RESEARCH & DEVELOPMENT

Development of IRI Limits and Targets for Network Management and Construction Approval Purposes

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NCDOT Project 2013-02

FHWA/NC/2013-02

December 2014

Development of IRI Limits and Targets for Network Management and Construction Approval Purposes

Final Report

(Report No. RP 2013-02)

To North Carolina Department of Transportation
(Research Project No. RP 2013-02)

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December 2014

1. Report No. *FHWA/NC/2013-02*	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Development of IRI Limits and Targets for Network Management and Construction Approval Purposes		5. Report Date December 2014
		6. Performing Organization Code
7. Author(s) Don Chen, John Hildreth, Vincent Ogunro, Xiazhi Fang, and Cassanni Laville		8. Performing Organization Report No.
9. Performing Organization Name and Address Smith 274, Dept. of Engineering Technology and Construction Management University of North Carolina at Charlotte Charlotte, NC 28223-0001		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address North Carolina Department of Transportation Research and Development 104 Fayetteville Street Raleigh, North Carolina 27601		13. Type of Report and Period Covered Final Report Final Report August 2012 – August 2014
		14. Sponsoring Agency Code RP 2013-02
Supplementary Notes:		

16. Abstract

The North Carolina Department of Transportation (NCDOT) considers International Roughness Index (IRI) an important indicator of pavement condition, and has collected IRI data since 1998. Although Federal Highway Administration (FHWA) recommended several IRI thresholds, they are not locally calibrated and thus do not reflect the ride smoothness perceived by the traveling public in North Carolina. To address this issue, researchers developed the relationship between perceived ride quality (comfort) and measured IRI. This task was completed by selecting candidate roadway sections, recruiting research participants, collecting in-vehicle and pavement condition data, and developing an ordinal categorical model. In addition, researchers developed IRI thresholds for use by the construction unit as acceptance criteria, and investigated the relationship between initial construction IRI and long term network performance IRI. Consequently, these IRI information can be used extensively by the Pavement Management Unit (PMU) to select timely pavement maintenance treatments, and thus to strategically manage North Carolina's roadway system in a cost effective manner.

17. Key Words International Roughness Index (IRI), ride quality, IRI index, categorical data analysis, IRI models	18. Distribution Statement		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 63	22. Price

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

DISCLAIMER

ACKNOWLEDGMENTS

This research was sponsored by the North Carolina Department of Transportation. The authors gratefully acknowledge the support and assistant from the following individuals:

Research Project Steering and Implementation Committee: Neil Mastin, P.E. (Chair), William Beatty - FHWA, Jerry Blackwelder, P.E., Judith Corley-Lay, Ph.D., P.E., Randy Finger, P.E., Clark Morrison, Ph.D., P.E., Nilesh Surti, P.E., Brad Wall, P.E., Mrinmay Biswas, Ph.D., P.E., and Mustan Kadibhai, P.E. (Project Manager).

NCDOT Governance Office: Douglas Cox.

NCDOT Data Center Operations: Amy Hoover.

The authors also would like to thank the following UNC Charlotte students for their participation in roadway surveys: Michael Dye, Steven James, Kristopher Grissom, Nicole Laville, and Dhanush Reddy,

EXECUTIVE SUMMARY

Roughness, or ride quality, is one of the most important pavement performance parameters. For DOT engineers, it is a measure of pavement surface distortion or variation in pavement surface elevation; it can be used to trigger appropriate maintenance treatments, approve new and rehabilitated roadways, and determine contractors' performance incentives. For the traveling public, roughness is an indicator of a comfortable ride; it is directly used by the public to judge pavement condition, it also affects user costs, including fuel, repairs, and vehicle depreciation.

Since 1986, the International Roughness Index (IRI) has been widely used to quantify pavement roughness, and is the parameter by which pavement smoothness is defined within the Mechanistic-Empirical Pavement Design Guide (MEPDG). IRI is measured during state DOTs' routine pavement surveys, and is required to be reported to the Highway Performance Monitoring System (HPMS) for the National Highway System (NHS) on an annual basis.

Although Federal Highway Administration (FHWA) has several recommended IRI thresholds, they are not locally calibrated and thus do not reflect the ride smoothness perceived by the traveling public in North Carolina. This research project was conducted to address this issue.

To ensure a geographically balanced sampling, a total of 9 counties, with at least 2 counties in each region of North Carolina (Mountains, Piedmont, and Coastal), were selected. Of the counties selected in each region, at least one was a rural county, and another one was an urban county. In each selected county, two roadway loops, one urban and one rural, were identified. These loops were selected based on the goal that each loop should include sections that have different pavement types (flexible or ASP and Jointed Concrete Pavement (JCP)), smoothness, and speed limits.

Research participants were recruited through face-to-face interviews. The recruitment process was designed to randomly enroll local drivers in selected counties at locations such as senior centers, community colleges, universities, grocery stores, supermarkets, hospitals, and public health service centers. A total of 241 participants were recruited and participated in this research project. Their perception of the smoothness of roadways were collected in both numerical (0-5) and categorical (Acceptable and Unacceptable) format. A total of 3,539 observations were collected. Among these observations, 158 were deleted due to missing values. Eventually, a total of 3,381 valid observations were used in further analyses.

The quality of the survey data was satisfactory. Sixty-five out of 88 Kendall's W coefficients are larger than 0.5 and also have a p-value that is less than 0.025, indicating that approximately 74% of participants agreed with each other when assessing the same roadway sections, and the null hypothesis that there is no agreement between ratings of all participants was rejected at a 0.05 level.

Through analyses of participants' perceived ride quality ratings, the following conclusions were obtained:

- The most influential factors in affecting perceived ride quality of a particular roadway section were measured IRI values, the speed limit, and participants' seating positions in the survey vehicles. Other factors, including types of survey vehicles, geographic regions

the roadway section is located, and the type of pavement of the section, were not statistically significant.

- Roadways that had greater measured IRI values and higher speed limits were more likely to be rated as “Unacceptable”.
- Participants seating in window positions were more likely to rate roadways favorably.
- Asphalt urban and rural sections were more likely to be rated as “Acceptable” than JCP sections.
- In North Carolina, if the measured IRI value of a roadway section is less than 103 inches/mile, most likely this section would be rated as “Acceptable” by the general driving public; most likely it would be rated as “Unacceptable” if its measured IRI value is greater than 151 inches/mile.
- The target initial IRI value for a new construction project should be between 60 and 70 inches/mile. For a “perfect” roadway section, its IRI value should be between 50 and 60 inches/mile. If the IRI value is greater than 182 inches/mile, the roadway section is considered as “Very Unacceptable”.
- IRI index was derived using a linear relationship (IRI vs. AGE) developed in this study. It was assumed that: 1) when IRI = 55 inches/mile, IRI Index value = 100 (perfect condition); and 2) when IRI = 182 inches/mile, IRI Index value = 0 (Very Unacceptable).
- IRI models were developed using the IRI index values determined in this study. It should be noted that currently the NCDOT uses distress models (distress index vs. pavement age) and performance models (PCR vs. pavement age) to make treatment decisions, and IRI models are not considered because they have not been developed before. Therefore, it is suggested that the developed IRI models should not be used to determine pavement service lives before these models are added to the decision tree as a separate branch.
- It was concluded that smooth pavements (smaller initial IRI values) deteriorated at a slower rate and therefore had longer service lives. In addition to initial IRI, other factors such as traffic volume and environmental factors also work jointly to impact how the network performance IRI values change over time.
- It should be noted that the results from the JCP sections are not sufficient to draw explicit conclusions because of the limited number of JCP sections that were surveyed in this study.

The following recommendations are proposed for future research:

- It is recommended that the developed IRI models to be included in the NCDOT treatment decision-making process for increased PMS performance. A separate branch can be developed using these models and added to the decision tree. IRI trigger values can be determined to suggest appropriate treatments.
- It is recommended that more JCP sections to be studied in order to develop IRI limits and targets for network management and construction approval purposes.
- It is recommended that balanced sampling (fixed sample size and stratification) of varying types of roadways (e.g., flexible, rigid, and composite) should be required whenever possible in order to obtain informative research results. In this study, some contrasts were not performed because of unbalance samples.
- The following data collection methods have proven to be effective in this research project, and are recommended for future studies in this research area:

  - The face-to-face recruiting method is more effective than the phone call method.
  - It is necessary to over-recruit participants in order to avoid “no-shows”. Essentially, this is to ensure that the appropriate sample sizes are achieved, and that the findings are statistically significant.
  - Locations of roadway loops should be close to each other. It took approximately 2 hours to complete one survey (including 3 roadway loops: one ASP urban, one ASP rural, and one JCP) in this research project, which caused uncertainties in logistics.
- It was concluded in this research project that initial IRI, traffic levels, and environmental factors are important factors that can affect long-term network IRI. Other factors, such as pavement designs, are recommended to be considered in future studies.

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CHAPTER 1 INTRODUCTION AND OBJECTIVES

1.1 Background

Roughness, or ride quality, is one of the most important pavement performance parameters. For DOT engineers, it is a measure of pavement surface distortion or variation in pavement surface elevation; it can be used to trigger appropriate maintenance treatments, approve new and rehabilitated roadways, and determine contractors' performance incentives. For the traveling public, roughness is an indicator of a comfortable ride; it is directly used by the public to judge pavement condition, it also affects user costs, including fuel, repairs, and vehicle depreciation.

Since 1986, the International Roughness Index (IRI) has been widely used to quantify pavement roughness, and is the parameter by which pavement smoothness is defined within the Mechanistic-Empirical Pavement Design Guide (MEPDG). IRI is measured during state DOTs' routine pavement surveys, and is required to be reported to the Highway Performance Monitoring System (HPMS) for the National Highway System (NHS) on an annual basis.

1.2 Research Needs and Significance

Every two years, North Carolina Department of Transportation (NCDOT) surveys the condition of 100% of asphalt pavements and 20% of concrete pavements. Condition data have been collected since 1982, and were used to develop a number of distress models to trigger maintenance treatments. The NCDOT Pavement Management Unit (PMU) will soon include IRI models in its toolbox. To effectively assign timely treatments using these IRI models, a set of appropriate trigger points, i.e., IRI thresholds, should be established. Because IRI thresholds are largely determined from a public perspective, a relationship between IRI values and perceived ride quality needs to be developed.

Pavements deteriorate over time. And previous evidences [1] [2] [3] indicates that pavements initially built smoother last longer. In other words, a pavement with a low initial construction IRI value is expected to deteriorate at a slower rate over its service life. This concept needs to be validated for IRI to be an appropriate acceptance criterion used by the NCDOT Construction Unit.

1.3 Research Objectives

To address the aforementioned needs, this research was conducted to:

- Develop a relationship between IRI values and perceived ride quality for North Carolina;
- Establish IRI limits and targets for network management and construction approval purposes;
- Develop an IRI Index from 0-100 and use this index to develop IRI models; and
- Investigate the relationship between initial construction IRI and network performance IRI.

To achieve these objectives, a total of 241 participants were randomly recruited from 8 counties across North Carolina, and were driven in two vans along pre-selected routes at three time slots on different dates to survey roadways. Twenty-four such roadway surveys were conducted. Perceived ride quality ratings were collected and were used to investigate their relationship with

NCDOT measured IRI values. Eight IRI limits and seven IRI targets were determined, which allow the NCDOT to better classify pavement performance, set up a construction approval mechanism for new and rehabilitated roadways, and more importantly involve more public input into its decision-making processes.

1.4 Report Organization

An introduction to the research project, research needs and objectives are presented in Chapter 1. A comprehensive literature review is provided in Chapter 2. The data collection process is described in Chapter 3. Chapter 4 focuses on data analysis and results. Chapter 5 provides conclusions drawn from this research and recommendations for future research.

Appendix A includes plots of cumulative percentages of "Acceptable" ratings vs. IRI. Appendix B presents IRI model curves. Estimates of contrasts are included in Appendix C.

CHAPTER 2 LITERATURE REVIEW

An extensive literature review was conducted to synthesize past and ongoing studies related to this research.

2.1 International Roughness Index (IRI)

In the early 1980s, the National Cooperative Highway Research Program (NCHRP) initiated the development of IRI [4]. This was to help different state agencies make amends to their traditional pavement roughness measuring equipment. Further, the World Bank continued the work of comparing and converting the data obtained from different countries, which were covered in the World Bank projects [5]. The World Bank then decided that if the measuring methods can be standardized, then most of the equipment in use could produce useful roughness measures on a single scale. Hence, the roughness scale that was defined and tested by the World Bank was eventually named the IRI.

According to American Association of State Highways and Transportation Officials (AASHTO) [6], "International Roughness Index (IRI) is a statistic which is calculated from a single longitudinal profile measured with a road profiler in both the inside and outside wheel paths of the pavement. The average of these two IRI statistics is reported as the final roughness of the pavement section."

2.2 IRI Thresholds

In 1998 [7], Federal Highway Administration (FHWA) specified the Mobility Goal for the National Highway System (NHS): within 10 years, 93% of the NHS mileage should achieve "acceptable ride quality". "Acceptable" pavements must have a reported IRI value of less than or equal to 170 inches per mile. In 2002 [8], the goal was increased to 95% of NHS roads with a reported IRI of 170 inches per mile or less. Additionally, a secondary goal was to achieve a reported IRI of 95 inches per mile or less. In 2006 [9], the goal was further adjusted to make NHS roads with the reported IRI of 95 inches per mile or less as the primary performance target, and the reported IRI of 170 inches per mile or less as the secondary performance target. As there was no study conducted to support these IRI thresholds, there are concerns that these national IRI values do not reflect ride comfort perceived by drivers in the specific jurisdictions.

Several studies have been conducted to investigate the relationship between perceived roughness and measured roughness, and corresponding IRI thresholds were suggested.

In 1999, Fernando and Lee explored the relationships between Present Serviceability Rating (PSR) and IRI [10]. In their study, 28 passenger evaluators, consisting of the Texas Transportation Institute (TTI) employees, Texas DOT employees, and Texas A&M students, were recruited to evaluate 63 roadway sections. The test vehicles were driven at a constant speed of 50 mph while the evaluators were asked to evaluate overall ride quality. They concluded that section roughness, vehicle type, the individual rater, and pavement type are significant factors. They also indicated that "raters had a tendency to rate PCC sections to be rougher than asphalt sections." The limitations of this study are that the evaluators were not randomly selected and that all the results were in terms of PSRs.

A series of studies were conducted in Wisconsin, Iowa, and Minnesota [11]. The goal was to "assess the public's perceptions of pavement improvement strategies, develop customer-based thresholds of satisfaction as related to the Departments' physical indices, such as pavement ride and conditions." Driver evaluators were recruited by phone and asked to drive their own vehicles over 450 selected rural highway segments. These evaluators were contacted later and asked their opinion about roughness of the segment, and 2,300 responses were collected across these three states. The IRI values at which 70% of drivers would be satisfied with a given section of highway were provided: 70 inches per mile for rigid sections and 44 inches per mile for asphalt sections. Data collected during these studies, however, were not controlled, other than the selection of the test section.

Shafizadeh and Mannering [12] studied individual-specific, pavement-specific, and vehicle-specific data, and developed a probit model to link users' roughness rankings to measured IRI values and other factors on urban highways. In their study, 56 participants drove on 40 predetermined roadway sections. Their opinions about pavement roughness and other relevant data were collected. The results indicated that measured IRI, the presence of pavement maintenance and joints or bridge abutments, the age of the pavement surface, the vehicle type, levels of in-vehicle noise, the speed of vehicle, and the gender and income of the driver are statistically significant factors. About 85% of participants ranked the roadways with an IRI rating of 170 in/mile "acceptable". This study has several limitations. Public participants were selected from the traffic stream close to the University of Washington campus and thus might not represent the typical roadway users. Only "smooth" roadway sections were studied; including "poor" pavements might provide more useful results.

2.3 Collection of Subjective Pavement Ride Quality Ratings

The Standard Guide for Conducting Subjective Pavement Ride Quality Ratings (ASTM E1927-98 (2007)) [13] describes the procedures to systematically collect pavement ride quality ratings. This ASTM standard was originally adopted in 1998, and was last revised in 2007. This guide covers "a procedure for generating a set of comparatively scaled ride ratings, subjectively derived, for a subgroup of pavement sections having a ride quality distribution approximating the general population of highways of interest." Recommendations were made in this guide regarding selection of test sections and route formation, panel selection, rating procedures, panel study, data reduction, and physical measurements. A sample rater form (Figure 1) was also recommended by this guide. These recommendations were adopted in this research project. It should be noted that in this research project, the term "Very Unacceptable" was used to replace the term "Impassible" in the abovementioned ASTM standard.

2.4 Categorical Data Analysis

In this research project, both qualitative and quantitative ratings of public perceived ride quality were collected. Each research participant was asked to rate a roadway section as either Acceptable or Unacceptable (qualitative measure) and provided a numerical rating that is between 0 and 5 (quantitative measure). These qualitative measures are ordinal in nature. In this case, categorical data analysis techniques, such as ordered logit or probit regression analysis, are appropriate methods that should be used [14]. There are several different types of categorical models. Binary categorical models are models that consider two order outcomes, and multinomial categorical models are models that consider three or more order outcomes. Multinomial probit models are used when the errors are assumed to be normally distributed. The outcome probabilities of multinomial probit models, however, are not closed form and estimation of the likelihood functions requires numerical integration [15]. Multinomial logit (MNL) models, on the other hand, can be used to determine outcome probabilities directly.

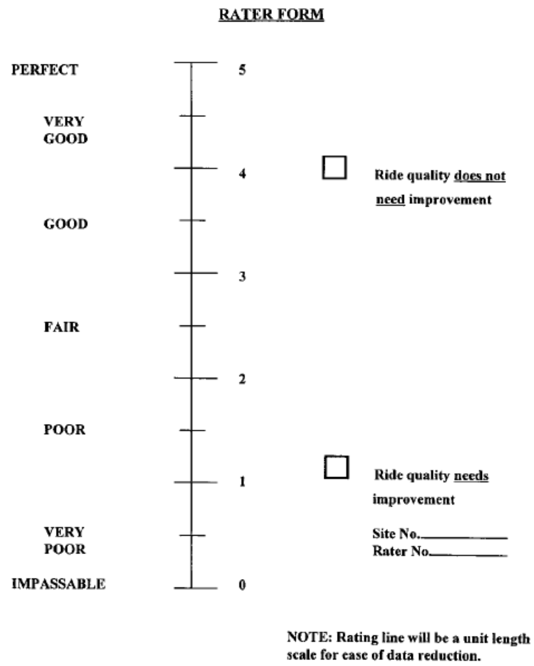


Figure 1: Sample Rater Form (ASTM E1927-98 (2007))

2.5 The Relationship between Initial IRI and Network IRI

NCHRP 1-31 [1] stated that "initial pavement smoothness has a significant effect on the future smoothness of the pavement in 80% of new construction (both AC and PCC pavements) and in 70% of AC overlay construction." Janoff [2] conducted a longitudinal study and the results showed that initial smoothness is directly related to long term roughness. Corley-Lay and Mastin [3] indicated that network performance IRI is largely determined by initial construction IRI. A study focusing on this relationship in North Carolina, however, was not found in the literature review.

2.6 Quality of Survey Data

The Kendall's coefficient of concordance (Kendall's W) has been used to evaluate to what extent raters agree with each other on how they rank a same set of objects [16] [17]. This coefficient ranges from 0 (no agreement) to 1 (full agreement), and can be used to assess quality of survey data. Since research participants' perceived ride quality was collected in this study, its quality was investigated using the Kendall's W coefficients.

CHAPTER 3 DATA COLLECTION

This chapter describes how candidate counties and roadways were selected, how research participants were recruited, and how survey data were collected. ASTM E1927-98 (2007) [13] was followed to complete these tasks.

3.1 Selection of Candidate Counties

To ensure a geographically balanced sampling, a total of 6 counties (highlighted in red circles in Figure 2), 2 counties in each region of North Carolina (Mountains, Piedmont, and Coastal), were initially selected. Of these two counties, one was a rural county, and another one was an urban county. Later, the number of candidate counties was increased to 9 (Figure 3) because it was difficult to find candidate rural roadways in urbanized counties, such as Mecklenburg county.

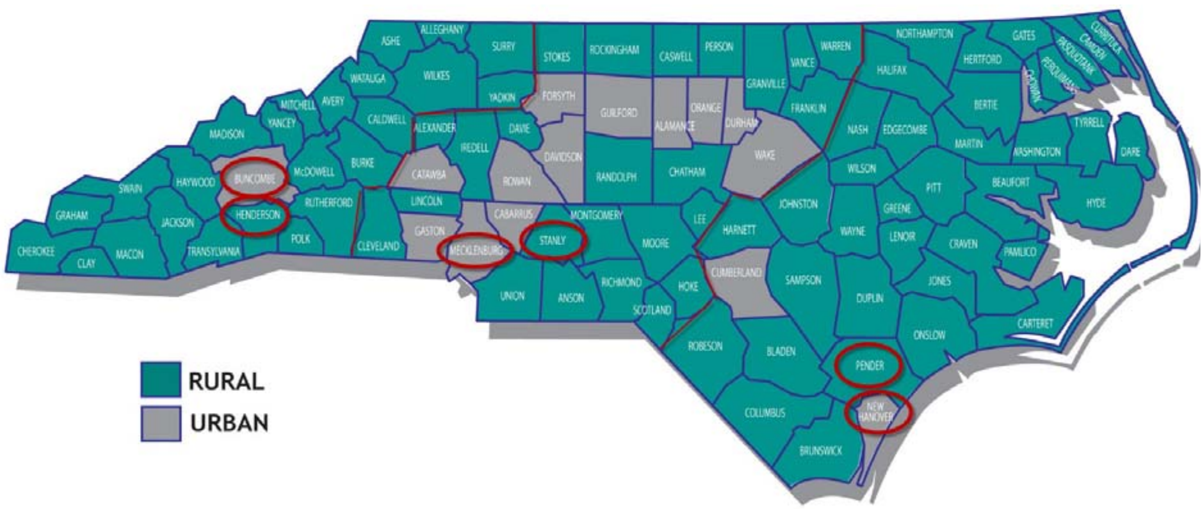


Figure 2: The Initial Candidate Counties

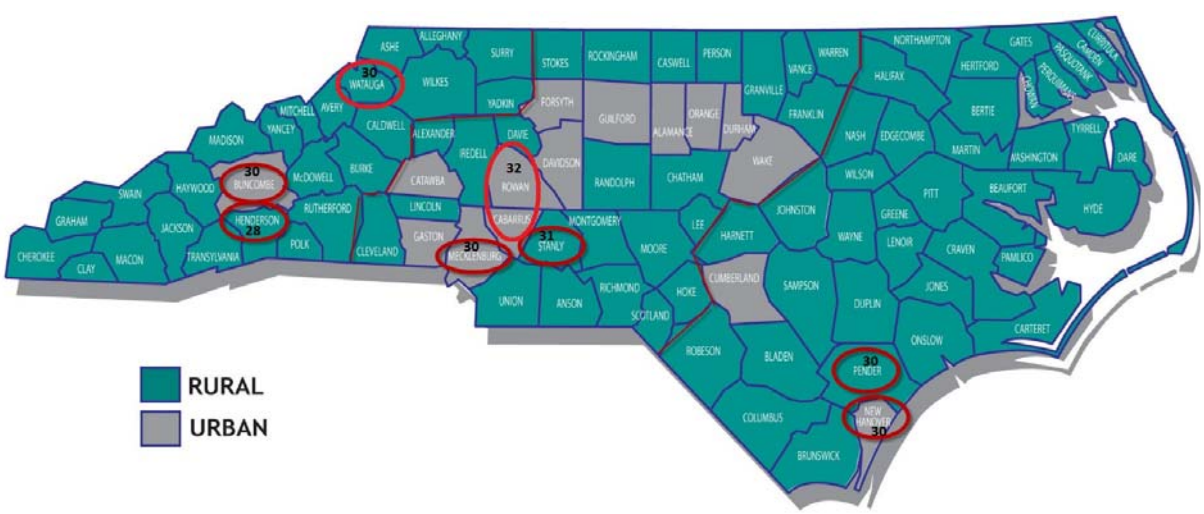


Figure 3: The Final Candidate Counties

In Figure 3, the numbers of research participants who completed the roadway surveys in each county are marked in black in the red circles.

A list of selected counties and the number of participants in each county is presented in Table 1.

Table 1: List of Selected Counties

Region	Initial Selected County	Final Selected County	Urban Loop	Rural Loop	JCP Loop	Number of Participants
Mountains	Buncombe	Buncombe	Yes	Yes	Yes	30
	Henderson	Henderson	Yes	Yes		28
		Watauga	Yes			30
Piedmont	Mecklenburg	Cabarrus		Yes*		32*
	Stanly	Mecklenburg	Yes		Yes	30
		Rowan		Yes*		32*
		Stanly	Yes	Yes		31
Coastal	New Hanover	New Hanover	Yes	Yes		30
	Pender	Pender	Yes	Yes		30

Note: *One rural loop that crosses Cabarrus and Rowan county was selected, and 32 participants took the survey.

3.2 Selection of Candidate Roadways

Candidate roadway sections were then selected based on the selection criteria presented in the matrix below (Table 2). The goal was to find two roadway loops, one urban and one rural, in each county, and each loop should include sections that have all three different pavement types (flexible, ASP and Jointed Concrete Pavement (JCP)) if possible, smoothness, and speed limits. There are 24 possible combinations in the matrix. Therefore, ideally, 24 roadway sections in each candidate county should be identified. However, some combinations are not realistic and no corresponding roadway sections was found. An example of unrealistic combination is a rural JCP section with a speed limit no greater than 35 MPH.

Table 2: Roadway Section Selection Matrix

Pavement Type	Pavement Smoothness	Urban Loop			Rural Loop		
		Speed Limit ≤ 35 MPH	35 ~ 55 MPH	≥ 55 MPH	≤ 35 MPH	35 ~ 55 MPH	≥ 55 MPH
Flexible (ASP)	Smooth (IRI < 90 in/mile)						
	Rough (IRI > 140 in/mile)						
JCP	Smooth (IRI < 90 in/mile)						
	Rough (IRI > 140 in/mile)						

It should be noted that in this research project, flexible pavements include both asphalt and composite pavements, and the IRI thresholds (90 inches/mile and 140 inches/mile) used to distinguish smooth and rough pavements are the existing values that the NCDOT PMU has used. At the end of this research project, a new set of IRI thresholds were derived from the data collected and recommended to the NCDOT.

The NCDOT PMU provided the researchers several data files, including county boundaries, IRI measures, and the most recent speed limit information. These files were brought into a GIS program ArcGIS to generate metadata maps that allowed researchers to select loops visually. A sample map is shown in Figure 4.

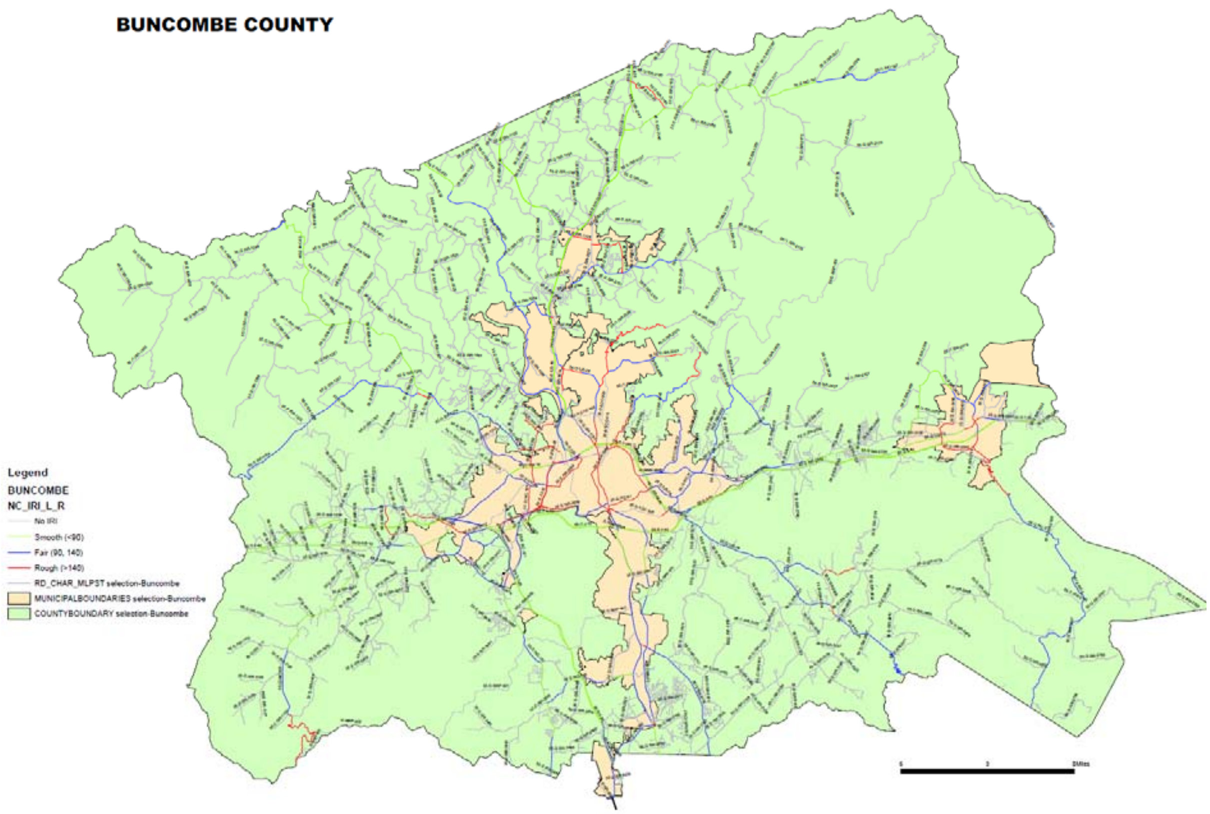


Figure 4: Buncombe County GIS Map

In Figure 4, each roadway section is designated by a number string. For example, 35/2/US-25, which means this section is a part of US-25, its speed limit is 35 MPH, and “2” indicates that it is an asphalt pavement. In addition, the center line of each roadway is color coded according to its IRI value measured by NCDOT: red represents rough condition (IRI ≥ 140 inches/mile); blue represents fair condition (90 inches/mile < IRI < 140 inches/mile), and green represent smooth condition (IRI ≤ 90 inches/mile).

These maps were used to perform the first round of loop selection. Specific attentions were given to the rural loops. Whenever possible, rural loops that are relatively far away from city limits were selected. The reason was that if a rural loop is very close to a city limit, research participants would still think they are driving on urban roads, and their ratings on roadway smoothness might be biased.

Two months before the actual roadway surveys, the researchers rode on all the selected roadway sections to identify any possible abnormalities, including recent pavement treatments which invalidates its IRI ratings; loops that are too far away from each other thus taking too long to complete one survey; and sections that have too many traffic lights that interrupt research participants' rating process. After this trip, a list of candidate roadway loops was finalized.

3.3 Recruitment of Research Participants

To ensure the results of this research project are unbiased and statistically significant, it was decided to randomly recruit 30 research participants from each county.

Previous studies [18] [19] [20] showed that calling candidates is one of the most effective methods to recruit research participants. Several hundreds of phone numbers were purchased from a telephone survey company. However, after making the first one hundred calls, only three participants were recruited.

The researchers then decided to use the face-to-face recruiting method. Even though this recruiting method involved much more planning effort and resources, it proved to be very successful. Two weeks before the survey date, the researchers traveled to the survey county and randomly recruited local residents from places that are close to the selected loops. These places included senior centers, community colleges, universities, grocery stores, supermarkets, hospitals, and public health service centers. Some candidates signed up for the survey right after being asked, others were given a flyer that has a sign up URL. Four days before the survey date, confirmation emails were sent out to remind participants of the time, date, and pick up location of the survey. Six more candidates in each county were over-recruited to avoid no shows. A gift card was offered to each participant as compensation for his/her time and participation. For each over-recruited candidate, a smaller amount gift card was offered and the individual was dismissed. A total of 241 participants participated in this research project (Table 1).

3.4 Survey Data Collection

The Day before the Survey

The researchers arrived in the survey county the day before and rode the roadway loops to get familiar with the routes. Odometer readings of the begin and end points of smooth and rough sections were recorded, they were used by the drivers (researchers from UNC Charlotte) during the survey to remind participants where to start/stop rating roadway smoothness. Some roadway sections were overlaid just before the survey, causing a change in the smoothness of these sections (e.g., a previously rough section became a smooth section because of the recent overlay). These situations were recorded and the smoothness information was updated accordingly.

The Surveys

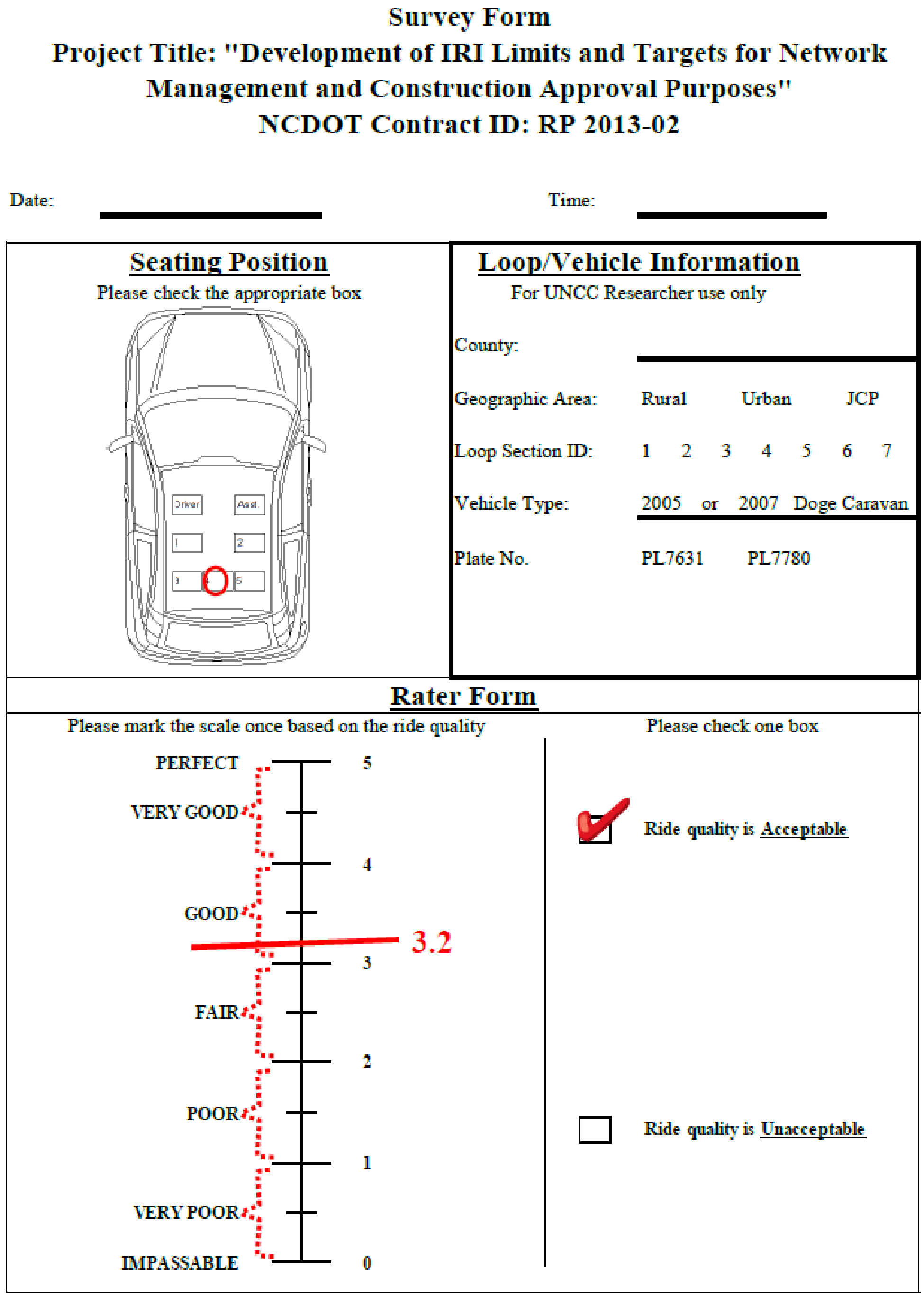
All the surveys were conducted on Saturdays to accommodate participants' schedules. On the survey date, participants were collected from the pick-up location which was specified during the recruitment process at three time slots: 10:00 A.M., 12:00 P.M., and 2:00 P.M. A tent, chairs, and soft drinks were provided to participants who arrived early. A short orientation (Figures 5 and 6) was given to participants before they boarded the vans. The orientation was a how-to guide to completing the rater form (Figure 7). Specific explanations regarding how to rate the smoothness of roadways, however, were not provided. This was to ensure that the ratings collected were independent and unbiased. During the survey, the drivers spoke out “Begin” and “End” to remind participants the begin and end points of survey sections. There was a time gap of around 8 to 10 seconds between sections to allow participants to complete the rater form of the previous section. At the end of the survey, rater forms were collected from participants, and gift cards were distributed.

To reduce data variability, the same two vans, with plate numbers PL 7631 and PL 7780, were rented from UNC Charlotte and used for all the surveys.

Figure 5: Roadway Survey – Research Assistants, the Tent, and Vans

Figure 6: Roadway Survey – the Orientation

In Figure 7, Date, Time, Loop, and Vehicle Information were pre-filled out by researchers. In each van, both the driver and the assistant were UNC Charlotte researchers. Participants were asked to circle their seating positions, draw a short line on the rating scale and provide a numerical rating, and check either “Acceptable” or “Unacceptable” regarding their perceived ride quality of a roadway section.



Survey Form
Project Title: "Development of IRI Limits and Targets for Network Management and Construction Approval Purposes"
NCDOT Contract ID: RP 2013-02

Date: ____________ Time: ____________

Seating Position
Please check the appropriate box

Loop/Vehicle Information
For UNCC Researcher use only

County: ____________
Geographic Area: Rural Urban JCP
Loop Section ID: 1 2 3 4 5 6 7
Vehicle Type: 2005 or 2007 Doge Caravan
Plate No. PL7631 PL7780

Rater Form

Please mark the scale once based on the ride quality

PERFECT 5
VERY GOOD
4
GOOD
3.2
3
FAIR
2
POOR
1
VERY POOR
IMPASSABLE 0

Please check one box

☑ Ride quality is Acceptable

☐ Ride quality is Unacceptable

Figure 7: Sample Rater Form

During the survey, information shown in Table 3 was also collected from the assistant and was used for further analyses.

Table 3: Sample Assistant Form

Name of Assistant: Weather Condition: Vehicle #:

Date:

Stanly County											
Segment #			Wet or Dry Pavement?	Noise Level (dB)			Driving Speed			Roughness (0 = Impassible, 5 = perfect)	Acceptable? (Yes or No)
	From_MP	To_MP		Start	Middle	End	Start	Middle	End		
Urban	**0.1**	**2.9**									
	2.9	**4.0**									
	4.0	**6.3**									
	6.3	**8.0**									
Rural	**0.0**	**1.7**									
	1.7	**4.0**									
	4.0	**6.3**									
	6.8	**9.2**									
	9.2	**11.4**									

CHAPTER 4 DATA ANALYSIS AND RESULTS

4.1 Quality of Survey Data

The degree of agreement of participants' perceived roadway smoothness was measured by the Kendall's W coefficients. The results are summarized in Table 4.

Table 4: Kendall's W Coefficients

Loop	Time Slot	Van	Kendall's W	Chi-SQ	DF	P-value
Buncombe County_ Asphallt Urban Loop	10:00 A.M.	PL 7631	0.4043	6.0700	3	0.1085
		PL 7780	0.3209	4.8135	3	0.1859
	12:00 P.M.	PL 7631	0.6893*	10.2245	3	0.0168**
		PL 7780	0.6653*	9.9795	3	0.0187**
	2:00 P.M.	PL 7631	0.6553*	9.8297	3	0.0201**
		PL 7780	0.6408*	9.6122	3	0.0222**
Buncombe County_ Asphalt Rural Loop	10:00 A.M.	PL 7631	0.6938*	13.8800	3	0.0077**
		PL 7780	0.7538*	11.3077	3	0.0102**
	12:00 P.M.	PL 7631	0.9021*	18.0426	4	0.0012**
		PL 7780	0.9327*	18.7755	4	0.0009**
Buncombe County_ JCP Loop	10:00 A.M.	PL 7631	0.6465*	16.1600	5	0.0064**
		PL 7780	0.8614*	21.5361	5	0.0006**
	12:00 P.M.	PL 7631	0.8702*	21.7560	5	0.0006**
		PL 7780	0.8670*	21.6765	5	0.0006**
	2:00 P.M.	PL 7631	0.9029*	22.5610	5	0.0004**
		PL 7780	0.8690*	21.7251	5	0.0006**
Cabarrus/Rowan County_ Asphallt Rural Loop	10:00 A.M.	PL 7631	0.6167*	101.7600	11	0.0000**
		PL 7780	0.6588*	36.2223	11	0.0002**
	12:00 P.M.	PL 7631	0.8218*	45.2013	11	0.0000**
		PL 7780	0.7009*	38.5548	11	0.0001**
	2:00 P.M.	PL 7631	0.7453*	14.9167	4	0.0049**
		PL 7780	0.9235*	18.4719	4	0.0010**
Henderson County_ Asphallt Rural Loop	10:00 A.M.	PL 7631	0.8430*	36.0050	9	0.0000**
		PL 7780	0.7911*	35.6005	9	0.0000**
	12:00 P.M.	PL 7631	0.7731*	20.8739	9	0.0132**
		PL 7780	0.5744*	11.4885	9	0.0425
	2:00 P.M.	PL 7631	0.8481*	38.1709	9	0.0000**
		PL 7780	0.1754	7.8943	9	0.5448
Henderson County_ Asphallt Urban Loop	10:00 A.M.	PL 7631	0.5626*	14.0663	5	0.0152**
		PL 7780	0.7822*	19.5562	5	0.0015**
	12:00 P.M.	PL 7631	0.7875*	11.8132	5	0.0374
		PL 7780	0.5744*	11.4885	5	0.0425
	2:00 P.M.	PL 7631	0.5650*	18.3841	5	0.0025**
		PL 7780	0.4726	11.8100	5	0.0340
Mecklenburg County_ Asphallt Urban Loop	10:00 A.M.	PL 7631	0.6029*	42.2100	14	0.0001**
		PL 7780	0.7984*	55.8883	14	0.0000**
	12:00 P.M.	PL 7631	0.6912*	48.3871	14	0.0000**
		PL 7780	0.7007*	49.0526	14	0.0000**
	2:00 P.M.	PL 7631	0.1868	7.4748	14	0.4864
		PL 7780	0.6037*	126.7950	14	0.0000**
Mecklenburg County_ JCP Loop	10:00 A.M.	PL 7631	0.3380	13.5200	8	0.0952
		PL 7780	0.4303	17.2138	8	0.0280
	12:00 P.M.	PL 7631	0.1868	7.4748	8	0.4864
		PL 7780	0.6516*	26.0671	8	0.0010**
	2:00 P.M.	PL 7631	0.3178	12.7130	8	0.1221
		PL 7780	0.4599	18.3986	8	0.0184**

Loop	Time Slot	Van	Kendall's W	Chi-SQ	DF	P-value
New Hanover County_ Asphallt Rural Loop	10:00 A.M.	PL 7631	0.6912*	20.7400	6	0.0020**
		PL 7780	0.4454	12.3636	6	0.0376
	12:00 P.M.	PL 7631	0.5680*	17.0400	6	0.0091**
		PL 7780	0.8142*	24.4286	6	0.0004**
	2:00 P.M.	PL 7631	0.7360*	22.0209	6	0.0012**
		PL 7780	0.7818*	23.4545	6	0.0007**
New Hanover County_ Asphallt Urban Loop	10:00 A.M.	PL 7631	0.4837	17.1400	7	0.0165**
		PL 7780	0.8648*	9.2494	7	0.2352
	12:00 P.M.	PL 7631	0.2642	9.2494	7	0.2352
		PL 7780	0.4185	14.6435	7	0.0408
	2:00 P.M.	PL 7631	0.6765*	23.6805	7	0.0013**
		PL 7780	0.6881*	24.0856	7	0.0011**
Pender County_ Asphallt Rural Loop	10:00 A.M.	PL 7631	0.7006*	28.0300	8	0.0005**
		PL 7780	0.5968*	23.8750	8	0.0024**
	12:00 P.M.	PL 7631	0.5174*	20.6954	8	0.0080**
		PL 7780	0.4003	16.0145	8	0.0422
	2:00 P.M.	PL 7631	0.6253*	25.0157	8	0.0015**
		PL 7780	0.7712*	30.8503	8	0.0001**
Pender County_ Asphallt Urban Loop	10:00 A.M.	PL 7631	0.2236	5.5300	5	0.3482
		PL 7780	0.4047	10.1190	5	0.0719
	12:00 P.M.	PL 7631	0.2088	5.0221	5	0.3896
		PL 7780	0.2070	5.1765	5	0.3947
	2:00 P.M.	PL 7631	0.1374	3.4356	5	0.6332
		PL 7780	0.7712*	30.8503	5	0.0001**
Stanly County_ Asphallt Rural Loop	10:00 A.M.	PL 7631	0.8949*	17.9000	4	0.0000**
		PL 7780	0.9595*	19.1919	4	0.0007**
	12:00 P.M.	PL 7631	0.8913*	17.8261	4	0.0013**
		PL 7780	0.8739*	17.4783	4	0.0016**
	2:00 P.M.	PL 7631	0.7458*	14.9167	4	0.0049**
		PL 7780	0.9235*	18.4719	4	0.0010**
Stanly County_ Asphallt Urban Loop	10:00 A.M.	PL 7631	0.9346*	14.0200	3	0.0000**
		PL 7780	0.9346*	14.0204	3	0.0029**
	12:00 P.M.	PL 7631	0.6765*	10.1489	3	0.0173**
		PL 7780	0.6685*	10.0213	3	0.0184**
	2:00 P.M.	PL 7631	0.5600*	8.4000	3	0.0384
		PL 7780	0.8577*	12.8667	3	0.0049**
Stanly County_ Asphallt Urban Loop	10:00 A.M.	PL 7631	0.5740*	22.9601	8	0.0034**
		PL 7780	0.5794*	22.9400	8	0.0034**
	12:00 P.M.	PL 7631	0.5734*	22.9392	8	0.0034**
		PL 7780	0.6431*	51.4591	8	0.0000**
	2:00 P.M.	PL 7631	0.7413*	29.6528	8	0.0002**
		PL 7780	0.5740*	22.9201	8	0.0034**

Note:
* : Kendall's W value greater than 0.50.
**: Two-tail test is significant at 0.05 level.

As shown in Table 4, 65 out of 88 Kendall's W coefficients are larger than 0.5 and also have a p-value that is less than 0.025. This means that approximately 74% of participants agreed with each other when assessing the same roadway sections, and the null hypothesis that there is no agreement between ratings of all participants was rejected at a 0.05 level. Therefore, the quality of the survey data was satisfactory.

4.2 Categorical Data Analysis

Two types of research participants' perceived smoothness of roadways were collected: numerical ratings (0-5) and categorical ratings ("Acceptable" and "Unacceptable"). In this section, categorical ratings were analyzed using logistic regression analysis to identify factors that affect perceived ride quality.

To process these categorical ratings, a logistic model that includes all collected factors was used:

$$\log\left(\frac{Acceptable}{Unacceptable}\right) = \beta_0 + \beta_1 \times IRI + \beta_2 \times Van + \beta_3 \times Region + \beta_4 \times UrbanRuralJCP + \beta_5 \times SeatingPosition + \beta_6 \times SpeedLimit \quad (1)$$

where
Acceptable, Unacceptable: perceived smoothness of roadways;
IRI: IRI values measured by the NCDOT;
Van: Two UNC Charlotte vans used for surveys (plate numbers are PL 7631 and PL 7780);
Region: three regions in North Carolina – Mountains, Piedmont, and Coastal;
UrbanRuralJCP: type of roadway loops – ASP urban, ASP rural, and JCP;
SeatingPosition: participants' seating positions in the van – 1 through 6 (Figure 8);
SpeedLimit: speed limits of selected roadway sections: 30, 35, 45, 55, 60, 65, or 70 MPH.

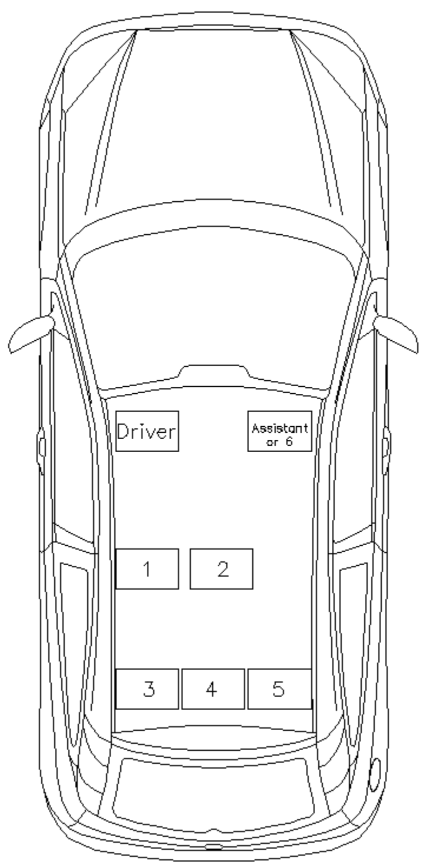


Figure 8: Vehicle Seating Positions

Parameter estimates of the logistic regression analysis are shown in Table 5. Three factors in the full model (1), IRI, Speed Limit, and Seating Position, are significant. The other three, Van, Region, and UrbanRuralJCP, are not significant.

Table 5: Logistic Regression Analysis Results of the Full Model

Analysis of Maximum Likelihood Estimates						
Parameter		DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept		1	5.9180	0.4181	200.3792	<.0001
Position	2	1	-0.0270	0.1649	0.0268	0.8700
Position	3	1	0.1179	0.1693	0.4849	0.4862
Position	4	1	-0.2688	0.1611	2.7830	0.0953
Position	5	1	0.3992	0.1768	5.0962	0.0240
Position	6	1	-0.7519	0.3940	3.6418	0.0563
Speed1		1	-0.0357	0.00614	33.8838	<.0001
IRI		1	-0.0178	0.00106	283.0929	<.0001

Although UrbanRuralJCP was not significant, it was still included in the further analysis because the researchers were interested in what information could be obtained from this factor. Thus, a new logistic model was used for the next analysis:

$$\log\left(\frac{Acceptable}{Unacceptable}\right) = \beta_0 + \beta_1 \times IRI + \beta_2 \times UrbanRuralJCP + \beta_3 \times SeatingPosition + \beta_4 \times SpeedLimit \quad (2)$$

Parameter estimates of the new model are included in Table 6.

Table 6: Logistic Regression Analysis Results of the New Model

Analysis of Maximum Likelihood Estimates						
Parameter		DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept		1	5.7955	0.4417	172.1625	<.0001
Speed1		1	-0.0321	0.00742	18.7171	<.0001
IRI		1	-0.0181	0.00108	281.3855	<.0001
Position	2	1	-0.0279	0.1650	0.0286	0.8656
Position	3	1	0.1169	0.1694	0.4758	0.4903
Position	4	1	-0.2702	0.1612	2.8100	0.0937
Position	5	1	0.3986	0.1769	5.0751	0.0243
Position	6	1	-0.7594	0.3949	3.6973	0.0545
UrbanRuralJCP	JCP	1	-0.2862	0.2149	1.7732	0.1830
UrbanRuralJCP	Rural	1	0.0495	0.1227	0.1632	0.6863

Odds Ratio (OR) estimates are presented in Table 7 and Figure 9.

Table 7: Odds Ratio Estimates

Odds Ratio Estimates and Wald Confidence Intervals			
Label	Estimate	95% Confidence Limits	
UrbanRuralJCP JCP vs Rural	0.715	0.489	1.044
UrbanRuralJCP JCP vs Urban	0.751	0.493	1.145
UrbanRuralJCP Rural vs Urban	1.051	0.826	1.336
Speed1	0.968	0.954	0.983
IRI	0.982	0.980	0.984
Position 1 vs 2	1.028	0.744	1.421
Position 1 vs 3	0.890	0.638	1.240
Position 1 vs 4	1.310	0.955	1.797
Position 1 vs 5	0.671	0.475	0.950
Position 1 vs 6	2.137	0.985	4.634
Position 2 vs 3	0.865	0.623	1.202
Position 2 vs 4	1.274	0.932	1.742
Position 2 vs 5	0.653	0.463	0.921
Position 2 vs 6	2.078	0.960	4.501
Position 3 vs 4	1.473	1.068	2.031
Position 3 vs 5	0.754	0.531	1.072
Position 3 vs 6	2.402	1.104	5.223
Position 4 vs 5	0.512	0.366	0.718
Position 4 vs 6	1.631	0.755	3.522
Position 5 vs 6	3.183	1.454	6.969

In the logistic regression analysis, "Acceptable" was set as the reference level. Therefore, in Table 7, if an OR value is larger than 1.0, it means that the roadway section is more likely to be rated as "Acceptable". Similarly, if an OR value is less than 1.0, it means that the roadway section is more likely to be rated as "Unacceptable". Graphically, in Figure 9, the solid vertical line represent an OR values that is equal to 1.0.

The following example explains how to interpret OR values both visually and mathematically:
For the first row in Table 7, the OR of JCP vs. Urban is 0.751, which is less than 1.0. Therefore, in Figure 9, the corresponding blue dot lies to the left of the vertical line. This means that overall when compared to Urban asphalt roadway sections, JCP roadway sections were less likely to be rated as "Acceptable", and more likely to be rated as "Unacceptable". Specifically, it is 1.0/0.715 = 1.3987 times more likely to be rated as "Unacceptable".

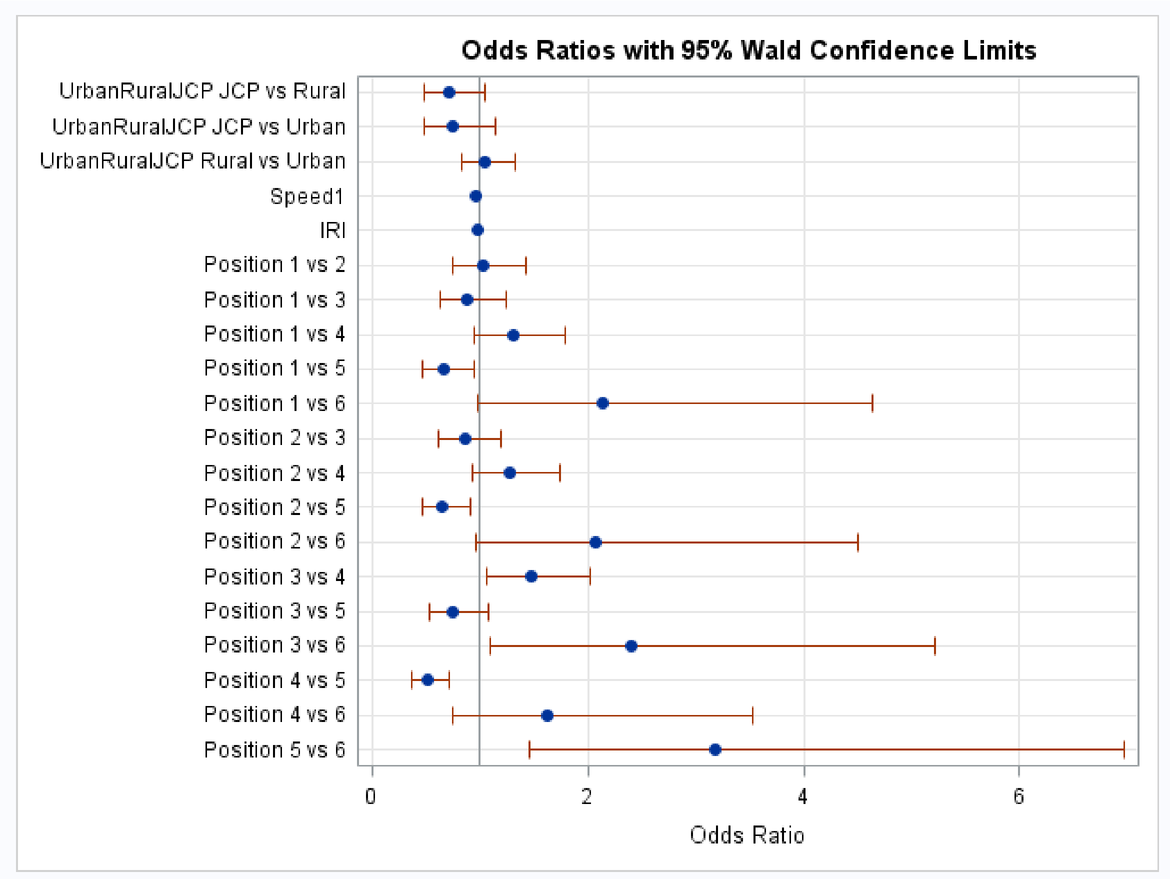


Figure 9: Odds Ratios with 95% Wald Confidence Limits

Detailed interpretations of the odds ratio results are presented in Table 8.

Table 8: Interpretation of Odds Ratio Results

Odds Ratio Estimates and Wald Co		Interpretation
Label	Estimate	
UrbanRuralJCP JCP vs Rural	0.715	compared to JCP, Rural is 1.398 times more likely to be rated as "Acceptable"
UrbanRuralJCP JCP vs Urban	0.751	compared to JCP, Urban is 1.332 times more likely to be rated as "Acceptable"
UrbanRuralJCP Rural vs Urban	1.051	compared to Urban, Rural is 1.051 times more likely to be rated as "Acceptable"
Speed1	0.968	when Speed Limit increases by 1.0 mph, roadways are 1.033 times more likely to be rated as "Unacceptable"
IRI	0.982	when IRI increases by 1.0 in/mile, roadways are 1.018 times more likely to be rated as "Unacceptable"
Position 1 vs 2	1.028	compared to passenger 2, passenger 1 is 1.028 times more likely to give "Acceptable" ratings
Position 1 vs 3	0.890	compared to passenger 1, passenger 3 is 1.124 times more likely to give "Acceptable" ratings
Position 1 vs 4	1.310	compared to passenger 4, passenger 1 is 1.31 times more likely to give "Acceptable" ratings
Position 1 vs 5	0.671	compared to passenger 1, passenger 5 is 1.49 times more likely to give "Acceptable" ratings
Position 1 vs 6	2.137	compared to passenger 6, passenger 1 is 2.137 times more likely to give "Acceptable" ratings
Position 2 vs 3	0.865	compared to passenger 2, passenger 3 is 1.156 times more likely to give "Acceptable" ratings
Position 2 vs 4	1.274	compared to passenger 4, passenger 2 is 1.274 times more likely to give "Acceptable" ratings
Position 2 vs 5	0.653	compared to passenger 2, passenger 5 is 1.531 times more likely to give "Acceptable" ratings
Position 2 vs 6	2.078	compared to passenger 6, passenger 2 is 2.078 times more likely to give "Acceptable" ratings
Position 3 vs 4	1.473	compared to passenger 4, passenger 3 is 1.473 times more likely to give "Acceptable" ratings
Position 3 vs 5	0.754	compared to passenger 3, passenger 5 is 1.326 times more likely to give "Acceptable" ratings
Position 3 vs 6	2.402	compared to passenger 6, passenger 3 is 2.402 times more likely to give "Acceptable" ratings
Position 4 vs 5	0.512	compared to passenger 4, passenger 5 is 1.953 times more likely to give "Acceptable" ratings
Position 4 vs 6	1.631	compared to passenger 6, passenger 4 is 1.631 times more likely to give "Acceptable" ratings
Position 5 vs 6	3.183	compared to passenger 6, passenger 5 is 3.183 times more likely to give "Acceptable" ratings

Goodness-of-Fit statistics are shown in Table 9. The Percent Concordant value of 75.8 indicates that the new model (2) was able to correctly predict 75.8% of the response variable, “Acceptable” and “Unacceptable”, in this research project. This means that the model fit the data well.

Table 9: Goodness-of-Fit statistics

Association of Predicted Probabilities and Observed Responses			
Percent Concordant	75.8	Somers' D	0.516
Percent Discordant	24.1	Gamma	0.517
Percent Tied	0.1	Tau-a	0.126
Pairs	1392480	c	0.758

4.3 Determination of IRI Thresholds Using Categorical Ratings

In this section, categorical ratings (“Acceptable” and “Unacceptable”) were analyzed to determine IRI thresholds. The procedures of determining IRI thresholds using numerical ratings (0-5) are described in the next section.

Distributions of categorical ratings were studied and the results indicated that both “Acceptable” and “Unacceptable” ratings are not normally distributed (Figure 10).

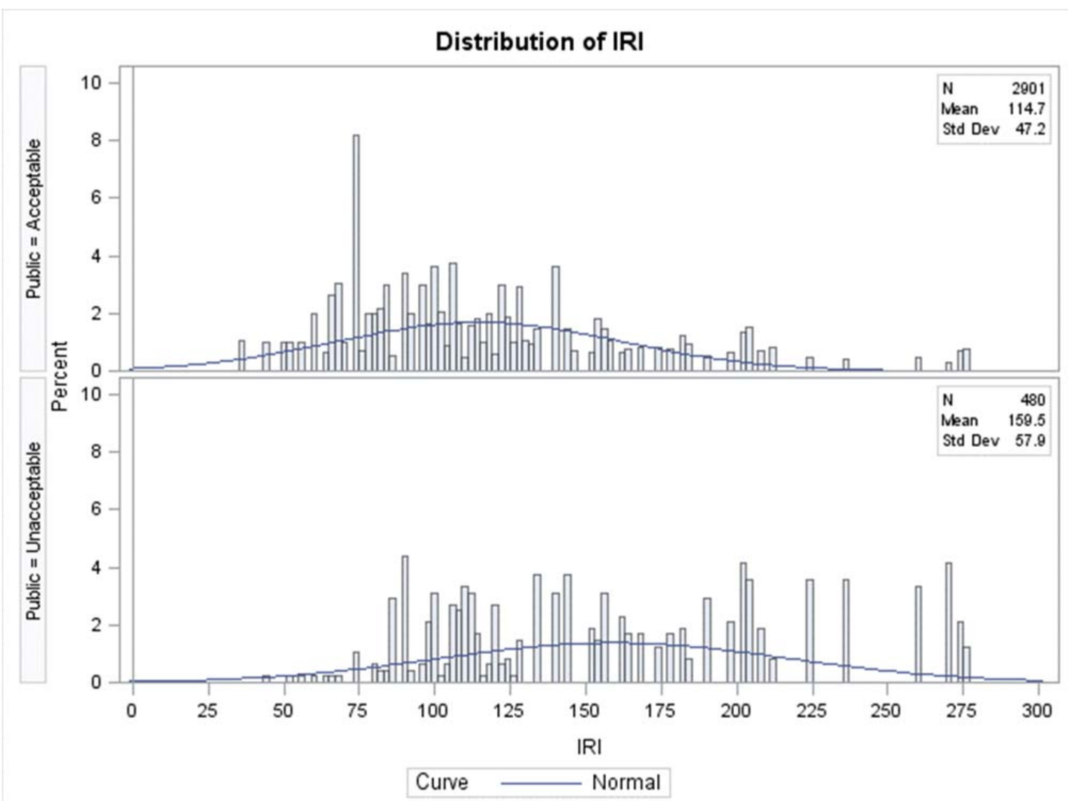


Figure 10: Normality Test of Collected Ride Quality Ratings

The percentages of both “Acceptable” and “Unacceptable” ratings for given IRI values were then investigated. As shown in Figure 11, for a roadway with a measured IRI value of 50 inches/mile, approximately 100% of participants would rate its smoothness as “Acceptable”. For the FHWA recommended IRI threshold value of 170 inches/mile, approximately 60% of participants would rate this smoothness as “Acceptable”, and approximately 40% of participants would rate it as “Unacceptable”.

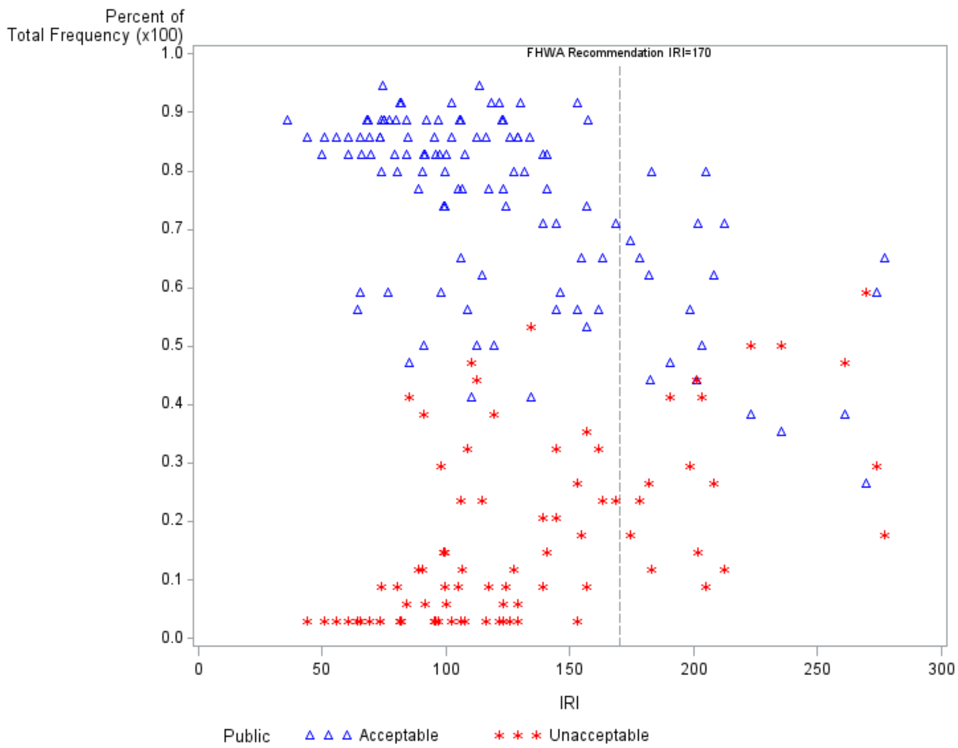


Figure 11: Percentages of Categorical Ratings vs. IRI

The spread of the distribution of data points in Figure 11 is large, making it challenging to obtain accurate IRI thresholds. To overcome this issue, cumulative percentages of “Acceptable” ratings from participants who gave “Acceptable” ratings were plotted against measured IRI values. As shown in Figure 12, approximately 12% of participants would rate an IRI value of 170 inches/mile as “Acceptable”. The 50% “Acceptable” rating occurs at an IRI value of approximately 103 inches/mile. Cumulative percentages of “Unacceptable” ratings from participants who gave “Unacceptable” ratings were also plotted against measured IRI values (Figure 13). The 50% “Unacceptable” rating occurs at an IRI value of approximately 151 inches/mile. These two IRI thresholds provide a general guidance with regard to at what IRI levels the driving public’s perceived ride quality will change from “Acceptable” to “Unacceptable”. To determine appropriate IRI thresholds for construction acceptance criteria, however, further analyses are needed. As described in the next sections, the IRI thresholds for new pavement construction projects were determined using categorical ratings and numerical ratings. These IRI thresholds were compared, and the final IRI threshold was recommended to the NCDOT.

To determine the IRI threshold for new pavement construction projects using categorical ratings, cumulative percentages of public perceived ratings and their corresponding IRI thresholds are summarized in Table 10.

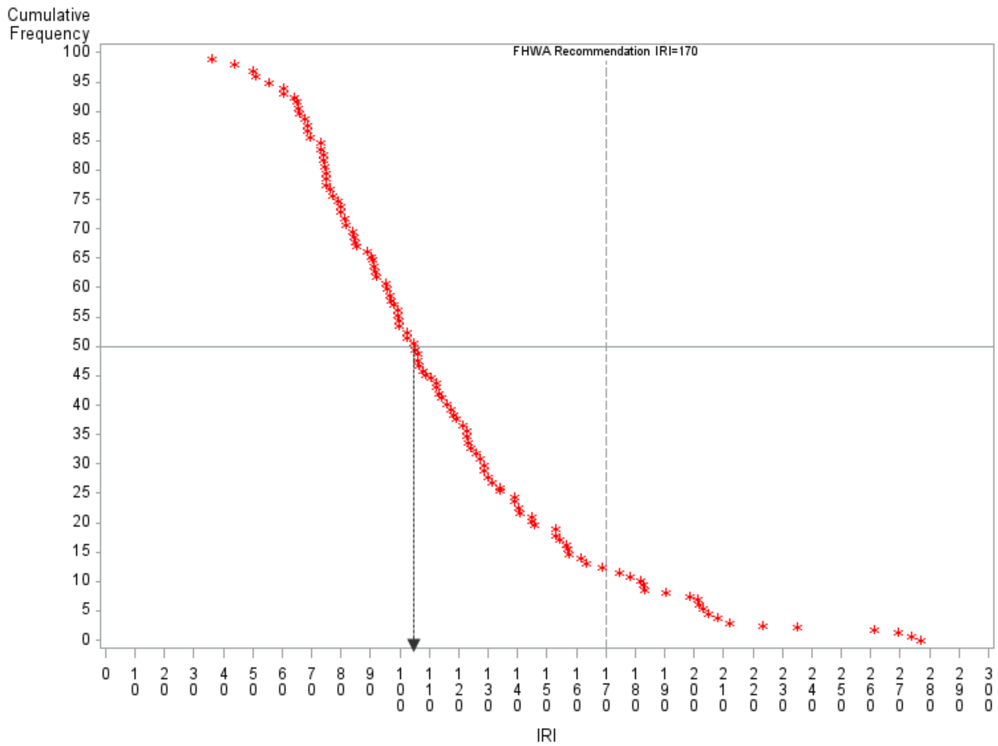


Figure 12: Cumulative Percentages of “Acceptable” Ratings vs. IRI

Table 10: Cumulative Percentages of “Acceptable” Ratings and IRI Thresholds

Cumulative Percentage of "Acceptable"	IRI Threshold (inch/mile)	Cumulative Percentage of "Acceptable"	IRI Threshold (inch/mile)
100%	35	45%	110
95%	55	40%	117
90%	65	35%	123
85%	70	30%	129
80%	75	25%	137
75%	78	20%	146
70%	83	15%	158
65%	91	10%	182
60%	95	5%	203
55%	100	0%	278
50%	103		

It can be concluded from Table 10 that:

- With the cumulative percentage of "Acceptable" at 95% (55 inches/mile), it seems that 50 to 60 inches/mile is a "Perfect" IRI range;
- With the cumulative percentage of "Acceptable" at 90% (65 inches/mile), it seems that 60 to 70 inches/mile is a "Good" IRI goal range for new pavement construction; and
- With the cumulative percentage of "Acceptable" at 10% (182 inches/mile), it seems that IRI values greater than 182 inches/mile would be considered as "Very Unacceptable".

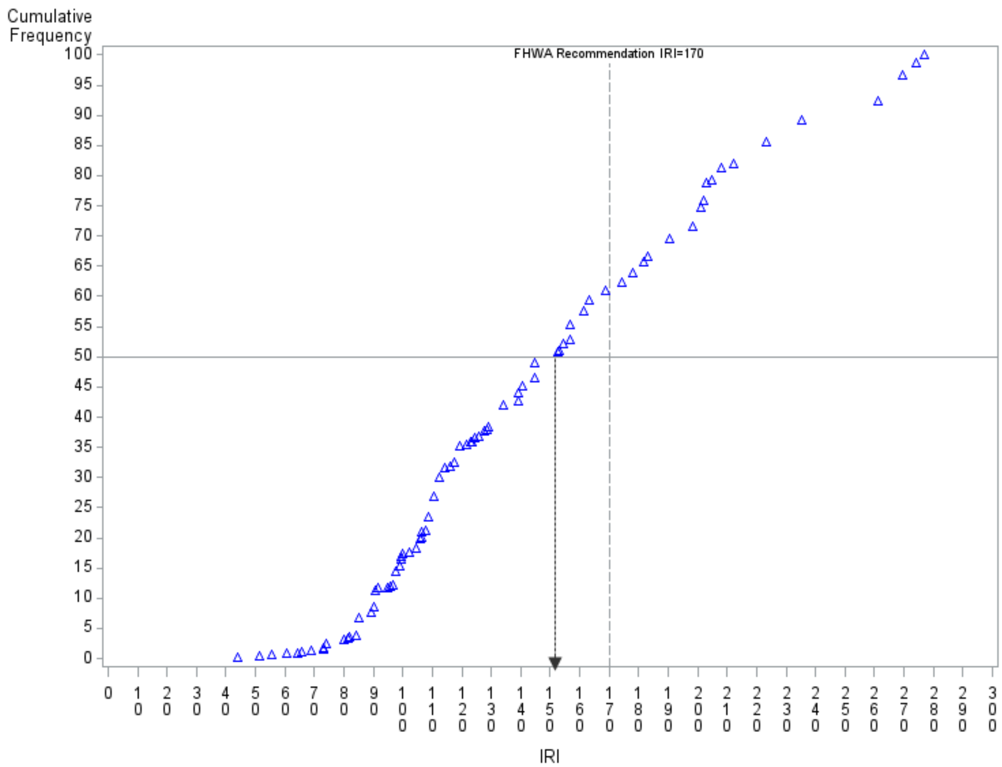


Figure 13: Cumulative Percentages of “Unacceptable” Ratings vs. IRI

To study the impact of pavement type (ASP and JCP), location (urban and rural), and region (Mountains, Piedmont, and Coastal) on IRI thresholds, their corresponding cumulative percentages of “Acceptable” ratings were plotted against measured IRI values (Appendix A). The results are summarized below in Tables 11 and 12. In Table 11, the IRI thresholds for ASP urban and rural pavements are close. Therefore, 106 inches/mile was chosen to ensure that ASP pavements can obtain timely treatments.

In Table 12, the threshold for JCP pavements in the Mountains region is small (50 inches/mile). In this study, it should be noted that the results from the JCP sections are not sufficient to draw explicit conclusions because of the limited number of JCP sections that were surveyed in this study.

Table 11: IRI Thresholds by Pavement Type and Location

Pavement Type	Location	IRI Threshold for "Acceptable" (inch/mile)
ASP	Urban	< 110
	Rural	< 106
JCP	Urban & Rural	< 77

Table 12: IRI Thresholds by Region and Pavement Type

Region	Pavement Type	IRI Threshold for "Acceptable" (inch/mile)
Mountains	ASP	< 113
	JCP	< 50
Piedmont	ASP	< 106
	JCP	< 86
Coastal	ASP	< 113
	JCP	N/A

4.4 Determination of IRI Thresholds Using Numerical Ratings

The previous section presents the procedures to obtain IRI thresholds using categorical ratings ("Acceptable" and "Unacceptable"). In this section, the procedures of determining IRI thresholds using numerical ratings (0-5) are described.

Regression analyses were conducted to identify the relationships between IRI and numerical ratings, pavement type (ASP and JCP), location (urban and rural), and region (Mountains, Piedmont, and Coastal). The trend lines are shown in Figures 14 through 20.

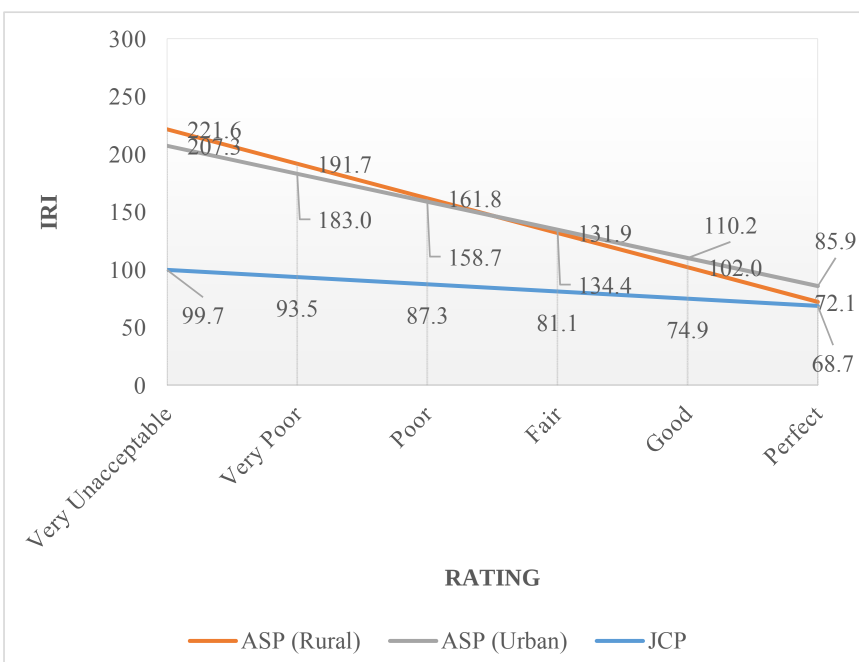


Figure 14: Numerical Ratings vs. IRI (by ASP and JCP)

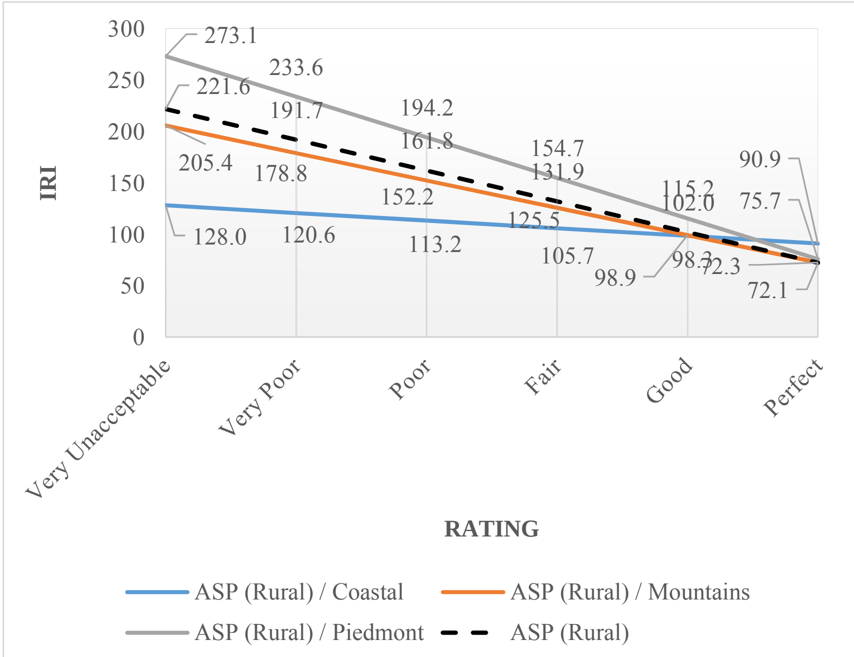


Figure 15: Numerical Ratings vs. IRI (by ASP Rural and Regions)

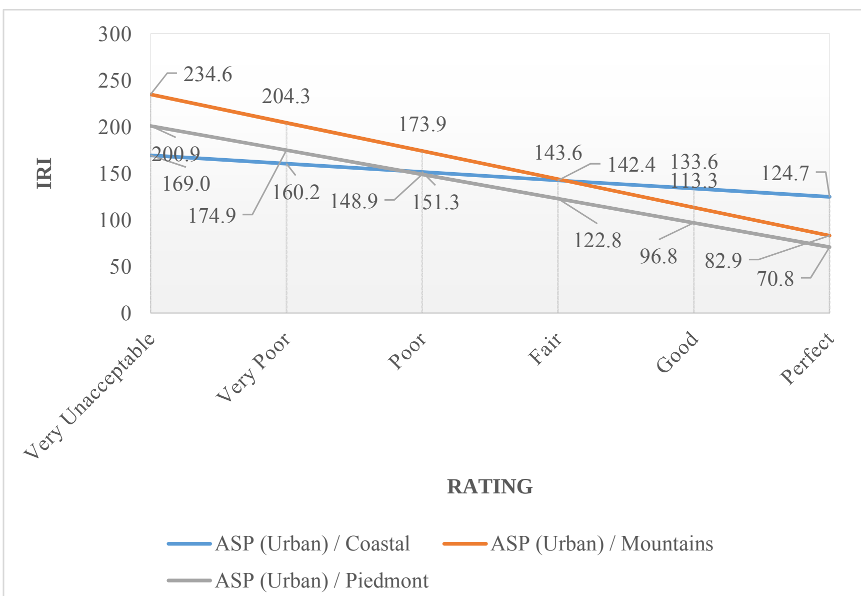


Figure 16: Numerical Ratings vs. IRI (by ASP Urban and Regions)

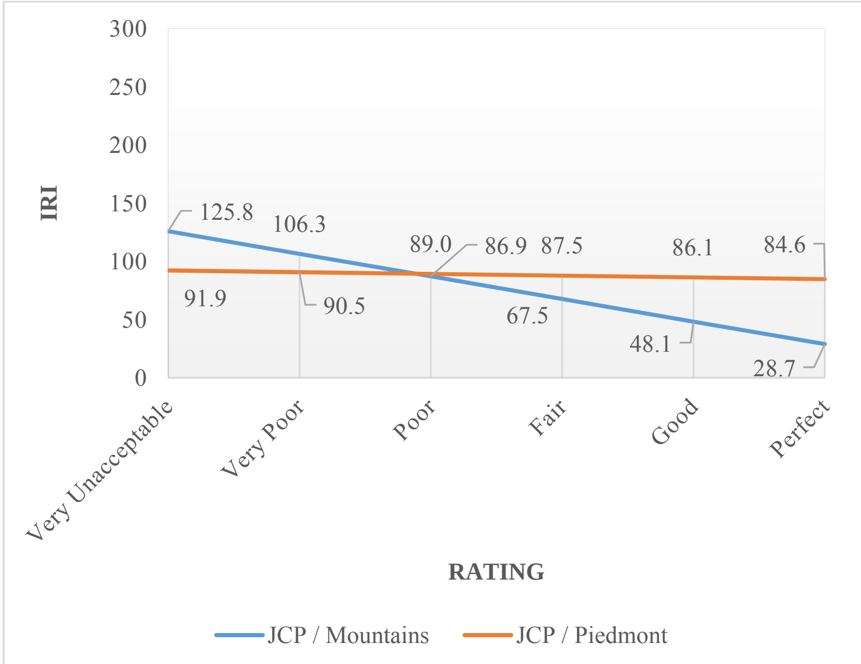


Figure 17: Numerical Ratings vs. IRI (by JCP and Regions)

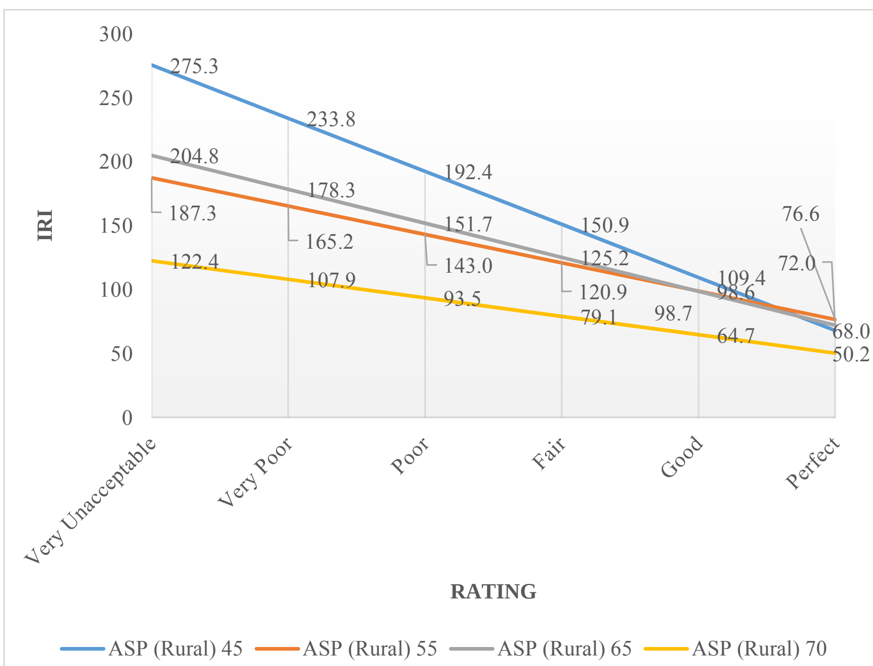


Figure 18: Numerical Ratings vs. IRI (by ASP Rural and Speed Limits)

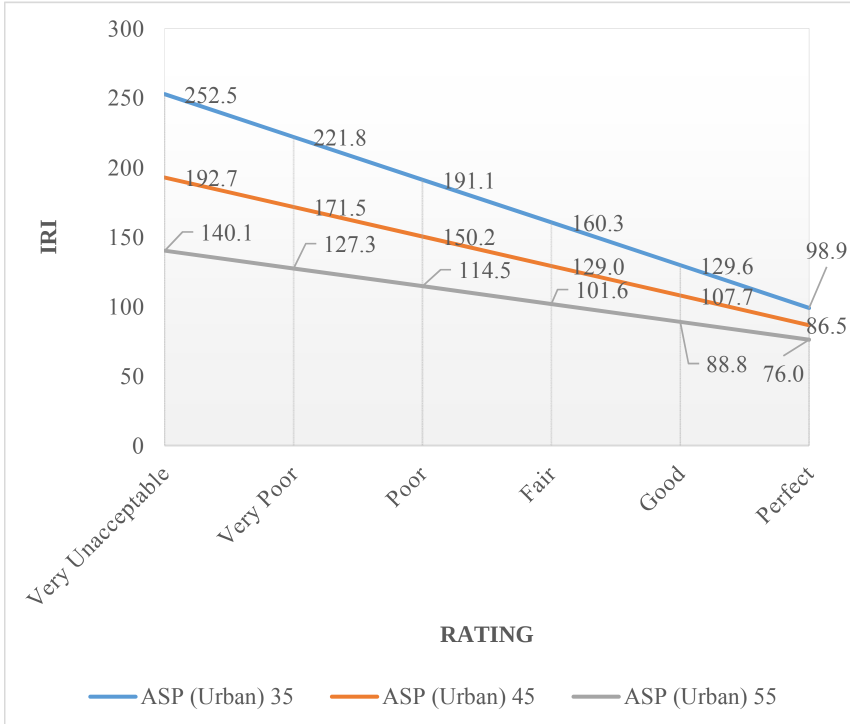


Figure 19: Numerical Ratings vs. IRI (by ASP Urban and Speed Limits)

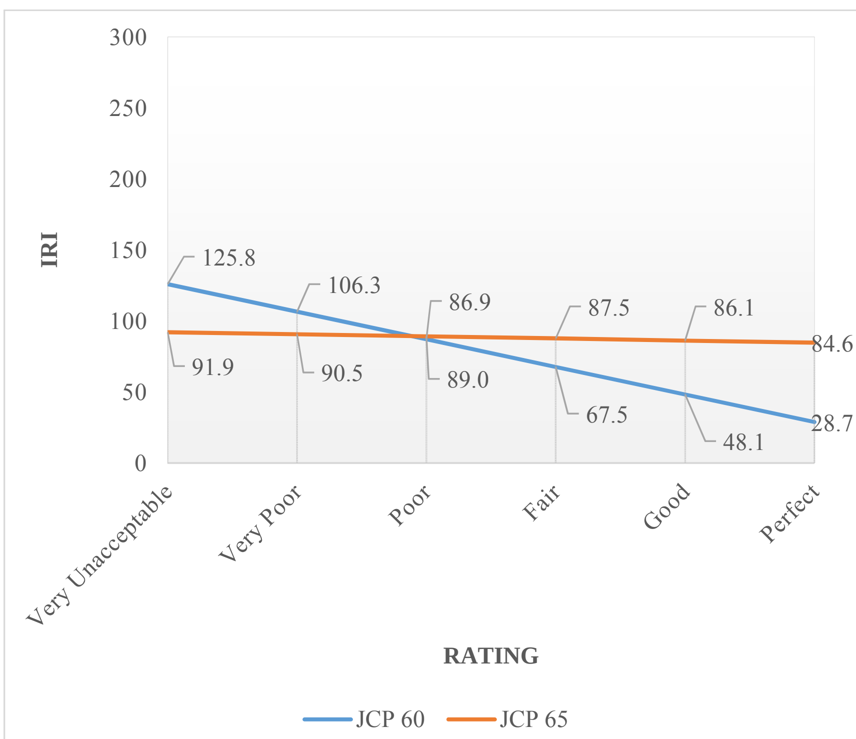


Figure 20: Numerical Ratings vs. IRI (by JCP and Speed Limits)

Figure 14 shows that participants tended to rate JCP sections more strictly than ASP sections. It should be noted that only a few JCP loops were surveyed in this research project because of a limited existence of JCP routes in North Carolina. Figures 18 through 19 clearly show that participants trended to rate ASP sections stricter as the speed limit increases. Numerical ratings for JCP sections, in this case, were still considered biased due to the very limited amount of data.

To determine the IRI threshold for new pavement construction projects using numerical ratings, IRI thresholds corresponding to “Perfect”, “Good”, and “Impassable (also referred to as “Very Unacceptable”)” are tabulated and their descriptive statistics are summarized in Table 13. To avoid the impact of extreme values, the averages of medians were calculated and it was concluded that:

- With the average of median of 78 inches/mile, it seems that 70 to 80 inches/mile is a "Perfect" IRI range;
- With the average of median of 104 inches/mile, it seems that 100 to 110 inches/mile is a "Good" IRI goal range for new pavement construction; and
- With the average of median of 203 inches/mile, it seems that IRI values greater than 200

Table 13: IRI Thresholds from Numerical Ratings

Pavement	Perfect			Good			Very Unacceptable		
	Rating	Average	Median	Rating	Average	Median	Rating	Average	Median
ASP (Rural)	72.1	79	79	102	106	106	221.6	214	214
ASP (Urban)	85.9			110.2			207.3		
ASP (Rural)/Coastal	90.9	86	79	98.3	109	106	128	202	203
ASP (Rural)/Mountains	72.3			98.9			205.4		
ASP (Rural)/Piedmont	75.7			115.2			273.1		
ASP (Urban)/Coastal	124.7			133.6			169		
ASP (Urban)/Mountains	82.9			113.3			234.6		
ASP (Urban)/Piedmont	70.8			96.8			200.9		
ASP (Rural)/45 MPH	68	75	76	109.4	100	99	275.3	196	193
ASP (Rural)/55 MPH	76.6			98.6			187.3		
ASP (Rural)/65 MPH	72			98.7			204.8		
ASP (Rural)/70 MPH	50.2			64.7			122.4		
ASP (Urban)/35 MPH	98.9			129.6			252.5		
ASP (Urban)/45 MPH	86.5			107.7			192.7		
ASP (Urban)/55 MPH	76			88.8			140.1		
Average			78			104			203

inches/mile would be considered as "Very Unacceptable".

A comparison of IRI thresholds for construction acceptance criteria derived using categorical ratings and numerical ratings is shown in Table 14. It is recommended that the IRI threshold obtained from categorical ratings (60-70 inches/mile) to be used by the NCDOT Construction Unit as the construction acceptance criterion. The reason is that, during the surveys, it was observed that most research participants were able to quickly determine if the smoothness of the roadway section was acceptable or not, but were uncertain what an appropriate numerical rating should be. Oftentimes they had to select a numerical rating at the last second before they started surveying the next roadway section. As a result, numerical ratings are more variable than

Table 14: Comparison of IRI Thresholds

	Perfect	Good/New Construction	Very Unacceptable
Categorical Rating	50-60 inch/mile	60-70 inch/mile	>182 inch/mile
Numerical Rating	70-80 inch/mile	100-110 inch/mile	>200 inch/mile

categorical ratings, and the IRI threshold derived from numerical ratings can be less accurate.

4.5 Development of the IRI Index

Based on the analysis results of the categorical ratings, the following assumptions were made to develop the IRI index:

- When IRI = 55 inches/mile, IRI Index value = 100 (perfect condition); and
- When IRI = 182 inches/mile, IRI Index value = 0 (Very Unacceptable condition).

With these assumptions, the equation to derive the IRI index from IRI values is:

$$IRI\_IDX = 143.307 - 0.7874 * IRI \quad (3)$$

where IRI_IDX is the IRI index, and IRI is the NCDOT measured IRI rating.

This relationship is illustrated in Figure 21. From equation (3), for an IRI value of 103 inches/mile, the corresponding IRI index value is 50.

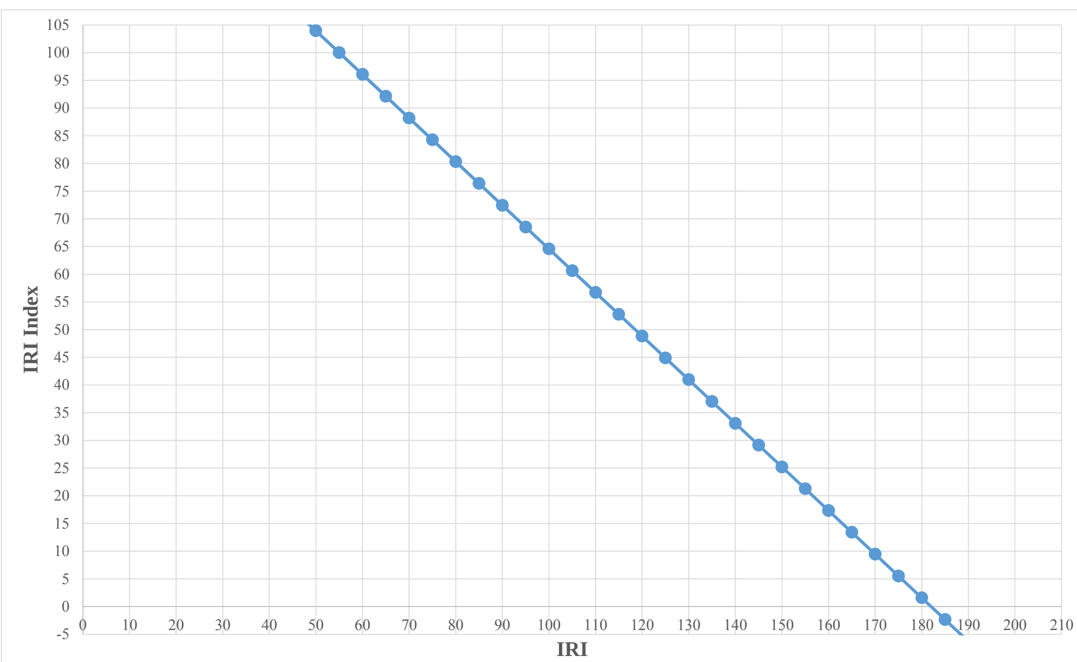


Figure 21: The IRI Index

4.6 Development of IRI Models

IRI index values were calculated for IRI ratings collected using equation (3), and were then used to develop IRI models for asphalt pavements. The nonlinear sigmoidal model form was used in this research project. The model form can be written as:

$$IRI\_IDX = a + \frac{b}{1+e^{-\frac{(AGE-c)}{d}}} \qquad (4)$$

where IRI_IDX is IRI Index, AGE is pavement age, *a, b, c*, and *d* are model parameters.

Model parameters for 8 roadway families are included in Table 15. In this table, US 5-15k represents a roadway family that includes US routes with Annual Average Daily Traffic (AADT) between 5,000 and 15,000. SR represents Secondary Routes.

Table 15: IRI Model Parameters

Family	*a*	*b*	*c*	*d*
Interstate	17.4005	83.2975	10.2039	-2.1468
US 0-5k	9.5364	90.6060	8.9859	-1.3923
US 5-15k	13.8097	86.2227	9.4789	-1.2021
US 15kplus	13.9738	85.9696	9.4014	-1.3182
NC 0-1k	12.2099	93.1391	8.9980	-3.2134
NC 1-5k	10.8656	89.7020	10.6332	-2.1029
NC 5kplus	3.6272	97.1205	8.8690	-1.8804
SR	0.9845	99.3379	7.7592	-1.3565

Model curves are presented in Figures 22 through 26. The Interstate family curve is included in Figure 22. All three US family curves are included in Figure 23. All three NC family curves are included in Figure 24. The SR family curve is included in Figure 25. All 8 family curves are included in Figure 26. Individual family curves are included in Appendix B.

It should be noted that currently the NCDOT uses distress models (distress index vs. pavement age) and performance models (PCR vs. pavement age) to make treatment decisions, and IRI models are not considered because they have not been developed before. Therefore, it is suggested that the developed IRI models should not be used to determine pavement service lives before these models are added to the decision tree as a separate branch.

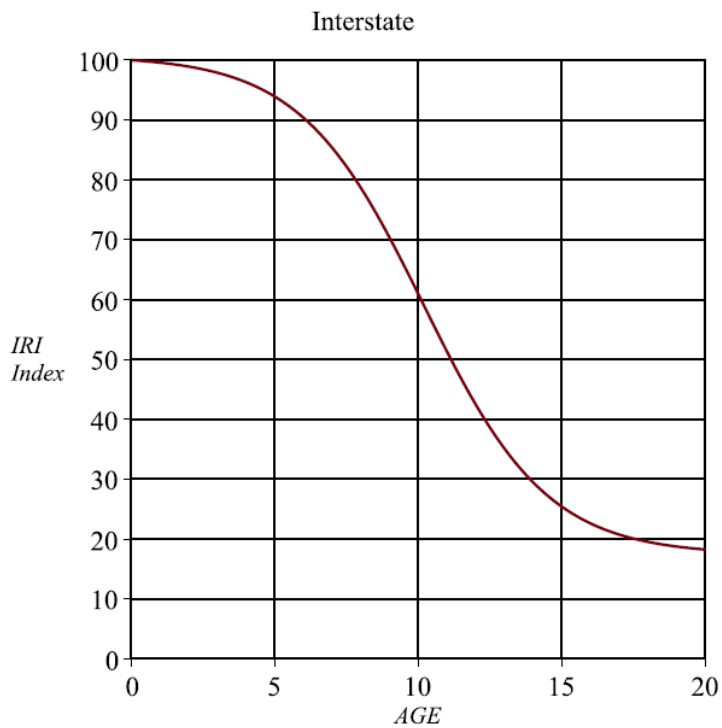


Figure 22: Interstate IRI Curve

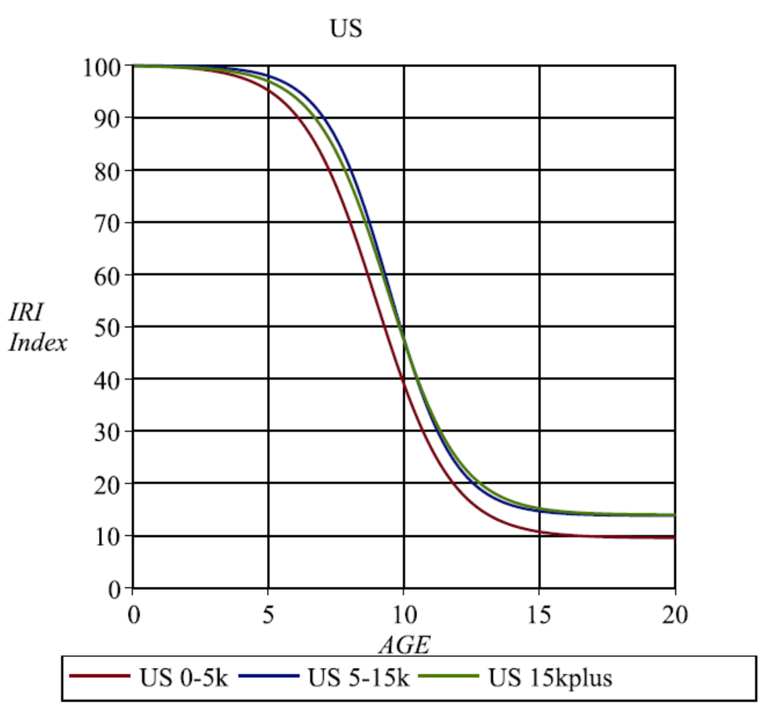


Figure 23: US IRI Curves

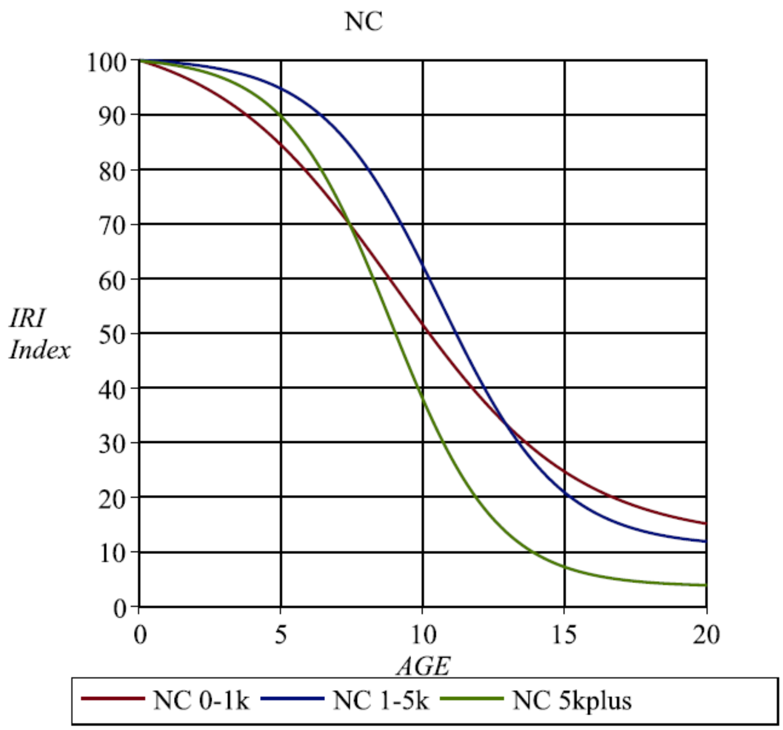


Figure 24: NC IRI Curves

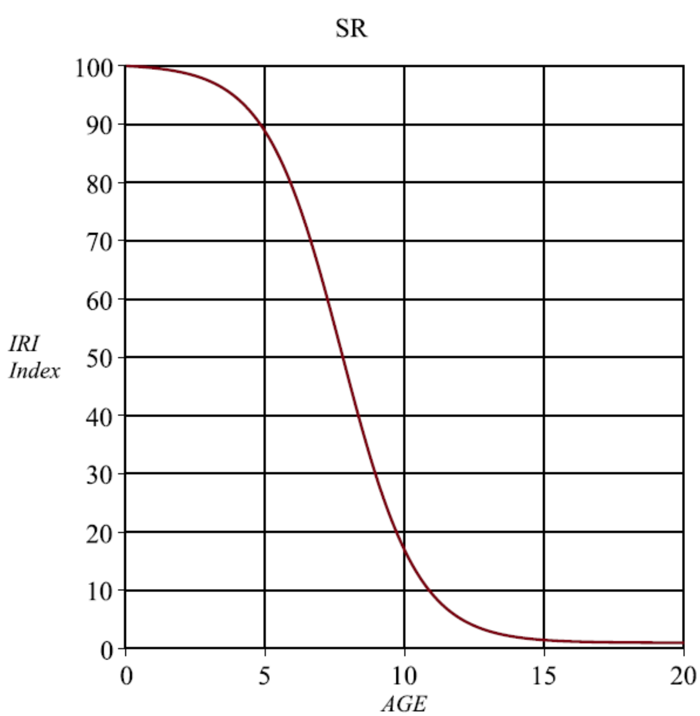


Figure 25: SR IRI Curve

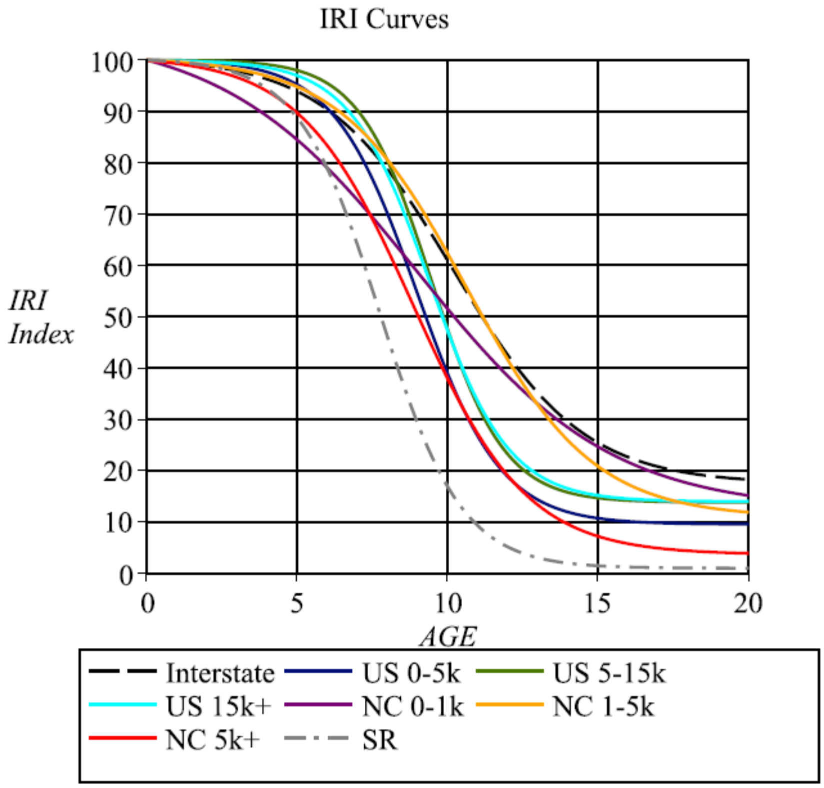


Figure 26: All IRI Curves

4.7 The Relationship between Initial Construction IRI and Network Performance IRI

To answer the question that if a smoother pavement will last longer, the relationship between initial construction IRI and network performance IRI should be identified. This was achieved by studying the rates of change in IRI values for 18 roadway families listed in Table 16. In this process, each roadway family was subdivided into several subgroups using the following conditions:

- If the initial construction IRI of a roadway is between 50 ~ 60 inches/mile, it belongs to the IRI_{60} subgroup;
- If the initial construction IRI of a roadway is between 60 ~ 70 inches/mile, it belongs to the IRI_{70} subgroup; and
- If the initial construction IRI of a roadway is between 70 ~ 80 inches/mile, it belongs to the IRI_{80} subgroup.

Roadways with initial IRI values greater than 80 inches/mile were not included in the further analyses. The reason was that these initial IRI values are close to the IRI threshold value of 103 inches/mile, and they were considered unrealistic ratings that more likely were caused by resurfacing with a thin lift without a leveling course on an initially fairly rough road.

Within each roadway family, IRI was regressed against pavement age using the following linear regression equation:

$$IRI = \beta_0 + \beta_1 * Age + \beta_2 * IRI_0 + \beta_3 * Age * IRI_0 \quad (5)$$

In this equation, $\beta's$ are model parameters, IRI_0 represents IRI subgroups. To compare the rates of change in IRI values among IRI subgroups, the following assumptions were made:

- $IRI_0 = 0$ if the initial IRI belongs to the IRI_{60} subgroup;
- $IRI_0 = 1$ if the initial IRI belongs to the IRI_{70} subgroup; and
- $IRI_0 = 2$ if the initial IRI belongs to the IRI_{80} subgroup;

Then for a given IRI subgroup, equation (5) can be written as:

For IRI_{60}: $IRI = \beta_0 + \beta_1 * Age$ (6)
For IRI_{70}: $IRI = \beta_0 + \beta_1 * Age + \beta_2 + \beta_3 * Age$ (7)
For IRI_{80}: $IRI = \beta_0 + \beta_1 * Age + 2\beta_2 + 2\beta_3 * Age$ (8)

The parameters in these three models can be interpreted in terms of the slopes and intercepts associated with their corresponding regression lines. In particular,

β_0: y-intercept for IRI_{60} regression line;
β_1: slope of IRI_{60} regression line;
β_2: difference in y-intercepts of regression lines for IRI_{60} and IRI_{70}, and for IRI_{70} and IRI_{80};
β_3: difference in slopes of regression lines for IRI_{60} and IRI_{70}, and for IRI_{70} and IRI_{80};

Since the goal was to study the rates of change in IRI values over time for the three IRI subgroups, the null hypothesis $\beta_3 = 0$ was tested. Essentially this null hypothesis states that the rates are the same for all three subgroups. The results of t-tests are tabulated in Table 16. In this table, BSS represents Bituminous Slurry Subdivision routes, BSR represents Bituminous Slurry Rural routes, PS represents Plant Mix Subdivision routes, and PR represents Plant Mix Rural routes. It should be noted that IRI values are not available for some subgroups of certain roadway families, and thus were designated as "N/A".

As shown in Table 16, the null hypothesis was rejected for 9 out of 16 families at the 0.05 significance level (P values less than 0.05), meaning that the rates are different for 56% of roadways. For other 44% of roadways, the rates of change in IRI are the same among IRI subgroups. It was difficult to reach an explicit conclusion regarding if the rates are the same based on these results.

Table 16: Regression analysis of Rates of Change in IRI Values

Family	**Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Interstate 0-50k	-0.0172	0.2393	-0.07	0.943
Interstate 50kplus	0.2241	0.2178	1.03	0.304
US 0-5k	0.0538	0.0063	8.6	<.0001
US 5-15k	0.0128	0.0070	1.85	0.065
US 15-30k	0.0025	0.0080	0.31	0.755
US 30kplus	-0.0051	0.0078	-0.66	0.511
NC 0-1k	-0.0163	0.0035	-4.62	<.0001
NC 1-5k	-0.0438	0.0029	-14.99	<.0001
NC 5-15k	-0.0255	0.0031	-8.15	<.0001
NC 15kplus	0.0207	0.0051	4.07	<.0001
SR 0-1k BSR	0.1241	0.0393	3.16	0.0017
SR 0-1k BSS	N/A			
SR 0-1K PR	-0.0072	0.0153	-0.47	0.638
SR 0-1K PS	N/A			
SR 1-5k PR	-0.0291	0.0072	-4.02	<.0001
SR 1kplus BSR	0.1744	0.0283	6.16	<.0001
SR 5-15k PR	-0.0165	0.0090	-1.82	0.068
SR 15kplus PR	0.0648	0.0186	3.48	0.0005*

Previous research indicated that the initial construction IRI is not the only factor that can affect the network performance IRI, other factors, such as traffic volume and environmental factors can also work jointly to impact how the network performance IRI values change over time. Thus, initial IRI, traffic levels, and an additional factor, i.e., regional factor, representing environmental effects were included in the next analysis. The new regression equation was:

$IRI = \beta_0 + \beta_1 * Region_C + \beta_2 * Region_M + \beta_3 * Region_P + \beta_4 * IRI_{60} + \beta_5 * IRI_{70} + \beta_6 * IRI_{80} + \beta_7 * (Region_C * IRI_{60}) + \beta_8 * (Region_C * IRI_{70}) + \beta_9 * (Region_C * IRI_{80}) + \beta_{10} * (Region_M * IRI_{60}) + \beta_{11} * (Region_M * IRI_{70}) + \beta_{12} * (Region_M * IRI_{80}) + \beta_{13} *$

$(Region_P * IRI_{60}) + \beta_{14} * (Region_P * IRI_{70}) + \beta_{15} * (Region_P * IRI_{80}) + \beta_{16} * Age$ (9)

This equation includes main effects of initial IRI, regional factors and their interaction effects, as well as pavement age. In this equation, $\beta_0 \sim \beta_{16}$ are model parameters. The region factor has three levels, n_C, $Region_M$, and $Region_P$, representing the Coastal, Mountains, and Piedmont, respectively. The initial IRI has three levels, IRI_{60}, IRI_{70}, and IRI_{80}, representing individual subgroups as described in the previous section. All 18 roadway families were classified by AADT values, therefore, traffic levels have already been accounted for in this analysis.

In this analysis, it was decided to use contrasts to investigate the differences in IRI values at any age among three IRI subgroups. The following contrasts that can quantify the differences in group means were analyzed and their estimates were calculated to test the corresponding null hypotheses:

- $IRI_{60} – IRI_{70} = 0$ in the Coastal region
- $IRI_{60} – IRI_{80} = 0$ in the Coastal region
- $IRI_{70} – IRI_{80} = 0$ in the Coastal region
- $IRI_{60} – IRI_{70} = 0$ in the Mountains region
- $IRI_{60} – IRI_{80} = 0$ in the Mountains region
- $IRI_{70} – IRI_{80} = 0$ in the Mountains region
- $IRI_{60} – IRI_{70} = 0$ in the Piedmont region
- $IRI_{60} – IRI_{80} = 0$ in the Piedmont region
- $IRI_{70} – IRI_{80} = 0$ in the Piedmont region

The Interstate families (0-50k and 50kplus) had unbalanced sample sizes: among 47,500 observations of the Interstate 0-50k family, 30 were in the IRI_{80} subgroup, 47,470 were in the IRI_{60} subgroup, and none were in the IRI_{70} subgroup; among 15,880 observations of the Interstate 50kplus family, 148 were in the IRI_{70} subgroup, 15,732 were in the IRI_{60} subgroup, and none were in the IRI_{80} subgroup. Therefore, contrasts for the Interstate families were not performed. For most of the remaining roadway families, the null hypothesis of group means being equal was rejected at the 0.05 level, indicating that the group means are different from each other. In addition, the results also showed that long-term network IRI of three IRI subgroups were in ascending order, i.e., IRI60 < IRI70 < IRI80, as shown by an example below. This finding essentially proved the statement that smoother pavements (smaller initial IRI values) deteriorated at a slower rate and therefore had longer service lives.

Estimates of contrasts of two roadway families are presented in Tables 17 and 18 as examples. All the results are included in Appendix C.

As shown in Tables 17 and 18, small P-values (< 0.001) were obtained, thus all the null hypothesis were rejected indicating the averages of network IRI of three subgroups were different from each other. In Table 17, for the coastal region, average (IRI60) – average (IRI70) = -24.4151956, average (IRI60) – average (IRI80) = -36.4759628, and average (IRI70) – average (IRI80) = -12.0607672. Therefore, average (IRI60) < average (IRI70) < average (IRI80). This same result was obtained for the other regions in Table 17 and for three regions of the NC 1-5k family in Table 18.

Table 17: Estimates of Contrasts: US 0-5k

Parameter	Estimate	Standard Error	t Value	Pr > |t|
IRI60 vs IRI70 in Coastal	-24.4151956	0.89000430	-27.43	<.0001
IRI60 vs IRI80 in Coastal	-36.4759628	1.60324528	-22.75	<.0001
IRI70 vs IRI80 in Coastal	-12.0607672	1.83041992	-6.59	<.0001
IRI60 vs IRI70 in Mountains	-23.3083271	0.88002490	-26.49	<.0001
IRI60 vs IRI80 in Mountains	-40.9133128	0.95962144	-42.63	<.0001
IRI70 vs IRI80 in Mountains	-17.6049857	1.29274341	-13.62	<.0001
IRI60 vs IRI70 in Piedmont	-17.1448368	0.73903714	-23.20	<.0001

Table 18: Estimates of Contrasts: NC 1-5k

Parameter	Estimate	Standard Error	t Value	Pr > |t|
IRI60 vs IRI70 in Coastal	-14.6868605	0.38886823	-37.77	<.0001
IRI60 vs IRI80 in Coastal	-23.1472314	0.68021819	-34.03	<.0001
IRI70 vs IRI80 in Coastal	-8.4603708	0.77889368	-10.86	<.0001
IRI60 vs IRI70 in Mountains	-20.4796813	0.32929951	-62.19	<.0001
IRI60 vs IRI80 in Mountains	-23.0014258	0.63734757	-36.09	<.0001
IRI70 vs IRI80 in Mountains	-2.5217445	0.68385808	-3.69	0.0002
IRI60 vs IRI70 in Piedmont	-10.2046217	0.28974465	-35.22	<.0001
IRI60 vs IRI80 in Piedmont	-21.3725720	0.86847472	-24.61	<.0001
IRI70 vs IRI80 in Piedmont	-11.1679503	0.90964756	-12.28	<.0001

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research project was conducted to establish a relationship between public perceived ride quality and NCDOT measured IRI ratings. To this end, 241 residents of 9 counties in North Carolina were randomly recruited. Their opinions regarding the smoothness of carefully pre-selected roadway loops were collected and analyzed, and the following conclusions were drawn from the results of the data analysis process:

- The quality of collected public perceived ride quality ratings was satisfactory. Research participants were given instructions regarding how to complete the survey forms. Guidelines that explain how to rate the smoothness of roadway loops, however, was not provided to ensure that all participants rate roadways unbiasedly and independently. An analysis of Kendall's W coefficients indicates that approximately 74% of participants agreed with each other when assessing the same roadway sections.
- NCDOT measured IRI values, speed limits, and seating positions in the survey vans are significant factors that affect public perceived ride quality.
  - Roadways that had greater measured IRI values and higher speed limits were more likely to be rated as "Unacceptable", as expected.
  - Participants seating in positions 1, 3, and 5 (window positions) were more likely to rate roadways favorably. One of the possible reasons was that when compared to middle-seated participants (positions 2 and 4) who rated the roadways mainly using their kinesthetic sense, these participants were also able to do so more confidently using their visual perception of roadway conditions as well. Another possible reason was due to different seat belt configurations of window seats and middle seats. People in the middle seats were less likely secured snuggly by their seat belts. Therefore, they could feel more vehicle movement and thus provide less favorable ratings.
  - Participants' ratings were not affected by the two vehicles used by this research project. The reason was that the vehicles used for all surveys were selected to avoid potential biased perceptions: the conditions of two vehicles were very similar; both of them are Dodge Grand Caravan; they were manufactured in 2005 and 2007, and had similar mileages prior to the surveys.
  - Statistical analysis indicated that the regions in North Carolina did not significantly affect participants' ratings. Participants who lived close to roadways being surveyed were recruited to ensure that they were familiar to roadway conditions. It appeared that participants in different regions tended to rate familiar roadways in a very similar manner.
  - It was unexpected that pavement types (ASP urban, ASP rural, and JCP) were not a significant factor. Most likely this was caused by the rather small numbers of ratings collected from JCP sections. Realizing that practically pavement types do affect perceived ride quality, this factor was included in further analyses. It was concluded that ASP urban and rural sections were more likely to be rated as "Acceptable" than JCP sections.
- In North Carolina, if the measured IRI value of a roadway section is less than 103 inches/mile, most likely this section would be rated as "Acceptable" by the general

driving public; most likely it would be rated as “Unacceptable” if its measured IRI value is greater than 151 inches/mile. These two IRI thresholds can be used as goals for general maintenance of roadways in North Carolina.

- The target initial IRI value for a new construction project was determined to be between 60 and 70 inches/mile. For a “perfect” roadway section, its IRI value was determined to be between 50 and 60 inches/mile. If the IRI value is greater than 182 inches/mile, the roadway section is considered as “Very Unacceptable”.
- IRI index was derived using a linear relationship (IRI vs. AGE) developed in this study. It was assumed that: 1) when IRI = 55 inches/mile, IRI Index value = 100 (perfect condition); and 2) when IRI = 182 inches/mile, IRI Index value = 0 (Very Unacceptable).
- IRI models were developed using the IRI index values determined in this study. It should be noted that currently the NCDOT uses distress models (distress index vs. pavement age) and performance models (PCR vs. pavement age) to make treatment decisions, and IRI models are not considered because they have not been developed before. Therefore, it is suggested that the developed IRI models should not be used to determine pavement service lives before these models are added to the decision tree as a separate branch.
- It was concluded that smooth pavements (smaller initial IRI values) deteriorated at a slower rate and therefore had longer service lives. In addition to initial IRI, other factors such as traffic volume and environmental factors also work jointly to impact how the network performance IRI values change over time.
- It should be noted that the results from the JCP sections are not sufficient to draw explicit conclusions because of the limited number of JCP sections that were surveyed in this study.

5.2 Recommendations

- It is recommended that the developed IRI models to be included in the NCDOT treatment decision-making process for increased PMS performance. A separate branch can be developed using these models and added to the decision tree. IRI trigger values can be determined to suggest appropriate treatments.
- It is recommended that more JCP sections to be studied in order to develop IRI limits and targets for network management and construction approval purposes.
- It is recommended that balanced sampling (fixed sample size and stratification) of varying types of roadways (e.g., flexible, rigid, and composite) should be required whenever possible in order to obtain informative research results. In this study, some contrasts were not performed because of unbalance samples.
- The following data collection methods have proven to be effective in this research project, and are recommended for future studies in this research area:
    - The face-to-face recruiting method is more effective than the phone call method.
    - It is necessary to over-recruit participants in order to avoid “no-shows”. Essentially, this is to ensure that the appropriate sample sizes are achieved, and that the findings are statistically significant.
    - Locations of roadway loops should be close to each other. It took approximately 2 hours to complete one survey (including 3 roadway loops: one ASP urban, one

ASP rural, and one JCP) in this research project, which caused uncertainties in logistics.

- It was concluded in this research project that initial IRI, traffic levels, and environmental factors are important factors that can affect long-term network IRI. Other factors, such as pavement designs, are recommended to be considered in future studies.

CITED REFERENCES

1. Smith, K.L., K. D. Smith, L.D. Evans, T.E. Hoerner, and M.I. Darter. 1997. *Smoothness Specifications for Pavements*. Final Report. NCHRP 1-31, Washington, DC: Transportation Research Board, March 1997.

2. Janoff, M.S. I. Volume 111 of Information series. National Asphalt Pavement Association (NAPA). 1991.

3. Corley-Lay, J., and Mastin, N. *Evaluation of Long-Term Pavement Performance Profile Data for Flexible Pavements*. Transportation Research Record 2093, Transportation Research Board, Washington, D.C., 25-30, 2009.

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

5. Sayers, M. W., Gillespie, T. D. and Queiroz, C. A. V. 1986, *The International Road Roughness Experiment: Establishing Correlation and a Calibration Standard for Measurements*, The World Bank, Washington, D.C.

6. American Association of State Highway and Transportation Officials (AASHTO), 2013. *Standard Practice for Quantifying Roughness of Pavements.*

7. Federal Highway Administration (FHWA). *National Strategic Plan*. 1998.

8. Federal Highway Administration (FHWA). *National Strategic Plan*. 2002.

9. Federal Highway Administration (FHWA). *National Strategic Plan*. 2006.

10. Fernando, E. and N.Y. Lee. Technical Memorandum. *Documentation of Ride Surveys Conducted in Project 4901.* Texas Transportation Institute. Texas A&M University System. College Station, TX. December, 1999.

11. Kuemmel, D.A., R.K. Robinson, R.J. Griffin, R.C. Sonntag, and J.K. Giese.
    a. *Public Perceptions of the Midwest's Pavements –Final Phase III Report – Iowa*. Report CHTE 2001-02. WisDOT Highway Research Study #94-07. January 2001. Available on-line at: http://www.trc.marquette.edu/public_perception/.
    b. *Public Perceptions of the Midwest's Pavements –Executive Summary –Minnesota*. Report CHTE 2001-02. WisDOT Highway Research Study #94-07. February 2001. Available on-line at: http://www.trc.marquette.edu/public_perception/.

c. *Public Perceptions of the Midwest's Pavements –Executive Summary –Wisconsin*. Report WI/SPR-01-01. WisDOT Highway Research Study #94-07. January 2001. Available on-line at: http://www.trc.marquette.edu/public_perception/.

12. Shafizadeh, K., Mannering, F., and Pierce, L. *A Statistical Analysis of Factors Associated with Driver-Perceived Road Roughness on Urban Highways*. Washington State Transportation Center (TRAC), 2002.

13. ASTM E1927-98. 2007. *Standard Guide for Conducting Subjective Pavement Ride Quality Ratings.*

14. Agresti, A. *Categorical Data Analysis*. Second edition, Wiley-Interscience. 1990.

15. Washington, S.P., Karlaftis, M.G., and Mannering, F.L. *Statistical AND Econometric Methods FOR Transportation Data Analysis*. Second Edition. Chapman and Hall/CRC. 2003.

16. Kendall, M., and Gibbons, J. D. 1990. *Rank Correlation Method,* 5th Ed., Hodder and Stoughton, U.K.

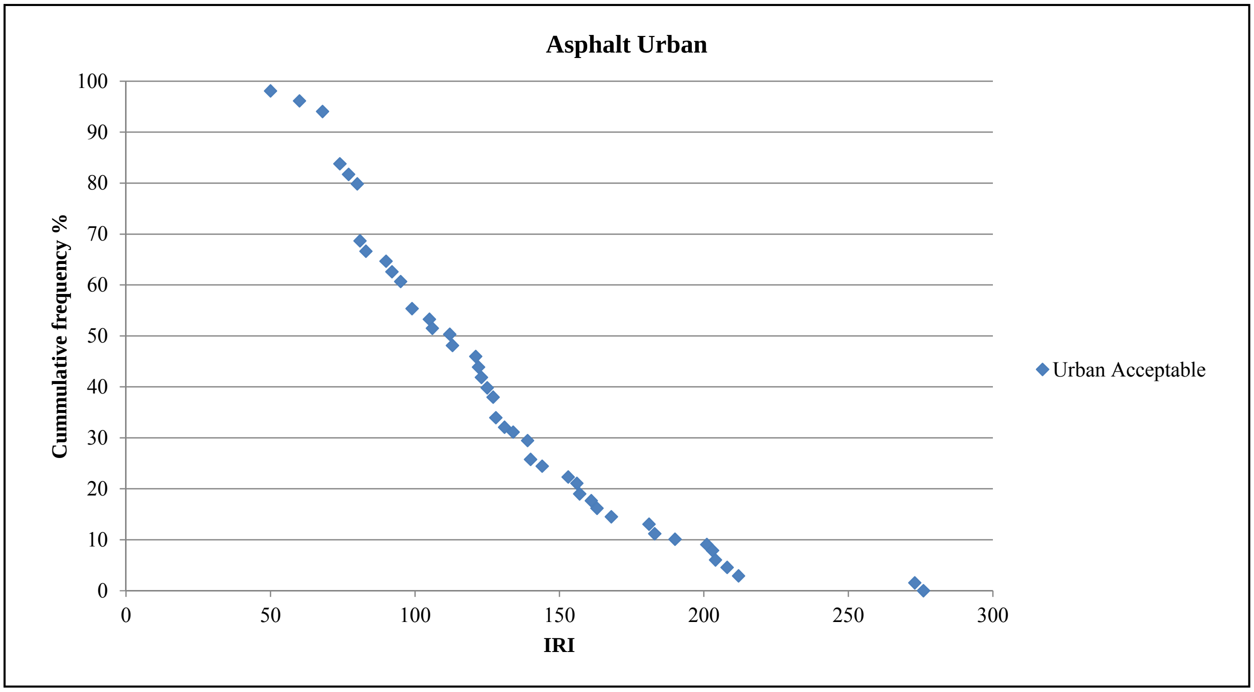
17. Siegel, S. and Castellan, N.J. 1998. *Nonparametric Statistics for the Behavioral Sciences*, 2nd edition, McGraw-Hill.

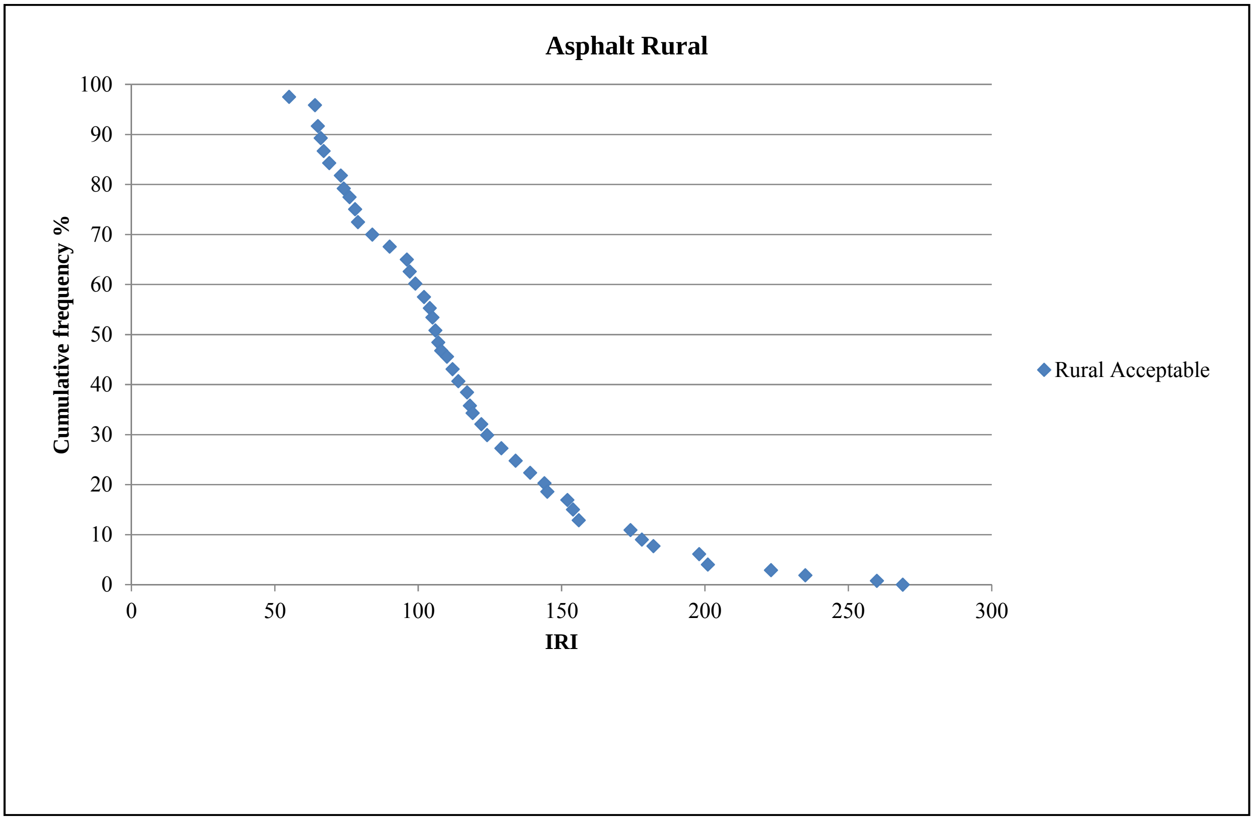
18. Casady, R.J. and Lepkowski, J.M. 1993. *Stratified Telephone Survey Designs*.

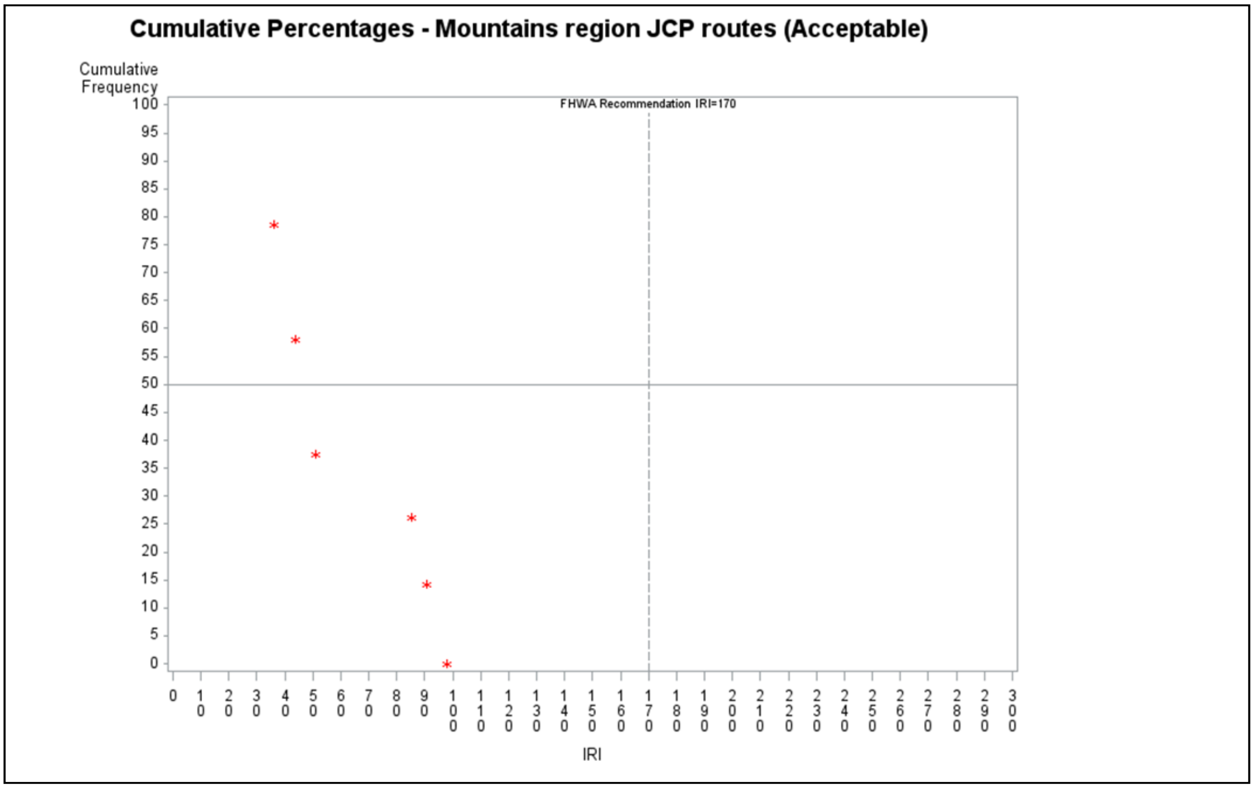
19. Curtin, R., Singer, E., and Presser, S. 2007. *Incentives in Random Digit Dial Telephone Surveys: A Replication and Extension. Journal of Official Statistics*, Vol. 23, No. 1, pp. 91-105.

20. Battaglia, M.P., Frankel, M.R., and Link, M.W. 2008. *Incentives in Random Digit Dial Telephone Surveys A Replication and Extension*. Survey Research Methods, Vol. 2, No. 1, pp. 11-19.

Appendix A. Cumulative Percentages of “Acceptable” Ratings vs. IRI



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Cumulative Frequency
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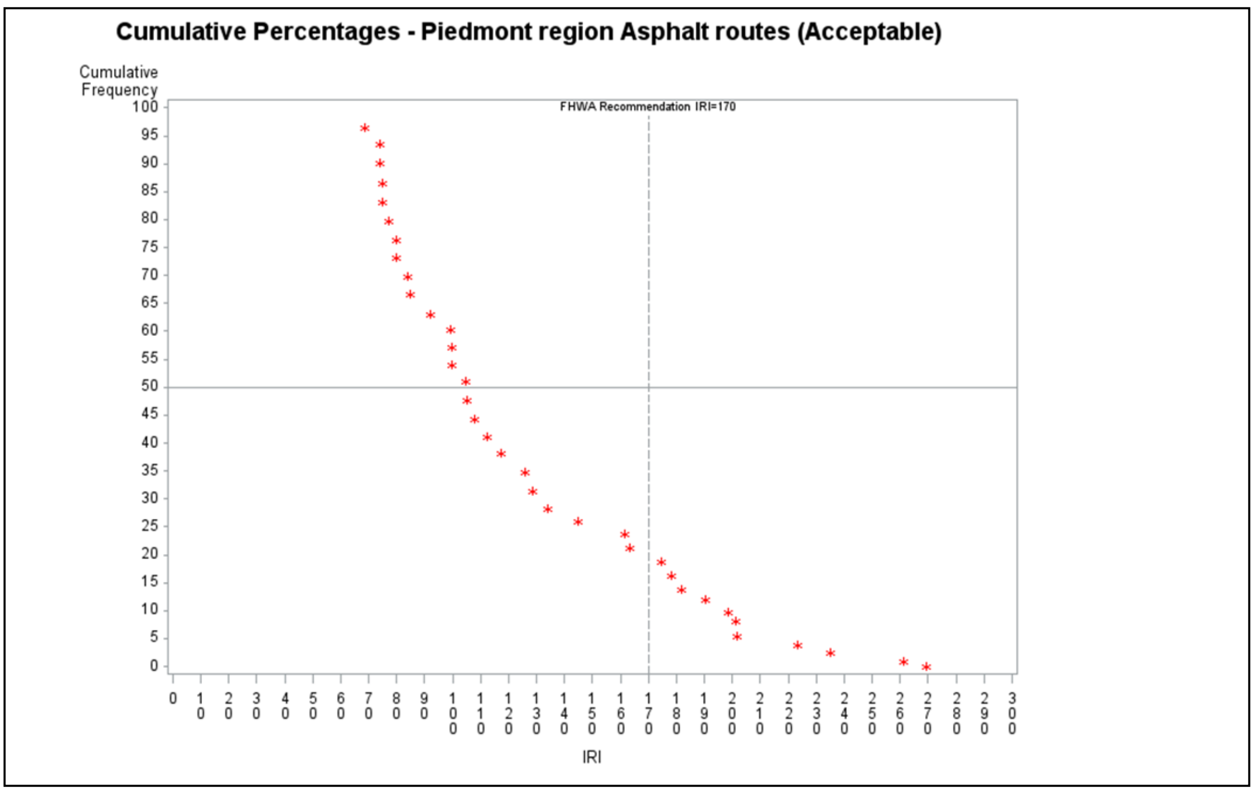
IRI


Cumulative Percentages - Piedmont region Asphalt routes (Acceptable)
Cumulative Frequency
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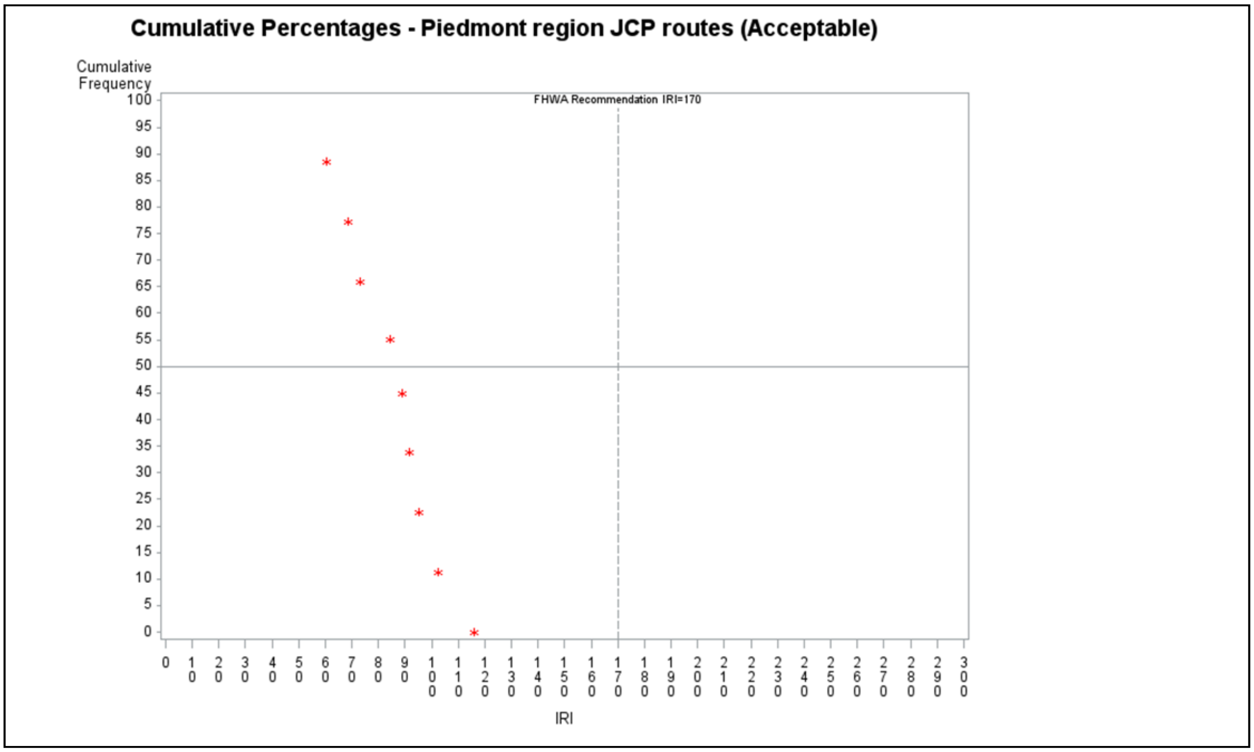
IRI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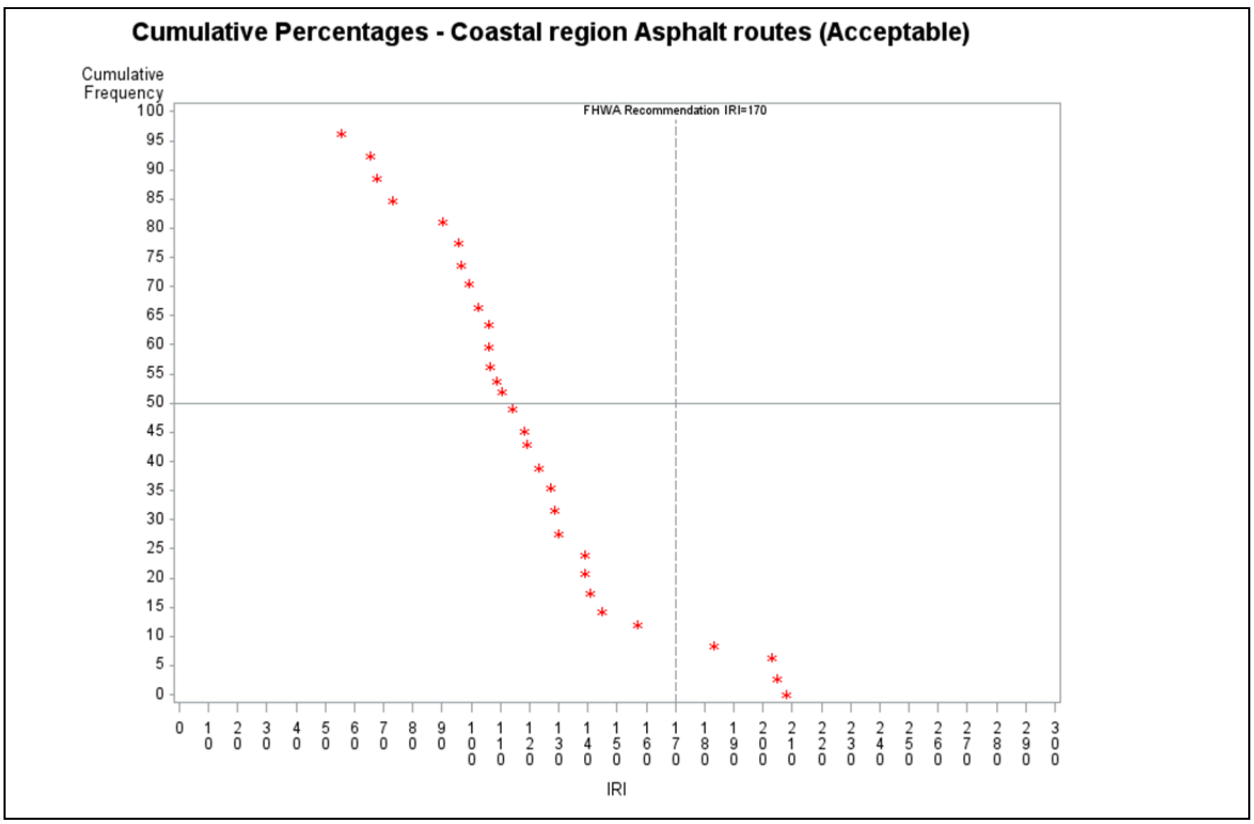
IRI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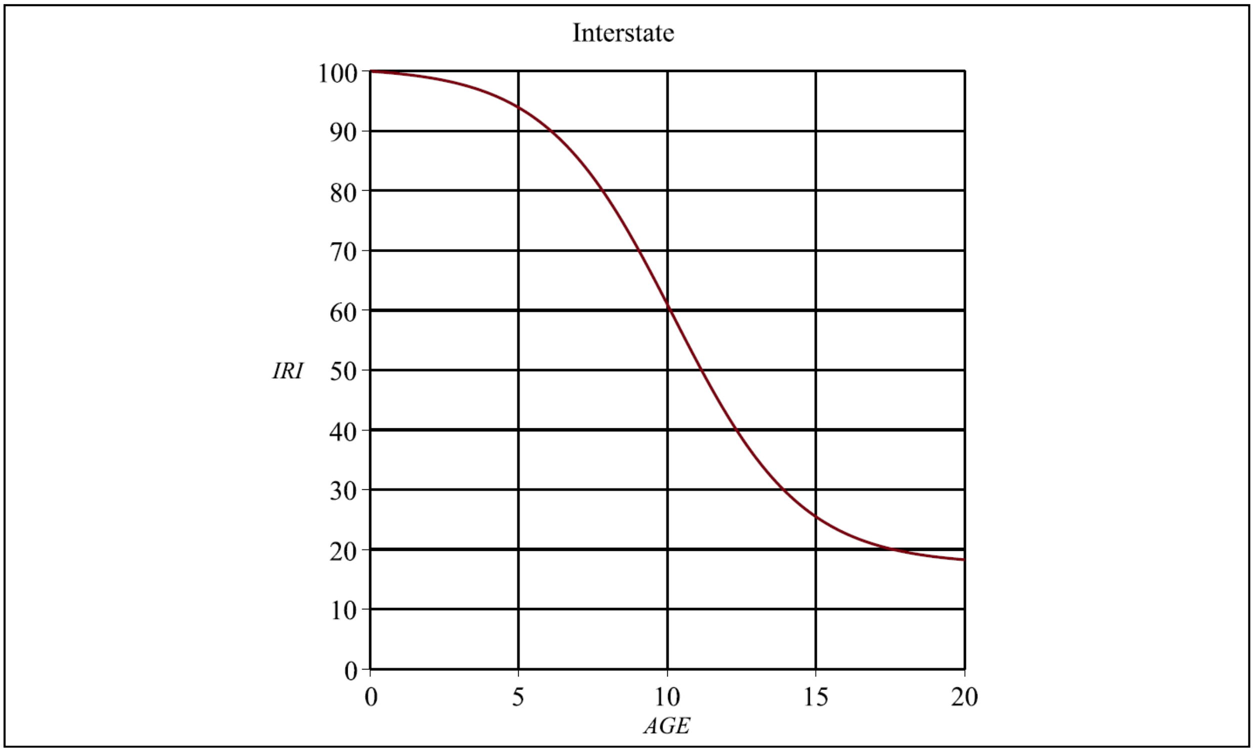
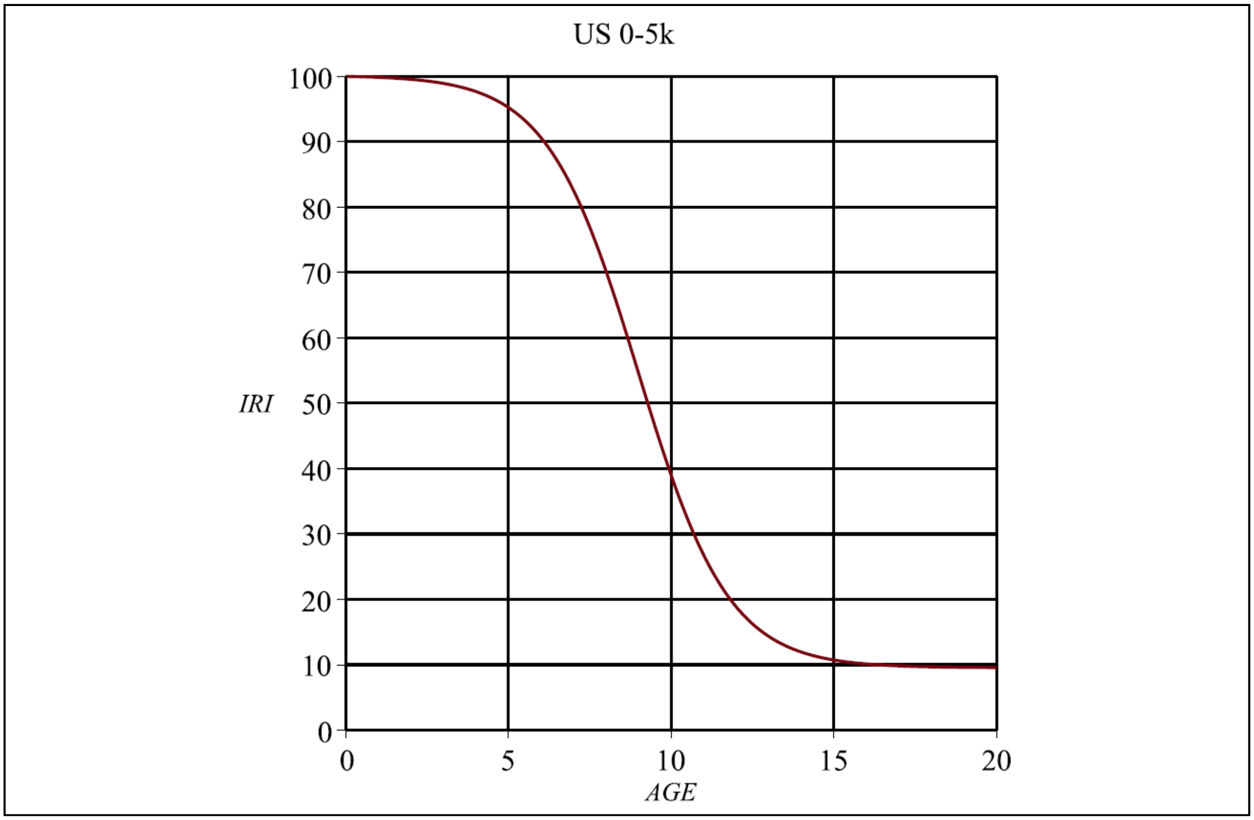
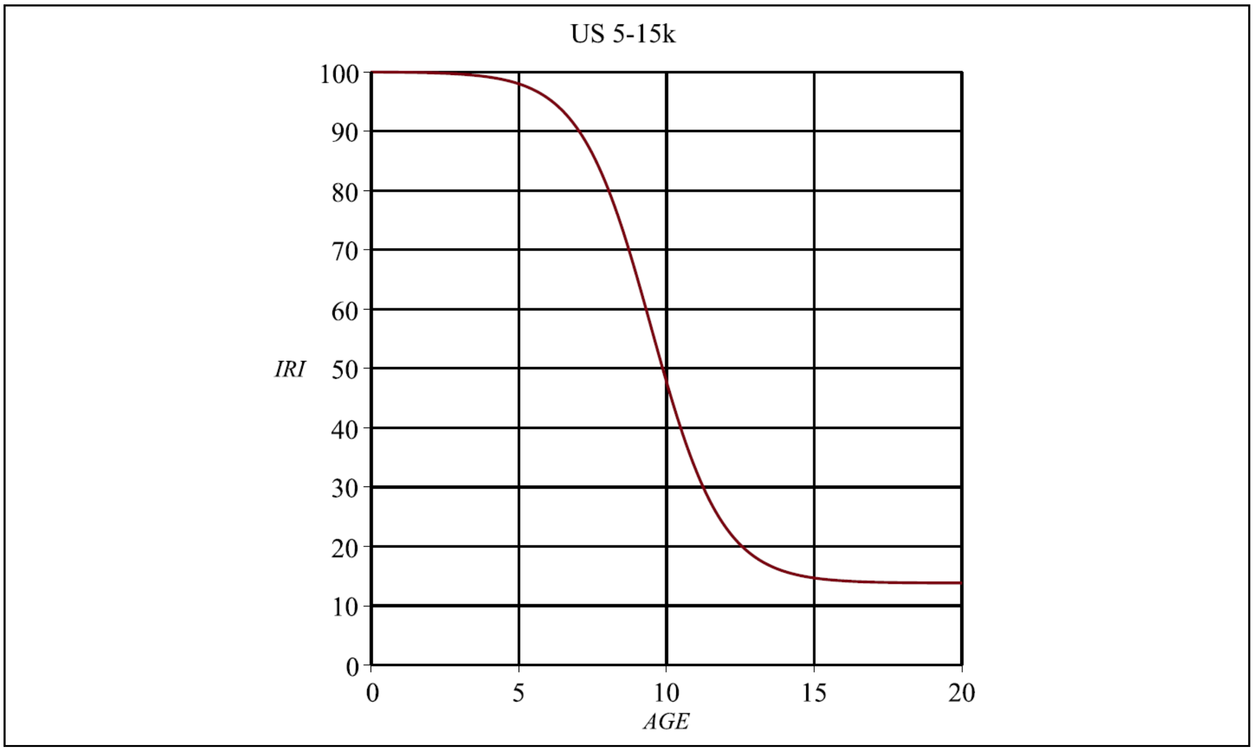
IRI

Appendix B. IRI Curves



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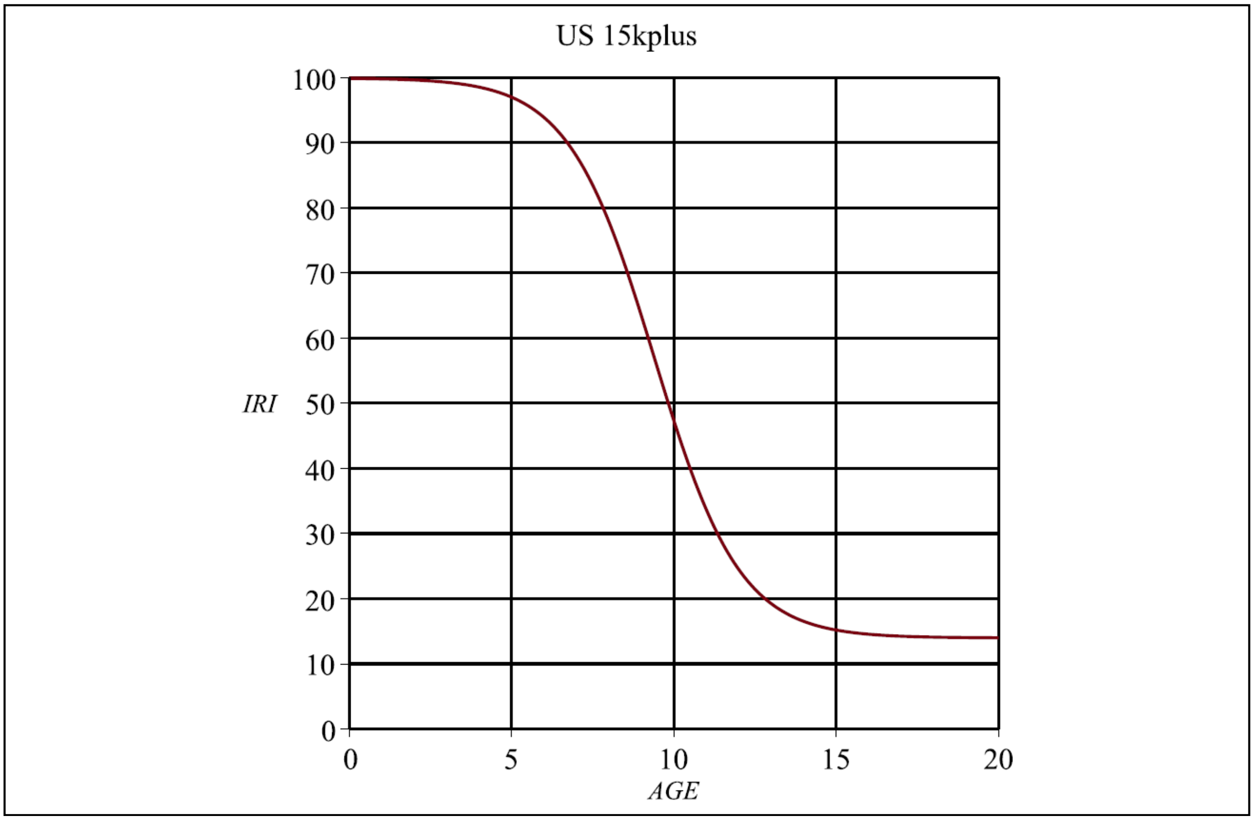
80
70
60
IRI
50
40
30
20
10
0
0
5
10
15
20
AGE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90
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70
60
IRI
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40
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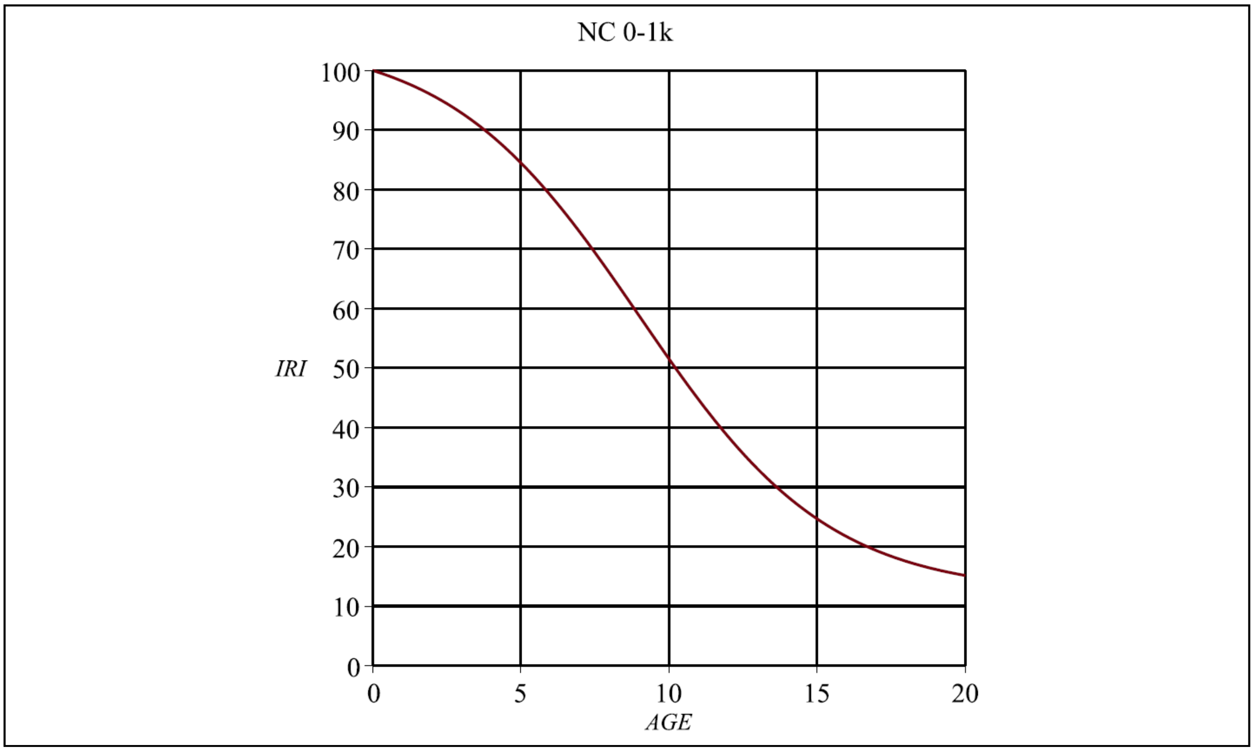
20
10
0
0
5
10
15
20
AGE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80
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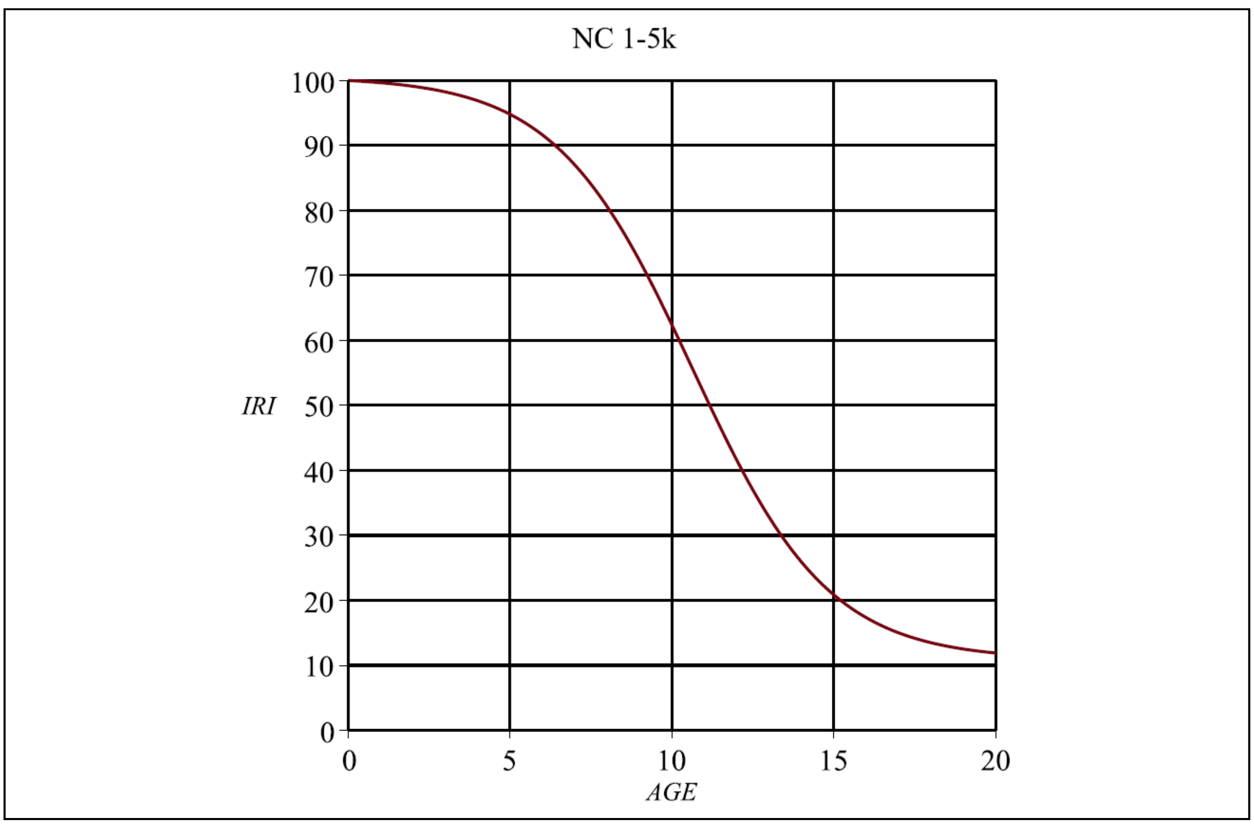
60
50
40
30
20
10
0
IRI
0
5
10
15
20
AGE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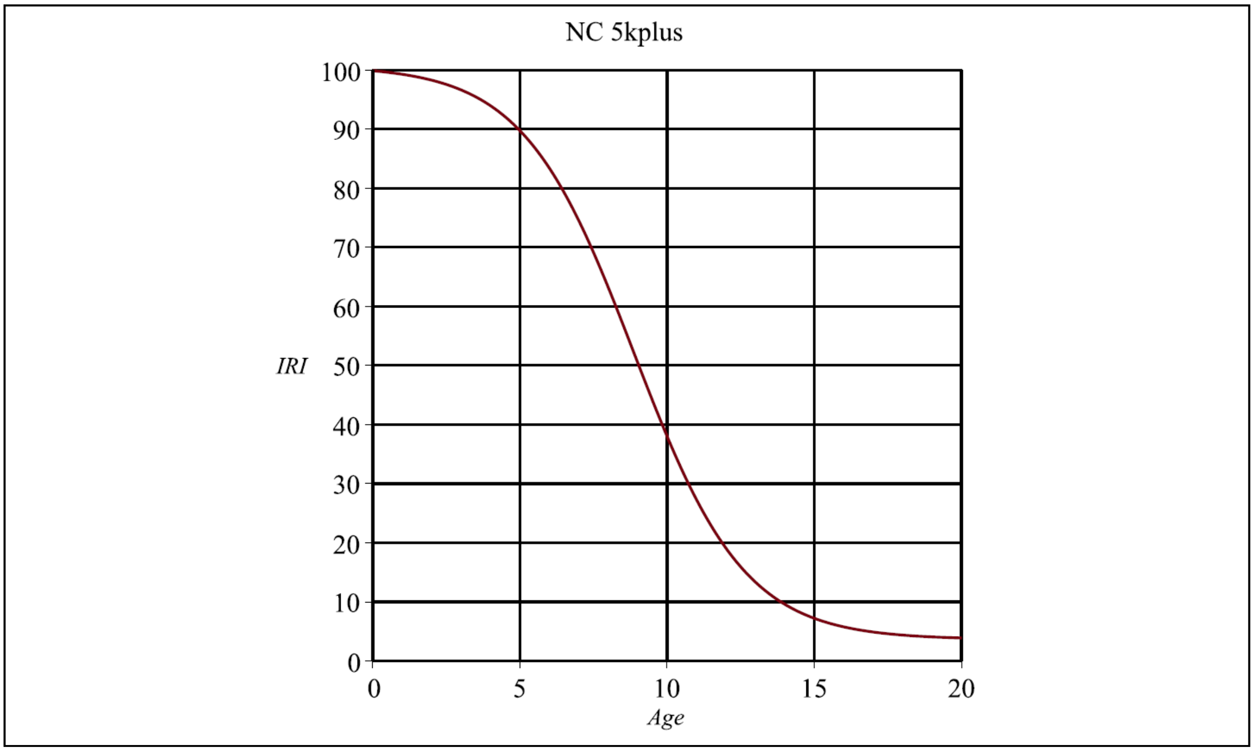
AGE


NC 5kplus
IRI
Age
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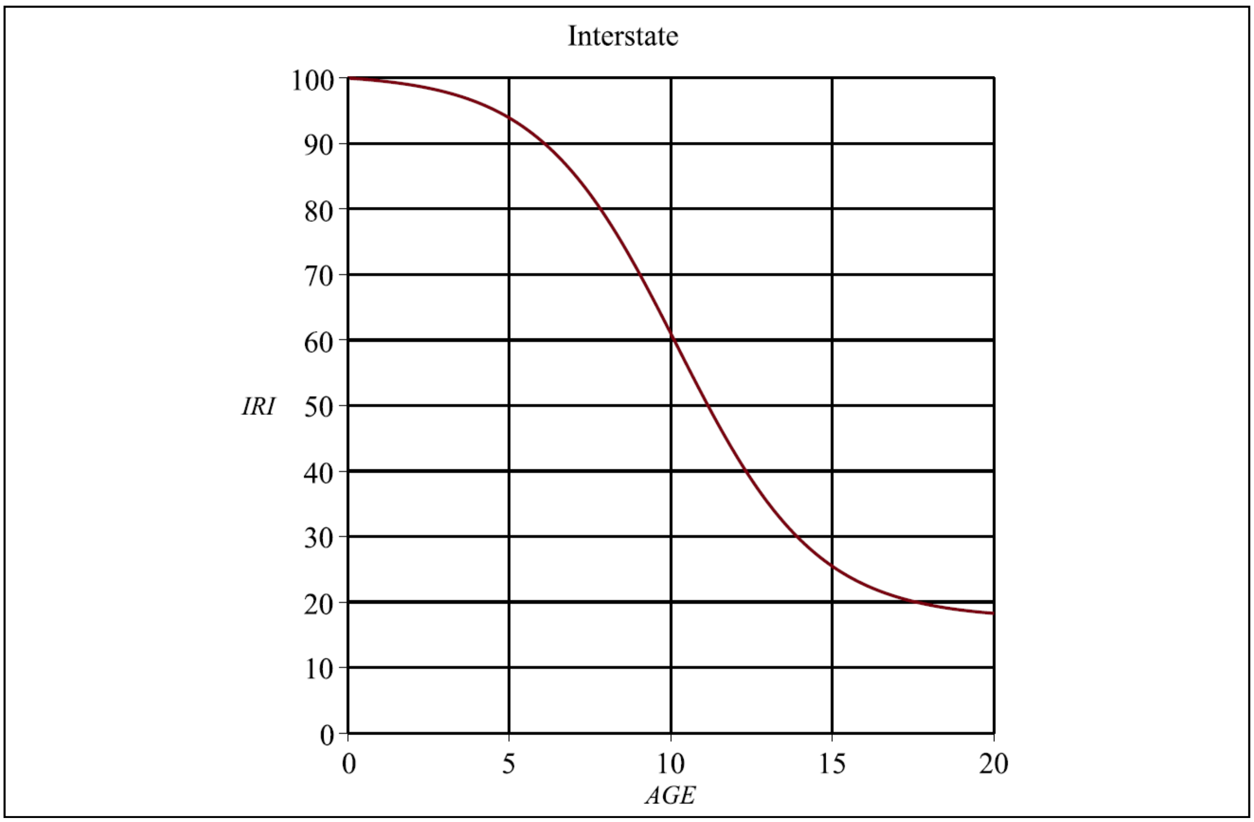
Interstate
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AGE
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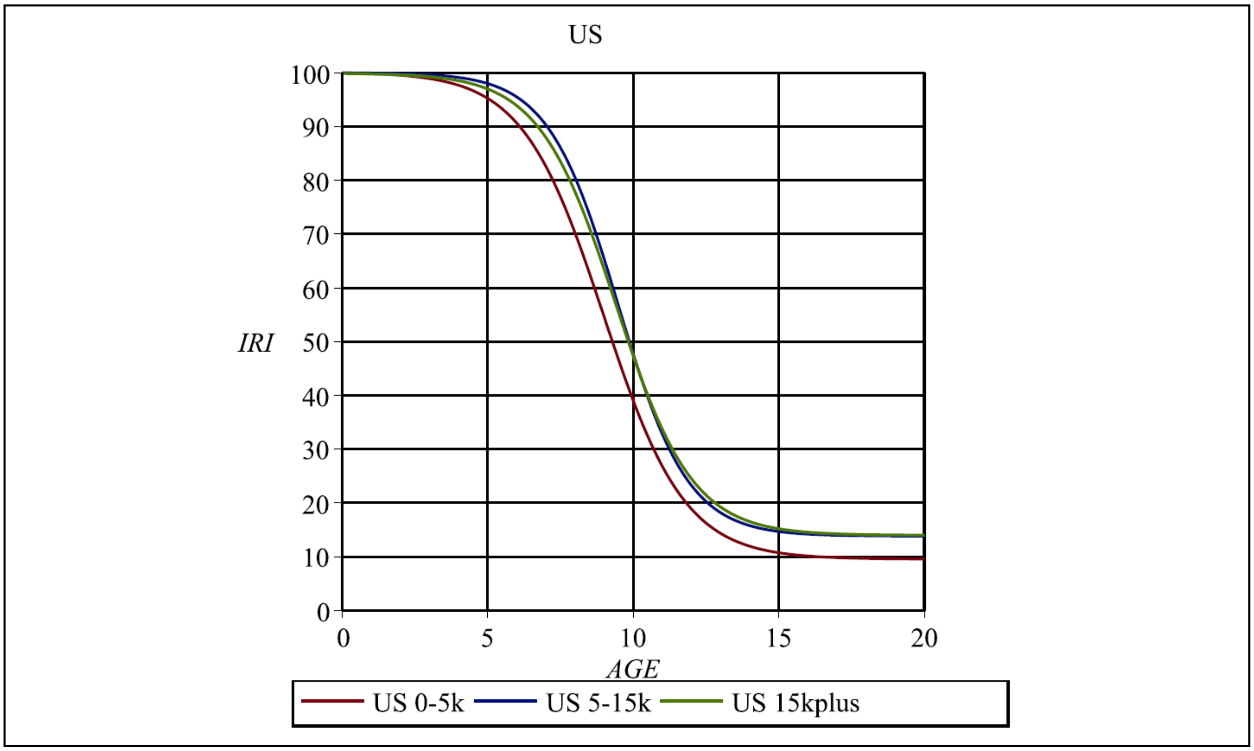
30
20
10


US
100
90
80
70
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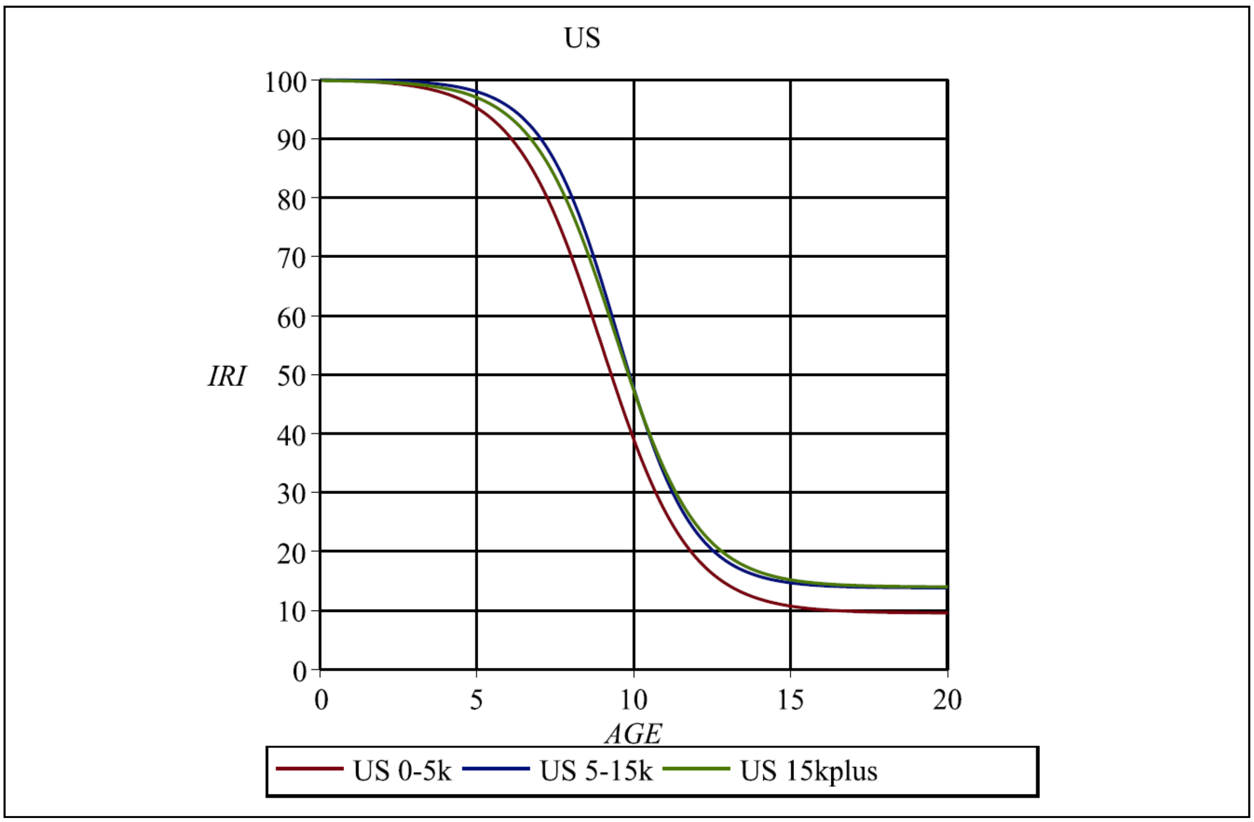
10
0
IRI
0
5
10
15
20
AGE
US 0-5k
US 5-15k
US 15kplus


US
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IRI
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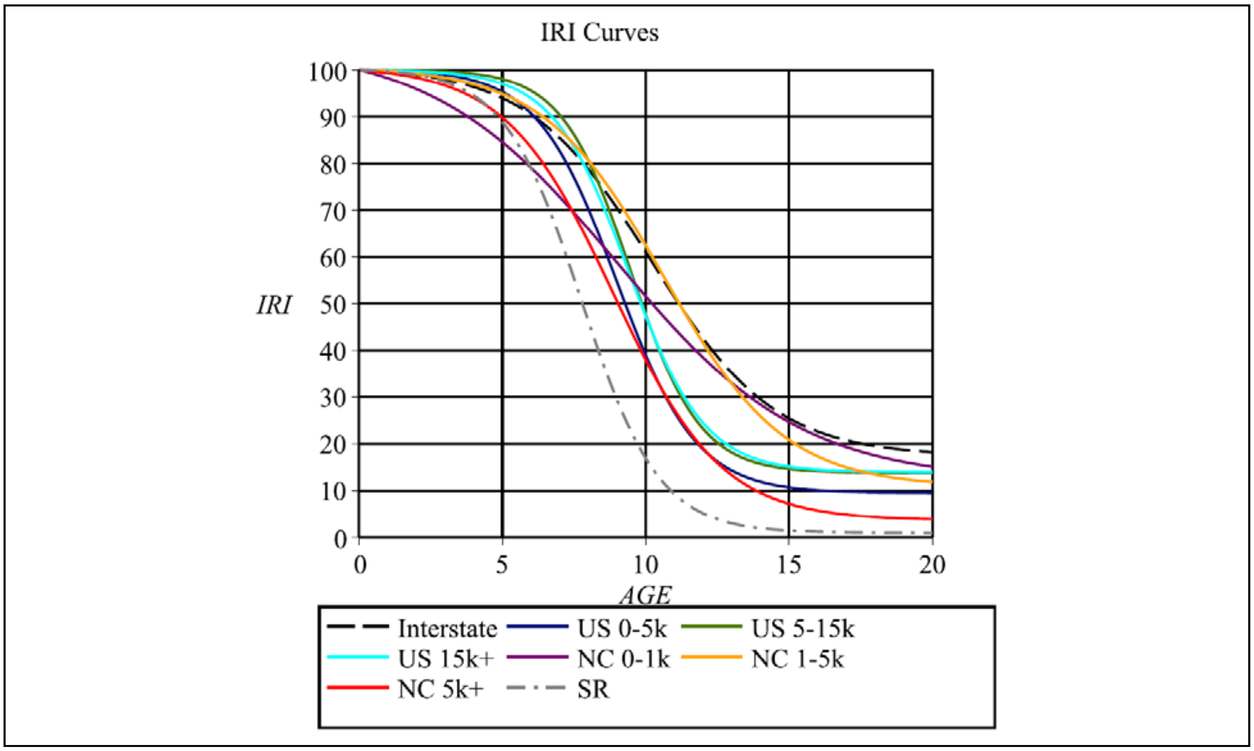
AGE
US 0-5k
US 5-15k
US 15kplus


IRI Curves
IRI
AGE
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
Interstate
US 0-5k
US 5-15k
US 15k+
NC 0-1k
NC 1-5k
NC 5k+
SR

Appendix C. Estimates of Contrasts

US_0_5k_d4 GLM Contrast

The GLM Procedure

Parameter	Estimate	Standard Error	t Value	Pr > |t|
IRI60 vs IRI70 in Coastal	-24.4151956	0.89000430	-27.43	<.0001
IRI60 vs IRI80 in Coastal	-36.4759628	1.60324528	-22.75	<.0001
IRI70 vs IRI80 in Coastal	-12.0607672	1.83041992	-6.59	<.0001
IRI60 vs IRI70 in Mountains	-23.3083271	0.88002490	-26.49	<.0001
IRI60 vs IRI80 in Mountains	-40.9133128	0.95962144	-42.63	<.0001
IRI70 vs IRI80 in Mountains	-17.6049857	1.29274341	-13.62	<.0001
IRI60 vs IRI70 in Piedmont	-17.1448368	0.73903714	-23.20	<.0001

US_5_15k_d4 GLM Contrast

The GLM Procedure

Parameter	Estimate	Standard Error	t Value	Pr > |t|
IRI60 vs IRI70 in Coastal	-21.9458727	0.69316788	-31.66	<.0001
IRI60 vs IRI80 in Coastal	-20.3783899	1.19411463	-17.07	<.0001
IRI70 vs IRI80 in Coastal	1.5674828	1.37694771	1.14	0.2550
IRI60 vs IRI70 in Mountains	-12.2827448	1.10417552	-11.12	<.0001
IRI60 vs IRI80 in Mountains	-15.7353948	1.54616988	-10.18	<.0001
IRI70 vs IRI80 in Mountains	-3.4526500	1.89395704	-1.82	0.0683
IRI60 vs IRI70 in Piedmont	-29.9020306	1.93178996	-15.48	<.0001
IRI60 vs IRI80 in Piedmont	-27.1911641	1.63261989	-16.65	<.0001
IRI70 vs IRI80 in Piedmont	2.7108665	2.52698299	1.07	0.2834

US_15_30k_d4 GLM Contrast

The GLM Procedure

Parameter	Estimate	Standard Error	t Value	Pr > |t|
IRI60 vs IRI70 in Coastal	-34.9817679	0.71845630	-48.69	<.0001
IRI60 vs IRI80 in Coastal	-37.5854301	2.16327012	-17.37	<.0001
IRI70 vs IRI80 in Coastal	-2.6036622	2.27283747	-1.15	0.2520
IRI60 vs IRI70 in Mountains	-25.6035821	1.28897937	-19.86	<.0001
IRI60 vs IRI80 in Mountains	-24.7496575	3.14224850	-7.88	<.0001
IRI70 vs IRI80 in Mountains	0.8539246	3.38497488	0.25	0.8008
IRI60 vs IRI70 in Piedmont	-7.7582962	0.97185882	-7.98	<.0001
IRI60 vs IRI80 in Piedmont	-51.6575891	2.42642817	-21.29	<.0001
IRI70 vs IRI80 in Piedmont	-43.8992929	2.60816762	-16.83	<.0001

US_30kplus_d4 GLM Contrast

The GLM Procedure

Parameter	Estimate	Standard Error	t Value	Pr > |t|
IRI60 vs IRI70 in Coastal	-13.1658478	0.79281460	-16.61	<.0001
IRI60 vs IRI80 in Coastal	-29.5141384	1.57484883	-18.74	<.0001
IRI70 vs IRI80 in Coastal	-16.3482906	1.71470449	-9.53	<.0001
IRI60 vs IRI70 in Mountains	4.6330760	2.66422504	1.74	0.0820
IRI60 vs IRI80 in Mountains	-38.0902056	2.80973385	-13.56	<.0001
IRI70 vs IRI80 in Mountains	-42.7232816	3.77834576	-11.31	<.0001
IRI60 vs IRI70 in Piedmont	-19.1425609	0.74018551	-25.86	<.0001

NC_0_1k_d4 GLM Contrast

The GLM Procedure

Parameter	Estimate	Standard Error	t Value	Pr > |t|
IRI60 vs IRI70 in Coastal	-12.9621334	0.37147584	-34.89	<.0001
IRI60 vs IRI80 in Coastal	-13.1283238	1.07414648	-12.22	<.0001
IRI70 vs IRI80 in Coastal	-0.1661903	1.11838231	-0.15	0.8819
IRI60 vs IRI70 in Mountains	-2.0531125	0.50911486	-4.03	<.0001
IRI60 vs IRI80 in Mountains	-20.9591234	0.63040253	-33.25	<.0001
IRI70 vs IRI80 in Mountains	-18.9060110	0.66957826	-28.24	<.0001
IRI60 vs IRI70 in Piedmont	-17.2903499	0.40560825	-42.63	<.0001
IRI60 vs IRI80 in Piedmont	-20.2836169	0.71912403	-28.21	<.0001
IRI70 vs IRI80 in Piedmont	-2.9932670	0.77923743	-3.84	0.0001

NC_1_5k_d4 GLM Contrast

The GLM Procedure

Parameter	Estimate	Standard Error	t Value	Pr > |t|
IRI60 vs IRI70 in Coastal	-14.6868605	0.38886823	-37.77	<.0001
IRI60 vs IRI80 in Coastal	-23.1472314	0.68021819	-34.03	<.0001
IRI70 vs IRI80 in Coastal	-8.4603708	0.77889368	-10.86	<.0001
IRI60 vs IRI70 in Mountains	-20.4796813	0.32929951	-62.19	<.0001
IRI60 vs IRI80 in Mountains	-23.0014258	0.63734757	-36.09	<.0001
IRI70 vs IRI80 in Mountains	-2.5217445	0.68385808	-3.69	0.0002
IRI60 vs IRI70 in Piedmont	-10.2046217	0.28974465	-35.22	<.0001
IRI60 vs IRI80 in Piedmont	-21.3725720	0.86847472	-24.61	<.0001
IRI70 vs IRI80 in Piedmont	-11.1679503	0.90964756	-12.28	<.0001

NC_5_15k_d4 GLM Contrast

The GLM Procedure

Parameter	Estimate	Standard Error	t Value	Pr > |t|
IRI60 vs IRI70 in Coastal	-11.9700963	0.36390532	-32.89	<.0001
IRI60 vs IRI80 in Coastal	-16.6633429	0.77722722	-21.44	<.0001
IRI70 vs IRI80 in Coastal	-4.6932467	0.84542680	-5.55	<.0001
IRI60 vs IRI70 in Mountains	-16.1738076	0.47512304	-34.04	<.0001
IRI60 vs IRI80 in Mountains	-20.2296733	0.96087757	-21.05	<.0001
IRI70 vs IRI80 in Mountains	-4.0558656	1.02794141	-3.95	<.0001
IRI60 vs IRI70 in Piedmont	-10.7058982	0.29768797	-35.96	<.0001
IRI60 vs IRI80 in Piedmont	-12.8245262	0.58056775	-22.09	<.0001
IRI70 vs IRI80 in Piedmont	-2.1186280	0.63926963	-3.31	0.0009

NC_15kplus_d4 GLM Contrast

The GLM Procedure

Parameter	Estimate	Standard Error	t Value	Pr > |t|
IRI60 vs IRI70 in Coastal	-10.5565158	0.73359621	-14.39	<.0001
IRI60 vs IRI80 in Coastal	-7.0906304	1.29114853	-5.49	<.0001
IRI70 vs IRI80 in Coastal	3.4658854	1.43063165	2.42	0.0154
IRI60 vs IRI70 in Mountains	4.7735922	1.29656550	3.68	0.0002
IRI60 vs IRI80 in Mountains	-5.1706572	1.83168155	-2.82	0.0048
IRI70 vs IRI80 in Mountains	-9.9442494	2.04622734	-4.86	<.0001
IRI60 vs IRI70 in Piedmont	-8.2893556	0.86373511	-9.60	<.0001
IRI60 vs IRI80 in Piedmont	-10.7763938	0.77026070	-13.99	<.0001
IRI70 vs IRI80 in Piedmont	-2.4870382	1.12418663	-2.21	0.0270

SR_0_1k_PR_d4 GLM Contrast

The GLM Procedure

Parameter	Estimate	Standard Error	t Value	Pr > |t|
IRI60 vs IRI70 in Coastal	-15.1605892	2.66700443	-5.68	<.0001

SR_1_5k_PR_d4 GLM Contrast

The GLM Procedure

Parameter	Estimate	Standard Error	t Value	Pr > |t|
IRI60 vs IRI70 in Coastal	-9.0935923	1.17043171	-7.77	<.0001
IRI60 vs IRI80 in Coastal	-31.2590936	2.45416699	-12.74	<.0001
IRI70 vs IRI80 in Coastal	-22.1655013	2.42460309	-9.14	<.0001
IRI60 vs IRI70 in Mountains	10.0341066	2.21049808	4.54	<.0001
IRI60 vs IRI80 in Mountains	-7.2658057	2.36827729	-3.07	0.0022
IRI70 vs IRI80 in Mountains	-17.2999123	1.95448251	-8.85	<.0001
IRI60 vs IRI70 in Piedmont	0.8420814	1.33020654	0.63	0.5267
IRI60 vs IRI80 in Piedmont	-4.9542068	1.05707976	-4.69	<.0001
IRI70 vs IRI80 in Piedmont	-5.7962882	1.25557479	-4.62	<.0001

SR_5_15k_PR_d4 GLM Contrast

The GLM Procedure

Parameter	Estimate	Standard Error	t Value	Pr > |t|
IRI60 vs IRI70 in Coastal	-11.7827734	1.65340637	-7.13	<.0001
IRI60 vs IRI80 in Coastal	-19.5911393	1.89949381	-10.31	<.0001
IRI70 vs IRI80 in Coastal	-7.8083659	2.00685618	-3.89	0.0001
IRI60 vs IRI70 in Mountains	-6.2676929	3.68309594	-1.70	0.0889
IRI60 vs IRI80 in Mountains	-29.0668155	4.29617136	-6.77	<.0001
IRI70 vs IRI80 in Mountains	-22.7991226	4.30261043	-5.30	<.0001
IRI60 vs IRI70 in Piedmont	1.5895682	1.41798180	1.12	0.2623
IRI60 vs IRI80 in Piedmont	-6.7538316	1.40373716	-4.81	<.0001
IRI70 vs IRI80 in Piedmont	-8.3433998	1.14060289	-7.31	<.0001

SR_15kplus_PR_d4 GLM Contrast

The GLM Procedure

Parameter	Estimate	Standard Error	t Value	Pr > |t|
IRI60 vs IRI70 in Coastal	-30.9702381	4.12353101	-7.51	<.0001