ILLINOIS CENTER FOR TRANSPORTATION

CIVIL ENGINEERING STUDIES
Illinois Center for Transportation Series No. 20-015
UILU-ENG-2020-2015
ISSN: 0197-9191

Development of IDOT's Proposed Smoothness Specification Based on the International Roughness Index

Prepared By
Hyung S. Lee, PhD, PE
William Vavrik, PhD, PE
Hesham Abdualla, PhD
Applied Research Associates, Inc.

Research Report No. FHWA-ICT-20-009

A report of the findings of

ICT PROJECT R27-199
Optimizing the Benefits of Smoother Roads against the Increased Costs to Build Them

https://doi.org/10.36501/0197-9191/20-015

Illinois Center for Transportation

September 2020

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-ICT-20-009	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A
4. Title and Subtitle Development of IDOT's Proposed Smoothness Specification Based on the International Roughness Index		**5. Report Date** September 2020 **6. Performing Organization Code** N/A
7. Authors Hyung S. Lee (https://orcid.org/0000-0003-1616-7449), William Vavrik (https://orcid.org/0000-0002-2377-2252), and Hesham Abdualla		**8. Performing Organization Report No.** ICT-20-015 UILU-ENG-2020-2015
9. Performing Organization Name and Address Illinois Center for Transportation Department of Civil and Environmental Engineering University of Illinois at Urbana-Champaign 205 North Mathews Avenue, MC-250 Urbana, IL 61801		**10. Work Unit No.** N/A **11. Contract or Grant No.** R27-199
12. Sponsoring Agency Name and Address Illinois Department of Transportation (SPR) Bureau of Research 126 East Ash Street Springfield, IL 62704		**13. Type of Report and Period Covered** Final Report 8/16/18–10/15/20 **14. Sponsoring Agency Code**
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. https://doi.org/10.36501/0197-9191/20-015		
16. Abstract The existing smoothness specification implemented by the Illinois Department of Transportation (IDOT) was based on profile-index measurement, which was also widely used by other agencies. There is a national and international trend, however, toward using the international roughness index (IRI) as a standard smoothness index for pavement management as well as construction acceptance. Therefore, the primary objective of this study was to develop an IRI-based smoothness specification for IDOT. It was desired that IRI thresholds be developed objectively by quantifying the benefit of pavement smoothness. The benefits quantified within the framework of life cycle cost analysis and benefit-cost analysis generally revealed that smoother pavements are anticipated to exhibit increased service life, reduced life cycle cost (including agency and user costs), and improved safety. IRI is also a crucial component of user comfort, especially for high-speed facilities. IDOT's new IRI-based specification was developed while considering these benefits along with the increased cost quantified as the incentive payments to be made for smoother pavements. In addition, several aspects of IRI thresholds and the smoothness assessment schedule were investigated for achievability and risk. Although the risk of moving from a profile-index-based specification to an IRI-based specification was found to be relatively low (i.e., 4.4% and 6.6% risk assessed for high-speed and low-speed facilities, respectively), it indicated that IDOT and IDOT's contractors may need to work together to adapt to the new specification and continue to refine the IRI-based specification as more experience is gained.		

17. Key Words Smoothness, International Roughness Index, Incentive, Specification	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 62 + appendices	**22. Price** N/A

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

ACKNOWLEDGMENT, DISCLAIMER, MANUFACTURERS' NAMES

This publication is based on the results of **ICT-R27-199: Optimizing the Benefits of Smoother Roads against the Increased Costs to Build Them**. ICT-R27-199 was conducted in cooperation with the Illinois Center for Transportation; the Illinois Department of Transportation; and the U.S. Department of Transportation, Federal Highway Administration.

Members of the Technical Review Panel (TRP) were the following:

- John Senger, IDOT Engineer of Pavement Technology, TRP Chair
- Douglas Dirks, IDOT Project Review Engineer, TRP Co-chair
- LaDonna Rowden, IDOT Bureau Chief of Research
- Michael Ayers, Illinois Chapter—American Concrete Pavement Association
- Kevin Burke, Illinois Asphalt Pavement Association
- Justin Mann, IDOT Engineer of Construction Operations
- Megan Swanson, IDOT Technical Research Coordinator
- Charles Wienrank, IDOT Pavement Design Engineer
- Cindy Williams, Illinois Tollway Deputy Chief of Program Implementation
- Dennis Bachman, Illinois Division of Federal Highway Administration

The contents of this report reflect the view 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 views or policies of the Illinois Center for Transportation, the Illinois Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Trademark or manufacturers' names appear in this report only because they are considered essential to the object of this document and do not constitute an endorsement of product by the Federal Highway Administration, the Illinois Department of Transportation, or the Illinois Center for Transportation.

EXECUTIVE SUMMARY

Smoothness is one of the most important factors affecting both the structural and functional performance of pavement structures. As such, many agencies have adopted smoothness specifications for newly constructed pavements and are monitoring the smoothness of their pavements at a network level.

The existing smoothness specification for the Illinois Department of Transportation (IDOT) was based on profile-index (PI) measurement, which was widely used by other agencies. However, there is a national and international trend toward using the international roughness index (IRI) as a standard smoothness index for pavement management as well as construction acceptance. Therefore, this study was initiated to develop an IRI-based smoothness specification for IDOT. It was desired that the IRI thresholds be developed objectively by quantifying the benefit of pavement smoothness in terms of user comfort (i.e., public perception), pavement life, and life cycle cost.

To quantify the level of comfort that users may experience from smooth pavements, acceleration data was collected at various speeds from different types of pavements exhibiting a wide range of IRI values. Analysis of the acceleration data revealed that, in general, the higher the speed of travel, the higher the chance of discomfort regardless of pavement smoothness. The effect of IRI on user comfort is also more pronounced for high-speed facilities (i.e., speed limit greater than 40 mph) than low-speed facilities. Based on this research, IRI values below 66 in/mi and 186 in/mi are generally desirable for user comfort on high-speed and low-speed facilities, respectively.

In addition, life cycle cost analysis (LCCA) was carried out to assess the benefits of smoother pavements in terms of agency and user costs as well as pavement life. LCCA also provided a means for quantifying the benefits needed for the subsequent benefit-cost analysis (BCA). LCCA was generally conducted according to IDOT's standard procedures along with the empirical IRI performance model developed from IDOT's historical IRI data for determining the pavement age at which major and minor rehabilitation activities are conducted. The results from LCCA indicated that pavements initially constructed to be smooth (i.e., lower initial IRI) remain smoother in the long run and last longer and pavements with lower initial IRI also exhibit reduced life cycle cost, both in terms of agency and user costs.

Based on the results and findings of the accelerometer analysis and LCCA as well as engineering judgement, the following IRI thresholds were recommended for new construction projects.

- For high-speed facilities (i.e., speed limit greater than 40 mph), IRI values of 45 in/mi, 75 in/mi, and 100 in/mi were recommended for lower full pay, upper full pay, and upper disincentive IRI thresholds, respectively.

- For low-speed facilities (i.e., speed limit less than or equal to 40 mph), IRI values of 55 in/mi, 95 in/mi, and 125 in/mi were recommended for lower full pay, upper full pay, and upper disincentive IRI thresholds, respectively.

To determine if the above thresholds are realistic, the distribution of IRI values from recent construction projects and the relationship between IRI values before and after construction were used to calculate the probabilities of an arbitrary 0.1 mi sublot falling under incentive, full pay, disincentive, and corrective action zones. The results generally indicated that the chances are higher for full pay or incentive than those for disincentive or corrective action, leading to a conclusion that the developed IRI thresholds are realistic and achievable.

Despite the achievable thresholds, moving to an IRI-based specification represents a major departure from the existing PI-based specification because IRI and PI are two different smoothness indices. As such, it is anticipated that both IDOT and contractors will need to bear some risk and adapt to the IRI-based specification when it is implemented. After defining "risk" as the probability of the PI-based and IRI-based specifications producing different outcomes (e.g., a 0.1 mi segment being accepted based on PI specification but rejected based on IRI specification, and vice versa), the risk was estimated to be 4.4% and 6.6% for high-speed and low-speed facilities, respectively. While the probabilities suggest that slightly more discrepancies are to be expected for low-speed facilities, the assessed risks are reasonable (less than 10%).

Another important component of the smoothness specification is the pay schedule, also known as the "Smoothness Assessment Schedule," which defines the amount of incentive and disincentive payments to be used with the IRI thresholds. The smoothness assessment schedule was developed primarily based on engineering judgement, considering the current economy and recent cost for pavement construction.

IRI thresholds and the smoothness assessment schedule were then used with the LCCA results for carrying out the BCA. By defining "reference pavement life" and "reference life cycle cost" as those corresponding to the upper full-pay IRI threshold, the benefit was quantified as the additional pavement life or reduced life cycle cost resulting from IRI values below the threshold. Similarly, the loss was quantified as the reduced pavement life or increased life cycle cost resulting from IRI values above the full-pay threshold. In addition, cost was defined within the BCA framework as the incentive payments to be made in accordance with the smoothness assessment schedule.

In terms of pavement life, the BCA results indicated that IDOT may anticipate at least nine years of additional pavement life for any sublot where an incentive payment has been made. Similarly, for any sublot where a disincentive payment has been made, IDOT may expect up to five years of reduced pavement life.

The BCA further revealed that for an arbitrary, high-speed, 0.1 mi sublot, the expected benefit and cost were $4.7K and $144, respectively, yielding a benefit-to-cost (B/C) ratio of 32.5. Similarly, the expected benefit and cost of an arbitrary, low-speed, 0.1 mi sublot were $7.9K and $495, respectively, yielding a B/C ratio of 15.9. Both the expected benefit and cost are higher for a low-speed roadway compared to a high-speed roadway of equal length. In contrast, the B/C ratio calculated for the high-speed facility is significantly (almost doubled) higher than that for the low-speed facility. This means that for every dollar spent by IDOT on incentive payments, a higher rate of return may be expected from high-speed facilities (approximately twice the rate of return when compared to low-speed facilities).

Despite the efforts put into developing a realistic, achievable, and implementable IRI-based specification, moving from a PI- to IRI-based specification is not expected to be seamless. Although several aspects of IRI thresholds and the smoothness assessment schedule were investigated for reasonableness, the risk associated with implementing a new specification cannot be eliminated. As such, both IDOT and IDOT's contractors will need to adapt to and become familiar with the new specification and continue to refine the IRI-based specification as more experience is gained.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

BACKGROUND

Smooth pavements are recognized as good roadways by the driving public and provide additional benefits such as increased fuel efficiency and improved safety (Robbins and Tran, 2015, 2016). From a highway owner's perspective, a pavement initially constructed to be smooth not only remains smooth in the long term but also increases service life as well as reduces maintenance and life cycle cost (Smith et al., 1997; Massucco and Cagle, 1999; Chatti and Zaabar, 2012). Therefore, pavement smoothness is widely accepted as one of the most important factors affecting the structural and functional performance of pavement structures. As such, many agencies have adopted smoothness specifications for newly constructed pavements and are monitoring the smoothness of their pavements at a network level (Flintsch and McGhee, 2009).

Agencies and industry have quantified smoothness using indices such as present serviceability rating, ride number, profile index, international roughness index, etc. Among these, IRI is currently the most frequently used index worldwide. Federal programs use IRI as a key performance metric for evaluating progress toward the National Highway Performance Program goals set forth in Moving Ahead for Progress in the 21st Century (MAP-21) and Fixing America's Surface Transportation (FAST) Act that were signed into law in 2012 and 2015, respectively.

Due to the national and international trend toward using IRI as a standard index for pavement smoothness, many states in the United States have implemented IRI for pavement management and evaluation purposes as well as construction acceptance. However, because of a limited history of IRI-based specifications, many agencies experienced confusion over thresholds for incentives and disincentives as well as those for localized roughness or "must-correct" areas (Merritt et al., 2015). Furthermore, limited history and experience have also caused contractors that were used to PI-based specifications to struggle to achieve the same level of quality under IRI ones.

Therefore, there is a need to evaluate and quantify the benefits of smoother pavements. The benefits should provide a basis for establishing objective IRI thresholds that avoid confusion over the required or desired level of IRI. In addition, the quantified benefits should be compared to the increased cost for constructing smoother pavements in order to maximize benefits and optimize available resources.

RESEARCH OBJECTIVES

The objectives of this study are:

1. To identify empirical methods to correlate pavement smoothness and pavement life.
2. To identify the range of smoothness acceptable to users.
3. To determine the benefit-cost ratio, considering pavement life and construction costs.
4. To develop a preliminary, IRI-based smoothness specification.

REPORT ORGANIZATION

This report is composed of four chapters and appendices. Chapter 1 provides brief background information and discusses the need for this research.

Chapter 2 documents the analysis conducted for quantifying the benefits of smoother pavements. The benefits are quantified in terms of pavement life; life cycle cost, including agency and user costs; and public perception (i.e., user comfort). The agency portion of the life cycle cost provided a foundation for the benefit-cost analysis conducted in the next chapter.

Chapter 3 builds on the analysis conducted in Chapter 2 and discusses how the IRI-based specification was developed for the Illinois Department of Transportation (IDOT). The relationship between IRI and user comfort level was used to define the speed categories (i.e., high-speed vs. low-speed facilities) and provided a basis for IRI threshold development. The IRI thresholds were then analyzed for practical achievability based on recent IRI distributions and further analyzed for risk. Discussion is also provided on the established payment schedule (i.e., smoothness assessment schedule), which is subsequently used for the benefit-cost analysis.

Chapter 4 provides conclusions of this study along with practical recommendations for implementing the new IRI-based specification.

CHAPTER 2: QUANTIFYING THE BENEFITS OF SMOOTH PAVEMENTS

This chapter documents the efforts made to quantify the benefits of smoother pavements. The studied benefits include those in terms of sustainability, financial, safety, and public perception. The term "pavement sustainability" is a relatively broad term that encompasses not only engineering factors but also environmental, social, and economic factors. According to Muench and Van Dam (2014), there are four general measures that can be used to quantify pavement sustainability. These measures are pavement performance (or pavement life), life cycle cost, life cycle assessment, and rating systems. Among these, only the first two were studied for this project, as these measures were directly related to the benefit/cost of the agency.

PAVEMENT LIFE

As discussed in Chapter 1, pavements initially built smooth remain smooth and last longer. Therefore, an initial effort was made to quantify the benefit of smooth pavements in terms of extended pavement life. The initial effort involved developing the relationship between pavement age and IRI and estimating the pavement life as the age at which the IRI reaches a certain threshold.

In order to quantify the benefits of smoother pavements in terms of the service life of Illinois' pavements, a relationship between IRI and pavement age was deemed necessary. The purpose of this relationship is to assess the impact of initial IRI (i.e., the IRI value immediately after construction or at pavement age zero) on long-term IRI and, consequently, pavement life. However, this relationship was not readily available based on IDOT data. As such, the IRI data included in the Illinois Roadway Information System (IRIS) database were extracted and studied.

Gathering and Preparing Data

The IRIS database provided by IDOT contained historical pavement data that included IRI as well as other performance measures such as condition rating survey (CRS) score (which ranges from 1.0 to 9.0, with 9.0 representing the best surface condition [i.e., free of cracks]), rut depth, and faulting. Because of the large amount of data included in the database (25.6 Gb), IRIS data for 44 years (from 1973 to 2017) were provided on a year-by-year basis.

To develop the relationship between IRI and pavement age, the year-by-year IRIS data were integrated into a single database and pavement segments less than 0.1 mi in length were eliminated to keep the size of the integrated database relatively small and, more importantly, to avoid any significant noise caused by these short segments. The integrated IRIS database was then used to develop the initial time-series performance data for different pavement types. The pavement types were identified using the "Surface Type" code within the IRIS database. The following shows the different pavement types and corresponding IRIS surface type codes:

- Full-depth hot-mix asphalt (HMA): Surface type 560.
- Jointed plain concrete pavement (JPCP): Surface types 700, 710, 720, 725, and 730.

- Continuously reinforced concrete pavement (CRCP): Surface type 740.
- HMA-resurfaced jointed concrete pavement (HMA/JCP): Surface types 600, 610, 615, 620, 625, and 630.
- HMA-resurfaced CRCP (HMA/CRCP): Surface type 640.
- Portland cement concrete overlay (PCC overlay): Surface types 765, 780, 790, and 792.

As examples of the initial time-series data assembled from IRIS, Figure 1 and Figure 2 show the raw IRI and CRS scores of full-depth HMA pavements plotted against pavement age, respectively. Pavement age was obtained as the difference between the year the pavement survey was conducted and the year the pavement was constructed (both years were available in the IRIS database). Similarly, Figure 3 and Figure 4 show the IRI and CRS time-series plots for JPCPs, respectively.

These figures show that there is an overall trend. In other words, IRI is generally increasing with pavement age while the CRS score is generally decreasing over time. Nonetheless, these plots show that there is a lot of noise within the initial time-series data. For example, in Figure 1 and Figure 3, there are many segments showing a significant reduction in IRI in the middle of their service life. Similarly, Figure 2 and Figure 4 show many sections where the CRS score was increased to 8.0 or above at a pavement age greater than five years.

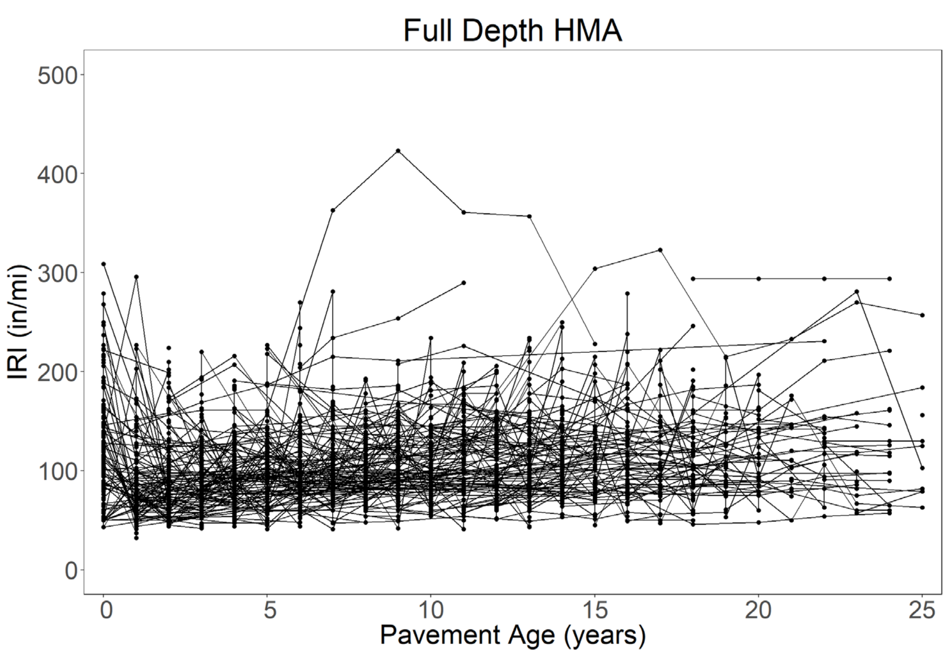


Figure 1. Graph. Initial IRIS time-series plot between IRI and pavement age for full-depth HMA.

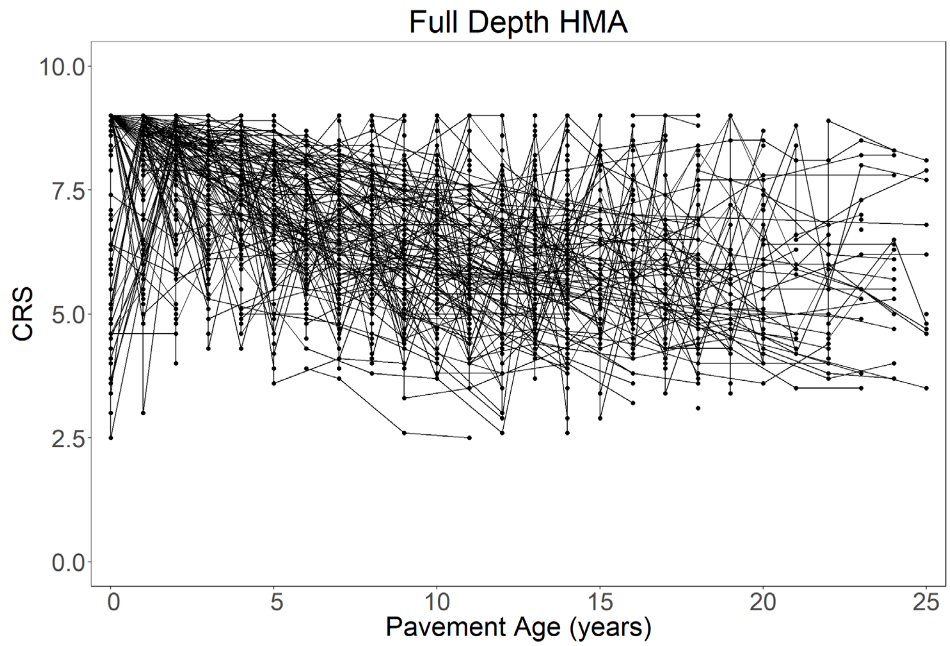


Figure 2. Graph. Initial IRIS time-series plot between CRS and pavement age for full-depth HMA.

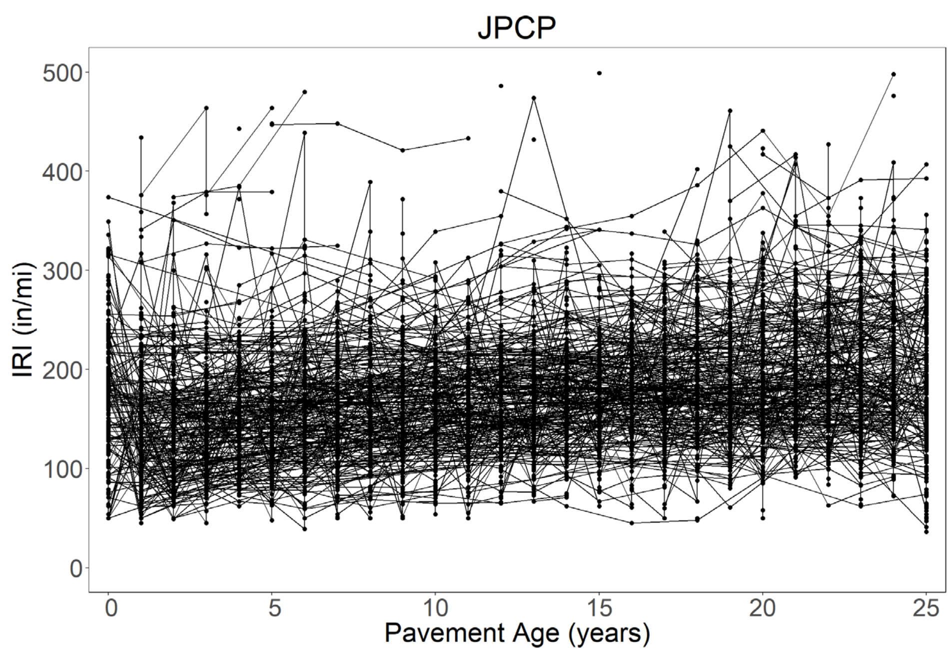


Figure 3. Graph. Initial IRIS time-series plot between IRI and pavement age for JPCP.

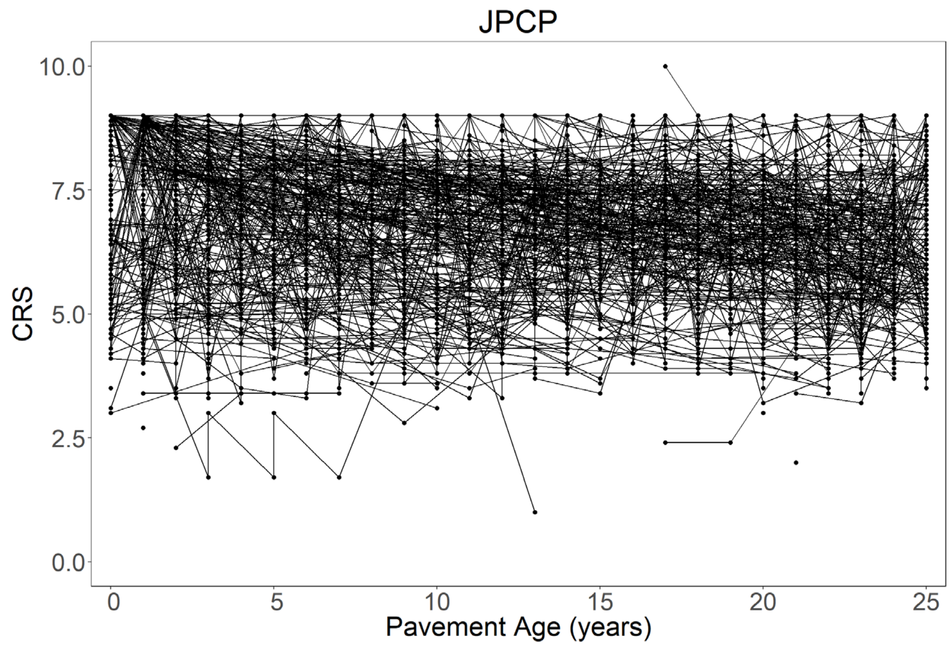


Figure 4. Graph. Initial IRIS time-series plot between CRS and pavement age for JPCP.

Because of the significant amount of noise observed in the initial IRIS time-series data, the data must be cleaned prior to developing the empirical performance models. After a consultation with IDOT, the primary causes of the noise in IRIS data were found to be the following.

1. The pavements may have been under construction when the condition survey was being performed, in which case an IRI value of 50 in/mi and a CRS score of 9.0 were manually entered into the IRIS database.

2. The pavements may have received preservation and/or maintenance treatments that increased the CRS score by 0.5 to 1.0. These treatments, however, were not considered as major construction activities and the construction date (or treatment date) has not been updated in the IRIS database.

The following effort was made to the initial IRIS time series to eliminate the noise caused by the above.

1. All rows of data with an IRI value of 50 in/mi and a CRS score of 9.0 were identified. For these data rows, the survey year was compared to the construction year, and if the survey year was one or two years prior to the construction year, the data row was eliminated from the database.

2. While preservation treatments may fix or seal the cracks at the pavement surface, these treatments may or may not improve the IRI to a significant extent. As such, pavement sections with a sudden increase in CRS (more than 0.5) were identified and checked for IRI trend.

a. If the IRI trend showed a significant reduction (i.e., by more than 15 in/mi) in the same year, then it was considered a major construction effort and the construction year was updated.

b. If the IRI did not show a significant reduction despite the CRS increase, it was considered a preservation treatment, and the IRI trend or the construction date was not updated.

Figure 5 through Figure 8 show the cleaned time-series plots for those corresponding to Figure 1 through Figure 4. These cleaned performance trends were subsequently used for establishing the empirical performance models.

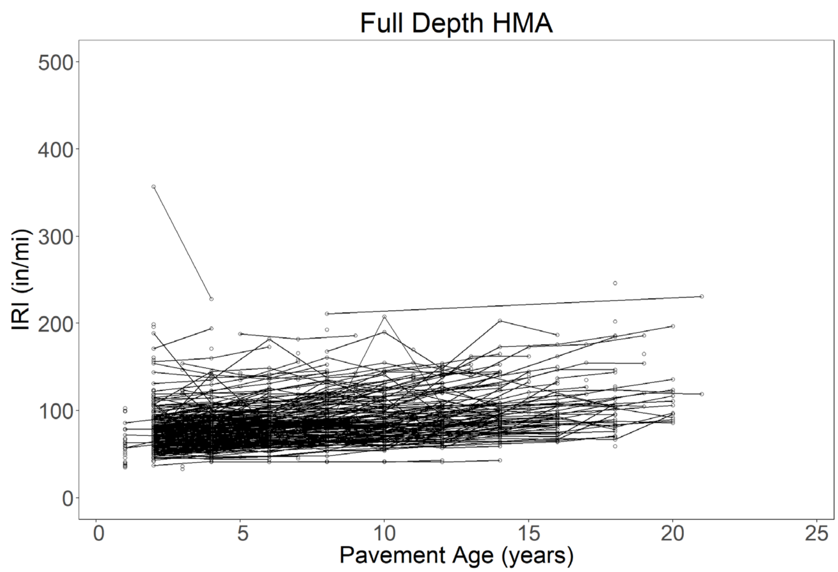


Figure 5. Graph. Cleaned IRIS time-series plot between IRI and pavement age for full-depth HMA.

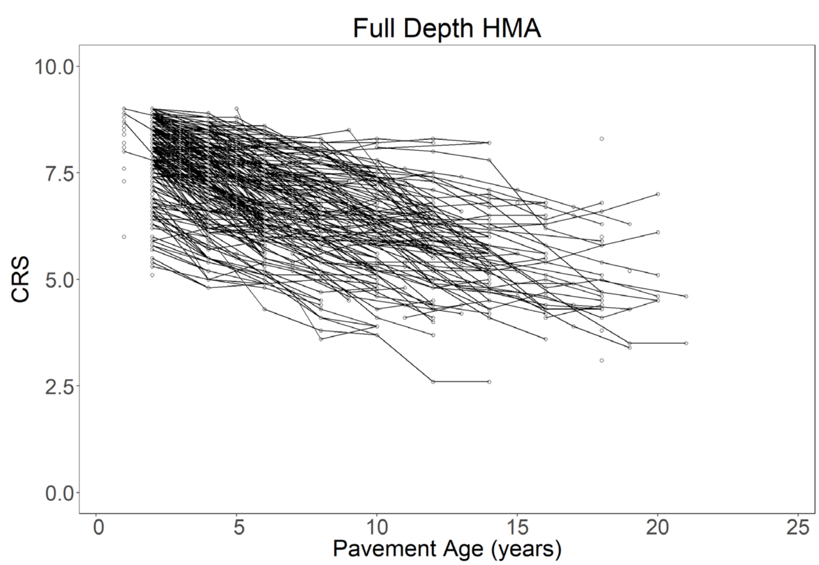


Figure 6. Graph. Cleaned IRIS time-series plot between CRS and pavement age for full-depth HMA.

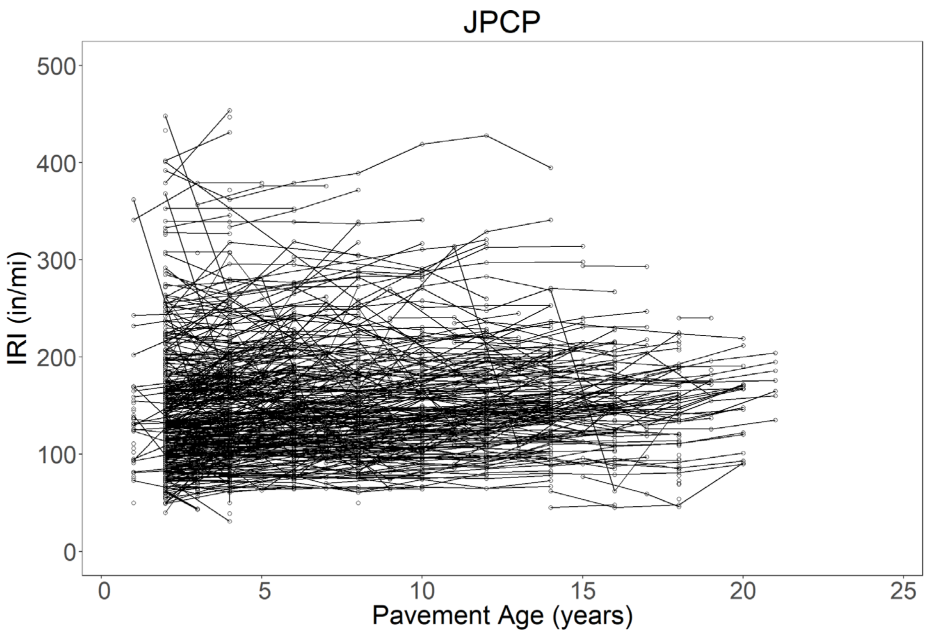


Figure 7. Graph. Cleaned IRIS time-series plot between IRI and pavement age for JPCP.

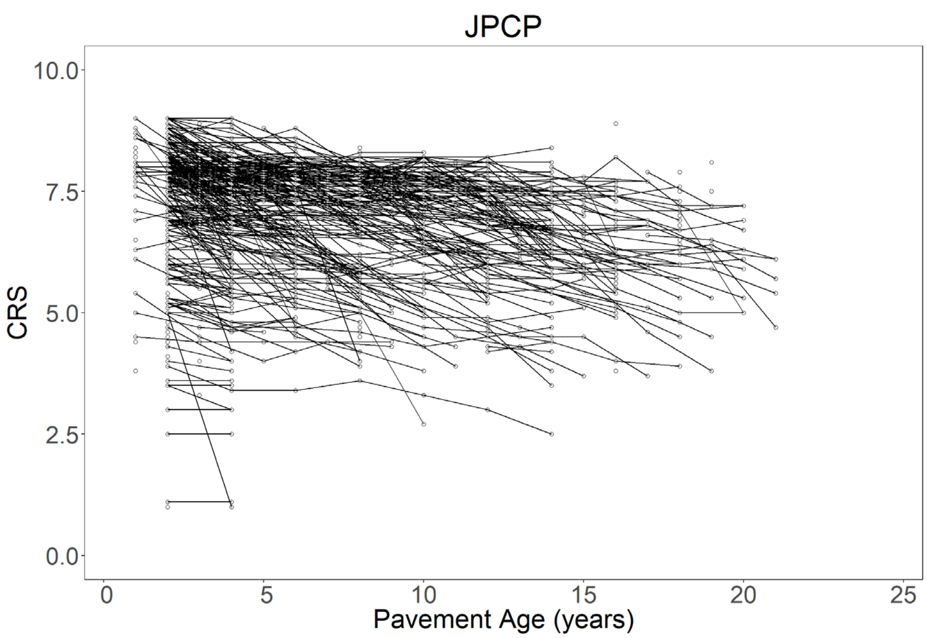


Figure 8. Graph. Cleaned IRIS time-series plot between CRS and pavement age for JPCP.

Empirical IRI Models

The primary purpose of the empirical IRI model is to assess the impact of initial IRI (i.e., the IRI value immediately after construction or at pavement age zero) on long-term IRI and pavement life. As such, the empirical model must incorporate, at a minimum, the initial IRI and pavement age as independent variables. However, complicated models with an excessive number of input variables were not desired because of the possible noise coming from other variables in the IRIS database.

Based on these considerations, a simple equation shown in Figure 9 was selected as the empirical IRI model form for this study.

$$IRI_n = IRI_0 \cdot e^{a \cdot n}$$

Figure 9. Equation. Empirical IRI model form.

In Figure 9, n is the pavement age in years, IRI_n is the IRI value at pavement age n, IRI_0 is the initial IRI, and a is the regression constant.

Another issue was identified when fitting the equation shown in Figure 9 to the cleaned IRIS time-series data shown in Figure 5 and Figure 7. As shown in these time-series plots, the data-cleaning effort did not remove all the noise present in the IRIS data. While the remaining noise did not have a significant impact on fitting the empirical equation, a more prudent issue that resulted from the cleaning effort is that the majority of the sections do not have IRI values at pavement age less than three years. (Note that data with an IRI value of 50 in/mi and a CRS score of 9.0 were eliminated as discussed.) This means that the initial IRI (IRI_0 in Figure 9) was not available for most of these time-series data.

To overcome the above issue, pavement sections not having the IRI data at pavement age from zero to two years have been filtered out. For the remaining sections, it was assumed that IRI does not increase significantly within the first two years after construction and the first available IRI value for each pavement section was assumed to be equal to the initial IRI.

Figure 10 shows the filtered time-series data for full-depth HMA as well as the fitted model curves for IRI_0 corresponding to 40 in/mi, 70 in/mi, and 100 in/mi. Figure 11 shows a comparison between the measured and the predicted IRI values for the same pavement type. Similarly, Figure 12 shows the filtered time-series data for JPCP and the model curves for IRI_0 of 75 in/mi, 150 in/mi, and 225 in/mi, while Figure 13 shows the plot between measured versus predicted IRI values for JPCP.

A comparison between Figure 10 (full-depth HMA) and Figure 12 (JPCP) indicates that the range of initial IRI is relatively wide and may differ significantly for different pavement types. The initial IRI values of JPCP span a wider range and are generally higher than those of full-depth HMA. However, the empirical model coefficient (i.e., the *a*-coefficient in Figure 9) was 0.0242 for full-depth HMA and 0.0096 for JPCP, indicating that JPCPs may experience a slower rate of IRI increase over time. Note that these are general observations made from the fitted empirical model that only consider IRI and do not represent the overall performance characteristics (e.g., cracking, rutting, faulting, etc.) of different pavement types. Nevertheless, the model curves shown in Figure 10 and Figure 12 indicate that lower initial IRI results in reduced rate of IRI growth over time, regardless of pavement type.

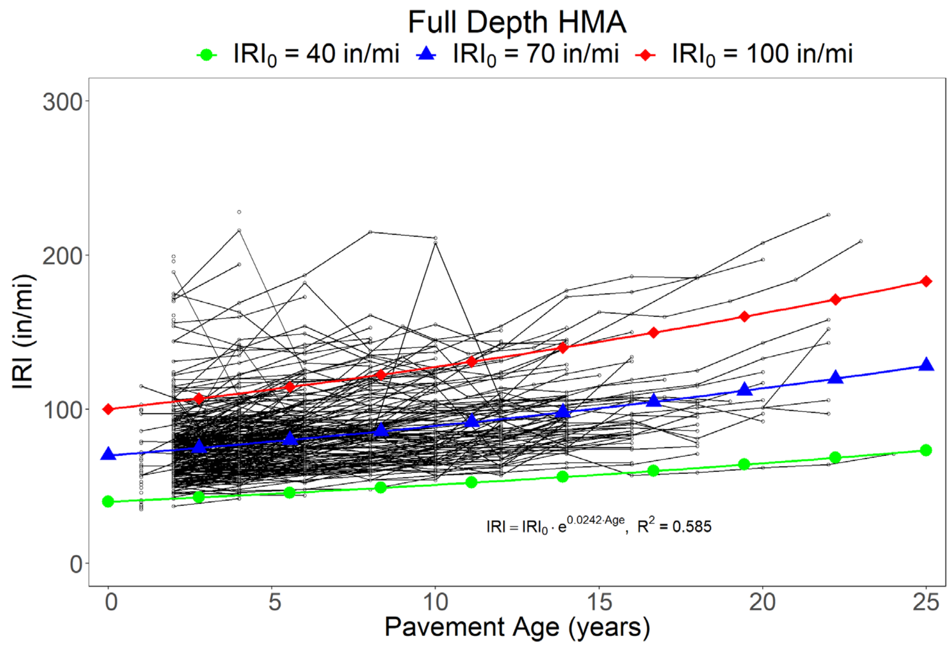


Figure 10. Graph. Empirical IRI model for full-depth HMA.

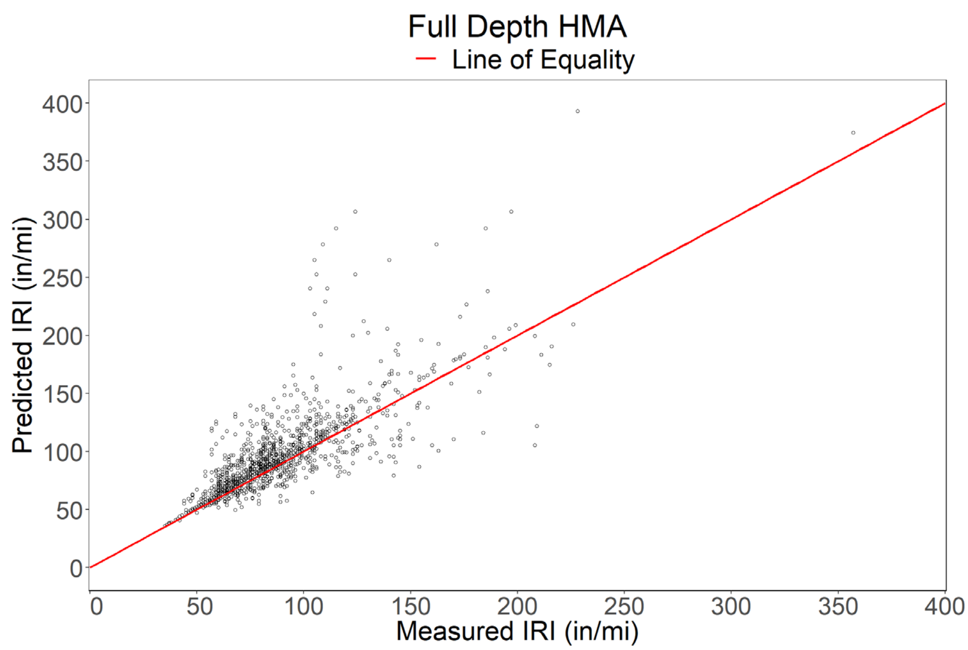


Figure 11. Graph. Measured vs. predicted IRI from the empirical model for full-depth HMA.

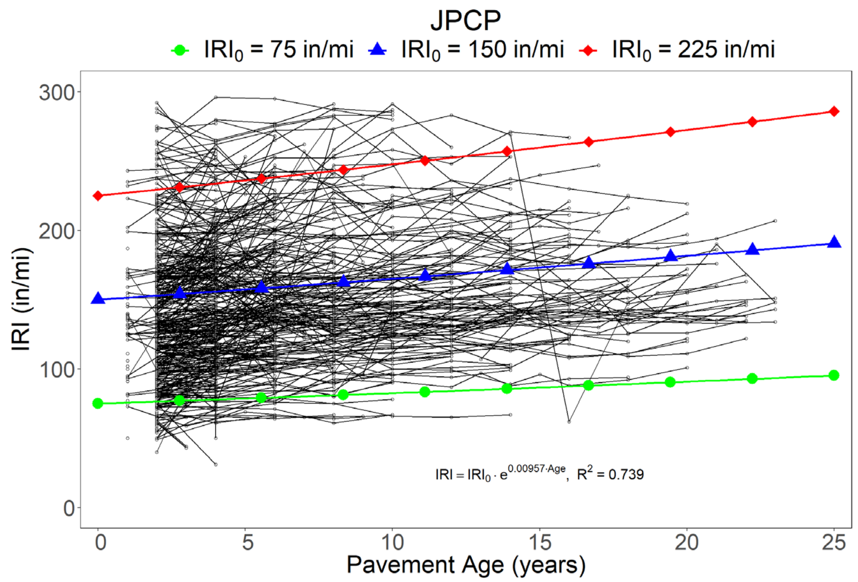


Figure 12. Graph. Empirical IRI model for JPCP.

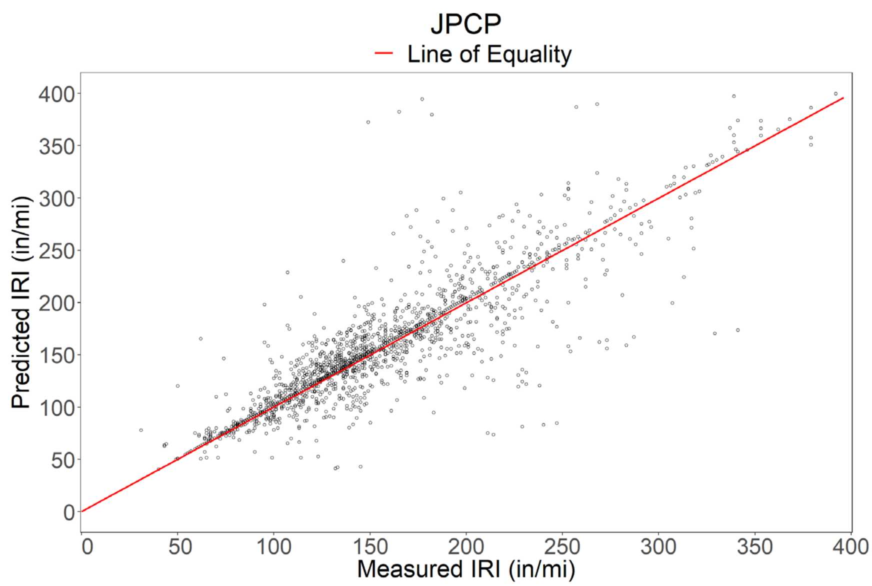


Figure 13. Graph. Measured vs. predicted IRI from the empirical model for JPCP.

Effect of Initial IRI on Pavement Life Based on Empirical IRI Model

The empirical IRI models developed in the previous section indicated that, in general, the lower the initial IRI, the lower the rate of IRI growth. More importantly, these empirical models facilitated a simple means for estimating IRI growth over time, given an initial IRI value. This relationship can be used for estimating the pavement life defined herein as the pavement age at which a certain IRI threshold is reached. An IRI threshold of 175 in/mi has been adopted for this preliminary pavement life assessment, as IDOT's Bureau of Design and Environment (BDE) manual indicates that this level of IRI is considered unacceptable (IDOT, 2020).

Figure 14 shows the pavement life of both full-depth HMA and JPCP pavements estimated from the above procedure for different initial IRI values. The figure shows that the range of pavement life calculated from this procedure is, in general, significantly greater than typical, realistic pavement lives (e.g., a full-depth HMA pavement with an IRI_0 of 75 in/mi corresponds to a pavement life of 35 years and a JPCP with the same IRI_0 shows 88 years of pavement life). Again, the pavement life estimated in Figure 14 is based on simple, empirical IRI models with an IRI threshold of 175 in/mi. In other words, the pavement life does not consider other distresses (e.g., cracking) that may affect pavement life. Furthermore, using a different IRI threshold level will result in different estimates of pavement life. As such, pavement life will be estimated again with a slightly different approach as part of the life cycle cost analysis (to be discussed in the next section). Nevertheless, the figure shows that smoother pavements (i.e., lower initial IRI) exhibit longer pavement life.

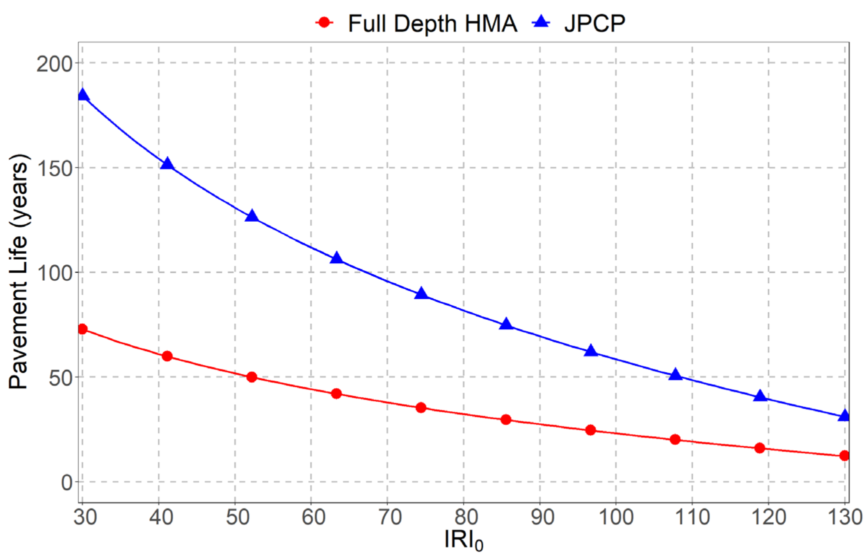


Figure 14. Graph. Pavement life predicted from the empirical IRI models.

LIFE CYCLE COST ANALYSIS

A preliminary effort was presented previously for quantifying the benefits of smoother pavements in terms of pavement life. To translate the pavement life benefits into economic benefits, life cycle cost analysis (LCCA) was carried out in accordance with IDOT's LCCA framework.

The estimated life cycle cost (LCC) will also be used subsequently for the benefit-cost analysis in Chapter 3. As detailed in Chapter 3, assessment of the benefit-cost ratio required a distribution of IRI values measured on new pavement surfaces for estimating the expected benefit as well as the expected cost. While it was possible to estimate the distributions from IRIS data (e.g., the time-series data shown in Figure 10 and Figure 12), such estimates were not made because of the uncertainties within the data (e.g., missing values of IRI_0). As such, the IRI distribution for recently constructed HMA surfaces was obtained from a different database provided by IDOT. However, the relevant data for PCC surfaces was not readily available. Because of these data limitations, the LCCA procedure discussed herein is confined to HMA pavements.

LCCA is primarily used by IDOT for pavement type selection of new construction and reconstruction projects. IDOT's LCCA is typically conducted using an analysis period of 45 years and a discount rate of 3.0% for calculating the present worth factor as well as the capital recovery factor. Additional details regarding IDOT's LCCA procedure are documented in Chapter 54 of IDOT's BDE manual (IDOT, 2020).

For full-depth HMA, the BDE manual suggests that the life cycle include major rehabilitation activities (e.g., milling and overlay) every 15 years and minor maintenance activities (e.g., joint sealing and patching) every five years. The cost associated with these activities can be found in IDOT's BDE Template No. 5401, which represents the full implementation of IDOT's LCCA.

Assumptions for Life Cycle Cost Analysis

Although the above LCCA procedure has served IDOT well for its main purpose of pavement type selection, the procedure is not adequate for the purpose of this study. This is because the life cycle activities in the BDE manual are prescribed to take place at predetermined pavement ages without considering pavement deterioration, e.g., major rehabilitation activities are designed to occur every 15 years, regardless of the pavement condition, including IRI. Such prescribed activities are independent of IRI growth and, more importantly, the initial IRI. Hence, the LCC calculated with the prescribed activities does not vary with initial IRI and, consequently, the LCCA cannot be used to assess the financial benefits of smoother pavements. As such, it was necessary to alter IDOT's existing LCCA procedure to meet the needs of this study. The assumptions and adjustments adopted in LCCA are provided in the following.

1. Pavement smoothness was assumed to affect only future rehabilitation and maintenance costs. In other words, the initial construction cost was assumed to be independent of the initial IRI achieved at the end of construction.

2. The empirical IRI model developed in the previous section was used to provide the "pavement deterioration" curve. The purpose of using an IRI-based deterioration curve was to eliminate the use of predetermined pavement ages at which rehabilitation or maintenance activities are conducted and to determine the timing of the life cycle activities based on IRI performance over time.

   The original premise of this approach was that the major life cycle activities are to be conducted at the end of the pavement life. However, as shown in Figure 14, the pavement life estimated as the pavement age at which the IRI reaches 175 in/mi was often significantly greater than typically expected pavement life. For example, a full-depth HMA pavement with an initial IRI of 60 in/mi shows approximately a predicted life of 45 years, which is equal to the LCCA analysis period. In this case, LCCA becomes pointless, as the pavement will not experience any major life cycle activities during the entire LCCA analysis period.

   To overcome the above issue, another threshold must be defined and used for LCCA. Note that while IRI is an important factor for determining rehabilitation decisions, it is not the only factor considered in decision-making. As such, an attempt was made to develop the relationship between IRI and CRS, which is another primary measure of pavement condition for rehabilitation decisions. Figure 15 shows the relationship between IRI and CRS developed based on the same dataset used for developing the empirical IRI model.

Starting with an average IRI_0 value of 71 in/mi obtained from the filtered time-series data for full-depth HMA (Figure 10), the corresponding CRS value is obtained as 7.3 from the regression line in Figure 15. This CRS value is in the “satisfactory” category, defined as pavements with CRS values between 6.1 and 7.5 according to Chapter 53 of the BDE manual (IDOT, 2020). However, when the IRI is increased from 71 in/mi to 120 in/mi (i.e., approximately a 50 in/mi increase), the CRS value drops down to 5.9, which is in the “fair” category and requires a major improvement in the near future (IDOT, 2020).

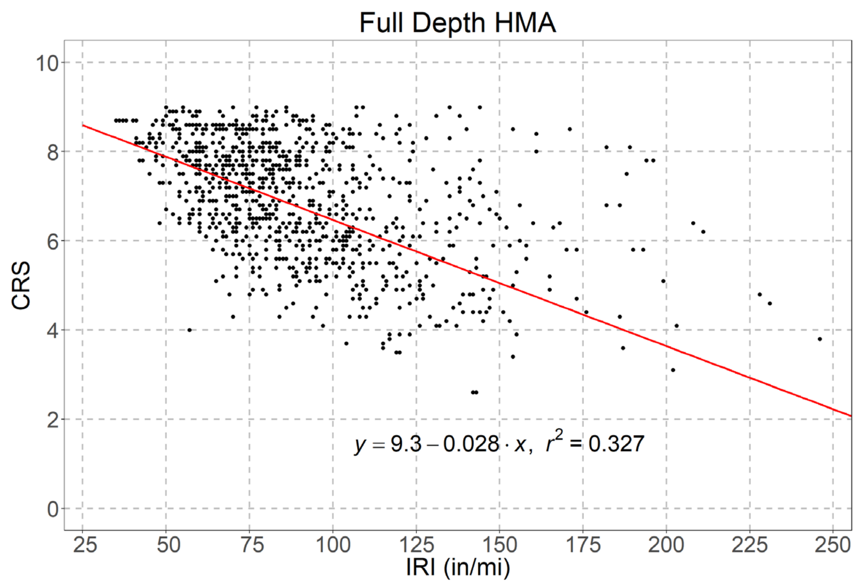


Figure 15. Graph. IRI vs. CRS for full-depth HMA sections used for developing empirical IRI model.

Based on the above observation, the following was decided for the timing of major and minor life cycle activities.

1) Major life cycle activities are conducted when the IRI increases by 50 in/mi from IRI_0 or when an absolute IRI threshold of 175 in/mi is reached (whichever occurs first).

2) Minor life cycle activities are conducted when the IRI increases by 15 in/mi from IRI_0 or since the last activity. This threshold was chosen to ensure two minor activities are conducted in between the consecutive major activities (similar to IDOT’s current LCCA practice).

3) Major rehabilitation activities (e.g., overlays) were assumed to be the only option for improving pavement smoothness during the LCCA analysis period, which resets the IRI back to the initial value (IRI_0). In addition, minor maintenance activities such as longitudinal joint sealing and patching were assumed to have no effect on IRI performance.

Effect of Initial IRI on Pavement Life from Life Cycle Cost Analysis

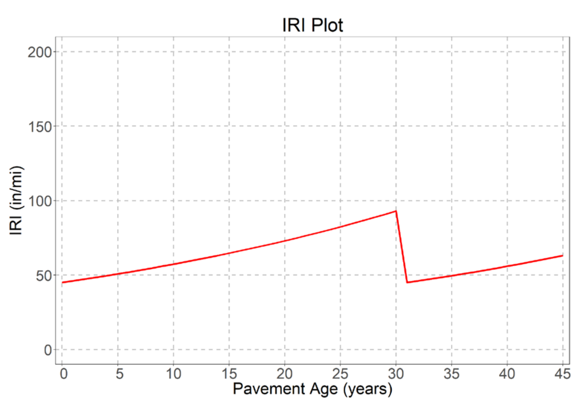
Figure 16 shows examples of the IRI-based pavement deterioration curves for three different IRI_0 values (45 in/mi, 75 in/mi, and 100 in/mi) generated with the assumptions described above. A sudden downward drop in the IRI curve indicates that the IRI reached the threshold and a major rehabilitation has taken place.

The figure also shows that for a pavement with an initial IRI of 45 in/mi, the major rehabilitation activity only occurred once during the 45-year LCCA analysis period. For pavements with initial IRI values of 75 in/mi and 100 in/mi, the major activities occurred twice during the analysis period with the duration between successive activities being shorter for the pavement with higher IRI. Such a trend is believed to be reasonable and more adequate in capturing the effect of initial IRI on LCC.

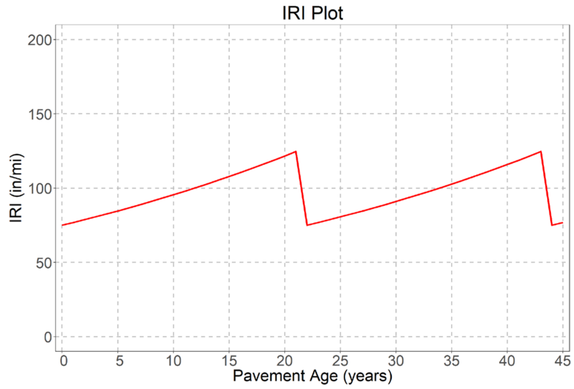
Another observation made from Figure 16 is that the IRI values have never reached the absolute threshold of 175 in/mi. This indicates that the pavement life—defined as the pavement age at which the first major rehabilitation occurs—will be different from those obtained previously based on the empirical models. As such, the pavement lives corresponding to different initial IRI values have been calculated again.

Figure 17 shows the pavement life estimated within the LCCA framework as a function of initial IRI. The pavement life shown in this figure seems to be more reasonable compared to those shown in Figure 14. For example, Figure 14 showed that a full-depth HMA pavement with an IRI_0 of 75 in/mi may have up to 35 years of life, while Figure 17 shows 22 years of pavement life for the same IRI_0.

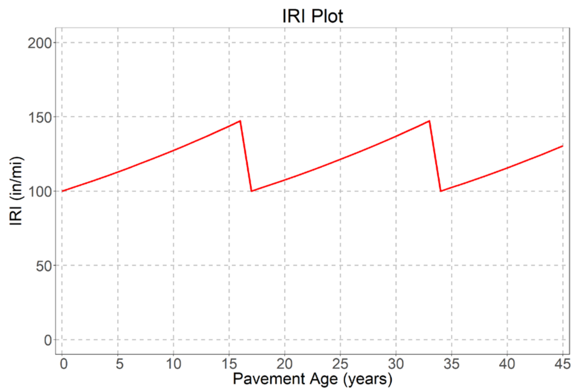
Note that the pavement lives shown in Figure 14 and Figure 17 are based solely on IRI performance without considering other distresses that may affect pavement life. Although the relationship between IRI and CRS was considered as a simple means for establishing the IRI threshold for rehabilitation, the CRS performance over time has not been considered in the actual pavement life estimation. Furthermore, the predicted pavement lives should only be considered as crude estimates due to the uncertainties associated with the empirical IRI model and the IRI versus CRS relationship. Nonetheless, the IRI trends shown in Figure 16 and the pavement life shown in Figure 17 are believed to be reasonable for the purpose of LCCA, as they are capable of quantifying (at least roughly) the effect of initial IRI on pavement life.



A. Initial IRI 45 in/mi.



B. Initial IRI 75 in/mi.



C. Initial IRI 100 in/mi.

Figure 16. Graph. IRI curves for LCCA with initial IRI values of 45 in/mi, 75 in/mi, and 100 in/mi.

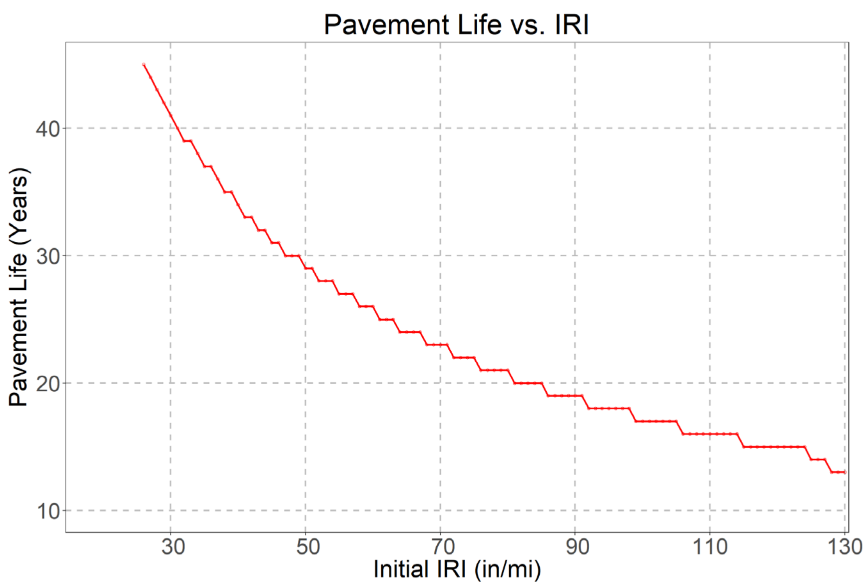


Figure 17. Graph. Pavement life predicted from LCCA framework.

Agency Cost

The purpose of LCCA was to assess the economic benefits of smoother pavements. The economic benefits are divided into two categories: agency cost and highway user cost. This section focuses on the procedures and results of LCCA pertaining to agency cost.

Using the IRI-based pavement-deterioration curves obtained previously, the agency cost, including the initial construction cost as well as the maintenance / rehabilitation cost, was calculated using IDOT's BDE Template No. 5401. The pavement was assumed to be a full-depth HMA located on a rural, interstate route and 1.0 mi in length. To keep the analysis simple, only one lane was considered in LCCA, which was further assumed to be 12.0 ft wide and constructed with 12.0 in. of HMA. Default inputs in the BDE template was used for all other LCCA input variables. Because the initial construction cost was assumed to be independent of the achieved IRI_0, this cost was calculated to be $600k for all scenarios to be presented herein.

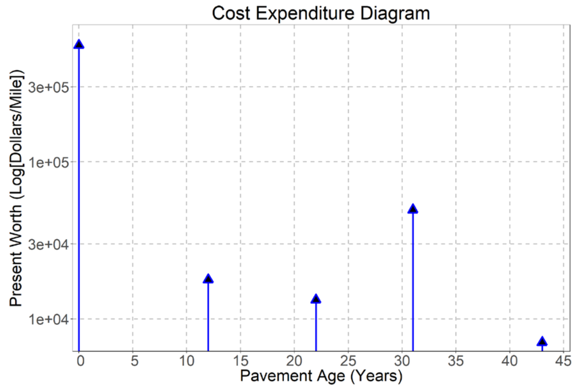
For the major and minor life cycle activities, the maintenance and rehabilitation strategies provided in the BDE manual were adopted without any modification. The major rehabilitation activities included the following items for a total cost of $134k:

- Milling 2.0 in. of pavement and shoulder surface.
- Partial depth patching 1.0% of lane area.
- Overlaying pavement and shoulder with 2.0 in. of HMA.

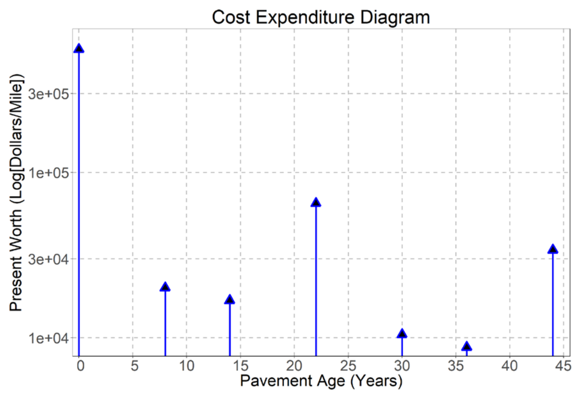
The minor maintenance activities consisted of the following with a total cost of $29k. Note that these activities were assumed to have no effect on IRI within the LCCA framework.

- Routing and sealing 100.0% of longitudinal shoulder joint.
- Routing and sealing 100.0% of centerline joint.
- Routing and sealing 50.0% of random and thermal cracks.
- Partial depth patching 0.5% of lane area.

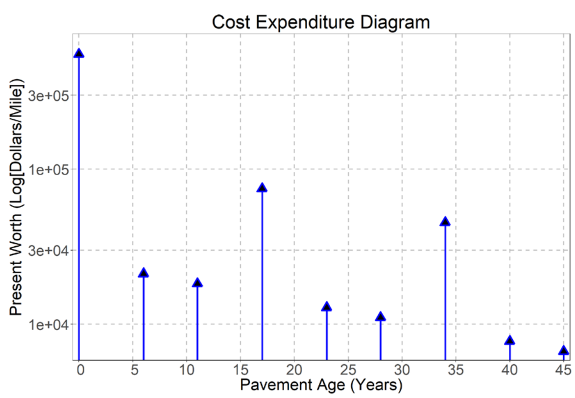
Figure 18 shows the agency cost expenditure diagrams corresponding to the IRI deterioration curves, previously shown in Figure 16. Note that the cost was converted into present worth value in accordance with the BDE manual.



A. Initial IRI 45 in/mi.



B. Initial IRI 75 in/mi.



C. Initial IRI 100 in/mi.

Figure 18. Graph. LCCA cost expenditure diagrams for initial IRI values of 45 in/mi, 75 in/mi, and 100 in/mi.

For each IRI_0, the total agency cost was calculated as the sum of all individual costs (or present worth) within the LCCA analysis period. Figure 19 shows the outcome: the trend of the agency cost gradually increases with increasing IRI_0. Furthermore, for the ranges of IRI_0 considered, the total cost may become as high as \$900k (i.e., rehabilitation and maintenance cost being as high as 50.0% of the initial construction cost), indicating that a rough pavement may require a significant amount of cost over the 45-year analysis period. The agency cost obtained within the LCCA framework will be considered again in Chapter 3 as part of the benefit-cost analysis.

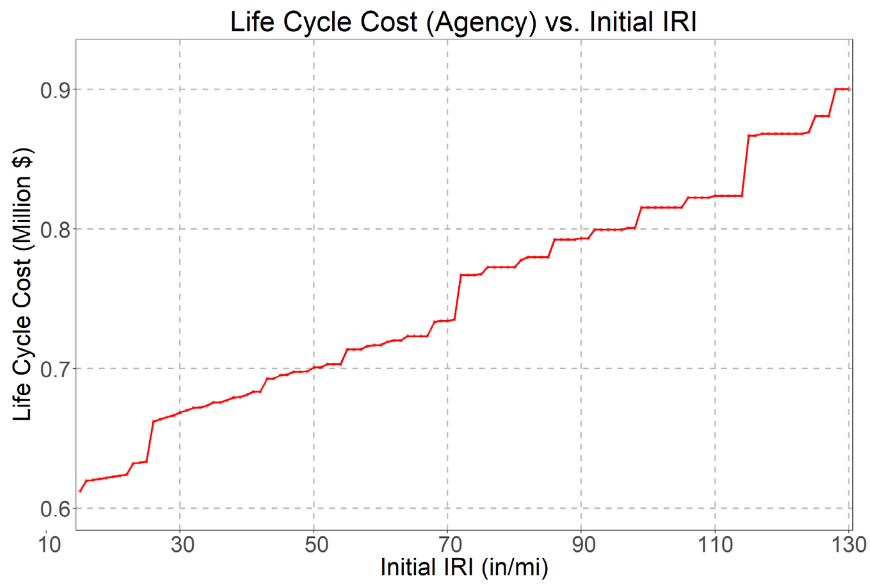


Figure 19. Graph. Agency life cycle cost versus initial IRI.

User Cost

Previous studies have shown that smoother pavements not only benefit the owner agency but also highway users (Robbins and Tran, 2015, 2016; Chatti and Zaabar, 2012). As such, an effort was made to capture the economic and safety benefits that highway users may experience from smoother pavements. The components of the user cost considered within the current LCCA framework include the vehicle-operating cost and the expected cost due to crashes.

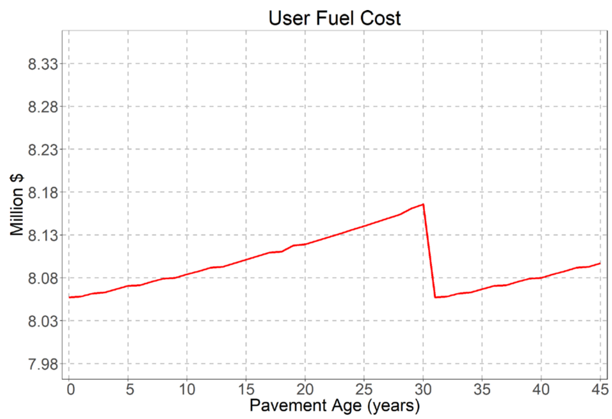
Vehicle-Operating Cost

The vehicle-operating cost (VOC) was calculated based on the spreadsheet tool that was developed as part of the National Cooperative Highway Research Program (NCHRP) Project No. 01-45 (Chatti and Zaabar, 2012). VOC includes fuel cost, vehicle repair and maintenance (R&M) cost, and the cost associated with tire wear, all of which are calculated based on IRI as an input.

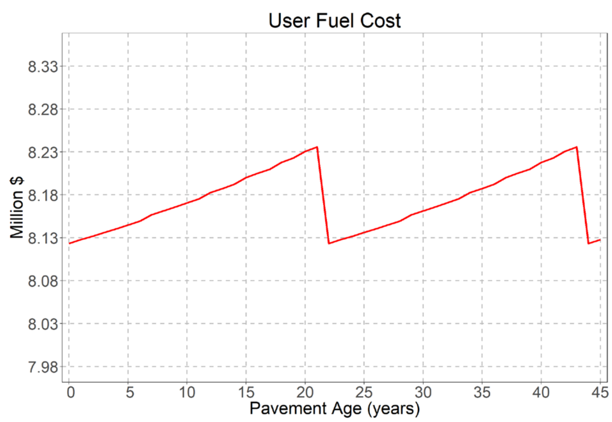
The pavement modeled for the VOC analysis was a rural, interstate highway that is 1.0 mi in length, surfaced with HMA, and located on a flat terrain (i.e., without grade and super elevation). A surface texture in terms of mean profile depth value of 0.017 in., vehicle speed of 65 mph, and air temperature of 70°F were used throughout the analysis. The VOC was obtained for a traffic amount of 100,000 annual average daily traffic (AADT) with 18% heavy trucks and buses.

Using the IRI deterioration curves previously shown in Figure 16, the user cost for fuel, vehicle R&M, and tire wear were calculated and shown in Figure 20, Figure 21, and Figure 22, respectively. While the cost relating to fuel and tire wear showed clear trends, R&M cost did not vary significantly with

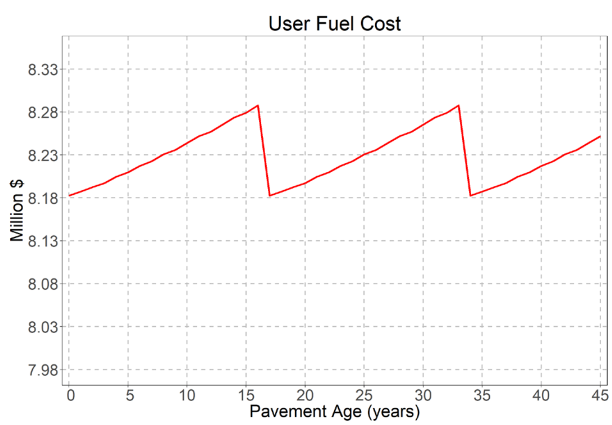
IRI. Chatti and Zaabar (2012) also observed this trend, finding that the R&M cost stays relatively unaffected (i.e., flat) when the IRI value is approximately below 190 in/mi.



A. Initial IRI 45 in/mi.

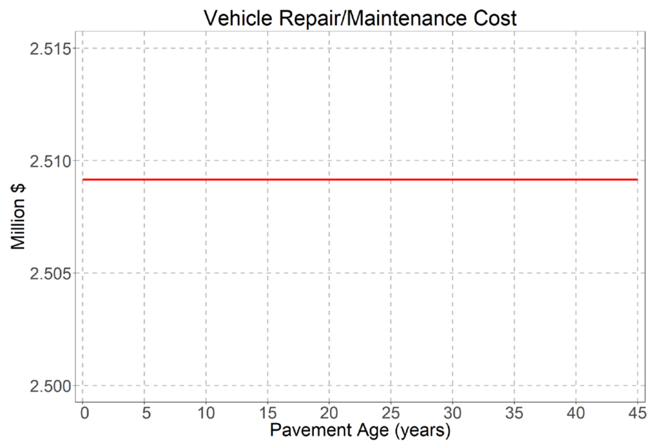


B. Initial IRI 75 in/mi.

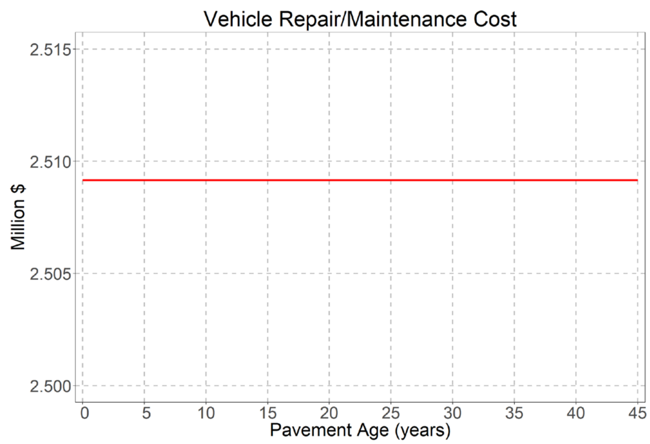


C. Initial IRI 100 in/mi.

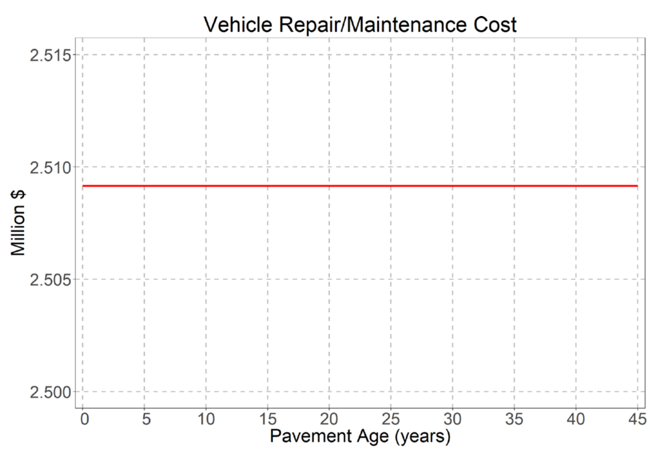
Figure 20**. Graph. LCCA user fuel cost curves for initial IRI values of 45 in/mi, 75 in/mi, and 100 in/mi.**



A. Initial IRI 45 in/mi.

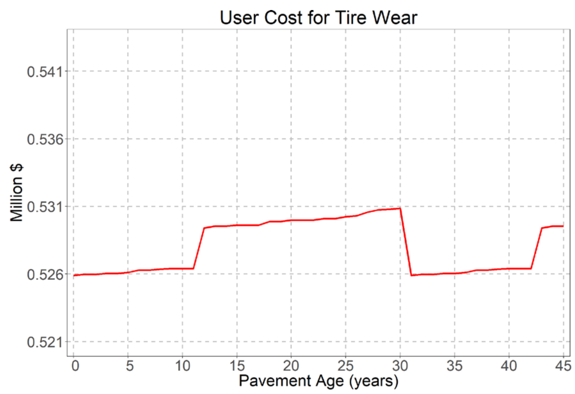


B. Initial IRI 75 in/mi.

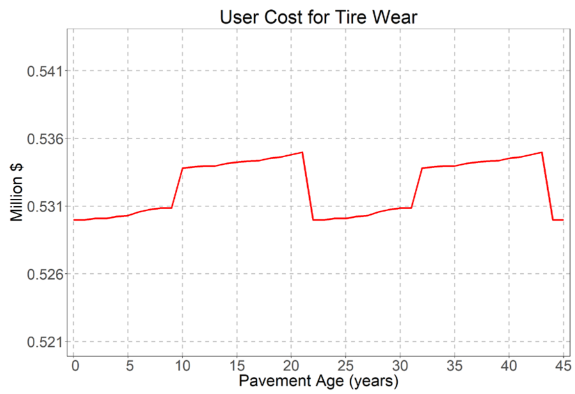


C. Initial IRI 100 in/mi.

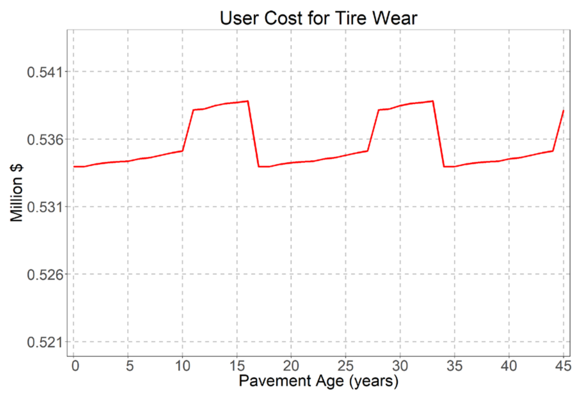
Figure 21**. Graph. LCCA vehicle repair and maintenance user cost curves for initial IRI values of 45 in/mi, 75 in/mi, and 100 in/mi.**



A. Initial IRI 45 in/mi.



B. Initial IRI 75 in/mi.



C. Initial IRI 100 in/mi.

Figure 22. Graph. LCCA user cost for tire wear with initial IRI values of 45 in/mi, 75 in/mi, and 100 in/mi.

Safety (Crash) Cost

Previous studies indicated that smoother roads also result in a reduced number of crashes (Chan et al., 2009; Li and Huang, 2014, Lee et al., 2019). As such, it was also of interest to assess safety benefits in terms of estimated reduction in number of crashes or the estimated cost reduction due to increased safety.

The Federal Highway Administration and American Association of State Highway and Transportation Officials recommend that a safety performance function (SPF) be used for estimating the crash counts (Srinivasan and Bauer, 2013). The SPF usually takes an exponential form and is frequently used to identify roadway sites that may benefit from a safety treatment by estimating the number of crashes before and after the treatment. For the state of Illinois, Tegge et al. (2010) developed SPFs for different crash types (e.g., injury, fatal, or both injury and fatal) and for different groups of roadways (e.g., rural vs. urban highway). For this study, a four-lane rural freeway will be considered, whose SPF for injury crashes is shown in Figure 23.

$$\mu = L \cdot e^{-4.897+0.548\cdot\ln(AADT)}$$

Figure 23. Equation. Safety performance function for a four-lane rural freeway (Tegge et al., 2010).

However, the SPF shown in the above figure represents the most basic form of SPF and only takes the minimum required variables as inputs, namely the length of the roadway segment, *L*, and AADT (Tegge et al., 2010). IRI was not considered during the SPF development for Illinois' conditions and it was not an input into the SPF.

FHWA Office of Safety recommends that the basic form of SPF can be generalized to include additional site factors such as the lane width, shoulder width, horizontal curvature, and the presence of turn lanes, intersections, and traffic control (Srinivasan and Bauer, 2013). A few studies were identified in which IRI was considered as an input variable in the SPF. Chan et al. (2009) reported a regression coefficient of 0.005 based on data from Tennessee, while Lee et al. (2019) reported slightly higher regression coefficients ranging from 0.007 to 0.008 based on data from Florida. Because IRI was not considered in the SPF shown in Figure 23, it was modified to include IRI with a constant of 0.005. The modified SPF is shown in Figure 24.

$$\mu = L \cdot e^{-4.897+0.548\cdot\ln(AADT)+0.005\cdot IRI}$$

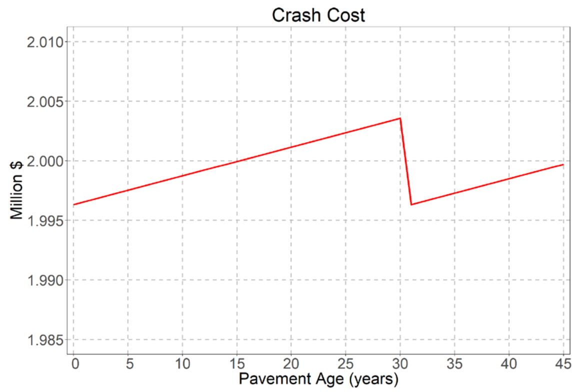
Figure 24. Equation. Updated safety performance function including IRI.

In theory, updating the SPF in the above manner is not statistically valid, as the existing coefficients (i.e., the constant value of −4.897 and the AADT coefficient of 0.548) will change when the SPF is redeveloped with additional parameters. However, developing new SPFs values for this purpose was beyond the scope of this study. Nevertheless, such a crude estimate of SPF including IRI was deemed reasonable for this study due to the following reasons:

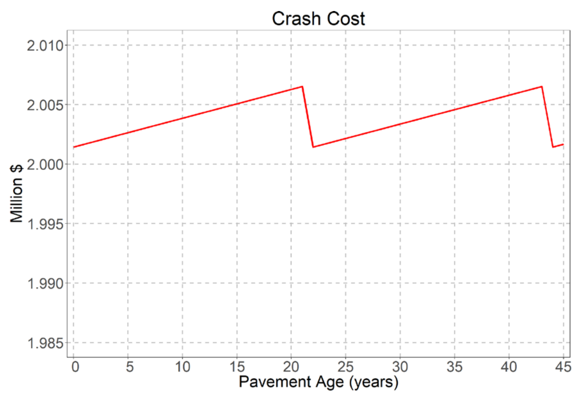
1. The purpose of this exercise is to establish a rough estimate of the number of crashes, rather than developing a thorough SPF.
2. The independent variables in the SPF shown in Figure 24 are the segment length (*L*), AADT, and IRI. Because the focus of this study is on IRI, AADT and *L* will be not be varied but fixed at

100,000 and 1.0 mi, respectively, to be consistent with the VOC analysis, i.e., IRI will be the only variable that affect the estimated crash counts.

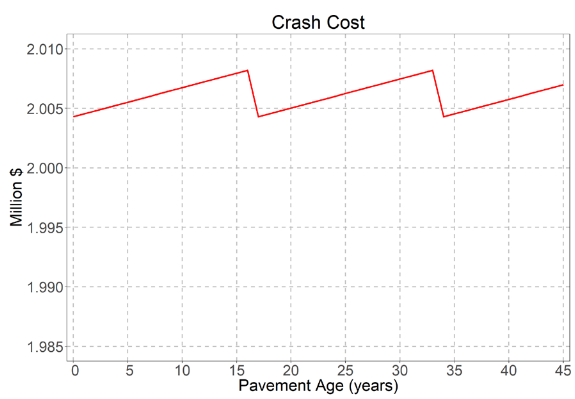
Based on the above discussion, the expected number of crashes was calculated based on the SPF in Figure 24 along with the IRI deterioration curves shown in Figure 16. Then, the crash cost was estimated by assuming an average cost of $150k per crash. Figure 25 shows the resulting crash cost plots for different initial IRI values.



A. Initial IRI 45 in/mi.



B. Initial IRI 75 in/mi.



C. Initial IRI 100 in/mi.

Figure 25. Graph. LCCA crash cost for initial IRI values of 45 in/mi, 75 in/mi, and 100 in/mi.

Total User Cost

Based on the VOC and crash cost presented above, the total user cost was calculated as the sum of all individual costs (fuel, R&M, tire wear, and crash) within the LCCA analysis period for each IRI_0. The total user cost calculated in this manner is shown in Figure 26.

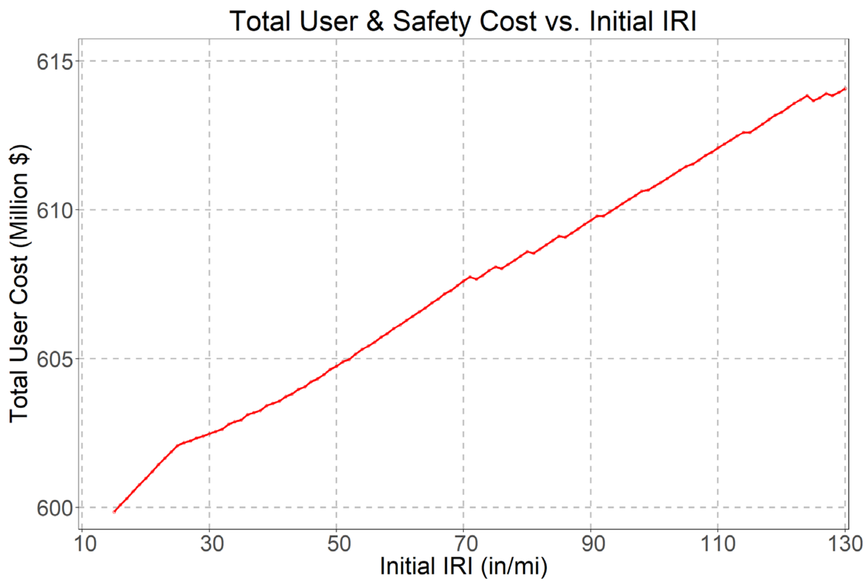


Figure 26. Graph. Total user and safety life cycle cost versus initial IRI.

The user cost shown in Figure 26 is significantly higher than the agency cost shown in Figure 19. The issue of user cost being several orders of magnitude greater than agency cost is frequently encountered in LCCA (FHWA, 2002). Furthermore, user cost does not affect the agency's budget directly. For these reasons and other uncertainties associated with its calculation (e.g., monetizing user delay time), user cost is often not considered in an agency's decision-making process.

Accordingly, user cost will not be considered further for assessing the benefit of smoother roads in this study. However, for the purpose of an agency's smoothness specification development, the excessive amount of user cost generally suggests that any corrective action for pavement smoothness should be conducted prior to the road being open to the driving public. This is because the user cost, which is excessive already, will likely increase even further if the roadway needs to go through another round of traffic maintenance.

PUBLIC PERCEPTION (USER COMFORT)

One of the primary benefits of a smooth pavement is that it feels comfortable when driven over. In addition, highway users first recognize good roadways by the smoothness of the pavement. As such, an effort was made to quantify the level of comfort that users may experience from pavements exhibiting different levels of IRI. Note that the resulting public perception (or user comfort) will not be monetized, but it will serve as an important factor for determining the IRI thresholds in IDOT's new smoothness specification.

The International Organization for Standardization (ISO) indicates that the human comfort level under vibrating conditions can be assessed by calculating the root mean square (RMS) of acceleration (ISO, 2020). The standard also provides the level of comfort corresponding to different levels of acceleration RMS, as shown in Table 1.

Table 1. Comfort Levels Related to RMS Values of the Vehicle Seat Acceleration (ISO 2631-1)

Comfort Level	RMS of Acceleration (m/s^2)
Not uncomfortable	<0.315
A little uncomfortable	0.315–0.63
Fairly uncomfortable	0.5–1
Uncomfortable	0.8–1.6
Very uncomfortable	1.25–2.5
Extremely uncomfortable	>2

The comfort levels shown in Table 1 are somewhat subjective, as evidenced by the overlapping regions of RMS for different comfort levels. For example, if the RMS was found to be 0.6 m/s^2, some individuals may feel a little uncomfortable while some others may feel fairly uncomfortable. The same argument can be made between uncomfortable and very uncomfortable levels for an RMS value of 1.4 m/s^2.

Despite the subjectivity associated with the level of comfort, an RMS value of 0.5 m/s^2 (i.e., the lower RMS limit for "fairly uncomfortable" in Table 1) was selected in this study as a threshold between acceptable and unacceptable level of comfort for newly constructed pavement surfaces. This threshold was selected based on the premise that if many individuals feel fairly uncomfortable at a given level of vibration, then most individuals are likely to feel or at least notice the vibration.

Data Collection

The acceleration data needed for assessing the user comfort level was collected using the PaVision system developed and operated by Applied Research Associates, Inc. The PaVision data collection hardware consists of forward-facing and downward-facing high-resolution digital cameras, an accelerometer, a GPS antenna, and an onboard computer to control the systems and integrate the data. The PaVision system is portable and can be used with any vehicle with a trailer hitch. For this study, the PaVision system was used with a Ford Escape vehicle shown in Figure 27, with the accelerometer mounted below the front passenger seat, as shown in Figure 28. The accelerometer was intentionally mounted under the passenger seat rather than the driver seat to eliminate the effect of the driver's weight. The passenger seat was not occupied by any individual during the data collection period.

Figure 27. Photo. Ford Escape vehicle used for acceleration data collection with PaVision system.

Figure 28. Photo. PaVision accelerometer mounted below the passenger seat.

The pavement sections surveyed with the PaVision system for accelerometer data collection include those from IDOT's "Before and After Sections" and "Mechanistic Pavement Sections." These sections were chosen because the raw pavement elevation data (for calculating IRI) and the corresponding GPS coordinates were readily available for the research team. Such data was necessary to ensure the acceleration RMS is calculated within the same limits as the IRI. Additional details and the IRI data from the Before and After sections will be discussed in Chapter 3.

Figure 29 shows the location of pavement sections tested with PaVision. Although most of the sections were located in northern Illinois, these pavement sections covered a variety of pavement types and speed limits ranging from 25 mph to 70 mph.

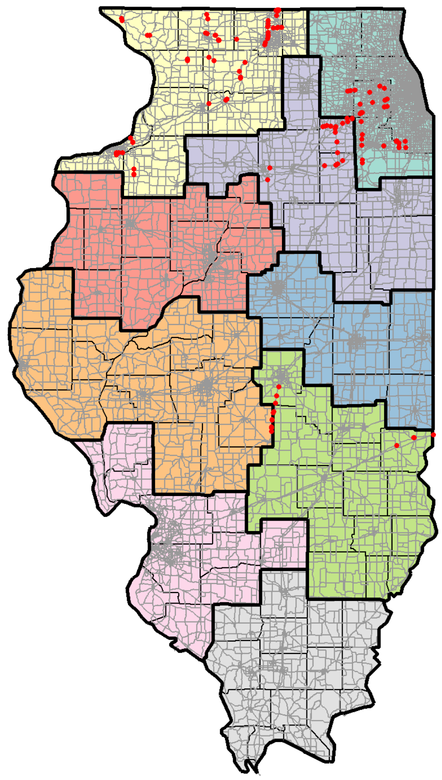


Figure 29. Map. Location of pavement sections tested with PaVision system.

For each pavement section, the accelerometer data was collected first at the prevailing speed limit followed by one or two slower speeds. For the lower speeds, the driver was instructed to test at 10 mph and 20 mph below the speed limit, if the field condition was feasible and safe enough to achieve them. However, because the data collection was carried out without any traffic control, this plan was not always feasible. In such cases, the driver was allowed to reduce the number of lower speed runs and/or to test at 5 mph and 10 mph below the speed limit (especially for low-speed facilities).

Accelerometer Results

Vehicle Speed versus Acceleration RMS

IDOT's existing PI-based smoothness specification defines high-speed roadways as those having a speed limit of 50 mph or greater. Accordingly, the existing specification defines low-speed roadways as those with a speed limit of 45 mph or less. While these definitions worked well with the PI-based specification, it was questioned whether the same definitions should be carried over to the IRI-based specification. As such, a decision was made to study the range of acceleration RMS values at different speeds to determine if there is a speed at which the user may start feeling uncomfortable.

Figure 30 shows the acceleration RMS calculated for different speeds. A horizontal red line corresponds to the acceleration RMS threshold of 0.5 m/s^2. Most data points above this RMS threshold (i.e., uncomfortable ride) are found at higher speeds. Nevertheless, this figure exhibits a lot of noise, and it is difficult to identify the speed at which the user may start to feel uncomfortable. A box plot of the acceleration RMS data was generated to study further the distribution of RMS values (Figure 31).

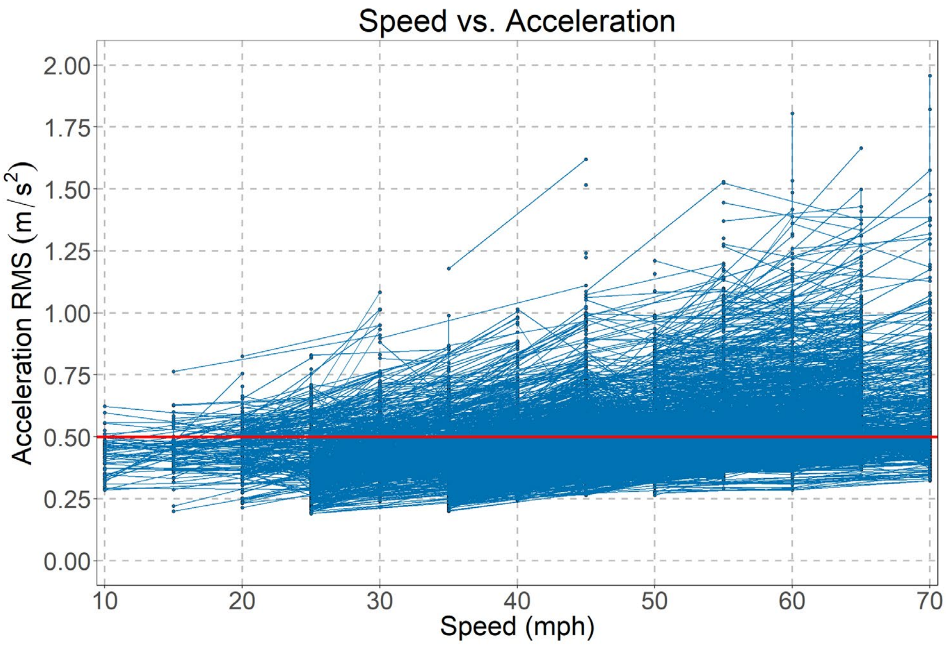


Figure 30. Graph. Speed versus acceleration RMS.

Figure 31 shows that the acceleration RMS is mostly below 0.5 m/s^2 for travelling speeds less than or equal to 35 mph. On the other hand, a good portion of RMS values were observed above 0.5 m/s^2 when the speed is increased to 50 mph or above. However, the RMS distributions for the remaining speeds, i.e., 40 mph and 45 mph, were not as clear.

For a speed of 40 mph, the RMS threshold of 0.5 m/s^2 corresponds to the 70th percentile, i.e., there is approximately a 70% chance that the acceleration RMS will be below the threshold (i.e., comfortable). Given this level of probability for user comfort, 40 mph zones were included in the low-speed category.

RMS values for a speed of 45 mph, however, were somewhat different. At this speed, the RMS threshold of 0.5 m/s^2 corresponds to the 58th percentile, i.e., there is approximately a 58% chance that the user may feel comfortable and a 42% chance for an uncomfortable ride. In addition, the median (i.e., 50th percentile) RMS value was found to be 0.47 m/s^2. For practical considerations, this RMS value of 0.47 m/s^2 was believed to show no significant difference when compared to the threshold value of 0.5 m/s^2. Furthermore, 45 mph is only 5 mph less than the speed at which IRI is simulated (i.e., 50 mph). This difference in speed is also believed to be insignificant. For these reasons, it was recommended that the definition of high-speed facilities be modified to include 45 mph speed-limit zones.

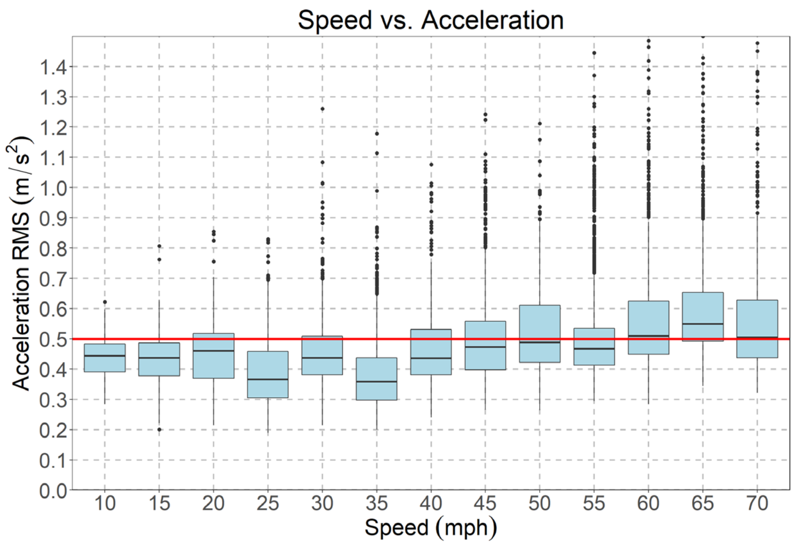


Figure 31. Graph. Box plot for speed versus acceleration RMS.

IRI versus Acceleration RMS

In the previous section, the acceleration RMS was studied at different speeds, and new definitions of speed categories were recommended. However, the results shown previously only involved actual vehicle speed and did not involve the actual pavement smoothness as measured by IRI. The goal of accelerometer data collection was to correlate the acceleration RMS (or user comfort) with IRI, which is studied herein.

Figure 32 shows a plot between IRI and acceleration RMS for high-speed facilities (i.e., > 40 mph). A linear regression between IRI and RMS indicates that the threshold RMS value of 0.5 m/s^2 corresponds to an IRI value of 66 in/mi, meaning an IRI value of 66 in/mi or less may be desired for ride quality of high-speed facilities.

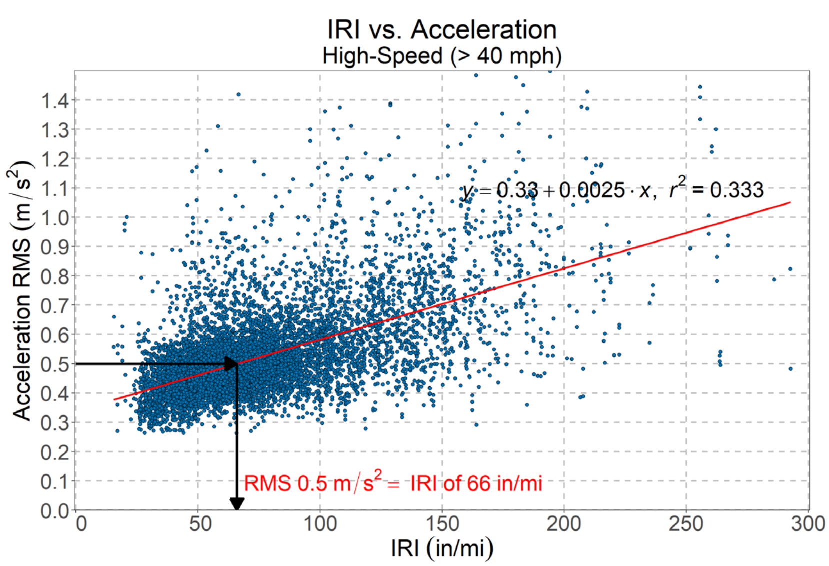


Figure 32. Graph. IRI versus acceleration RMS for high-speed facilities.

The scatterplot in Figure 32, however, shows that the results are highly variable. As such, the RMS values were grouped into different IRI bins having an increment of 10 in/mi, and a box plot was generated to study the RMS distributions within the respective IRI bins. Figure 33 shows the box plot, in which the label of the horizontal axis represents the upper limit of each IRI bin (e.g., the horizontal axis labeled as 75 in/mi represents the IRI bin corresponding to 65 in/mi < IRI ≤ 75 in/mi). The figure also shows the RMS threshold of 0.5 m/s^2 as a horizontal red line.

Figure 33 confirms the trend shown in Figure 32: the higher the IRI, the higher the acceleration RMS and the lower the ride quality. The figure also indicates that the RMS is mostly greater than the threshold value when the IRI is increased beyond 105 in/mi. However, for IRI ranges between 45 in/mi and 95 in/mi, the range of RMS values are relatively in close proximity to the threshold value of 0.5 m/s^2. To further study the RMS distributions for these IRI ranges, the median and 75th percentile RMS values for the respective IRI bins are tabulated in Table 2.

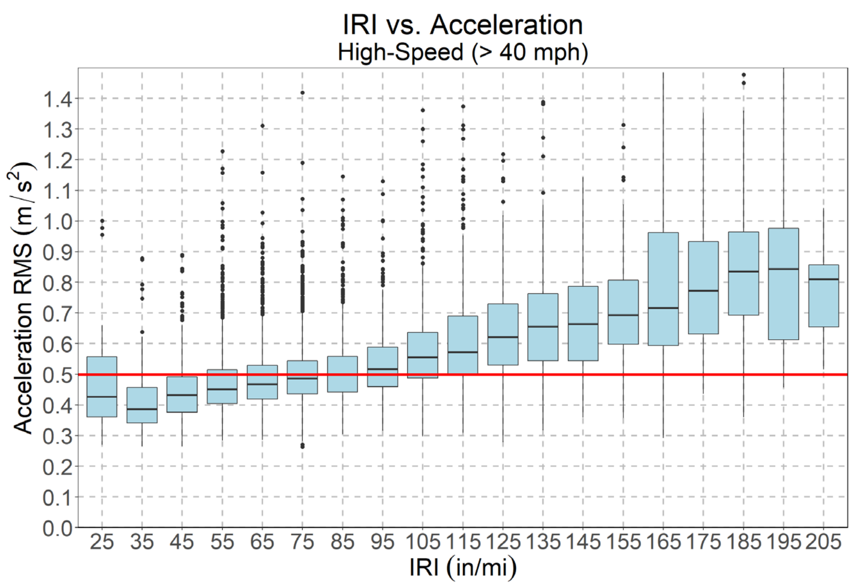


Figure 33. Graph. Box plot for IRI versus acceleration RMS obtained from high-speed facilities.

Table 2. Median and 75th Percentile Acceleration RMS for Selected IRI Bins

IRI Bin or Range (in/mi)	Median Acceleration RMS (m/s^2)	75th Percentile Acceleration RMS (m/s^2)
35 < IRI ≤ 45	0.43	0.49
45 < IRI ≤ 55	0.45	0.52
55 < IRI ≤ 65	0.47	0.53
65 < IRI ≤ 75	0.49	0.54
75 < IRI ≤ 85	0.50	0.56
85 < IRI ≤ 95	0.52	0.59
95 < IRI ≤ 105	0.56	0.64

The median and 75th percentile values in Table 2 show a relatively narrow range of RMS values. Table 2 shows that the chances of ensuring user comfort increase with lower IRI. For example, if the IRI is between 65 in/mi and 75 in/mi, there is approximately a 50% chance for the RMS to be above or below 0.49 m/s^2. However, if the IRI is lowered to a range between 35 in/mi and 45 in/mi, there is approximately a 75% chance of achieving an RMS value less than 0.49 m/s^2 (i.e., improved comfort level).

Based on the above observations and discussions, lower IRI values are desired to allow highway users to feel comfortable when driving on high-speed facilities. For low-speed facilities, acceleration RMS values were mostly below the threshold value of 0.5 m/s^2 (see Figure 31). This indicates that for user comfort considerations, the IRI at low-speed facilities may not be as critical as the high-speed facilities. However, a relationship between IRI and acceleration RMS can be derived for low-speed facilities, as shown in Figure 34. Similarly, Figure 35 shows the corresponding box plot. Both figures confirm the expected trend (lower IRI provides lower RMS and, hence, increased comfort).

Although the data is significantly scattered, the linear regression line in Figure 34 indicates that the threshold RMS value of 0.5 m/s^2 corresponds to an IRI value of 186 in/mi. This generally indicates that the user may not feel too uncomfortable when driving on low-speed facilities, as long as the IRI is approximately below 186 in/mi.

When user comfort is concerned, the effect of IRI is more pronounced for high-speed facilities. In contrast, IRI may have less impact on user comfort for low-speed facilities. More specifically, the RMS threshold of 0.5 m/s^2 corresponds to an IRI value of 66 in/mi and 186 in/mi for high-speed and low-speed facilities, respectively. This generally indicates that compared to the IRI requirement for high-speed facilities, the IRI requirement for low-speed facilities may be relaxed to a certain degree without jeopardizing the level of user comfort significantly. However, user comfort should not be the only factor determining the IRI requirement. Other factors and benefits (e.g., improved pavement performance, increased pavement life, reduced user cost such as fuel consumption, etc.) must be considered in determining the IRI requirements.

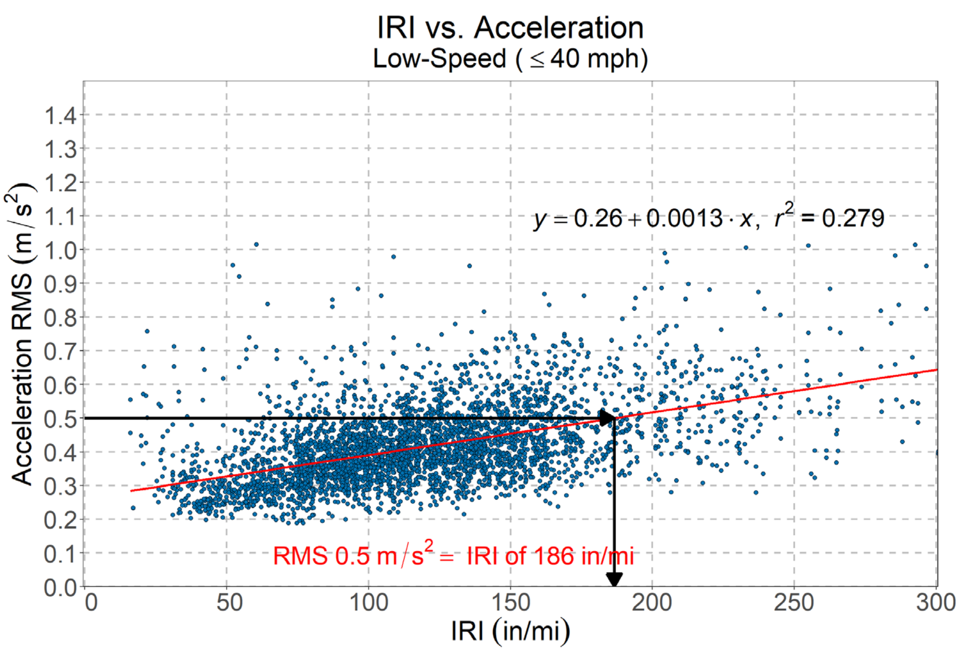


Figure 34. Graph. IRI versus acceleration RMS for low-speed facilities.

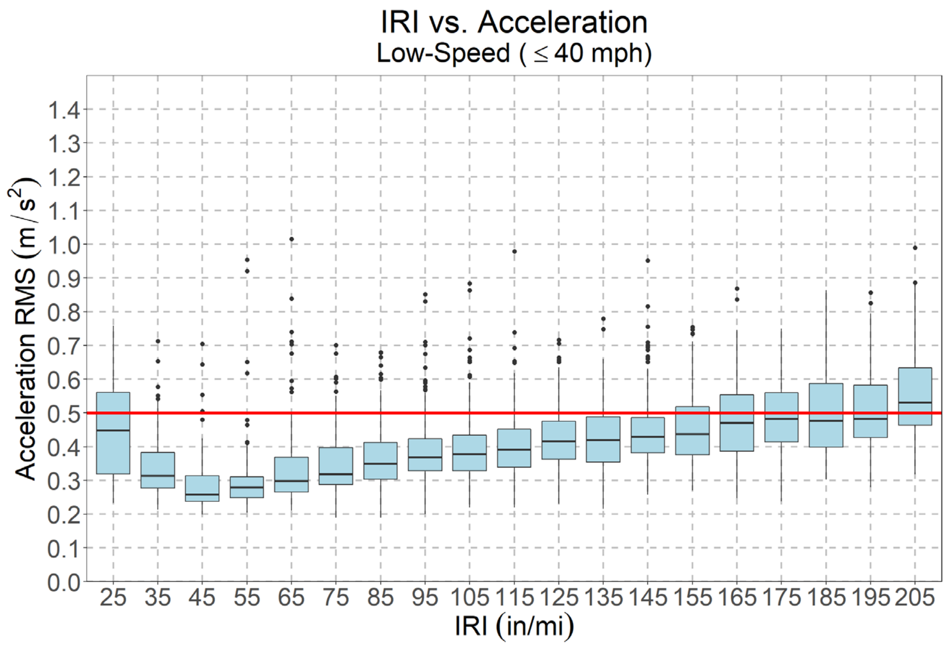


Figure 35. Graph. Box plot for IRI versus acceleration RMS obtained from low-speed facilities.

CHAPTER 3: DEVELOPMENT OF IRI SMOOTHNESS SPECIFICATION

Chapter 2 documented the efforts made to assess the benefits of smoother pavements in terms of pavement performance (i.e., pavement life), life cycle cost (i.e., agency and user costs), safety, and user perception (i.e., comfort level). The focus of this chapter is on the development of IDOT's new IRI-based smoothness specification. The components of the smoothness specification discussed in this chapter include IRI thresholds for full pay, incentive, and disincentive; smoothness assessment schedule (i.e., payment schedule); and area of localized roughness (ALR).

IRI THRESHOLDS

This section documents the IRI thresholds developed for high-speed and low-speed facilities. Because IDOT's existing smoothness specification is based on a different smoothness index (namely the profile index), the potential impact of moving towards an IRI-based specification is assessed using a simple, risk analysis approach.

High-Speed Facilities

High-speed facilities are defined as roadways with a posted speed limit greater than 40 mph. Because user comfort level was more sensitive to IRI at higher speeds, the IRI thresholds for high-speed facilities will be discussed first.

Development of IRI Thresholds

As shown in Figure 32, a linear regression between IRI and the acceleration RMS indicated that the RMS threshold of 0.5 m/s^2 corresponds to an IRI of 66 in/mi for high-speed facilities. This observation suggests that, at least roughly, the IRI value should be reasonably close to 66 in/mi in order to provide users with smooth-riding pavements. Due to the large amount of scattered data found above and below the regression line, the IRI distributions shown in Figure 33 and Table 2 were considered for establishing the IRI thresholds, as described in the following.

- It would be ideal if the IRI thresholds for full pay could be established at the levels that guarantee user comfort (i.e., acceleration RMS mostly below 0.5 m/s^2). However, this is likely impractical and unrealistic, as user comfort is a subjective parameter with many uncertainties. Therefore, an IRI value of 75 in/mi was selected for the upper limit of the full-pay threshold. According to Table 2, this IRI value corresponds to the upper IRI limit, which provides a 50% chance of having comfortable ride quality (more specifically, a 50% chance of the acceleration RMS being below 0.49 m/s^2).

- An IRI value of 45 in/mi was selected for the lower limit of the full-pay threshold (or equivalently the upper limit of the incentive threshold). IRI values below 45 in/mi qualify for incentive payments. According to Table 2, the IRI value of 45 in/mi corresponds to the upper IRI limit, which provides a 75% chance of having comfortable ride quality (more specifically, a

75% chance of the acceleration RMS being below 0.49 m/s^2). Furthermore, IRI values below this range are expected to have higher chances of providing improved ride quality.

- An IRI value of 100 in/mi was selected for the upper limit of the disincentive threshold (or equivalently the lower limit at which corrective action is required). As shown in Figure 33, the acceleration RMS mostly exceeds 0.5 m/s^2, starting at this level of IRI. This level of discomfort is unacceptable, especially for newly constructed pavement surfaces.

Note that the above thresholds were determined solely based on the inferences made from the relationship between IRI and user comfort level. As such, the above thresholds should be applied to all types (e.g., full-depth HMA, JPCP, etc.) of newly constructed pavements to ensure that IDOT continues to provide roadway users with smooth pavements.

In the case of major rehabilitation such as HMA overlays, past studies have shown that IRI achieved after construction of the overlay may be affected by IRI of the existing pavement (before construction) or the HMA lift directly below the final lift (Clark and McGhee, 2003; Kwon et al., 2015). As such, it was deemed feasible to relax the IRI requirement for HMA overlays to be constructed in areas where the existing IRI was significantly higher than the abovementioned IRI thresholds.

To study the effect of existing IRI on the IRI achieved after HMA overlay, IDOT's data included in the "Before and After Sections" were investigated. The data consisted of IRI values collected on IDOT's roadways before any construction began for the HMA overlay, which will be designated as "Before IRI." In addition, the IRI values were collected again within the same section limits after the HMA overlay had been placed, which will be referred to as "After IRI."

Figure 36 shows the scatterplot between Before and After IRI for all 0.1 mi sections included in the database. Despite the significant amount of scatter, the figure generally confirms the findings from the literature: the After IRI is highly variable and likely higher when the Before IRI is high to begin with. A linear regression line is also shown, which has a slope of approximately 0.2. The regression line further indicates that the After IRI of 75 in/mi (i.e., the upper full-pay threshold discussed above) corresponds to a Before IRI of approximately 125 in/mi. Therefore, the following IRI thresholds were established for HMA overlays.

- Pavements with existing IRI (IRI_{Before}) less than or equal to 125 in/mi will be subjected to the same IRI thresholds as new construction projects. In other words, the IRI thresholds of 45 in/mi, 75 in/mi, and 100 in/mi will be used for upper limit of incentive ($IRI_{Incentive}$), upper limit of full pay ($IRI_{FullPay}$), and upper limit of disincentive ($IRI_{Disincentive}$), respectively.

- Pavements with IRI_{Before} greater than 125 in/mi will be subjected to higher IRI thresholds, increasing linearly with a slope of 0.2. The equations for determining $IRI_{Incentive}$, $IRI_{FullPay}$, and $IRI_{Disincentive}$ are shown in Figure 37, Figure 38, and Figure 39, respectively. The intercept of the linear equation was determined to ensure continuity of the threshold value. For example, one obtains $IRI_{FullPay}$ of 75 in/mi by substituting IRI_{Before} of 125 in/mi in Figure 38.

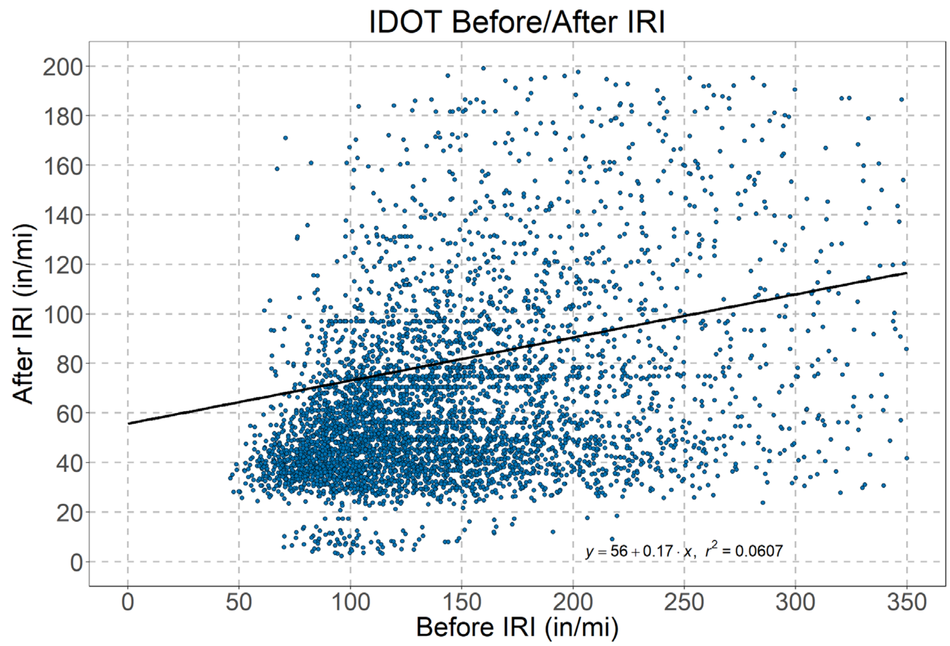


Figure 36. Graph. IRI of existing pavement vs. IRI after construction.

$$IRI_{Incentive} = 0.2 \cdot IRI_{Before} + 20$$

Figure 37. Equation. High-speed upper incentive IRI threshold for existing IRI greater than 125 in/mi.

$$IRI_{FullPay} = 0.2 \cdot IRI_{Before} + 50$$

Figure 38. Equation. High-speed upper full pay IRI threshold for existing IRI greater than 125 in/mi.

$$IRI_{Disincentive} = 0.2 \cdot IRI_{Before} + 75$$

Figure 39. Equation. High-speed upper disincentive IRI threshold for existing IRI greater than 125 in/mi.

Figure 40 shows a graphical illustration of the IRI thresholds described above. There is a vertical dashed line corresponding to the Before IRI value of 125 in/mi, below which the IRI thresholds remain constant (i.e., same thresholds as new construction projects).

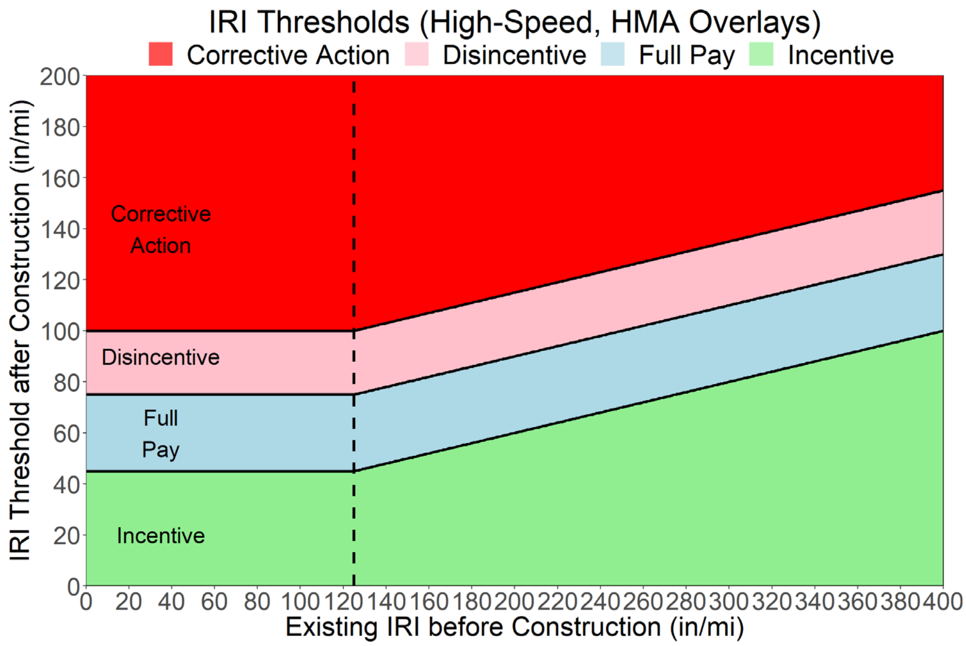


Figure 40. Graph. IRI of existing pavement vs. IRI thresholds after construction for high-speed facilities.

Assessment of Practical Achievability

In order for the IRI thresholds to be practical, it is important to check that the thresholds are realistic and achievable. For this purpose, the distribution of After IRI values is studied first and shown in Figure 41. The distribution is clearly skewed with most of the IRI values below 100 in/mi.

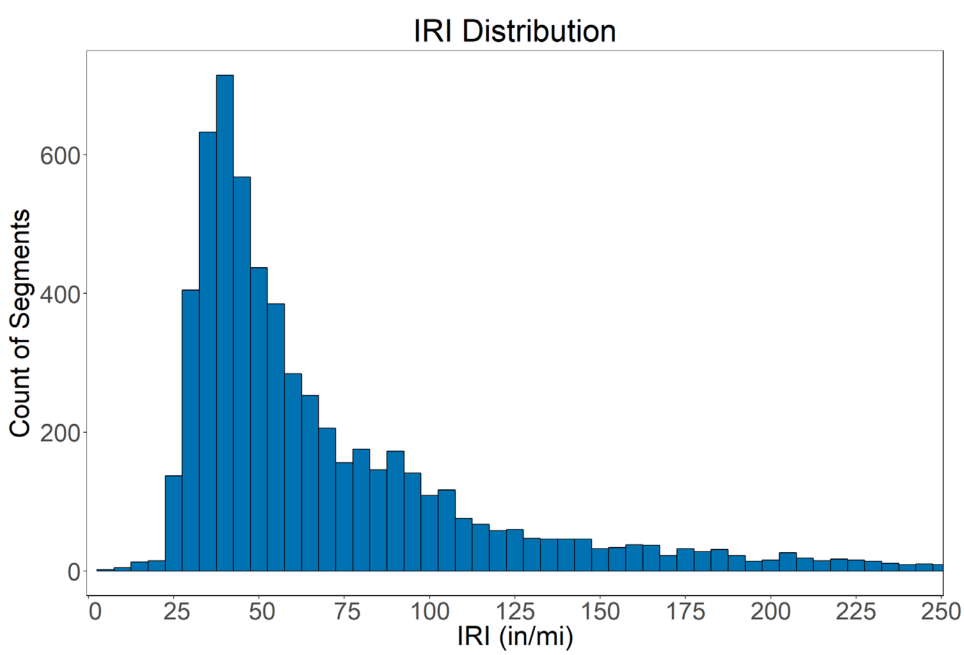


Figure 41. Graph. Distribution of After IRI.

From the After IRI distribution shown in Figure 41, the percentiles corresponding to IRI values of 45 in/mi, 75 in/mi, and 100 in/mi were calculated to be 36th, 67th, and 79th, respectively. These numbers generally indicate that the new IRI requirements are achievable, as they can be interpreted as the following.

- There is approximately a 67% chance that the After IRI will be below 75 in/mi. In other words, there is a 67% chance that an arbitrary 0.1 mi segment will receive full pay or incentive, with the following breakdown.
    - There is approximately a 36% chance of incentive (i.e., IRI below 45 in/mi).
    - There is approximately a 31% chance of full pay (i.e., IRI between 45 in/mi and 75 in/mi).
- There is approximately a 33% chance that the After IRI will be above 75 in/mi. In other words, there is a 33% chance that an arbitrary 0.1 mi segment will receive disincentive or corrective action, with the following breakdown.
    - There is approximately a 12% chance of disincentive (IRI between 75 in/mi and 100 in/mi).
    - There is approximately a 21% chance of corrective action (i.e., IRI above 100 in/mi).

Note, however, that the above estimates are crude at best because the After IRI distribution shown in Figure 41 and the corresponding percentiles were obtained without considering Before IRI. In other words, increased IRI thresholds for existing pavements with IRI greater than 125 in/mi were not considered in the probability estimates. Nonetheless, these crude estimates can be used as conservative measures of probability when Before IRI data is not available.

In order to gain a better estimate of the probabilities for incentive, full pay, and disincentive, the Before/After data shown in Figure 36 was superimposed on top of the threshold levels shown in Figure 40. The resulting graph is shown in Figure 42, from which the following estimates were made.

- There is approximately a 72% chance that a 0.1 mi segment will receive full pay or incentive, with the following breakdown.
    - There is approximately a 39% chance of incentive.
    - There is approximately a 33% chance of full pay.
- There is approximately a 28% chance that a 0.1 mi segment will receive disincentive or corrective action, with the following breakdown.
    - There is approximately a 10% chance of disincentive.
    - There is approximately an 18% chance of corrective action.

Note that the probabilities of full pay and incentive increased and the probabilities of disincentive and corrective action decreased with the incorporation of Before IRI and the increased IRI thresholds for Before IRI values greater than 125 in/mi.

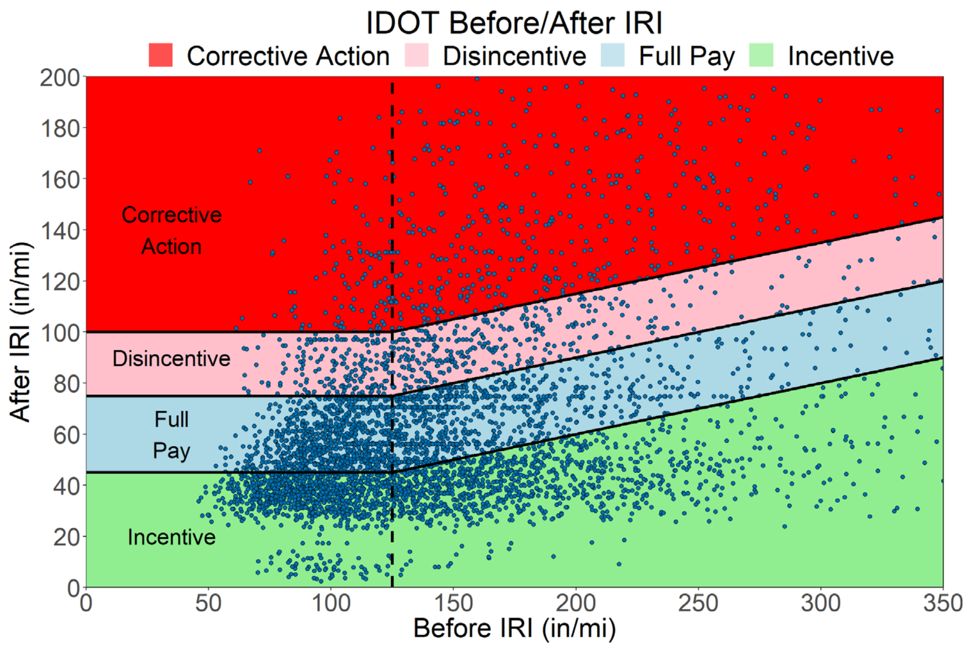


Figure 42. Graph. Before/After data superimposed on top of high-speed IRI thresholds.

The probabilities discussed above generally indicate that the chances are higher for full pay or incentive than those for disincentive or corrective actions, irrespective of Before IRI (and the increased IRI threshold) consideration. Based on these findings, it is concluded that the IRI thresholds are realistic and achievable.

Risk Analysis

Because the new smoothness specification will be based on IRI, which is different from the PI that has been used in IDOT's existing specification, it is also of interest to assess the impact or risk associated with moving to a new (or different) smoothness index.

The "risk" discussed herein is not truly a risk in the sense that it is not associated with the probability of constructing rougher pavements. Instead, the risk should be taken as the probability of disagreement between the PI-based and IRI-based specifications (e.g., a 0.1 mi segment being accepted based on PI specification but rejected based on IRI specification, and vice versa). Accordingly, the "reliability" in this context does not represent the reliability of constructing smoother pavements but represents the probability of obtaining the same result (accept vs. reject) from the two specifications.

Figure 43 shows a plot between PI and IRI values obtained from the After dataset of Before/After sections. The same pavement profiles used for calculating the After IRI were used again to calculate PI. Although the figure shows a strong relationship between the two smoothness indices with an R^2

value of 0.93, the correlation between PI and IRI is not perfect, as evidenced by the data scattered above and below the regression line.

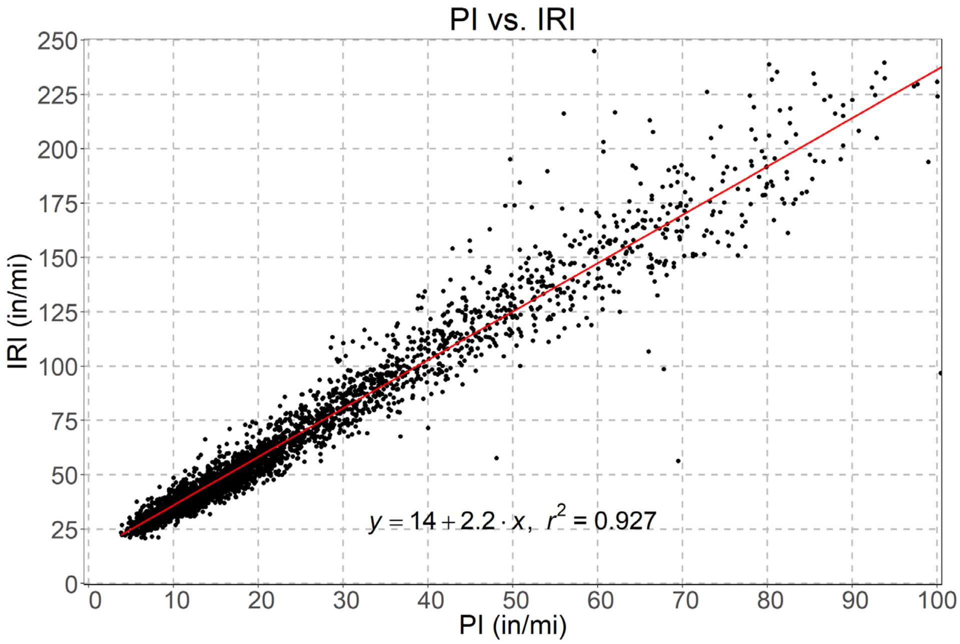


Figure 43. Graph. PI versus IRI.

The scattered data and associated uncertainties in the PI versus IRI relationship may produce different conclusions when used in their respective specifications. To demonstrate this point, Figure 44 shows the same scattered data previously shown in Figure 43 without the regression line. Instead, this figure shows a horizontal line corresponding to 75 in/mi (i.e., the upper full-pay IRI threshold for new construction projects) and a vertical line at 30 in/mi (i.e., the upper full-pay PI threshold for new construction projects) that are used to divide the plot into four quadrants.

The data points in the lower left quadrant correspond to the 0.1 mi segments that are accepted (i.e., incentive or full pay) by both specifications (PI and IRI). The upper right quadrant includes those that are rejected (i.e., disincentive or corrective action) by both specifications. Although the two specifications are based on two different smoothness indices, they both produced the same result in terms of accepting or rejecting the pavement. In contrast, the data points within the upper left and lower right quadrants represent the pavement segments that are accepted by one of the two specifications, but rejected by the other (i.e., disagreement or risk within this context).

The reliability (i.e., the probability of IRI-based specification producing the same outcome as PI-based specification) can be estimated simply as the percent occurrence of the data points within the agreement region (i.e., lower left and upper right quadrants in Figure 44). Similarly, the risk (i.e., the probability of disagreement) can be estimated from the data points in the disagreement region (i.e., upper left and lower right quadrants). For the case shown in Figure 44, the reliability and risk were found to be 95.6% and 4.4%, respectively.

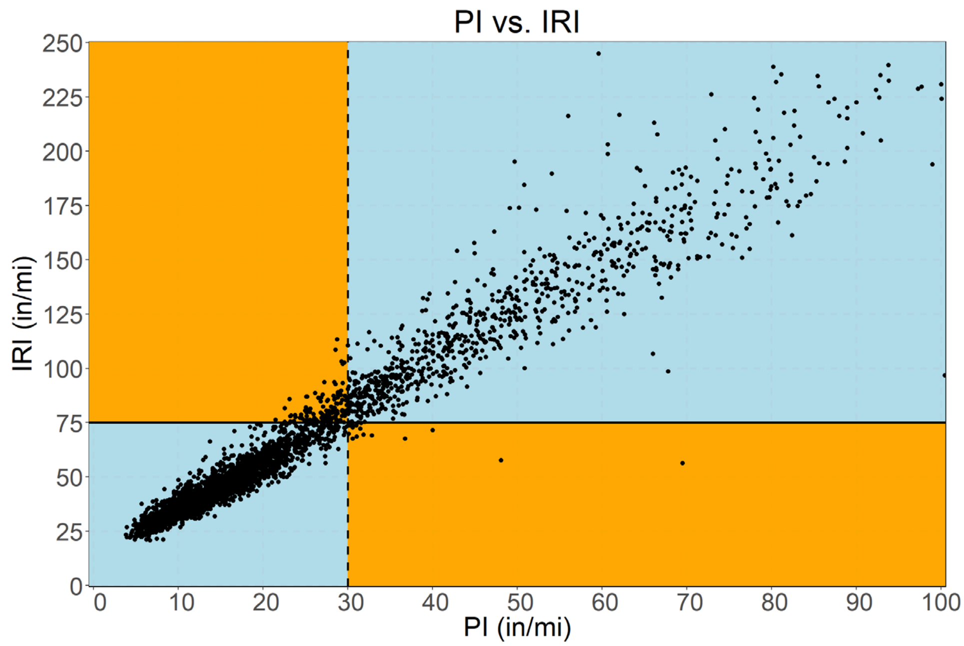


Figure 44. Graph. PI versus IRI with respective thresholds for high-speed facilities.

Note that the above reliability and risk depend on the IRI threshold. If the upper full-pay IRI threshold is changed from 75 in/mi to a different value in Figure 44, then both the reliability and risk will be affected. Figure 45 shows how the reliability and risk varies with different full-pay IRI thresholds. The figure shows that one may expect over 95% reliability and less than 5% risk when the IRI threshold for full pay is set between 74 in/mi and 92 in/mi.

Figure 45 also indicates that the highest reliability (and the lowest risk) may be achieved when the IRI threshold is set to 82 in/mi. The corresponding reliability and risk are found to be 97.1% and 2.9%, respectively. Although one may think that this level of IRI should be selected as the threshold to minimize the risk, it is important to understand that the purpose of risk analysis was not necessarily to establish new IRI thresholds. Instead, the purpose was to assess the effect of transitioning from a PI-based specification to an IRI-based specification with the IRI thresholds determined from other factors such as user comfort (i.e., independent of PI).

Note that the risk analysis was carried out based on the inherent scattered data found in the relationship between PI and IRI. As such, the assessed reliability and risk should only be used to acknowledge that when implemented, the IRI-based specification may produce different results compared to the PI-based specification. Furthermore, the risk within this context does not imply which smoothness index is better or worse. Higher (or lower) risk only means that there are more (or less) differences between the two specifications being compared and both IDOT and the contractors may need to spend more (or less) effort to adapt to the new specification.

Based on the above discussions, the upper full-pay IRI threshold of 75 in/mi, which produced a reliability of 95.6% and a corresponding risk of 4.4%, is reasonable.

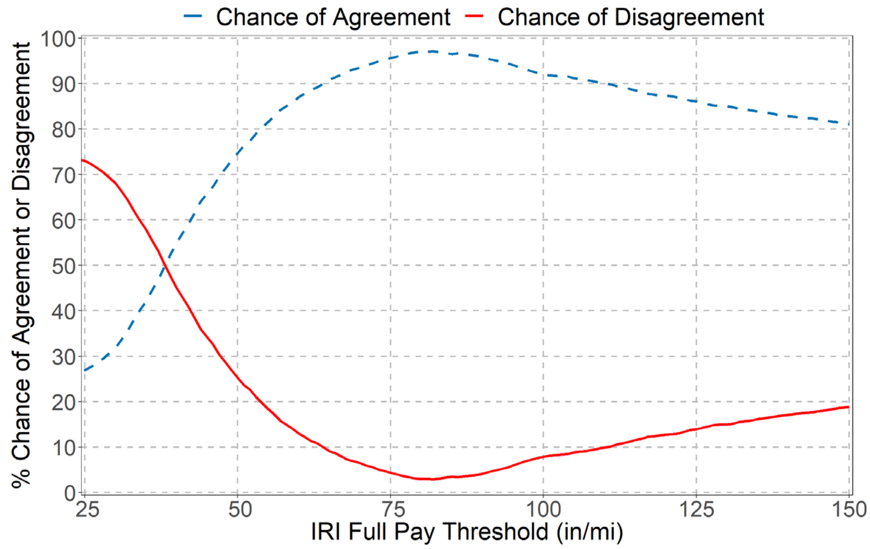


Figure 45. Graph. Reliability and risk curves for high-speed facilities.

Low-Speed Facilities

Development of IRI Thresholds

Unlike high-speed facilities, IRI values for low-speed facilities were less critical when user comfort is considered. Figure 34 indicated that the acceleration RMS threshold value of 0.5 m/s^2 corresponds to an IRI value of 186 in/mi, and Figure 35 showed that the acceleration RMS values are mostly below 0.5 m/s^2 for IRI values less than 155 in/mi.

While the above IRI values may be adequate when user comfort levels are considered, these values were excessively high for smoothness specification purposes. As discussed in the previous chapter, pavements with lower initial IRI values may result in increased pavement life, lower life cycle cost, and improved safety. As such, the following IRI thresholds were determined based on engineering judgement after discussions with IDOT.

- An IRI value of 95 in/mi has been selected for the upper limit of the full-pay threshold.
- An IRI value of 55 in/mi has been selected for the lower limit of the full-pay threshold (or equivalently the upper limit of the incentive threshold).
- An IRI value of 125 in/mi has been selected for the upper limit of the disincentive threshold (or equivalently the lower limit at which corrective action is required).

Again, the above thresholds are to be applied to all types of newly constructed pavements. For HMA overlay projects with higher existing IRI, the Before/After IRI regression (Figure 36) indicated that the After IRI of 95 in/mi corresponds to a Before IRI of approximately 220 in/mi. Therefore, the following IRI thresholds were established for HMA overlays (similar to those for high-speed facilities).

- Pavements with existing IRI (IRI_{Before}) less than or equal to 220 in/mi will be subjected to the same IRI thresholds as new construction projects. In other words, the same IRI thresholds of 55 in/mi, 95 in/mi, and 125 in/mi mentioned above will be used for upper limit of incentive ($IRI_{Incentive}$), upper limit of full pay ($IRI_{FullPay}$), and upper limit of disincentive ($IRI_{Disincentive}$), respectively.

- Pavements with IRI_{Before} greater than 220 in/mi will be subjected to higher IRI thresholds, increasing linearly with a slope of 0.2. The equations for determining $IRI_{Incentive}$, $IRI_{FullPay}$, and $IRI_{Disincentive}$ are shown in Figure 46, Figure 47, and Figure 48, respectively. The intercept of the linear equation was determined to ensure continuity of the threshold value. For example, one obtains $IRI_{FullPay}$ of 95 in/mi by substituting IRI_{Before} of 220 in/mi in Figure 47.

$$IRI_{Incentive} = 0.2 \cdot IRI_{Before} + 11$$

Figure 46. Equation. Low-speed upper incentive IRI threshold for existing IRI greater than 220 in/mi.

$$IRI_{FullPay} = 0.2 \cdot IRI_{Before} + 51$$

Figure 47. Equation. Low-speed upper full-pay IRI threshold for existing IRI greater than 220 in/mi.

$$IRI_{Disincentive} = 0.2 \cdot IRI_{Before} + 81$$

Figure 48. Equation. Low-speed upper disincentive IRI threshold for existing IRI greater than 220 in/mi.

The above IRI thresholds are graphically illustrated in Figure 49, which also shows a vertical dashed line corresponding to the Before IRI value of 220 in/mi, below which the IRI thresholds remain constant (i.e., same thresholds as new construction projects).

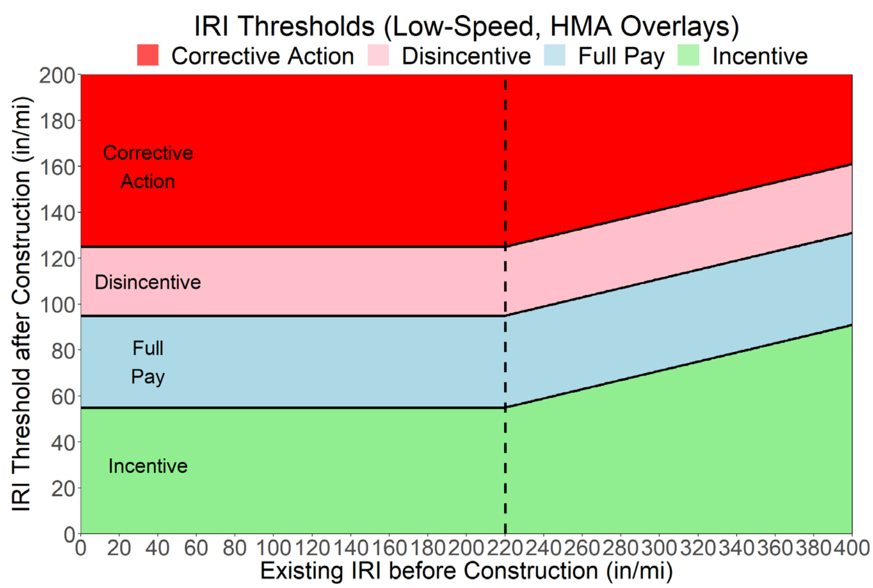


Figure 49. Graph. IRI of existing pavement vs. IRI thresholds after construction for low-speed facilities.

Assessment of Practical Achievability

Similar to the method for high-speed facilities, the probabilities for incentive, full pay, and disincentive were determined by superimposing the Before/After data shown in Figure 36 on top of the threshold levels shown in Figure 49. Figure 50 shows the superimposed graph, from which the following estimates were made.

- There is approximately a 78% chance that a 0.1 mi segment will receive full pay or incentive, with the following breakdown.
    - There is approximately a 48% chance of incentive.
    - There is approximately a 30% chance of full pay.
- There is approximately a 22% chance that a 0.1 mi segment will receive disincentive or corrective action, with the following breakdown.
    - There is approximately an 8% chance of disincentive.
    - There is approximately a 14% chance of corrective action.

Based on the above probabilities, or more specifically the higher percent chances observed for full pay and incentive, the IRI thresholds for low-speed facilities are realistic and achievable.

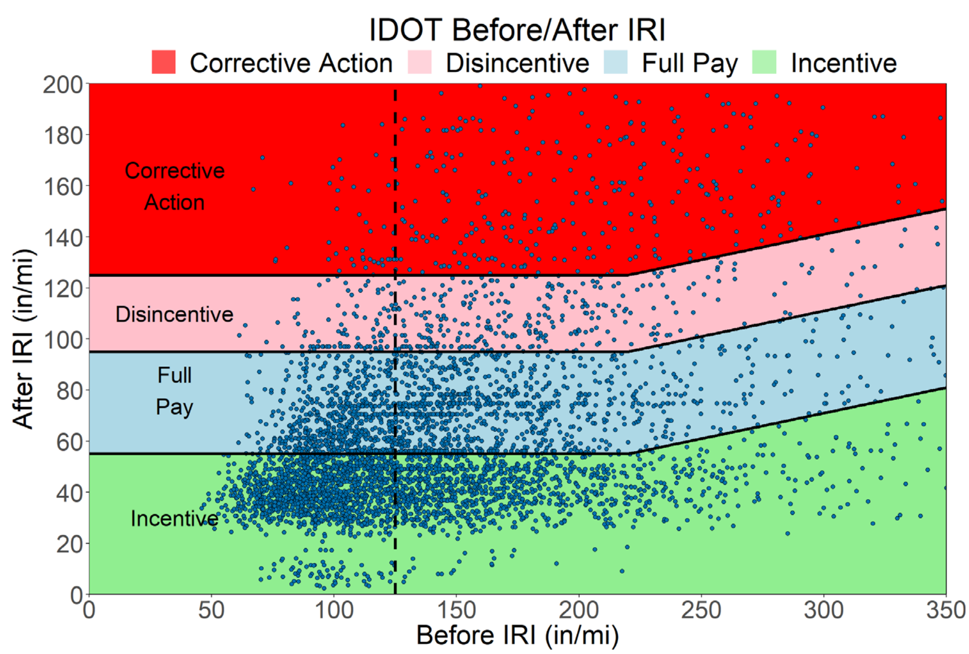


Figure 50. Graph. Before/After data superimposed on top of low-speed IRI thresholds.

Risk Analysis

The risk analysis for low-speed facilities followed the same procedure as high-speed facilities. Figure 51 shows the PI vs. IRI data scattered with the plot area divided into four quadrants by a horizontal line corresponding to 95 in/mi (i.e., the upper full-pay IRI threshold for low-speed new construction projects) and a vertical line at 45 in/mi (i.e., the upper full-pay PI threshold for low-speed new construction projects). Compared to its counterpart for high-speed facilities (Figure 44), the increased number of data points are observed in the disagreement zones of Figure 51 (especially in the upper left quadrant). This suggests that a higher risk is expected for low-speed facilities.

Figure 52 shows the reliability and risk curves for different full-pay IRI thresholds. The figure indicated that the IRI thresholds need to be within 98 in/mi and 141 in/mi for the reliability to be greater than 95% and the risk to be less than 5%. The full-pay IRI threshold determined previously (95 in/mi) was outside this range and provided a slightly lower reliability of 93.4% with a corresponding risk of 6.6%. Nevertheless, for practical considerations, these numbers are considered to be reasonable.

The above numbers indicate that a higher risk is expected on low-speed facilities than high-speed facilities. This means that the disagreement between the PI-based specification and the IRI-based specification is expected to occur more frequently on low-speed facilities. Said differently, implementation of the IRI-based specification may face more challenges on low-speed facilities than on high-speed facilities.

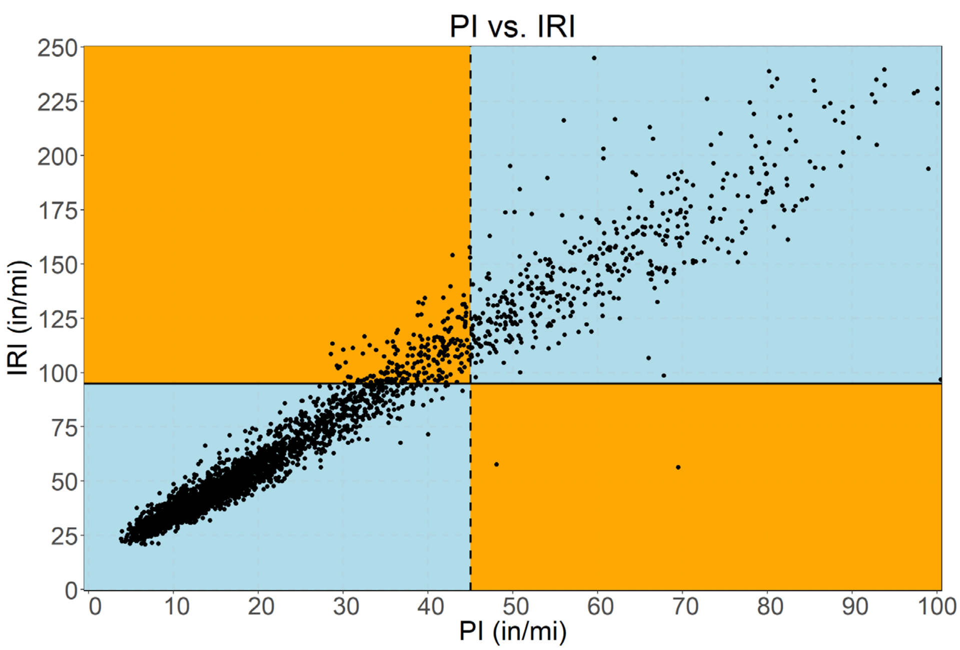


Figure 51. Graph. PI versus IRI with respective thresholds for low-speed facilities.

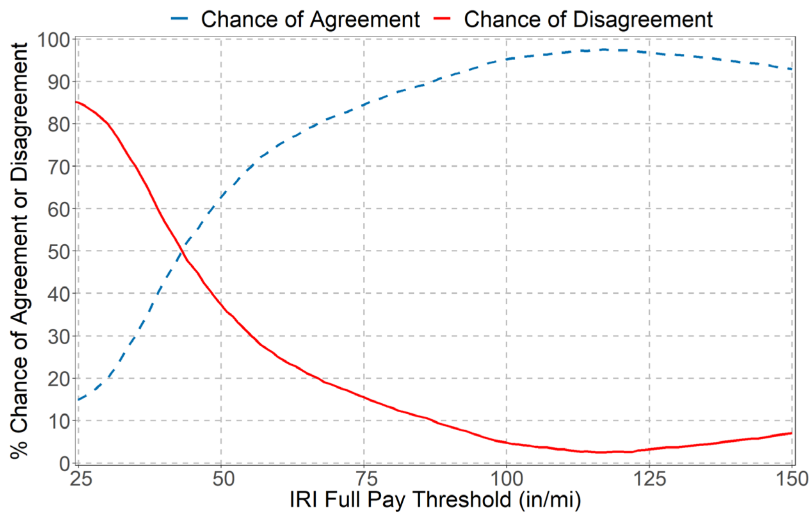


Figure 52**. Graph. Reliability and risk curves for low-speed facilities.**

SMOOTHNESS ASSESSMENT SCHEDULE

The previous section focused on the development of IRI thresholds for incentive, full pay, and disincentive zones, both for high-speed and low-speed facilities. In addition, risk analyses were performed to assess the potential impact of moving from a PI-based specification to an IRI-based specification with the developed IRI thresholds.

Another important component of the smoothness specification is the pay schedule, which will also be referred to as the "Smoothness Assessment Schedule." The purpose of the smoothness assessment schedule is to define the incentive and disincentive payment amounts to be used with IRI thresholds.

Development of Smoothness Assessment Schedules

Development of the smoothness assessment schedule involved the following.

1. Considering the current economy and recent cost for pavement construction, IDOT recommended that the following limits are feasible for incentive and disincentive payments of a 0.1 mi sublot.

    a. For full-depth HMA, the incentive payment shall not exceed $1,200 and the disincentive payment shall not exceed −$750.

    b. For HMA overlays, the incentive payment shall not exceed $500 and the disincentive payment shall not exceed −$500.

    c. For Portland cement concrete (PCC) roadways, the incentive payment shall not exceed $1,800 and the disincentive payment shall not exceed −$1,125.

2. The range of IRI values have been determined for which of the above incentive and disincentive limits are to be applied.

a. For high-speed facilities, the maximum incentive amount is to be paid for any sublot with an achieved IRI of 30 in/mi or less. For low-speed facilities, the maximum incentive is to be paid for any sublot with an IRI value less than 40 in/mi.

b. The maximum disincentives are applied to any sublots having an IRI value greater than or equal to the upper IRI limit of the disincentive threshold (or equivalently the lower IRI limit at which corrective action is required) determined previously. These IRI values correspond to 100 in/mi for high-speed facilities and 125 in/mi for low-speed facilities.

3. To ensure continuity within the smoothness assessment schedule, the remaining regions are connected back to the full-pay region (where there is no incentive or disincentive) in a linear fashion.

A graphical illustration of the smoothness assessment schedule established based on the above procedure is shown in Figure 53 for high-speed facilities. For HMA overlays, the assessment schedule shown in Figure 53 applies only if the IRI of the existing pavement was less than or equal to 125 in/mi. As noted earlier, if the IRI of the existing pavement was higher than 125 in/mi, the IRI thresholds are relaxed according to the equations shown in Figure 37, Figure 38, and Figure 39. Graphically, this is equivalent to shifting the HMA overlay curve shown in Figure 53 toward the right-hand side.

As an example, Figure 54 shows the updated assessment schedule to be used on pavements with existing IRI of 200 in/mi. Note that for this particular condition, the contractor receives full pay when the achieved IRI is between 60 in/mi and 90 in/mi (rather than 45 in/mi to 75 in/mi). Moreover, the maximum incentive can be paid at IRI less than or equal to 45 in/mi (rather than 30 in/mi) and the maximum disincentive threshold (above which corrective action is required) has also been relaxed to 115 in/mi (from 100 in/mi).

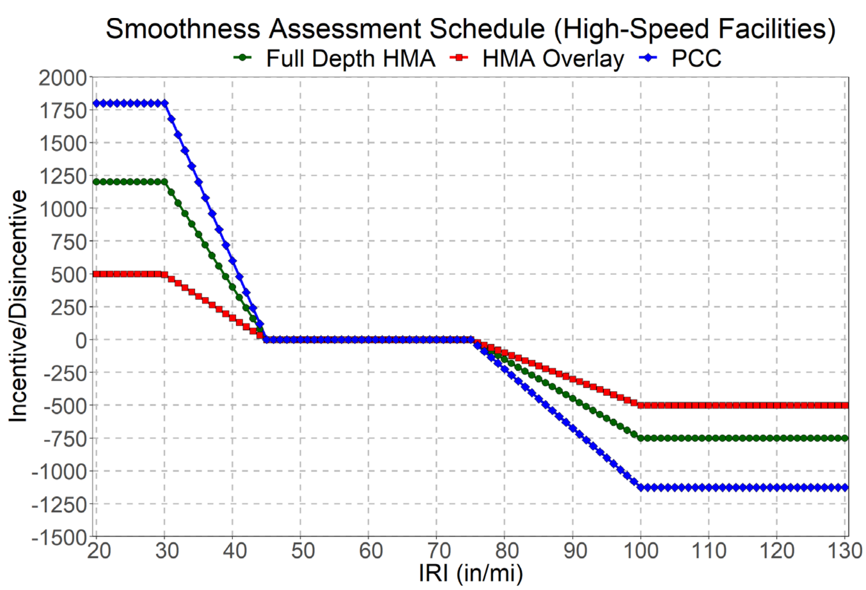


Figure 53. Graph. Smoothness assessment schedule for high-speed full-depth HMA, HMA overlay, and PCC.

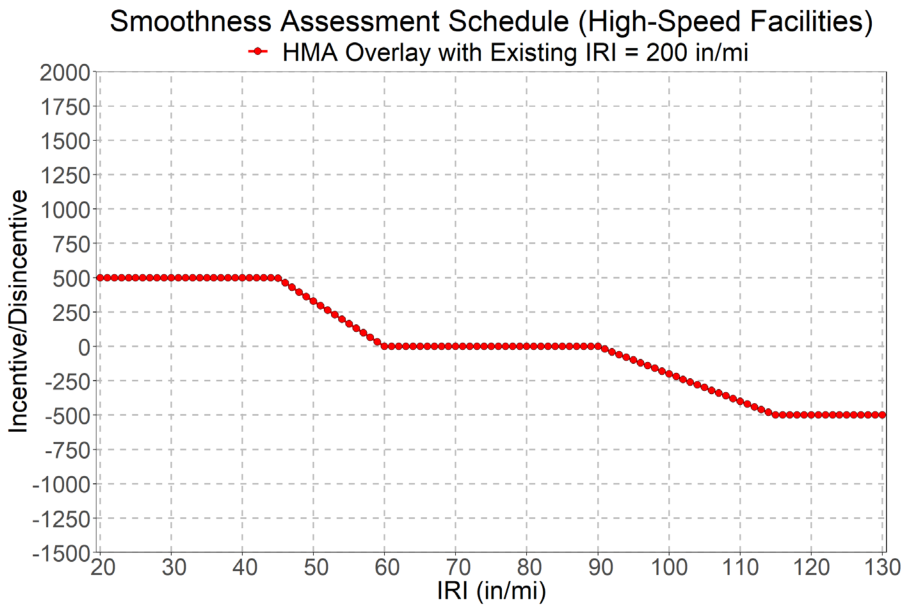


Figure 54. Graph. Smoothness assessment schedule for HMA overlay on high-speed roadways with existing IRI of 200 in/mi.

Similarly, Figure 55 shows the smoothness assessment schedule for low-speed facilities. The HMA overlay assessment schedule shown in this figure applies only if the IRI of the existing pavement was less than or equal to 220 in/mi. For pavements with higher existing IRI, the assessment curve shown in the figure should be shifted to the right. An example corresponding to the existing IRI of 350 in/mi is shown in Figure 56.

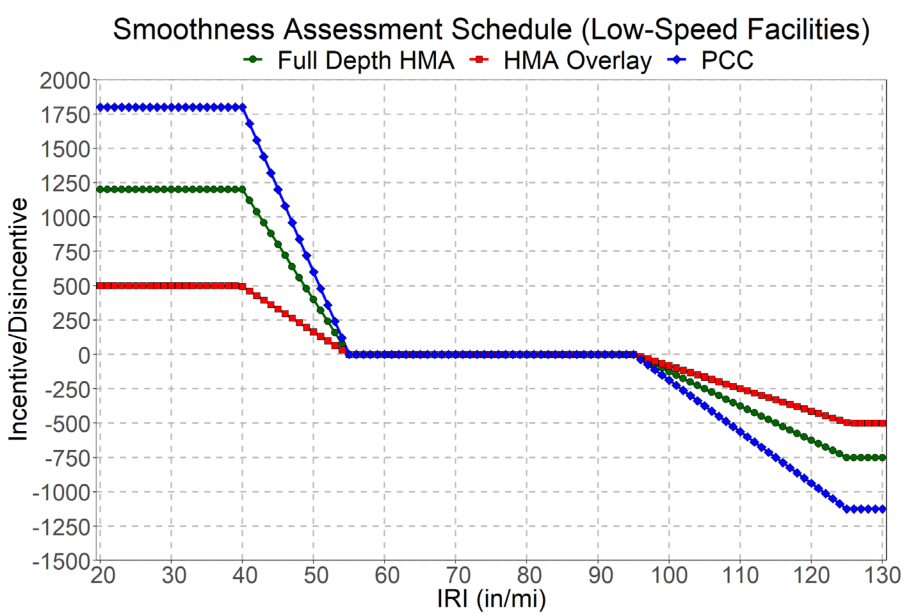


Figure 55. Graph. Smoothness assessment schedule for low-speed full-depth HMA, HMA overlay, and PCC.

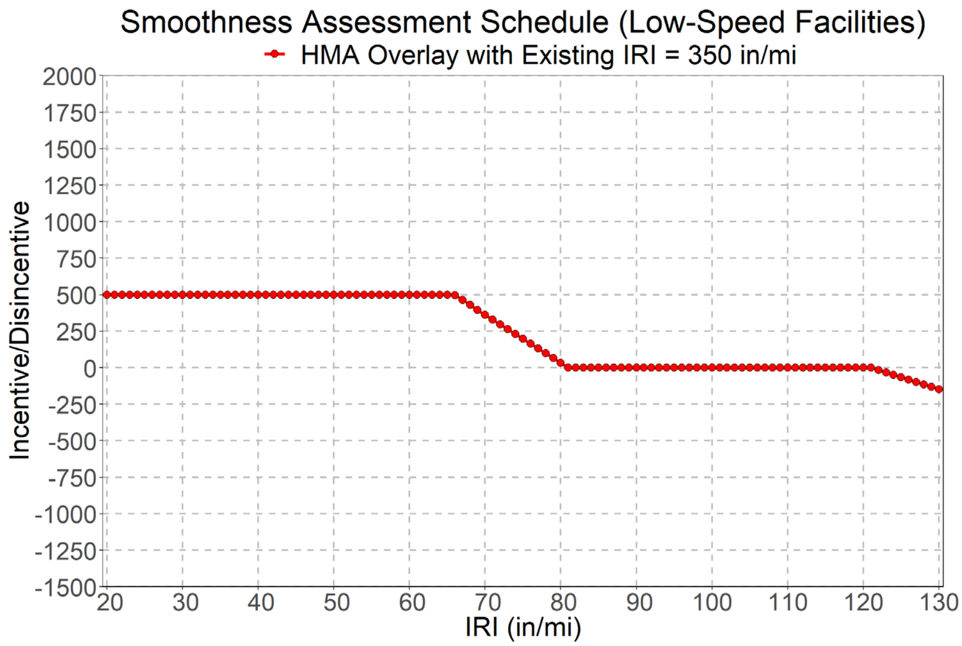


Figure 56. Graph. Smoothness assessment schedule for HMA overlay on low-speed roadways with existing IRI of 350 in/mi.

Benefit versus Cost

Based on the IRI thresholds as well as the smoothness assessment schedule developed in the previous sections of the report, a benefit-cost analysis (BCA) was carried out with the following objectives:

1. To calculate the expected benefit and cost for any given (i.e., arbitrary) sublot.
2. To compare the benefit and cost expected from high-speed and low-speed facilities.
3. To provide a cursory check that the benefit exceeds agency cost.

The BCA was carried out as a continuation of the LCCA described in the previous chapter. As such, the benefits pertaining to pavement life and life cycle cost will be reexamined.

Pavement Life Benefits

For the context of pavement life, the benefit is defined herein as the extended pavement life expected due to lower initial IRI (i.e., smoother pavement). Within the LCCA framework, Figure 17 showed that, in general, smoother pavements may exhibit longer pavement life. However, the figure does not necessarily quantify the benefit in the sense that it lacks a reference pavement life from which the benefit (i.e., life extension) or loss (i.e., life reduction) is estimated.

Owing to the IRI thresholds developed previously, it is believed that the feasible “reference pavement life” can be obtained as the expected pavement life corresponding to the initial IRI equal to the upper full-pay IRI threshold (i.e., 75 in/mi for high speed and 95 in/mi for low speed). From Figure 17, the reference pavement lives are found to be 22 years and 18 years for high-speed and low-speed facilities, respectively.

The benefit or the extended pavement life was then calculated as the reference pavement life subtracted from the expected pavement life corresponding to any IRI_0. Equivalently, the extended life curve can be obtained by shifting the pavement life curve shown in Figure 17 downwards such that IRI_0 of 75 in/mi (for high speed) or 95 in/mi (for low speed) coincides to an extended pavement life of zero. Figure 57 and Figure 58 show these results obtained for high-speed and low-speed facilities, respectively. Observations made from these figures are provided in the following.

- For high-speed facilities, nine years of extended pavement life can be expected if the initial IRI is reduced from 75 in/mi (i.e., upper full-pay threshold) to 45 in/mi (i.e., lower full-pay threshold).
    - This also means that IDOT may expect at least nine years of additional pavement life for any sublot that received an incentive payment.
- For high-speed facilities, five years of reduced pavement life can be expected if the initial IRI is increased from 75 in/mi (i.e., upper full-pay threshold) to 100 in/mi (i.e., upper disincentive threshold or lower threshold at which corrective action is required).
    - This also means that IDOT may expect up to five years of reduced pavement life for any sublot that received a disincentive payment.
- For low-speed facilities, nine years of extended pavement life can be expected if the initial IRI is reduced from 95 in/mi (i.e., upper full-pay threshold) to 55 in/mi (i.e., lower full-pay threshold).
    - This also means that IDOT may expect at least nine years of additional pavement life for any sublot that received an incentive payment.
- For low-speed facilities, four years of reduced pavement life can be expected if the initial IRI is increased from 95 in/mi (i.e., upper full pay threshold) to 125 in/mi (i.e., upper disincentive threshold or lower threshold at which corrective action is required).
    - This also means that IDOT may expect up to four years of reduced pavement life for any sublot that received a disincentive payment.

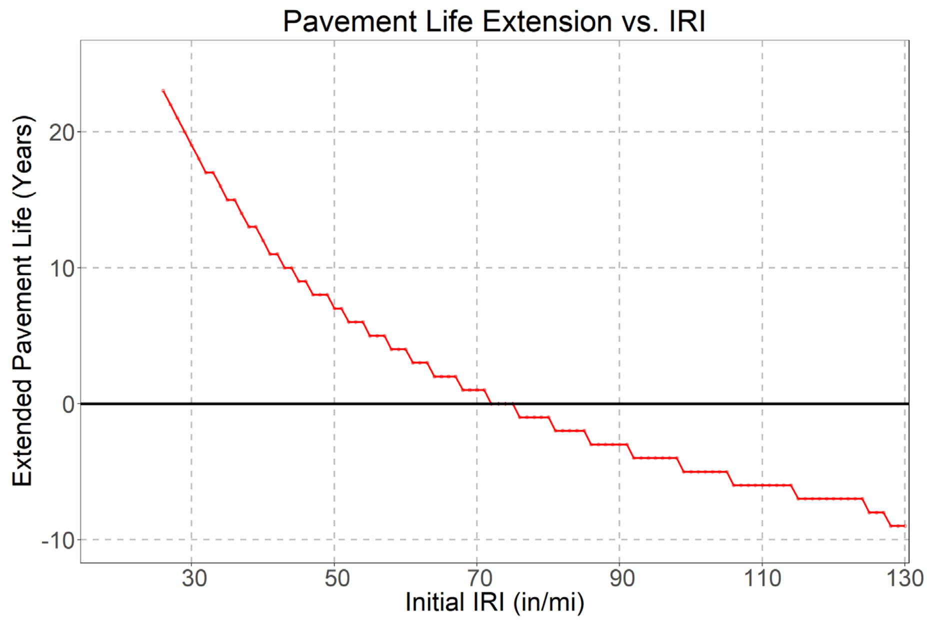


Figure 57. Graph. Estimated pavement life extension for high-speed facilities.

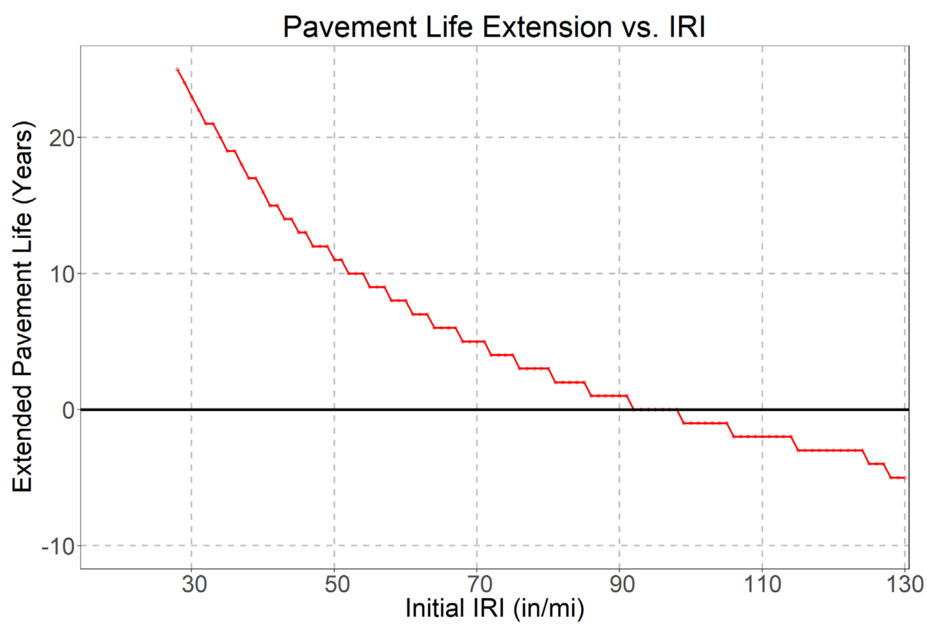


Figure 58. Graph. Estimated pavement life extension for low-speed facilities.

The above inferences made for the extended pavement life do not consider other distresses (e.g., cracking) or design parameters (e.g., pavement thickness) having significant effects on pavement life. Instead, these observations were made solely based on IRI performance in the interest of quantifying the benefits of smoother pavements and should only be used for general information purposes.

Life Cycle Cost Benefits

Although the benefits of smoother pavements were captured in terms of extended pavement life for the interest of constructing pavements that last longer, the extended pavement life cannot be used in BCA as it is not a monetized term. Therefore, the BCA is carried out using the life cycle cost obtained in the previous chapter.

Similar to the reference pavement life defined previously, the reference LCC is defined as the expected LCC corresponding to the initial IRI equal to the upper full-pay IRI threshold (i.e., 75 in/mi for high speed and 95 in/mi for low speed). Furthermore, the benefit is defined as the reduction in LCC (relative to the reference LCC) gained by lower initial IRI. Note that only the agency portion of LCC is used for this purpose (i.e., user cost is not considered).

One of the assumptions in LCCA was that the initial construction cost is independent of the initial IRI achieved. Therefore, it is further assumed that the amount of incentive payment is the only cost associated with constructing pavements with lower initial IRI. In other words, the cost within the context of BCA is defined as the incentive amount previously specified in the smoothness assessment schedule.

Figure 59 and Figure 60 show the benefit and cost curves obtained for high-speed and low-speed facilities, respectively. Note that both the benefit and cost curves shown are for 0.1 mi sublots. Both figures indicate that for initial IRI values below the full-pay threshold (75 in/mi for high speed and 95 in/mi for low speed), the benefit is significantly higher than the cost. This is somewhat expected as the benefit is calculated over a period of 45 years (corresponding to the LCCA analysis period) whereas the cost is only applied at the beginning of LCCA. Note that the significant amount of benefit (observed from initial IRI values below the full-pay threshold) is also accompanied by a significant amount of loss (i.e., negative benefit) for higher initial IRI.

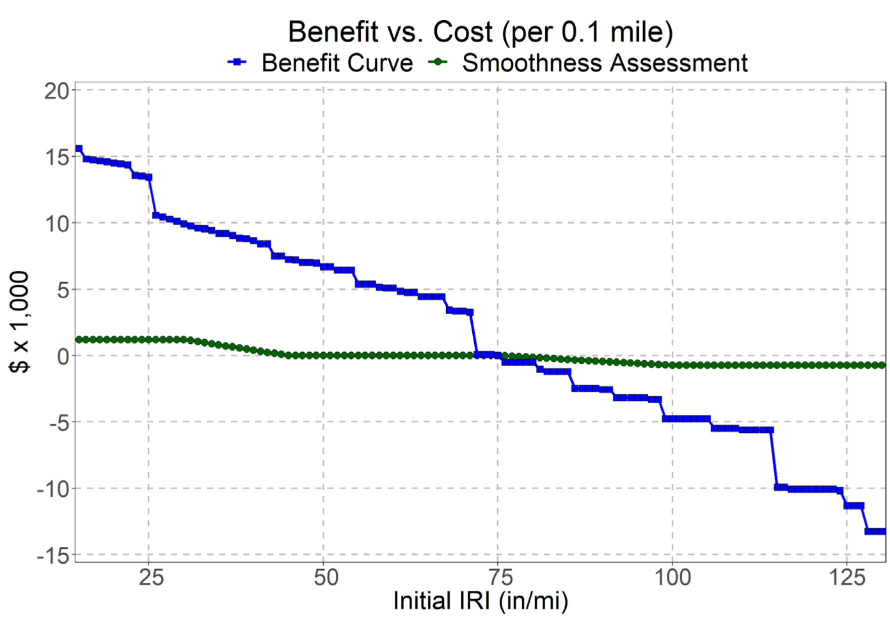


Figure 59. Graph. Estimated benefit and cost curves for high-speed facilities.

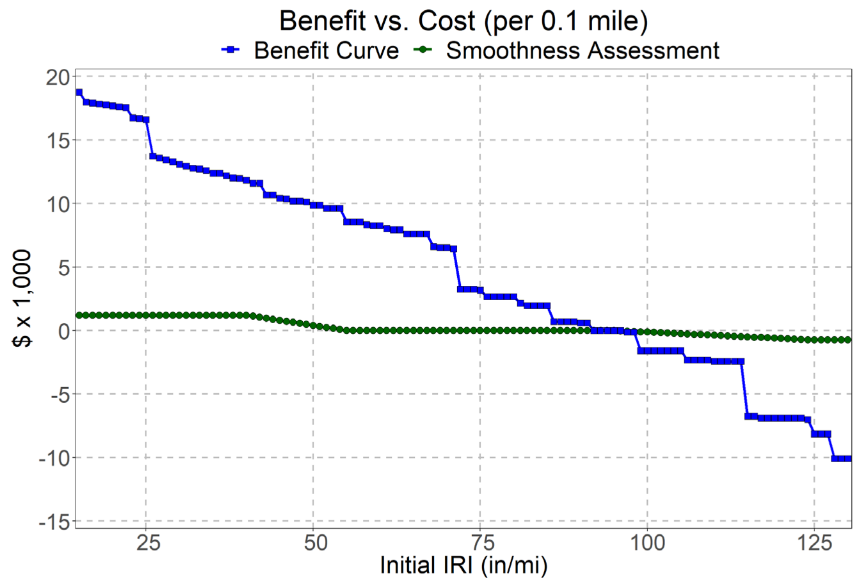


Figure 60. Graph. Estimated benefit and cost curves for low-speed facilities.

Some specific observations made from Figure 59 and Figure 60 are listed below.

- For a high-speed, 0.1 mi sublot, an approximated benefit of $7.2K can be expected over the course of 45 years (or approximately $160 per year) if the initial IRI is reduced from 75 in/mi (i.e., upper full-pay threshold) to 45 in/mi (i.e., lower full-pay threshold).
- For a high-speed, 0.1 mi sublot, an approximated loss of $4.8K can be expected over the course of 45 years (or approximately $107 per year) if the initial IRI is increased from 75 in/mi (i.e., upper full-pay threshold) to 100 in/mi (i.e., upper disincentive threshold or lower threshold at which corrective action is required).
- For a low-speed, 0.1 mi sublot, an approximated benefit of $8.6K can be expected over the course of 45 years (or approximately $190 per year) if the initial IRI is reduced from 95 in/mi (i.e., upper full-pay threshold) to 55 in/mi (i.e., lower full-pay threshold).
- For a low-speed, 0.1 mi sublot, an approximated loss of $8.1K can be expected over the course of 45 years (or approximately $180 per year) if the initial IRI is increased from 95 in/mi (i.e., upper full-pay threshold) to 125 in/mi (i.e., upper disincentive threshold or lower threshold at which corrective action is required).

In addition to the general observations made above, it was also of interest to calculate the benefit and cost that are expected for any given (i.e., arbitrary) 0.1 mi sublot. The expected benefit and cost can also be interpreted as the "average" benefit and cost that IDOT may anticipate upon implementation of the IRI-based specification.

To calculate the expected benefit and cost, the After IRI distribution previously shown in Figure 41 was used to calculate the probability of occurrence for the range of initial IRI values. The expected benefit (or cost) was then obtained as the sum of the multiplied product between the probability and the benefit (or cost) shown in Figure 59 and Figure 60. The results were obtained as the following.

- For high-speed facilities, the expected benefit and cost of an arbitrary 0.1 mi sublot were \$4.7K and \$144, respectively, yielding a benefit-to-cost (B/C) ratio of 32.5.
- For low-speed facilities, the expected benefit and cost of an arbitrary 0.1 mi sublot were \$7.9K and \$495, respectively, yielding a B/C ratio of 15.9.

The results indicate that both the expected benefit and cost are higher for a low-speed roadway compared to a high-speed roadway of equal length. In contrast, the B/C ratio calculated for the high-speed facility is significantly (almost double) higher than that for the low-speed facility. This means that for every dollar spent by IDOT on incentive payments, a higher rate of return is expected from high-speed facilities (approximately twice the rate of return when compared to low-speed facilities).

AREA OF LOCALIZED ROUGHNESS

As implied by its name, area of localized roughness (ALR) refers to the “hot spots” that exhibit excessive level of roughness over a short length. ALRs are not desirable because of their effect on ride quality and pavement life and their potential effect on roadway safety. Furthermore, Lee (2019) pointed out that the additional suspension movement (i.e., dynamic load) caused within the ALR may continue even after the vehicle passed through the area of excessive roughness. In other words, the area after the ALR becomes rougher over time (i.e., roughness propagation).

It is customary that an ALR provision is included within an IRI-based smoothness specification. The ALR provision could be specified using a different smoothness index (e.g., bumps identified from straightedge measurements rather than IRI) and may work well for quality control purposes during construction. However, the ALR identified from a different smoothness index generally does not explain the cause of localized roughness expressed in terms of IRI and, more importantly, the long-term IRI (Merritt et al., 2015). For these reasons, IDOT recommended to use IRI as the smoothness index of the new ALR provisions for high-speed and low-speed facilities. Furthermore, IDOT recommended that an IRI baselength of 25 ft (which is frequently used by other states) be used for the ALR requirement. The following thresholds were determined for ALR.

- For high-speed facilities, an IRI value of 150 in/mi was selected for the ALR provision. This value corresponds to twice the upper full-pay IRI threshold of 75 in/mi.
    - According to the empirical IRI performance model developed for full-depth HMA, a pavement with an initial IRI of 150 in/mi will last approximately 7.5 years before its IRI reaches the unacceptable threshold of 175 in/mi specified in the BDE manual.

      As mentioned, the reference pavement life (corresponding to upper full-pay IRI threshold of 75 in/mi) was predicted to be 22 years. Given this reference life, the 7.5 years of pavement life corresponds to a 66% reduction in pavement life, which was considered unacceptable even for a short stretch of newly constructed pavement segment (i.e., ALR).

- For low-speed facilities, an IRI value of 220 in/mi was selected for the ALR provision.
    - Given that the upper full-pay IRI threshold for low-speed facility is 95 in/mi, the research team recommended an ALR threshold of 190 in/mi (i.e., twice the upper full-pay threshold, to be consistent with high-speed provision). Nevertheless, IDOT's recommendation was to increase the ALR threshold to 220 in/mi for the following reasons.
        - Construction of low-speed facilities may face additional challenges due to intersections, existing driveways and parking lots, manhole covers, etc., all of which may adversely affect the IRI calculated over a short baselength of 25 ft.
        - Considering the user comfort level, the IRI values for low-speed facilities are not as crucial as those for high-speed facilities. As such, the difference in user comfort (or discomfort) may not be significant between IRI values of 190 in/mi and 220 in/mi, especially when short segments are concerned.

CHAPTER 4: SUMMARY AND CONCLUSIONS

Smoothness is one of the most important factors affecting both the structural and functional performance of pavement structures. From an agency's point of view, the benefits of smoother pavements include increased service life, reduced maintenance activities, and reduced life cycle cost. In addition, smoother pavements benefit the driving public in terms of improved ride quality as well as reduced vehicle-operating cost and improved safety. Consequently, most highway agencies are monitoring the smoothness characteristics of their pavements. In addition, many agencies have developed and implemented a smoothness specification for newly constructed pavements.

Traditionally, pavement smoothness has been quantified using various indices such as present serviceability rating, ride number, profile index, and international roughness index. IDOT's existing smoothness specification was based on PI measurements, which was also widely used by other agencies in the past. However, due to the national and international trend toward using IRI as a standard index for pavement management as well as construction acceptance, there was a need for developing an IRI-based smoothness specification for IDOT's implementation.

One of the most important components of an IRI-based smoothness specification is the IRI thresholds determined for full pay, incentive, and disincentive payments. However, many agencies have established the IRI thresholds based on past experience and engineering judgement. As a result, the IRI thresholds implemented by different agencies vary considerably, mostly due to a significantly debated difference in opinion over the appropriate level of IRI to be required by the specification.

The primary objective of this study was to develop an IRI-based smoothness specification for IDOT. However, the IRI thresholds should be developed in an objective manner (to the extent possible) while considering the various benefits discussed above. As such, the secondary objective of this study was to identify, determine, and consider the following during the development of the IRI-based smoothness specification:

- Range of smoothness acceptable to users.
- Empirical methods correlating pavement smoothness and pavement life.
- Benefit-cost ratio considering pavement life and construction costs.
- Encourage contractors to consider technologies that will provide smoother pavements but are not required by IDOT specifications.

To quantify the level of comfort that users may experience from pavements exhibiting different levels of IRI, a vehicle was equipped with an accelerometer and was used to gather vehicle-seat acceleration data. The acceleration data was collected at various speeds from different types of pavements exhibiting a wide range of smoothness characteristics. The results and findings from the acceleration data analysis are summarized as the following.

- In general, the higher the speed of travel, the higher the chance of discomfort regardless of pavement smoothness. The chance of discomfort is higher at speeds greater than 40 mph. For the purpose of smoothness specification, high-speed facilities should be defined as roadways with a prevailing speed limit greater than 40 mph while low-speed facilities should be defined as those with speed limits less than or equal to 40 mph.

- The effect of IRI on user comfort is more pronounced for high-speed facilities than for low-speed facilities. Using an acceleration root mean square threshold value of 0.5 m/s^2, it was determined that IRI values below 66 in/mi and 186 in/mi are generally desirable for user comfort on high-speed and low-speed facilities, respectively.

Life cycle cost analysis (LCCA) was also carried out as part of an effort to assess the benefits of smoother pavements in terms of agency cost, user cost, and pavement life. Another purpose of LCCA was to provide a means for quantifying the benefits needed for the subsequent benefit-cost analysis (BCA). LCCA was generally conducted in accordance with the procedures outlined in IDOT’s Bureau of Design and Environment manual with some modifications that were necessary to incorporate the effect of IRI. More specifically, the empirical IRI performance model developed from IDOT’s historical IRI data was used to determine “pavement deterioration” and the timing at which major and minor rehabilitation activities are conducted. Some of the general findings from LCCA include the following. Additional findings will be discussed subsequently (after LCCA has been incorporated into BCA).

- The empirical IRI models developed based on IDOT’s historical data indicated that pavements initially constructed to be smooth (i.e., lower initial IRI) remain smoother in the long run and last longer.

- Pavements with lower initial IRI also exhibit reduced life cycle cost, both in terms of agency and user costs.

  - For agency cost, the future maintenance cost (expressed in terms of present worth) calculated over a 45-year life cycle may become as high as 50% of the initial construction cost for pavements with higher initial IRI.

  - Total user cost was obtained as the sum of vehicle-operating cost (which included fuel consumption, vehicle repair and maintenance cost, and cost associated with tire wear) and crash cost. User cost showed an expected trend, i.e., higher initial IRI resulted in increased user cost. However, the user cost was by orders of magnitude greater than the agency cost and was not considered in the subsequent BCA.

Based on the results and findings of accelerometer analysis and LCCA combined with engineering judgement, the following IRI thresholds were recommended.

- For high-speed facilities (i.e., speed limit greater than 40 mph), IRI values of 45 in/mi, 75 in/mi, and 100 in/mi were recommended for lower full pay, upper full pay, and upper disincentive IRI thresholds, respectively.

- The above thresholds are also recommended for Portland cement concrete (PCC) pavements and hot-mix asphalt (HMA) overlays on existing pavements with IRI (i.e., IRI_{Before}) less than or equal to 125 in/mi.

- Higher IRI thresholds are recommended for pavements with IRI_{Before} greater than 125 in/mi. It is recommended that the above thresholds be increased at a rate of 1.0 in/mi for every 5.0 in/mi of IRI_{Before} in excess of 125 in/mi (e.g., if IRI_{Before} is equal to 130 in/mi, the upper full pay threshold for the HMA overlay becomes 76 in/mi).

- For low-speed facilities (i.e., speed limit less than or equal to 40 mph), IRI values of 55 in/mi, 95 in/mi, and 125 in/mi were recommended for lower full pay, upper full pay, and upper disincentive IRI thresholds, respectively.

  - The above thresholds are also recommended for PCC pavements and hot-mix asphalt (HMA) overlays on existing pavements with IRI (i.e., IRI_{Before}) less than or equal to 220 in/mi.

  - Higher IRI thresholds are recommended for pavements with IRI_{Before} greater than 220 in/mi. It is recommended that the above thresholds be increased at a rate of 1.0 in/mi for every 5.0 in/mi of IRI_{Before} in excess of 220 in/mi (e.g., if IRI_{Before} is equal to 225 in/mi, the upper full pay threshold for the HMA overlay becomes 96 in/mi).

In order to determine if the above thresholds are realistic, the distribution of IRI values obtained from IDOT's recent HMA overlay sections was studied. The distribution was used to assess the probabilities of an arbitrary 0.1 mi sublot falling under incentive, full pay, disincentive, and corrective action zones. In addition, the relationship between IRI values before and after construction was used to calculate these probabilities for HMA overlays. The calculated probabilities generally indicated that the chances are higher for full pay or incentive than those for disincentive or corrective action, which led to the conclusion that the IRI thresholds recommended above are realistic and achievable.

Despite the achievable thresholds, moving to an IRI-based specification represents a major departure from the existing PI-based specification because IRI and PI are two different smoothness indices. As such, it is anticipated that both IDOT and the contractors will need to bear some risk and adapt to the IRI-based specification when it is implemented. It is emphasized that the risk discussed in this report is not the "risk" associated with constructing rougher pavements. Instead, it is defined as the probability of the PI-based and IRI-based specifications producing different outcomes (e.g., a 0.1 mi segment being accepted based on PI specification but rejected based on IRI specification, and vice versa). The risk analysis was conducted based on the IRI vs. PI relationship as well as the acceptance thresholds from the respective specifications and produced the estimated risk probabilities of 4.4% and 6.6% for high-speed and low-speed facilities, respectively. While the probabilities suggest that slightly more discrepancies are to be expected for low-speed facilities, the assessed risks are reasonable (less than 10%).

With the above IRI thresholds developed and checked for reasonableness, the smoothness assessment schedule (also known as payment schedule) was developed primarily based on engineering judgement considering the current economy and recent cost for pavement construction. A notable change in the smoothness assessment schedule is that while the PI-based specification used a stepwise schedule, the IRI-based specification uses a continuous schedule until a maximum incentive or disincentive is reached. The purpose of such continuous schedule is to avoid any sudden jumps in the incentive/disincentive amount when there is only a negligible difference in the achieved smoothness (e.g., achieved IRI values of 75 in/mi vs. 76 in/mi—the former receives full pay and the latter receives a disincentive of $30 rather than $750). The continuous payment schedule is also believed to encourage the contractors to aim for the maximum incentives by building smoother pavements.

The IRI thresholds and smoothness assessment schedule were then used with the LCCA results to carry out the BCA. By defining the "reference pavement life" and the "reference life cycle cost" as those corresponding to the upper full-pay IRI threshold, the benefit was quantified as the additional pavement life or reduced life cycle cost resulting from IRI values below the threshold. Similarly, the loss was quantified as the reduced pavement life or increased life cycle cost resulting from IRI values above the full-pay threshold. In addition, cost was defined within the BCA framework as the incentive payments to be made in accordance with the smoothness assessment schedule. The findings from BCA are summarized in the following.

- For both the high-speed and low-speed facilities, IDOT may anticipate at least nine years of additional pavement life for any sublot where an incentive payment has been made. Similarly, for any sublot where a disincentive payment has been made, IDOT may expect up to five years and four years of reduced pavement life for high-speed and low-speed facilities, respectively.

- For a high-speed, 0.1 mi sublot, an approximated benefit of $7.2K can be expected over the course of 45 years (or approximately $160 per year) if the initial IRI is reduced from 75 in/mi (i.e., upper full-pay threshold) to 45 in/mi (i.e., lower full-pay threshold). Similarly, an approximated loss of $4.8K (or approximately $107 per year) can be expected if the initial IRI is increased from 75 in/mi (i.e., upper full-pay threshold) to 100 in/mi (i.e., upper disincentive threshold or lower threshold at which corrective action is required).

- For a low-speed, 0.1 mi sublot, an approximated benefit of $8.6K can be expected over the course of 45 years (or approximately $190 per year) if the initial IRI is reduced from 95 in/mi (i.e., upper full-pay threshold) to 55 in/mi (i.e., lower full-pay threshold). Similarly, an approximated loss of $8.1K (or approximately $180 per year) can be expected if the initial IRI is increased from 95 in/mi (i.e., upper full-pay threshold) to 125 in/mi (i.e., upper disincentive threshold or lower threshold at which corrective action is required).

- For an arbitrary, high-speed, 0.1 mi sublot, the expected benefit and cost were $4.7K and $144, respectively, yielding a benefit-to-cost (B/C) ratio of 32.5. Similarly, the expected benefit and cost of an arbitrary, low-speed, 0.1-mi sublot were $7.9K and $495, respectively, yielding a B/C ratio of 15.9.

Based on the results and findings discussed above, it is believed that IDOT's IRI-based specification is not only achievable and realistic, but also anticipated to produce sufficient benefit. Nonetheless, moving from a PI-based to an IRI-based specification is not expected to be seamless. Although several aspects of IRI thresholds and smoothness assessment schedule were investigated for reasonableness, the risk associated with implementing a new specification cannot be eliminated. As such, both IDOT and IDOT's contractors will need to adapt to and become familiar with the new specification and continue to refine the IRI-based specification as more experience is gained.

The recent IRI data included in this study was limited to those from HMA overlay sections. As such, it is also recommended that the IRI-based specification be tested in real life via shadow or pilot projects prior to a full implementation.

REFERENCES

Chan, C. Y., Huang, B., Yan, X., and Richards, S. Effects of Asphalt Pavement Conditions on Traffic Accidents in Tennessee Utilizing Pavement Management System. Transportation Research Board 88th Annual Meeting Compendium of Papers. No. 09-2054. Washington, D.C., 2009.

Chatti, K., and Zaabar, I. Estimating the Effects of Pavement Condition on Vehicle Operating Costs. NCHRP Report 720. Transportation Research Board of the National Academies, Washington, D.C., 2012.

Clark, T. M., and McGhee, K. K. VDOT's IRI-Based Ride Quality Specification: From Inception to 2001. Symposium on Constructing Smooth Hot Mix Asphalt Pavements. Dallas, TX, 2003.

Federal Highway Administration (FHWA). Life-Cycle Cost Analysis Primer. Office of Asset Management. FHWA, Washington, D.C., 2002.

Flintsch, G., and McGhee, K. K. Quality Management of Pavement Condition Data Collection. NCHRP Synthesis No. 401, National Cooperative Highway Research Program (NCHRP), Transportation Research Board of the National Academies, Washington, D.C., 2009.

Illinois Department of Transportation (IDOT). Illinois Highway Information System Roadway Information and Procedure Manual. IDOT, Springfield, IL, 2014.

Illinois Department of Transportation (IDOT). Bureau of Design and Environment (BDE) Manual. IDOT, Springfield, IL, 2020.

International Organization for Standardization (ISO). Mechanical Vibration and Shock—Evaluation of Human Response to Whole-Body Vibration. Part I: General Requirements. ISO 2631-1, Geneva, 1997.

Kwon, O., Lee, H. S., Chun, S., Holzschuher, C., and Choubane, B. Probabilistic Relationship between Smoothness of Final Asphalt Surface and Underlying Layer. Transportation Research Board 88th Annual Meeting Compendium of Papers. No. 15-5375. Washington, D.C., 2015.

Lee, H. S. Effect of Moving Dynamic Loads on Pavement Performance. Presentation at the Falling Weight Deflectometer User Group Meeting. Alpharetta, GA, 2019. Last accessed June 2020. https://drive.google.com/file/d/1PihIdvIK3jllYHdTP7ag3EwZ-tosFoRo/view.

Lee, H. S., Hall, J., and Stanley, M. Develop Statistical Models Quantifying the Relationship between Pavement Surface Friction Characteristics and Traffic Accident Rates. Final Report BE 385. Florida Department of Transportation, Gainesville, FL, 2019.

Li., Y., and Huang, J. Safety Impact of Pavement Conditions. Transportation Research Record: Journal of the Transportation Research Board, Vol. 2455, pp. 77–88, 2014.

Massucco, J., and Cagle, J. Getting Smoother Pavement: An Arizona Success Story That's Adaptable Nationwide. Public Roads, Vol. 62, No. 5, FHWA, U.S. Department of Transportation. March/April 1999.

Merritt, D. K., Chang, G. K., and Rutledge, J. L. Best Practices for Achieving and Measuring Pavement Smoothness, A Synthesis of State-of-Practice. Report No. FHWA/LA.14/550. Louisiana

Transportation Research Center, Baton Rouge, LA, 2015.

Muench, S., and Van Dam, T. Pavement Sustainability. Technical Brief. FHWA-HIF-14-012. Federal Highway Administration, Washington, D.C, 2014.

Robbins, M. M., and Tran, N. Literature Review: The Impact of Pavement Roughness on Vehicle Operating Costs. NCAT Report 15-02. National Center for Asphalt Technology, Auburn, AL, 2015.

Robbins, M. M., and Tran, N. A Synthesis Report: Value of Pavement Smoothness and Ride Quality to Roadway Users and the Impact of Pavement Roughness on Vehicle Operating Costs. NCAT Report 16-03. National Center for Asphalt Technology, Auburn, AL, 2016.

Smith, K. L., Smith, K. D., Evans, L. D., Hoerner, T. E., and Darter, M. I. Smoothness Specifications for Pavements. NCHRP Web Document 1. Transportation Research Board of the National Academies, Washington, D. C., 1997.

Srinivasan, R., and Bauer, K. Safety Performance Function Development Guide: Developing Jurisdiction-Specific SPFs. Report No. FHWA-SA-14-005. Federal Highway Administration. Washington, D.C, 2013.

Tegge, R. A., Jo, J. H., and Ouyang, Y. Development and Application of Safety Performance Functions for Illinois. Final Report, ICT-R27-20. Illinois Center for Transportation, Urbana, IL, 2010.

APPENDIX A: SMOOTHNESS GUIDANCE

CHAPTER 1: INTRODUCTION

BACKGROUND

The primary objective of the research project, "ICT-R27-199: Optimizing the Benefits of Smoother Roads against the Increased Costs to Build Them," was to develop an international roughness index (IRI)-based smoothness specification for the Illinois Department of Transportation (IDOT). The IRI-based smoothness specification represents a significant departure from the existing profile index (PI)-based specification due to the use of a different smoothness index (i.e., IRI).

The IRI-based smoothness specification was developed while considering the relationship between IRI and user comfort level measured by the acceleration of a vehicle seat, as well as the benefits of smoother pavements in terms of pavement life, life cycle cost (agency and user costs), and safety. In addition, risk analyses were performed to assess the impact of moving from a PI-based to an IRI-based specification. Although the risk was found to be relatively low (i.e., 4.4% and 6.6% risk assessed for high-speed and low-speed facilities, respectively), it still indicates that IDOT and IDOT's contractors may need to work together to adapt to the new specification and continue to refine the IRI-based specification as more experience is gained.

OBJECTIVE AND SCOPE

The objective of this document is to serve as a quick reference document for IDOT and IDOT's contractors that are anticipated to be the primary users of the IRI-based specification. The document provides background information on IRI as well as the components of the IRI specification. In addition, the document provides some of the technologies and tools that can be used for constructing smoother pavements.

CHAPTER 2: FUNDAMENTALS OF INTERNATIONAL ROUGHNESS INDEX

Because the new specification is based on IRI, which is different from the smoothness index used in the existing specification (i.e., PI), the definition and some relevant characteristics of IRI are briefly reviewed in this chapter.

DEFINITION OF IRI

Similar to many other smoothness indices being used, IRI is an index calculated from a longitudinal pavement surface profile. More specifically, IRI is calculated by simulating the response of a "Golden Car," which is a quarter-car model with specific suspension parameters, as shown in Figure A-1.

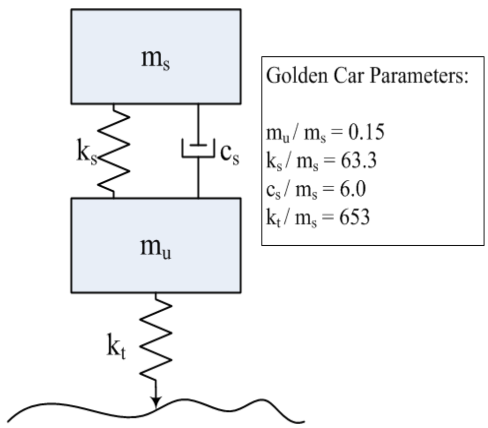


Figure A-1. Diagram. Golden car model and its parameters.

According to Sayers (1995), IRI is fully defined by the following:

1. IRI is computed from a single longitudinal profile.
2. The profile is assumed to have a constant slope between sampled elevation points.
3. The profile is smoothed with a moving average with a base length of 10 in. (250 mm).
4. The smoothed profile is filtered using the golden car simulation, at a simulation speed of 50 mph (80 km/hr).
5. IRI is obtained as the linear accumulation of the simulated suspension motion (i.e., the relative movement between m_s and m_u in Figure A-1) divided by the length of the profile.

🕮 By definition, IRI is the accumulated suspension motion of the golden car model travelling at a speed of 50 mph divided by the length of the pavement profile input (i.e., the distance travelled by the golden car), and is expressed in units of slope such as in/mi or m/km.

📖 As seen from the above definition, IRI is calculated from a single longitudinal profile (obtained from a single-wheel path). Note that IDOT's specification is based on the average of the IRI values computed from the left and right wheel paths, also known as the mean roughness index (MRI).

PROPERTIES OF IRI

The calculation of IRI requires solving a system of ordinary differential equations corresponding to the golden car model. However, the mathematical details are beyond the scope of this document and shall not be discussed. Interested readers are referred to Sayers (1995).

📖 In reality, a computerized algorithm is necessary to calculate IRI. One of the most frequently used software is ProVAL, which is freely available from https://www.roadprofile.com/.

Because IRI is calculated from the golden car simulation, it is worthwhile to discuss the components of the pavement profile to which IRI is sensitive. For this purpose, Figure A-2 shows the power spectral density (PSD) of the golden car filter.

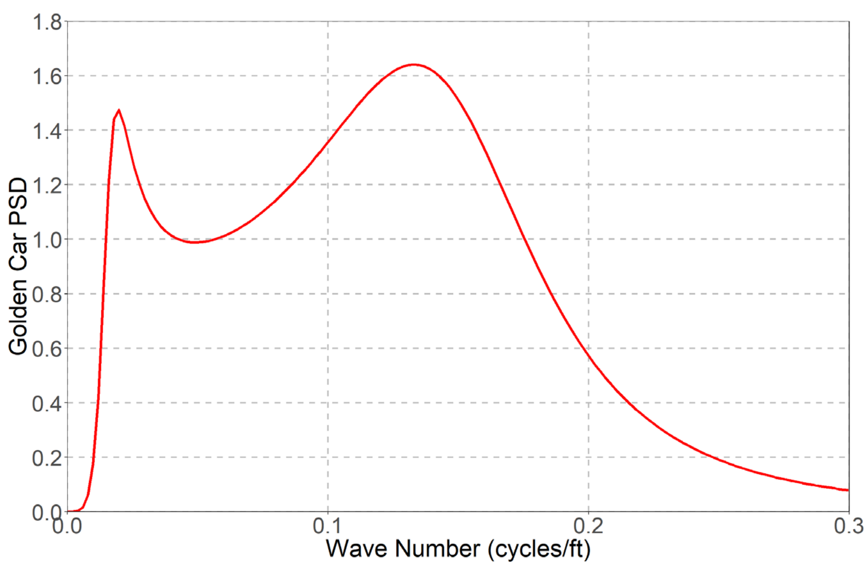


Figure A-2. Graph. Golden car filter.

The above figure indicates that the IRI transfer function is sensitive to wave numbers, ranging approximately from 0.0105 cycles/ft to 0.240 cycles/ft with their peaks located at 0.0193 cycles/ft and 0.133 cycles/ft. This also means that IRI is most sensitive to sine (or cosine) waves with wavelengths of approximately 51.8 ft and 7.5 ft. The sine curves corresponding to these wavelengths are shown in Figure A-3. Although the sine curves shown in this figure are not realistic pavement profiles, the figure illustrates that IRI is not only sensitive to localized "bumps and dips" that make up the shorter wavelength (i.e., longer wave number) components of the pavement profile, but also the "hills and valleys" that make up the longer wavelength (i.e., shorter wave number) components.

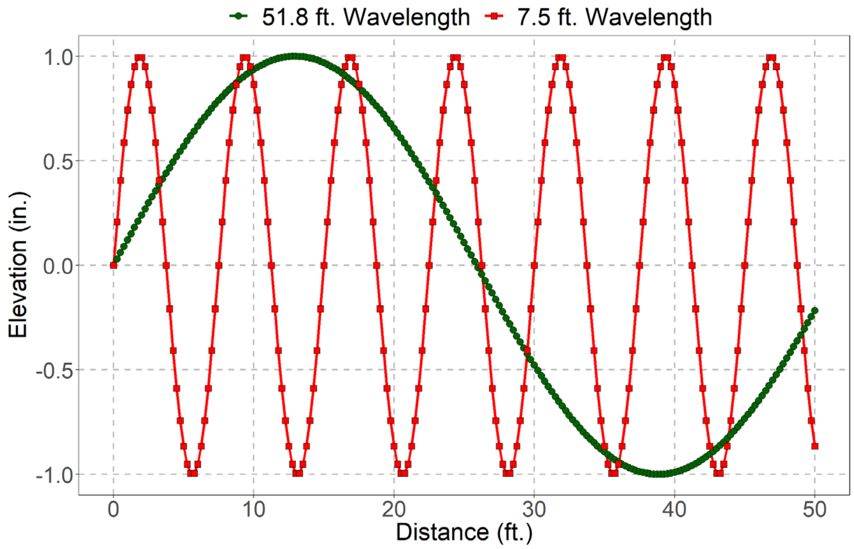


Figure A-3. Graph. Sine curves corresponding to wavelengths of 51.8 ft and 7.5 ft.

> 🕮 IRI is sensitive to wave numbers ranging approximately from 0.0105 cycles/ft to 0.240 cycles/ft. These wave numbers correspond to wavelengths of 95.2 ft and 4.2 ft., respectively.
>
> IRI is affected not only by localized "bumps" or "dips" having shorter wavelengths but also the "hills" and "valleys" having longer wavelengths.

Most computerized software for analyzing pavement profiles such as ProVAL allow for computing the PSD of a given pavement profile. Although the user may use such features to check if the pavement profile contains (and if so, how large or small the corresponding amplitude is) the wavelengths that will largely affect IRI.

Although the PSD analysis can reveal the wavelength content for a given pavement profile, it also has limitations for the purpose of practical application. Because the PSD is calculated for the entire length of the profile input, the calculated PSD results also correspond to the entire length of the profile. In other words, the PSD does not reveal "where" in the profile a particular wavelength is dominant. For practical considerations, this means that the PSD does not provide the specific limits of the locations that are responsible for the higher IRI achieved (i.e., it is impossible to determine the limits of grinding operation for corrective action). Therefore, PSD should only be studied for the overall wavelength content. Determining the limits for corrective action should utilize other practical methods, as will be discussed in Chapter 4 of this document.

CHAPTER 3: IDOT'S IRI-BASED SMOOTHNESS SPECIFICATION

In this chapter, IDOT's IRI-based specification—more specifically, the IRI thresholds, pay schedule, and consideration of area of localized roughness—is reviewed.

DEFINITION OF HIGH-SPEED AND LOW-SPEED FACILITIES

Compared to the existing PI-based specification, the IRI-based specification has different definitions for high-speed and low-speed facilities.

> 🕮 Within the IRI-based specification, high-speed facilities are defined as the mainline roadways with a posted speed limit of greater than 40 mph. Accordingly, low-speed facilities are defined as those with a posted speed limit of less than or equal to 40 mph.

The only difference between the above definitions and those adopted in the PI-based specification is on the roadways with a 45 mph speed limit. In other words, a roadway with a speed limit of 45 mph is considered a high-speed facility under the IRI-based specification, whereas the same roadway is considered a low-speed facility under the PI-based specification.

IRI THRESHOLDS

One of the major premises undertaken during the development of IRI-based specification was that when a new pavement is constructed or an existing pavement has been overlaid, the new pavement surface should provide an acceptable (or at least a reasonably comfortable) level of ride quality to the driving public. In addition, it was presumed that such level of ride quality should be accomplished on IDOT's future roadways regardless of the pavement type—i.e., HMA versus PCC pavements.

The IRI thresholds developed based on the above premise are summarized in Table A-1 for all pavement types to be constructed in high-speed roadways. The table shows that the HMA overlays will be subjected to the same IRI thresholds if the IRI of the existing roadway (IRI_{Before}) is less than or equal to 125 in/mi. For HMA overlays where IRI_{Before} is found to be greater than 125 in/mi, higher IRI thresholds increasing linearly with a slope of 0.2 will be applied.

Figure A-4 graphically shows the IRI thresholds for high-speed, HMA overlays. The figure also shows a vertical, dashed line corresponding to the Before IRI value of 125 in/mi, below which the IRI thresholds remain constant (i.e., same thresholds as new construction projects).

Table A-1. IRI Thresholds for High-Speed Facilities

Thresholds	IRI (in/mi) thresholds for new construction projects (HMA & PCC) and HMA overlays with IRI_{Before} less than or equal to 125 in/mi	IRI (in/mi) thresholds for HMA overlays with IRI_{Before} greater than 125 in/mi
Upper Incentive Limit ($IRI_{Incentive}$)	45	$0.2 \cdot IRI_{Before} + 20$
Upper Full Pay Limit ($IRI_{FullPay}$)	75	$0.2 \cdot IRI_{Before} + 50$
Upper Disincentive Limit ($IRI_{Disincentive}$)	100	$0.2 \cdot IRI_{Before} + 75$

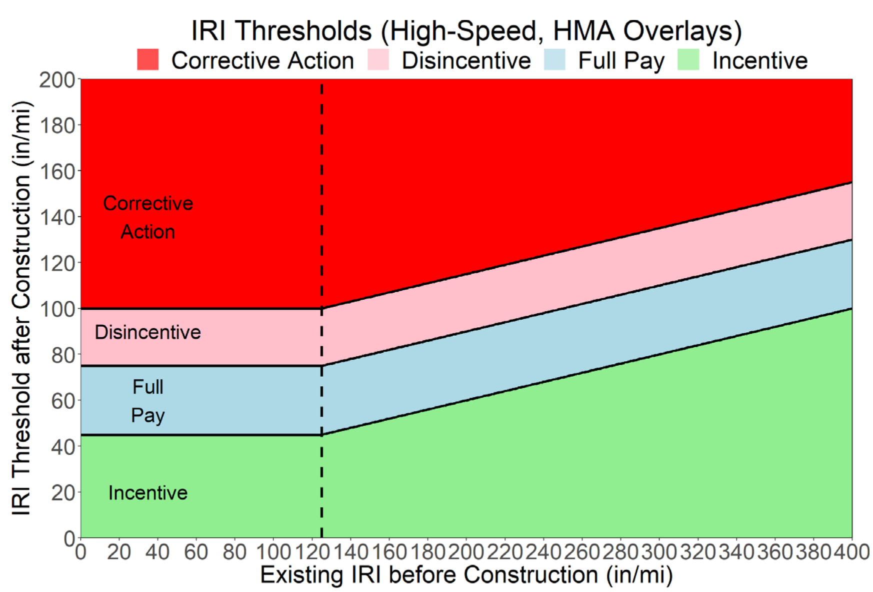


Figure A-4. Graph. IRI of existing pavement vs. IRI thresholds after construction for high-speed facilities.

Similarly, Table A-2 shows the IRI thresholds developed for low-speed mainline pavements. HMA overlays are to be subjected to the same IRI thresholds if the IRI of the existing roadway (IRI_{Before}) is less than or equal to 220 in/mi. If IRI_{Before} is greater than 220 in/mi, the IRI thresholds are also increased with a slope of 0.2.

Figure A-5 graphically shows the IRI thresholds for low-speed HMA overlays. The figure also shows a vertical dashed line corresponding to the Before IRI value of 220 in/mi, below which the IRI thresholds become the same as those for new construction projects.

Table A-2. IRI Thresholds for Low-Speed Facilities

Thresholds	IRI (in/mi) thresholds for new construction projects (HMA & PCC) and HMA Overlays with IRI_{Before} less than or equal to 220 in/mi	IRI (in/mi) thresholds for HMA Overlays with IRI_{Before} greater than 220 in/mi
Upper Incentive Limit ($IRI_{Incentive}$)	55	$0.2 \cdot IRI_{Before} + 11$
Upper Full Pay Limit ($IRI_{FullPay}$)	95	$0.2 \cdot IRI_{Before} + 51$
Upper Disincentive Limit ($IRI_{Disincentive}$)	125	$0.2 \cdot IRI_{Before} + 81$

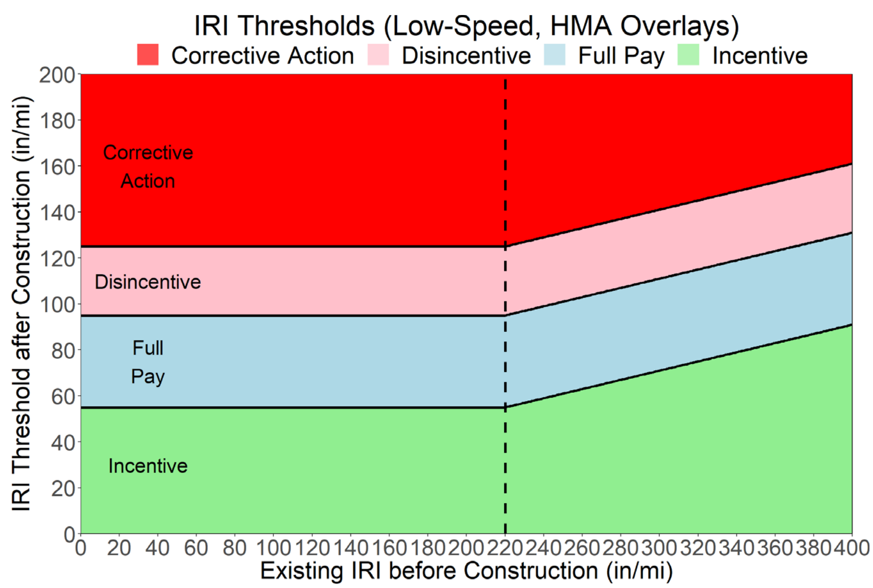


Figure A-5. Graph. IRI of existing pavement vs. IRI thresholds after construction for low-speed facilities.

📖 The primary variable for determining the IRI threshold is the speed limit. Higher IRI thresholds are to be applied to low-speed pavements than high-speed pavements. These thresholds are to be applied regardless of the pavement type.

For overlays, a secondary variable for determining the IRI threshold is the IRI of existing pavement (IRI_{Before}).

As an example, consider a 2.5 mi long, low-speed mainline pavement that is to be overlaid with HMA, whose existing IRI evaluated at every 0.1 mi is shown in Figure A-6. The figure shows that most of the sublots are exhibiting IRI_{Before} values below 220 in/mi and will be subjected to the fixed IRI thresholds shown in Table A-2. However, there are two sublots with IRI_{Before} in excess of 220 in/mi and will be subjected to higher IRI thresholds. The IRI thresholds computed in accordance with Table A-2 and plotted against the station distance is shown in Figure A-7. This example will be revisited in the next section, after discussing the smoothness assessment schedule.

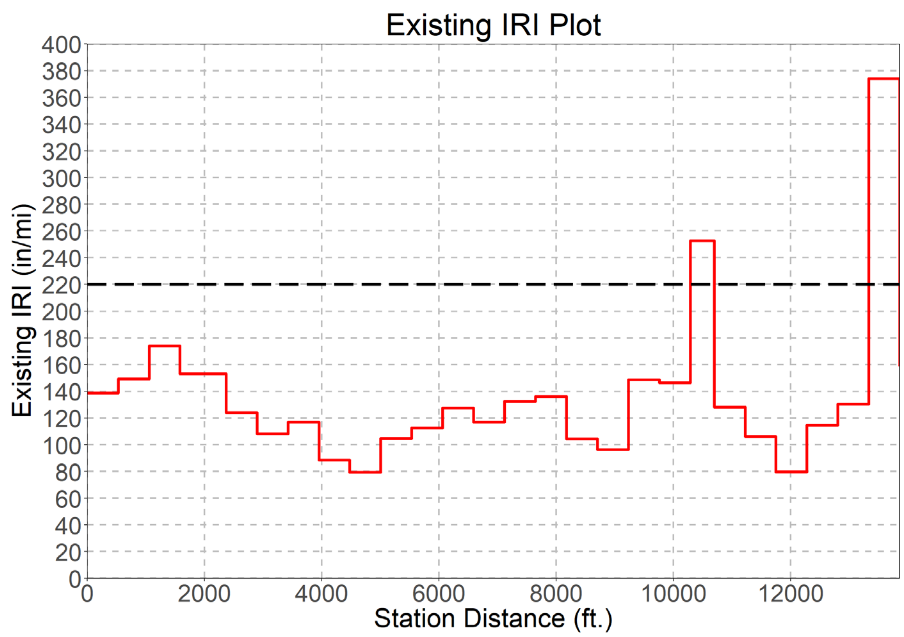


Figure A-6. Graph. IRI of an existing pavement.

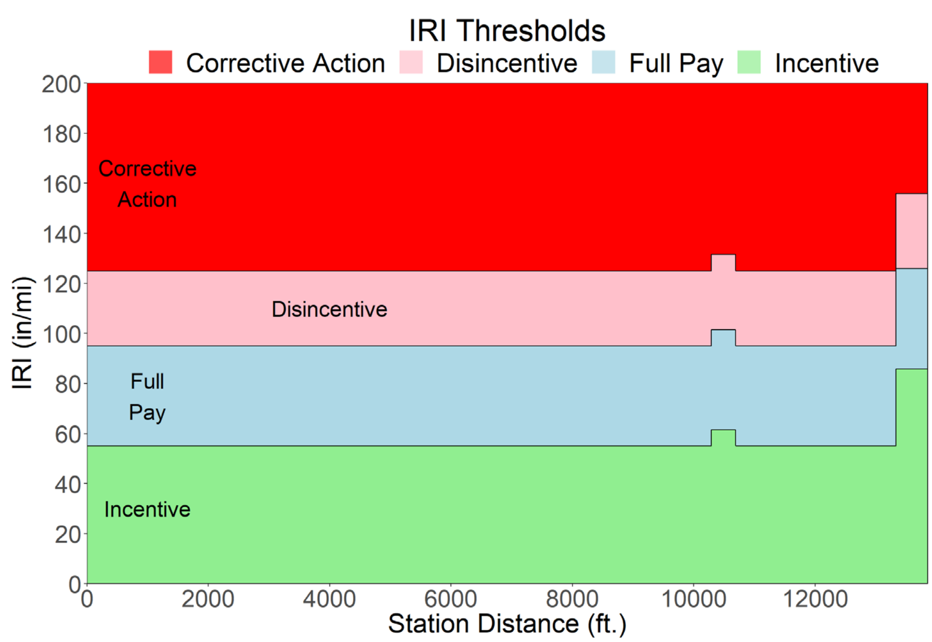


Figure A-7. Graph. IRI threshold versus station distance.

SMOOTHNESS ASSESSMENT SCHEDULE

Another important component of the smoothness specification is the smoothness assessment schedule (also known as the pay schedule), which is used to determine the amount of incentive and disincentive payments based on the IRI achieved from newly constructed pavement surfaces.

Table A-3 and Table A-4 show the assessment schedule for high-speed and low-speed pavements, respectively. As shown in these tables, the IRI thresholds are used to define the following payment zones.

- Incentive zone ($IRI \le IRI_{Incentive}$)
    - For full-depth HMA, HMA overlay, and PCC pavements, the contractor receives an incentive payment of \$80, \$33, and \$120 for every 1.0 in/mi of achieved sublot IRI below $IRI_{Incentive}$, respectively. These incentive amounts are consistent for high-speed and low-speed facilities.
- Full-pay zone ($IRI_{Incentive} < IRI \le IRI_{FullPay}$)
    - If the achieved IRI is between $IRI_{Incentive}$ and $IRI_{FullPay}$, the contractor receives no bonus or penalty and the full contract amount is paid.
- Disincentive zone ($IRI_{FullPay} < IRI \le IRI_{Disincentive}$)
    - If the achieved IRI is greater than $IRI_{FullPay}$, the contractor should correct the sublot to bring the IRI below $IRI_{FullPay}$. If the IRI after correction is still higher than $IRI_{FullPay}$, the contractor will receive disincentives as described below.
    - For high-speed full-depth HMA, HMA overlay, and PCC pavements, the contractor receives a disincentive payment of \$30, \$20, and \$45 for every 1.0 in/mi of achieved sublot IRI above $IRI_{Disincentive}$, respectively.
    - For low-speed full-depth HMA, HMA overlay, and PCC pavements, the contractor receives a disincentive payment of \$25, \$16.5, and \$37.5 for every 1.0 in/mi of achieved sublot IRI above $IRI_{Disincentive}$, respectively.
- Corrective action zone ($IRI > IRI_{Disincentive}$)
    - If the achieved IRI is greater than $IRI_{Disincentive}$, the contractor must correct the sublot to bring the IRI below $IRI_{FullPay}$ or may choose to remove and replace the sublot.
    - If the IRI after correction is still higher than $IRI_{Disincentive}$, the contractor receives maximum disincentives of \$750, \$500, and \$1,125 for full-depth HMA, HMA overlay, and PCC pavements, respectively.

Table A-3. Smoothness Assessment Schedule for High-Speed Facilities

IRI Range	Full Depth HMA[1)]	HMA Overlay[2)]	PCC[3)]
$IRI \leq IRI_{Incentive}$	$(IRI_{Incentive} - IRI) \times \$80$	$(IRI_{Incentive} - IRI) \times \$33$	$(IRI_{Incentive} - IRI) \times \$120$
$IRI_{Incentive} < IRI \leq IRI_{FullPay}$	+ \$0.0	+ \$0.0	+ \$0.0
$IRI_{FullPay} < IRI \leq IRI_{Disincentive}$	$-(IRI - IRI_{FullPay}) \times \$30$	$-(IRI - IRI_{FullPay}) \times \$20$	$-(IRI - IRI_{FullPay}) \times \$45$
$IRI > IRI_{Disincentive}$	–\$750	–\$500	–\$1,125

1) Incentive payment not to exceed \$1,200 for each 0.1 mi sublot
2) Incentive payment not to exceed \$500 for each 0.1 mi sublot
3) Incentive payment not to exceed \$1,800 for each 0.1 mi sublot

Table A-4. Smoothness Assessment Schedule for Low-Speed Facilities

IRI Range	Full Depth HMA[1)]	HMA Overlay[2)]	PCC[3)]
$IRI \leq IRI_{Incentive}$	$(IRI_{Incentive} - IRI) \times \$80$	$(IRI_{Incentive} - IRI) \times \$33$	$(IRI_{Incentive} - IRI) \times \$120$
$IRI_{Incentive} < IRI \leq IRI_{FullPay}$	+ \$0.0	+ \$0.0	+ \$0.0
$IRI_{FullPay} < IRI \leq IRI_{Disincentive}$	$-(IRI - IRI_{FullPay}) \times \$25$	$-(IRI - IRI_{FullPay}) \times \$16.5$	$-(IRI - IRI_{FullPay}) \times \$37.5$
$IRI > IRI_{Disincentive}$	–\$750	–\$500	–\$1,125

1) Incentive payment not to exceed \$1,200 for each 0.1 mi sublot
2) Incentive payment not to exceed \$500 for each 0.1 mi sublot
3) Incentive payment not to exceed \$1,800 for each 0.1 mi sublot

As an example, Figure A-8 shows the IRI achieved after construction, on top of the IRI thresholds previously shown in Figure A-7. The figure shows that while most of the achieved IRI values are within the full-pay zone, there are four and five sublots within the incentive and disincentive zones, respectively. Table A-5 summarizes the achieved IRI values for each sublot along with the corresponding incentive and disincentive amounts calculated in accordance with Table A-4. Summing up all the payment amount for this example produced a total disincentive amount of $726.

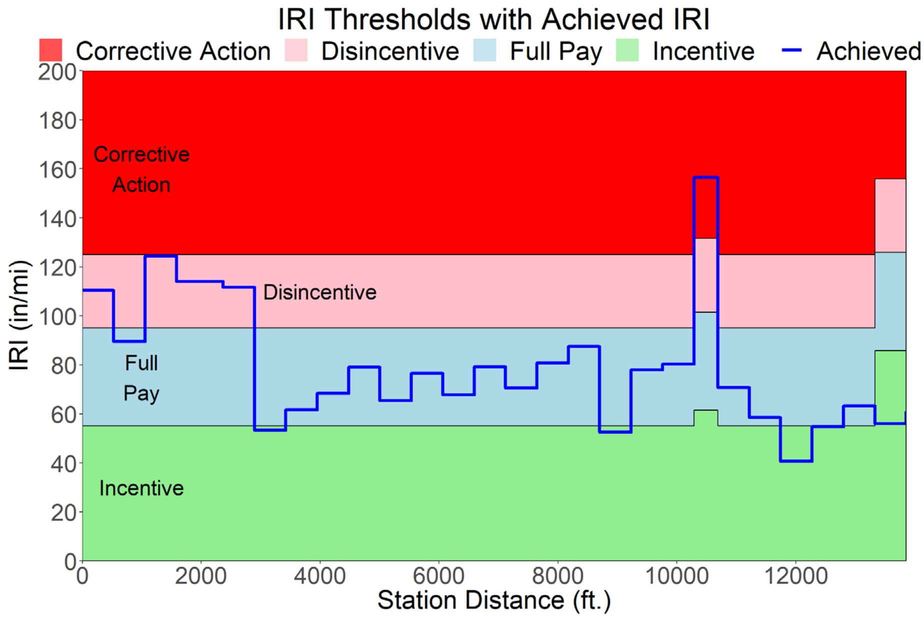


Figure A-8. Graph. IRI thresholds and IRI achieved after construction.

📖 The smoothness assessment schedule determines the incentive or disincentive payment along with the IRI thresholds. Therefore, it is important to understand which equation (or table) is applicable for a given sublot.

For convenience, IDOT is in the process of automating the calculation of IRI thresholds as well as the incentive/disincentive payments.

Table A-5. Calculated IRI thresholds and incentive/disincentive payment

Station	Before IRI	$IRI_{Incentive}$	$IRI_{FullPay}$	$IRI_{Disincentive}$	Achieved IRI	Payment
0	139	55	95	125	110	−$247.5
528	149	55	95	125	89	$0
1056	174	55	95	125	124	−$478.5
1584	153	55	95	125	114	−$313.5
2367	124	55	95	125	112	−$280.5
2895	108	55	95	125	53	$66
3423	117	55	95	125	62	$0
3951	88	55	95	125	68	$0
4479	79	55	95	125	79	$0
5007	105	55	95	125	65	$0
5535	113	55	95	125	76	$0
6063	128	55	95	125	68	$0
6591	117	55	95	125	79	$0
7119	133	55	95	125	71	$0
7647	136	55	95	125	81	$0
8175	105	55	95	125	87	$0
8703	96	55	95	125	53	$66
9231	149	55	95	125	78	$0
9759	146	55	95	125	80	$0
10287	253	62	102	132	157	−$500
10691	128	55	95	125	71	$0
11219	106	55	95	125	58	$0
11747	80	55	95	125	41	$462
12275	115	55	95	125	55	$0
12803	131	55	95	125	63	$0
13331	374	86	126	156	56	$500

AREA OF LOCALIZED ROUGHNESS CONSIDERATIONS

Area of localized roughness (ALR) refers to the “hot spots” that exhibit excessive level of roughness over a short length. ALRs are not desirable because of their effect on ride quality and pavement life and their potential effect on roadway safety.

The ALR provision adopted in the new specification is based on the IRI calculated at a baselength of 25 ft. The IRI requirements for ALR are shown as the following.

- For high-speed facilities, the 25 ft IRI value shall not exceed 150 in/mi.
- For low-speed facilities, the 25 ft IRI value shall not exceed 220 in/mi.

If any of the 25 ft IRI does not meet the above requirement, the 0.1 mi sublot is rejected (even if the sublot IRI is below $IRI_{FullPay}$) and the contractor is required to take corrective action for the localized roughness.

For example, consider a high-speed sublot with an achieved IRI of 50 in/mi. Although this IRI value is below $IRI_{FullPay}$ shown in Table A-1, the sublot shows an excessive localized IRI of 169 in/mi (centered at station distance of 200 ft) which is greater than the ALR threshold of 150 in/mi and hence the sublot is rejected.

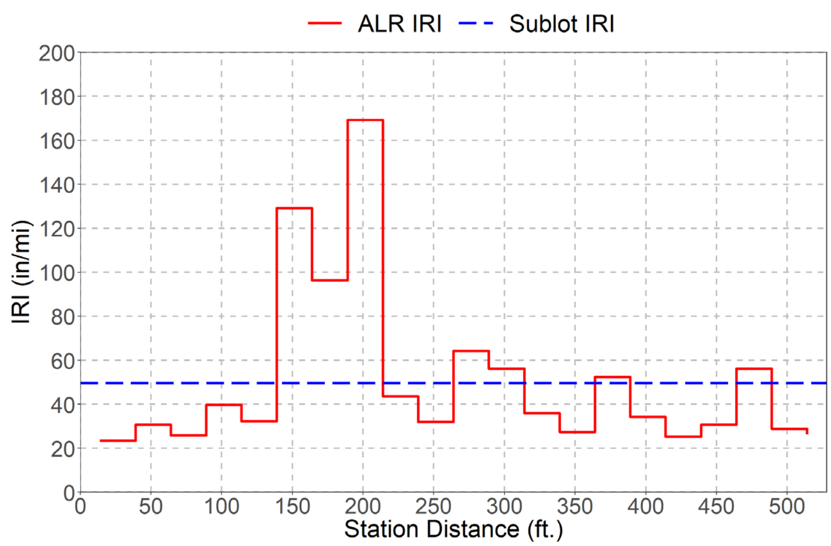


Figure A-9. Graph. Acceptable sublot IRI with unacceptable ALR IRI.

For the sublot shown in the above example, the contractor is required to correct (e.g., grind) the problematic area of localized roughness. However, it should be noted that the IRI plot shown in Figure A-9 is the “Fixed Interval IRI,” meaning that IRI was calculated within the respective 25 ft intervals.

It is also possible to calculate the IRI in a continuous manner, which may be useful for determining the limits of the corrective action to be performed. Similar to a moving average, the continuous IRI is calculated within a sliding window having a certain baselength. For example, the 25 ft continuous IRI is shown in Figure A-10 for comparison with the fixed interval IRI. The continuous IRI reveals the following.

1. It is not the entire 25 ft segment centered at 200 ft that is showing localized roughness.
2. The localized roughness may also extend to the next 25 ft segment centered at 225 ft.
3. The 25 ft segments centered at 150 ft and 175 ft may also exhibit highly localized roughness.

Based on the above observations, the contractor may choose to grind over a 100 ft length, between stations 125 ft and 225 ft. Such corrective action may allow the contractor not only to remove the problematic ALR but also to lower the sublot IRI further to a point where incentive payment may be eligible.

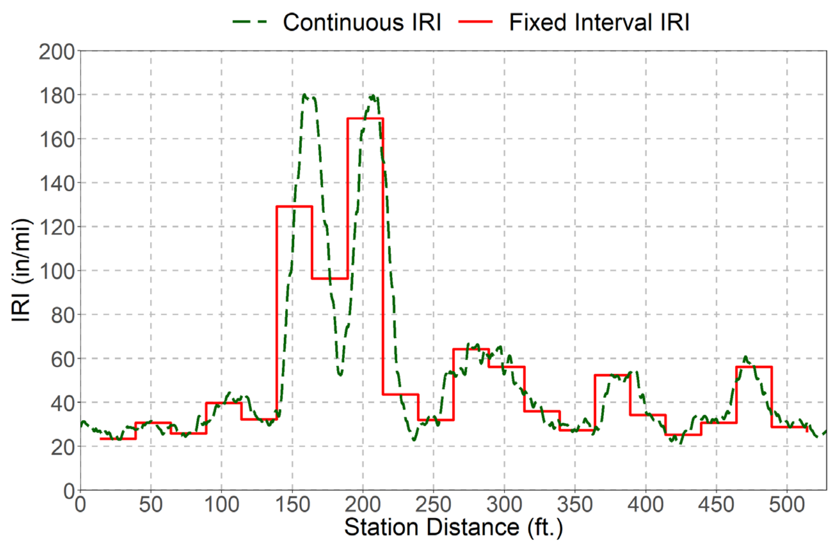


Figure A-10. Graph. Fixed interval IRI versus continuous IRI for ALR.

As discussed in the previous chapter, IRI is sensitive to a range of profile wavelengths rather than a single wavelength. As such, the goal of any corrective action is to reduce (or eliminate) these wavelengths causing higher IRI. However, due to the nature of such activities, it is possible that reducing the wavelengths within a certain range may increase the wavelengths within a different range. It is also possible that certain wavelengths simply cannot be eliminated due to other constraints (e.g., intersections and driveways). As such, it is generally recommended that both the fixed interval IRI and the continuous IRI be studied for determining the limits for corrective action, although the latter is not required by IDOT's new specification.

📖 PSD analysis does not reveal "where" in the pavement profile a particular wavelength is dominant. In other words, it cannot be used for determining the limits of corrective action.

Instead, it is recommended that both the fixed interval IRI and the continuous IRI be examined for determining the limits for corrective action. However, the use of continuous IRI is not required by IDOT's new specification.

CHAPTER 4: TECHNOLOGIES FOR SMOOTHER PAVEMENTS

This goal of this chapter is to document recent technologies for constructing smoother pavements. Note that these technologies are not required by IDOT's smoothness specification. In addition, there are other factors that need to be considered for constructing smoother pavements such as consistent delivery of material to the job site and avoiding paver stops. Therefore, these technologies are introduced solely for reference purposes.

TECHNOLOGIES FOR CONSTRUCTING SMOOTHER RIGID PAVEMENTS

Real-Time Smoothness Measurements for Rigid Pavements

Real-time smoothness has been identified as a promising technology for constructing smoother rigid pavements. Rasmussen et al. (2016) identified several potential technologies for real-time smoothness measurements, evaluated the most viable technologies, and developed the necessary specifications and guidelines. Brief summaries of the following real-time smoothness technologies are provided.

- GOMACO Smoothness Indicator (GSI): GOMACO Corporation
- Real-Time Profiler (RTP): Ames Engineering
- Sliding Profiler: Texas DOT
- Dynamic Surface Profiler: Surface Systems & Instruments

GOMACO Smoothness Indicator

The GOMACO Smoothness Indicator (GSI) is a noncontact surface smoothness instrument that provides multi-application usage. GSI equipment, which can be operated while it is mounted on the paver or on the bridge, can monitor and report the smoothness readings instantly. Figure A-11 shows the bridge-mounted GSI machine. The system can take up to eight traces or four lanes in one pass of a single pass, directly behind the paver. The GSI system provides instant data, which allows for making on-the-go adjustments so that concrete surface can be repaired while still in its plastic state. The on-the-go surface smoothness information includes station and footage documentation for analysis of bumps and smoothness locations in the future. It prints surface smoothness statistics such as IRI and PI along with job information and bump location. In general, the real-time smoothness (i.e., IRI and PI) values calculated in real time vary from the IRI calculated on the hardened surface.

Figure A-11. Photo. GSI machine (Source: GOMACO Corporation).

Several studies have investigated the effectiveness of GSI technology (Karamihas 2004; Cable et al. 2005; Rasmussen et al. 2013; Fick et al. 2020). Cable et al. (2005) evaluated the GSI and Ames Engineering Real-Time Profiler (RTP) technologies to identify the causes of undulation in the pavement surface and how to prevent them from occurring. The two technologies were used to measure profile on wet concrete during construction to adjust and improve concrete smoothness before the setting of the concrete. Both devices were found to accurately measure the profile on plastic concrete surface as well as the profile measured from the top of the base materials in front of the slip-form paver and the top of finished concrete surface behind the paver for evaluating pavement thickness.

Real-Time Profiler: Ames Engineering

The real-time profiler (RTP) is a laser-based profiler that mounts directly onto the paving equipment and measures smoothness indices directly behind the paver. It calculates and displays the profile as concrete is placed and instantly calculates and displays IRI and PI. It also locates areas such as bump or localized roughness in real time to allow the contractor to adjust paving operation to achieve target smoothness. The RTP mounts directly off the back of a slip-form paver as shown in Figure A-12. The RTP system has various features, including collecting measurements at speed between 0 and 50 ft/min, laser height sensors with a range of 5 in. and a resolution of 0.01 in., profile wavelength range 1.8 to 300 ft.

Figure A-12. Photo. Ames Engineering real-time profiler (Source: Ames Engineering)

Sliding Profiler: Texas DOT

The Sliding Profiler was developed by the University of Texas at Arlington and the Texas Transportation Institute. The device was designed to allow early bump detection on fresh concrete so that contractors could fix the defects while the concrete is still fresh (Walker and Fernando 2007). This device was developed as an economical alternative (but promising) technology to the Ames Engineering RTP and the GSI, which were under development at that time. The device includes a sliding platform (snowboard) that carries the hardware and software to measure the slope and distance as it is towed directly behind the paver on wet concrete (see Figure A-13).

Figure A-13. Photo. Sliding profiler on wet concrete surface (Raikar 2015)

The Sliding Profiler was demonstrated on a construction project on SH 161 in Grand Prairie, Texas, in August 2006. The unit was mounted on a work bridge and towed on fresh concrete to detect and record bumps in wet concrete. A few false bumps were identified because of lurching of the work bridge. False bumps were not noticed when the device was attached directly to the paver. The Sliding Profiler has the potential to eliminate the need for using grinding operation in many cases to improve ride quality of CRCP pavements, which reduces contractor costs.

Dynamic Surface Profiler: Surface Systems and Instruments

The Dynamic Surface Profiler was developed by Surface Systems and Instruments (SSI), Inc. and it can be used for both asphalt and concrete pavers (Figure A-14). The device measures and displays the profile, speed, ride values, areas of localized roughness, power spectral density (PSD), and other profile statistics in real time. The system also provides the dimensions of bumps/dips as measured by the maximum amplitude of peaks and troughs. The profile measurements are collected by a proprietary laser and inclinometer platform. The Dynamic Surface Profiler has an adjustable sampling interval with a default value of 1 in., high measurements accuracy of ±0.015 inch per 50 yards, and precision of ±0001 inch per 12 in. wheelbase. A concrete paving crew can use a PSD plot and elevation data to visually show the profile of the pavement and make corrections directly before the pavement is textured. The PSD plot can be used to show recurring frequencies in the pavement, a trait benefitting the procedures of concrete paving.

Figure A-14. Photo. Dynamic surface profiler for asphalt and concrete (Source: Surface Systems & Instruments, Inc.)

Diamond Grinding of Concrete Pavements

Diamond grinding is a technique that is used to restore a smooth-riding surface with the desirable friction characteristics on concrete pavements. This technique was first used in 1965 on a 19-year-old section of I-10 in southern California to eliminate excessive faulting (Rao 1999). Diamond grinding has been commonly used for concrete pavements rather than asphalt pavements and has become a major element of concrete restoration projects. The immediate effect of diamond grinding on concrete pavement provides a significant improvement in smoothness and can achieve a level of smoothness comparable to that of a new concrete pavement or an AC overlay (Rao 1999).

Stringless Paving Technology

Stringless paving (sometimes referred to as 3D paving) is the process of monitoring the paving machine's position with surveying instruments and comparing the results to a digital model to control the movements of steering and elevation without the use of stringline (Snyder 2019). Figure A-15 illustrates stringless paving using robotic total stations for machine control. Stringless paving has the potential to achieve more accurate and smoother paving. Stringless operations eliminate the time of setting and removing the stringline and is generally safer than traditional operation. It can be used for asphalt application in addition to concrete.

The benefits of stringless paving technology, when implemented properly, include concrete pavements with better ride quality and more accurate profile and cross slopes, resulting in smoother pavements (Snyder 2019). Stringless paving also produces a consistent pavement thickness, which enhances the long-term pavement performance and increases cost-savings paving because of the reduced need for surveyors prior to and during paving operation.

The use of stringless paving involves three basic steps: development of the pavement surface model, transfer of the model to the paver's on-board computer for use in paving, and establishment of survey control points for paver operation (Snyder 2019). Stringless technology requires less maintenance of the control points that are typically located away from the construction sites, resulting in saving construction costs and improving paving ride quality. In contrast, string lines require more effort to prevent damage and disturbance of string lines during all phases of construction. The potential problems of string lines include sag from string line expansion in hot weather, errors in setting string lines, and deviations caused by excessive crew adjustments of the sensor controls (Reeder and Nelson 2015). The string lines are a crucial element in controlling pavement quality and smoothness.

Stringless paving technology demonstrated in Washington County, Iowa, indicated that the use of stringless paving using GPS system was feasible and approached the desired goals of guidance and profile control with the use of three-dimensional design models (Cable et al. 2004).

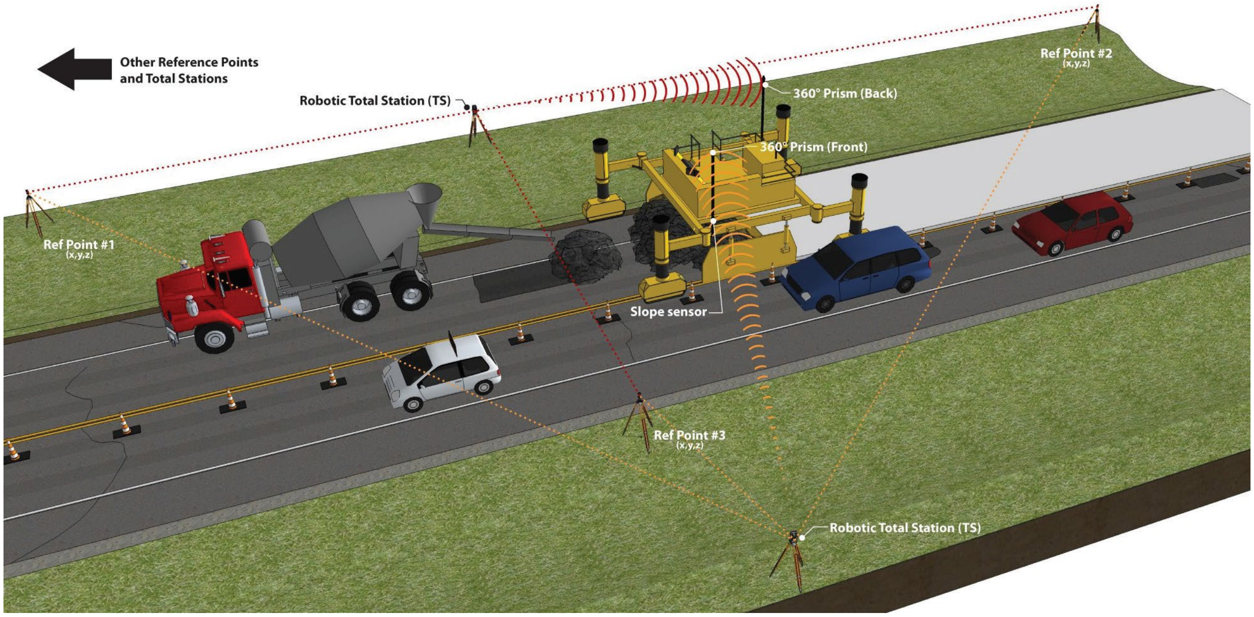


Figure A-15. Diagram. Illustration of stringless paving (Reeder and Nelson 2015).

TECHNOLOGIES FOR CONSTRUCTING SMOOTHER ASPHALT PAVEMENTS

Material Transfer Vehicles: Roadtech

The material transfer vehicle (MTV) is a patented technology developed by Roadtech and Astec Industries in 1989. MTV equipment is designed to be placed between the hot-mix asphalt truck and paver to eliminate segregation, as shown in Figure A-16. It also has the potential to allow nonstop paving, resulting in a much smoother surface, to reduce the number of haul trucks needed, decrease temperature differential, and reduce aggregate segregation. There are three different design models of the MTV that can handle 10 to 25 tons of asphalt mix capacity. Additional features of the MTV are remixing asphalt that provides uniform flow across the entire pavement width, equipped with infrared camera behind the paver to show temperature differences. When temperature of pavement surface is uniform, uniform density of the mix can be achieved, resulting in long-term performance.

Figure A-16. Photo. Material transfer vehicle (source: Roadtech).

Infrared Thermal Profiler Technology

Significant temperature differentials in asphalt paving operations can cause segregation and inadequate and nonuniform density in the resulting asphalt pavements coupled with poor performance and service life. Commonly used quality control methods, including visual uniformity checking, are subjective assessment methods with significantly varying measurement levels.

Infrared (IR) has been proven as a viable nondestructive technology for providing asphalt pavement temperature differentials and uniformity information in real-paving time, while covering full paving areas. In addition, recent advances in thermal-imaging technology, including fast camera detector readouts and high-performance electronics, allow high-speed or time-lapse thermography to feasibly detect internal defect potentials in asphalt pavements. The IR scanner is referred to as the IR paver-mounted thermal profiler. Figure A-17 shows IR scan screen that used to see/monitor mat temperature in real time.

The IR technology was demonstrated as part of the SHRP2 Technologies to Enhance Quality Control on Asphalt Pavements (R06C) (Von Quintus and Reiter 2018). Field demonstration projects were completed to demonstrate the use and effectiveness of the IR thermal profiler for control of AC mixture temperature uniformity and to confirm the short- and long-term benefits of the IR technology. The type of delivery truck and the impact of using a material transfer vehicle (MTV) on the percentage of severe mat surface temperature differentials were evaluated. The percentage of severe temperature differentials were significantly lower for the demonstration projects employing the use of an MTV. More importantly, pavement performance is not going to increase or maintenance costs decrease simply because the IR thermal profiler is used on a project. The contractor must take some corrective action when cold spots or moderate to severe temperature differentials are observed on the IR monitor along a project.

Figure A-17. Photo. Pave-IR scan screen (Source: MOBA Corporation).

Diamond Grinding of Asphalt Pavements

Smooth asphalt surfaces can also be obtained by diamond grinding. Diamond grinding has the potential to remove a thin layer of the pavement surface using closely spaced diamond saw blades. The benefits of diamond grinding include improving smoothness, increasing friction, and reducing noise. Figure A-18 shows an asphalt pavement undergoing diamond-grinding operation. Diamond grinding should be used for asphalt pavements that are in structurally sound condition with minor surface defects (e.g., slight to moderate rutting, shallow top-down cracking, or oxidation). Diamond grinding is used on new asphalt pavement to mitigate bleeding and loss of texture and at the time of construction (IGGA 2016).

Figure A-18. Photo. Diamond grinding of asphalt (IGGA 2016).

REFERENCES

Ames Engineering 2020. Accessed July 2020.https://amesengineering.com/products/real-time-profiler/.

Cable, J. K., S. M. Karamihas, M. Brenner, M. Leichty, T. Tabbert, and J. Williams. 2005. *Measuring Pavement Profile at the Slip-Form Paver.* Report FHWA DTFH61-01-X-00042 (Project 12). Center for Portland Cement Concrete Pavement Technology, Iowa State University, Ames.

Cable, J. K., C. R. Bauer, E. J. Jaselskis, and L. Li. 2009. Stringless Portland Cement Concrete Paving. Report No. TR-490, Iowa Department of Transportation, Ames, Iowa.

Fick, G., D. Merritt, P. Taylor, T. Hanke, H. Torres, and R. Rasmussen. 2020. Implementation Support for Second Strategic Highway Research Program (SHRP2) Renewal R06E Real-Time Smoothness Measurements on Portland Cement Concrete Pavements During Construction (No. FHWA-HIF-18-020), Federal Highway Administration Office of Pavement Technology.

GOMACO Corporation. 2020. Accessed July 2020. https://www.gomaco.com/Resources/gsi.html.

International Grooving and Grinding Associate (IGGA). 2016. Asphalt Pavement Preservation and Diamond Grinding; Diamond Grinding Saves Money, Prolongs Asphalt Pavement Life. Accessed July 2020. https://www.igga.net/wp-content/uploads/2018/08/CSMay2016_MO_diamond_grinding.pdf.

International Grooving and Grinding Associate (IGGA). 2010. CPR – Rebuilt to Last; I-90 Diamond Grinding of Asphalt, Wall, SD. Accessed July 2020. http://www.concreteisbetter.com/library/CaseStudyWallSD.pdf.

Karamihas, S. M. 2004. The Great Pavement Profiler Round-Up. FHWA-HRT-04-026, U.S Department of Transportation Federal Highway Administration.

Rasmussen, R. O., S. M. Karamihas, and F. Gary. 2016. Real-Time Smoothness Measurements on Portland Cement Concrete Pavements During Construction. SHRP 2 Report S2-R06E-RR-1. Strategic Highway Research Program (SHRP) 2. Transportation Research Board, Washington, D.C.

Raikar, A. 2015. Embedded Data Acquisition Platform for Surface Measurements on Wet Concrete. Master of Science in Electrical Engineering, The University of Texas at Arlington.

Rao, S., H. T. Yu, and M. I. Darter. 1999. The Longevity and Performance of Diamond-ground Pavements. Research and Development Bulletin. Portland Cement Association. RD118, Portland Cement Association, Skokie, Illinois.

Reeder, G. D., and G. A. Nelson. 2015. Implementation Manual—3D Engineered Models for Highway Construction: The Iowa Experience. Report No. RB33-014, Federal Highway Administration, Washington, D.C.

Roadtech and Astec Industries Company. 2006. Accessed July 2020. https://www.roadtec.com/products/material-transfer-vehicles.

Sayers, M. W. 1995. On the Calculation of International Roughness Index from Longitudinal Road Profile. Transportation Research Record: Journal of the Transportation Research Board, 1501, 1–12.

Stroup-Gardiner, M. 2015. Methods and Practices on Reduction and Elimination of Asphalt Mix Segregation, NCHRP Synthesis 477, Project No. 20-05, Topic 45-12, Transportation Research Board of The Nation Academies.

Surface Systems & Instruments (SSI). 2020. Accessed July 2020. https://www.smoothroad.com/dynamic-and-custom-profilers/.

Snyder, M. 2019. Stringless Paving. FHWA-HIF-18-011.Tech Brief, Federal Highway Administration (FHWA) Pavement Design and Analysis Team (HIAP-10).

Von Quintus, H. L., and J. Reiter. 2018. SHRP2 Case Study: Infrared Thermal Profiler Use for Improving Mat Uniformity and Long-Term Performance. Strategic Highway Research Program Federal Highway Administration

Walker R. W., and E. Fernando. 2007. Pilot Implementation of Bump Detection Profilers for CRCP Construction. Project 5-4385-01. Texas Department of Transportation.

APPENDIX B: DRAFT IRI-BASED SMOOTHNESS SPECIFICATION

SURFACE TESTING OF PAVEMENTS—IRI (BUREAU OF RESEARCH)

Effective: Month, Day, Year

Description. This work shall consist of testing the ride quality of the finished surface of pavements, according to Illinois Test Procedure XXX, "Ride Quality Testing using the International Roughness Index." Work shall be according to Sections 406, 407, or 420 of the Standard Specifications, except as modified herein.

Hot-Mix Asphalt (HMA) Overlays

Delete Article 406.03(h) of the Standard Specifications.

Add the following to Article 406.03 of the Standard Specifications:

"(j) Pavement Surface Grinding Equipment.. 1101.04"

Revise Article 406.11 of the Standard Specifications to read:

"**406.11 Surface Tests.** The finished surface of the pavement shall be tested in the presence of the Engineer and before opening to traffic. Mainline pavement shall be identified as High-Speed, Low-Speed, or Miscellaneous as defined in Illinois Test Procedure XXX and evaluated accordingly.

(a) Corrective Work. Corrective work shall be completed according to the following.

(1) High-Speed Mainline Pavements. For High-Speed Mainline Pavement, any 25 ft (7.6 m) interval with an Area of Localized Roughness (ALR) in excess of 150 in./mile (2400 mm/km) will be marked and shall be corrected as directed by the Engineer. Any sublot having a MRI within the range of greater than 75.0 to 100.0 in./mile (1190 to 1580 mm/km), including ALR, shall be corrected to reduce the MRI to 75.0 in./mile (1190 mm/km) or less. Any sublot having a MRI greater than 100.0 in./mile (1580 mm/km), including ALR, shall be corrected to reduce the MRI to 75.0 in./mile (1190 mm/km) or less, or replaced at the Contractor's option.

(2) Low-Speed Mainline Pavement. For Low-Speed Mainline Pavement, any 25 ft (7.6 m) interval with an Area of Localized Roughness (ALR) in excess of 220 in./mile (3470 mm/km) will be marked and shall be corrected as directed by the Engineer. Any sublot having a MRI within the range of greater than 95.0 to 125.0 in./mile (1500 to 1975 mm/km), including ALR, shall be corrected to reduce the MRI to 95.0 in./mile (1500 mm/km) or less. Any sublot having a MRI greater than 125.0 in./mile (1975 mm/km), including ALR, shall be corrected to reduce the MRI to 95.0 in./mile (1500 mm/km) or less, or replaced at the Contractor's option.

(3) Miscellaneous Pavement. Surface variations which exceed the 3/8 in. (10 mm) tolerance will be marked by the Engineer and shall be corrected by the Contractor.

Corrective work shall be completed with pavement surface grinding equipment or by removing and replacing the pavement. Corrective work shall be applied to the full lane width. When completed, the corrected area shall have uniform texture and appearance, with the beginning and ending of the corrected area squared normal to the centerline of the paved surface.

Upon completion of the corrective work, the surface of the sublot(s) shall be retested. The Contractor shall furnish the data and reports to the Engineer within two working days after corrections are made. If the MRI and/or ALR still do not meet the requirements, additional corrective work shall be performed. For sublots that are replaced, assessments will be based on the MRI determined after replacement.

Corrective work shall be at no additional cost to the Department.

(b) Smoothness Assessments. Assessments will be paid to or deducted from the Contractor for each sublot of mainline pavement, per the Smoothness Assessment Schedule. Assessments will be based on the Mean Roughness Index (MRI) of each sublot prior to performing any corrective work unless the Contractor has chosen to remove and replace the sublot. For sublots that receive corrective work, assessments will be based on the MRI determined after corrective action.

(1) High-Speed Mainline Pavement. The upper MRI thresholds for Incentive (MRI_I), Full Pay (MRI_F), and Disincentive (MRI_D) are dependent on the MRI of the existing pavement before construction (MRI_0) and shall be determined as the following.

MRI Thresholds (High-Speed, HMA Overlays) 1/

Upper MRI Thresholds 1/	$MRI_0 \le 125.0$ in./mile ($\le$ 1975 mm/km)	$MRI_0 > 125.0$ in./mile (> 1975 mm/km)
Incentive (MRI_I)	45.0 in./mile (710 mm/km)	$0.2 \times MRI_0 + 20$
Full Pay (MRI_F)	75.0 in./mile (1190 mm/km)	$0.2 \times MRI_0 + 50$
Disincentive (MRI_D)	100.0 in./mile (1975 mm/km)	$0.2 \times MRI_0 + 75$

1/ MRI_0, MRI_I, MRI_F, and MRI_D are in in./mile for calculation.

Smoothness assessment for High-Speed Mainline Pavement shall be determined according to the following.

SMOOTHNESS ASSESSMENT SCHEDULE (High-Speed, HMA Overlays) 1/

Mainline Pavement MRI Range	Assessment per sublot
$MRI \le MRI_I$	$+ (MRI_I - MRI) \times \$33.00$ 2/
$MRI_I < MRI \le MRI_F$	+ \$0.00
$MRI_F < MRI \le MRI_D$	$- (MRI - MRI_F) \times \$20.00$
$MRI > MRI_D$	– \$500.00

1/ MRI_I, MRI_F, and MRI_D are in in./mile for calculation.

2/ The maximum incentive amount shall not exceed \$500.00.

(2) Low-Speed Mainline Pavement. The upper MRI thresholds for Incentive (MRI_I), Full Pay (MRI_F), and Disincentive (MRI_D) are dependent on the MRI of the existing pavement before construction (MRI_0), and shall be determined as the following.

MRI Thresholds (Low-Speed, HMA Overlays) [1/]

Upper MRI Thresholds [1/]	$MRI_0 \leq 220.0$ in./mile (3470 mm/km)	$MRI_0 > 220.0$ in./mile (3470 mm/km)
Incentive (MRI_I)	55.0 in./mile (870 mm/km)	$0.2 \times MRI_0 + 11$
Full Pay (MRI_F)	95.0 in./mile (1500 mm/km)	$0.2 \times MRI_0 + 51$
Disincentive (MRI_D)	125.0 in./mile (1975 mm/km)	$0.2 \times MRI_0 + 81$

[1/] MRI_0, MRI_I, MRI_F, and MRI_D are in in./mile for calculation.

Smoothness assessment for Low-Speed Mainline Pavement shall be determined according to the following.

SMOOTHNESS ASSESSMENT SCHEDULE (Low-Speed, HMA Overlays) [1/]

Mainline Pavement MRI Range	Assessment per sublot
$MRI \leq MRI_I$	$+ (MRI_I - MRI) \times \$33.00$ [2/]
$MRI_I < MRI \leq MRI_F$	+ \$0.00
$MRI_F < MRI \leq MRI_D$	$- (MRI - MRI_F) \times \$16.50$
$MRI > MRI_D$	– \$500.00

[1/] MRI_I, MRI_F, and MRI_D are in in./mile for calculation.

[2/] The maximum incentive amount shall not exceed \$500.00.

Hot-Mix Asphalt (HMA) Pavement (Full-Depth)

Revise the first paragraph of Article 407.03 to read:

"**407.03 Equipment.** Equipment shall be according to Articles 406.03."

Revise Article 407.09 of the Standard Specifications to read:

"**407.09 Surface Tests.** The finished surface of the pavement shall be tested in the presence of the Engineer and before opening to traffic. Mainline pavement shall be identified as High-Speed, Low-Speed, or Miscellaneous as defined in Illinois Test Procedure XXX and evaluated accordingly.

Although surface testing of intermediate lifts will not be required, testing may be performed at the Contractor's option. When this option is chosen, the testing shall be performed and a report generated as described below.

The Engineer may perform testing at any time for monitoring and comparison purposes.

(a) Corrective Work. Corrective work shall be completed according to the following.

(1) High-Speed Mainline Pavement. Any 25 ft (7.6 m) interval with an Area of Localized Roughness (ALR) in excess of 150 in./mile (2400 mm/km) for High-Speed facilities or 220 in./mile (3470 mm/km) for Low-Speed facilities will be marked and shall be corrected as directed by the Engineer. Any sublot having a MRI within the range of greater than 75.0 to 100.0 in./mile (1190 to 1580 mm/km), including ALR, shall be corrected to reduce the MRI to 75.0 in./mile (1190 mm/km) or less. Any sublot having a MRI greater than 100.0 in./mile (1580 mm/km), including ALR, shall be corrected to reduce the MRI to 75.0 in./mile (1190 mm/km) or less, or replaced at the Contractor's option.

(2) Low-Speed Mainline Pavement. Any 25 ft (7.6 m) interval with an Area of Localized Roughness (ALR) in excess of 150 in./mile (2400 mm/km) for High-Speed facilities or 220 in./mile (3470 mm/km) for Low-Speed facilities will be marked and shall be corrected as directed by the Engineer. Any sublot having a MRI within the range of greater than 95.0 to 125.0 in./mile (1500 to 1975 mm/km), including ALR, shall be corrected to reduce the MRI to 95.0 in./mile (1500 mm/km) or less. Any sublot having a MRI greater than 125.0 in./mile (1975 mm/km), including ALR, shall be corrected to reduce the MRI to 95.0 in./mile (1500 mm/km) or less, or replaced at the Contractor's option.

(3) Miscellaneous Pavement. Surface variations which exceed the 3/8 in. (10 mm) tolerance will be marked by the Engineer and shall be corrected by the Contractor.

Corrective work shall be completed with pavement surface grinding equipment or by removing and replacing the pavement. Corrective work shall be applied to the full lane width. When completed, the corrected area shall have uniform texture and appearance, with the beginning and ending of the corrected area squared normal to the centerline of the paved surface.

Upon completion of the corrective work, the surface of the sublot(s) shall be retested. The Contractor shall furnish the data and reports to the Engineer within two working days after corrections are made. If the MRI and/or ALR still do not meet the requirements, additional corrective work shall be performed.

Corrective work shall be at no additional cost to the Department.

(b) Smoothness Assessments. Assessments will be paid to or deducted from the Contractor for each sublot of mainline pavement, per the Smoothness Assessment Schedule. Assessments will be based on the MRI of each sublot prior to performing any corrective work unless the Contractor has chosen to remove and replace the sublot. For sublots that are replaced, assessments will be based on the MRI determined after replacement.

(1) High-Speed Mainline Pavement. Smoothness assessment for High-Speed Mainline Pavement shall be determined according to the following.

SMOOTHNESS ASSESSMENT SCHEDULE (High-Speed, Full-Depth HMA)

Mainline Pavement MRI, in./mile (mm/km)	Assessment per sublot [1/]
45.0 (710) or less [2/]	+ (45 – MRI) × $80.00
> 45.0 (710) to 75.0 (1190)	+ $0.00
> 75.0 (1190) to 100.0 (1580)	– (MRI – 75) × $30.00
Greater than 100.0 (1580)	– $750.00

[1/] Use MRI in in./mile for calculation.

[2/] The maximum incentive amount shall not exceed $1,200.00.

(2) Low-Speed Mainline Pavement. Smoothness assessment for Low-Speed Mainline Pavement shall be determined according to the following.

SMOOTHNESS ASSESSMENT SCHEDULE (Low-Speed, Full-Depth HMA)

Mainline Pavement MRI, in./mile (mm/km)	Assessment per sublot [1/]
55.0 (870) or less [2/]	+ (55 – MRI) × $80.00
> 55.0 (870) to 95.0 (1500)	+ $0.00
> 95.0 (1500) to 125.0 (1975)	– (MRI – 95) × $25.00
Greater than 125.0 (1975)	– $750.00

[1/] Use MRI in in./mile for calculation.

[2/] The maximum incentive amount shall not exceed $1,200.00.

Smoothness assessments will not be paid or deducted until all other contract requirements for the pavement are satisfied. Pavement that is corrected or replaced for reasons other than smoothness, shall be retested as stated herein.

Smoothness assessments will not be applied to miscellaneous pavement sections."

Portland Cement Concrete Pavement

Delete Article 420.03(i) of the Standard Specifications.

Revise Article 420.03(j) of the Standard Specifications to read:

"(i) Coring Machine (Note 1)"

Revise Article 420.10 of the Standard Specifications to read:

" **420.10 Surface Tests.** The finished surface of the pavement shall be tested in the presence of the Engineer and before opening to traffic. Mainline pavement shall be identified as High-Speed, Low-Speed, or Miscellaneous as defined in Illinois Test Procedure XXX and evaluated accordingly.

The finished surface of the pavement shall be tested for smoothness once the pavement has attained a flexural strength of 550 psi (3800 kPa) or a compressive strength of 3000 psi (20,700 kPa).

Membrane curing damaged during testing shall be repaired as directed by the Engineer at no additional cost to the Department.

(a) Corrective Work. Corrective work shall be completed according to Article 407.09(a) except as follows:

No further texturing for skid resistance will be required for areas corrected by grinding. Protective coat shall be reapplied to ground areas according to Article 420.18 at no additional cost to the Department.

Pavement corrected by removal and replacement, shall be corrected in full panel sizes.

(b) Smoothness Assessments. Assessments will be paid to or deducted from the Contractor for each sublot of mainline pavement, per the Smoothness Assessment Schedule. Assessments will be based on the MRI of each sublot prior to performing any corrective work unless the Contractor has chosen to remove and replace the sublot. For sublots that are replaced, assessments will be based on the MRI determined after replacement.

(1) High-Speed Mainline Pavement. Smoothness assessment for High-Speed Mainline Pavement shall be determined according to the following.

SMOOTHNESS ASSESSMENT SCHEDULE (High-Speed, PCC)

Mainline Pavement MRI, in./mile (mm/km)	Assessment per sublot [1/]
45.0 (710) or less [2/]	+(45 – MRI) × $120.00
> 45.0 (710) to 75.0 (1190)	+ $0.00
> 75.0 (1190) to 100.0 (1580)	– (MRI – 75) × $45.00
Greater than 100.0 (1580)	– $1,125.00

[1/] Use MRI in in./mile for calculation.

[2/] The maximum incentive amount shall not exceed $1,800.00.

(2) Low-Speed Mainline Pavement. Smoothness assessment for Low-Speed Mainline Pavement shall be determined according to the following."

SMOOTHNESS ASSESSMENT SCHEDULE (Low-Speed, PCC)

Mainline Pavement MRI, in./mile (mm/km)	Assessment per sublot [1/]
55.0 (870) or less [1/]	+(55 – MRI) × $120
> 55.0 (870) to 95.0 (1500)	+ $0.00
> 95.0 (1500) to 125.0 (1975)	– (MRI – 95) × $37.50
Greater than 125.0 (1975)	– $1,125.00

[1/] Use MRI in in./mile for calculation.

[2/] The maximum incentive amount shall not exceed $1,800.00.

Testing Equipment

Delete Article 1101.10 of the Standard Specifications.

Illinois Department of Transportation

ILLINOIS