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16. Abstract

The Texas Department of Transportation (TxDOT) is implementing a ride specification that uses profile data collected with inertial profilers for acceptance testing of the finished surface. The ride specification, Item 585, is applicable for either hot-mix asphalt or Portland cement concrete pavements and uses the international roughness index computed from profile measurements to quantify the level of ride quality achieved from construction. Prior to this project, TxDOT did not have a standard ride specification for surface treatments over flexible base courses. Since this pavement type comprises a significant percentage of the state highway network, improving the ride quality of surface treatments is of concern to TxDOT engineers responsible for achieving ride quality standards within their districts. To this end, a standard ride specification was necessary to assure (among other factors) that surface treatments are built with acceptable levels of ride quality. This report documents the work performed to establish applicable criteria for a flexible base ride specification. Through a cooperative effort with TxDOT engineers, researchers evaluated proposed criteria using ride data collected from district projects and investigated the effect of texture on ride quality measurements. Based on the analyses of data collected from laboratory and field tests, researchers found that the requirements given in the flexible base ride specification are appropriate to use for acceptance testing of the ride quality of flexible base on surface treatment projects. Applicable recommendations for implementing the specification are provided in the report.

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FLEXIBLE BASE RIDE SPECIFICATION DEVELOPMENT AND EVALUATION

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DISCLAIMER

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

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The work reported herein was conducted as part of a research project sponsored by the Texas Department of Transportation and the Federal Highway Administration. The authors are grateful for the support and guidance of Carl Bertrand and Brian Michalk, the two directors that served this research project. In addition, the contributions of the following individuals are noted and sincerely appreciated:

- Caroline Herrera of TxDOT's Construction Division took the lead in developing a standard flexible base ride specification. She prepared the initial draft of this specification that researchers evaluated in this project.
- Steve Smith of the Odessa District, Glen Dvorak of the Yoakum District, and Jim Voss of the Atlanta District provided ride data on surface treatment projects that researchers used to assess the applicability of proposed criteria in the flexible base ride specification.
- Gerry Harrison and Lee Gustavus of the Texas Transportation Institute (TTI) set up the equipment and fabricated the specimens of simulated surface treatments that researchers tested to investigate the effects of texture on ride quality measurements. Gerry Harrison also ran the laboratory and field tests conducted as part of this investigation.

TABLE OF CONTENTS

Page

LIST OF FIGURES

FIGURE Page

FIGURE Page

LIST OF TABLES

TABLE Page

CHAPTER I. INTRODUCTION

The Texas Department of Transportation (TxDOT) is implementing a ride specification that uses profile data collected with inertial profilers for acceptance testing of the finished surface. The ride specification, Item 585, is applicable for either hot-mix asphalt or Portland cement concrete (PCC) pavements and uses the international roughness index (IRI) computed from profile measurements to quantify the level of ride quality achieved from construction. Prior to this project, TxDOT did not have a standard ride specification for surface treatments over flexible base courses. However, two districts, Atlanta and Yoakum, have each implemented a ride specification for surface treated pavements. In addition, a number of western districts (Odessa, Brownwood, and San Angelo) were already in the process of developing a smoothness specification for construction of surface-treated roads. Since this pavement type comprises a significant percentage of the state highway network, improving the ride quality of surface treatments is of concern to TxDOT engineers responsible for achieving ride quality standards within their districts. To this end, TxDOT conducted a cooperative research project with the Texas Transportation Institute to establish a standard ride specification that all districts can use for evaluating flexible base smoothness on surface treatment projects. To assist TxDOT in developing a smoothness specification for surface treatments, researchers in this project:

- reviewed current district practices for quality assurance (QA) testing of pavement smoothness on construction projects where the final surface consists of one- or two-course treatments over flexible base;
- with the cooperation of participating districts, conducted shadow testing of surface treatment projects to compile ride data on finished flexible base courses and surface treatments with which to establish levels of ride quality that can be achieved to verify proposed smoothness criteria on these pavements;
- conducted tests to verify the applicability of using inertial profilers for quality assurance testing of surface smoothness in a ride specification for surface-treated pavements; and
- participated in meetings conducted by TxDOT engineers with industry representatives to discuss proposed provisions in a draft smoothness specification for surface-treated roads.

PROBLEM STATEMENT

TxDOT districts are concerned with the poor ride quality that is being achieved on projects where the final surface consists of one-or two-course treatments overlying flexible base. The standard ride specification, Item 585, is not applicable for these projects. There is a clear and pressing need to develop a similar ride specification for surface-treated roads in order to improve the level of ride quality from construction. Already, a number of districts have taken the initiative to develop and implement general notes to assure the ride quality of finished flexible base. A special specification or provision in this regard will enable districts to test the ride quality from construction and provide remedial work to improve ride quality on areas of a project not meeting the requirements. By establishing a flexible base ride smoothness specification for statewide use, TxDOT can help promote uniformity in the current practice among the districts.

REVIEW OF DISTRICT PRACTICE

At the start of this project, the Atlanta and Yoakum Districts have already implemented a ride specification for surface-treated pavements. Atlanta began implementing a general note on flexible base ride smoothness in 2002. The initial version of the specification used by the district read as follows:

> *Lane smoothness will be accepted on the basis of an IRI profile of less than or equal to 125.0 inches per mile. The profile will be measured by the Department previous to the application of the surface treatment.*

In this initial specification, acceptance was based on the average IRI of the lane tested as computed from profile measurements collected by the district on the finished flexible base after application of the prime. Atlanta later revised its general note to require an average IRI (i.e., average of left and right wheel path IRIs) no greater than 125.0 inches per mile on 0.1-mile sections. The revised general note is presented below:

> *Roadway profile smoothness will be accepted on the basis of an IRI profile measured by the Department previous to the application of the surface treatment. No tenth (0.1) mile section will have an average IRI of greater than 125.0 inches per mile.*

Atlanta observed that average IRI values on projects involving surface treatments have decreased since implementation of its flexible base ride specification. The district also noted that contractors, for the most part, are able to provide the level of workmanship required to satisfy the IRI requirement in the specification.

In addition to Atlanta, the Yoakum District began implementing a flexible base ride specification in 2004. Unlike Atlanta's specification, Yoakum stipulates an IRI no greater than 125 inches per mile per wheel path (in lieu of an average IRI) as computed on 0.1-mile sections from inertial profile measurements provided by the contractor. Yoakum's general notes associated with ride quality on flexible base are given as follows:

> *Measure the ride quality of the base course for acceptance with a high-speed or lightweight inertial profiler certified at the Texas Transportation Institute located at the Riverside Campus near Bryan, Texas. Provide equipment and personnel certifications in accordance with Item 585. This work will not be paid for directly but will be subsidiary to pertinent bid items.*
>
> *Measure the ride quality of the base course after placement of the prime coat (see plans for type of prime coat). Ride quality will be accepted on an IRI value of 125 inches per mile or less for each wheel path for each 0.1-mile section of travel lane. Correct any individual 0.1-mile section not meeting the specified value by approved methods until the ride quality requirement is met. Provide all profile measurements to the Engineer within three days after placement of the prime coat in electronic data files using the format specified in Tex-1001S.*
>
> *Sections the Engineer determined to have failed to maintain the ride quality after placement of the prime coat (see plans for type of prime coat) will be re-profiled. Correct re-profiled sections that have an IRI value greater than 125 inches per mile for each wheel path for each 0.1-mile section of travel lane. Correct re-profiled sections until the ride quality requirement is met and perform the work at no additional expense to the Department.*
>
> *The above ride quality requirements are in addition to providing the geometric typical section as detailed on the plans.*

Yoakum noted that the IRI limit of 125 inches per mile is acceptable for the type of prime coat (RC250 with Grade 5 aggregate) the district typically places on flexible base. This criterion was established based on test data collected in-house. Yoakum's construction engineer commented that the IRI criterion may need to be lowered if an emulsion or MC30 is used to prime the base.

INITIAL DEVELOPMENT EFFORTS

A number of districts were also in the process of developing a smoothness specification for surface treatments at the beginning of this project. Specifically, Odessa, Brownwood, and San Angelo were collecting profile data on rehabilitation projects and reviewing historical data from TxDOT's pavement management information system (PMIS) to establish appropriate smoothness criteria for a ride specification on surface-treated pavements. These districts were considering a draft specification patterned after Item 585 with quality assurance tests done on the final riding surface and a pay adjustment schedule considered to be achievable based on historical IRI data from district projects. Preliminary data collected during this early development stage suggested using 100 inches per mile as a candidate break point between as-bid and penalty provisions and specifying a limiting IRI between 130 to 140 inches per mile to determine the need for corrective work.

During the initial year of this project, TxDOT's Construction Division also drafted a preliminary special provision to Item 585, which included amendments to this existing standard that specifically covered QA testing of ride quality for pavements consisting of surface treatments over flexible base. Among the proposed provisions in this preliminary draft specification are:

- Quality assurance tests are done on the finished base, with profiles measured after placement of the prime coat, unless otherwise directed by the engineer;
- Transverse profile of the finished base is measured using a straightedge. Corrections are made where grade deviations exceed 0.25 inch in 16 ft (measured longitudinally) or where grade deviations exceed 0.25 inch over the entire cross-section width.
- On 0.1-mile sections where the average IRI is greater than 125 inches per mile, the contractor performs corrective work to reduce the IRI to 125 inches per mile or less for each wheel path.

No pay adjustments (similar to the schedules used in Item 585) were included in this preliminary draft ride specification for surface treatments. In this project, researchers verified the proposed criteria by examining ride data collected on these pavements from shadow tests done of the draft specification on district construction projects. This approach was followed as the projects tested were let before the draft flexible base specification was approved. In addition to verifying the proposed draft criteria, researchers verified the applicability of using inertial profile data for acceptance testing of ride quality on pavements where the final surface consists of one- or two-course treatments over flexible base. To this end, researchers also conducted laboratory tests on samples of simulated surface treatments and field tests on full-scale sections to determine the effect of textured surfaces on IRIs computed from profile measurements. The remainder of this report documents the work performed to establish applicable criteria for a flexible base ride specification.

CHAPTER II. EXAMINATION OF RIDE DATA FROM DISTRICT PROJECTS

During the first year of this project, researchers examined ride data from surface treatment projects in the Atlanta, Odessa, and Yoakum Districts to determine the levels of ride quality that can be achieved on these pavements and establish the applicability of using inertial profilers for quality assurance testing of surface smoothness in a ride specification for surface-treated pavements. The districts provided ride data (consisting of profiles or summary ride statistics) on the following projects:

- Atlanta – FM9, FM699, FM1520, FM2517, FM2625, FM3098, SH8, SH49, and US259
- Odessa – FM307, FM2401, and SH349
- Yoakum – FM529, FM530, and FM2437

Since surface treatments are thin courses that are primarily placed to provide a riding surface and prevent surface moisture infiltration into the base and subgrade, the ride quality of the finished pavement will primarily depend on how well the flexible base has been placed. Consequently, researchers examined the IRIs determined from profile measurements made on the flexible base to verify the levels of smoothness that can be achieved on this layer.

RIDE QUALITY MEASUREMENTS ON FLEXIBLE BASE

Table 2.1 presents summary IRI statistics from projects in the Atlanta and Odessa Districts where ride measurements on the finished base (before placement of surface treatment) were available. The statistics shown characterize the distributions (illustrated in Figure 2.1) of the average IRIs determined at 0.1-mile intervals from the measured profiles. The authors note the following observations from the data presented:

- The average IRI criterion of 125 inches per mile in TxDOT's draft flexible base ride specification was readily achieved on the projects presented. On the Atlanta projects, about 81 percent of the sections met this criterion, while on the Odessa projects, the average IRIs on all sections were within 125 inches per mile.
- The average IRIs on the Odessa projects are markedly lower than the average IRIs on the Atlanta projects as reflected in the distributions given in Figure 2.1.

- The projects covered sections where the contractor achieved average IRIs on the flexible base that are comparable to average IRIs determined on rehabilitated or newly constructed dense-graded hot-mix asphalt concrete pavements. This observation is particularly evident on the Odessa projects where 80 percent of the sections tested had average IRIs ≦ 76 inches per mile.

Table 2.1. Summary Statistics on Average Flexible Base IRIs from District Projects.*

Statistic (inches/mile)	District	
	Atlanta	Odessa
Mean	104	67
Standard deviation	24	13
Minimum	50	40
Maximum	177	112
80^{th} percentile	124	76
85^{th} percentile	129	80
90^{th} percentile	132	83
95^{th} percentile	139	89
99^{th} percentile	175	96

* Data shown apply to flexible base before placement of surface treatment from measurements collected on Atlanta and Odessa projects. Yoakum uses RC250 with Grade 5 aggregate as prime coat on flexible base.

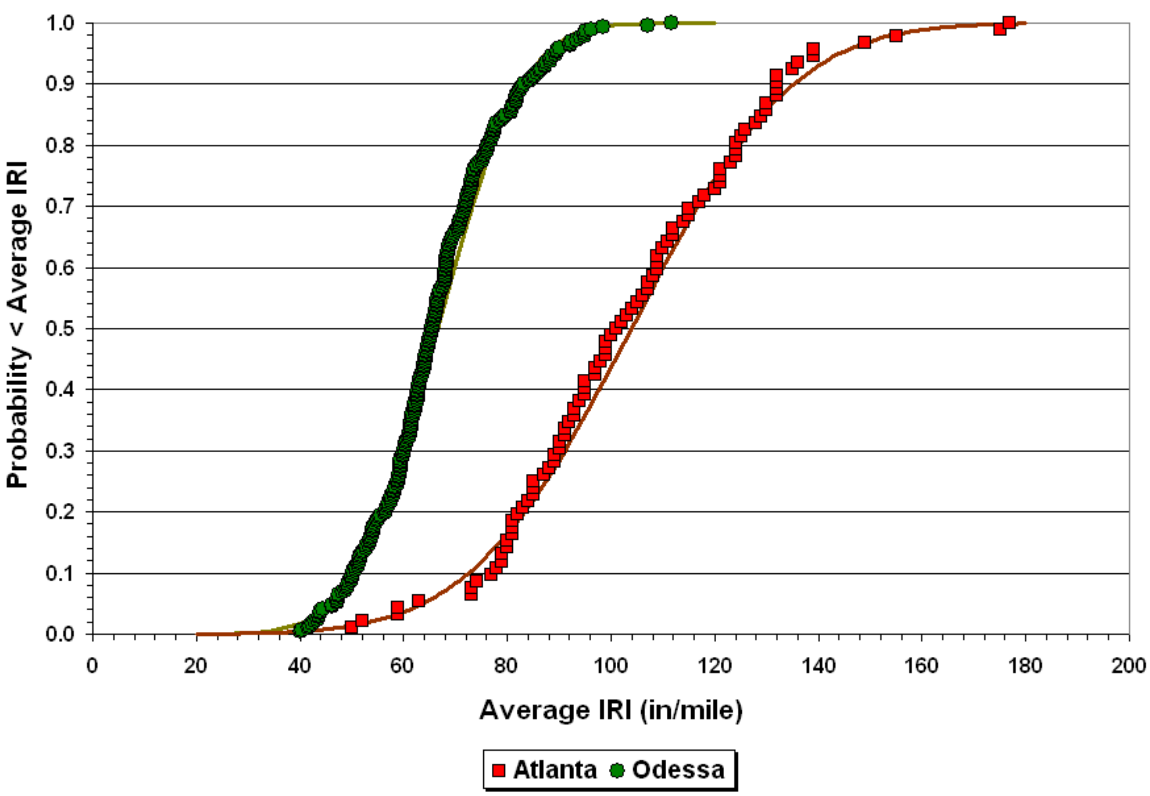


Figure 2.1. Cumulative Distributions of Average Flexible Base IRIs on Atlanta and Odessa Projects.

The above observations indicate that the proposed criterion of 125 inches per mile is realistic to use for quality assurance testing of flexible base smoothness on surface treatment projects. However, it also appears that there is room for reducing the average IRI criterion in the draft specification, particularly for projects located in areas with conditions similar to those found in the Odessa District where the average IRIs on the flexible base are markedly lower than the average IRIs on the Atlanta projects. This difference between the IRI distributions probably reflects the influence of a number of factors that can appreciably affect the quality of placement of the base material. Among these factors are:

- Terrain – a project that runs through terrain with vertical and horizontal curves poses a greater challenge to a contractor trying to achieve good ride quality on flexible base compared to a project situated on flat terrain with a straight alignment.
- Climate – rainfall can create problems in placing the base and affects the contractor's production, which is important to achieving good quality work. Obviously, projects located in drier areas encounter fewer weather-related problems compared to projects located in the wetter regions of the state.
- Base material – the type of base material specified for the project can affect the ease with which the contractor is able to finish the base by blading. Materials such as iron ore base (typically used in Atlanta) and the Type A Grade 6 flexible base typically specified in Odessa are easier to finish compared to materials such as granite and sandstone, which have been used on some surface-treatment projects in Atlanta.
- Construction traffic – vehicular traffic is usually permitted on surface treatment projects during construction with the contractor using flagmen to direct traffic and a pilot vehicle to guide motorists passing through the construction zone. After the day's work, the contractor typically removes the barricades and opens the project to traffic until construction resumes the following work day. Obviously, the amount of traffic and the type of traffic (heavy trucks versus light cars and pickups) can change the profile of the surface that has just been placed. Coping with the disturbances produced by vehicular traffic is another challenge contractors deal with on surface treatment projects.
- Control points – the contractor is usually responsible for setting up control points to establish slopes and grades following the existing highway centerline on rehabilitation projects where Item 5.6.C of the 2004 TxDOT standard specifications is

used. An inadequate number of control points or lack thereof can lead to inferior ride quality due to poor control of the finishing operations on the flexible base, resulting in improper or variable cross-slopes and surface defects.

- Motor grader operator – the ride quality of the flexible base is tied to the quality of the finishing work provided by the motor grader operator. Poor workmanship during finishing of the flexible base due to unskilled or inexperienced operators is often the reason why good ride quality is not achieved on surface treatment projects.

Given that profile measurements on the district projects were collected using profilers with conventional lasers that project dot-sized footprints, quality assurance testing of the base smoothness as stipulated in the draft specification appears to be appropriate based on the results obtained. As noted previously, numerous sections on the Odessa projects exhibited average flexible base IRIs comparable to values determined on resurfaced or newly constructed dense-graded hot-mix asphalt concrete pavements. Relative to the distribution of the average flexible base IRIs on the Odessa projects, the criterion of 125 inches per mile appears quite high given the level of smoothness achieved on the sections tested. This criterion appears to be more applicable to the Atlanta projects.

The average flexible base IRIs in Figure 2.1 follow a normal distribution as indicated by the good fit observed between the data points and the cumulative normal distribution curve fitted to the data. For each district, researchers used the average and standard deviation of the base IRIs to determine the cumulative normal distribution curves plotted as solid lines in Figure 2.1. Assuming the cumulative normal distribution to be representative for each district, researchers determined the interval about the mean that covers 95 percent of the area under the normal distribution curve. It was found that this interval ranges from 56 to 152 inches per mile for Atlanta and 41 to 93 inches per mile for Odessa. Note that the criterion of 125 inches per mile falls within the 95 percent interval for Atlanta, while for Odessa, the same criterion is outside the corresponding 95 percent interval. In terms of the probability of exceeding 125 inches per mile, researchers note that the probability is about 19 percent based on the cumulative normal distribution of the Atlanta flexible base IRIs. For this same probability of 19 percent, the corresponding IRI based on the cumulative normal distribution for Odessa is about 78 inches per mile. This number is quite a bit less than the proposed criterion of 125 inches per mile in the draft flexible base ride specification. Thus, while 125 inches per mile might be considered a suitable criterion in a flexible base ride specification intended for statewide use, the authors are of the opinion that language should be provided within the specification permitting a district to specify a different criterion if there is ample justification based on local experience.

RIDE QUALITY MEASUREMENTS AFTER PLACING SURFACE TREATMENTS

As part of providing information to TxDOT for establishing acceptance criteria applicable for surface-treated pavements, researchers also examined the IRIs from profile measurements collected on the surface treatments. Table 2.2 presents summary IRI statistics on the surface treatments from projects in the Atlanta, Odessa, and Yoakum Districts. The statistics shown characterize the distributions (illustrated in Figure 2.2) of the average IRIs determined at 0.1-mile intervals from the measured profiles. The authors note the following observations from the data presented:

- If the average IRI criterion of 125 inches per mile in TxDOT's draft flexible base ride specification is applied to the surface treatment, the number of 0.1-mile sections that meet this criterion are 66 and 84 percent, respectively, of the sections tested on the Yoakum and Atlanta projects. On the Odessa projects, all but one of the sections profiled have average IRIs ≦ 125 inches per mile.
- The average IRIs on the Odessa projects are markedly lower than the average IRIs determined on the Atlanta and Yoakum projects, as reflected in the distributions given in Figure 2.2. In addition, the average IRIs on the Odessa projects exhibit a narrower spread compared to the distributions from the Atlanta and Yoakum projects.

Table 2.2. Summary Statistics on Average IRIs Determined on Surface Treatments from District Projects.

Statistic (in/mile)	District		
	Atlanta	Odessa	Yoakum
Mean	99	80	115
Standard deviation	26	11	25
Minimum	49	59	55
Maximum	172	135	204
80^{th} percentile	122	88	133
85^{th} percentile	126	90	140
90^{th} percentile	133	93	148
95^{th} percentile	142	100	162
99^{th} percentile	157	114	183

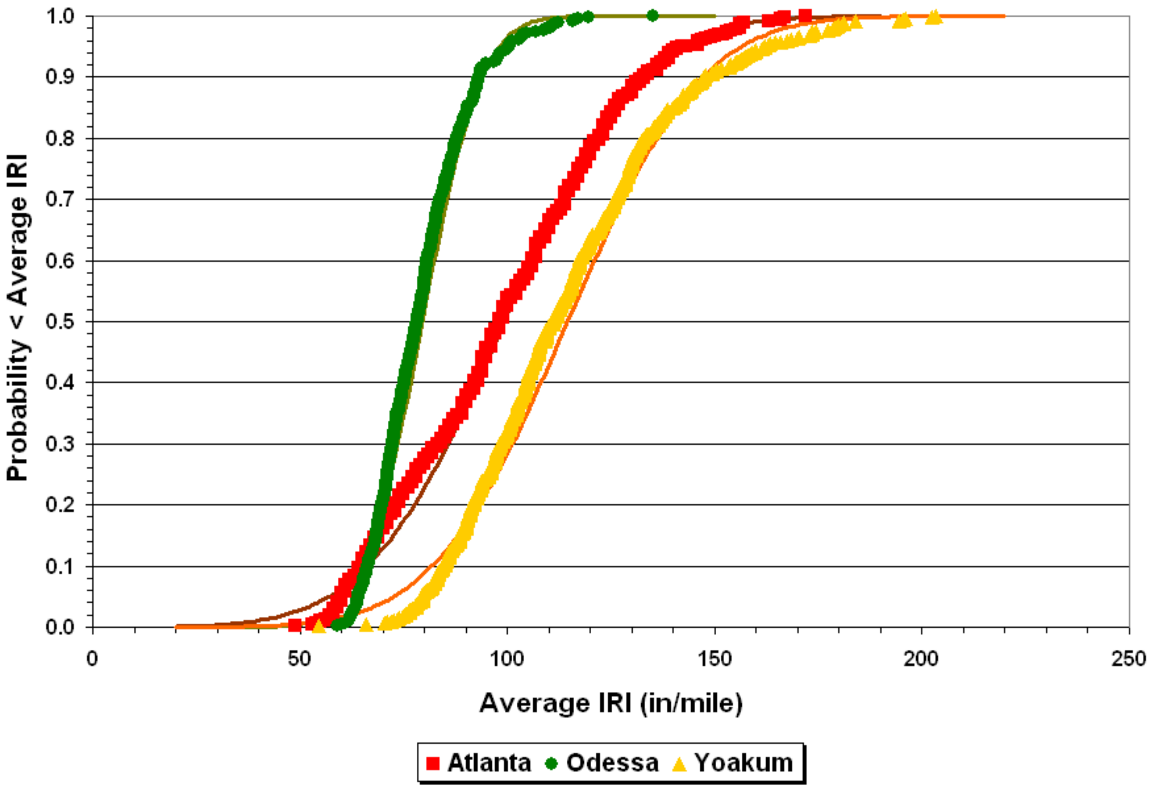


Figure 2.2. Cumulative Distributions of Average IRIs Determined on Surface Treatments from District Projects.

- Comparing the statistics given in Tables 2.1 and 2.2, it is observed that the Atlanta sections exhibit more similarity in the distributions of the average IRIs on the flexible base and on the surface treatment than the Odessa sections. This observation is more readily discerned in Figure 2.3, which shows that the average IRIs on the surface treatment (ST) are markedly higher than the average IRIs determined on the flexible base for the Odessa sections. In comparison, the distributions of the average IRIs on the Atlanta sections are closer to each other.

Figure 2.3 compares the distributions of average IRIs based on all of the data from the Atlanta and Odessa projects. It is also appropriate to examine the distributions on individual projects where ride data on both the flexible base and surface treatment are available. Figures 2.4 to 2.10 compare the distributions of average IRIs for these projects while Tables 2.3 to 2.9 provide summary statistics characterizing the distributions shown. Except for the FM2517 project, the data generally show an increase in the average IRIs after placement of the first course surface treatment. This increase ranges from 6 to 27 inches per

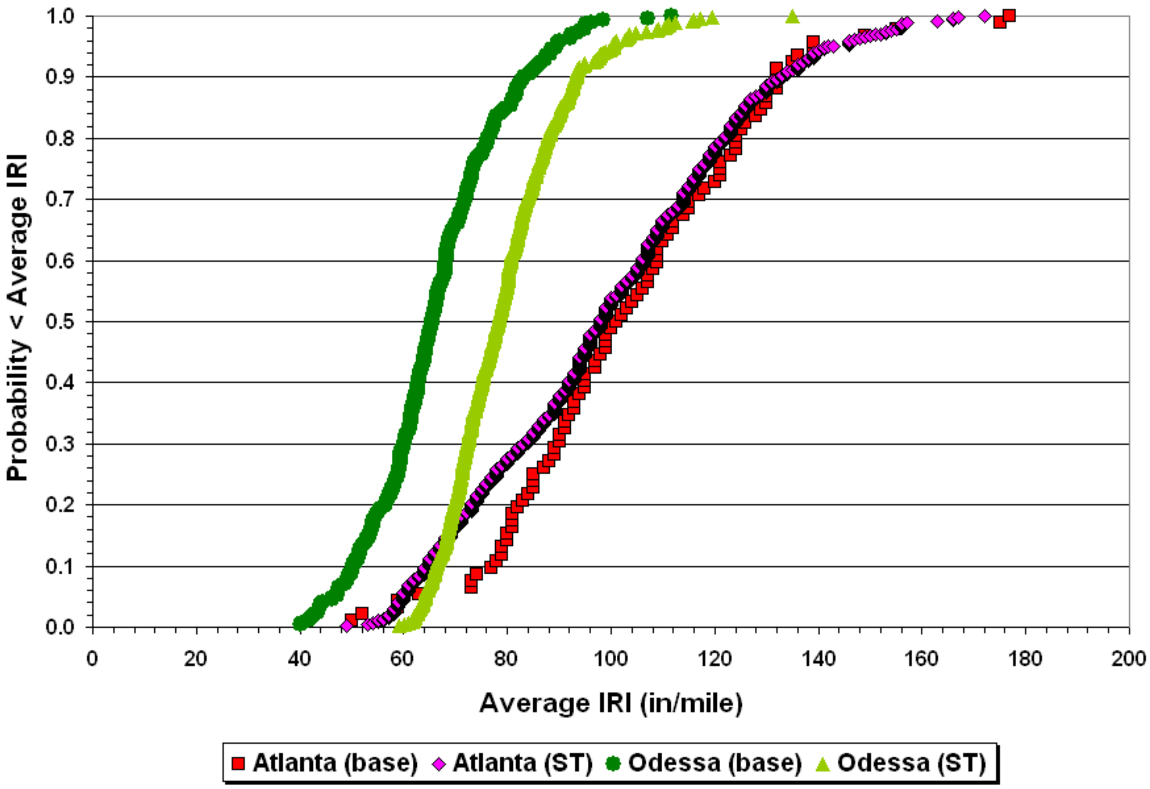


Figure 2.3. Comparison of Cumulative Distributions of Average IRIs on Flexible Base and on the Surface Treatment from Atlanta and Odessa Projects.

mile based on the differences between the means of the average IRIs before and after placement of the first course treatment, as given in Tables 2.4 to 2.9. Considering the thickness of a one-course treatment, the apparent increase in roughness suggests that surface texture might be influencing the IRIs determined from profiles taken on the surface treatment. Thus, researchers investigated the effects of surface texture in controlled laboratory and field experiments that are presented later in this report.

Notwithstanding the observed increase in IRI after placement of the first course, the ride data from the districts indicate that requiring an average IRI no greater than 125 inches per mile is also a reasonable target to use in an alternative ride specification where the final surface (consisting of a one- or two-course surface treatment) is tested. This criterion was readily achieved on the Odessa projects where the average IRIs on the surface treatments are generally less than 125 inches per mile. On the Atlanta and Yoakum projects, 84 and 66 percent, respectively, of the sections tested met this criterion. Finally, for the three projects where ride data on the second course are available, the IRI distributions on the second course

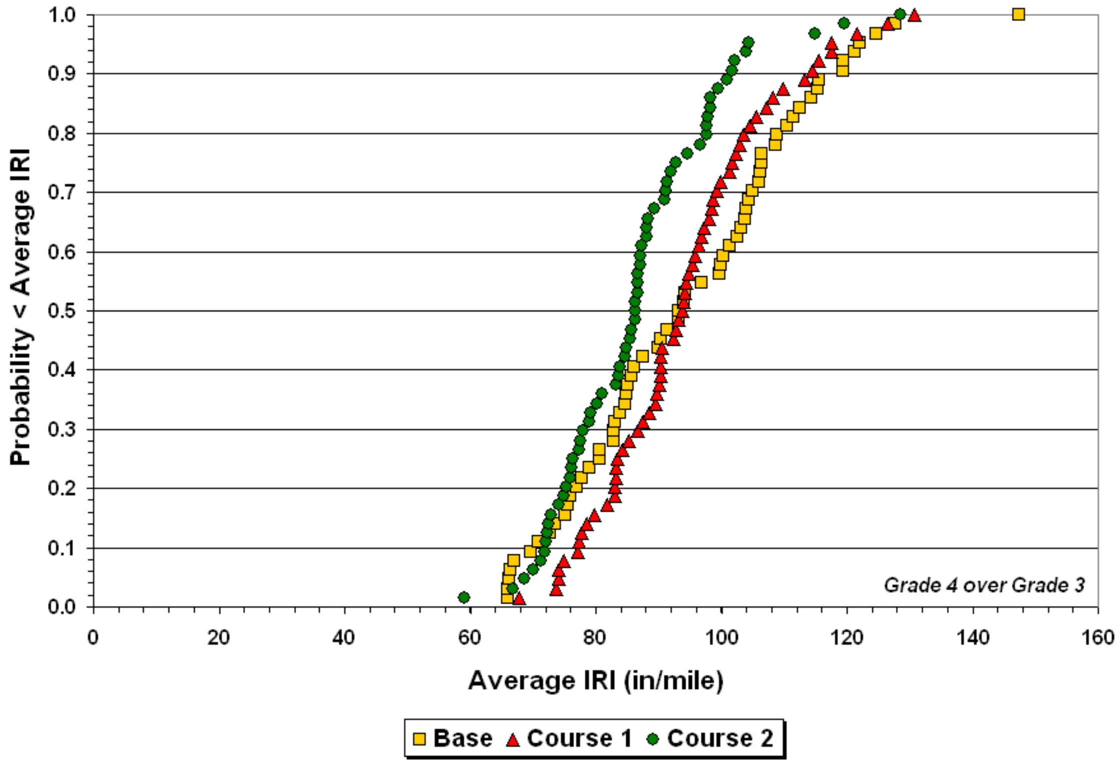


Figure 2.4. Distributions of Average IRIs on Flexible Base and Surface Treatments Placed on FM2517 Project in the Atlanta District.

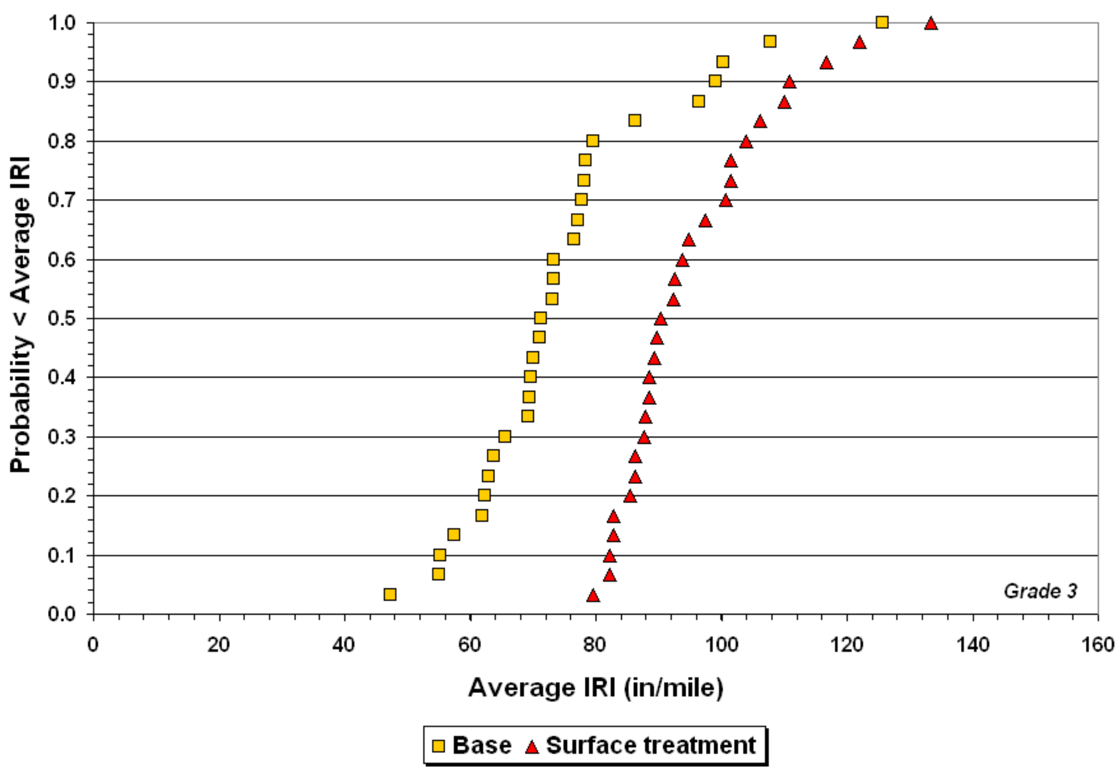


Figure 2.5. Distributions of Average IRIs on Flexible Base and First Course Surface Treatment on FM3098 Project in the Atlanta District.

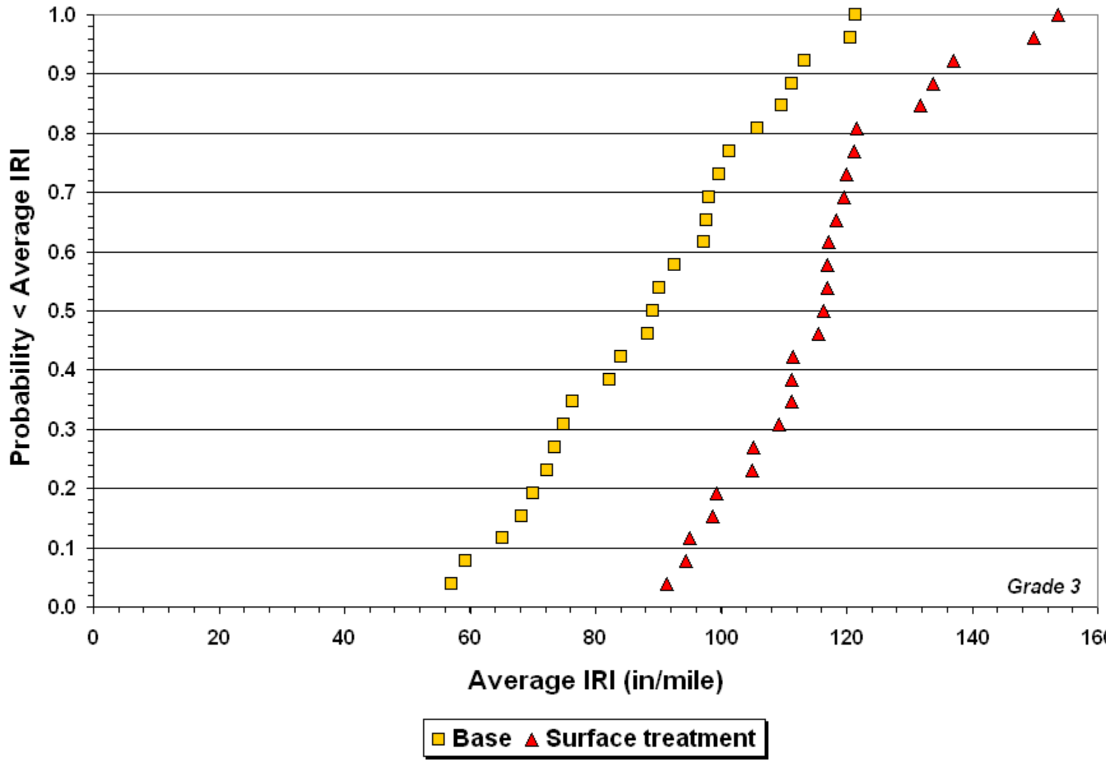


Figure 2.6. Distributions of Average IRIs on Flexible Base and First Course Surface Treatment on SH49 Project in the Atlanta District.

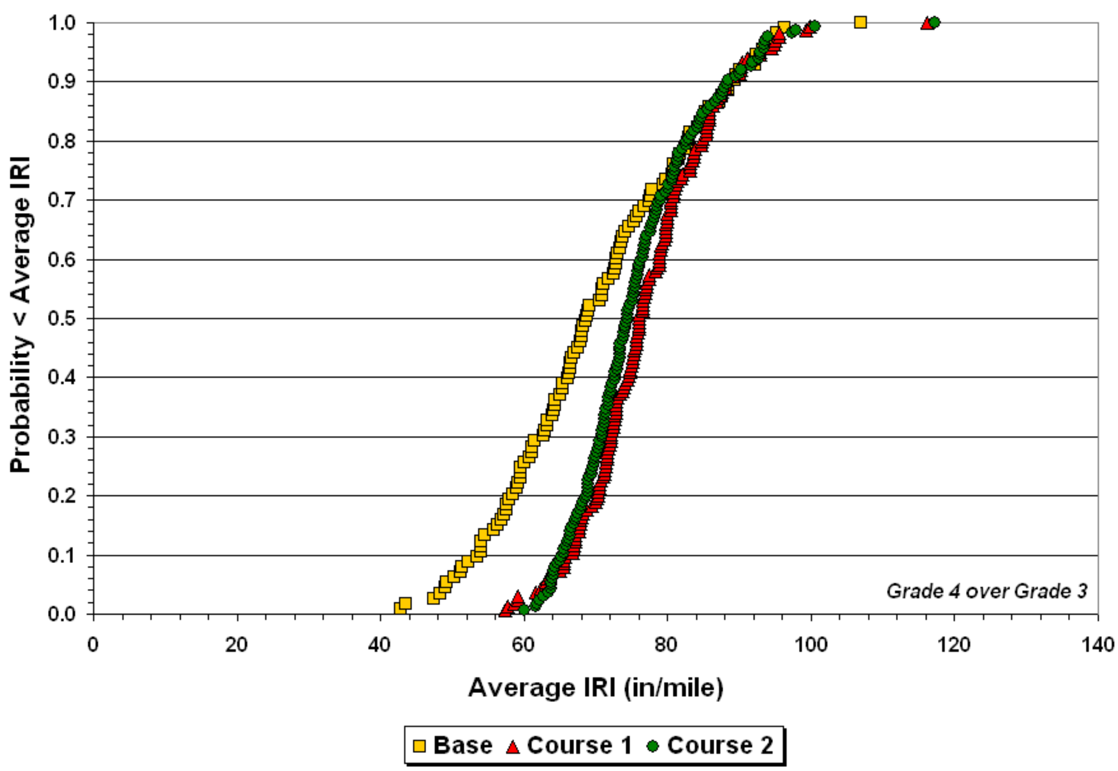


Figure 2.7. Distributions of Average IRIs on Flexible Base and Surface Treatments Placed on North Segment of SH349 Project in the Odessa District.

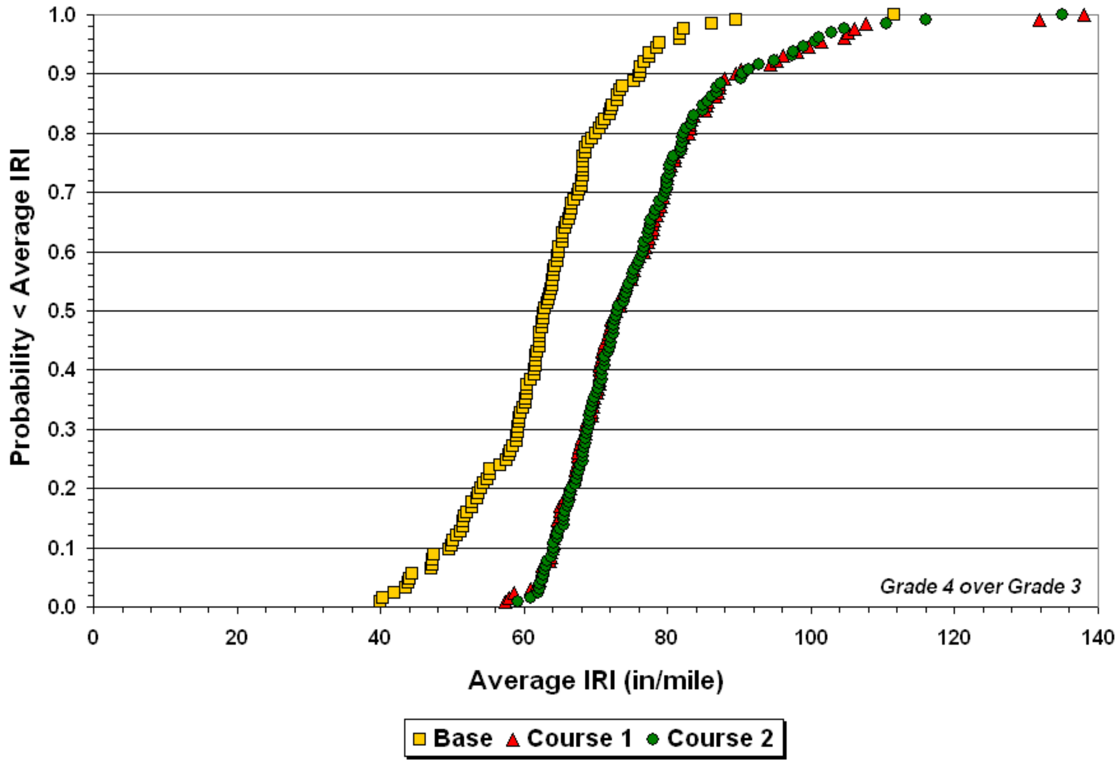


Figure 2.8. Distributions of Average IRIs on Flexible Base and Surface Treatments Placed on South Segment of SH349 Project in the Odessa District.

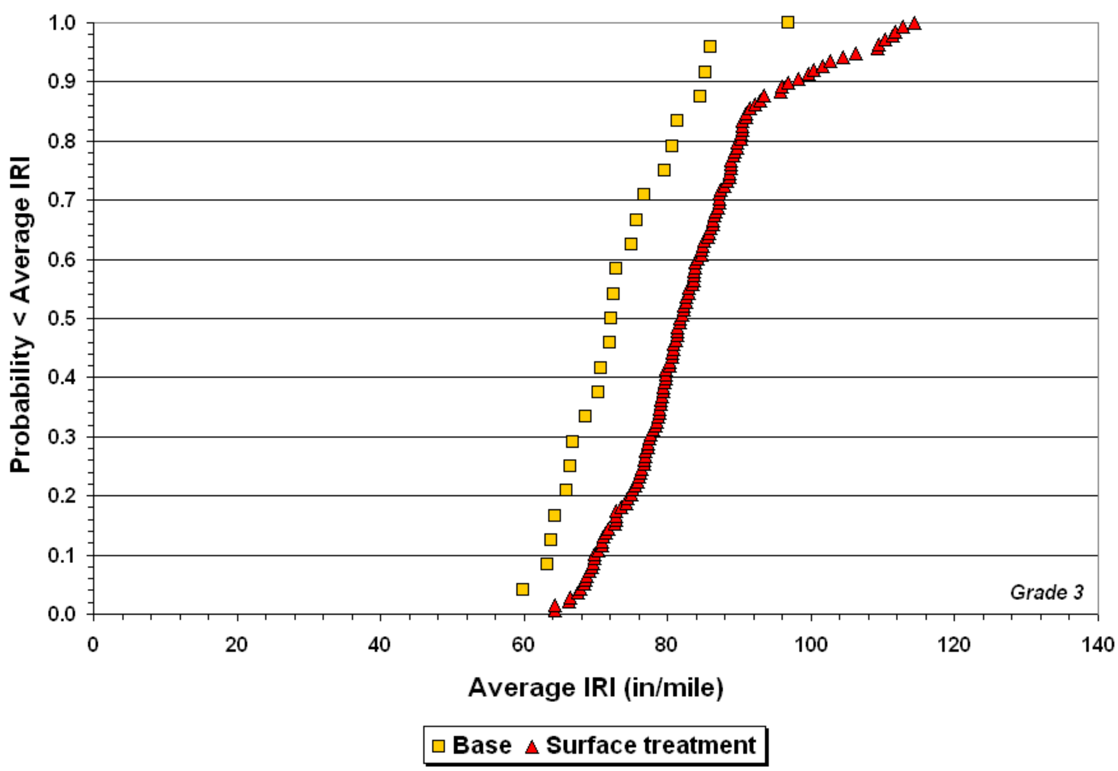


Figure 2.9. Distributions of Average IRIs on Flexible Base and First Course Surface Treatment on FM307 Project in the Odessa District.

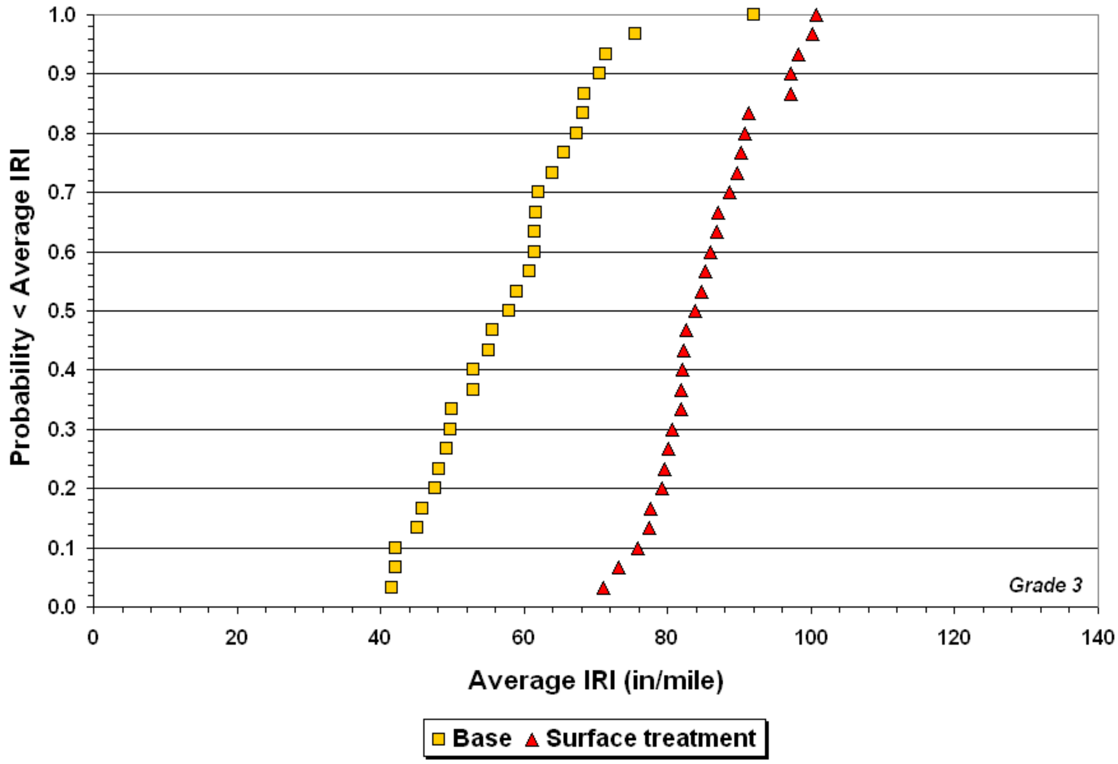


Figure 2.10. Distributions of Average IRIs on Flexible Base and First Course Surface Treatment on FM2401 Project in the Odessa District.

Table 2.3. Summary Statistics on Distributions of Average IRIs on the FM2517 Project in the Atlanta District.

Statistic (in/mile)	Lift		
	Base	1st Course	2nd Course
Mean	95	94	87
Standard deviation	18	14	13
Minimum	66	68	59
Maximum	148	131	129
80th percentile	109	104	98
85th percentile	114	108	98
90th percentile	118	114	101
95th percentile	122	118	104
99th percentile	135	128	123

Table 2.4. Summary Statistics on Distributions of Average IRIs on the FM3098 Project in the Atlanta District.

Statistic (in/mile)	Lift	
	Base	1st Course
Mean	75	96
Standard deviation	17	13
Minimum	47	80
Maximum	126	134
80th percentile	81	104
85th percentile	93	109
90th percentile	99	111
95th percentile	105	120
99th percentile	121	130

Table 2.5. Summary Statistics on Distributions of Average IRIs on the SH49 Project in the Atlanta District.

Statistic (in/mile)	Lift	
	Base	1st Course
Mean	89	116
Standard deviation	19	16
Minimum	57	91
Maximum	122	154
80th percentile	106	122
85th percentile	110	132
90th percentile	112	136
95th percentile	119	147
99th percentile	121	153

Table 2.6. Summary Statistics on Distributions of Average IRIs on the North Segment of the SH349 Project in the Odessa District.

Statistic (in/mile)	Lift		
	Base	1st Course	2nd Course
Mean	70	77	76
Standard deviation	13	9	9
Minimum	43	57	60
Maximum	107	116	117
80th percentile	83	85	83
85th percentile	85	86	85
90th percentile	89	88	88
95th percentile	93	93	93
99th percentile	96	100	99

Table 2.7. Summary Statistics on Distributions of Average IRIs on the South Segment of the SH349 Project in the Odessa District.

Statistic (in/mile)	Lift		
	Base	1st Course	2nd Course
Mean	63	76	76
Standard deviation	11	13	12
Minimum	40	57	59
Maximum	112	138	135
80th percentile	70	81	82
85th percentile	73	83	85
90th percentile	76	86	91
95th percentile	79	97	100
99th percentile	89	105	114

Table 2.8. Summary Statistics on Distributions of Average IRIs on the FM307 Project in the Odessa District.

Statistic (in/mile)	Lift	
	Base	1st Course
Mean	74	83
Standard deviation	9	11
Minimum	60	64
Maximum	97	114
80th percentile	81	90
85th percentile	83	91
90th percentile	85	97
95th percentile	86	107
99th percentile	94	112

Table 2.9. Summary Statistics on Distributions of Average IRIs on the FM2401 Project in the Odessa District.

Statistic (in/mile)	Lift	
	Base	1st Course
Mean	58	85
Standard deviation	11	8
Minimum	42	71
Maximum	92	101
80th percentile	68	91
85th percentile	68	95
90th percentile	71	97
95th percentile	74	99
99th percentile	87	101

were either found to be close to or shifted to the left of the IRI distributions determined on the first course. On the SH349 segments, Figures 2.7 and 2.8 show that the IRI distributions are similar between the first and second course treatments, while on the FM2517 project (Figure 2.4), the average IRIs determined after placement of the second course are generally lower than the average IRIs determined on the first course.

CONCLUDING REMARKS

Based on examination of the ride data from district projects, the average flexible base IRIs were found to vary over a wide range. In particular, researchers observed that the Odessa projects exhibited lower flexible base IRIs than the Atlanta projects. From the IRI distributions, about 81 percent of the Atlanta sections met the proposed average IRI criterion of 125 inches per mile, while on the Odessa projects, the average flexible base IRIs were all within 125 inches per mile. Recognizing that the draft flexible base specification came about in an effort to get a standard that all districts can use for evaluating flexible base smoothness on surface treatment projects, the proposed criterion of 125 inches per mile is considered realistic from the perspective of a requirement that contractors can reasonably be expected to achieve given the differences in geographic conditions, climate, and construction practices across the state. Researchers note that the difference between the Atlanta and Odessa flexible base IRIs was presented in a specification meeting attended by TxDOT engineers and contractors in 2005. During that meeting, 125 inches per mile was deemed a suitable criterion to start with for a standard TxDOT specification. Notwithstanding the need for a criterion that has general applicability for statewide use, researchers are of the opinion that language should be provided within the specification permitting a district to specify a different criterion if there is ample justification based on local experience. This allowance would permit a district to tailor the specification to its specific conditions as experience is gained with its implementation.

CHAPTER III. CONTROLLED EXPERIMENTS TO INVESTIGATE TEXTURE EFFECTS

INTRODUCTION

The road profile consists of long wavelengths with features such as hills, short wavelengths that are characteristic of bumps and dips, and much shorter wavelengths within the range of macro-texture features. For ride quality evaluation, inertial profilers are commonly used to collect profile measurements. The basic design of these profilers has not changed since Spangler and Kelly (1966) first developed the concept in the mid-1960s while working at General Motors. These profilers all have inertial reference, height, and distance measurement subsystems. Following the original design, today's profilers use an accelerometer to establish the inertial reference. However, unlike previous generations of profilers that used potentiometer-based road following wheels for height measurements, current systems use non-contact sensors with the laser being the instrument of choice among equipment manufacturers and users. The accelerometer and laser are used for measuring the vehicle body and road-body displacements. The accelerometer signals are double integrated, and the results of this integration are added to the corresponding road-body displacements to compute the road profile. A distance encoder ties each profile elevation to its actual position on the road surveyed, thus permitting users to locate features of interest in the road profile, such as defects that need to be corrected to improve ride quality. There is a laser-accelerometer set for each wheel path to be measured.

The accelerometer is the primary sensor for measuring the lower frequency or longer wavelengths. The laser, on the other hand, measures the shorter wavelengths and would be the sensor most affected by texture of the surface being measured. Surface characteristics with wavelengths in the macro-texture range have negligible effect on the vertical movement of the vehicle body, and thus, cannot be detected by the accelerometer. To investigate the effect of texture on ride quality determinations, its effect on the laser measurements and resulting calculations of pavement profile would have to be studied. For this purpose, researchers conducted laboratory tests on various textured specimens to collect laser data with which to estimate the effect of texture on ride quality determinations based on the computed profile.

LABORATORY SETUP

As explained in the previous section, the laser is the sensor that would be most affected by surface texture. To investigate the effect of texture on ride quality measurements, researchers fabricated the test cart shown in Figure 3.1 to collect laser measurements on various textured specimens under controlled conditions in the laboratory. During testing, a motor under the top deck of the cart spins a platter that holds the specimen on which laser readings are taken. The laser is positioned above the specimen on a stand that is independent of the test cart. As the specimen spins, laser measurements are collected along a circular track using a data acquisition system controlled by a program running on a notebook computer. The rotational velocity for a given test is set with a speed control module. The rotational speed in revolutions per minute (RPM) is displayed on a digital tachometer, which is wired to a distance encoder mounted on the shaft of the motor. During testing, a protective transparent cover made of lexan surrounds the platter to prevent injury and/or damage from projectiles that might spin out of the specimen.

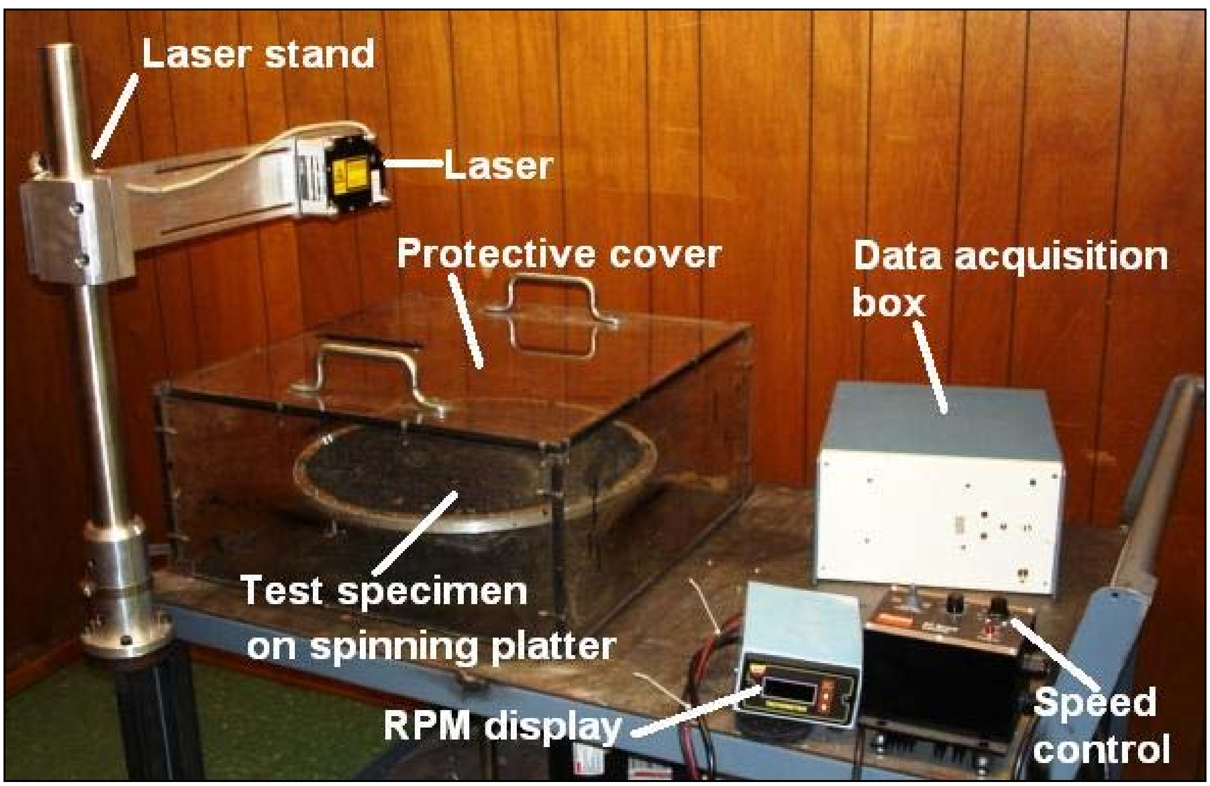


Figure 3.1. Test Cart Used for Laser Measurements on Textured Specimens.

During setup, researchers would position the laser such that its beam targets marks placed at a radial distance of 8 inches from the center of the platter (see Figure 3.2). The specimen is then placed on the platter by matching the alignment pin (Figure 3.3) on the platter with the corresponding alignment hole drilled on the outside edge of the specimen. This procedure ensures that each specimen is positioned only one way on the platter and that laser measurements are collected on the same circular track of 8-inch radius on each specimen. The specimen is then secured onto the platter using six socket head cap screws. Researchers then place the protective cover on the cart such that the slot (Figure 3.4) is directly underneath the laser and the beam is not refracted by the transparent lexan cover.

TEST SPECIMENS

Researchers prepared specimens simulating a range of one- and two-course surface treatments of various aggregate sizes. Surface treatments were placed on circular plates as shown in Figure 3.5. To characterize the surface texture of each specimen, researchers conducted sand patch tests following TxDOT Test Method Tex-436-A. As shown in Figure 3.5, sand patch tests were conducted at four different positions on the specimen spaced 90° apart along the same circular track on which laser measurements were taken. Table 3.1 summarizes the texture depths determined from the sand patch tests.

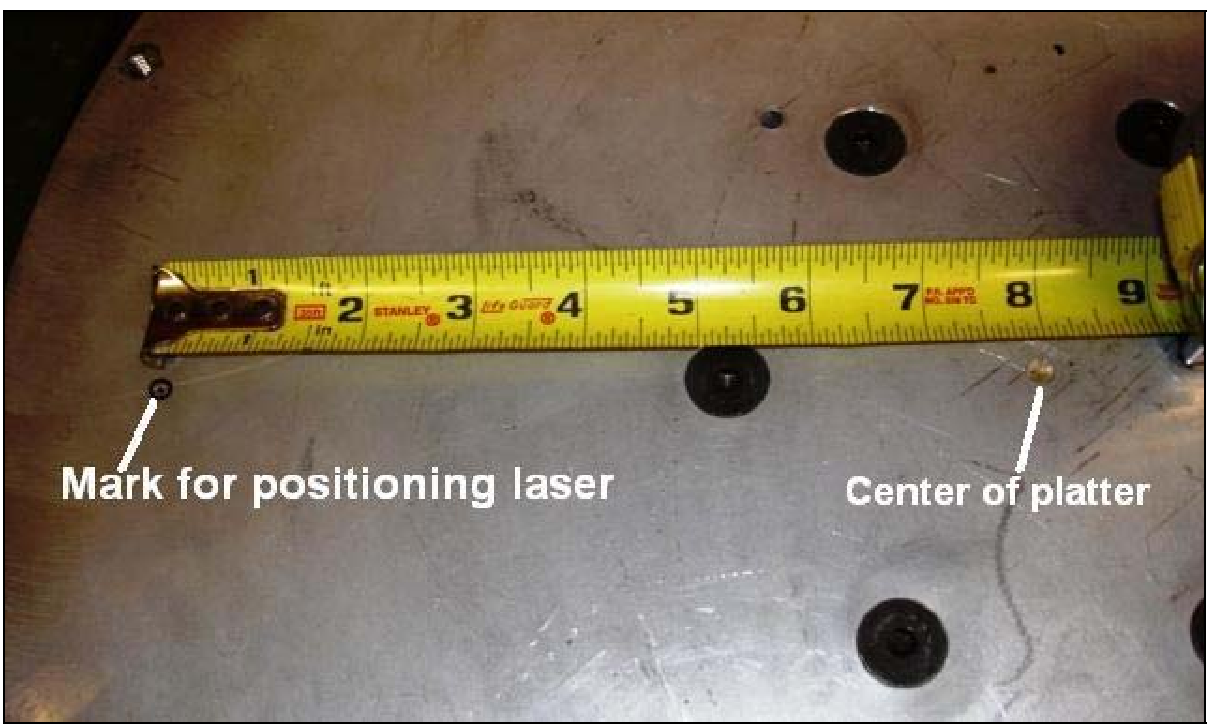


Figure 3.2. Mark Used to Position Laser above Test Specimen.

Figure 3.3. Alignment Pin Used to Position the Test Specimen on the Platter.

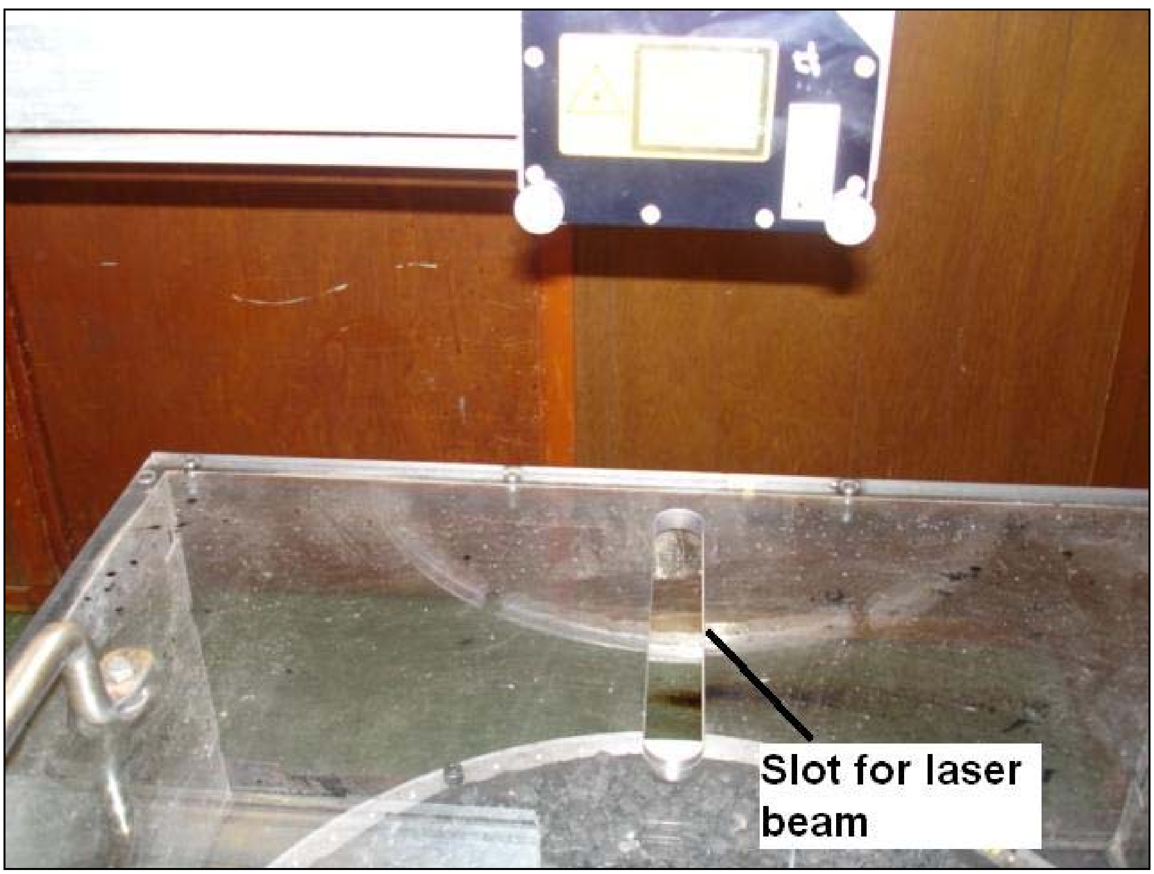


Figure 3.4. Picture of Protective Cover Showing Slot for Laser Beam.

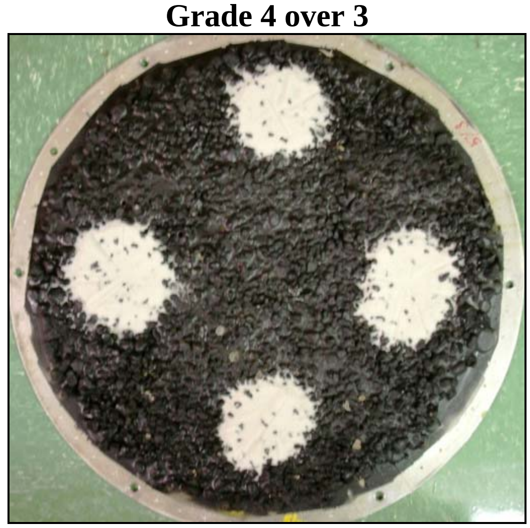
Grade 3

Grade 3 over 3

Grade 4

Grade 4 over 3

Grade 5



Grade 5 over 3

Figure 3.5. Specimens of Surface Treatments Tested in the Laboratory.

Table 3.1. Texture Depths from Sand Patch Tests.

Specimen	Texture Depth at Test Position (mm)				Mean Texture Depth (mm)
	1	2	3	4	
Grade 3	5.215	5.317	4.894	5.051	5.119
Grade 4	5.051	5.215	5.352	6.302	5.480
Grade 5	3.507	3.261	3.621	2.938	3.332
Grade 3 over 3	6.392	5.568	5.019	5.317	5.574
Grade 4 over 3	5.720	5.283	6.127	6.579	5.927
Grade 5 over 3	4.335	3.295	4.260	3.329	3.805

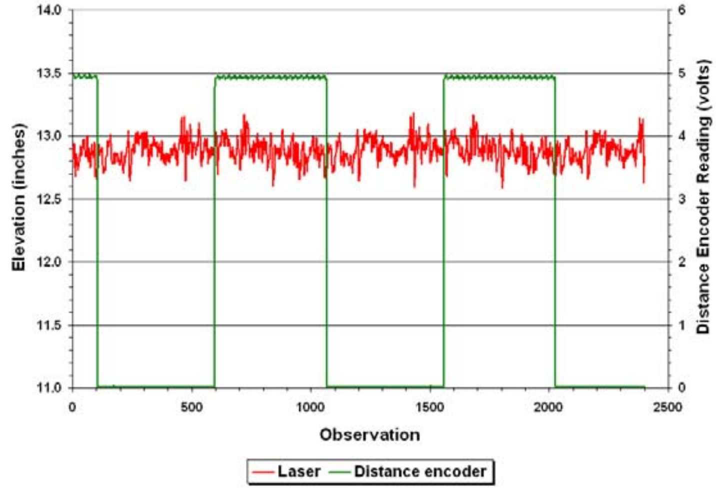
Initially, specimens were prepared using asphalt emulsion as the binder for the aggregates. The specimens were then tested after curing in the laboratory. However, during testing, researchers found that the asphalt flowed with increasing revolutions of the specimen, resulting in loss of aggregates. Consequently, new specimens were prepared using high-strength epoxy as the binder. Figure 3.5 shows these specimens. To simulate the color of surface treatments, researchers painted each specimen black prior to testing. With epoxy as the adhesive, the new specimens did not exhibit the problem of aggregate loss that researchers experienced with the initial set of disks tested.

ANALYSIS OF LASER TEST DATA

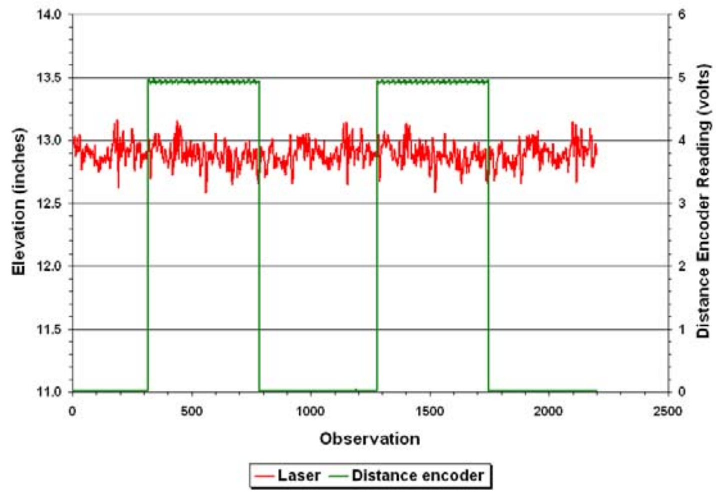
Researchers collected laser measurements on each specimen at different speeds, with each run made to get at least 528 ft of data on the specimen. The task of processing the data from these runs required the following steps:

- lining up the raw laser data from repeat runs,
- calculating profiles after aligning the test data,
- applying a filter to remove the effect of specimen wobble, and
- computing ride statistics.

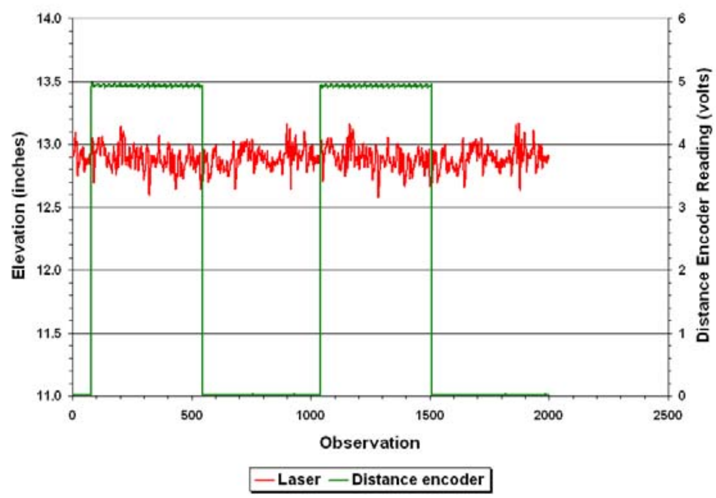
Researchers used the first full distance pulse on each run to line up the raw laser readings from repeat runs made at a given test speed. This simple method of lining up the data was possible because of the type of distance encoder used on the drive shaft and the concurrent sampling of the laser and distance encoder voltages during testing. Figures 3.6 and 3.7 illustrate data from three repeat runs on the Grade 5 specimen before and after aligning the data, respectively, to the first full distance pulse on each run. Note the agreement observed in Figure 3.7 after the data from repeat runs were lined up.



a) Run 1



b) Run 2



c) Run 3

Figure 3.6. Example Data from Repeat Runs before Alignment.

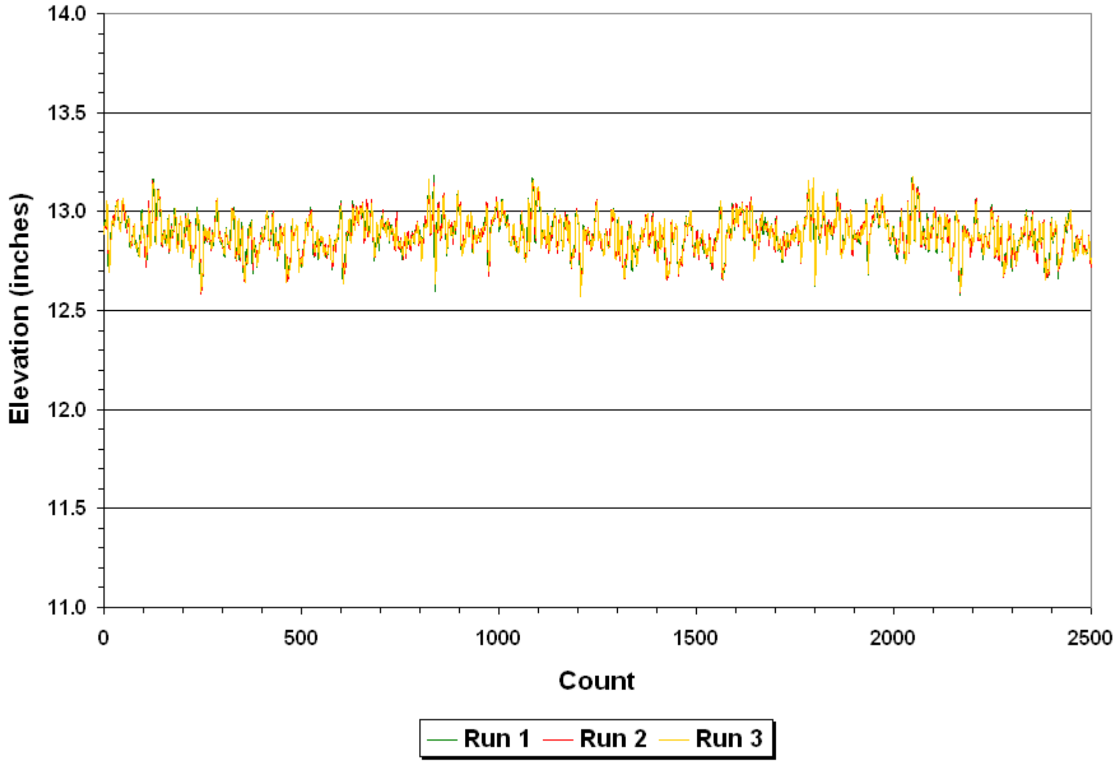


Figure 3.7. Example Data from Repeat Runs after Aligning to the First Full Distance Pulse.

After aligning the laser data from repeat runs made at a given test speed, researchers computed the profile in a similar manner as is done for TxDOT's inertial profilers that use a modified version of the South Dakota profiling method developed by Huft (1984, 1987). Researchers modified this algorithm to exclude the accelerometer component that is used in inertial profiling methods to account for vehicle body movement. No accelerometer readings were necessary since the test setup (Figure 3.1) had the laser positioned at a fixed distance above the specimen on a stand that was independent of the test cart. Thus, the laser displacement readings were simply converted to profile. Researchers then applied a filter to remove the wobble observed during the test runs. This wobble was attributed to slight imperfections in the platter on which the specimen was placed and the imbalance of the specimen itself due to non-uniformity in placement of the aggregates that constituted the specimen. Figure 3.8 illustrates the wobble observed during testing. Note the undulating trend in the laser readings taken from the test. Each vertical line in Figure 3.8 marks one complete rotation of the specimen. Thus, the figure covers data for a little over three complete rotations.

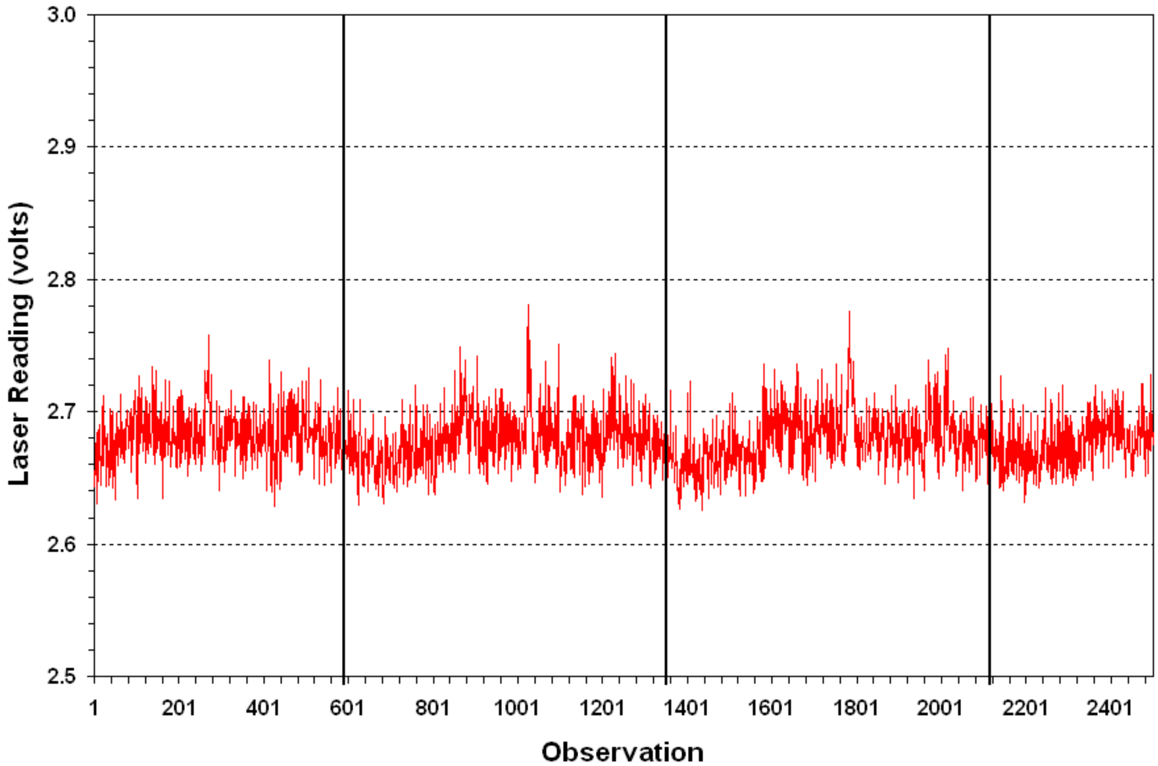


Figure 3.8. Illustration of Wobble Observed during Testing.

In order to account for the observed wobble in the data, researchers used a high pass finite impulse response (FIR) filter that was designed for a cut-off frequency corresponding to a wavelength of one-half the circumference of the platter. This cutoff frequency was selected to attenuate data from the wobble, but not affect the texture readings. For a circular track radius of 8 inches, the circumference is approximately 50.3 inches. Thus, the desired FIR filter would be one that would remove frequencies with wavelengths greater than 25.15 inches (equal to 50.3 divided by 2) or frequencies below 0.04 cycles per inch. Figure 3.9 shows the actual frequency response of the wobble filter used. Note the rapid attenuation at the cut-off frequency. As shown, frequencies above this threshold are not modified by the filter (i.e., the gain is unity) while frequencies below the threshold are attenuated.

After removing the effect of the wobble, researchers computed ride statistics based on the wobble-corrected profiles. Table 3.2 summarizes the IRIs for the specimens tested with the conventional laser used on TxDOT's profilers. Also presented are the new serviceability indices (NSIs) determined using the NSI equation developed from TxDOT Project 7-4901 (Walker and Fernando, 2002). To provide a reference for assessing the significance of

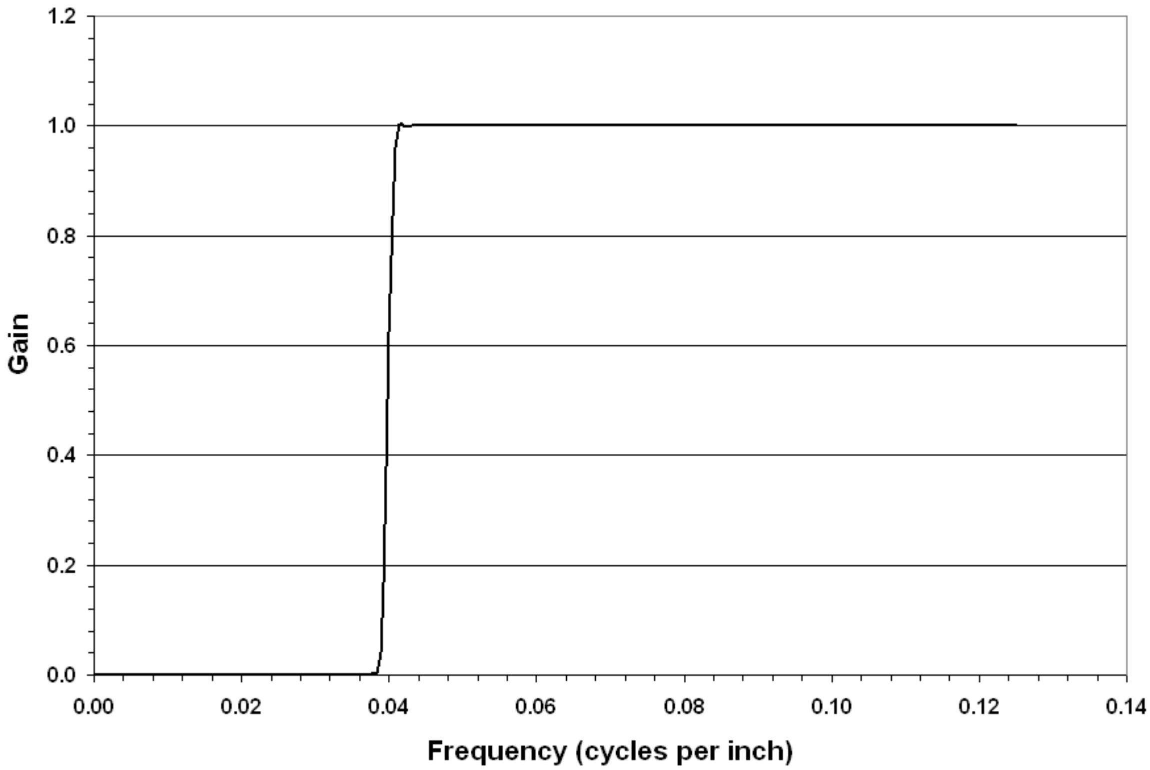


Figure 3.9. Frequency Response Function of Wobble Filter.

Table 3.2. Ride Statistics Computed from Test Data Collected with Conventional Laser on Specimens of Various Surface Treatments and on Platter.

Specimen	Test RPM	IRI (inches/mile)		NSI	
		Average[c]	Std. deviation	Average[c]	Std. deviation
Grade 3	315[a]	25	0.86	4.96	0.010
Grade 4	315	23	0.36	4.93	0.020
Grade 5	315	10	0.21	4.98	0.030
Grade 3 over 3	315	19	0.29	4.97	0.020
Grade 4 over 3	315	33	0.51	4.98	0.030
Grade 5 over 3	315	15	0.93	4.98	0.030
Platter	315	3	0.01	4.99	0.040
Grade 3	630[b]	25	0.93	4.98	0.018
Grade 4	630	23	0.35	4.95	0.012
Grade 5	630	11	0.22	4.97	0.008
Grade 3 over 3	630	18	0.30	4.97	0.008
Grade 4 over 3	630	36	0.56	4.98	0.018
Grade 5 over 3	630	15	0.41	4.98	0.018
Platter	630	3	0.01	4.99	0.028

[a]Equivalent to a linear velocity of 15 mph
[b]Equivalent to a linear velocity of 30 mph
[c]Averages and standard deviations computed from 10 runs on each surface treatment specimen and 3 runs on platter

differences in ride statistics between specimens and between test speeds, researchers also computed the IRIs and NSIs based on profiles determined from laser measurements collected directly on the platter. Since this disk has a flat and smooth surface, the platter's IRI should be near zero, and its NSI should be close to five. From the test data, researchers computed the platter's IRI and NSI to be 3 inches per mile and 4.99, respectively. Based on the results presented in Table 3.2, the authors note the following observations from the analysis of laboratory test data:

- Test speed has minimal effect on the computed IRIs. The differences in corresponding IRIs determined at the two RPMs range from 0 to 3 inches per mile, with the maximum difference observed on the Grade 4 over 3 specimen. On three specimens (Grade 3, Grade 4, and Grade 5 over 3), no differences in corresponding IRIs at the two test speeds are observed, while on the other two specimens (Grade 5 and Grade 3 over 3), the difference is only 1 inch per mile. Relative to the platter's IRI of 3 inches per mile, the differences in corresponding IRIs determined at the two test speeds is of minimal practical significance, in the authors' opinion. Since the ride statistics were determined based on profiles computed from the laser data, this finding is logical as the profile should not be affected by test speed.
- Using the platter's IRI of 3 inches per mile as the baseline and subtracting this value from the IRIs determined on the test specimens, it is found that the effect of surface irregularities is to increase the IRI between 7 to 33 inches per mile for the range of surface treatments considered in the laboratory experiment. This range is comparable to what was found from examination of the ride data on district projects, where the observed differences between means of the average IRIs on the flexible base and the surface treatment varied from 6 to 27 inches per mile.
- As observed in Table 3.2, the NSIs are all close to five and do not vary significantly between specimens and the two test speeds. These observations suggest that the NSI equation is not affected by frequency components in the macro-texture range, at least based on the laboratory test results. Thus, NSI appears to be a suitable alternative statistic for assessment of ride quality on textured surfaces, and its use for this application should be further explored.

To further evaluate the effect of texture on IRI, researchers examined the relationship between the mean texture depths determined from the sand patch tests on the specimens and the differences in IRIs between the specimens and the platter. Figure 3.10 shows this relationship where a positive correlation is observed between the dependent and independent variables. Note the strong linear relationship between these variables, as inferred from the R^2 of 70 percent in the regression line plotted in Figure 3.10. The relationship shown verifies the effect of texture on IRI based on the laboratory tests conducted in this project.

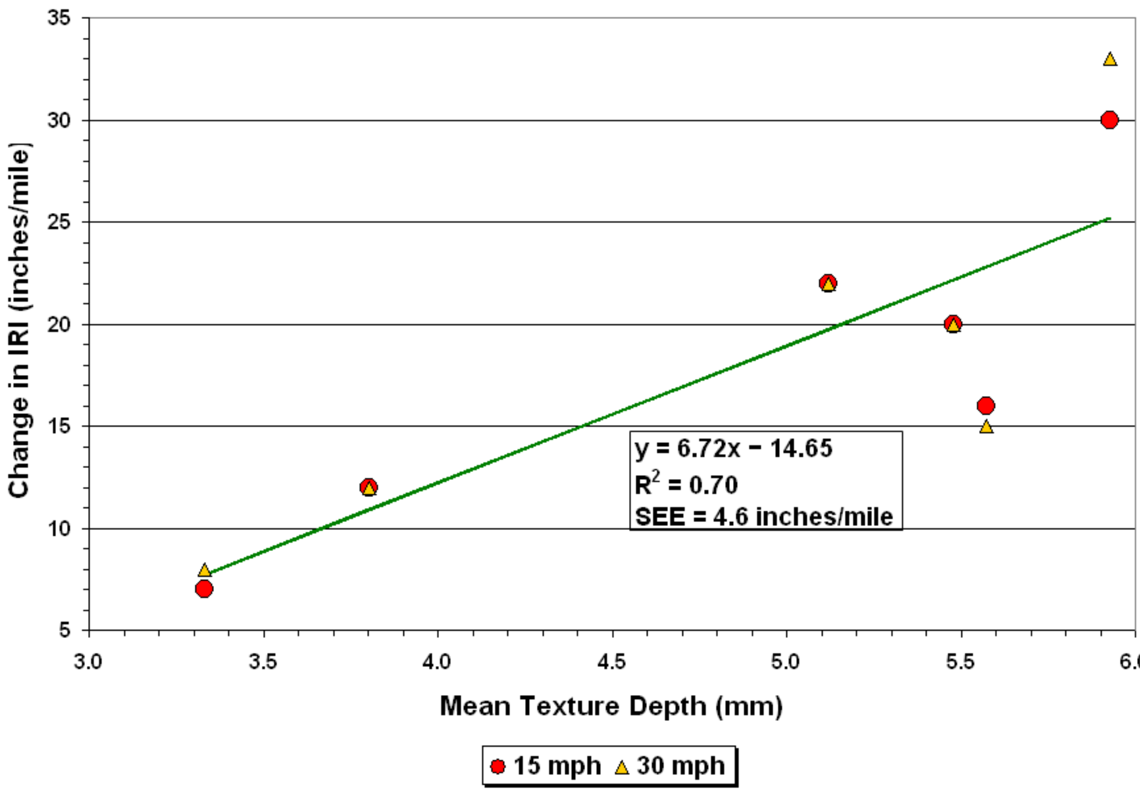


Figure 3.10. Illustration of Relationship between IRI and Texture.

FIELD TESTS TO VERIFY TEXTURE EFFECT

Recent comparative evaluations of profiling devices have reported the problem of achieving repeatable and reproducible IRIs on textured surfaces, specifically on Portland cement concrete where the surface has been longitudinal tined or diamond ground (Karamihas and Gillespie, 2003; Karamihas, 2005a). This problem is attributed to the interaction between surface texture and the footprint of lasers used with most inertial profilers. For example, with conventional lasers that project a dot-sized footprint, the laser beam will measure in and out of the trough on longitudinally tined PCC pavements, depending on the consistency with which the profiler operator tracks the test wheel path and on the uniformity of the tining process. Consequently, equipment manufacturers have developed lasers with footprints that provide a wider coverage of the target area, such as the wide-footprint RoLine laser manufactured by LMI Selcom and the multi-point Ames TriODS laser module developed by Ames Engineering. In a Federal Highway Administration pooled fund study, Karamihas (2005b) proposed several profiler accuracy requirements that include recommendations on footprint requirements for reference profilers. One such recommendation requires the footprint to have a width of at least 70 mm (2.76 inches) and a length of at least the same amount for profile measurement methods that contact the surface.

To provide a reference for verifying the effect of texture on the field tests performed in this project, researchers collected profiles using the Walking Profiler (WP) and rod and level. The plan was to compare the IRIs determined from inertial profile measurements with the corresponding statistics determined from WP and rod and level data. Figures 3.11 to 3.13 show the footprints of the devices used to measure profiles on the field tests.

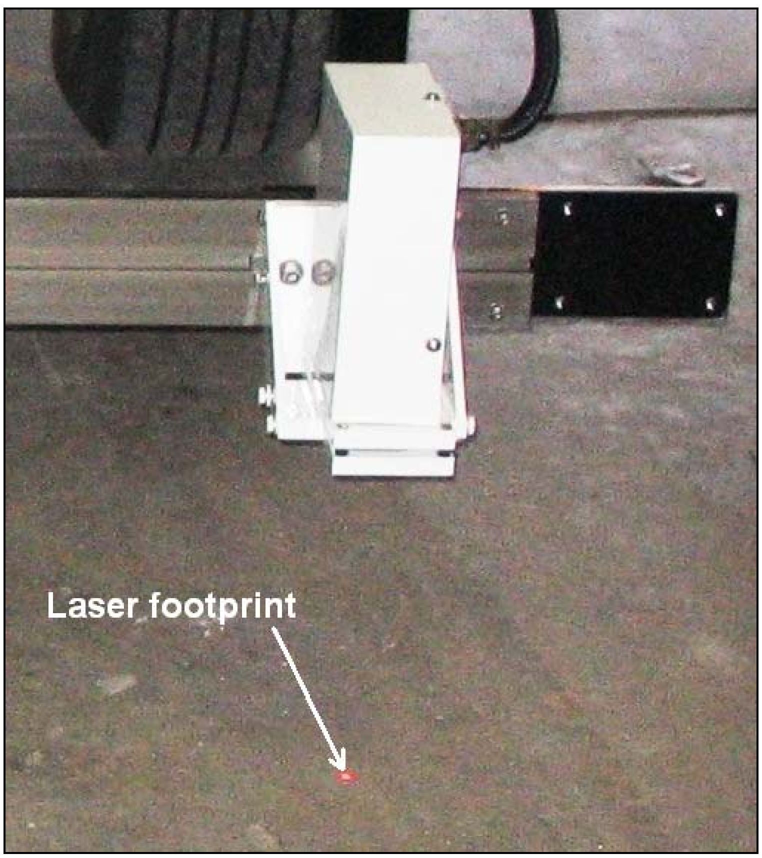


Figure 3.11. Dot-Sized Projection of Laser Beam.

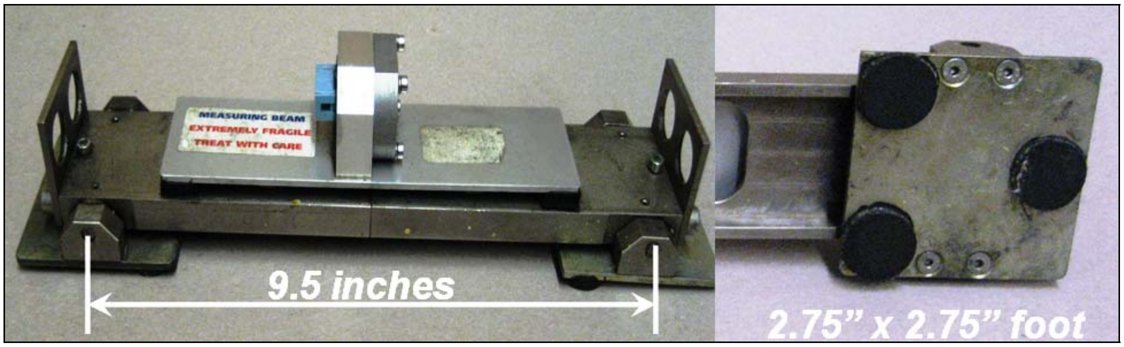


Figure 3.12. Walking Profiler Measuring Beam with Close-Up View of Footpad.


Figure 3.13. Rod Footpad.

Since the researchers' experience in using the Walking Profiler on surface treatments is very limited, the field tests assessed the applicability of using this instrument for collecting profile data on such surfaces. For these tests, researchers established a 95-ft test wheel path on an old seal coat pavement located at the Riverside Campus of Texas A&M University. Figure 3.14 shows the section tested. The painted dots on the figure delineate the wheel path tracked during profile measurements.

The 95-ft section length was selected to provide a whole multiple of the 9.5-inch foot length of the Walking Profiler. To assess the applicability of using the Walking Profiler on surface treatments, researchers collected rod and level data on the test wheel path at the same interval as the Walking Profiler. For these measurements, marks were placed at 9.5-inch intervals along the test wheel path to position the rod during the tests. Researchers made

Figure 3.14. Old Seal Coat Pavement Used for Profile Measurements.

three repeat runs of the Walking Profiler and two repeat runs of the rod and level on the given path. In addition, inertial profiler measurements were taken.

Figure 3.15 compares the IRIs determined from the tests. It is observed that the Walking Profiler IRIs exhibit greater variability than the corresponding ride statistics computed from the inertial profiler (IP) and rod and level (RL) data. Researchers observed that the Walking Profiler would rock as its wheels went over the aggregates on the surface as well as the cracks that cut at a number of locations across the wheel path on the old seal coat pavement. The authors are of the opinion that this behavior affected the measurements at each station from the repeat runs made and contributed to the lack of repeatability, as reflected in a standard deviation of the IRIs of 40.3 inches per mile. Figure 3.15 also shows that the inertial profiler IRIs are more comparable to the rod and level IRIs, with means of 155.7 and 149.2 inches per mile, respectively. In comparison, the mean of the Walking Profiler IRIs is 212.1 inches per mile.

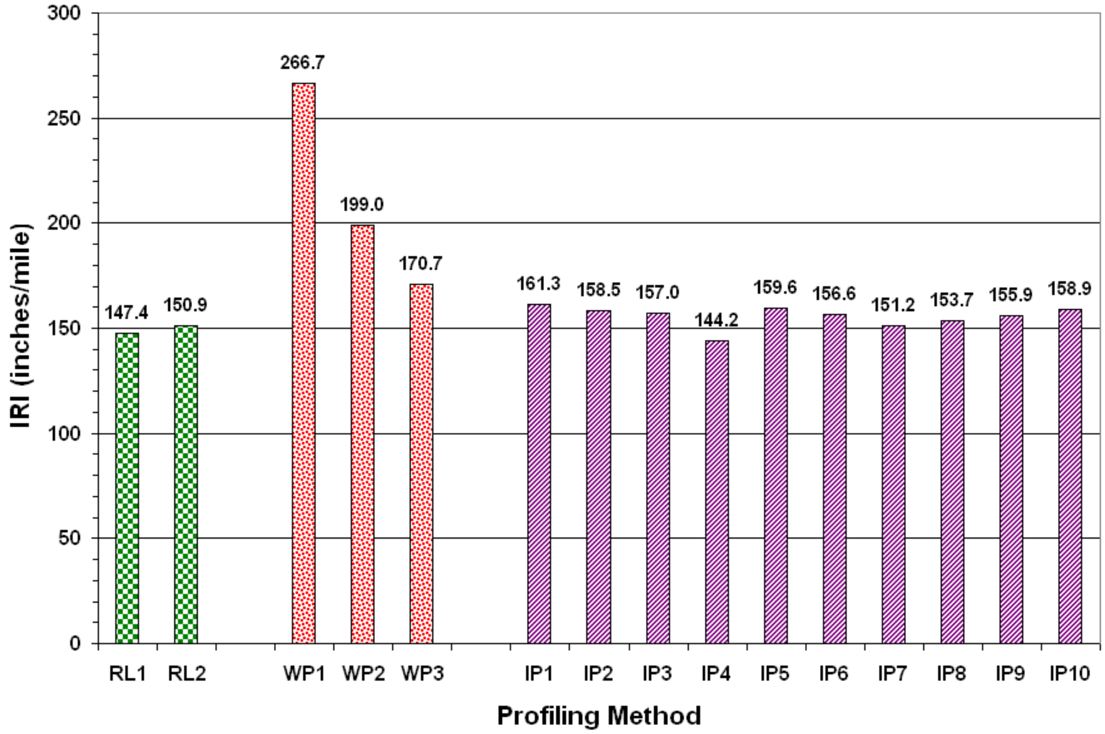


Figure 3.15. IRIs Computed from Test Data on Old Seat Coat Pavement.

To check whether the lack of repeatability of the IRIs might be due to a malfunctioning piece of equipment, researchers also conducted similar tests on a 95-ft section with a conventional dense-graded hot-mix asphalt concrete surface. Figure 3.16 shows the IRIs from these tests. Note that the Walking Profiler IRIs are all comparable to the corresponding ride statistics determined from the other two methods. The mean of the WP IRIs is 34.3 inches per mile compared to mean IRIs of 35.2 and 33.8 inches per mile from the rod and level and inertial profiler, respectively. It is also observed that the Walking Profiler IRIs are very repeatable, with a standard deviation of 0.65 inches per mile. These results suggest that the Walking Profiler is functioning properly and that the lack of IRI repeatability on the old seal coat section is due to other factors. While these factors include operator variability, the authors are of the opinion that the lack of IRI repeatability more likely stems from exceeding the operational limits of the Walking Profiler on the old seal coat pavement. In particular, the coarse aggregate surface and the presence of cracks probably introduced errors in the elevation measurements as the Walking Profiler was pushed over the wheel path from run to run.

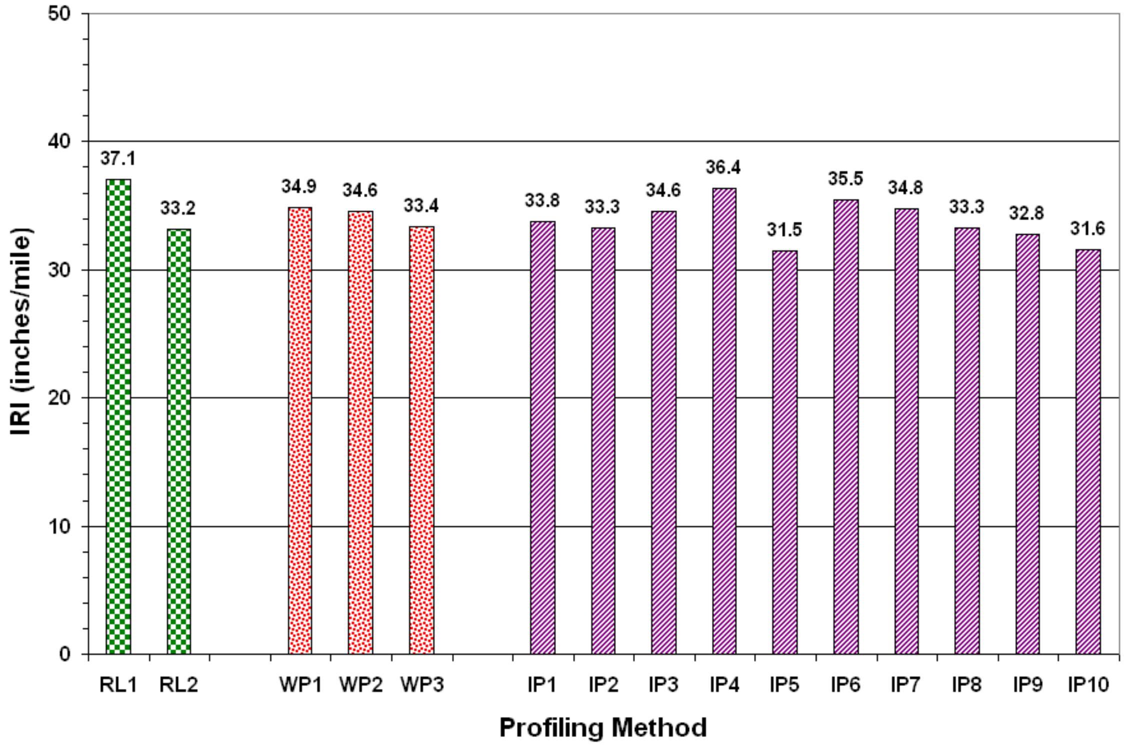


Figure 3.16. IRIs Computed from Test Data on a Conventional Dense-Graded Hot-Mix Asphalt Concrete Pavement.

To collect additional data, researchers conducted profile measurements during construction of a new road along SH6 north of Calvert in the Bryan District. These measurements were made on a Grade 4 seal that was placed on the flexible base prior to placement of the hot-mix asphalt concrete surface. Figure 3.17 shows the IRIs determined from these measurements. Similar to the results on the old seal coat section, the Walking Profiler IRIs exhibit a lack of repeatability on the surface tested, as reflected in a standard deviation of the IRIs of 20.4 inches per mile. The Walking Profiler IRIs are also generally higher, with a mean IRI of 204.8 inches per mile, compared to the mean IRIs of 131.6 and 137.3 from the inertial profiler and rod and level, respectively. Between the three profiling methods, it is again observed that the mean IRIs from the inertial profiler and rod and level are more comparable. However, researchers note the big difference between the rod and level IRIs on the Grade 4 seal (148.9 versus 125.7). For this particular case, comparing the inertial profiler and rod and level IRIs is problematic since it is not clear what the reference IRI is on the wheel path tested. Unlike the results from the old seal coat section where the rod and level IRIs from repeat runs are more consistent and are less than the inertial profiler IRIs on all but one of the 10 runs, the difference between the inertial profiler and rod and

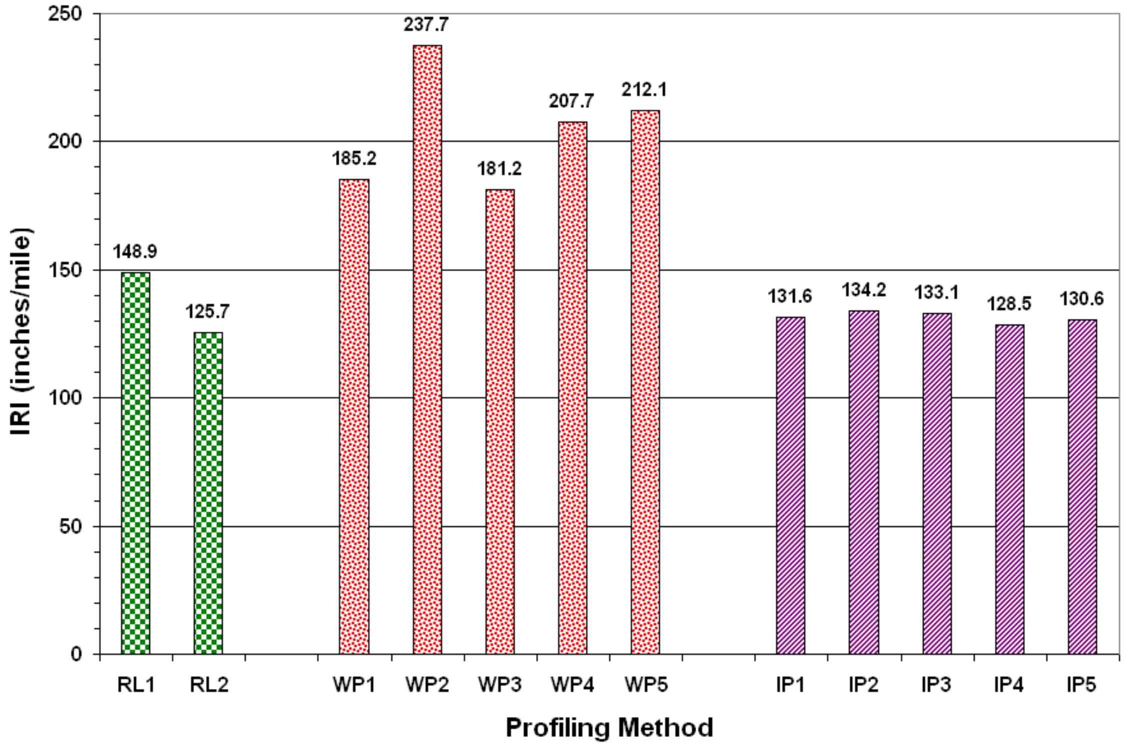


Figure 3.17. IRIs Computed from Test Data on a Grade 4 Seal.

level IRIs on the Grade 4 seal is not as clear. If 148.9 inches per mile is used as the reference, the inertial profiler would appear to underestimate the wheel path roughness. On the other hand, if 125.7 inches per mile is used, the opposite conclusion is made. Thus, in this particular case, the direction of the IRI difference or offset is not clear. Clearly, there is a need to collect more data on surface treatments or seal coats to establish the direction of this offset with confidence. However, for this task to be feasible, researchers are of the opinion that another reference profiling device is needed that is easier to use than the rod and level and that provides elevation profiles with the same or higher level of accuracy and with better resolution. This opinion is based on the experience with the field tests where researchers found no success in using the Walking Profiler on the seal coats tested in terms of achieving IRI repeatability and agreement with the other two profiling methods. In addition, repeat runs to determine reference IRIs are difficult to accomplish with the rod and level, which proved to be tedious and time consuming. Clearly, if inertial profilers are to be used in an IRI smoothness specification based on acceptance testing of the surface treatment, a better and easier method of reference profiling to establish the direction of the IRI offset is warranted. This investigation will provide data to establish IRI allowances for pay adjustment schedules, as well as to decide on the proper application or use of wide-footprint lasers, multi-point lasers, or tire-bridging filters for quality assurance testing in an IRI smoothness specification. While the repeatability of the IRIs from wide-footprint and multi-point lasers has been demonstrated, little verification has been made of the IRIs determined with these newer sensors, particularly on surface treatments or seal coats.

CHAPTER IV. INVESTIGATION OF METHODS TO MINIMIZE TEXTURE EFFECTS

INTRODUCTION

This project investigated a number of alternatives for addressing the effects of texture on ride quality measurements. These investigations aimed to develop recommendations on how ride quality of textured surfaces should be assessed for quality assurance purposes. The investigations covered the following areas:

- comparison of ride statistics in terms of sensitivity to surface texture, and
- tests of alternative lasers that provide measurements over a wider footprint or permit over-sampling of elevation data to investigate techniques for filtering out texture.

This chapter presents the findings from these investigations.

COMPARISON OF THE SENSITIVITY OF IRI AND NSI TO SURFACE TEXTURE

The laboratory tests presented in Chapter III showed that, unlike IRI, the new SI statistic is insensitive to texture effects. In view of this finding, researchers further investigated the sensitivity of NSI to texture based on ride data collected from district projects monitored during this study. Using the profiles taken on these projects, researchers determined the NSIs and compared the values obtained at various stages of construction, i.e., on the flexible base, on the first course surface treatment, and on the final course treatment to verify the effect of surface texture on NSI based on field measurements. Before presenting the results from this investigation, the authors provide a brief description of the NSI statistic in the following section of this chapter.

Background on NSI

The NSI statistic was originally developed by Walker and Fernando (2002) on TxDOT Project 7-4901. In that project, researchers conducted two ride panel rating sessions that provided data with which to evaluate the relationship between pavement profile and road user ratings of ride quality. From this work, researchers developed a wavelength-based ride model (also referred to as the NSI equation) that relates road user perception of ride quality to frequency components of pavement profile. Figure 4.1 shows the power spectral components of measured pavement profiles for different rating intervals based on the data

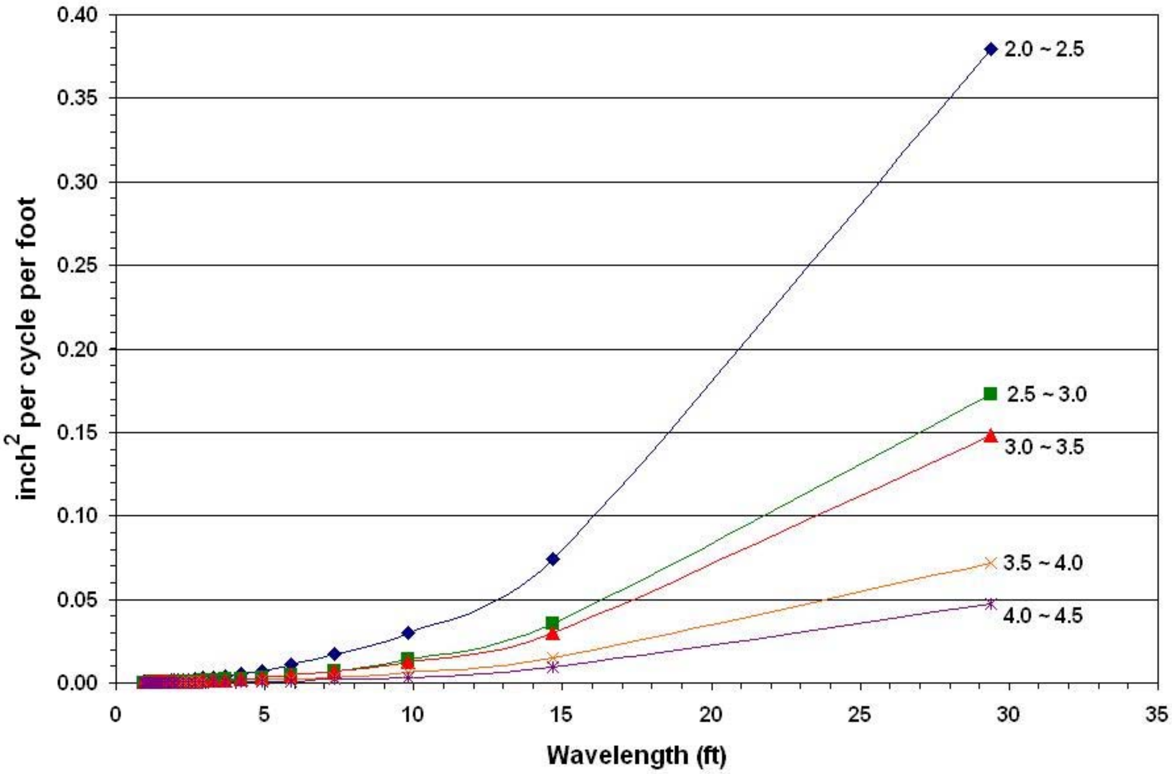


Figure 4.1. Power Spectral Estimates for Various Rating Groups from Texas Ride Rating Sessions (Walker, Fernando, and Bertrand, 2004).

collected from the rating sessions. Researchers note that the sections tested in the experiments were rated on a scale of 0 to 5 with 0 representing an extremely rough pavement and 5 representing a pavement of excellent ride quality. It is observed from Figure 4.1 that the power spectral estimates from the measured profiles are quite distinct for the different rating intervals and that the higher mean panel ratings are associated with lower power spectral estimates of the wavelength components of the surface profile.

In developing the new ride equation, the mean panel ratings were correlated with various frequency components of the pavement profile. From this work, researchers developed a model that related the mean panel ratings to the power spectral estimates of frequencies corresponding to wavelengths of 1 to 8 meters (3.28 to 26.25 ft). The current form of the NSI model is given as follows:

$$NSI = 5\, e^{-(\alpha_1 P_1 + \alpha_2 P_2 + \alpha_3 P_3 + \ldots + \alpha_8 P_8)}$$

where,

α_i = regression coefficients (i = 1 to 8)

P_i = power spectral estimates corresponding to wavelengths of 1 to 8 meters

Using the above model, researchers determined the NSIs from profiles taken on the district projects monitored during this study. These calculations were done using a computer program that applied a discrete Fourier transform to the measured profiles to get the power spectral estimates for 1 to 8 meter wavelength components. The NSIs determined at various stages of construction are presented in the succeeding section.

NSI Statistics Computed from Profile Measurements on District Projects

Figures 4.2 to 4.4 compare the distributions of the NSIs at various stages of construction on the FM2517 project in the Atlanta District, as well as the north and south segments of the SH349 project in the Odessa District. For comparison, the corresponding distributions of the average IRIs are also shown. The IRIs are expressed in units of inches/mile on the secondary x-axis at the top of each chart for TxDOT reporting purposes. If one wants to convert the IRIs from inches/mile to mm/m to bring the statistic on the same 0 to 5 scale as NSI, divide the IRI values in the charts by 63.3465.

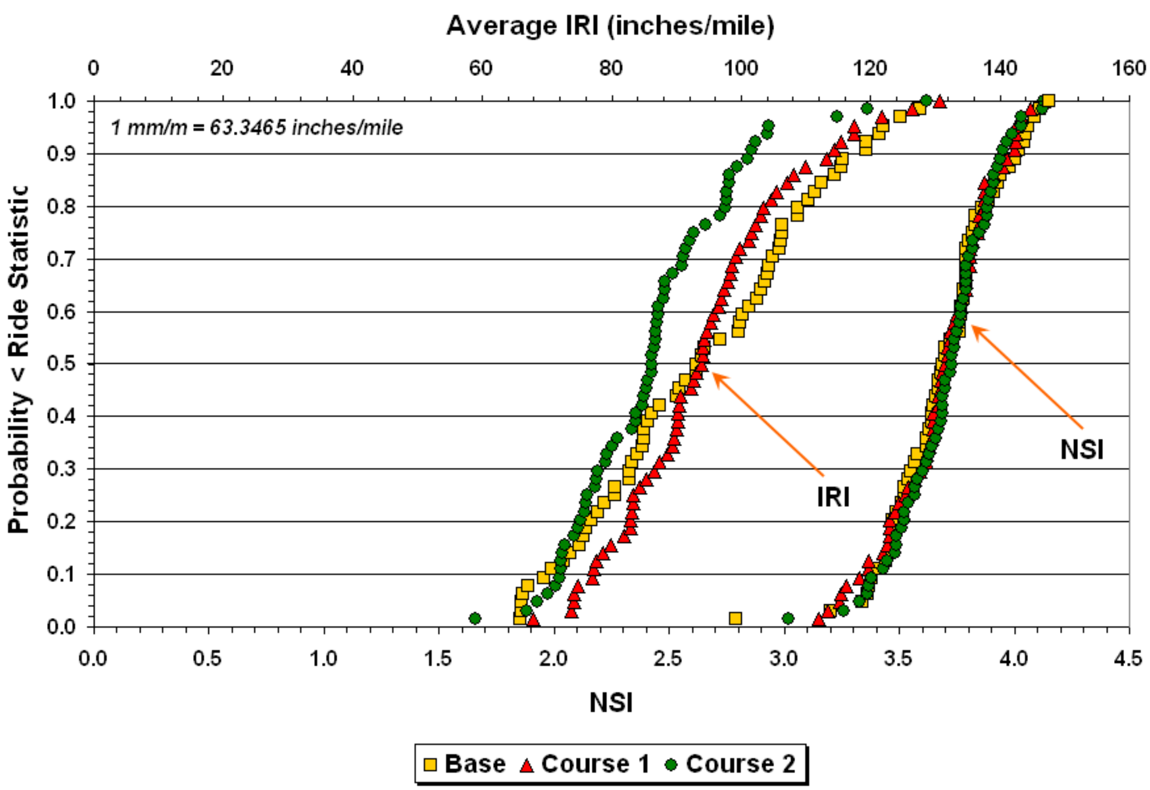


Figure 4.2. Cumulative Distributions of Ride Statistics on the FM2517 Project.

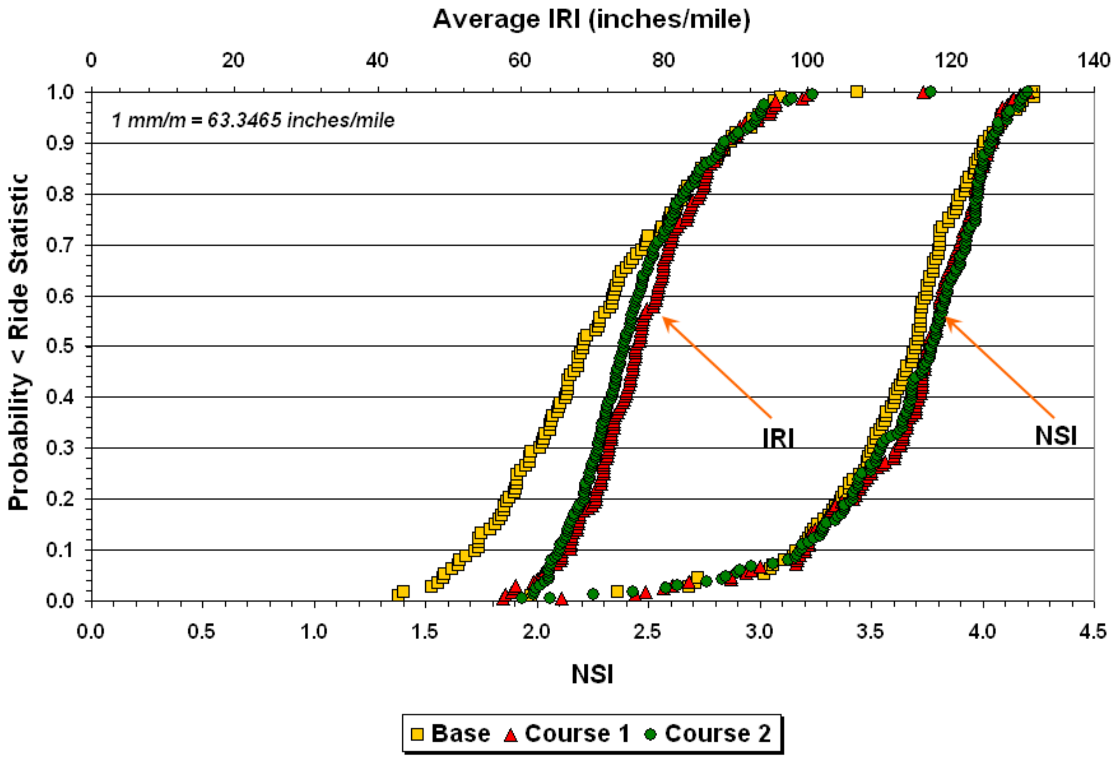


Figure 4.3. Cumulative Distributions of Ride Statistics on the North Segment of the SH349 Project.

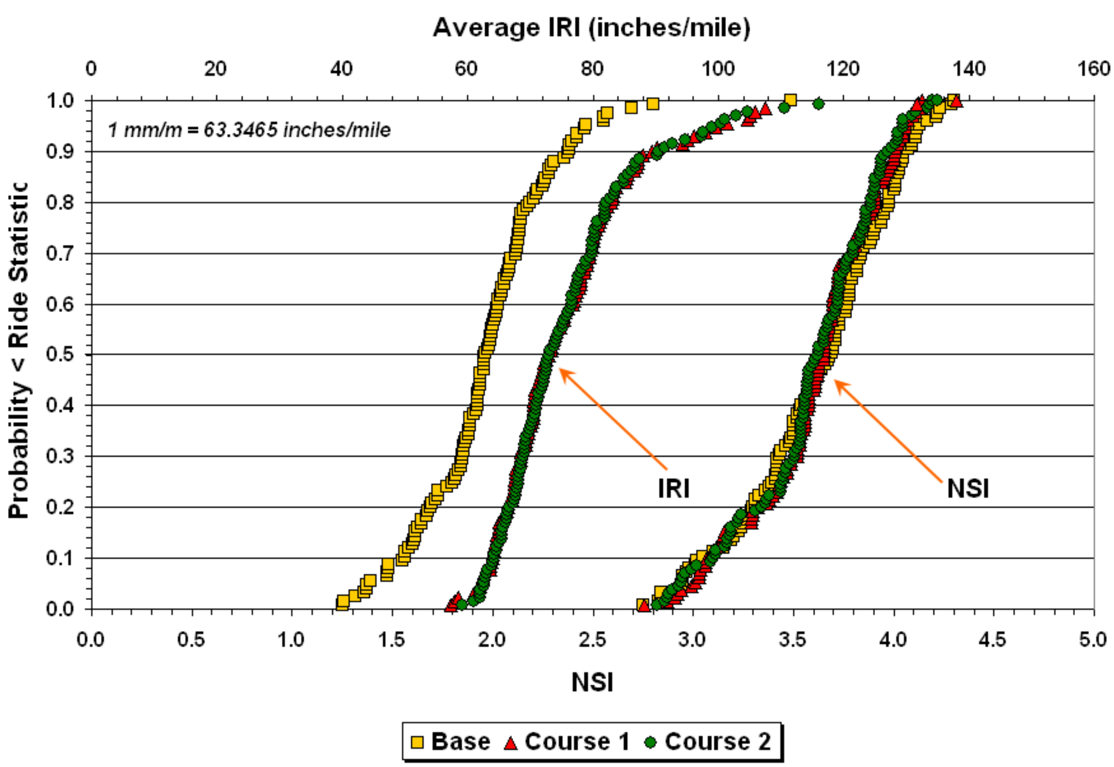


Figure 4.4. Cumulative Distributions of Ride Statistics on the South Segment of the SH349 Project.

Tables 4.1 to 4.3 characterize the cumulative distributions of the NSIs for the different lifts profiled on the FM2517 and SH349 projects. The similarity of the distribution statistics for the different lifts reflects the similarity of the NSI distributions plotted in Figures 4.2 to 4.4. Compared to the distributions of the average IRIs, the greater overlap in the NSI distributions for the flexible base and the two-course surface treatments indicates that NSI is less sensitive to texture of the surface treatments on these projects than the average IRI.

Researchers also examined the distributions of the NSIs on the other Atlanta and Odessa projects where ride data on the flexible base and the first-course surface treatment are available. Figures 4.5 to 4.8 show the cumulative distributions of the NSIs on these projects while Tables 4.4 to 4.7 present statistics that characterize the cumulative distributions of the NSIs. While the distributions of the NSIs on the flexible base and the first-course treatment are closer to each other compared to the corresponding distributions of the average IRIs on the same project, the NSI distributions do not overlap to the same degree as the distributions shown in the earlier figures, indicating an apparent effect of texture on NSI on these projects. However, researchers note that NSI is determined by wavelength components of the measured profile in the 1 to 8 meter range. Thus, the apparent effect of surface texture observed in Figures 4.5 to 4.8 might actually be caused by other factors, such as:

- differences in the wheel paths tracked between tests on the flexible base and the surface treatment, i.e., the measurements on the surface treatment are not on the same path as corresponding measurements made on the flexible base at an earlier time; and
- differences in the measured profiles between the surface treatment and the flexible base that are introduced during placement of the surface treatment.

Researchers note that the above factors can also contribute to the differences between the average IRIs on the flexible base and the surface treatment that are in addition to the effect of texture on IRI, as verified from the laboratory tests presented in Chapter III of this report. Recall that after removing wavelengths associated with the wobble in the specimens tested, the resulting profiles still showed a dependency of IRI on texture, as observed in Table 3.2 and Figure 3.10 of the previous chapter. Table 3.2 shows that the IRIs determined from the wobble-filtered profiles ranged from 10 to 36 inches per mile. In contrast, the NSIs determined from the same profiles varied only over a narrow range (4.93 to 4.99), indicating that NSI is insensitive to the texture of the specimens tested. In the researchers' opinion, the effects of the factors noted previously, combined with the effect of texture on IRI as demonstrated in the laboratory experiments, account for the larger differences (relative to NSI) between the cumulative distributions of the average IRIs shown in Figures 4.2 to 4.8.

Table 4.1. Summary Statistics on Cumulative Distributions of NSIs on the FM2517 Project in the Atlanta District.

Statistic	Lift		
	Base	1st Course	2nd Course
Mean	3.69	3.68	3.70
Standard deviation	0.24	0.23	0.21
Minimum	2.79	3.15	3.02
Maximum	4.15	4.13	4.13
80th percentile	3.87	3.88	3.88
85th percentile	3.94	3.89	3.91
90th percentile	4.01	3.99	3.95
95th percentile	4.06	4.01	4.02
99th percentile	4.12	4.09	4.12

Table 4.2. Summary Statistics on Cumulative Distributions of NSIs on the North Segment of the SH349 Project in the Odessa District.

Statistic	Lift		
	Base	1st Course	2nd Course
Mean	3.62	3.67	3.67
Standard deviation	0.37	0.37	0.39
Minimum	1.97	2.11	2.06
Maximum	4.23	4.20	4.20
80th percentile	3.91	3.97	3.98
85th percentile	3.97	4.00	4.00
90th percentile	4.01	4.04	4.04
95th percentile	4.08	4.08	4.11
99th percentile	4.22	4.15	4.18

Table 4.3. Summary Statistics on Cumulative Distributions of NSIs on the South Segment of the SH349 Project in the Odessa District.

Statistic	Lift		
	Base	1st Course	2nd Course
Mean	3.63	3.61	3.60
Standard deviation	0.37	0.32	0.33
Minimum	2.75	2.76	2.82
Maximum	4.30	4.14	4.19
80th percentile	3.98	3.91	3.89
85th percentile	4.01	3.96	3.92
90th percentile	4.06	4.01	3.97
95th percentile	4.13	4.06	4.05
99th percentile	4.28	4.13	4.18

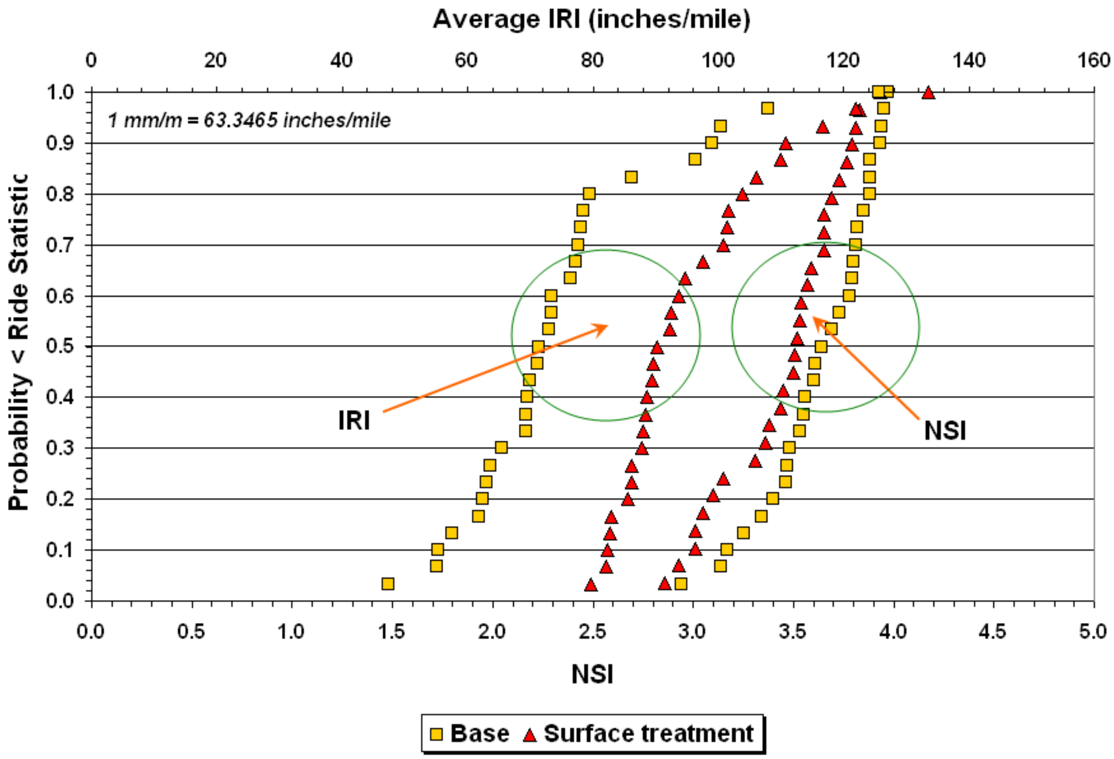


Figure 4.5. Cumulative Distributions of Ride Statistics on Flexible Base and First Course Surface Treatment on FM3098 Project.

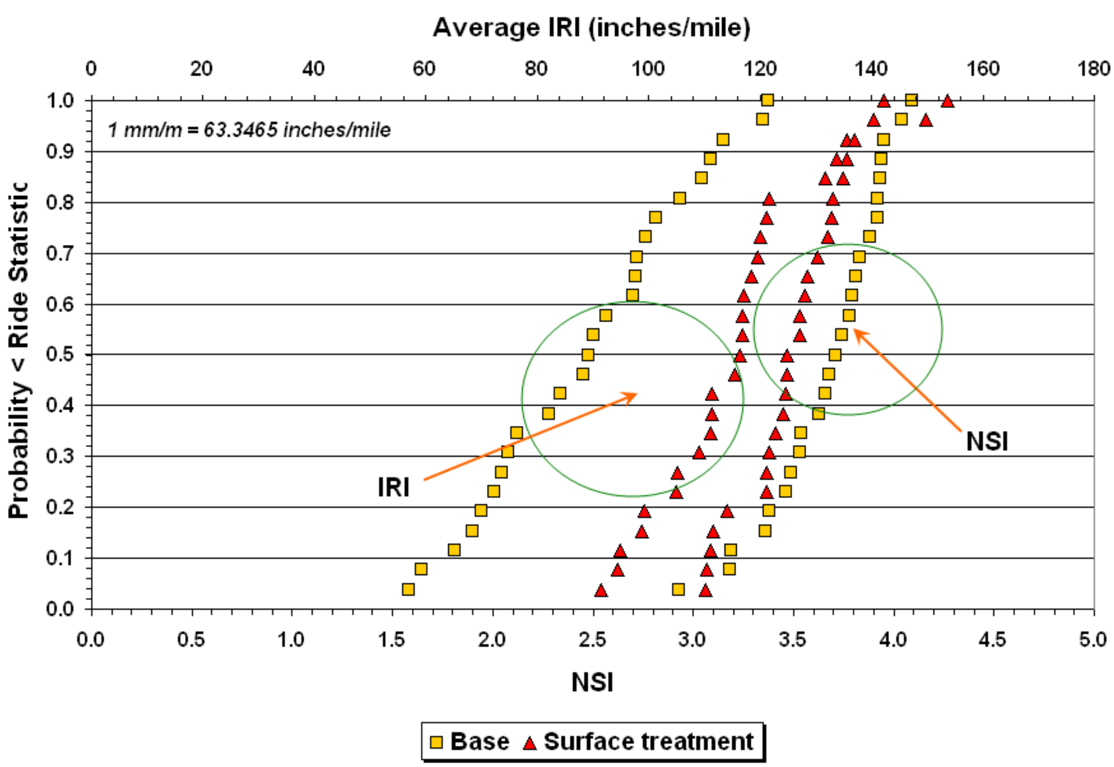


Figure 4.6. Cumulative Distributions of Ride Statistics on Flexible Base and First Course Surface Treatment on SH49 Project.

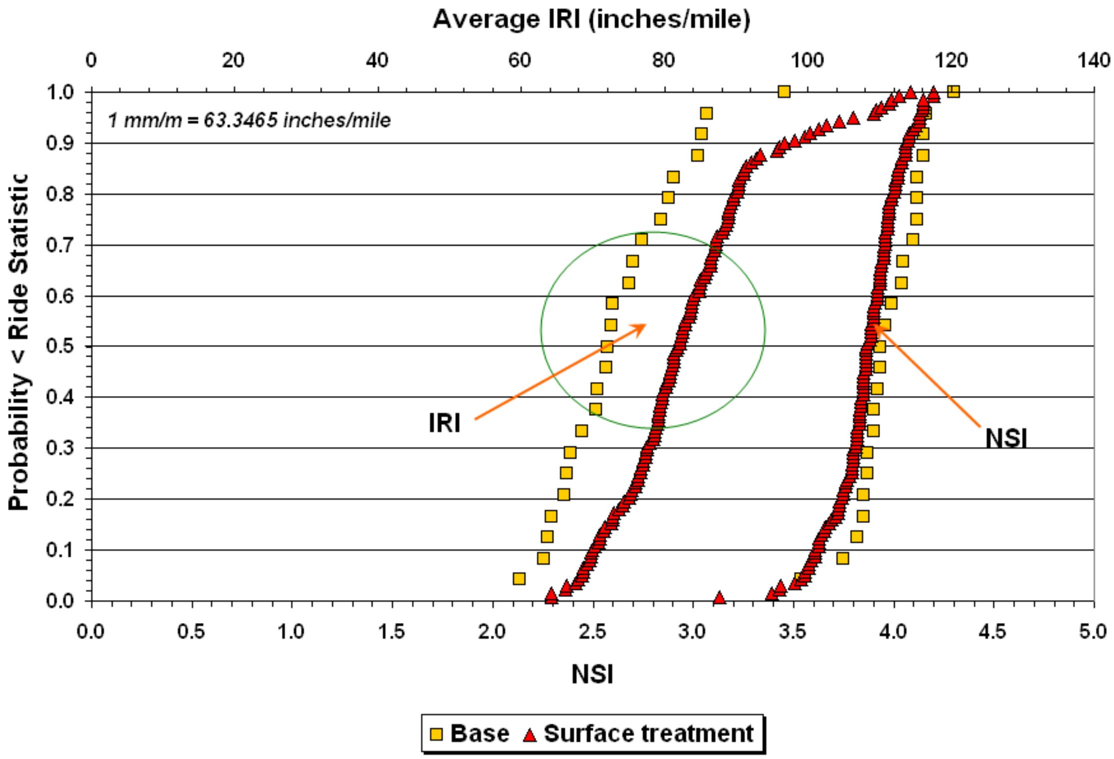


Figure 4.7. Cumulative Distributions of Ride Statistics on Flexible Base and First Course Surface Treatment on FM307 Project.

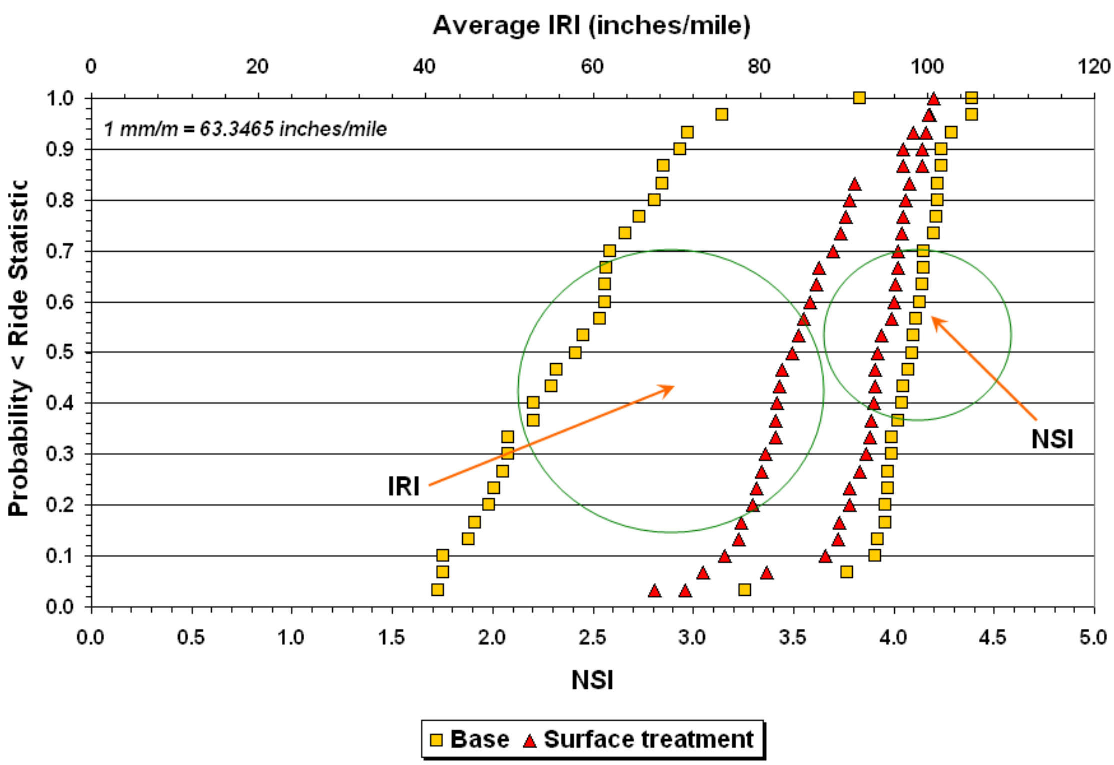


Figure 4.8. Cumulative Distributions of Ride Statistics on Flexible Base and First Course Surface Treatment on FM2401 Project.

Table 4.4. Summary Statistics on Cumulative Distributions of NSIs on the FM3098 Project in the Atlanta District.

Statistic	Lift	
	Base	1st Course
Mean	3.63	3.46
Standard deviation	0.27	0.30
Minimum	2.94	2.86
Maximum	3.97	3.93
80th percentile	3.88	3.71
85th percentile	3.88	3.76
90th percentile	3.93	3.79
95th percentile	3.95	3.82
99th percentile	3.96	3.90

Table 4.5. Summary Statistics on Cumulative Distributions of NSIs on the SH49 Project in the Atlanta District.

Statistic	Lift	
	Base	1st Course
Mean	3.67	3.50
Standard deviation	0.29	0.25
Minimum	2.93	3.06
Maximum	4.09	3.95
80th percentile	3.92	3.70
85th percentile	3.93	3.76
90th percentile	3.95	3.77
95th percentile	4.02	3.87
99th percentile	4.08	3.94

Table 4.6. Summary Statistics on Cumulative Distributions of NSIs on the FM307 Project in the Odessa District.

Statistic	Lift	
	Base	1st Course
Mean	3.97	3.86
Standard deviation	0.16	0.18
Minimum	3.54	3.13
Maximum	4.30	4.20
80th percentile	4.12	4.00
85th percentile	4.14	4.02
90th percentile	4.15	4.06
95th percentile	4.16	4.13
99th percentile	4.27	4.18

Table 4.7. Summary Statistics on Cumulative Distributions of NSIs on the FM2401 Project in the Odessa District.

Statistic	Lift	
	Base	1st Course
Mean	4.07	3.90
Standard deviation	0.21	0.27
Minimum	3.26	2.81
Maximum	4.39	4.20
80th percentile	4.22	4.06
85th percentile	4.23	4.12
90th percentile	4.25	4.14
95th percentile	4.35	4.17
99th percentile	4.39	4.19

TESTS OF ALTERNATIVE LASERS

The laser of an inertial profiler measures the short wavelength components of pavement profile and is the sensor that would be most affected by surface texture. The effect of this factor varies with the size of the laser footprint and the way point-to-point variations in surface elevations within the footprint area are processed (either internally by the sensor or externally by the profiler's data processing program). To verify the effect of footprint size on ride statistics computed from pavement profile, researchers conducted tests with a 19 mm wide footprint laser manufactured by LMI/Selcom and compared the ride statistics from this laser with the corresponding statistics from the conventional laser used in the earlier tests. The conventional laser projects a dot-sized footprint and is the same laser used by the districts to collect profile data.

Before proceeding, researchers note that an attempt was made to test a 178 KHz texture laser developed by Liu et al. (2000) at the University of Houston. This effort aimed to support further investigations of filtering techniques to minimize texture effects. However, as documented in Appendix A, researchers were not successful at using the texture laser for profile measurements due to difficulties in interpreting the laser's height calibration data provided by the TxDOT project director. Thus, no meaningful results were obtained from tests of the texture laser.

Laboratory Tests Conducted with Wide-Spot Laser

Researchers used the wide-spot laser to collect elevation measurements on the same specimens of simulated surface treatments tested earlier with the conventional laser. These tests employed the same laboratory setup described in Chapter III with the wide-spot laser positioned such that its footprint was perpendicular to the track measured on the earlier tests. The raw laser data were then processed the same way as the conventional laser data to generate profiles from which IRIs and NSIs were computed. Table 4.8 compares the ride statistics determined from the generated profiles.

Table 4.8. Ride Statistics Determined from Conventional and Wide-Spot Laser Measurements on Specimens of Simulated Surface Treatments.

Specimen	Test RPM	IRI (inches/mile)				NSI			
		Conventional		Wide-Spot		Conventional		Wide-Spot	
		Avg.[c]	Std. dev.	Avg.[c]	Std. dev.	Avg.[c]	Std. dev.	Avg.[c]	Std. dev.
Grade 3	315[a]	25	0.86	13	0.21	4.96	0.010	4.98	0.024
Grade 4	315	23	0.36	14	0.21	4.93	0.020	4.97	0.014
Grade 5	315	10	0.21	8	0.12	4.98	0.030	4.98	0.024
Grade 3 over 3	315	19	0.29	16	0.52	4.97	0.020	4.96	0.004
Grade 4 over 3	315	33	0.51	32	0.47	4.98	0.030	4.97	0.014
Grade 5 over 3	315	15	0.93	10	0.09	4.98	0.030	4.98	0.024
Platter	315	3	0.01	2	0.01	4.99	0.040	4.99	0.034
Grade 3	630[b]	25	0.93	13	0.19	4.98	0.018	4.98	0.015
Grade 4	630	23	0.35	15	0.31	4.95	0.012	4.96	0.005
Grade 5	630	11	0.22	9	0.24	4.97	0.008	4.98	0.015
Grade 3 over 3	630	18	0.30	15	0.31	4.97	0.008	4.97	0.005
Grade 4 over 3	630	36	0.56	35	0.40	4.98	0.018	4.98	0.015
Grade 5 over 3	630	15	0.41	10	0.12	4.98	0.018	4.98	0.015
Platter	630	3	0.01	2	0.01	4.99	0.028	4.99	0.020

[a]Equivalent to a linear velocity of 15 mph
[b]Equivalent to a linear velocity of 30 mph
[c]Averages and standard deviations computed from 10 runs on each surface treatment specimen and 3 runs on platter

Based on the results presented in Table 4.8, the authors note the following observations from the analysis of laboratory test data:

- Test speed has minimal effect on the computed IRIs from both sets of laser data. The differences in corresponding IRIs determined at the two RPMs range from 0 to 3 inches per mile. Relative to the platter's IRIs of 3 and 2 inches per mile computed, respectively, from the conventional and wide-spot laser data, the differences in corresponding IRIs determined at the two test speeds is of minimal practical significance, in the researchers' opinion.

- The IRIs based on the wide-spot laser are consistently lower than the corresponding IRIs from the conventional laser, with an average difference of about 5 inches per mile. This consistent difference is somewhat expected since the elevations from the wide-spot laser represent averages over the 19 mm footprint of the laser, unlike the conventional laser where measurements are taken over a dot-sized footprint. This observed difference in IRIs indicates that the wide spot is less affected by surface texture. However, it does not mean that the laser is not affected by texture, as shown next.
- The IRIs determined from the wide-spot laser range from 8 to 35 inches per mile for the different specimens tested. This result shows that texture still affected the wide-spot laser measurements. Using the platter's IRI of 2 inches per mile as the baseline and subtracting this value from the IRIs determined based on the 19 mm wide-spot laser, it is found that the effect of surface irregularities is to increase the IRI between 6 to 33 inches per mile for the range of surface treatments considered in the laboratory experiment. Figure 4.9 plots the change in IRI with respect to the mean texture depth from the sand patch tests. A positive correlation is observed between the dependent and independent variables. The linear relationship shown in the figure is statistically significant and quantifies the effect of texture on the IRIs determined from the wide-spot laser measurements done in controlled laboratory tests.
- Table 4.8 shows that the NSIs based on the conventional and wide-spot laser measurements are all close to five and do not vary significantly between specimens and test speeds. Once more, the laboratory tests show that NSI is not affected by frequency components in the macro-texture range.

Field Tests Conducted with Wide-Spot and Conventional Lasers

To supplement the laboratory tests done with the wide-spot laser, researchers collected data with both the conventional and wide-spot lasers on three old seal coat sections located at the Texas A&M Riverside Campus. Figures 4.10 to 4.12 show the sections tested by researchers. On these tests, both lasers were mounted on a bar with the sensors positioned such that the laser footprints were aligned to track the same wheel path on a given run. As with the laboratory tests, researchers oriented the wide-spot laser such that its footprint was

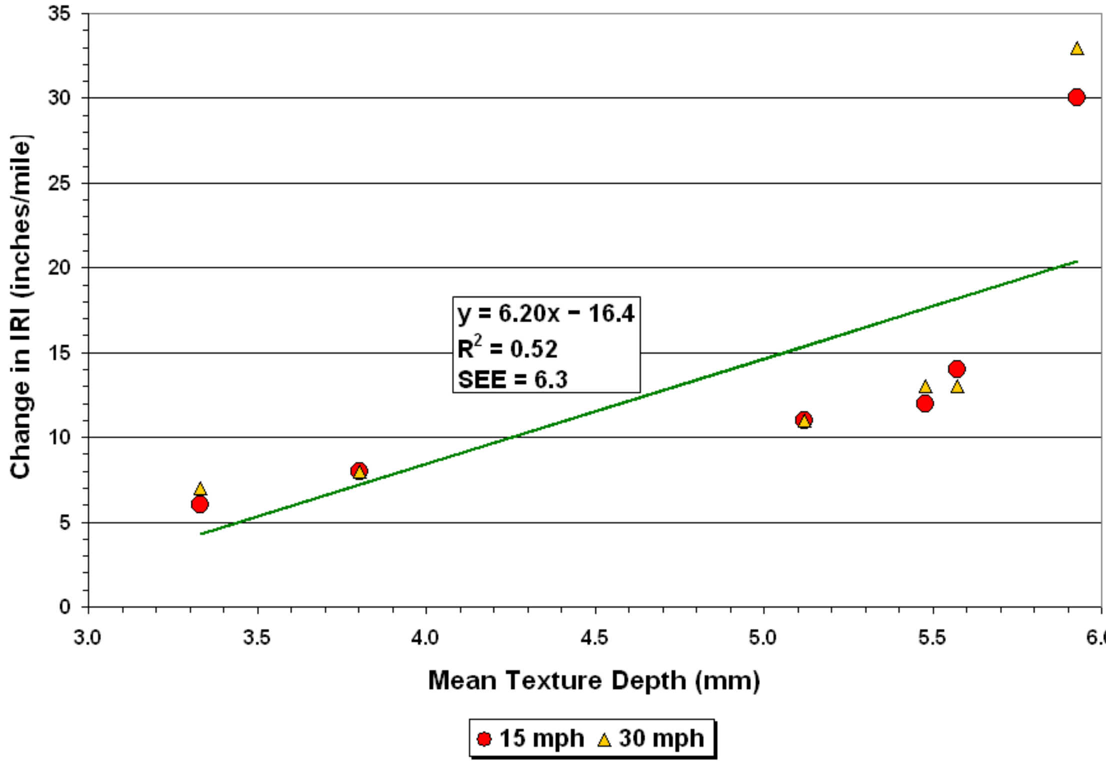


Figure 4.9. Illustration of Relationship between IRI and Texture Based on Laboratory Measurements with Wide-Spot Laser.

Figure 4.10. Left Seal Coat Section Used for Laser Testing.

Figure 4.11. Middle Seal Coat Section Used for Laser Testing.

Figure 4.12. Right Seal Coat Section Used for Laser Testing.

perpendicular to the travel path. Data from both lasers were collected simultaneously over a 528-ft wheel path established on each test section.

Table 4.9 shows the IRIs and NSIs determined from profile measurements made with the lasers on TTI's inertial profiler. It is observed that the IRIs based on the wide-spot laser measurements are generally lower than the corresponding IRIs determined from the conventional laser data. Conversely, the wide-spot NSIs are generally higher than the conventional laser NSIs. Researchers conducted statistical tests to verify the significance of the differences between corresponding means of ride statistics determined from the conventional and wide-spot laser profiles collected on each section. For these tests, researchers tested the null hypothesis that the means of the ride statistics from both lasers on a given section were the same. Table 4.10 summarizes the results from these statistical tests.

Table 4.9. Ride Statistics Based on Profiles Collected on Old Seal Coat Sections.

Test Section	Test Run	IRI (in/mile)		NSI	
		Conventional	Wide-Spot	Conventional	Wide-Spot
Left	1	91.2	85.4	3.15	3.23
	2	92.9	88.6	3.16	3.20
	3	89.7	85.4	3.16	3.27
	4	91.6	87.1	3.05	3.15
	5	89.4	85.8	3.23	3.26
	Average*	91.0 (1.44)	86.5 (1.36)	3.15	3.22
	Std. deviation*	1.4 (0.02)	1.4 (0.02)	0.06	0.05
Middle	1	184.4	186.5	2.27	2.39
	2	196.4	193.3	2.22	2.33
	3	199.3	198.0	2.31	2.39
	4	193.8	193.9	2.28	2.37
	5	198.7	195.6	2.27	2.38
	Average*	194.5 (3.07)	193.5 (3.05)	2.27	2.37
	Std. deviation*	6.1 (0.10)	4.3 (0.07)	0.03	0.02
Right	1	169.4	162.8	2.50	2.59
	2	168.9	162.6	2.47	2.57
	3	178.7	171.8	2.36	2.41
	4	169.6	166.9	2.46	2.46
	5	171.1	163.7	2.52	2.59
	Average*	171.5 (2.71)	165.7 (2.61)	2.46	2.52
	Std. deviation*	4.1 (0.06)	3.9 (0.06)	0.06	0.08

* Statistics given in parentheses are in units of mm/m.

Table 4.10. Significance Testing of Differences between Means of Ride Statistics.*

Test Section	Conventional vs. Wide-Spot IRI	Conventional vs. Wide-Spot NSI
Left	Wide-spot IRI significantly less	Not different
Middle	Not different	Wide-spot NSI significantly more
Right	Not different	Not different

* Based on a significance level $\propto$ of one percent.

For each ride statistic, Table 4.10 shows that the null hypothesis was not rejected on two of the three sections. Examination of the data given in Tables 4.9 and 4.10 reveals that the variability between repeat runs strongly influenced the results from the statistical tests done on each section. The left seal coat section has the least standard deviation of the IRIs while the middle section has the least standard deviation of the NSIs. Thus, in terms of practical significance, the researchers are of the opinion that the field test results are inconclusive with respect to the differences between IRIs and NSIs computed from conventional and wide-spot laser profiles. More field tests are needed to establish whether or not the two lasers give significantly different ride statistics. More importantly, the direction of this difference needs to be established based on comparisons with reference profile measurements. On this project, it was not possible to collect good reference profile data on the sections tested. As was pointed out in Chapter III, researchers experienced problems with using the Walking Profiler on textured surfaces and found the rod and level to be too time-consuming and tedious to use for collecting reference profiles to investigate the direction and magnitude of the IRI offset. Thus, researchers are of the opinion that a suitable reference profiler is needed to support this investigation and the additional data collection that is required.

SUMMARY

Based on the results of the tests presented in this chapter, researchers found the NSI statistic to be a potentially useful statistic for evaluating the ride quality of textured surfaces. This conclusion is supported by the following findings:

- The laboratory tests demonstrated that NSI is insensitive to the texture of the specimens tested in contrast to IRI, which was found to be significantly correlated with the mean texture depths of the same specimens.
- The laboratory tests showed that NSI is much more effective at eliminating texture effects than the 19 mm wide-spot laser. In particular, the IRIs computed from the conventional and wide-spot laser profiles both showed a significant relationship with

the mean texture depths of the specimens tested, whereas the NSIs computed from the same profiles showed no such relationship.

- The ride data from the districts also showed that NSI is less sensitive to texture of surface treatments compared to the IRI. Given that NSI is determined by wavelength components of the measured profile in the 1 to 8 meter range, the apparent effect of surface texture observed on some district projects might actually have been due to variability in the wheel paths tracked between tests made on the flexible base and the surface treatment and/or differences in the measured profiles between these two lifts that are introduced during placement of the surface treatment. However, test data are needed to verify this statement.
- Relative to NSI, the cumulative distributions of the IRI statistics determined on the district projects tend to show more differences between the surfaces or lifts tested. The larger spread in the IRI distributions for the different lifts appears logical, given the relationship between IRI and texture from the laboratory tests and the possible effects of the other factors noted previously.

The sensitivity of the IRI statistic to texture as observed from the laboratory test results is rather interesting, particularly when this observation is viewed against the IRI gain function shown in Figure 4.13. This figure shows that at frequencies of 2 cycles/meter and higher (corresponding to wavelengths of about 20 inches and shorter) the gain is zero. Thus, based on Figure 4.13, the IRI statistic should not be affected by texture. However, the laboratory test results presented herein show otherwise. Given this finding, there is a need for additional research to determine why texture is affecting the IRI statistic. In the researchers' opinion, this investigation should clarify the IRI gain function in order to determine the frequencies that the IRI statistic is sensitive to. This understanding is important to resolving the texture issue.

Between the NSI and the 19 mm wide-spot laser, researchers are of the opinion that the test data clearly show NSI to be the better alternative to use for evaluating the ride quality of textured surfaces, i.e., seal coats and surface treatments. The application of NSI is particularly attractive since it will not require any changes to the existing profilers used by TxDOT or paving contractors. In contrast, the options that include use of other lasers, hardware filters, or software filters such as tire-bridging filters, will all require changes to existing inertial profiling systems, which may be difficult to implement. Researchers note

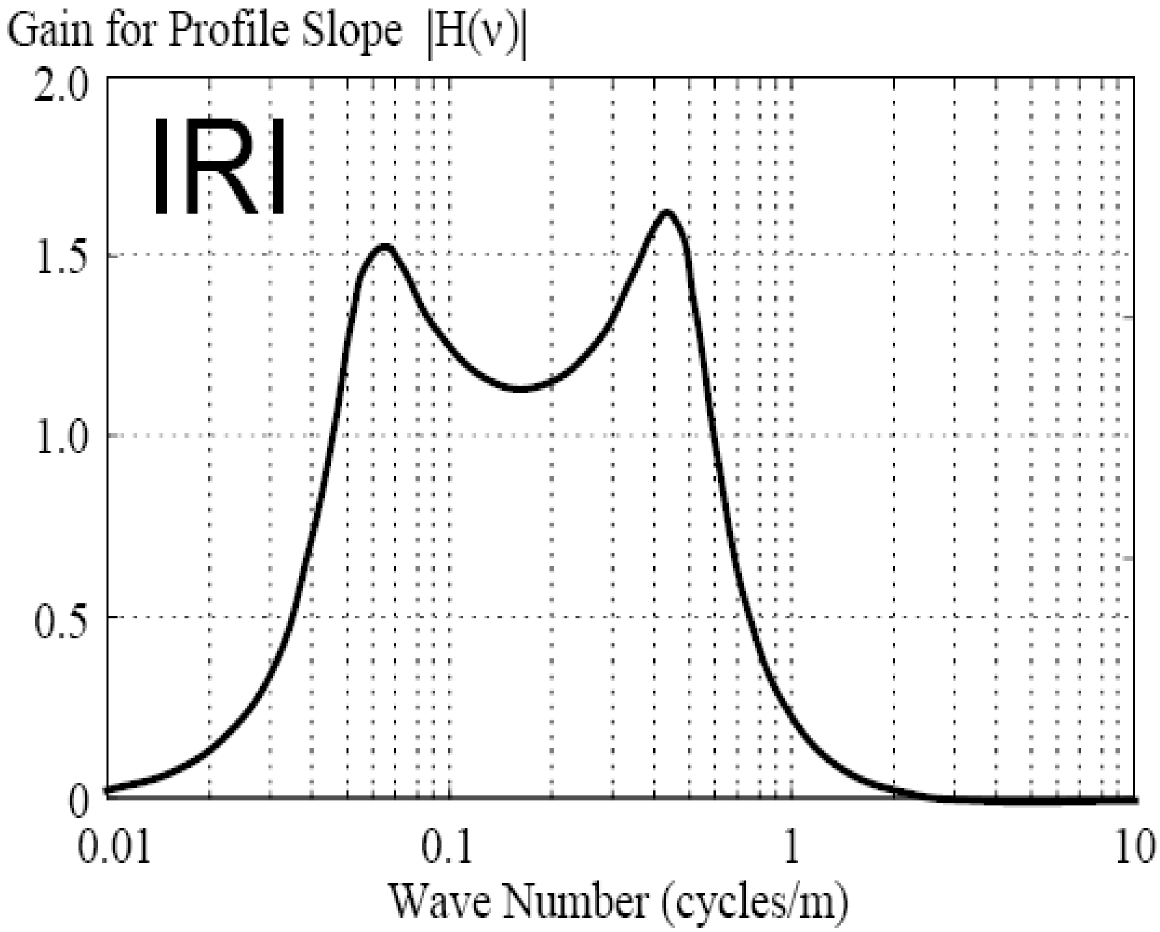


Figure 4.13. IRI Gain Function (Sayers and Karamihas, 1997).

that attempts were also made in this project to investigate filtering methods to reduce the effect of texture. These methods involved the application of the texture laser developed by Liu et al. (2000) on TxDOT Project 7-3969 and a tire-bridging filter developed by the project director. However, as documented in Appendix A, more time was required than was available on this project to further investigate and develop these methods.

Notwithstanding the potential implementation difficulties associated with using wide-footprint lasers or filters to reduce the effect of surface texture, the application of NSI in a smoothness specification is not without its share of additional work. In particular, the authors note the following:

- Since the NSI equation is based on profile measurements and ride ratings collected on 0.1-mile sections, the equation needs to be modified to permit computation of NSIs for short sections (defined as segments between 50 and 528 ft in length).

- Additional work is recommended to verify the applicability of the existing equation to predict road user ratings of ride quality for seal coats and surface treatments. Researchers note that while 20 of the 63 flexible pavement sections included in the Project 7-4901 ride rating sessions had seal coat surfaces, all of these sections were on an existing farm-to-market road characterized by a medium to rough riding surface. In the researchers' opinion, additional tests are needed to verify and re-calibrate (as necessary) the NSI equation on seal coats and surface treatments representative of those found on recently completed rehabilitation projects.

CHAPTER V. SUMMARY ASSESSMENT OF FLEXIBLE BASE RIDE SPECIFICATION

As noted in the first chapter of this report, TxDOT's Construction Division drafted a special provision to Item 585 during the initial year of this project. This special provision included amendments to the ride specification that specifically covered QA testing of ride quality for pavements consisting of surface treatments over flexible base. Among the stipulations in this initial special specification are:

- Quality assurance tests are done on the finished base, with profiles measured after placement of the prime coat, unless otherwise directed by the engineer.
- Transverse profile of the finished base is measured using a straightedge. Corrections are made where grade deviations exceed 0.25 inch in 16 ft (measured longitudinally) or where grade deviations exceed 0.25 inch over the entire cross-section width.
- On 0.1-mile sections where the average IRI is greater than 125 inches per mile, the contractor performs corrective work to reduce the IRI to 125 inches per mile or less for each wheel path.

This cooperative project evaluated the applicability of the provisions on quality assurance testing of the longitudinal profile in the draft special specification. As documented in the preceding chapters, researchers conducted this evaluation by comparing the proposed IRI criterion in the specification against ride data collected from shadow tests done of the draft specification on surface treatment projects and by investigating the effect of texture on ride quality measurements. This approach was followed as the projects tested were let before the draft flexible base specification was approved. Based on the analyses of test data collected on this research project, the authors submit that the requirements for quality assurance testing as drafted in the special specification are appropriate to implement for acceptance testing of the ride quality of flexible base. This opinion is based on the following findings from this project:

- The contractors readily achieved the average IRI criterion of 125 inches per mile (as computed over a 0.1-mile interval) on the construction projects tested by the districts. On the Atlanta projects, about 81 percent of the sections met this criterion, while on the Odessa projects, the average IRIs were within 125 inches per mile on all 0.1-mile sections.

- The projects covered sections where the average IRIs achieved on the flexible base were comparable to average IRIs determined on rehabilitated or newly constructed dense-graded hot-mix asphalt concrete pavements. On the Odessa projects, about 80 percent of the sections had average IRIs ≤ 76 inches per mile.
- The laboratory tests showed that the IRI determined from profile is influenced by surface texture. Given this finding, and considering previous district experience on successful implementation of general notes governing the ride quality of flexible base, the provision to test the flexible base in the draft IRI ride specification makes good sense.

While the proposed IRI criterion of 125 inches per mile is realistic to use for QA testing of flexible base ride quality, researchers note that a lower IRI criterion may be more applicable to specify, particularly for projects located in areas with conditions similar to those found in the Odessa District. For example, if 125 inches per mile corresponds to 81 percent compliance on the Atlanta projects, the IRI value corresponding to this same level of compliance is about 78 inches per mile on the Odessa projects (i.e., 81 percent of the sections tested had average IRIs ≤ 78 inches per mile). Thus, for conditions similar to those found in the Odessa District, the data suggest that a lower IRI criterion between 78 to 125 inches per mile is more appropriate to specify.

Recognizing that the draft flexible base specification came about in an effort to get a standard that all districts can use for evaluating flexible base smoothness on surface treatment projects, the proposed criterion of 125 inches per mile is considered realistic from the perspective of a requirement that contractors can reasonably be expected to achieve given the differences in geographic conditions, climate, and construction practices across the state. Researchers note that the difference between the Atlanta and Odessa flexible base IRIs was presented in a specification meeting attended by TxDOT engineers and contractors in 2005. During that meeting, 125 inches per mile was deemed a suitable criterion to start with for a standard TxDOT specification. Notwithstanding the need for a criterion that has general applicability for statewide use, researchers are of the opinion that language should be provided within the specification permitting a district to specify a different criterion if there is ample justification based on local experience.

Researchers note that the special ride provision approved by TxDOT's specification committee does have a provision that permits a district to use a criterion other than 125 inches per mile. Figure 5.1 shows the flexible base ride specification adopted by TxDOT, which the department added as a special provision to Item 247, "Flexible Base," of the 2004 TxDOT standard specifications. As written, the language of the flexible base ride specification permits other criteria to be used for QA testing of flexible base as shown on the plans. Specifically, the specification reads:

> *Correct 0.1-mi. sections having an average international roughness index (IRI) value greater than 125.0 in. per mile to an IRI value of 125.0 in. per mile or less for each wheel path, unless otherwise shown on the plans.*

Researchers are of the opinion that the above language makes the specification more useful and relevant as it permits the districts to adopt the specification as written and then tailor it to their specific conditions as experience is gained with its implementation. In addition, as more data are compiled with this implementation, TxDOT can further improve and standardize the flexible base ride specification within the framework of the department's 10-year specification review cycle.

Researchers note a philosophical difference between the Item 585 standard specification and the flexible base ride specification. Unlike the Item 585 standard, the flexible base ride specification requires testing the flexible base in lieu of the final surface. This philosophical difference elicited significant discussions between and among TxDOT engineers and industry representatives during the specification development and review process. While the argument has been made that the as-built profile of the flexible base controls the ride quality on surface-treated pavements, the general consensus, particularly within the industry, was that it would be more difficult to correct deficient sections after placement of the surface treatment. Thus, the specification stipulates QA tests on the flexible base after placement of the prime coat and before placement of the surface treatment.

With respect to the prime coat, researchers note that four different types of prime coats are typically used. According to Senadheera and Vignarajah (2007), these are:

- spray prime,
- worked-in prime,
- covered prime, and
- mixed-in prime.

Brief descriptions of these prime coats are given in Appendix B, which presents guidelines for preparing the flexible base to improve ride quality. Of particular interest to the

SPECIAL PROVISION
247---011
Flexible Base

For this project, Item 247, "Flexible Base," of the Standard Specifications, is hereby amended with respect to the clauses cited below, and no other clauses or requirements of this Item are waived or changed hereby.

Article 247.4. Construction is supplemented by the following:

F. Ride Quality. This section applies to the final travel lanes that receive a 1 or 2 course surface treatment for the final surface, unless otherwise shown on the plans.

Measure ride quality of the base course after placement of the prime coat and before placement of the surface treatment. Use a high speed or lightweight inertial profiler certified at the Texas Transportation Institute. Provide the Engineer with equipment certification documentation. Display a current decal on the equipment indicating the certification expiration date. Use a certified profiler operator from the Construction Division's approved list. When requested, furnish the Engineer documentation for the person certified to operate the profiler.

Within 3 days after placement of the prime coat, provide all profile measurements to the Engineer in electronic data files using the format specified in Tex-1001-S. The Engineer will use Department software to evaluate longitudinal profiles to determine areas requiring corrective action. Correct 0.1-mi. sections having an average international roughness index (IRI) value greater than 125.0 in. per mile to an IRI value of 125.0 in. per mile or less for each wheel path, unless otherwise shown on the plans.

Re-profile and correct sections that fail to maintain ride quality after placement of the prime coat, as directed by the Engineer. Correct re-profiled sections until specification requirements are met. Perform this work at no additional expense to the Department.

Figure 5.1. TxDOT Flexible Base Ride Specification.

measurement of ride quality on flexible base are tests on surfaces where covered prime has been used. This prime coat is placed by first applying RC-250 cutback to the finished base, then covering with Grade 5 aggregate to provide a temporary wearing course for traffic. In view of the effect of texture on IRI that was demonstrated in the laboratory tests conducted on specimens of simulated surface treatments, IRIs determined on prime coats with Grade 5 aggregate might exhibit this texture effect. While the criterion of 125 inches per mile was established based on data that also included projects where covered prime coats were used, occasions may arise where the contractor might take issue with the possible effect of texture on the IRIs determined from profile measurements on the covered prime, particularly in borderline cases where the average IRI on a 0.1-mile section is just above 125.0 inches per mile. For such cases, the next section presents a set of guidelines that the engineer can use to check the results from the quality assurance tests.

NSI CHECK ON THE PRIMED SURFACE

The laboratory tests on simulated surface treatments demonstrated that NSI is insensitive to the texture of the specimens tested. In addition, the ride data from the district projects showed NSI to be less sensitive to the texture of surface treatments compared to the IRI. This finding is illustrated in the district ride data summarized in Figure 5.2, which clearly shows the consistency between the NSIs computed on the flexible base layers and the surface course treatments of corresponding projects. This figure also shows the average IRIs plotted in units of inches per mile for TxDOT reporting purposes. If one wants to bring this roughness statistic on the same 0 to 5 scale as NSI, divide the IRI values in the charts by 63.3465. Note the more distinct differences between the cumulative distributions of the average IRIs determined on the flexible base layers and the surface course treatments.

In terms of the distributions of NSIs determined from profiles taken on the flexible base, Table 5.1 provides statistics that characterize these distributions for the Atlanta and Odessa projects. Corresponding statistics characterizing the distributions of the flexible base IRIs were given earlier in Table 2.1 of Chapter II. Recall that the criterion of 125 inches per mile corresponds to an IRI value such that the *probability (IRI > 125 inches per mile) = 0.19*, based on the Atlanta data. Considering that ride quality diminishes with increasing IRI and increases with increasing NSI, researchers determined the NSI value corresponding to a 19 percent probability under the NSI cumulative distribution curves shown in Figure 5.3. Specifically, researchers determined the value of NSI_c such that the *probability* $(NSI < NSI_c)$ *equals 0.19*, where NSI_c is an equivalent NSI criterion. From this analysis, researchers determined NSI_c to be 3.4.

Thus, for 0.1-mile sections with covered prime that fail to meet the IRI criterion of 125.0 inches per mile, researchers recommend that the ride quality be checked against the NSI determined using the measured profiles on the given section. If the NSI is found to be greater than 3.4 (i.e., 3.5 and higher), researchers recommend that the engineer accept the section. Otherwise, the section is corrected as required in TxDOT's flexible base ride specification. This recommendation, along with other pertinent guidelines, can be included

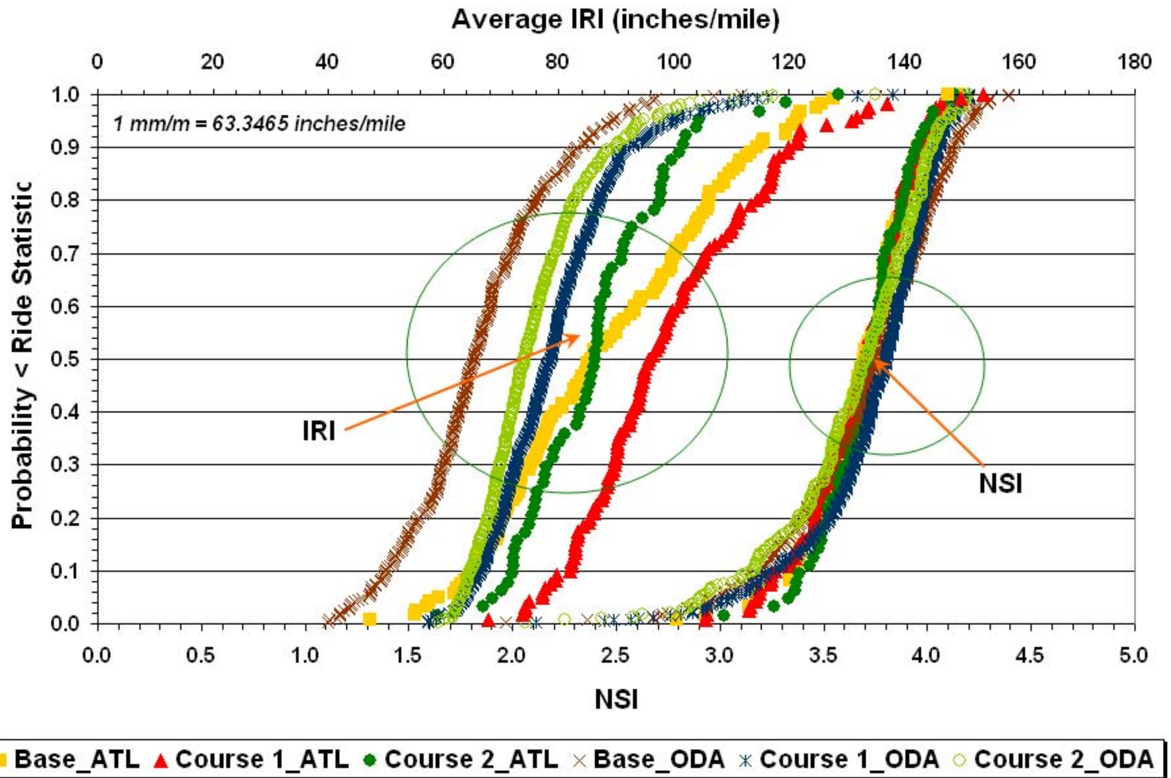


Figure 5.2. Cumulative Distributions of Average IRIs and NSIs on Atlanta (ATL) and Odessa (ODA) District Projects.

Table 5.1. Summary Statistics on Flexible Base NSIs.

Statistic	District	
	Atlanta	Odessa
Mean	3.67	3.70
Standard deviation	0.26	0.38
Minimum	2.79	1.97
Maximum	4.15	4.39
80^{th} percentile	3.88	4.02
85^{th} percentile	3.93	4.07
90^{th} percentile	3.95	4.12
95^{th} percentile	4.04	4.21
99^{th} percentile	4.11	4.30

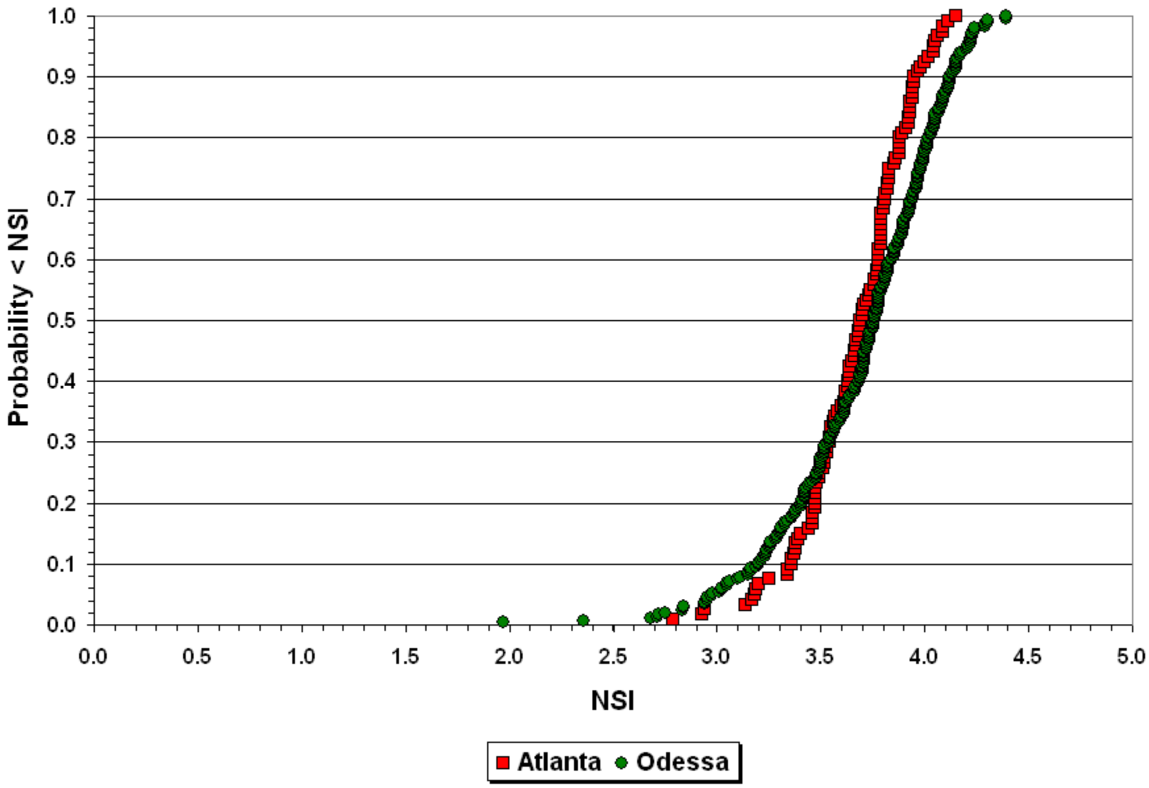


Figure 5.3. Cumulative Distributions of NSIs Computed from Flexible Base Profiles.

in a guidance document for using the flexible base ride specification on district projects. It is noted that a similar document for Item 585, "Ride Quality for Pavement Surfaces," has been prepared by TxDOT.

IMPLEMENTATION RECOMMENDATIONS

Based on the findings from analyses of test data collected on this project, the authors submit the following recommendations for implementing TxDOT's flexible base ride specification:

- A district implementing the specification should create and maintain a data base of IRIs from QA tests done on flexible base ride projects, at least within the first 2 to 3 years of implementing the specification. Further, researchers recommend that the NSIs be determined from the measured profiles on the flexible base and that these statistics be included in the data base. The district can use the data base compiled within the first 2 to 3 years of implementation to assess the applicability of the 125 inches per mile IRI criterion and to change the criterion as necessary to tailor the specification to its specific conditions. As need be, the district can also use the data base to assess the applicability of the proposed NSI criterion for checking flexible base sections with covered prime coats. Researchers recommend that the districts use a standard data base format to facilitate information sharing, with a view towards achieving a harmonized flexible base ride specification statewide.

- The relative insensitivity of NSI to surface texture will also be useful for pavement management purposes, particularly for monitoring and reporting the ride quality of seal coats and surface treatments over the state highway network. Researchers note that the current serviceability index (SI) reported in TxDOT's pavement management information system is determined directly from IRI. Thus, the current SI is just as affected by texture as IRI. However, the NSI is different from IRI and is computed directly from the measured profiles, as explained in Chapter IV. The researchers recommend that NSI be included among the pavement condition indicators reported in TxDOT's PMIS.
- Flexible base surface preparation is crucial to achieving good ride quality after placement of the surface treatment. Unfortunately, some of the techniques used to create a smooth flexible base surface may result in a weak interface that may be detrimental to the performance of the surface treatment. In this regard, Appendix B presents guidelines for preparing the flexible base to achieve the desired base profile and a good bond between the flexible base and the surface course treatment. TxDOT can use the guidelines presented, along with the NSI check proposed herein, to prepare a guidance document for engineers using the flexible base ride specification.
- The IRI criterion in the flexible base ride specification was established based on ride data taken with inertial profilers equipped with conventional lasers that project a dot-sized footprint. In view of recent concerns on the effect of surface texture on ride quality measurements, inertial profilers equipped with wide-footprint or multi-point lasers will likely find increased use by contractors for monitoring ride quality on their projects. Researchers recommend that TxDOT consider placing a temporary restriction on certification testing of new profilers equipped with multi-point and wide-footprint lasers until data from comparative profiler testing are collected and a determination is made on the applicability of the use of these new lasers for QA testing under TxDOT's current ride specifications (both the flexible base ride specification and Item 585). Researchers consider this action to be prudent in view of

the findings from the laboratory tests conducted in this project. In particular, the test results showed that the IRIs determined from profiles taken with the 19 mm wide-spot lasers are still affected by texture. In addition, the 19 mm wide-spot IRIs were found to be consistently lower than the corresponding IRIs determined from profiles taken with the conventional laser. Considering that the criteria used in TxDOT's ride specifications are based on data taken with profilers equipped with conventional lasers, switching to the use of wide-spot lasers without verifying their applicability for QA testing under TxDOT's existing ride specifications would be ill-advised, in the authors' opinion. The proposed temporary restriction would cover only purchases of new profilers or modifications of existing equipment (such as changing from the conventional single-spot laser to a multi-point or wide-footprint laser). It is emphasized that the laboratory test results presented herein are based only on data taken with the 19 mm wide spot laser. Other new sensors (such as the RoLine wide-footprint laser and the Ames Tri-ODS multi-point laser) should be included in the proposed comparative evaluation. Based on the test results, TxDOT can then make an informed decision on whether to permit other laser types, and if so, establish applicable criteria for QA testing of pavement smoothness with profilers that use non-conventional lasers, as well as criteria for certification testing of these profilers.

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APPENDIX A. OTHER INVESTIGATIONS OF METHODS TO MINIMIZE TEXTURE EFFECTS

INTRODUCTION

Chapter IV presented the results from analyses of laboratory and field test data to compare the IRI and NSI ride statistics in terms of sensitivity to surface texture using data collected with two different lasers, one having a dot-sized footprint (the conventional laser), and the other, a 19 mm wide footprint (wide-spot). These investigations showed that NSI is much less sensitive to texture than IRI and provides a suitable, practical approach for evaluating ride quality in a smoothness specification for surface treatments and seal coats. In addition to these investigations, this research project considered the possible application of the texture laser developed from TxDOT Project 7-3969 and a tire-bridging filter developed by the project director for reducing the effect of texture on ride quality measurements. The efforts made in this regard showed that more time is needed than was available in this project to further investigate and develop these methods to where they can be used in practice for evaluating the ride quality of textured pavements. The following sections document these preliminary efforts.

APPLICATION OF TEXTURE LASER FOR PROFILE MEASUREMENTS

The approach of using the 178 KHz texture laser came out of an idea by the project director to over-sample the elevation measurements during data collection and use the resulting profiles to evaluate filtering methods to reduce the effect of surface texture. For this evaluation to proceed, it thus became necessary to determine if the texture laser from TxDOT Project 7-3969 can be used for profile measurements. Since the researchers were not involved with the development of the texture laser, the project director provided guidance on how to collect and process data from this sensor. Researchers note that the project director was directly involved with the development work conducted on Project 7-3969 and actually filled the same role of director on that project.

TTI obtained, on temporary loan, one of TxDOT's texture lasers and its accompanying data processing and power module for the purpose of running tests on the laboratory specimens of simulated surface treatments and on textured pavements. Figure A1 illustrates the data acquisition system used by researchers to collect displacements with

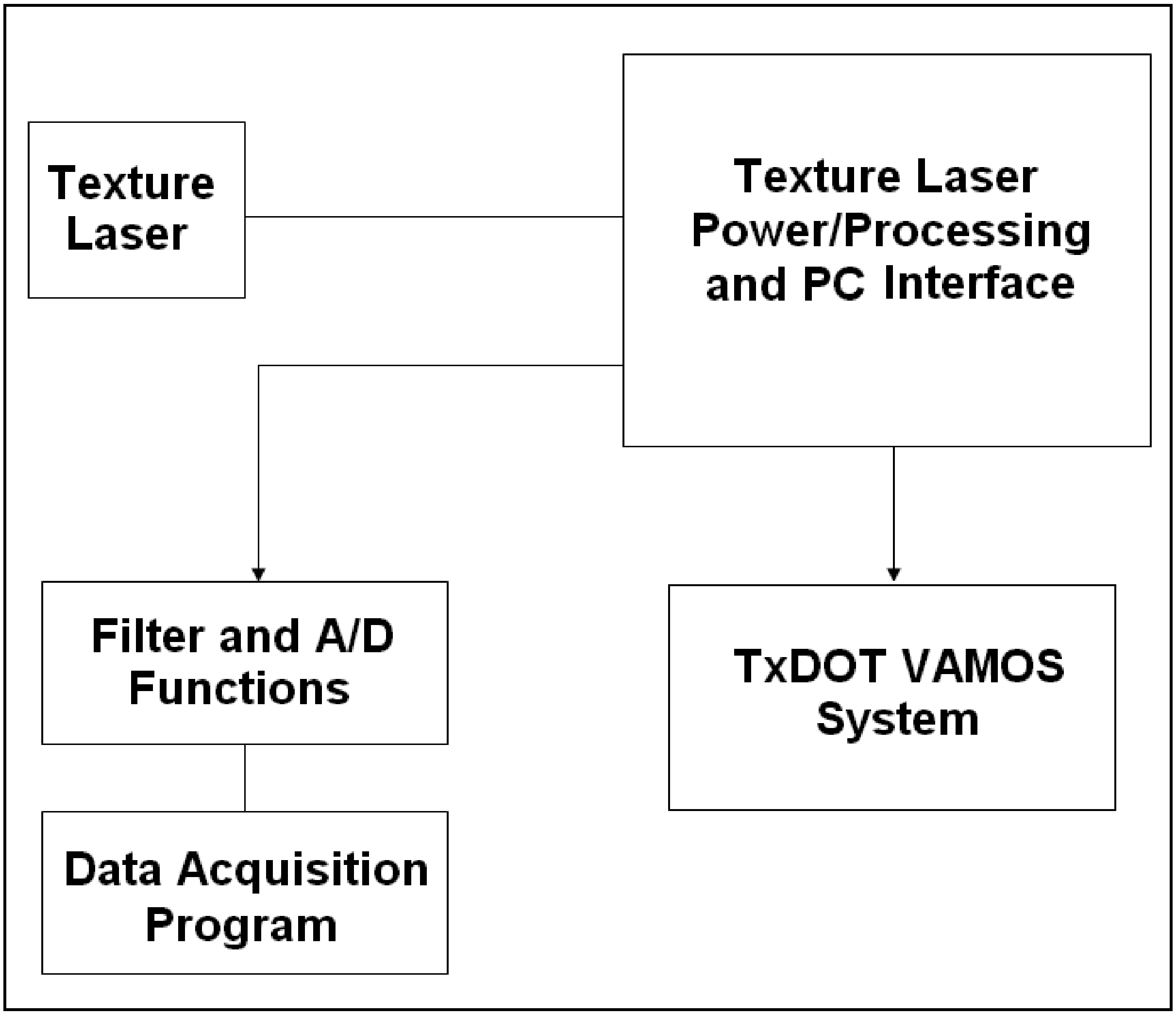

Figure A1. Data Acquisition System Used on Tests of Texture Laser.

TxDOT's texture laser. The system supplied by TxDOT included the texture laser and a control unit housing the power supply for the laser and an embedded personal computer (PC). The embedded PC, among other things, provided a digital interface of the laser displacement readings to a TxDOT VAMOS client program. The project director instructed the researchers to connect the analog displacement signal from the texture laser directly to the data acquisition system via a low pass filter. The low pass filter, according to the project director, was to account for the noise that might result from using the analog signal without the data synch signal used by the control unit.

To collect displacement readings, researchers connected the analog signal directly to a low pass filter and then to a Data Translation™ analog-to-digital (A/D) module. A data acquisition program running on a notebook PC was used to control the Data Translation™ A/D process. The digitized laser voltage readings were saved to a file for processing.

To convert the voltage readings to elevation measurements, researchers used the laser calibration table provided by the project director. Table A1 gives the calibration numbers for the specific texture laser obtained from TxDOT. This table was generated at TxDOT by taking readings with the texture laser in a fixed position while moving a target perpendicular to the laser in increments of 0.1 inch over a displacement range of 0 to 6.6 inches. During this process, the technician recorded the raw laser readings (column 2 of Table A1) for each position (shown in column 1) to generate the calibration table. The table provided by the project director also includes the slope of each displacement reading (column 3) to the actual target location. This slope is related to a corrected displacement reading (given in column 4) that is determined from the following equation provided by the project director:

$$Corrected\ reading = INTEGER\left[\frac{x + \dfrac{\beta_2\, x}{\beta_1\, x + \beta_0}}{2}\right] \tag{A1}$$

where,

x = raw reading from the texture laser,

β_0 = an intercept coefficient equal to -4527.350873,

β_1 = a slope term equal to -0.211607572, and

β_2 = a normalizing constant equal to -18,395.05309.

Figure A2 provides a plot of the raw and corrected texture laser readings versus the corresponding actual target displacements. Observe that the raw readings do not vary linearly with the target displacements. It appears that the corrections made by the project director are intended to linearize the calibration curve for the sensor. However, the corrections have not completely linearized the curve, as may be observed in Figure A2. This observation is significant, as will become clear shortly.

Since the texture laser displacements from actual tests will typically be something other than a value in the calibration table, the suggested procedure from the project director for computing displacements was as follows:

- Correct the raw reading using equation A1.
- Compute the target displacement from the estimated counts per inch between two arbitrary displacements, for example, the closest 1-inch displacements that cover the reading.

Table A1. Texture Laser Calibration Table.

Stage Position (inches)	Raw Reading (counts)	Slope	Corrected Reading (counts)
0.0	65154.00		65297
0.1	63386.67	-17673.33	64189
0.2	61740.00	-16466.67	63149
0.3	60123.33	-16166.67	62119
0.4	58252.33	-18710.00	60915
0.5	56508.67	-17436.67	59782
0.6	54853.00	-16556.67	58695
0.7	53130.67	-17223.33	57552
0.8	51622.67	-15080.00	56540
0.9	50256.00	-13666.67	55614
1.0	48865.00	-13910.00	54661
1.1	47526.33	-13386.67	53735
1.2	46180.00	-13463.33	52793
1.3	44782.33	-13976.67	51804
1.4	43342.00	-14403.33	50771
1.5	42016.67	-13253.33	49808
1.6	40703.00	-13136.67	48841
1.7	39437.67	-12653.33	47897
1.8	38223.67	-12140.00	46978
1.9	37004.33	-12193.33	46043
2.0	35775.00	-12293.33	45086
2.1	34537.33	-12376.67	44107
2.2	33299.33	-12380.00	43112
2.3	32036.33	-12630.00	42078
2.4	30811.33	-12250.00	41058
2.5	29654.67	-11566.67	40076
2.6	28537.67	-11170.00	39110
2.7	27455.67	-10820.00	38156
2.8	26436.67	-10190.00	37241
2.9	25430.00	-10066.67	36320
3.0	24476.67	-9533.33	35430
3.1	23553.67	-9230.00	34553
3.2	22582.67	-9710.00	33610
3.3	21651.67	-9310.00	32687
3.4	20767.00	-8846.67	31792
3.5	19928.33	-8386.67	30925
3.6	19116.33	-8120.00	30068
3.7	18310.67	-8056.67	29199
3.8	17523.33	-7873.33	28332
3.9	16724.33	-7990.00	27431
4.0	15918.67	-8056.67	26502

Table A1. Texture Laser Calibration Table (continued).

Stage Position (inches)	Raw Reading (counts)	Slope	Corrected Reading (counts)
4.1	15159.33	-7593.33	25604
4.2	14440.33	-7190.00	24734
4.3	13775.67	-6646.67	23912
4.4	13052.67	-7230.00	22995
4.5	12325.00	-7276.67	22049
4.6	11647.00	-6780.00	21144
4.7	10977.00	-6700.00	20227
4.8	10332.33	-6446.67	19320
4.9	9719.67	-6126.67	18437
5.0	9071.00	-6486.67	17476
5.1	8465.67	-6053.33	16555
5.2	7856.33	-6093.33	15602
5.3	7248.67	-6076.67	14623
5.4	6668.67	-5800.00	13662
5.5	6084.00	-5846.67	12665
5.6	5477.67	-6063.33	11598
5.7	4897.67	-5800.00	10545
5.8	4355.33	-5423.33	9529
5.9	3797.00	-5583.33	8449
6.0	3281.00	-5160.00	7419
6.1	2753.33	-5276.67	6332
6.2	2257.67	-4956.67	5277
6.3	1781.00	-4766.67	4230
6.4	1298.00	-4830.00	3135
6.5	810.67	-4873.33	1992
6.6	329.00	-4816.67	822

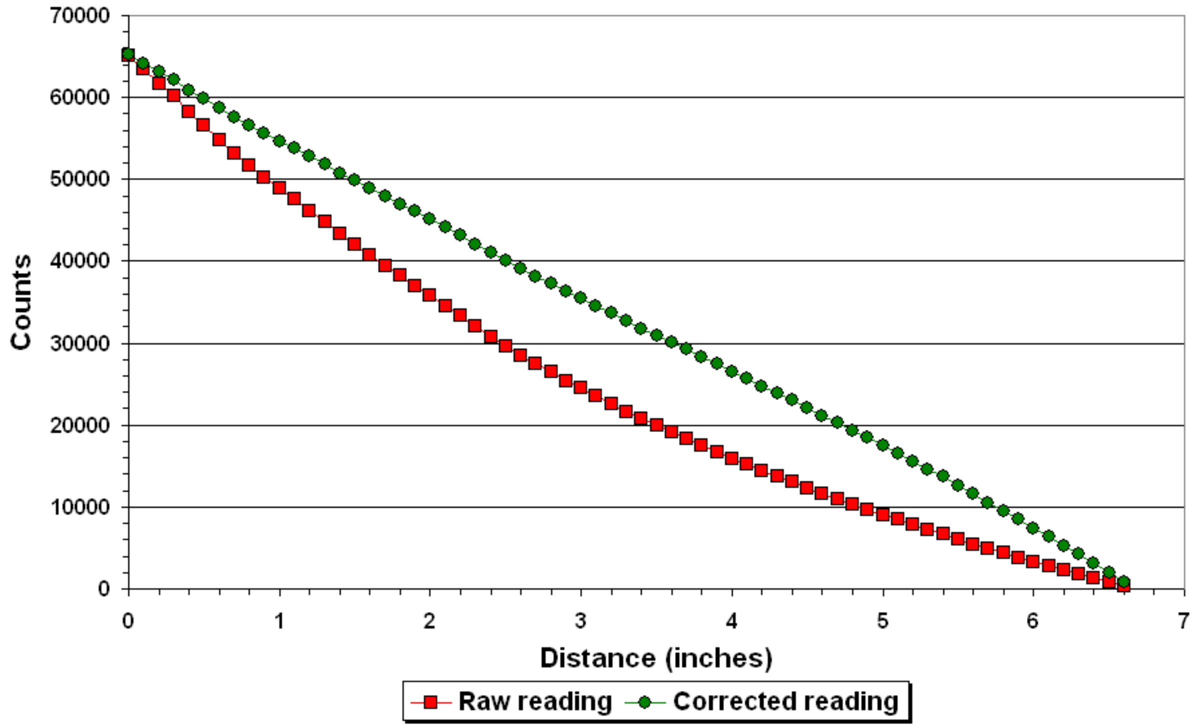

Figure A2. Plot of Raw and Corrected Readings versus Displacements.

As an example, suppose that a reading of 18,000 counts was obtained from a test of the texture laser. Looking at Table A1, this value is between the two table readings of 3.7 and 3.8 inches. Following the procedure given by the project director, the raw reading of 18,000 is first corrected according to equation A1, giving a corrected reading of 28,859. From Table A1, the corrected counts for the two closest 1-inch readings correspond to target displacements of 3 and 4 inches, for which the corrected readings are 35,430 and 26,502 counts, respectively. The target displacement corresponding to the raw reading of 18,000 is then determined by interpolation, as follows:

$$Displacement_{18,000} \quad = \quad 3.0 + \frac{(35{,}430 - 28{,}859)}{(35{,}430 - 26{,}502)} \quad = \quad 3.736\ inches$$

Since the lasers that are commonly used with inertial profilers provide linear displacement readings, a calibration is routinely done prior to data collection by taking a laser reading on a machined block (or readings on a set of such blocks) to determine the displacement counts per inch. This calibration is done to check for proper operation of the laser and data acquisition system and any slight variations in the analog signals due to aging and other factors. Since Table A1 already provides the 1-inch displacements, researchers verified the method for computing displacements by taking readings with the texture laser on a set of machined blocks of known thicknesses. However, the computed displacements following the method suggested by the project director did not compare well with the known block thicknesses. Moreover, one can get different thickness estimates, depending on the "closest" 1-inch range used in the calculations. Depending on the displacement range, the number of counts per inch (based on the corrected readings) changes, as illustrated in Table A2. Given the results shown, how would one determine what calibration factor to use when the height of the laser above the test surface is unknown? The distance of the laser from a target is the measurement variable in practical applications.

Table A2. Differences in Corrected Readings for Various 1-inch Steps.

Stage Position (inches)	Corrected Reading (counts)	Calibration Factor for 1-inch step (counts/inch)
0.0	65,297	10,636
1.0	54,661	9,575
2.0	45,086	9,656
3.0	35,430	8,928
4.0	26,502	9,026
5.0	17,476	10,057
6.0	7,419	

Researchers were unable to clarify the interpretation and proper use of the texture laser's calibration table, despite repeated testing, equipment checks, and conversations with the TxDOT project director. While it is possible that some additional adjustments are made in the embedded PC of the texture laser's control unit, the researchers did not have access to the code that the embedded PC runs. Thus, no meaningful results were obtained from tests with the texture laser. For future testing, researchers are of the opinion that the issues with the interpretation and application of the texture laser's calibration table need to be resolved before further efforts are made to use the sensor for profile measurements.

TIRE-BRIDGING FILTER

The laboratory tests conducted in this project demonstrated the effect of texture on IRI. To minimize this effect, some engineers have suggested the use of a filter to simulate the bridging of surface irregularities that occurs within the tire footprint. Brian Michalk, the director for this project, developed such an algorithm and named it the Michalk Tire Bridging

(MTB) algorithm. He provided researchers with a C program of his filter to evaluate in this project.

From examining the C code, researchers identified the computational steps that comprised the filtering method written into the MTB program. The steps are as follows:

- De-glitching: For each data point read, a "de-glitching" process is done to identify and remove abnormal data points. The program initially reads the laser data set. It then compares each point to a specified de-glitching parameter. For each point found out of range, the program replaces the abnormal reading by the previous valid point.
- DC offset: The next step performed is referred to in the program as the "DC Offset." This step consists of finding and removing the minimum value of the valid data points established from step 1.
- Main computational process: Once steps 1 and 2 are completed, the program applies a "sliding window filter" to the data. In this process, a new value for each point is computed by finding the standard deviation and average of the next N points, where the parameter N is the window size. The filtering is done according to the following code:

```
for i = 1: length(data)
   new_data(i) = Zx * std(data( i+1: N ) ) + avg( data( i+1: N ) )
end
```

  where the parameter Z_x is referred to in the program as the "z-transform." In actual use, this parameter is a multiplier to the standard deviation of the N data points in the sliding window and controls how much the average elevation is shifted.

An understanding of the parameter Z_x may be inferred from a comment included in the program that reads:

> *Given normally distributed data, the Z transform allows the calculation of the value that is the boundary for a percentage of that data.*

Further comments in the code provide for specific values of Z_x that correspond to different areas under the standard normal distribution curve. The program's author gave an initial value of 1.28 for Z_x (corresponding to a significance level of 10 percent).

From the preceding program description, one can see that three parameters need to be determined to use the tire-bridging filter:

- the sliding window size *N*,
- the value of Z_x, and
- the de-glitching criterion.

Each of these parameters can significantly affect the resulting profiles computed from the laser, accelerometer, and distance measurements, particularly the first two. Attempts at including this algorithm in the profile computations did not produce good results. Because of the late addition of this task and the inconclusive results that were obtained, it was not possible to fully determine the appropriate parameters to successfully use the algorithm by the time the project terminated.

Researchers note that characterizing the parameters of the MTB filter is a significant project by itself. Given the resulting tire-bridged profile from a set of filter parameters and the IRI associated with that profile, to what reference should the results be compared? In addition, given the IRI gain function reported in the literature, why is the IRI statistic affected by texture? In the researchers' opinion, answering these questions is important to properly identify the frequencies that any tire-bridging filter should operate on. Finding answers to these questions would require more time than was available in this project to properly characterize the MTB filter to ensure that realistic results are obtained and no profile frequency components are removed that would distort the ride quality evaluation of the surface tested.

An earnest attempt was made to investigate the MTB filter within the four-month time frame given for this task. Test data were collected on specimens that researchers fabricated based on drawings provided by the project director. The specimens, shown in Figures A3 and A4, were tested using the same test cart described in Chapter III, and data were collected using the conventional laser as illustrated in Figures A5 and A6. These last two figures show that the features of the potholed and tined specimens were captured during testing. However, while the tests were completed, the project director was unable to provide the tire-bridged profiles as originally planned. It is noted that the project director recognized the need for more work and time to further investigate the MTB filter than can be accommodated in the four months originally allocated for this task. Among the issues that would have to be resolved is an investigation of the IRI gain function to identify the frequencies that the tire-bridging algorithm should filter out. The project director tried to get additional funding from TxDOT's research management committee. However, his request was not realized.

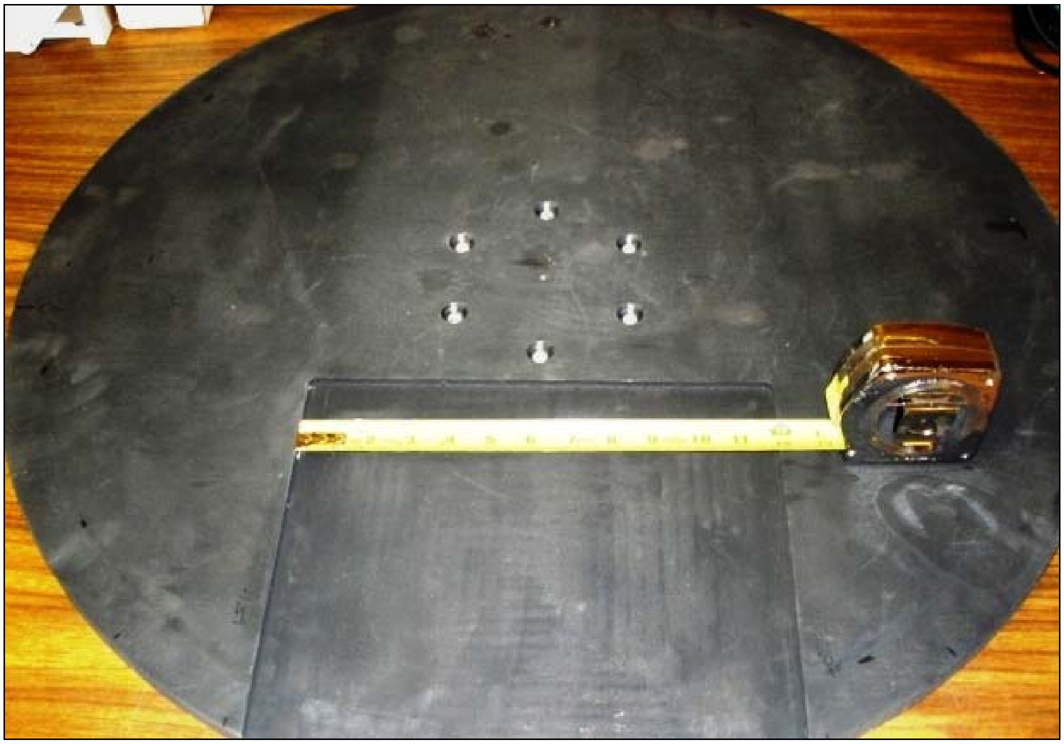

Figure A3. Potholed Specimen Fabricated for MTB Filter Investigation.

Figure A4. Tined Specimen Fabricated for MTB Filter Investigation.

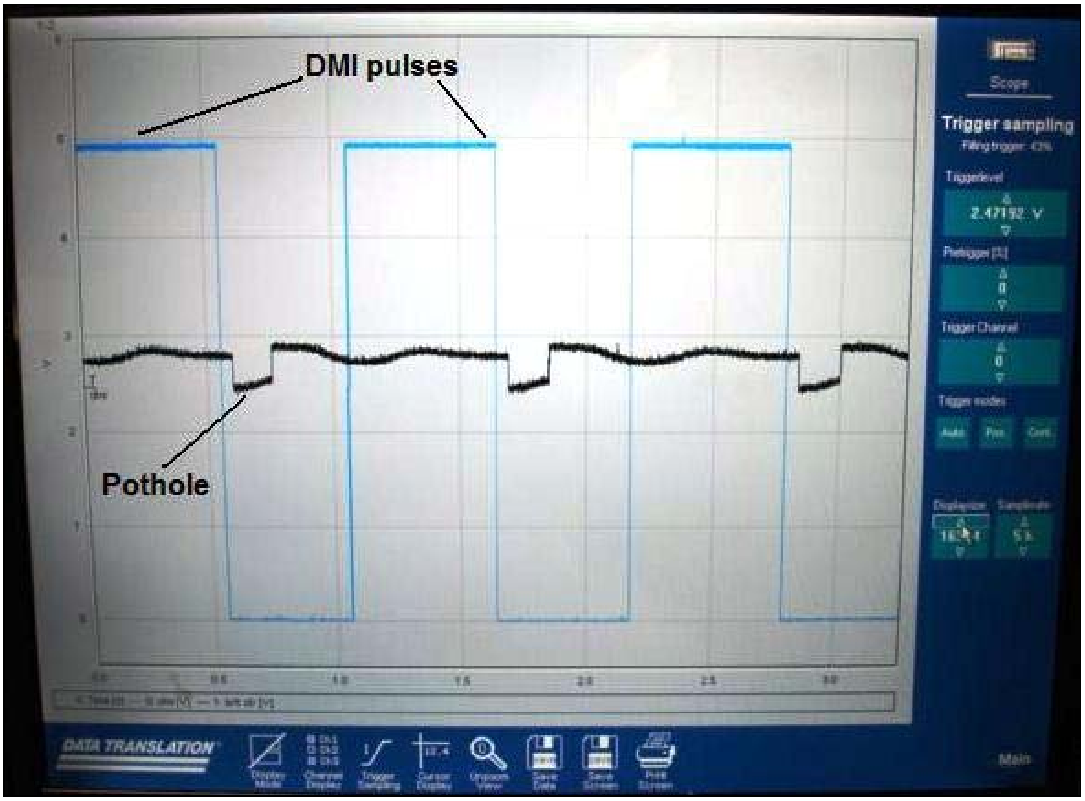

Figure A5. Illustration of Data from Testing Potholed Specimen.

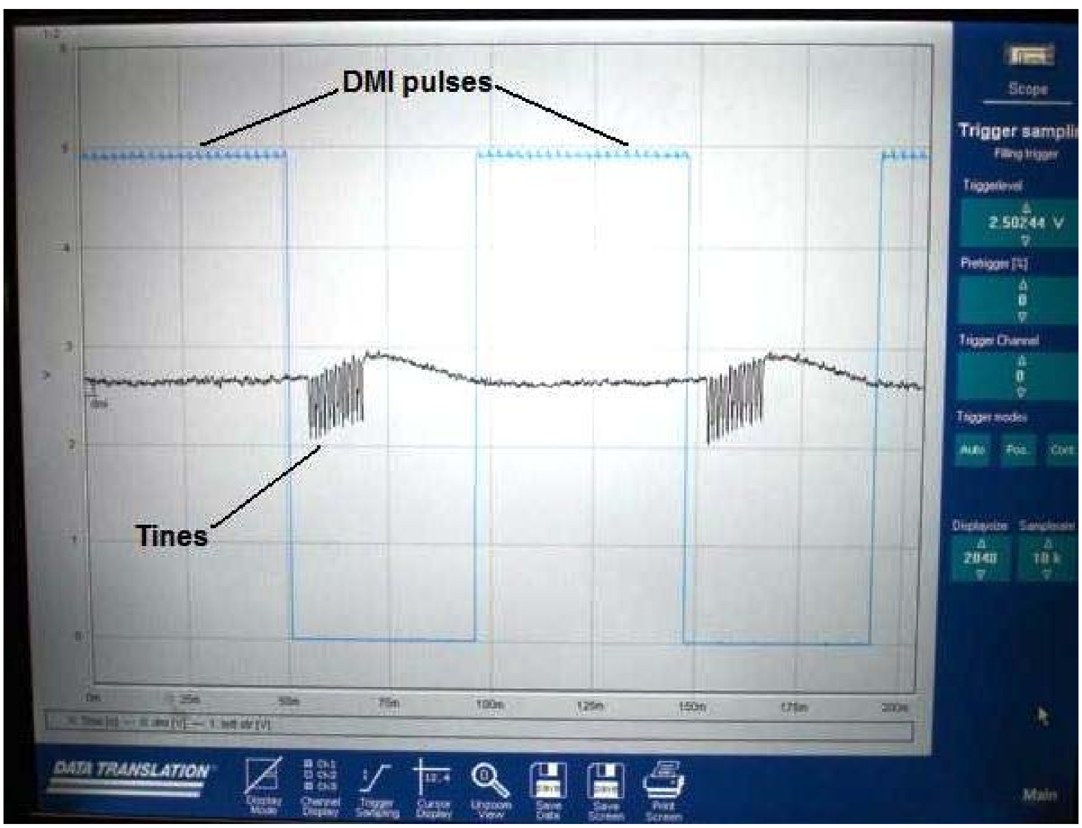

Figure A6. Illustration of Data from Testing Tined Specimen.

APPENDIX B. GUIDELINES FOR BASE COURSE SURFACE PREPARATION TO IMPROVE RIDE QUALITY

BACKGROUND

When a surface treatment is placed on a base course as the final riding surface, creating a smooth surface on the base is critical to the ultimate ride quality. Equipment operators use various techniques to achieve a smooth final surface on the base. Unfortunately, some of the techniques used to create this smooth surface may result in a weak interface and can be detrimental to the performance of the surface treatment. This appendix is intended to provide guidelines for preparation of the base layer prior to application of the surface treatment.

Senadheera and Vignarajah (2007) of the Center for Multidisciplinary Research in Transportation at Texas Tech University published the *Design and Construction Guide for Surface Treatments over Base Courses* under TxDOT Research Project 0-5169. The reader is encouraged to review the Project 0-5169 guidelines since the information presented herein is supplemental to those guidelines.

PLACEMENT OF BASE MATERIALS

Some of the predominant types of base materials used in the state include limestone, caliche, gravel, sandstone, and granite. Limestone, caliche, and even some sources of gravels can have a large quantity of fines (minus No. 40 material), which are usually easier to finish to a smooth surface. Sandstones and granites provide for a very high-quality base material but generally have much fewer fines and are more difficult to finish to a smooth surface prior to placement of the surface treatment.

The caliche used in the Pharr District and uncrushed gravel used in the Yoakum District are usually treated with a small amount of lime (2 percent), which can significantly increase the stiffness of these types of materials. Base materials such as limestone are sometimes stabilized with as much as 6 percent cement. Regardless of the quantity of stabilizer, base finishing operations should be completed soon after compaction.

Base materials should be spread and shaped into a uniform layer with an approved spreader. Some new types of equipment and/or methods are now available for spreading and shaping base materials that can help the contractor achieve better ride quality. The base lay-down machine is a relatively new piece of equipment in the pavement construction market.

It is similar to an asphalt concrete paving machine and is capable of placing flexible or stabilized base material. The material is usually mixed in a pugmill away from the job site and trucked to the project. Experience with a limited number of projects has shown this system of mixing in a pugmill provides a better finish of the base and better control of base moisture content. The thickness of base that could be laid down in one pass would depend on the efficiency with which the material could be compacted. Equipment specifications suggest that thicknesses as high as 7 inches could be laid down in one pass.

The equipment has a hopper with a conveyor taking the base material to the screed area. Trucks bring the material from the pugmill to the job site where it is then loaded into the hopper of the lay-down machine. The equipment can move at speeds in the range of 15 to 20 feet per minute (or 0.2 miles per hour). The material is laid down and compacted by two bars that oscillate vertically.

FINISHING BASE COURSES

One way to better achieve the desired ride quality on a finished base material is through the use of automated grade control systems. Researchers have seen these systems used by contractors in the Yoakum District. One type of automated grade control system is shown in Figure B1. On the motor grader, the system consists of a computer and display unit, a prism atop a mast, and a radio receiver. Additional system elements include controls that link the system to the grader's hydraulic blade controls, a robotic total station (resembling a surveying instrument), and a radio transmitter connected to the robotic total station. The robotic total station should be located over a base hub, and as the grader moves, the total station automatically tracks the prism atop the mast on the grader so that the total station receives location information about the blade.

The radio transmitter (adjacent to the total station) uses a data cable to receive grader blade coordinates from the robotic total station. The radio transmitter sends the information to a receiver onboard the grader. The onboard computer takes the location information from the receiver inside the cab and computes where the blade should run to accomplish the design elevation. The computer issues instructions that control the blade through the grader's hydraulic controls. Cost for this type of system is about $100,000. The equipment can be used to control the grade to within 0.01 ft. Benefits that can be realized by the contractor include:

Figure B1. Automated Grade Control System for Motor Grader.

- Accurate control of the subgrade elevations (no low spots) is achieved, resulting in less waste of base materials.
- A motor grader operator with less experience can still achieve the desired performance.
- Grading can be achieved in less time since there is no need to set stakes and stringlines.

Prior to application of a prime, the base should be prepared and compacted, then bladed to grade. Slush rolling is sometimes used to create a smooth surface on the base course. This practice varies among the districts in the amount of water that is used. If too much water is used, excess fines may be floated to the surface of the base and may result in a delamination of the surface treatment. The contractor should be mindful about creating a weak interface to prevent this condition from developing when slush rolling the flexible base.

The Atlanta District inspectors report that the implementation of a ride specification on the finished base has given them a tool with which to require contractors to provide a better end product. They report that when a conventional motor grader is used, the ride quality of the finished base is directly related to the experience of the motor grader operator. Blue top or grade stakes are typically located every 50 feet. Inexperienced operators will tend to be at the correct grade on the stakes and too low in between. Inspectors should watch for this condition because the only way to correct the low points in the finished surface is to rework the base in these areas. Also, inspectors should look for missing grade stakes to make sure that the operator did not plow up the stakes by striking off the high points as a means of smoothing out low points between the stakes.

When stabilized bases are used, caution should particularly be exercised regarding application of excess water during finish rolling. Excess water applied to the surface of the base material dilutes the effect of the stabilizer and may cause a weak interface. Base finishing techniques should employ a process that does not use excess water.

The surface of the fully-compacted base should be broomed until all loose or caked fines and foreign materials have been removed and some stone particles are exposed. A light sprinkling of water may be used in case of a dry finished base that has dust on the surface.

PRIMING THE BASE

Senadheera and Vignarajah (2007) identified at least four different prime coat types that are typically used during construction of surface treatments:

- Spray prime with or without blotting material – asphalt such as MC-30 cutback or AE-P prime coat binders are sprayed using an asphalt distributor at a typical rate of 0.2 gallons per square yard.
- Worked-in (or cut-in) prime – diluted emulsified asphalt is sprayed on the finished base, which is then covered with a thin coating of fine base material dust using the motor grader to work the windrow. This process is repeated two to three times to get a total emulsion application rate of 0.2 gallons per square yard and an asphalt-sand layer about 0.125-inch thick.
- Covered prime (inverted prime) – RC-250 cutback is applied to the finished base then covered with Grade 5 aggregate, providing a temporary wearing course.
- Mixed-in prime – Once base is completed to the blue-tops, the top 2 to 3 inches of base is remixed with a diluted emulsion and then re-compacted.

Spray-on applications of prime (such as an MC-30) should be at a rate sufficient to coat the surface thoroughly and uniformly with no puddles and no tackiness that would cause vehicle tires to dislodge the prime surface. If puddles or a tacky surface are evident after the prime has been allowed to cure for as long as possible, these areas may be covered with a light application of small aggregate or preferably pre-coated stone (Grade 5). Sand and crusher dust used for this purpose may diminish the bonding ability of the prime and create a shear susceptible surface. Excess stone and dust must be swept from the surface prior to application of the surface treatment.

Emulsified asphalts are generally not recommended for a spray-on application since they do not penetrate the base sufficiently. When using emulsified asphalt for prime, it is usually desirable to mechanically mix the prime with the uppermost 2 to 3 inches of base to achieve desirable penetration depth. Complete guidelines on the use of emulsified asphalts as prime materials are presented by Mantilla and Button (1994) in TTI Research Report 1334-1F, *Prime Coat Methods and Materials to Replace Cutback Asphalt.*

Senadheera and Vignarajah (2007) note that the timing of the prime coat application is of great significance in achieving a good bond with the base. The moisture content needs to be "just right" for the prime to penetrate into the base. If a base is too dry, a fine dust coating can be generated that inhibits the bond of the prime to the base. If the base is very dry, it is recommended that the surface be lightly sprinkled prior to prime coat application. On the other hand, it is also undesirable to apply the prime coat binder when the base is too wet. Shaded areas tend to dry slower than non-shaded areas, and this may cause the prime coat and ultimately the surface treatment to not bond well in these areas.

After the prime coat is applied, it cures through the loss of water or volatiles. Drying time depends on a number of factors, such as type of prime, rate of application, base permeability, and weather conditions (temperature, solar radiation, humidity, and wind velocity). A prime is considered fully cured when it is no longer tacky and will permit light traffic without excessive pick-up of material from the primed surface. One advantage of emulsions over cutbacks is that they cure faster and may be trafficked sooner since evaporation of large quantities of solvent is not necessary.

Traffic must be kept off the primed surface until it has dried or until material is no longer picked up by vehicle tires. Where it is necessary to allow traffic to use the road before the prime has dried, the primed surface must be covered with a layer of small stone. Before proceeding with the surface treatment, loose stones must be removed from the surface. The stone layer should not be applied unless required.