PB2002-104722

A Center of Excellence for Rural and Intermodal Transportation

MPC REPORT NO. 02-130

Utilizing the Long-Term Pavement Performance Database in Evaluating the Effectiveness of Pavement Smoothness

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March 2002

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
March 2002

3. REPORT TYPE AND DATES COVERED
project technical

4. TITLE AND SUBTITLE
Utilizing the Long-Term Pavement Performance Database in Evaluating the Effectiveness of Pavement Smoothness

5. FUNDING NUMBERS

6. AUTHOR(S)
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University of Wyoming

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Mountain-Plains Consortium
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Fargo, ND 58105

8. PERFORMING ORGANIZATION REPORT NUMBER
MPC 02-130

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Dot
RSPA
Washington, DC

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

State Highway Agencies (SHAs) in the United States use smoothness specifications to insure that they are providing the public with quality roads. Monetary incentives/disincentive policies based on the initial roughness values are used by SHAs to encourage contractors to build smoother roads. To justify the extra costs associated with smoothness specifications, it is important to demonstrate that smoother roadways do stay smooth over time. This research study was conducted at the University of Wyoming to examine if the initial roughness of a pavement section has any effects on its long-term performance. A large number of test sections from the long-term pavement performance (LTPP) database was included in the study. The statistical tests performed indicate that asphalt and concrete pavements with low initial smoothness stay smooth over tie. This study also emphasized the importance of utilization of LTPP database.

14. SUBJECT TERMS
roads, pavement, concrete, asphalt, smoothness, LTPP, database

15. NUMBER OF PAGES
119

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT
UL

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March 2002

Disclaimer

Preface

State Highway Agencies (SHAs) in the United States use smoothness specifications to insure that they are providing the public with quality roads. Monetary incentives / disincentive policies based on the initial roughness values are used by SHAs to encourage contractors to build smoother roads. To justify the extra costs associated with smoothness specifications, it is important to demonstrate that smoother roadways do stay smooth over time. This research study was conducted at the University of Wyoming to examine if the initial roughness of a pavement section has any effects on its long-term performance. A large number of test sections from the long-term pavement performance (LTPP) database was included in the study. The statistical tests performed indicate that asphalt and concrete pavements with low initial smoothness stay smooth over time. This study also emphasized the importance of utilization of LTPP database.

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CHAPTER 1. INTRODUCTION

BACKGROUND

The general public perception of a good road is one that provides a smooth ride. A pavement section that has a high level of roughness causes users discomfort and more wear and tear on vehicles. Consequently, a major focus of state highway agencies in management of their highway networks has been to determine the ride quality of the pavement, which is derived from roughness characteristics. Smoother pavements not only produce a better ride, but also can save money. In the recent National Quality Initiative (NQI) survey, pavement smoothness is listed as the most significant measure that the traveling public uses to judge the quality of pavements [1]. As smoothness is the public's measure of quality workmanship, the Federal Highway Administration (FHWA) is working closely with industry, academia, and state highway agencies (SHAs) to: [1]

1. Identify construction practices that will improve pavement smoothness;
2. Determine the most efficient, timely, and accurate ways to measure pavements smoothness; and
3. Develop draft guide specifications and procedures to ensure pavement smoothness and widely disseminate this information to all parties involved in the construction and maintenance of pavements.

Based on a survey conducted by the FHWA in 1995, smoothness of ride was found to be one of the most important factors in increasing public satisfaction with the highway system. [1]

Over the years, pavement roughness measuring devices have improved with new technological discoveries. The earliest form of roughness measuring devices was a sliding straightedge, which was used to measure roughness. Other devices were later developed, including rolling straightedges, profilographs, response-type road roughness measuring systems, and profilometers. Each new device incorporated some improvements over the earlier measuring devices. Such improvements included speed of operation, accuracy, repeatability, or a combination of these factors. Although all roughness devices can be used to determine the roughness of new and old pavements, profilographs are widely used devices in accepting new concrete pavements. Profilographs measure the profile of a pavement section and give a Profilograph Index (PI). This PI value can be converted to some other easily interpretable values, such as the International Roughness Index (IRI) by computer softwares. Earlier, most of the state's highway agencies have implemented smoothness specifications based on the PI ensuring good ride quality. The course of action for pavements that do not meet the required smoothness levels depends on the SHA and its policies. Some SHAs require contractors to perform corrective work on rough sections. Other SHAs assess penalties for rough pavement sections. In addition, some SHAs pay incentives for those sections that are "significantly" smoother than certain limits.

PROBLEM STATEMENT AND OBJECTIVES

A number of SHAs have set a minimum acceptance level for pavement smoothness. In addition, many SHAs have incentive/disincentive policies encouraging contractors to build smoother pavements. Building a pavement smoother is directly related to the initial construction cost. It is a critical question for the SHAs, whether it is cost effective to build a pavement with a smoother surface or not. If it can be shown that future roughness values of pavements depend on the initial roughness values, then it would be cost effective to spend more money on building smoother pavements. Today, most incentive/disincentive policies are developed without in-depth studies to determine their cost effectiveness. There are major differences in SHA specifications. The main objective of this study is to conduct a nation-wide study to find the effect of the initial smoothness of a pavement surface on the long-term pavement performance. Such determination will help in evaluating effectiveness of current pavement smoothness specifications.

REPORT ORGANIZATION

This research project was performed in two phases. The first phase concentrated on previous related literature review and a nationwide survey to find out the current practices of smoothness specifications. The second phase dealt with collecting and analyzing yearly roughness data for asphalt and concrete sections in IRI unit from the long-term pavement performance (LTPP) database and evaluating the effect of initial roughness on the long-term performance of pavements. Some important conclusions from the previous related research and the present practices of roughness measurements are summarized in chapter II. Also, the current practices of Datapave software use are mentioned. Chapter III summarizes the findings of a nation-wide survey on pavement smoothness policies. Chapter IV outlines the design of the experiment for this research project. In Chapter V, different statistical analyses were performed on the data set to evaluate the effect of initial roughness on future roughness. Finally, a summary of the entire research, conclusions, and recommendations for future research are presented in Chapter VI.

CHAPTER 2

LITERATURE REVIEW

Highway agencies use pavement roughness to monitor the condition and performance of their road networks due to its effects on ride quality and vehicle operating costs. The existing conditions of pavements, measured by roughness, determine distribution of available funds for highway allocation, such as providing routine maintenance or reconstruction of pavement sections. Road roughness can be defined as "the deviations of a pavement surface from a true planner surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic pavement loads, and pavement drainage" [2]. In other words, roughness can be described as vertical surface undulations that affect vehicle operating costs and the riding quality of that pavement as perceived by the user [3].

In general, road roughness can be caused by any of the following factors [4] :

a. construction techniques, which allow some variations from the design profile;

b. repeated loads, particularly in channelized areas, causing pavement distortion by plastic deformation in one or more of the pavement components;

c. frost heave and volume changes due to shrinkage and swell of the subgrade;

d. non-uniform initial compaction.

Pavement roughness is measured for several reasons, several which can be stated from records of the Transportation Research Board Committee on Pavement Condition Evaluation [5]. According to that report, pavement roughness is measured to:

1. Measure acceptability for newly constructed pavements.
2. Assist maintenance engineers and highway administrators to determine optimum maintenance programs.

3. Aid in the establishment of priority for major maintenance, reconstruction, and relocation projects.
4. Furnish information needed for sufficiency ratings and need studies. This involves a comprehensive study of pavement systems in a given area.
5. Assist in determining the load carrying capacity of pavement pertaining to volume of traffic and loads.
6. Aid the design engineer in determination of the degree of success with which his design has met the design criteria and help him learn causes of failure.
7. Serve as the basis for new concepts and designs.

In the last few decades, several studies pointed out major penalties of roughness to the user. In 1960, Carey and Irick [6] showed that the driver's opinion of the quality of serviceability provided by a pavement surface primarily is influenced by roughness. Between 1971 and 1982, the World Bank supported several research activities in Brazil, Kenya, the Caribbean, and India. The main purpose of these studies was to investigate the relationship between road roughness and user costs. In 1980, Rizenbergs [7] pointed to the following penalties associated with roughness: rider non-acceptance and discomfort, less safety, increased energy consumption, road-tire loading and damage, and vehicle deterioration. Gillespie et al. (1981) [8] examined the relationship between road roughness and vehicle ride to illustrate the mechanism involved and to reveal those aspects of road roughness that play the major role in determining the public's perception of road serviceability. It is widely suspected that the initial roughness of a pavement section will affect long-term performance. In his 1991 study, Michael Janoff [9] shows a positive correlation between smoothness and long-term pavement performance.

Due to the importance of pavement roughness, most SHAs have established smoothness specifications for new pavement construction. About one-half of the states require that a specific limit of smoothness be met, whereas the reminder of states are using a variable scale with pay adjustments, depending on the degree of smoothness achieved [10].

PAVEMENT ROUGHNESS MEASURING DEVICES

Primarily two types of equipment measure road roughness in the United States: Equipment that measures a vehicle's response to roughness, or response-type road roughness meters (RTRRMs), and equipment that measures the road profiles or profiling devices [11]. Table 2.1 summarizes various equipment available for measuring longitudinal roughness. The section below discusses some of the pavement-roughness-measuring equipment.

Straightedge

A straightedge is the simplest device to measure pavement roughness. At one time it was undoubtedly the only tool to evaluate pavement roughness. It is usually 8 to16 feet long and is made of wood or metal. When it is placed on the pavement surface, variations in distance from the bottom of the straightedge to the pavement surface is readily observed, and measurements of these variations can be made. This tool is labor intensive for large projects; thus most applications are limited to the evaluation of localized areas [12].

Rolling Straightedge

A rolling straightedge is merely a straightedge with a wheel or wheels under each end. A wheel located at its midpoint is linked to an indicator that shows deviations from the plane of the rolling straightedge.

Profilographs

Road profilographs are low-speed devices (hand push at walking speed) designed to measure roughness of road surfaces [13]. They are used primarily to measure roughness of new or newly surfaced pavements before they are open for traffic. Profilographs consist of a rigid beam or frame with a system of support wheels that serve to establish a datum from which deviation can be evaluated. A profile wheel is located at the midpoint of the unit, which creates a profile by recording vertical variations from the datum on a strip chart recorder. This analog trace usually has a true vertical scale and a horizontal scale of 1 inch = 25 feet. A blanking band is then used on the analog trace to "blank" out minor aberrations and provides a measurement called the Profilograph Index (PI).

Profilographs have a few definite advantages over other roughness measuring devices. They are somewhat more sophisticated than the rolling straightedge, can be used on pavement surfaces a few hours after placement, field personnel also easily understand them, and the strip chart provides the precise location of surface irregularities. The main disadvantage of this device is its slow operating speed (approximately 3 mph) and the time required evaluating the charts and calculating the PI. In addition, the blanking band can hide certain cyclic features associated with some aspects of construction. Two models of profilographs are in wide use today. These are the Rainhart and the California-type profilographs.

Response-Type-Road-Roughness-Measuring Systems (RTRRMS)

RTRRMS evaluate road roughness by measuring the dynamic response of a mechanical device traveling over a pavement surface at a given speed. Automobiles and standardized trailers may be used with measurements taken of the vertical movements of the rear axle with respect to the vehicle frame [11]. Accordingly, a relative measure of roughness that depends on the mechanical system and the speed of the travel is obtained. The most widely used profilometers are Bureau of Public Roads (BPR), Road Meters, PCA road meters, and the Mays Ride meter.

Profilometers

The main reason for developing profilometers was the need for a high-speed profiling system that would yield a "true" portrayal of pavement surface characteristics. This led to the development of the inertial profilometers in the early 1960's. Response type measurements are not reproducible over time while profile measurements are repeatable. In practice, the range and resolution of such systems are limited to a minor degree. However, within the wavelength and amplitude limitations of the systems, a profile measurement may be called "absolute." In other words, it does not require comparison to any other system, but requires only calibration of its own sensors and associated electronics, together with proper functioning of its computer hardware and software. They are able to duplicate roughness measurement output of several RTRRMS roughness indices, including IRI, Mays Meter, BPR Roughmeter, PCA meter, and others. The main types of profilometers are the South Dakota Road Profilometer, GM profilometer, K.J. Law 690DNC, Automatic Road Analyzer (ARANA), Portable Universal Roughness Device (PURD), Swedish Laser Road Tester, Law Model 8300 A Pavement Roughness Surveyor, PRORUT-FHWA System, Dynatest 5000 Roughness and Distress Meter (RDM), and the French Longitudinal Profile Analyxer (APL).

A list of most widely used roughness measuring devices is given in Table 2.1. Table 2.2 [14] summarizes the pavement roughness testing devices used by various states. This table shows that only Vermont still is using a response type roughness device while all other states are using various types of profilometers. Most states are using K.J. Law profilometers.

Table 2.1 List of Roughness Measuring Devices

Device	***Operating Principal***	Source
Straightedge	Actual Variation in Road Profile	-
Rolling Straightedge	Actual Variation in Road Profile	-
Mays Ride Meter	Response Type	Rainhart Co.,TX
Model T 6600	Inertial Profilometer	K.J Law Engg
Profilometer/PCA	Response Type	James Cox Co.
PURD / ARAN	Housing Mounted	PI-Ontario
Swedish Laser RST	Accelerometer Multipurpose	Novak, Dempsey & Assoc., IL
FHWA PSM	***Non-contact Sensors***	Earthech, Inc.,Baltimore,MD
Rainhart Profilograph	Multi wheel Profilograph	Rainhart Co, TX
California Profilograph APL	Multi wheel Profilograph	California
South Dakota Road Profiler	Profilometer principle	South Dakota DOT
RODRECON	Accelerometer and laser sensor	PASCO, JAPAN

Table 2.2 Equipment Used by Various SHAs to Collect Roughness Data

Equipment	States That Are Using	Number of States
ICC Profiler	AK, FL, GA, IA, KS, MT, NE, NV, OH, SD, PA, UT, WA	13
K.J. Law Profiler	AZ, KY, NH, OH	4
Roadware Profiler	AR, CO, CT, IA, ME, MD, MA, MO, NJ, NM, SD	11
Not Specified	MI, MS, RI, VA	4
DOT Profiler	CA, TX	2*
Pathway Profiler	MN, ND, WY	3*
Pavetech Profiler	MN, WI	2*
Mays Meter	VT	1*

* Several states have more than one type of equipment

ROUGHNESS INDICES

The measurement of pavement roughness is accomplished by using several different indices and devices. Some of these indices are: Profilograph Index (PI), International Roughness Index (IRI), Root-Mean-Square Vertical Acceleration (RMSVA), Pavement Serviceability Index (PSI), Quarter-Car Index (QI), South Dakota Index, Average Rectified Velocity (ARV), Ride Number (RN) and Average Rectified Slope (ARS) [4]. These indices require different algorithms to rate pavement roughness.

As shown in Table 2.3, the majority of states are relying on the IRI to summarize the roughness of roadways, which is described in the next section.

Table 2.3. Roughness Index Used in PMS

IRI	PSI	RN	PSR	RQI	RMSVA	SDI	HCS
AK, AZ, AR, CA, CO, CT, FL, IA, KS, KY, MA, MD, ME, MN, MO, MS, MT, NE, NH, NM, ND, NV, OH, OR, PA, RI, VT, VA, WA, WI, WY	FL, MN, MS, TX, NE, WI	MD, TX, OH	MA, NH	MI, NJ	MO	SD, NH	GA, OH, UT
31*	6*	3*	2*	2*	1*	2*	3*

* Several states produce more than one index

International Roughness Index (IRI)

Almost every automated road profiling system includes software to calculate a statistic called the International Roughness Index (IRI). Since 1990, the Federal Highway Administration

(FHWA) has required states to report road roughness on the IRI scale for inclusion in the Highway Performance Monitoring System (HPMS). The World Bank sponsored several large-scale research programs in the 1970s that investigated some basic choices facing developing countries [15]. It turns out that poor roads also are costly to the country as a whole, due to user costs, such as damage to vehicles. Road roughness was identified as a primary factor in the analyses and trade-offs involving road quality versus user cost. The problem was, roughness data from different parts of the world could not be compared. Even data from the same country were suspect because the measures were based on hardware and methods that were not stable over time. In 1982, the World Bank initiated a correlation experiment in Brazil to establish correlation and a calibration standard for roughness measurements. In processing the data, it became clear that nearly all roughness measuring instruments in use throughout the world were capable of producing measures on the same scale, if that scale were suitably selected.

The IRI can be defined as: the simulation of the roughness response of a car traveling at 80 km/hr. It is the Reference Average Rectified Slope, which expresses a ratio of the accumulated suspension motion of a vehicle, divided by the distance traveled during the test [15].

The computation of IRI often is done by simulating the response of a generic vehicle with standard mass, spring constants, and damping constraints [15]. This numerical procedure is simplified by using only one corner of the vehicle in the computations, leading to the term "quarter car simulation" (US Department of Transportation). Figure 2.1 shows a quarter-car model for the computation of IRI. IRI is the only existing roughness index that has been demonstrated to be reproducible with a wide variety of equipment, which include RTRRMS, rod and level, single and two track profiling systems [16].

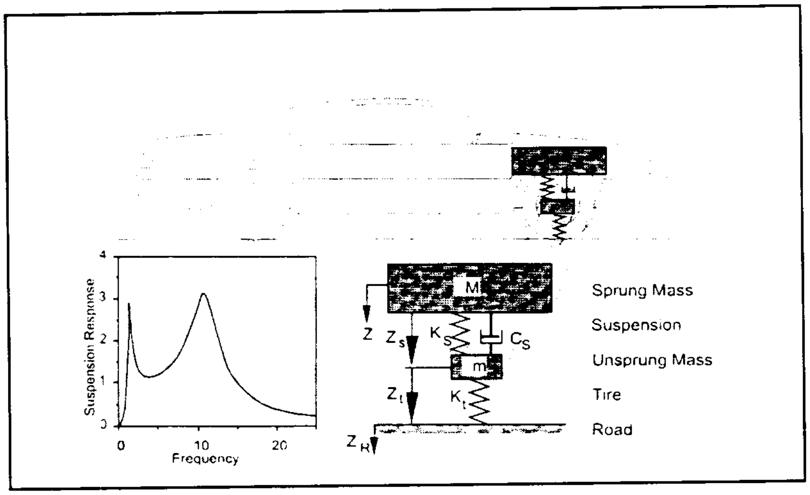

Figure 2.1 The Quarter Car Model

Table 2.4 shows how most states use data from both wheel paths when calculating IRI. Seven states use right wheel path data while only three states use left wheel path data in IRI calculations.

Table 2.4 Data Used in IRI Calculations

Left Wheel Path Only	Right Wheel Path Only	Left and Right Wheel Path	Half Car Simulation
AK, MN, WI	CT, FL, KS, NE, NH, NV, VT	AR, CO, IA, NJ, MD, MA, MS, MO, MT, NM, ND, OH, OR, PA, RI, SD, TX, VA, WA, WY	AZ, CA, GA, UT
3	7	20	4

The use of IRI in the USA has grown rapidly because the Federal Highway Administration (FHWA) requires that all SHAs report pavement roughness measurements in these units. Also, most SHAs have on working pavement Management Systems (PMS) in place. These PMS use IRI measurements in prioritizing maintenance, rehabilitation and reconstruction of pavement projects.

PAVEMENT CONDITION RATING AND IRI

Pavement condition ratings are based on a Pavement Serviceability Rating (PSR) system. The PSR scale runs from 0.0 to 5.0, with 5 being the best. Factors considered in determining the PSR for a given section of roadway are ride quality in terms of the IRI, average rut depth and age of the surface course. IRI values and average rut depth are taken directly from profiler data.

Because of similarity in the response between various modes of vehicle performance, roughness measured on the IRI scale is closely related to each mode of performance. Figure 2.2 shows data from the International Road Roughness Experiment [15] relating the Pavement Serviceability Index (PSI) to IRI. As serviceability ratings are dominated by vehicle ride perception, a close correlation with IRI roughness is expected. The data in the Figure 2.2 show a precise relationship, which is approximated by the simple equation:

$$PSI \approx 5.0 - IRI/100 \qquad \text{For } 0 < IRI < 300 \text{ (in/mile)}$$

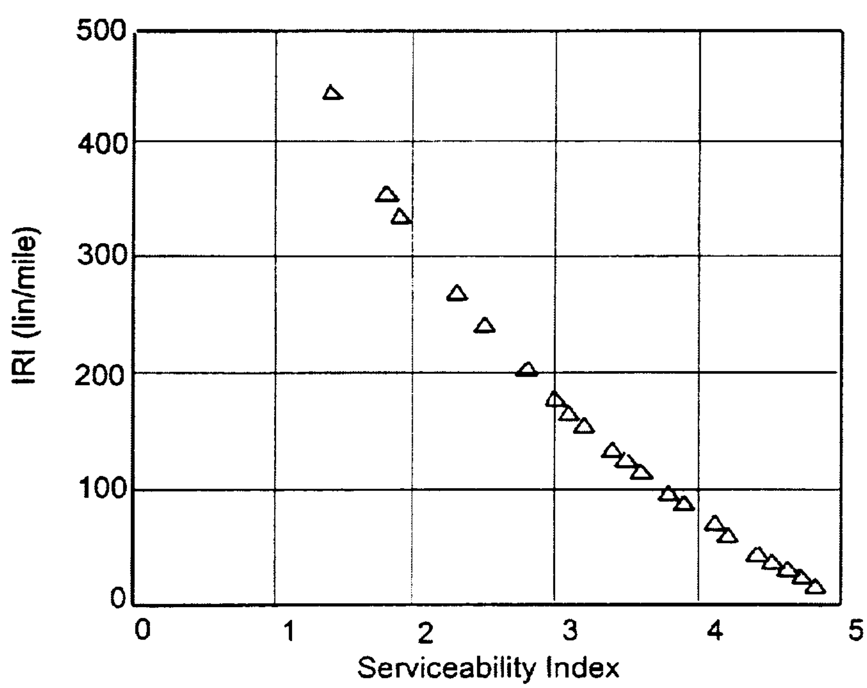

Figure 2.2 Correlation of IRI with Serviceability Index

In the latest research study, performed outside Indiana, Al-Omari and Darter obtained data from Louisiana, Michigan, New Jersey, New Mexico, Indiana, and Ohio and they recommended the following models: [17]

$PSI = 5 * e^{(-0.26 * IRI)}$, Where, IRI is in millimeters per meter or

$PSI = 5 * e^{(-0.0041 * IRI)}$, Where, IRI is in inches per mile.

LONG-TERM PAVEMENT PERFORMANCE (LTPP)

The Long Term Pavement Performance (LTPP) study is the largest pavement study ever conducted. As such, it is becoming the primary source of pavement performance information for the North American Highway community. The 20-year LTPP program was initiated as part of the Strategic Highway Research Program (SHRP) in 1987. One of the basic objectives or goals of the SHRP was to establish a National Pavement Performance Data Base (NPPDB) in which to store all of the data being collected or generated, or both, under the LTPP program. The type of data collected in the LTPP program and stored in NPPDB include inventory (as built), materials testing, profile, deflection [Falling Weight Deflectometer (FWD)], cross profile, distress, friction, maintenance, rehabilitation, climate and traffic. Today, the program has approximately 2,400 test sections at 900 locations on in-service highways throughout North America.

The Information Management System (IMS) developed in the SHRP-LTPP program to service NPPDB is composed of five nodes – the central node and four regional nodes. The National Information Management System (NIMS) is the central node, which is administered by and resides at Transportation Research Board (TRB). The four regional nodes are represented by the Regional Information Management Systems (RIMS). Data generally are checked and entered at the RIMS by the four regional coordination office contractor personnel under the direction of a

SHRP regional engineer. Periodic uploads are made from RIMS to NIMS at TRB. Data flow in the LTPP database is shown in Figure 2.3 [18].

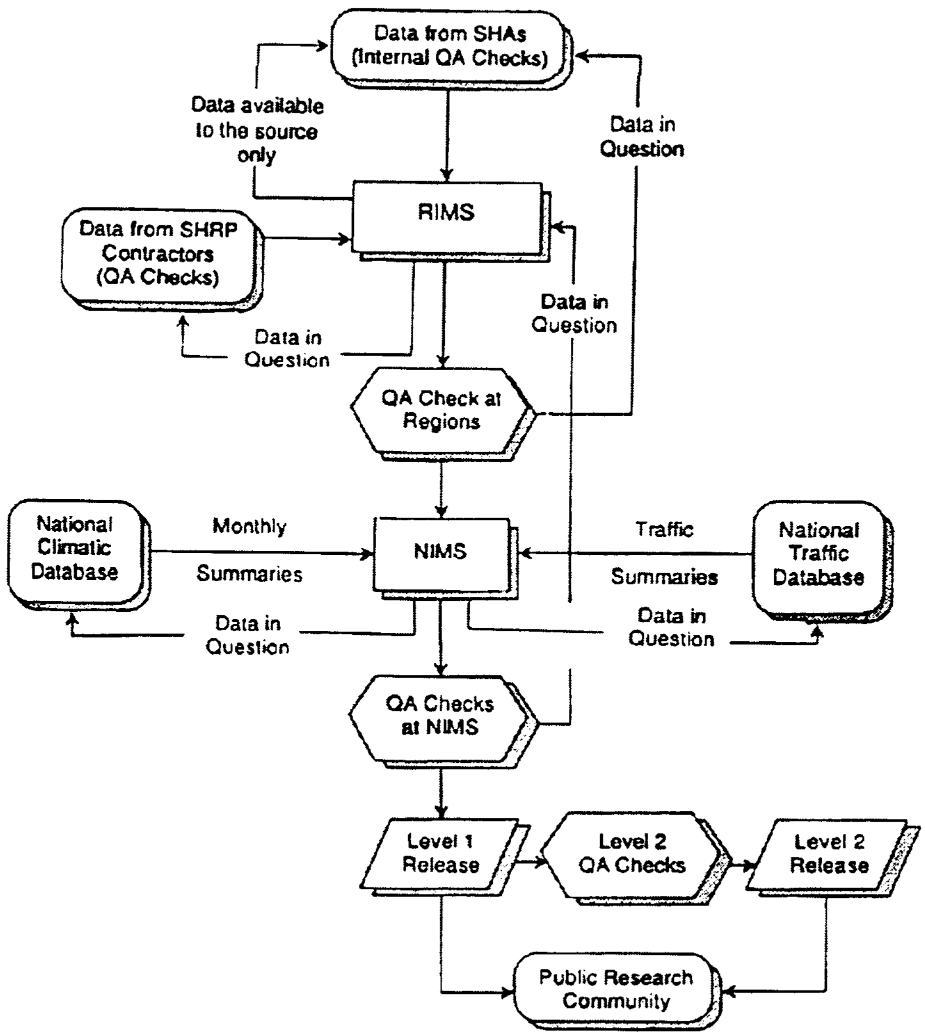

Figure 2.3 Data flow in the LTPP IMS

Current Practices of Utilization of Datapave

The University of Wyoming mailed a survey to all 50 states and the District of Columbia to determine current practices of LTPP database utilization. This survey is shown in Appendix A

[19]. In this section, the major findings of responses are summarized. Table 2.5 shows states responding to the survey. From Table 2.6, it is clear that, of the 36 responding states, only 9 states currently are using Datapave software. However, Table 2.7 shows that 13 states are planning on using Datapave in the near future. Only 14 of the 36 states indicated that they will not use Datapave in the future. Datapave currently is not in widespread use, but it is anticipated that it will be more utilized in the future.

Table 2.5 Datapave Questionnaire Response

States That Responded	States That Did Not Respond
AK, AL, AR, CT, DC, FL GA, ID, IL, KS, LA, MD, ME, MI, MN, MO, MS, MT, NC, NE, NH, NJ, NM, NV, NY, OH, OK, OR, PA, RI, SC, TX, UT, VA, WI, WY	AZ, CA, CO, DE, HI, IA, IN, KY, MA, ND, SD, TN, VT, WA, WV
Total: 36	Total: 15

Table 2.6 States That Use Datapave

States That Responded That Use Datapave	States That Responded That Do Not Use Datapave
KS, MI, MN MO, NC, NE, NY, TX, WY	AK, AL, AR, CT, DC, FL, GA, ID, IL, LA, MD, ME, MS, MT, NH, NJ, NM, NV, OH, OK, OR, PA, RI, SC, UT, VA, WI
Total: 9	Total: 27

Table 2.7 States That Plan To Use Datapave in Near Future

States That Plan To Use Datapave in Near Future	States That Do Not Plan To Use Datapave in Near Future
AL, FL, GA, ID, IL, LA, ME, MS, MT, NJ, OK, PA, UT, WI	AK, AR, CT, DC, MD, NH, NM, NV, OH, OR, RI, SC, VA
Total: 14	Total: 13

CHAPTER SUMMARY

This chapter described in detail various devices developed over the years to measure pavement roughness. It also described roughness indices that currently are in use by different SHAs. Finally, the importance and development of LTPP database software Datapave was described.

CHAPTER 3

PAVEMENT SMOOTHNESS POLICIES ACROSS THE NATION

It has long been believed that roughness of a pavement section is dependent on its initial roughness, age, and other factors. It also has long been believed that a section with a low initial roughness will last longer, require less maintenance, and remain smoother than a section that has a high initial roughness. Therefore, many SHAs have implemented pavement smoothness policies. These policies were developed to encourage construction of smooth pavements. In some states, contractors may receive incentive payments if the initial PI or IRI is less than a preset limit. Contractors also may incur disincentives if the PI is above a certain level. According to the Arizona DOT, some contractors have earned as much as $280,000 in incentive payments per project, and in an unexpected bonus, some contractors are reducing up-front bid prices, with the expectation of earning an incentive later. Some SHAs require that a specific limit of smoothness be met. For example, FHWA, in their performance plan for the President's Fiscal Year 2001 budget, set the IRI value for acceptable ride quality as 2.68 m/km (170 inch/mile). Alaska DOT defines good roads with the IRI value of approximately 1.0 m/km and critical roads having IRI value of 3.0 m/km or greater. Other SHAs use a variable scale with pay adjustment factors related to the degree of smoothness achieved. These pay adjustments are made based on the assumption that lower initial pavement roughness will result in better long-term pavement performance. This chapter summarizes findings from a nationwide survey, which was performed to determine the techniques and equipment used by various SHAs and to examine the variations in smoothness specifications across the nation. This chapter mainly covers a survey done in 1998.

OBJECTIVES OF SURVEY

Copies of the smoothness specifications survey were mailed to all 50 state highway agencies in 1998. The objectives of the survey were to:

1. Determine the national trends for accepting the smoothness of asphalt and concrete pavements.
2. Determine the techniques and equipment used by various DOTs for accepting pavement smoothness.
3. Obtain feedback about the effectiveness of smoothness specifications in different states.

SAMPLE OF SURVEY

The construction smoothness survey included seven different questions aimed at satisfying the objectives stated above. Appendix B shows the survey that was sent out to all SHAs.

RESULTS FROM SURVEY

As shown in Table 3.1, 36 of the 50 states responded to the survey. The responses were reduced and summarized in the following section.

Table 3.1 State DOTs Responding to the Survey

States Responding to the Survey	States with No Response
AK, AZ, AR, CA, CO, CT, FL, GA, IA, KS, KY, MA, MD, ME, MI, MN, MO, MS, MT, NE, NH, NJ, NM, ND, NV, OH, OR, PA, RI, SD, TX, VT, VA, WA, WI, WY	AL, DE, HI, ID, IL, IN, LA, NC, NY, OK, SC, TN, UT, WV
TOTAL : 36	TOTAL : 14

State Highway Agencies with Smoothness Specifications

Only Massachusetts, Rhode Island, and Vermont indicated that they currently do not have any type of smoothness specifications. This implies that most highway agencies perceive initial pavement smoothness as important, and most SHAs collect roughness data on their pavement sections on a regular basis. Table 3.2 shows the frequency of roughness data collection for Pavement Management Systems (PMS). Most states collect data annually to determine overall health of the pavement network. Some states collect data every other year, while only two states collect data every three to four years. As shown in Table 3.3, most states rely on using their own equipment when collecting roughness data. Twenty-seven of the responding states use their own profilers, while only six states rely exclusively on consultants for collecting the necessary data.

Table 3.2 Frequency of Roughness Data Collection for PMS

Annual	Biennial	Interstate Annual Others Biennial	Every Three Or Four Years
AK, AZ, CO, CT, FL, GA, KS, KY, MD, MN, MO, MT, NE, NM, ND, OH TX,UT,WI	CA, IA, ME, MI, MS, NH, NJ, SD, VT, WY	AR, NV, OR, PA, WA	MA, RI
19	10	5	2

Table 3.3 Responsibility of Roughness Data Collection for PMS

States	Consultant	State & Consultant
AK, AZ, AR, CA, CT, FL, GA, KS, KY, MA, MD, ME, MN, MO, MT, NE, NH, NJ, NM, ND, NV, OH, OR, SD, TX, WA, WI	CO, MI, MS, RI, VA, WY	IA, PA, VT
27	6	3

Profilograph Based Specifications

As shown in Table 3.4, nine out of the 36 states responding to the survey indicated that they do not use profilographs for smoothness specifications. Twenty-six states indicated using profilographs for accepting rigid pavements while 19 use profilographs for accepting asphalt pavements. The number of states using profilographs on asphalt pavements has been increasing steadily in the last few years.

Table 3.4 **States Using Profilographs for Smoothness Specifications**

No Profilograph Smoothness Specification	Profilograph Specifications	
	Rigid	Flexible
KY, ME, MA, MN, NH, NJ, RI, VT,WA	AZ, AR, CA, CO, IA, KS, MD, MI, MN, MS, MO, NE, NM, ND, NV, OH, OR, PA, SD, TX, VA, WI, WY	AK, AR, CA, CO, IA, KS, MD, MI, MN, MS, MO, NE, NM, NV, OH, OR, PA, TX, VA
9	26	19

Specifications of Texas DOT

Table 3.5 shows the Texas DOT specifications, which are based on 5 mm (.2") blanking band. Those incentives/disincentives apply for concrete and asphalt pavements. However, for concrete pavements, compliance with the profilograph index is determined by subtracting 4.0 from the actual filed measured profilograph rating. This 4.0 deduction is intended to compensate for any roughness induced to the freshly placed concrete, such as those due to required "tinning" of the surface.

Table 3.5 Pavement Smoothness Specification of Texas DOT

Profilograph Index for	Posted Speed > 45 MPH	Posted Speed <45 MPH
1.5 or less	+ $90	+$90
1.6 thru 2.0	+$70	+$70
2.1 thru 3.0	+$50	+$50
3.1 thru 4.0	+$35	+$35
4.1 thru 6.	$0	$20
6.1 thru 8.0	-$35	$0
8.1 thru 9.0	-$50	-$20
9.1 thru 10.0	-$70	-$50
10.1 thru 11.0	-$105	-$105
11.1 thru 12.0	-$140	-$140
Over 12.0	Corrective Work Needed	Corrective Work Needed

ROAD PROFILER BASED SPECIFICATIONS

Early this decade, state DOTs started replacing their response type roughness measuring devices with road profilers. Today all state DOTs use road profilers for roughness measurements. Eight states currently are using road profilers for accepting rigid pavements and 12 states are using road profilers to accept flexible pavements. These states use various roughness indexes in their smoothness specifications. As shown in Table 3.6, IRI from both wheel paths is the most widely used index for accepting pavements. Most of the DOTs are now developing smoothness specifications based on IRI values. As an example and at the time of this survey the Pennsylvania DOT was using smoothness specifications based on PI values, but now they have proposed a new smoothness specification based on IRI values. The data collected for smoothness specification normally is divided into lots. Most states using road profilers in smoothness specifications use 0.16 km (.1 mile) lot size. Some of the state smoothness specifications in IRI unit are described below.

Table 3.6 Road Profiler Roughness Index Used in PMS

IRI Both Wheel Paths	IRI HCS	DOT Index	PSI	RN	IRI Right Wheel Path
AZ, CT, MA, PA, VA	GA	MI, KY	MO	FL, NH	NM
5	1	2	1	2	1

Specifications of Connecticut DOT for Asphalt Pavements

Payment to the contractors will be based on the IRI, according to the following Table 3.7. The percent adjustment will be applied to payment(s) for the total quantity of the top two surface courses. According to the Connecticut DOT, the newly constructed pavement is divided into 160-meter length segments and an average IRI value will be computed for each 160-meter segment. Each segment average IRI value then is classified into one of the five IRI ranges shown in Table 3.7 and the applicable payment factor (PF) value is derived for each individual section. The payment factor will be multiplied by the length of that segment to compute a segment adjustment factor. The total pay adjustment factor is determined by taking the sum of all the segment adjustment factors and dividing by the sum of lengthsof all individual segments for the project. It is considered here as the Rideability Adjustment. This method can be described as

$$RA = (AF_{s1} + AF_{s2} + AF_{s3} \ldots AF_{sx}) / (L_{s1} + L_{s2} + L_{s3} + \ldots L_{sx}) * 100$$

Where:
- RA = Rideability Adjustment for complete project.
- AF_{sx} = Adjustment factor for each segment (x).
- PF = Pay factor value derived for each individual section according to Table 3.7
- L_{sx} = Length of applicable segment (160 meters unless otherwise noted).
- x = Number of segments.

AF_{sx} can be determined by multiplying the length of that section (L_{sx}) by Pay Factor (PF) of that section based on the IRI value.

Table 3.7 Pay Factor of Connecticut DOT for Asphalt Pavements

IRI (meters per kilometer)	PERCENT ADJUSTMENT (PF)
<0.789	10
0.789-0.947	63.29 (0.947-IRI)
0.948-1.262	0
1.263-1.893	39.68 (1.263-IRI)
>1.893	- 50

Specifications of Connecticut DOT for Cement Concrete Pavements

In this situation too, the project is divided into some individual segments of 160 meter each. The readings of the profilograph for each 160 meter segment are taken to determine preliminary profile index. Then the pay factor for each segment is determined from Table 3.8. This price includes the cost of all materials, equipment, and labor necessary to clean the milled surface and place, spread, consolidate, finish, texture, cure, and sawcut the PCC.

Table 3.8 Pay Factor of Connecticut DOT for Concrete Pavements

Profile Index (mm/km)	Percent Paid
0 – 40	105
41 – 80	104
81 – 120	103
121 – 160	102
161 – 180	101
181 – 200	100
200+	Grind

This work will be paid for at the contract unit price per square meter for "Portland Cement Concrete Overlay" completed in place.

Specifications of Montana DOT for Asphalt Pavements

The surface smoothness is measured by the Montana DOT using the International Roughness Index (IRI). The pavement in question is evaluated by individual sections. A section is defined as a single paved lane, 12 feet (3.60 meter) wide or greater, 0.20 mile (0.3 km) long. Partial sections will be prorated or added to an abutting section. The classification pay adjustment factors described in Table 3.9 should be applied to each section.

Table 3.9 Pay Factor of Montana DOT for Asphalt Pavements

Pavement Classification	Actual IRI (inches/mi)	Actual IRI (meters/km)	Pay Factor
Class I	<40	<0.63	1.25
	40-45	0.63-0.71	1.10
	46-65	0.72-1.03	1.00
	>65	>1.03	0.90
Class II	<45	<0.71	1.25
	45-55	0.71-0.87	1.10
	56-75	0.88-1.19	1.00
	>75	>1.19	0.90
Class III	<45	<0.71	1.25
	45-55	0.71-0.87	1.10
	56-80	0.88-1.26	1.00
	>80	>1.26	0.90
Class IV	<50	<0.79	1.25
	50-60	0.79-0.95	1.10
	61-90	0.96-1.42	1.00
	>90	>1.42	0.90

The pay factor will be applied to the unit price for each type of plant mix surfacing placed in each section. The quantity of surfacing for each individual section is calculated as follows:

Quantity of Surfacing = (L x W x D) x Unit Weight

Where,

L = Length of the lot measured
W = Width of the travel lane measured (including the shoulder)
D = Depth of the entire bituminous surfacing section placed under this Contract
Unit Weight = 98 percent of mix design density for each type of bituminous Surfacing.

Specifications of Virginia DOT

The Virginia DOT proposed these smoothness specification charts for asphalt pavements based on the lowest site average IRI produced by a minimum of two test runs, using a South Dakota-style road profiling device and reported for each travel lane. An IRI number in inches per mile will be established for each 0.01-mile section for each travel lane of the overlay. The last

0.01-mile section before a bridge, the first 0.01-mile section after a bridge, and the beginning and end 0.01-mile sections of the overlay will not be subject to a pay adjustment.

The following Tables 3.10 and 3.11 provide the acceptance quality of pavement based on the finished rideability for interstate and primary roadways. Pay adjustments will be applied to the theoretical tonnage of the surface mix asphalt material for the lane width and section length tested (generally 12 feet wide and 52.8 feet long) based on testing prior to any corrective action directed by the engineer.

Table 3.10 Specification Chart for Interstate System of Virginia DOT for Asphalt Sections

IRI after Completion (Inch per Mile)	Pay Adjustment (Percent Pavement Unit Price)
45.0 and Under	110
45.10 - 55.0	105
55.10 – 70.0	100
70.10 - 80.0	90
80.10 – 90.0	80
90.10 – 100.0	60
Over 100.10	Subject to Corrective Action

Table 3.11 Specification Chart for Non-Interstate System of Virginia DOT for Asphalt Sections

IRI after Completion (Inch/Mile)	Pay Adjustment Percent Pavement Unit Price (Percent Pavement Unit Price)
55.0 and Under	110
55.10 – 65.0	105
65.10 – 80.0	100
80.10- 90.0	90
90.10 – 100.0	80
100.10 – 110.0	60
Over 100.10	Subject to Corrective Action

Specifications of Wyoming DOT

Recently, the Wyoming Department of Transportation (WYDOT) developed smoothness specifications for asphalt pavements based on IRI. Figures 3.1 and 3.2 illustrate the pay adjustment policy of WYDOT for asphalt pavements without seal coat and pavements with a plant mix wearing course. IRI values are expressed in inch/mile. In these figures, pay adjustments are placed on the Y-axis (The dollar change is assessed per square yard of material placed), while IRI values are shown on the X-axis. The IRI values are determined for every 1/10 mile, then averages and the standard deviation of the data set are calculated. For asphalt pavements with seal coat, the number of smoothening opportunities (Opps) is used. A single lift overlay would have only 1 Opp but most projects will have 2 Opps. According to Figure 3.1, there are no incentives or disincentives for IRI values ranging from 55.01 to 70 inch/mile. For pavements with IRI values ranging from 55 to 40 inch/mile, the dollar change/Square yard values increase linearly. The maximum incentive material cost per square yard is $0.35. For pavements with IRI values greater than 70 inch/mile, disincentives increase linearly. Pavements IRI values of 100 inch/mile have a disincentives equal to $ 0.60 per square yard. Figure 3.2 summarizes the incentives/disincentives policy of WYDOT for asphalt pavements with a plant mix wearing course.

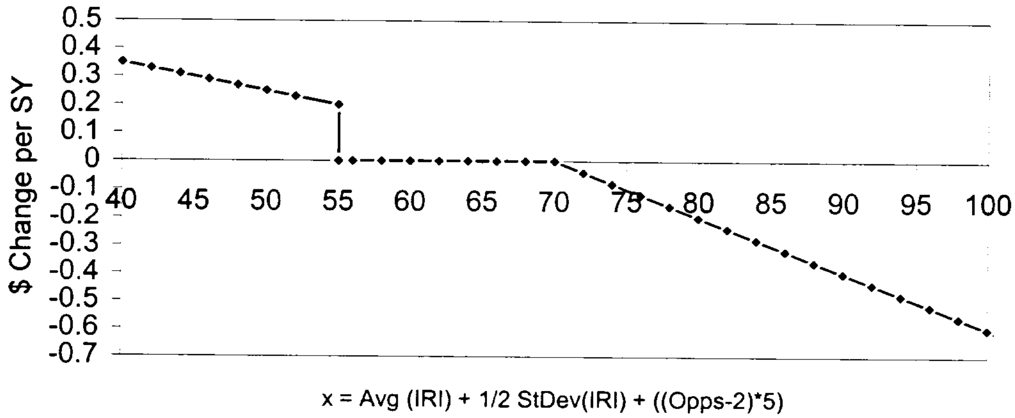

Figure 3.1 WYDOT Pay Adjustment for Asphalt Pavements without Seal Coats

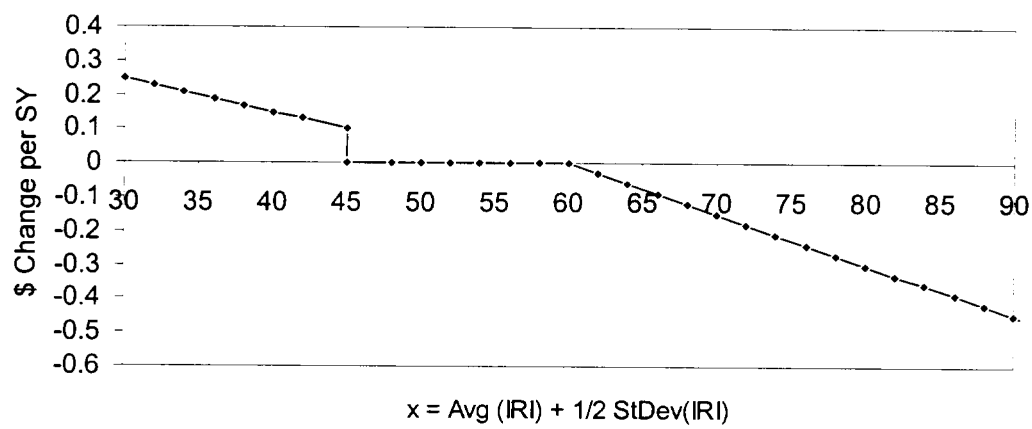

Figure 3.2 WYDOT Smoothness Pay Adjustments for Asphalt Pavements with a Plant Mix Wearing Course

INCENTIVE/DISINCENTIVE POLICIES

The majority of states have incentive and disincentive policies. Due to using various roughness indexes, smoothness specifications of various states cannot be summarized. The information received on the actual incentive/disincentive policies varied greatly with, at most, two SHAs having similar policies. However, most SHAs had a similar upper range adjustment pay factor of 110 percent for incentives and 90 percent for disincentives. The immense variance of incentive/disincentive policies among SHAs indicates the variability of opinion on what smoothness values indicate smooth or rough roads.

CHAPTER SUMMARY

In this chapter, responses to the smoothness specifications survey sent to all 50 states were summarized. The responses indicated major variations in smoothness specifications among SHAs. Due to these variations, specifications of different SHAs cannot be fully compared.

CHAPTER 4

DESIGN OF EXPERIMENT

In this experiment, all GPS (general pavement studies) asphalt and concrete test sections were identified from the Long Term Pavement Performance (LTPP) database. Datapave-2 software was used to obtain all necessary data for the analysis. GPS sections use existing pavements as originally constructed or after the first overlay. The LTPP database contains data on test sections between 1989 and 1999. After identifying these sections, pavement roughness measurements in IRIs and pavement layer information were extracted on all of the asphalt and concrete GPS sections and compiled in a computerized database.

ASPHALT TEST SECTIONS

Searching the Data pave software resulted in 377 GPS asphalt sections located across the country. In this study, only the asphalt sections (no composite sections) were selected. Table 4.1 summarizes the number of sections in every state. Texas had the largest number of sections while District of Columbia, Wisconsin and Rhodes Island did not have any sections that can be included in this experiment. All IRI data available on test sections were extracted from Data pave. IRI values were not available on all sections for every year between 1989 and 1999. In addition, some sections showed significant drops in IRIs due to maintenance and /or rehabilitations. To simplify the analysis, the first year with available roughness data on every section was labeled as year 1, the second year was labeled as year 2, etc. Some sections had roughness data between 1989 and 1999 and therefore, they had IRIs for 10 years while other sections had usable IRIs for a period as low as two years only. The IRI values for all test sections are summarized in Appendix C.

To show that the test sections reflected wide variations of pavement cross sections and traffic loadings, pavement thickness information, as well as traffic data were obtained. The pavement thicknesses, truck traffic, structural number and Equivalent Single Axle Loads (ESALs) were obtained for each test section. This information is summarized in Table 4.1.

Table 4.1 General Information on Asphalt Test Sections Included in the Experiment

State	No. Of Test Sections	Pavement Layer Information				Traffic Information	
		Sub Base Thickness (cm)	Base Thickness (cm)	Surface Thickness (cm)	Structural Number	Truck Traffic Per Day	Annual ESAL's
Alabama	12	11.94-48.52	4.83-48.52	2.54-33.28	2.5-6.8	(0-1022)	(0-1,297,513)
Alaska	5	15.24-33.02	11.43-35.56	5.34-13.72	2.1-4.5	(55-411)	(0-66,040)
Arizona	21	10.67-15.24	63.5-31.75	6.60-13.80	2.5-6.5	(0-3,581)	(0-1,159,678)
Arkansas	4	-	16.77-26.67	8.64-15.24	3.5-6.5	(75-1,370)	(0-290,248)
California	21	11.18-82.04	83.82-41.48	9.65-20.58	2.9-6.4	(61-1,997)	(0-878,958)
Colorado	11	27.94-59.69	9.65-24.63	8.38-21.85	(2.9-6.4)	(0-962)	(0-311,305)
Connecticut	1	-	30.48	-	4.3	202	-
Delaware	1	-	15.8	23.63	-	-	-
Florida	16	14.48-44.45	15.24-55.12	6.60-29.21	1.9-4.9	(117-1,559)	(0-552,943)
Georgia	12	-	16.0-32.26	4.32-21.09	3.0-5.0	(151-5,339)	-
Hawaii	1	34.55	19.82	9.65	5.1	-	53,917
Idaho	9	-	13.47-59.95	9.15-26.93	2.2-6.5	70-994	0-1,004,386
Illinois	3	-	-	-	4.9-5.9	45-301	13,243-233,037
Indiana	2	-	13.47-16.51	15.75-36.58	5.4-7.2	547-1,800	0-609,667
Iowa	3	-	-	12.19-24.38	-	265-1,134	-
Kansas	5	-	-	19.30-35.56	3.9-7.5	37-713	0-30,357
Kentucky	5	-	27.94-35.56	17.02-24.45	4.2-6.0	0-676	0-177,661
Louisiana	1	-	20.07	-	5.8	391	25,527
Maine	4	50.29-65.54	12.19-49.79	14.48-28.70	-	-	-
Maryland	4	10.67-33.02	10.93-15.24	9.15-25.15	-	-	-
Massachusetts	3	-	10.16-65.03	16.76-24.38	4.1-6.7	245-446	0-167,531
Michigan	6	35.06-47.25	12.19-31.50	5.59-17.02	2.2-7.5	113-744	11,140-87,896
Minnesota	9	7.62-83.82	10.16-30.48	6.35-26.67	2.0-7.1	88-556	0-603,754
Mississippi	15	5.08-49.53	9.15-20.32	4.32-26.93	1.2-5.9	45-2301	0-733,104
Missouri	7	-	10.16-11.43	4.58-28.96	3.7-9.4	97-3,443	0-1,348,387
Montana	7	12.19-56.90	23.87-35.31	7.12-26.93	3.9-8.3	48-1,902	(0-0)
Nebraska	2	-	-	-	3.2-4.1	113	0-50,444
Nevada	5	7.12-16.26	-	14.48-26.17	3.5-5.1	126-1,020	0-430,383
New Hampshire	1	36.58	49.03	21.34	-	296	-
New Jersey	6	35.06-63.25	17.53-27.94	15.24-28.19	-	232-1,415	0-668,573
New Mexico	11	15.24-30.23	14.23-29.72	11.94-22.61	2.6-5.7	0-515	0-232,811
New York	3	18.29-36.83	16.0-38.36	2.80-26.42	3.8-6.1	65-784	0-453,483
North Carolina	16	13.47-60.96	15.24-36.58	6.1-23.63	1.3-5.2	138-2,393	0-161,596
North Dakota	1	7.2	16.0	6.10-6.60	3.0	278	28,291
Oklahoma	11	-	13.72-28.71	3.36-26.42	2.3-5.5	68-533	0-151,574
Oregon	3	-	-	14.74-29.72	3.7-7.4	662-3,257	0-2,245,923
Pennsylvania	5	-	24.39-41.66	12.7-31.25	3.2-6.4	51-846	0-481,909

State	No. Of Test Sections	Pavement Layer Information				Traffic Information	
		Sub Base Thickness (cm)	Base Thickness (cm)	Surface Thickness (cm)	Structural Number	Truck Traffic Per Day	Annual ESAL's
South Carolina	5	-	12.20-25.66	2.80-9.40	1.1-2.6	8-700	0-223,537
South Dakota	3	7.62-25.4	12.7-16.51	8.89-14.98	-	-	-
Tennessee	16	9.66-30.48	10.42-58.42	3.31-29.47	-	0-3,356	-
Texas	56	11.43-36.58	12.20-45.47	2.29-25.66	1.2-7.5	77-2,300	0-1,338,354
Utah	7	-	11.94-23.37	10.42-28.96	-	-	-
Vermont	4	30.48-57.92	8.64-65.35	6.60-21.59	4.6-7.1	-	33,067-98,826
Virginia	8	9.15-21.34	12.95-19.56	14.48-25.66	3.4-5.3	-	0-1,075,865
Washington	12	9.15-16.51	7.62-33.02	4.83-24.13	2.2-6.4	266-2,326	0-219,202
West Virginia	1	12.95	10.42	31.25	4	210-2,180	136,535
Wyoming	13	-	12.45-41.66	5.59-14.74	2.1-6.1	24-583	0-184,523
Total	377	5.08-83.82	4.83-65.35	2.29-35.56	1.1-9.4	0-5,339	0-2,245,923

- Information is not available

CONCRETE TEST SECTIONS

Searching the Datapave software revealed 283 Portland Cement Concrete (PCC) pavement sections that can be used in this experiment. There were no IRI data for the states of Alaska, Hawaii, Massachusetts, Montana, New Hampshire, Ohio and Rhodes Island. All IRI data for test sections are summarized in Appendix D. The database was prepared in the same way as the asphalt sections. Also the pavement layer information was found from the Datapave-2 software. Table 4.2 summarizes the layer thicknesses, truck traffic and ESALs for every concrete section.

Table 4.2 General Information on Concrete Test Sections Included in the Experiment

State	No. Of Test Sections	Pavement Layer Information		Traffic Information	
		Base Thickness (cm)	Surface Thickness (cm)	Truck Traffic Per Day	Annual ESAL
Alabama	5	14.0-17.5	20.5-25.5	639-2836	0-479,085
Arizona	3	10.0-13.0	22.5-32.5	1635-16,959	204,028-6,821,253
Arkansas	10	-	20.0-27.5	309-1197	0-414,775
California	15	8.0-15.5	20.25-38.0	667-3938	1-2,118,062
Colorado	4	11.25-39.0	21.5-41.0	384-2309	0-651,571
Connecticut	3	22.0-39.0	20.5-25.5	-	-
Delaware	4	9.75-19.5	20.0-23.0	-	-
Florida	6	12.0-23.5	17.75-32.5	65-1335	18,757-2,081,739
Georgia	10	2.5-21.5	20.5-40.5	280-2240	0-475,108
Idaho	3	10.0-13.5	20.75-25.75	0-1428	0-7,798,049
Illinois	12	7.75-15.80	18.0-26.75	153-2907	333,54-3,464,379
Indiana	12	9.5-16.5	18.75-28.0	453-5656	0-2,324,706
Iowa	9	8.0-12.5	19.5-26.5	317-1715	0-648,483
Kansas	10	8.5-10.8	22.75-38.25	0-967	0-729,390
Kentucky	2	-	24.5-29.5	2293-2361	0-2,301,381
Louisiana	1	16.75	24.5	1502	660,058-662,255
Maine	2	11.0-58.0	32.5	-	-
Maryland	1	12.0	22.5	-	-
Michigan	6	8.5-12.0	20.25-25.0	429-2210	0-1,391,562
Minnesota	17	7.5-15.5	18.75-25.0	185-3023	0-1,335,569
Mississippi	10	9.25-21.5	19.75-32.5	149-2411	0-1,246,862
Missouri	10	8.25-10.8	19.25-24.5	332-3873	0-2,806,798
Nebraska	8	6.0-14.0	19.0-35.75	196-2542	0-1,822,556
Nevada	3	6.0-14.0	20.75-24.25	1008-2005	0-1,434,518
New Jersey	1	30.5	22.25	-	-
New Mexico	1	17.25	19.75	-	0-136,991
New York	2	-37.5	22.0-23.5	-	-
North Carolina	8	4.5-38.8	19.5-25.0	-	-
North Dakota	3	5.0-10.0	20.0-21.0	156-448	33,534-87,318
Ohio	9	9.0-17.0	20.75-25.75	66-3548	0-1,683,510
Oklahoma	8	5.5-12.0	22.25-26.25	0-1420	0-500,691
Oregon	6	8.75-19.5	20.0-28.75	1398-3667	0-2,038,984
Pennsylvania	12	12.0-60.0	21.75-31.75	-	-
South Carolina	4	12.25-14.0	19.25-25.0	684-1400	0-1,753,149
South Dakota	9	3.25-12.0	19.75-25.25	105-662	0-368,559
Texas	32	3.25-19.5	15.5-61.25	161-4780	0-912,060
Utah	7	10.0-19.0	23.5-28.0	-	-
Vermont	1	24.0	19.75-22.75	-	-
Virginia	4	15.0-17.3	20.0-26.0	-	-
Washington	7	3.75-35.0	20.0-26.0	346-1551	0-648,590
West Virginia	3	15.0-27.0	20.75-24.75	-	-
Wisconsin	15	8.0-22.3	17.75-27.0	0-13979	0-288,373
Wyoming	1	-	-	1563	0-1,112,964
Total	283	3.25-60.0	15.5-61.25	0-16,959	0-7,798,049

- Information is not available

DATA ANALYSIS

After the necessary data were obtained for asphalt and concrete sections, a comprehensive statistical analysis was performed. The main objective of the analysis was to correlate initial and future pavement roughness. Such correlation will help justify the need for pavement smoothness specifications. The data analysis is described in Chapter 5.

CHAPTER SUMMARY

This chapter described the research project organization and the test sections selection process. In addition, the data utilized in the analysis included IRI values for different years, different pavement layer thickness, pavement structural numbers for the asphalt sections, truck traffic per day, and descriptions of ESALs per year.

CHAPTER 5. DATA ANALYSIS

GENERAL STATISTICAL TERMINOLOGY

Two statistical tests were used in this research project. This chapter describes important terminologies of these statistical tests and then summarizes results from the data analysis.

Regression Analysis

Regression analysis is a statistical tool that models and describes the relation between two or more quantitative variables so that one variable (the response) can be predicted from the others. In general models can be linear or curvilinear.

Coefficient of Determination of Regression Analysis

The coefficient of determination, usually denoted as R^2, is interpreted as the proportion of variability in a response variable that can be explained by a model fit to the data. In other words, it measures strength of the relationship between the response variable and the predictor variables in a data set. R^2 Varies between zero and one. If the R^2 value is close to zero, the regression relationship obtained is weak. The closer R^2 is to one, the stronger the relationship.

Chi-Square Test

Pearson's Chi-Square test tests for association (non-independence) in a two-way classification. This procedure is used to test if the probability of items or subjects being classified for one variable depends upon the classification of the other variable [16]. The Chi-Square variable can be used to test whether the observed frequencies are close enough to frequencies expected under an assumption, usually independence, that we can conclude they came from the same probability distribution. Suppose, n randomly selected items are classified according to two different criteria. Tabulation of the results could be presented as in Table 5.1, where Oij represents the number of items belonging to the ij th cell of the r * c Table. Such data can be used to test the hypothesis that the two classifications, represented by rows and columns, are statistically independent. If the hypothesis is rejected, we conclude that two classifications are not independent and we say that there is some interaction between the two criteria of classification. The P-value of the test will determine whether or not the hypothesis of independence is rejected [20].

Table 5.1 Contingency Table of Chi-Square Test

Row	Column				Row Total
	1	2	...	c	
1	O_{11}	O_{12}	...	O_{1c}	R_1
2	O_{21}	O_{21}	...	O_{2c}	R_2
.					.
.					.
r	O_{r1}	O_{r2}	...	Orc	Rr
Column Total	C_1	C_2	...	C c	n

P-Value

The P-value of a test is a measure of how likely the observed data are if the tests null hypothesis is true, testing any statistical hypothesis for a particular level of significance. In this study, the P-value will be used to examine null and alternative hypothesis at the 95 percent confidence level. If the P-value relative to any significance level is small enough, then the null hypothesis can be rejected and the alternative hypothesis is taken.

ANALYSIS OF ASPHALT TEST SECTIONS

These statistical tests described above were used to perform a comprehensive data analysis on the asphalt test sections data. This analysis consisted of the following steps: First, several graphs were prepared for the test sections to examine the change in IRI values over time. These graphs clearly showed that IRI values increase over time in a linear fashion. In the second step, linear regression models were developed to compare roughness measurements from Year 1 with other years. This comparison considered the Year 1 data as the initial roughness. All the regression models developed showed that initial roughness values do affect future roughness values of pavements. Finally, the Chi-Square test was performed on the data to determine if a pavement constructed with a smoother surface will remain smooth over time.

Results from Regression Analysis for Asphalt Sections

In this study, the method of least square estimation was used to get the following best fit simple linear model:

$$Y = bo + b_1X$$

Where, Y: is the future IRI value.

X: is the initial IRI value.

b_1: is the slope of the fitted line .

bo: is the intercept of the fitted line.

As mentioned earlier, IRI values of asphalt test sections in Year 1 were labeled as initial roughness values, while IRI values from Years 2 to 10 were labeled as future roughness values. Scatter graphs of IRI values over time were developed for individual test sections to determine if there was any obvious trend. Most of the scatter plots showed a linear increment of IRI values over time. Two of these plots are presented in figures 5.1 and 5.2.

Additional graphs were developed for the combined data sets of all test sections. These graphs showed initial IRI measurements on the X-axis and IRIs from one of the future years on the Y-axis. Figures 5.3 and 5.4 show two samples of these graphs for Years 1 and 2, and Years 1 and 10. A linear regression relationship was developed for each of these scatters graphs. All relationships resulted with an upward (positive) trend. As shown in Table 5.2, the highest R^2 value was .97 for the Years 1 and 2 while the lowest R^2 value was .53 for Years 1 and 10. This statement is true for all the combined scatter graphs. The P-values of the slopes for all the regressions are 0 meaning that at almost 100 percent confidence, the initial roughness values and the final roughness values are related. It is clear from the Figures 5.3 and 5.4 that, pavement sections with low initial IRI values stay smoother over time. It is clear that R^2 for the relationships between initial and the future roughness drop over time, as shown in Figure 5.5 where R^2 values are plotted against time. That means, the linear relationship between the initial and the future IRI values is time dependent.

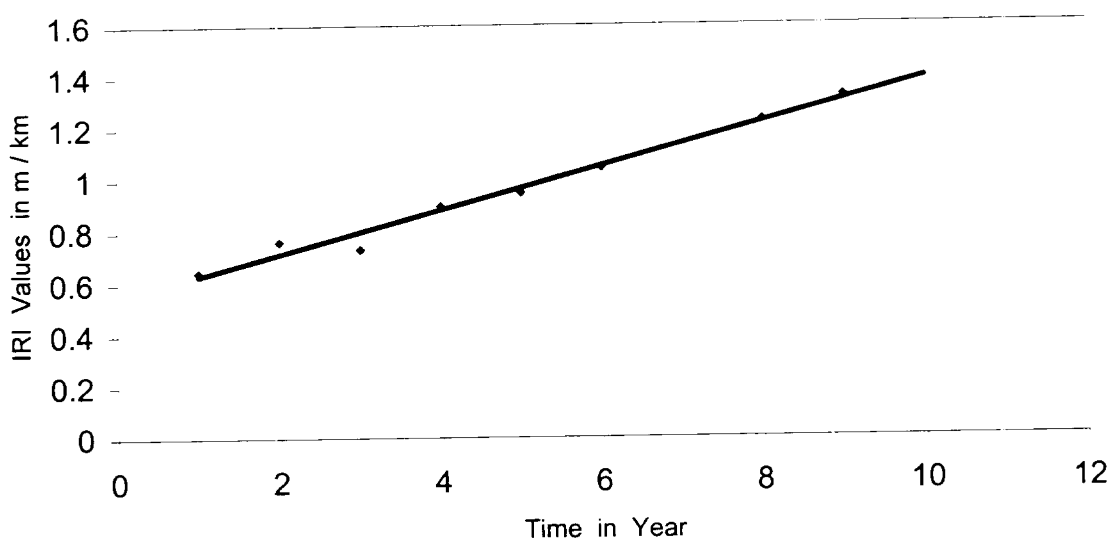

Figure 5.1 Variations in IRI Values over Time for Asphalt Section 46-9187 from South Dakota

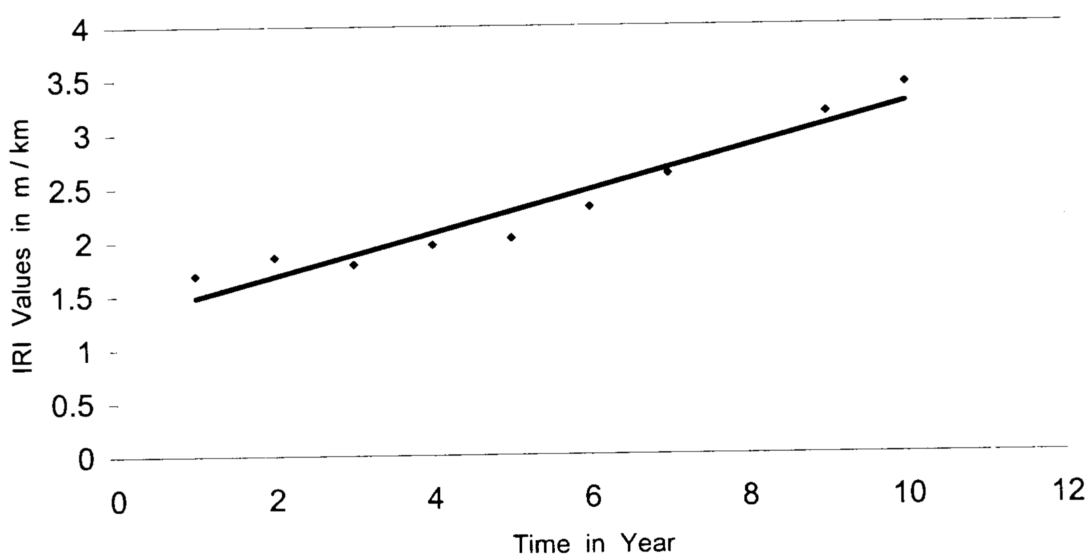

Figure 5.2 Variations in IRI Values over Time for Asphalt Section 42-1597 from Pennsylvania

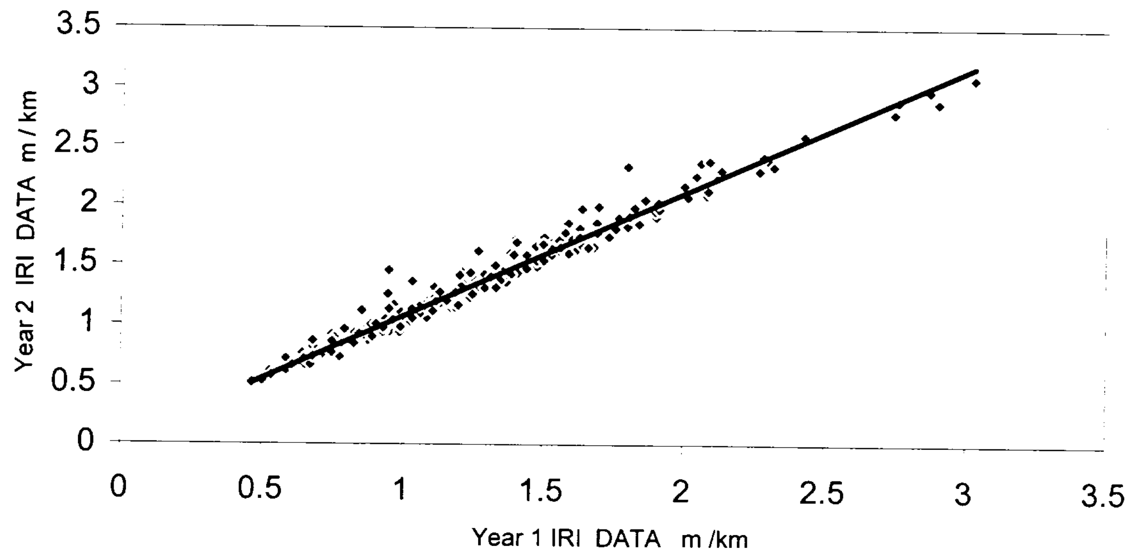

Figure 5.3 Regression Relationship for IRI Measurements Collected in Years 1 and 2 for Asphalt Sections

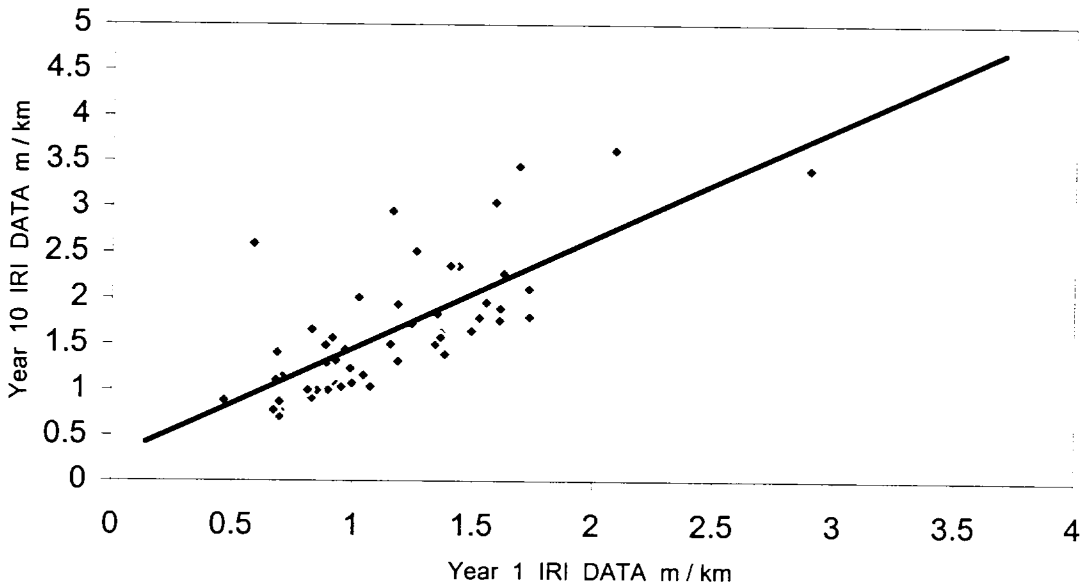

Figure 5.4 Regression Relationship for IRI Measurements Collected in Years 1 and 10 for Asphalt Sections

Table 5.2 Results Obtained from the Regression Analysis for Asphalt Sections

Years Compared	R^2 Value	Intercept m/km	Coefficient Of Slope	P-Value of The Slopes
1-2	.97	.03	1.04	0
1-3	.89	.06	1.06	0
1-4	.83	.07	1.10	0
1-5	.78	.13	1.08	0
1-6	.74	.12	1.16	0
1-7	.63	.16	1.16	0
1-8	.62	.21	1.22	0
1-9	.62	.22	1.21	0
1-10	.53	.25	1.20	0

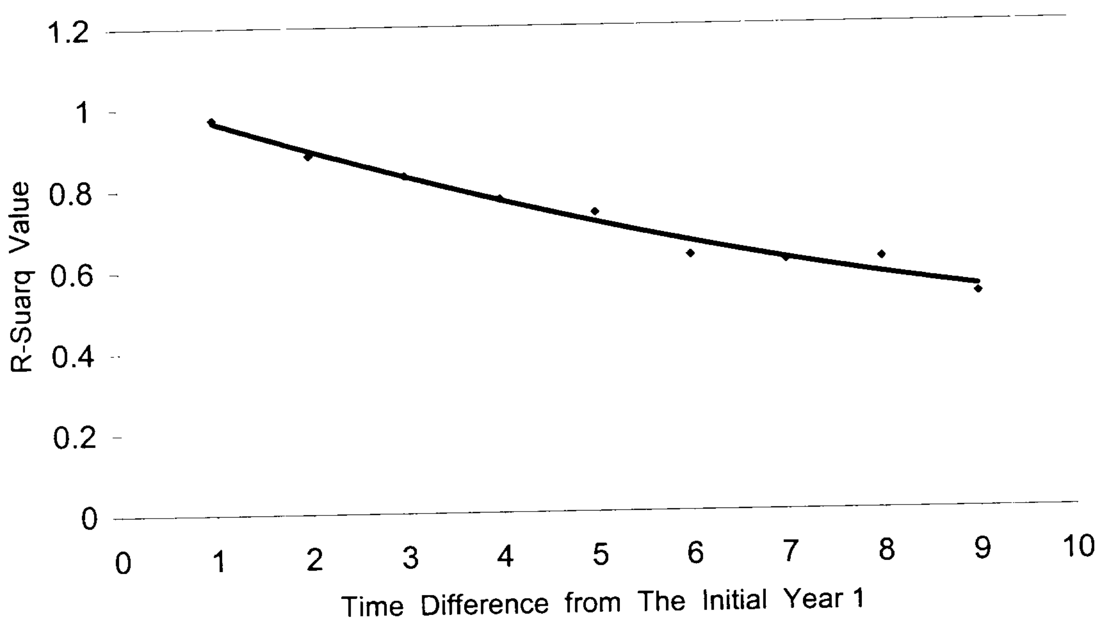

Figure 5.5 Relationship of Regression Equation's Strength (R-Square) with Time for Asphalt Sections

Interpretation of the Combined Regression Plots for the Asphalt Sections

The models developed in this study were used to calculate future roughness based on initial IRI values between 0.5 and 3.0 inch/mile. These calculated values were plotted as shown in Figure 5.6. The intercepts and the Coefficients of slopes have physical interpretations. An intercept .25 (for the Year 1-10) means that, the average pavement roughness values will be increased by .25 in IRI unit after nine years in being service. The intercept 1.20 (for the Year 1-10) means that the average pavement roughness will be increased by 20 percent after nine years of being in service. So, the average pavement roughness will be increased by .25 plus 20 percent of the initial roughness in IRI.

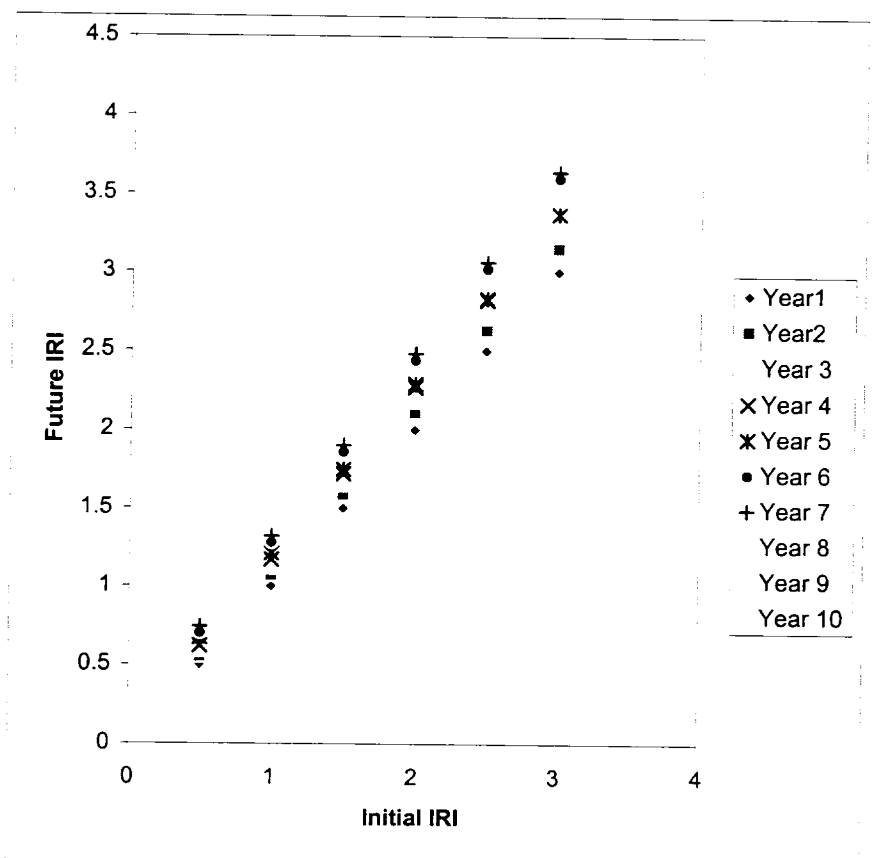

Figure 5.6 Scatter Plots of Predicted Future IRI's for Asphalt Sections

This figure clearly shows that the increase in IRI over 10 years (ΔIRI) for smooth sections is less than the increase experienced by rough sections. Table 5.3 summarizes ΔIRI while Figure 5.7 shows those values graphically. It is clear that ΔIRI values are significantly higher for sections with high initial IRI.

Table 5.3 The increase in IRI Values over 10 Years for Asphalt Sections

IRI Values		Increase in IRI Over 10 Years
Year 1	Year 10	
.5	.85	.35
1.0	1.45	.45
1.5	2.05	.55
2.0	2.65	.65
2.5	3.25	.75
3.0	3.85	.85

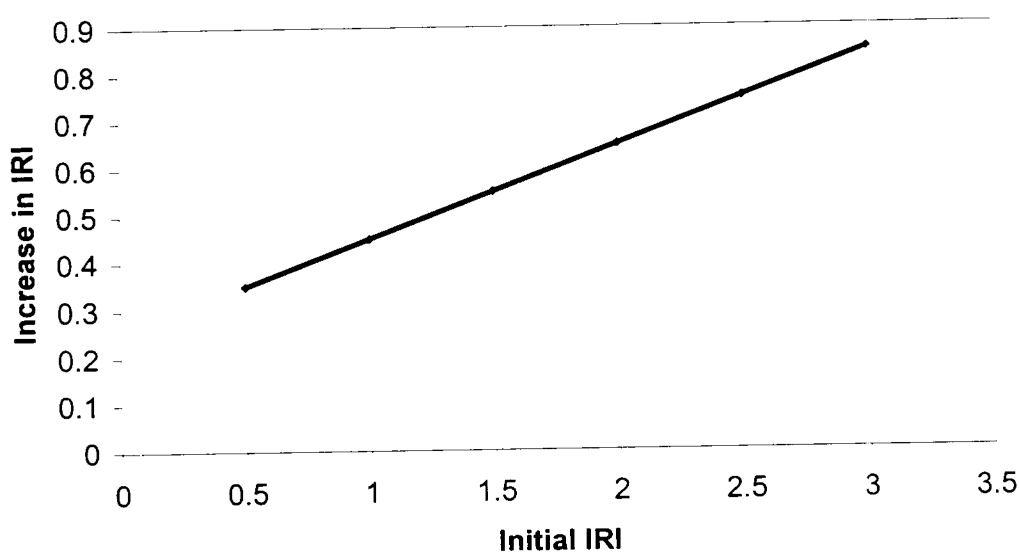

Figure 5.7 ΔIRI Variations (Increase in IRI) versus Initial IRI for Asphalt Sections

Results from Chi-Square Test for the Asphalt Sections

The Chi-Square test was performed on the data set to determine if a pavement constructed with a smoother surface will remain smooth after years of being in service. The Chi-Square test can be done for association (non-independence) in a two-way classification. This procedure is used to test if the probability of items or subjects being classified for one variable depends on classification of the other variable [16]. In this study, the null hypothesis of the test was:

$$Ho : Pss = Psr$$

And the alternate is, $Ha : Pss \neq Psr$

Where, Pss is the proportion of pavements, which starts with smoother surfaces and ends up with smoother surfaces. Similarly, Psr is the proportion of pavements, which starts with smoother surfaces and ends up with rougher surfaces. In this study, each individual test section is examined at the initial condition and at the final condition to determine whether this section starts up and ends with a rough or smooth surface. Then the total numbers of pavement sections, starting with smoother surface and ends up with smoother surface and pavement sections starting with smoother surface and ends up with rougher surface, are determined. If the summation of these two categories are considered as the denominator, then, Pss will be the ratio of dividing the number of test sections starting with smoother surface and ending with smoother surface over that denominator. Then the Chi-Square test was done to examine the probability of getting these two proportions equal or not. If the P-value of the test is found low, then the null hypothesis will be rejected and the alternate decision will be taken. An example of this analysis is given below for the Years 1 and 2.

The data set is divided into two categories, smooth and rough with respect to their median values. The sections with the roughness values lower than the median value of that series are stated as smooth, and the sections with the roughness values higher than the median value of that series are stated as rough. A table was prepared (Table 5.4) using Years 1 and 2 data as initial and final roughness. This Table helped to determine the number of test sections starting with smoother surface and ending up with smoother surface, and pavement sections starting with smoother surface and ending up with rougher surface and so on. If a test section starts with a smoother surface and ends up with smoother surface, then it is placed in the cell (2,2), if a section starts smooth and ends up rough, then it is placed in the cell (2,3) and so on. Then the total number of each cell is counted. Here, the Pss will be the ratio of the total number in cell (2,2) divided by the summation of cell (2,2) and cell (2,3). Psr will be the ratio of the total number in cell (2,3) divided by the summation of cell (2,2) and cell (2,3). Here, Pss is found to be 135 / (135+10) = .93 and Psr = 10 / (135+10) = .07. The ratio Pss is significantly larger than the ratio Psr. Similar Tables were prepared for Year 1 with other years, considering Year 1 data as the initial roughness. These Tables are shown in Appendix E.

As shown in Table 5.5, for all of the combinations from the Year1-2 to the Year 1-10, the P-values are 0 meaning that at almost 100 percent confidence level, the proportions Pss and Psr are not equal. In other words, if a section starts with a smoother surface, then it will remain smooth after years of being in service.

Table 5. 4 Table of Chi-Square Test for the IRI Values of Year 1 - 2 for the Asphalt Sections

	Smooth	Rough	Total
Smooth	135	10	145
Rough	7	121	128
Total	142	131	273

Table 5.5 Results Obtained from the Chi-Square Test for Asphalt Sections

Year Compared	Total Number Of Observations	P-Value
1-2	273	0
1-3	328	0
1-4	253	0
1-5	245	0
1-6	214	0
1-7	102	0
1-8	137	0
1-9	120	0
1-10	52	0

ANALYSIS OF PORTLAND CEMENT CONCRETE (PCC) SECTIONS

The analysis performed on the PCC sections was identical to the one performed on the asphalt sections. First, several graphs were prepared for the test sections to examine change in IRI values over time. Two of the graphs are shown in Figure 5.8 and 5.9. These graphs clearly showed that IRI values increase in a linear fashion over time. In the second step, regression models were developed to compare roughness measurements from Year 1 with other years. This comparison also considered the Year 1 data as the initial roughness. All the regression models developed showed that initial roughness values do affect future roughness values of pavements.

Finally, the Chi-Square test was performed on data to determine if a pavement constructed with a smoother surface will remain smooth over time.

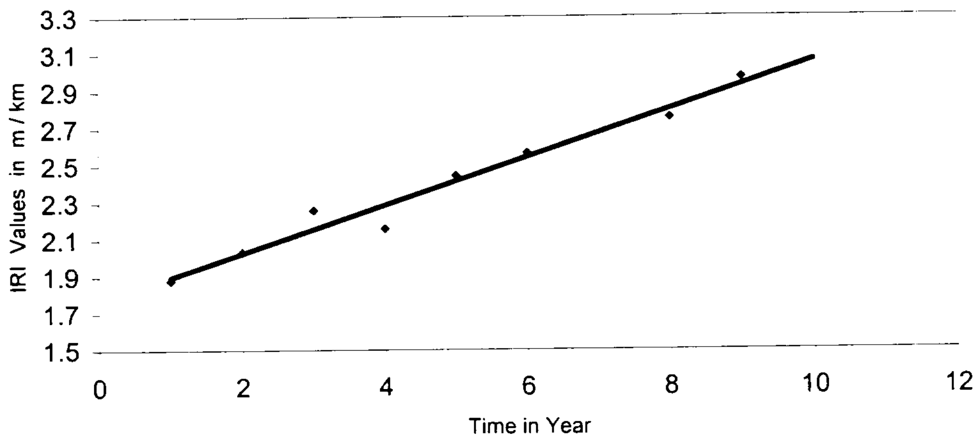

Figure 5.8 Variations in IRI Values over Time for Concrete Section 55-3010 from Wisconsin

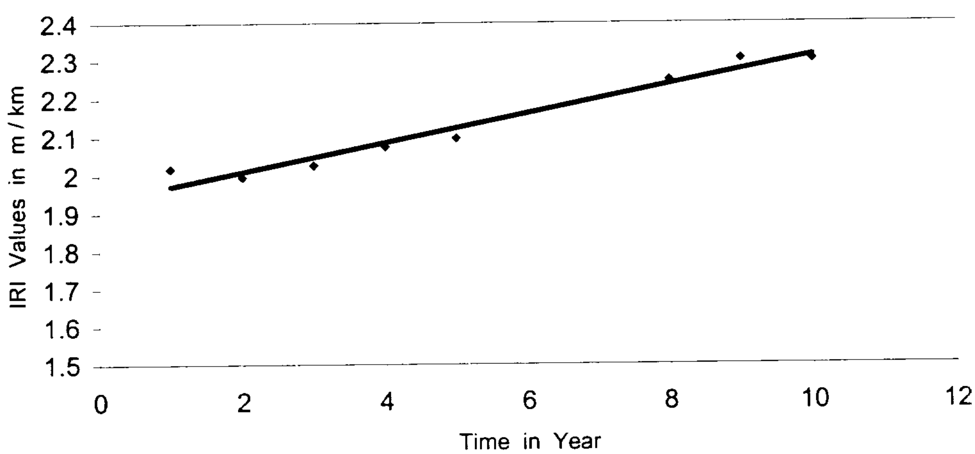

Figure 5.9 Variations in IRI Values over Time for Concrete Sections 29-5000 from Missouri

Results from Regression Analysis for Concrete Sections

Regression models of simple linear form were developed. IRI values of concrete test sections in Year 1 were labeled as initial roughness values, while IRI values from Years 2 to 10 were labeled as future roughness values, then regression analysis was done as the asphalt test sections. Similar results were found. All relationships resulted with an upward (positive) trend. Two of the combined regression plots are shown in Figure 5.10 and 5.11. The highest R^2 value was .96 for Years 1 and 2, while the lowest R^2 value was .70 for Years 1 and 10. As shown in Figure 5.12, relationships between initial and future roughness drop over time. This means that the linear relationship between the initial and final IRI values of the concrete sections also are time dependent. For concrete sections, the value dropped from .97 (for the Year 1-2) to .70 (for the Year 1-10) , whereas for the asphalt sections the value dropped from .96 to .70 for the same time span. For concrete sections, the R^2 values were smaller than the corresponding values of the asphalt sections with a single exception for the Year 1-2. So, it can be said that the strength of the linear relationship between initial and future IRI values of concrete sections is not as strong as for the asphalt sections. If Figures 5.5 and 5.12 are compared, it can be seen that the slope of the curve of the asphalt sections is steeper than the slope of the curve of the concrete sections. That means, the effect of time in the relationship of initial and future IRI is less for the concrete sections than for the asphalt sections. The P-values of the slopes for all the regressions are 0, meaning that at almost 100 percent confidence, initial roughness values and final roughness values are linearly related. Table 5.6 shows the major findings from regression analysis of concrete sections.

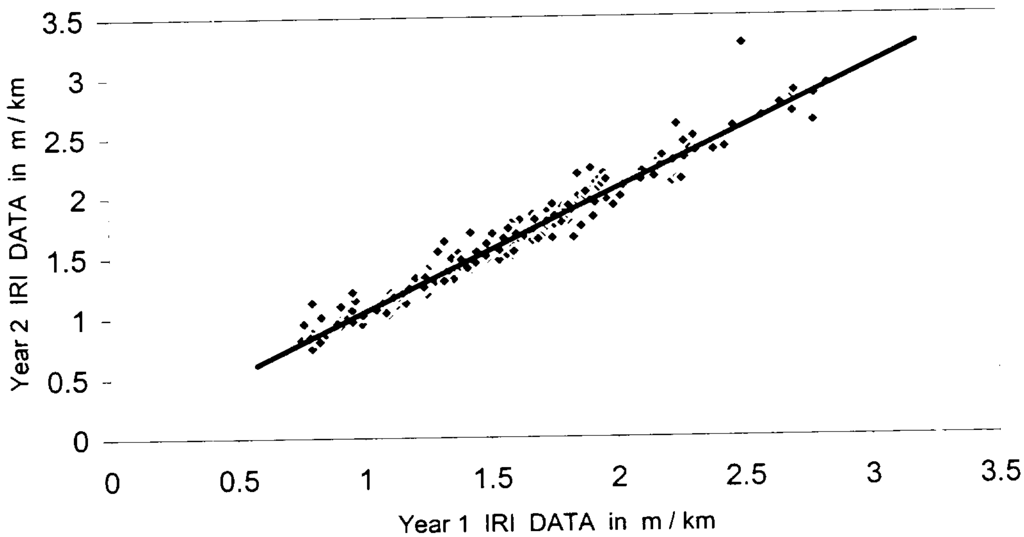

Figure 5.10 Regression Relationship for IRI Measurements Collected in Years 1 and 2 for Concrete Sections

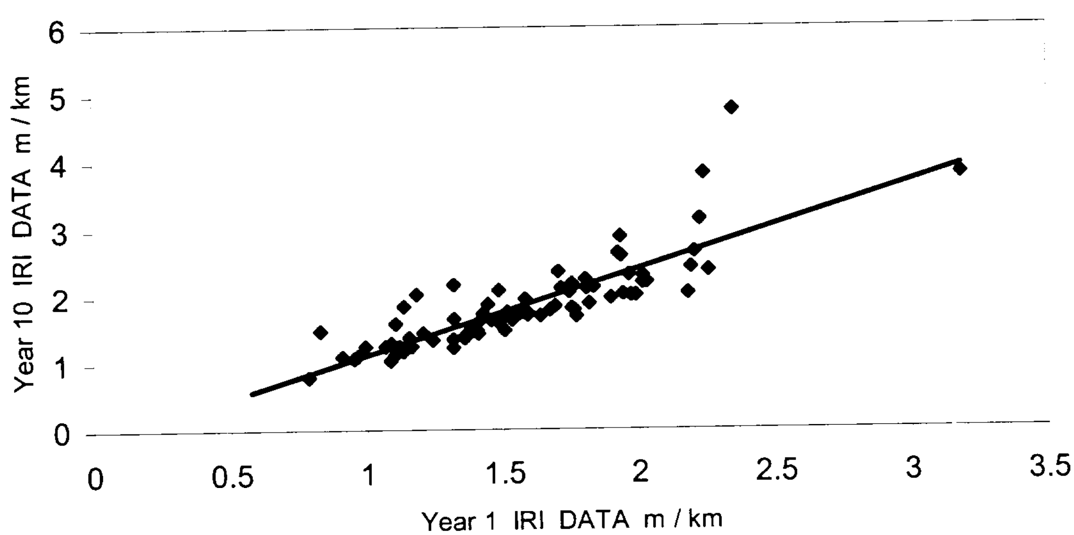

Figure 5.11 Regression Relationship for IRI Measurements Collected in Years 1 and 10 for Concrete Sections

Table-5.6 Results Obtained from the Regression Analysis for the Concrete Sections

Year Interval	R^2 Value	Intercept	Coefficient Of Slope	P-Value of The Slope
1-2	.96	.028	1.02	0
1-3	.92	-.030	1.06	0
1-4	.91	.038	1.02	0
1-5	.88	.012	1.06	0
1-6	.89	-.018	1.10	0
1-7	.88	.001	1.11	0
1-8	.75	.0423	1.09	0
1-9	.73	.068	1.10	0
1-10	.70	-.17	1.29	0

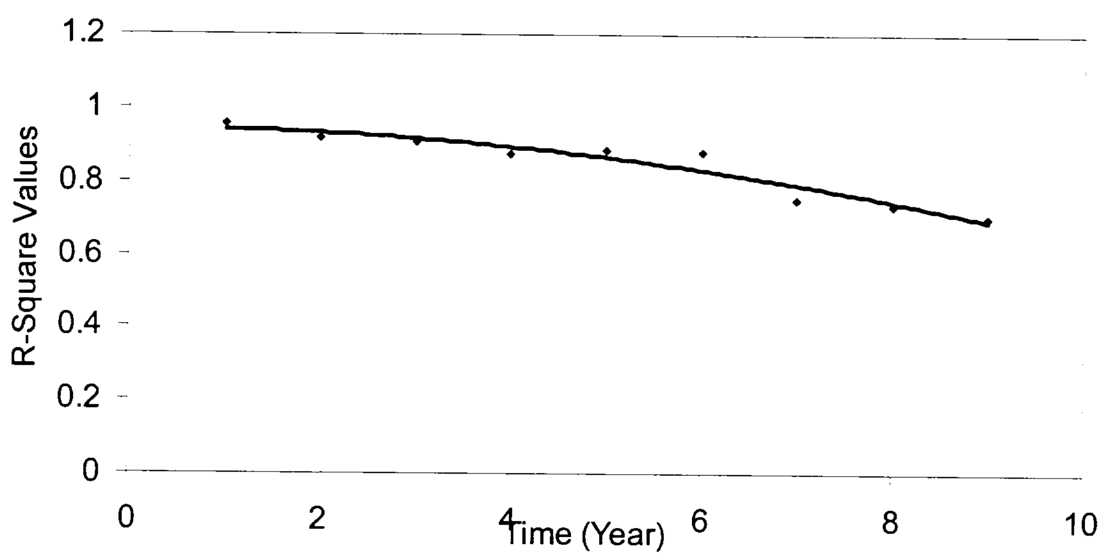

Figure 5.12 Relationship of Regression Equation's Strength (R-Square) with Time for Concrete Sections

Interpretation of the Combined Regression Plots for the Concrete Sections

The Concrete models developed in this study were used to calculate future roughness based on initial IRI values between 0.5 and 3.0 inch/mile. These calculated values were plotted as shown in Figure 5.13.

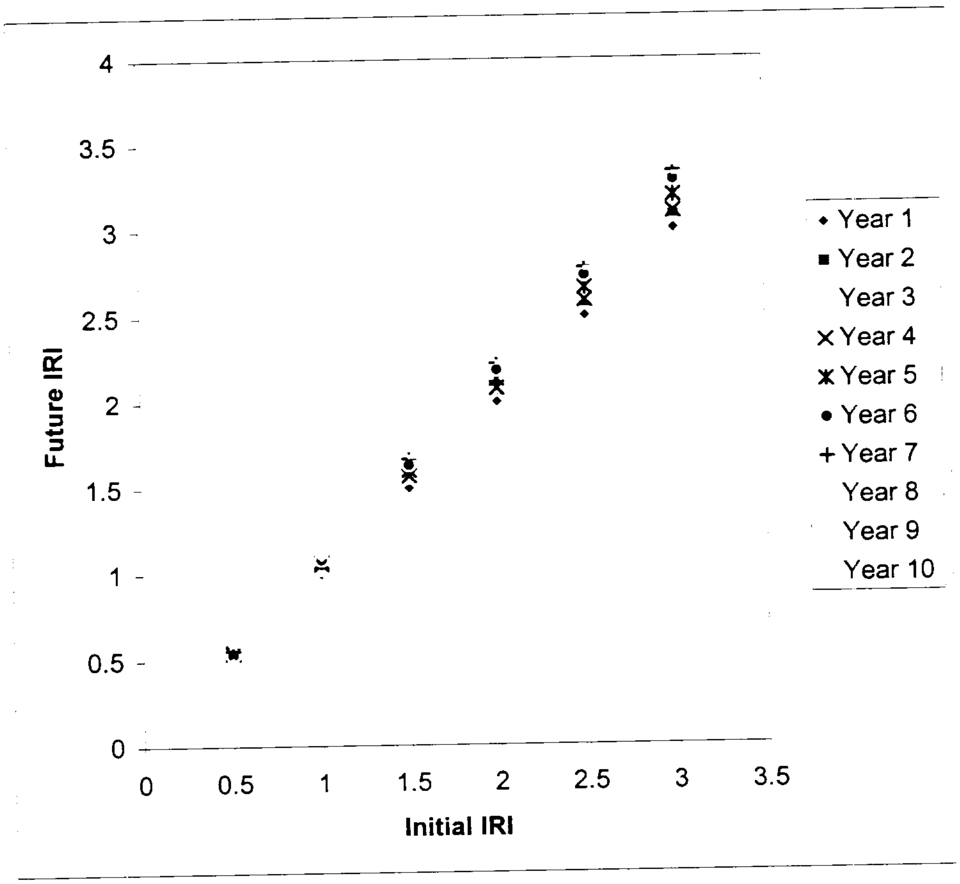

Figure 5.13 Scatter Plots of Predicted Future IRI's for Concrete Sections

This figure clearly shows that the increase in IRI over 10 years (Δ IRI) for smooth sections is less than the increase experienced by rough sections. Table 5.7 summarizes ΔIRI, while Figure 5.14 shows those values graphically. It is clear that ΔIRI values are significantly higher for sections with high initial IRI. By comparing Tables 5.3 and 5.7, it is clear that for all levels of initial IRIs, the increase in IRI values for the concrete sections are less than the asphalt sections.

This is because asphalt sections would be near the end of their service lives after 10 years, while the concrete sections would be only halfway through their service life.

Table 5.7 The Increase in IRI Values over 10 Years for Concrete Sections

IRI Values		Increase in IRI Over 10 Years
Year 1	Year 10	
.5	.5	0
1.0	1.20	.20
1.5	1.76	.26
2.0	2.41	.41
2.5	3.05	.55
3.0	3.61	.61

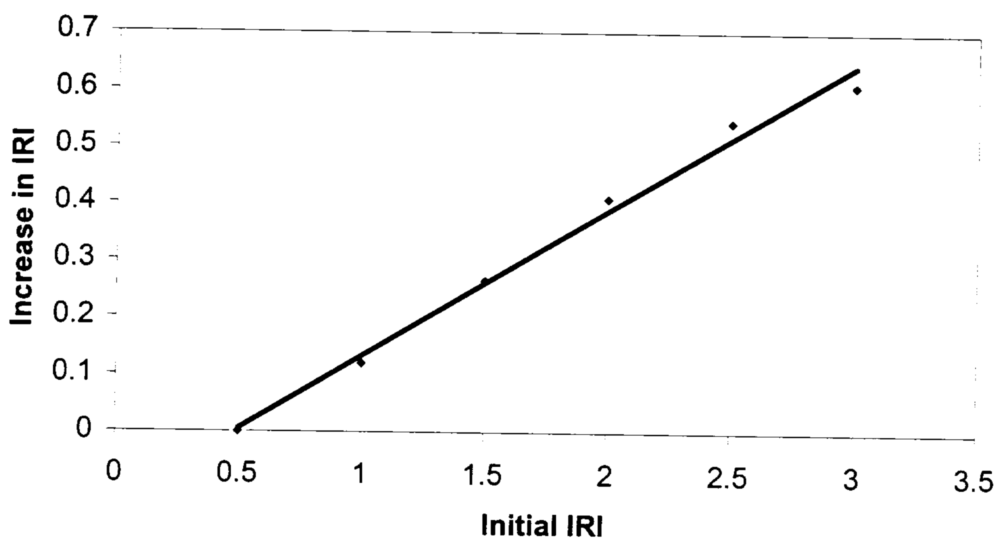

Figure 5.14 ΔIRI Variations (Increase in IRI) versus Initial IRI for Concrete Sections

Results Obtained from the Chi-Square Test for the Concrete Sections

The Chi-Square test for the concrete sections also was performed identically as it was for the asphalt sections. The following hypothesis was used:

$$Ho: \ Pss = Psr$$

And the alternate is, $Ha : Pss \neq Psr$

The notations used are as the same as described in the section of analysis of Chi-Square test for asphalt sections. The data set was divided into two categories, smooth and rough with respect to their median values. The sections with the roughness values lower than the median value of that series were stated as smooth, and the sections with the roughness values higher than the median value of that series were stated as rough. Using the Year 1 data as the initial roughness, contingency tables were prepared in the same manner as for the asphalt sections — Year 1-2 to the Year 1-10. A sample contingency table for the Year 1-2 is shown in Table 5.8. Contingency Tables for the other years are shown in Appendix F. Then the P-values of the Chi-Square tests are determined as shown in Table 5.9. For all of the combinations from the Year 1-2 to the Year 1-10, the P-values are 0, meaning that at almost 100 percent confidence level, the proportions Pss and Psr are not equal. In other words, if a section starts with a smoother surface, then it will remain smooth after years of being in service.

Table 5.8 Table of Chi-Square Test for the IRI Values of Year 1-2 for the Concrete Sections

	Smooth	Rough	Total
Smooth	95	6	101
Rough	4	98	102
Total	99	104	203

Table 5.9 Results Obtained from the Chi-Square Test for Concrete Sections

Year Interval	Total Number of Observations	P-Value
1-2	203	0
1-3	227	0
1-4	217	0
1-5	192	0
1-6	133	0
1-7	104	0
1-8	133	0
1-9	140	0
1-10	86	0

CHAPTER SUMMARY

In this chapter, statistical analysis was described and the results were summarized. These analyses included plotting the variations in IRI values over time for several individual sections, performing linear regression analysis to examine the relationship between initial and future roughness of test sections, and performing Chi-Square test to determine whether a pavement section built with a smoother surface will remain smoother over time.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The main objective of this research project was to examine effects of initial pavement roughness on future roughness values for asphalt and concrete pavements. Such examination would help in evaluating the need for pavement smoothness specifications. Many asphalt and concrete test sections from nearly all fifty states were identified for inclusion in the study. The Regression analysis on the asphalt and concrete sections examined relationships between initial IRI and later IRI measurements and developed simple linear models. The Chi-Square test examined whether a pavement section built with a smoother surface will remain smooth with time. This chapter summarizes conclusions from the statistical analysis. In addition, recommendations for future needed studies are included in this chapter.

CONCLUSIONS FROM ASPHALT PAVEMENT ANALYSIS

A total of 377 asphalt pavement test sections were included in this research study. Yearly IRI measurements were obtained for each test section from the LTPP database. Test sections were grouped based on yearly IRI values. Regression and Chi-Square statistical analysis were performed and the following conclusions were drawn:

1. The graphs and regression relationships indicate that initial IRI measurements correlate linearly with future IRI values for asphalt pavements. This implies that initial IRI values of asphalt pavements do affect future IRI values.
2. The R^2 of the relationship between initial and future IRIs decreases over time, meaning that the relationship between initial and final roughness is time dependent and decreases over time.

3. The Chi-Square statistical tests strongly support the fact that, asphalt pavements constructed with a smoother surface do remain smoother over time.
4. The Asphalt pavements with high initial IRI show a higher increase in future roughness than the sections with low initial IRI.

CONCLUSIONS FROM PCC PAVEMENT ANALYSIS

A total of 283 test sections were included in this research experiment from 43 states. Initial and later IRI measurements were obtained for each concrete test section. The test sections were grouped based on their yearly IRI values with ascending values. Regression analysis and Chi-Square test then performed and the following conclusions were drawn:

1. The graphs and regression relationships indicate that initial IRI measurements correlate linearly and positively with future IRI values for concrete pavements.
2. The R^2 of the relationship between initial and future IRIs decreases over time. The effect of time on the relationship of the PCC pavements is not so strong as for the asphalt pavements.
3. Chi-Square statistical tests strongly support the fact that concrete pavements constructed with smoother surfaces do remain smooth over time.
4. The concrete pavements with high initial IRI show a higher increase in future roughness than the sections with low initial IRI.

RECOMMENDATIONS

Based on the results of this research project, the following recommendations are suggested:

1. The results of this research emphasize the importance of low initial roughness and support the need for smoothness specifications for both asphalt and concrete pavements.
2. A more controlled study should be performed; such a study should obtain the initial IRI measurements of new pavements as soon as possible after construction.
3. A study should be done to determine the effect of initial pavement smoothness on pavement maintenance costs and vehicle operating costs.

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Appendix A

Datapave LTPP Questionnaire

Datapave LTPP Questionnaire

Datapave is a software that allows the users to interfare with the Long term Pavement Performance (LTPP) database. The LTPP database includes pavement test sections from all over North America. Your co-operation in the following survey will help in determining the most useful applications for DataPave. The survey is broken into four different sections. The first section will determine which DOT's are currently using Datapave. The second section asks about the modules most frequently used in DataPave. The third section determines the research applications of DataPave. The fourth section is a request for the distribution of the results. We thank you for your corporation.

Part A - DataPave

1) **Does your agency currently use DataPave software?**

☐ Yes ☐ No

If yes, please go to part B:

If no, please answer the following:

a) Do you plan to use Datapave in the near future?

☐ Yes ☐ No

If yes, when? ________________

b) Do you use any other national or regional database for research?

☐ Yes ☐ No

If yes, what database?____________________

Please go to Part D.

Part B – DataPave

1) Which Modules(s) do you find most useful within Datapave? Please check all that apply.

☐ Map Module

Chart /Trend Module:

☐ IRI	☐ Rutting	☐ Punchouts
☐ Long Cracking	☐ Fatigue Cracking	☐ Spalling
☐ Transverse Cracking	☐ Falting	

Section Presentation Module:

☐ FWD Deflections	☐ Pavements Layers	☐ Detailed Report

Data Extraction Module:

☐ Climatic	☐ SMP	☐ SPS1 Specific
☐ General	☐ SPS 2 Specific	☐ SPS 3 Specific
☐ Inventory	☐ SPS 4 Specific	☐ SPS5 Specific
☐ Maintenance	☐ SPS 6 Specific	☐ SPS 7 Specific
☐ Monitoring	☐ SPS 8 Specific	☐ SPS 9 Specific
☐ Rehabilitation	☐ Testing	☐ Traffic

Part C - Research

The main objective of part C is to determine your research applications using the LTPP data at the state, region, and/or country levels. Please feel free to add any comments which can define your applications better.

1) Does your agency use Datapave for research on:

a) Factors affecting roughness?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ______________________________

b) Pre-rehabilitation roughness on rate of deterioration of overlaid pavements?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ______________________________

C) Feasibility of using falling-weight defelectometer (FWD) data for rapid field characterization of pavement quality?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ______________________________

d) Determination of service life for rehabilitation options?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ______________________________

e) Pavement maintenance and rehabilitation options?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

f) Structural factors?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

g) Laboratory materials data?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

h) Layer thickness data?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

i) Climatic data?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

j) Strategic highway research program (SHRP) asphalt specification and mix design?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

k) Laboratory resilient modulus for AC materials?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

l) The assessment of filed materials data?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

m) Evaluation and characterization of pavement drainage?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

n) Timing and effectiveness of maintenance treatments for flexible pavements?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

o) Procedures for estimating seasonal variations in load carrying capacity?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

p) Variation of AC air voids as a function of specifications and its significance and its significance to performance?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

q) Significance of traditional material pay factors to pavement performance?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

r) Moisture and temperature effects on materials properties?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

s) Common characteristics of good-and-poor-performing pavements?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

t) Benefits of accurate pavement traffic loading data?

☐ Yes ☐ No

If yes, at which level? ☐ State ☐ Regional ☐ Country

Comments ____

2) **Please list any other Datapave research applications used by your agency?**

____

____

Part D – Contact Information

Contact Information:

Name: ______________________________________

Title: ______________________________________

Organization: ______________________________

Address: ___________________________________

City: ____________ State _____ Zip Code: ________

Phone: ____________ E-Mail: __________________

Would you like a copy of questionnaire results?

☐ Yes ☐ No

Appendix B

Profiler User's Questionnaire
Florida Department of Transportation

PROFILER USER'S QUESTIONNAIRE

FLORIDA DEPARTMENT OF TRANSPORTATION

Your assistance in answering the following questions will help in the evaluation of our program and how it relates to other states. The questionnaire is broken into four parts. Part One pertains to the use of profilers for pavement management purposes. Part Two pertains to the use of profilers for the reporting of Highway Performance Monitoring System (HPMS) sample sections to the Federal Highway Administration (FHWA). Part Three pertains to the use of profilers for ride acceptance on flexible and rigid pavement wearing surfaces. Part four is an agency request for the distribution of the results.

We thank you in advance for your time and cooperation, and would be glad to provide you with a copy of the survey results.

PART I – Pavement Management Systems (PMS)

1) Does your agency collect roughness (ride) data on the state highway system for pavement management purposes? ☐ Yes ☐ No

If yes please answer the following:

a) Who provides the service?

☐ State ☐ Consultant ☐ Other ____________________

b) What type of equipment is used and how many?

☐ Profiler ☐ K.J.Law 690 ☐ K.J. Law 8300

☐ Mays Ride Meter ☐ Other ____________________

If more than one type of equipment is used, please separate the following responses:

c) Who is the Manufacturer?____________________________

d) What type Sensors are used?

☐ Ultrasonic ☐ Laser ☐ Light ☐ Laser and Ultrasonic

☐ Other ____

e) Number of Sensors used? ____________________________

f) Number of Accelerometers?____________________________

g) Sensor Spacing used? ________________________________

h) Number of Crew Members per Unit? ______________________

i) On what time interval is roughness (ride) data collected?

☐ Annual ☐ Biannual ☐ Other ______________________

j) How many lane miles are tested per year? ____________________

☐ Lane miles ☐ Center line miles

k) What percent of the state highway system is represented by the above miles?

____

l) What roughness (ride) value is used for pavement management?

☐ IRI ☐ RN ☐ HCS ☐ PSI ☐ PSR ☐ Other ____________

m) If IRI is used, what calculations are reported?

☐ Left wheel path ☐ Right wheel path ☐ Half car simulation

☐ Unfiltered wavelength ☐ 300 ft wavelength ☐ 500 ft wavelength

☐ Other ______________________________

n) Is corrective action required at some level? ☐ Yes ☐ No

o) If corrective action is required, at what level?

____

2) **Does your agency collect rut depth data using profilers for pavement management?** ☐ Yes ☐ No

If yes, please answer the following:

a) How many sensors are used for rut depth?

☐ Three ☐ Five ☐ Other

b) Is any correction required at some level? ☐ Yes ☐ No

c) Is any correction factor used? ☐ Yes ☐ No

d) If corrective action is required, at what level?

____

Part II – Highway Performance Monitoring System

1) **Does your agency collect roughness (ride) data for HPMS?** ☐ Yes ☐ No

If yes, please answer the following?

a) Who provides the service? ☐ Sate ☐ Consultant ☐ Other __________

b) Is HPMS data collected in a separate run from pavement management data?

☐ Yes ☐ No

c) What does your agency do with HPMS sample sections less than 0.500 miles in length?

☐ Test or break out exact length

☐ Test longer lengths to represent sample section

☐ Other (Explain) ____________________

d) What IRI is reported for HPMS sections?

☐ Left wheel path ☐ Right wheel path ☐ Average of both wheel paths

☐ Other (explain) ____________________

e) Is IRI filtered differently from standard World Bank Equation?

☐ Yes ☐ No

If yes, please specify filtering:

☐ 300 ft wavelength ☐ 500 ft wavelength ☐ Other ____________

Part III – Ride Acceptance for New Wearing Surfaces

1) Does your agency use profilographs for accepting testing on new construction?

Flexible Pavements ☐ Yes ☐ No

Rigid Pavements ☐ Yes ☐ No

If yes, please answer the following:

a) What type profilographs are acceptable?

☐ Cox☐ McCracken ☐ Ames ☐ Light Weight Profilograph

b) Are computerized profilographs used or manual computed profile index?

☐ Computerized ☐ Manual ☐ Computerized & Manual

c) If computerized profilographs is used what type filter and cut off length value is used?

☐ Butterworth; third order ☐ Other ____________

☐ Two Foot ☐ Other ____________________

d) Who provides the services? ☐ Sate ☐ Consultant ☐ Contractor

Other ____________________

e) What blanking band is used?

Flexible: ☐ 0.2 inch ☐ 0.1 inch ☐ 0.0 inch ☐ Other ________

Rigid: ☐ 0.2 inch ☐ 0.1 inch ☐ 0.0 inch ☐ Other ________

f) Does your agency use incentive/disincentive specifications?

Flexible:	Incentive	☐ Yes	☐ No
	Disincentive	☐ Yes	☐ No
Rigid:	Incentive	☐ Yes	☐ No
	Disincentive	☐ Yes	☐ No

(Please attach specification if possible)

g) What profilograph Index (PI) level is used?

Flexible Pavements	Rigid Pavements
Acceptable ________	Acceptable ________
Incentive ________	Incentive ________
Disincentive ________	Disincentive ________
Must Correct ________	Must Correct ________

h) Does your agency feel that the use of incentive/disincentive specifications have improved the overall quality of ride on your highway system?

☐ Yes ☐ No

i) Has incentives/disincentives increased the cost of construction?

☐ Yes ☐ No If yes, how much? ____________________

2) Does your agency use profiler measurements for acceptance testing on new construction?

Flexible Pavements ☐ Yes ☐ No

Rigid Pavements ☐ Yes ☐ No

If yes, please answer the following:

a) What roughness (ride) value is used for acceptance?

☐ IRI — ☐ Left wheel path ___

☐ Right wheel path ___

☐ Average of both wheel paths ____

☐ RN ☐ Left wheel path ____

☐ Right wheel path ____

☐ Average of both wheel paths ____

☐ HCS _____

☐ PSI _____

☐ PSR _____

☐ Other ____

b) Values reported are for what length?

☐ 0.1 mile ☐ 0.5 mile ☐ 1.0 mile ☐ Project Length

☐ Other ____________________

c) How many profile runs are used for acceptance testing? ________

If more than one run, please describe the procedure followed ______

____

____

d) Who is responsible for acceptance testing?

☐ State ☐ Consultant ☐ Contractor ☐ Other ________________

e) Does your agency use incentive/disincentive specifications for …?

☐ Flexible: ☐ Incentive ☐ Disincentive

☐ Rigid: ☐ Incentive ☐ Disincentive

(Please attach specification if possible)

f) What ride level is used?

	Flexible Pavements		Rigid Pavements
Acceptable	________________	Acceptable	____________
Incentive	________________	Incentive	____________
Disincentive	________________	Disincentive	____________
Must Correct	________________	Must Correct	____________

g) **If using incentive/disincentive specifications, does your agency feel that they have improved the overall quality of ride on your highway system?**

☐ Yes ☐ No

Part – IV- Problems and Questionnaire

1) **Problems:**

   a) What types of problems are being encountered, if any, with profiler or profilograph equipment?

2) **Would you like a copy of questionnaire results?**

   ☐ Yes ☐ No

   If yes, please send to:

   Name: ______________________________

   Title: ______________________________

   Organizations: ______________________________

   Address: ______________________________

   City: ______________ State _____ Zip Code: ______________

   Phone: ______________ E-Mail: ______________________

Appendix C

Roughness Data For Asphalt Sections

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
9 1803	1.494	1.6262	1.5884	1.5132	1.5436	1.6559	1.591	1.6522	1.6348	1.6479
10 1450	1.1514	1.2142	1.1588	1.2368	1.2808	1.264		1.3504	1.412	
11 1400	3.0263	3.081	2.9024	3.0594	3.098	3.1272				
23 1009	0.9664	1.0612	0.9704	0.9826						
23 1009	0.763	0.7802	0.7832							
23 1012	0.7238	0.7526	0.715		0.805	0.803		0.7964	0.7866	
23 1026	1.3498	1.3582	1.4378	1.4039	1.4502					
23 1028	1.0832	1.0908	1.1218							
24 1632	0.7772	0.8622	0.8612	0.8592	0.9058	0.9166		0.9993	1.0294	
24 1634	0.9646	1.0204	1.0142	0.9334	0.94	0.9188	0.9011	0.929		
24 2401	0.8194	0.867	0.9022		0.9664	0.887		0.8944	0.959	
24 2805	1.2624	1.3172	1.4668							
24 2805	0.989	0.9988	0.9868	0.9658	0.996	1.0544				
25 1002	1.1644	1.1964	1.1886	1.132	1.1856	1.35295	1.5556	2.1982	2.5693	2.9468
25 1003	1.1938	1.296	1.3482	1.3946			1.3228	1.3844		
25 1004	1.074		1.0446	1.0868	1.0152				1.017	1.0374
33 1001	0.5746	0.6168	0.611	0.6516	0.81527					
33 1001	0.7428	0.782	1.1614	1.2622						
34 1003	1.3083	1.3165	1.4198	1.4586						
34 1011	1.6094	1.6182	1.7132	1.612	1.7238	1.8252	1.8268		1.8616	
34 1031	1.7558	1.8106	1.9222	1.8166	1.998	2.4528	2.2838			
34 1033	2.743	2.7874	2.9042	2.868	2.9016	3.1426				
34 1034	1.3454	1.3486	1.3914	1.3838	1.4022	1.4334	1.4722		1.486	1.4988
34 1638	0.8984	0.942	0.959	0.8992	0.9228	0.9606			1.03	0.999
36 1011	1.0834	1.1612	1.1409	1.2112						
36 1643	1.3544	1.4692	1.8066	2.1176	2.608	2.8008				
36 1644	0.958	0.9892	1.0618	1.0782	1.0926	0.998				
37 1006	0.6978		0.7436	0.732	0.746				0.9414	
37 1024	0.968	1.1648	1.1867	1.381	1.387			1.3768		1.4406
37 1028	0.8359	0.8804	0.9274	0.9192	0.9134		0.9314	0.952	1.0207	
37 1030	1.0448	1.1028	1.1042	0.9996	1.0624	1.1084	1.1546		1.1872	1.1636
37 1040	1.228	1.2536	1.2478	1.3034	1.3122					
37 1352	1.1721	1.142	1.1018	1.1252	1.127			1.2064		
37 1645	0.7762	0.8034	0.825	0.9292	0.8782	0.9572			0.9568	
37 1801	1.0417	1.0608		1.0964						
37 1802	0.8432	0.8968	0.8656	1.0898		1.647	2.2652			
37 1803	0.8326	0.8264	0.8384	0.8362				0.8714		0.909
37 1814	0.7796	0.8094	0.901	0.8762			1.0678		1.2234	
37 1817	0.8858	0.9072	0.9963	1.2536		1.2666				
37 1992	1.1272	1.2188	1.2924			1.2924				
37 2819	0.9624	1.094	1.1566							
37 2819	0.797	0.827		0.8654		1.019				
37 2824	0.7648	0.8016	0.9432	0.9848	0.9946			1.0242		
37 2825	1.6149	1.6558	1.611	1.6312	1.6902			1.8662		1.8924
42 1597	1.689	1.8583	1.7888	1.9674	2.0282	2.3114	2.6162		3.1808	3.4424

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
42 1605	1.9013	1.9086	1.9402	1.942	2.1178					
42 1608	1.6124	1.6204	1.6556	1.6364	1.7112		1.675		1.7232	1.7626
42 1618	1.6494	1.644	1.7132	1.7382	1.6822		1.6664		1.6992	
50 1002	1.0736	1.1158		1.2641	1.2741	1.2332	1.3022	1.2926		
50 1004	1.458	1.473	2.0784	2.08	2.0928		2.0438	2.0108		
50 1681	0.8006				0.8482		0.9212	0.892		
50 1683	2.122	2.25	2.229							
51 1002	2.2946	2.3926	2.4354	2.4936		2.4874		2.7264		
51 1023	1.5164	1.6197	1.5704	1.782	1.7886	1.807				
51 1417	1.1863	1.1452	1.1166	1.1678	1.2076	1.2516		1.7843		
51 1419	1.3634	1.3518	1.3556	1.3728	1.3994	1.4018				
51 1423	1.7996	1.8278	1.9556	2.0654			2.1215			
51 1464	1.1694		1.2128	1.1788			1.2476			
51 2004	1.3223	1.407	1.4798	1.5804	1.6072		1.8102	2.5342		
51 2021	1.4598	1.5098	1.464	1.6086	1.7526					
54 1640	0.758	0.8026	0.7958	0.8042						
17 1002	1.1495	1.181	1.1754		1.3514	1.4368			1.5332	
17 1003	0.9540	0.9422	0.9732		0.9274	0.965		1.0038		1.0202
17 6050	0.7478	0.8042	0.8342		0.8428	0.8424		0.9546		
18 1028	1.113	1.311	1.2376	1.389		1.3568	1.5392			
18 1037	1.8232	1.9876	2.0024		2.0732					
18 2009	1.526	1.6996	1.7424		1.9286	2.2754			3.4154	
18 6012	1.2676	1.6182	1.8672			2.9566				
19 1044	1.6362	1.9775	1.736	1.8448	1.847					
19 6049	1.4008	1.721	1.6976			2.0922	2.1262			
19 6150	1.2574	1.2224	1.3448	1.31	1.272			1.8302		
20 1005	2.8981	2.88	2.9013	2.911	2.8332	2.9636	2.9482	3.1638	3.3692	3.4078
20 1006	1.4684	1.491	1.5066	1.6152	1.539	1.5486	1.5486	1.6282		
20 1009	1.8974	1.9586	2.001	1.96	1.9722	2.023				
20 1009	0.742	0.781	0.7932							
20 1010	1.321	1.3598	1.3396	1.3066	1.4064	1.5218	2.194			
20 6026	0.7792	0.7988	0.8134	0.9108	0.9098					
21 1010	1.0657	1.1134		1.144	1.1744	1.5146				
21 1014	1.4404		1.6002		1.6314	2.0172	2.23		2.11	2.3502
21 1034	1.0894	1.0818	1.0824		1.1176					
21 1034	0.5882	0.6222	0.623							
21 6040	1.5166		1.5099		1.6714					
21 6043	0.9972		1.0187		1.0336	1.0444	1.0202		1.0436	1.0764
26 1001	0.7344	0.7514	0.8218							
26 1004	1.3502	1.462	1.415	1.3742						
26 1004	1.2876	1.3778		1.3378	1.4284					
26 1010	1.1774	1.196	1.7698							
26 1010	1.2736	1.4339	1.457			1.6494				
26 1012	0.9392	1.0442	1.1084	1.193	1.4178	1.4654	1.8842			
26 1013	1.1792	1.2676	1.3469	1.3744	1.6326		1.5464		2.1861	

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
26 6016	0.8508	0.884	0.8896	0.9778		1.015		1.2713		
27 1016	1.9114	1.974	2.2542	2.1954	2.205			3.1302		
27 1019	1.4782	1.4898	1.6042							
27 1023	1.5922	1.7428	1.7654	1.9184	1.9806	2.2442	2.2442			3.0462
27 1028	2.0432	2.2566	2.308	2.2452	2.5007	2.3856		2.5904		
27 1029	1.691	1.7748	1.8626	1.9286	1.9854					
27 1085	2.7576	2.8912	2.8616	3.0908	3.1406			3.3484	3.4592	
27 1087	1.382	1.5994	1.6166	1.8094	1.7962			2.3906	2.6906	
27 6064	0.8644		0.8866				1.167	1.2498		
27 6251	1.211	1.4416	1.652	1.7054	1.8117	1.8945		2.578		
29 1002	1.2624		1.3016	1.365	1.5104			2.286	2.373	2.5122
29 1005	0.7702	0.7856	0.7956							
29 1008	1.5902	1.602	1.6342							
29 1010	1.2348	1.2348	1.402	1.518	1.7562			2.4366	2.9284	
29 6067	1.4386	1.4488	1.4964	1.4904	1.6298	2.2178	2.3176			
29 5403	1.026	1.026	1.1322	1.0982			1.3396	1.6188	1.8328	
29 5413	0.933	0.9714	0.9434	0.9794	0.9512			1.0068	1.0406	1.062
31 1030	1.1	1.224	1.5916	1.712	2.0936	2.1583				
31 1030	1.027	1.0476	1.8132							
31 6700	1.2926	1.446	1.3892	1.5716	1.9376	2.0614		2.411		
38 2001	1.696	1.9938	1.9924	2.1476		2.426				
46 9106	0.8498	0.9136	0.931			1.123	1.2976			
46 9187	0.6446	0.7618	0.7316	0.897	0.9492	1.0447		1.2288	1.3204	
46 9197	0.8246		0.9248	0.916	0.9843	1.0184				
1 1001	0.8592	0.9386	0.9038							
1 1011	0.7944	0.9606		0.954						
1 1019	1.373	1.422	1.4118		1.51	1.5102		1.6962	1.7906	
1 1021	0.962		0.9484		0.9882	1.0054				
1 4073	0.8534		0.8912		0.8862	0.9566				0.9952
1 4125	0.9264		1.0976	1.1042				1.3016		
1 4126	0.8148		0.8338		0.8404		0.9486			0.998
1 4127	0.9032		0.933		0.8752	0.891			1.0122	
1 4129	1.0092		1.0102		1.0712	1.483		1.9292		
1 4155	0.9503		0.955		1.078		1.061			
1 6012	1.192		1.6088		1.9116	2.422				
1 6019	0.6587		0.7832							
5 2042	2.8682	2.9772		3.498						
5 3048	1.6402	1.6616		1.689	1.6738				2.0306	
5 3058	0.7922	0.837		0.8324		0.972				
5 3071	0.5938	0.594		0.6458	0.7056			0.7968		
12 1030	1.1084		1.1672			1.5004		1.8378		
12 1060	0.6538		0.6702		0.6266				0.713	
12 1370	1.3459		1.3714						1.4722	
12 3995	1.0136		1.0022					1.1398		
12 3996	1.0733		1.1202		1.0808					
12 3997	1.108	1.12	1.1082		1.2662					

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
12 4096	0.5986		0.6186		0.602				0.6994	
12 4097	0.7004		0.7162						0.8126	
12 4101	0.5222		0.535		0.5874					
12 4103	0.6526		0.646		0.6208				0.8112	
12 4105	0.811		0.8466							
12 4106	0.5996		0.6164		0.6206				0.9822	
12 4107	1.1496		1.2016		1.1536				1.4912	
12 4108	0.7022		0.7352							
12 4153	2.176		2.4202		2.5108				2.8008	
12 4154	1.5872	1.857	2		1.893		2.5986			
12 9054	0.9466	0.9938	0.985		1.041		1.176			
13 1001	0.802		0.8196		0.8458			0.911		
13 1004	0.8421		0.7819				0.9486			
13 1005	0.9534		0.9816	1.0288	1.0074	0.986	1.0497	1.0226	1.1722	1.033
13 1031	0.777		0.8581	0.883	0.9902		1.4462			
13 4092	0.7017		0.6968		0.6924		0.7704			0.771
13 4093	0.6976		0.7244		0.72		0.7852			0.8728
13 4096	0.9221		0.905		0.9006		1.0402			
13 4111	0.7194		0.7198							
13 4112	1.2554		1.4592		1.3996			1.4974	1.4876	
13 4113	0.8468		0.9056		1.0302			1.117	1.1782	
13 4119	0.9766		0.9772		0.9454					
13 4420	1.3906		1.2219							
22 3056	0.7358		0.8456		0.8134	0.9682			1.4602	
28 1001	0.7913		0.8694		0.9368	1.247		1.378		
28 1016	1.0444		1.0739	1.0516	1.0776	1.104	1.09	1.0638		
28 1802	0.8952	1.0106	1.1642	1.2514	1.7218	2.1013				
28 1802	1.9086	2.0292	1.9912							
28 2807	1.472		1.541	1.5452	1.5392				1.913	
28 3056	0.7358		0.8456		0.8134	0.9682			1.4602	
28 3081	0.7648		0.7746		0.8251	1.0554				
28 3082	1.0496		1.1042		1.1498	1.2874			1.4424	
28 3083	1.4612		1.4614		1.3924	1.7132			1.601	
28 3085	1.688		1.7488		1.7158	2.1374			2.064	
28 3087	1.0034		1.258		1.3392	2.01				
28 3089	1.081		1.1538		1.2634	1.6868			2.0628	
28 3090	1.21		1.2434		1.175	1.4244			1.3868	
28 3091	1.3082		1.5		1.7538	2.1638				
28 3093	0.9849		0.9986		0.9532	1.0252			1.3166	
28 3094	0.8292		0.895		0.8678	0.9396			1.1666	
35 1002	0.6826	0.8138		1.0492		0.9762		1.1838		
35 1003	0.8779	0.9852		1.0426		1.1582		1.6708		
35 1005	0.5294	0.6112		0.6652		0.6294		0.6954		
35 1022	0.6828	0.735		0.765		0.7818		0.853	0.8424	
35 1112	0.7734	0.7536	0.7826		0.8419	0.8365		0.8771		
35 2006	1.4084	1.4344								

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
35 2007	0.466	0.5134		0.5466		0.5942		0.7532		0.8866
35 2118	1.135	1.1668		1.2494		1.2936		1.414		
35 6033	1.2674	1.31		1.4624		1.6384		1.6218		
35 6035	1.1284	1.1692		1.426		1.4964		1.6926		
35 6401	0.5862	0.7146				1.3782		2.5192		2.5952
40 1015	1.5138	1.5838		1.5888					1.7504	
40 1017	0.1429		1.5708		1.552					
40 4086	0.895		1.1162		1.3282			1.8896		
40 4087	1.0596		1.1066	1.1176			1.1892			
40 4088	2.6738		3.3696							
40 4154	1.2481		1.2782		1.325			1.4632		
40 4161	1.256	1.4174		1.6404		1.5584		1.919		
40 4163	0.7783				0.7624			0.8726		
40 4164	0.9468	1.2568		1.333						
40 4165	2.013	2.078		2.0056	2.0278	1.975		2.0357		
40 6010	1.4838	1.6576		1.6184		1.6448		2.9224		
45 1008	1.4156		1.6332							
45 1011	1.3526		1.5522		1.5178		1.6262			1.8318
45 1023	0.7818	0.841	0.7808		0.7876					
45 1024	1.3844	1.4233	1.3804	1.424		1.4608			1.393	
45 1025	2.3304		2.9136	2.8182						
47 1023	0.7818	0.841	0.7808		0.7876					
47 1024	1.3844		1.4233	1.3804	1.424		1.4608			1.393
47 1028	1.209		1.398		1.3632		1.452			
47 1029	0.7061				0.7502	0.899			0.924	
47 2001	0.5996		0.6958		1.071					
47 2008	1.182		1.2168				1.1884			
47 3075	1.8512	1.8586			2.0534		1.8682			
47 3101	1.0632	1.1462	1.0924		1.4694	1.268				
47 3104	2.1014		2.408		2.4668		3.178			
47 3108	0.5343	0.5748	0.5646		0.5838		0.614			
47 3109	1.1584		1.1698		1.154		1.226			
47 3110	0.6482		0.7116		0.7136		0.7772			
47 6015	0.7848		0.8506		0.8596		0.9616			
47 6022	1.0042		1.246							
47 9024	1.4496		1.4334							
47 9025	1.5066		1.5792		1.8448	1.9234				
48 001	0.6736		0.7104	0.7206		0.7464		0.7554	0.763	
48 1039	1.034	1.361		2.2852						
48 1046	1.3301	1.4374		1.4992	1.4942				2.3944	
48 1047	2.0802	2.095		2.1644						
48 1047	1.5838				3.5458					
48 1048	1.6296	1.8124		1.786	2.01					
48 1049	1.1096		1.2686	1.352		1.444	2.626			
48 1050	1.2124	1.35	1.3788		1.7356		2.0368			

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
48 1056	1.287	1.4096		2.0676		1.9586				
48 1060	1.246	1.2672		1.3413	1.3736	1.4292		1.6699		1.722
48 1065	2.0844	2.131		2.429	2.6568					
48 1068	1.0992	1.1292		1.2277	1.2441	1.2242		1.3617		
48 1069	1.3298	1.496		1.4342	1.4884			2.2138		
48 1070	1.0158	1.0754		1.1456	1.0374			1.555		
48 1076	1.841	1.852		1.9052	1.6594			2.083		
48 1077	1.1922	1.2468		1.2486		1.2651		1.416	1.7598	
48 1087	1.1056							1.399		
48 1092	0.9494	1.453	1.4294		1.6554				1.8484	
48 1093	0.7052	0.755		0.7802		0.7894			1.2622	
48 1096	2.1317	2.3058	2.3098		2.3276				2.8088	
48 1109	1.3946	1.5886		1.6886		1.8282	1.8746		1.9666	
48 1111	1.5474	1.6026		1.684				2.3112		
48 1113	0.7482	0.917								
48 1113	0.6386		0.6898			0.8262				
48 1116	0.9479		1.5872							
48 1116	1.0466		1.0466			1.3834				
48 1119	1.0128	1.0172		1.033	1.0124			1.1888		
48 1122	1.0863	1.0586	1.0146	1.0621	1.1176	1.1235		1.3475		
48 1123	0.7597	0.7992	0.9184							
48 1130	3.7046		3.748							
48 1130	0.9858		1.0236			1.111				
48 1168	1.025	1.1228		1.1834		1.4686			1.6212	
48 1169	1.3178	1.3416		1.4002				2.2912		
48 1174	1.1899	1.1786	1.3216	1.4238		1.7736			2.0452	
48 1178	1.7635		2.4586	3.129						
48 1181	1.68	1.6552	1.9846	1.8938						
48 1181	1.467				1.7908					
48 1183	2.2816	2.4218	2.385		3.2416					
48 2108	1.477	1.5362		1.551		1.6492			1.7192	
48 2133	0.8132	0.8506		0.8396		0.8392			0.9656	
48 2172	0.7258	0.7538	0.7482		1.0158					
48 2176	1.2484	1.2368		1.3242	1.3412			1.4618		
48 3559	0.877	0.8688	0.8468		1.0845					
48 3579	1.3094	1.38		1.4098	1.377			2.5066		
48 3609	2.3172	2.3368								
48 3669	1.2074	1.3238		1.4332		1.5378			1.5274	
48 3679	1.7988	2.3352		2.7262		2.2892				
48 3689	1.405	1.6918		1.8854		2.1826			2.4746	2.355
48 3729	1.525	1.5516	1.6302	1.6674					1.8802	
48 3739	2	2.1726	2.2314	2.5346	2.4514	2.598		2.5063		
48 3749	1.2448	1.2248	1.3156	1.6106	1.8444			3.0696		
48 3769	1.4406	1.586	1.7144					2.2798		
48 3835	1.5014	1.7356	1.8308			1.8286	1.94			
48 3855	1.3175		1.2824	1.362		1.367			1.5176	

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
48 3865	1.1899	1.2456		1.3872						1.314
48 3875	1.0506		1.1346					1.98		
48 6079	2.4396	2.5914		2.9647	2.899			3.7084		
48 6086	0.7776	0.7298		0.7562		0.8048			1.0246	
48 6160	1.7682	1.9018		2.1506						
48 6179	0.9654	1.0394		1.0822	1.4196				1.434	
48 9005	1.2026	1.413	1.4778		1.8002				2.7938	
2 1001	1.2442	1.402	1.478				1.531			
2 1004	1.66		1.822		1.956		2.002			
2 1008	0.8294	0.929				1.214				
2 6010	1.077	1.162		1.136		1.177				
2 9035	1.4278					1.421				
4 1001	1.0652		1.073	1.101		1.1312		1.2418	1.301	
4 1002	1.5686		3.0646	3.164						
4 1002	0.5878	0.615	0.646							
4 1003	0.7884			1.0966						
4 1003	0.5674		0.6607	0.7248						
4 1006	0.7586		0.9302	1.1						
4 1006	0.802		0.8365	0.8588						
4 1007	1.3348		1.8234	1.8076						
4 1016	0.8078		0.8831	0.946				1.5506		
4 1017	1.0502		1.1936	1.3288	1.3488					
4 1018	0.9636		1.029	1.072						
4 1021	1.1294	1.2608		1.298						
4 1021	0.7528	0.7804	0.7948							
4 1022	0.6568		0.6682	0.7458		0.7344				
4 1022	0.5018	0.5308	0.5388							
4 1024	0.931			0.9322	1.0458	1.0856	1.1796	1.4486		
4 1025	0.8546	1.1156		1.0066	1.1062	1.1572	1.1546	1.2656		
4 1034	1.0614	1.0934	1.3032	1.2	1.4678		1.399	1.8142		
4 1036	0.714			1.7124	1.9304		1.9622		1.8734	
4 1037	1.7412		1.995	2.3576		2.5154		2.4154	2.4676	
4 1062	0.8006		0.8806	0.852	0.9474					
4 1065	0.9386		0.984		1.0344	1.1326	1.1494			
4 6053	1.2192		1.3542	1.3926				1.336		
4 6054	0.7516		0.8028	0.9304	0.9872			1.134	1.2428	
4 6055	0.626		0.6744	0.6974		0.6888		0.7696	0.7646	
4 6060	0.6696	0.7298				0.7946				
6 1253	1.7332	1.7436	1.7228	1.7551	1.7736	1.8416				2.1024
6 2002	1.3209	1.3832	1.4046	1.436				1.9102		
6 2004	1.473	1.6603	1.8384	2.1134						
6 2004	1.196		1.2492	1.35	1.4278					
6 2038	1.0598	1.1516	1.1554	1.1604			1.206	1.3064		
6 2040	1.0236		1.059	1.1816	1.4384	1.2818				2.0114
6 2041	1.2784		1.2818	1.4002	1.4194	1.6746				
6 2051	0.916		1.025	1	1.0396	1.0096	1.0516		1.5092	1.5694

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
6 2053	1.319		1.3863	1.359	1.409			1.464	1.4498	
6 2647	0.894		0.9524	0.9178	0.9436				1.1705	
6 6044	0.8492		0.8803	0.8754	0.8842	0.9074			0.9586	
6 7452	1.367		1.4059		1.4722	1.4668				1.5756
6 7454	1.7364		1.7268	1.6968	1.841	1.9334			1.753	1.802
6 7491	1.5766	1.7746	1.9876	2.2826		2.9446		3.208		
6 8149	0.8644	0.9126	1.0936							
6 8149	0.6548		0.654	0.6558	0.68					
6 8150	0.6087	0.6598	0.741		0.8942		0.99	1.0018	0.9954	
6 8153	1.2404	1.4342	1.5474		1.6496					
6 8156	1.5395	1.7088	1.7618		1.9448		2.3278			
6 8201	1.3206	1.31	1.3962	1.418		1.3686		1.5282	1.544	
6 8202	1.861	2.0548	2.0876		2.2574		2.4124	2.3558		
6 8534	0.6822	0.6906		0.7014		0.7332	0.7554	0.7952		
6 8535	0.7484	0.765		0.7458		0.7638	0.782	0.7816		
8 1029	2.266	2.3002	2.387	2.4476						
8 1029	1.5846			1.7574	1.774					
8 1053	1.1986	1.1628	1.2162	1.2328	1.2203	1.2455	1.2868	1.28805	1.342	
8 1057	1.112	1.126	1.1524	1.2194	1.2392			1.3368	1.4366	
8 2008	2.0585	2.3702	2.3998	2.5164						
8 7780	1.24	1.2252		1.2714		1.3394	1.3642			
8 6002	2.4248	2.5972	2.6648	3.0054		3.3698				
8 6013	1.807	1.9118	2.3254							
8 6013	2.188		2.303		2.6062	2.8008				
8 7783	0.9944	1.1038	1.129		1.1882	1.212		1.2946	1.303	
8 2008	2.0585	2.3702	2.3998	2.5164						
8 7781	1.1148	1.2263	1.3065		1.6054		2.2756	2.3774		
8 6002	2.4248	2.5972	2.6648	3.0054	3.3698					
15 1008	1.874		1.918		1.84		1.936			
16 1009	1.4398	1.473	1.5606							
16 1009	1.0055	1.0554		1.2754	1.341					
16 1005	1.345		1.7909	1.99		1.869		2.1398	2.3748	
16 1007	1.0868	1.1386	1.2328	1.2596	1.3182	1.3064		1.4092		
16 1010	1.3048	1.3433	1.3828	1.511	1.474	1.5161	1.6045	1.616	1.7519	
16 1020	0.697	0.698	0.708	0.7324	0.6948	0.6922	0.6944		0.7218	0.7094
16 1021	1.2479	1.255	1.2848	1.2406				1.2426	1.268	
16 6027	1.2914	1.3092	1.3738	1.3806	1.6384					
16 9032	1.5556	1.7116	1.8108	1.8302	1.8892	1.8528		1.8756	1.9774	1.9582
16 9034	1.5268	1.5816	1.6562	1.679	1.6742	1.6906		1.7238	1.8124	1.7884
30 1001	1.0279	1.0254	1.0576	1.0782	1.1156	1.0816	1.1272	1.096	1.2566	
30 6004	1.5614	1.6516	1.836	1.8372	1.8988		2.1622	2.3676	2.5558	
30 7066	0.7592	0.8900	0.8500	0.8725	0.8746	0.8982	0.9182	0.9576	1.0226	
30 7075	0.8926	0.8966	0.8874	0.9808	0.9798	1.0136		1.0432	1.1932	1.2928
30 7076	0.7096	0.7396	0.8759	0.9954	0.9718	0.9318		1.023	1.0638	1.146
30 7088	0.685	0.7016	0.6998			0.788	0.903			
30 8129	0.7494	0.8586	1.0176	1.0358	1.0177	1.143	1.0792	1.2442	1.4166	

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
32 1020	0.687	0.7212		0.9226	0.9704	1.0288			1.1882	1.409
32 1021	1.5018	1.5408	1.5732	1.981				3.0422		
32 1030	0.8752		0.9326	1.045		0.993	1.0202	1.0186		
32 2027	1.1183	1.1947	1.3436							
32 2027	1.0022		1.2662		1.3158					
32 7000	1.0322	1.1262		1.1574		1.2178				
41 2029			1.3192	1.3556	1.5184					
41 6011	0.8456	0.922	1.1826			1.0978	1.1172	1.1628	1.1606	
41 6020	0.6628	0.6862	0.6706	0.6758	0.6502	0.6558		0.7366	0.7798	
49 1001	0.991	0.9384	1.0422	1.0712	1.0678	1.1021	1.0949	1.2528	1.23875	1.2368
49 1004	2.0898	2.3834	2.615	2.8232	3.04		2.8524		3.5584	3.622
49 1005	0.6548	0.6612	0.6106	0.926		0.881	0.8588			
49 1006	0.6934		0.787	0.7372	0.8372					
49 1006	0.7122		0.7666	0.8474						
49 1007	1.0352	1.0528	1.061	1.091	1.1736		1.2634			
49 1008	1.2912	1.4214	1.5174	1.5178		1.6846		1.8858	2.2516	
49 1017	1.3678	1.3571	1.396	1.5184			1.4666		1.5346	
53 1002	1.5278	1.6438	1.6514	1.656		1.5854		1.6512	1.7856	
53 1005	0.651	0.7136	0.842							
53 1005	0.7618		0.7706		0.8608	0.9048	0.9288			
53 1006	0.8306	0.8432	0.8498	0.905	0.98882	1.0172	1.1564		1.679	1.6592
53 1007	1.002		1.5604	1.533	1.5234	1.4852	1.4702	1.4882	1.5166	
53 1008	1.0248	1.1063	1.3682	1.5607						
53 1008	0.9498		1.0514	1.1034	1.1554					
53 1501	0.8882	1.002	1.0798	1.1452	1.2652	1.1404	1.2692	1.331	1.469	1.4884
53 1801	0.9302	0.936		0.963	1.1126			1.237	1.208	1.3216
53 6020	0.673	0.6628	0.6862	0.6706	0.6758	0.6502	0.6558		0.7366	0.7798
53 6048	0.993	0.9806	0.9972	1.0144	1.0348	1.0326				
53 6049	1.1318	1.2718		1.212	1.2326	1.3412				
53 6056	0.9316	0.9754	1.0006	1.0608	1.1856	1.1564				
53 7322	0.6814	0.7338	0.7532		0.9987	0.8884		1.0528	1.0754	1.1106
56 2015	1.628	1.738	1.823	1.904	1.841	1.9218		2.137	2.1576	2.2712
56 2017	1.1874	1.2694	1.2404	1.4158	1.474	1.4474		1.708	1.937	1.935
56 2018	0.9064	1.0054	1.0494	1.0498						
56 2019	1.3132	1.4024	1.5068	1.542	1.6244	1.6678				
56 2020	0.9522	1.1295	1.3234	1.6888	1.8218	2.0522		2.323	2.3426	
56 2037	1.347	1.3714	1.372	1.3792						
56 2037	1.3312	1.3131			1.3728	1.3826				
56 7772	1.659	1.6502	1.725	1.7132	1.7624			1.8704		
56 7773	1.1248		1.1456	1.157	1.1706		1.1878	1.1996	1.2046	
56 6029	1.1572	1.2	1.1912	1.302	1.239	1.2324	1.3456			1.5
56 6031	1.5	1.677	1.8446	1.8102	1.9146	1.9984				
56 6032	1.1074	1.114	1.1738	1.251	1.2096	1.35	2.7672			
56 1007	0.8269	0.8412	0.8988	0.9098	0.92358	1.06707	1.1044	1.147	1.2836	
56 7775	0.6815	0.8654	0.9604	0.9914		1.2175		1.437	1.813	

Appendix D

Roughness Data for Concrete Sections

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1 3028	3.1838		3.4218		3.3747	3.6334				3.801
1 3998	0.6612		0.6946	0.8194				0.6734		
1 4007	1.4862		1.6306		1.5488	1.651				1.6254
1 4084	2.9494		3.2906		3.3688	3.6178				
1 5008	0.9482		0.9278	0.9316				0.9326		
4 7079	1.0308		0.9846	1.0746		1.0754		1.1056	1.103	
4 7613	1.6123		1.5002	1.6016				1.5714	1.7458	
4 7614	1.0222		1.0508	0.9876		1.0878		1.1354	1.2336	
5 3011	1.1297	1.1026		1.169	1.2224				1.1904	
5 3059	1.6527	1.6404		1.7348	1.8198			1.557		
5 3073	1.899	2.038		1.999	1.9566				1.9928	
5 3074	1.8954			2.2962	2.4658				2.8436	
5 4019	1.705	1.7478		1.621	1.6684			1.6102		
5 4021	1.8359	1.9104		1.8554	1.8764			1.9038		
5 4023	2.5775	2.6584		2.5684	2.4936				2.6108	
5 4046	1.5876	1.7096		1.726	1.6506	2.0708		1.9602		
5 5803	1.3693	1.5354		1.481	1.4597			1.4332		
5 5805	1.2389	1.3534		1.274	1.3086				1.269	
6 3005	2.3526		2.5832	2.7824	3.0648	3.3124		4.2986		4.7628
6 3010	1.2273	1.2814	1.2674		1.2606		1.2724	1.2762	1.3572	
6 3013	1.8328	1.6549								
6 3013	1.4402	1.493		1.7494		1.7687	1.6628	1.7436		
6 3017	1.4344	1.4478	1.496		1.4604		1.7106	1.6144	1.6498	
6 3019	1.4299	1.4596	1.4788		1.5654		1.71	1.7688	1.7402	
6 3021	1.4001	1.3905	1.3765	1.4136						
6 3021	1.2854		1.4158	1.3392	1.346					
6 3024	1.5174	1.513	1.567	1.6148		1.6767		1.7766	1.7376	1.7628
6 3030	1.2732	1.2788	1.2952	1.3058				1.5178		
6 3042	0.9436	0.955	0.9616	0.925	0.988	0.9917	0.9636	1.0789		
6 7455	1.1408	1.1764	1.172			1.1892	1.1662			
6 7456	2.2064		2.3002	2.0796	2.1788	2.102			2.2768	2.6534
6 7493	1.4102	1.4309	1.3712	1.386		1.3702		1.3724	1.395	1.4354
6 9048	1.6182	1.8022	1.7142		1.8424		1.8926	1.9946	1.9628	
6 9049	1.136		1.0938	1.0598	1.1426	1.1236			1.6038	1.845
6 9107	1.1834		1.2803	1.3698	1.4426	1.7304				2.0254
8 3032	1.488	1.4802	1.476	1.397		1.3892		1.3604	1.4178	
8 7776	1.3906	1.5036	1.5266	1.4366		1.4176		1.542	1.6092	
8 9019	1.3795	1.4562	1.8094	1.6768		1.6578		1.8284	1.7406	
8 9020	1.0248		1.7298	1.3812		1.4078		1.4314	1.2802	
9 4008	1.3276	1.3742	1.515	1.4738		1.469	1.4836			
9 4020	1.6396	1.6586	1.5248	1.5536	1.5234	1.6096	1.6092		1.6196	1.7034
9 5001	1.8534	2.0046	1.8676	1.7712	1.8588	1.8668	1.8204	1.812		

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
10 1201	1.73	1.878	1.8636	1.825		1.964	1.967			
10 4002	0.7954	0.7496		0.7924	0.9396					
10 5004	1.2504	1.1952	1.1332	1.2131	1.3338					
10 5005	1.0695	1.0748	1.0132	1.1096	1.1708					
10 5005	0.8408	0.8486								
12 3804	1.5234		1.769		1.9798				1.9916	
12 3811	1.6696	1.848	1.7674		1.8674				2.5564	
12 4000	1.6464	1.6504								
12 4057	0.7622		0.7512		0.8322				0.9064	
12 4059	0.9905		1.0316		0.9868				1.3364	
12 4109	1.901		1.9674		1.8424				2.002	
12 4138	1.5186		2.7624		2.8684				3.3462	
13 3007	1.765		1.8212		1.7898		1.9564			1.7858
13 3011	1.1332		1.1334		1.0538		1.185			1.1652
13 3015	1.2072		1.2596		1.2304		1.5046			1.4472
13 3016	1.3842		1.3092		1.327	1.4254				
13 3017	1.2413		1.278		1.1944			1.282	1.2834	
13 3018	0.9716	0.9962		1.0066			1.1644		1.1906	
13 3019	1.4583		1.5028	1.585	1.4518		1.6377	1.4857	1.6613	1.6316
13 3020	1.3708		1.3078		1.3954			1.4692		1.4472
13 4118	0.5756		0.599		0.5976		0.6716			
13 5023	1.421		1.4042				1.4176		1.4306	
16 3017	1.4912	1.5982	1.6088	1.5702	1.668	1.9058		1.8474	1.9942	
16 3023	1.5088	1.5446	1.543	1.5321	1.488	1.4892	1.4106		1.5174	1.48
16 5025	2.1602	2.2104	2.253	2.1586	2.3674	2.4512				
16 5025	1.011	1.0182								
17 4074	1.7082	1.7176	1.653		1.7648				1.773	
17 4082	1.4282	1.3984	1.3792	1.6312		1.4512	1.511		1.713	1.727
17 5020	1.1996	1.2198	1.176		1.168	1.2572		1.2104	1.1667	
17 5151	1.0426		1.2176	1.1868	1.4872			2.4706		
17 5217	2.2868	2.405	2.504							
17 5217	0.907	0.9818			1.3296	1.4808				
17 5843	1.1904	1.2638	1.466		1.3636	1.4086			1.6997	
17 5849	1.3694	1.3358		1.3524	1.3782		1.3938	1.4172		
17 5854	2.105	2.2056		2.3062	2.3274	2.4334		2.8362		
17 5869	1.6382		1.66	1.6528	1.7472			1.7747		
17 5908	2.017	2.0232	2.013		2.0276	2.0754		2.1904		2.197
17 9267	1.1094	1.1052	1.1432	1.1288	1.1372			1.1176		
17 9327	2.78		2.9546							
17 9327	0.9896				1.2086	1.2332				
18 3002	1.7563	1.7792	1.838	1.7492		1.7418	1.9463	1.7968	1.8944	1.816
18 3003	1.6844	1.6932	1.606	1.7886						
18 3030	1.5512	1.4918	1.5005	1.5265		1.6902	1.572			1.7559
18 3031	1.5446		1.5572	1.5297		1.5186	1.5534			
18 4021	2.1954		2.2671	1.9976		2.1496	2.066			2.4266
18 4042	2.205		2.4044	21,762		2.3154	2.313		2.5308	

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
18 5022	2.1492		2.1362							
18 5022	0.9223		0.9272	0.946		0.989		1.0168		
18 5043	2.1414		2.3756	2.3678		2.1828	2.3064		2.3754	
18 5518	1.3332		1.3502	1.4894						
18 5518	0.8058		0.7622		0.804		0.8466			
18 5528	0.9124		1.0848	1.0788			1.1213			
18 5538	0.8128		0.815	0.8074			0.938			
18 9020	1.515	1.556	1.5342	1.513		1.5292	1.5548			
19 3006	2.783	2.8388	3.1768	3.1548	3.2374			3.377	4.0328	
19 3009	2.2722	2.3178	2.2528	2.2842	2.2712			2.3512	2.3142	
19 3028	1.6906	1.7008	1.6582	1.6814	1.7188			1.7698	1.9234	
19 3033	1.6858	1.7298	1.6738	1.618	1.6714			1.6134	1.5986	
19 3055	1.7112	1.7658	1.8416	1.7964	1.9872			2.3013	2.3036	
19 5042	1.701	1.6656	1.6642	1.6864	1.718			1.7318	1.7506	
19 5046	1.5356	1.5572	1.5746	1.5492	1.5432			1.6508	1.692	
19 9116	0.796	0.8778	0.833			0.8262	0.826			
19 9126	1.2058	1.235	1.2396		1.2931			1.4292	1.4618	
20 3013	1.5924	1.507	1.5836	1.5806	1.5114		1.6484	1.6092	1.8302	1.7154
20 3015	1.1042	1.1126	1.0816	1.095	1.1082		1.3244	1.2356	1.1906	1.1196
20 3060	1.1066	1.2034	1.2416	1.312	1.32		1.434	1.5314	1.6078	1.5866
20 4016	1.406	1.4058	1.4368	1.4172	1.394		1.4348	1.4638	1.4856	1.4872
20 4052	1.4872	1.6092	1.6026	1.6412	1.663	1.8415		1.913	2.036	2.0798
20 4053	1.38	1.3926	1.4292	1.5746	1.591		1.6112	1.3776	1.664	1.441
20 4054	1.5844	1.7744	1.675	1.8264	1.6256	1.655	1.764	1.8153	1.8605	1.9446
20 4063	1.945	2.0428	2.0678	1.9744	2.0542		2.0692	2.0572	2.1752	2.0232
20 4067	1.9216	2.1112								
20 4067	0.8036	0.8292	0.837	0.9278	0.8554	0.939	0.9098			
20 9037	1.787	1.91	2.0592	1.9816	2.0744					
21 3016	1.4589		1.4776	1.5554			1.4236	1.5716	1.422	
21 4025	2.5234		2.663		2.7908		3.4938			
22 4001	1.7472	1.9314		1.9816		2.2156			2.378	
23 3013	2.033	2.0582	2.2288	2.106	2.1335	2.1778	2.2574		2.2166	2.2028
23 3014	1.4254	1.4334	1.6068							
23 3014	1.451	1.5544	1.521	1.5784		1.5666	1.5862			
24 5807	2.6494	2.765								
24 5807	1.2544	1.2722	1.3136	1.3832	1.4732		1.4132	1.4714		
26 3038	2.2238	2.1158	2.0296	2.185	2.0282					
26 3068	2.2238	2.1158	2.0296	2.185	2.0282					
26 3069	1.3612	1.3188	1.3556	1.2878	1.2814	1.3072			1.3808	1.3664
26 4015	1.5988	1.6211	1.6424	1.6328	1.6102	1.6288			1.7356	
26 5363	1.7542	1.8024	1.8356	1.8048	1.829		1.8604		2.3162	
26 9029	1.8195	1.8762	1.8686	1.8196	1.8492	1.8722			1.8863	1.8828
26 9030	1.8108	1.9194	1.8977	1.8194	1.7978	1.9888			2.0426	2.1098
27 3003	1.9436	2.0624	2.0758		2.141			2.124	1.9066	
27 3005	1.3612	1.5388								
27 3007	1.0978	1.025								

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
27 3010	1.5406	1.4724								
27 3012	1.5482	1.4946								
27 3013	1.2826	1.2974	1.2318	1.3308	1.3206			1.4024	1.5562	
27 4033	1.2526	1.402	1.2888	1.4982	1.2964			1.3488	1.542	
27 4034	1.6764	1.7754	1.7638	1.7562				1.8258	1.8772	
27 4037	1.374	1.5322	1.4064	1.5608	1.436			1.4084	1.6538	
27 4040	1.715		1.9	1.7562	1.8036	1.9089	1.9709		2.0804	2.1116
27 4050	1.3508		1.2886	1.373	1.477				1.3576	
27 4054	1.7534	1.8332	1.9472		1.9233			2.0956	2.2602	
27 4055	1.1606	1.185	1.0658	1.1944	1.0834			1.204	1.2694	
27 5076	0.7622	0.949	0.8186	0.8796				0.9894	1.0424	
27 6300	1.3476	1.4856		1.6388				1.7306	1.7248	
27 9075	1.9206	1.9772		1.9148	2.056					
28 7012	1.5096	1.6916			1.5556	1.5974			1.849	
28 9030	1.0205		1.0902		0.9416	1.106			1.138	
29 4036	1.321	1.2908	1.3042	1.3506	1.3612			1.5348	1.6046	1.65
29 4069	1.1712	1.2076			1.4236	1.4748	1.519			
29 5000	2.0184	1.9956	2.0268	2.0752	2.0966			2.2488	2.3042	2.3016
29 5047	1.5642	1.5106	1.549	1.513	1.5462			1.599		1.7427
29 5058	1.5938	1.5798	1.6172	1.623	1.5802			1.6922	1.6984	1.7476
29 5081	1.791	1.8546	2.0108	2.07			2.22	2.2746	2.3134	
29 5091	1.5298	1.5466	1.577	1.64			1.683	1.7534	1.7672	
29 5393	1.3648	1.3498	1.324			1.3522	1.4326	1.3482		
29 5473	1.0708	1.106	1.0703	1.0894			1.1562	1.211	1.1538	
29 5483	0.8564			0.9396	1.6257					
29 5503	1.2446	1.3556	1.2152			1.2682	1.2736	1.3212		
31 3018	1.2938	1.544	1.4866	1.6342	1.5754		1.8102		2.108	
31 3023	1.1344	1.1592	1.1497	1.156	1.1814			1.1794	1.1822	
31 3024	1.4296	1.4358	1.4288	1.5022	1.414		1.5522	1.6386		
31 3028	1.078	1.129	1.0792		1.0936		1.1346	1.2036		
31 3033	0.8304		0.9402	0.879	1.0624	0.9864			1.1134	1.487
31 4019	1.7074		1.9546	1.8824	1.8344	2.1538			2.194	2.356
31 5052	1.0682		1.08	1.1028	1.0854	1.0788			1.2398	1.2472
31 6701	1.9258		2.1024	2.144	2.3652	2.4206	2.6404		2.5776	2.6328
31 6702	0.6934		0.7162	0.7006	0.84	0.7328		0.826	0.9338	
32 3010	2.2276	2.2786	2.3521	2.6015	2.3771	2.494	2.4718	2.5208	2.593	3.1378
32 3013	1.7564	1.7644	1.8128	1.9482	1.9564		2.089		2.1656	2.1736
32 7084	1.2114	1.2634		1.1878	1.3738	1.3028	1.2684	1.2012		
34 4042	1.8372		1.9062	1.7196	1.9822	1.9122	2.0148		2.0166	2.1304
35 3010	1.3822	1.4176	1.2784			1.2886		1.4084		
36 4017	1.9376	2.148	1.8998	2.064	2.0012			2.3204	2.4626	2.5914
36 4018	1.7126	1.7234	1.6746	1.8498	1.7758	1.6662		1.8578	1.8782	
37 3008	1.7469	1.6524	1.6344	1.6844	1.7672		1.79	1.8872		2.0494
37 3011	1.5728	1.6954	1.6578	1.755	1.6638		1.6628			
37 3044	1.8808	1.9904	1.928	1.9664	2.0148					

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
37 3807	1.811	1.7962	1.7884	1.7833	1.7802		1.813	1.8554		
37 3816	2.1599	2.1462	2.2766	2.0396	2.1958	2.2046			2.133	
37 5036	1.16583	1.1206	1.0192	1.1216	1.0584			1.1126	1.1422	1.2416
37 5827	0.992	0.9512	0.9048	0.9428		0.9758	0.9755	1.011		
38 3005	0.7952	1.1246	1.0862	1.2084			1.5054	1.2404		
38 3006	0.8314	1.007	0.8324	0.953			0.9642	1.1844		
38 5002	1.2438		1.2984	1.2448	1.2224	1.288			1.348	
39 3801	1.9008	2.2316	1.9574	1.9202		1.9716				1.9697
39 4018	1.6942	1.7112	1.803	1.6796		1.664				1.8446
39 4031	1.9358	1.9806	1.9888			2.025				2.8764
39 5003	1.0872	1.0426	1.0194	1.1338		1.1236				1.0367
39 5010	0.7526	0.8166		0.7636				0.8984		
39 5569	2.2278	2.2798		2.279				2.3336		
39 9006	1.4832	1.5062	1.5588		1.4982					1.6086
39 9022	1.3516	1.3653	1.5304	1.521		1.423				
40 3018	1.9332	2.0664		2.1024		2.233			2.4598	
40 4155	0.9987		0.9554		0.983			0.9374		
40 4158	0.9603		1.073		1.0424			1.0974		
40 4160	1.7135		1.7508		1.7622			1.7346	1.9102	
40 4162	1.7264		1.7032		1.7038			1.5094		
40 4166	0.8752		1.011		0.9036			1.011		
40 5021	0.9358		0.9246		0.9212			0.9464		
41 5005	1.3178		1.2958	1.2358	1.2504			1.1844	1.2366	1.225
41 5006	1.356	1.317	1.3772	1.373	1.3644	1.3346			1.4072	1.381
41 5008	0.91	0.9386	0.941	0.9588	0.9404			1.0502	1.019	1.0906
41 5021	1.0034	1.0372	1.0692			1.026	1.0514	1.2124	1.0646	
41 5022	0.9368	1.0034	1.0094			1.0852	1.082	1.0936	1.0808	
41 7081	0.7862	0.8362	0.7472	0.7556	0.7808	0.7466			0.8146	0.7916
42 1598	1.676	1.682	1.6184	1.5696	1.7024	1.7132	1.8096		1.806	1.7916
42 1606	1.4098	1.4614	1.3662	1.4595	1.5312	1.4816	1.5262	1.4852	1.53	1.6035
42 1613	1.0432		1.0518	1.0236	0.9905	1.039		0.9736	0.976	
42 1614	0.9956	1.0216	1.0842	1.079	1.0944	1.1662	1.147		1.2078	1.241
42 1617	0.8262	0.8052	0.8536	0.8545	0.8552		0.8714	0.9032		
42 1623	1.319	1.2994	1.2632	1.244	1.2682	1.3196	1.353		1.3435	1.353
42 1627	1.9098	1.8264		1.7124	1.8328	1.841		1.8402	1.8732	
42 1690	1.7289	1.7928	1.7572	1.7128	1.7654	1.7944		1.8202	1.8204	
42 1691	1.1056	1.1502	1.1964	1.2614			1.3386	1.3862		
42 5020	1.7926	1.809	1.8392	1.8843	1.969		1.9828	2.0668	2.3768	
42 9027	2.6974	2.6938	2.6698	2.7356	2.756	2.7622	2.7756	2.9106		
45 3012	1.12		1.2088		1.1844		1.2246			1.249
45 5017	1.9743		2.0478		2.038		2.0802			2.0028
45 5034	1.4182		1.4346		1.4726			1.544		
46 3009	2.7013	2.8272	2.999	3.0764	2.9236					
46 3010	1.8486	2.184	2.2726	1.9318			2.4842	2.1618		
46 3012	2.8338	2.925	2.947	2.822	2.8388	2.9964			3.0934	
46 3013	1.4532	1.4628	1.6624	1.4872			1.4638	1.6922		

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
46 3052	0.9468	0.9574	0.9086				0.871	0.9464		
46 3053	1.1564	1.193	1.1208	1.116	1.249	1.349			1.2326	1.272
46 5020	0.9532	1.0612	0.985	0.9658	0.9716	0.9918			1.0026	1.0672
46 5025	1.2426	1.242	1.2998	1.2698	1.2846	1.3042			1.3368	1.3416
46 5040	1.9922		2.1348	2.132	2.0802	2.0322			1.9492	2.0098
46 6600	2.3854	2.379	2.3452			2.7216	2.7906			
48 3003	2.099	2.1362		2.025	2.2008			2.4066		
48 3010	2.1698	2.2968		2.186		2.2198			2.0824	
48 3569	1.204	1.3276		1.3112		1.3976			1.3766	
48 3699	1.5552	1.6514	1.6916		1.7618			1.93	1.9906	
48 3719	2.4296	2.4054		2.384		2.2812			2.3218	
48 3779	2.244	2.143	2.1178		2.1892			2.0392		
48 3845	1.6786	1.8038		1.7102		1.6804			1.7588	
48 4142	1.9172	1.9412		1.9595	2.0145	1.9972		1.8815		
48 4143	2.2274	2.2932	2.2112	2.2322	2.316	2.292		2.2672		
48 4146	2.1524	2.1594		2.1282		2.1938			2.1856	
48 4152	2.7798	2.615		2.7174			2.8802			
48 5024	2.4628	2.5766		2.5486		2.3338			2.7784	
48 5026	1.7032	1.6792		1.6736		1.6844			1.7738	
48 5035	1.7714	1.837		1.716	1.8586					1.6902
48 5154	1.5958	1.5416		1.54		1.649			1.5194	
48 5274	1.595	1.7164		1.6254	1.658				1.6238	
48 5278	1.7032	1.6646		1.6596	1.6658				1.76	
48 5283	1.1372	1.168		1.15	1.178				1.3554	
48 5284	1.9524	2.1888		1.9658	2.4186				2.3212	
48 5287	1.8622	1.7491		1.8776	2.0272				1.953	
48 5301	1.6034	1.6914		1.6244	1.6692				1.5842	
48 5310	1.946	2.098		19,222	1.997				1.8378	
48 5317	2.1806	2.2558		2.2688	2.3462				2.4632	
48 5323	1.7826	1.7836		1.735	1.8096				1.8642	
48 5328	1.6706	1.6332		1.5892	1.63				1.5432	
48 5334	1.11	1.1602		1.0696		1.1008			1.0966	
48 5335	2.0296	2.0858		2.0018	2.0134				1.9696	
48 5336	1.4054	1.4678		1.4556	1.435				1.3384	
48 9167	1.7576	1.834		1.7664		1.8036			1.7284	
48 9335	0.8942	0.9526		0.91		0.9224			0.8748	
49 3010	1.3856	1.4758	1.8062	1.7372	1.697		1.9086		1.6704	1.508
49 3011	1.3203	1.6274	1.6216	1.7814	1.9502	1.8202	1.767	2.2589	2.1058	2.168
49 3015	1.9656	1.9668	1.9784	2.0186	1.974	2.0446	2.1956		2.025	2.3082
49 7082	0.9086	1.096	1.0056	0.918	0.8872		1.0044	1.0356		
49 7083	1.1178	1.1708		1.054		1.3696	1.43			
49 7085	1.4108	1.4072	1.373		1.6344	1.5788				
49 7086	1.4238	1.6984	1.307		1.6396	1.8462				
50 1682	2.3066	2.4964	2.4316							
50 1682	0.947			1.1204		1.2162	1.2732			
51 2564	0.9558	0.9696	0.9814	0.8938	0.9722	1.0042	1.0138		1.0047	

Section	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
51 5008	2.1836	2.3384	2.0848	2.0115	1.9328	1.9878		1.9954	2.015	2.0328
51 5009	2.2594	2.1358		2.217	2.2342	2.2788	2.1576		2.271	2.3732
51 5010	1.537	1.4728	1.5998	1.5584	1.601	1.6766	1.5958		1.6128	1.6398
53 3011	1.447	1.5396		1.5556	1.5826	1.5754	1.6492	1.8848	1.906	1.872
53 3014	0.9654	1.1432	0.8994	1.0376	0.9128	0.988	0.9004		0.9808	1.107
53 3019	1.1558	1.2042	0.903	1.025	0.9146	1.0654	0.9918		1.307	1.3796
53 3812	1.1806	1.238		1.2176	1.2438	1.2902				
53 3813	1.8044		1.7282	1.8298	1.966		1.9786	1.9986	2.1118	2.2416
53 7409	0.9558	1.2138	1.0678	1.1904	1.11		1.1544	1.3014	1.4022	
54 4003	1.5734	1.7338	1.5824	1.5214		1.5934	1.6392		1.8412	
54 4004	2.705	2.8672	2.8682	3.0938	3.4538	3.5664	3.6168			
54 5007	2.269	2.4494	2.4402							
54 5007	1.0494	1.066	0.9916							
55 3009	2.5044	3.268	3.5055	3.4712						
55 3009	0.9736		1.5564	1.7246						
55 3010	1.8804	2.0326	2.2586	2.1565	2.4432	2.5644		2.7544	2.9702	
55 3012	1.691	1.6446	1.616		1.7442			1.8992	2.0634	
55 3014	1.5384	1.5526		1.9194	2.275					
55 3015	1.9612	2.1372	2.0192	2.1112	2.2676	2.6232		2.3418	2.5938	
55 3016	1.2438	1.3324	1.253	1.2835	1.3666			1.2566	1.4214	
55 3019	1.0886		1.2188	1.2264	1.239	1.1384	1.1282		1.4156	1.2888
55 5037	1.1546		1.2082	1.1192		1.1172	1.13		1.1744	
55 5040	2.3144	2.3746	2.3426	2.3312	2.3842	2.47		2.3432		
55 6351	1.9904	1.92	1.906		2.17	2.0712		2.1708	2.1728	
55 6352	1.2342	1.2275	1.2538		1.2396	1.2666		1.312	1.3028	
55 6353	1.4432	1.451		1.582	1.7312		1.658	1.6892		
55 6354	1.2378	1.2524	1.2338		1.1988	1.2688		1.2542	1.2266	
55 6355	1.4756		1.6092	1.6204		1.5816	1.6138			
56 3027	2.243	2.5952	2.5792	3.0098	3.1054	3.0274			3.4778	3.82

Appendix E

Contingency Tables for the Chi-Square Test of Asphalt Sections

Table of Chi-Square Test For The IRI Values of Year 1 – 3.

	Smooth	Rough	Total
Smooth	156	14	170
Rough	6	152	158
Total	162	166	328

Table of Chi-Square Test For The IRI Values of Year 1 – 4.

	Smooth	Rough	Total
Smooth	122	14	136
Rough	11	106	117
Total	133	120	253

Table of Chi-Square Test For The IRI Values of Year 1 – 5.

	Smooth	Rough	Total
Smooth	95	18	113
Rough	20	112	132
Total	115	130	245

Table of Chi-Square Test For The IRI Values of Year 1 – 6.

	Smooth	Rough	Total
Smooth	93	20	113
Rough	15	86	101
Total	108	106	214

Table of Chi-Square Test For The IRI Values of Year 1 – 7.

	Smooth	Rough	Total
Smooth	48	2	50
Rough	4	48	52
Total	52	50	102

Table of Chi-Square Test For The IRI Values of Year 1 – 8.

	Smooth	Rough	Total
Smooth	63	10	73
Rough	4	60	64
Total	67	70	137

Table of Chi-Square Test For The IRI Values of Year 1 – 9.

	Smooth	Rough	Total
Smooth	52	9	61
Rough	8	51	59
Total	60	60	120

Table of Chi-Square Test For The IRI Values of Year 1 – 10.

	Smooth	Rough	Total
Smooth	19	4	23
Rough	6	23	29
Total	25	27	52

Appendix F

Contingency Tables for the Chi-Square Test of Concrete Sections

Table of Chi-Square Test For The IRI Values of Year 1 – 3.

	Smooth	Rough	Total
Smooth	109	8	117
Rough	5	105	110
Total	114	113	227

Table of Chi-Square Test For The IRI Values of Year 1 – 4.

	Smooth	Rough	Total
Smooth	101	12	113
Rough	8	96	104
Total	109	108	217

Table of Chi-Square Test For The IRI Values of Year 1 – 5.

	Smooth	Rough	Total
Smooth	82	10	92
Rough	6	94	100
Total	88	104	192

Table of Chi-Square Test For The IRI Values of Year 1 – 6.

	Smooth	Rough	Total
Smooth	57	6	63
Rough	5	65	70
Total	62	71	133

Table of Chi-Square Test For The IRI Values of Year 1 – 7.

	Smooth	Rough	Total
Smooth	48	4	52
Rough	4	48	52
Total	52	52	104

Table of Chi-Square Test For The IRI Values of Year 1 – 8.

	Smooth	Rough	Total
Smooth	62	9	71
Rough	3	59	62
Total	65	68	133

Table of Chi-Square Test For The IRI Values of Year 1 – 9.

	Smooth	Rough	Total
Smooth	62	8	70
Rough	4	66	70
Total	66	74	140

Table of Chi-Square Test For The IRI Values of Year 1 – 10.

	Smooth	Rough	Total
Smooth	38	12	50
Rough	4	32	36
Total	42	44	86