TECHNICAL REPORT 0-6853-1

TXDOT PROJECT NUMBER 0-6853

A PROPOSAL FOR REVISING TXDOT RIDE SPECIFICATION TO ACCOUNT FOR RIDE QUALITY IMPROVEMENT

Jorge A. Prozzi
Prasad Buddhavarapu
Sareh Kouchaki
Andre de Fortier Smit

CENTER FOR TRANSPORTATION RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

Technical Report Documentation Page

1. Report No.
FHWA/TX-16/0-6853-1

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
A Proposal for Revising TxDOT Ride Specification to Account for Ride Quality Improvement

5. Report Date
August 2016; Published March 2017

6. Performing Organization Code

7. Author(s)
Prozzi, J.A., P. Buddhavarapu, S. Kouchaki and A. de Fortier Smit

8. Performing Organization Report No.
0-6853-1

9. Performing Organization Name and Address
Center for Transportation Research
The University of Texas at Austin
1616 Guadalupe St., Suite 4.202
Austin, TX 78701

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
0-6853

12. Sponsoring Agency Name and Address
Texas Department of Transportation
Research and Technology Implementation Office
P.O. Box 5080
Austin, TX 78763-5080

13. Type of Report and Period Covered
Technical Report
January 2015–August 2016

14. Sponsoring Agency Code

15. Supplementary Notes
Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

16. Abstract

The objectives of this project were to i) develop a rational and financially justifiable pay adjustment system that incorporates "new" versus "old" ride quality and ii) evaluate the existing techniques to measure ride quality using Surface Test Type B or inertial profilers on short projects. To achieve these objectives, the researchers conducted an extensive review of ride specifications from other states, focusing on common ride measuring devices and roughness indices, and payment adjustment systems. A survey of past studies was also conducted that focused on the relationship between pre- and post-construction roughness and pavement performance, evaluating the need for incorporating the improvement in ride quality into the pay adjustment system. A comprehensive database was developed integrating SiteManager, Design and Construction Information System (DCIS), and Pavement Management Information System (PMIS) databases. The ride quality data was extracted from a total of 565 asphalt projects constructed from 2001 to 2011. Statistical analyses were applied to establish a pay adjustment scheme based on the gain in pavement life due to the ride improvement relative to ride quality prior to the project construction. As a result, a performance-based pay adjustment system was proposed that incentivizes or penalizes pavement projects according to the combination of change in the ride quality and post-construction ride quality.

In terms of roughness measurement on short projects, the research team administered a survey questionnaire with specific and direct questions and in-person interviews designed to obtain insight into the practical issues associated with operating inertial profilers on short projects. A field experiment was also carried out to investigate the feasibility of using inertial profilers to measure roughness on short projects. The results of the field experiment and the survey revealed that an inertial profiler operated by an experienced driver could be used to measure the roughness on short projects, provided that sufficient data is collected for stabilization and initialization of the algorithms before that target section.

17. Key Words
Ride Quality, Pay Adjustment Factor, Construction Roughness, Inertial Profiler, International Roughness Index, IRI, Straightedge

18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161; www.ntis.gov.

19. Security Classif. (of report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of pages
80

22. Price

THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

A Proposal for Revising TxDOT Ride Specification to Account for Ride Quality Improvement

Jorge A. Prozzi
Prasad Buddhavarapu
Sareh Kouchaki
Andre de Fortier Smit

CTR Technical Report:	0-6853-1
Report Date:	August 2016; Published March 2017
Project:	0-6853
Project Title:	Improvements to Ride Specifications
Sponsoring Agency:	Texas Department of Transportation
Performing Agency:	Center for Transportation Research at The University of Texas at Austin

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Center for Transportation Research
The University of Texas at Austin
1616 Guadalupe St, Suite 4.202
Austin, TX 78701

http://ctr.utexas.edu/

Disclaimers

Author's 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 herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation.

Patent Disclaimer: There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

Engineering Disclaimer

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES.

Research Supervisor: Dr. Jorge Prozzi

Acknowledgments

The authors express appreciation to all personnel from the Texas Department of Transportation that contributed to this research project and provided the research team with useful guidance and continuous support. In particular, we would like to thank Joe Adams and Kevin Pete from the Research and Technology Implementation Office. In addition, the following people are acknowledged for their technical contribution and advice: Ryan Jackson, Eric Lykins, and Brad Martin.

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

1.1 Roughness

The American Society of Testing and Materials defines pavement roughness as “the deviations of a pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads, and drainage, for longitudinal profile, transverse profile, and cross slope (ASTM E867-06, 2012).”

Pavement smoothness has become the primary indicator for assessing the overall quality of the road infrastructure over time. Pavement roughness causes vibration and bumps during vehicle’s motion; hence, roughness adversely affects driving quality (Wang et al., 2013). According to the experience from American Association of State Highway Officials (AASHO) Road Test, road users judge a pavement condition primarily by the ride quality. Road design, construction and life span are secondary. The National Highway User Survey conducted in 1995 and the Federal Highway Administration (FHWA) Infrastructure Survey conducted in 2000 found that the pavement ride quality is the third most desired highway improvement, after traffic flow and safety, according to the traveling public. In addition, several earlier studies reported that smoother roads last longer, due to reduction in the vehicle dynamic loads, and are safer for the road user, due to reduced deterioration of the surface friction. Smoother roads also reduce the vehicular wear and tear, thereby decreasing vehicle operating costs. Smoother roads are indeed economical for the highway agencies as well as road users in the long run. To achieve smoother pavements, highway agencies have been developing and implementing ride specifications.

1.2 TxDOT Ride Specification

The Texas Department of Transportation (TxDOT) has been implementing a ride specification containing incentive/disincentive policy that has been in existence for more than a decade. TxDOT specification is broadly divided into two components: i) Equipment selection for road profile data collection, and ii) Measurement and pay adjustment (Texas Department of Transportation, 2015). The TxDOT standard specifies two types of ride quality measuring equipment: i) Surface Test Type A, which involves a 10-ft. straightedge, and ii) Surface Test Type B, which involves high-speed or lightweight inertial profiler, certified at the Texas A&M Transportation Institute. The ride specification, Item 585, specifies that Surface Test Type A shall be used for ride quality measurements on ramps, service roads, leave-out sections, bridge structures, and short projects (less than 2,500 ft). The ride quality on the other travel lanes shall be measured using inertial profilers or Surface Test Type B. The variation between any two contact points on a 10-ft straightedge shall not exceed 1/8 inch in order to comply with the ride specification. Surface Test Type B involves calculation of International Roughness Index (IRI) using TxDOT’s Ride Quality software program.

TxDOT uses the guidelines provided as part of the Item 585 specification to determine the pay adjustment schedule for ride quality requirements of hot mix pavements. The current ride quality pay adjustment provides a fixed dollar amount (bonus/penalty) for achieving a given as-constructed ride quality that is measured in terms of IRI (inches/mile) per 0.1-mile length of the project. The amount of bonus/penalty changes linearly with as-constructed ride quality, with a maximum possible bonus of $600 at 30 inches/mile and a maximum possible penalty of $600 at

95 inches/mile. The pay adjustment system is divided into three schedules (as shown in Figure 1.1), which are applied depending on the ease of achieving the desired post-construction ride quality in a given project. Schedule 1 of the current ride specification rewards pavement projects that are smoother than 60 inches/mile, while it penalizes projects that are rougher than 65 inches/mile. Schedule 2 of the specification is slightly less restrictive, only penalizing projects that are rougher than 75 inches/mile. Schedule 3 does not penalize any projects, while the bonus is reduced to one-half of the bonus awarded by the Schedules 1 and 2. TxDOT's Construction Division provides the necessary guidelines for selection of the appropriate pay schedule. The procedure takes note of the existing IRI, facility type, posted speed, the number of smoothness opportunities, and other mitigating factors before identifying the pay adjustment schedule that fits the profile of the specific job.

In order to account for localized roughness, such as bumps and dips, the current pay adjustment system specifies a penalty per occurrence. A localized roughness penalty of $500 and $250 per occurrence will be assessed under Schedule 1 and 2 respectively. For Schedule 3, localized roughness penalties will not be assessed (Texas Department of Transportation, 2015).

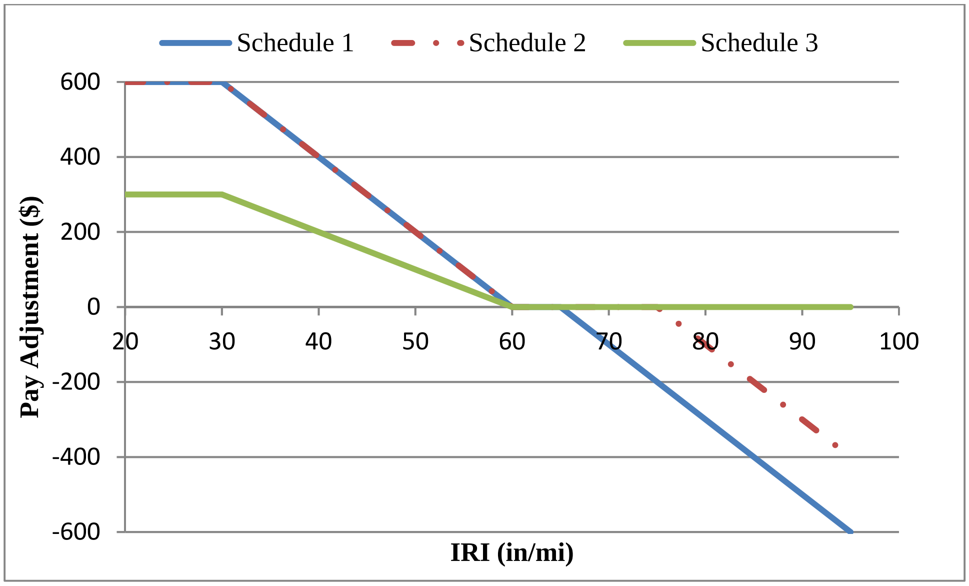


Figure 1.1 TxDOT ride quality pay adjustment schedules

1.3 Description of the Problems

The existing TxDOT pay adjustment specification is merely dependent on the ride quality of the final delivered pavement surface and does not account for the magnitude of ride improvement from the existing pavement surface. For example, based on the current specification, the bonus received by a contractor who has improved a roadway with an average IRI of 120 inches/mile (before rehabilitation) to an IRI of 40 inches/mile (after rehabilitation) is identical to the bonus paid to another contractor who improves an existing IRI of 75 inches/mile to 40 inches/mile. A more reasonable pay adjustment system would take into account the magnitude of roughness improvement between before and after rehabilitation. In other words, a contractor who has enhanced a roadway from 120 to 40 inches/mile should earn a higher bonus than the one that improves the riding quality from 75 to 40 inches/mile. A rational ride specification that can distinguish the difference in contractors' effectiveness is imperative.

Additionally, as-constructed ride quality measured immediately after the project completion alone does not provide enough information on the performance improvement from the existing pavement surface. The bonus/penalty awarded for a superior/inferior as-constructed ride quality is not completely economically justifiable unless the change in the ride quality is accounted for. Thus, the pay adjustment shall be normalized against the existing pavement condition. A performance-based pay adjustment system that incorporates both the new and existing riding quality would enable TxDOT to reward/penalize contractors based on the gain/loss in the expected life of the pavement.

The existing specification specifies a 10-ft straightedge when project pavement length is less than 2,500 ft. Although this approach is simple, it is time consuming and laborious to straight-edge a roadway and to get consistent readings especially under traffic. The straightedge also cannot capture roughness beyond its base-length. The use of straightedge could not be link to a bonus/penalty system because of its lack of consistency. On the other hand, an inertial profiler (or Surface Test Type B) is an efficient and objective approach in the ride quality data collection and avoids such traffic delays. The other advantage of using the inertial profiler is its rapid and accurate data collection and processing. Using the inertial profiler, both construction and evaluation practices will be conducted more quickly. Considering all advantages, the inertial profiler measurements are more reliable and consistent than measures obtained from the straightedge. The existing ride specification needs to be revised to address the equipment and data collection methods for measuring ride quality on short pavement sections.

1.4 Research Scope

The objectives of this research project are as follows:

- Develop a revised pay adjustment schedule that incorporates pre-construction ride quality into incentive and disincentive computation
- Develop a revised pay adjustment system that accounts for the existing pavement ride quality and ride quality improvement based on performance considerations.
- Revise the existing ride specification for using an inertial profiler to measure ride quality on road segments shorter than 2,500 ft.

1.5 Report Organization

This report presents a complete description of the objectives, research performed, methodologies used, and the results achieved during the project. Chapter 1 provided the basic information on roughness, TxDOT ride specification, problems with the current ride specification, and research objectives. Chapter 2 is dedicated to the review of state DOTs' ride specifications and past studies related to the pavement roughness. Details on roughness measurement devices, roughness indices, and pay adjustment systems are also provided in this chapter. This chapter also highlights the findings of the past research studies that studied the relationship between existing, new ride quality and expected pavement life. State ride specifications that account for improvement in the ride condition of pavements are also included in this chapter.

The remainder of this research report is organized into two distinctive parts:

Part 1: Developing a rational pay adjustment system

Chapter 3 presents an overview of the databases used in this project as well as a visualization of a few features of the extracted pavement projects. Chapter 4 is devoted to describing the data analysis procedure and subsequently the development of a performance based pay adjustment model corresponding to a combination of post-construction IRI and drop in IRI.

Part 2: **Measuring ride quality using an inertial profiler on short projects**

Chapter 5 discusses the results of a survey questionnaire and an in-person interview conducted to address the following issues of interest: i) identifying practical issues associated with measuring ride quality on short projects, ii) gathering more information about an inertial profiler operation, and iii) providing guidelines for a field study. Chapter 6 describes a field experiment program and includes test site selection, data collection procedure, and the results of data analysis. Finally, Chapter 7 provides a summary of findings from Parts 1 and 2, preliminary conclusions, and recommendations.

Chapter 2. Literature Review

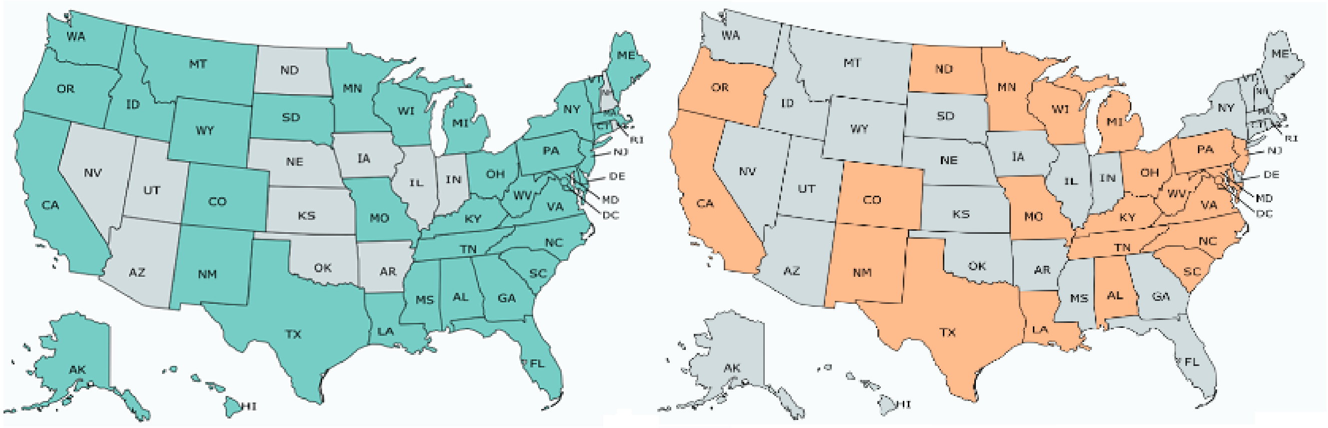
2.1 Introduction

The main purpose of the literature review was to gather information on short projects ride quality specifications and pay adjustment systems in used in other state departments of transportations (DOT) and highway agencies. Smoothness specifications from 46 state DOTs was gathered. The smoothness standards were reviewed in order to find devices currently being used on short and long projects and also collect relevant information in terms of the common roughness indices and pay adjustment systems.

2.2 Roughness Measurement Devices

The literature review identified different methods of measuring roads ride quality including rod and level, dipstick, straightedge, profilograph, high-speed inertial profilers, and lightweight inertial profilers. The most common devices currently used by highway agencies to measure road roughness on short and long pavement roads are the straightedge and the inertial profiler, respectively.

A point of interest of this literature review was to find out which US states are using the inertial profiler on short projects. The review of DOTs ride specifications (as illustrated in Figure 2.1) indicated that 37 out of 46 US states operate an inertial profiler for asphalt pavements, and 22 states use it for concrete pavements. However, state highway agencies such as TxDOT, the Alabama and California DOTs, and others specify a minimum length for the pavement projects to be measured using inertial profilers. For instance, as mentioned earlier, TxDOT's current specification does not allow operating the inertial profiler on projects shorter than 2,500 ft. According to these states' ride specifications, a straightedge shall be used on projects excluded from the inertial profiler measurement. Table 2.1 presents a comparison of specifications in terms of the project length. The results indicated that Alabama and Hawaii standards allow using the inertial profiler on projects with length equal or more than 528 ft. Accordingly, the inertial profiler is able to be used on short length projects less than 2500 ft. It should be noted that for those states that are using inertial profilers but are not included in Table 2.1, the inertial profiler is operated on the entire length of a project from beginning to the end point and there is no limitation regarding the length of the project.



Inertial Profiler Categorization for asphalt pavement

Inertial Profiler Categorization for Concrete Pavement

Figure 2.1 State classification based on using an inertial profiler

Table 2.1 Minimum length of pavement projects for using an inertial profiler

States	Length (ft.)
Texas	2500
Alabama	528
California	1000
Georgia	5280
Minnesota	1000
Mississippi	1000
Montana	1056
Ohio	5280
Virginia	2640
West Virgin	1100
Wisconsin	1500
New York	1320
Connecticut	2115
Hawaii	528
Vermont	2640
Oregon	auxiliary lanes: 2500
Massachusetts	Mainline pavement: 2640 Side road pavement: 528
South Carolina	Asphalt pavement: 2640 Concrete pavement: 528
Maryland	2640 (after elimination of areas such as shoulders, ramps, short acceleration and deceleration lanes (less than 0.1 mile)

2.2.1 Rigid Straightedge

The straightedge was the first method used for road roughness measurement, which started in the early 1900s (Mucka, 2012). As shown in Figure 2.2, it is based on the variation in elevation between two contact points once the straightedge is placed on the pavement.

The straightedge approach has both advantages and disadvantages. Although this approach is simple and relatively effective, it is time consuming and inconsistent. Also, several operators are necessary to conduct ride quality measurement using this device. They should make a considerable effort to collect accurate measurements of pavement irregularities. Furthermore, the major concern about the straightedge is that it cannot address wavelengths longer than its base length. In fact, this device is not accurate in measuring bumps or depressions with the length beyond half of its base length (Hearne et al., 1996; Woodstorm, 1990). Therefore, there will be a bias as compared with IRI measurements using inertial profilers. The two measurements are not consistent or equivalent.

Figure 2.2 The straightedge

2.2.2 Rolling Straightedge

A rolling straightedge (shown in Figure 2.3) is a wheel-based type of straightedge that consists of a metal beam, a wheel under each end, and a wheel at the middle. The middle wheel can go up and down when the straightedge faces surface rough spots. An indicator is connected to the middle point that can show depressions and bumps (Woodstorm, 1990).

The rolling straightedge is inefficient for measuring pavement roughness and it is not very popular nowadays. It is time-consuming and its operation requires traffic closure. The other disadvantage of this approach is that the results could be misleading. For example, as shown in Figure 2.4, sometimes the straightedge encounters a bump, but the indicator shows depression at this point. It also might encounter a depression but it records it as a bump. As a result, because of these aforementioned shortcomings, this device is not effective means to measure surface roughness.

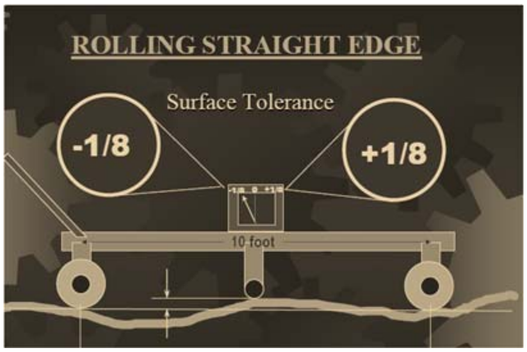


Figure 2.3 The rolling straightedge (Vitillo, 2016)

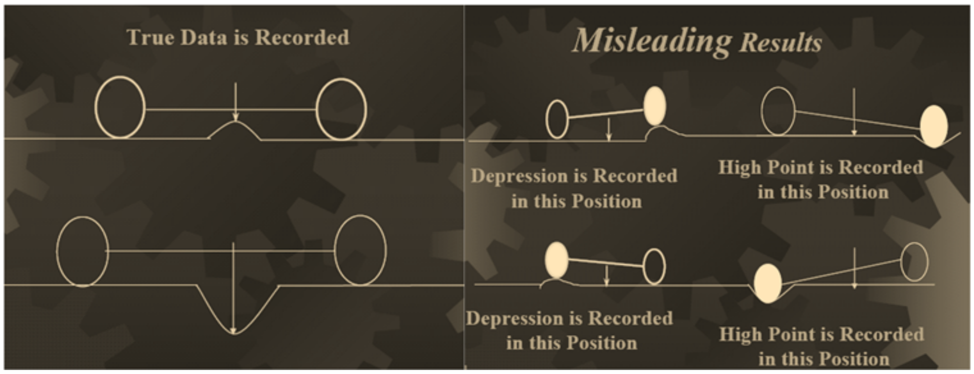


Figure 2.4 An example of accurate and inaccurate results from a rolling straightedge's recording (Vitillo, 2016)

2.2.3 Inertial Profiler

Inertial profilers (shown in Figure 2.5) include three fundamental components: accelerometer(s), sensor(s), and a distance measuring system. There are two types of motion for the inertial profiler vehicle: longitudinal and vertical motion. The accelerometer measures the vertical motion and then the data is processed by an algorithm that converts the vertical vehicle's acceleration into the elevation data of the road surface. In order to be able to measure the distance between the pavement surface and the inertial profiler vehicle, a non-contact sensor is installed on the vehicle. This sensor could be an optical, laser, or infrared transducer. The road profile is calculated by subtracting the distance measured by the sensor from the elevation data obtained from accelerometer measurements. The longitudinal distance traveled by the vehicle is recorded by the distance measuring system through either direct measurements of rotation of one tire, or by speedometer installed on the vehicle (Vitillo, 2016; Sayers and Karamihas, 1998).

Measurements from inertial profilers are more reliable and consistent than measurements obtained from a straightedge. The inertial profiler is computerized and it is not labor intensive and it is more objective. In addition, it is superior in terms of time efficiency and it eliminates human errors. This device can yield more reasonable measurements of surface roughness for short and long wavelengths.

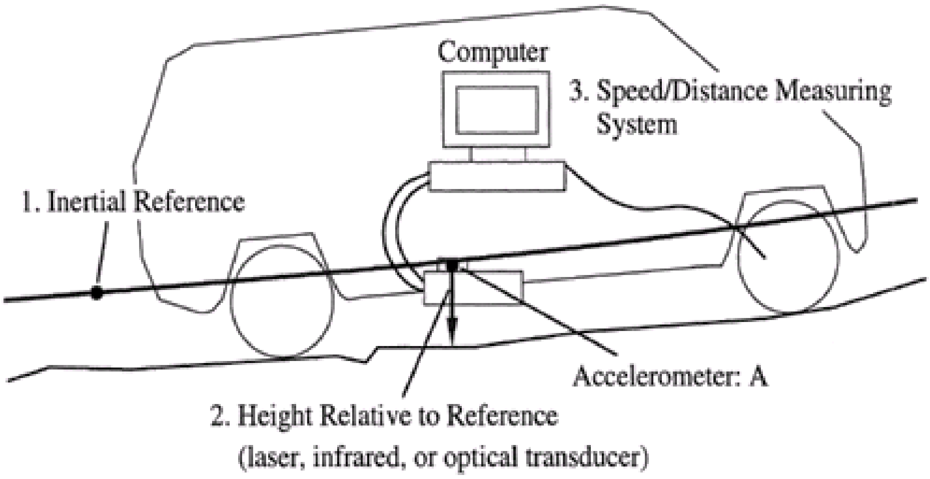


Figure 2.5 The inertial profiler (Sayers and Karamihas, 1998)

2.2.4 Alternative Devices for Short Projects

There are a handful of devices in the market that are capable of measuring the ride quality on short segments. For instance, a prototype Ultra-Light Inertial Profiler (ULIP) (as shown in Figure 2.6a) was proposed to fulfill two primary needs of the pavement smoothness program of the Federal Highway Administration (FHWA): i) development of an efficient method of measuring certification sites for reference, and ii) development of an accurate low-speed device. The prototype ULIP is a SEGWAY Human Transporter equipped with triggers, a laser, and accelerometers. The recent versions of ULIP improved inertia profiling by using a gyroscope.

As another example, the AMSKAN IRIS 2000 (as shown in Figure 2.6b), an advanced road surface condition-measuring instrument, is designed to measure the IRI on short sections of roadway. It is particularly effective for road construction contractors, providing instant feedback on surface construction work quality, as the work proceeds. At the end of the section to be measured, the IRI is instantly calculated and stored automatically, and the result is available immediately on the operator display panel.

Figure 2.6 Alternative devices: a) ULIP Segway, b) AMSKAN IRIS 2000

2.3 Roughness Calculation Index

The specifications review found that IRI, profile index, and ride number are the main roughness statics used in the US. IRI is widely accepted and has become a standard tool for measuring roughness and ride quality of the pavement surfaces in the US and worldwide. Twenty-nine states specify using IRI for either asphalt or concrete pavements ride quality. In addition, four states use mean roughness index (MRI) as an index for roughness measurements. MRI is computed by averaging the IRI values obtained from right and left wheel-path profiles. North Carolina applies both IRI and MRI statistics for roughness measurements.

Addressing the issues of collecting ride quality data on short projects using IRI requires an understanding of IRI calculation algorithm, and the factors which influence ride quality measurements. For that reason, the following section provides a description of the IRI calculation algorithm.

2.3.1 International Roughness Index (IRI)

The IRI was established in 1986 by the World Bank, and has been widely used to measure road roughness since then. This index indicates how comfortable drivers and passengers feel in a moving vehicle. IRI is repeatable, auditable, time-stable, and a geographically transferrable measure of ride quality. To employ the Surface Test Type B or inertial profilers on short projects, it is essential to thoroughly understand the standard IRI calculation methodology or profile data processing algorithms. Thus a brief description of the IRI concept and a discussion of the important features of the IRI algorithm as provided below.

In the early 1980s the available methods used to characterize road roughness were not reproducible by different agencies using different measuring equipment and methods. The methods were not even stable within a highway agency and not stable with time. The National Cooperative Highway Research Program (NCHRP) initiated a research project (NCHRP 1-18) to help state highway agencies improve their use of roughness measuring equipment (Gillespie et al., 1980). A set of parameters to perform vehicle simulation was established such that it produces a roughness index that is significantly correlated with the ride meter data; the set of parameters is often referred to as the *Golden Car* parameters. The World Bank continued the work with the objective to identify a methodology to compare or convert data obtained from different countries involved in World Bank projects. The World Bank funded a study known as the International Road Roughness Experiment (IRRE) to establish standards for road roughness. This experiment found that all methods of testing roughness could be calibrated to a single scale, which is where the idea for developing the IRI was initiated. The study ensured that the IRI scale was transportable across all kinds of testing equipment. A roughness definition to characterize the data collected from the IRRE testing was selected based on the vehicle simulation using *Golden Car* parameters. In the end, a quarter-car model using *Golden Car* parameters at a simulation speed of 49.7 mph (80 km/h) was designated as the standard simulation scenario. The quarter-car simulation speed of 49.7 mph was selected because at that speed, the IRI was found to be very sensitive to the profile wavelengths that cause vehicle vibrations during typical highway use (Sayers, 1995). Thus, a standard for characterizing pavement roughness was developed and tested and was eventually named the International Roughness Index or IRI.

IRI is a summary roughness index defined as the accumulated displacement output from a quarter-car model over a unit profile length with units of slope. IRI is defined as a mathematical property of the true profile and, therefore, it can be computed from the profile measured with any valid profiler. IRI is computed for single longitudinal profiles, such as along the wheel paths. The raw road profile is constructed digitally by sampling profile elevations at a fixed interval or resolution. A minimum resolution of 300 mm is required for accurate IRI calculations; finer resolution is needed on smoother roads. Sayers mentioned that a resolution of 0.5 mm is suitable for any road condition (Sayers, 1995). TxDOT currently requires a minimum sampling resolution of 3 in. or 76.2 mm as per Tex-1001-S specification. This will change to 2 in. with next specification.

The standard IRI algorithm assumes a constant slope between sampled elevation points. Based on a computer simulation study, a linear interpolation method was found to be most accurate in terms of IRI calculation for a wide range of sampling intervals (Sayers, 1995). It was also reported that sampling intervals that are higher than 600 mm potentially produced inaccurate results. Larger sampling intervals do not capture localized roughness such as small potholes, and tar strips.

Any road profile can be mathematically expressed as an infinite sum of sinusoids and subsequently the frequency content of the profile can be extracted. The frequencies of the sinusoids that construct the complete road profile are very informative and describe unique characteristics of the underlying road surface. For instance, road roughness is particularly caused by sinusoids within certain ranges of frequencies or wave bands. The roughness is calculated using an appropriate smoothness statistic that summarizes the relevant frequency content that is responsible for the road roughness. The IRI algorithm filters the wavebands that do not contribute towards the road roughness at highway speeds.

The IRI calculation algorithm involves two distinct filters: i) moving average filter and ii) quarter-car filter. The moving average filter simulates the potential enveloping behavior of pneumatic tires on highway vehicles. The length of the contact area of a typical highway vehicle is approximately 250 to 300 mm. The standard IRI algorithm includes a moving average filter of 250 mm base length. A quarter-car filter is used to calculate the suspension deflection. An imaginary quarter-car (or one tire) is simulated over the pavement profile using a computer program in order to obtain the respective suspension deflection. The imaginary quarter-car is mathematically represented with a vertical spring, the mass of the axle supported by the tire, a suspension spring and damper, and the mass of the body supported by the suspension for that tire as shown in Figure 2.7. First-order ordinary differential equations are used to mathematically represent the quarter-car model system and to iteratively calculate the simulated suspension of the imaginary quarter-car (Sayers et al., 1986). The accumulated suspension displacement per unit length of the profile is defined as IRI, which has units of slope (in./mi or m/km).

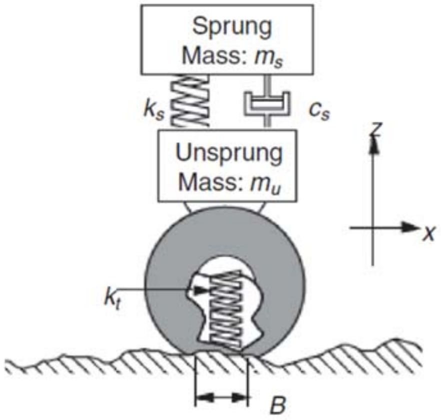


Figure 2.7 The quarter-car model (Sayers et al., 1986)

Figure 2.8 shows gain for the IRI quarter-car filter corresponding different wave numbers. Gain is defined as the ratio of the input amplitude to the output amplitude (Sayers and Karamihas, 1998). It can be seen that IRI is largely sensitive to the wavelengths ranging between 5.5 ft. (a wave number of 0.60 cycle/meter) and 73 ft. (a wave number of 0.045 cycle/meter); this is because the gain corresponding to these wavelengths is more than one (Rawool and Fernando, 2005). The quarter-car model is primarily influenced by wavelengths ranging from (3.9 to 98.4 ft.). So, we would need at least a project length of 196.8 ft. to measure IRI; otherwise, the larger wavelengths cannot be detected. An accurate vertical profile that encompasses the entire range of wavelengths of interest is required as input to the IRI model (Gagarin and Mekemson, 2006).

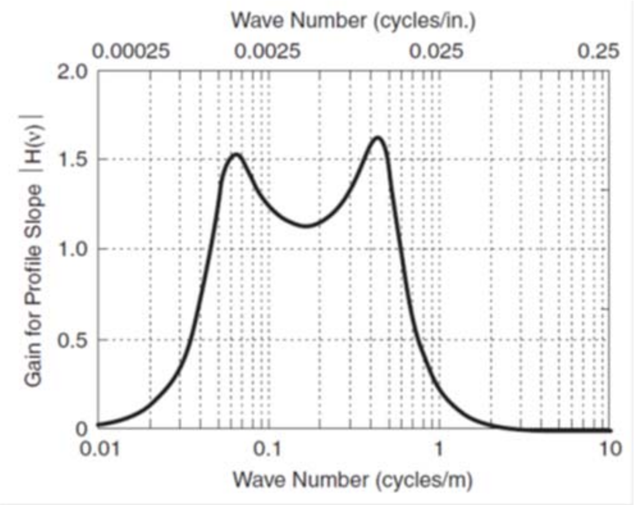


Figure 2.8 IRI gain vs. wave number (Sayers and Karamihas, 1998)

2.3.2 Effect of Test Segment Length on IRI Measurement

A pavement project profiled using a high speed inertial profiler must be divided into unit length test segments over which the IRI is calculated. The length of test segment influences strongly the IRI values. According to Sayers (1995), IRI can be calculated over different lengths. Various test segment lengths provide different illustration of a pavement roughness (Sayers, 1995). When IRI is calculated for 528 ft. sections, the maximum value of the IRI is lower than the maximum value of the IRI over 50 ft. sections. In fact, the IRI calculated for a long segment shows overall ride condition of a pavement and diminishes the effect of localized roughness. In contrast, IRI values calculated for short test segments depict the effect of localized roughness such as cracking and joints. Gillespie (1999) suggested that 500 ft. or longer is an appropriate interval length in the network-level roughness evaluation; however, interval length of 200 ft. or shorter could be applicable in more detailed roughness survey (Gillespie et al., 1999).

NCHRP 10-47 documented essential guidelines for longitudinal pavement profile measurement (Karamihas et al., 1999). The guidelines highlighted the importance of segment length, longitudinal positioning, lateral positioning, speed changes and other variables on the IRI calculation while using inertial profilers. The segment length used for reporting roughness considerably affects the IRI values. Longer road segments are typically used for network level roughness measurements. However, it is necessary to summarize IRI over shorter segments in a project level diagnostic roughness measurements; summaries over shorter segments often produce inflated IRI values, particularly on sections with significant localized roughness. Relatively extreme values of roughness are not unusual on short segments. NCHRP guidelines recommended segments that are 525 ft. long or longer for network level roughness measurements. In the case of roughness measurement of bridge approaches, railroad tracks, and other rough events, segments that are 82 ft. long are recommended (Karamihas et al., 1999).

Smoothness specifications review illustrated that a segment length of 528 ft. (0.1 mile) is a common length among state transportation agencies to summarize IRI values. However, 3,000 ft., 500 ft., and 52.8 ft. were also observed in some specifications.

2.3.3 IRI Measurement on Short Projects

Measurement of road profile and calculation of IRI on short sections is often complex due to several statistical, mathematical and practical reasons. As mentioned earlier, IRI is the simulated cumulative displacement of quarter-car suspension system over the measured road profile. The influence of localized features that could potentially contribute towards the pavement roughness is inflated while calculating the IRI over short sections relative to that of longer segments. For instance, Reggin et al. (2008) explored factors that affect IRI on urban roadways in Canada. They found that urban road segments are typically short segments with curbed cross-sections, lower operating speeds, frequent intersections and numerous at-grade railway crossings. The research study found that the effect of localized roughness caused by rail road crossings and rutted intersections is more pronounced on shorter road segments. The authors mentioned that over long segments, the IRI associated with the localized roughness would be averaged out; however, on a short segment the average IRI may be more representative of the localized roughness effects than the overall pavement condition (Reggin et al., 2008).

2.4 Incentive/Disincentive (I/D) Payment Schedules

In an effort to improve roads ride quality, highway agencies have established smoothness specifications including incentive/disincentive (I/D) schemes and pay adjustment schedules. According to the results of a survey conducted in 1994, the initial roughness of pavement projects reduced significantly by applying smoothness specifications (Smith et al., 1997a). I/D ride specifications are used to encourage road builders to produce smoother surfaces while controlling for unacceptable ride quality on pavement projects. These specifications enforce an acceptance level of smoothness by applying a bonus or penalty. The logic behind paying a bonus is that this additional cost improves contractors’ performance, thereby assures pavements with better ride quality and lower future maintenance costs. A project with superior quality must be rewarded based on actual savings to the agency (Buddhavarapu et al., 2014). On the other hand, McGhee and Gillespie (McGhee and Gillespie, 2006) asserted that the purpose of disincentive is not only to financially penalize the contractors, but it plays an important role to demonstrate the actual financial burden of an inferior construction practice to highway agencies and road users. A construction project that deviates from the required quality level should always result in a reduction in contractor payment to recover the costs incurred by the agency for additional future maintenance costs.

The review of state DOTs’ ride specifications has shown that policies such as positive or negative adjustment to contractors’ payment, and correction activities are included in the majority of highway agencies’ smoothness specifications. In 2014, the Transtec Group summarized the smoothness pay adjustment specifications among the US states as part of an FHWA study (Merritt et al., 2014). As shown in Table 2.2, this study revealed that 89% and 83% of the US states are using some type of I/D pay schedule policy for asphalt pavement projects and concrete pavement projects, respectively.

Table 2.2 US states' pay adjustment systems

Pay schedule policy	% of state DOTs	
	Asphalt pavements	Concrete Pavements
Incentive/Disincentive	89	83
Incentive/Only-Correct	3	8
Only Disincentive	3	3
Only Correct	5	6

2.4.1 Pay Adjustment based on Ride Improvement

Generally, state highway agencies base their incentive or disincentive payments on the roughness which is measured immediately after construction. A rational payment schedule would be better established on a combination of pre- and post-construction roughness rather than on as-constructed roughness values only. As-constructed ride quality measured immediately after the project completion alone does not provide enough information on the performance improvement from the existing pavement surface. To develop a performance based smoothness specification corresponding to a combination of "new" and "old" IRI, a model which is showing the dependency of the pavement expected life to as-constructed IRI and pre-constructed IRI is required. A numbers of studies have investigated the influence of old IRI on new IRI as well as the impact of as-constructed roughness on the future roughness and pavement service life. Some of these studies are provided in the following paragraphs.

McGhee (2000) found that smoothness of the pre-existing surface prior to the overlay has a significant impact on the post-construction ride quality. A positive correlation (as shown in Figure 2.9) between pre- and post-construction MRI was reported, which emphasizes the importance of pre-existing ride quality (McGhee, 2000). In 2006, the Virginia Department of Transportation (VDOT) initiated a research to evaluate the influence of implementing ride specification with I/D program on pavement maintenance projects. In this research, VDOT compared after paving IRI and before paving IRI of projects and realized that conducting ride specification led to 27% improvement in ride quality of roads. This enhancement brought benefits such as smoother roads, which reduces the consumption of fuel and cost of rehabilitation actions, and also defers the time of maintenance activity (Perera and Kohn, 2006).

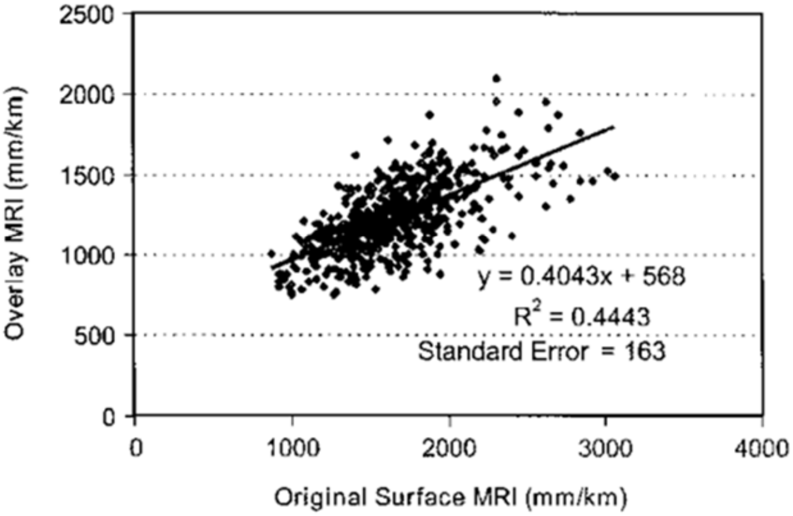


Figure 2.9 Ride quality of original surface compared with overlay (McGhee, 2000)

Smith et al. in 1997 recognized how the initial pavement roughness influences the effective life of a pavement and its roughness progression. In their study, roughness values of asphalt concrete and Portland cement concrete pavements and asphalt overlays located in different states were evaluated using roughness regression and pavement failure methodology. One of the key findings of this study was that a pavement with the lower as-constructed roughness lasted longer and remained smoother for several years. A higher level of initial smoothness results in extension of service life. Therefore, initial roughness has a substantial impact on pavement service life. The authors mentioned that other factors such as pavement type, location, and construction facility can also affect the percentage of life extension. However, it was observed among a large number of pavement projects that a 25% decrease in as-constructed roughness would add 9% in a pavement life (Smith et al. 1997b).

Ksaibati and Al Mahmood conducted a study in 2002 to investigate the relationship between the initial roughness and future roughness. The researchers collected a considerable number of concrete and asphalt pavements IRI values from the federal Long-Term Pavement Performance database. A linear correlation was found between initial roughness and future roughness values, demonstrating that a pavement built with lower as-constructed roughness stay smoother during its service life. As a result, pavements constructed with low initial roughness values show a smaller increase in future roughness than the pavements constructed with high initial IRI (Ksaibati and AlMahmood, 2002).

Buddhavarapu et al. in 2014 focused on quantifying the importance of smoother ride in producing long lasting pavements. A performance-based pay adjustment system that incentivizes or penalizes pavement projects according to the as-constructed ride quality was developed in this study. An evaluation was carried out by the research team using a large dataset comprising more than 600 hot mix and concrete pavements across Texas with available ride quality data and performance records spanning 3 to 10 years (Buddhavarapu et al., 2014). The findings of this research suggested that as-constructed ride quality measured immediately after construction is directly associated with field performance. The statistical analysis confirmed that flexible pavements with larger initial IRI tend to deteriorate faster and vice versa, everything else remaining unchanged. Figure 2.10 shows a relationship between the as-constructed ride quality and the corresponding pavement performance. Two different curves corresponding to different facility types and project locations are shown. This figure emphasizes the importance of incorporating facility type and other project-specific attributes into the pay adjustment specification. The improvement in the pavement performance is quite significant corresponding to a unit improvement in as-constructed ride quality. The results indicated that reducing the as-constructed roughness levels from 60 inches/mile to 30 inches/mile corresponds to an average increase of 50% in pavement life during the first ten years. As another example, reducing the as-constructed roughness levels from 90 inches/mile to 60 inches/mile translates into an average increase of 30% in pavement life. This indicates that the gain in pavement life reduces non-linearly with the as-constructed roughness levels (Buddhavarapu et al., 2014).

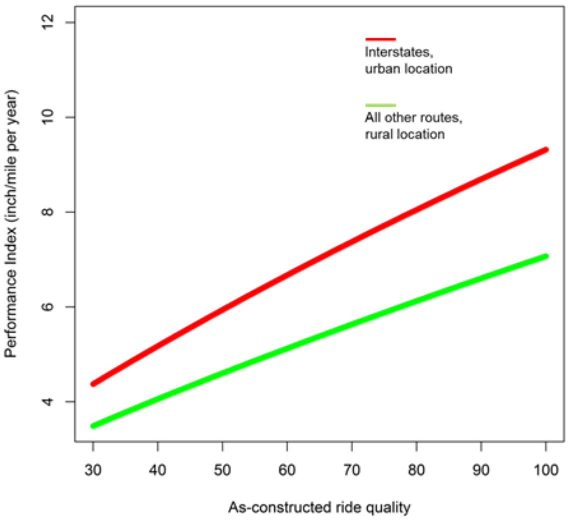


Figure 2.10 Performance vs. as-constructed ride quality (Buddhavarapu et al., 2014)

It should be stated that these studies merely investigated the impact of pre-construction roughness on ride quality obtained after construction, or the effect of new roughness on pavement life. However, none of them accounts for the impact of ride improvement on the extension of service life. This present research study has added to this by exploring the association between ride improvement and pavement life.

2.4.2 Other States' Pay Adjustment Systems

The goal of reviewing the ride pay adjustment systems was to gain better insight on how incentive and disincentive are being applied to pavement projects. Most of the existing pay adjustment specifications, including TxDOT's system, are rely solely on the ride quality of the final delivered pavement surface and do not account for the magnitude of ride improvement from the existing pavement surface. However, state DOTs such as Minnesota, Michigan, Missouri, and Colorado measure the smoothness prior to the start of construction (initial IRI) and after the completion of construction (final IRI) with the same stationing and the same profiler. The percentage of improvement (%I) is calculated using Equation (2.1).

$$I\% = \frac{Smoothness\ before\ paving - Smoothness\ after\ paving}{Smoothness\ before\ paving} \times 100 \tag{2.1}$$

As per the Minnesota's ride specification (Minnesota Department of Transportation, 2016), a contractor is entitled to receive a maximum possible bonus of $180 per 0.1 mile for 65% or greater improvement in the ride relative to the pre-existing surface. On the other hand, corrective action is required for pavement jobs with less than 33% ride improvement. For the IRI improvement in the range of 33 to 64%, the amount of bonus/penalty changes with percentage of improvement (I%).

The Michigan specification (Michigan Department of Transportation, 2012) does not provide any equations for pay adjustment calculation but indicates a range of MRI (IRI averaged across wheel paths) for acceptance and correction. The engineer measures pre- and post-construction MRI for overlay projects to estimate the percentage of improvement in ride quality. A minimum percentage ride improvement of 25% (relative to the pre-existing surface) is required for acceptance as per the specification for hot mix overlay projects.

The Missouri smoothness specification (Missouri Department of Transportation, 1999) adjusts a contractor's payment based on ride improvement for resurfacing projects. Missouri standard does not specify any equation for incentive and disincentive computation. A contractor will receive 3% more than the contract price when deliver a pavement with 35% or greater improvement in the ride quality relative to an initial IRI. Note that the bonus will be apply only to segments with an initial IRI greater than 60 inches/mile. In contrast, 3% of the contract price is deducted for projects with improvement between 0 to 19.9%.

The Colorado ride specification (Colorado Department of Transportation, 2016) considers two pay adjustment schedules based on two different facility areas: rural and urban. As shown in Figure 2.11, a rural project will receive a maximum bonus equal to $0.32 per square yard for 60% ride improvement, while an urban project will receive the same maximum bonus for the 50% ride improvement. For rural constructions with 45% to 60% ride improvement and also urban projects with 5% to 50% ride improvement, the amount of incentive changes with the percentage of ride improvement. Disincentives also are adjusted based on the percentage of improvement on a specific range of the ride improvement value for both rural and urban projects. The maximum penalty is applied to rural projects with 25% or lesser improvement in ride quality and urban projects with ride improvement less than 20%. The Colorado ride specification highlighted that penalties and corrective work are not required for the sections with roughness value less than 80 in./mi.

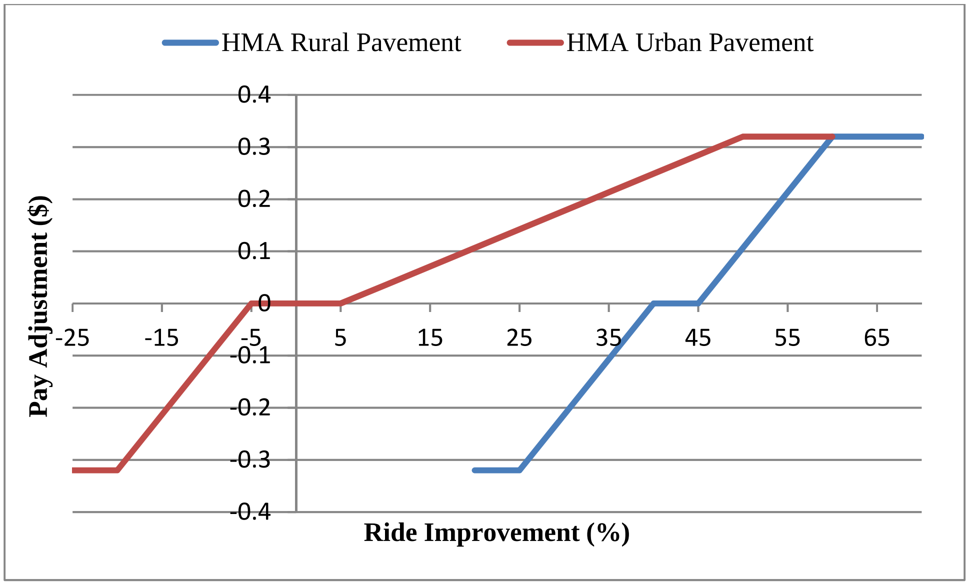


Figure 2.11 Colorado ride improvement scale

2.5 Findings of Literature Review

The research team reviewed the ride specifications of most US states and previous research reports to develop a comprehensive understanding on road roughness measuring devices, roughness indices, and pay adjustment systems. This review produced the following findings:

- A variety of approaches is currently available to measure pavement ride quality. Among them straightedge and inertial profiler are the most common methods being used by state highway agencies on short and long projects, respectively.
- More than 50% of US states that are employing inertial profilers in roughness evaluation specify a minimum length for the pavement projects be measured using this method. This cut-off value varies in the range of 500 to 5,280 ft.
- IRI has become a common summary index for measuring ride quality of the pavement surfaces. IRI is defined as the accumulated displacement output from a quarter-car model over a unit profile length. The minimum length required to measure IRI is at least 200 ft.
- The length of a profile considered in the roughness calculation influences strongly the IRI value. The IRI calculated for a long test segment shows the overall ride condition of that segment. In contrast, IRI calculated for a short test segment depicts the effect of localized roughness.
- In an effort to reduce the as-built roughness of pavements, highway agencies have developed and successfully implemented ride specifications including I/D pay adjustment systems.
- Most of the existing pay adjustment specifications depend solely on the ride quality of the final delivered pavement surface and do not account for the magnitude of ride improvement from the existing pavement surface. The literature review conducted as part of this study highlights the benefits of using I/D ride specifications and the

importance of incorporating the pre-existing ride quality into the pay adjustment. The impact of the pre-construction ride quality on the post-construction ride quality has been addressed by numerous studies. State highway agencies from Minnesota, Michigan, Missouri, and Colorado have already incorporated the ride improvement in the pay adjustment factor for overly projects.

Chapter 3. Data Acquisition and a Database Development

3.1 Introduction

One of the technical objectives of this research project is to develop an objective, rational, economically, and financially justifiable pay adjustment system that incorporates both the new and the pre-existing riding quality. To achieve this objective, a comprehensive database was developed that links some of TxDOT's major material, construction, and performance databases. Integration of these databases facilitates the data analysis that is essential to investigate the financial implications of the current as well as revised pay adjustment specifications. The following information is included in the newly developed database:

- Project location information, including traffic volume, facility type, weather, etc.
- Ride quality data collected after the construction.
- Pavement performance history data in terms of distress, condition, ride scores, and roughness measurements of the identified projects. The performance data was collected both before and after the pavement rehabilitation to monitor the drop in IRI due to new overlay construction.

This chapter discusses the various fields of the databases that are relevant to the study and the integration process. A detailed discussion on data quality control and outlier detection procedures employed to enhance the data reliability is also provided in this chapter.

The empirical information relevant to the current research project purpose is routinely collected by TxDOT and stored in different databases. TxDOT's databases included in this research project are the following: SiteManager (SM), Design and Construction Information System (DCIS), and Pavement Management Information System (PMIS). A brief description of each database along with the fields related to the research project is presented in the next paragraphs.

3.2 Site Manager (SM)

SM is a database used by TxDOT to store the material information at the item level. It consists of asphalt mixture properties such as binder content, mixture air voids and density, aggregate specific gravity and other material information. Table 3.1 summarizes the SM database fields that are relevant to this research project. CONT_ID helps to identify each construction contract approved by TxDOT. Each contract may consist of several projects that are labeled with a unique PRJ_NBR. Therefore, a combination of CONT_ID and PRJ_NBR is used to uniquely identify a project. COMPL_YR field indicates the project completion year or the year in which the project was accepted by TxDOT. Each project comprises several items depending on the size of the project; each item is uniquely identified by LN_ITM_NBR. LN_ITM_NBR is the field that stores the sequence of the items in an increasing order, which helps TxDOT to keep track of all change orders of its projects. The quantity of the item is stored in three fields: BID_QTY, PRJ_QTY and FNL_QTY. BID_QTY stands for the bidding quantity of the item, PRJ_QTY represents the planned quantity of the item, and FNL_QTY reports the final quantity of the item that is actually being placed.

Hot-mix asphalt (HMA) items are typically divided into several lots and sub-lots during the production and placement phase. Material quality control testing is conducted in these phases and the QA/QC information is stored in SM database. Hot mix type, design gyrations, binder performance grade, aggregate specific gravity, mixture voids in mineral aggregate, and voids filled with asphalt were some of the extracted hot mix properties for this study. The study team also extracted the as-constructed ride quality and the respective pay adjustments of various hot mix projects. However, as-constructed ride quality was only available for about 300 projects.

Table 3.1 SM database and the extracted fields

Field	Format	Description
CONT_ID	TEXT	Control section job number
PRJ_NBR	TEXT	Project control number
ITM_CD	TEXT	Item code
LN_ITM_NBR	TEXT	Line item number
COMPL_YR	TEXT	Project completing year
MIX_TYPE	TEXT	Mixture mix type
DESIGN_GYRATIONS	INT	Design gyrations
PRODUCTION_HWTD_CYCLES	INT	Hamburg Wheel Tracking cycles
PG_CLEANED	TEXT	Binder performance grade
FILLER_CONTENT	DECIMAL(2,3)	Filler (passing #200) content %
AGG_SPGRAVITY_GA	DECIMAL(2,3)	Aggregate specific gravity – G_a
AGG_SPGRAVITY_G1	DECIMAL(2,3)	Aggregate specific gravity – G_1
MAX_SPGRAVITY_RICE_DESIGN	DECIMAL(2,3)	Design maximum specific gravity
MAX_SPGRAVITY_RICE_LAB	DECIMAL(2,3)	Production max. specific gravity (lab)
MAX_SPGRAVITY_RICE_ROADWAY	DECIMAL(2,3)	Placement max specific gravity (roadway)
ASPHALT_IGINITIONOVEN	DECIMAL(2,3)	Asphalt content measured in ignition oven
LAB_DENSITY	DECIMAL(2,3)	Mixture density in laboratory
INPLACE_VOID	DECIMAL(2,3)	In-place air voids
LAB_VMA	DECIMAL(2,3)	Voids in mineral aggregate in laboratory
ROADWAY_VMA	DECIMAL(2,3)	Voids in mineral aggregate on roadway
LAB_VFA	DECIMAL(2,3)	Voids filled with asphalt in laboratory
LAB_VFA	DECIMAL(2,3)	Voids filled with asphalt on roadway

3.3 Design and Construction Information System (DCIS)

The DCIS database contains the location, the project completion year, items, and quantities. CONT_ID is a key field that helps to integrate the SM and the DCIS databases. The integration of SM and DCIS facilitates to identify the location and completion years of the hot mix projects. As shown in Table 3.2, DIST_NUM and COUNTY_NUM fields provide the district and county numbers of the hot mix projects. Table 3.3 provides the information about the district number and the corresponding name. The PROJ_LENGTH field contains a real number representing the length of the project in miles. The PROJ_DESC provides a brief description of the project. The highway number and the Texas Reference Markers (TRMs) help to locate the project and help to establish a link between the DCIS (or SM) database with the PMIS database.

Table 3.2 DCIS database and its extracted fields

Field	Format	Description
CONT_ID	TEXT	Control section job number
DISTRICT	TEXT	District name
COUNTY	TEXT	County name
PROJ_LENGTH	DECIMAL(1,3)	Project length
PROJ_DESC	TEXT	Project description
HWY_NUM	TEXT	Highway number
BEG_REF_MARKER_NBR	TEXT	Beginning TRM – integer part
BEG_REF_MARKER_DISP	DECIMAL(1,3)	Beginning TRM – decimal part
END_REF_MARKER_NBR	TEXT	Ending TRM – integer part
END_REF_MARKER_DISP	DECIMAL(1,3)	Ending TRM – decimal part

Table 3.3 District number and its corresponding name

District number	District name	District number	District name
1	Paris	14	Austin
2	Fort Worth	15	San Antonio
3	Wichita Falls	16	Corpus Christi
4	Amarillo	17	Bryan
5	Lubbock	18	Dallas
6	Odessa	19	Atlanta
7	San Angelo	20	Beaumont
8	Abilene	21	Pharr
9	Waco	22	Laredo
10	Tyler	23	Brownwood
11	Lufkin	24	El Paso
12	Houston	25	Childress
13	Yoakum		

3.4 Pavement Management Information System (PMIS)

The PMIS database contains the annual pavement performance measurements collected by TxDOT across the Texas highway network. Table 3.4 shows the descriptions of all of the extracted fields from the PMIS database. Each row in the PMIS database typically represents a 0.5-mile highway section. Annually, the TxDOT visual raters travel along the side of the road at no more than 15 miles per hour to rate the targeted lane, and log all the distresses they found at a 0.5-mile interval (Texas Department of Transportation, 2009).

FISCAL_YEAR indicates the year in which the data collection is performed. SIGNED_HIGHWAY_RDBD_ID is represented by two letters indicating the highway system, four numbers indicating the route number and one letter indicating the roadbed type of the section. Table 3.5 shows the abbreviation of the PMIS highway system and its full name. As shown in Table 3.6, the roadbed type of the section has five different classes depending on whether the traffic is divided by the median; the section is on the main lane or on the frontage road. The traffic volume including the annual average daily traffic (AADT) and the equivalent single axle loads (ESALs) are also stored in the database.

Table 3.4 PMIS database and its extracted fields

Field	Format	Description
FISCAL_YEAR	INT	Data collection year
SIGNED_HIGHWAY_RDBD_ID	TEXT	Highway number and roadbed ID
BEG_REF_MARKER_NBR	TEXT	Beginning reference marker – integer part
BEG_REF_MARKER_DISP	DECIMAL	Beginning reference marker – decimal part
END_REF_MARKER_NBR	TEXT	Ending reference marker – integer part
END_REF_MARKER_DISP	DECIMAL	Ending reference marker – decimal part
PVMNT_TYPE_BROAD_CODE	CHARACTER	Pavement type
AADT_CURRENT	INT	Annual average daily traffic
CURRENT_18KIPS_MEAS	INT	Design equivalent single axle load
SPEED_LIMIT	INT	Speed limit
NUMBER_THRU_LANES	INT	Number of traffic lanes
CONDITION_SCORE	INT	Condition score
DISTRESS_SCORE	INT	Distress score
RIDE_SCORE	INT	Ride score
IRI_LEFT_SCORE	INT	IRI on left-wheel path
IRI_RIGHT_SCORE	INT	IRI on right-wheel path

Pavement condition measurements stored in the PMIS database may be used to monitor the highway network and to schedule maintenance activities accordingly. Based on TxDOT's PMIS Data Dictionary (Texas Department of Transportation, 2003), pavement condition information includes the type and quantity of distresses (e.g., cracks, patches, etc.), the depth of deformation (e.g., rutting), and the roughness (e.g., ride score and IRI). The numbers of distresses and deformation are converted into the distress score by using utility curves (Stampley et al., 1995). The roughness is converted into the ride score. The combination of the distress score and the ride score is used to calculate the condition score, which is an overall performance indicator. In this study, only distress score, ride score, condition score, and IRI were extracted. The research team decided to use the IRI as the major performance measure, which is arguably the most consistent and reliable performance measure in PMIS.

Table 3.5 PMIS highway system

ID	Highway system
IH	Interstate Highway
US	US Highway
UA	US Alternate
UP	US Highway Spur
SH	State Highway
SA	State Highway Alternate
SL	State Highway Loop
SS	State Highway Spur
BI	Off Interstate Business Route
BU	Off US Highway Business Route
BS	Off State Highway Business Route
BF	Off farm or Ranch to Market Road Business Route
FM	Farm to Market Road
RM	Ranch to Market Road
RR	Ranch Road
PR	Park Road
RE	Recreation Road
FS	Farm to Market Road Spur
RS	Ranch to Market Road Spur
RU	Ranch Road Spur
RP	Recreation Road spur
PA	Principal Arterial Street System (PASS)
MH	Metropolitan Highway

Table 3.6 PMIS roadbed type

Roadbed	Description
K	Undivided main lane
L	Left divided main lane
R	Right divided main lane
X	Left frontage road
A	Right frontage road

3.5 Database Integration and Data Extraction

The GIS-based Texas Cartographic Information Technology System (TxCIT) database, which was developed as part of a TxDOT inter-agency program, provides the framework for the development of this study's data warehouse. The TxCIT database ties together as-constructed ride quality data and performance history of road projects across the state. TxCIT establishes a link between the SM and PMIS databases by using TRM information obtained from DCIS and a geographical TRM database developed by TxDOT. Thus, TxCIT links as-constructed ride quality of road projects, stored within the SM database, and the respective performance data from PMIS database.

For this research project, 1,443 HMA projects were extracted from the SM database. A link is required to be established between pavement performance data and the construction information in order to investigate a relationship between them. The pavement performance measurements (e.g., IRI in this study) were linked to the information obtained from SM/DCIS databases using highway numbers and TRMs. Each project in this integrated database contains the PMIS performance measurements over the entire project length. For example, the performance of a 1.5-mile-long project is the average (and standard deviation) of performance data corresponding to three PMIS sections (0.5 miles long for each). Furthermore, PMIS data ranging from 2001 to 2014 was extracted to monitor the historical performance of individual hot mix projects. Therefore, a single hot mix project consists of fourteen rows in the integrated database. This was not always the case since a few PMIS data points were missing.

The total number of HMA projects got reduced to 1,082 upon integrating with the PMIS database. A few projects were lost due to one or more of the following reasons: i) projects located on the frontage roads (A or X) were excluded and ii) missing values in the highway number or TRM field in the SM or DCIS databases. Table 3.7 presents the fields of the integrated database upon combining SM, DCIS and PMIS databases. As mentioned earlier, each project can be identified by a unique combination of CONT_ID and PRJ_NBR. The general information of the project including the completion year, the description, and project length are provided in COMPL_YR, PROJ_DESC and PROJ_LENGTH data fields respectively. Several other fields were described in Table 3.7.

In the integrated database, the IRI information is presented based on the roadbed type of the section. To be more specific, the location information in the DCIS database does not contain the roadbed type of the section, whereas there are five different types of roadbed in the PMIS database. The project may span over different types of roadbeds, which creates the following four cases: i) only the undivided main lane (roadbed K), ii) only divided main lane (roadbed L or R), iii) both undivided and divided main lanes, and iv) divided main lane, but with a letter "W" representing west. Table 3.8 presents these four cases and corresponding numbers of projects in each category. In the third case, there are 152 projects found to cover K and L/R highway sections in its range, making the calculation of performance measurements and traffic volumes difficult and possibly biased. In the fourth case, 13 projects are located on IH-35W or IH-35, in which case the researchers cannot verify the actual location of them due to the lack of roadbed information in SM and DCIS. In this study, the above two cases (ii and iv above) were excluded, further reducing the total number of hot mix projects from 1,082 to 917. Although some projects were lost during the data pre-processing step, a sample of 917 projects is considered large enough for a reliable statistical analysis.

IRI measurements corresponding to both left and right wheel paths are stored in PMIS. An average IRI is calculated for all 0.5-mile section, except for the case that one of the IRI values is missing. Sections with missing IRIs on either of the wheel paths were excluded. In the context of the projects on the divided main lane (L/R), the IRI values corresponding to L roadbed and R roadbed are extracted, and summarized as LEFT_IRI, LEFT_IRI_STDEV, RIGHT_IRI and RIGHT_IRI_STDEV data fields. The LEFT_IRI and RIGHT_IRI data fields correspond to the left and right roadbeds and not to be confused with the IRI corresponding to the wheel paths. IRI is summarized in AVG_IRI and STDEV_IRI data fields in the case of the projects on the undivided main lane (K).

Table 3.7 Description of project-level database

Field	Format	Description
CONT_ID	TEXT	Control section job number
PRJ_NBR	TEXT	Project control number
COMPL_YR	TEXT	Project completion year
PROJ_DESC	TEXT	Project description
PROJ_LENGTH	DECIMAL(2,3)	Project length
FISCAL_YEAR	INT	Data collection year
COUNTY	TEXT	County name
DISTRICT	TEXT	District name
HIGHWAY_NUMBER	TEXT	Highway name
BEG_TRM	DECIMAL(3,3)	Beginning TRM
END_TRM	DECIMAL(3,3)	Ending TRM
SPEED_LIMIT	INT	Speed limit
AVG_AADT	INT	Annual average daily traffic
AVG_18KIPS	INT	Design equivalent single axle load
NUM_LANES	INT	Number of traffic lane
AVG_IRI	DECIMAL(3,3)	Average IRI
STDEV_IRI	DECIMAL(3,3)	Standard deviation of IRI
LEFT_IRI	DECIMAL(3,3)	Left IRI
LEFT_STDEV_IRI	DECIMAL(3,3)	Standard deviation of left IRI
RIGHT_IRI	DECIMAL(3,3)	Right IRI
RIGHT_STDEV_IRI	DECIMAL(3,3)	Standard deviation of right IRI
MIX_TYPE	TEXT	Mixture mix type
DESIGN_GYRATIONS	INT	Design gyrations
PRODUCTION_HWTD_CYCLES	INT	Hamburg Wheel Tracking cycles
PG_CLEANED	INT	Binder performance grade
FILLER_CONTENT	DECIMAL(2,3)	Filler (passing #200) content %
AGG_SPGRAVITY_GA	DECIMAL(2,3)	Aggregate specific gravity – G_a
AGG_SPGRAVITY_G1	DECIMAL(2,3)	Aggregate specific gravity – G_1
MAX_SPGRAVITY_DESIGN	DECIMAL(2,3)	Design maximum specific gravity
MAX_SPGRAVITY_LAB	DECIMAL(2,3)	Production max. specific gravity (lab)
MAX_SPGRAVITY _ROADWAY	DECIMAL(2,3)	Placement max specific gravity (roadway)
ASPHALT_IGINITION	DECIMAL(2,3)	Asphalt content measured in ignition oven
LAB_DENSITY	DECIMAL(2,3)	Mixture density in laboratory
INPLACE_VOID	DECIMAL(2,3)	In-place air voids

Field	Format	Description
LAB_VMA	DECIMAL(2,3)	Voids in mineral aggregate in laboratory
Roadway_VMA	DECIMAL(2,3)	Voids in mineral aggregate on roadway
LAB_VFA	DECIMAL(2,3)	Voids filled with asphalt in laboratory
LAB_VFA	DECIMAL(2,3)	Voids filled with asphalt on roadway

Table 3.8 Four cases in the combined database

Case	Description	Number of project
K	Projects located on the undivided main lane	596
L/R	Projects located on the divided main lane	323
K or L/R	Projects located on either the undivided or divided main lane	152
L/R/WL/WR	Interstate 35W	13

Figure 3.1 shows the distribution of the projects with respect to the construction year within project database. Data was available only for a few older projects. A large portion of projects were constructed between 2005 and 2011. Figure 3.2 shows the distribution with respect to the highway system. The hot mix projects were well distributed across the different highway systems.

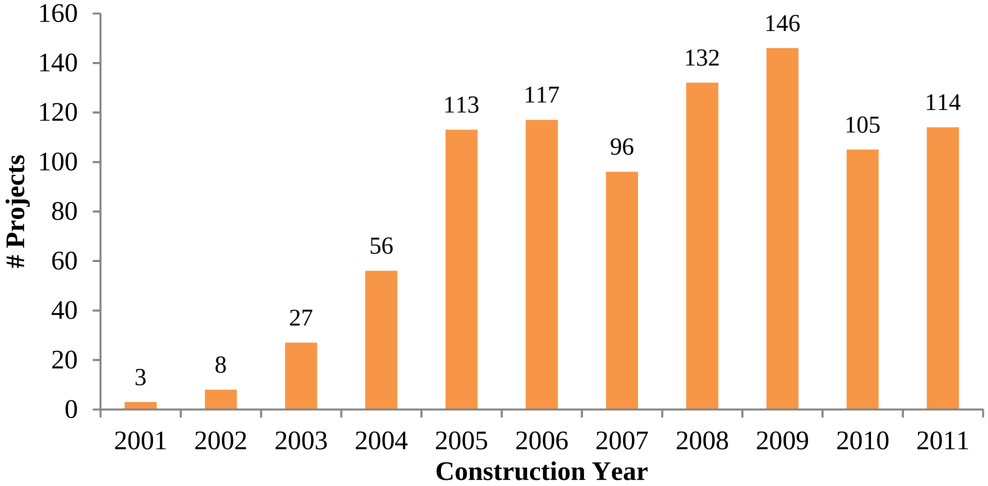


Figure 3.1 HMA projects ranging from 2001 to 2012

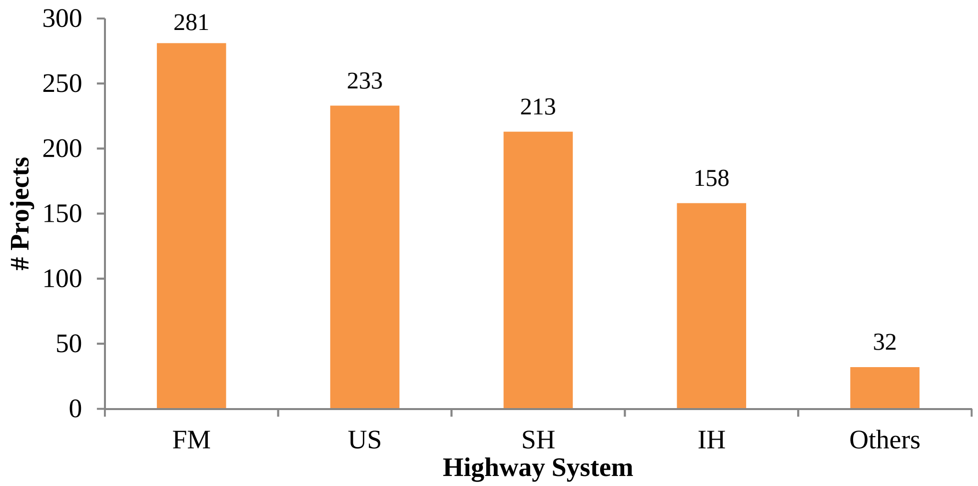


Figure 3.2 HMA projects distributed on different highway systems

3.6 Data Processing

IRI measurements ranging from 2001 to 2014 were plotted for each project using R programming language for statistical computing and graphics. Figure 3.3 shows an example of a project on an undivided main lane. The project specific information is included at the top of each plot, including control section job number (CON), project control number (PRJ), highway number (Route), county (Cnty), district (Dist), number of lanes (#Lane), beginning and ending TRMs (TRMs), speed limit (SpdLim), AADT (AADT), ESALs (18KIPS), binder (PG), pavement type (Pavement), project length (Prj Length) and number of PMIS sections (Num Sections). The x-axis represents the year in which the IRI measurements were collected, and the y-axis is the average IRI value across the entire project. The solid red line indicates the average IRI and the dashed red lines indicate the range of the IRI within two standard deviations. The pink vertical line represents the project completion/construction year. In this example, the project was completed and opened to traffic in 2007. A significant drop in the IRI value is evident immediately after the construction. The positive slopes of IRI change across the time both before and after the construction indicate the deterioration of pavement roughness.

Figure 3.4 and Figure 3.5 show two examples of the projects on the divided main lanes. For these projects, two sets of lines are plotted to show the IRI values corresponding to the L roadbed (blue line) and the R roadbed (red line). In Figure 3.4, it can be seen that the construction project is possibly located on both of the roadbeds, since both sets of IRI values show a drop at the year of construction. In Figure 3.5, the construction project should only be located on the R roadbed, since the IRI improvement is shown on the red line.

Figure 3.3 An example project on the undivided main lane

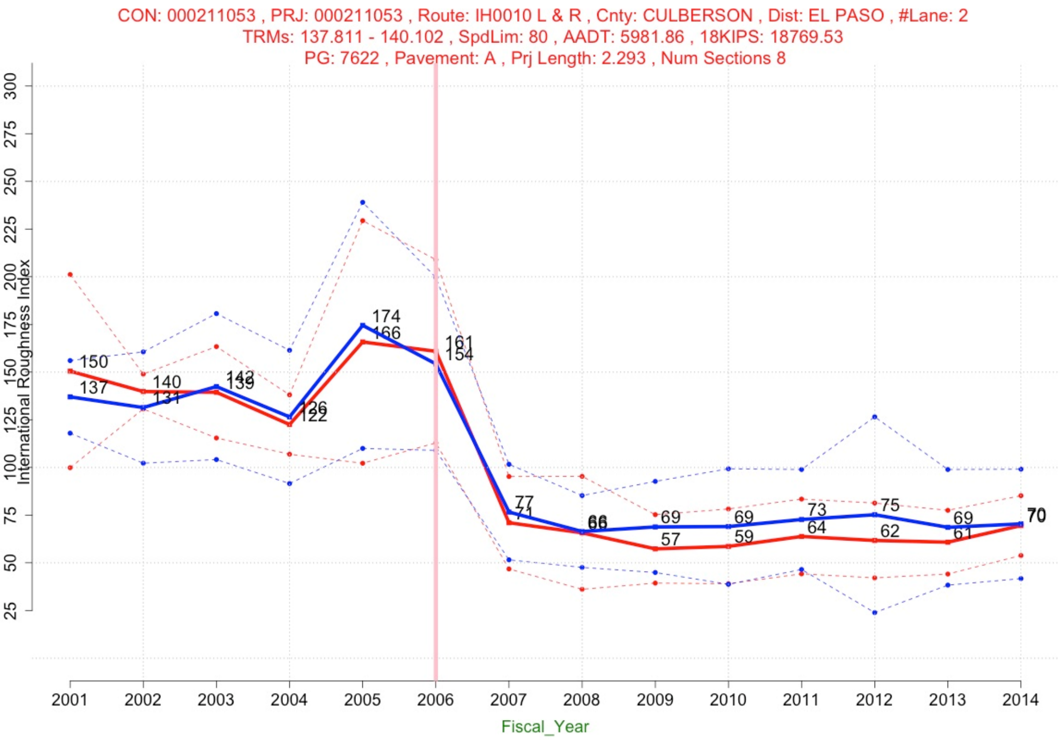


Figure 3.4 An example project on the divided main lane – the distinguishable case

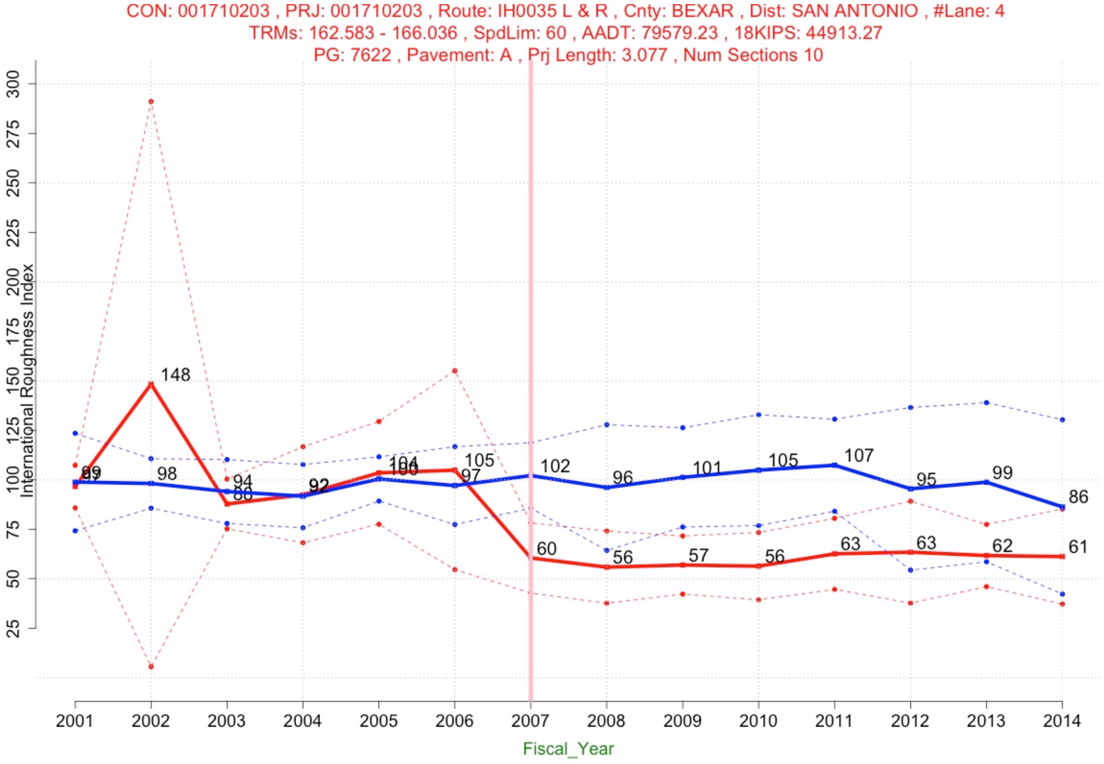


Figure 3.5 An example project on the divided main lane – the indistinguishable case

It should be mentioned that the performance history is not always as clear as shown in the previous examples. The research team manually inspected the performance histories of 917 hot mix projects to ensure the reliability of the data. Although it is tedious and time-consuming, the exercise was intentionally kept manual (rather than automating) to avoid any unforeseen inconsistencies in the data. Several projects containing missing values, unrealistic and outlier data points, and unexpected patterns were discarded. A total of 565 hot mix projects were retained at the end of manual data cleaning exercise.

Figure 3.6 shows an example of a selected project. It should be noted that multiple IRI values are available for each project depending on the length of the project. In this example, the project was completed and opened to traffic between 2008 and 2009 PMIS measurements. The project level IRI prior to the construction appears to be 117 inch/mile (Figure 3.6) and the IRI dropped to 75 inch/mile post-construction. The raw project-level IRI values are subjected to the measurement error. The study team used the available IRI data during both prior and post-construction periods to estimate trend lines. Linear regression analyses were performed to estimate the trend line equations (shown in red dots). Subsequently, the trend line equations were used to estimate the pre- and post-construction IRI values, and to estimate the drop in IRI due to the construction. A similar regression exercise was performed for each project to estimate the respective drops, initial ride quality values, and deterioration rate after construction. Deterioration rate is determined using the slope of regression lines corresponding to IRI values after construction year.

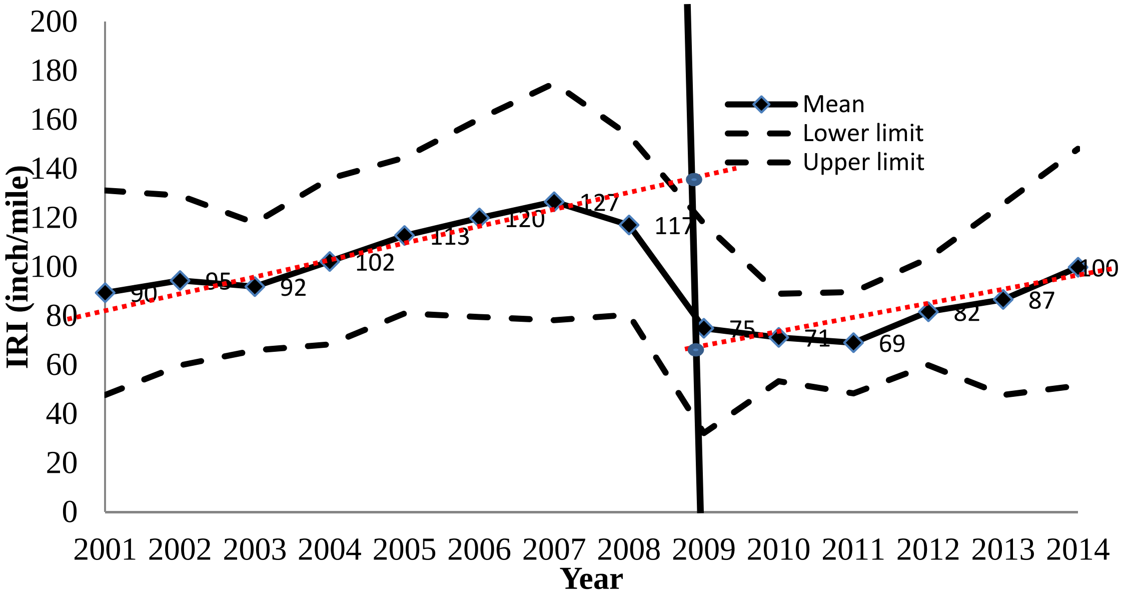


Figure 3.6 Performance history of a hot mix overlay

3.7 Data Description

A comprehensive description of the characteristics of explanatory variables is important to better understand the wide range of projects included in this research. Table 3.9 shows the descriptive statistics (mean, standard deviation, maximum, and minimum) of several variables included in the empirical analysis. The new database contains both shorter and longer projects ranging from about one to 17 miles long with an average length of 4.6 miles. About 19% of the projects were less than 2-mile long. Approximately 3% of the pavements are constructed on routes with a maximum speed limit of 45 mph and 53% of the projects were located in rural areas. The projects selected for the analysis included approximately 12% on interstate highways, 37% on FM roads and the remaining being other facility types such as US highways and state highways. Left and right shoulder width varied from zero feet to about 16 ft. The dataset included three different measurements of traffic: i) AADT, ii) ESAL of 18 kips, and iii) estimated daily average of the ten heaviest wheel loads traveling a particular traffic section. The descriptive statistics of the traffic measurements are provided in Table 3.9.

Additionally, Table 3.9 shows that about 42% % of the hot mix surface projects included in the dataset used Type C mix and about 53% of the surface projects used Type D mix. In Texas, type C mix stands for ½” dense-graded mix and Type D mix consists of 3/8” mix. The remaining projects contain either SMA or Superpave mixes. Relatively 33% of hot mix projects are constructed using an asphalt binder with performance grade PG-76, while 20% used an asphalt binder with PG-64. Table 3.9 indicates that the dataset includes hot mix projects with an initial IRI value in the range of 35 inches/mile to 194 inches/mile with a mean of 72.6 inches/mile. IRI drop value also varies between 0 inches/mile to 220.5 inches/mile with a mean of 52.8 inches/mile. Production and placement related features such as laboratory VMA, laboratory density, in-place air voids, asphalt content, and also maximum specific gravity are described statistically in Table 3.9.

Finally, the dataset includes analysis periods ranging from 3 to 12 years, with a mean analysis period of 7 years. The deterioration rate is estimated using the available performance data corresponding to post-construction period. The deterioration rate changes in the range of 0 to 34 inches/mile/year. Thus, the deterioration rate represents the early deterioration rate and not the deterioration rate expected during the entire life of the project.

Table 3.9 Descriptive statistics

	Variables	**Mean**	**Std.Dev**	**Min**	**Max**
Project Location features	Project Length (mi)	4.59	3.05	0.001	16.89
	Indicator variable: small project	0.19	0.19	0	1
	Indicator variable: Low speed	0.03	0.17	0	1
	Indicator variable: rural area	0.53	0.5	0	1
	Indicator variable: facility - IH	0.12	0.33	0	1
	Indicator variable: facility - FM	0.37	0.48	0	1
	Left shoulder width (ft)	6.62	2.67	0	16.16
	Right shoulder width (ft)	6.65	2.62	0	16
	AADT	11,806	16,723	109	125,186
	ESAL – 18 kips	6,218	9,270	41	58,685
	Traffic load estimate – 100lb	128.48	16.55	82.50	165.25
As -constructed features	Hot mix – Type C	0.42	0.5	0	1
	Hot mix – Type D	0.53	0.5	0	1
	Indicator variable: PG-76	0.33	0.47	0	1
	Indicator variable: PG 64	0.2	0.39	0	1
	Ride quality (initial IRI-in./mi)	72.62	21.79	35.53	194.12
	IRI Drop (in./mi)	52.77	31.24	0	220.47
Production and placement features	Laboratory VMA (%)	14.66	1.06	7.75	19.34
	Laboratory density (%)	96.39	0.46	94.75	98.36
	In-place air void (%)	7.24	0.95	4.02	12.27
	Asphalt content (%)	4.83	0.48	3.54	7.75
	Maximum specific gravity	2.46	0.05	2.29	2.62
	Analysis Period	6.55	2.25	3	12
	Deterioration (in./mi per year)	2.9	3.46	0	34

Chapter 4. Revised Pay Adjustment

4.1 Introduction

Ride quality pay-adjustment schemes are often based on as-constructed roughness measured immediately after the overlay construction. On the other hand, data collected from PMIS and SiteManager suggested that contractors delivering better ride quality are not necessarily significantly improving the roughness from the pre-existing surface. Evaluating the new versus the existing ride quality could be a more realistic way of providing a bonus/penalty to contractors for the actual work they perform. It is rational to provide a pay adjustment system that is based on the gain in pavement life due to the ride improvement relative to that of the existing pavement prior to the project construction (particularly for rehabilitation projects).

This chapter presents the methodology employed for developing a performance-based pay adjustment system corresponding to a combination of drop in IRI and as constructed ride quality. The following steps were performed for establishing the revised pay adjustment system. These steps are described in more details in this chapter.

- Explore the empirical relationship between the project construction characteristics and the pavement deterioration rate.
- Investigate the distribution plots of pre-/post-construction IRI and drop in IRI.
- Develop a revised pay adjustment system that jointly accounts for as-constructed ride quality measured immediately after the construction and the improvement in the ride quality relative to that of existing pavement.

4.2 Model Development

A statistical model development exercise was carried out to investigate the relationship between the pavement field performance (i.e., deterioration rate in terms of ride quality) of a project and the project specific construction attributes such as ride quality immediately after the construction, drop in IRI due to construction, volumetric properties (QC/QA), traffic, etc. The underlying distribution of the dependent variable (deterioration rate) plays a vital role in the selection of the model structure. The deterioration rate (dependent variable) takes either a zero or non-zero value, which corresponds to projects not showing or showing signs of deterioration during the analysis period. In this study, a type I Tobit model structure was used for handling dependent variables dominated by a particular response (zero in this case); these are so-called corner solution problems in econometrics. A standard type I Tobit model can be written as follows.

$$y_i = \max(0, y_i^*) \quad \textbf{(4.1)}$$

$$y_i^* = X_i\beta + u_i \quad \textbf{(4.2)}$$

$$u_i \sim \text{Normal}(0, \sigma^2) \quad \textbf{(4.3)}$$

Where:

y_i: Observed deterioration rate of i^{th} project
y_i^*: Latent deterioration rate
X_i: Vector of i^{th} project attributes
β : Vector of regression coefficients
u_i: Idiosyncratic error term

σ: Standard deviation of the error term

$$E(y_i|y_i > 0) = E(y_{1i}|y_{1i} > 0) = X_i\beta + \sigma \frac{\phi\left(\frac{X_i\beta}{\sigma}\right)}{\Phi\left(\frac{X_i\beta}{\sigma}\right)} \quad \textbf{(4.4)}$$

$$P(y_i = 0|X) = \Phi(X_i\beta) \quad \textbf{(4.5)}$$

The Tobit model is similar to a linear regression except that the model recognizes the dichotomization of the dependent variable into zero and non-zero sets. The Tobit model allows estimating the probability of a section to exhibit zero deterioration rate, which is useful to identify the factors that contribute to maintain the road conditions fairly unchanged for long time. By applying such model, the regression parameters corresponding to the explanatory variables will be unbiased. The performance prediction, or the expected value of the deterioration rate for a given set of explanatory variables, is estimated using Equation 4.4. $P(y_i = 0|X_i)$ or the probability of a section to remain unchanged in terms of IRI may also be estimated using Equation 4.5.

4.2.1 Endogeneity

Deterioration may be influenced by several unobserved features in addition to the observable features represented by the matrix X_1. Such unobservable features are included as part of the idiosyncratic error term. For example, the pre-existing condition of the road arguably influences the post-construction pavement performance. However, the pre-existing road condition governs the initial ride quality, particularly in the case of hot mix surface projects. The potential correlation between the initial ride quality and the unobserved pre-existing road condition violates the Tobit regression assumptions. Moreover, the deterioration rate and the initial IRI were computed by regressing the average ride quality (annual IRI at project-level) over time. This also potentially induces a correlation between the estimated initial IRI and the idiosyncratic error term. Correlation between the explanatory variables and the idiosyncratic error is termed as endogeneity, which produces a bias in the estimates of the Tobit regression model parameters. To circumvent the problem, this study uses a two-stage regression approach using endogenous Tobit regression models.

The aforementioned model was reformulated into a two-stage specification using selected instrumental variables; the latent deterioration rate y_i^* is modified as shown below.

$$y_i^* = y_{2i}\alpha_1 + X_{1i}\beta_1 + \varepsilon_i \quad \textbf{(4.6)}$$

$$y_{2i} = X_{1i}\gamma + X_{2i}\beta_2 + \delta_i \quad \textbf{(4.7)}$$

$$(\varepsilon_i, \delta_i) \sim N\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \tau_1^2 & \eta_1 \\ \eta_1 & \tau_2^2 \end{bmatrix}\right) \quad \textbf{(4.8)}$$

where:

X_{1i}: i^{th} project attributes
β_1: regression coefficients corresponding to the attribute vector X_1
γ: regression coefficients corresponding to X_1 while using as an instrument
X_{2i}: i^{th} project instrumental variables
β_2: regression coefficients corresponding to X_2
y_{2i}: endogenous covariate (natural logarithm of initial IRI)
ε_i: error term in the structural model (Equation 4.6)

δ_i: error term in the reduced form model (Equation 4.7)
τ_1^2: variance of ε_i
τ_2^2: variance of δ_i
η_1: covariance of ε_i and δ_i

The explanatory variables are non-linearly related to the performance prediction; thus, the interpretation of regression parameters (β) is not straightforward. For that reason, the research team used the concept of elasticity to examine the sensitivity of explanatory variables on the deterioration rate. Elasticity is defined as the change in deterioration rate value per unit change in any explanatory variable while keeping the remaining unchanged. Equation 4.9 is used to estimate the econometric elasticity of a continuous explanatory variable x_j.

$$\frac{\partial E(y_i|X)}{\partial x_j} = \Phi\left(\frac{X\beta}{\sigma}\right)\beta_j \qquad \textbf{(4.9)}$$

Both magnitude and the corresponding standard errors of this endogenous Tobit model parameters were obtained through maximum likelihood estimation using STATA software. A final specification was chosen carefully based on a rigorous model development process. Model refinement was carried out through exclusion of statistically insignificant variables by following standard step-wise procedures and statistical tests (e.g., F-test). Practical considerations played a role in the removal of insignificant variables, rather than solely adopting a statistics based mechanical approach. Table 4.1 presents the final specification estimates of the Tobit regression.

4.3 Estimation Results

As mentioned earlier, the researchers used a two-stage endogenous model structure: the first stage and the main stage. Both first and main stage regression are detailed in this section.

The first stage involves modeling the endogenous covariate, i.e., logarithmic transformed initial IRI. The logarithmic transformation was used to allow for negative values within the modeling framework, which accommodates the normally distributed error term. All the explanatory variables are included while constructing the first stage regression model; exclusion of the any explanatory variables may potentially bias the coefficient estimates of the instrumental variables. A comprehensive description of both sign and magnitude of the instrumental variables is provided in Table 4.1. The model only includes the statistically significant variables with at least 95% significance level.

Table 4.1 Model estimation results

Model	Dependent Variables	Coefficient	Std.error	*t*	*P* > |*t*|
Deterioration Main Regression	Initial IRI	14.728	4.498	3.27	0.001
	IRI drop	4.671	0.772	6.05	0.000
	In – place air voids	0.438	0.206	2.13	0.034
	Indicator variable: Facility - FM	-0.995	0.463	-2.15	0.032
	Analysis period	-0.260	0.087	-2.98	0.003
	Constant	-33.307	9.289	-3.59	0.000
Initial IRI – First Stage	IRI drop	-0.992	0.018	-5.53	0.000
	In – place air voids	-0.0002	0.005	-0.04	0.967
	Indicator variable: Facility - FM	0.038	0.012	3.03	0.003
	Analysis period	-0.003	0.002	-1.12	0.263
	Mix Type D	-0.025	0.01	-2.44	0.015
	Small project	0.050	0.013	-3.57	0.000
	Low speed	0.118	0.028	4.20	0.000
	Maintenance cost per section	3.36e-06	1.43e-06	2.34	0.020
	AADT	1.51e-06	3.83e-07	3.94	0.000
	Traffic load estimate – 100lb	-0.002	0.00045	3.95	-0.002
	Constant	2.185	0.082	26.89	0.000

Number of observations: 509
83 left censored at 0 and 426 uncensored observations
Instrumented: Initial IRI
Wald Test of exogeneity: Chi-Square(1) = 15.20; Prob > Chi-Square = 0.000

4.3.1 First Stage Regression

The initial IRI after the construction is likely influenced by the construction quality, road geometric features, material properties, and the pre-existing road condition. As shown in Table 4.1, data suggest that asphalt mixture type significantly influences the ride quality. The negative sign of the indicator variable corresponding to the indicator variable for Type-D asphalt mix shows that pavement constructions with Type-D (a finer mix) mixes are likely associated with smoother surface finishes with lower initial ride quality. A mixture with smaller aggregates is likely more workable and allows for better compaction thereby results in a smoother post-construction surface. The positive sign on low-speed facility indicator shows that the facilities with lower (than 45 mph) posted speed limits are likely to be associated with higher initial pavement roughness. Pavement sections with lower posted speed limits are typically harder to achieve smoother finishes probably due to inherent geometric characteristics. Moreover, the measurement of the roughness using inertial profilers would be slightly biased towards higher side on the pavements with lower posted speed limits. Similarly, the short pavement projects are likely result in a higher post-construction surface roughness as indicated by the positive coefficient corresponding to the respective indicator variable. The negative coefficient on the traffic load variable shows that the pavements carrying higher loads are likely associated with lower initial ride quality. Pavements carrying higher traffic loads are typically structurally sound and well-maintained pavements, which enhances the ease of achieving a smoother post-construction surface in a surface overlay project. On the other hand, the negative coefficient on the AADT variable indicates that pavements carrying higher traffic volumes are likely to be associated with higher initial ride quality after an overlay. Similarly, data suggest that pavements with higher annual maintenance costs (per unit length) are likely to be associated with higher initial ride quality following an overlay construction project. Higher maintenance costs may indicate frequent issues with the pavement surface which may lead to increased difficulty in delivering a post-construction smoother surface.

The aforementioned variables appear to be directly related to the post-construction ride quality. Note that the variables indirectly influence the future pavement performance via their influence on the initial ride quality. The interpretation of the remaining variables (that are also included in the main model) in the first stage regression is omitted, and the detailed descriptions are provided as part of the main model below.

4.3.2 Main Stage Regression

Data suggests that both the initial IRI post construction as well as the drop in IRI that is attributable to construction activity influence the future performance of the pavement. The positive sign of the initial IRI in the main regression model indicates that the pavements with higher initial IRI are likely to deteriorate faster over the time. The pavements with higher ride quality increases the vehicular impact loads thereby results in faster deterioration rates over the time. The model indicates that pavement constructions with higher drop in IRI relative to the pre-existing surface are associated with higher future deterioration rates as indicated by the positive coefficient on the respective variable. Pavements that required a significant effort in reducing the pre-existing surface roughness are likely the pavements with relatively moderate to poor structural condition. A mere surface project may temporarily reduce the pavement smoothness but the underlying pavement likely witness a higher deterioration over the time. It is important to recognize the significant “extra-effort” of the contractor in reducing the surface roughness of such pavements, which temporarily delay the rapid deterioration of the pavement. Two hot mix construction jobs delivering equivalent initial IRI should not be rewarded the same; the pre-existing conditions and thereby the effort to bring down the initial IRI are different.

In summary, the aforementioned empirical findings are important and indicate the overall economic value of building smoother pavement structures. The findings confirm that a pay adjustment system that uses both the initial IRI and the drop in IRI (a measure of the contractor’s effort in reducing the road roughness) would render a rationale performance-related pay adjustment specification. Pavement constructions that involve a significant effort in reducing the roughness (of the pre-existing surface) while delivering a smoother finished pavement shall be rewarded for expected superior pavement performance. The aforementioned empirical model allows to quality the extra performance gains of building smoother surface finishes and allows to account for measured drop in IRI (relative to the pre-existing surface) while calculating the performance incentives.

The positive sign on the coefficient corresponding to the in-place air voids indicates that the pavements with higher in-place air voids are likely to be associated with higher deterioration rates. The empirical finding highlights the importance of compaction during the hot mix overlay construction projects. The model allows to quantify the performance gains of extra compaction efforts (up to a threshold), and facilities to develop an incentive system rewarding construction jobs with significant compaction efforts. The analysis period was also included in the model to account for the differences in terms of performance data availability across different hot mix projects (as the overlay construction may be constructed at different times). The model suggests that deterioration rates may be different across different facilities. Farm-To-Market roads are likely to experience lower deterioration rates relative to other facilities on an average as indicated by a negative sign on the respective coefficient. This may be due to the lower traffic. It may be important to account for the facility type while designing a performance related incentive system.

4.4 Developing Pay Adjustment Scheme based on Drop in IRI

4.4.1 IRI Data Analysis

Analysis of IRI data was intended to investigate the distributions of the pre- and post-construction IRI values to understand the typical ride quality provided by contractors in Texas. Significant efforts were made to identify as many asphalt projects as possible that contain performance data before the pavement construction, as-constructed ride quality measured immediately after the construction, and at least three years of pavement performance data. The research team used the collected data to develop the pre- and post-construction ride quality distributions. Figure 4.1 shows the distributions of pre-/post-construction and the drop in ride qualities of all the HMA pavements analyzed.

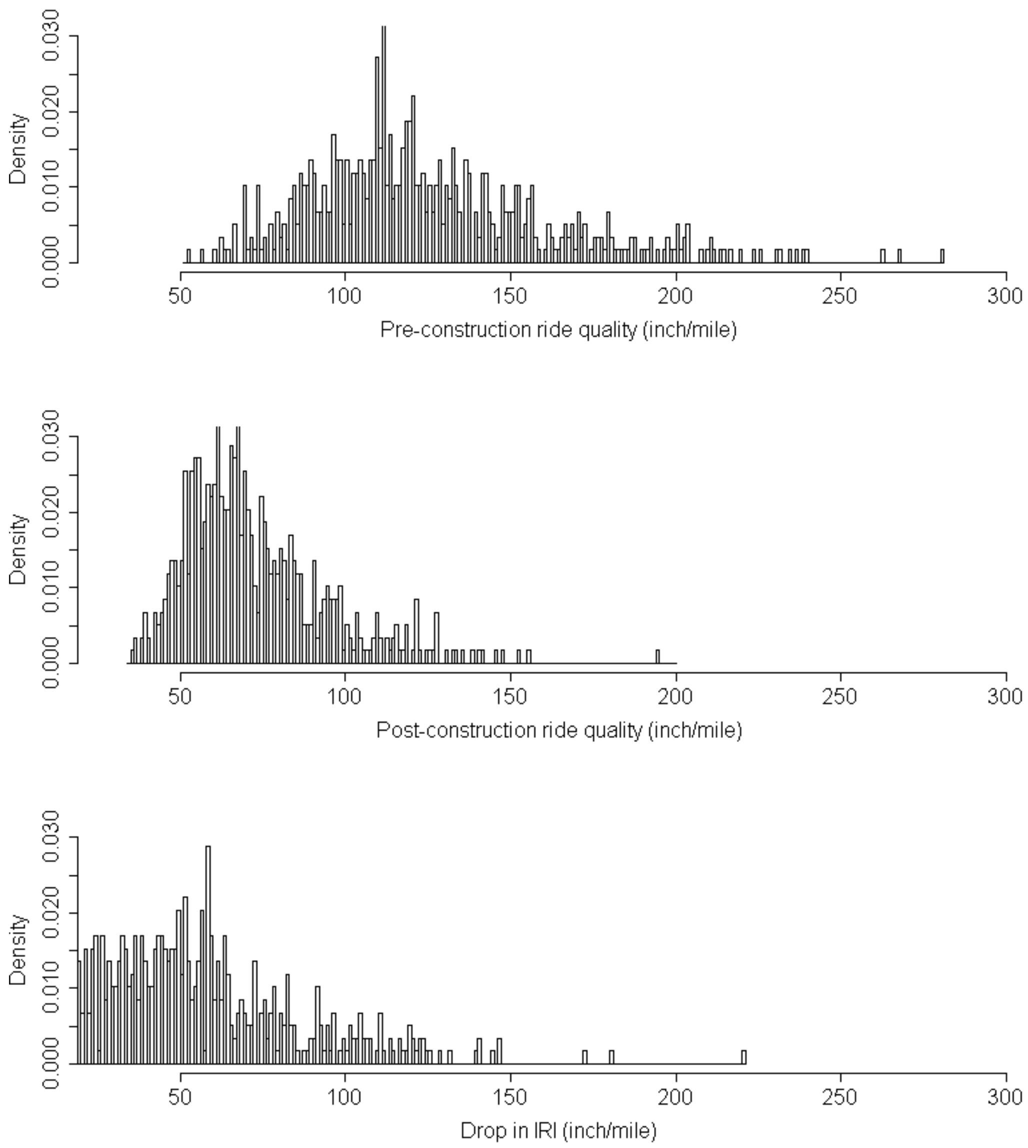


Figure 4.1 Distributions of pre- and post-construction ride qualities, and drop in IRI

The pre-construction roughness mean is higher than that of post-construction values as expected. Moreover, the pre-construction ride quality is more spread out than the post-construction ride quality. The post-construction roughness is generally controlled by the ride specification; thereby it is relatively more uniform as represented by a narrower distribution in Figure 4.1; that is, lower standard deviation.

From the data shown in Figure 4.1, the quantiles of the distributions were calculated. These quartiles were used to identify preliminary thresholds for using in the proposed ride specification. About 25% of the contractors are delivering very smooth surfaces below 57.5 inch/mile (or 0.9m/km). Another 25% of the projects were delivered with slightly rough surfaces, that is, rougher than 83.5 inch/mile (1.3 m/km). The median post-construction roughness is 67.5 inch/mile (or 1.07 m/km). It is relatively easier to deliver a smoother pavement surface by resurfacing a smoother pre-existing surface. Therefore, the pre-existing ride quality before the construction is equally important to assess the true quality of the construction project. In Texas, about 25% of the pavements were smoother than 100 inch/mile (1.6 m/km), while another 25% of the pavements were rougher than 144 inch/mile (2.3 m/km) prior to the construction. The median pre-existing roughness was estimated as 118 inch/mile (1.9 m/km).

One way to account for the pre-existing condition while assessing the true quality of the project in order to determine the bonus/penalty is to incorporate the drop in IRI due to construction into the ride quality specification. The research team examined the distribution of the IRI drop in Texas to identify reasonable preliminary thresholds for developing a new ride quality specification. Figure 4.1 shows the distribution of the drop in IRI due to construction for the 565 projects analyzed. The quantiles of the distribution of the drop in IRI were also estimated. About 25% of the projects reduced IRI by 30 inch/mile (or 0.47m/km); on the other hand, a few projects reduced IRI by more than 68.5 inch/mile (or 1.08 m/km). The median IRI drop due to overlay construction was estimated as 48.1 inch/mile (or 0.76 inch/mile). The new ride specification should reward projects whose quality if above average while not necessarily rewarding marginal improvements over a pre-existing smooth pavement.

The study team also investigated the relationship between the drop in IRI and post-construction IRI to better understand the ride quality. Figure 4.2 shows scatter plot between drop in IRI and the post-construction IRI along with a bivariate density contours. The plot suggests no strong correlation between the IRI drop and the post-construction IRI. The findings highlights that the projects resulting in smoother pavements are not necessarily those that improve the riding quality the most.

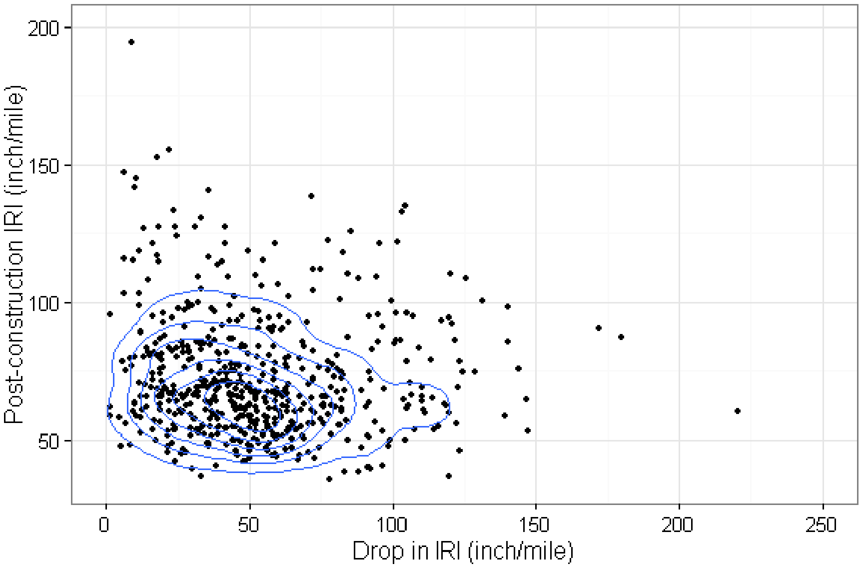


Figure 4.2 Relationship between drop in IRI and post-construction IRI

Depending on the pre-existing pavement conditions, a project may only marginally improve the ride quality but still receive a bonus as per the current specification. The relationship shown in Figure 4.2 further emphasizes the need to revise the existing ride specification to incorporate the drop in IRI due to construction. Due to lack of strong correlation, the thresholds for bonus and penalty corresponding to post-construction IRI and drop in IRI may be designed independently rather than using quantiles from a joint distribution.

4.5 Proposed Preliminary Pay Adjustment System

Smoothness pay adjustment factors are often intended to motivate the contractor to deliver pavements with better ride quality. But, most importantly, it better riding quality (or lower initial roughness) translates into longer lasting pavements and lower operation costs. As mentioned earlier, the ride quality of the existing pavement prior to the construction plays an important role in achieving smoother pavements post construction. The objective of this section is to propose an interim ride specification based on actual field data that accounts for the pre-existing ride quality while allocating bonus/penalty for a given as-constructed ride quality. It is important to note that the proposed model is directly based on the IRI measured instead of the calculated ride score. The suggested framework reflects the ride quality data of pavements that were actually delivered in Texas. The ride specification accounting for the pre-existing ride quality is arguably rational and fairer across a wide variety of pavement projects.

Table 4.2 shows the proposed ride specification that incorporates IRI drop and as-constructed IRI (initial IRI). Each cell describes the total pay adjustment corresponding to the respective bins. The left top quarter of the table corresponds to projects delivering relatively rougher pavements with minimal ride improvement from the pre-existing pavement surface; this region is dominated by penalties and corrective actions (shaded in red). On the other hand, the bottom right corner corresponds to projects delivering relatively smoother pavements despite starting from a relatively rougher pre-existing pavement; this region is dominated by bonuses (shaded in green).

A neutral region is also included which does include neither a bonus nor a penalty. The left bottom region of the table corresponds to projects delivering smoother pavements with marginal ride improvement from the pre-existing ride quality. Similarly, the top right region of the table corresponds to projects delivering a relatively rough surface, however, with a significant improvement with reference to the pre-existing ride quality. The bonus and penalty in left-bottom and top-right regions is governed by the penalty and bonus equations, which may result in either a bonus or penalty for a pair of initial IRI and drop in IRI.

Table 4.2 Proposed pay adjustment scheme

IRI drop / Initial IRI	0 to 32 inch/mile or < 0.5 m/km	32 to 55 inch/mile or 0.5 to 0.87 m/km	55 to 63.4 inch/mile or 0.87 to 1 m/km	63.4 to 95 inch/mile or 1 to 1.5 m/km	>95 inch/mile or > 1.5m/km
> 95 inch/mile or > 1.5m/km	Corrective action	Corrective action	Corrective action	No bonus/penalty or Corrective action	No bonus/penalty or Corrective action
63.4 to 95 inch/mile or 1 to 1.5 m/km	0.5*(Penalty.IRI + Penalty.Drop)	0.5*(Penalty.IRI + Penalty.Drop)	0.5*(Penalty.IRI + Zero.Drop)	0.5*(Penalty.IRI + Bonus.Drop)	0.5*(Penalty.IRI + Max.Bonus.Drop)
55 to 63.4 inch/mile or 0.87 to 1 m/km	0.5*(Zero.IRI + Penalty.Drop)	0.5*(Zero.IRI + Penalty.Drop)	0.5*(Zero.IRI + Zero.Drop)	0.5*(Zero.IRI + Bonus.Drop)	0.5*(Zero.IRI + Max.Bonus.Drop)
32 to 55 inch/mile or 0.5 to 0.87 m/km	0.5*(Bonus.IRI + Penalty.Drop)	0.5*(Bonus.IRI + Penalty.Drop)	0.5*(Bonus.IRI + Zero.Drop)	0.5*(Bonus.IRI + Bonus.Drop)	0.5*(Max.Bonus.IRI + Max.Bonus.Drop)
< 32 inch/mile or < 0.5 m/km	0.5*(Max.Bonus.IRI + Penalty.Drop)	0.5*(Max.Bonus.IRI + Penalty.Drop)	0.5*(Max.Bonus.IRI + Zero.Drop)	0.5*(Max.Bonus.IRI + Bonus.Drop)	0.5*(Max.Bonus.IRI + Max.Bonus.Drop)

Note: 1. Zero.Drop = 0; Zero.IRI = 0
2. Bonuses and penalties are per 0.1 mile of the project.

Bonus equations: (4.10)

B1. Based on drop (Bonus.Drop) ($): 0.0316*Drop - 2.006
B2. Based on initial IRI (Bonus.IRI) ($): -0.0435*IRI + 2.391
Max.Bonus.Drop = $1 and Max.Bonus.IRI = $1

Penalty equations: (4.11)

P1. Based on IRI drop (Penalty.Drop) ($): 0.0182*Drop – 1
P2. Based on initial IRI (Penalty.IRI) ($): -0.0316*IRI+2.006
Max.Penalty.Drop = -$1 and Max.Penalty.IRI = -$1

The proposed ride specification computes the pay adjustment in a modular fashion. For each pair of initial IRI and the drop, a pay adjustment is assessed by averaging the individual pay adjustments corresponding to the initial IRI and the drop. The individual pay adjustments are designed to be proportional to the respective ride measure (initial IRI or drop) within the thresholds. Pavements smoother than 32 inch/mile (or 0.5 m/km) receive a maximum bonus with respect to initial IRI; however, the overall pay adjustment also depends on the drop in IRI relative to the pre-existing ride quality. Similarly, projects are rewarded with a maximum bonus with respect to their efforts in significantly reducing the IRI of the pre-existing pavement by over 95 inch/mile (or 1.5 m/km); however, the overall pay adjustment also depends on the ride quality of final delivered pavement.

Corrective action may be required on newly overlaid pavements rougher than 95 inch/mile (or 1.5 m/km) depending on the pre-existing ride quality prior to the construction. The engineer may choose to waive the corrective action despite delivering a rougher (than 95 inch/mile) pavement in the case of a significant ride improvement from pre-construction ride quality. For demonstration purposes, the maximum bonus and penalty corresponding to initial IRI as well as drop in IRI are nominally set to $1.00. The final specification need to be scaled to any maximum bonus/penalty depending on the highway agency and local pay adjustment history. The maximum bonus and penalty arguably play a vital role and should be set to reasonable values. For example, a maximum penalty should always be higher than the cost of corrective action; otherwise, a contractor may choose to receive the penalty and deliver a post-construction surface that is unacceptably rough. On the other hand, the maximum bonus should be at least sufficient to financially encourage a contractor to strive for achieving the incentive. The bonus/penalty in the other regions is governed by the bonus/penalty equations shown in Equations 4.10 and 4.11. The equations ensure the pay adjustment to vary linearly between the respective thresholds.

The thresholds within the proposed specification were selected based on the distributions of the initial IRI and drop in IRI of the pavements analyzed. To ensure that the specification thresholds are realistic, it is important to compute the percentage of projects that had actually delivered pavements within the proposed ride quality bins.

Table 4.3 shows the percentage of the hot mix projects that were delivered in Texas within each ride specification bins. The analysis was based on the aforementioned integrated database comprising about 565 asphalt projects across the Texas constructed between 2001 and 2011.

About 36% of the hot mix pavements were rougher than 75 inch/mile (or 1.2 m/km). The existing specification using only initial IRI penalizes these projects equally for delivering a rougher pavement. However, about 22% of these projects actually improved the ride quality of pre-construction surface by more than 75 inch/mile (or 1.2 m/km).

Table 4.3 Proportion of historical overlay projects

IRI drop Initial IRI	0 to 32 inch/mile or < 0.5 m/km	32 to 55 inch/mile or 0.5 to 0.87 m/km	55 to 63.4 inch/mile or 0.87 to 1 m/km	63.4 to 95 inch/mile or 1 to 1.5 m/km	>95 inch/mile or > 1.5m/km
> 95 inch/mile or > 1.5m/km	6%	4%	1%	2%	2%
63.4 to 95 inch/mile or 1 to 1.5 m/km	13%	15%	5%	7%	5%
55 to 63.4 inch/mile or 0.87 to 1 m/km	4%	6%	3%	4%	2%
32 to 55 inch/mile or 0.5 to 0.87 m/km	4%	7%	3%	5%	2%
< 32 inch/mile or < 0.5 m/km	0%	0%	0%	0%	0%

The proposed preliminary system addresses the issue by adding a bonus for the significant ride improvement (drop in IRI), thereby reducing or nullifying the overall penalty. Similarly, about 64% of the projects were smoother than 75 inch/mile (or 1.2 m/km) and receiving a bonus (or not receiving any penalty). However, about 56% of these projects achieved such smoother finished surface due to a smooth pre-existing pavement, marginally improving the ride quality (with drop in IRI less than 55 inch/mile). The proposed preliminary system also addresses the issue by adding a penalty for marginal ride improvement (drop in IRI), thereby reducing or nullifying the overall bonus.

The analyzed data suggest that a significant proportion of projects resulted in marginal ride quality improvements. This is indicated by larger percentages in the top left portion of Table 4.3

This proposed preliminary schedule is arguably rational and acknowledges the contractors’ efforts toward high quality, long-lasting pavements. Implementing the proposed schedule (as revised and adjusted by TxDOT) is expected to financially motivate the contractors to deliver smoother pavements while significantly improving the ride quality of the existing pavements. However, most importantly, pavements with lower initial roughness will last longer and will reduce vehicle operating costs. The total savings to the state and to the people of the state are significant and could be estimated in millions of dollars annually.

Chapter 5. Survey Questionnaire and Interview

5.1 Introduction

TxDOT often executes short projects or projects that are upgrades to a roadway with a total length of less than 2,500 ft. The existing ride specification specifies the use of a 10 ft. straightedge for assessing the quality of such short projects. However, it is very difficult to straightedge and to get consistent roughness readings especially under traffic. Ride quality measurement using inertial profilers (or Surface Test Type B) is efficient in data collection and avoids such traffic delays. This research project conducted a feasibility study of measuring ride quality using an inertial profiler on short projects. This study included four steps: i) collecting information using a survey questionnaire, ii) conducting an in-person interview with subject matter experts, iii) performing a field investigation experiment, and iv) analyzing the field measurements. The survey questionnaire and in-person interview were aimed at better understanding the practical and other perceived issues associated with ride measurement on short projects. The received answers to the survey and the results of the interview are presented in this chapter. The field study using an inertial profiler was performed to collect a dataset containing longitudinal profiles, IRI values, and speed data. Chapter 6 of this report discusses the field experiment program in more details.

5.2 District Survey

An electronic message was sent to several TxDOT construction engineers to gather their responses on the following questions pertaining to ride quality on short and long projects:

- Do you distinguish between short and long projects based on roughness data?
- If so, what is the cut-off between short and long?
- How do you measure roughness for long project? And for short projects?
- Have you experienced any problem with any of these? Do you have any comment?
- Do you use pay adjustment factors for long projects? And for short projects?

The objective of the survey was primarily to identify issues, if any, with ride measurements on short sections in Texas. Eight engineers provided feedback on the survey. With respect to the survey questions outlined above, the following was observed from the survey:

- A mixed response was obtained but in general the districts use the current specification to distinguish between short and long projects based on roughness data. There is an indication that some districts do not distinguish between short and long projects and opt to use the Type B (long project) specifications for all sections unless there are notable rough patches on the pavement.
- The survey responders indicated that per the specifications, the length dividing short and long projects is 2,500 ft.
- Type A and Type B schedules are used for short projects and long projects, respectively.

- In general no “major” problems have been experienced with roughness measurements on long or short projects although some of the responders indicate specific issues (as quoted):
  - “Depending on the existing condition of the pavement and whether we are doing a rehab project or total reconstruction, different criteria should be used for total reconstruction vs on a rehab project. Contractor complained that Type B is too stringent if the condition of existing pavement is poor and there are inlets and/or manhole in the lane also. Intersections and driveways also create an issue with using the ride quality.”
  - “Contractors come back after their post-construction inertial profile results are in, and make excuses to try to influence the application of the specification. Two tried and true ones are “the whole road was rough before we got there and we could only improve it so much”, and “that bump was there before and we could not fix it all the way”. Both of those can be resolved by adding a requirement for a pre-construction ride quality test, to compare with post-construction. And make bonus and penalty related to how much improvement or degradation was documented between the two tests.”
  - “In my experience, if it says surface test Type A it rarely ever gets done unless there is a very noticeable rough spot in the pavement. That is the problem I have with the Type A is it requires someone to actually go measure with a 10’ straightedge, which takes a lot of time and effort for our inspectors. We use the pay adjustment factors on every project and really have no problem with the actual factors. However, we do try to stay away from Schedule 3 as much as we can because it does not require corrective action unless we go with a 10’ straightedge, which, again, rarely gets done.”
  - “When a project is shorter than 2,500 ft. or when the pavement is widened where a wheelpath rides on old pavement and the other on new pavement, we emphasize to the inspectors the importance of properly performing Surface Test Type A.
- Although some responders indicate that pay adjustment factors are used for both short and long projects, the general consensus is that these are only applied to long projects or those specified as Surface Test Type B.

The survey responses in general appear to emphasize approval of the current specifications but indicate the benefits of applying Type B procedures for short projects as well as implementing procedures to base post-construction roughness payment schedules on pre-existing roughness conditions.

5.3 In-Person Interview

The research team met with Dr. Magdy Mikhail, Mr. Jeff Howdeshell, Dr. Robin Huang, and Dr. Feng Hong of TxDOT to interview them about the inertial profiler and field experiences. A number of questions about the data collection process and filters applied to obtain IRI results were asked in this meeting. Furthermore, the inertial profiler filter stabilization and the effect of pavement type were discussed during the meeting. One of the questions was about the part of Tex-1001-S specification that necessitates a pre-section of 200 ft. length before starting the profiling process. To answer this question, Mr. Howdeshell explained that the inertial profiler requires a distance interval to initiate its operation and filters. The initial distance should be long enough to reduce the error in profiler data. According to his explanation, the inertial profiler can profile a very short section provided that it collects sufficient data for stabilization and initialization before that target section. Mr. Howdeshell also indicated that the pavement type of the pre-section does not affect the filter stabilization and data collection. For example, if one considers a 50-ft. section paved with HMA, it could be profiled using an inertial profiler even if it located after a concrete section. Again, it should be noticed that the profiler must cover enough distance before the starting point of this 50-ft. section.

Mr. Howdeshell informed the research team of two important points. Firstly, it is impossible to profile a road at a speed lower than 20 mph. He noted that the inertial profiler processes the lasers and accelerometers data using an unknown algorithm or “black box.” This black box is designed for specific parameters so that if the inertial profiler operates at 5 mph, no data are going to be recorded. This depends on the equipment manufacturer. Secondly, he pointed out that, considering that the IRI is summarized over a 0.1-mi length, a few stop points along a fairly short section (e.g., a two-mile section) do not appreciably affect the IRI calculation.

At the end, he recommended operation of the inertial profiler on sections with different lengths. This process will help to get insight about the black box and the filters inside of it. This exercise in fact will help to find the minimum length on which an inertial profiler can collect roughness data.

Chapter 6. Field Measurements and Data Analysis

6.1 Introduction

This chapter describes a field experiment that was carried out to assess the effect of several experimental variables on the determination of roughness. Some of the variables assessed include speed, roughness level, and number of stops. A certified operator from Pavetex collected the data using a high-speed profiling van. The field test involved six runs at different speeds over a selected loop. During each run, the speed value, elevation profile, and IRI data were recorded. Detailed discussions on test site selection and data collection procedure are provided at the beginning of this chapter. This is followed by a section discussing the effect of speed values on ride quality data and the statistical analysis on mean and standard deviation of IRI values. Correlation analysis results that provide insight into the relationship between IRI data and a simulated straightedge index are also discussed. The final part of this chapter provides a methodology employed to assess how a shorter length segment affects IRI calculations.

6.2 Test Site Selection

A 7.4-mile circular loop on East Pflugerville Parkway, Texas State Highway 130 (SH 130), Cameron Road, and Weiss Lane around Pflugerville Lake near Austin was selected. Figure 6.1 shows a map of the loop. This loop was chosen because of its several traffic signals, stop signs, and one sharp turn. Speed changes (braking and acceleration) can cause the accelerometer to tilt, which may have an effect on the profile data. Therefore, the data collected on this loop helped researchers to study the effect of speed changes on IRI values. In addition, another advantage of this loop is that all segments were paved with asphalt, so it could be assumed that the loop is continuous in terms of pavement type.

Once the loop was identified, roughness data were measured using an inertial profiler certified at the Texas A&M Transportation Institute. The loop was driven six times at different speeds ranging from 30 to 70 mph. Three runs (Runs 1, 2, and 4) were made on Section 1, which includes East Pflugerville Parkway, TX-130, Exit 432, Cameron Road, and Weiss Lane. Three other runs (Runs 3, 5, and 6) were made on Section 2 that includes East Pflugerville Parkway, TX-130, Exit 431, TX 130 service road, Cameron Road, and Weiss Lane.

6.3 Data Collection

The following data were collected during the field measurement process:

1) Elevation Profile
2) IRI
3) Speed

The inertial profiler collects voltage signals from the accelerometer and other sensors. Accelerometer and sensors signals are processed using a signal processing algorithm. This process samples the imported signals at a given interval of time and distance to obtain a sequence of readings. These sampled readings are imported and processed through another filter to calculate the elevation of locations where the signals were sampled. TxDOT currently specifies a sampling interval of 3 in. (or 76.2 mm). Figure 6.2 presents the elevation profile for the third run of this field experiment.

Figure 6.1 The map of selected loop

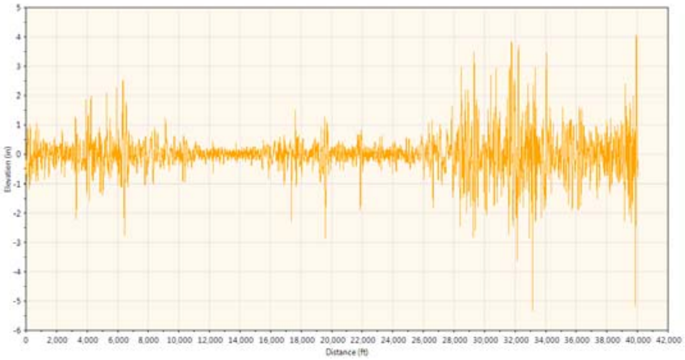


Figure 6.2 The elevation profile

After completing the profiling process, the operator provided two reports for each run. One of them included elevation data recorded every three inches. The other report provided IRI values of every 0.1-mile test segment and the area of localized roughness. It should be mentioned that both elevation and IRI values were generated for the left and right wheel paths. In this study, the research group focused on the right elevation and IRI data. The results from the left wheel were similar.

To obtain an accurate measurement of roughness, several factors that affect the accuracy of the profile must be considered during the measurement and processing steps. The operator was asked to travel the same test segments in the same lane for each repetition. Furthermore, the operator was asked to operate the inertial profiler at a constant speed on every 0.1mile segment. However, areas such as loops and frontage roads present challenges because of numerous stop points, traffic signals, changes in speed limit, and local access of traffic and intersections. However, the operating speed should be kept constant on every test segment to obtain valid data, and it is also important to collect data from the same test segments in every run.

6.4 Speed Effect Analysis

For this part of the analysis, two segments of the selected loop were considered. The first segment was a 2.3-mile section on East Pflugerville Parkway, from 0.0 to 2.3 miles. This section was driven six times in the same direction. The start points were identical at all runs. The second segment considered was a 2.4-mile section on Cameron Road from 5.0 to 7.4 miles. The roughness data of these two sections are summarized in the following figures.

Figure 6.3 presents IRI values every 0.1 mile at different speeds. In Figure 6.3, the continuous curves represent the speed of the profiler in each run, and the dots represent the IRI values calculated in the six runs. In calculating IRI, TxDOT's ride quality software was used following the procedure established by TxDOT specification. As can be seen, IRI values for the first segment ranged from 77 to 420 inches/mile.

In this field experiment, pavement roughness data were measured at six different speeds. As Figure 6.3 indicates, on most sections, the inertial profiler calculated almost identical IRI values for the six runs regardless of speed. Some small variation in IRI was observed at specific locations, but this cannot necessarily be attributed to variations in speed.

The research team calculated mean, standard deviation (STD), and coefficient of variation (COV) of the six IRI values at every 0.1-mile segment. The results are presented in Figure 6.4 and Figure 6.5. Figure 6.6 shows the plots of IRI standard deviations versus IRI mean values and IRI coefficient of variations versus IRI mean values. As shown in the plot of STD versus mean values (Figure 6.6a), the data are randomly distributed and there is no clear relationship between STD and mean values. Likewise, no obvious relationship could be found between COV and IRI data (Figure 6.6b). This indicates that the standard deviation and coefficient of variation are not proportional to the roughness mean values.

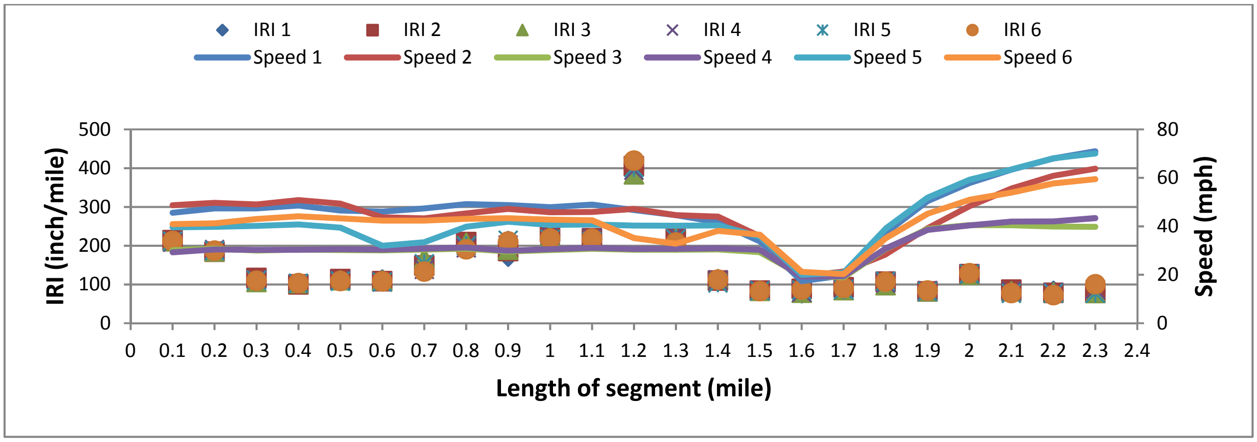


Figure 6.3 IRI and speed values for Section 1

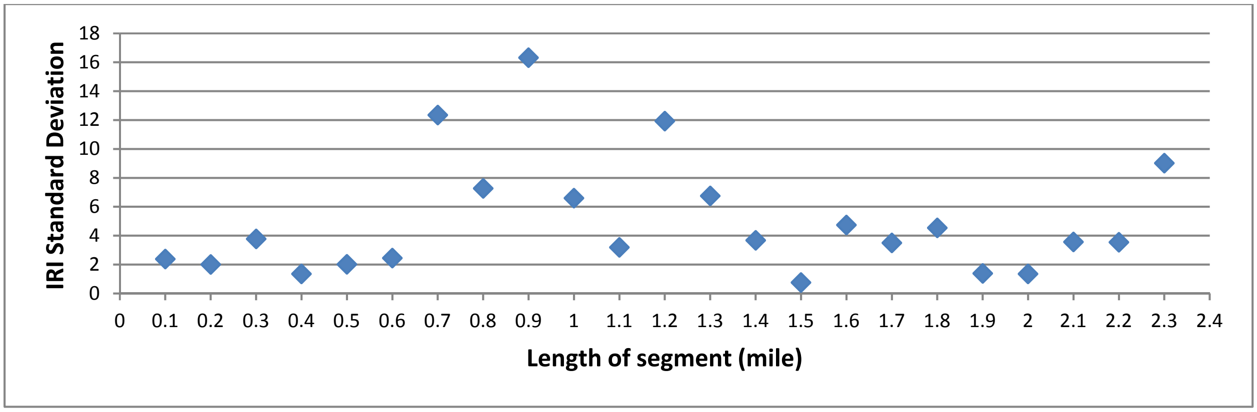


Figure 6.4 IRI standard deviation (inch/mile) for Section 1

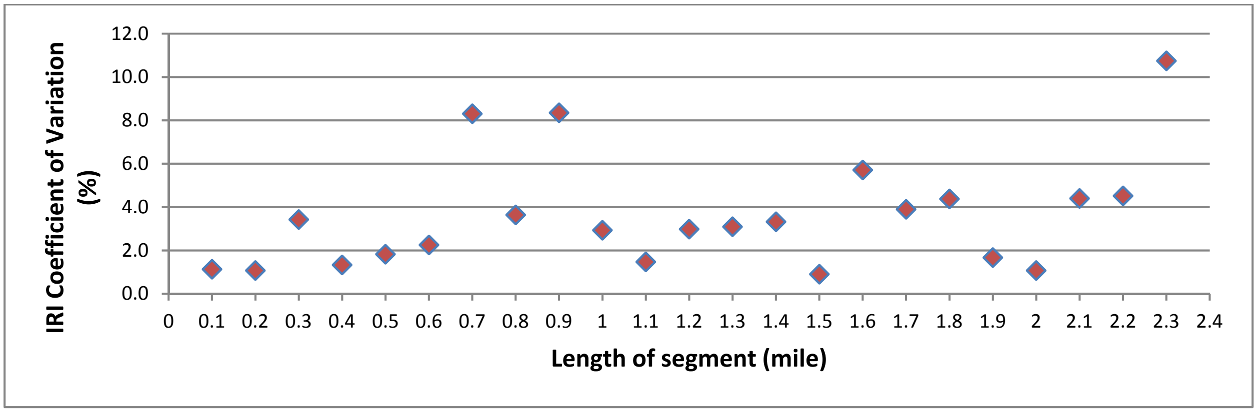


Figure 6.5 IRI coefficient of variation (%) for Section 1

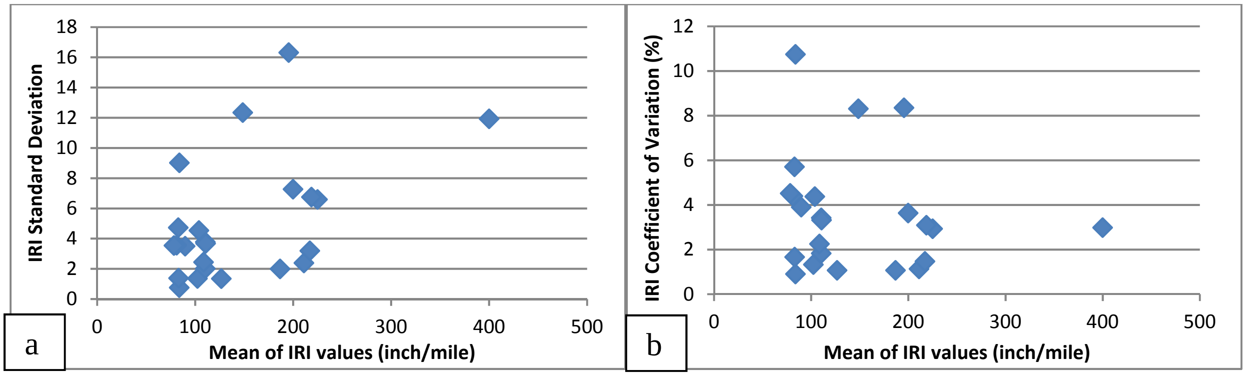


Figure 6.6 (a) IRI STD vs. IRI mean, (b) IRI COV vs. IRI mean for Section 1

The same procedure as for the first segment was applied to the second segment. Initially, the inertial profiler was used to determine the IRI values for every 0.1-mile section. This process was repeated six times, once for each run. The plots of IRI values at different speeds are provided in Figure 6.7. The same statistical analysis as for segment one was applied. The results are presented in Figure 6.8, Figure 6.9, and Figure 6.10. The obtained results indicate that the IRI variation observed in some sections are not related to the speed variations. Additionally, IRI standard deviation and IRI coefficient of variation do not depend on IRI values. In fact, this analysis demonstrates that the IRI variations in some segments are related to other factors that needs further investigation.

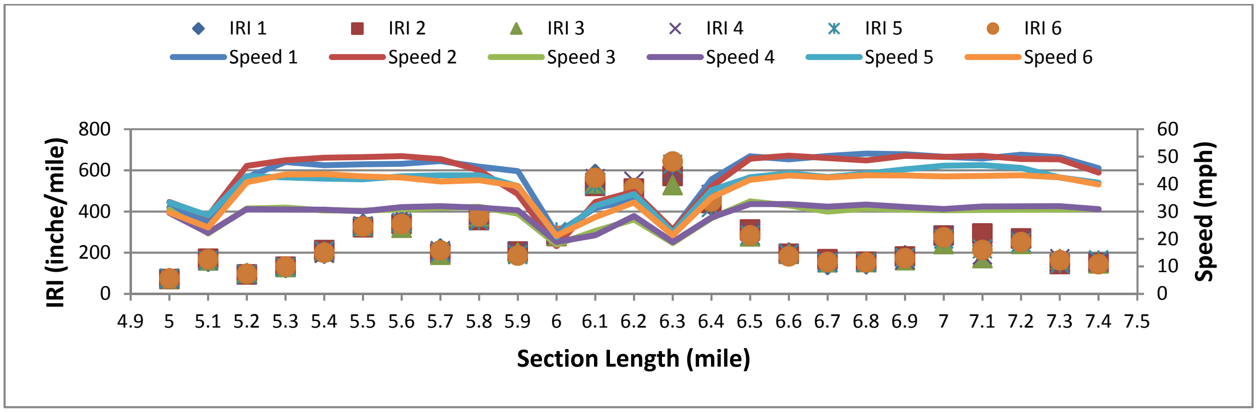


Figure 6.7 IRI and speed values for Section 2

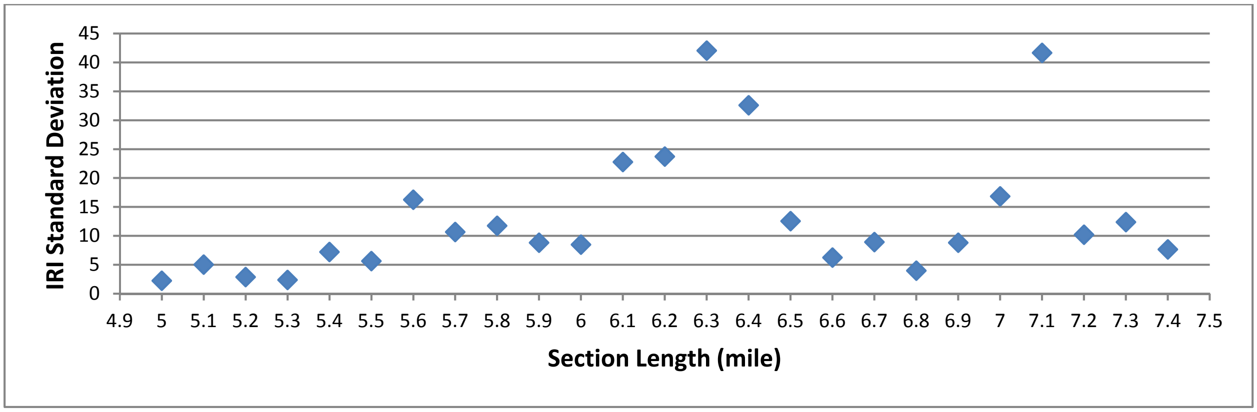


Figure 6.8 IRI standard deviation (inch/mile) for Section 2

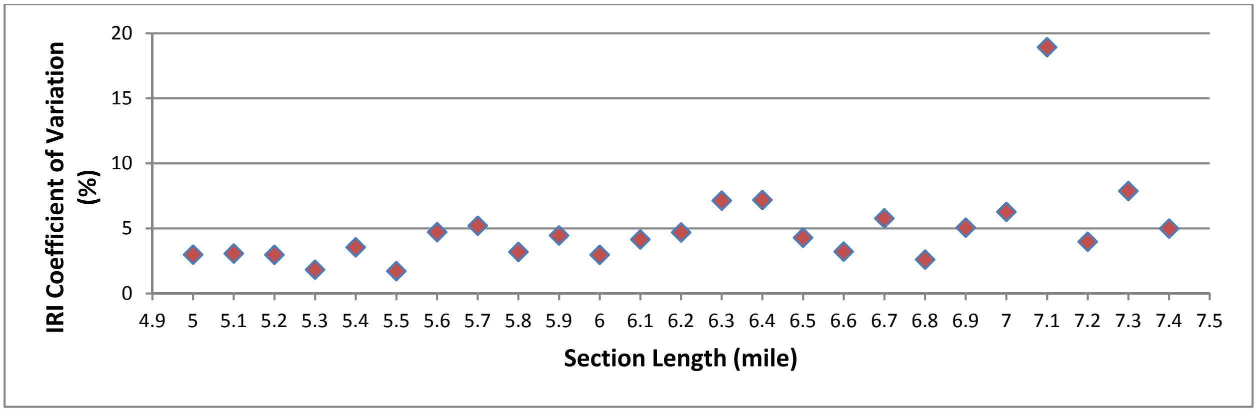


Figure 6.9 IRI coefficient of variation (%) for Section 2

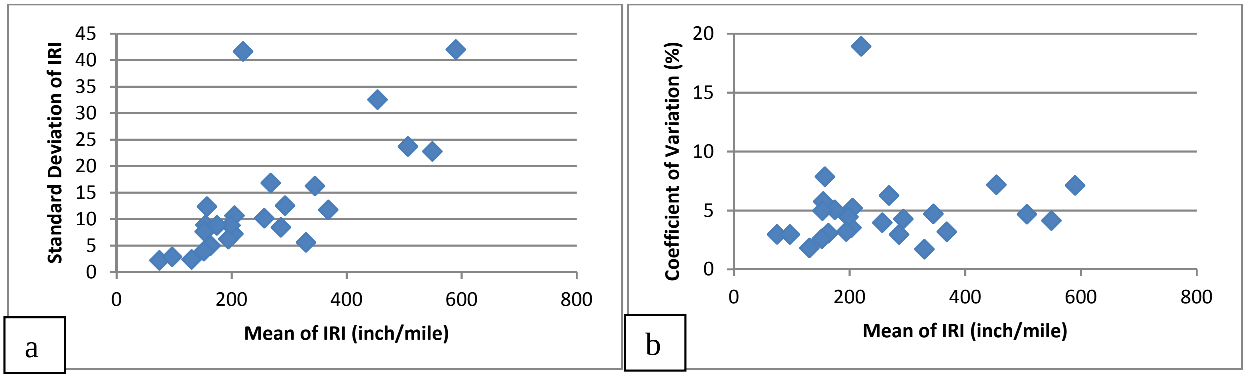


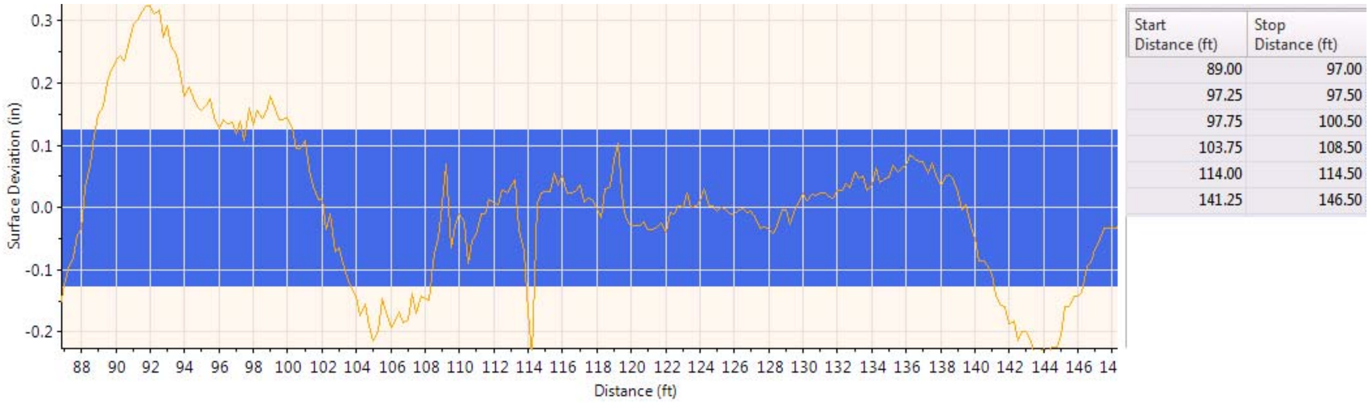
Figure 6.10 (a) IRI STD vs. IRI mean, (b) IRI COV vs. IRI mean for Section 2

6.5 Simulation Analysis

The simulation study was accomplished using the ProVAL 3.5. This software was developed under FHWA financial support. The ProVAL software can be used to quantify pavement ride quality by different indices such as IRI, profilograph index (PI), and rolling straightedge index. Using the software, the rolling straightedge approach was simulated on the profiles measured using the inertial profiler. The goal was to find the relationship between the IRI values and straightedge outcomes. This section provides the simulation analysis methodology and the results obtained.

6.5.1 Methodology

A 7.5-mile-long elevation profile with a 3-in. sampling interval was used to analyze and process a rolling straightedge simulation. To conduct the simulation, the ProVAL software requires the length of straightedge and the deviation threshold as inputs. According to the TxDOT ride specification, 10 ft. and 0.125 in. must be assigned to the straightedge length and the deviation threshold, respectively. As reported in ProVAL user's guide, the rolling straightedge shifts by one sampling interval along the given road profile and records the vertical deviation between the midpoint of the straightedge and the profile at every sampling interval. When the analysis is completed, the software provides a table indicating the location of points whose deviations are beyond the smoothness specification threshold (1/8 in.). Figure 6.11 illustrates the zoomed-in view of the given profile and the table of defective locations. In this figure, the blue colored area shows the range of acceptable surface deviation. Outside this area, the deviations are unacceptable, according to TxDOT specification.



Start Distance (ft)	Stop Distance (ft)
89.00	97.00
97.25	97.50
97.75	100.50
103.75	108.50
114.00	114.50
141.25	146.50

Figure 6.11 The zoomed-in view of the profile and the length of defective parts

To calculate a straightedge index, the length of the defective parts in each 0.1-mile segment was first summed. This is the defective part. The straightedge index (SI) value was determined by dividing the defective part by 0.1 mi (or 528 ft). In this way, SI represents the percentage of the test segment that fails the straightedge specification.

6.5.2 Results

A correlation study was carried out to understand any potential relationship between IRI and SI values. Figure 6.12 is the plot of IRI along SI values. As can be seen in this plot, SI values follow the same trend as the trend between IRI values. For instance, in a segment with IRI value as high as 580 inches/mile, the straightedge index is also high and equal to 55.2% of that segment. Likewise, in a segment with the IRI equals to 67 inches/mile, SI value is very low and equal to 1%. This trend demonstrates that IRI values and SI values are correlated. Another attempt was made to verify the relationship between IRI and SI. Figure 6.13 is the plot of IRI values versus SI values. The results show that the larger the IRI, the greater the SI. The equation of the trend-line and the R-square value also confirm this relationship. By considering the relationship between IRI and SI, it can be concluded that the straightedge approach and SI could be replaced by using an inertial profiler and IRI. It should be noted, however, that although the correlation is high, this does not mean that the two statistics are capturing the same features of the surface profile.

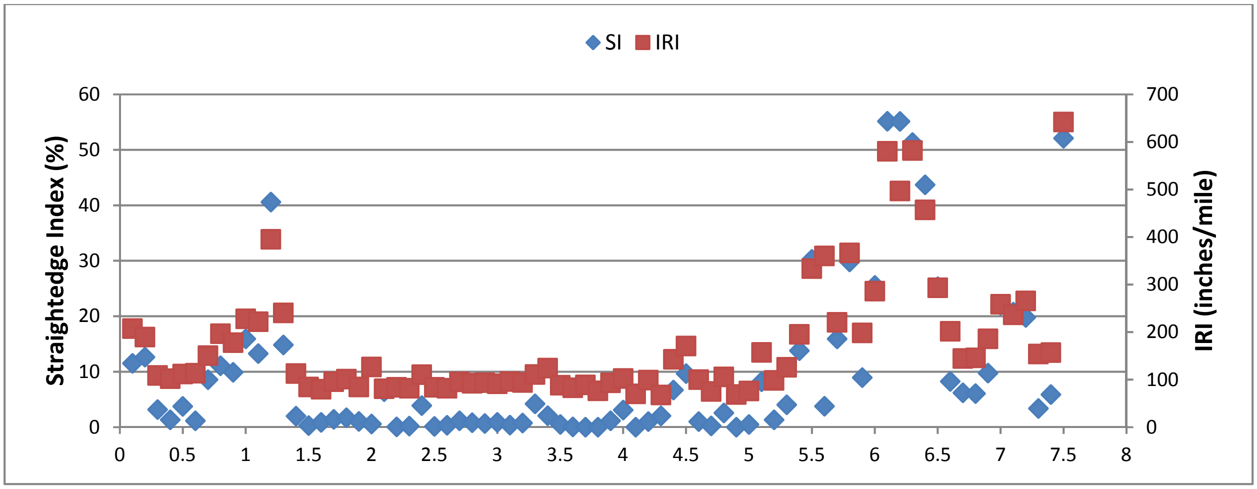


Figure 6.12 The plot of IRI values and SI values

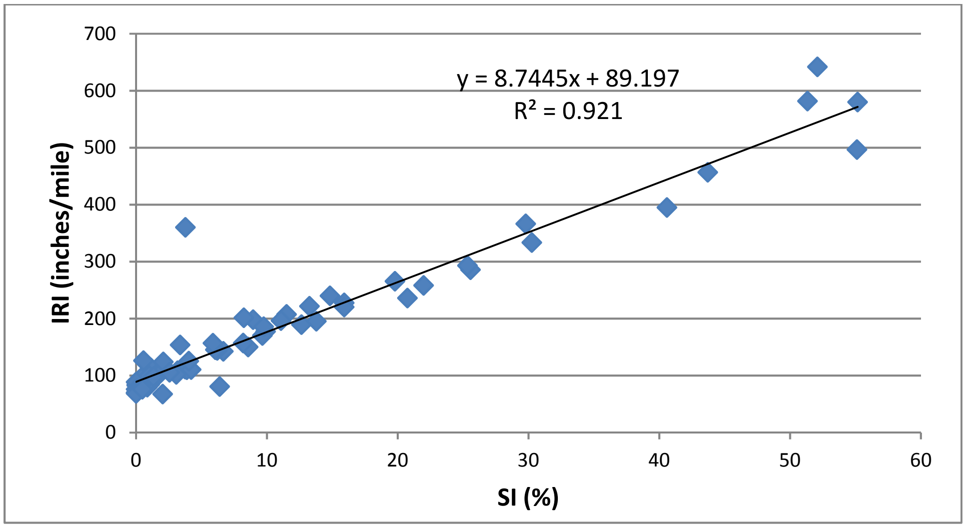


Figure 6.13 The plot of IRI values vs SI values

6.6 Base Length Analysis

In this part of the analysis, the effect of the base length on the IRI calculation was investigated. As mentioned earlier, the standard IRI algorithm divides the accumulated displacement of the quarter-car model over the 0.1-mi length of a profile. However, the literature review revealed that the IRI can be calculated over different profile lengths. Sayers (1995) pointed out that the IRI value is associated to the length over which it is summarized. For example, when IRI is calculated for 50 ft. sections, the maximum value of the IRI is higher than the maximum value of the IRI over a 0.1 mi section on a similar surface profile. This is just natural as the average converges to the mean as the number of sampled points increase. Localized roughness such as cracks and faults influence the IRI values of shorter segments and make them larger (Sayers, 1995). A comparative statistical analysis was performed to investigate the influence of the shorter profile length on the IRI values. A brief description of the base length analysis and results are provided below.

6.6.1 Methodology

The base length evaluation was carried out using ProVAL. The software requires the elevation profile as an input to calculate the IRI. A random 528 ft. section was chosen from the same experiment described earlier and the profile of this section was imported. As Sayers (1995) mentioned, the first 20 meters (66 ft.) of the profile are used to stabilize the quarter-car filter. Therefore, the IRI calculated on the portion of the selected section is not reliable. Sayers also stated that the impact of initialization reduces as the quarter-car algorithm processes more data on the profile. Accordingly, a 528-ft section before the selected section was incorporated into the analysis. Thus, two sections were combined and the profile was imported into the software. The software also needs the base length as an input. Five different base lengths were considered for this analysis: 528, 264, 132, 33, and 16 feet. Figure 6.14 illustrates the IRI values for these five base lengths. It should be pointed out, that the IRI values corresponding to the first section are discarded when the IRI calculation is completed.

6.6.2 Results

The IRI for the selected section is 189.9 inches/mile over the 0.1-mi length. When the IRI is calculated for 16 ft. base length (IRI_{16}), the variation between IRI values increases. Differences of 64.6 to 484.6 inches/mile between the lowest and the largest values of IRI_{16} can be observed in Figure 6.14. As mentioned earlier, localized roughness effect on the IRI_{16}values and magnify them. However, the effect of localized roughness is attenuated by averaging IRI over 0.1-mile length (i.e., convergence to the mean value).

Table 6.1 provides the IRI value for the entire test section (528 ft.), the average of IRI, and STD for four selected base lengths. As this table indicates, the average of IRI for any base length does not change noticeably, but the standard deviation increases as the base length decreases. The maximum standard deviation could be observed on the 16-ft. base length.

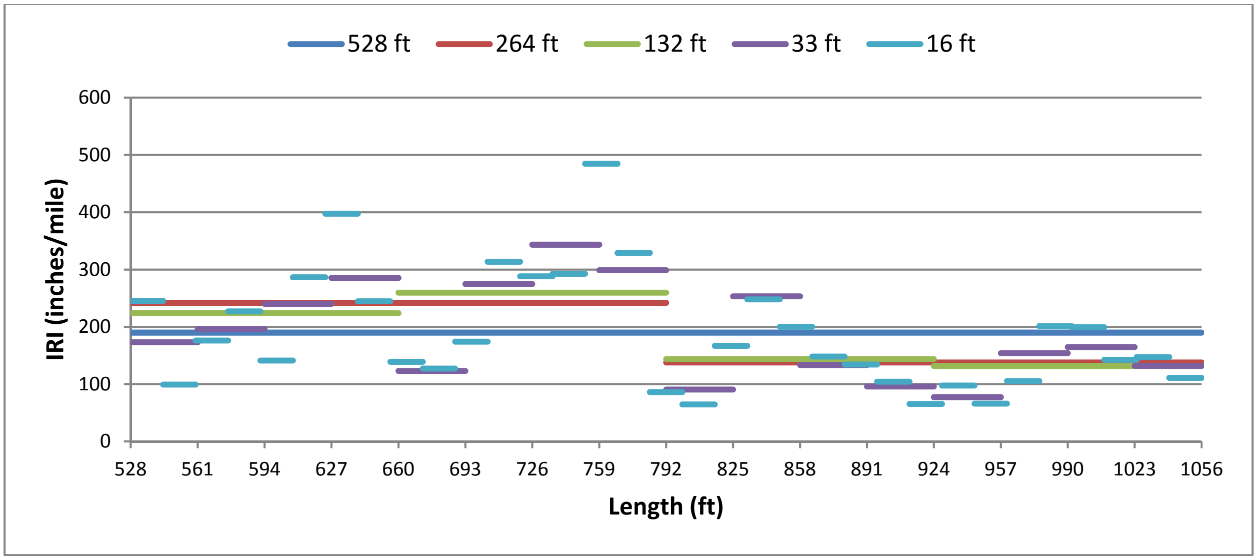


Figure 6.14 The IRI values of one section for different segment lengths

Table 6.1 Comparison between IRI value of whole section and mean of IRI values over shorter segment length

Length (ft.)	**IRI (in./mi)**	
528	189.91	
	Average of IRI (in./mi)	STD (in./mi)
264	189.89	73.60
132	189.73	61.98
33	189.73	82.83
16	189.51	99.79

The IRI values corresponding to different base lengths were calculated for the six measured profiles on the selected test section using the ProVAL. The COV was also calculated for the segments by dividing the standard deviation of six IRI values to their mean value. COV represents the degree of variation in a data group. Figure 6.15 presents five plots of six IRI values calculated over different base lengths. Coefficient of variation of six runs was also calculated and presented in these plots (except the last plot due to lack of enough space). Comparing the COV values indicates that the shorter base length increases the variation between six IRI values. This analysis indicates that the average IRI for shorter sections is unbiased; however, its standard deviation changes significantly. Thus, a pay adjustment specification based on mean values would not be affected but one based on a given confidence level would be.

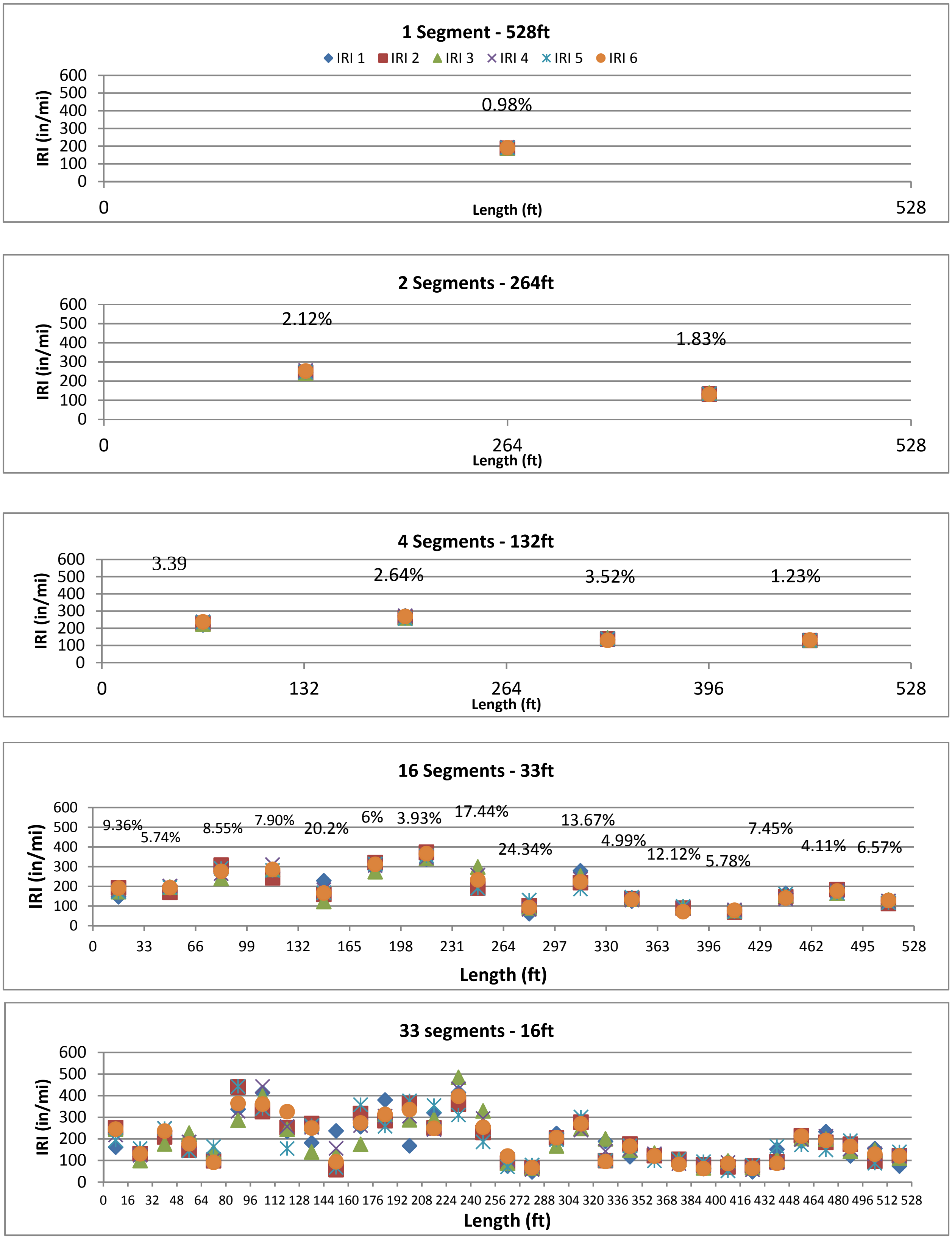


Figure 6.15 The six IRI values calculated on different length segments

Figure 6.15 demonstrates that the only potential problem of using shorter sections is that the variability increases and, therefore, the confidence in the calculated value decreases. The significance is a specification is based on a given confidence level. It is important to highlight that, as the section is shorter than 200 ft, wavelengths that affect the value of IRI (as originally defined) will be missing from the data and therefore, the calculated IRI will be biased. This bias, however, could be systematically corrected. So, in principle, there is no problem with using the inertial profiler for shorter sections. However, it is important to highlight that for sections shorter than 0.1 mile, the obtained values are more variable. It is also important to highlight that, independently of the section length, the profiler should be initialized before the section start to stabilize the data processing algorithms.

6.6.3 Variability Analysis

The data collected on the second segment described earlier were used to examine the variability of the inertial profiler measurements with regard to different base lengths. In this section, 25 0.1-mile sections were profiled six times using one inertial profiler. The IRI_{528} values were arranged from low to high and then 25th, 50th, and 75th percentile of segments were selected for this evaluation. The profiles of these segments were imported to the ProVAL software separately to calculate the IRI at different intervals. It should be pointed out that the same methodology as for base length analysis was used for this part of the evaluation. In other words, a 0.1-mile section before the selected section must be incorporated every time into the ProVAL process to get the IRI values. Once the IRI values were obtained at different base length, the within and between standard deviations and sum of squared deviations from the mean were calculated for these three sections. Figure 6.16 shows the variability analysis results. Clearly, as the section length increases the between standard deviation (sum of squares) decreases rapidly but the within standard deviation (sum of squares) decreases at a reduced rate.

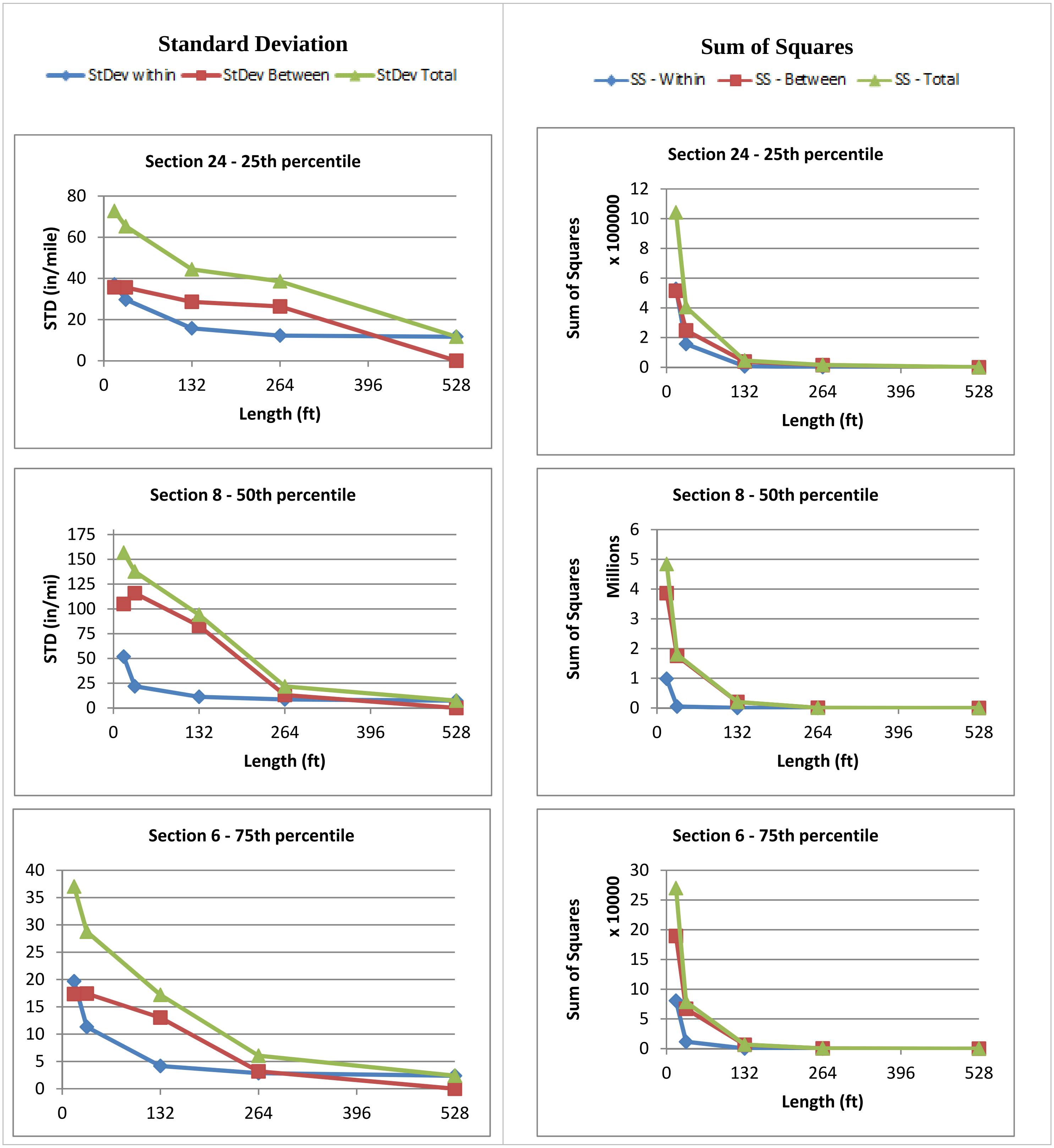


Figure 6.16 Plot of standard deviation and sum of squares on 25th, 50th and 75th percentile of sections

Chapter 7. Conclusions and Recommendations

This chapter provides conclusions and recommendations for revisions to the pay adjustment system and the use of inertial profiler on short projects.

7.1 Revising a Pay Adjustment System

The current TxDOT ride specification uses as-constructed IRI values in order to determine bonuses and penalties. The research team employed field performance and construction quality databases to understand the typical ride quality levels delivered by contractors in Texas. The ride quality data was extracted from a total of 565 hot mix overlay projects constructed during 2001–2011. The pre-/post-construction IRI values, project location features, and placement and production attributes were extracted from the performance histories of individual projects. The measurement error was removed using regression techniques while extracting the pre- and post-construction ride quality of the asphalt overlay projects. Regression analyses were conducted to develop relationships between the pavement field performance (i.e., deterioration rate in terms of ride quality) of a project and the project-specific construction attributes such as initial ride quality, IRI drop, volumetric properties (QC/QA), and traffic. The results indicated that both the initial IRI and the drop in IRI impact directly the future performance of the pavement.

The distribution of the pre- and post-construction IRI and drop in IRI were analyzed. Data suggested that contractors delivering better ride quality are not necessary significantly improving the IRI from the pre-existing surface. This research study found the necessity of developing a rational pay adjustment system that incentivizes or penalizes the construction processes based on their benefit (or detriment) to the state as a whole, that is, to the state agency and to the road users. Smoother roads last longer and result in lower user costs.

The quantiles of the distributions were computed to identify reasonable ride quality thresholds to incorporate into the proposed preliminary ride specification. The proposed ride specification computes the pay adjustment corresponding to a combination of as-constructed IRI and a drop in IRI (relative to the pre-existing IRI) in a modular fashion. The pay adjustment is calculated corresponding to as-constructed IRI as well as drop in IRI, and subsequently averaged to obtain the overall pay adjustment for the combination. Pay adjustment equations were specified for each combination of as-constructed IRI and drop in IRI. The proposed specification was designed with unit maximum bonus/penalties, and may be scaled to any dollar amount by the highway agency.

Data suggested that contractors delivering better ride quality are not necessary significantly improving the IRI from the pre-existing surface. The ride specification was found to be realistic based on the sample of projects that were evaluated. There was a significant number of contractors within each category of the proposed specification. A number of projects are delivered rougher than possibly achieved with marginal ride quality improvements. Implementation of the proposed specification acknowledges the contractors' "true efforts," and thereby financially motivates the contractors to deliver smoother pavements while significantly improving the ride quality of the existing pavements.

7.2 Using an Inertial Profiler on Short Projects

TxDOT smoothness standard specifies two types of ride quality measuring equipment: Surface Test Type A, which involves 10-ft. straightedge, and Surface Test Type B, which involves high-speed or lightweight inertial profiler. Surface Test Type A can be used for ride quality measurements on short length projects less than 2,500 ft., whereas inertial profilers or Surface Test Type B shall be employed to measure ride quality on travel lanes with length greater than 2,500 ft. The literature review indicated a number of practical disadvantages of using the 10ft. straightedge. The primary concern about this approach is that it cannot address wavelengths longer than its base length. Furthermore, several operators are necessary to straight-edge a project. Not only is this procedure time-consuming, but also the collected results might be inaccurate and variable. Roughness establish with one or other test type are not comparable and are not compatible, therefore, a pay adjustment system based on inertial profiler cannot be applied to roughness measure with a straightedge.

A survey questionnaire, a technical meeting, and a field experiment were conducted in this research study to identify obstacles that make inertial profilers operation impractical on short projects. The survey questionnaire including five direct questions was sent to TxDOT personnel in different districts. The field experiment was performed on a selected loop near Austin using an inertial profiler certified at the Texas A&M Transportation Institute and operated by a certified technician from Pavetex Engineering. The inertial profiler was operated following the TxDOT ride specification. The answers to the survey questionnaire point out the advantages of using inertial profilers on short projects. Summary of discussions at the meeting and also the results of correlation analysis between IRI and simulated rolling straightedge values indicate the possibility of using high-speed profiling vans to measure riding quality on short projects. It is important to note that when profiling both long and short projects, a pre-section with length at least 200 ft regardless of the pavement type is recommended (a minimum of 66 ft. is absolutely necessary) to initialize and stabilize the quarter-car filter. In addition, the profiler must be driven at a constant speed during measurements. Small changes in speed, however, will not significantly affect the IRI measurements.

Considering the aforementioned points, it is recommended that the inertial profiler calibrated and operated according to the existing Tex-1001-S specification could be used on short projects spanning between 528 ft. and 2500 ft. without further theoretical considerations. The use of the 10-ft. straightedge should be only considered if practical or economic considerations renders the use of the inertial profiler unacceptable.

In the case of projects with length between 200 and 528 ft. the inertial profiler can also be used but the IRI should be average over a base length less than 0.1 mi. This study discussed in detail the effect of the shorter base length on the IRI calculation. The results showed that the maximum value of the IRI increases when the IRI is summarized over a shorter base length. In fact, the IRI value accumulated over a very short base length represents the effect of localized roughness. Localized roughness such as cracks increases the IRI values. The effect of localized roughness is reduced when the IRI is averaged over a longer distance. Additionally, it should be stated that the shorter base length increases the variation among IRI values. It should be emphasized that it is not the actual value (mean) that is affected but it is the variability and the reliability of the IRI that changes. Therefore, the IRI obtained for these projects will not be biased but will be more variable and therefore the same bonus/penalty specification could not be applied.

Finally, IRI results obtained with the inertial profiler on segments shorter than 200 ft. were found to be biased. Several studies have shown that the quarter-car model captures wavelengths in the range of 4 to 98 feet, by definition. So, a minimum length of 200 ft. is necessary to obtain unbiased estimates of IRI. Otherwise, the larger wavelengths cannot be detected. Accordingly, IRI values obtained with the inertial profiler on the sections shorter than 200 ft. are biased. In this case, agencies should look for alternative ways to measure ride quality or develop systematic correction methods.

References

Alan Reggin, Ahmed Shalaby, Roger Emanuels, and G. Michel. *"Urban Considerations for Using Road Roughness to Manage Road Networks."* City of Winnipeg, Canada, 2008.

ASTM, American Society of Testing and Materials International, E867-06, Standard Terminology Relating to Vehicle-Pavement Systems. West Conshohocken, PA, 2012.

Buddhavarapu, P., Smit, A., Prozzi, J., Fan, W., and Gurmu, Z. *"Revised Pay Adjustment Factors for HMA and Concrete Pavements."* FHWA/TX-14/0-6675-1, Texas Department of Transportation, 2014.

Colorado Department of Transportation, Division 100 General Provisions, https://www.codot.gov/business/designsupport/2011-construction-specifications/2011-Specs/2011-specs-book/Section-100.pdf. Accessed May 20, 2016.

Gagarin, N., and Mekemson, J. R., *"Assessing IRI vs. PI as a Measurement of Pavement Smoothness."* Missouri Transportation Institute, Report No. OR06-17, June 2006.

Gillespie, T.D., Karamihas, S.M., Kohn, S.D., and Perera, R.W., "*Operational Guidelines for Longitudinal Pavement Profile Measurement*." National Cooperative Highway Research Program. Report No.434, February 1999.

Gillespie, T.D., Sayers, M.W., and Segel, L., "*Calibration of Response-Type Road Roughness Measuring Systems*." NCHRP Report. No. 228, December 1980.

Hearne, T., Barbee, C., and Helms, L., "Asphalt *Rideability: Construction Control with a Straightedge?"* Transportation Research Board, 1996.

Karamihas, S.M., Gillespie, T.D., Kohn, S.D., Perera, R.W. *"Guidelines for Longitudinal Pavement Profile Measurement."* NCHRP Project 10-47, University of Michigan Transportation Research Institute, Ann Arbor, February 1999.

Ksaibati, K., and Al Mahmood, S., "Utilizing the Long-Term Performance Database in Evaluating the effectiveness of Pavement Smoothness." The University of Wyoming, March 2002.

McGhee, K. *"Factors Affecting Overlay Ride Quality."* In Transportation Research Record: Journal of the Transportation Research Board, No. 1712, Washington, D.C., 2000, pp. 58-65.

McGhee, K., and Gillespie, J. *"Impact of a Smoothness Incentive/Disincentive on Hot-Mix Asphalt Maintenance Resurfacing Costs."* FHWA/VTRC 06-R28. Virginia Department of Transportation, 2006.

Merritt, D.K., Chang, G.K., and Rutledge, J.L. *"Best Practices for Achieving and Measuring Pavement Smoothness: A Synthesis of state-of Practice."* FHWA/LA.14/550. The Transtec Group, Inc. 2014.

Michigan Department of Transportation, Special Provision for Pavement Ride Quality. 2012. http://mdotcf.state.mi.us/public/dessssp/spss_source/12SP501(K)v2.pdf. Accessed July 1, 2015.

Minnesota Department of Transportation, Standard Specification for Construction. Department of ST. Paul, Minnesota, 2016. http://www.dot.state.mn.us/pre-letting/spec/2016/2016-spec-book.pdf. Accessed July 1, 2016.

Missouri Department of Transportation, Missouri Standard Specification for Highway Construction. 1999, http://www.modot.org/business/standards_and_specs/documents/Master.pdf Accessed May 20, 2016.

Mucka, P., "*Relationship between International Roughness Index and Straightedge Index"*. Journal of Transportation Engineering, ASCE, September 2012.

Perera, R.W., and Kohn, S.D. *"Ride Quality Performance of Asphalt Concrete Pavements Subjected to Different Rehabilitation Strategies."* American Society of Civil Engineering, Airfield and Highway Pavements, 2006.

Rawool, S., and Fernando, E. G., "*Methodology for Detection of Defect Locations in Pavement Profile."* Transportation Research Record: Journal of the Transportation Research Board 1905, No. 1 (2005): 140–47.

Sayers, M., and Karamihas, S. *"The Little Book of Profiling."* University of Michigan, September 1998.

Sayers, M.W. "*On the calculation of International Roughness Index from longitudinal Road Profile."* Transportation Research record 1501, 1995, pp: 1-12.

Sayers, M.W., Gillespie, T. D., and Paterson, W.D. "*Guidelines for the Conduct and Calibration of Road Roughness Measurements*." World Bank Technical Paper No. 46. The World Bank, Washington DC, 1986.

Smith, K.L, Smith, K.D., Evans, L.D., Hoerner, T.E., Darter, M.I. and Woodstrom, J.H., *"Smoothness Specifications for Pavements*." National Cooperative Highway Research Program, Transportation Research Board, Washington, DC, (1997), 221p.

Smith, K.L, Smith, K.D., Hoerner, T. E., and Darter, M. I. *"Effect of Initial Pavement Smoothness on Future smoothness and Pavement Life."* Transportation Research Record: Journal of the Transportation Research Board, Paper No. 971146, 1997.

Stampley, B.E., Miller, B., Smith, R.E., and Scullion, T. (1995). “Pavement Management Information System Concepts, Equations, and Analysis of Pavements,” Research Report 1989-1, Texas Transportation Institute, The Texas A&M University System.

Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges. Texas Department of Transportation. 2014. ftp://ftp.dot.state.tx.us/pub/txdot-info/des/spec-book-1114.pdf. Accessed June 28, 2015.

Texas Department of Transportation (TxDOT 2003). Pavement Management Information System Data Dictionary Report. August, 3, 2003.

Texas Department of Transportation (TxDOT 2009). Pavement Management Information System Rater’s Manual Fiscal Year 2010. Materials and Pavements Section, Construction Division, Texas Department of Transportation.

Vitillo, N. *“Ride Smoothness, Measurement and Specification Issues.”* New Jersey Department of Transportation. http://www.superpave.psu.edu/NEAUPG/docs/Meetings/2004/11Vitillo%20-RQ%20Measurement%20and%20Specification%20Issues.pdf. Accessed July 21, 2016.

Wang, H., Chen, Z., and Sun, L. “*Pavement Roughness Evaluation for Urban Road Management*.” American Society of Civil Engineering, ICTE 2013, pp.2709-2713

Woodstorm, J. *“Measurements, Specification, and Achievement of Smoothness for pavement Construction.”* Transportation Research board, 1990.