EVALUATION OF PAVEMENT NETWORK PERFORMANCE IN TEXAS CONSIDERING MULTIPLE PERFORMANCE METRICS

A Thesis

by

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ABSTRACT

Performance management is increasingly emphasized at the state and national levels. This is evident in the Moving Ahead for Progress in the 21st Century Act (MAP-21) and performance targets set by individual state Departments of Transportation (DOTs). This management approach requires the establishment of performance goals, measures, metrics for pavement networks, and systematic measurement of progress towards achieving these goals. MAP-21 and individual state DOTs use multiple metrics for assessing the performance of pavement networks. This thesis applies different performance criteria to the roadway network in Texas to determine the degree of consistency among the performance metrics used by the Texas Department of Transportation (TxDOT) and MAP-21. Statistical tests are used to compare different sets of results in order to determine if significant differences exist between these metrics, namely the International Roughness Index (IRI), and TxDOT's Condition Score (CS) and Distress Score (DS). The results of this research indicate that urban roads had significantly and consistently higher IRI than rural roads throughout the past nine years. However, the DS and CS data do not provide strong evidence to support the idea that rural and urban pavements perform. The results indicate that the three metrics agreed about 22 percent of the time when comparing pavement performance in rural and urban areas. Similar results were obtained when comparing different pavement types. When comparing two pavement types (ACP and CRCP), the IRI data yielded that CRCP roads had significantly and consistently higher IRI than ACP roads throughout the past nine years. However, the DS

and CS data do not provide strong evidence to support this idea. The three metrics agreed 30 percent of the time when comparing the performance of CRCP and ACP on a year-by-year basis. Additionally, statistical correlation models were developed to derive IRI threshold values consistent with the existing threshold values for CS and DS. The study area consists of the Houston district of TxDOT. The Houston district was selected for conducting this study because it includes both urban and rural areas and it includes different pavement types. This network consists of 2,386 lane-miles of urban roads and 1,571 lane-miles of rural roads. The data for conducting this research was obtained from TxDOT's Pavement Management Information System (PMIS) database.

DEDICATION

This thesis is dedicated to my family for their endless support on every step of my life.

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I would like to thank my committee chair, Dr. Ghariabeh, for all his support and guidance throughout my life at Texas A&M University as a graduate student. I would like to thank my committee members, Dr. Damnjanovic and Dr. Choi for their guidance and support throughout the course of this research.

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Contributors

This work was supervised by a thesis committee, consisting of Professor Nasir Gharaibeh and Professor Ivan Damnjanovic of the Zachry Department of Civil Engineering, and Professor Kunhee Choi of the Department of Construction Science.

The data analyzed for Section 3, Section 4 and Section 5 were obtained from the Pavement Management Information System (PMIS) at the Texas Department of Transportation (TxDOT).

All other work conducted for the thesis was completed by student independently.

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NOMENCLATURE

AAE	Average Absolute Error
ACP	Asphalt Concrete Pavement
ADT	Average Daily Traffic
CRCP	Continuously Reinforced Concrete Pavement
CS	Condition Score
DOC	Department of Commerce
DOT	Department OF Transportation
DS	Distress Score
FHWA	Federal Highway Administration
IRI	International Roughness Index
JCP	Jointed Concrete Pavement
MAP-21	Moving Ahead for Progress in the 21st Century Act
NPRM	Notice of Proposed Rulemaking
OI	Overall Index
OPI	Overall Pavement Index
PCC	Portland Cement Concrete
PCI	Pavement Condition Index
PCR	Pavement Condition Rating
PMIS	Pavement Management Information System
PSR	Present Serviceability Index
RMSE	Root Mean Square Error

RS	Ride Score
SCI	Surface Condition Index
SSI	Structural Strength Index
TxDOT	Texas Department of Transportation
UA	Urbanized Area
UC	Urban Cluster

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1. INTRODUCTION

1.1 Background

Performance management of transportation systems is increasingly emphasized at the state and national levels to monitor performance, provide accountability, and plan and prioritize projects (Grant et al. 2013). This is evident in the notices of proposed rulemaking (NPRMs) of The Moving Ahead for Progress in the 21st Century Act (MAP-21) (FHWA 2015) and performance targets set by individual state Departments of Transportation (DOTs). This management approach requires the establishment of performance goals, measures, and metrics for pavement networks. Within the context of pavement performance management, these terms are defined as follows:

- Metrics: These are measurable indicators of the performance or condition of individual pavement sections (FHWA 2015). An example pavement performance metric is the International Roughness Index (IRI).
- Measures: These measures are computed based on the performance metrics. They represent the overall performance of the pavement network. These measures are used to establish performance targets for pavement networks and to assess progress toward achieving these targets (FHWA 2015).
- Goals: These are broad statements that describe a desired end state (Grant et. al 2013). An example performance goal might be to maintain the highway system in a state of good repair.

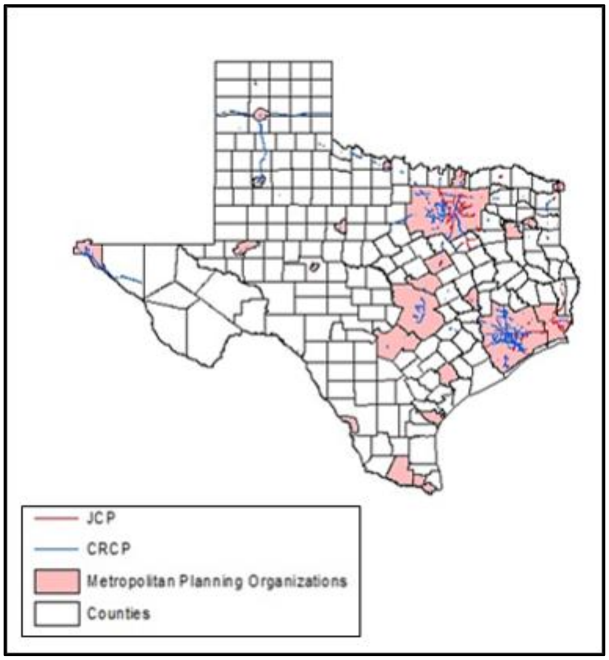
The performance of an individual pavement section is commonly measured in terms of multiple metrics that represent its functional and structural conditions, such as ride quality, distress, skid resistance, structural capacity, and remaining service life. The January 2015 NPRM of MAP-21, for instance, uses multiple metrics for measuring the performance of different pavement types, as follows:

- Asphalt concrete pavement (ACP): IRI, cracking percent, and rutting
- Jointed Concrete Pavement (JCP): IRI, cracking percent, and faulting
- Continuously Reinforced Concrete Pavement (CRCP): IRI and cracking percent

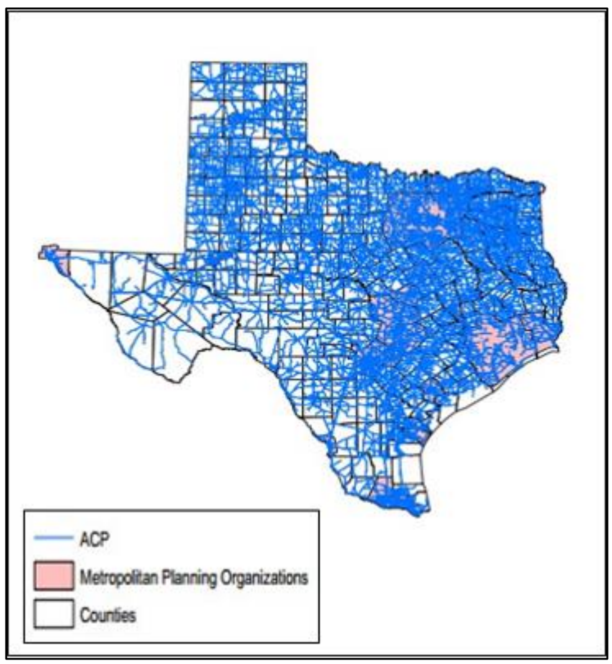
The Texas Department of Transportation (TxDOT) uses additional metrics for measuring pavement performance, including the distress score (DS) and condition score (CS). Currently, about six percent of TxDOT's roadway lane-miles is CRCP, about one percent is JCP, and about 93 percent is asphalt-surfaced pavement (**Table *1***). The asphalt-surfaced pavement category includes both ACP and old Portland Cement Concrete (PCC) pavement that has been overlaid with hot-mix asphalt. As shown in **Figure *1***, most of Texas CRCP is located in large urban and metropolitan areas (e.g., Houston and Dallas-Fort Worth).

Table 1-Current Composition of TxDOT's Roadway Pavement Network (Not Including Frontage Roads)

Pavement Type	Lane-Miles	Percent of Total Lane-Miles
JCP	2,554	1%
CRCP	10,309	6%
Asphalt-surfaced	162,603	93%



Concrete Pavement (CRCP and JCP) in Texas



Asphalt Pavement in Texas

Figure 1-Pavement Types Used in Texas

In MAP-21, each performance metric is rated as good, fair, or poor based on pre-defined threshold values. For example, an IRI value less than 95 in/mi may be considered good. Since a pavement section has multiple performance metrics, it is necessary to combine these metrics to describe the overall performance of the pavement section and consequently the overall performance of the network. For example, an ACP section is rated as good if rutting, cracking percent, and IRI are below pre-defined threshold values. The pavement performance measures, as outlined in the January 2015 NPRM of MAP-21, are as follows:

- Percentage of pavement lane-miles in good Condition
- Percentage of pavement lane-miles in poor Condition

State DOTs can establish separate targets for the National Highway System (NHS) and non-NHS for these performance measures.

1.2 Problem Statement and Research Objectives

In the MAP-21 rulemaking (FHWA 2015) and other sources in the literature (for example, La Torre et al. 2002), various metrics and threshold values are used for measuring the performance of pavement networks. However, very little is known about the effect of using multiple metrics and varying thresholds on the assessment of the overall performance of pavement networks. This study seeks to fill this gap in the literature, with application to the pavement network in the Houston district of the Texas Department of Transportation (TxDOT). The selection of the appropriate performance metrics and measures to evaluate the condition of pavement networks is of great importance because it affects the development of maintenance and rehabilitation plans and the allocation of funds for these plans.

The aim of this study is to assess the performance of the roadway network in the Houston District considering multiple metrics and to compare the network performance based on these various metrics. In this thesis, performance is evaluated on a year-by-year basis; rather than change in the performance metrics over time. The specific objectives are:

1. Assess the consistency among the metrics used by TxDOT and MAP-21 for measuring the performance of different pavement types.
2. Assess the consistency among the metrics used by TxDOT and MAP-21 for measuring the performance of pavements in urban and rural areas.
3. Investigate the relationship between IRI, CS, and DS to develop equivalent threshold values for pavements based on these metrics (**Figure *2***).

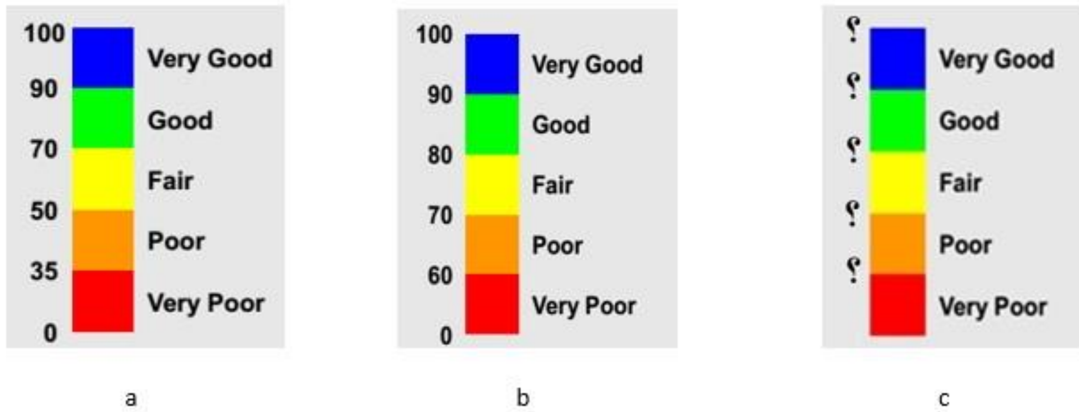


Figure 2-Proposed Thresholds of Different Performance Metrics, a) Condition Score b) Distress Score c) IRI

To accomplish the above objectives, empirical data were obtained from TxDOT's Pavement Management Information System (PMIS) database for the past nine years (2007-2015) on three performance metrics used in Texas: IRI, DS, and CS.

The study area consists of the Houston District of TxDOT. The Houston district was selected for conducting this study because it includes both urban and rural areas and it includes different pavement types (CRCP and ACP). This network consists of 2,386 lane-miles of urban roads and 1,571 lane-miles of rural roads.

1.3 Thesis Organization

This thesis consists of six main sections. The materials covered under each section are described as follows:

Section 1: Introduction and General Background

This section provides a general background of the research topic, describes the research problem, and specifies the research objectives.

Section 2: Literature Review

This section includes a comprehensive review of previous studies about the various metrics used for evaluating pavement performance, the criteria proposed by different agencies to assess the condition of pavement networks, and the relationship among the multiple performance metrics.

Section 3: Comparing the Performance of CRCP and ACP Using Multiple Metrics

In this section, the performance of CRCP and ACP in the Houston District is evaluated and compared using three performance metrics: IRI, CS, and DS. The performance management criteria outlined in MAP-21 and TxDOT's statewide pavement performance goal are used in this analysis.

Section 4: Comparing Pavement Performance in Rural and Urban Areas

This section investigates whether empirical pavement condition data support the use of different performance thresholds and targets for urban and rural areas. Similar to the pavement type analyses (Sections 3 and 4), the performance management criteria outlined in MAP-21 and TxDOT's statewide pavement performance goal are used in this analysis.

Section 5: Analysis of the Relationship Among Existing Performance Metrics

In this section of the thesis, a statistical analysis will be conducted to investigate the correlation between IRI and CS as well as IRI and DS. These mathematical relationships would be beneficial to develop equivalent rating scales for IRI, CS, and DS. In developing these relationships, the database will be classified into different families based on the pavement type, traffic level and urban or rural area.

Section 6: Summary, Conclusions, and Recommendations

This section provides a summary of the efforts completed throughout the research, the conclusions of the study, and recommendations for future studies.

2. LITERATURE REVIEW

2.1 Pavement Performance Metrics Used by TxDOT

Currently TxDOT uses following scores to rate the pavement condition (Stampley et. al 1995):

- DS: a 1-100 index indicating the condition of the pavement based on observed distresses (Stamply et al. 1995). DS is computed as a function of distress present in the pavement, as follows:
    - ACP: rutting, patching, failures, block cracking, alligator cracking, longitudinal cracking, and transverse cracking.
    - JCP: Failed joints and cracks, failures, shattered slabs, longitudinal cracks, and patching
    - CRCP: Spalled cracks, punchouts, and patching
- CS: a 1-100 index computed as a function of DS and ride quality.
- IRI: An indicator of the ride quality of the pavement measured in inches (of roughness) per mile. The PMIS database contains IRI for the right wheel path and left wheel path for each pavement section. The IRI values used in this study are the average IRI of the left and right wheel paths.
- Ride Score (RS): an indicator of pavement ride quality on a scale from 0.1 (roughest) to 0.5 (smoothest).
- Ride Score: described the overall ride quality of the data collection section.

- SSI Score: describes the overall structural strength of the data collection section. Currently, SSI is not fully implemented in PMIS.

Equations 1 to 3 are used for computing DS and CS. These equations were developed for Texas in the 1990s (Stamply et al. 1995).

$$U_i = \begin{cases} 1.0 & when\ L_i = 0 \\ 1 - \alpha e^{-\left(\frac{\rho}{L_i}\right)^{\beta}} & when\ L_i > 0 \end{cases} \tag{1}$$

$$DS = 100 \times \prod_{i=1}^{n} U_i \tag{2}$$

$$CS = U_{Ride} \times DS \tag{3}$$

L_i is the density of each distress type in the pavement section. U_i is a utility value (ranging between zero and 1.0) and represents the quality of a pavement in terms of overall usefulness (i.e., a U_i of 1.0 indicates that distress type i is not present and thus is most useful). α (maximum loss factor), β (slope factor), and ρ (prolongation factor) control the location of the utility curve's inflection point and the slope of the curve at that point. U_{Ride} is the surface roughness (ride) utility value. These formulas are discussed in details in Stamply et al. (1995) and Gharaibeh et al. (2012).

TxDOT has been collecting state-wide data on pavement performance annually since 1993. Collected data are stored in the Pavement Management Information System (PMIS) database. Currently, PMIS includes pavement performance data on more than 190,000 lane-miles of roadway, divided into individual pavement sections that are typically 0.5-mile long. TxDOT's roadway network consist of three main pavement types: ACP, CRCP, and JCP.

The PMIS database stores data on the condition score, distress score, left-wheel path IRI, right-wheel path IRI, and other performance indicators. TxDOT has developed rating scales for CS, DS, and RS in order to delineate good, fair, poor, etc. conditions (**Table *2***). However, TxDOT does not have a condition rating scale for IRI.

Table 2-Pavement Rating Thresholds Used by TxDOT

Classification	Condition Score	Distress Score	Ride Score
Very Good	90-100	90-100	4.0-5.0
Good	70-89	80-89	3.0-3.9
Fair	50-69	70-79	2.0-2.9
Very Poor	35-49	60-69	1.0-1.9
Poor	1-34	1-59	0.1-0.9

In August 2001, the Texas Department of Transportation (TxDOT) adopted the goal of 90 percent of the state-maintained pavement lane-miles would be in "good or better" condition by 2012. This goal is incorporated in TxDOT's 2015-2019 Strategic Plan. TxDOT measures progress towards achieving this goal on an annual basis; which has not been achieved yet. The term "good or better" is defined based on the CS metric. A CS of 70 or higher represents pavement in "good or better" condition.

2.2 Pavement Performance Metrics Used in MAP-21 Proposed Rules

In January 2015, the Federal Highway Administration (FHWA) issued an NPRM that addresses MAP-21 rules for assessing pavement and bridge conditions for the national highway performance program (FHWA 2015). The NPRM includes proposed performance goals, measures, and metrics for pavement conditions. Each state DOT is required to report to the FHWA on progress towards achieving its targets every two years. The NPRM includes proposed performance goals, measures, and metrics for pavement and bridge conditions (**Figure *3***). In this scheme, the performance metrics have threshold values (proposed by the FHWA) and the performance measures have target values (specified by each state DOT) (**Table *3***).

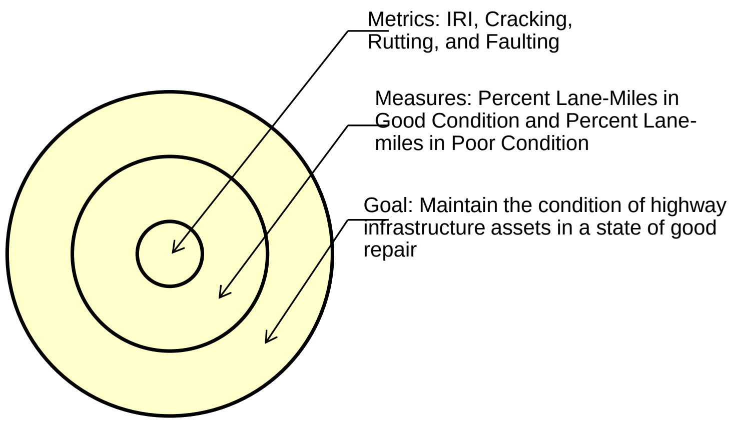


Figure 3-Performance Goal, Measures, and Metrics for Pavement

Table 3-Performance Measures, Metrics, and Example Targets for Pavement

Performance Measure	Metrics for Defining Performance Measures	Example Target for Interstate System	Example Target for non-Interstate NHS
Percentage of Pavement Lane-Miles in Good Condition	• Cracking • IRI • Faulting • Rutting	40%	35%
Percentage of Pavement Lane-Miles in Poor Condition	• Cracking • IRI • Faulting • Rutting	4%	7%

For pavements, each performance metric is rated as Good, Fair, or Poor based on the threshold values shown in Tables 4 through 6. The ratings of these metrics are then combined using the decision tree shown in **Figure *4*** to determine the performance measures for the pavement section. Each state DOT is required to submit reports on progress in achieving its established targets to the FHWA not later than October 1, 2016, and every two years thereafter.

Table 4-Metrics for Defining Performance Measures for Asphalt Pavement

Metric	Range	Rating
IRI	<95 in/mi	Good
	95–170 (220*) in/mi	Fair
	> 170 (220*) in/mi	Poor
Cracking_Percent	<5 %	Good
	5–10%	Fair
	> 10%	Poor
Rutting	<0.20 in	Good
	0.2–0.4 in	Fair
	> 0.40 in	Poor

* Areas with population of at least 1,000,000

Table 5-Metrics for Defining Performance Measures for Jointed Concrete Pavement

Metric	Range	Rating
IRI	<95 in/mi	Good
	95–170 (220*) in/mi	Fair
	> 170 (220*) in/mi	Poor
Cracking_Percent	<5 %	Good
	5–10%	Fair
	> 10%	Poor
Faulting	<0.05 in	Good
	0.05–0.15 in	Fair
	> 0.15 in	Poor

* Areas with population of at least 1,000,000

Table 6-Metrics for Defining Performance Measures for Continuously Reinforced Concrete

Metric	Range	Rating
IRI	<95 in/mi	Good
	95–170 (220*) in/mi	Fair
	> 170 (220*) in/mi	Poor
Cracking_Percent	<5 %	Good
	5–10%	Fair
	> 10%	Poor

* Areas with population of at least 1,000,000

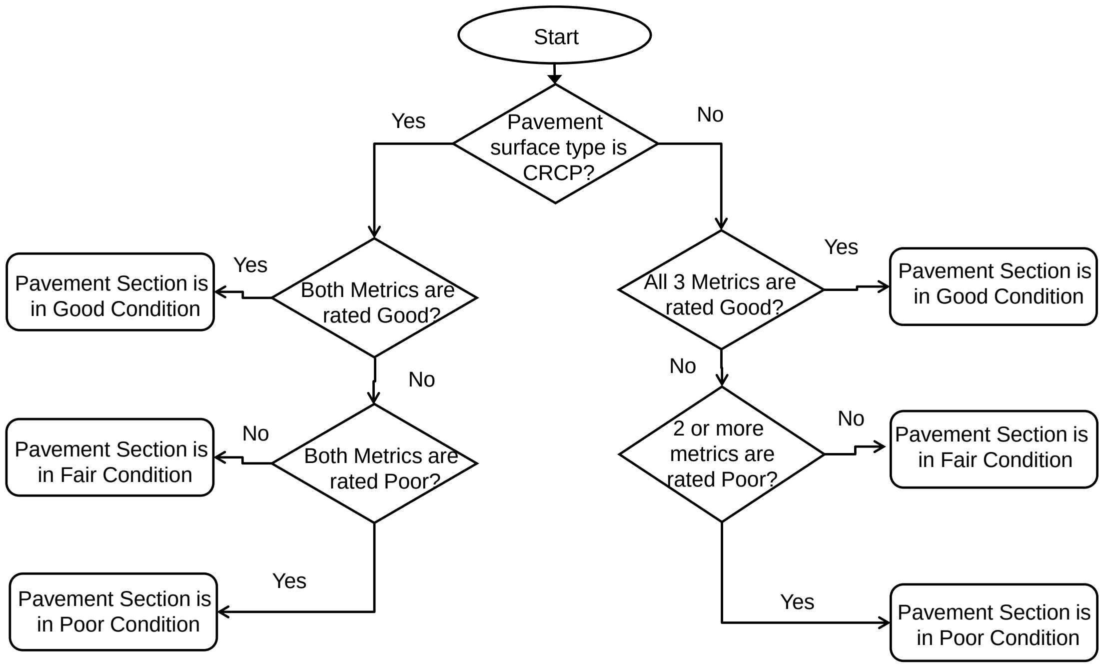


Figure 4-Decision Tree for Determining Performance Measure Values for Pavement

The pavement performance measures (as outlined in the January 2015 NPRM) are as follows:

- Percentage of pavement lane-miles in good Condition
- Percentage of pavement lane-miles in poor Condition

State DOTs can specify separate targets for the National Highway System (NHS) and non-NHS for these performance measures.

While MAP-21 provides the opportunity of evaluating pavement condition nation-wide in a consistent approach, the proposed performance metrics lack clear definitions and may not be available in current pavement management systems. For example, PMIS lacks data on faulting and cracking percent, creating serious difficulties in the implementation of these metrics.

2.3 Pavement Condition Assessment Criteria Used by State DOTs

Most state DOTs use pavement condition indexes as aggregate measures of the structural and material integrity of pavements. While these indexes appear to be similar (essentially a 0–100 scale, with 100 indicating ideal condition), the metrics can have significant difference. To ascertain the level of agreement among these indexes, Papagiannakis et al. (2010) compared six pavement condition indexes used by five state DOTs using actual field data. These indexes are TxDOT's CS and DS, South Dakota DOT's surface condition index (SCI), Ohio DOT's pavement condition rating (PCR), Pennsylvania DOT's overall pavement index (OPI), and Oregon DOT's overall index (OI). That study found that significant differences exist among seemingly similar pavement condition indexes.

Table *7* shows the good or better criteria for a sample of state DOTs that use 100-point scale to rate pavement sections, with 100 representing little to no distress situation. Similarly, **Table *8*** shows the good or better criteria for a sample of state DOTs that use 5-point scale to rate pavement sections.

Table 7-Pavement Rating Thresholds Used by State DOTs (100-Point Scale)

State	Good or Better Criteria
Georgia	75–100 is good to excellent
Iowa	60–80 is good, 80–100 is excellent
Montana	63–100 is good
Nebraska	70–89 is good; 90–100 is very good
New Hampshire	40–100 is acceptable
North Carolina	Greater than 80 is good
Ohio	75–90 is good; 90–100 is very good
Oregon	75.1–98 is good; 98.1–100 is very good for NHS
Vermont	40–100 is acceptable
Virginia	70–89 is good; greater is excellent
Washington	50–100 is good

Table 8-Pavement Rating Thresholds Used by State DOTs (5-Point Scale)

State	Good or Better Criteria
California	2 is good; 1 is excellent
Delaware	3–4 is good; 4–5 is very good
Idaho	3–5 is good
Kentucky	3.5–5 is good

Table 8-Continued

State	Good or Better Criteria
Michigan	1.0–2.5 is good
New Mexico	Greater than 3 is good for Interstate Highways; greater than 2.5 is good for all other highways
Oregon	2.0–2.9 is good; 1.0–1.9 is very good for non-NHS
South Carolina	3.4–4.0 is good; 4.1–5.0 is very good
Tennessee	3.5–4.0 is good; 4.0–5 is very good
West Virginia	4 is good; 5 is excellent

2.4 Relationship among Performance Metrics

Finding out the relationships among the performance metrics would be very helpful to establish consistent performance targets and to estimate values for metrics from other available ones. Several studies have been conducted to investigate the relationship between IRI and other performance metrics. Al-Omari et al. (1994) conducted a study to explore the correlation between IRI and the Present Serviceability Index (PSR). Abiola et al. (2014) performed a study to investigate the relationship between IRI and a pavement condition score used in Nigeria that combines the density and severity levels of multiple distress types. That study concluded that there is a linear relationship between the two metrics. Park et al. (2007) developed a power regression model which uses IRI to predict the Pavement Condition Index (PCI). Following is the calibrated model suggested by them for the pavement condition data in North Atlantic region:

$$PCI = K_1 IRI^{K_2} \tag{4}$$

Using the calibrated model, they developed rating thresholds for IRI based on the already available thresholds for PCI. Gulen et. al (1994) developed regression models between Present Serviceability Index (PSI) and IRI for both concrete and asphalt pavements and find out the critical PSI values for these pavement types in Indiana.

Lin et. al (2003) used an artificial neural network modeling approach to establish a deterioration prediction model for IRI based on the several distress types of the asphalt pavements. The established deterioration model of IRI in terms of each distress type to IRI is as follows:

$$\Delta IRI = K_{gp}[\Delta IRI_s + \Delta IRI_c + \Delta IRI_r + \Delta IRI_t] + \Delta IRI_e \tag{5}$$

Where:

ΔIRI: total incremental change in IRI during the analysis year

ΔIRI_e: incremental change in IRI due to environment during analysis year

ΔIRI_s: incremental change in IRI due to structure deterioration during analysis year

ΔIRI_c: incremental change in IRI due to cracking during analysis year

ΔIRI_r: incremental change in IRI due to rutting during analysis year

ΔIRI_t: incremental change in IRI due to potholing during analysis year

K_{gp}: calibration factor

Arhin et. Al (2015) performed a study to predict the pavement condition index using IRI in a dense urban area. They used the 2 years' data of IRI-PCI to model the relationship between PCI and IRI in Columbia District using a functional classification approach. The main objective of the developed model would be the elimination or a considerable reduction of the time to collect, review and process distress photographs for PCI and thereby the subjective assessment of pavement condition. Their study concluded to the establishment of a linear relationship between IRI and PCI classified by pavement function and pavement types. "The regression models between the IRI and PCI by functional classification and pavement type were determined to be statistically significant within the margin of error (5% level of significance), with R2 values between 0.56 and 0.82. The results of the ANOVA tests also showed statistically significant F - statistics ($p < 0.05$) in addition to statistically significant regression coefficients (from the t-tests, with $p < 0.05$). The residual plots for all the models also showed randomness about the zero line indicating their viability, in addition to the normal probability plots showing points near a straight line."

This research investigates various statistical models to establish a reasonable relationship between CS, DS, and IRI.

2.5 Pavement Performance in Urban and Rural Areas

In the MAP-21 rulemaking (FHWA 2015) and other sources in the literature (for example, La Torre et al. 2002), different performance threshold values are used for assessing the performance of pavements in urban and rural areas. This delineation between urbanized and non-urbanized roads is based on the recognition that urbanized roads have distinct characteristics compared to rural roads that affect their pavement condition and the user's perception of these condition, such as varying lane width and configuration, traffic flow, and the presence of utility cuts (Shahin et al. 2003). In MAP-21, the term non-urbanized is defined to include rural areas as well as small urban areas that do not have all the characteristics of urbanized areas. The Federal Highway Administration (FHWA) has proposed that urban boundaries be identified through the most recent U.S. Decennial Census.

A number of studies have been conducted previously to understand and quantify the differences in the performance of pavements in urban and rural areas. However, much of that literature has focused on ride quality. Prior to MAP-21, the literature recognized the differences between urban and rural roads in terms of roughness acceptability and roadway characteristics. One of the early studies in this area was conducted by La Torre et al. (2002) to investigate the correlation between pavement roughness and user perception in an urban area. The study found that urban drivers have higher tolerance for road roughness than rural divers. Also, that study developed a modified IRI (called IRI*) for measuring roughness of urban roads in Italy (La Torre at al. 2002). IRI* was developed to account for differences between urban roads and rural roads (e.g., lower speed, shorter pavement management sections, that different pavement types). Namur et al. (2009) addressed the issues involved in using IRI to measure roughness of unpaved rural roads. They concluded that conventional techniques of pavement roughness measurement are not appropriate for unpaved roads and suggested the use of visual inspection data to estimate IRI through correlations between IRI and various distress. Osorio et al. (2014) developed statistical models for measuring the condition of urban pavements as a function of distresses relevant to these types of pavements.

This study focuses on measuring the performance differences between urban and rural roads using a large set of historical data that include both ride quality and distresses.

United States Census Bureau has been using different criteria since 1910 to delineate the urban and rural areas. From 1910 Census to 1940 Census, the term “urban” was referred to any incorporated area containing at 2,500 people within its boundaries (DOC 2010). Census Bureau adopted the concept of “Urbanized Areas (UA)” for the 1950 Census due to the increasing rate of suburbanization outside the boundaries of incorporated urban areas. Consequently, “Urban” was defined as any territory, persons and housing units in incorporated or unincorporated areas inside urbanized areas or outside urbanized areas with more than 2,500 people (DOC 2010). This criterion to delineate urban and rural areas remained unchanged until Census 2000. Considering the possibility of having a densely settled area outside of an urban area’s boundaries with as much “urbanized features” as for those areas inside the boundaries, led to the definition of “Urban Clusters” after 2000 Census. Therefore, the Census Bureau identifies two types of urban areas:

- Urbanized Areas (UAs) of 50,000 or more people;
- Urban Clusters (UCs) of at least 2,500 and less than 50,000 people.

Based on the above definitions, the flowing criteria was defined to delineate the urban areas for Census 2000:

“For Census 2000, the Census Bureau classifies as "urban" all territory, population, and housing units located within an urbanized area (UA) or an urban cluster (UC). It delineates UA and UC boundaries to encompass densely settled territory, which consists of:

- core census block groups or blocks that have a population density of at least 1,000 people per square mile and
- surrounding census blocks that have an overall density of at least 500 people per square mile

In addition, under certain conditions, less densely settled territory may be part of each UA or UC.”

“For the 2010 Census, an urban area will comprise a densely settled core of census tracts and/or census blocks that meet minimum population density requirements, along with adjacent territory containing non-residential urban land uses as well as territory with low population density included to link outlying densely settled territory with the densely settled core. To qualify as an urban area, the territory identified according to criteria must encompass at least 2,500 people, at least 1,500 of which reside outside institutional group quarters.”

"Rural" encompasses all population, housing, and territory not included within an urban area.” (DOC 2010)

Based on this definitions, Census Bureau has developed a geographical database on a GIS platform to delineate the boundaries of urban areas. This geographical database was used through this study to delineate between urban and rural areas according to the MAP-21’s proposed urban and rural delineation criteria based on the most recent U.S. Decennial Census (Census 2010) [5]. **Figure *5*** is a graphical indication of the identified urban areas throughout the State of Texas in year 2014 based on the Census 2010 criteria. Using the geoprocessing tools of ArcMAP, the urban areas within the Houston District can be extracted and used for this study.

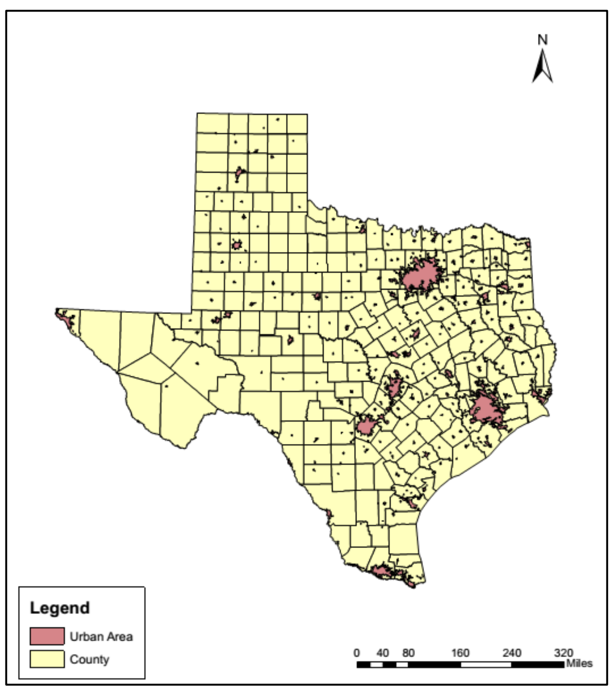


Figure 5-Urban Areas in Texas in Year 2015 Based on Censes 2000 Criteria

3. COMPARING THE PERFORMANCE OF CRCP AND ACP USING MULTIPLE METRICS*

As discussed earlier, currently, about six percent of TxDOT's roadway lane-miles is CRCP, about one percent is jointed concrete pavement (JCP), and about 93 percent is asphalt-surfaced pavement. This section analyzes the performance of CRCP and ACP in the Houston District based on three performance metrics used by TxDOT or proposed in MAP-21 rules. The map shown in **Figure *6*** displays these pavements in the Houston District. JCP is not considered in this analysis due to the very limited use of this pavement type in Texas.

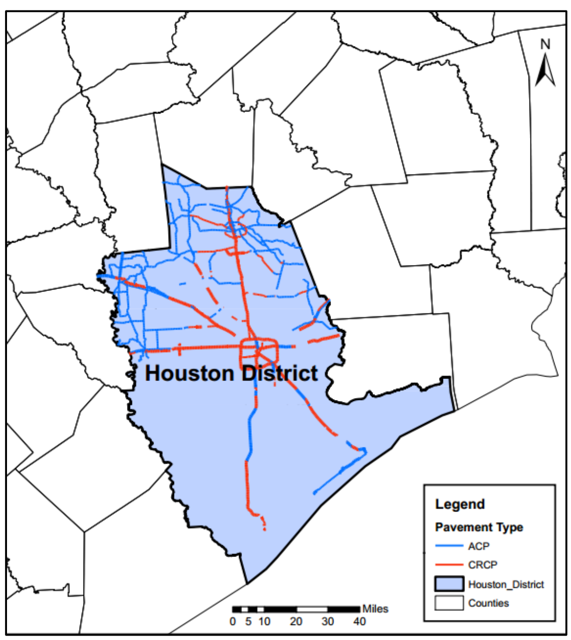


Figure 6-Map of CRCP and ACP Sections in the Houston District

* Part of the data reported in this chapter is reprinted with permission from "CRCP Performance Patterns Gleaned from Texas Pavement Management Data" by Authors Litao Liu, Amir Rashed, and Nasir G. Gharaibeh, 2016. 11th International Conference on Concrete Pavements, San Antonio, Texas, USA

3.1 CRCP Design and Management Practices in Texas

CRCP is a Portland Cement Concrete (PCC) pavement with continuous longitudinal reinforcement and without any transverse expansion or contraction joints. (PMIS Rater's Manual 2014). CRCP pavements are stored with code "01" in PMIS database as the detailed pavement type code.

Currently, the only officially approved design method for CRCP by TxDOT is the 1993 AASHTO Guide for Design of Pavement Structures. Typical input values used by TxDOT for this design method are shown in **Table *9***.

Previously, the concrete slab thickness required by TxDOT had a range between 8 inches and 15 inches. Currently, the design standard used by TxDOT specifies that the thickness of CRCP slab should be 6 inches to 13 inches. Thickness values outside this range need to be submitted to the District Engineer for approval along with justification.

TxDOT requires one of the following base layer combinations for concrete slab support:

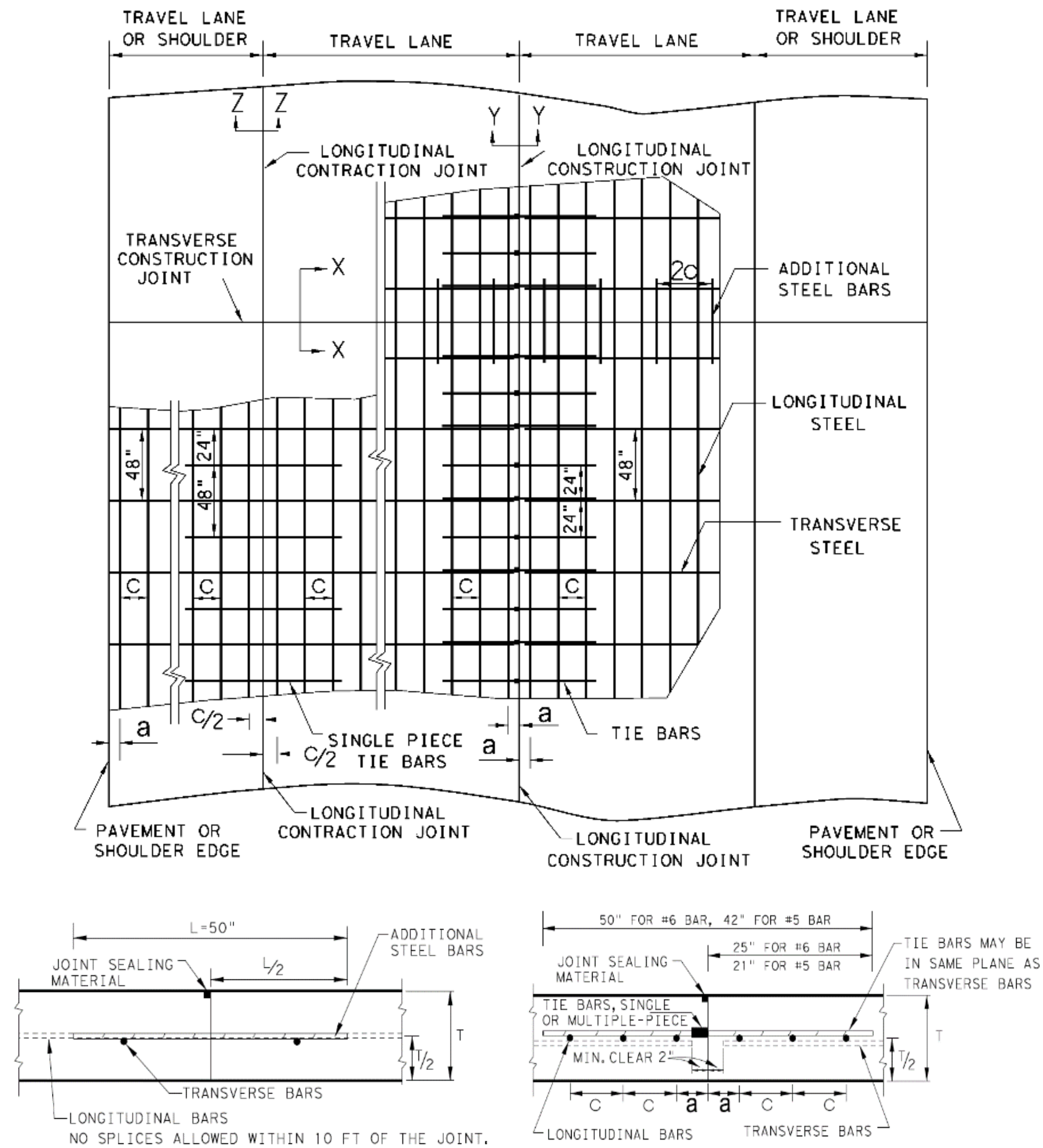
- 4-inch asphalt concrete pavement or asphalt stabilized base, or
- A minimum 1-inch asphalt concrete bond breaker over 6-inch cement stabilized base.

Tied PCC shoulders are normally used with CRCP. The width of shoulders varies from 2 to 10 feet, depending on the functional classification of the roadway under design. The PCC shoulder should have the same thickness and the same base layers as the main-lane pavement.

Table 9-Input Variables and Design Values Used in TxDOT CRCP Design

Input Variable	**TxDOT Design Value**
28-day concrete modulus of rupture, psi	620
28-day concrete elastic modulus, psi	5,000,000
Effective modulus of subgrade reaction, psi/in	300 – 700
Serviceability indices	4.5 (initial) – 2.5 (terminal)
Drainage coefficient	• 0.91 – 0.95 for annual rainfall 58 – 50 in. • 0.96 – 1.00 for annual rainfall 49 – 40 in. • 1.01 – 1.05 for annual rainfall 39 – 30 in. • 1.06 – 1.10 for annual rainfall 29 – 20 in. • 1.11 – 1.16 for annual rainfall 19 – 8 in.
Overall standard deviation	0.39
Reliability, %	95% for > 5 million design ESALs 90% for ≤ 5 million design ESALs
18-kip equivalent single axle load (ESAL)	Based on the traffic analysis report provided by the Transportation Planning and Programming Division

Figure *7* shows a typical CRCP pavement layout and **Table *10*** shows the longitudinal steel design for CRCP in Texas.



Section X - X

Section Y - Y

Figure 7-Typical CRCP Slab and Construction Joint Layout (Texas Department of Transportation (TxDOT), (2013), Continuously Reinforced Concrete Pavement One Layer Steel Bar Placement, CRCP (1)-13)

Table 10-Longitudinal Steel Design

Slab Thickness, in.	Steel Bar Size	Steel Bar Spacing, in.	First Spacing at Edge or Joint, in.	Additional Steel Bars at Transverse Construction Joint	
				Spacing, in.	Length, in.
7.0	#5	6.5	3 to 4	13	50
7.5	#5	6.0	3 to 4	12	50
8.0	#6	9.0	3 to 4	18	50
8.5	#6	8.5	3 to 4	17	50
9.0	#6	8.0	3 to 4	16	50
9.5	#6	7.5	3 to 4	15	50
10.0	#6	7.0	3 to 4	14	50
10.5	#6	6.75	3 to 4	13.5	50
11.0	#6	6.5	3 to 4	13	50
11.5	#6	6.25	3 to 4	12.5	50
12.0	#6	6.0	3 to 4	12	50
12.5	#6	5.75	3 to 4	11.5	50
13.0	#6	5.5	3 to 4	11	50

Unit Conversions: 1 inch = 25.4 mm.

3.2 ACP Design and Management Practices in Texas

The asphalt-surfaced pavement category includes both Asphalt Concrete Pavement (ACP) and old Portland Cement Concrete (PCC) pavement that has been overlaid with hot-mix asphalt. As mentioned earlier, about 93% of TxDOT's lane-miles is asphalt-surfaced pavements. Asphalt-surfaced pavements are stored with one of the codes "04" through "09" in the PMIS database indicating the detailed pavement type. The following are the descriptions these codes:

04: Thick Asphaltic Concrete (Over 5.5")

05: Medium Thickness Asphaltic Concrete (2.5 - 5.5")

06: Thin Asphaltic Concrete (Under 2.5")

07: Composite (Asphalt Surfaced Concrete)

08: Widened Composite Pavement

09: Overlaid and Widened Asphaltic Concrete Pavement

10: Surface Treatment Pavement (Or Seal Coat)

Currently, TxDOT accepts the following methods for designing flexible pavements:

- FPS-19W for flexible pavements
- AASHTO design procedure (1993)
- Modified Texas Triaxial Design Method for flexible pavements

Each method is briefly explained through the following sections.

TxDOT considers FPS-19W as the preferred method for designing of flexible pavements (especially for high volume highways). FPS-19W uses a mechanistic-empirical design procedure which is suggested to be used as a check for the design of all flexible pavements. **Table *11*** displays the five design types used by FPS-19W.

Table 11-FPS-19W Five Basic Design Types

1	**2**	**3**	**4**	**5**
HMA or Surface Treatment	HMA	HMA	HMA	HMA Overlay
Flexible Base	Asphalt Stabilized Base	Asphalt Stabilized Base	Flexible Base	Existing HMA
Subgrade	Subgrade	Flexible Base	Stabilized Subbase/ Subgrade	Existing Base
		Subgrade	Subgrade	Subgrade

The AASHTO 1993 Design Procedure is an empirical method that uses the concepts of Structural Number (SN). Structural Number is sum of a layer coefficient (a), layer thickness (D) and drainage coefficient (m) for each layer. (see equation 6)

$$SN = a_1D_1 + a_2D_2m_2 + a_3D_3m_3 + \cdots \tag{6}$$

The Modified Texas Triaxial design method uses the concept of the Texas Triaxial Classification of soils which was developed in 1940s. This method requires the use of subgrade or base Texas Triaxial class derived from laboratory test results. During recent years, this method has been automated and incorporated into the FPS-19W program as a post-design check modulus.

3.3 Performance of Pavements in Houston District

3.3.1 IRI

The PMIS database contains separate fields for IRI in the right wheel-path and IRI in the left wheel-path. The IRI values used in this study are the average IRI of the left and right wheel paths.

The box and whisker diagram depicted in **Figure *8*** shows that the IRI of the middle 68 percent of CRCP lane-miles in the Houston District consistently ranged between about 80 in/mi and 150 in/mi (with a mean value of approximately 120 in/mile) over the past nine years (2007-2015). **Figure *9*** shows that the IRI of the middle 68 percent of ACP lane-miles in the Houston District consistently ranged between about 50 in/mi and 120 in/mi (with a mean value of approximately 82 in/mile) over the past nine years (2007-2015).

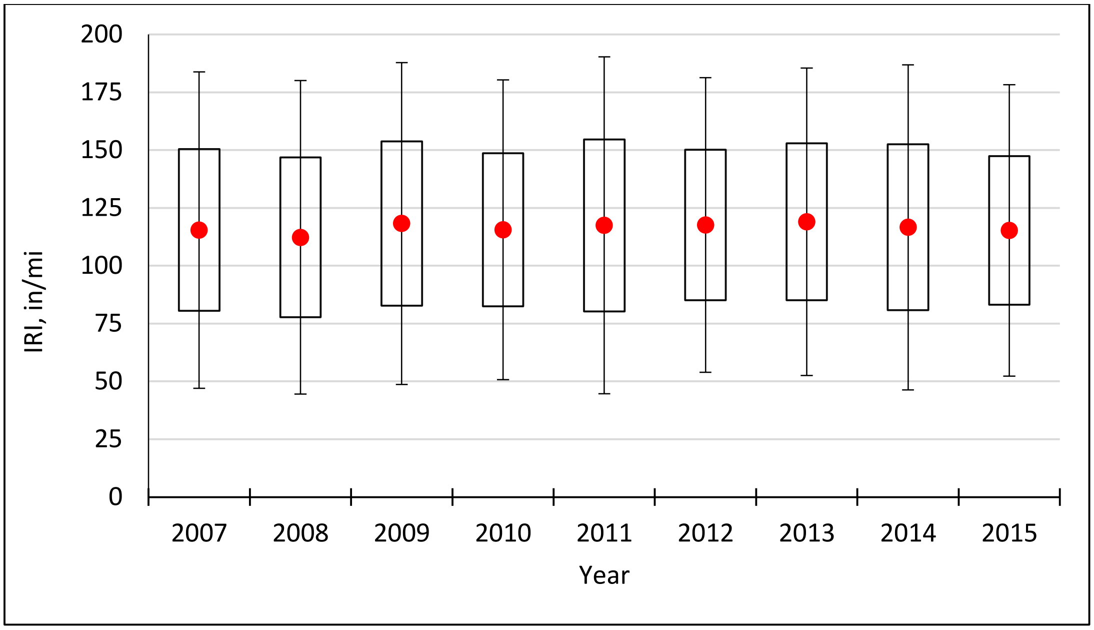


Figure 8-Box and Whisker Diagrams for CRCP IRI in the Houston District (Whiskers = 95% Confidence Interval; Solid Circle=Mean; Box = 68% Confidence Interval)

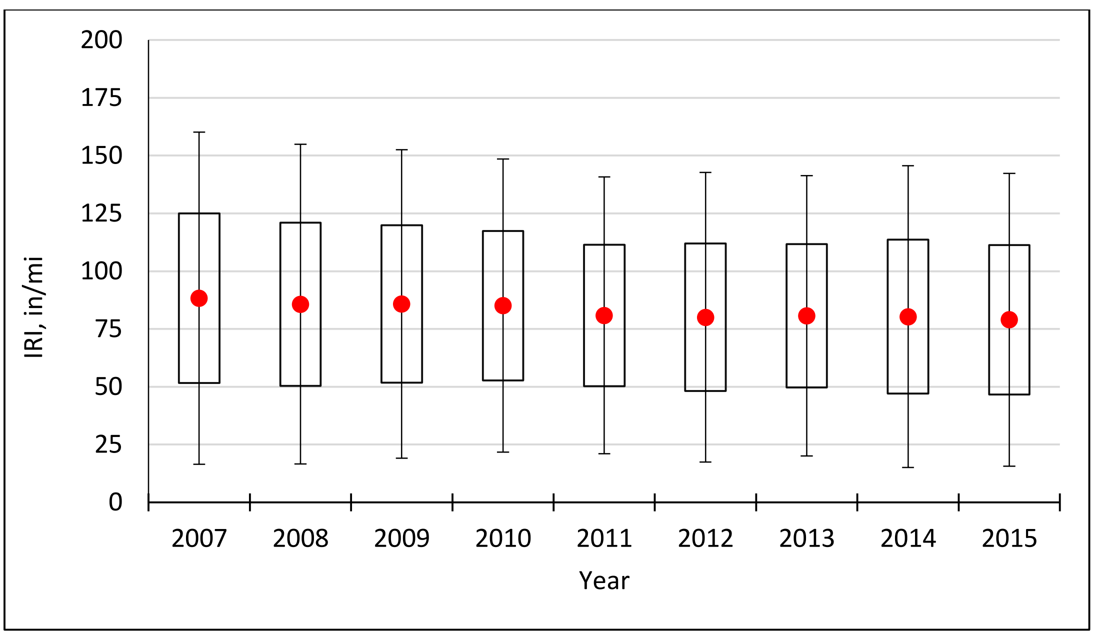


Figure 9-Box and Whisker Diagrams for ACP IRI in the Houston District (Whiskers = 95% Confidence Interval; Solid Circle=Mean; Box = 68% Confidence Interval)

Using the IRI thresholds proposed in the January 2015 NPRM of MAP-21, the majority of CRCP lane-miles would be classified as Fair and approximately 25 percent would be classified as Good (see **Figure *10***). Only less than one percent would be classified as Poor. On the other hand, the majority of ACP lane-miles would be classified as Good; approximately 35 percent would be classified as Fair; and less than one percent would be classified as Poor during the past nine years (**Figure *11***).

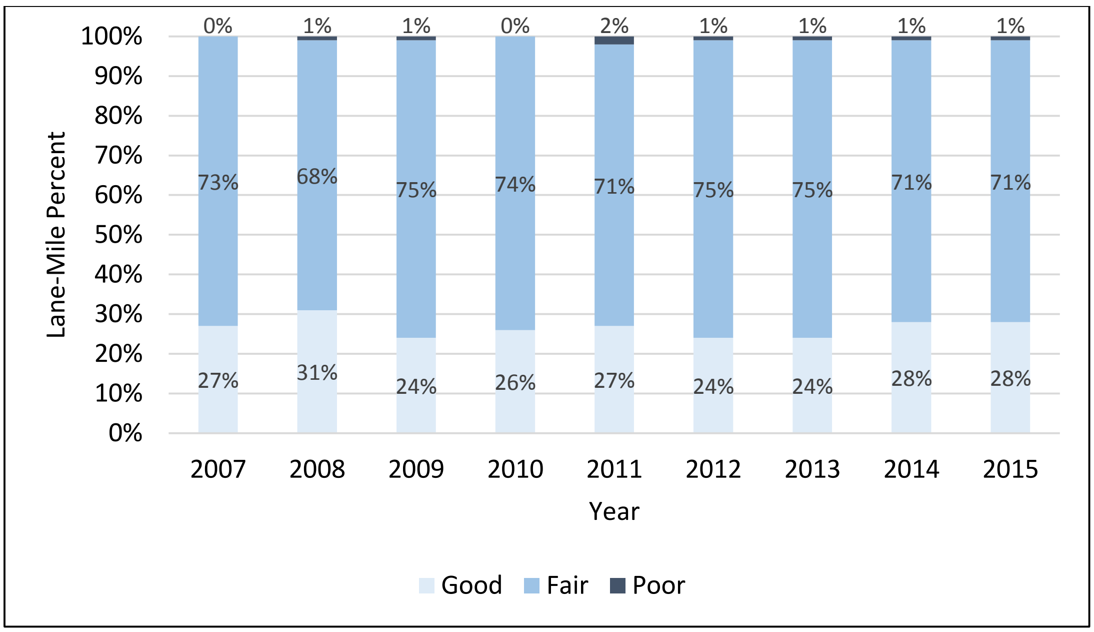


Figure 10-CRCP Performance in the Houston District Based on IRI Thresholds Proposed in the January 2015 NPRM of MAP-21

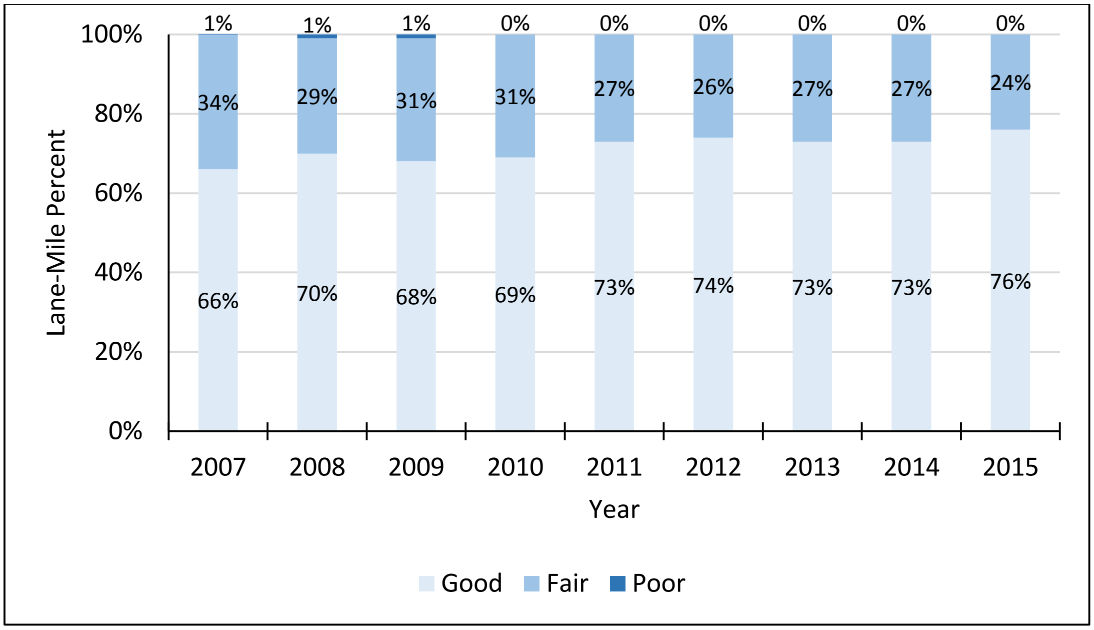


Figure 11-ACP Performance in the Houston District Based on IRI Thresholds Proposed in the January 2015 NPRM of MAP-21

3.3.1.1 Statistical Analysis of IRI Data

To further investigate the differences between the performance of different pavement types in Houston District, a t-test for samples with unequal variances is conducted on each pair of annual IRI data using a statistical analysis software, JMP. The null hypothesis and alternative hypothesis for this test are formulated as follows:

Null Hypothesis H_0: $\mu_1 = \mu_2$ (means are equal)

Alternative Hypothesis H_1: $\mu_1 \neq \mu_2$ (means are not equal)

This test uses the following t-statistic:

$$T_{\gamma} = \frac{\overline{X_1} - \overline{X_2}}{\sqrt{\frac{{S_1}^2}{N_1} + \frac{{S_2}^2}{N_2}}} \qquad (7)$$

X_1 and X_2 are sample means, S_1 and S_2 are sample standard deviations, N_1 and N_2 represent the sample sizes and γ is the t-distribution's degree of freedom. The degree of freedom for this test is estimated using the Welch-Satterthwaite equation:

$$\gamma = \frac{\left(\frac{{S_1}^2}{N_1} + \frac{{S_2}^2}{N_2}\right)^2}{\frac{\left(\frac{{S_1}^2}{N_1}\right)^2}{N_1 - 1} + \frac{\left(\frac{{S_2}^2}{N_2}\right)^2}{N_2 - 1}} \qquad (8)$$

Testing for the equality of means, the two-tailed P-Value is derived as the probability of getting an extreme value against the null hypothesis. This is computed as follows:

$$\mathrm{P-Value} = 2 \times \mathrm{Probability}\left[t_{\gamma} > T_{\gamma}\right] \qquad (9)$$

Applying the test on each pair of annual IRI data with a significance level of 0.05, the null hypothesis is rejected if resulting P-Value is less than 0.05. The results of the hypothesis tests are summarized in **Table *12***. The table also includes the average annual IRI values of urban and rural pavements and the P-Values of the test.

Table *12* shows that the null hypothesis is rejected for all annual data of IRI tests. This supports the fact of a significant difference between the behavior of CRCP and ACP sections in Houston District.

Table 12-Hypothesis Testing of Difference in Performance Between CRCP and ACP Based on IRI

Year	Mean IRI Value, in/mi (CRCP)	N_1 (Number of CRCP Sections)	Mean IRI Value, in/mi (ACP)	N_2 (Number of CRCP Sections)	P-Value	Reject Null Hypothesis?
2007	116.3	1437	87.9	1531	< 0.0001	Yes
2008	113.1	1445	85.1	1538	< 0.0001	Yes
2009	119.2	1446	85.3	1541	< 0.0001	Yes
2010	116.5	1448	84.3	1539	< 0.0001	Yes
2011	118.5	1450	80.4	1541	< 0.0001	Yes
2012	118.6	1449	79.6	1542	< 0.0001	Yes
2013	118.9	1433	79.3	1527	< 0.0001	Yes
2014	117.4	1446	79.0	1550	< 0.0001	Yes
2015	116.0	1455	77.5	1560	< 0.0001	Yes

3.3.2 Distress Score

The DS box and whisker diagram, depicted in **Figure *12***, shows that the DS of 68 percent of CRCP lane-miles in the Houston District consistently ranged between about 85 and 100 (with a mean value of approximately 92) over the past nine years (2007-2015).

On the other hand, **Figure *13*** shows that the DS of 68 percent of ACP lane-miles in the Houston District has had a considerable variation during three consecutive years from 2009 to 2011. During this period the DS of 68 percent of ACP lane-miles has ranged between 65 and 100 (with a mean value of approximately 82). Other annual data show similar results to those of CRCP with a mean value of approximately 90.

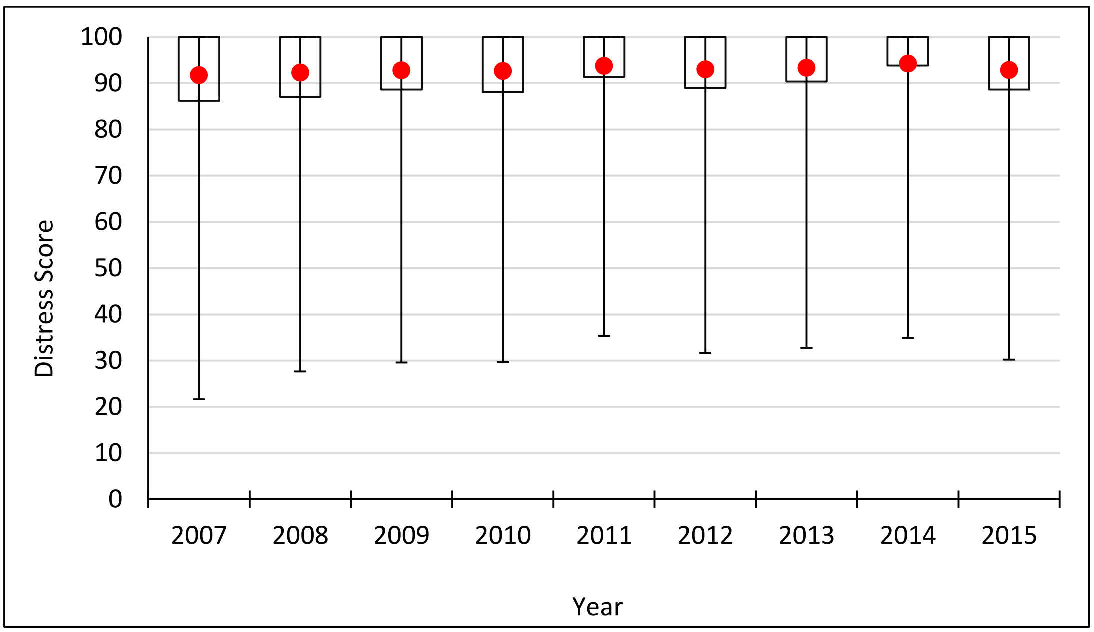


Figure 12-Box and Whisker Diagrams for CRCP DS in the Houston District (Whiskers = 95% Confidence Interval; Solid Circle=Mean; Box = 68% Confidence Interval)

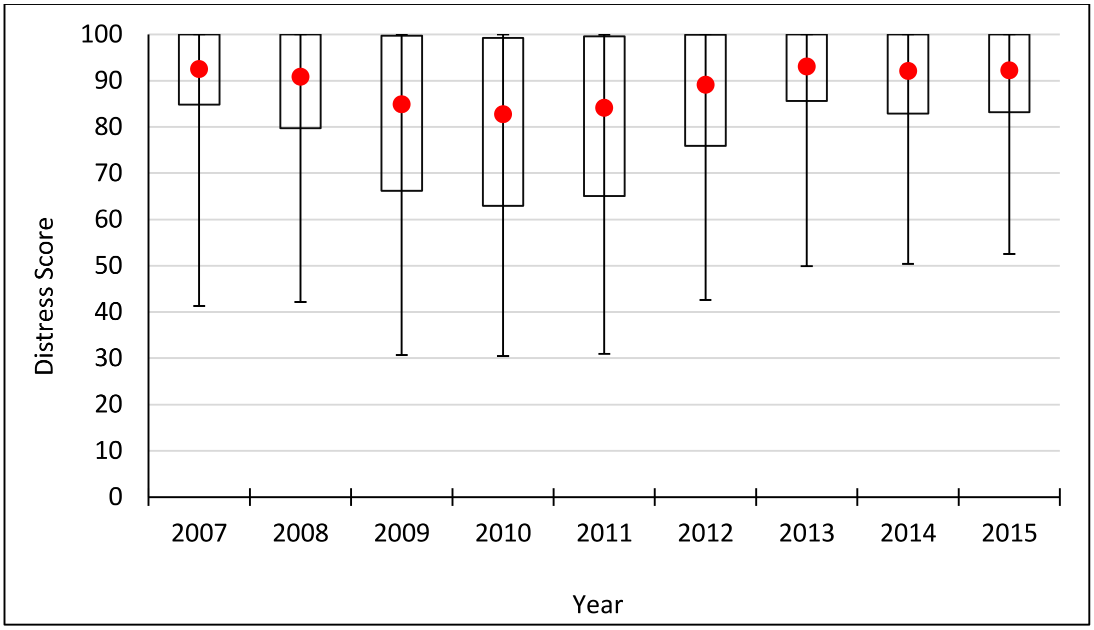


Figure 13-Box and Whisker Diagrams for ACP DS in the Houston District (Whiskers = 95% Confidence Interval; Solid Circle=Mean; Box = 68% Confidence Interval)

Using the DS threshold values specified by TxDOT, the majority (approximately 89 percent) of CRCP lane-miles would be classified as Good or Very Good, approximately three percent as Fair, and approximately eight percent as Poor (see **Figure *14***). Using the DS threshold values specified by TxDOT, the majority (62 percent to 88 percent on different years) of ACP lane-miles would be classified as Good or Very Good, approximately three percent as Fair. The percentage of lane-miles classified as poor are considerable between 2009 and 2011 which ranges between 26 percent and 30 percent. For the other annual data approximately eight percent of lane-miles would be classified as Poor (see **Figure *15***).

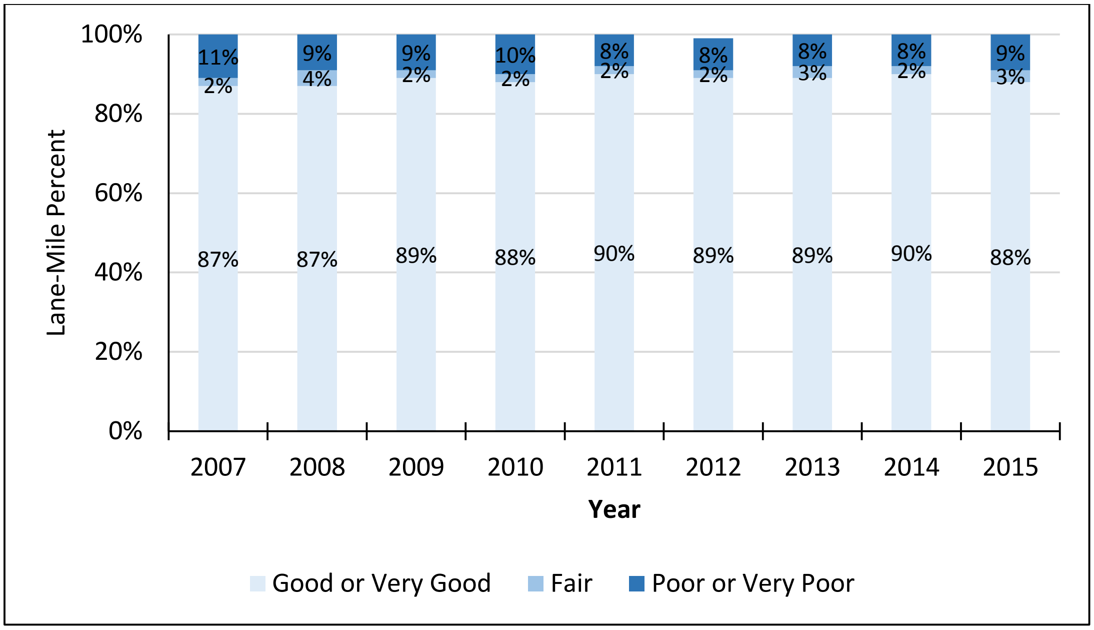


Figure 14-CRCP Performance in the Houston District Based on DS Thresholds Specified by TxDOT

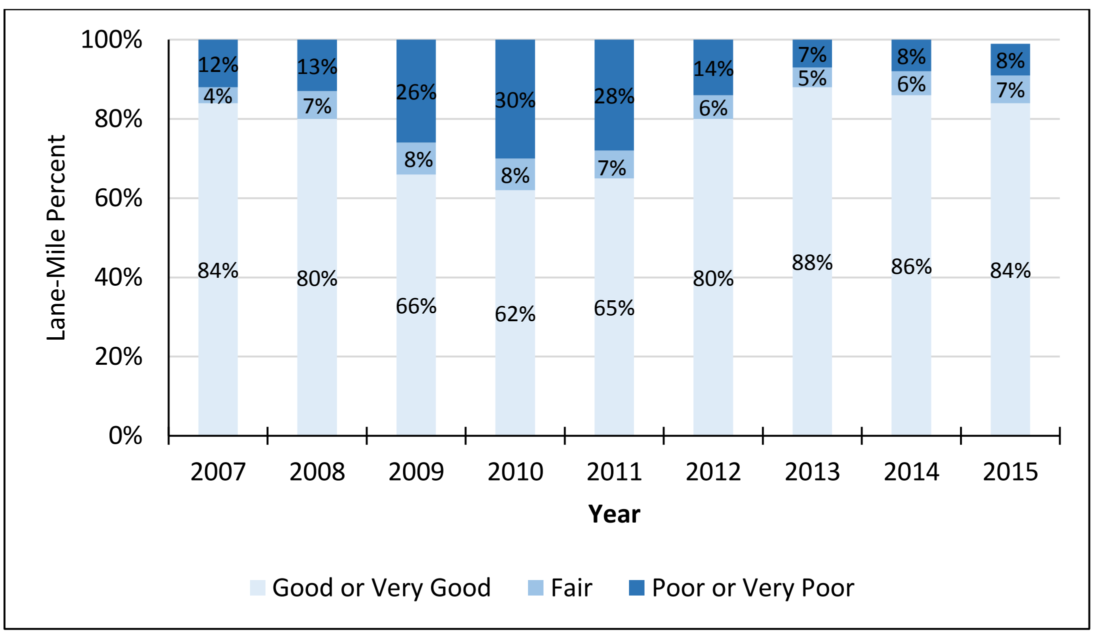


Figure 15-ACP Performance in the Houston District Based on DS Thresholds Specified by TxDOT

3.3.2.1 Statistical Analysis of Distress Score Data

To further analyze the difference between DS of different pavement types in Houston District, the same procedure and software used for statistical analysis of IRI are applied to DS. The results of the hypothesis tests are summarized in **Table *13***.

The null hypothesis for DS t-tests is rejected for six of the past nine years and is accepted for the other three years (2007, 2013 and 2015). Considering that the hypothesis of equal means is rejected for about 70 percent of the time (i.e. 6 out of 9 years), this test also makes a weaker evidence to conclude that there is a significant difference in the performance of different pavement types in Houston District based on their distresses.

Table 13-Hypothesis Testing of Difference in Performance Between CRCP and ACP Based on DS

Year	Mean DS Value (CRCP)	N_1 (Number of CRCP Sections)	Mean DS Value (ACP)	N_2 (Number of ACP Sections)	P-Value	Reject Null Hypothesis?
2007	92.7	1273	92.7	1501	0.9666	No
2008	92.8	1328	91.5	1540	0.0453	Yes
2009	93.2	1352	82.5	1538	< 0.0001	Yes
2010	93.1	1404	82.2	1544	< 0.0001	Yes
2011	94.0	1435	83.9	1544	< 0.0001	Yes
2012	93.4	1428	89.1	1541	< 0.0001	Yes
2013	93.5	1449	94.1	1529	0.3366	No
2014	94.8	1452	93.1	1539	0.0012	Yes
2015	93.2	1455	92.4	1560	0.1864	No

3.3.3 Condition Score

The CS box and whisker diagram, depicted in **Figure *16***, shows that the CS of 68 percent of CRCP lane-miles in the Houston District consistently ranged between about 75 and 100 (with a mean value of approximately 90) over the past nine years (2007-2015). The CS box and whisker diagram, depicted in **Figure *17***, shows that except for the annual data from 2009 to 2011, the CS of 68 percent of ACP lane-miles in the Houston District consistently ranged between about 75 and 100 (with a mean value of approximately 90) over the past nine years (2007-2015). The lower bottom of the boxes for CS of 68 percent of ACP lane-miles from 2009 to 2011 has dropped to 65 with a mean value of approximately 85.

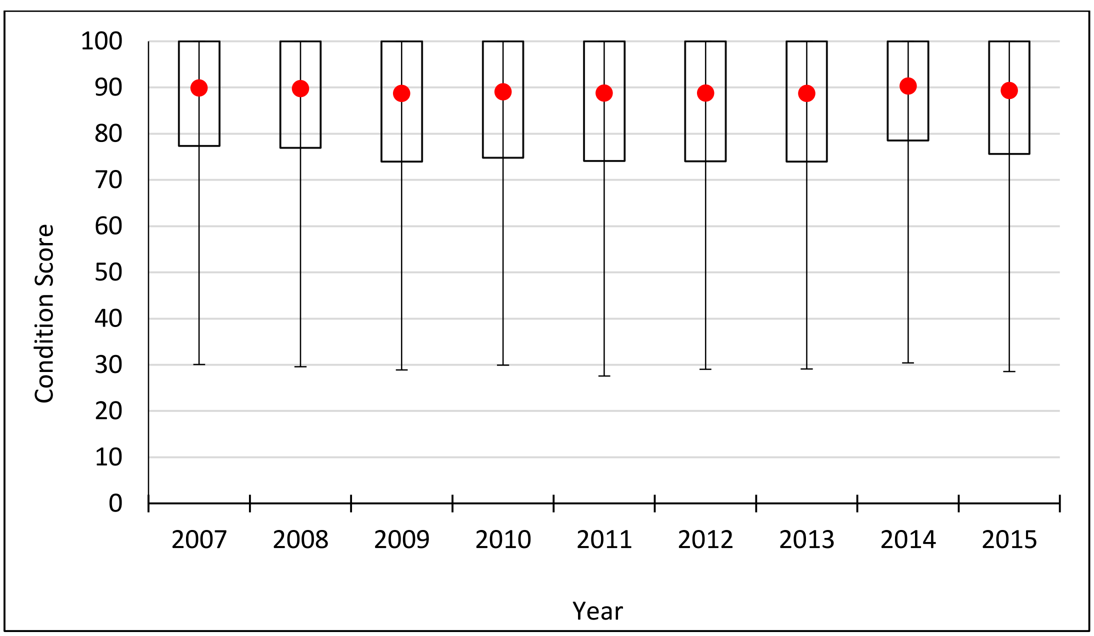


Figure 16-Box and Whisker Diagrams for CRCP CS in the Houston District (Whiskers = 95% Confidence Interval; Solid Circle=Mean; Box = 68% Confidence Interval)

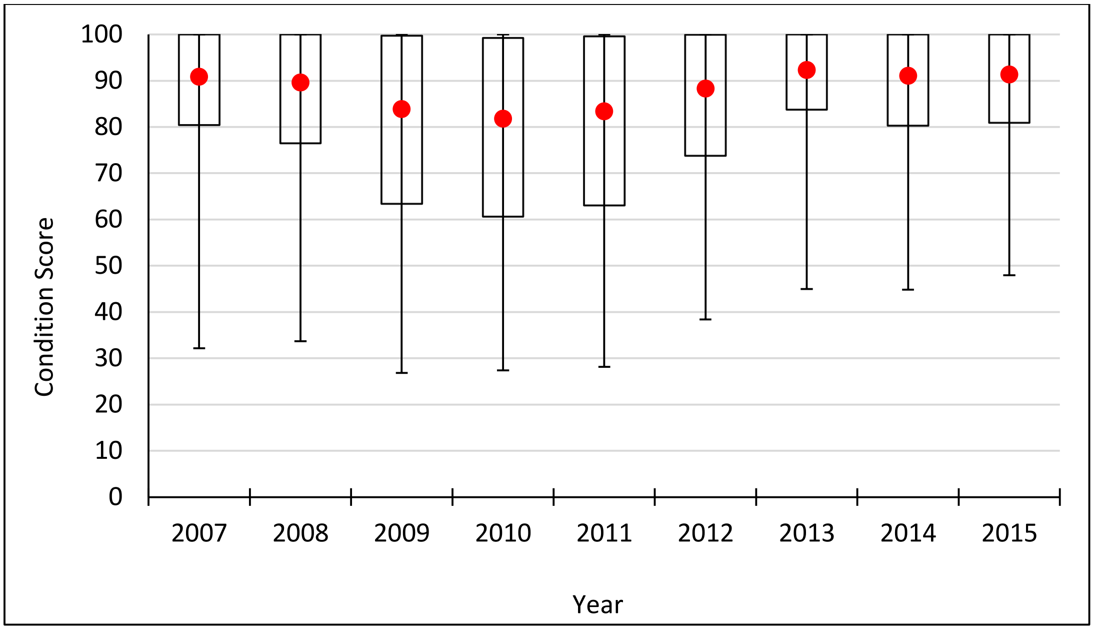


Figure 17-Box and Whisker Diagrams for ACP CS in the Houston District (Whiskers = 95% Confidence Interval; Solid Circle=Mean; Box = 68% Confidence Interval)

Using the CS threshold values specified by TxDOT, the majority (approximately 85 percent) of CRCP lane-miles would be classified as Good or Very Good, approximately seven percent as Fair, and approximately eight percent as Poor (see **Figure *18***). On the other hand, the majority (varied from 70 percent to 90 percent) of ACP lane-miles would be classified as Good or Very Good, approximately 10 percent to 24 percent as Fair, and approximately two percent as Poor (see **Figure *19***).

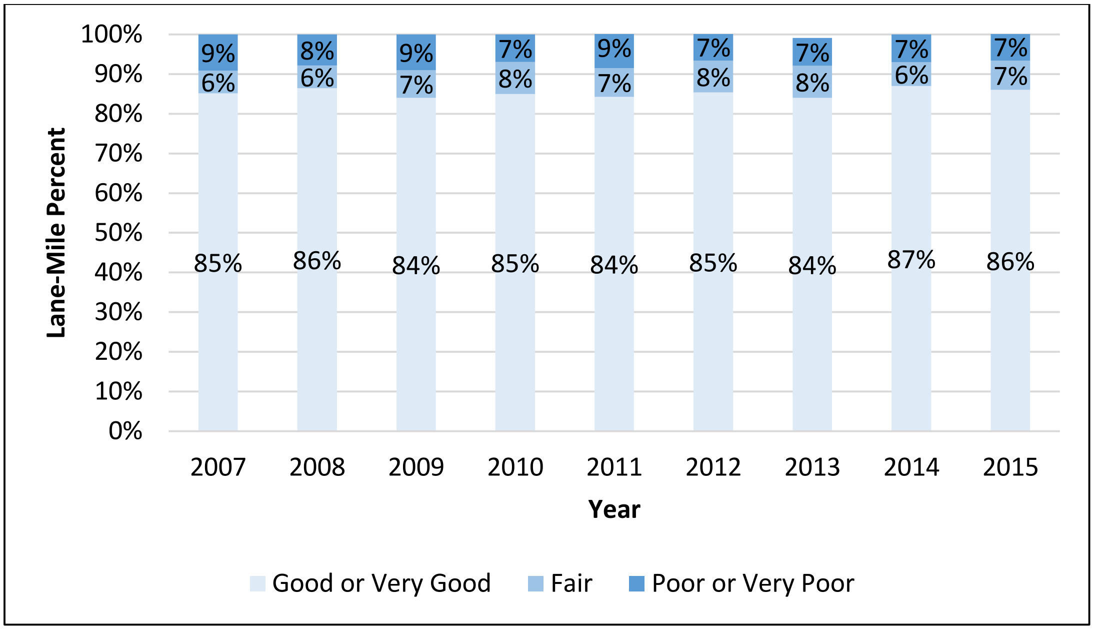


Figure 18-CRCP Performance in the Houston District Based on CS Thresholds Specified by TxDOT

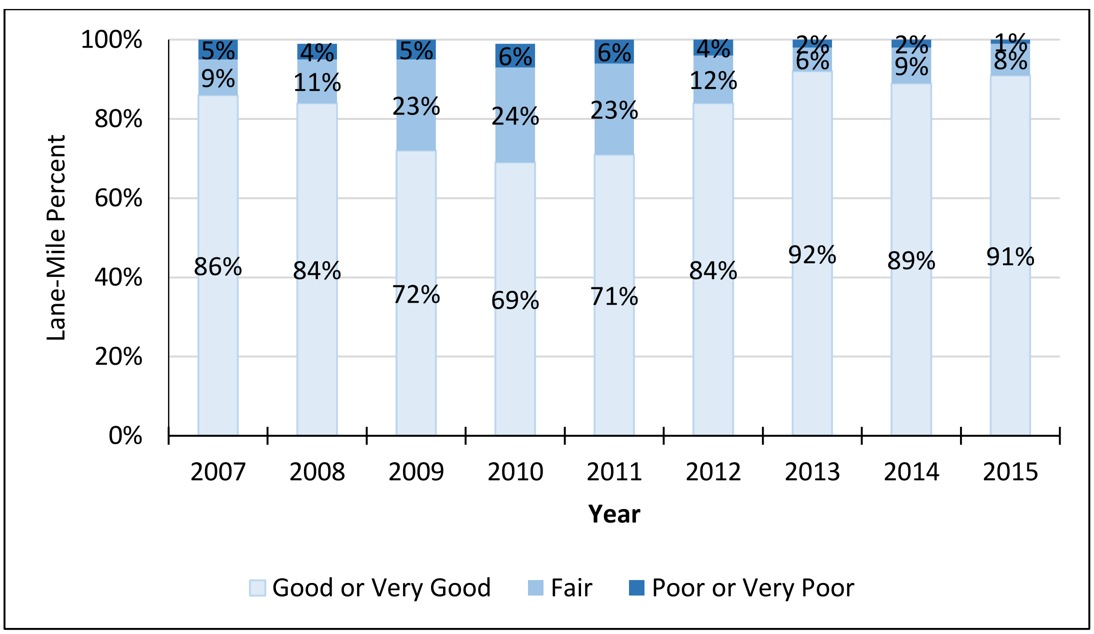


Figure 19-ACP Performance in the Houston District Based on CS Thresholds Specified by TxDOT

3.3.3.1 Statistical Analysis of Condition Score Data

To further analyze the difference between CS of different pavement types, the same procedure and software used for statistical analysis of IRI and DS are applied to CS. The results of the hypothesis tests are summarized in **Table *14***.

The null hypothesis for CS t-tests is rejected for six of the past nine years and is accepted for the other three consecutive years (2009, 2010, and 2011). Considering that the hypothesis of equal means cannot be rejected for 30 percent of the time (i.e. 3 out of 9 years), this test makes a weaker evidence to conclude that there is a significant difference in the performance of different pavement types based on their distresses.

Table 14-Hypothesis Testing of Difference in Performance Between CRCP and ACP Based on CS

Year	Mean CS Value (CRCP)	N_1 (Number of CRCP Sections)	Mean CS Value (ACP)	N_2 (Number of ACP Sections)	P-Value	Reject Null Hypothesis?
2007	87.9	1255	90.8	1448	0.0004	Yes
2008	88.4	1318	90.1	1481	0.0260	Yes
2009	87.1	1343	81.5	1376	< 0.0001	No
2010	87.4	1397	81.3	1490	< 0.0001	No
2011	86.8	1430	83.1	1493	< 0.0001	No
2012	87.0	1422	88.3	1485	0.0994	Yes
2013	86.9	1429	93.6	1477	< 0.0001	Yes
2014	88.7	1443	92.0	1489	< 0.0001	Yes
2015	87.7	1455	91.4	1511	< 0.0001	Yes

3.4 Consistency among Performance Metrics for ACP and CRCP

As summarized in **Table *15***, IRI and DS agreed about 67 percent of the time (i.e. 6 years out of 9 study years) when comparing the performance of ACP and CRCP. Similar agreement was found between IRI and CS. However, DS and CS agreed about 33.3 percent of the time (i.e. 3 years out of 9 study years) when comparing the performance of ACP and CRCP. The three metrics agreed about 33.3 percent of the time (i.e. 3 years out of 9 study years).

Table 15-Summary of Hypothesis Test Results for CRCP and ACP

Year	Reject Null Hypothesis based on IRI?	Reject Null Hypothesis based on DS?	Reject Null Hypothesis based on CS?
2007	Yes	No	Yes
2008	Yes	Yes	Yes
2009	Yes	Yes	No
2010	Yes	Yes	No
2011	Yes	Yes	No
2012	Yes	Yes	Yes
2013	Yes	No	Yes
2014	Yes	Yes	Yes
2015	Yes	No	Yes

4. COMPARING PAVEMENT PERFORMANCE IN URBAN AND RURAL AREAS

This section investigates the differences between the performance of roadway pavements in urban and rural areas based on IRI, CS, and DS. In this study, urban areas are defined as all densely settled core of census tracts and/or census blocks with minimum population of 2,500 people. Generally, a census block is the smallest geographic unit for which the Census Bureau tabulates decennial census data. In cities, many census blocks correspond to individual city blocks bounded by streets. Rural areas are areas that do not meet the definition of an urban area (DOC 2010).

4.1 Delineation of Urban and Rural Areas in Houston District

Using the Census 2010 criteria for delineation between the urban and rural areas, U.S. Census Bureau has created a geographic shapefile for graphically representation of the urban boundaries of the country for year 2014. The geographic representation of urban areas of year 2014 was used through this research to distinguish between the urban and rural areas. **Figure *20***, displays the urban boundaries in Houston District gleaned from this database.

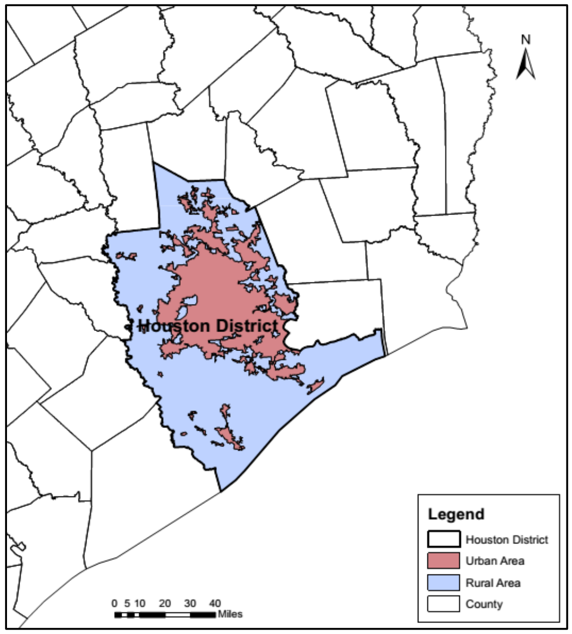


Figure 20-Urban and Rural Areas in Houston District

By identifying the urban and rural areas in Houston District, next step is to classify the pavement sections based on their location. In order to achieve this goal, the "clip" geoprocessing tool in ArcMAP is used to clip the pavement sections using the urban boundaries. Section lengths are updated afterward to obtain the new lengths for those pavements laying in both urban and rural areas. **Figure *21*** is a graphical indication of the urban and rural pavement sections obtained after this step:

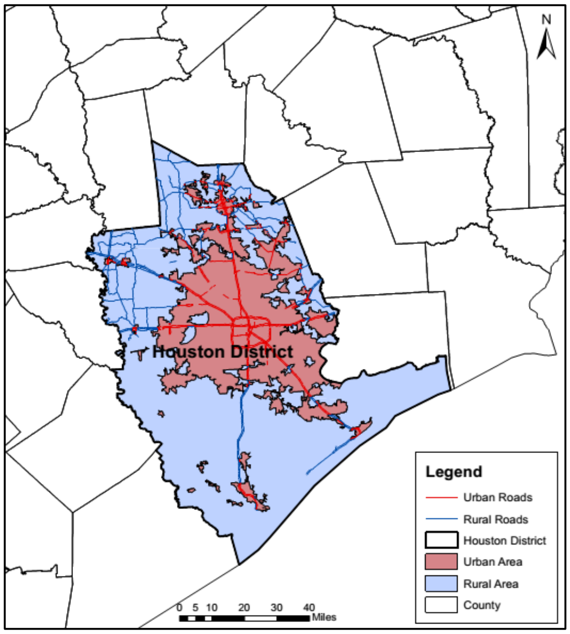


Figure 21-Urban and Rural Roads in Houston District

4.2 Performance of Pavements in Urban and Rural Areas

Next step after classifying pavements into urban and rural roads is to evaluate the performance of pavement in suggested urban or rural areas. Following sections include the performance assessment results of urban and rural pavements based on IRI, DS and CS and the statistical analysis to investigate the possible differences between their behaviors.

4.2.1 IRI

Figure *22* shows that the IRI of the middle 68 percent of urban lane-miles in the Houston District consistently ranged between about 75 in/mi and 150 in/mi (with a mean value of approximately 115 in/mile) over the past nine years (2007-2015). **Figure *23*** shows that the IRI of the middle 68 percent of rural lane-miles in the Houston District consistently ranged between about 60 in/mi and 125 in/mi (with a mean value of approximately 90 in/mile) over the past nine years (2007-2015). These results confirm the perception that IRI values in urban areas are typically higher than those in rural areas.

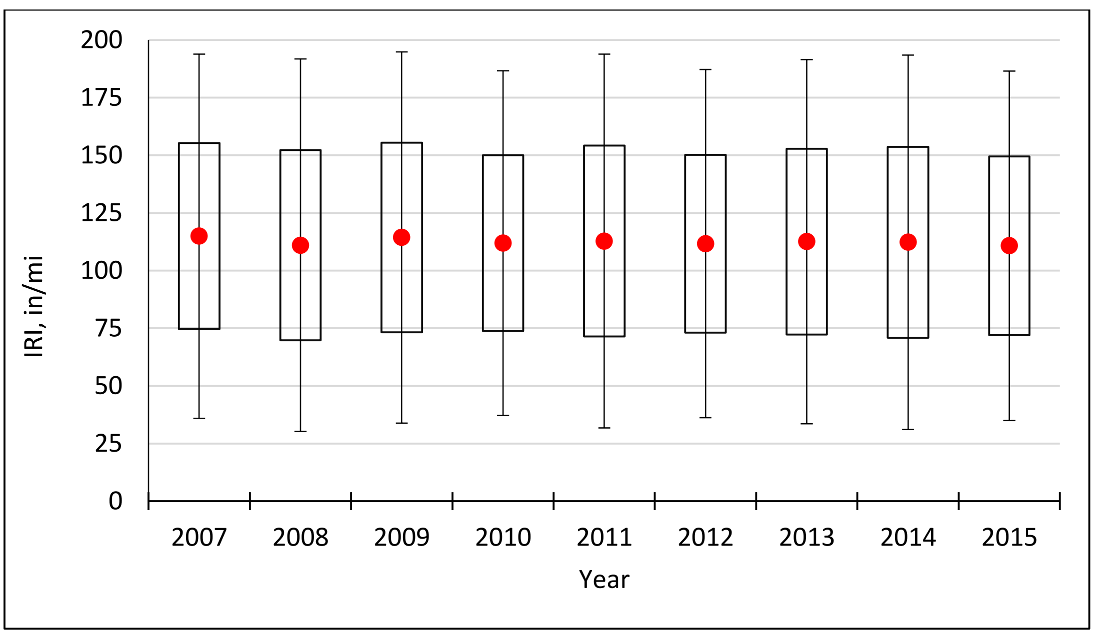


Figure 22-Box and Whisker Diagrams for IRI of Urban Roads in the Houston District (Whiskers = 95% Confidence Interval; Solid Circle=Mean; Box = 68% Confidence Interval)

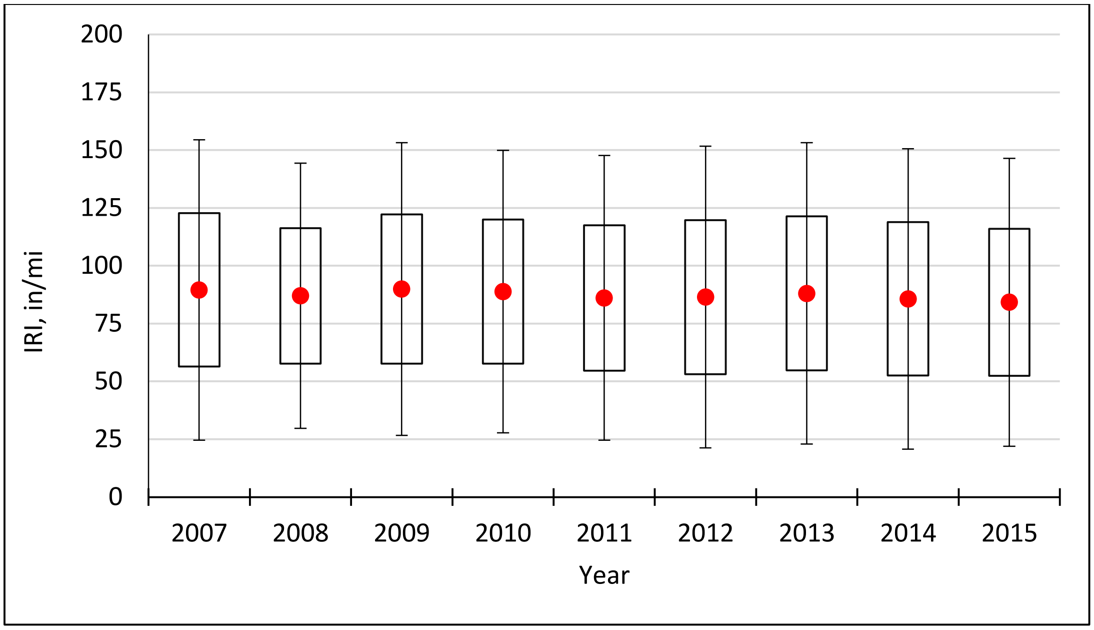


Figure 23-Box and Whisker Diagrams for IRI of Rural Roads in the Houston District (Whiskers = 95% Confidence Interval; Solid Circle=Mean; Box = 68% Confidence Interval)

Using the IRI thresholds proposed in the January 2015 NPRM of MAP-21 (shown earlier in **Table *4***), the majority of urban lane-miles would be classified as Fair; approximately 30 percent would be classified as Good; and about eight percent of urban lane-miles would be classified as Poor in the past nine years (**Figure *24***). On the other hand, the majority of rural lane-miles would be classified as Good; approximately 35 percent would be classified as Fair; and none would be classified as Poor during the past nine years (**Figure *25***).

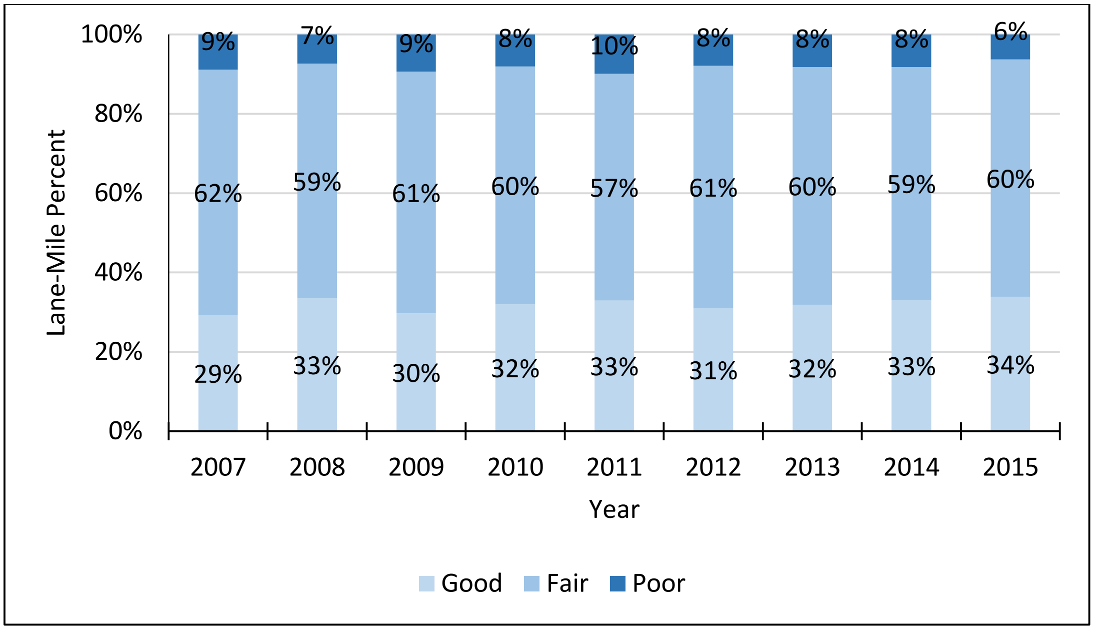


Figure 24-Performance of Urban Roads in the Houston District Based on IRI Thresholds Proposed in the January 2015 NPRM of MAP-21

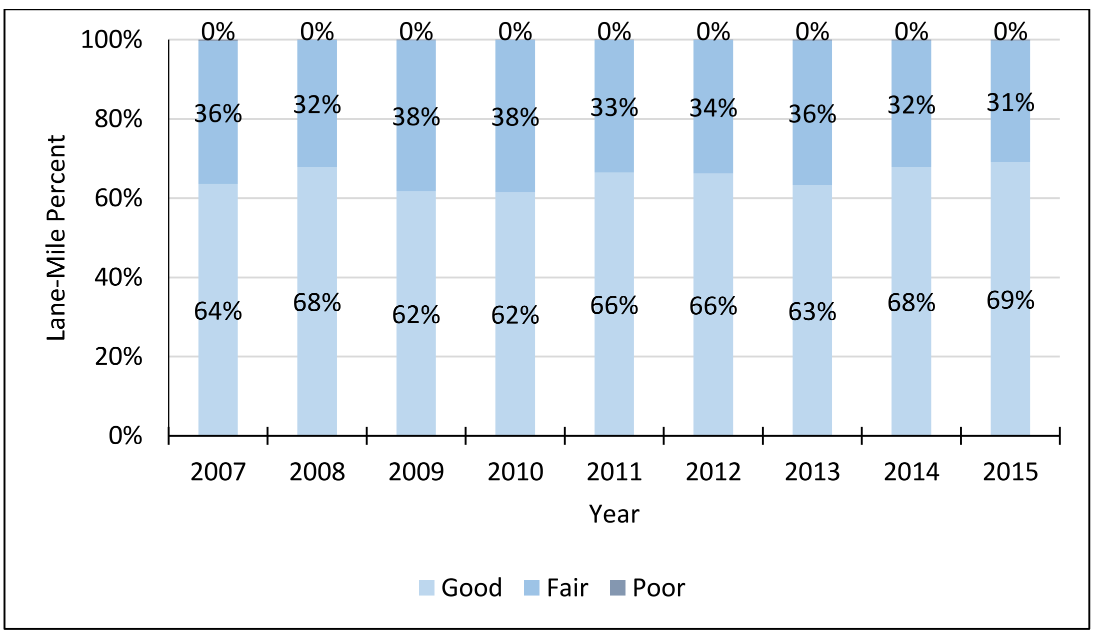


Figure 25-Performance of Rural Roads in the Houston District Based on IRI Thresholds Proposed in the January 2015 NPRM of MAP-21

4.2.1.1 Statistical analysis of IRI data

To further analyze the difference between IRI of urban and rural pavements, the same procedure and software used for statistical analysis of CRCP and ACP pavements are applied to urban and rural data sets. The results of the hypothesis tests are summarized in **Table *16***.

Table *16* shows that the null hypothesis is rejected for all annual data of IRI tests. This supports the fact of a significant difference between the behavior of pavements in urban and rural areas.

Table 16-Hypothesis Testing of Difference in Performance Between Urban and Rural Areas Based on IRI

Year	Mean IRI Value, in/mi (Rural)	N_1 (Number of Rural Sections)	Mean IRI Value, in/mi (Urban)	N_2 (Number of Urban Sections)	P-Value	Reject Null Hypothesis?
2007	89.7	1673	115.0	1663	< 0.0001	Yes
2008	87.0	1680	111.0	1673	< 0.0001	Yes
2009	90.0	1678	114.3	1676	< 0.0001	Yes
2010	88.9	1680	111.9	1679	< 0.0001	Yes
2011	86.1	1681	112.7	1682	<0.0001	Yes
2012	86.5	1686	111.7	1676	< 0.0001	Yes
2013	88.0	1657	112.6	1666	< 0.0001	Yes
2014	85.7	1688	112.2	1683	< 0.0001	Yes
2015	84.3	1694	110.9	1695	< 0.0001	Yes

4.2.2 Distress score

As displayed in **Figure *26***, the DS of the middle 68 percent of urban lane-miles in the Houston District consistently ranged between about 84 and 100 (with a mean value of approximately 91) over the past nine years (2007-2015). **Figure *27*** shows that the DS of the middle 68 percent of rural lane-miles in the Houston District consistently ranged between about 79 and 100 (with a mean value of approximately 90) over the past nine years (2007-2015). While the results for DS in urban and rural areas look less different than those for IRI, statistical tests are equally performed to investigate the significance of any difference between their behaviors.

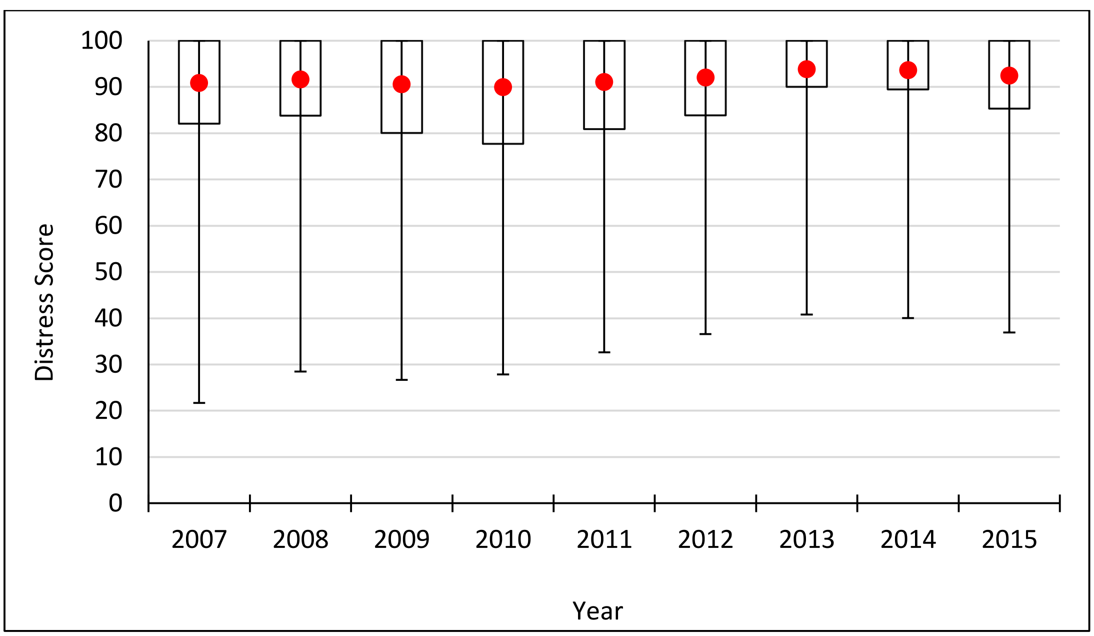


Figure 26-Box and Whisker Diagrams for DS of Urban Roads in the Houston District (Whiskers = 95% Confidence Interval; Solid Circle=Mean; Box = 68% Confidence Interval)

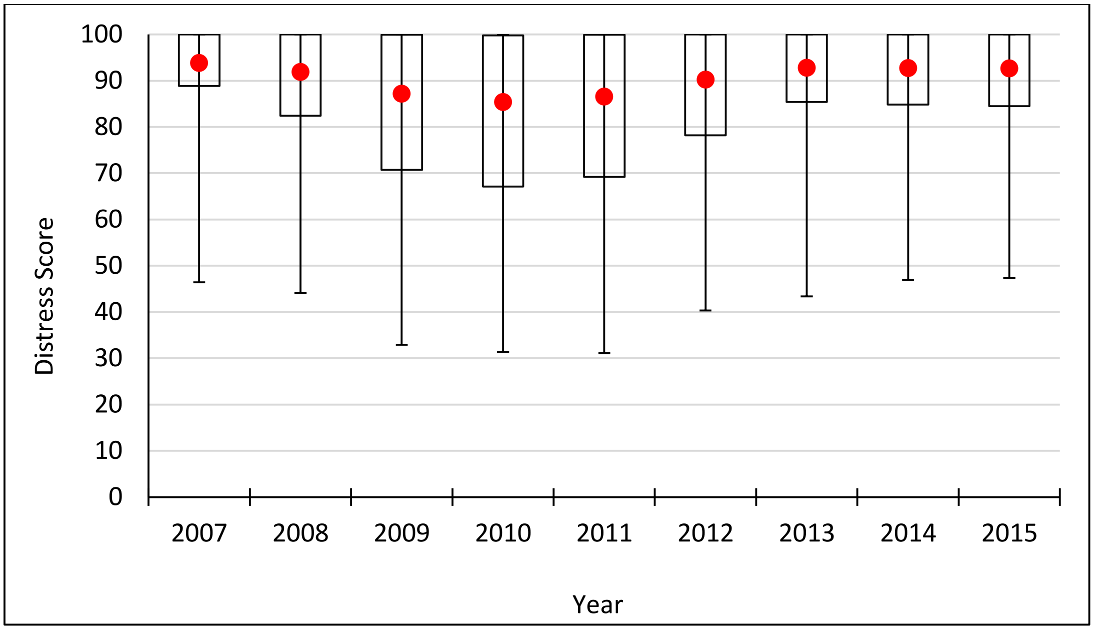


Figure 27-Box and Whisker Diagrams for DS of Rural Roads in the Houston District (Whiskers = 95% Confidence Interval; Solid Circle=Mean; Box = 68% Confidence Interval)

Using the DS thresholds specified by TxDOT, the majority of urban lane-miles (83-90%) would be classified as Good; approximately three percent would be classified as Fair; and an average of 11 percent would be classified as Poor during the past nine years (**Figure *28***). **Figure *29*** shows that 68-88 percent of rural lane-miles would be classified as Good; approximately 6 percent would be classified as Fair; and approximately 15 percent would be classified as Poor in the past 9 years. These results indicate that rural roads exhibit more distress than urban roads. This pattern is opposite to the IRI pattern discussed earlier.

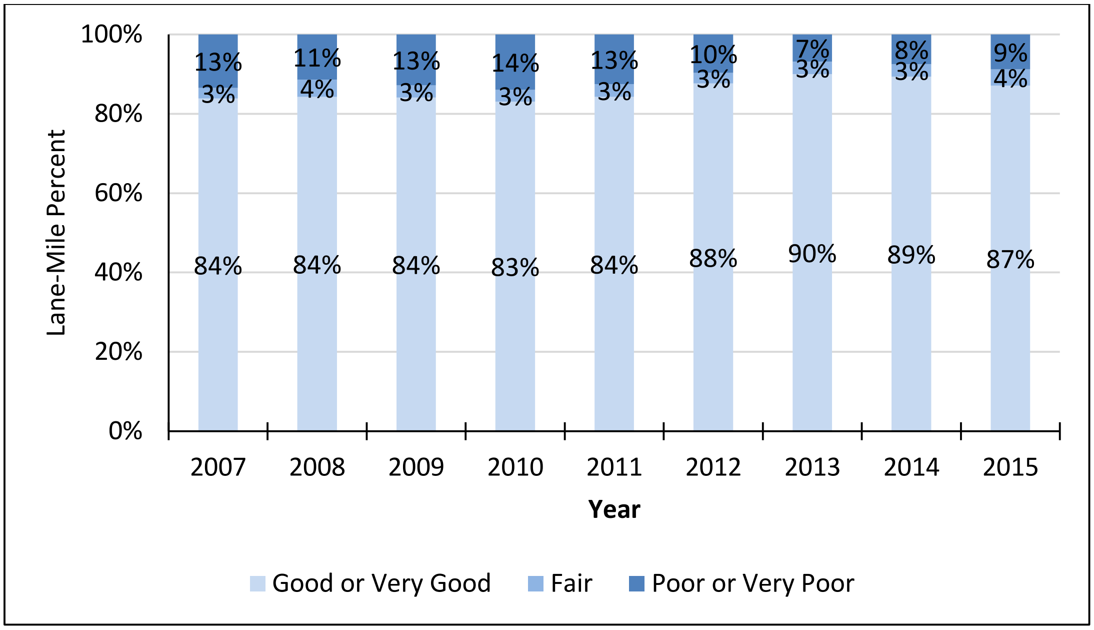


Figure 28-Performance of Urban Roads in the Houston District Based on DS Thresholds used by TxDOT

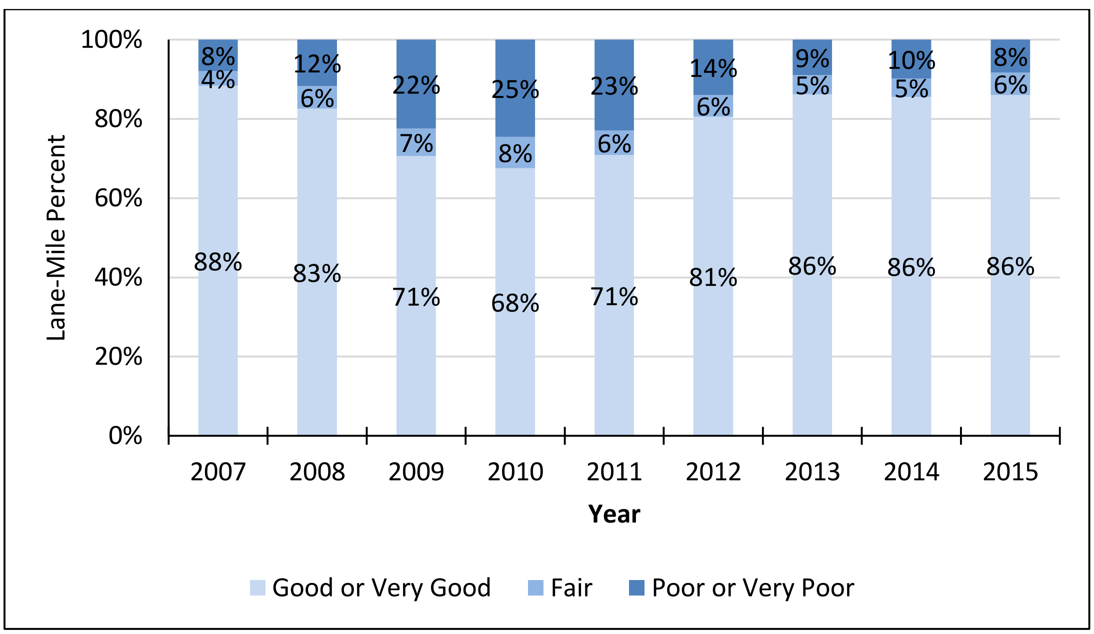


Figure 29-Performance of Rural Roads in the Houston District Based on DS Thresholds used by TxDOT

4.2.2.1 Statistical Analysis of Distress Score Data

To further analyze the difference between DS of urban and rural pavements, the same procedure and software used for statistical analysis of IRI are applied to DS. The results of the hypothesis tests are summarized in **Table *17***.

The null hypothesis for DS t-tests is rejected for five of the past nine years and is accepted for the other four years (2008, 2013, 2014 and 2015). Considering that the hypothesis of equal means cannot be rejected for about half the time (i.e. 4 out of 9 years), this test does not make a strong evidence to conclude that there is a significant difference in the performance of pavements in urban and rural areas based distresses.

Table 17-Hypothesis Testing of Difference in Performance Between Urban and Rural Areas Based on DS

Year	Mean DS Value (Rural)	N_1 (Number of Rural Sections)	Mean DS Value (Urban)	N_2 (Number of Urban Sections)	P-Value	Reject Null Hypothesis?
2007	93.8	1599	90.8	1521	< 0.0001	Yes
2008	91.9	1651	91.7	1581	0.6777	No
2009	87.1	1658	90.7	1587	< 0.0001	Yes
2010	85.4	1671	90.1	1645	< 0.0001	Yes
2011	86.6	1665	91.0	1678	< 0.0001	Yes
2012	90.3	1682	92.0	1660	0.0061	Yes
2013	92.8	1662	93.9	1681	0.0685	No
2014	92.7	1678	93.6	1684	0.0715	No
2015	92.7	1694	92.5	1695	0.7446	No

4.2.3 Condition score

As displayed in **Figure *30***, the CS of the middle 68 percent of urban lane-miles in the Houston District consistently ranged between about 66 and 100 (with a mean value of approximately 86) over the past nine years (2007-2015). **Figure *31*** shows that the CS of the middle 68 percent of rural lane-miles in the Houston District consistently ranged between about 76 and 100 (with a mean value of approximately 90) over the past nine years (2007-2015). These patterns reveal that the middle 68 percent of rural lane-miles have a better performance than urban lane-miles based on CS. A comparison of the lower bounds (whiskers) of **Figure *30*** and **Figure *31*** indicate that urban roads consistently have worse lower bound CS values.

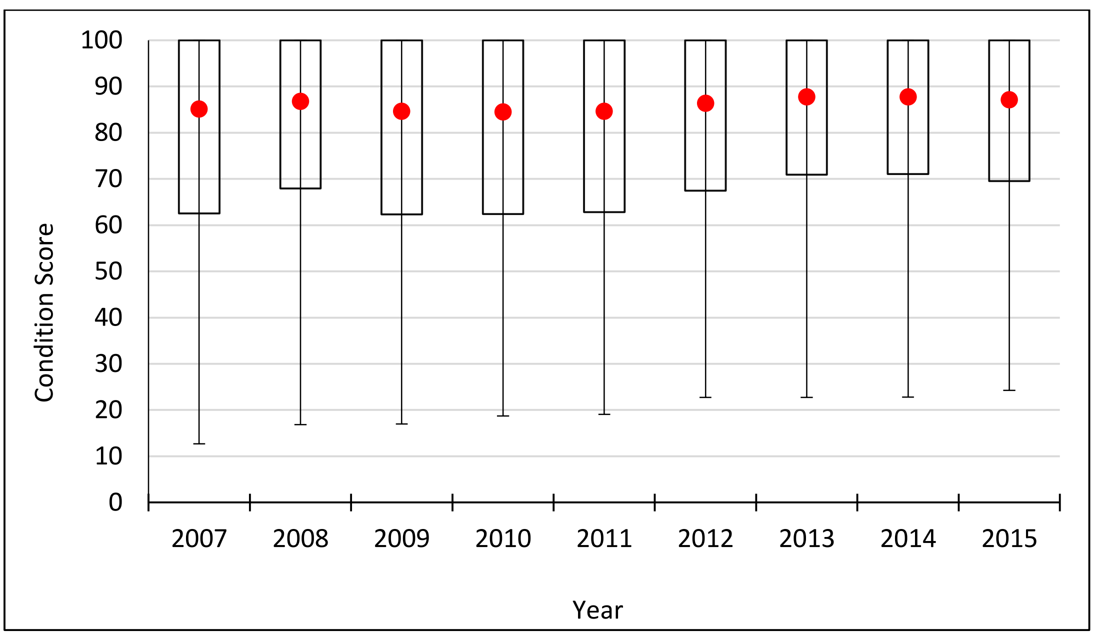


Figure 30-Box and Whisker Diagrams for CS of Urban Roads in the Houston District (Whiskers = 95% Confidence Interval; Solid Circle=Mean; Box = 68% Confidence Interval)

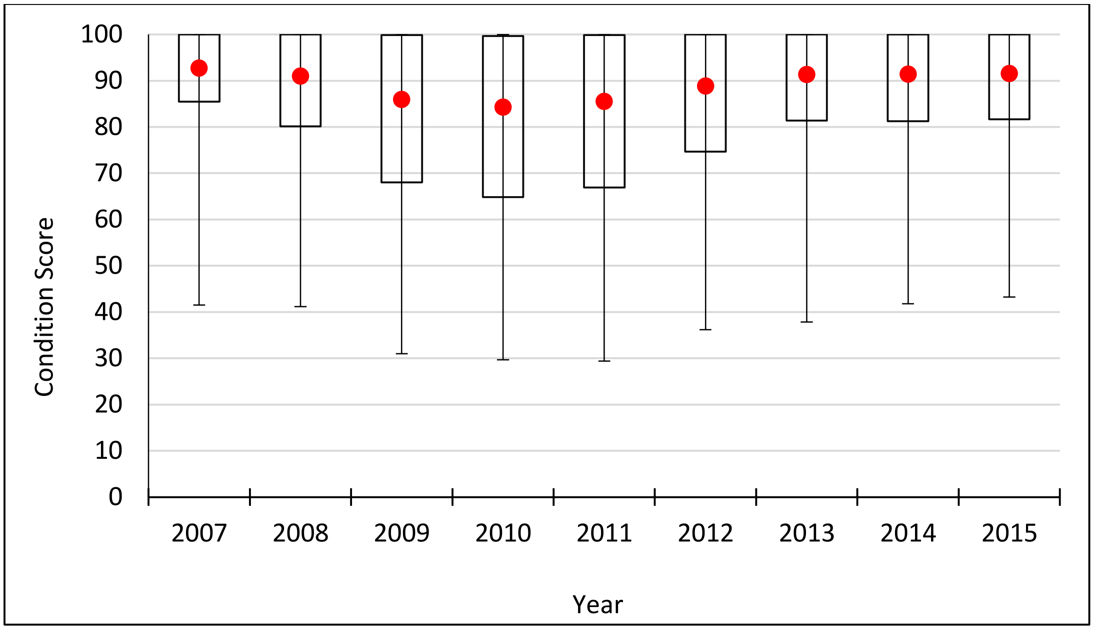


Figure 31-Box and Whisker Diagrams for CS of Rural Roads in the Houston District (Whiskers = 95% Confidence Interval; Solid Circle=Mean; Box = 68% Confidence Interval)

Using the CS thresholds specified by TxDOT, the majority (78-85%) of urban lane-miles would be classified as Good and approximately nine percent would be classified as Fair throughout the past nine years (**Figure *32***). An average of nine percent of urban lane-miles would be classified as Poor. **Figure *33*** reveals that the majority (74-91%) of rural lane-miles would be classified as Good and approximately 13 percent would be classified as Fair throughout the past nine years. Approximately three percent of rural lane-miles would be classified as Poor. Based on the CS thresholds used by TxDOT, it can be concluded that at the network level, rural lane-miles have a better performance (combination of distress and ride quality) than urban lane-miles.

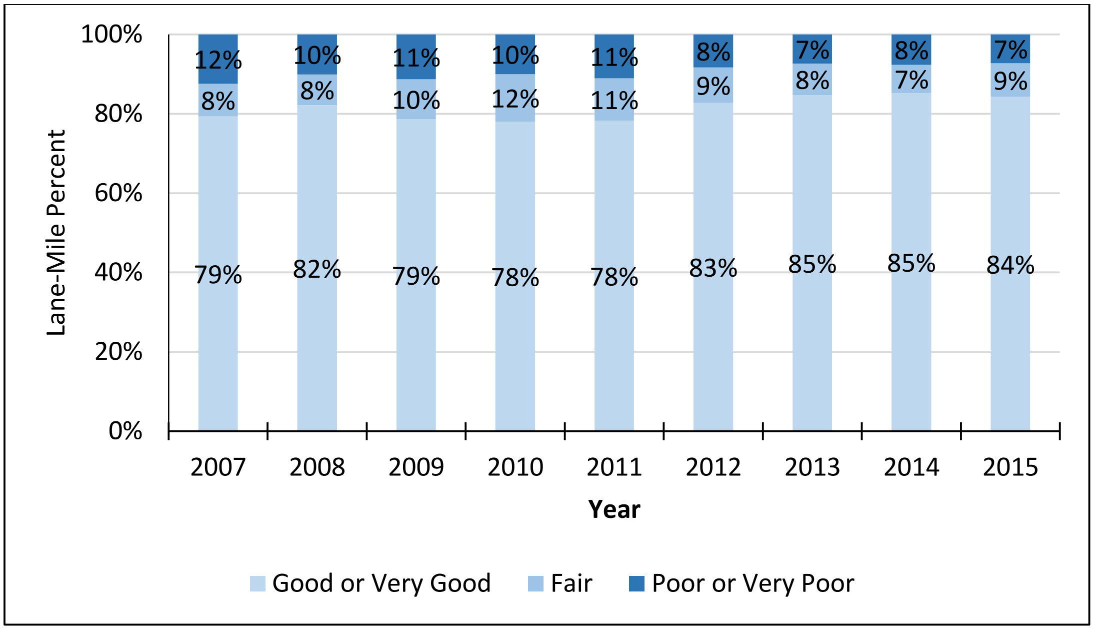


Figure 32-Performance of Urban Roads in the Houston District Based on CS Thresholds used by TxDOT

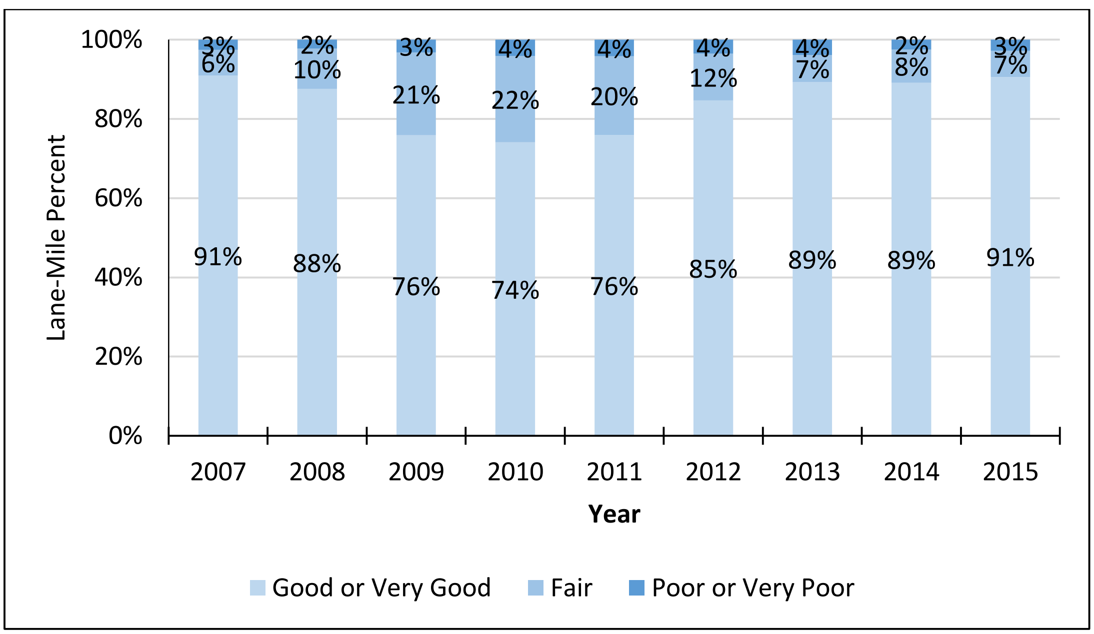


Figure 33- Performance of Rural Roads in the Houston District Based on CS Thresholds used by TxDOT

4.2.3.1 Statistical Analysis of CS Data

The difference between CS values for urban and rural pavements is further investigated using the same statistical procedure and software used for analysis of IRI and DS data. The results of the CS hypothesis tests are summarized in **Table *18***. The null hypothesis for CS t-tests is rejected for six of the nine past years and cannot be rejected for three consecutive years (2009, 2010 and 2011). Considering that CS represents the combined effects of both roughness and distresses, these results naturally lie between the results of IRI data analysis and DS data analysis.

Table 18-Hypothesis Testing of Difference in Performance Between Urban and Rural Areas Based on CS

Year	**Mean CS Value (Rural)**	**N_1 (Number of Rural Sections)**	**Mean CS Value (Urban)**	**P-Value**	**N_2 (Number of Urban Sections)**	**Reject Null Hypothesis?**
2007	92.5	1594	85.1	< 0.0001	1499	Yes
2008	91.1	1645	86.9	< 0.0001	1560	Yes
2009	85.8	1657	84.8	0.1983	1576	No
2010	84.3	1667	84.5	0.8340	1635	No
2011	85.6	1664	84.6	0.1694	1669	No
2012	88.9	1681	86.2	0.0002	1648	Yes
2013	91.4	1652	87.6	< 0.0001	1662	Yes
2014	91.4	1677	87.6	< 0.0001	1675	Yes
2015	91.7	1694	87.1	< 0.0001	1695	Yes

4.3 Consistency among Performance Metrics for Urban Versus Rural Areas

Table 19, IRI and DS agreed about 44.4 percent of the time (i.e. 4 years out of 9 study years) when comparing pavement performance in rural and urban areas. A higher agreement (about 67 percent) was found between IRI and CS. However, DS and CS agreed only about 22.2 percent of the time (i.e. 2 years out of 9 study years) when comparing pavement performance in rural and urban areas. The three metrics agreed about 22.2 percent of the time (i.e. 2 years out of 9 study years).

Table 19-Summary of Hypothesis Test Results for Urban and Rural Pavements

Year	Reject Null Hypothesis based on IRI?	Reject Null Hypothesis based on DS?	Reject Null Hypothesis based on CS?
2007	Yes	Yes	Yes
2008	Yes	No	Yes
2009	Yes	Yes	No
2010	Yes	Yes	No
2011	Yes	Yes	No
2012	Yes	Yes	Yes
2013	Yes	No	Yes
2014	Yes	No	Yes
2015	Yes	No	Yes

5. CORRELATIONS AMONG PERFORMANCE METRICS

This section of the thesis investigates possible correlations among IRI, DS, and CS based on Houston District data.

5.1 Data Adjustment

Development of a correlation model starts with identifying missing or erroneous data records. Since the parameters used in this study are IRI, CS and DS, the data verification approach has to be based on the pavement section's rating regarding these metrics. Therefore, the following steps were used to verify the validity of the data records:

- To develop a correlation model between IRI and CS it has to be considered that TxDOT rates a pavement with CS less than 35 as "Very Poor" which would require immediate maintenance and rehabilitation project to improve its condition. It would be very rare for such a pavement with a "Very Poor" rating in terms of CS to be rated as "Fair" or "Good" regarding its ride quality. Thus the pavement sections with CS < 35 and IRI < or equal 170 in/mi are excluded from the analysis. In addition, pavement sections with CS greater than or equal to 95 are rated as "Very Good" which would imply a very good performance of the section in terms of its roughness. Therefore, pavement sections with CS greater than or equal to 95 and IRI score greater than or equal to 95 (i.e. "Fair" or "Poor") are excluded from the analysis.
- In order to develop a correlation model between IRI and DS it has to be considered that TxDOT rates a pavement with DS less than 60 as "Very Poor" which would require immediate maintenance and rehabilitation project to improve it condition.

It would be very rare for such a pavement with a "Very Poor" rating in terms of DS to be rated as "Fair" or "Good" regarding its roughness. Thus the pavement sections with DS < 60 and IRI <= 170 are excluded from the analysis. In addition, pavement sections with DS greater than or equal to 95 are rated as "Very Good" which would imply a very good performance of the section in terms of its ride quality. Therefore, pavement sections with DS greater than or equal to 95 and IRI greater than or equal to 95 in/mi (i.e. "Fair") are excluded from the analysis.

5.2 Exploration of Possible Correlations

Using the statistical software JMP, the correlation coefficients were calculated for the most recent fiscal year's IRI, CS and DS data. Using the multivariate platform analysis by setting IRI and CS as the input variables as well as setting IRI and DS as the input variables at the second attempt, the Pearson Coefficient of Correlation is calculated for each pair. Following is the formula to calculate this coefficient:

$$\rho_{XY} = Corr(X,Y) = \frac{Cov(X,Y)}{SD(X) \times SD(Y)} = \frac{E(XY) - E(X)E(Y)}{SD(X)SD(Y)} \tag{10}$$

where ρ_{XY} is the coefficient of correlation, $Cov(X,Y)$ is the covariance, $E(X)$ and $E(Y)$ are the sample means, and $SD(X)$ and $SD(Y)$ are the sample standard deviations. The covariance divided by two standard deviations would result in a unitless value of ρ_{XY} which would be always between -1 and 1:

$$-1 \le \rho_{XY} \le 1 \tag{11}$$

The further the correlation coefficient is from “Zero”, the stronger would be the correlation between the variables.

Aforementioned statistical platform was applied to the adjusted IRI, CS and DS data sets to investigate the correlation of IRI with CS and DS. **Figure *34*** is the scatterplot graph of IRI and CS to visually display the correlation between these two variables. Coefficient of correlation is calculated as “- 0.7136” for this pair of data which implies a considerable negative correlation between IRI and CS.

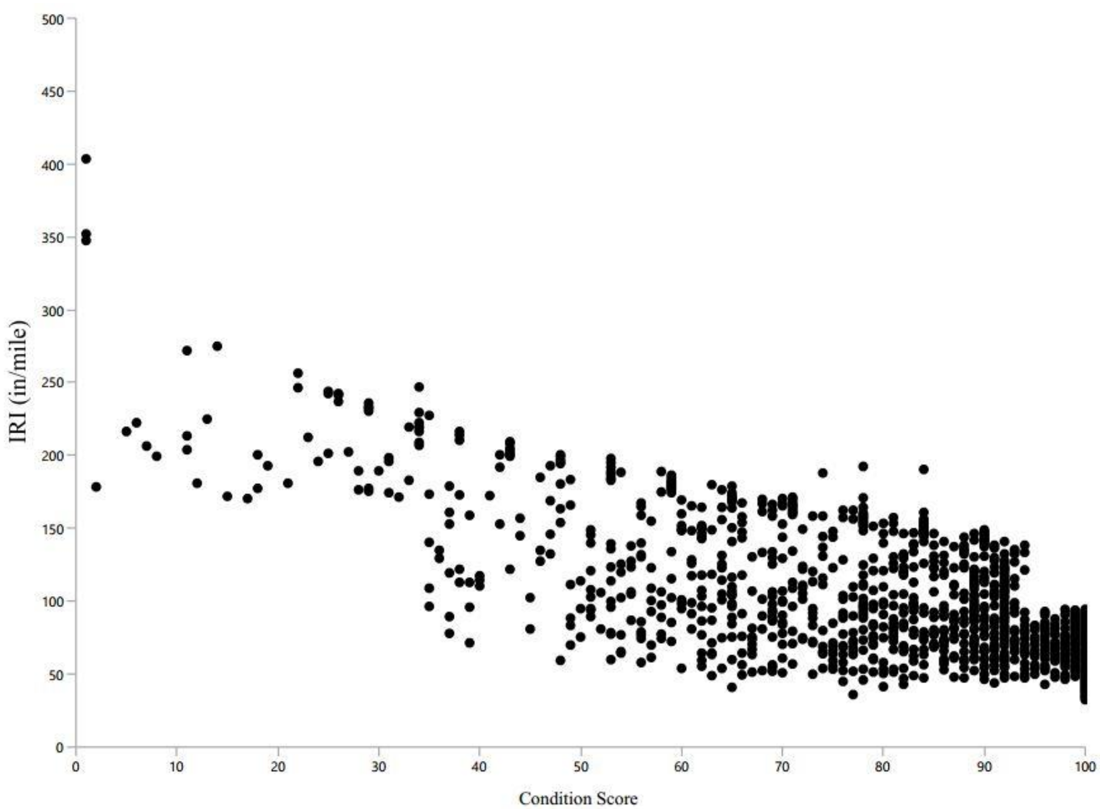


Figure 34-IRI Versus CS Scatterplot Graph

Figure *35* is the scatterplot graph of IRI and DS in order to visually illustrate the correlation between these two variables. Coefficient of correlation is calculated as "-0.5637" for this pair of data which implies a negative correlation between IRI and DS, however the correlation tends to be weaker than the one between IRI and CS.

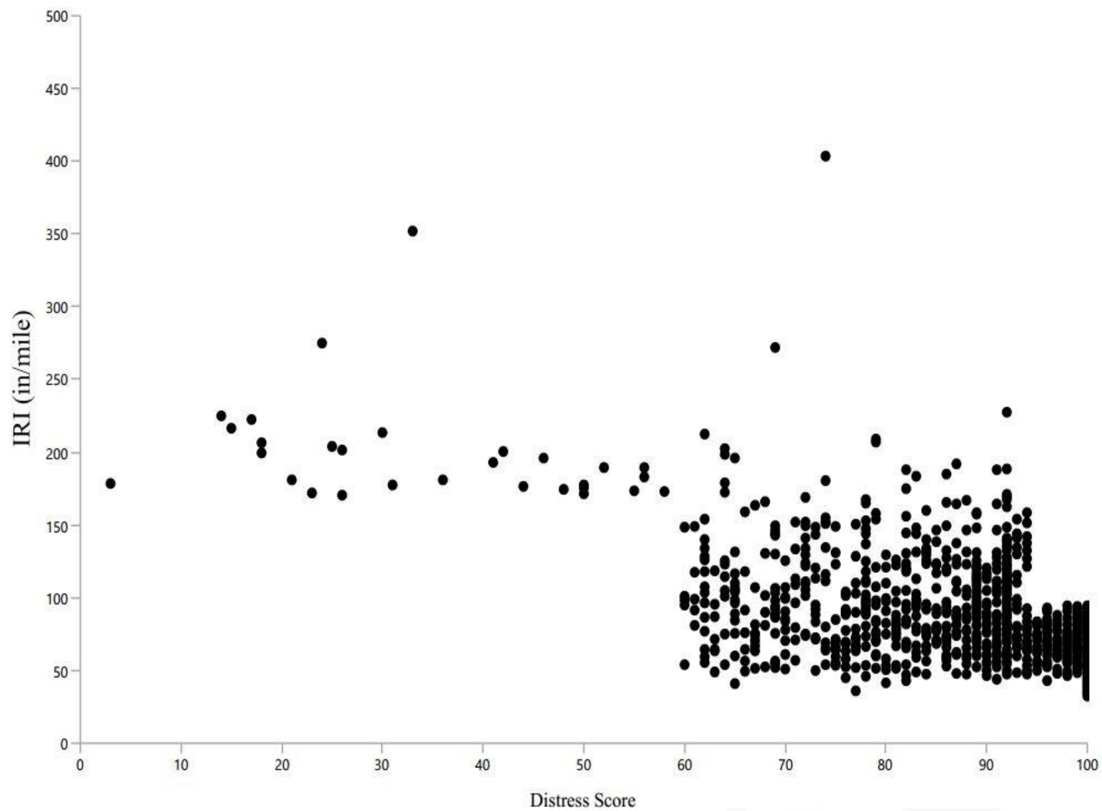


Figure 35-IRI Versus DS Scatterplot Graph

Graphs on **Figure *34*** and **Figure *35*** support the fact that there is a correlation between a pavement's IRI, and its condition score and distress score.

5.3 Classification

Due to large number of available data in the Houston District, data classification is of a great importance to perform the analysis and investigate the possible correlations. It is necessary to categorize the pavement sections into reasonable classes to include the pavement sections with uniform characteristics such as traffic class level and pavement type in a same family group. As mentioned earlier, Jointed Concrete Pavement (JCP) are excluded from the analysis due to very few available data on them. In order to categorize the pavement sections based on the traffic class, the product of Average Daily Traffic (ADT) and Speed limit was considered as the decision criteria. Then, a statistical approach was used to group pavements into three families. **Figure *36*** is the cumulative histogram of the pavement sections in Houston District with the frequency and the cumulative percentage on the vertical axes and the grouping bins on the horizontal axis.

Three traffic levels are identified using the 33%, 66% and 99% percentiles of the data. Therefore, traffic classes were assigned based on the following criteria:

- Low: ADT × Speed Limits: 1–240,000
- Medium: ADT × Speed Limits: 240,001–780,000
- High: ADT × Speed Limits: >780,000

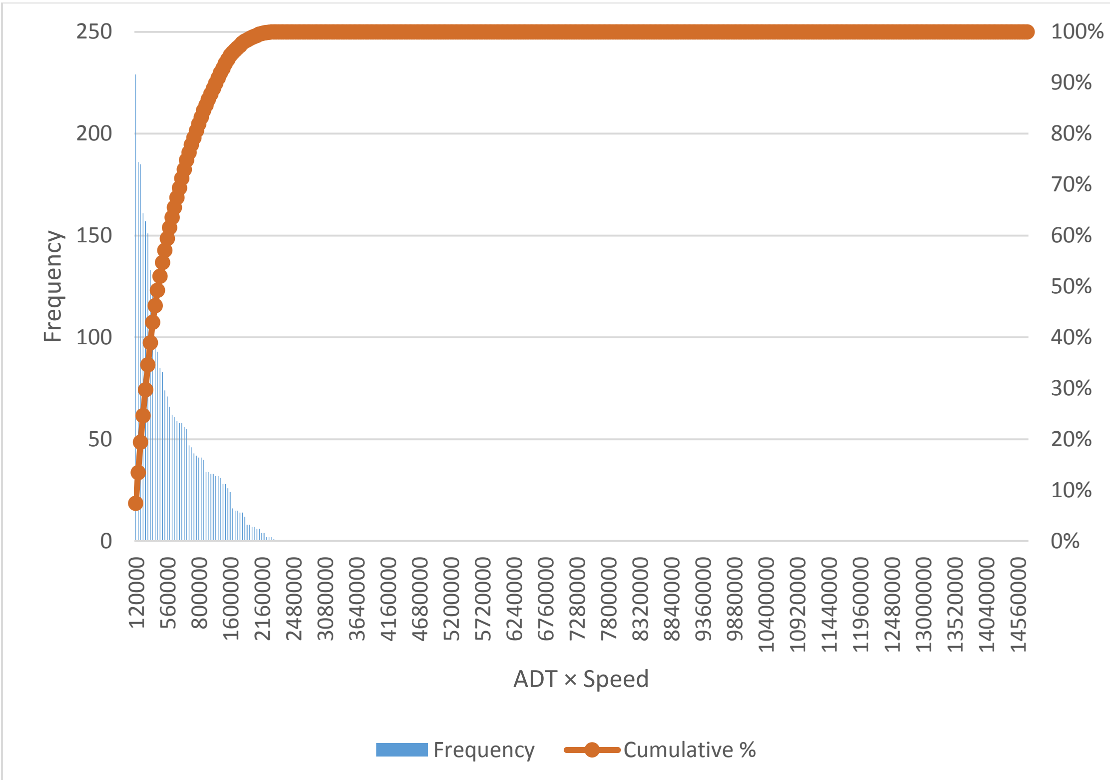


Figure 36-ADT × Speed Frequency and Cumulative Histogram Graphs

In addition, the t-test results from previous section imply the necessity of grouping pavement sections into urban and rural ones due to the significant difference among the behavior of CRCP and ACP pavements in urban and rural areas based on IRI performance metric. Implementing three grouping levels (i.e. ADT × Speed, Rural/ Urban Area and Pavement Type) results in the different combination illustrated per **Figure *37***. In order to display the pavement family types in a more understandable way, a summarized naming approach was used. For example, a pavement section which is classified as a "Low" traffic level, located in "Rural" area and is a "CRCP" section, is displayed as "LRC". Considering all possible combinations, total number of 12 groups are identified to develop the IRI-CS and IRI-DS correlation models.

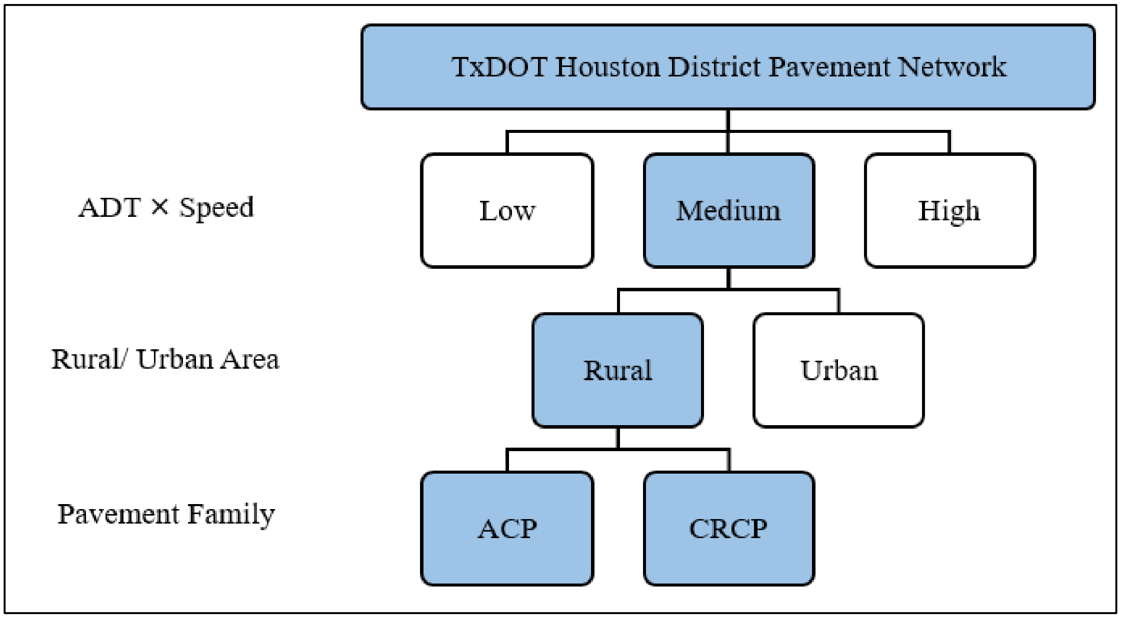


Figure 37 -Combination of Traffic Class, Urban-Rural Location, Pavement Type for IRI-CS and IRI-DS Correlation Models

5.4 Modeling

Modeling process starts with a literature review to find out the possible relationships between the selected performance metrics (i.e. IRI vs CS and IRI vs DS). As mentioned earlier in the literature review section, the most probable relationship to investigate between IRI, CS and DS is the linear relationship. Moreover, based on the equations provided in background section to calculate CS and DS, the exponential and logistic models might also make reasonable model fits. A linear logarithmic relationship was also taken into account. Therefore, the models listed in **Table *20*** were tested IRI-CS and IRI-DS data sets for further investigations in order to select the best fitting models of each correlation.

Table 20- General Modeling Equations

Regression Model	**General Equation**	**Parameters**
Linear Regression	$IRI = a + b \times X$	a, b
Exponential	$IRI = a \times e^{b \times X}$	a, b
Logistic	$IRI = \frac{c}{1 + e^{-a \times (X-b)}}$	a, b, c
Logarithmic	$IRI = a + b \times \log(X)$	a, b

* X: Predictor Variable (CS and DS)

Following are the steps performed in order to develop the best fitting correlation model of IRI-CS and IRI-DS:

5.4.1 Statistical Analysis

Using the JMP software, selected models were fitted to each family group of the pavements. Standard Least Square regression method was used to model the IRI-DS and IRI-CS correlations. Later on, a logarithmic transformation was employed on the predictor variable to develop the logarithmic prediction equation. Eventually, nonlinear regression modeling technique was used to develop the exponential and logistic models. The statistical significance of the developed models as well as the significance of the regression coefficients of the resulted models were tested at a significance level of 5%. **Figure *38*** and **Figure *39*** display the developed correlation models for IRI-DS and IRI-CS scenarios. General formula of the developed equations and each equation's coefficients are summarized in **Table *20***.

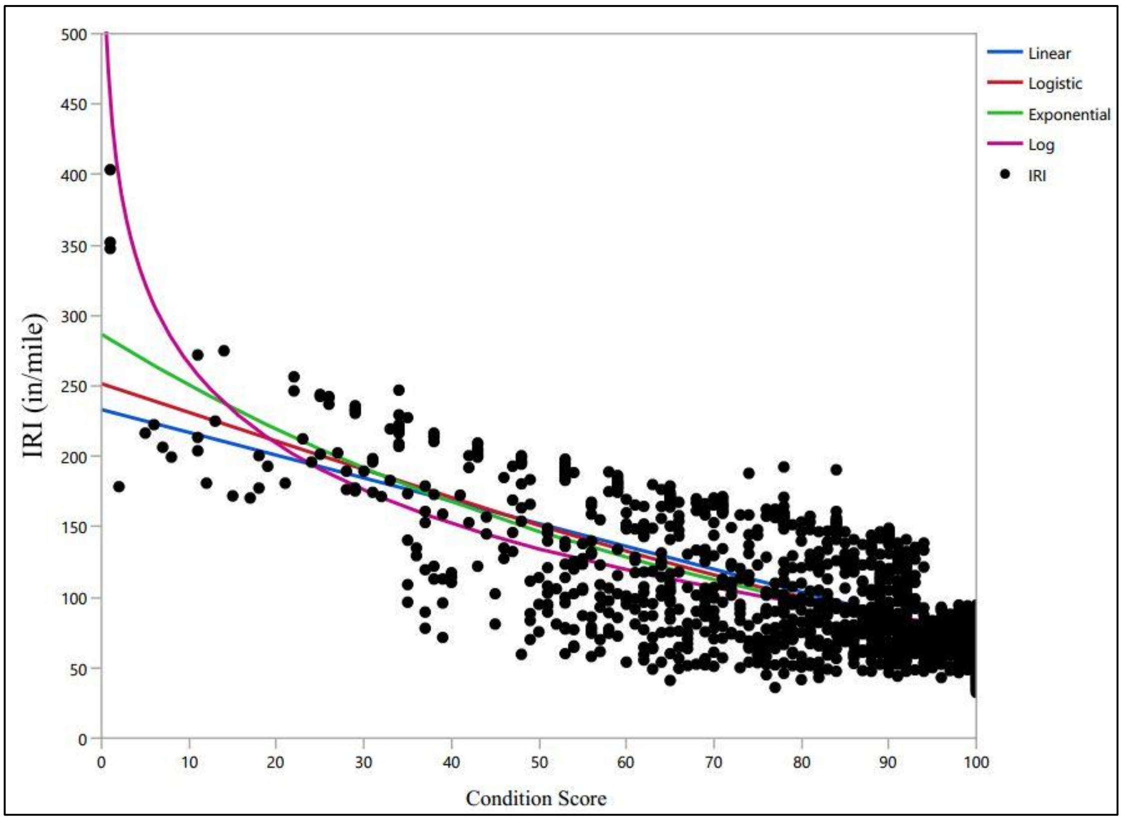


Figure 38-Developed Models of IRI-CS

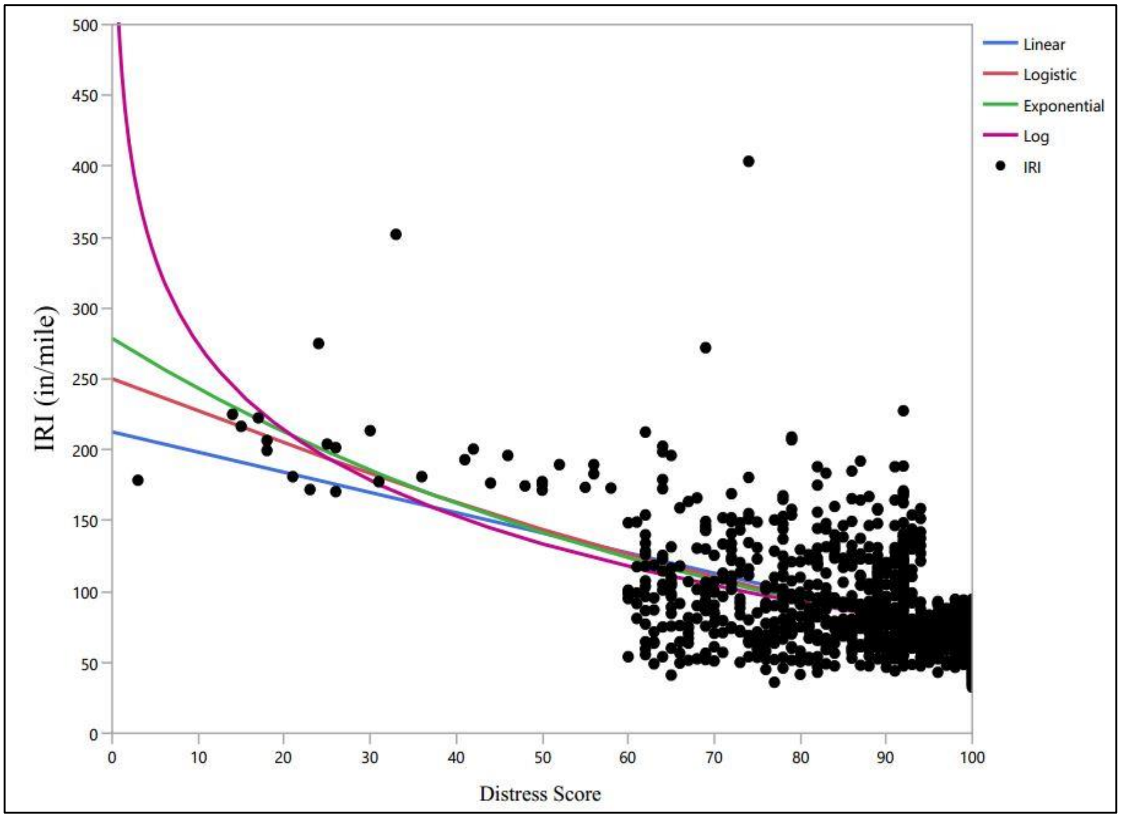


Figure 39-Developed Models of IRI-DS

5.4.2 Selection of Best Fitting Model

The process of selecting the best model starts with using the model comparison platform under the nonlinear modeling tool at JMP to compare the logistic, exponential, linear and logarithmic models. Following statistics were used to compare the first three fitted models:

- **RMSE:** Root Mean Square Error represents the standard deviation of the differences between the actual response variable values and the predicted ones which is calculated using the following formula:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\widehat{y_i} - y_i)^2}{n}} \quad (12)$$

where y_i is the ith response value, $\widehat{y_i}$ is the ith predicted response value and n is the sample size.

- **R-Square:** Coefficient of Determination represented by R-Square is the proportion of total variation explained by the model:

$$\mathrm{R-Square} = \frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{\sum_{i=1}^{n}(\widehat{y_i} - \bar{y})^2} \quad (13)$$

, where $\bar{y}$ is the average of the response values.

- **AAE:** Average Absolute Error which is the mean of the differences between the predicted values and the actual values:

$$\mathrm{AAE} = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \quad (14)$$

Aforementioned statistics were calculated for the fitted models of IRI-DS and IRI-CS. Results are summarized per **Table *21*** and **Table *22***. As noted in **Table *21***, the linear and logistic models between IRI and CS have the highest R-Square and least mean square errors. Implementing linear and logistic models on each family group, logistic model was selected as the best fitting model based on the number of groups with logistic models as their best fit. On the hand, the dominant correlation trend between IRI and DS is the logistic as displayed per **Table *22***. Similar approach was conducted on all family groups based on the selected models mentioned above to develop the correlation models for each subcategory of IRI-CS and IRI-DS datasets. Final models can be found per Appendix A.

Table 21-IRI-CS Developed Correlation Models

Regression Model	General Equation	RMSE	R-Square
Linear Regression	$\mathrm{IRI} = 233.18 - 1.62 \times \mathrm{CS}$	29.21	51 %
Exponential	$\mathrm{IRI} = 286.64 \times e^{-0.01 \times \mathrm{CS}}$	29.45	50 %
Logistic	$\mathrm{IRI} = \frac{423.39}{1 + e^{0.02 \times (\mathrm{CS} - 19.63)}}$	29.34	50 %
Logarithmic	$\mathrm{IRI} = 453.74 - 81.66 \times \log(\mathrm{CS})$	30.50	47 %

Table 22-IRI-DS Developed Correlation Models

Regression Model	General Equation	RMSE	R-Square
Linear Regression	$\mathrm{IRI} = 212.63 - 1.42 \times \mathrm{DS}$	26.29	31 %
Exponential	$\mathrm{IRI} = 278.59 \times e^{-0.01 \times \mathrm{DS}}$	26.26	32 %
Logistic	$\mathrm{IRI} = \frac{532.86}{1 + e^{0.02 \times (\mathrm{DS} + 7.04)}}$	26.23	32 %
Logarithmic	$\mathrm{IRI} = 476.28 - 87.60 \times \log(\mathrm{DS})$	26.7	29 %

5.5 IRI Assessment Thresholds Predicted from CS and DS

One objective of the thesis is to develop threshold values for IRI. The correlation models discussed earlier in this section are used to accomplish this objective. Consequently, rating thresholds of DS and CS illustrated in **Figure *2*** are used as the input variables to derive the IRI thresholds. **Figure *40*** and **Figure *41*** illustrate a sample procedure of determination of IRI thresholds predicted from DS and CS for LRA family class. (Numbers are rounded to the closest 10) (complete set of results can be found per Appendix B).

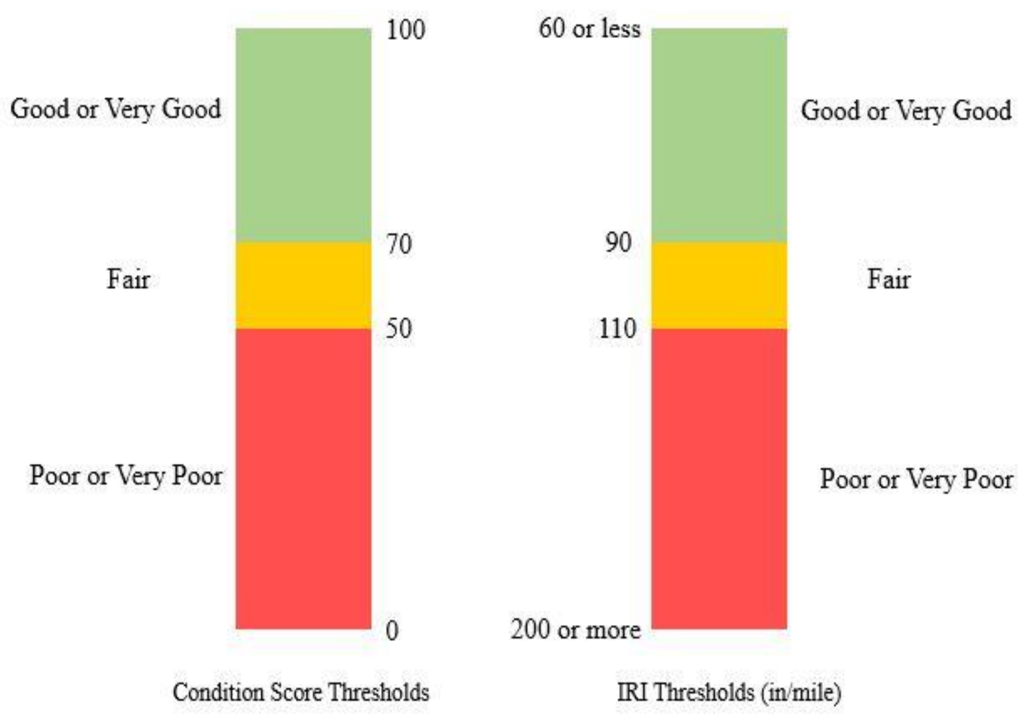


Figure 40-IRI Thresholds of LRA Family Class Predicted from CS

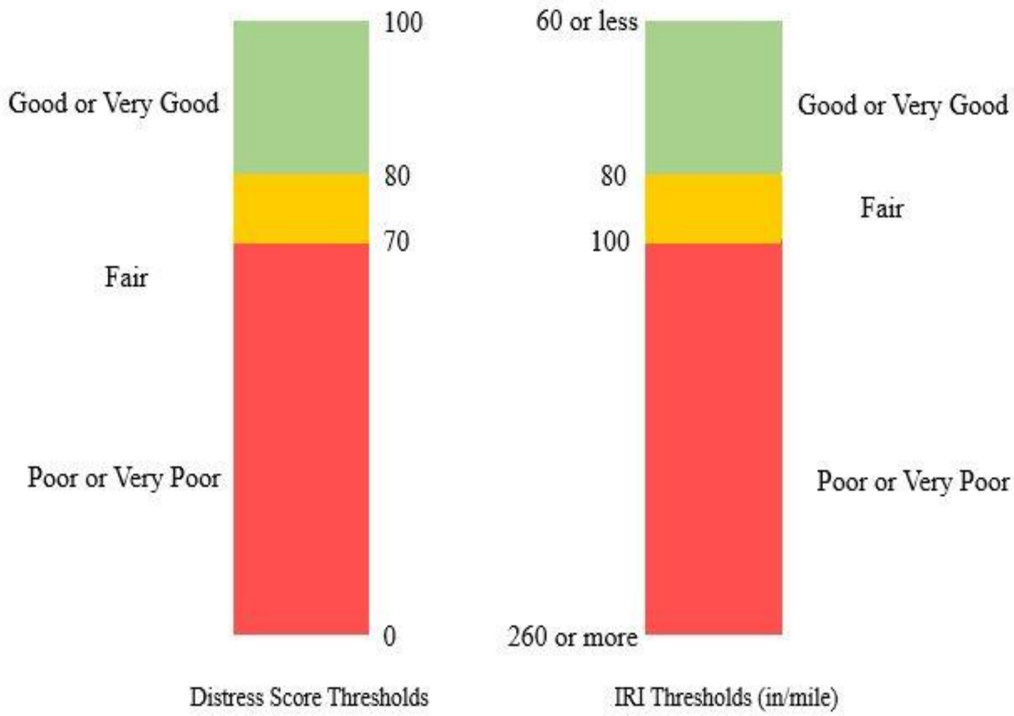


Figure 41-IRI Thresholds of LRA Family Class Predicted from DS

6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary

This study investigates the effect of using multiple metrics and varying thresholds on the assessment of the overall performance of pavement networks. The selection of the appropriate performance metrics and measures to evaluate the condition of pavement networks is of great importance because it affects the development of maintenance and rehabilitation plans and the allocation of funds for these plans. To perform this study, empirical data were obtained from TxDOT's Pavement Management Information System (PMIS) database for the past nine years (2007-2015) on three performance metrics used in Texas: IRI, DS, and CS. The study area consists of the Houston District of TxDOT. The Houston district was selected for conducting this study because it includes both urban and rural areas and it includes different pavement types (CRCP and ACP). This network consists of 2,386 lane-miles of urban roads and 1,571 lane-miles of rural roads.

6.2 Conclusions

The conclusions of this study are discussed as follows:

6.2.1 Pavement Performance in Rural and Urban Areas

Analysis of IRI data for the past nine years yielded that urban roads have significantly and consistently higher IRI than rural roads throughout the past nine years. However, the DS and CS data do not provide a strong evidence to support the idea that rural and urban pavements perform differently based on distresses only (i.e., DS) or combined distress and roughness (i.e., CS). The 9-year pattern of DS data indicates that at the network level, urban lane-miles tend to have a better performance than rural lane-miles in terms of distress; however, the CS pattern indicates that rural lane-miles tend to have a better performance than urban lane-miles in terms of the combination of distress and ride quality. The three metrics agreed about 22.2 percent of the time (i.e. 2 years out of 9 study years) when comparing pavement performance in rural and urban areas.

6.2.2 ACP versus CRCP

Analysis of IRI data yielded that CRCP roads have significantly and consistently higher IRI than ACP roads throughout the past nine years. However, the DS and CS data do not provide a strong evidence to support the idea of different performance of CRCP and ACP pavements based on distresses only (i.e., DS) or combined distress and roughness (i.e., CS). The 9-year pattern of DS data indicates that at the network level, CRCP roads tend to have a better performance than ACP roads in terms of distresses only as well as combined distress and ride quality (i.e., CS). The three metrics agreed 30 percent of the time (i.e. 3 years out of 9 study years) when comparing the performance of CRCP and ACP lane-miles.

6.2.3 Correlation Between Pavement Performance Metrics

Using the statistical analysis software "JMP", possible correlations between IRI and DS as well as IRI and CS were explored for several pavement families and traffic conditions in the Houston District. The Logistic model was selected as the best fit for establishing correlations between these performance metrics.

6.3 Recommendations

Recommendations for future research include:

- Consider change in pavement condition over time as a basis for evaluating pavement performance.
- Consider additional performance metrics suggested in FHWA's MAP-21 NPRM (e.g., rutting for ACP and cracking percent for CRCP).
- In Section 3 of this study, pavements were classified into urban and rural ones based on the criterion suggested by MAP-21 (i.e., most recent Census data). However, more specific criteria for classifying pavements into urban and rural ones such as traffic level and roadway design may need to be considered.
- Extend the study beyond the Houston District to take advantage of the large PMIS database in investigating the relationships among the various performance metrics used for pavements.
- Investigate the transformation of the response variable (i.e. IRI) in building IRI-DS models to rectify the skewness of the data to one side of the diagram depicted per **Figure *35*** (Carroll et al. 1984).
- Investigate the organizational and technical linkages between performance management and pavement management.

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APPENDIX A.

CORRELATION MODELS

IRI vs CS

General Developed Equation: $\text{IRI} = \frac{c}{1 + e^{-a \times (CS - b)}}$

Table 23-IRI Versus CS Correlation Model Statistics

Family Group	a	b	C	R-Square	RMSE	AAE
LRA	-0.01168725	-1257.49	493,793,812.20	34 %	20.18	14.43
LRC	-0.12972355	102.34	141.91	67 %	20.39	12.68
LUA	-0.02975193	82.01	177.44	32 %	30.14	23.72
LUC	-0.0168995	22.18	438.17	65 %	27.73	26.59
MRA	-0.01211358	-1188.44	368,265,975.16	20 %	21.63	15.88
MRC	-0.1361007	103.95	129.39	55 %	17.64	12.81
MUA	-0.01548849	-834.11	126,757,260.54	45 %	25.25	18.43
MUC	-0.04489462	91.96	207.55	69 %	21.98	15.46
HRA	-0.04064313	67.17	290.64	71 %	27.48	17.86
HRC	-0.26866859	101.19	142.17	58 %	22.99	14.59
HUA	-0.0212124	-8.1	850.37	84 %	25.71	19.85
HUC	-0.06741581	100.37	179.83	64 %	25.51	17.60

IRI vs DS

General Developed Equation: $\mathrm{IRI} = \frac{c}{1 + e^{-a \times (DS - b)}}$

Table 24-IRI Versus DS Correlation Model Statistics

Family Group	a	b	c	R-Square	RMSE	AAE
LRA	-0.0143228	-865.48	63,753,707.62	35 %	18.81	13.62
LRC	-0.10082565	102.63	145.43	67 %	18.93	10.93
LUA	-0.51243975	101.06	92.67	24 %	27.78	20.99
LUC	-0.13943386	100.46	163.52	52 %	32.78	19.43
MRA	-0.446164	102.97	75.85	13 %	18.90	14.32
MRC	-0.10689417	106.79	121.78	55 %	12.77	10.08
MUA	-0.01703566	-615.54	12,721,322.10	29 %	25.22	17.14
MUC	-0.01606125	21.65	393.42	30 %	18.80	12.09
HRA	-0.01799824	-527.33	4,817,771.77	24 %	19.99	13.82
HRC	-0.04110947	99.48	166.17	51 %	16.63	10.35
HUA	-0.1212074	92.12	228.28	43 %	45.40	23.52
HUC	-0.17946493	101.97	142.38	57 %	21.51	14.09

APPENDIX B.

IRI THRESHOLDS PREDICTED FROM DS AND CS

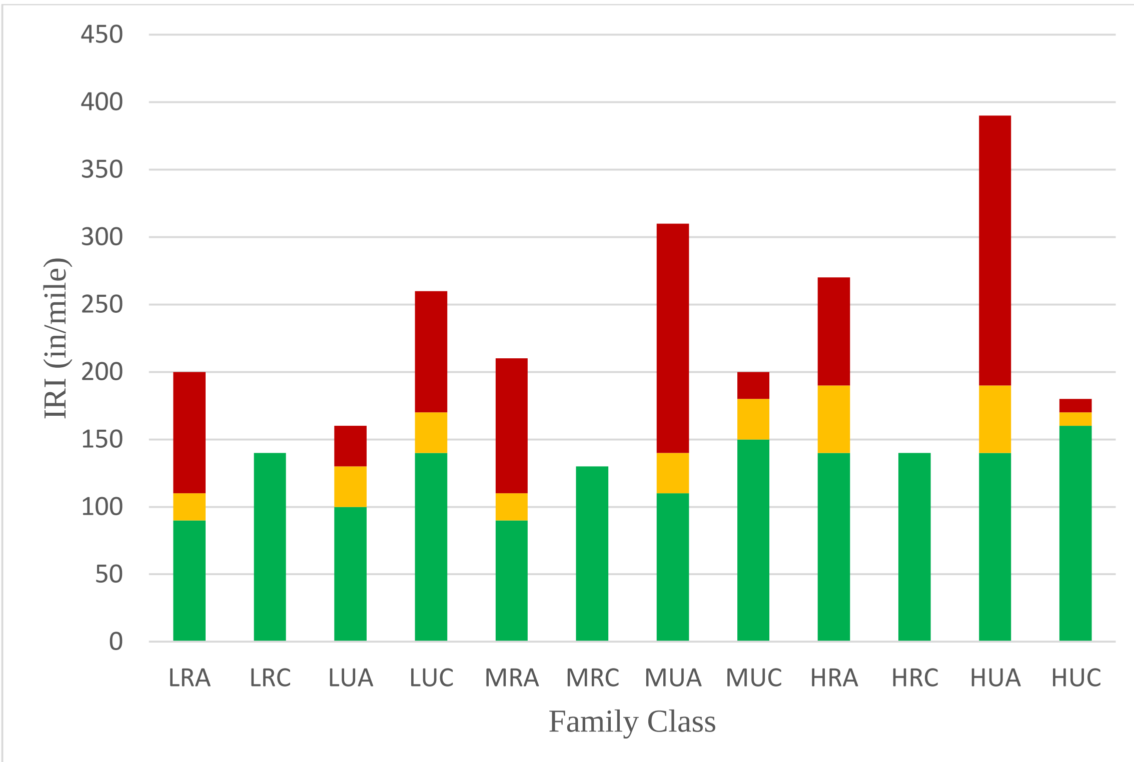

Figure 42-IRI Thresholds Predicted from CS

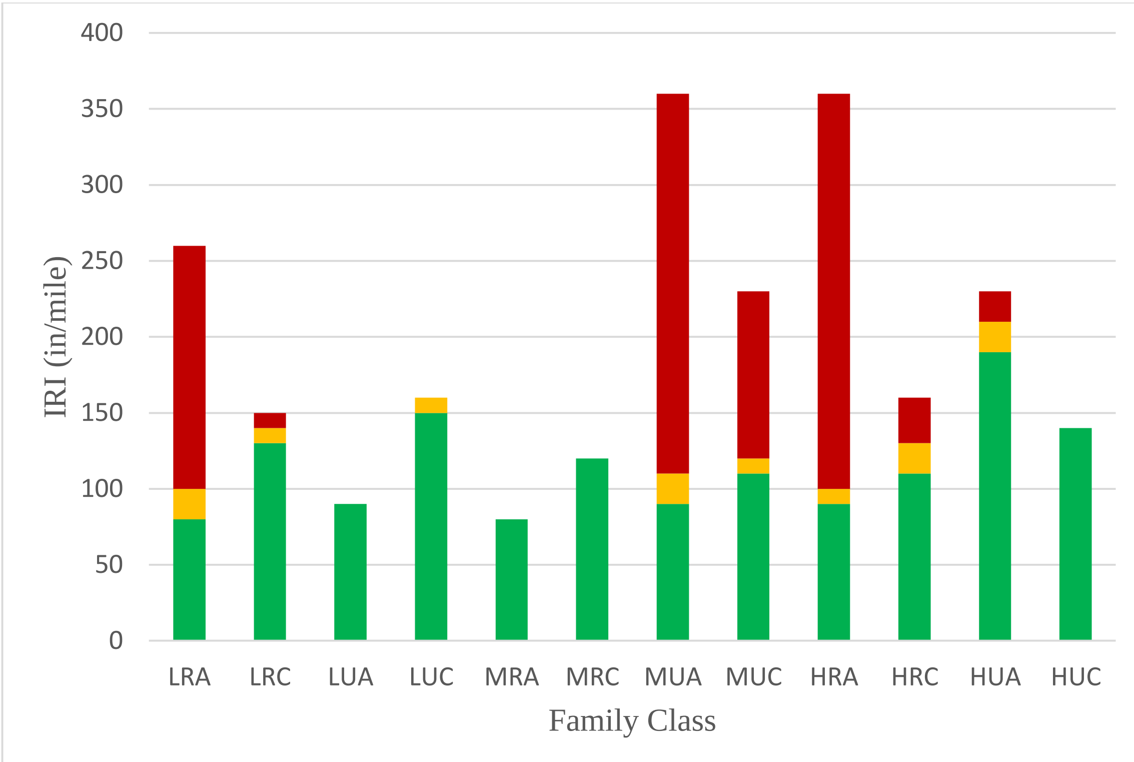

Figure 43-IRI Thresholds Predicted from DS