Reduction Results.

	$PI_{0.2}$ (in/mi)				$PI_{0.0}$ (in/mi)			
Roadway	Average	St.Dev	Max.	Min.	Average	St.D	Max.	Min.
US 52 (HMA)	1.92	1.57	6.00	0.00	15.03	3.46	22.50	7.50
SR 18 (HMA)	1.73	1.78	7.50	0.00	15.37	3.58	23.50	10.00
SR 71 (HMA)	5.12	2.64	10.00	0.50	16.05	3.71	25.00	8.50
US 231(PCCP)	10.20	13.70	45.00	0.50	32.94	15.03	70.50	17.00

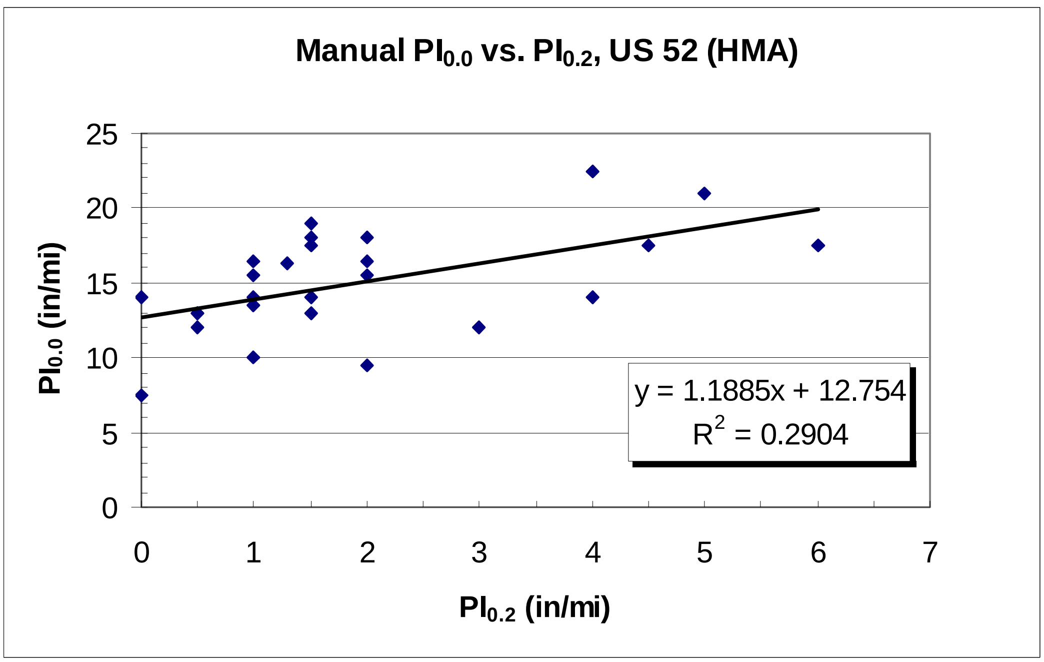

Figure 52. Comparison between Manual $PI_{0.0}$ and $PI_{0.2}$ Reduction Results, US 52.

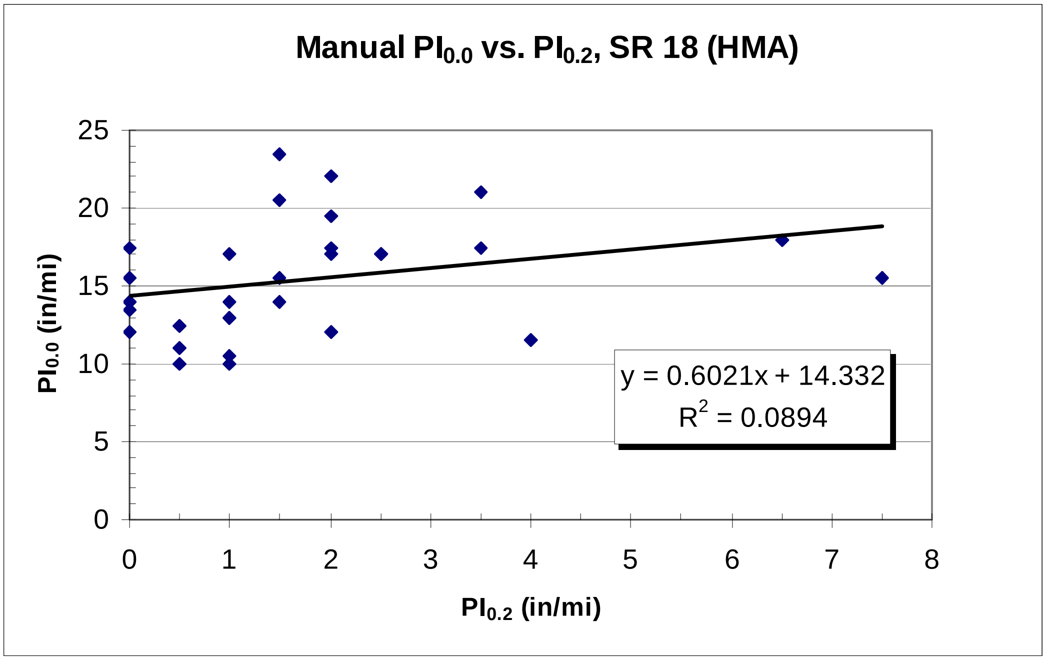

Figure 53. Comparison between Manual $PI_{0.0}$ and $PI_{0.2}$ Reduction Results, SR 18.

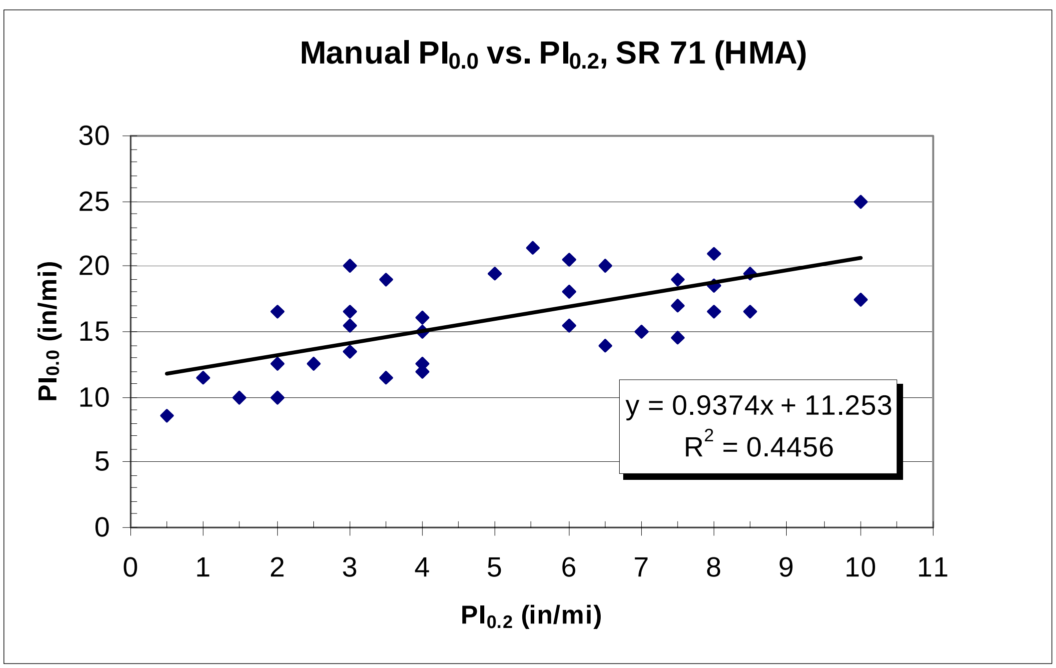

Figure 54. Comparison between Manual $PI_{0.0}$ and $PI_{0.2}$ Reduction Results, SR 71.

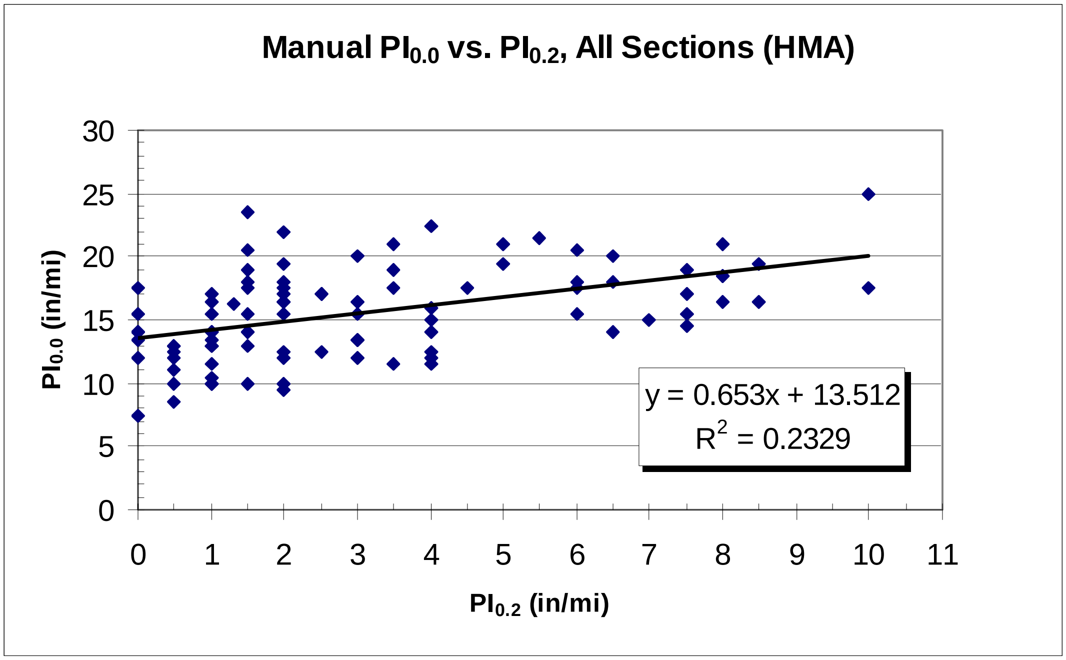

Figure 55 Comparison between Manual $PI_{0.0}$ and $PI_{0.2}$ Reduction Results, All Sections.

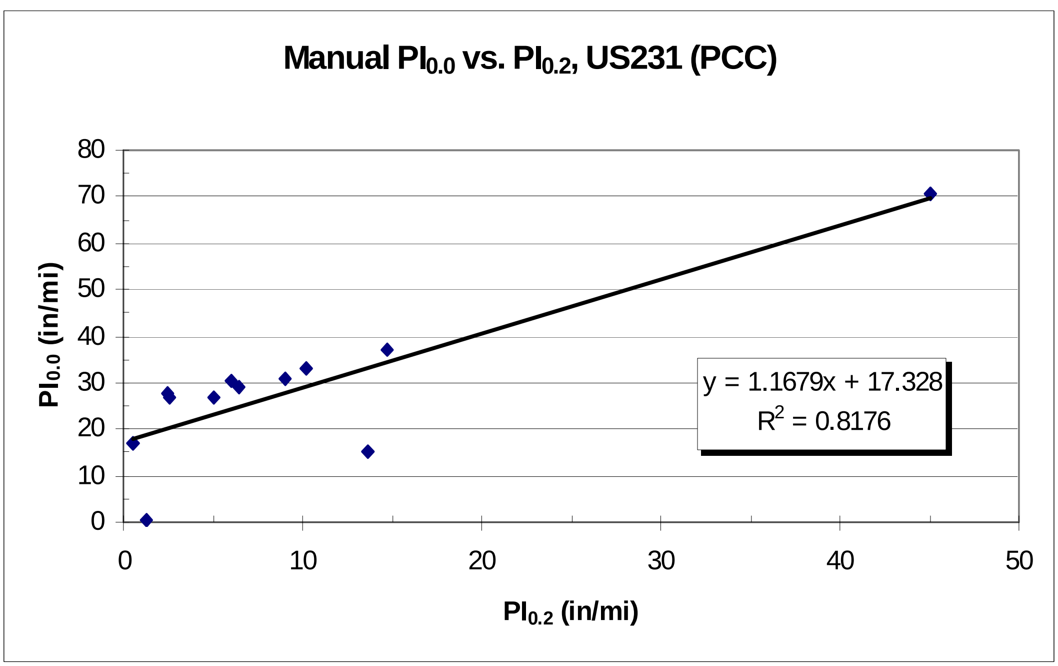

Figure 56. Comparison between Manual $PI_{0.0}$ and $PI_{0.2}$ Reduction Results, US 231.

7.2.2 Pay Factor Comparison (HMA Pavement)

INDOT Limits

For the convenience of the reader, the current INDOT $PI_{0.2}$ smoothness specifications as well as the new converted $PI_{0.0}$ specification for the HMA pavements, are shown again in Table 36. The pay factor comparison results between these two specifications are shown in Figure 57. Analysis results, shown in Figure 57, indicate that 95% of the total 94 HMA sections are in the bonus range and 5% are in the full pay range when the current $PI_{0.2}$ specification is applied. All 94 sections are in the bonus range when the $PI_{0.0}$ specification is applied. However, the number of sections receiving 105% bonus is reduced from 53% to 14%.

Table 36. INDOT Smoothness Specification for HMA Pavements.

% of Unit Price	Converted $PI_{0.0}$ (in/mi)	Current $PI_{0.2}$ (in/mi)
105	0-11.5	0.0-2.0
104	11.6-17.0	2.0-4.0
102	17.1-27.5	4.0-8.0
100	27.6-36.5	8.0-10.0
96	36.6-39.0	10.0-11.0
92	≥39.0	11.0-12.0

KDOT Limits

Table 37 summarizes the current KDOT $PI_{0.0}$ specification and the $PI_{0.2}$ specification used 10 years ago for the HMA pavements in Kansas. The conversion from dollar based pay schedule to percent of unit price for the $PI_{0.0}$ specification was performed in the previous chapter.

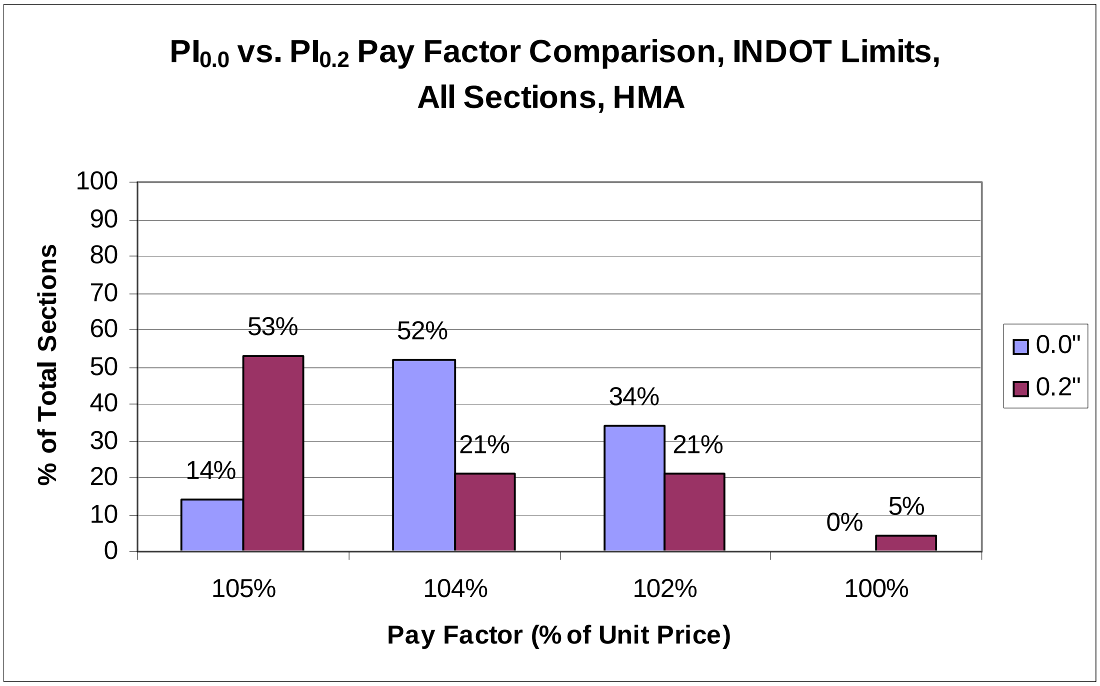

Figure 57. Pay Factor Comparison, INDOT Limits, All Sections, HMA.

Table 37. KDOT Smoothness Specification for HMA Pavements.

% of Unit Price	Current $PI_{0.0}$ (in/mi)	Previous $PI_{0.2}$ (in/mi)
106	0.0-7.0	0.0-2.0
103	7.1-10.0	2.1-3.0
100	10.1-40.0	3.1-9.0
96	NA	9.1-11.0
92	> 40.1	11.1-13.0
90	NA	13.1-15.0
88	NA	>15.1

Figure 58 shows the pay factor comparison using the KDOT limits. Only 9% of the HMA sections are in bonus range and 91% in the full pay range when the $PI_{0.0}$ limits were applied. All the bonus sections would receive 103% payment of unit price. The old $PI_{0.2}$ specification resulted in 63% bonus sections and 35% full pay sections. There are also 2 sections in the penalty range. Among the 59 bonus sections, 53% would receive 106% bonus and 10% would receive 103% bonus.

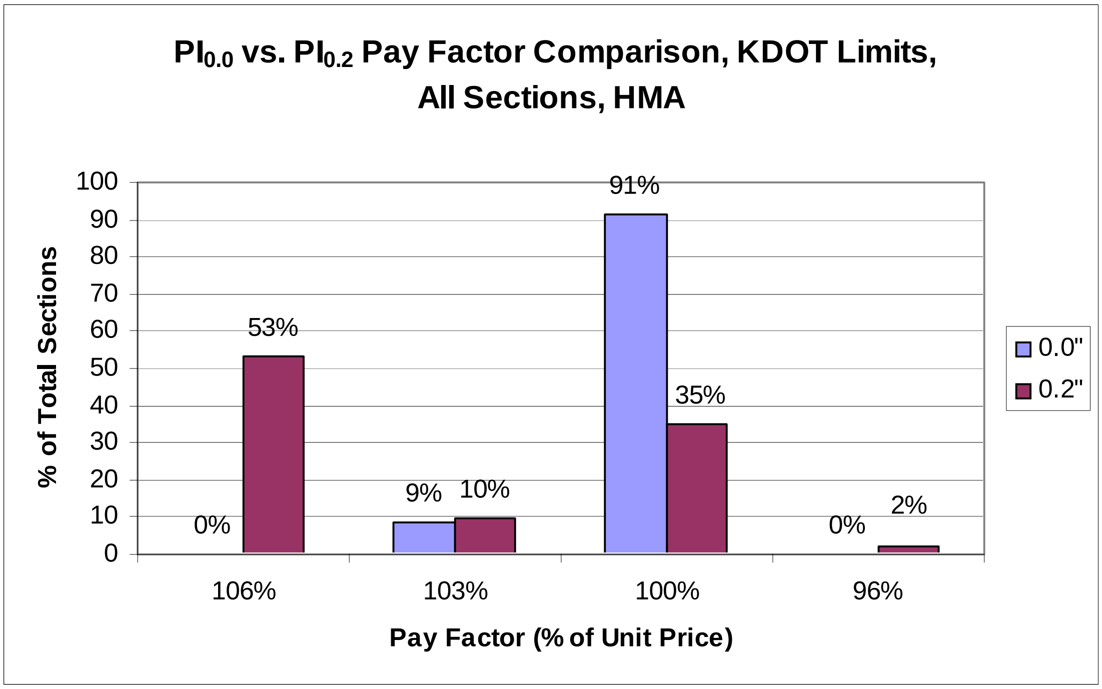

Figure 58. Pay Factor Comparison, KDOT Limits, All Sections, HMA.

Figure 59 shows the pay factor comparison between KDOT and converted INDOT $PI_{0.0}$ specification for all 94 HMA sections. Assuming the unit price for the construction is the same in Kansas and Indiana, a total pay will be equal to the product of the pay factor times the percentage of total number of sections. For instance, from Figure 59, the payment for the INDOT would be equal to 103.5% (100%*0 + 102%*34% + 104%*52% + 106%*14%) of total contract price. The KDOT would only have to pay 100.3% of total contract price. In other words, if the unit price is the same, INDOT would have to pay

3.2% more of the total contract price than KDOT if the converted specification is implemented.

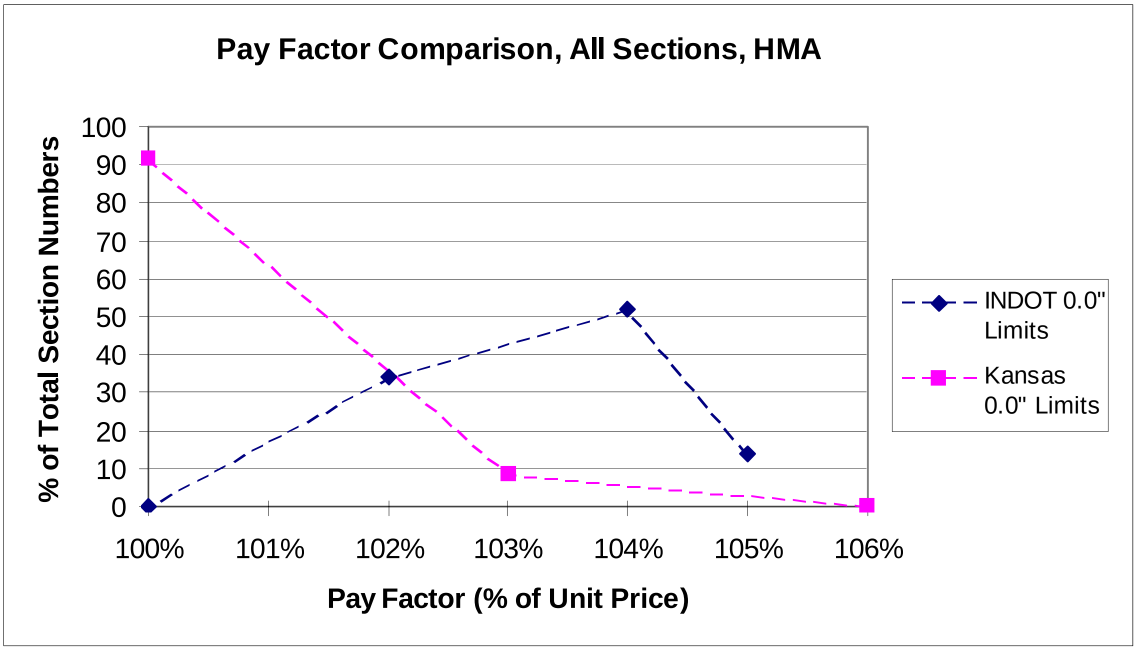

Figure 59. Pay Factor Comparison between INDOT and KDOT Limits, All Sections, HMA.

7.2.3 Pay Factor Comparison (PCC Pavement)

INDOT Limits

Current INDOT $PI_{0.2}$ smoothness specifications as well as the converted $PI_{0.0}$ specification for the PCC pavements are shown in Table 38 for convenience of the reader. Pay factor comparison results are shown in Figure 60. When current $PI_{0.2}$ specification is applied, 78% of sections are in the bonus range and 22% are in the full pay range. Among these bonus sections, 44% would receive 103% bonus, 22% would receive 102% bonus, and 11% would receive 101% bonus. Under the proposed $PI_{0.0}$ PCCP specification, 55% of sections are in the bonus range, and the rest would receive full pay.

Table 38. INDOT Smoothness Specification for PCC Pavements.

% of Unit Price	Converted $PI_{0.0}$ (in/mi)	Current $PI_{0.2}$ (in/mi)
103	0.0-22.0	0.0-5.0
102	22.1-26.0	5.1-7.0
101	26.1-29.9	7.1-9.0
100/corr.	>30.0	> 9.1

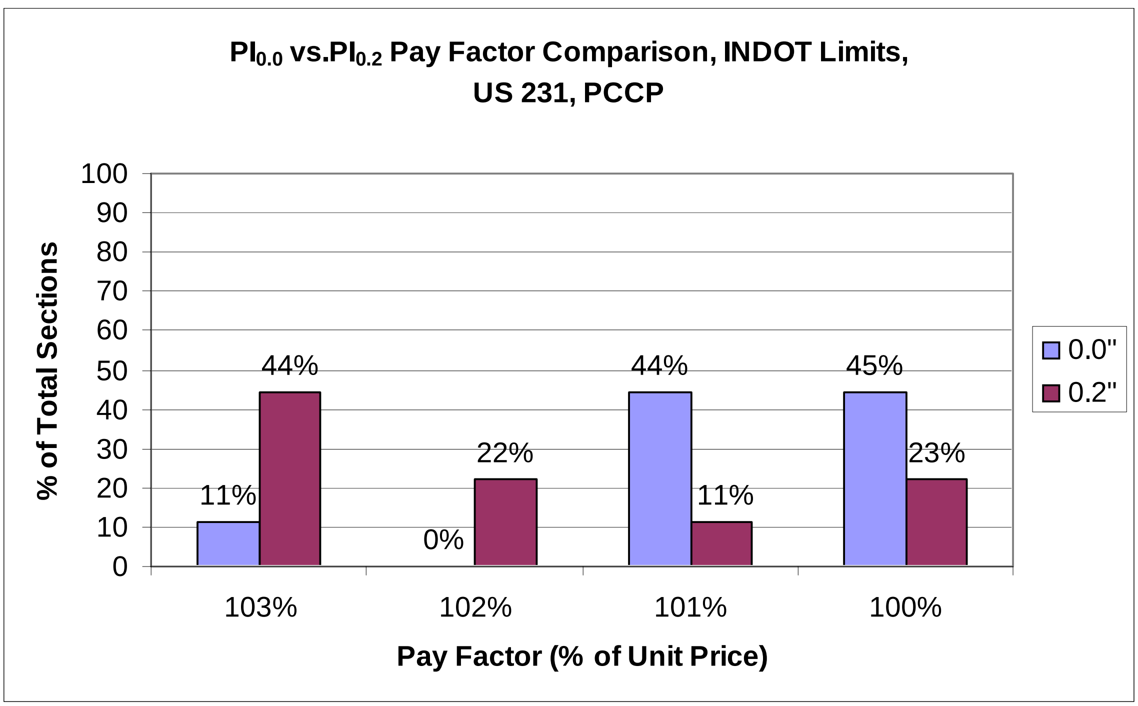

Figure 60. Pay Factor Comparison, INDOT Limits, PCCP.

KDOT Limits

Table 39 summarizes the current KDOT $PI_{0.0}$ specification and the $PI_{0.2}$ specification used 10 years ago for the PCC pavements in Kansas. The conversion from dollar based pay schedule to percent of unit price for the $PI_{0.0}$ specification was performed in the previous chapter.

Table 39. KDOT Smoothness Specification for PCC Pavements.

% of Unit Price	Current $PI_{0.0}$ (in/mi)	Previous $PI_{0.2}$ (in/mi)
108	0.0-6.0	NA
107	6.1-10.0	NA
106	NA	0.0-3.0
105	10.1-15.0	NA
103	NA	3.1-4.0
102	15.1-18.0	NA
100	18.1-40.0	4.1-10.0
96	NA	10.1-12.0
95	>40.1	NA
92	NA	12.1-14.0
90	NA	14.1-15.0
88/corr.	NA	>15.1

Figure 61 shows the pay factor comparison using KDOT limits. Only 11% of total sections are in the bonus range, 78% are in the full pay range, and 11% the penalty range (95% of unit price) when the $PI_{0.0}$ limits were applied. All the bonus sections received 102% payment of unit price. The old $PI_{0.2}$ specification resulted in 33% bonus sections and 45% full pay sections. There are also 2 sections in the penalty range.

In summary, 55% of total sections will receive bonus payment under the proposed INDOT $PI_{0.0}$ specification. However, under the KDOT specification, only 11% would receive bonus payment, 78% would get full pay, and 11% would receive penalty.

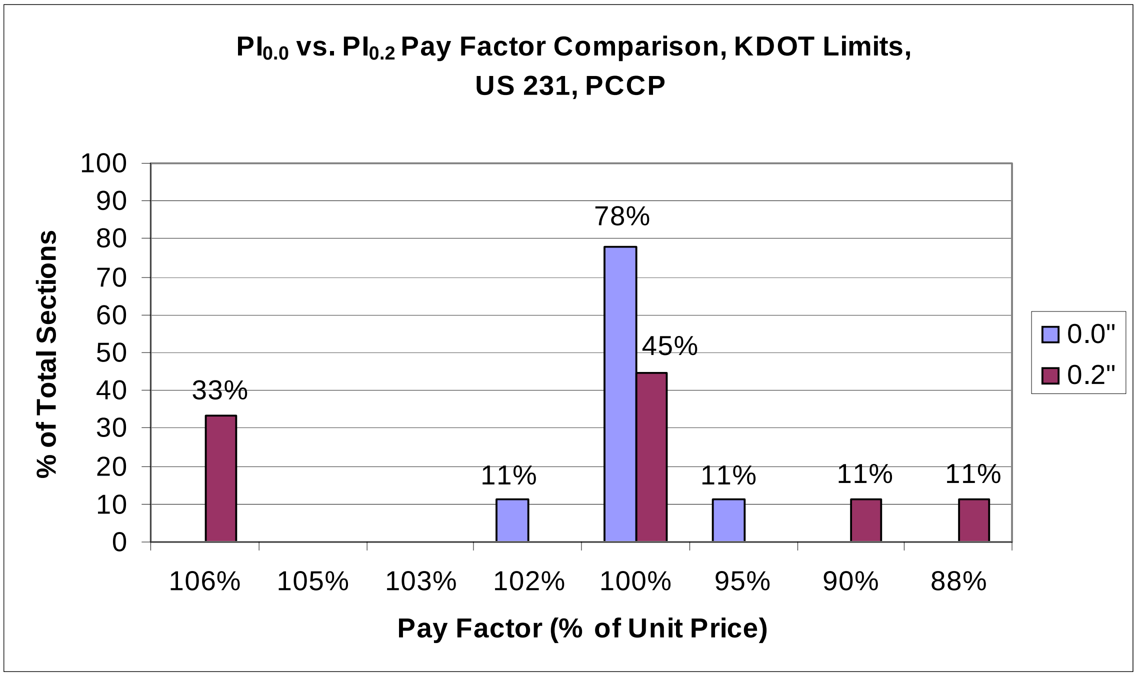

Figure 61. Pay Factor Comparison, KDOT Limits, PCCP.

Figure 62 shows the pay factor comparison between KDOT and converted INDOT $PI_{0.0}$ specification for all PCCP sections. Assuming the unit price for the construction is the same in Kansas and Indiana, by applying the same calculation performed in 7.2.1, INDOT would have to pay 101% of total contract price, while KDOT would only have to pay 100% of total contract price. In other words, if the unit price is the same, INDOT will have to pay 1% more of the total contract price than KDOT if the converted specification is implemented.

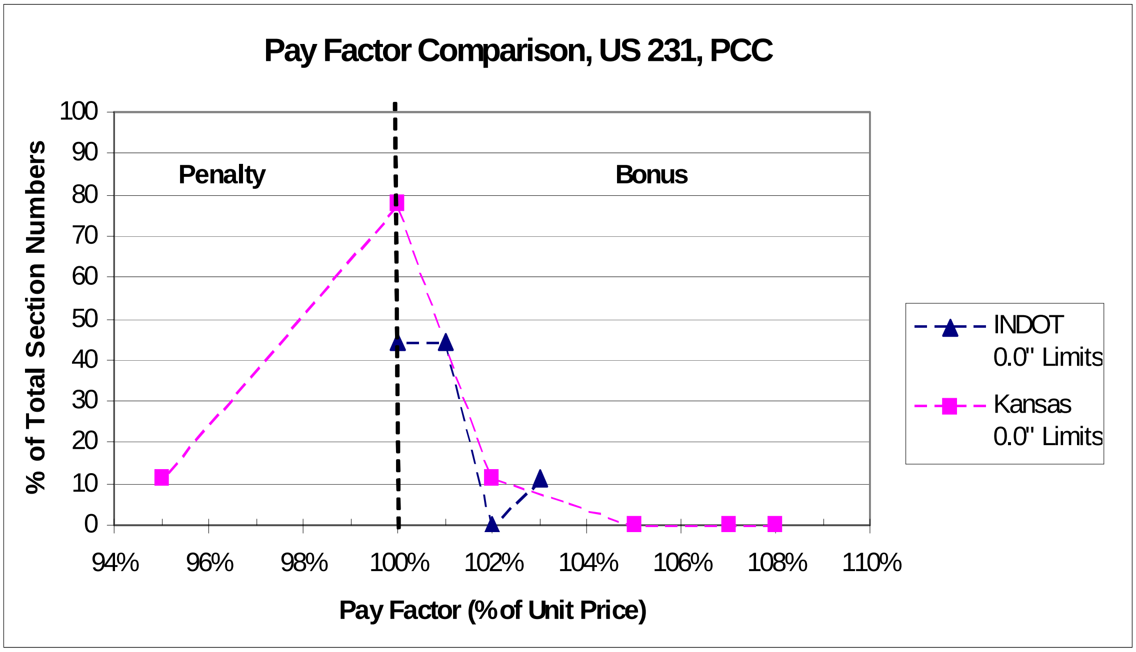

Figure 62. Pay Factor Comparison between INDOT and KDOT Limits, PCCP.

7.2.4 Comparison between Manual and Proscan Reduction Results

Profilograms generated in the field testing were first analyzed manually, and then automatically using the Proscan System. The manual and the Proscan reduction procedures are described in Appendix D. The reduction results are presented and compared in this section.

Table 40 summarizes the data statistics of reduction results for all field test sections. Similar statistical results, with slightly lower PI values from the Proscan measurement, were observed for both HMA and PCC pavements. The reduction results also showed that both the manual and the Proscan reduction identified the same maximum and minimum $PI_{0.0}$ sections for the HMA and PCC pavements.

Table 40. Statistics Summary of $PI_{0.0}$ Reduction Results for All Sections.

	HMA		PCCP	
	Manual (in/mi)	Proscan (in/mi)	Manual (in/mi)	Proscan (in/mi)
Average	15.6	13.4	32.9	27.9
SD	3.6	3.5	15.0	14.5
CV (%)	23.0	26.0	46.0	52.0
Max.	25.0	24.8	70.5	64.1
Min.	7.5	5.8	17.0	13.0
Range	17.5	19.0	52.5	51.1

While the variation in reduction results were similar, the magnitude of the PI values generated by the Proscan tended to be consistently lower than that of the manual reductions, as shown in Figure 63 and 64. A rather good correlation coefficient of R^2 = 0.77 for the HMA pavements and an excellent correlation coefficient of R^2 = 0.99 for the PCC pavements were observed. To investigate the reason for lower PI values, a further analysis was conducted and is shown in the following sections.

To investigate the causes for the differences in PI values, a Proscan parameter settings analysis, and review of the profilograph traces were performed. The investigation indicated that the constantly lower values of Proscan reduction results were due to the following reasons:

- Alignment of the 0.0 inch blanking band (the dashed centerline)
- Interpretation of profilograph traces by visual judgment
- Superelevated curves

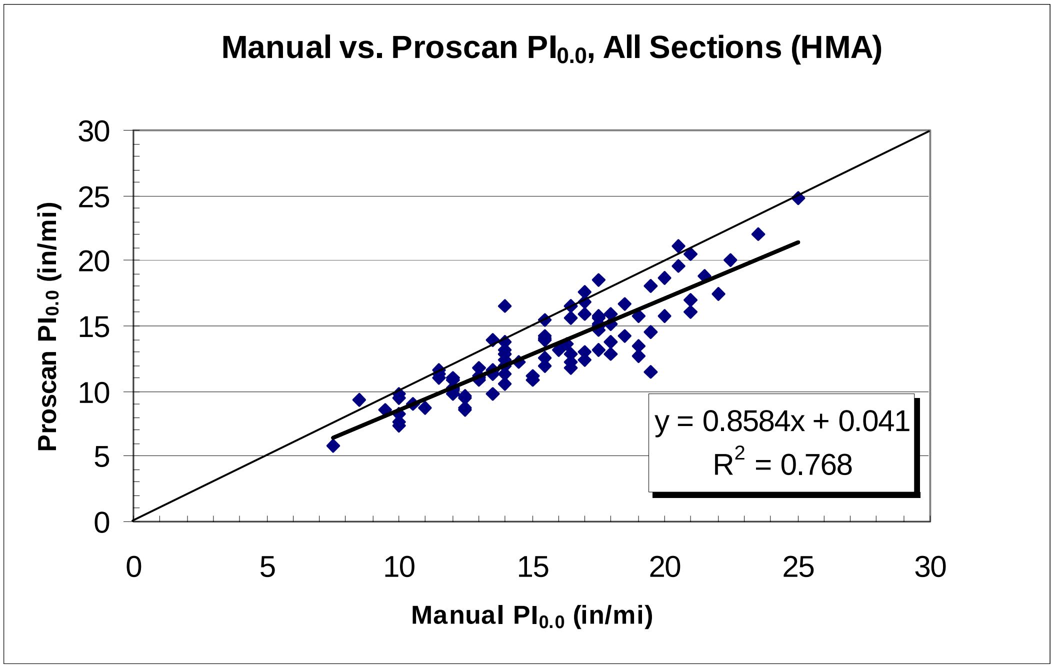

Figure 63. Correlation between Manual and Proscan Reduction Results (HMA).

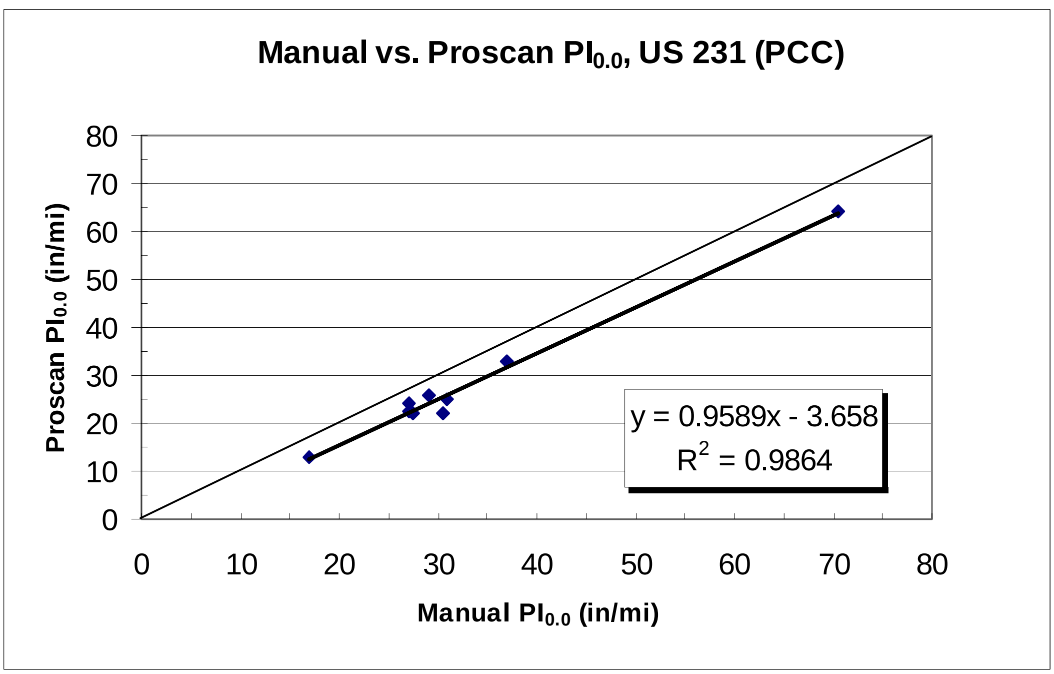

Figure 64. Correlation between Manual and Proscan Reduction Results (PCC).

<u>Alignment of the 0.0 inch blanking band (the dashed centerline)</u>:

Figure 65 shows an example of positioning the 0.0 inch blanking band reduced by the Proscan. The location of the dashed centerline was established by a linear regression analysis of every 0.1 mile section on the profilograph traces. This approach simulates the required manual reduction procedure, which is to place “the dashed reference line as nearly centered on the profile trace as possible.” Figure 68 shows a portion of the profilograph traces with multiple peaks but only the highest peak was counted by the software according to the reduction procedure. The profile index is 0.15 in/0.1mi. Figure 66 shows the positioning of the 0.0 inch blanking band established manually for the same profile trace. With the different positioning of the centerline, five different scallops are shown in Figure 66 and all of them have to be counted since they are distributed across the centerline. Accordingly, the profile index is 0.25 in/0.1mi, which is 1 in/mi lager than the automated Proscan reduction result.

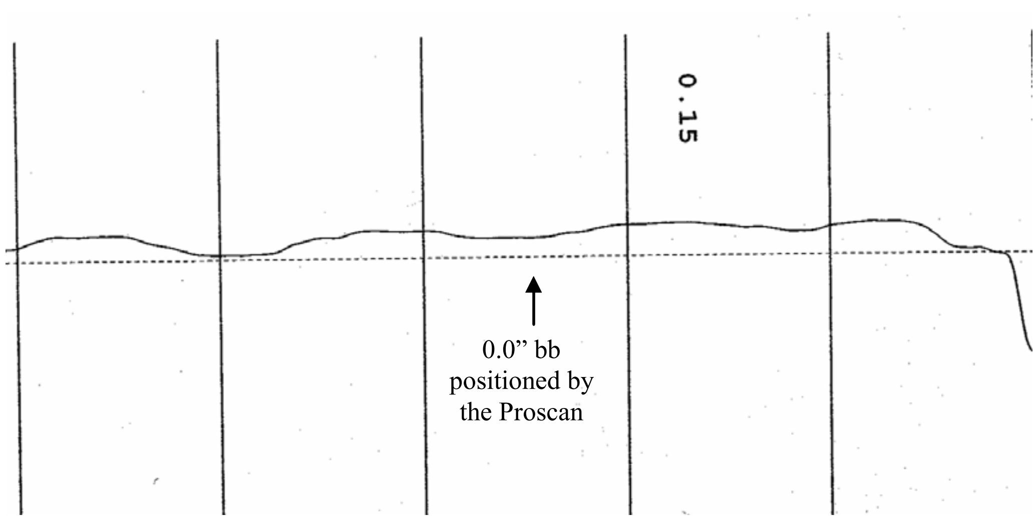

Figure 65. Example of Positioning the 0.0”-bb by Proscan.

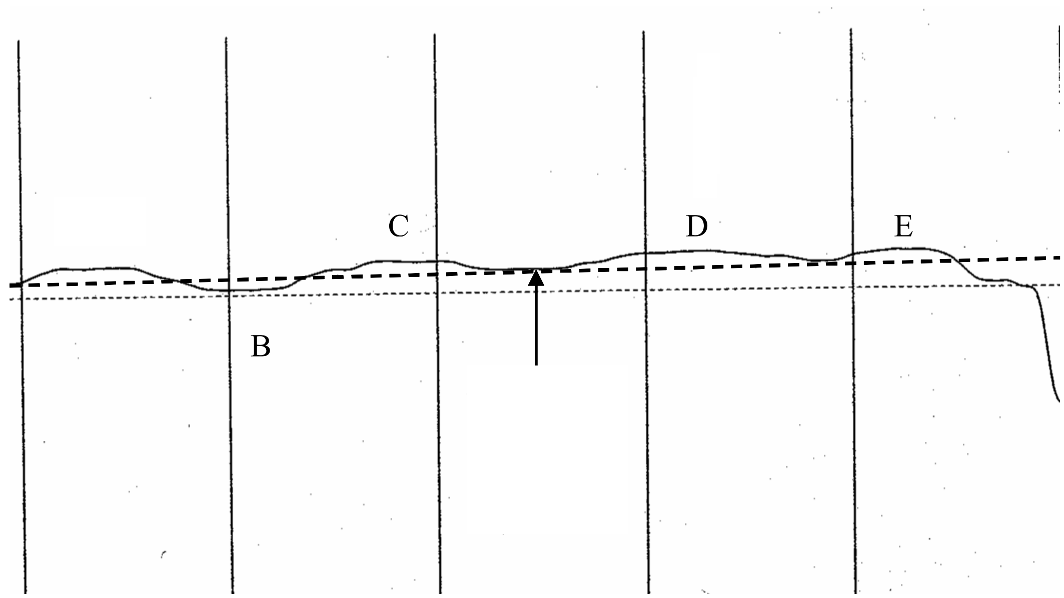

Figure 66. Example of Positioning the 0.0”-bb Manually.

Through the inspection and the comparison of the profilograph traces and reduction results, the differences varied from 0.5 in/mi to 2 in/mi per section due to the different alignment of the centerline as shown in this example. The manual reduction typically gave larger PI values.

Interpretation of profilograph traces by visual judgment:

Variation of manual reduction of profilograph traces is counted on the visual judgment of the interpreter. In most cases, by visually judging the trace, it is difficult to determine the height of the deviations, which may cause overestimation of the PI values. Figure 67 shows an example of the human error in manual interpretation of the profilograph traces. Firstly, at point A, B, and C, the manual reduction is very likely to give PI values of 0.2, 0.1, and 0.05, respectively. This will give 0.6 in/mi larger PI values than the Proscan analysis just for a small portion of the traces. In addition, it is difficult to judge visually whether or not the trace at point D crosses the centerline and consequently the counting of scallop E will give a larger PI value than the Proscan analysis, which can judge the position of the point D precisely.

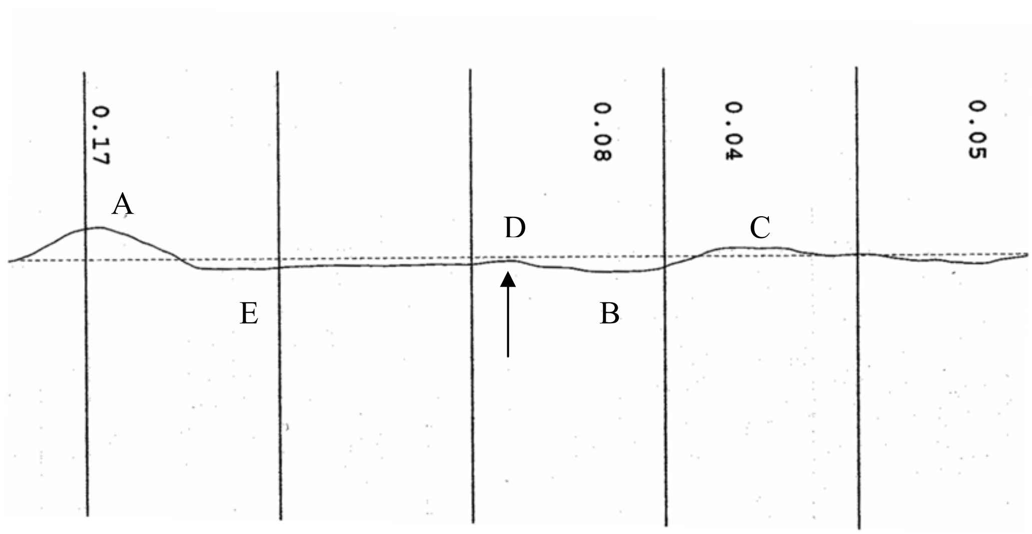

Figure 67. Example of Manual Interpretation of Profilograph Traces.

Superelevated curves:

According to the manual reduction procedure, the profile trace may move from a generally horizontal position, when going around superelevated curves, making it impossible to follow the central portion of the trace without shifting the blanking band. When such conditions occur, the profile should be broken into short sections and the blanking band repositioned. In this field testing, the superelevated curves were observed in the profile generated from State Road 71. However, instead of breaking the profile into short sections and repositioning the centerline, the Proscan reduces the profile continuously. This gave lower PI values than the manual reduction did for the same sections. The cause of variation is similar to the first reason and is illustrated in Figures 66 and 67.

7.3 Repeatability of the Proscan System

Figure 68 shows the results from the two different runs (data digitalization and analysis) of trace reduction using the Proscan System. The results indicate that a great repeatability is observed with the correlation coefficient $R^2 = 0.98$. In addition, the PI computed by the Proscan generally varied less than ± 5% from scan to scan for each 0.1-mile section.

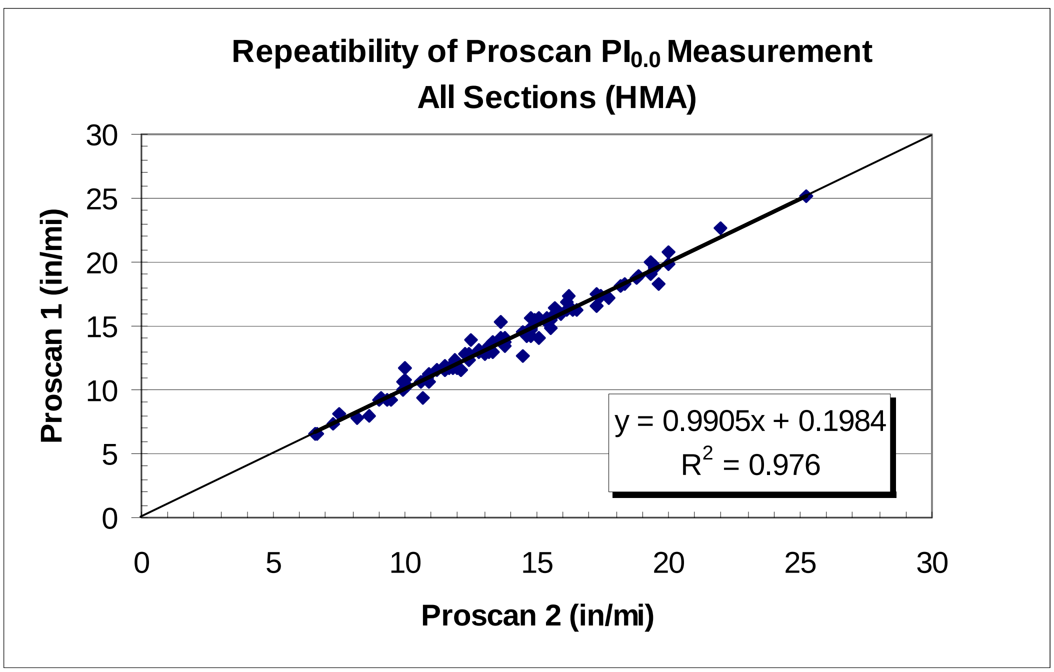

Figure 68. Repeatability of Proscan Reduction.

7.4 Comparison of Measurements by California Profilograph and LISA

The profile measurement obtained by the California Profilograph and Ames Lightweight Profiler (LISA) are analyzed in this section to investigate if both measuring devices produce comparable PI values.

Table 41 shows that the summary statistics for both measuring device are very similar. This suggests that, in general, the lightweight profiler provided measurements which were consistent with measurements of the California Profilograph.

Table 41. $PI_{0.0}$ Measurement Statistics Summary for All Sections.

	HMA		PCCP	
	Manual (in/mi)	LISA (in/mi)	Manual (in/mi)	LISA (in/mi)
Average	15.6	17.0	32.9	31.4
St.Dev.	3.6	3.7	15.0	14.7
CV (%)	23.0	22.0	46.0	47.0
Max.	25.0	25.1	70.5	69.2
Min.	7.5	8.5	17.0	20.1
Range	17.5	16.6	52.5	49.1

Correlation of the LISA and California Profilograph measurements is presented in Figures 69 and 70. Analysis shows that correlation was very poor for the HMA pavements with correlation coefficient R^2 of 0.38. Correlation for the PCCP pavements was good with R^2 of 0.90. This good correlation was driven by one single data point (in the upper right hand corner in Figure 70) and without that point the R^2 decreases to 0.24. Table 42 shows the correlation coefficients for all individual test sections.

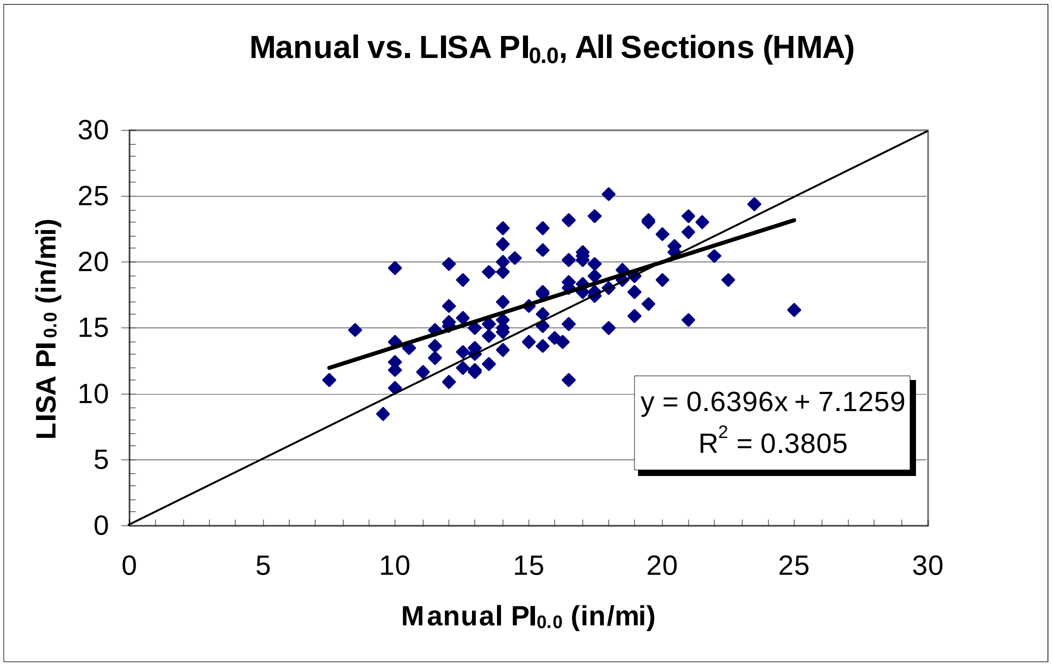

Figure 69. Correlation between LISA and California Profilograph (Manual) Measurement Results (HMA).

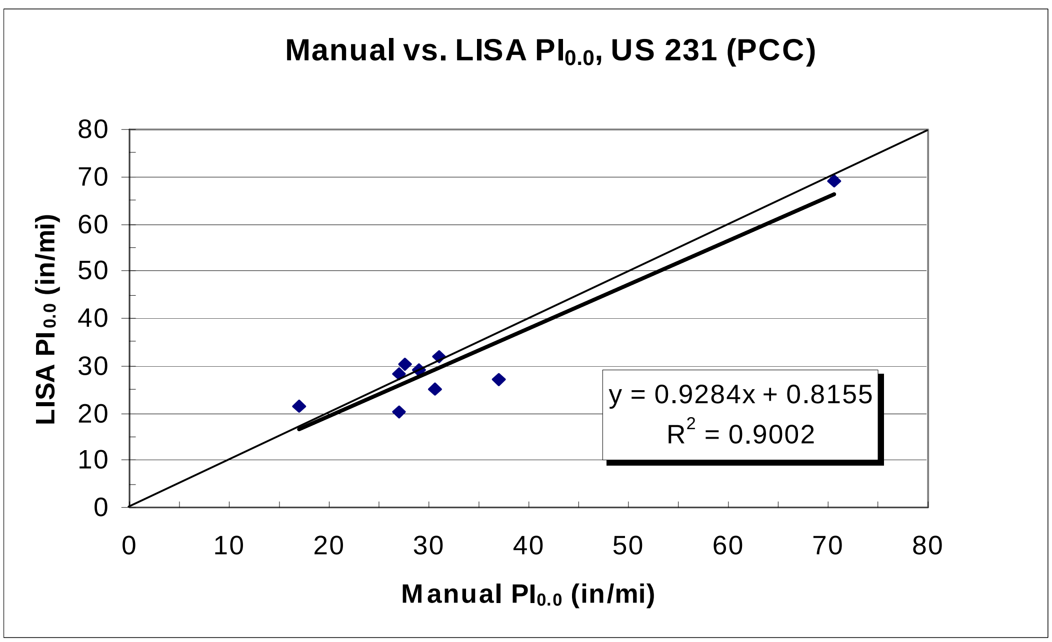

Figure 70. Correlation between LISA and California Profilograph (Manual) Measurement Results (PCCP).

Table 42. Correlation between LISA and California Profilograph (Manual) Reduction Results for All Sections.

Project	LISA vs. Manual (0.0")	LISA vs. Manual (0.2")
US 52 (HMA)	0.16	0.18
SR 18 (HMA)	0.62	0.76
SR 71 (HMA)	0.37	0.42
All HMA Sections	0.38	0.58
US 231 (PCC)	0.90 (0.24*)	0.97 (0.71*)

* Elimination of outlier

The poor correlation is likely due to the following reasons:

- These two devices were not measuring the exact same sections. Although the starting and finishing points were marked clearly during the field testing, some human errors might occur due to the visual judgment of the starting and finishing point of measurement, which resulted in the poor correlation.
- The lightweight profiler employed software filters to simulate the California Profilograph and calculate the Profile Index accordingly. It is likely that the simulation still cannot mimic the Profilograph very well, thus causing the poor correlation.

Figure 71 shows the pay factor analysis based on LISA outputs. The converted $PI_{0.0}$ specification was applied to the LISA reduction results, and the analysis indicates that the pay schedule was similar to the California Profilograph reduction results despite the poor correlation of measurements. Table 43 summarizes the pay factor comparison between LISA and manual reductions using converted $PI_{0.0}$ specification. The percentage in the right two columns represents the percentage of total section numbers. This analysis suggests that the lightweight profilers are a viable option to be used in the QA operations in the future.

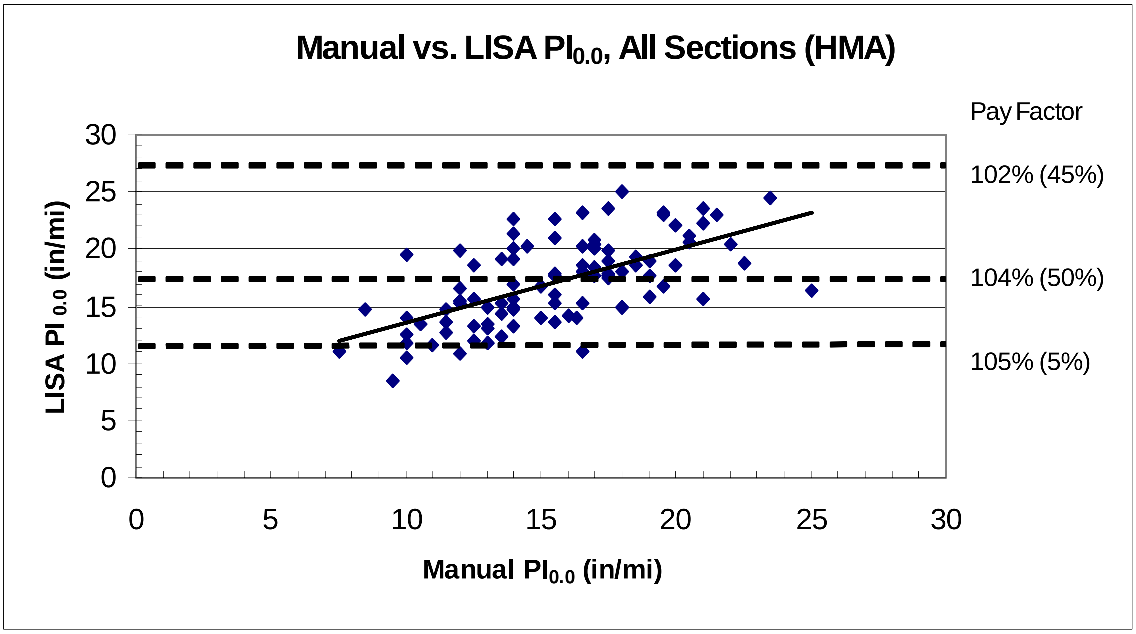

Figure 71. Pay Factor Analysis Based on LISA Outputs (HMA).

Table 43. Pay Factor Comparison between LISA and Manual Reductions Using Proposed $PI_{0.0}$ Specification.

Pay Factor (%)	LISA Results (%)	Manual Results (%)
105	5	14
104	50	52
102	45	34

7.5 Modification of the Converted INDOT $PI_{0.0}$ Specification

Based on the comparison between the Proscan and the manual reduction results in the previous section, the Proscan showed consistently lower values compared to the manual reduction results. The converted $PI_{0.0}$ specification (page109) was developed based on the analysis of manual reduction results. Therefore, it is necessary to modify the converted specification to comply with the Proscan analysis.

Two correlation equations developed in the previous section using the field test data were used to convert the "manual" $PI_{0.0}$ specifications into the "automated" $PI_{0.0}$ specifications for the Proscan. Table 44 shows the conversion equations and Tables 45 and 46 summarize the final converted INDOT $PI_{0.0}$ smoothness specifications.

Table 44. Conversion Equations between Proscan and Manual $PI_{0.0}$.

Type of Pavement	Conversion Equation (in/mi)	R^2
HMA	Proscan $PI_{0.0}$= 0.86 Manual $PI_{0.0}$ + 0.04	0.77
PCCP	Proscan $PI_{0.0}$ = 0.96 Manual $PI_{0.0}$ – 3.66	0.99

Table 45. $PI_{0.0}$ HMA Smoothness Specification, Proscan Version.

$PI_{0.0}$ (in/0.1mi)	$PI_{0.0}$ (mm/0.16km)	% of Unit Price
0.00-1.00	0.00-25	105
1.01-1.40	25.1-35.0	104
1.40-2.40	35.0-60.0	102
2.41-3.00	60.1-75.0	100
3.01-3.50	75.1-87.5	96
≥ 3.51	≥ 87.5	92 / correct back to 3.0 in/0.1mi (75 mm/0.16km)

Table 46. $PI_{0.0}$ PCCP Smoothness Specification, Proscan Version.

$PI_{0.0}$ (in/0.1mi)	$PI_{0.0}$ (mm/0.16km)	% of Unit Price
0.00-1.80	0.00-45.0	103
1.81-2.20	45.1-55.0	102
2.21-2.50	55.1-62.5	101
≥ 2.51	≥ 62.6	100 / correct back to 2.5 in/0.1mi (62.5 mm/0.16km)

The automated reduction method possesses several advantages over the manual reduction method: 1) It reduces substantially the time needed for the data processing, 2) It eliminates the human error resulting from the manual interpretation of the profilograph traces, and 3) It has excellent repeatability between reductions. Therefore, it is recommended that INDOT should use the Proscan System to process the profilograph traces with the 0.0" blanking band method.

A procedure to analyze the traces using the Proscan system is included in the new Indiana Test Method (ITM) protocol that has been developed to be used with the new $PI_{0.0}$ specifications, see Appendix D.

8 SUMMARY AND CONCLUSIONS

Pavement smoothness is considered to be the most important indicator of pavement riding comfort. Currently, Indiana Department of Transportation (INDOT) is using the California Profilograph as the standard measuring device in its smoothness specifications. The output derived from the profilograph is called Profile Index (PI). PI represents the total accumulated deviations of the profilograph output traces beyond a tolerance zone (blanking band). At present, INDOT is using 0.2-inch blanking band to evaluate the profile traces. The use of 0.2-inch blanking band has raised some concerns because in some instances small unpleasant surface irregularities are covered by the blanking band and are not counted in the roughness index value.

The major objective of this study was to develop a rational method for interpreting profilograph traces using 0.0-inch blanking band method and to establish corresponding pavement smoothness specifications. The secondary objective was to develop/adopt an automated system for the pavement profile analysis from profilograph traces.

The study was divided into two parts. In the first part, a synthesis study was conducted to obtain more information about the problem. The main task in part two of the study was to develop a quality control/quality assurance construction smoothness specification for HMA and PCC pavements in Indiana using the 0.0” bb procedure to analyze the profilograph traces.

Synthesis Study

In the first part (synthesis study) a literature review was conducted to gather information about the smoothness measuring techniques, indices and methods to develop/establish smoothness specifications. Also, existing profilograph profiles provided by INDOT were analyzed to develop a new manual 0.0" blanking band reduction procedure. The PI values obtained using this new procedure and current INDOT 0.2" bb methods were then compared to analyze the repeatability and reproducibility of both methods.

Two automated profilogram reduction systems developed by Kansas DOT (KDOT), Proscan System, and Louisiana DOT, APPARE, were reviewed. Both systems showed good ability to reduce the profilograph traces. However, the APPARE system was never fully implemented by the Louisiana DOT due to the changes in technology in both scanner equipment and computer operating software. The development of the software and the hardware for the Proscan system was the result of a research study conducted by Kansas State University in conjunction with KDOT. It has been implemented for about ten years and the KDOT is content with the results from this system.

Five state DOTs' smoothness specifications, Missouri, Kansas, Pennsylvania, Minnesota, and Wisconsin, using 0.0-inch blanking band were compared in the literature review. How the $PI_{0.0}$ smoothness specification, especially the incentive/disincentive policy developed for each DOT, was studied through personal contact. Recent studies regarding how the roughness progression and the inclusion of user costs affected the smoothness specifications were also summarized. The gathered information was used as a reference to develop the new smoothness specification for INDOT.

Manual reductions of Profilograph traces obtained from INDOT using 0.2-inch and 0.0-inch blanking band and the corresponding statistical analysis were performed to develop the $PI_{0.0}$ manual reduction procedure. The within-operator repeatability and the between-operators reproducibility for the $PI_{0.0}$ manual reduction were analyzed. The statistical analysis results of the repeatability were good with relatively low standard deviation and coefficient of variance. The reproducibility from different interpreters varied a lot, with 60% of the reduction results obtained from interpreter A and B were statistically different at 5% significance level, due to different interpretation of the trace deviations and the positioning of the 0.0" blanking band. Therefore, it was necessary to adopt an automated system with good repeatability and reproducibility to reduce the Profilograph traces.

The results also showed that the correlation between PI values using 0.2" and 0.0" blanking band was poor. This indicated that the 0.2" bb reduction made pavements look smoother than they really were and smooth pavement sections resulting from 0.2"bb reduction were not as smooth as they appeared to be when reduced using 0.0"bb. In other words, $PI_{0.0}$ showed the ability of revealing the small deviations covered by the 0.2" blanking band improved the ability of evaluating the as-built pavement smoothness.

To further evaluate the performance of the Proscan system, a part of the same initial dataset analyzed in Chapter 3 was analyzed at KDOT and reduced using their Proscan System. The analysis results showed good agreement between the Proscan reductions and the manual reductions using the 0.0 inch blanking band. Several advantages of the automated reduction were also observed: 1) Significant reduction of time in the data processing: it took 30 seconds to scan one 0.1-mile section and compute the PI, which is much faster than the manual reduction of 2 minutes per section. 2) Elimination of human error resulted from the manual interpretation of the profilograph traces. 3) Excellent repeatability between reductions.

Development of $PI_{0.0}$ Specification

Phase II of the study was continued based on the findings obtained from Phase I. It comprised of three major tasks: 1) Development of the $PI_{0.0}$ construction smoothness specification, 2) Validation of the proposed converted specification, and 3) Evaluation of automated profile trace reduction system (the Proscan System).

To develop the converted $PI_{0.0}$ smoothness specification, the first step was to analyze and compare currently available $PI_{0.0}$ specifications of various SHAs', especially for the incentive/disincentive policies. KDOT smoothness specifications were selected as the reference for the development and the assessment of INDOT $PI_{0.0}$ specifications since KDOT has used the $PI_{0.0}$ smoothness specification for ten years and they are satisfied with their current specifications. In general, KDOT specification is stricter in the range of bonus payments but is more lenient in the penalty range than the other specifications for both HMA and PCC pavements. On the other hand, KDOT is more lenient in the bonus range for the PCC pavments than for the HMA pavements. This suggested that, from KDOT's experience, smooth PCC pavement was harder to achieve in comaprison with the HMA pavement and KDOT tried to encourage the PCC contractors to improve the smoothness of PCC pavements by applying a more lenient incentive policy compared to the HMA incentive policy.

Comparison between INDOT and KDOT $PI_{0.2}$ specificatons for HMA and PCC pavements were also performed. The current INDOT specifications appeared more lenient for the "average" and very rough pavements than the KDOT $PI_{0.2}$ specifications did, which were used ten years ago. However, due to the differences in the analysis procedures between these two states, the actual applied smoothness evaluation policies may be closer than the result indicated.

Several Profile Index conversion models, including the IRI-PI model developed by Mondal et al. (2000), the PI model developed from the study data, and the IRI-PI model developed from the LTPP database, were selected and evaluated to perform the conversion of the current $PI_{0.2}$ smoothness specification to the $PI_{0.0}$ specification. The applicability of conversions was judged by comparing them to the conversion curve of the KDOT 0.2" versus 0.0" blanking band specification. Finally, the conversion equations obtained from the study data as well as its 95% Confidence Interval of the intercept were chosen to convert the current Indiana $PI_{0.2}$ specifications into the $PI_{0.0}$ limits. The developed conversion was then compared to the current KDOT and other $PI_{0.0}$ specifications to further determine the final INDOT $PI_{0.0}$ specifications, which are summarized in Tables 47 and 48.

Table 47. Converted $PI_{0.0}$ Smoothness Specification for the HMA pavements.

$PI_{0.0}$, in/0.1mile	$PI_{0.0}$, mm/0.16km	% of Unit Price
0.00-1.15	0.00-29.0	105
1.16-1.70	29.1-42.5	104
1.71-2.75	42.6-69.0	102
2.76-3.65	69.1-91.5	100
3.66-3.90	91.6-97.5	96
≥3.91	≥ 97.6	92 /correct back to 3.65 in/0.1mi (91.5 mm/0.16km)

Table 48. Converted $PI_{0.0}$ Smoothness Specification for the PCC pavements.

$PI_{0.0}$, in/0.1mile	$PI_{0.0}$, mm/0.16km	% of Unit Price
0.00-2.20	0.0-55.0	103
2.21-2.60	55.1-65.0	102
2.61-2.99	65.1-72.5	101
3.00	72.6-97.5	100
≥3.01	≥ 97.6	Correct back to 3.00 in/0.1mi (97.5 mm/0.16km)

<u>Verification of the Converted Specifications</u>

The pavement smoothness of several recently completed paving projects was measured for the verification of the proposed converted specifications. Two smoothness measuring devices, California Profilograph and Ames Lightweight Profiler (LISA), were used to perform the field testing. The smoothness reduction was performed manually and automatically by the Proscan System. Again, KDOT's $PI_{0.0}$ smoothness specification was used as a measuring stick to evaluate where the proposed specification stands. The analysis results showed that, in comparison with the INDOT's $PI_{0.2}$ specification, the proposed $PI_{0.0}$ specifications reduced the amount of bonus payments due to the unearthing of the small deviations covered by the 0.2" blanking band. However, when compared to the KDOT's specification, the proposed specification was more lenient, which may result in bonus payment for the "mediocre" quality of construction.

The correlation between LISA and California Profilograph measurement results were poor, which may be due to the following reasons: 1) These two devices were not measuring the exact same sections because the visual judgment of starting and finishing point of measurement was different by different operators. 2) The lightweight profiler employed software filters to simulate the California Profilograph and calculate the Profile Index accordingly. It is possible that the simulation cannot mimic the Profilograph very well, thus causing the poor correlation.

Good correlation was observed between manual and Proscan $PI_{0.0}$ reduction results. Both manual and Proscan reduction identified the same maximum and minimum $PI_{0.0}$ sections for the HMA and PCC pavements. However, the Proscan results consistently generated lower PI values than the manual reduction did. Further analysis indicated that the variation was a result of human error, such as the visual judgment of the centerline alignment, determination of the minimum height of scallop, and counts of multiple peaks, occurred by the manual interpretation and the different reduction procedure for the superelevated curves. Excellent repeatability of the Proscan System was observed with the correlation coefficient of $R^2 = 0.98$ between two different runs of trace reduction. Additionally, it also saved a lot of time for trace reduction and $PI_{0.0}$ computation. In summary, the Proscan System showed good ability to evaluate the pavement smoothness with the 0.0" blanking band. It is recommended that INDOT adopt this automated reduction system to reduce the $PI_{0.0}$ from the profilograph traces.

Determination of the highest pay factor was performed based on the pay factor analysis and the smoothness-pavement life analysis. The result suggested that the proposed smoothness specification with the highest pay factor of 105 percent is sufficient to regulate the as-built pavement smoothness.

The proposed converted specification was modified to comply with the Proscan reduction results. Correlation equations developed using the field testing data was used to convert the $PI_{0.0}$ specifications into the modified $PI_{0.0}$ specifications of the Proscan version.

Tables 49 and 50 summarize the modified INDOT $PI_{0.0}$ smoothness specifications for the Proscan. This converted specification does not include the incentive/disincentive policy changes. Although the result from the comparison with KDOT's specification suggested some changes to the policy, the task of policy change will remain to be decided by the INDOT pavement engineers based on the evaluation over the coming construction season on a trial basis.

Table 49. $PI_{0.0}$ HMA Smoothness Specification, Proscan Version.

$PI_{0.0}$ (in/mi)	$PI_{0.0}$ (mm/0.16km)	% of Unit Price
0.0-10.0	0.0-25.0	105
10.1-14.0	25.1-35.0	104
14.0-24.0	35.0-60.0	102
24.1-30.0	60.1-75.0	100
30.1-35.0	75.1-87.5	96
≥ 35.1	≥ 87.5	92 / correct back to 30 in/mi (75 mm/0.16km)

Table 50. $PI_{0.0}$ PCCP Smoothness Specification, Proscan Version.

$PI_{0.0}$ (in/mi)	$PI_{0.0}$ (mm/0.16km)	% of Unit Price
0.0-18.0	0-45.0	103
18.1-22.0	45.1-55.0	102
22.1-25.0	55.1-62.5	101
≥ 25.1	≥ 62.6	100 / correct back to 25 in/mi (62.5 mm/0.16km)

9 IMPLEMENTATION REPORT

9.1 Verification of the Initial $PI_{0.0}$ Smoothness Specifications

A first step towards implementing the new $PI_{0.0}$ smoothness specification has already been initiated by the Study Advisory Committee (SAC) of the research project. The SAC committee took the converted $PI_{0.0}$ specifications and modified them to construct the initial INDOT $PI_{0.0}$ specifications for the HMA and PCC pavements. These specifications are shown in Tables 51 and 52, respectively. The converted specifications have been modified to include some incentive/disincentive policy changes initiated by INDOT. A new Indiana Test Method (ITM) protocol has been developed (Appendix D) to be used with the new $PI_{0.0}$ specifications.

Table 51. Initial $PI_{0.0}$ Smoothness Specification for HMA by SAC.

Profile Index ($PI_{0.0}$), in/0.1mile	Profile Index ($PI_{0.0}$), mm/0.16km	Pay Factor
0.00–1.00	0.00–25.0	106
1.01-1.20	25.1-30.0	105
1.21-1.40	30.1-35.0	104
1.41-1.70	35.1-42.0	103
1.71-2.00	42.1-50.0	102
2.11-2.40	50.1-60.0	101
2.41-2.80	60.1-70.0	100
2.81-3.60	70.1-90.0	96
3.61-3.80	90.1-95.0	92
≥ 3.81	≥ 95.1	correct back to 2.80 in/0.1mi (70.0 mm/0.16km)

Table 52. Initial $PI_{0.0}$ Smoothness Specification for PCC by SAC.

Profile Index ($PI_{0.0}$), in/0.1mile	Profile Index ($PI_{0.0}$), mm/0.16km	Pay Factor
0.00–1.20	0.00–30.0	106
1.21-1.40	30.1-35.0	105
1.41-1.70	35.1-42.0	104
1.71-2.00	42.1-50.0	103
2.01-2.40	50.1-62.0	102
2.41-2.80	62.1-70.0	101
2.81-3.80	70.1-95.0	100
≥ 3.81	≥ 95.1	correct back to 3.80 in/0.1mi (95.0 mm/0.16km)

A first implementation phase of the initial $PI_{0.0}$ specification will be conducted during summer and fall of 2003. Several paving contractors will provide California Profilograph traces to Purdue University to be analyzed using Proscan system using the current $PI_{0.2}$ and new initial $PI_{0.0}$ specifications. At the end of the summer, Purdue will summarize the analysis findings. This analysis work will give the feedback to the contractors and INDOT about the new specifications.

The second implementation phase includes purchasing six to seven new Proscan devises for INDOT districts to automate the trace reduction operation. Purdue University will provide training during summer and fall construction season to use the new analysis system.

The $PI_{0.0}$ specification and automated analysis of printed profilograph traces is intended to be a temporary solution until the new lightweight profilographs are developed enough that they can be used for construction QA smoothness measurements. The new lightweight devices will print the trace analysis through the onboard computer and software and separate manual or automated trace reduction will not be needed in the future.

9.2 Pay Factor Comparison between Specifications

A comparison between different specifications was made in order to better understand how different pay factors are affecting the total payments. In addition to the specifications studied in the previous sections, the initial $PI_{0.0}$ specification constructed by the SAC committee was incorporated in this analysis. Figure 72 shows the pay factor comparison for the field test data between current INDOT $PI_{0.0}$, Converted $PI_{0.0}$, SAC $PI_{0.0}$ and current Kansas $PI_{0.0}$ specifications.

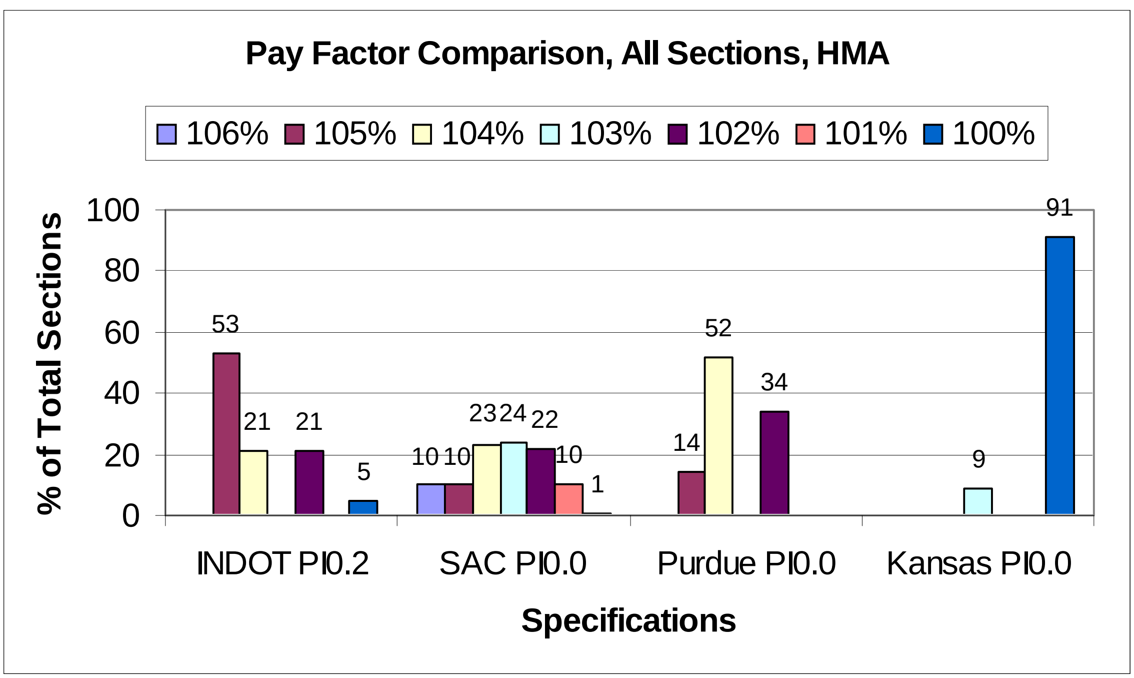

Figure 72. Pay Factor Comparison for HMA.

As shown in Figure 72, both SAC and Purdue $PI_{0.0}$ specifications would reduce the amount of bonus payments compared to the existing INDOT $PI_{0.2}$ specification. However, both specifications would pay more bonuses compared to the Kansas $PI_{0.0}$ specification.

Table 53 shows the comparison of total payments under different specifications. SAC $PI_{0.0}$ (w/o 106%) represents the SAC specification if the highest pay factor would be 105% with the corresponding PI limit of 0.0 to 1.2 in/0.1mi. Assuming that the bid prices are the same, the total payment can be calculated using the following method: Total pay = Summation of each percentage of total section numbers in each pay category times its corresponding pay factor. For example, the total pay for the Kansas $PI_{0.0}$ = (9 * 103%) + (91 * 100%) = 100.27%. For this data set, there is 0.1% difference in the paid bid price between 106 and 105% pay factors.

Table 53. Payment Comparison between Specifications.

	% of Sections in the pay factor category							
Pay Factor (%)	106	105	104	103	102	101	100	Total Pay (%)
INDOT $PI_{0.2}$	0	53	21	0	21	0	5	103.91
SAC $PI_{0.0}$	10	10	23	24	22	10	1	103.28
Kansas $PI_{0.0}$	0	0	0	9	0	0	91	100.27
Purdue converted $PI_{0.0}$	0	14	52	0	34	0	0	103.46
SAC $PI_{0.0}$ (w/o 106%)	0	20	23	24	22	10	1	103.18

9.3 Initial Smoothness and Pay Factor Limits

The pay factor limits should be set so that the maximum benefit could be obtained in terms of pavement service life while determining incentives and disincentives. The smoothness-pavement life relationships developed by Smith et al. (1997) based on the data obtained from several SHAs' was applied in this analysis. The relationship between pavement life and initial smoothness was estimated based on IRI values. The initial $PI_{0.0}$ smoothness limits were converted to IRI vales using equation of C-2 (Table x) based on the study conducted by Mondal et al. (2000). Table 54 shows the smoothness-life relationships developed by Smith et al. (1997).

Table 54. Smoothness-Life Relationships by Smith et al. (1997).

Pavement Family	Smoothness-life relationships	Equation
Illinois AC	Life = -0.080IRI+14.196	L-1
Michigan AC	Life = -0.040IRI+17.147	L-2
Minnesota AC	Life = -0.113IRI+18.060	L-3

Table 55 summarizes the predicted pavement life for the SAC $PI_{0.0}$ HMA specification. The percent of life increase in Table 55 represents the percentage of the pavement life increased, when the initial smoothness would improve from one pay factor category to the next higher category, starting from the PI limit of 92% pay factor. For instance, based on the Illinois model, the pavement life would increase 3.82% when the initial smoothness improves from 12 in/mi to 10 in/mi (from the PI limit in the 105% to the 106% factor category).

Figure 73 shows the percent of pavement life increase for each pay factor category. The largest increase of the pavement life occurs when the initial smoothness improves from the PI limit of the 96% to the 100% pay factor. In other words, the full pay PI limit specified in the SAC specifications is appropriate since it prevents the largest decrease in the pavement life by applying penalty to the contractor. The increase in pavement life between 106 and 105% pay factors is negligible, suggesting that 105% pay factor is sufficient to regulate the initial pavement smoothness.

Table 55. Predicted Pavement Life for SAC Specification.

Pay Factor (%)	PI_{00} (in/mi)	Life(IL) (year)	Life Increase (%)	Life(MI) (year)	Life Increase (%)	Life(MN) (year)	Life Increase (%)
106	10	10.60	3.82	15.35	1.29	12.98	4.44
105	12	10.21	3.98	15.15	1.30	12.43	4.64
104	14	9.82	6.34	14.96	2.00	11.88	7.49
103	17	9.23	6.77	14.67	2.04	11.05	8.09
102	20	8.65	9.93	14.37	2.79	10.22	12.09
101	24	7.87	11.02	13.98	2.87	9.12	13.76
100	28	7.09	28.27	13.59	6.09	8.02	37.96
96	36	5.52	7.61	12.81	1.55	5.81	10.49
92	38	5.13	0.00	12.62	0.00	5.26	0.00

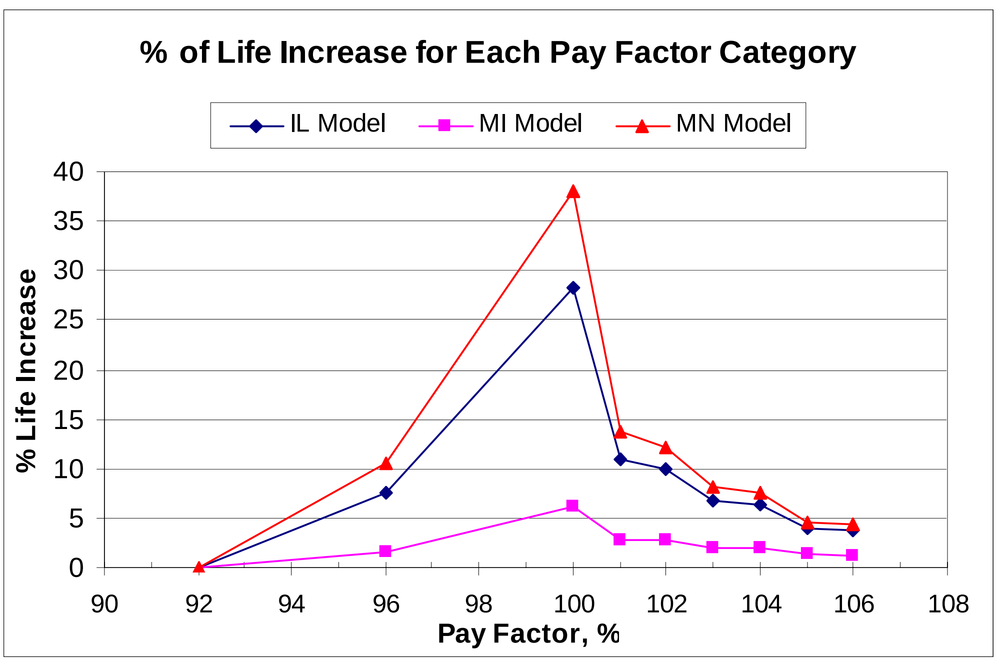

Figure 73. Percent of Life Increase for Each Pay Factor Category.

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APPENDIX A
The Proper Use of the Profilograph and the Interpretation of Profilograms
ITM No. 901-01T

INDIANA DEPARTMENT OF TRANSPORTATION
MATERIALS AND TESTS DIVISION

THE PROPER USE OF THE PROFILOGRAPH AND THE INTERPRETATION OF PROFILOGRAMS
ITM No. 901-01T

1.0 SCOPE.

1.1 This test method covers the testing with a profilograph to evaluate the final smoothness of portland cement concrete and HMA pavement. Such testing is performed to determine the profile indexes of all 0.1 mi (0.16 km) sections, and the locations of all individual high or low points having a deviation in excess of 0.3 in. (8 mm).

1.2 The values stated in either acceptable English or SI metric units are to be regarded separately as standard, as appropriate for a specification with which this ITM is used. Within the text, SI metric units are shown in parenthesis. The values stated in each system may not be exact equivalents; therefore each system shall be used independently of the other, without combining values in any way.

1.3 This ITM may involve hazardous materials, operations, and equipment. This ITM does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this ITM to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2.0 TERMINOLOGY.

2.1 **Profilograph.** An instrument used to measure vertical irregularities of pavement.

2.2 **Profilogram.** A continuous paper chart which records irregularities of the profile wheel from the reference plane established by the profilograph.

2.3 **Profile Wheel.** A wheel at the midpoint of the profilograph frame which is mechanically linked to the recorder which plots the profilogram.

2.4 **Recorder.** An assembly which mechanically records vertical irregularities of the profile wheel onto the profilogram.

2.5 **Scallop.** Vertical deviations recorded on the profilogram.

2.6 Blanking Band. Opaque band on a plastic scale within which scallops are not included in the profile index.

2.7 Profile Index. Cumulative total of scallops extending beyond the blanking band measured over a distance on the pavement of 0.1 mi (0.16 km).

3.0 SIGNIFICANCE AND USE.

3.1 There shall be one profilograph test performed in the right wheel path of each lane equaling or not exceeding 12 ft (3.6 m) in width. The profilograph test shall be conducted approximately 3 ft (1 m) from and parallel to the edge of pavement in the direction of traffic movement.

3.2 There shall be two profilograph tests performed in a lane exceeding 12 ft (3.6 m) in width. The two profilograph tests shall be performed and each shall be conducted approximately 3 ft (1 meter) from and parallel to each edge of the lane's pavement.

3.3 The profile index for each lane equaling or not exceeding 12 ft (3.6 m) in width will be evaluated from the one profile for each 0.1 mi (0.16 km) segment. The profile index for a lane exceeding 12 ft (3.6 m) in width will be evaluated and computed as the average of the two profiles over each 0.1 mi (0.16 km) segment. Termini for each 0.1 mi (0.16 km) segment will be determined during the evaluation of the profile.

4.0 APPARATUS.

4.1 Profilograph. The condition of the profilograph shall be checked periodically. The profilograph shall be inspected at least once each year before the start of construction activity. Repairs and replacement of damaged or worn parts shall be made before the annual certification of the machine. The following checklist will be used for the inspection.

4.1.1 Certification Checklist.

(a) Check for roundness and excessive wear to the profile wheel. Excessive wear is defined as the horizontal scale on the profilogram being incorrect by more than 2%.
(b) Check the return spring in the recorder for straightness or signs of overstressing. With the profilograph on a level surface, the spring should have at least 1 1/2 in. (38 mm) extension between the profile wheel in the up and the down positions.

(c) Check the cable and bead chain in the recorder for kinks and makeshift repairs.

(d) Check for missing frame alignment pins at each joint. Check for any appreciable movement at the frame joints.

(e) Check the carriage wheels for less than a 1 in. (25 mm) worn area across each tire.

(f) Check the steering rods for straightness and all joints for tightness when assembled.

(g) Check the rear wheels for tracking within 4 in. (100 mm) of the front wheels.

(h) Check the profile paper for smooth forward and reverse winding and snug fitting over the recording drum.

(i) Check the recorder pen assembly for proper drag on the guide rod. No adjustment should be necessary.

(j) The horizontal scale is checked by running the profilograph a known distance, normally 528 ft (0.16 m), and measuring the length of the profilogram. The horizontal scale of the profilogram to the pavement being profilographed is 1:300. Normally, the only adjustment to be made will be the replacement of the profile wheel when it becomes excessively worn.

(k) The vertical scale on the profilogram is a scale of 1:1. Before checking the vertical scale, the return spring shall be adjusted as in (b) above. A 1/8 in. (3.2 mm) piece of masonite or similar material is then placed under the profile wheel to provide a reference plane. The chart is then turned by hand to mark the paper. By adding strips under the profile wheel at 1/4 in. (6.3 mm), 1/2 in. (12.7 mm), and 3/4 in. (19.0 mm) thickness increments and marking each step on the paper as above, the actual scale may be determined. The pen assembly has a built-in dampening device where it connects to the cable, allowing approximately 0.01 in. (0.25 mm) movement of the cable before the pen moves. Because of this, the pen assembly should always be reset by moving the paper before and after each block is placed under the wheel.

4.2 Plastic Scale. The profile index is determined using a plastic scale 1.70 in. (43 mm) wide and 21.12 in. (536 mm) long. The profile index represents a pavement length of 0.1 mi (0.16 km) at a scale of 1:300. Near the center of the scale is the blanking band 0.2 in. (5 mm) wide extending the entire length of 21.12 in. (536 mm). On either side of this band are scribed lines 0.1 in. (2.5 mm) apart, parallel to the blanking band. These lines serve as a convenient scale to measure scallops.

4.3 Plastic Template. A plastic template is used for determination of high or low points. The template shall have a line 1 in. (25 mm) long scribed on one face with a small hole or scribe mark at either end, and a slot 0.3 in. (7.5 mm) from the parallel to the scribed line. See Figure 2. The 1 in. (25 mm) line corresponds to a horizontal distance of 25 ft (7.5 m) on the horizontal scale of the profilogram. The plastic template may be obtained from the Materials and Tests Division.

5.0 PROCEDURE.

5.1 Profile Index.

5.1.1 Profilograph Testing Limits. Testing with a profilograph will begin or end in accordance with the following:

- **(a)** All profilograph testing shall begin or end 50 ft (15 m) from each structure or existing pavement joined by new pavement.
- **(b)** The profilograph testing of sections 0.1 mi (0.16 km) or less containing a structure shall be conducted as if the structure plus 50 ft (15 m) on either side were not there.
- **(c)** The last 50 ft (15 m) of the day's paving operation shall be included with the profilograph testing of the next day's paving operation.
- **(d)** The profilogram will be recorded in such a manner so as to produce a continuous record from the beginning to the end of the pavement to be tested with the profilograph.
- **(e)** The profile index for each 0.1 mi (0.16 km) section of pavement represented on the profilogram shall be calculated separately.
- **(f)** The profile index for each section of pavement less than 0.1 mi (0.16 km) shall also be calculated separately.

5.1.2 Method of Counting. Place the plastic scale over the profile in such a way as to blank out as much of the profile as possible. When this is done, scallops above and below the blanking band will be approximately balanced. See Figure 1.

The profile trace will proceed from the generally horizontal alignment, proceeding around short radius curves, making it impossible to blank out the central portion of the trace without shifting the scale. The profile should be broken into short sections and the blanking band repositioned on each section while counting as shown in the upper part of Figure 2. The sum of the short sections will equal 21.12 in. (536 mm).

Starting at the right end of the scale, measure and cumulatively total the height of all the scallops appearing both above and below the blanking band, measuring each scallop to the nearest 0.05 in. (1 mm). For multiple peaked scallops, only the highest peak is counted. Write this total on the profile sheet near the left end of the scale together with small horizontal and vertical marks to align the scale when moving to the next section. Short portions of the profile line may be visible outside the blanking band due to rocks or dirt on the pavement. Unless the profile line projects vertically 0.3 in. (8 mm) or more above the zero line and extend longitudinally for 2 ft (610 mm) on the pavement, the bump will not be included in the count. See Figure 1 for illustration of these special conditions.

When scallops occurring in the first 0.1 mi (0.16 km) are totaled, slide the scale to the left, aligning the right end of the scale with the small marks previously made, and begin the counting the second 0.1 mi (0.16 km) in the same manner. If the last section counted is not an even 0.1 mi (0.16 km), its length should be scaled to determine its length in miles to the nearest 0.001 mi (1.5 m). From the example shown in Figure 1, the profile index is determined as follows for the 0.1 mi (0.16 km) section shown:

Length	=	0.1 mi (0.16 km)
Total Count	=	13.5 tenths of an in. or 1.35 in. (34 mm)
Profile Index	=	1.35 in. (34 mm)

5.2 High or Low Points in Excess of 0.3 in. (8 mm).

5.2.1 At each prominent high or low peak on the profile trace, place the template so that the small holes or scribe marks form a chord across the base of the peak or indicated bump. The line on the template need not be horizontal. With a sharp pencil draw a line using the narrow slot in the template as a guide. Any portion of the trace extending above this line for a high point or below this line for a low point will indicate the approximate length and height of the deviation in excess of 0.3 in. (8 mm).

There may be instances where the distance between easily recognizable high or low points is less than 25 ft (7.5 m) or 1 in. (25 mm) on the profilogram. In such cases a shorted chord length will be used in marking the scribed line on the template tangent to the trace at the high or low points. It is the intent of this requirement that the horizontal distance for measuring the height of bumps be as nearly 25 ft (7.5 m) or 1 in. (25 mm) on the profilogram as possible, but in no case to exceed this value. When the distance between prominent high or low points is greater than 25 ft (7.5 m) or 1 in. (25 mm) on the profilogram, position the ends of the scribed line to intersect the profilogram with the template in a nearly horizontal position. A few examples of the procedure are shown in the lower portion of Figure 2.

6.0 REPORT.

6.1 Responsibility. The Engineer will determine the profile index and high or low points from the original profilogram produced by either the Department or Contractor personnel. The Department will either operate the profilograph or closely monitor the profilograph being operated by the Contractor. Both the before grinding and after grinding profilograms will become part of the contract documentation. All computations for bonus incentive will be the responsibility of the Engineer.

6.2 Corrective Measures for Profile Indexes Outside Specified Tolerances. If the 0.1 mi (0.16 km) or less section of pavement exceeds the specified profile index, the Contractor shall select the individual areas to be ground. The Engineer will assist in this section at the written request of the Contractor.

The 0.1 mi (0.16 km) or less section of pavement having been ground will be retested with profilograph to determine compliance with specifications.

6.3 Corrective Measures for High or Low Points in Excess of 0.3 in. (8mm). The Engineer will verify that each individual high or low point in excess of 0.3 in. (8mm) requires bump grinding. Individual high or low points requiring grinding will be marked on the pavement from known check points on the profilogram.

Individual high or low points in excess of 0.3 in. (8mm) shall be reduced by grinding until such points do not exceed 0.3 in. (8mm) as indicated by additional runs of the profilograph.

Figure 1

English

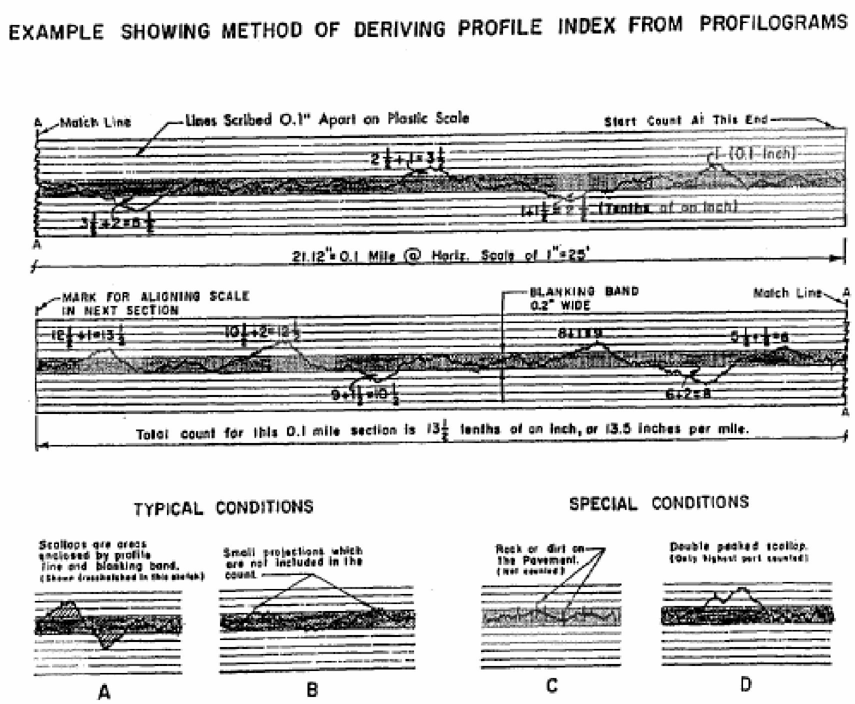


Figure 2

English

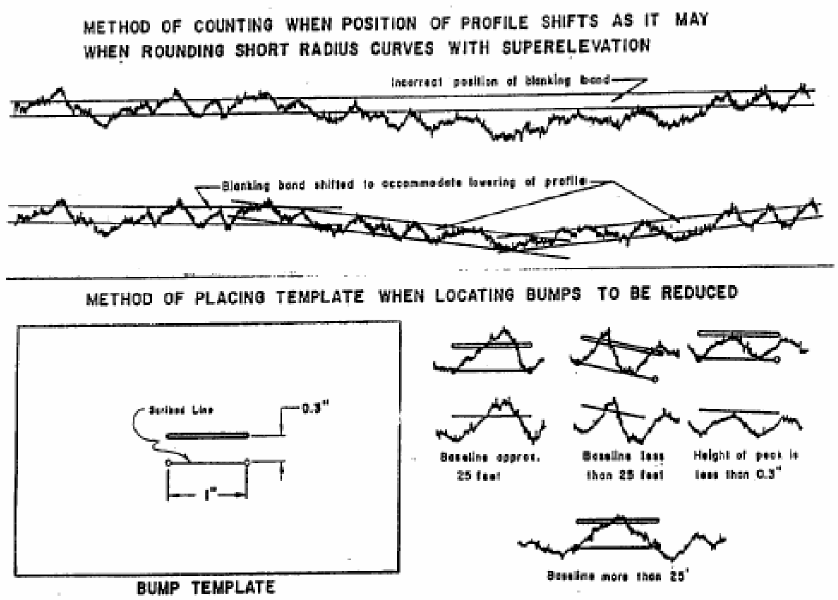


Figure II

APPENDIX B
Kansas Test Method KT-46
Determination of Pavement Profile with the Profilograph

5.16.46 DETERMINATION OF PAVEMENT PROFILE WITH THE PROFILOGRAPH
(Kansas Test Method KT-46)

a. SCOPE

This method of test covers the procedure for determining the smoothness, profile index, of both concrete and bituminous pavement using the California type 25-foot profilograph or equivalent. This version uses english units only. See **KT-54** for the SI metric version.

b. REFERENCED DOCUMENTS

b.1. KT-54; Determination of Pavement Profile with the Profilograph - “Metric Version”

c. APPARATUS

c.1. California type, 25-foot, profilograph or equivalent (Figure 1), with pointer. The 25-foot profilograph is a rolling straight edge; which measures vertical deviations from a moving 25-foot reference plane. The pavement profile is graphically recorded on a profilogram with scales of 300:1 longitudinally and 1:1 vertically.

c.2. Blanking band which is a plastic scale 1.70 inch wide and 21.12 inch long representing a pavement length of 528 ft or 0.1 mile at a scale of 1 inch = 25 feet. Near the center of the scale is a dashed line extending the entire length of the plastic scale. On either side of this dashed line are scribed lines 0.1 inch apart, parallel to the dashed line. These lines serve as a convenient scale to measure deviations of the profile trace above or below the dashed reference line. These deviations are called "scallops".

c.3. Scale graduated in 0.1 inch.

c.4. Medium point ballpoint pen with red ink or other color contrasting to the profile trace.

c.5. Electronic calculator.

c.6. Plain recording chart paper ***as specified by the manufacturer of the profilograph.***

c.7. Bump template which is a plastic template having a marked length one-inch long on one face, and a slot (or edge) parallel to the marked length. A distance equal to the maximum bump specified, 0.40 inch, separates the two reference lengths (Example, Figure 2). The 1 inch line corresponds to a longitudinal distance of 25 feet on the longitudinal scale of the profilogram.

d. CALIBRATION

d.1. ***All profilographs used on KDOT projects must be calibrated at least annually. Calibration must be checked any time the profilograph has been altered or repaired. The certification includes establishing the proper tire inflation pressure, checking the trueness of the tire travel, checking the chart scale factor, and checking vertical displacement of the sensing wheel.***

d.2. Each District and contractor using a profilograph shall establish a 500 to 1000 foot distance calibration test section on or near each project. This test section should be fairly straight, relatively flat and used periodically to check the longitudinal calibration ***and trace reproduction***.

d.3. Longitudinal calibration consists of pushing, at walking speed (approximately 3 mph), the profilograph over a pre-measured test distance (500 to 1000 feet) and determining the chart scale factor. Dividing the premeasured test distance in inches by the profilogram trace length, for the test distance, in inches will determine the scale factor. This factor ***shall*** be 300 ± 0.5. If the profilograph produces charts with a different scale factor, adjustment of the profilograph must be made to bring the scale factor within the tolerances specified above.

d.4. ***Vertical calibration consits of placing the center recording wheel of the profilograph on a base plate and recording the base elevation. Two plates 0.5 inches thick each are added under the center wheel one at a time and the change in elevation noted. The two plates are removed one at a time and the change in elevation noted. Each step in the process shall show a change in height of 0.5 inches ± 0.01 inch. If the profilograph produces results not conforming to the above limits, it must be adjusted to within the tolerance specified.***

d.5. The automatic trace reduction capability of a machine so equipped shall be checked by comparing the machine's results to the results obtained through manual trace reduction. The comparison shall be made for the trace obtained at the Materials and Research test section and for each project, at the project test section. The results of the comparison may not differ by more than 2.0 inches/mile. All calibration traces and calculations shall be submitted to the Materials and Research Center or to the appropriate construction office to become part of the project file.

e. TEST PROCEDURE

e.1. The profilograph is propelled at walking speed (approximately 3 mph) in the paths indicated for each section of pavement (see Figure 1). Propulsion may be provided by manually pushing or by a suitable propulsion unit such as a garden tractor. **DO NOT** push or pull a profilograph with a vehicle. More than one person may be required to hold the back end of the profilograph exactly in the required path on superelevated or sharp horizontal curves.

e.2. Use of the pointer to maintain the required trace path is mandatory.

e.3. If excessive "spikes" are encountered, decrease the rate of travel. An excessive number of "spikes" on a trace make it difficult to evaluate and may affect test results.

e.4. If possible, assemble the profilograph ahead of the location on the pavement where testing is to start. With the distance measuring wheel down and the pen in place on the trace paper, push the machine to the start position in the direction the test will be conducted. The center wheel should be the reference wheel. While the profilograph is stationary ***at the start location***, move the cable attached to the pen thus creating a spike mark on the trace and label that mark as the start location. ***Using t***his procedure ***at the beginning and end of each trace*** will ensure that all systems are working properly, that slack has been removed from the drive chains, and will clearly define the start ***and end*** location. ***Also mark which direction is up on the trace and the direction the profilograph was pushed.***

e.5. Push the profilograph in the same direction when recording each trace for a given section of pavement.

e.6. Indicate stationing on the profilogram at least every 500 feet***, using the procedure outlined in e.4.*** More frequent station references of every 100 feet or every 200 feet are highly desirable where possible. Station referencing on the trace is used to accurately locate 0.40 inch bumps. Notation of landmarks, roadway signs, etc. should also be made on the trace for additional referencing.

e.7. Completely label both ends of the profilogram with the project number, stationing represented on the roll and name of profilograph operators. Fill out a report form and secure it around the trace roll. This report insures that the person reducing the trace and reporting results will have all necessary information.

e.8. A little dirt or debris will spike out and not effect profilograph readings, however, excessive mud or caked mud must be removed prior to testing. Anything on the pavement surface longer than 2 to 3 inches may not be considered a spike when reducing the trace and should be removed.

e.9. When operating the profilograph, all wheels should always be on the pavement for which the contractor is responsible. Test from header to header whenever possible.

e.10. Pavement not tested at the end of a day's run due to barrier fences, machinery or other obstructions shall be included in a subsequent test run.

f. TRACE REDUCTION AND BUMP/*DIP* LOCATING PROCEDURE

f.1. Using a red (or other contrasting color), medium point, ballpoint pen; retrace the profilogram through the middle of any spikes. This outlining procedure removes spikes and minor deviations and generally smooths the trace for easier reduction and analysis.

f.2. Use a 0.40 inch bump template (scribed side down) to locate bumps***/dips*** for removal. At each prominent bump***/dip*** or high***/low*** point on the profile trace, place the template so that the scribe marks at each end of the scribed line intersect the profile trace to form a chord across the base of the peak***/valley*** or indicated bump***/dip***. The line on the template need not be horizontal. With a sharp pencil, draw a line using the narrow slot in the template (or edge) as a guide. Any portion of the trace extending above***/below*** this line will indicate the approximate length and height of the bump***/dip*** in excess of the specification.

There may be instances where the distance between easily recognizable low***/high*** points is less than 1 inch. In such cases a shorter chord length shall be used in making the scribed line on the template tangent to the trace at the low***/high*** points. It is the intent, however, of this requirement that the baseline for measuring the height of bumps ***(or depth of dips)*** will be as nearly 1 inch as possible, but in no case to exceed this value. When the distance between prominent low***/high*** points is greater than 1 inch, make the ends of the scribed line intersect the profile trace when the template is in a nearly horizontal position. A few examples of the procedure are ***shown in*** Figure 2.

After marking the bump***/dip*** on the profilogram, determine the station number of the center of the bump***/dip*** by scaling from the nearest reference mark. Enter the track identification and station on the KDOT Form 242 as shown in Figure 6.

f.3. Place the blanking band (scribed side down) over the profile with the dashed reference line as nearly centered on the profile trace as possible.

The profile trace **may** move from a generally horizontal position when going around superelevated curves making it impossible to follow the central portion of the trace without shifting the blanking band. When such conditions occur, the profile should be broken into short sections and the blanking band repositioned on each section as shown in the upper part of Figure 2.

Indicate the beginning and ending of superelevated curves on the profilogram at the time the profile trace is being made.

f.4. Begin evaluating each trace from the same point on the road so that sections representing the same length of road can be aligned on the test report form. Measure and total the height of all the scallops appearing both above and below the dashed reference line, measuring each scallop to the nearest 0.05 inch. Do not count a scallop as 0.05 inch just because you see the profile line or there is space under the line. Short sections of the profile line may be visible above or below the dashed reference line, but unless they project 0.03 inch or more vertically and extend longitudinally for 0.08 inch or more on the profilogram, they are not included in the count. Spikes are not counted. Double-peaked scallops are only counted once as the highest peak (Figure 3).

Write the total count in inches on the profilogram above the profile line (toward the center of the section) and circle it. Outline the position of the blanking band when reducing the trace for later repositioning to check trace reduction procedure. Rotate the blanking band about the previous end position when evaluating the next section (Figure 4).

When a scallop occurs at the end of the blanking band, count the scallop only once. Place the scallop in the 0.1 mile section where the peak is highest (Figure 4).

Always use the measured trace length in computations. This length may not agree exactly with distance by subtracting stationing. Always use ± after the total length on the report.

The measured roughness for each 0.1 mile section and for each track shall be entered on KDOT Form 242 in the appropriate column as shown in Figure 6.

f.5. The last section counted is generally not an even 0.1 mile. If not, its length should be scaled to determine its length in miles (Calculated to three decimal places). For the example shown below, the last section measures 7.60 ***inches*** in length.

(7.60 in) (25 ft/in)
------------------- = 0.036 miles 5,280 ft/mile

If the last section is less than or equal to 250 ft (0.047 mile), it is added to and included with the previous 0.1 mile section to determine compliance with the profile index. If the last section is more than 250 ft (0.047 mile), it is treated as a separate section.

When the profilograph must be picked up or partially disassembled and moved around an unpaved area or structure, a new section will be started.

The profile index is determined as inches/mile using the ***"zero"*** blanking band but is simply called the profile index. The procedure for converting counts (inches of roughness) to profile indices is illustrated in Figure 5. For 0.1 mile sections, the profile index can be determined from the counts (inches of roughness) by moving the decimal point one position to the right. For odd length sections, the profile index is determined by dividing the counts (inches of roughness) by the section length in miles. The weighted average for a day's run is determined by dividing the total counts (inches of roughness) for the day's run by the total length (in miles) of the day's run. (See Figure 6.)

g. REPORT

g.1. Contractors shall furnish and certify profilograph test reports, KDOT Form No.242. (Figure 6)

g.2. All profile traces (profilograms) become part of the Engineer's permanent project records.

h. OPERATOR CERTIFICATION

h.1. Basis of operator certification is attendance at an approved training school and comprehension of the material presented, or by having proof of certification by another agency with requirements similar to KDOT.

h.2. A contractor's personnel may be decertified if the test results vary from the KDOT results by more than what is regarded as normal test variation.

h.3. When a contractor's personnel are decertified to issue profilograph reports, such reports will not be recognized until corrections in testing, trace reduction and reporting are made to the satisfaction of the Engineer.

LOCATION OF PROFILE WHEEL

LANE EDGE OR CONSTRUCTION JOINT (PAINT STRIPE)

TRACE 3 ft FROM LANE EDGE

TRACE 3 ft FROM CONSTRUCTION JOINT

CONSTRUCTION JOINT OR LANE EDGE

PROFILOGRAPH

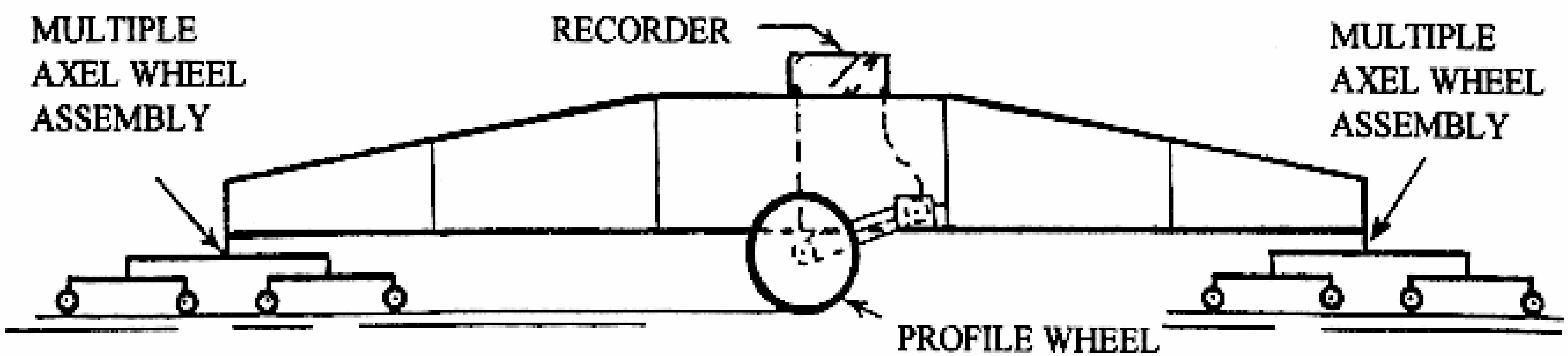
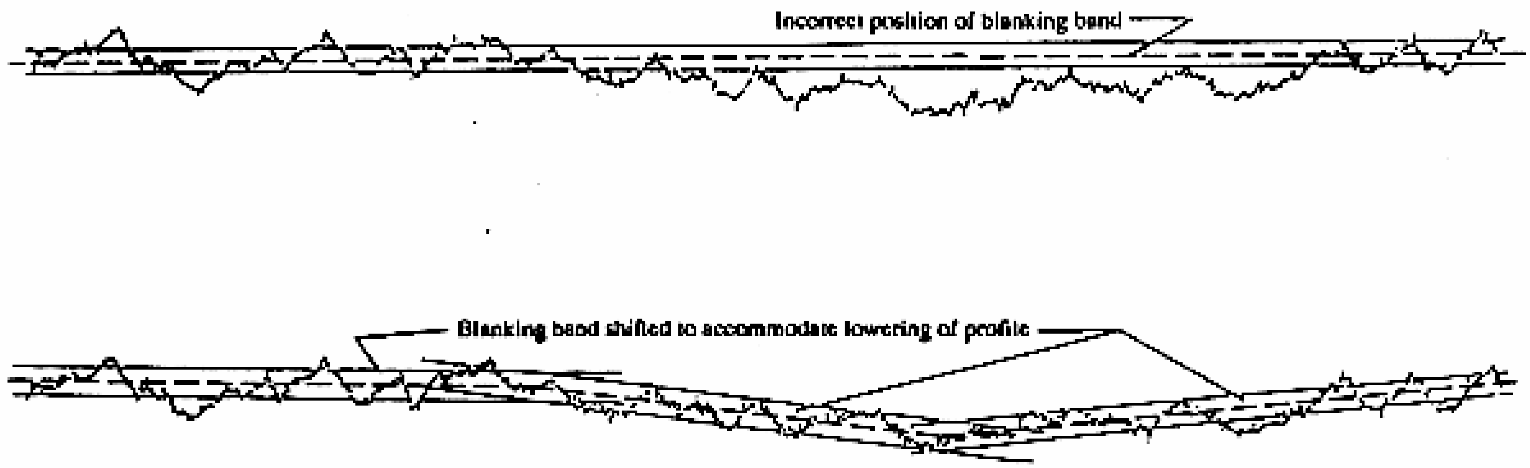


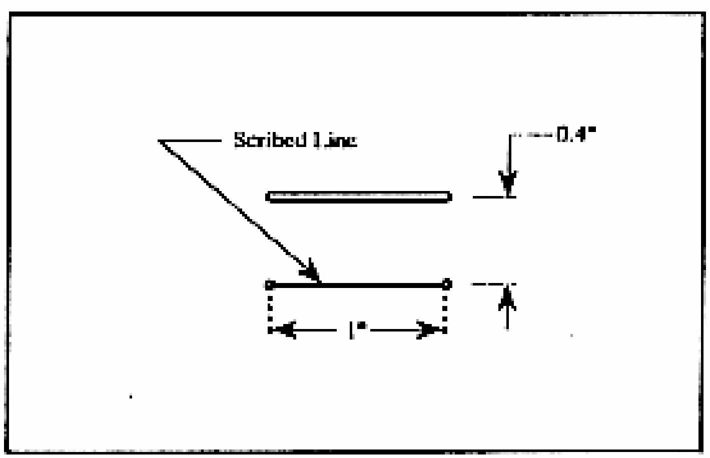
Figure 1.

Figure 3

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



METHOD OF PLACING TEMPLATE WHEN LOCATIONG BUMPS TO BE REDUCED



BUMP TEMPLATE

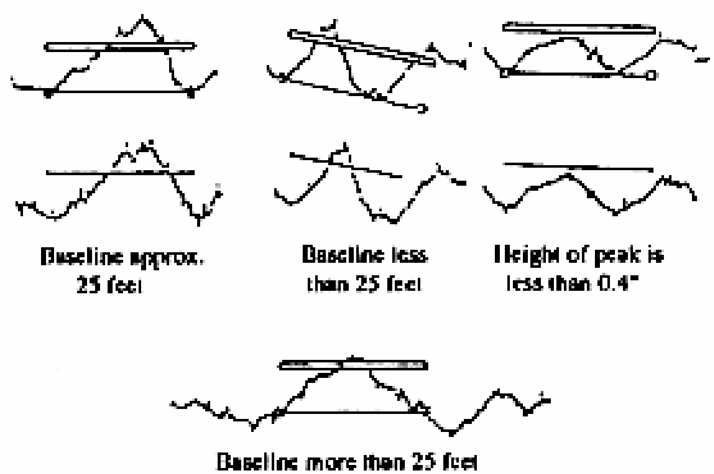
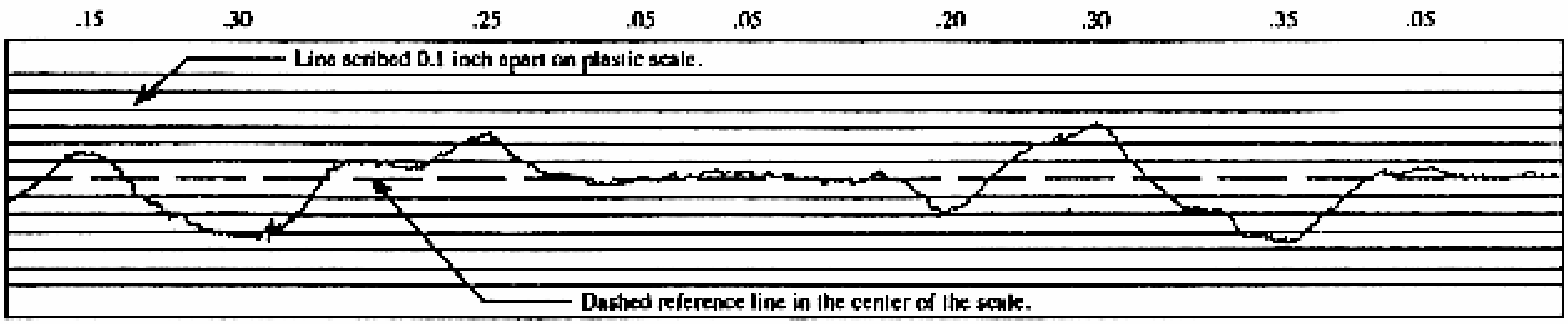


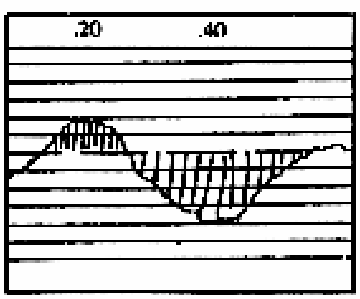
Figure 3

Example Showing Method of Deriving Profile Index From Profilogram

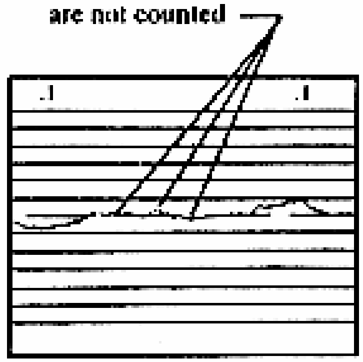


Total count for this 0.1 mile section is 1.70 inches (1.70 tenths of an inch).
Profile index for this 0.1 mile section is 1.70 inches per mile. (1.70 ÷ 0.1 = 17.0)

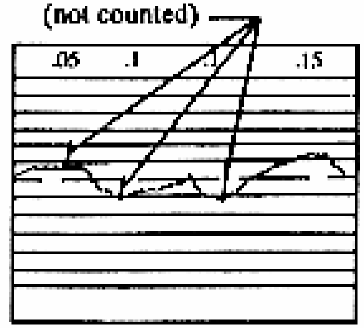
Scallops are areas enclosed by profile line and dashed reference line



Small projections which are not counted



Spikes caused by dirt or rock on the pavement (not counted)



Double scallop - only count the highter peak

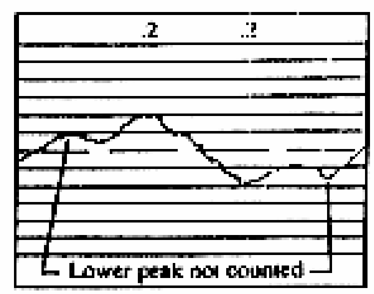
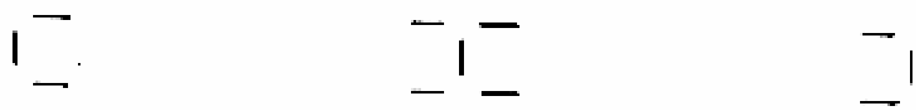


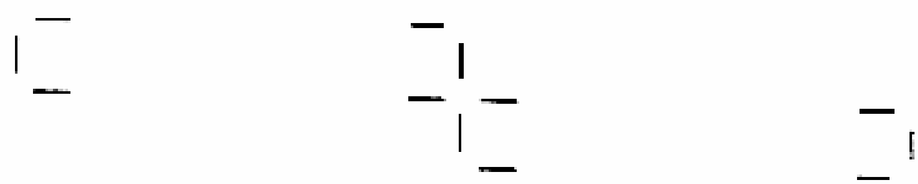
Figure 4

ROTATING BLANKING BAND ABOUT
LAST END POINT

This



Not This



SCALLOPS OCCURRING AT END
OF BLANKING BAND

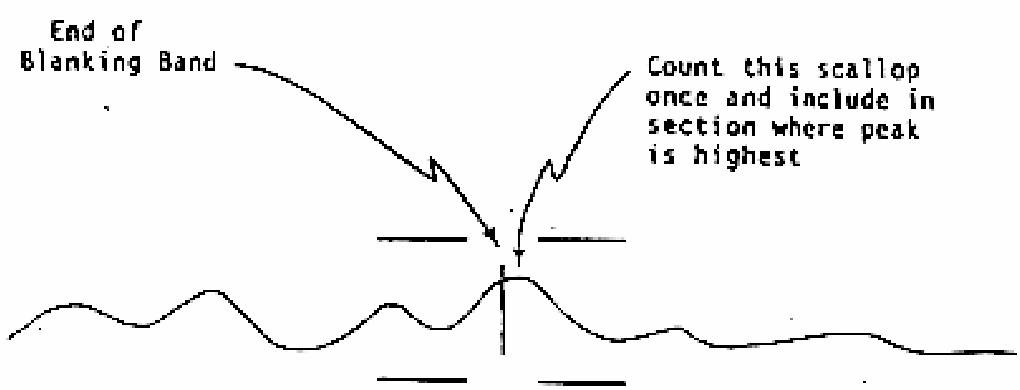


Figure 5

Procedure for Determining Profile Index

Segment Length (miles)	Inches of Roughness Shown on Trace	Reported Roughness (inches/mile)
Example A		
0.1	1.35	13.5
0.1	1.15	11.5
0.1	0.25	2.5
0.1	0.85	8.5
0.1	0.30	3.0
0.1	0.80	8.0
0.1	0.35	3.5
0.1	0.35	3.5
0.055 *	0.20	3.6(1)
0.855	5.60	6.5(2)

$$(1)\ \frac{0.20}{0.055} = 3.6$$

$$(2)\ \frac{5.60}{0.855} = 6.5$$

Segment Length (miles)	Inches of Roughness Shown on Trace	Reported Roughness (inches/mile)
Example B		
0.1	0.80	8.0
0.1	0.40	4.0
0.1	0.35	3.6(1)
0.037 *	0.15	----
0.337	1.70	5.0(2)

$$(1)\ \frac{0.35 + 0.15}{0.1 + 0.037} = 3.6$$

$$(2)\ \frac{1.70}{0.337} = 5.0$$

* See section (e)(5) of this test method.

Figure 6.

__X__ Information
Initial
___ Intermediate
___ Final

PROFILOGRAPH REPORT OF PAVEMENT SMOOTHNESS

Project No. 75-98 K 1234-01 County Trego

Contractor John Doe Construction Company Pavement Type PCC

Station 153+00 to Station 168+00 Traffic Direction EB

No. of Lanes 2 Direction of Paving EB

Date Placed (corrected) 8-9-94 Date Tested 8-10-94

Tested and Evaluated by Norman Lee

Paving Action 9 inch Reinforced PCC

Length (Miles)	Track 1 Measured Roughness (Inches)	Track 1 Profile Index (In./Mi.)	Track 2 Measured Roughness (Inches)	Track 2 Profile Index (In./Mi)	Track 3 Measured Roughness (Inches)	Track 3 Profile Index (In./Mi.)	Average Profile Index (In./Mi)
0.1	0.75	7.5	0.65	6.5			7.0
0.1	0.35	3.5	0.40	4.0			3.8
0.084	0.95	11.3	0.80	9.5			10.4
0.284	2.05	7.2	1.85	6.5			6.9 weighted Daily Average

Wheighted Daily Average Computation

2.05
1.85
3.90 inches / 2 tracks = 1.95 inches / 0.284 mile = 6.9 Average inches/mile

Bump Locations Track 2-None; Track 1-None

Certified by: Norman Lee

Title Chief Profilograph Pusher

Org'n John Doe Const. Co.

Figure 7.

PROFILOGRAPH REPORT OF PAVEMENT SMOOTHNESS

KDOT Form 242 Back Side

This form shall be prepared and submitted, along with the profilogram, within two working days of the placement or correction of concrete pavement or one working day for bituminous pavement.

The type of report is as follows:

Information - For check testing by Ks DOT and other situations not required to have testing.

Initial - All required testing of pavement for the first time (may be the only one).

Intermediate - After some corrective action that has not yet been completed.

Final - After all corrective action has been completed.

Pavement Type - PCC, HR, BM-1, etc.

Traffic Direction and direction of paving - NB, SB, EB, or WB depending on the design traffic flow of the numbered route.

Number of Lanes – the number of lanes placed at one time.

Paving Action – Mill (2"), Hot Recycle (2"), BM-1 (1 1/2"), etc.

Always compute a weighted daily average Wdt Daily Avg =

$$\frac{\textbf{Total count in inches}}{\textbf{No. of tracks x length}}$$

Bump locations are by station.

Distribution Field Office (1)
District Office (1)
Bureau of Const. & Maint. (1)
Pavement Surface Research Engineer (1)

APPENDIX C
INDOT Profilograph Traces

R-23925 (I-465, HMA)

WBDL		EBDL	
Site Number	$PI_{0.2}$, in/mi	Site Number	$PI_{0.2}$, in/mi
17+612-17+452	3.00	10+148-10+308	0.00
17+452-17+292	2.50	10+308-10+468	0.50
17+292-17+132	0.70	10+468-10+628	1.00
17+132-16+972	1.90	10+628-10+788	4.00
16+972-16+812	1.00	10+788-10+948	1.50
16+812-16+652	0.00	10+948-11+108	1.00
16+652-16+492	3.50	11+108-11+268	0.00
16+492-16+332	2.00	11+268-11+428	1.50
16+332-16+172	1.50	11+428-11+588	5.50
16+172-16+012	1.00	11+588-11+748	0.00
16+012-15+852	0.50	11+748-11+908	0.00
15+852-15+692	0.50	11+908-12+068	1.00
15+692-15+532	1.00	12+068-12+228	0.00
15+532-15+372	1.50	12+228-12+388	0.00
15+372-15+212	0.50	12+388-12+548	1.00
15+212-15+052	1.50	12+548-12+708	0.00
15+052-14+892	0.50	12+708-12+868	0.00
14+892-14+732	0.00	12+868-13+028	0.00
14+732-14+572	1.00	13+028-13+118	1.50
14+572-14+412	1.50	13+118-13+348	2.50
14+412-14+252	0.50	13+348-13+508	0.00
14+252-14+092	0.00	13+508-13+668	2.00
14+092-13+932	0.00	13+668-13+828	0.00
13+932-13+772	0.00	13+828-13+988	0.00
13+772-13+612	1.00	13+988-14+148	0.00
13+612-13+452	0.50	14+148-14+308	0.00
13+452-13+292	0.50	14+308-14+468	0.00
13+292-13+132	1.00	14+468-14+628	0.00
13+132-12+972	1.00	14+628-14+788	0.00
12+972-12+812	0.50	14+788-14+948	0.00
12+812-12+652	0.50	14+948-15+108	0.50
12+652-12+492	0.00	15+108-15+268	0.00
12+492-12+332	0.50	15+268-15+428	0.00
12+332-12+172	0.00	15+428-15+588	0.00
12+172-12+012	0.50	15+588-15+748	0.00
12+012-11+852	0.50	15+748-15+908	0.00
11+852-11+692	0.00	15+908-16+068	0.00
11+692-11+532	0.00	16+068-16+228	0.50
11+532-11+372	0.50	16+228-16+388	0.00

Continued from previous page

WBDL		EBDL	
Site Number	$PI_{0.2}$, in/mi	Site Number	$PI_{0.2}$, in/mi
11+372-11+212	0.50	16+388-16+548	1.00
11+212-11+052	0.00	16+548-16+708	0.00
11+052-10+892	0.00	16+708-16+868	4.00
10+892-10+732	0.00	16+868-17+028	0.00
10+732-10+572	3.00	17+028-17+188	0.50
10+572-10+412	1.00	17+188-17+348	0.00
10+412-10+252	1.00	17+348-17+508	2.00
10+252-10+092	0.00	17+508-17+668	2.00

R- 23901 (I-465, PCC)

WBML		WBRL	
Site Number	$PI_{0.2}$, in/mi	Site Number	$PI_{0.2}$, in/mi
20+130-19+969	1.50	20+135-19+974	1.00
19+969-19+808	0.00	19+974-49+813	0.00
19+808-19+647	0.00	19+813-19+652	0.00
19+647-19+532	0.00	19+652-19+532	1.00
19+410-19+251	2.00	19+417-19+256	2.00
19+124-18+963	0.00	19+256-19+242	0.00
18+963-18+802	2.00	19+124-18+963	0.50
18+802-18+641	0.50	18+963-18+802	1.50
18+641-18+480	2.00	18+802-18+641	0.50
18+480-18+319	1.00	18+641-18+480	2.50
18+319-18+158	0.00	18+480-18+319	1.00
18+158-17+997	0.00	18+319-18+158	0.00
17+997-17+836	0.50	18+158-17+997	0.50
17+836-17+675	0.00	17+997-17+836	0.00
17+675-17+514	0.00	17+836-17+675	0.50
17+514-17+353	2.00	17+675-17+514	0.00
17+353-17+192	0.50	17+514-17+353	6.00
17+192-17+031	0.50	17+353-17+192	1.00
17+031-16+870	1.50	17+192-17+031	1.50
16+870-16+709	1.00	17+031-16+870	0.00
16+709-16+549	0.50	16+870-16+709	0.50
16+549-16+388	1.00	16+709-16+549	0.50
16+388-16+227	2.50	16+549-16+388	1.00
16+227-16+159	1.00	16+388-16+227	1.00
16+046-15+952	1.00	16+227-16+159	1.00
–	–	16+046-15+952	0.00

R- 24290 (U-24, PCC)

WBPL		WBDL		EBDL		EBPL	
Site Number	$PI_{0.2}$, in/mi	Site Number	$PI_{0.2}$, in/mi	Site Number	$PI_{0.2}$, in/mi	Site Number	$PI_{0.2}$, in/mi
466+70-471+98	4.50	466+70-471+98	4.50	466+70-471+98	1.00	466+70-471+98	2.00
471+98-477+26	1.50	471+98-477+26	3.00	471+98-477+26	1.50	471+98-477+26	3.50
477+26-482+54	2.00	477+26-482+54	6.00	477+26-482+54	4.00	477+26-482+54	9.50
482+54-487+82	0.50	482+54-487+82	4.00	482+54-487+82	1.00	482+54-487+82	0.50
487+82-493+10	3.50	487+82-493+10	4.50	487+82-493+10	1.50	487+82-493+10	2.00
493+10-498+38	0.00	493+10-498+38	1.00	493+10-498+38	1.50	493+10-498+38	0.50
498+38-503+66	0.00	498+38-503+66	0.50	498+38-503+66	1.00	498+38-503+66	0.50
503+66-508+94	0.00	503+66-508+94	1.50	503+66-508+94	0.50	503+66-508+94	0.50
508+94-514+22	1.50	508+94-514+22	4.00	508+94-514+22	0.00	508+94-514+22	0.50
514+22-519+50	0.50	514+22-519+50	2.00	514+22-519+50	0.50	514+22-519+50	0.50
519+50-524+78	0.00	519+50-524+78	1.00	519+50-524+78	3.50	519+50-524+78	2.50
524+78-530+06	0.50	524+78-530+06	2.50	524+78-530+06	0.50	524+78-530+06	0.50
530+06-535+34	0.00	530+06-535+34	0.50	530+06-535+34	2.00	530+06-535+34	0.50
535+34-540+62	0.00	535+34-540+62	1.00	535+34-540+62	1.50	535+34-540+62	1.00
540+62-545+90	0.00	540+62-545+90	1.50	540+62-545+90	0.50	540+62-545+90	0.00
545+90-551+18	0.50	545+90-551+18	3.00	545+90-551+18	1.00	545+90-551+18	1.00
551+18-556+46	0.50	551+18-556+46	1.00	551+18-556+46	1.00	551+18-556+46	1.50
556+46-561+74	1.50	556+46-561+74	0.00	556+46-561+74	0.00	556+46-561+74	0.50
561+74-567+02	0.50	561+74-567+02	1.00	561+74-567+02	0.00	561+74-567+02	0.00
567+02-569+72	0.50	567+02-569+72	1.00	567+02-569+72	0.5	567+02-569+72	0.00

R-23719 (U-24, PCC)

EBRL		EBML	
Site Number	$PI_{0.2}$, in/mi	Site Number	$PI_{0.2}$, in/mi
139+50-134+15	0.00	102+05-107+40	0.50
134+15-128+80	1.00	107+40-112+75	1.00
128+80-123+45	1.00	112+75-118+10	1.00
123+45-118+10	1.00	118+10-123+45	1.00
118+10-112+75	1.00	123+45-128+80	4.50
112+75-107+40	0.00	128+80-134+15	0.00
107+40-102+05	1.50	134+15-139+50	0.00
WBRL		WBDL	
585+00-590+35	3.00	571+00-574+30	1.50
590+35-595+70	1.50	574+30-579+65	6.00
595+70-601+05	3.50	579+65-585+00	4.50
601+05-606+40	0.50	WBPL	
606+40-611+75	2.00	571+00-574+30	2.50
611+75-617+10	0.50	574+30-579+65	7.00
EBLL		579+65-585+00	5.50
102+05-107+40	0.50	WBLL	
107+40-112+75	0.50	617+70-611-75	4.00
112+75-118+10	3.50	611+75-606+40	5.50
118+10-123+45	0.00	606+40-604+05	1.00
123+45-128+80	2.00	601+05-595+70	5.50
128+80-134+15	1.00	595+70-590+35	6.00
134+15-139+50	0.50	590+35-585+00	2.50
WBLL		WBRL	
686+55-681+20	6.00	617+00-622+35	1.50
681+20-675+85	9.00	622+35-627+70	0.50
675+85-670+50	4.00	627+70-633+05	0.50
670+50-659+80	7.50	633+05-638+40	2.50
659+80-654+45	1.00	638+40-643+75	1.50
654+45-649+10	2.50	643+75-649+10	3.00
649+10-643+75	1.50	649+10-654+45	1.00
643+75-638+40	2.00	654+45-659+80	2.50
638+40-633+05	3.50	659+80-665+15	1.50
633+05-627+70	2.50	665+15-670+50	7.00
627+70-622+35	1.50	670+50-675+85	3.00
622+35-617+00	4.00	675+85-681+20	3.00
–	–	681+20-686+55	2.50

R-23719 (U-24, PCC)

EBPL		EBDL	
Site Number	$PI_{0.2}$, in/mi	Site Number	$PI_{0.2}$, in/mi
706+45-701+10	5.00	706+45-701+10	5.50
701+10-695+75	5.50	701+10-695+75	2.00
695+75-690+40	2.00	695+75-690+40	0.50
690+40-685+05	9.50	690+40-685+05	6.00
685+05-679+70	4.50	685+05-679+70	2.50
679+70-674+35	6.50	679+70-674+35	1.50
674+35-669+00	4.50	674+35-669+00	2.50
669+00-663+65	7.50	669+00-663+65	4.00
663+65-658+30	9.00	663+65-658+30	2.50
658+30-652+95	11.00	658+30-652+95	3.00
652+95-647+60	8.50	652+95-647+60	8.50
647+60-642+25	6.00	647+60-642+25	3.50
642+25-636+90	8.50	642+25-636+90	4.50
636+90-631+55	8.00	636+90-631+55	7.00
631+55-626+20	5.00	631+55-626+20	1.00
626+20-620+85	8.50	626+20-620+85	3.00
620+85-615+50	8.00	620+85-615+50	1.00
615+50-610+15	6.00	615+50-610+15	5.50
610+15-604+80	6.00	610+15-604+80	6.50
604+80-599+45	5.00	604+80-599+45	1.00
599+45-594+10	3.00	599+45-594+10	6.00
594+10-588+75	6.00	594+10-588+75	2.50
588+75-583+40	10.50	588+75-583+40	7.50
583+40-578+05	13.50	583+40-578+05	15.50
578+05-572+70	8.00	578+05-572+70	4.00
572+70-567+35	1.50	572+70-567+35	3.00

R-24058 (U-24, PCC)

WBDL		WBPL	
Site Number	$PI_{0.2}$, in/mi	Site Number	$PI_{0.2}$, in/mi
424+00-429+28	3.00	424+00-429+28	1.00
429+28-434+56	2.00	429+28-434+56	1.50
434+56-439+84	1.50	434+56-439+84	1.50
439+84-445+12	3.50	439+84-445+12	1.50
445+12-450+40	1.00	445+12-450+40	0.50
450+40-451+30	4.00	450+40-451+30	3.00
454+87-459+26	4.00	454+87-459+26	3.00
459+26-464+54	2.50	459+26-464+54	1.50
464+54-469+82	0.00	464+54-469+82	1.00
469+82-475+10	2.00	469+82-475+10	1.00
475+10-480+38	3.50	475+10-480+38	4.50
480+38-485+66	0.50	480+38-485+66	0.00
485+66-490+94	0.50	485+66-490+94	0.00
490+94-496+22	3.00	490+94-496+22	2.00
496+22-501+50	1.00	496+22-501+50	1.50
501+50-506+78	5.50	501+50-506+78	2.00
506+78-512+06	4.50	506+78-512+06	3.00
512+06-517+34	1.00	512+06-517+34	0.00
517+34-522+62	3.50	517+34-522+62	3.00
522+62-527+90	7.50	522+62-527+90	5.00
527+90-533+18	1.50	527+90-533+18	1.50
533+18-538+46	4.00	533+18-538+46	1.00
538+46-543+74	5.00	538+46-543+74	4.50
543+74-549+02	9.50	543+74-549+02	16.00
549+02-554+30	7.50	549+02-554+30	11.00
554+30-559+58	0.50	554+30-559+58	0.50
559+58-564+86	2.00	559+58-564+86	1.50
564+86-570+14	2.00	564+86-570+14	2.00
570+14-575+42	4.00	570+14-575+42	3.00

R-23900 (I-465, PCC)

NBCL		NBRL		NBLL		SBCL		SBLL	
Site Number	PI, mm/km	Site Number	PI, mm/km	Site Number	PI, mm/km	Site Number	PI, mm/km	Site Number	PI, mm/km
24+820-24+980	2.50	24+820-24+980	2.50	24+820-24+980	0.00	27+860-27+610	7.50	27+860-27+610	12.50
24+980-25+141	0.00	24+980-25+141	0.00	24+980-25+141	0.00	27+610-27+449	25.00	27+610-27+449	20.00
25+141-25+302	5.00	25+141-25+302	2.50	25+141-25+302	0.00	27+449-27+288	15.00	27+449-27+288	0.00
25+302-25+458	5.00	25+302-25+458	7.50	25+302-25+458	5.00	27+288-27+123	0.00	27+288-27+123	5.00
25+458-25+618	2.50	25+458-25+618	12.50	25+458-25+618	2.50	27+123-26+962	5.00	27+123-26+962	0.00
25+618-25+779	2.50	25+618-25+779	7.50	25+618-25+779	7.50	26+962-26+801	2.50	26+962-26+801	7.50
25+779-25+944	2.50	25+779-25+944	5.00	25+779-25+944	10.00	26+801-26+518	2.50	26+801-26+518	2.50
25+944-26+100	2.50	25+944-26+100	0.00	25+944-26+100	7.50	26+518-26+357	5.00	26+518-26+357	7.50
26+100-26+262	0.00	26+100-26+262	2.50	26+100-26+262	12.50	26+357-26+195	0.00	26+357-26+195	5.00
26+262-26+423	0.00	26+262-26+423	0.00	26+262-26+423	5.00	26+195-26+035	2.50	26+195-26+035	2.50
26+423-26+584	7.50	26+423-26+584	12.50	26+423-26+584	5.00	26+035-25+873	7.50	26+035-25+873	2.50
26+584-26+857	25.00	26+584-26+857	5.00	26+584-26+857	12.50	25+873-25+712	0.00	25+873-25+712	2.50
26+857-27+016	2.50	26+857-27+016	5.00	26+857-27+016	0.00	25+712-25+552	0.00	25+712-25+552	0.00
27+016-27+179	5.00	27+016-27+179	15.00	27+016-27+179	15.00	25+552-25+389	5.00	25+552-25+389	15.00
27+179-27+338	0.00	27+179-27+338	20.00	27+179-27+338	5.00	25+389-25+229	5.00	25+389-25+229	2.50
27+338-27+500	12.50	27+338-27+500	5.00	27+338-27+500	7.50	25+229-25+058	2.50	25+229-25+058	0.00
27+500-27+661	5.00	27+500-27+661	5.00	27+500-27+661	17.50	25+058-24+899	2.50	25+058-24+899	0.00
27+661-27+860	20.00	27+661-27+860	5.00	27+661-27+860	22.50	24+899-24+824	0.00	24+899-24+824	0.00

APPENDIX D
The Proper Use of the Profilograph and the Interpretation of Profilograms with 0.0-inch Blanking Band

Revised 05/01/03

INDIANA DEPARTMENT OF TRANSPORTATION
MATERIALS AND TESTS DIVISION

THE PROPER USE OF THE PROFILOGRAPH AND THE INTERPRETATION OF PROFILOGRAMS WITH 0.0-INCH BLANKING BAND
ITM No. 901-01T

1.0 SCOPE.

1.1 This test method covers the testing with a profilograph to evaluate the final smoothness of Portland Cement Concrete and HMA pavements. Such testing is performed to determine the profile indexes of all 0.1 mi (0.16 km) sections, and the locations of all individual high or low points having a deviation in excess of 0.3 in. (0.75 mm).

1.2 The values stated in either acceptable English or SI metric units are to be regarded separately as standard, as appropriate for a specification with which this ITM is used. Within the text, SI metric units are shown in parenthesis. The values stated in each system may not be exact equivalents; therefore each system shall be used independently of the other, without combining values in any way.

1.3 This ITM may involve hazardous materials, operations, and equipment. This ITM does not purport to address all of the safety problems associated with its use. It is the responsibility of whoever uses this ITM to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2.0 TERMINOLOGY.

2.1 **Profilograph.** An instrument used to measure vertical irregularities of pavement.

2.2 **Profilogram.** A continuous paper chart which records irregularities of the profile wheel from the reference plane established by the profilograph.

2.3 **Profile Wheel.** A wheel at the midpoint of the profilograph frame which is mechanically linked to the recorder which plots the profilogram.

2.4 **Recorder.** An assembly which mechanically records vertical irregularities of the profile wheel onto the profilogram.

2.5 **Scallop.** Vertical deviations recorded on the profilogram.

2.6 **Profile Index.** Cumulative total of scallops extending beyond the dashed reference center line on the plastic scale measured over a distance on the pavement of 0.1 mi (0.16 km).

3.0 SIGNIFICANCE AND USE.

3.1 There shall be one profilograph test performed in the right wheel path of each lane equaling or not exceeding 12 ft (3.6 m) in width. The profilograph test shall be conducted approximately 3 ft (1 m) from and parallel to the edge of pavement in the direction of traffic movement.

3.2 There shall be two profilograph tests performed in a lane exceeding 12 ft (3.6 m) in width. The two profilograph tests shall be performed and each shall be conducted approximately 3 ft (1 m) from and parallel to each edge of the lane's pavement.

3.3 The profile index for each lane equaling or not exceeding 12 ft (3.6 m) in width will be evaluated from the one profile for each 0.1 mi (0.16 km) segment. The profile index for a lane exceeding 12 ft (3.6 m) in width will be evaluated and computed as the average of the two profiles over each 0.1 mi (0.16 km) segment. Termini for each 0.1 mi (0.16 km) segment will be determined during the evaluation of the profile.

4.0 APPARATUS.

4.1 **Profilograph.** The condition of the profilograph shall be checked periodically. The profilograph shall be inspected at least once each year before the start of construction activity. Repairs and replacement of damaged or worn parts shall be made before the annual certification of the machine. The following checklist will be used for the inspection.

4.1.1 Certification Checklist.

(l) Check for roundness and excessive wear to the profile wheel. Excessive wear is defined as the horizontal scale on the profilogram being incorrect by more than 2%.

(m) Check the return spring in the recorder for straightness or signs of overstressing. With the profilograph on a level surface, the spring should have at least 1 1/2 in. (38 mm) extension between the profile wheel in the up and the down positions.

(n) Check the cable and bead chain in the recorder for kinks and makeshift repairs.

(o) Check for missing frame alignment pins at each joint. Check for any appreciable movement at the frame joints.

(p) Check the carriage wheels for less than a 1 in. (25 mm) worn area across each tire.

(q) Check the steering rods for straightness and all joints for tightness when assembled.

(r) Check the rear wheels for tracking within 4 in. (100 mm) of the front wheels.

(s) Check the profile paper for smooth forward and reverse winding and snug fitting over the recording drum.

(t) Check the recorder pen assembly for proper drag on the guide rod. No adjustment should be necessary.

(u) The horizontal scale is checked by running the profilograph a known distance, normally 528 ft (0.16 km), and measuring the length of the profilogram. The horizontal scale of the profilogram to the pavement being profilographed is 1:300. Normally, the only adjustment to be made will be the replacement of the profile wheel when it becomes excessively worn.

(v) The vertical scale on the profilogram is a scale of 1:1. Before checking the vertical scale, the return spring shall be adjusted as in (b) above. A 1/8 in. (3.2 mm) piece of masonite or similar material is then placed under the profile wheel to provide a reference plane. The chart is then turned by hand to mark the paper. By adding strips under the profile wheel at 1/4 in. (6.3 mm), 1/2 in. (12.7 mm), and 3/4 in. (19.0 mm) thickness increments and marking each step on the paper as above, the actual scale may be determined. The pen assembly has a built-in dampening device where it connects to the cable, allowing approximately 0.01 in. (0.25 mm) movement of the cable before the pen moves. Because of this, the pen assembly should always be reset by moving the paper before and after each block is placed under the wheel.

4.2 **Plastic Scale.** The profile index is determined using a plastic scale 1.70 in. (43 mm) wide and 21.12 in. (536 mm) long. The profile index represents a pavement length of 0.1 mi (0.16 km) at a scale of 1:300. At the center of the scale is a dashed line extending the entire length of 21.12 in. (536 mm). On either side of this band are scribed lines 0.1 in. (2.5 mm) apart, parallel to the dashed line. These lines serve as a convenient scale to measure scallops.

4.3 **Plastic Template.** A plastic template is used for determination of high or low points. The template shall have a line 1 in. (25 mm) long scribed on one face with a small hole or scribe mark at either end, and a slot 0.3 in. (7.5 mm) from the parallel to the scribed line. See Figure 1. The 1 in. (25 mm) line corresponds to a horizontal distance of 25 ft (7.5 m) on the horizontal scale of the profilogram. The plastic template may be obtained from the Materials and Tests Division.

4.4 Proscan System. An automated system for reduction of profilogram into Profile Index and for identifying locations of bumps and dips following the algorithm of manual reduction procedures.

5.0 PROCEDURE.

5.1 Profile Index.

5.1.1 Profilograph Testing Limits. Testing with a profilograph will begin or end in accordance with the following:

- **(g)** All profilograph testing shall begin or end 50 ft (15 m) from each structure or existing pavement joined by new pavement.
- **(h)** The profilograph testing of sections 0.1 mi (0.16 km) or less containing a structure shall be conducted as if the structure plus 50 ft (15 m) on either side were not there.
- **(i)** The last 50 ft (15 m) of the day's paving operation shall be included with the profilograph testing of the next day's paving operation.
- **(j)** The profilogram will be recorded in such a manner so as to produce a continuous record from the beginning to the end of the pavement to be tested with the profilograph.
- **(k)** The profile index for each 0.1 mi (0.16 km) section of pavement represented on the profilogram shall be calculated separately.
- **(l)** The profile index for each section of pavement less than 0.1 mi (0.16 km) shall also be calculated separately.

5.1.2 Manual Method of Counting.
Using a red (or other contrasting color), medium point, ballpoint pen, retrace the profilogram through the middle of any spikes. This outlining procedure removes spikes and minor deviations and generally smoothes the trace for easier reduction and analysis.

Place the blanking band (scribed side down) over the profile with the dashed reference line as nearly centered on the profile trace as possible.

The profile trace ***may*** move from a generally horizontal position when going around superelevated curves making it impossible to follow the central portion of the trace without shifting the blanking band. When such conditions occur, the profile should be broken into short sections and the blanking band repositioned on each section as shown in the upper part of Figure 1. Indicate the beginning and ending of superelevated curves on the profilogram at the time the profile trace is being made. The sum of the short sections will equal 21.12 in. (536 mm).

Starting at the right end of the scale, measure and cumulatively total the height of all the scallops appearing both above and below the dashed reference line, measuring each scallop to the nearest 0.05 in. (1 mm). For multiple peaked scallops, only the highest peak is counted. Write this total on the profile sheet near the left end of the scale together with small horizontal and vertical marks to align the scale when moving to the next section. Short portions of the profile line may be visible outside the blanking band due to rocks or dirt on the pavement. Unless the profile line projects vertically 0.03 in. (0.8 mm) or more above the zero line and extend longitudinally for 0.08 inch (2 mm) on the profilogram, the bump will not be included in the count. See Figure 2 for illustration of these special conditions.

When scallops occurring in the first 0.1 mi (0.16 km) are totaled, slide the scale to the left, aligning the right end of the scale with the small marks previously made, and begin the counting the second 0.1 mi (0.16 km) in the same manner. If the last section counted is not an even 0.1 mi (0.16 km), its length should be scaled to determine its length in miles to the nearest 0.001 mi (1.5 m).

5.1.3 Automated Method of Counting using Proscan System.

Begin by plugging in the scanner cord into the scanner port on the side of the Paper Transport Unit (PTU). Next, connect the computer and PTU with a serial cable. Place the trace to be scanned on the PTU and set the handheld scanner into the holding bracket.

Draw a 1 inch (25 mm) or longer line across the two ends of the section to be scanned as the start and end mark to tell the scanner where to begin and end scanning. Make sure that the paper is placed such that the start mark will pass under the scanner after the paper starts moving. It is also important that the line marking the end of the section be perpendicular to the length to the profilogram. Figure 3 shows an example of the starting mark.

Place the scanner bar into the guides on the side of the PTU, and slide the scanner so that the trace is centered in the window. Plug in the power cord and after approximately 20 seconds, the motor will start for 2 seconds and the paper will move forward a short distance. At this point the system should be ready to run.

Start the Proscan software that had been installed previously. A dialogue box will be prompted by the program to enter a file name. To begin collecting data, click on the ***Collect Data*** button at the top of the window (See Figure 4). This will start the scanning software and produce the window as shown in Figure 5.

Click the large ***Scan Trace*** button at the top left of the window and fill in the various dialogue boxes with the requested data and press the ***Accept Data*** to start acquiring the trace. The PTU should begin moving the paper. Once the scanner sees the start mark it will begin recording the data. It will continue until it reaches the end mark, which is identical in description to a start mark. Once the end mark is reached, the scanner will stop recording and the paper will no longer advance. When done collecting data, close the scanner window and return to the base Profiler window.

Once all the data has been collected, the collected information may be viewed by exiting the collection window and returning to the Profiler window. The track could be viewed by clicking the ***Analyze Data*** button or double clicking on the track listed in the window. The window as shown in Figure 6 will appear that will display the report and different features could be selected to be displayed.

For detailed description of the trace reduction procedure and the Parameter settings, please refer to the Proscan user manual by Devore Systems, Inc.

5.1.4 Parameter Setting of the Proscan System.

Segment Length: 528ft (0.16km) (Required by the specification)
Blanking Band: 0.0 inch (0.0mm) (Required by the specification)

Min Scallop Height: 0.03 inch (0.75mm) (Required by the specification)

Min Scallop Width: 2 feet (0.6m) (Required by the specification)

Scallop Resolution: 0.01 inch (0.25mm) (Recommended by the manufacturer. Refer to the user manual for the detailed description)

Filter Type: Moving Average (Recommended by the Manufacturer. Refer to the user manual for the detailed description)

Filter Gain: 1(Recommended by the Manufacturer. Refer to the user manual for the detailed description)

Defect Height: 0.3 inch (7.5mm) (Required by the specification)

Defect Width: 25 ft (7.5m) (Required by the specification)

5.2 High or Low Points in Excess of 0.3 in. (7.5 mm).

5.2.1 Manual Method of Counting.

At each prominent high or low peak on the profile trace, place the template so that the small holes or scribe marks form a chord across the base of the peak or indicated bump. The line on the template need not be horizontal. With a sharp pencil draw a line using the narrow slot in the template as a guide. Any portion of the trace extending above this line for a high point or below this line for a low point will indicate the approximate length and height of the deviation in excess of 0.3 in. (7.5 mm).

There may be instances where the distance between easily recognizable high or low points is less than 25 ft (7.5 m) or 1 in. (25 mm) on the profilogram. In such cases a shorted chord length will be used in marking the scribed line on the template tangent to the trace at the high or low points. It is the intent of this requirement that the horizontal distance for measuring the height of bumps be as nearly 25 ft (7.5 m) or 1 in. (25 mm) on the profilogram as possible, but in no case to exceed this value. When the distance between prominent high or low points is greater than 25 ft (7.5 m) or 1 in. (25 mm) on the profilogram, position the ends of the scribed line to intersect the profilogram with the template in a nearly horizontal position. A few examples of the procedure are shown in the lower portion of Figure 1.

5.2.2 Automated Method of Counting.

The locations of bumps and dips are identified following the manual procedures in the Proscan System and will be presented in the report automatically with their corresponding station numbers.

6.0 REPORT.

6.1 Responsibility. The Engineer will determine the profile index and high or low points from the original profilogram produced by either the Department or Contractor personnel. The Department will either operate the profilograph or closely monitor the profilograph being operated by the Contractor. Both the before grinding and after grinding profilograms will become part of the contract documentation. All computations for bonus incentive will be the responsibility of the Engineer.

6.2 Proscan Report. The Proscan report could be viewed and printed under the function of ***Analyze Data***. To print the report, click the ***Report*** button. Then, to print the current plot, click the ***Plot*** button. To print all the plots in the file, click the ***Plot All*** button. To preview either of these, click on the appropriate ***Preview*** button at the bottom of the window. After finished, click the ***Close*** button and exit the program. An example of the Proscan report is shown in Figure 7.

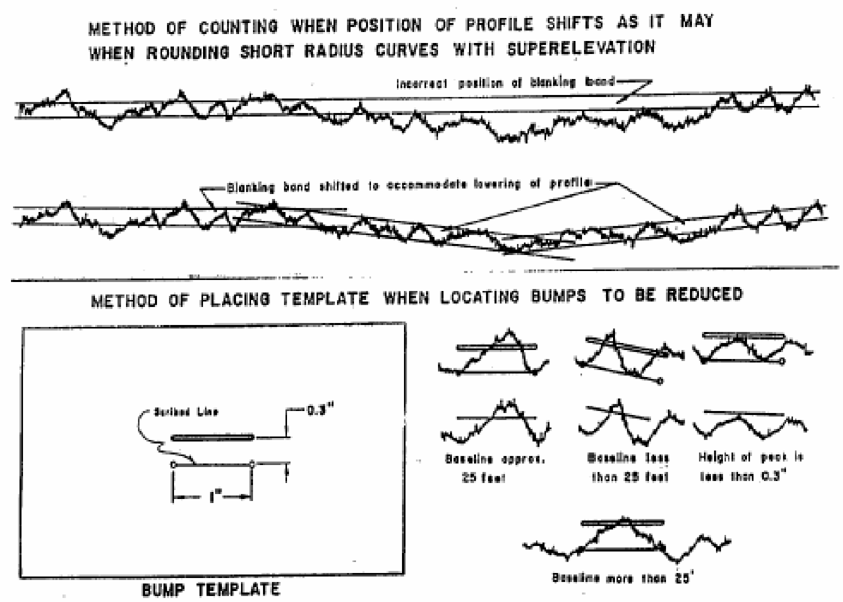
6.3 Corrective Measures for Profile Indexes Outside Specified Tolerances. If the 0.1 mi (0.16 km) or less section of pavement exceeds the specified profile index, the Contractor shall select the individual areas to be ground. The Engineer will assist in this section at the written request of the Contractor.

The 0.1 mi (0.16 km) or less section of pavement having been ground will be retested with profilograph to determine compliance with specifications.

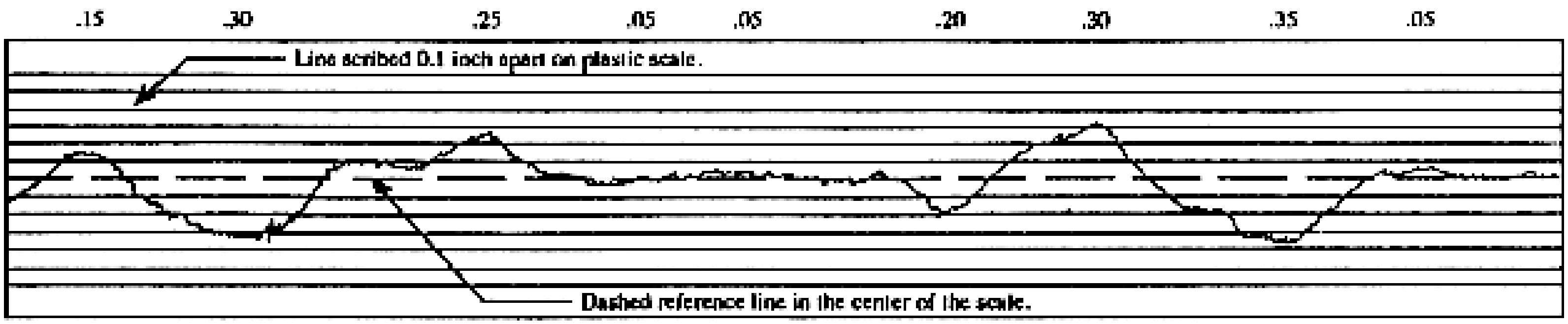
6.4 Corrective Measures for High or Low Points in Excess of 0.3 in. (7.5mm). The Engineer will verify that each individual high or low point in excess of 0.3 in. (7.5mm) requires bump grinding. Individual high or low points requiring grinding will be marked on the pavement from known check points on the profilogram.
Individual high or low points in excess of 0.3 in. (7.5mm) shall be reduced by grinding until such points do not exceed 0.3 in. (7.5mm) as indicated by additional runs of the profilograph.

Figure 1

English



Example Showing Method of Deriving Profile Index From Profilogram



Total count for this 0.1 mile section is 1.70 inches (1.70 tenths of an inch).
Profile index for this 0.1 mile section is 1.70 inches per mile. (1.70 ÷ 0.1 = 17.0)

Scallops are areas enclosed by profile line and dashed reference line

Small projections which are not counted

Spikes caused by dirt or rock on the pavement (not counted)

Double scallop - only count the highter peak

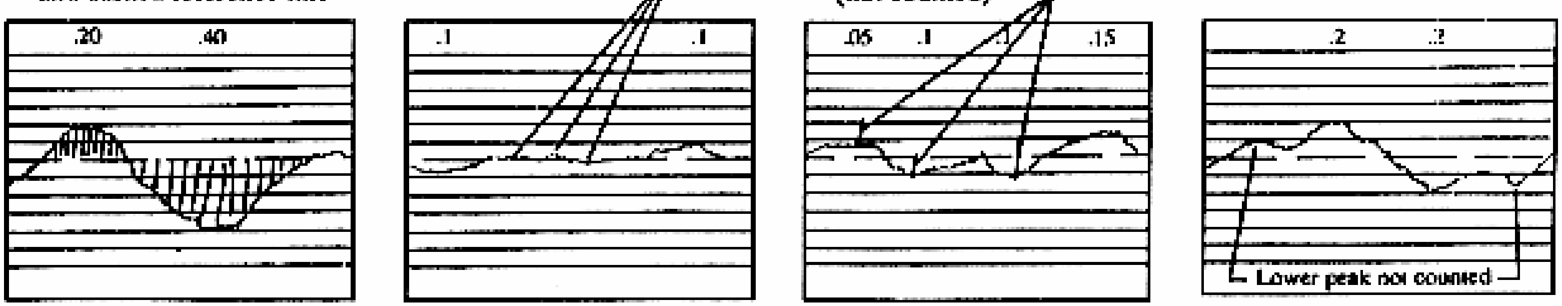


Figure 3

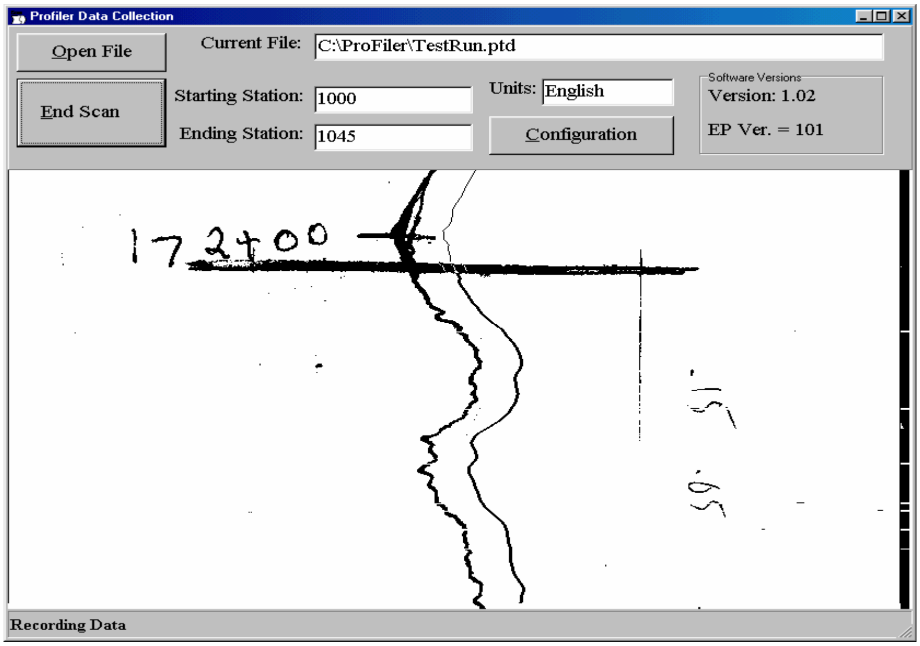


Figure 4

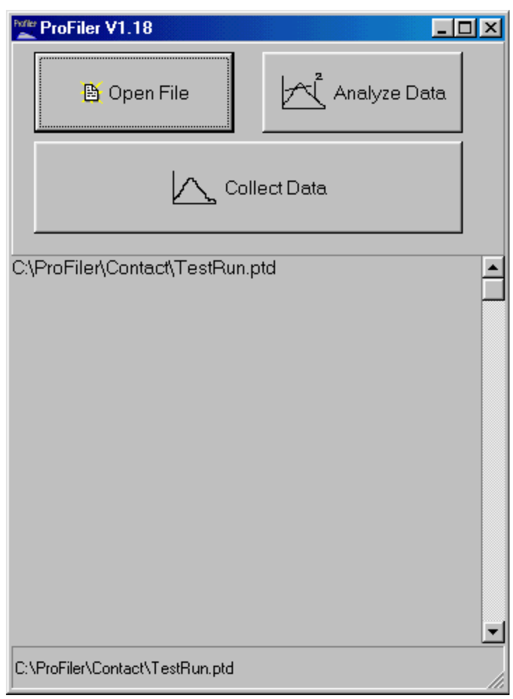


Figure 5

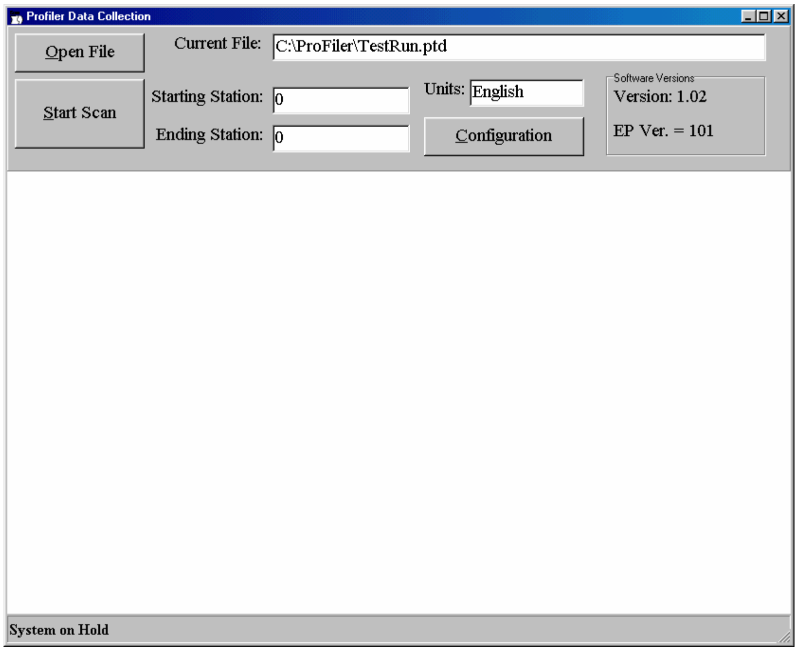


Figure 6

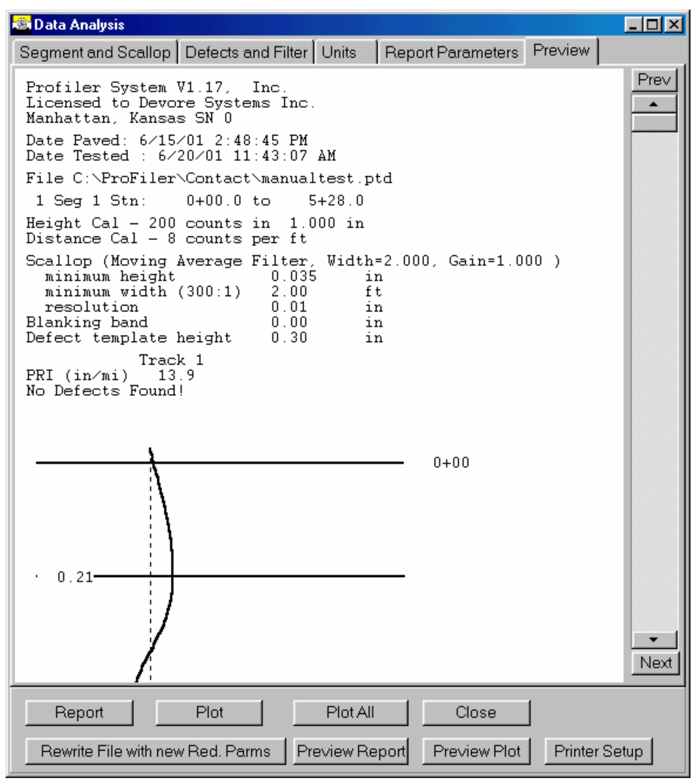


Figure 7

```
ProFiler - Report of Pavement Smoothness
  Licensed to Purdue University
          of West Layfwayette, IN
             Serial # 18

Project No: 1
County: White
Contractor: Rieth Riley
Pavement Type: Asphalt
Station    0+00.0 to station   21+09.4
Traffic Direction: Up
Number of Lanes: 2
Direction of Paving: North
Date [Paved/Corrected]: 3/1/2003 9:42:00 PM
Date Tested: 3/1/2003 9:55:00 PM
Tested by Shao-Fan Chou
      (Using ProFiler V1.20)
Paving Action:
Special Prov:
Weather: XX
```

Seg	Leng (mi)	Track 1 Rough (in)	Track 1 PRI (in/mi)	Avg PRI (in/mi)
1	.100	1.52	15.2	15.2
2	.100	0.84	8.4	8.4
3	.100	1.13	11.3	11.3
4	.100	1.07	10.8	10.8
	.400	4.56	11.4	11.4

```
Defect Locations:
 (d,1,1)    0+02.0 to    0+13.5

Scallop (Moving Average Filter width 1.88)

     min height      0.030 in
     min width       2.00  in
     resolution      0.01  in
   Blanking band     0.00  in
   Defect template   0.30  in


   Certified by:________________________________________

   Title:       ________________________________________

   Organization:________________________________________

   File C:\ProScan\Data\18new1.ptd
```

APPENDIX E
Profilograph Field Test Data

Road	Site Number	Manual 0.0"	Manual 0.2"	LISA 0.0"	LISA 0.2"	Proscan 0.0”
US -52 (SBDL)	19+20-19+30	12.00	0.50	19.90	1.30	10.20
	19+30-19+40	22.50	4.00	18.70	1.20	20.00
	19+40-19+50	17.50	1.50	23.50	4.00	15.00
	19+50-19+60	18.00	2.00	18.00	1.40	13.80
	19+60-19+70	21.00	5.00	15.60	1.10	16.10
	19+70-19+80	14.00	1.00	20.00	1.80	12.90
	19+80-19+90	18.00	1.50	15.00	1.00	15.90
	19+90-20+00	16.50	1.00	23.20	3.10	12.90
	20+00-20+10	14.00	0.00	14.70	0.00	12.40
	20+10-20+20	15.50	1.00	16.00	0.70	14.00
	20+20-20+30	19.00	1.50	19.00	0.60	15.80
	20+30-20+40	14.00	1.50	22.60	2.70	10.50
	20+60-20+70	10.00	1.00	14.00	0.60	9.50
	20+70-20+80	13.00	0.50	13.50	0.30	11.20
	20+80-20+90	7.50	0.00	11.00	0.60	5.80
	20+90-21+00	17.50	4.50	17.70	4.70	15.60
	21+00-21+10	16.50	2.00	11.00	0.40	12.20
	21+10-21+20	14.00	4.00	19.20	4.20	12.90
	21+20-21+30	17.50	6.00	17.50	2.30	18.50
	21+30-21+40	12.00	3.00	15.50	5.00	9.80
	21+40-21+50	9.50	2.00	8.50	0.50	8.60
	21+50-21+60	15.50	2.00	13.70	1.00	13.90
	21+60-21+70	13.50	1.00	19.20	2.80	11.70
	21+70-21+80	13.00	0.50	13.00	1.10	10.80
	21+80-21+90	13.00	1.50	15.00	0.40	11.80
	21+90-22+00	16.30	1.30	14.00	1.30	13.60
SR -18 (EBDL)	29+62-29+72	18.00	6.50	25.10	11.90	15.20
	29+72-29+82	12.50	0.50	12.00	0.00	8.60
	29+82-29+92	14.00	1.50	16.90	1.50	11.30
	29+92-30+02	13.00	1.00	11.70	0.70	11.00
	30+22-30+32	14.00	1.00	13.30	0.80	13.70
	30+32-30+42	17.50	2.00	17.80	2.20	13.20
	30+42-30+52	14.00	0.00	15.60	1.30	12.00
	30+52-30+62	14.00	0.00	15.00	0.30	13.10
	30+62-30+72	13.00	1.00	11.80	0.50	11.80
	30+72-30+82	10.00	1.00	11.80	0.00	7.40
	30+82-30+92	13.50	0.00	12.30	0.40	11.30
	30+92-31+02	12.00	2.00	10.90	0.40	10.90
	31+02-31+12	11.50	4.00	12.70	3.40	11.30
	31+12-31+22	11.00	0.50	11.60	0.00	8.70
	31+22-31+32	15.50	1.50	17.60	1.50	14.30
	31+32-31+42	10.50	1.00	13.50	0.70	9.00
	31+42-31+52	17.50	0.00	18.90	0.60	14.70
	31+52-31+62	23.50	1.50	24.40	1.70	22.00
	31+62-31+72	19.50	2.00	23.20	1.30	18.00
	31+72-31+82	17.00	2.50	18.40	1.10	13.00

Road	Site Number	Manual 0.0"	Manual 0.2"	LISA 0.0"	LISA 0.2"	Proscan 0.0”
SR -18 (EBDL)	31+82-31+92	21.00	3.50	23.50	2.30	17.00
	31+92-32+02	17.00	1.00	20.40	1.20	16.80
	32+02-32+12	20.50	1.50	20.70	1.40	21.10
	32+12-32+22	17.00	2.00	20.10	2.30	15.90
	32+22-32+32	12.00	0.00	16.60	0.40	11.00
	32+32-32+42	15.50	7.50	15.20	7.00	14.10
	32+42-32+52	17.50	3.50	19.80	6.50	15.10
	32+52-32+62	22.00	2.00	20.40	1.90	17.50
	32+62-32+72	15.50	0.00	22.60	0.00	12.60
	32+72-32+82	17.00	2.50	20.80	2.00	17.60
	32+82-32+92	10.00	0.50	19.60	0.00	9.80
	32+92-33+02	12.50	4.00	15.70	2.30	9.50
SR- 71 (EBDL)	220+63-225+91	19.50	5.00	23.00	7.40	14.60
	225+91-231+19	16.50	2.00	15.30	0.30	16.60
	231+19-236+47	21.50	5.50	23.00	4.80	18.80
	236+47-241+75	8.50	0.50	14.80	0.90	9.30
	241+75-247+03	12.50	2.00	13.20	0.70	8.80
	247+03-252+31	12.00	4.00	15.20	3.20	10.10
	252+31-257+59	18.50	8.00	18.60	8.30	14.30
	257+59-262+87	10.00	1.50	10.50	2.30	7.60
	262+87-268+15	19.00	3.50	17.70	4.30	12.70
	268+15-273+43	14.50	7.50	20.30	6.90	12.20
	273+43-278+71	16.50	8.50	18.00	5.30	11.80
	278+71-283+99	16.50	3.00	18.50	6.30	16.60
	283+99-289+27	20.50	6.00	21.20	4.90	19.60
	289+27-294+55	20.00	6.50	18.60	9.50	15.70
	294+55-299+83	13.50	3.00	15.30	1.40	9.80
	299+83-305+11	15.00	4.00	14.00	3.10	10.80
	305+11-310+39	17.00	7.50	17.70	5.20	12.40
	310+39-315+67	18.50	8.00	19.40	6.80	16.70
	315+67-320+95	21.00	8.00	22.30	9.90	20.50
	320+95-326+23	18.00	6.00	15.00	2.30	12.80
	326+23-331+51	19.00	7.50	15.90	3.10	13.50
	331+51-336+79	14.00	6.50	21.30	5.60	16.60
	336+79-342+07	16.50	8.00	20.20	1.90	15.60
	342+07-347+35	15.50	6.00	17.80	7.30	15.50
	347+35-352+63	19.50	8.50	16.80	8.40	11.50
	352+63-357+91	15.00	7.00	16.70	3.00	11.10
	357+91-363+19	15.50	3.00	20.90	4.80	12.00
	363+19-368+47	25.00	10.00	16.40	3.70	24.80
	368+47-373+75	17.50	10.00	17.70	8.80	15.80
	373+75-379+03	20.00	3.00	22.10	2.30	18.70
	379+03-384+31	13.50	3.00	14.40	3.00	13.90
	384+31-389+59	11.50	3.50	13.70	3.40	11.70
	389+59-394+87	11.50	1.00	14.80	1.60	11.00

Road	Site Number	Manual 0.0"	Manual 0.2"	LISA 0.0"	LISA 0.2"	Proscan 0.0”
SR- 71 (EBDL)	394+87-400+15	16.00	4.00	14.20	1.50	13.10
	400+15-405+43	10.00	2.00	12.50	2.20	8.20
	405+43-410+71	12.50	2.50	18.60	2.80	9.70
SR-231 (NBDL)	285+00-290+28	20.10	3.00	27.00	2.60	22.60
	290+28-295+56	27.20	7.90	37.00	14.70	33.00
	295+56-300+84	28.20	6.60	27.00	5.00	24.20
	300+84-306+12	25.20	4.50	30.50	6.00	22.00
	306+12-311+40	21.40	0.60	17.00	0.50	13.00
	311+40-316+68	31.90	8.80	31.00	9.00	24.80
	316+68-321+96	29.00	6.10	29.00	6.50	25.70
	321+96-327+24	30.40	3.60	27.50	2.50	22.00
	327+24-332+52	69.20	40.10	70.50	45.00	64.10
	285+00-290+28	20.10	3.00	27.00	2.60	22.60