EVALUATIONS OF RIDE EQUATION

RESEARCH REPORT 4901F

PROJECT TITLE: EVALUATION OF RIDE EQUATION USING CURRENT PROFILER SYSTEMS AND NEW SENSOR TECHNOLOGY

THE UNIVERSITY OF TEXAS AT ARLINGTON
TRANSPORTATION INSTRUMENTATION LABORATORY
THE TEXAS TRANSPORTATION INSTITUTE
TEXAS A&M UNIVERSITY

Research Supervisors: Roger S. Walker, Ph.D., P.E
and Emmanuel Fernando, Ph.D., P.E

Date: January 2002

Notice – The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear solely because they are considered essential to the object of the report.

DISCLAIMER(S)

The contents of this report reflect the views of the author(s), who is (are) responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

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

ACKNOWLEDGEMENTS

The authors would like first of all to acknowledge Carl Bertrand of the Texas Department of Transportation. Without his support, this research project would not have been possible. Acknowledgements are also due the students and staff personnel at the Transportation Instrumentation Laboratory facility at the University of Texas at Arlington and the Texas Transportation Institute at the Texas A&M University who participated in the rating panel and in analyzing the rating and profile data

Table of Contents

DISCLAIMER(S) ii

ACKNOWLEDGEMENTS iii

LIST OF FIGURES VI

LIST OF TABLES VIII

CHAPTER 1 1

INTRODUCTION 1

HISTORY OF CURRENT RIDE EQUATION 2

REPORT CONTENTS 9

CHAPTER 2 10

RIDE PANEL RATINGS 10

INTRODUCTION 10

PLAN OF FIELD EXPERIMENTS 11

SELECTION OF TEST SECTIONS 14

PLACEMENT OF MARKERS TO LOCATE TEST SECTIONS 18

ASSEMBLY OF RATING PANELS 19

DATA COLLECTION 20

STATISTICAL DATA ANALYSIS 22

ANALYSIS OF DATA FROM TESTS ON CONTROL SECTIONS 23

ANALYSIS OF DATA FROM MAIN EXPERIMENT 27

EVALUATION OF SPATIAL INDEPENDENCE OF RIDE RATINGS 28
EFFECT OF RATER FATIGUE 29
EFFECT OF PAVEMENT TYPE 33
EFFECTS OF SECTION ROUGHNESS, RATER, AND VEHICLE ON SUBJECTIVE RATINGS OF RIDE QUALITY 36
EVALUATION OF RATINGS FROM ROSEANNA AND WILLARD 40
EVALUATION OF RATINGS FROM VINATHA AND YUE 41
EVALUATION OF SARAH'S RATINGS 43
EVALUATION OF SARAH'S RATINGS 44
EVALUATION OF DUCHWAN'S RATINGS 44
EVALUATION OF SIDNEY'S RATINGS 47
SUMMARY AND IMPLICATIONS OF FINDINGS 48
CHAPTER 3 52
RIDE PANEL RATINGS CONDUCTED IN DALLAS/FORT WORTH 52
INTRODUCTION 52
PLAN OF DFW RIDE SURVEY 58
EVALUATION OF DFW RIDE SURVEY DATA 58
SPATIAL INDEPENDENCE OF RIDE RATINGS 59
DIFFERENCES BETWEEN PSRs AND PSIs 59
SUMMARY OF FINDINGS 62
CHAPTER 4 64
DATA COLLECTION AND ANALYSIS 64
PROFILE DATA ACQUISITION 64

DATA PROCESSING PROCEDURES 65
DATA ANALYSIS AND THE CURRENT RIDE EQUATION........ 66
CHAPTER 5 72
NEW RIDE MODEL........ 72
PROFILE SPECTRAL CHARACTERISTICS 72
MODEL DEVELOPMENT........ 73
PSI COMPUTATION PROCEDURES........ 82
MODEL VERIFICATION 84
CHAPTER 6 90
SUMMARY AND CONCLUSIONS 90
SUMMARY........ 90
CONSIDERATION OF FUTURE APPLICATION OF NEW RIDE STATISTIC IN TXDOT'S SMOOTHNESS SPECIFICATION 91
CONCLUSIONS 95
REFERENCES 96
APPENDIX........ 98

List of Figures

Figure 1.1 Wavelength vs Power Spectral Data 4

Figure 1.2 PSI vs IRI – Current Ride Model....8

Figure 2.1 Distribution of Rating Sections (total of 63)....18

Figure 2.2 Rating Form Used in the Ride Surveys....21

Figure 2.3 Effect of Section Roughness on Ride Quality Rating....25

Figure 2.4 Illustration of Differences in User-Perception of Ride Quality....26

Figure 2.5 Illustration of Differences in User-Perception of Ride Quality....27

Figure 2.6 Comparison of Mean PSRs from AM and PM Runs (Survey #2)....31

Figure 2.7 Comparison of Mean PSRs from AM and PM Runs (Survey #1)....32

Figure 2.8 Comparison of Mean PSRs and AM and PM Runs (Survey #3)....33

Figure 2.9 Comparsion of Mean PSRs of Asphalt and PCC Sections....36

Figure 2.10 Mean PSRs and Mean IRIs of AC Sections Surveyed in Main Experiment....38

Figure 2.11 Mean PSRs and Mean IRIs of PCC Sections Surveyed in Main Experiment....39

Figure 2.12 Evaluation of Ratings From Roseanna and Willard....41

Figure 2.13 Illustration of Effect of Vehicle Type on Ratings by Vinatha and Yue....43

Figure 2.14 Illustration of Rater*Section Interaction in Ratings by Vinatha and Yue....43

Figure 2.15 Variation in Sarah's Ratings between Sections of the Main Experiment....45

Figure 2.16 Comparison of Mean PSRs Between Vehicles Used by Sarah....46

Figure 2.17 Variation in Duchwan's Ratings by Section and Vehicle Type....47

Figure 2.18 Illustration of Vehicle Effect on Sidney's Ratings....49

Figure 3.1 Driving Route for DFW Ride Survey *(a)*....56

Figure 3.2 Driving Route for DFW Ride Survey *(b)*....57

Figure 3.3 Differences Between PSRs and PSIs from 1999 Survey Data....60

Figure 3.4 Differences between PSRs and PSIs from 2000 Ride Survey....61

Figure 4.1 Multiple Sections in One Data Collection....65

Figure 4.2 Description of Section Separation....66

Figure 4.3 Summary of PSR vs Rater Car Class....67

Figure 4.4 Comparisons of PSI equations related to IRI....68

Figure 4.5 Wavelength vs Power Spectral Rating Data – 1999 Data....70

Figure 5.1 **Wavelength vs Power Spectral Rating 64 Bands for Combined Sessions 74**

Figure 5.2 **Wavelength vs Power Spectral Rating 32 Bands for Combined Sessions 75**

Figure 5.3 **PSR vs. PSI of Two Models...81**

Figure 5.4 **Residual of two models...82**

Figure 5.5 **Comparisons of Current and New Model to Verification Sections...86**

Figure 5.6 **Comparisons of Residuals for Current and New Model for Verification Sections......................87**

Figure 5.7 **Comparisons of PSI for Current and New Model for Austin Test Sections.................................88**

Figure 6.1. **Proposed Pay Adjustment Schedules in TxDOT's New Ride Specification. 92**

Figure 6.2 **Relationship between PSI from New Model and IRI. 93**

Figure 6.3 **Alternative Pay Adjustment Schedule Based on PSI..94**

LIST of TABLES

Table 2.1 **Text Matrix for Field Surveys 12**

Table 2.2 **Vehicles used in Ride Survey** **13**
Table 2.3 **Schedule of Ride Surveys** **14**
Table 2.4 **Test Sections Selected for the Ride Survey** **17**
Table 2.5 **ANOVA from Analysis of Data Taken on Control Sections** **24**
Table 2.6 **Results From the Runs Text of Spatial Independence** **30**
Table 2.7 **Results From Paired *t*-Tests to Evaluate Effect of Rater Fatigue** **31**
Table 2.8 **Results from Evaluation of Effect of Pavement Type** **35**
Table 2.9 **Individuals Who Rated in More Than One Field Survey in the Main Experiment** **40**
Table 2.10 **Evaluation of Effect of Vehicle on Ratings Given by Vinatha and Yue** **42**
Table 3.1 **List of Test Sections for DFW Ride Survey** **55**
Table 3.2. **Average Differences Between PSRs and PSIs.** **62**
Table 5.1 **PSR vs PSI New and Current Model** **80**
Table 5.2 **Model Verification Runs** **85**

CHAPTER 1

INTRODUCTION

The Texas Department of Transportation (TxDOT) annually collects profile data over the state-maintained highway network. TxDOT uses the profile data to determine ride quality based on the present serviceability index (PSI). The indices determined are stored in the Pavement Management Information System (PMIS) database, and are published in the PMIS reports prepared annually by the Materials and Pavements Section of the Construction Division.

The existing equation for determining PSI from measured profile is based on ride measurements obtained from a rating session conducted in the late 1960s. Since its original development over 30 years ago, a number of changes have taken place that requires a re-evaluation of the current equation. These include: changes in vehicle design, such as improvements in vehicle suspension and handling characteristics, and the switch from the predominantly large automobiles used in the late 1960s to the smaller and more fuel efficient mid-sized and compact cars of today; migration from the response-type roughness measuring devices, i.e., the Mays ride meters used by TxDOT in the 1970s and early 80s, to the inertial profilers that are now standard within the department; and change in the interval used to report PSI, from 0.2- to 0.1-mile.

In view of the above changes, TxDOT funded a research project with the University of Texas at Arlington (UTA) and the Texas Transportation Institute (TTI) to investigate the adequacy of the current ride equation to estimate ride quality under present-day conditions. To accomplish this objective, the researchers and project monitoring committee conducted two ride surveys on asphalt and Portland cement concrete pavements for the purpose of collecting user opinions of ride quality with which to evaluate the existing equation. It was decided in the initial project meeting held during the fall of 1998 between researchers and TxDOT project members, to limit the length of each survey section to 0.1 mile intervals to maintain consistency with the standard PSI reporting interval. The present report documents the research efforts conducted in this project. Before discussing the research effort, a short history will describe the evolution of the current ride equation or PSI.

HISTORY OF CURRENT RIDE EQUATION

The current ride equation is considerably different from the original ride equation used by TxDOT for estimating ride or PSI from profile data. The original model was developed from a rating session that was held in 1968-1969. This rating procedure was similar to the one conducted during the early AASHO tests. For this session sections were rated in three geographical areas of Texas by what was considered the 'typical highway user' and the 'typical vehicle'. The profile of each section was then measured and various statistics from the profile computed. The first model developed by Roberts and Hudson (1970) estimated ride primarily from the slope variance statistic of the road profile. The model however, was never implemented. Instead, an equation relating these ratings to profile spectral estimates of each section was used. The motivation behind the use of the spectral estimates in a model for predicting ride was driven by the relationship noted when grouping PSR from raters to the power spectral estimates of the road profile (see Figure 1.1).

For this model, the wavelength amplitudes were computed from the profile and correlated to the present serviceability rating (PSR) obtained from the raters. This first or original equation from Walker and Hudson (1973) is given below:

$$
\begin{aligned}
SI = {} & 3.41 - 1.43_1 - .306X_2 - .180X_4 - .644X_5 + 1.25C_1 \\
& - .458X_2^2 - 1.05X_4^2 - 0.986X_5^2 + .841X_7^2 + 1.76X_1X_4 \\
& - 1.35X_1X_6 - 1.06X_1X_8 - 1.84X_1X_9 + 2.16X_xX_{10} \\
& + 1/21X_2X_5 + .741X_4X_9 + 1.51X_5X_7 - 1.65X_5X_{10} \\
& - 2.03X_7X_8 + 1.81X_8X_{10} + .679T
\end{aligned}
$$

where

$$
\begin{aligned}
X_1 &= \log A_{0.012} - .426 \\
X_2 &= \log A_{0.023} - 0.895 \\
X_3 &= \log A_{0.035} + 1.481 \\
X_4 &= \log A_{0.046} + 1.893 \\
X_5 &= \log A_{0.058} + 2.139 \\
X_6 &= \log A_{0.069} + 2.351 \\
X_7 &= \log A_{0.081} + 2.500 \\
X_8 &= \log A_{0.092} + 2.593 \\
X_9 &= \log A_{0.1.04} + 2.670 \\
X_{10} &= \log A_{0.116} + 2.744 \\
C_1 &= \log CP_{0.012} - .3389
\end{aligned}
$$

T = Pavement type (1 for concrete and 0 for asphalt)

And,

A_i = average of the left and right wheel path amplitudes (inches) for frequency band *i* in cfp

$CP_{0.012}$ = cross amplitude for the 0.012 cpf frequency band

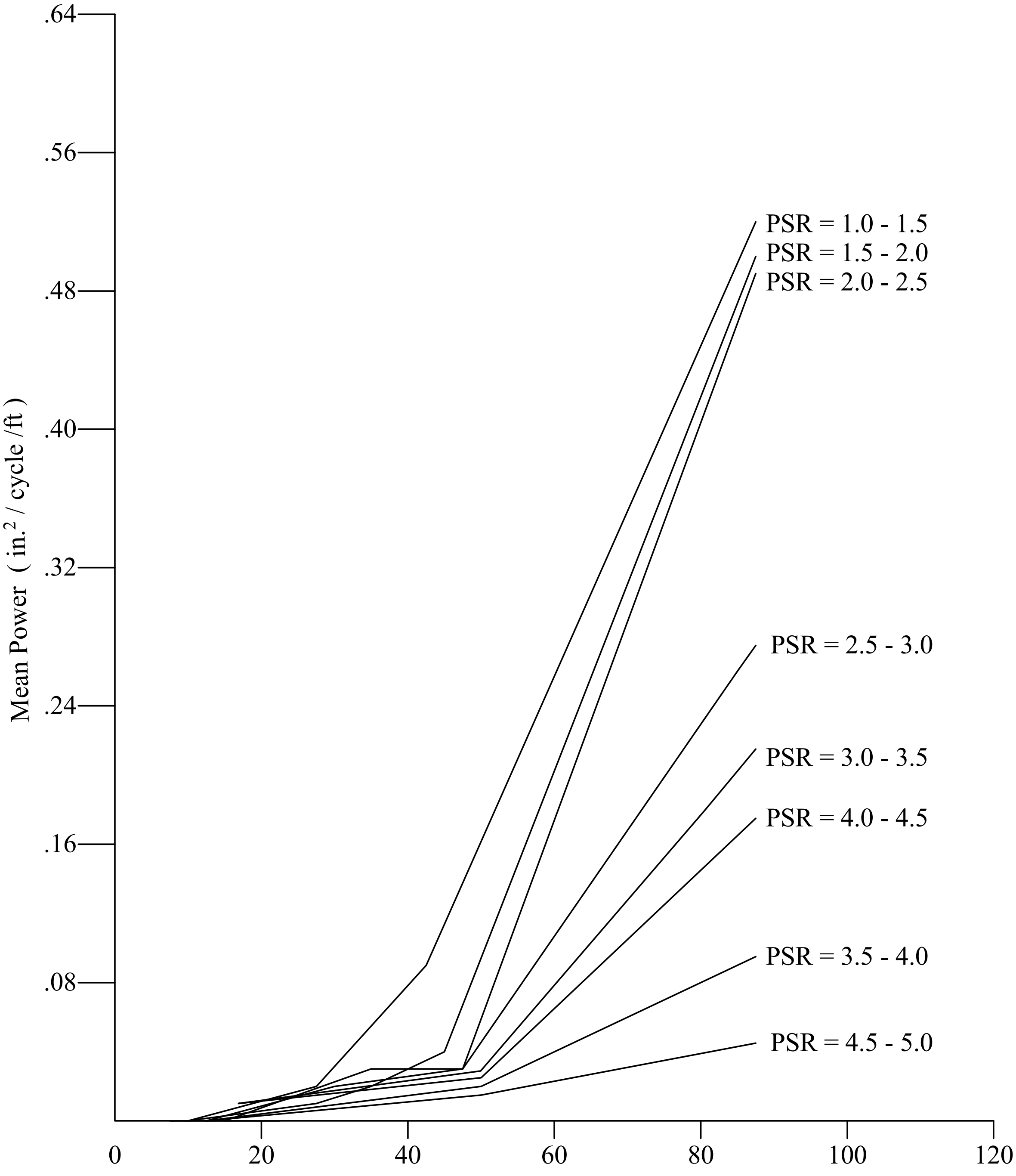


Figure 1.1 Wavelength vs Power Spectral Data

Since the time this first equation was developed, several modifications have been made, the first occurring in the early part of the 1980's. The device used for measuring road profile and used in the first rating session (the Surface Dynamics Profilometer or SDP) was not easy to use or maintain. First, the device performed all onboard profile computing using an analog computer with filters that had to be manually selected depending on wavelength and measurement speed. Second, it required two potentiometers and road following wheels (one for each wheel path) that limited operating speed. Speeds in excess of 20 miles per hour were difficult to obtain without significant wheel bounce. Thus, typical measurement speeds were at 10 and 20 MPH. The analog circuitry for the sensors continually required adjustments. These are just a few of the problems that rendered the device unacceptable for wide scale usage. The Mays Ride Meter (Rainhart, 1972) was a much simpler, easier to use, and less costly device for measuring ride. But the device did not provide profile and was vehicle dependent. In order to use these devices, a procedure was developed by Walker and Hudson (1973) whereby each MRM device could be related to PSI from the MRM readings, and where a table was provided to the user for obtaining the appropriate estimated PSI readings. With this method, the SDP would not be required except for calibrating the MRM. However, even with this calibration procedure the readings from the MRM were still vehicle dependent. In an effort to minimize these differences, a standard Mays Trailer was developed for each MRM that helped to reduce this variation. In 1981, it was found that a better relationship between MRM and PSI could be obtained (McKenzie et al., 1982). First a common relationship between the various MRM devices and the road profile was determined (MO), and then this was correlated to PSI in a kind of an 'MRM rating session'. The readings from the Mays Ride Meters in the study were correlated to the root mean square vertical acceleration (RMSVA) statistic of the road profile. The result of this established a 'standard MRM'. The 'standard MRM' was then calibrated to PSI in accordance with the procedure of McKenzie et al. (1982). These two equations for predicting PSI from the road profile are:

$$MO = -20 + 23VA_4 + 58\ VA_{16}$$

$$PSI = 5e^{-\left[\frac{\ln(32\ \ MO)}{8.4933}\right]^{9.3566}}$$

The terms VA_4 and VA_{16} are the RMSVA statistics from the road profile for the 4 and 16 foot base lengths, respectively. This model was used until about 1987. The old analog SDP was replaced by a newer digital version in 1983. Although the accelerometer, filtering, and computing improved significantly, it still used the analog road following wheels, thus once again limiting measurement speeds. In 1987, the analog wheels were replaced with lasers. However, during this time period, the digital computer and other circuitry were shorted, rendering the measurement portion of the system useless. Either a new system would have to be obtained from KJ Law, the manufacturer, or another version developed. The latter was selected and an emulated version of the SDP was built. This system had a number of advantages over the first and even second generation in that lasers were used instead of the mechanical road following wheels, allowing measurement speeds to 70 miles per hour. Also, an 'off the shelf PC' was used for the digital computing requirements. This system was used until about 1995.

In 1995, TxDOT acquired a system board with a modified version of the South Dakota method for profile estimation that had been used in Europe for profile and rut measurements. With these boards TxDOT was able to build and maintain a fleet of profiler systems (the Texas Profilers) and which are still in use today.

One of the problems with these systems, however, is that the distance sensor used for reporting profile values is not usually an integer divisor of 0.5 feet or six inches as used by the SDP. This distance interval was one of the bases of the VERTAC model. Thus, a decision was made at that time to relate the estimated PSI from the VERTAC model to the International Roughness Index, or IRI. This model was later refined in 1996 so that it would better estimate the PSI. This model also had the added advantage in that different PSI reporting intervals could be selected as the previous models were all based on 0.2 miles. This model is specified with the 'C' function code below and is depicted in Figure 1.2.

}

```
float IRIToPSI(float iri) {
float psi;

#ifdef CC_ENGLISH
   iri = INCH_PER_MILE_TO_MM_PER_M(iri);
#endif

psi = 8.8532704+ (-4.425873)*pow(iri,0.35);

if (psi <0)
   psi = 0;
else if (psi > 4.7) {
   if (psi >=5.38)
      psi = 5.0;
   else
      psi = 4.7 + (psi-4.7) * (5.0-4.7)/(5.38-4.7);
}
return psi;
}
return psi;
```

Current Ride Model

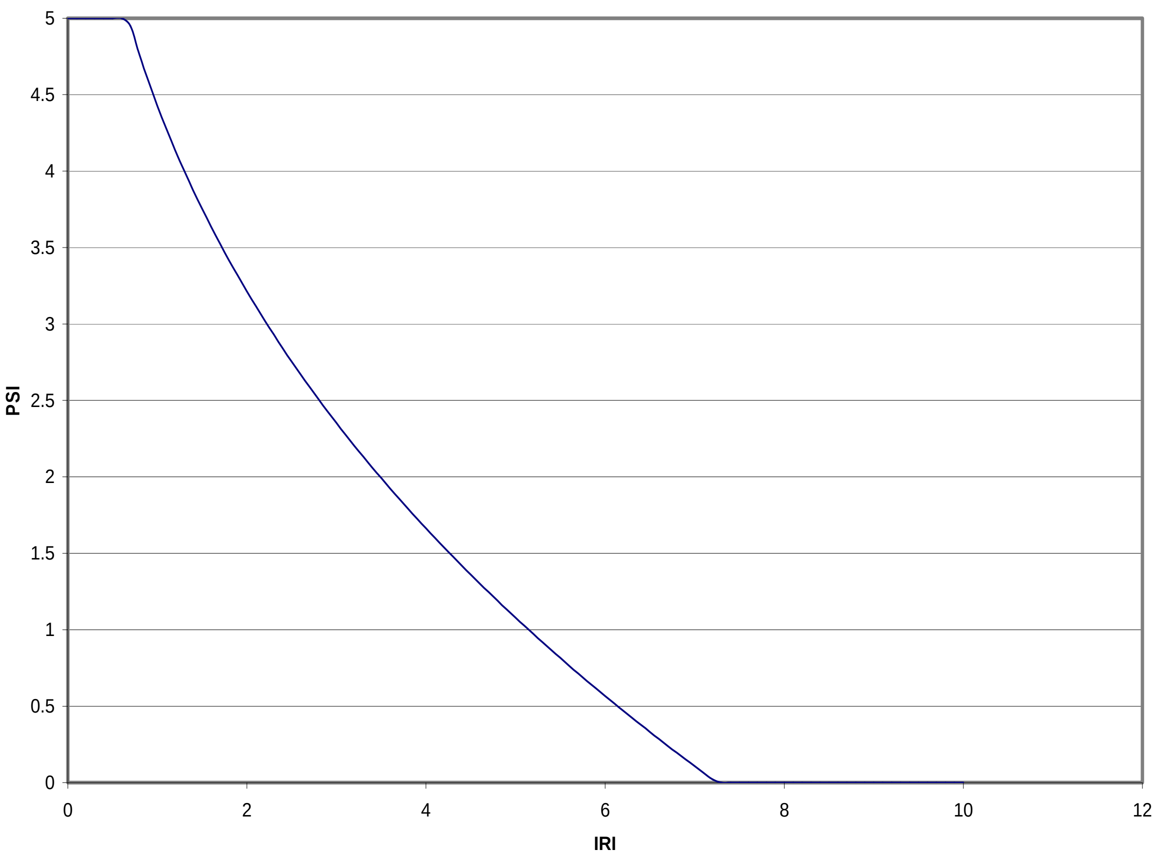


Figure 1.2 PSI vs IRI – Current Ride Model

REPORT CONTENTS

With this short historical background the following chapters will discuss the project, rating panel and corresponding analysis, data collection, and the development of a new PSI model. In particular:

Chapter I provides background material that include the reasons for conducting the project and a historical overview of the ride equation developments in Texas;

Chapter II describes the first ride survey conducted in 1999 and presents the results from this survey;

Chapter III documents the second ride survey conducted in 2000 and provides an evaluation of the existing ride equation against the ratings collected from the 1999 and 2000 surveys;

Chapter IV documents the data collection and processing required for both rating sessions and for the development of a new ride equation;

Chapter V describes the development of a new ride equation using data from the ride surveys; and

Chapter VI provides a summary of the research findings and recommendations for implementing the ride equation developed from this project.

CHAPTER 2

RIDE PANEL RATINGS

INTRODUCTION

As discussed in Chapter 1, one objective of TxDOT Project 4901 was to evaluate the applicability of using the current ride equation for reporting the surface smoothness of Texas highways at 0.1-mile intervals. Since the current equation was originally developed based on ride data taken at 0.2-mile intervals, surveys of selected test sections were initially conducted in which subjective ratings of ride quality were solicited from a panel of raters representing a sample of highway users. For this purpose, researchers established 0.1-mile test sections on which surface profile measurements and ride panel ratings were made. This provided data that allowed researchers to evaluate the correlation between subjective ratings of ride quality made on the test sections, and the predicted ratings determined using the existing equation with the profiles taken from the same sections. The evaluation of the current equation against the panel ratings from the surveys is presented in a subsequent chapter of this report. The present discussion focuses on the ride surveys and covers the following material:

Plan of field experiments;
Selection of test sections;
Placement of markers to locate test sections;
Assembly of rating panels;
Data collection; and
Statistical data analysis to establish significant variables.

PLAN OF FIELD EXPERIMENTS

The plan for the field surveys was established jointly with the project monitoring committee of TxDOT. Table 2.1 shows the test matrix established for the field surveys. In planning these surveys, researchers reviewed the findings from the ride quality evaluation study reported by Nair, Hudson, and Lee (1985). The purpose of this review was to identify the factors that have a significant influence on subjective ride ratings so that these may be incorporated into the ride surveys planned for this study. This was particularly important in view of funding constraints for conducting the ride panel ratings, which made it prudent to review the experience from the last ride study, conducted in the early to mid-1980s. The factors identified from this previous study as significantly influencing subjective ride ratings were:

1. Surface roughness;
2. The individual rater;
3. Rater fatigue;
4. Vehicle wheelbase;
5. Vehicle size;
6. Pavement type; and
7. Pavement maintenance.

It is noted that the effects of other factors were evaluated but these were not found to be statistically significant by Nair, Hudson, and Lee (1985). These additional factors were:

1. Position in car (front or rear);
2. Rater's gender;
3. Rater's age;
4. Whether the rater possessed technical knowledge of roads or not;
5. Time of day (morning, afternoon, or evening);
6. Whether the rater was a driver or passenger;

Test Matrix for the Field Surveys.

Pavement Type	Vehicle Wheelbase	Ride Quality		
		Smooth	Medium-Smooth	Rough
Asphalt Concrete	Short			
	Long			
Portland Cement Concrete	Short			
	Long			

Table 2.1 Text Matrix for Field Surveys

7. Vehicle speed;
8. Road surface texture (coarse or fine);
9. Location of road (rural or urban);
10. Road width; and
11. Surroundings (scenic or unattractive).

In light of the above findings, researchers considered the seven significant variables identified by Nair, Hudson, and Lee in planning the ride surveys. Thus, the test matrix included ride quality as a factor, and sections were established that covered the range in surface profile from smooth to rough, and included both asphalt and Portland cement concrete (PCC) pavements.

The vehicles used in the surveys comprised three mid-size cars, a minivan, a full-size van, and an extended cab pickup. The vehicles selected, given in Table 2.2, are considered as representative of the types of vehicles typically used in the state. Because of the popularity of trucks in Texas, a pickup truck was included in the ride surveys. In terms of the wheelbase, Table 2.2 shows that the cars and the minivan fall into the short wheelbase category, while the full-size van and the extended cab pickup fall into the long wheelbase category. All test vehicles used in the surveys were provided by TxDOT and driven by agency personnel.

Vehicles Used in Ride Surveys

Vehicle ID	Description	Wheelbase (inches)
C-1	1996 four-door Ford Taurus (4687 lbs GVWR[1])	109
C-2	1997 four-door Chevy Lumina (4322 lbs GVWR)	108
C-3	1993 four-door Chevy Lumina (4322 lbs GVWR)	108
T-1	1995 GMC Extended Cab 1500 Series Pickup (6200 lbs GVWR)	139
V-1	1998 Chevrolet 2500 Series Van (8600 lbs GVWR)	135
V-2	1995 Chevrolet Astro Van (5950 lbs GVWR)	111

[1]Gross Vehicle Weight Rating

Table 2.2 Vehicles used in Ride Survey

The ride surveys were divided into two experiments. In one experiment, designated herein as the control, raters were asked to rate four test sections, covering smooth to rough flexible pavements, in each of the six test vehicles used in the surveys. On the other hand, the main experiment involved ratings on 59 test sections. To evaluate the effect of rater fatigue, four of these sections were rated twice, once in the morning, at the beginning of the surveys, and the other in the afternoon, just before the end of the surveys. Due to practical constraints, no vehicle switching was planned in the main experiment.

While pavement maintenance was identified to be a significant factor, this was not explicitly included in the test matrix established for the ride surveys in this study. As explained by Nair, Hudson and Lee (1985), pavement maintenance referred to patched or unpatched sections. To the extent that the effect of patches are reflected in the surface profile of a given test section, the effect of maintenance will be coupled to pavement ride quality which is included in the test matrix. Thus, pavement maintenance was not explicitly considered in establishing the test sections for the ride surveys planned in this study. Table 2.3 shows the schedule of the ride surveys. Prior to the surveys, researchers held a briefing to provide drivers with guidelines on how the surveys should be conducted, and to familiarize them with the locations of the test sections. For this training, a

Schedule of Ride Surveys

<table>
<tr><th rowspan="2">Time of Day</th><th colspan="7">Date (1999 calendar year)</th></tr>
<tr><th>May 24
Mon.</th><th>May 25
Tues.</th><th>May 26
Wed.</th><th>May 27
Thurs.</th><th>May 28
Fri.</th><th>June 2
Wed.</th><th>June 3
Thurs.</th></tr>
<tr><td>AM</td><td>Driver training</td><td>Driver training</td><td rowspan="2">Main survey #1</td><td></td><td rowspan="2">Main survey #2</td><td></td><td rowspan="2">Main survey #3</td></tr>
<tr><td>PM</td><td>Driver training</td><td>Control survey #1</td><td>Control survey #2</td><td>Control survey #3</td></tr>
</table>

Table 2.3 Schedule of Ride Surveys

driver briefing notebook was prepared that is included as Appendix A to this report. Researchers accompanied the drivers on site visits to the test sections. In this way, the locations of the sections as well as the survey routes were made known to the drivers. During these site visits, drivers and researchers also rated the test sections as a rehearsal for the actual rating sessions.

Three control, and three main rating sessions were scheduled, as noted in Table 2.3. For these surveys, a panel of raters was assigned for each control/main survey combination. Thus, three rating panels were established with 12 members per panel. The control survey included a training session for the panel of raters wherein the TxDOT project director and researchers briefed participants on the purpose of the study, and the plan for the survey, gave instructions for rating test sections, and assigned raters to the different vehicles. The rater briefing and control survey were done in one day. The survey of the main experiment test sections was then conducted the following day. This sequence of activities was repeated until all surveys in Table 2.3 were completed.

SELECTION OF TEST SECTIONS

To establish the test sections for the ride rating sessions, candidate sites were first identified by querying the Pavement Management Information System (PMIS) database. Queries were confined to highway segments within Williamson, Brazos, Madison, and Montgomery counties. From this initial search, a candidate list of test sections was drawn that covered pavements from smooth to rough on the basis of the reported ride scores in the database. Visits were then made to these sections that resulted in a pared down list of candidate sites for the ride surveys. The visits resulted in dropping test sections from the original list based on observations of traffic conditions, presence of curves and turnarounds, and discrepancies between the serviceability indices from the 1998 PMIS surveys and the observed condition of the surface at the time of the site visits. It was obvious that several sections had been resurfaced since the 1998 PMIS ride surveys.

TxDOT then profiled the sections in the updated list so researchers can establish the current ride quality of each section. In addition, to identify additional PCC segments, profile measurements on concrete sections located along Loop 336 in Conroe were made. The Present Serviceability Indices (PSIs) of the segments profiled were then determined by researchers, and the final list of rating sections were thus, established. Table 2.4 identifies the sections selected for the ride surveys. Altogether, there were 63 rating sections. The International Roughness Indices (IRIs) and PSIs of the test sections are also given in Table 2.4.

Figure 2.1 shows the distribution of the PSIs for these sections. In this figure, smooth sections (Class A) are those with PSIs of 4 and above; medium-smooth sections (Class B) have PSIs between 3 and 4; and rough sections (Class C) have PSIs below 3. Following the recommendation of the project monitoring committee, test sections were selected such that the distribution of the PSIs was consistent with the observed distribution of the ride scores in the PMIS database. This distribution indicates that the majority of Texas roads have PSIs falling into the Class B category.

Table 2.4 shows that the test sections may be divided into groups according to the highway and lane the sections are on. Within any group, the sections were established such that they may be driven and rated in succession. However, no two sections were contiguous. Instead, sections were

Test Sections Selected for the Ride Surveys

Number	County	Highway	Begin MP	End MP	LANE	LWP IRI (mm/m)	RWP IRI (mm/m)	Avg. IRI (mm/m)	PSI
2	Brazos	FM2154	622.6	622.7	K1	1.78	1.50	1.64	3.6
3	Brazos	FM2154	622.9	623.0	K1	1.89	1.32	1.61	3.6
4	Brazos	FM2154	623.5	623.6	K1	1.06	1.10	1.08	4.3
5	Brazos	FM2154	623.9	624.0	K1	0.92	1.18	1.05	4.4
6	Brazos	FM2154	624.2	624.3	K1	1.44	1.70	1.57	3.7
7	Brazos	FM2154	628.5	628.6	K1	2.08	3.83	2.96	2.4
8	Brazos	FM2154	628.8	628.9	K1	1.34	2.96	2.15	3.1
9	Brazos	FM2154	629.2	629.3	K1	2.29	5.10	3.70	1.9
10	Brazos	FM2154	629.6	629.7	K1	1.77	2.24	2.01	3.2
11	Brazos	FM2154	629.9	630.0	K1	1.97	1.89	1.93	3.3
12	Brazos	FM2154	632.5	632.6	K1	2.73	3.98	3.36	2.1
13	Brazos	FM2154	633.0	633.1	K1	2.93	4.25	3.59	1.9
14	Brazos	FM2154	633.3	633.4	K1	1.24	2.26	1.75	3.5
15	Brazos	FM2154	635.1	635.2	K1	1.77	1.91	1.84	3.4
16	Brazos	FM2154	635.5	635.6	K1	2.15	2.16	2.16	3.1
17	Brazos	FM2154	635.8	635.9	K1	2.41	3.08	2.75	2.6
18	Brazos	FM2154	636.1	636.2	K1	1.49	1.81	1.65	3.6
19	Brazos	FM2154	636.6	636.7	K1	2.78	3.48	3.13	2.3
20	Brazos	FM2154	636.9	637.0	K1	1.58	1.91	1.75	3.5
21	Brazos	FM2154	637.3	637.4	K1	1.56	1.56	1.56	3.7
22	Brazos	SH30	629.1	629.2	K1	1.41	1.69	1.55	3.7
23	Brazos	SH30	629.4	629.5	K1	1.38	1.50	1.44	3.8
24	Brazos	SH30	629.8	629.9	K1	1.41	2.14	1.78	3.4
25	Brazos	SH30	630.3	630.4	K1	1.98	2.47	2.23	3.0
26	Brazos	SH30	630.7	630.8	K1	1.59	1.89	1.74	3.5
27	Brazos	SH30	631.0	631.1	K1	1.75	1.81	1.78	3.4
28	Brazos	SH30	631.6	631.7	K1	2.06	1.88	1.97	3.2
29	Brazos	SH30	632.2	632.3	K1	1.02	1.25	1.14	4.2
30	Brazos	SH30	632.8	632.9	K1	1.36	1.55	1.46	3.8
31	Brazos	SH47	413.2	413.3	R1	1.14	0.93	1.04	4.4
32	Brazos	SH47	413.5	413.6	R1	1.36	1.37	1.37	3.9
33	Brazos	SH47	414.0	414.1	R1	2.74	2.70	2.72	2.6
34	Brazos	SH47	414.4	414.5	R1	3.00	3.24	3.12	2.3

Number	County	Highway	Begin MP	End MP	LANE	LWP IRI (mm/m)	RWP IRI (mm/m)	Avg. IRI (mm/m)	PSI
35	Brazos	SH47	414.2	414.1	L1	2.26	1.75	2.01	3.2
36	Brazos	SH47	413.9	413.8	L1	2.63	3.14	2.89	2.4
37	Brazos	SH47	413.5	413.4	L1	1.62	1.56	1.59	3.6
38	Brazos	SH47	413.0	412.9	L1	0.99	0.83	0.91	4.6
39	Madison	IH45	150.4	150.3	L1	1.04	1.22	1.13	4.2
40	Madison	IH45	150.0	149.9	L1	0.82	0.95	0.89	4.6
41	Madison	IH45	149.3	149.2	L1	0.89	1.08	0.99	4.5
42	Madison	IH45	149.0	148.9	L1	0.98	0.98	0.98	4.5
43	Madison	IH45	148.2	148.1	L1	0.81	0.88	0.85	4.7
44	Madison	IH45	147.5	147.6	R1	0.69	1.05	0.87	4.6
45	Madison	IH45	147.9	148.0	R1	0.74	0.94	0.84	4.7
46	Madison	IH45	148.2	148.3	R1	0.88	0.87	0.88	4.6
47	Madison	IH45	148.5	148.6	R1	1.63	1.52	1.58	3.7
48	Madison	IH45	148.9	149.0	R1	0.98	1.11	1.05	4.4
49	Madison	IH45	149.2	149.3	R1	1.26	1.75	1.51	3.7
50	Madison	IH45	149.9	150.0	R1	1.02	1.14	1.08	4.3
51	Madison	IH45	151.2	151.3	R1	0.85	1.03	0.94	4.5
52	Madison	IH45	151.5	151.6	R1	0.80	1.05	0.93	4.5
53	Montgomery	SL336	674.3	674.4	K1	2.02	2.02	2.02	3.2
54	Montgomery	SL336	675.1	675.2	K1	1.41	1.84	1.63	3.6
55	Montgomery	SL336	676.2	676.3	K1	2.02	1.86	1.94	3.3
56	Montgomery	SL336	676.8	676.9	K1	1.97	1.98	1.98	3.2
57	Montgomery	SL336	677.3	677.4	K1	1.93	1.97	1.95	3.3
58	Montgomery	SL336	677.8	677.9	K1	2.04	2.73	2.39	2.9
61	Montgomery	SL336	677.7	677.6	K6	1.16	1.16	1.16	4.2
62	Montgomery	SL336	677.4	677.3	K6	1.95	1.68	1.82	3.4
63	Montgomery	SL336	676.7	676.6	K6	1.70	1.59	1.65	3.6
64	Montgomery	SL336	675.5	675.4	K6	1.73	1.75	1.74	3.5
65	Montgomery	SL336	675.2	675.1	K6	1.62	1.82	1.72	3.5
66	Montgomery	SL336	674.4	674.3	K6	2.21	2.25	2.23	3.0

Table 2.4 Test Sections Selected for the Ride Survey

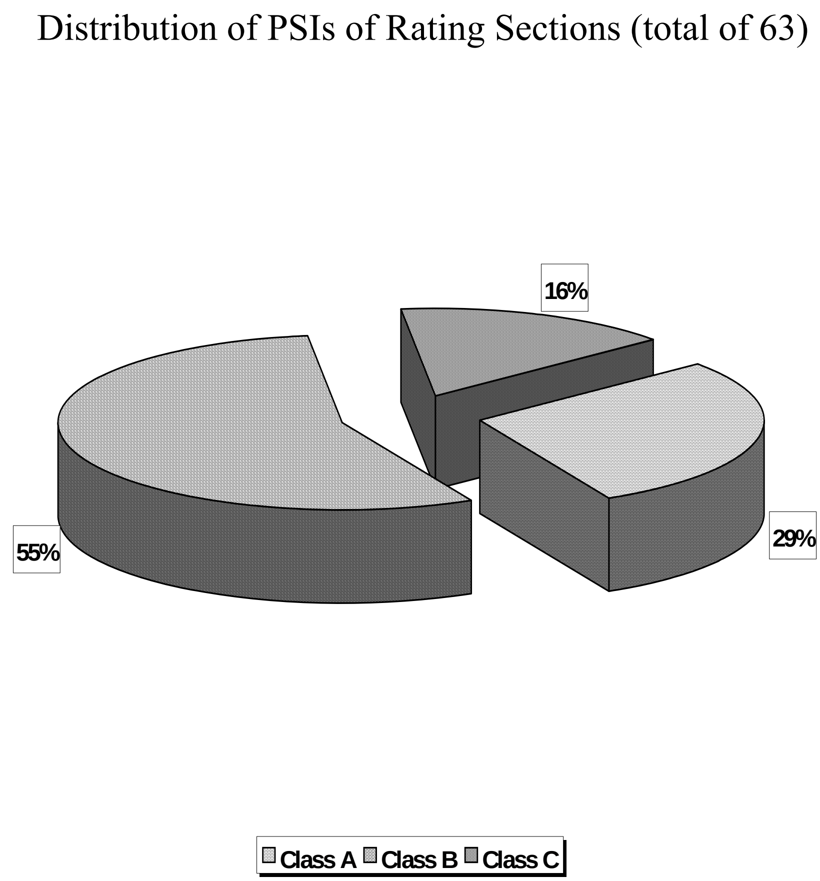


Figure 2.1 Distribution of Rating Sections (total of 63)

spaced at least 0.2 miles apart to provide raters and drivers enough lead-time to get ready for the next section.

PLACEMENT OF MARKERS TO LOCATE TEST SECTIONS

To assist drivers in locating the test sections during the surveys, markers were placed at the beginning and end of each section. At the starting location, personnel from TTI and TxDOT painted the surface with a white stripe perpendicular to the traffic direction, and sprayed the section number on the pavement surface at the same location. In addition, a wooden stake with yellow green flagging tape was hammered into the shoulder adjacent to the start of the section. At the ending location, a white stripe was also painted on the pavement surface, and a wooden stake with light red flagging tape was driven into the adjacent shoulder.

So that drivers would have a reference for locating the first section within a group, a marker was established at a known distance from the start of the first section of each group. Drivers were then instructed to reset the vehicle's trip meter as they pass these markers so they could determine their distance from the beginning section. In this way, drivers had advanced warning of the approach of the first section, and sufficient reaction time to get the raters ready.

Except for the sections along SH47 in Brazos County, TxDOT reference markers were used as aids in locating the first section within each group. To identify these markers, a light red flagging tape was tied to each marker. The driver briefing notebook in Appendix A documents all the markers established for locating the test sections during the ride surveys.

ASSEMBLY OF RATING PANELS

Three panels of raters were assembled for the three combinations of control/main experiments planned for the study (Table 2.3). Each panel consisted of twelve volunteers, a number of whom participated in more than one ride survey. Altogether, there were 28 individuals, of various backgrounds, who rated in the surveys. Thirteen of the raters are males and 15 are females. All participants are licensed to drive in Texas, and use Texas roads on a regular basis. The makeup of this pool of raters is described as follows:

1. Two retirees from Arlington, Texas;
2. Four graduate students - one civil engineering and one statistics student from Texas A&M, and two computer science engineering students from the University of Texas at Arlington (UTA);
3. Three undergraduate students - two with Texas A&M University and the other with Sam Houston State University. One of the three is a civil engineering major at Texas

A&M who was employed at the time of the surveys as a summer engineering technician with the Bryan District;

4. Four technicians from TTI;
5. Six TTI administrative personnel;
6. Two TTI professional staff members with backgrounds in geotechnical engineering and geology; and
7. Seven TxDOT employees - one secretary, one maintenance supervisor, two engineering assistants, two environmental specialists, and one sign shop technician.

DATA COLLECTION

Each rater was asked to give his or her rating on the form illustrated in Figure 2.2. The rating scale shown in the figure is the same one used in the AASHO Road Test (1962), and in the two previous ride evaluation studies conducted in Texas by Roberts and Hudson (1970), and by Nair, Hudson and Lee (1985). Prior to the surveys, raters underwent a briefing to familiarize them with the scale used for rating pavement ride quality, as well as the plan for the surveys. For the control experiments, ratings on the four control sections were obtained for each vehicle-rater combination. However, no vehicle switching was done for the main experiments because it was not feasible to do. For these surveys, raters were randomly assigned to the different test vehicles, with a pair of raters per vehicle plus the driver. All ratings from the pair were then made on the particular vehicle. It is noted that drivers were not asked to rate the sections for safety reasons. Moreover, since drivers were given the responsibility for the conduct of the surveys in the field, researchers believed that rating the sections would be a distraction that would hinder the driver's ability to effectively carry out his function.

On the way to a test site, raters were asked to prepare the rating forms so that by the time they got to the site, the ratings may commence. As used herein, a test site refers to a group of sections located along a particular highway. The travel time between sites ranged from about 40 minutes to two hours giving ample time for raters to perform this activity. A rater would prepare a

RIDE RATING FORM

Rater ______________________ **Section ID**______________

Vehicle_________________ **Date**_________ **Time** _________

5
Very Good
4
Good
3
Fair **Rating** _________
2
Poor
1
Very Poor
0

Rating Scale

Comments:

____
____
____
____
____

Figure 2.2 Rating Form Used in the Ride Surveys form for each section by writing his or her name, the vehicle identification (ID), the section number, and the date on each form. The driver would distribute the forms to the raters on their way to a site, and tell them the ID of the test vehicle, and the sections at the site they were going to. The raters would then prepare their forms accordingly. During the rating sessions, the vehicle was driven at a constant speed of 50 mph, consistent with the two previous ride evaluation studies. Test vehicles were equipped with overhead flashing lights that were turned on during tests at a given site. Drivers were asked to give raters advanced warning of the approach of a section. In particular, they were instructed to tell raters the ID of the section coming up, as well as to notify raters of the start and end of the section. Raters were instructed to check that the section ID on their forms matches what the driver stated as they approached a test section.

Each survey participant was asked to rate his or her ride experience, from the time the driver said, “Start,” to the time he said, “Stop” on the given section. To record his or her rating on the form given in Figure 2.2, the rater was instructed to draw a line segment across the point on the scale that corresponded to his or her rating of the section tested. The rater was not asked to write his or her rating on the blank line to the right of the scale in Figure 2.2. Researchers filled in this field during data reduction when the forms were read.

After tests on a site were completed, raters were asked to check their forms for completeness, and to note on the forms the time of completion of the ratings. They then proceeded to the next test site.

STATISTICAL DATA ANALYSIS

There were about 3000 rating forms collected during the field surveys that had to be reduced before any analysis can be made. This task entailed reading each form to assign a numerical value to the mark made by the rater on the scale provided. To facilitate the data reduction, researchers constructed a template of the rating scale on a transparency sheet, with scale divisions in tenths of a rating point. This template was then placed on top of each form so that the rating scales overlapped. Thus, the rating was read off the scale and recorded on the form at the space provided. The ride quality ratings, herein referred to as Present Serviceability Ratings (PSRs), were then entered into electronic files for data analysis. The findings from the statistical analysis of the data are presented in the subsequent sections. This analysis identified the variables that significantly influence subjective ratings of ride quality.

ANALYSIS OF DATA FROM TESTS ON CONTROL SECTIONS

Since raters switched vehicles in the control experiments, the data collected permits the evaluation of the effects of the rater, vehicle, and section roughness on the PSRs. In evaluating the significance of these factors and their two-way interactions, researchers first established the confidence level with which to assess the significance of the effects. For this purpose, researchers selected a 95 percent confidence level.

Table 2.5 shows the analysis of variance (ANOVA) table determined from the analysis of the ride panel ratings on the control sections. The Statistical Analysis System (SAS, 1988) was used to analyze the data. The *p* value given in the table for each effect is an indicator of statistical significance. The smaller the *p* value, the more significant is the effect. For a 95 percent confidence level, the *p* value must be 0.05 or smaller for the effect to be significant. Based on this criterion, all of the main and two-way interaction effects listed in Table 2.5 are significant.

Figure 2.3 illustrates the effect of section roughness on the mean PSRs collected from the ride surveys. Higher IRIs in the figure indicate more surface roughness. It is observed that the ride ratings decrease with increase in surface roughness of the sections tested. Two-way comparisons of the mean PSRs were conducted to identify which sections are statistically different in terms of the ride ratings. It was found that the mean PSR of each section is statistically different from the mean PSRs of the other sections indicating that each may be considered distinct based on the ride panel ratings.

ANOVA Table From Analysis of Data Taken on Control Sections.

Source of Variation	Degrees of Freedom (df)	Sum of Squares (SS)	Mean Square (MS)	*F*-statistic	*p* value[1]
Section roughness	3	298.02	99.34	787.05	0.0001
Rater	27	130.96	4.85	38.43	0.0001
Vehicle	5	4.81	0.96	1.91	0.0067
Rater*Section	81	95.08	1.17	9.30	0.0001
Vehicle*Section	15	5.89	0.39	3.11	0.0001
Rater*Vehicle	135	31.97	0.24	1.88	0.0001
Error	671	51.12	0.13		

[1] A *p* value of 0.05 or smaller indicates significance at the 95 percent confidence level.

Table 2.5 ANOVA from Analysis of Data Taken on Control Sections

Effect of Section Roughness on Ride Quality Rating

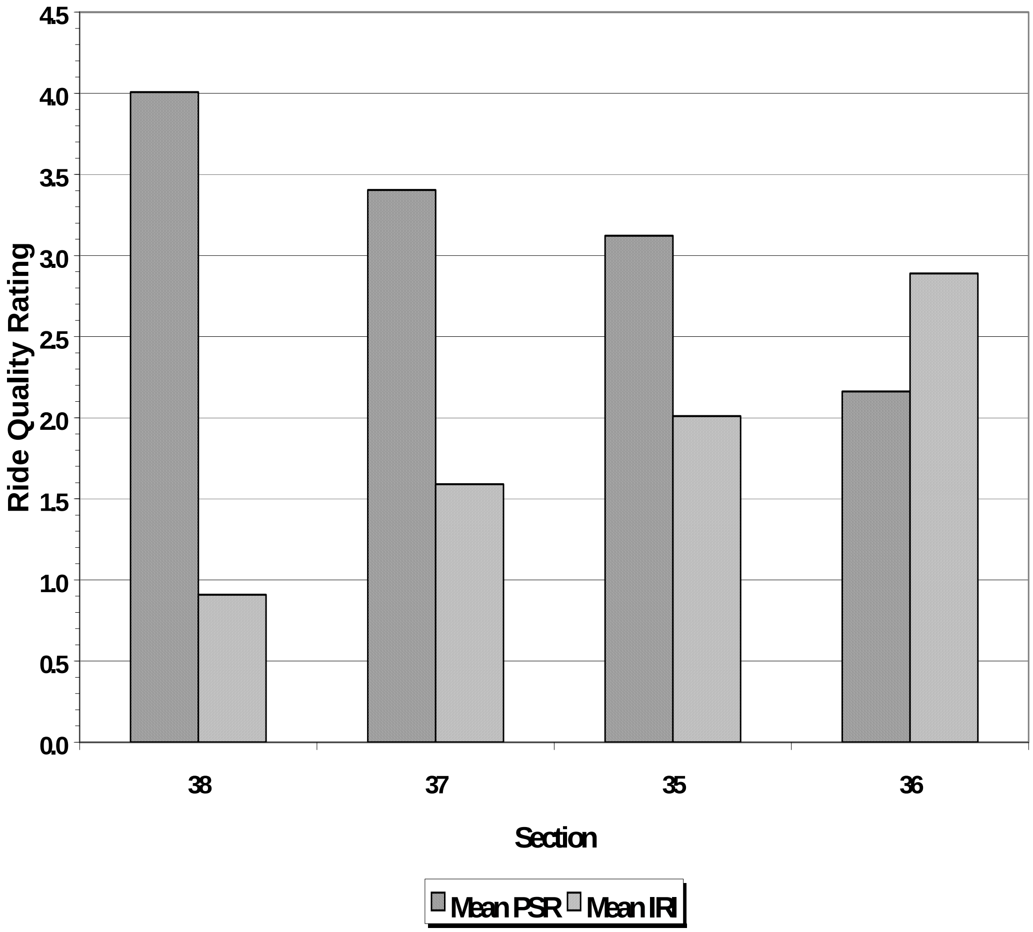


Figure 2.3 Effect of Section Roughness on Ride Quality Rating

Figure 2.4 illustrates the effect of the rater on the subjective evaluation of pavement ride quality. Observe that the mean PSRs vary between raters indicating differences in opinions regarding the ride quality of the sections tested. Comparisons of the mean PSRs revealed statistically significant differences between raters in this regard. Figure 2.4 also illustrates the effect of section roughness. It is observed that the mean PSRs are generally highest for the smooth section (No. 38), and lowest for the rough section (No. 36).

Illustration of Differences in User Perception of Ride Quality

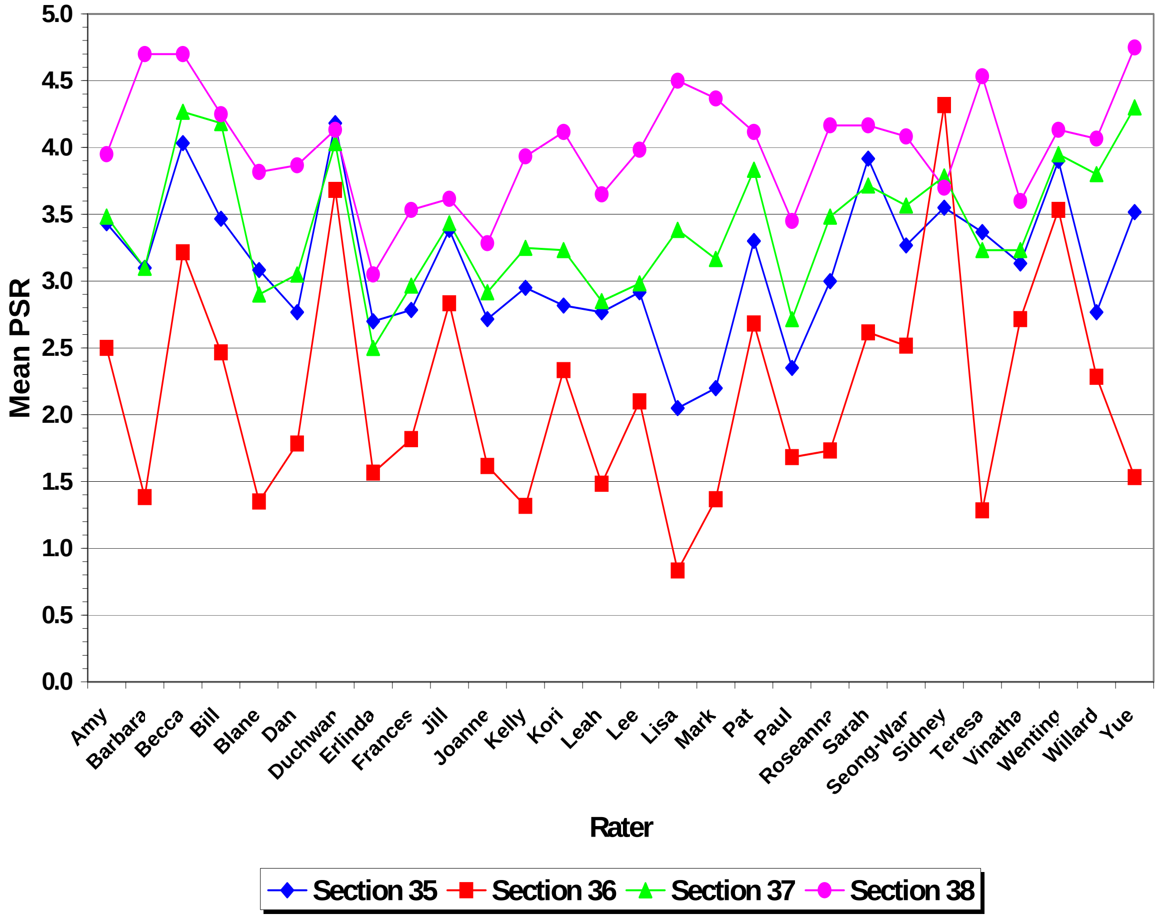


Figure 2.4 Illustration of Differences in User-Perception of Ride Quality

The effect of vehicle on the ride panel ratings is illustrated in Figure 2.5. From two-way comparisons of the mean PSRs, researchers found that the test vehicles may be divided into two groups. One group, consisting of the three mid-size cars and the full-size van, were found to have mean PSRs statistically higher than those of the other group, comprising the minivan and the extended cab pickup truck. It appears, therefore, that the raters felt a better ride on the first group of vehicles than on the second, indicating that vehicle characteristics influence user perception of ride quality.

Illustration of Differences in User-Perception of Ride Quality

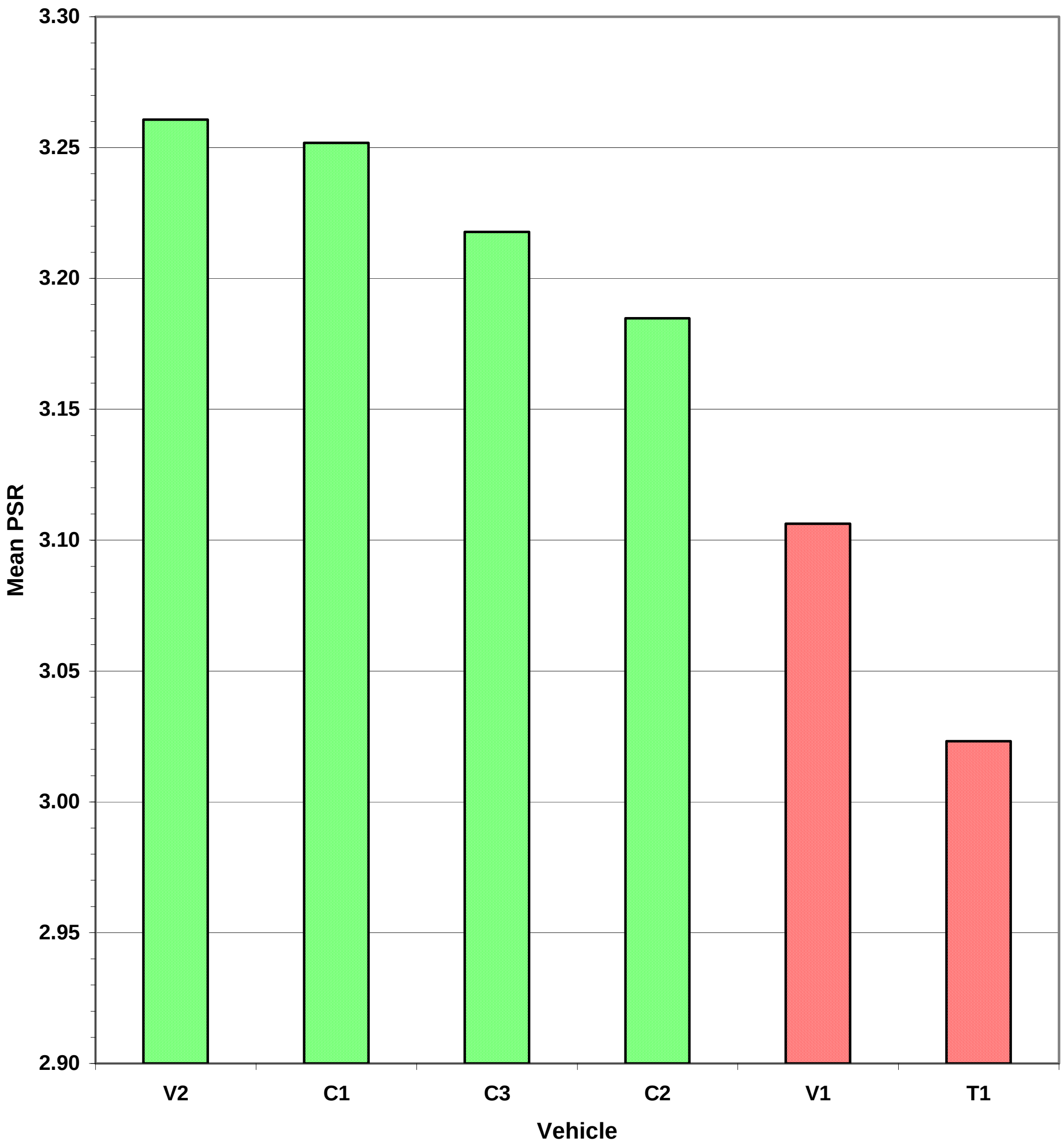


Figure 2.5 Illustration of Differences in User-Perception of Ride Quality

ANALYSIS OF DATA FROM MAIN EXPERIMENT

Three surveys were conducted as part of the main experiment that involved rating 59 test sections located in Brazos, Madison, and Montgomery counties. Table 2.4 shows the 63 sections established for the ride ratings. Four of these, Sections 35, 36, 37, and 38, were used in the control surveys. The remaining sections were assigned to the main experiment. In the following, the findings from the analysis of the ride ratings from these surveys are presented. Four different topics are discussed:

1. Evaluation of the spatial independence of the ride ratings;
2. Effect of rater fatigue;
3. Effect of pavement type; and
4. Effects of section roughness, rater, and vehicle on subjective ratings of ride quality.

EVALUATION OF SPATIAL INDEPENDENCE OF RIDE RATINGS

For the ride surveys, tests were conducted in a certain sequence corresponding to the most efficient way of traversing the sections to be rated. It was not feasible to test the sections randomly because of the distances between test sites, and constraints on time and resources available for conducting the ride surveys. Because of the sequence in which the tests were run, there is a concern that the ratings may be autocorrelated, similar to observations that are made sequentially in time, i.e., time series data. Thus, researchers first evaluated the spatial independence of the ride ratings from the surveys in the main experiment. This was done using the nonparametric runs test, as explained by Mason, Gunst, and Hess (1989). This test involves examining the sign arrangement of time-ordered residuals. An unusually large or small number of runs is indicative of correlated observations, where a run is a sequence of observations all of which have the same sign. For the sample size of the data from each field survey, the test requires computing a *z*-statistic based on the number of runs, the number of positive residuals, and the number of negative residuals. This statistic is then compared with the critical value obtained from a standard normal distribution table corresponding to the selected confidence level.

Table 2.6 shows the *z*-statistics computed from the test data. The statistic was determined for each survey conducted, and by pavement type. For a 95 percent confidence level, the critical *z* value is 1.96 from a standard normal distribution table. Since the absolute values of the *z*-statistics are all less than this critical value, the runs test indicates the spatial independence of the ride ratings. This finding may also be inferred from the *p* values in Table 2.6 that are all greater than 0.05, indicating that the *z*-statistics are not significant enough to reject the null hypothesis that the data satisfy the assumption of independence. In view of this finding, the analysis of factor effects was conducted using the usual statistical tests of inference involving the *F* or *t* statistics that assume a linear model.

EFFECT OF RATER FATIGUE

Sections 31, 32, 33, and 34 of the main experiment were rated twice, once in the morning at the beginning of the survey, and again in the afternoon before the end of the survey. The purpose of repeating the tests on these sections was to evaluate the effect of rater fatigue. It typically took five and a half hours to finish the survey of the 59 sections included in the main experiment, which are located along highways in Brazos, Madison, and Montgomery counties. While this included a break for lunch, the project staff was interested in determining whether the length and duration of the survey affected the raters physically and mentally to have a perceptible influence on their evaluations of pavement ride quality. The repeat runs on Sections 31, 32, 33, and 34 provided researchers with data to evaluate the significance of this test variable.

For each of the three surveys conducted in the main experiment, researchers used the paired *t*-test (Clark and Schkade, 1979) to evaluate the significance of rater fatigue. In this test, the differences between corresponding ratings made in the morning and in the afternoon were determined. A *t*-test was then conducted to establish whether the mean of the differences of paired observations is significantly different from zero. If it is, the differences between the morning and afternoon ratings may be associated with the effect of rater fatigue.

Results From the Runs Test of Spatial Independence.

Survey Date	Pavement Type			
	Asphalt Concrete		Portland Cement Concrete	
	z-statistic	*p* value[1]	*z*-statistic	*p* value
May 26, 1999	0.20	0.84	0.91	0.36
May 28, 1999	-0.04	0.97	0.43	0.67
June 3, 1999	0.81	0.42	1.28	0.20

[1] A *p* value of 0.05 or smaller indicates significance at the 95 percent confidence level.

Table 2.6 Results From the Runs Text of Spatial Independence

Table 2.7 shows the results of the paired *t*-tests conducted using the data collected from each survey of the main experiment. Based on the reported *p* values in the table, it is observed that the means of the differences of paired ratings are not significantly different from zero for the first and last surveys. However, the *p* value for the second survey shows the opposite result, indicating that rater fatigue might have influenced the ratings on Sections 31, 32, 33, and 34. This effect is illustrated in Figure 2.6 that shows the mean PSRs for these sections. Observe that the mean PSRs from the morning runs are generally lower than the corresponding PSRs from the afternoon runs. In contrast, the mean PSRs determined from the first and third surveys do not show this trend, as evident from Figures 2.7 and 2.8. In particular, no clear systematic differences may be observed between the morning and afternoon PSRs from these surveys. The results from this evaluation thus indicate that rater fatigue may influence subjective evaluations of pavement ride quality but its effect may not always be present.

Results From Paired *t*-Tests to Evaluate Effect of Rater Fatigue.

Date of Survey	Number of Observations	*t*-statistic	*p* value[1]
May 26, 1999	48	0.37	0.7118

May 28, 1999	48	-3.99	0.0002
June 3, 1999	48	-0.74	0.4641

[1] A *p* value of 0.05 or smaller indicates significance at the 95 percent

Table 2.7 Results From Paired *t*-Tests to Evaluate Effect of Rater Fatigue

Comparison of Mean PSRs from AM and PM Runs (Survey #2)

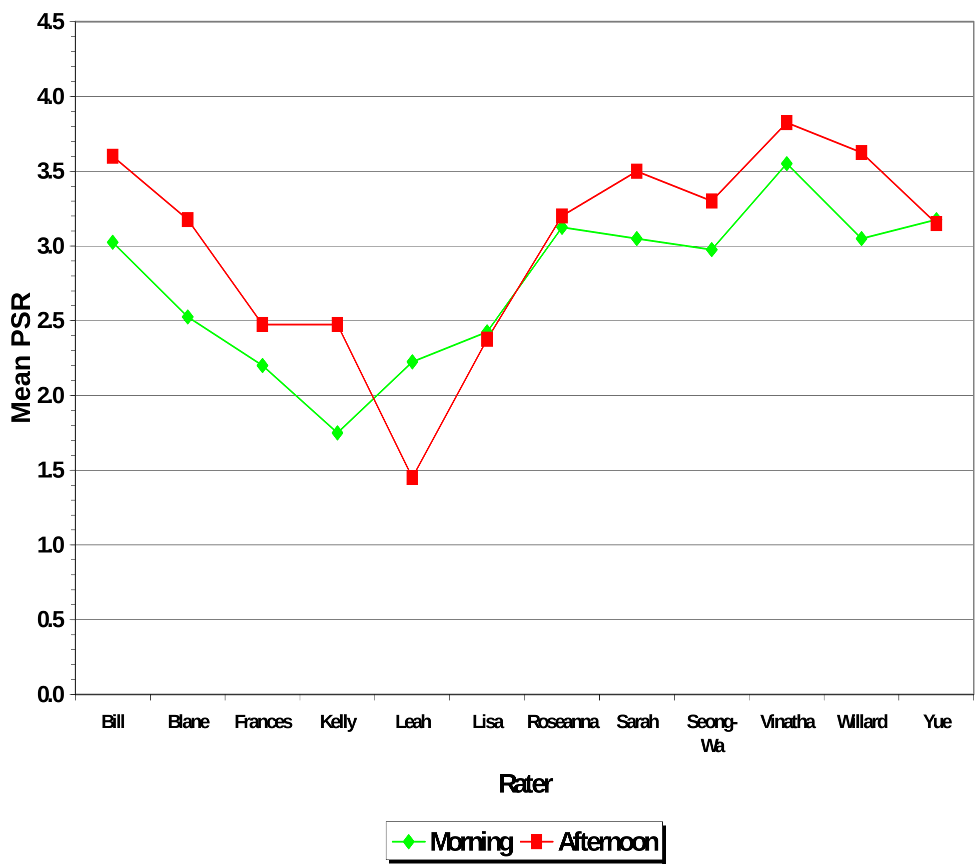
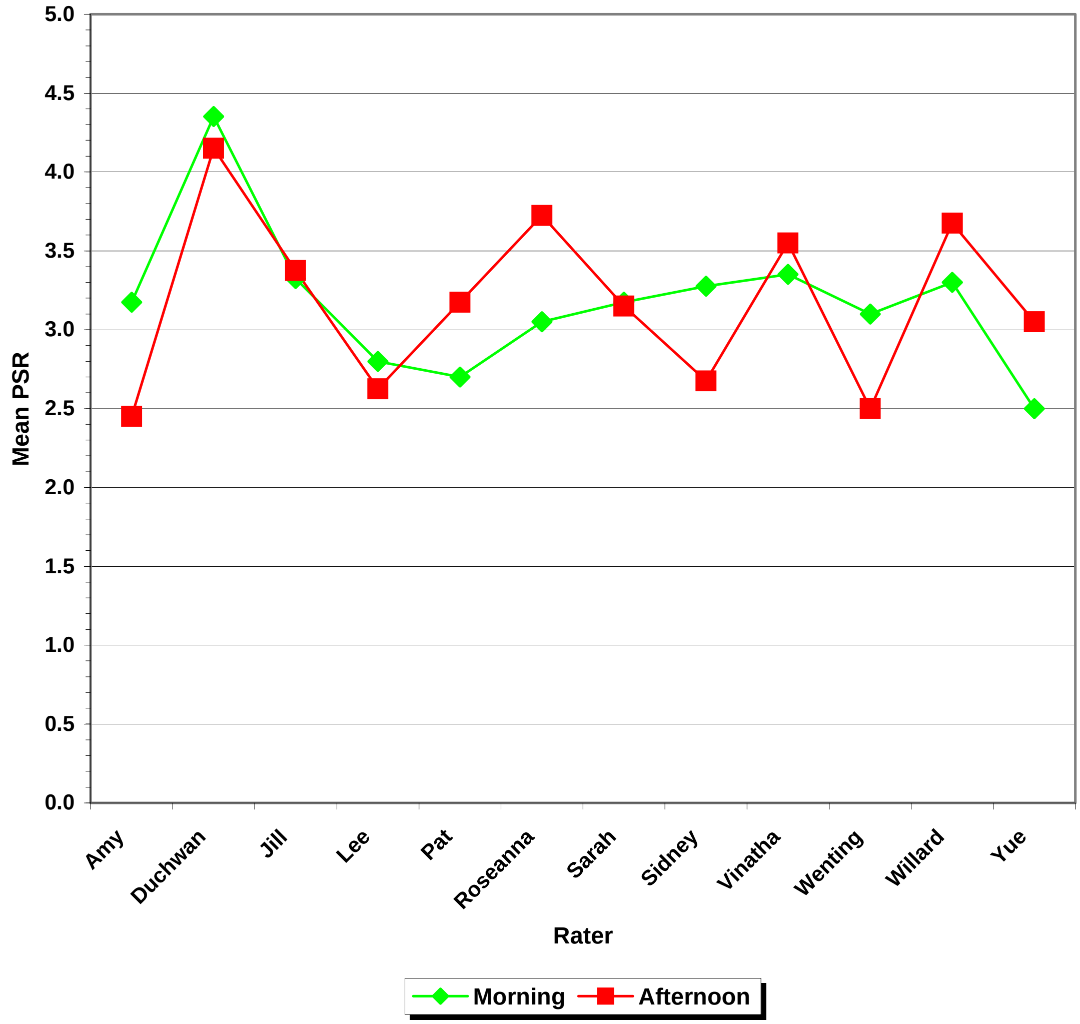


Figure 2.6 Comparison of Mean PSRs from AM and PM Runs (Survey #2)

Comparison of Mean PSRs from AM and PM Runs (Survey #1)



Fig

ure 2.7 Comparison of Mean PSRs from AM and PM Runs (Survey #1).

Comparison of Mean PSRs and AM and PM Runs (Survey #3)

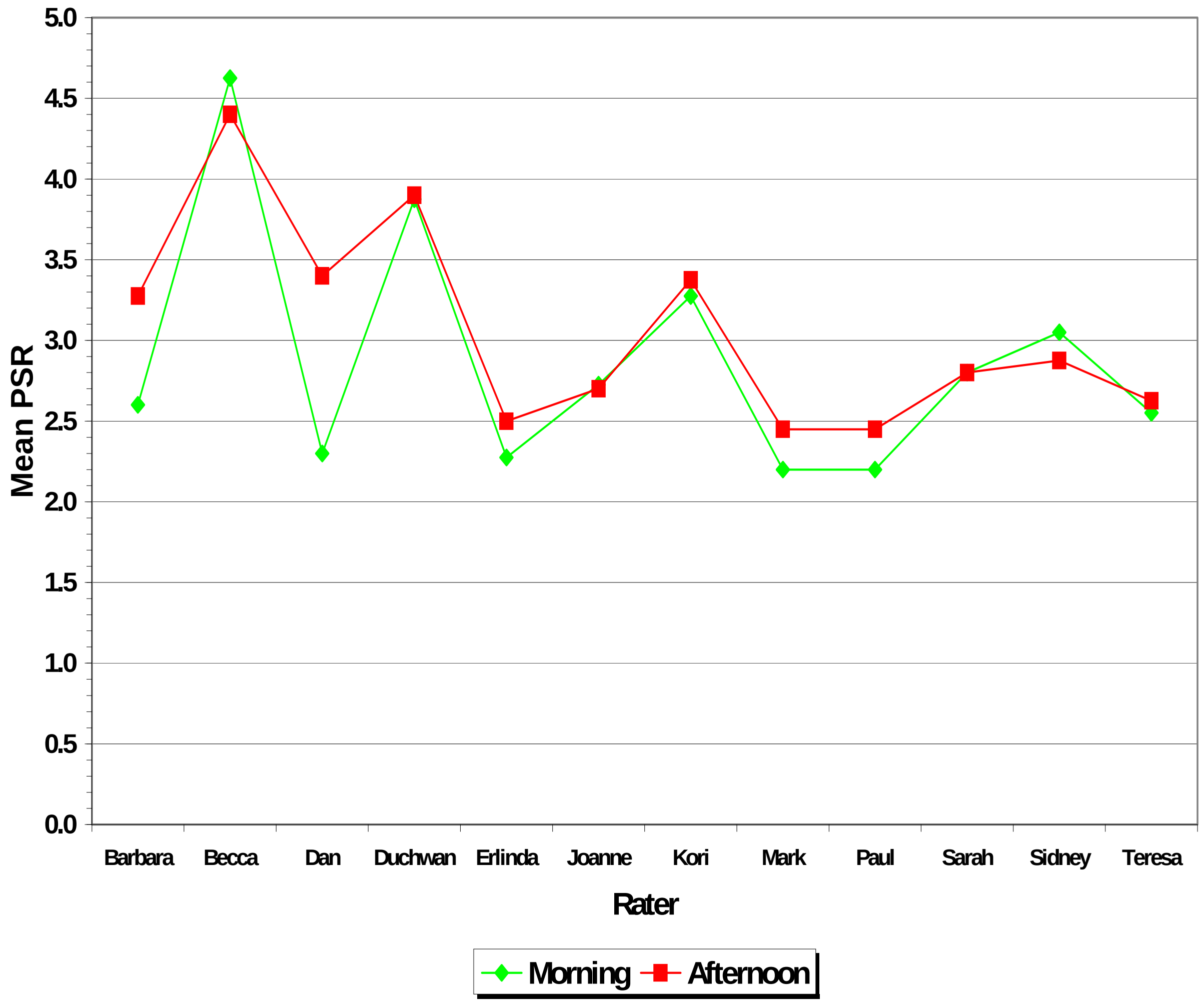


Figure 2.8 Comparison of Mean PSRs and AM and PM Runs (Survey #3)

EFFECT OF PAVEMENT TYPE

Twelve Portland cement concrete sections are included among the list of test sections shown in Table 2.4. These sections are along Loop 336 in Conroe, and are designated as Sections 53 to 58, and 61 to 66 in the table. An analysis was made to evaluate the effect of pavement type on the ride ratings obtained from the surveys conducted in the main experiment. In particular, the means of the ratings for asphalt and Portland cement concrete sections were compared to test if the means differ significantly. This test was done on the data obtained from each field survey as well as the combined data from all three surveys in the main experiment.

Table 2.8 shows the *t*-statistics and corresponding *p* values for evaluating the difference between the mean ratings on asphalt and Portland cement concrete sections. For a 95 percent confidence level, the results indicate that the mean ratings, determined using the data from the second and third field surveys, are significantly different. However, the same cannot be said concerning the difference between the mean ratings from the first field survey. Table 2.8 shows the *p* value of 0.0532 for this survey is higher than the critical value of 0.05. However, the *p* is very close to the critical, indicating that the difference between the mean ratings of asphalt and Portland cement concrete sections is close to being statistically significant. Overall, the mean ratings for the two pavement types are significantly different based on the combined data from all three surveys.

The *t*-statistics in Table 2.8 are all negative reflecting the lower ride ratings given for the asphalt concrete sections. This observation is illustrated in Figure 2.9 that compares the mean ratings for asphalt and Portland cement concrete sections. It is of interest to establish if this observation reflects a difference in the surface profiles between the asphalt and PCC sections selected for the ride panel ratings. Specifically, are the asphalt sections rougher than the PCC sections? To answer this question, researchers compared the mean IRIs for the two pavement types. It was determined that the mean IRI for the asphalt sections is lower than the mean IRI for the PCC sections (1.74 versus 1.85 mm/m, respectively). To check whether this difference is significant, a *t*-test was conducted. This showed that the mean IRIs are not significantly different, indicating that the asphalt and Portland cement concrete sections have comparable levels of roughness. Thus, it appears that the PCC sections were rated higher in the field surveys than the asphalt concrete sections, a finding consistent with the results of the previous ride quality evaluation studies conducted in Texas by Roberts and Hudson (1970), and by Nair, Hudson and Lee (1985).

Results from Evaluation of Effect of Pavement Type

Date of Survey	t-statistic	p value[1]
May 26, 1999	-1.94	0.0532
May 28, 1999	-3.31	0.0011
June 3, 1999	-3.48	0.0006
Combined Data	-5.11	0.0001

[1] A *p* value of 0.05 or smaller indicates significance at the 95 percent confidence level.

Table 2.8 Results from Evaluation of Effect of Pavement Type

Comparison of Mean PSRs of Asphalt and PCC Sections

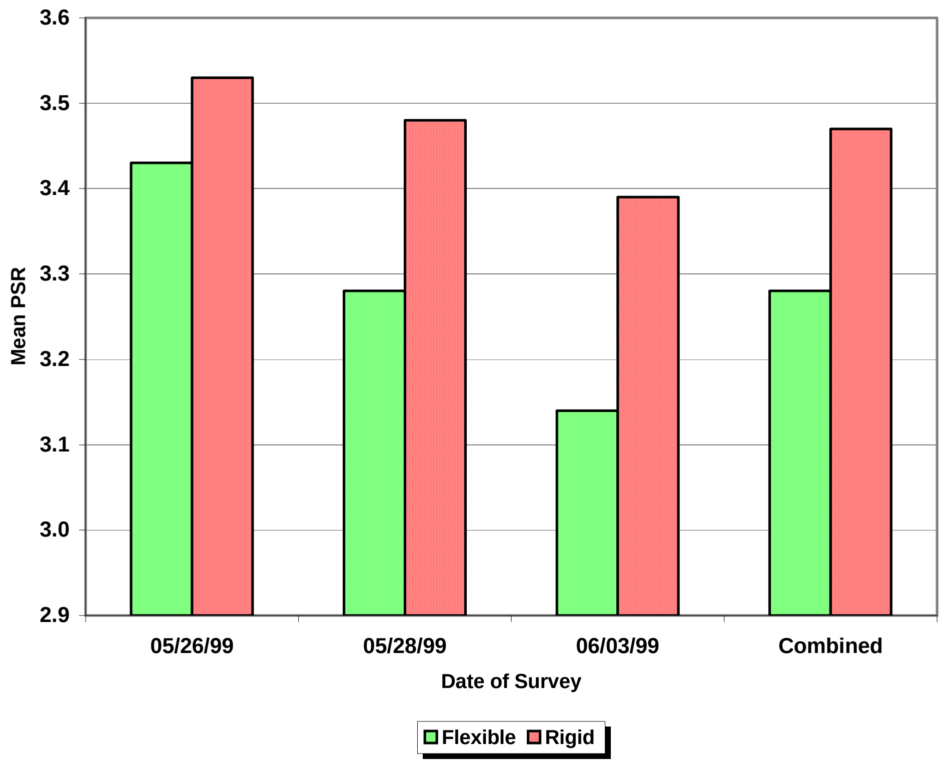


Figure 2.9 Comparisons of Mean PSRs of Asphalt and PCC Sections

EFFECTS OF SECTION ROUGHNESS, RATER, AND VEHICLE ON SUBJECTIVE RATINGS OF RIDE QUALITY

The ride sections vary in surface smoothness as evident from Table 2.4, which gives the calculated IRIs and PSIs from profile measurements taken on these sections. In the analysis of the ratings from the control sections, it was shown that section roughness significantly affected user perception of ride quality, as would be expected. The same finding was reached from the analysis of the ratings from the surveys done on the test sections included in the main experiment. The effect of section roughness is illustrated in Figures 2.10 and 2.11. In these figures, the mean PSRs and mean IRIs for the test sections are plotted. Figure 2.10 shows the ratings for the asphalt concrete sections while Figure 2.11 shows the ratings for the Portland cement concrete sections. Observe that the mean PSRs are correlated with the mean IRIs from the profile measurements. Sections with higher PSRs generally show lower IRIs and vice-versa, reflecting the inverse relationship between these two smoothness statistics. There is also a consistency in the mean PSRs from the three different surveys that indicates that the effect of section roughness is consistent among the different raters, i.e., smooth pavements got higher ratings than rough pavements. From statistical analysis, the effect of section roughness was found to be significant above the 99 percent confidence level for both asphalt and Portland cement concrete pavements. This finding indicates why surface profile is a good predictor of pavement ride quality.

The effects of rater and vehicle are illustrated by analyzing the ratings from individuals who participated in more than one field survey in the main experiment. Table 2.9 identifies these individuals along with the dates on which they rated and the vehicles they used. The ratings of these individuals are discussed in the following sections.

Mean PSRs and Mean IRIs of AC Sections Surveyed in Main Experiment

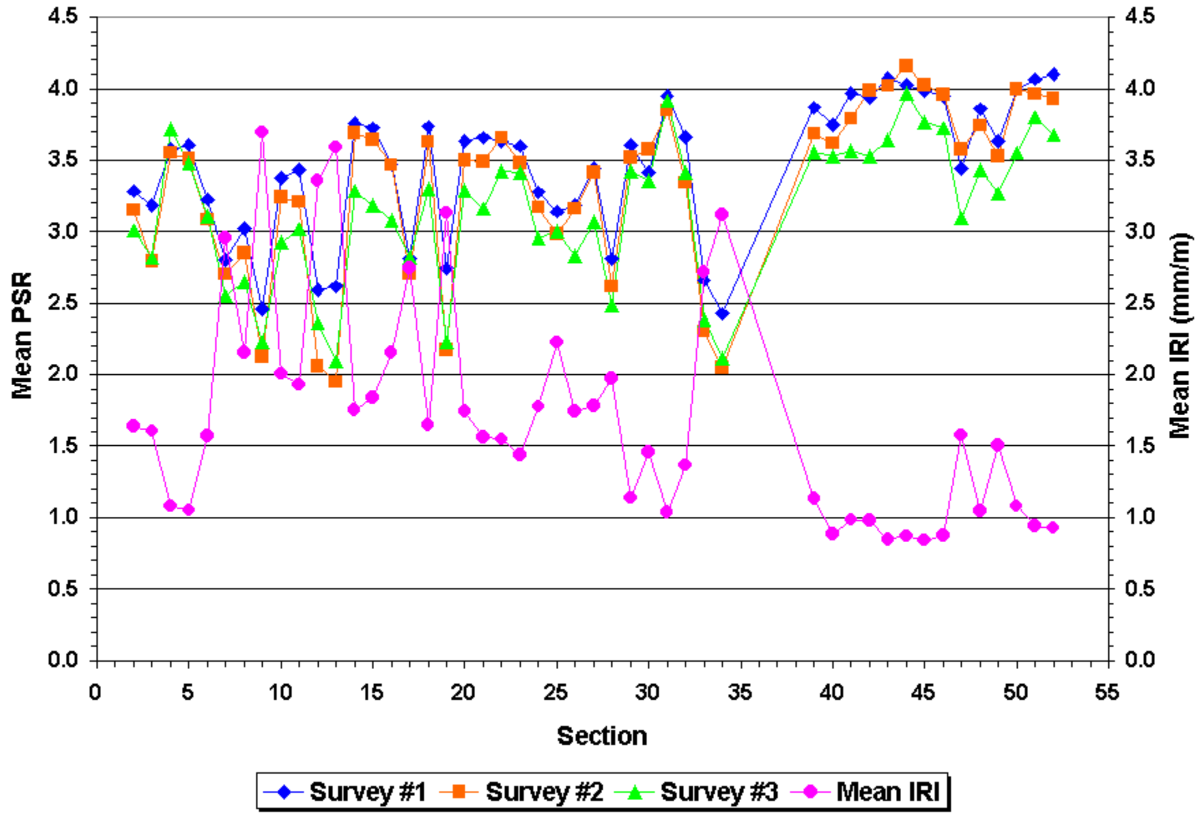


Figure 2.10 Mean PSRs and Mean IRIs of AC Sections Surveyed in Main Experiment

Mean PSRs and Mean IRIs of PCC Sections

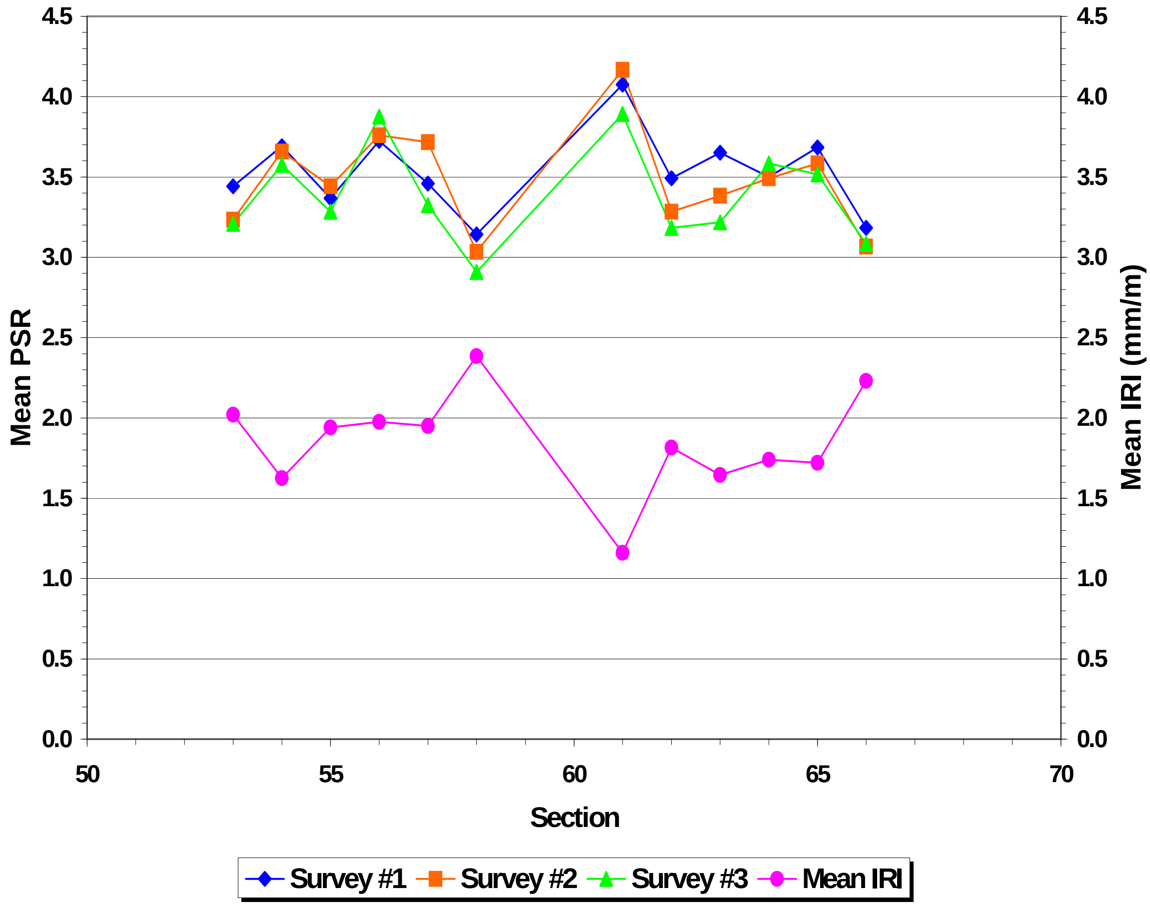


Figure 2.11 Mean PSRs and Mean IRIs of PCC Sections Surveyed in Main Experiment

Individuals Who Rated in More Than One Field Survey in the Main Experiment

Vehicle	Survey Date (1999 Calendar Year)		
	May 28	May 28	June 3
C1	Roseanna & Willard	Vinatha & Yue	
C3	Duchwan & Sarah		Sidney
T1	Sidney	Sarah	
V1			Duchwan
V2	Vinatha & Yue	Roseanna & Willard	Sarah

Table 2.9 Individuals Who Rated in More Than One Field Survey in the Main Experiment

EVALUATION OF RATINGS FROM ROSEANNA AND WILLARD

The ratings from Roseanna and Willard reveal a significant two-way interaction effect between rater and vehicle. This interaction is illustrated in Figure 2.12. Researchers determined from statistical analysis that the rater-vehicle interaction is significant above the 95 percent confid... er for vehic... tings from ... e the 99 pe... nding rating...

... V2 is highe... effect obser... the

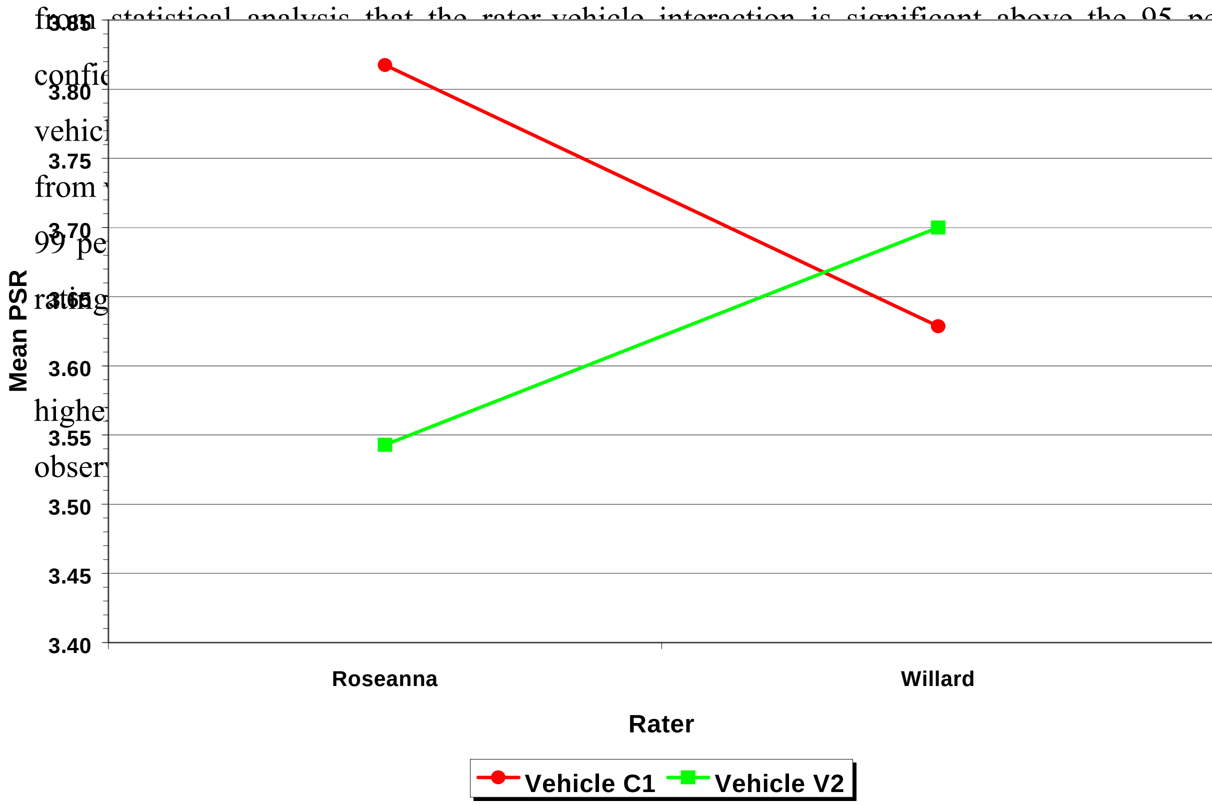


Figure 2.12 Evaluation of Ratings From Roseanna and Willard

difference associated with Roseanna's ratings. In fact, the paired *t*-test showed that the effect of vehicle type on Willard's ratings is not significant.

In view of the significance of the interaction illustrated in Figure 2.12, the rater effect must be evaluated for each vehicle type. For this purpose, researchers conducted a paired *t*-test on the differences between the ratings of Roseanna and Willard for each vehicle type. The results showed significant differences between the ratings from these two individuals, for both vehicle types. On vehicle C1, Roseanna's ratings were found to be significantly higher (above the 99 percent level of confidence) than the corresponding ratings by Willard. This result is consistent with the finding presented earlier regarding the effect of vehicle type on Roseanna's ratings. It also reflects her preference for cars, which she expressed after the surveys were completed.

In addition, Roseanna's ratings on vehicle V2 were found to be significantly lower (at a 95 percent level of confidence) than the corresponding ratings by Willard. Again, this is consistent with her stated preference for cars. The results therefore illustrate how user perception of ride quality is tied to his or her preferences. Since these vary between individuals or groups, it is logical to expect that the rater effect will be significant.

EVALUATION OF RATINGS FROM VINATHA AND YUE

Table 2.10 summarizes the results of paired t-tests on the differences between ratings made by Vinatha and Yue for vehicles C1 and V2. The effect of vehicle type is significant based on the reported *p* values. Observe that the *t*-statistics are positive which indicates that the ratings made by both individuals in vehicle C1 tended to be higher than the corresponding ratings made in vehicle V2. This vehicle effect is similar to that reported earlier for Roseanna. Figure 2.13 illustrates the vehicle effect. Since the direction of this effect is the same for both raters, it may be inferred that the interaction between rater and vehicle is not significant. This was confirmed from the statistical analysis of the ratings from Vinatha and Yue. From the same analysis, it was determined that the mean of the ratings from Vinatha (averaged over all sections) was not significantly different from the corresponding mean rating by Yue for both vehicles C1 and V2. However, Figure 2.14 indicates that there are certain sections for which the mean PSRs (averaged over vehicles C1 and V2) differ significantly. This figure illustrates the significant interaction between section and rater identified from the statistical analysis. From an *F*-test, this interaction was found to be significant above the 99 percent confidence level. Because of this, it cannot be concluded that the rater effect is not significant, even though the means of the ratings (averaged over all sections for each vehicle type), were determined to be not different, statistically.

Evaluation of Effect of Vehicle on Ratings Given by Vinatha and Yue

Rater	***t*-statistic**	***p* value**[1]
Vinatha	6.97	0.0001
Yue	2.59	0.0120

[1] A *p* value of 0.05 or smaller indicates significance at the 95 percent confidence level.

Table Yue

Illustra ie

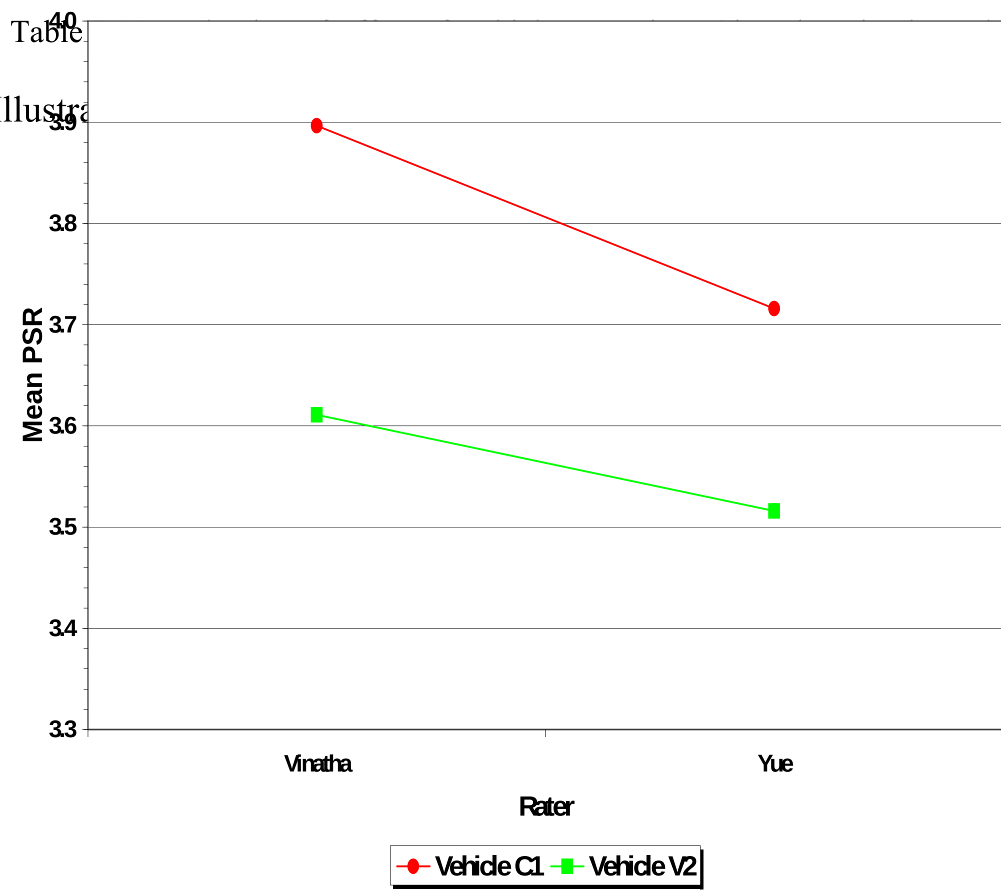


Figure 2.13 Illustration of Effect of Vehicle Type on Ratings by Vinatha and Yue

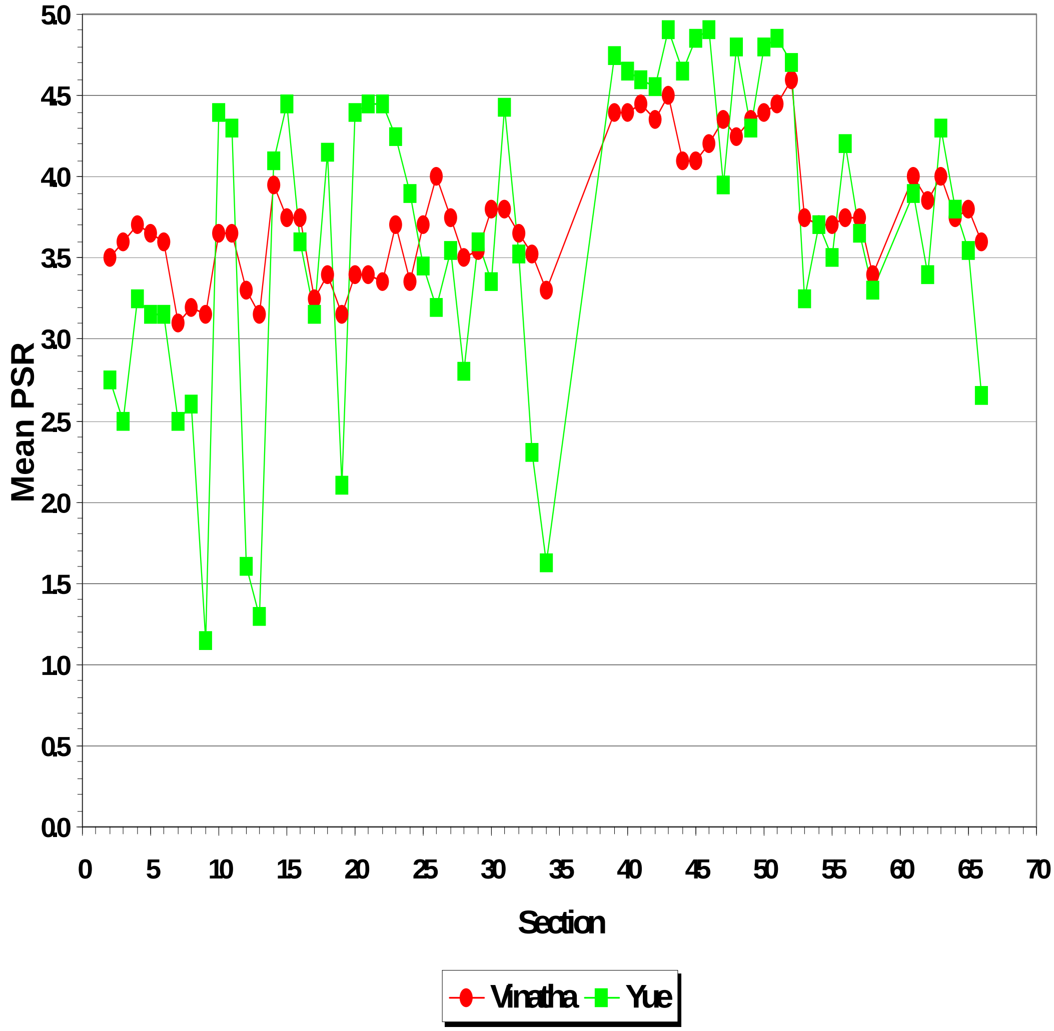


Illustration of Rater*Section Interaction in Ratings by Vinatha and Yue

Figure 2.14 Illustration of Rater*Section Interaction in Ratings by Vinatha and Yue

EVALUATION OF SARAH'S RATINGS

Sarah participated in all three surveys conducted in the main experiment. An analysis of variance on her ratings showed that the effects of vehicle and section are significant above the 99 percent level of confidence. Figure 2.15 illustrates the effect of section on Sarah's ratings. In this figure, the mean of her ratings (averaged over vehicles C3, T1, and V2) is given for each section. In addition, the mean IRIs determined from profile measurements are plotted. There is a noticeable correlation between the ratings by Sarah and the computed IRIs. Sections with lower PSRs generally show higher IRIs and vice-versa, reflecting the inverse relationship between these two smoothness statistics. This illustrates the effect of surface roughness on Sarah's ratings.

The vehicle effect is illustrated in Figure 2.16 that shows the mean of Sarah's ratings (averaged over all sections) for each vehicle in which she rated. From statistical tests, the mean PSRs for vehicles C3 and T1 were not found to be significantly different. However, the mean PSR for V2 is significantly different from the corresponding means of the other two vehicles. It appears from the test data that Sarah rated the sections lower in vehicle V2 than in vehicle C3 or T1.

EVALUATION OF DUCHWAN'S RATINGS

The effects of vehicle and section on Duchwan's ratings were found to be significant. These effects are illustrated in Figure 2.17 that shows Duchwan's ratings by section and vehicle type. The variability in the ratings between sections reflects the effect of this variable, which was determined to be significant above the 95 percent confidence level.

To evaluate the vehicle effect, researchers conducted an *F*-test on the difference between the mean ratings for vehicles C3 and V1. This test showed the difference to be significant above the 99 percent confidence level. From Figure 2.17, it is observed that the majority of the ratings made in vehicle V1 are generally lower than the corresponding ratings in C3.

Variation in Sarah's Ratings between Sections of the Main Experiment

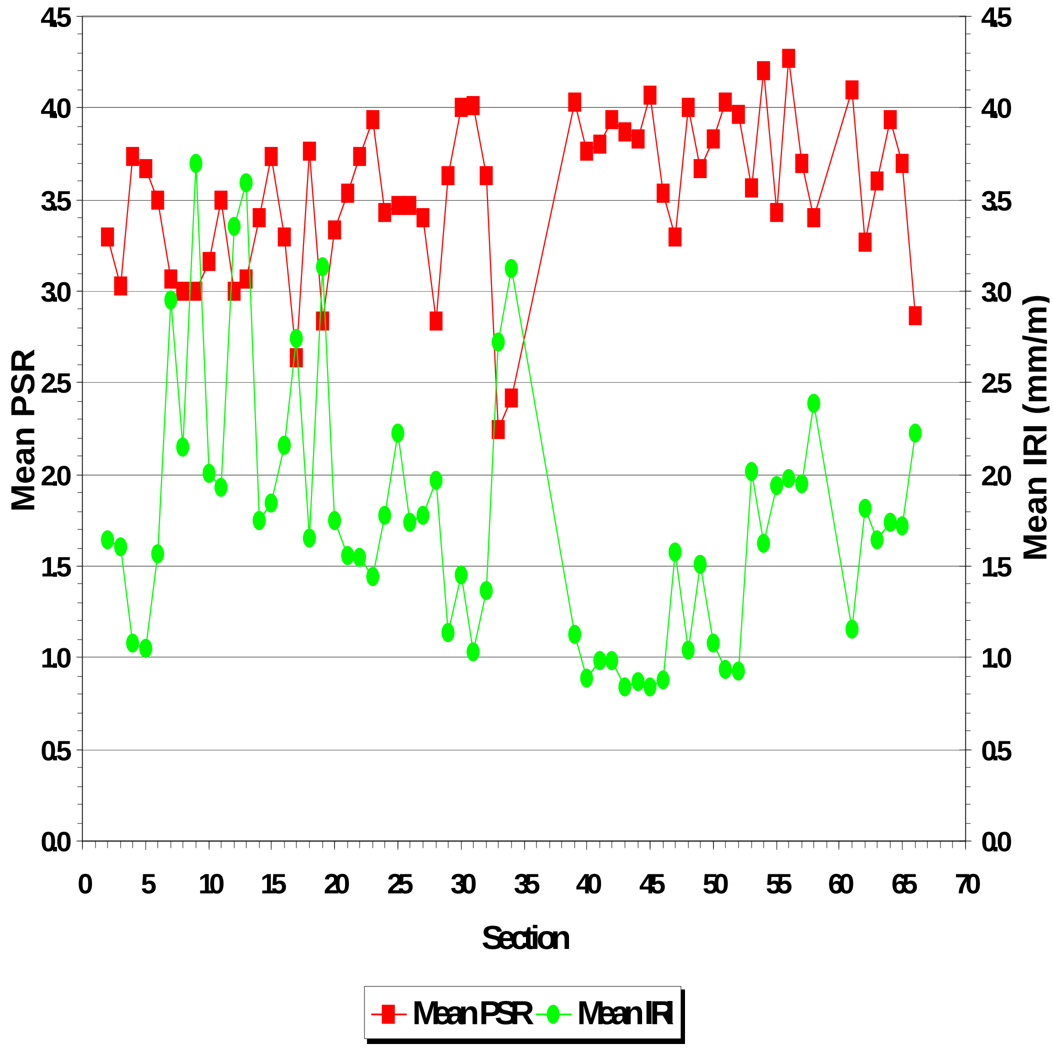


Figure 2.15 Variation in Sarah's Ratings between Sections of the Main Experiment

Comparison of Mean PSRs Between Vehicles Used by Sarah

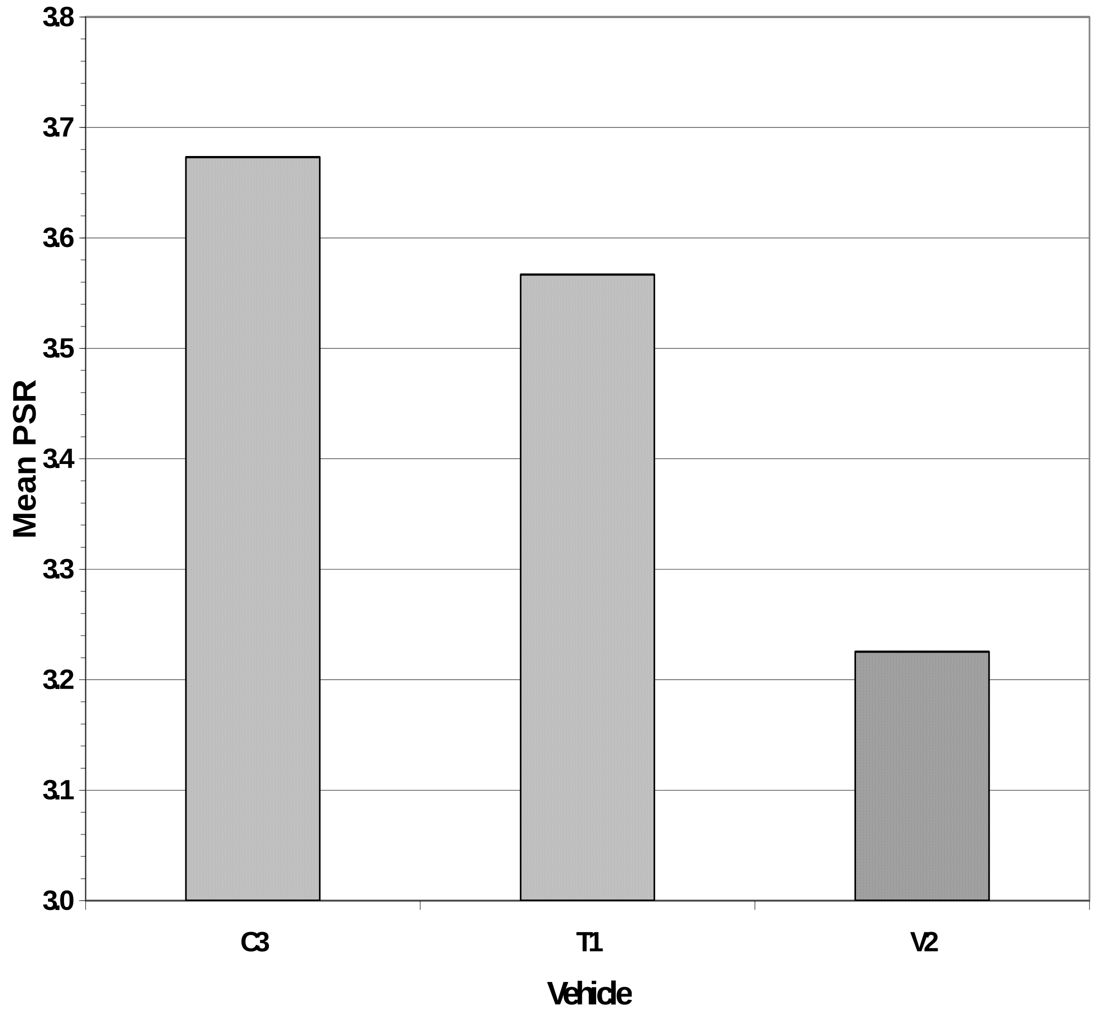


Figure 2.16 Comparison of Mean PSRs Between Vehicles Used by Sarah

Variation in Duchwan's Ratings by Section and Vehicle Type

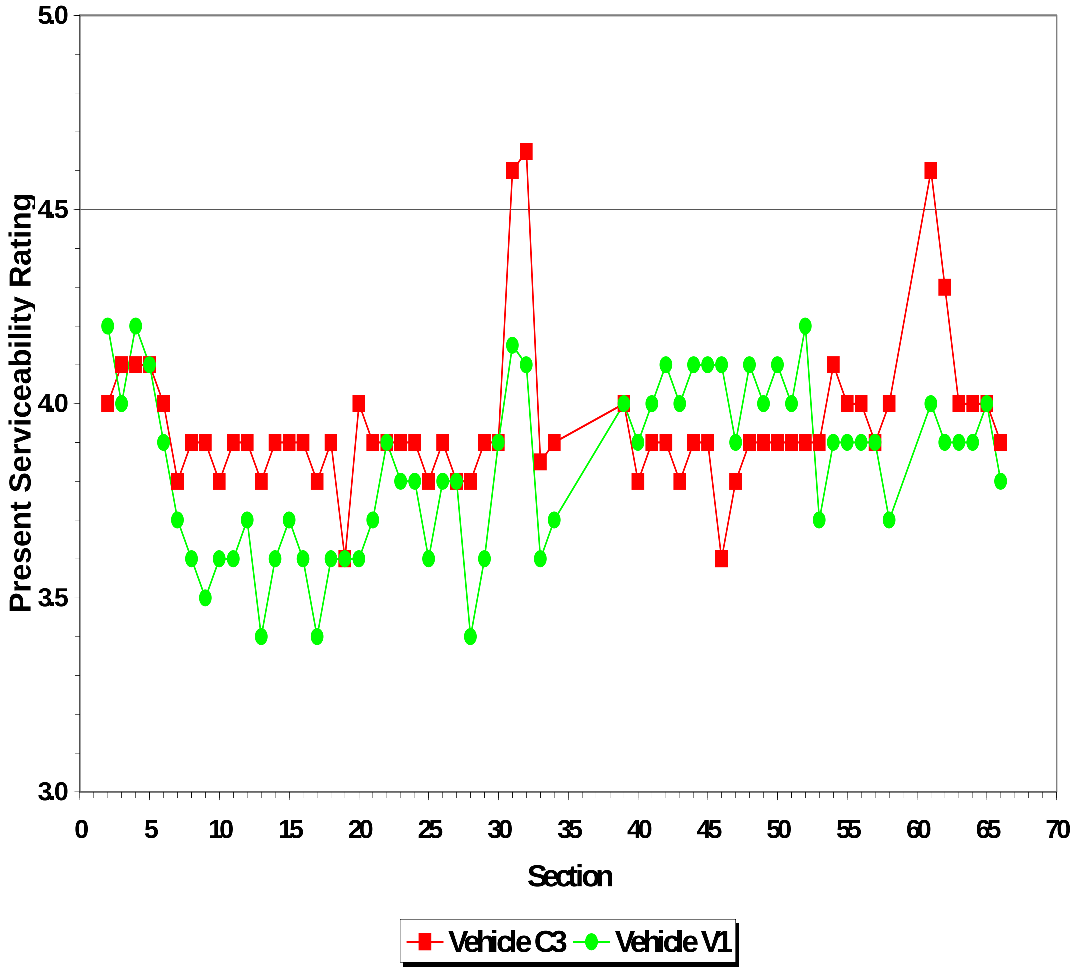


Figure 2.17 Variation in Duchwan's Ratings by Section and Vehicle Type

EVALUATION OF SIDNEY'S RATINGS

Sidney participated in two of the surveys conducted in the main experiment. From an analysis of his ratings, researchers identified vehicle type as significant above the 99 percent confidence level. The effect of this variable is illustrated in Figure 2.18, which shows that the mean of the section ratings for vehicle C3 is higher than the corresponding mean for vehicle T1. Researchers determined this difference to be statistically significant.

The section effect was not found to be significant at the 95 percent level of confidence. This is unlike the previous findings for the other raters that showed this variable to be significant at the 95 percent confidence level or higher. However, the effect is significant at the 93 percent level, which shows that it just missed satisfying the selected criterion for identifying significant effects by a narrow margin.

SUMMARY AND IMPLICATIONS OF FINDINGS

From the analysis of the data reported, the following findings are noted:

1. The ratings from the surveys in the main experiment appear to be spatially independent even though the sections were rated in a certain sequence. In view of this finding, the evaluation of main effects and interactions between the study variables was accomplished using the usual *F*-tests and *t*-tests that are based on the assumption of a linear model.
2. The effects of the following factors on subjective ratings of ride quality were found to be significant at a confidence level of 95 percent or higher:
    a. section roughness, which showed a noticeable correlation with the panel ride ratings,
    b. vehicle type,
    c. the individual rater, and
    d. pavement type.

Illustration of Vehicle Effect on Sidney's Ratings

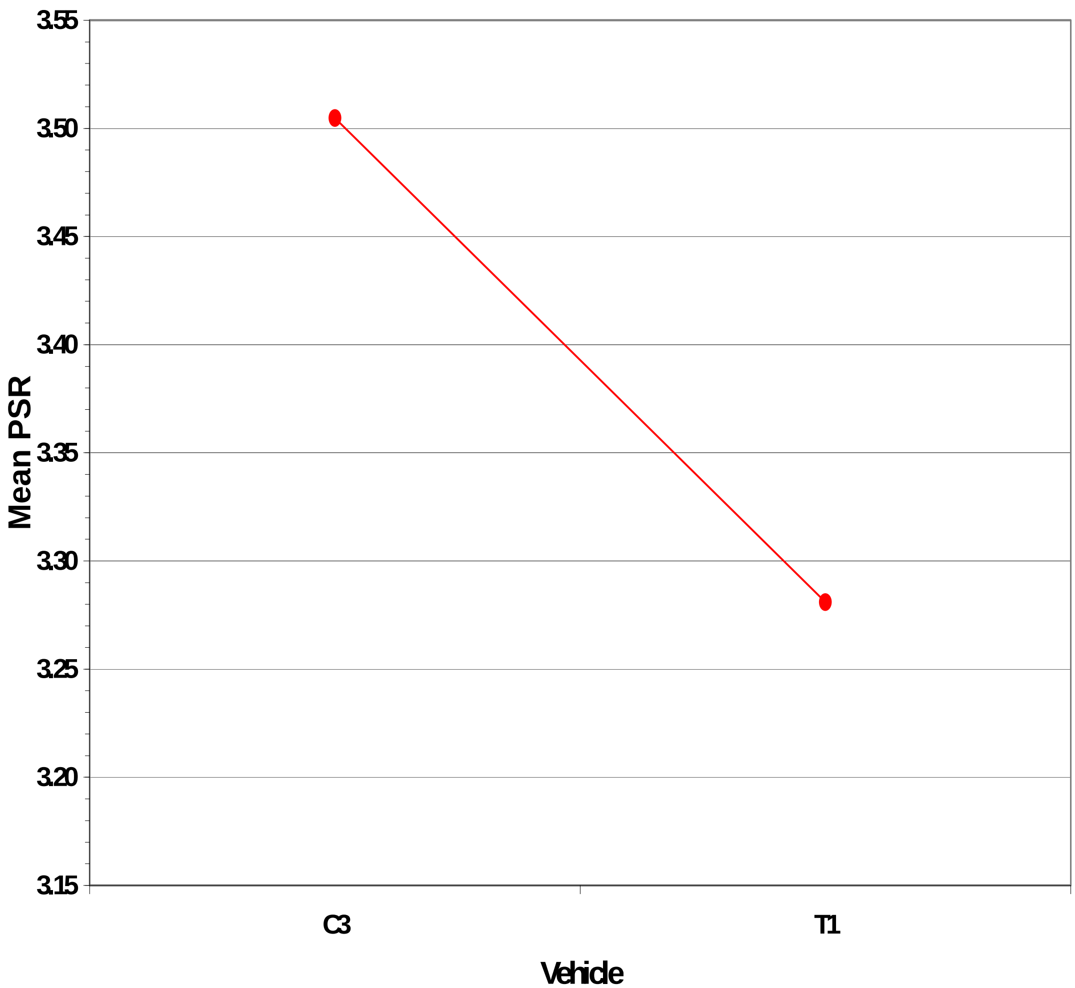


Figure 2.18 Illustration of Vehicle Effect on Sidney's Ratings

In view of the significant influence of section roughness, there appears to be a strong basis for using surface profiles to develop relationships for predicting ride quality. The significant correlation between surface profile and user-perception of ride quality has been observed in previous research (AASHO, 1962; Roberts and Hudson, 1970; and Nair, Hudson and Lee, 1985).

Because user-perception of ride quality is largely subjective, it is not surprising that the ratings collected from the surveys reflect the influence of the rater. In addition, since vehicle design, e.g., suspensions, mass distributions, geometry, and tire properties, affect its response to surface profile, it is reasonable for the data to show the significant influence of vehicle type on the panel ratings. While these findings suggest that relationships for evaluating ride quality should include rater and vehicle factors, the evaluation of such relationships would require a much larger effort than planned for this project. In addition, the implementation of any relationships developed from such a study is likely to be difficult. The need to incorporate rater and vehicle factors in a ride equation was discussed with the project monitoring committee. While these factors significantly influence user perception of ride quality, the difficulty in implementing a ride equation that includes these variables precluded their consideration in the development of the new ride equation.

Finally, the effect of pavement type was determined to be significant. Since the average IRIs of the asphalt and Portland cement concrete sections were found to be comparable, the results reflect a tendency by the raters in the surveys to rate PCC sections higher than asphalt concrete sections. This result was also noted in the two previous ride evaluation studies conducted in Texas.

Currently, pavement type is not a factor in the ride equation implemented by TxDOT. Based on the finding just noted, there seemed to be good reason to consider this variable in modifying the existing equation or developing a new equation based on data from the ride surveys. Implementation of such an equation would have required distinguishing between asphalt and Portland cement concrete sections, which is achievable with current technology. However, the researchers and project monitoring committee saw a need to supplement the data on the concrete sections by conducting an additional ride survey involving PCC sections only. Consequently, researchers conducted a second survey in 2000 to confirm the effect of pavement type, and to establish the magnitude and direction of its effect for developing a ride equation that includes this variable.

CHAPTER 3

RIDE PANEL RATINGS CONDUCTED IN DALLAS/FORT WORTH

INTRODUCTION

As reported in the previous chapter, analysis of the data from the ride panel ratings conducted in 1999 revealed pavement type as a significant factor influencing user opinions of ride quality. This finding indicated a need to include a blocking factor for PCC pavements. Researchers note that a blocking factor was included in the original ride equation (see Chapter 1). However, it was omitted in later versions, partly because the task of tracking changes in pavement type during a ride survey was not feasible with the technology that existed at that time. However, given the technological advances that have taken place since the equation's original development, and the observed effect of pavement type on ride panel ratings, the need arose to re-evaluate the PCC blocking factor in the current project.

Of the 63 test sections included in the 1999 ride survey, 12 were PCC pavements. In order to obtain additional data with which to evaluate a blocking factor, a second ride survey was conducted in June 2000 that primarily covered PCC sections located in the Dallas/Fort Worth (DFW) area. Table 3.1 presents a list of the test sections established for this survey while Figures 3.1 and 3.2 show the locations of the test sections. Locations of test sections are indicated by the numbers 0 to 6 written adjacent to the route in the figures. These numbers refer to the test section groups identified in Table 3.1. Altogether, 42 sections were rated. Of these, 33 were PCC pavements and nine were asphalt pavements. Researchers note that the nine asphalt pavements were not intended to supplement the asphalt sections included in the 1999 surveys.

List of Test Sections for DFW Ride Survey

Group	Section [A]	County	Highway	Reference	Start (distance from reference)	Lane	Direction	Posted Speed (mph)	Estimated SI
0	T1	Tarrant	I20 Frontage	40 mph speed limit sign	0.1198 miles near Church of Abundant Life	X1	Westbound	40	3.3
0	T2	Tarrant	I20 Frontage	40 mph speed limit sign	about 0.18 miles at sign for Pleasant View Drive	A1	Eastbound	40	2.7
0	T3	Tarrant	I20 Frontage	RM 448 on westbound shoulder	0.1925 miles at sign for Park Spring - Kelly Elliot Road Exit (447)	X1	Westbound	40	3.1
1	1	Tarrant	US287	RM 476	0.4 miles	L1	Northbound	70	3.7
1	2[T]	Tarrant	US287		1.2 miles				3.3
1	3	Tarrant	US287		2.0 miles				3.8
1	4	Tarrant	US287		2.5 miles				3.6
1	5[T]	Tarrant	US287		3.0 miles				3.9
1	6	Tarrant	US287		3.5 miles				3.1
1	7	Tarrant	US287		3.9 miles				4.1
1	8[T]	Tarrant	US287		4.6 miles				2.7
1	9	Tarrant	US287	70 mph speed limit sign after Little Road entrance ramp	0.3 miles	R1	Southbound	70	2.7
1	10	Tarrant	US287		2.4 miles				4.0
1	11	Tarrant	US287		3.2 miles				3.4
1	12	Tarrant	US287	70 mph speed limit sign after Little Road entrance	4.2 miles	R1	Southbound	70	2.7
1	13	Tarrant	US287		4.9 miles				3.9

List of Test Sections for DFW Ride Survey

Group	Section A	County	Highway	Reference	Start (distance from reference)	Lane	Direction	Posted Speed (mph)	Estimated SI
1	14	Tarrant	US287	ramp	5.7 miles				3.1
2	39	Tarrant	SH 121	SH 121 and Grapevine Mills Blvd. intersection	0.1 mile	L1	Northbound	55	4.3
2	16	Denton	SH121	McArthur and SH121 intersection	0.2 miles				1.7
2	17	Denton	SH121	I35E and SH121(east) intersection	1.0 mile				3.1
2	18	Denton	SH121		1.3 miles				3.9
2	19	Denton	SH121	SH121 and Hebron Pkwy. Intersection	0.5 miles	L1	Northbound	65	3.4
2	20	Denton	SH121		1.0 mile			65	3.2
2	21	Denton	SH121		1.4 miles	L1	Northbound	55	3.6
3	33*	Denton	SH121	RM 264	0.1 mile	R1	Southbound	60	4.1
3	34*	Denton	SH121		0.3 miles				4.2
3	35*	Denton	SH121		0.5 miles				3.0
3	36*	Denton	SH121		0.7 miles				3.0
3	37*	Denton	SH121		0.94 miles	R1	Southbound	55	4.0
4	22	Denton	FM2281	FM2281 and FM544 intersection	0.2 miles	R1	Southbound	55	2.7
4	23	Denton	FM2281		0.4 miles				3.3
4	24	Denton	FM2281		0.6 miles				2.8

List of Test Sections for DFW Ride Survey

Grou p	Section [A]	County	Highway	Reference	Start (distance from reference)	Lan e	Direction	Posted Speed (mph)	Estimated SI
4	25	Denton	FM2281		1.1 miles				3.0
4	26	Denton	FM2281	FM2281 and Hebron Pkwy. intersection	0.5 miles	L1	Northboun d	55	3.1
4	27	Denton	FM2281		0.7 miles				3.2
4	28	Denton	FM2281		1.0 mile				3.8
5	29*	Denton	FM423	RM 244	0.3 miles	L1	Northboun d	55	2.5
5	30*	Denton	FM423		0.7 miles				2.1
5	31*	Denton	FM423		0.91 miles				1.6
5	32*	Denton	FM423	RM 244	0.5 miles	R1	Southboun d	55	3.0
6	38	Denton	SH121	SH121 and Hebron Pkwy. intersection	0.7 miles	R1	Southboun d	65	3.8
6	15	Denton	SH121	I35E and SH121 intersection (west)	0.4 miles	R1	Southboun d	55	2.9

Table 3.1 List of Test Sections for DFW Ride Survey

[A] All sections are 0.1-mile long and PCC unless otherwise noted
* Asphalt surface
[T] Training section

Driving Route for DFW Ride Survey *(a)*

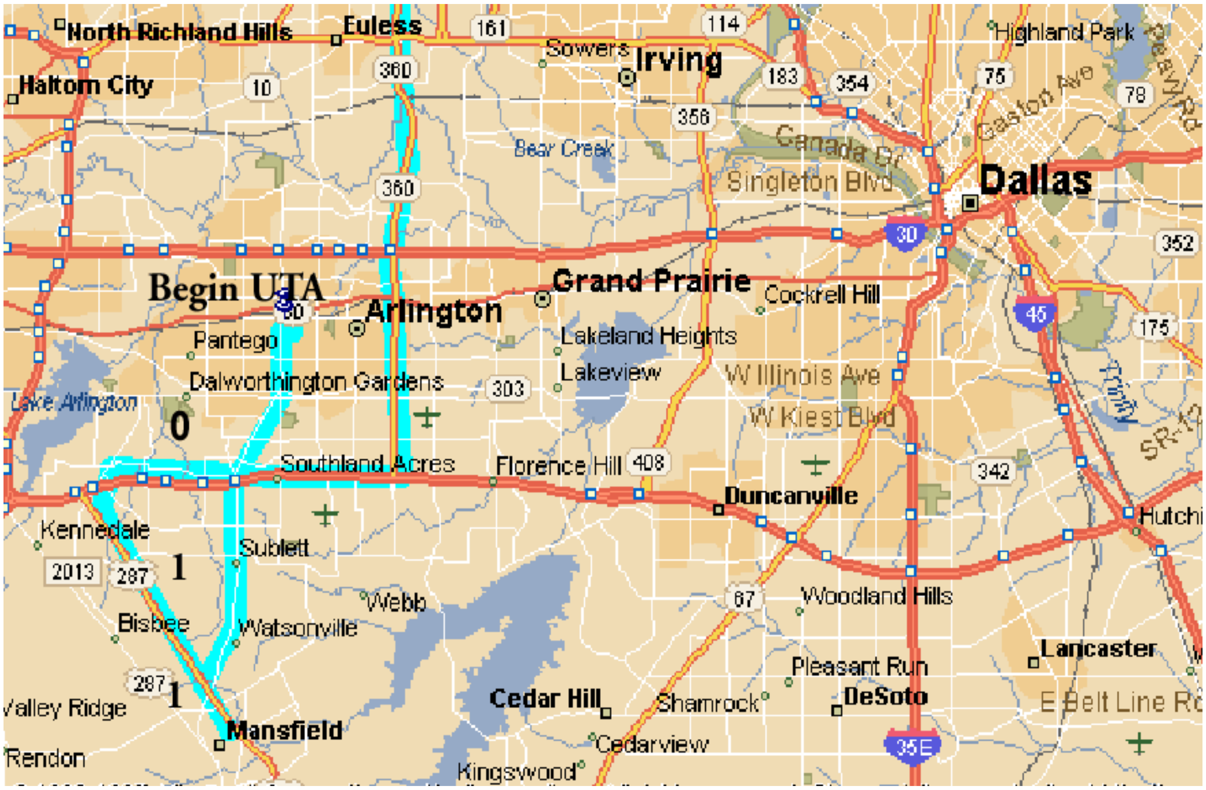


Figure 3.1 Driving Route for DFW Ride Survey *(a)*

Driving Route for DFW Ride Survey *(b)*

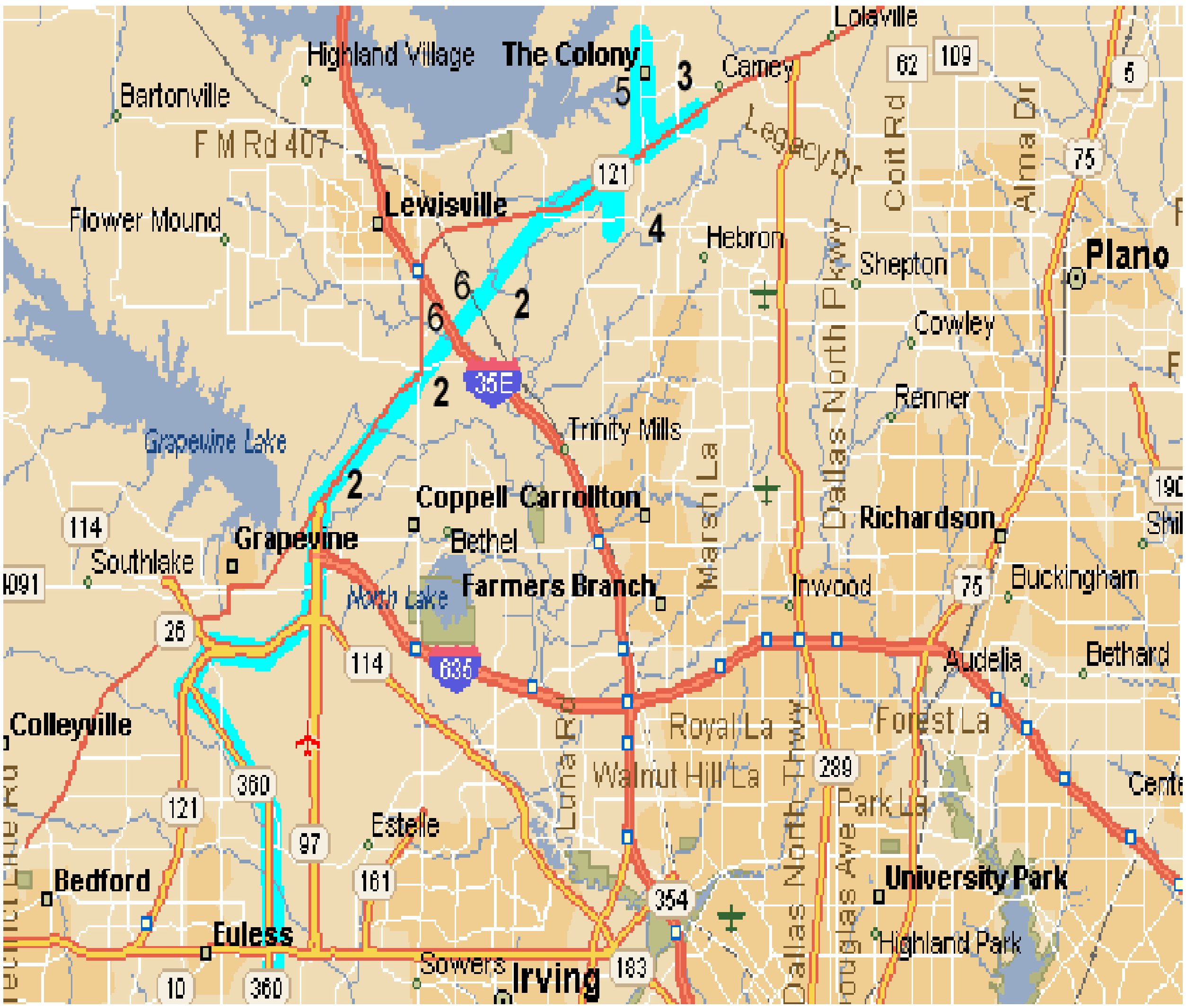


Figure 3.2 Driving Route for DFW Ride Survey *(b)*

At the time the project director and researchers were setting up the DFW survey, there was a concern that raters may go on “auto-pilot” if only PCC sections were included in the survey.

Thus, researchers added asphalt sections to provide a break in the ratings of the PCC sections. This chapter presents the field experiment and the analysis of the ride panel ratings for the 2000 survey.

PLAN OF DFW RIDE SURVEY

As previously indicated, the main purpose of the DFW survey is to gather additional data for evaluating the PCC blocking factor. For this purpose, test sections were selected so as to cover the range in surface profile from smooth to rough. However, unlike the first survey, no attempt was made to vary the vehicle type or to evaluate the effect of rater fatigue.

Three Chevy Luminas and a Ford Taurus were used as test vehicles. While the initial plan was to use cars of the same make and model (i.e., the Chevy Luminas provided by TxDOT), the Ford Taurus (a TTI vehicle) was added on the day of the survey to transport an additional participant who became available that day. However, even though this vehicle was of different make than the other three, its size and in particular its wheelbase, are very comparable to the Chevy Luminas. For the survey, researchers assembled a panel of 10 raters. Similar to the 1999 survey, drivers were given a briefing notebook and site visits were made the day before the survey so that drivers may familiarize themselves with the route (Figures 3.1 and 3.2) and the locations of the test sections. On the day of the survey, three raters were assigned to each of the Chevy Luminas while the remaining rater rode in the Ford Taurus. Each individual was asked to give his or her rating on the same form used in the first ride survey (see Figure 2.2). Prior to rating the sections, researchers and the project director conducted a briefing session to familiarize participants with the rating scale, provide instructions on how the form is to be filled up during the survey, and identify the survey route. Thereafter, practice runs were made on three test sections selected for training purposes. Once these runs were completed, the raters were then driven over the survey route. Sections were rated with the test vehicles driven at a speed of 55 mph. In general, the field ratings were conducted in a similar fashion as reported for the first ride survey.

EVALUATION OF DFW RIDE SURVEY DATA

This section presents findings from the evaluation of the DFW ride panel ratings. For this purpose, panel ratings were initially read from the forms using a template of the rating scale with divisions in tenths of a rating point. The panel ratings were then entered into a spreadsheet and analyzed using SAS (1988). The following items were evaluated:

1. spatial independence of the ride panel ratings, and
2. differences between the present serviceability ratings given by raters and the estimated present serviceability indices computed from the profiles.

SPATIAL INDEPENDENCE OF RIDE RATINGS

Since the test sections were rated in a certain sequence as opposed to a random order, researchers first evaluated the spatial independence of the ride ratings. For this purpose, researchers applied the runs test described in Chapter 2 to evaluate the spatial independence of the 1999 ride ratings. The results from this analysis showed that there is no basis for rejecting the assumption that the ratings are independent, similar to the result determined from the 1999 survey. In view of this finding, the significance of differences between ratings was also evaluated using statistical tests of inference involving the F or t statistics.

DIFFERENCES BETWEEN PSRs AND PSIs

The 1999 survey data showed that participants rated the concrete sections higher compared to the PSIs determined using the existing ride equation. This observation is illustrated in Figure 3.3 which shows the difference between the average PSR and the average PSI for each section surveyed in the main experiment. The darker bars in the figure indicate sections where the differences are statistically significant at the 95 percent confidence level. Note that all but one of the concrete sections (53 through 66) show a positive difference indicating that the ratings given by the raters are higher than the corresponding PSIs determined from the profiles. If the averages of the differences between the PSRs and PSIs are determined, it is found that the average difference is –0.10 for the asphalt sections and +0.19 for the concrete sections. Thus, it appears from these results that a blocking factor for pavement type may have to be added to the

Comparison of PSRs and PSIs (1999 Survey)

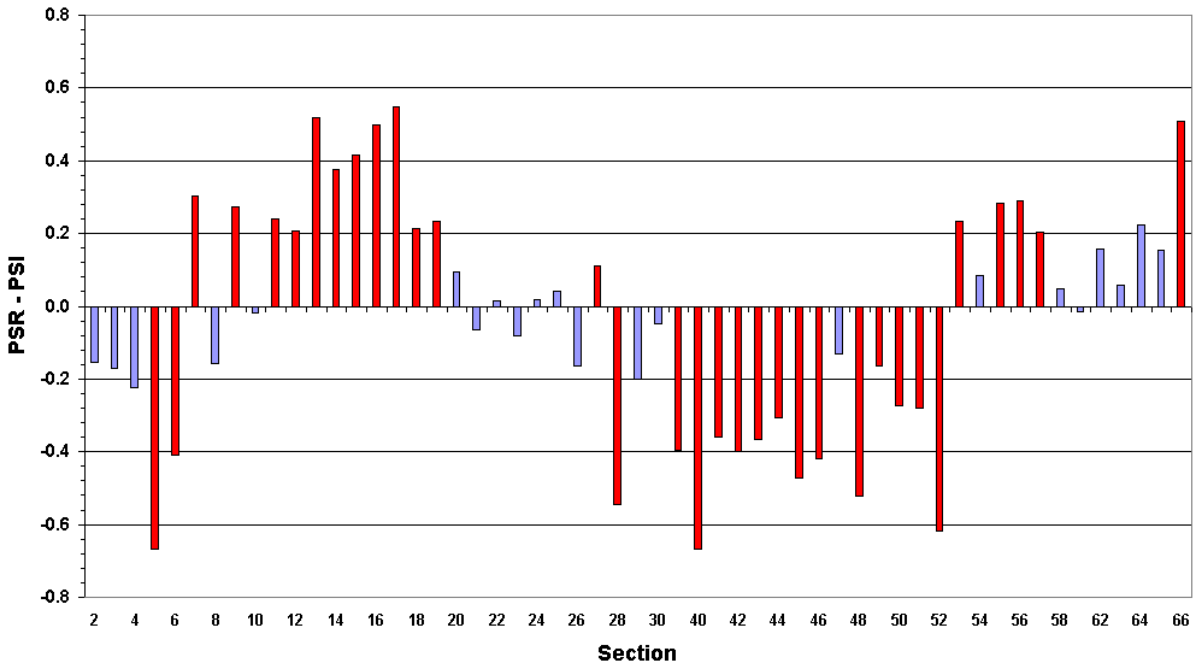


Figure 3.3 Differences Between PSRs and PSIs from 1999 Survey Data

existing equation. However, since there were only 12 PCC sections in the 1999 survey, researchers and members of the project monitoring committee felt that there were not enough concrete sections to make this determination. Thus, a decision was made to organize a second ride survey, which was conducted in June 2000.

Evaluation of the 2000 ride survey data showed that the PCC sections were generally rated lower by the participants compared to the PSIs determined from the profiles. This is illustrated in Figure 3.4, which shows the differences between the average PSRs and PSIs for the PCC sections. It is noted that the mean PSR and mean PSI differ quite a bit on section 21 with raters rating the section higher compared to the PSIs from the profile runs. Because of the proximity of sections with one another and with the traffic conditions in the DFW area, it was often necessary to collect profile continuously through several sections. Specific sections were located by its distance from the beginning of the profile run to the section start. This was true on

Comparison of PSRs and PSIs (1999 Survey)

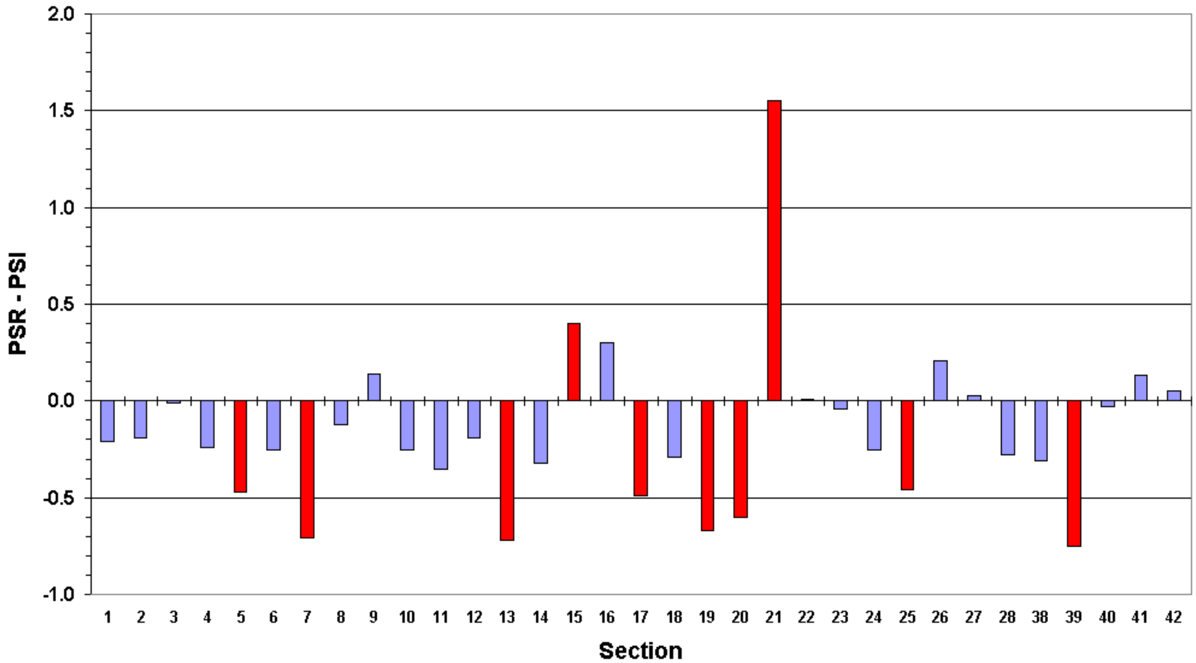


Figure 3.4 Differences between PSRs and PSIs from 2000 Ride Survey.

sections 19 to 21. However, during the time the profile was collected on these sections, a dump truck was parked on the outside lane between sections 20 and 21. The profiler had to change lanes to go around the truck. This was not considered to be a problem at the time. However, it was later discovered that, the start point could not be exactly determined as the distance traveled would not be the same as the actual straight line distance to the section. This, along with the pavement characteristics before the section start point, resulted in an error between the section measured by the raters and the one measured by the profiler. Table 3.2 summarizes the average differences between PSRs and PSIs.

For the PCC sections, researchers note that the average difference is –0.22 in 2000 compared to +0.19 in 1999. Observe that the trends are reversed so that when the data from both surveys are considered, the average difference for the PCC sections becomes –0.11. In addition,

Average Differences Between PSRs and PSIs.

Pavement Type	Ride Survey		
	1999	2000	Combined
Asphalt	–0.10	—	–0.10
PCC	+0.19	–0.22	–0.11
All	–0.04	–0.22	–0.10

Table 3.2 Average Differences Between PSRs and PSIs.

the apparent bias exhibited by the current ride equation is in the same direction for both asphalt and PCC sections. The average differences based on combining the data from both surveys are negative, –0.10 for the asphalt sections and –0.11 for the PCC sections, with an overall average of –0.10. In view of these results, there does not appear to be any compelling reason to modify the existing equation to include a blocking factor for pavement type.

SUMMARY OF FINDINGS

From the analysis reported, the following findings are noted:

1. The 2000 ride panel ratings were found to be spatially independent, similar to the result determined for the 1999 survey.
2. Using the data from both surveys, there was inconclusive evidence to support the need to include a blocking factor for pavement type in the ride equation.
3. The ratings from both surveys indicate that the existing ride equation tends to over estimate user opinions of ride quality. This finding points to the need for

calibrating or revising the existing ride equation to improve the agreement with the panel ratings from the surveys conducted.

The development of the new ride equation is presented in the next two chapters of this report.

CHAPTER 4

DATA COLLECTION AND ANALYSIS

PROFILE DATA ACQUISITION

The procedures used for data acquisition are described in this chapter. Profile data were collected soon after each of the rating sessions as described in Chapters 2 and 3. For the profile measurements, five repeat profile runs were made for each section. On each run, two profiles were collected, one on each wheel path. Two different profilers were used, one for the 1999 session and a second for the 2000 session. Because of this, the sample interval was different for the 1999 and 2000 data sets. As discussed in Chapters 2 and 3, sixty-three 0.1-mile sections were rated and profiled in the 1999 survey, and 42 sections in the 2000 session. For each session, the profile data was collected soon after the rating panel. Problems in the power system of the profiler during the first session resulted in spreading the data collection over a two week period, and could had been responsible for the lack of obtaining valid data on all five repeat runs on some of the sections. For example, analyzing the data from the first session, it was noted that on one section only three repeat runs were valid, and three other sections only had four.

Originally, researchers planned to run multiple profiler vehicles with other sensors types over each section in order to determine if these additional sensors could help explain differences between the existing ride equation and today's raters. Accelerometers were placed over each of the four axles of the profiler vehicle, along with heading information from a 3-axis solid-state gyroscope. Modifications were made to the interface hardware and software so that the sensor data could be synchronized with the profile data collection. However, because of several factors including problems in the data collection and later project funding, the data were not used. Furthermore, it was questionable whether it was desirable to tie the PSI equation more closely with the specific profile-measuring device. Additional sensor data were not collected in the second session.

DATA PROCESSING PROCEDURES

As mentioned, two data sets, each consisting of profile for each of the test sections, were collected for the 1999 and 2000 sessions. In both sessions multiple runs were made for each section; however, in many cases, particularly for the 2000 session, it was necessary to make several continuous data runs that included more than one section. Before using this data for processing and analysis, the separate consecutive sections from each of the continuous data files were broken out. For example, consider a continuous data set consisting of three sections as illustrated in Figure 4.1.

Multiple Sections in One Data Collection

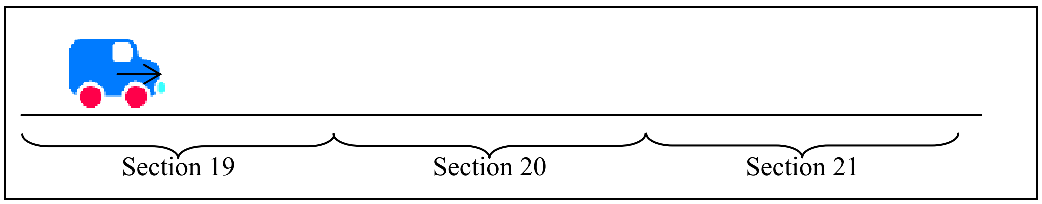


Figure 4.1 Multiple Sections in One Data Collection

The length of each separate section is 0.1 mile (160.9 m). To measure each of the 0.1-mile sections, the profiler is driven continuously throughout the three adjacent sections. (The zero separation between consecutive sections is only for this the example. Separation distances were typically from 0.3 to 2 miles). Each of the three sections are separated in accordance with the number of points collected, the interval length between successive points, and the total distance for each section. The MATLAB language was used to break out and rewrite the separated data files. The section number was used for each file and the extent indicated the repeat run number. For combined sets, such as the example, the file name would include the first and last section numbers. For example, if sections 21 through 23 were continuously collected, the file name assigned during data collection would be 2123.x, where x would indicate the repeat run number as shown in Figure 4.2. The MATLAB script would generate from the set of five continuous profile runs, 3 sets of five 0.1-mile data files for each of the three sections 21, 22, and 23.

Description of Section Separation

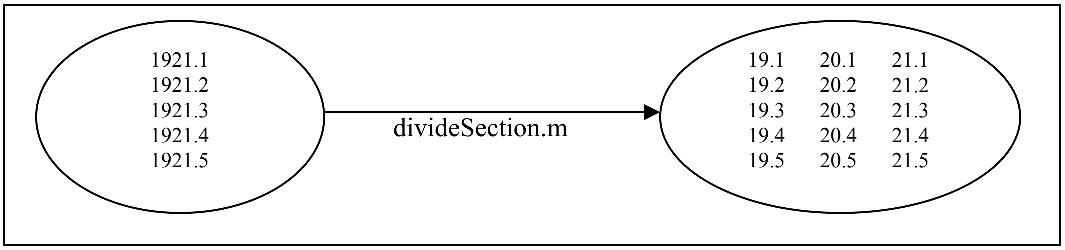


Figure 4.2 Description of Section Separation

The individual data sections along with the separated files were then used for computing the IRI and PSI as discussed in Chapters 2 and 3. The files, along with the MATLAB power spectrum and regression routines, are used in the next chapter for developing a new ride model based on the direct spectral or physical characteristics of the road profile.

DATA ANALYSIS AND THE CURRENT RIDE EQUATION

From the profile of the repeat runs of each rating section, IRI and the current Texas ride equation were computed. As discussed in Chapter 1, the current ride equation is directly related to IRI. Although this has several advantages over the original equation or even the one developed in the early 1980's, it was not computed as a regression with a rating panel. It does have the advantage that it can be used with a range of sampling intervals and measurement distances. Additionally, as discussed in Chapter 3, it does follow the panel ratings, overall. However, it does not directly relate to raters. For example, car class affects ratings, whereas IRI is not. Several different vehicle types were used by the 1999 rating panel. The selection was made knowing that people will rate roads differently depending on car classes. Thus, the classes selected were done so as to include the most commonly found classes used today. Figure 4.3 illustrates the average relationship noted between PSR and the Texas ride equation or PSI for each of these vehicle classes for the 1999 rating session.

Summary of PSR vs Rater Car Class

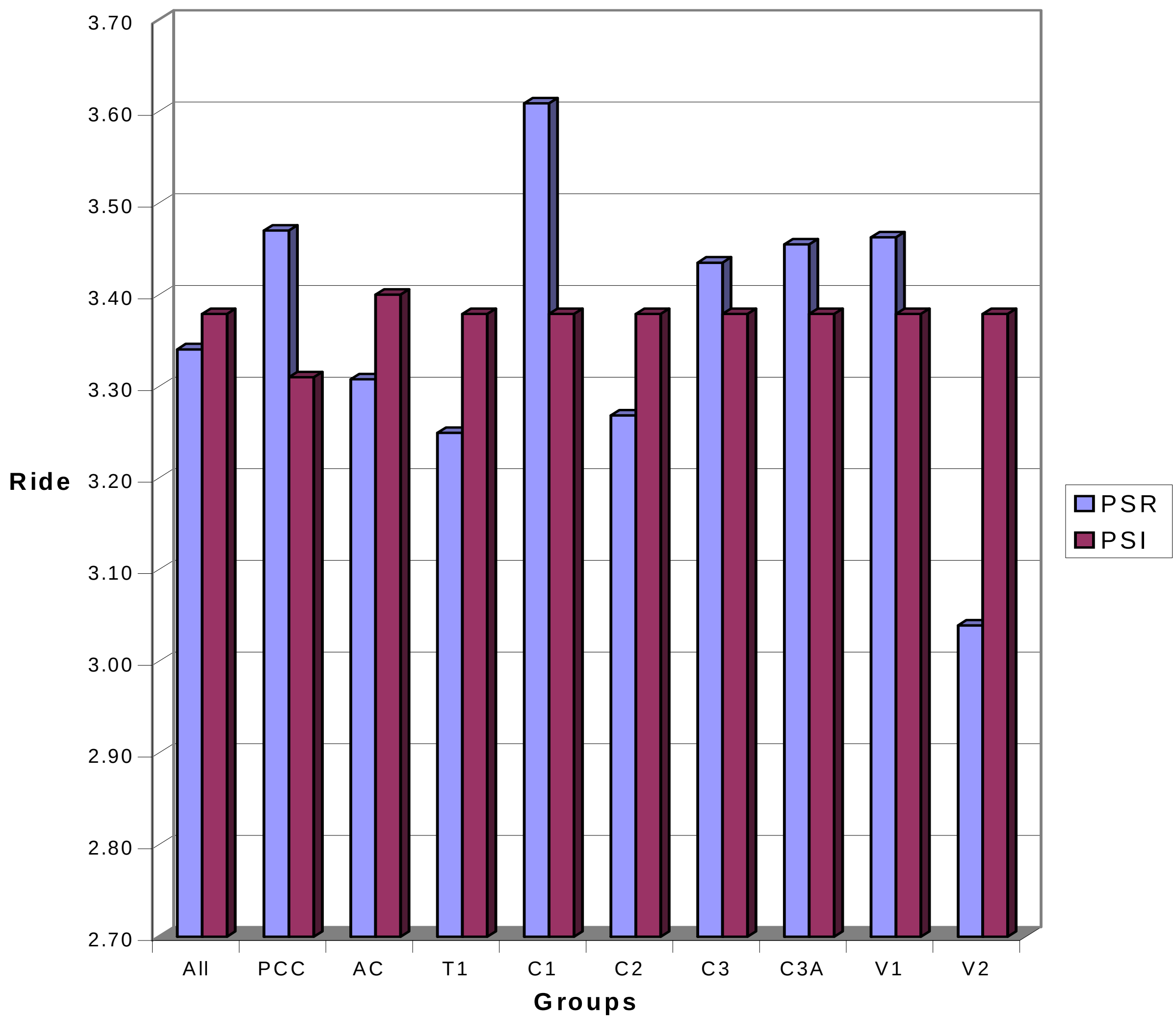


Figure 4.3 Summary of PSR vs Rater Car Class

Comparisons of PSI equations related to IRI

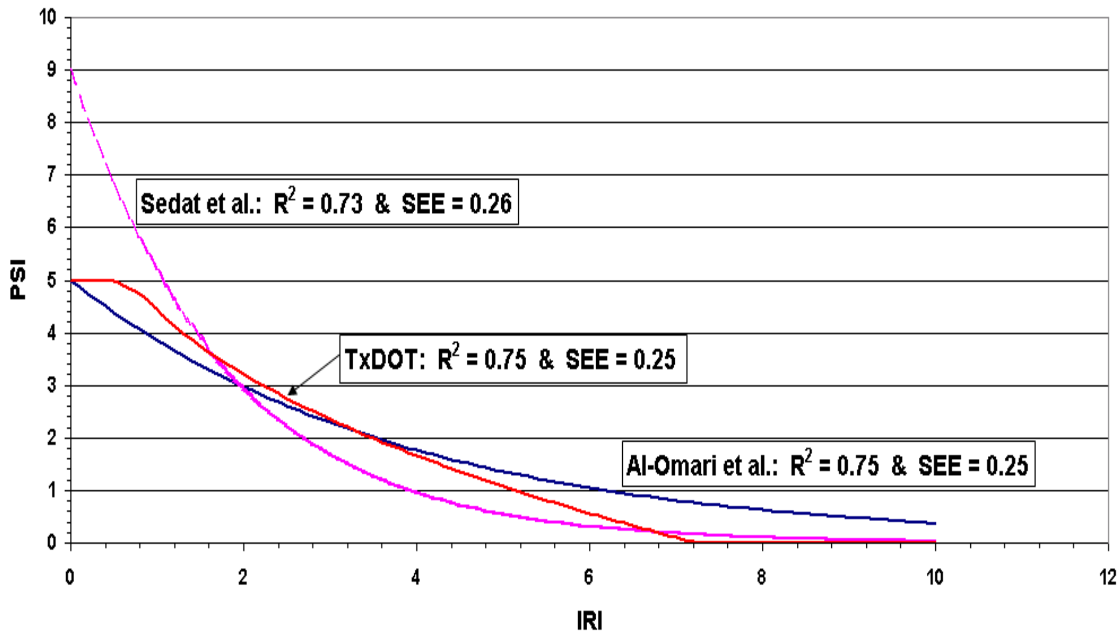


Figure 4.4 Comparisons of PSI equations related to IRI

The move away from the original ride equation computed in 1971 to the current equation was discussed in Chapter 1. Texas is not the only state to use a ride equation related to IRI. There have been other rating sessions performed, where a ride equation was directly related to IRI. The equations from two of the more recent studies (see Transportation Research Record #1435), one by Al-Omari, et al., and the other by Sedat, et al., were compared with the Texas ride equation as illustrated in Figure 4.4. As noted from the figure, a correlation between these two ride equations and the current Texas ride equation to the overall average of the 1999 and 2000 panel raters indicates that the current equation is as good as or better than those found in these other two studies.

It would have been useful if the first ride equation of 1970 could be used, but it was based on profile from the original analog profiler and with a different sampling interval. An attempt was made to apply this original equation to the 1999 and 2000 rating sessions but was not successful. It was just not possible to repeat the original conditions or parameters used. But it is worth noting that, during processing of the 1999 rating session profile data, that the same type of grouping of PSR readings to the spectral estimates occurred. This is shown in Figure 4.5. For this plot, the power spectrum is computed for each file after dividing into 64 segments with 32 frequency bands. Dropping the DC or zero frequency, this results in 16 frequency bands each with approximately 128 degrees of freedom per estimate. The files are grouped according to their respective PSR. The average power for each band and for each file are next computed. For instance, if there are 10 sections in a group with a PSR between 4.0 and 5.0, and each section had 5 runs, there would be 50 files in the group. Then the power found in each of the 16 frequency bands for each file would be averaged with their respective bands in the other files. The result of this averaging provides one file with a total of 16 bands each group. The plot is similar to the one that was done for the 1968 data. In fact, by examining this plot more closely, a better delineation between groups occurs at the lower wavelength bands. In the 1968 data, the power or amplitudes

Wavelength vs Power Spectral Rating Data – 1999 Data

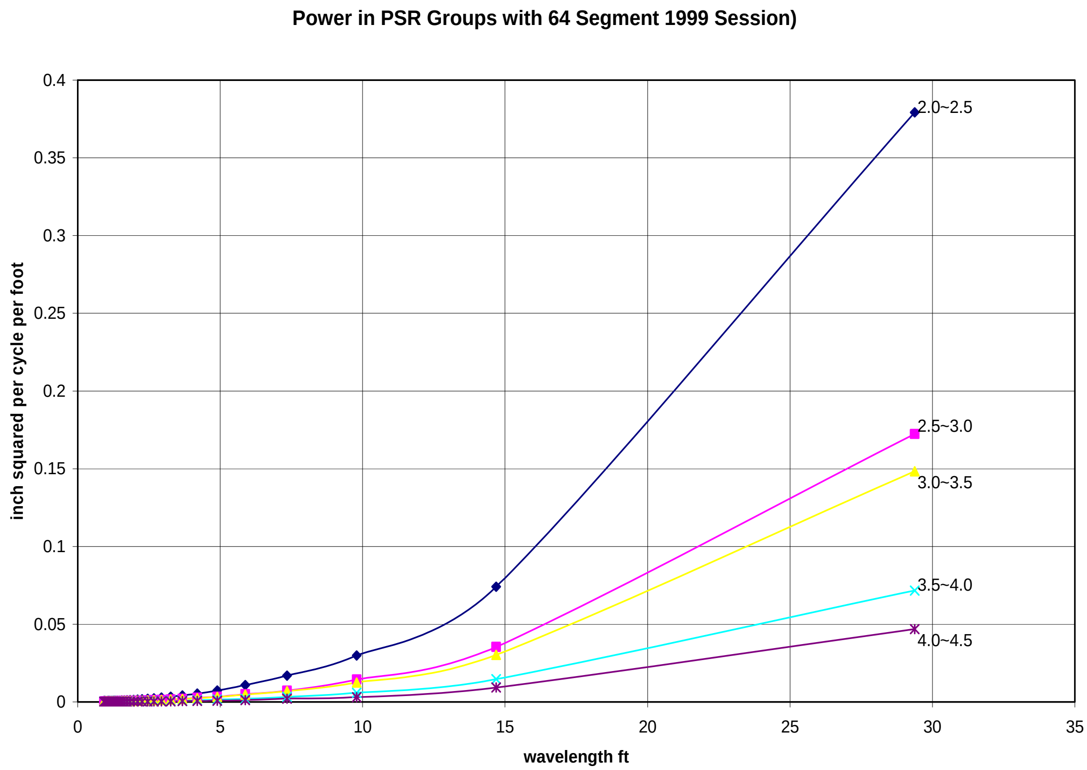


Figure 4.5 Wavelength vs Power Spectral Rating Data – 1999 Data

in these lower wavelengths or higher frequencies crossed one another. This does not occur in the new set. This would seem to imply that a similar or better equation than the original one might be found. The more distinct results are probably because of the more accurate and repeatable profile measuring system that is used now than was used or even available at the time the data was collected in 1968.

Because of this similar relationship, research focused on developing a model that directly related the spectral characteristics of road profile to the panel ratings. In the next chapter, such a new ride equation was developed from the 1999 and 2000 rating sessions. This new equation directly relates the road profile spectral density characteristics to the mean panel ratings. The model allows for a wider range of sampling and measurement intervals than the original 1970 model.

CHAPTER 5

NEW RIDE MODEL

PROFILE SPECTRAL CHARACTERISTICS

As discussed in Chapter 3, the differences between the predicted PSIs from the current ride equation and the mean panel ratings on a number of sections were found to be statistically significant. This is not surprising, considering the fact that the PSI equation is directly related to IRI and not the PSR. On the other hand, it was noted in Chapter 4 that the current equation is as good as or better than similar equations found in studies done in other states. Thus, if the goal is to have a ride equation based on IRI, the current TxDOT equation appears suitable. In the last chapter, it was noted though that the spectral characteristics of the profiles of the various sections were found related in a somewhat similar manner as was noted in the original ride study conducted in the late 1960's. The similarities are illustrated graphically in Figures 1.1 and 4.7. Figure 4.7 suggests that a model similar to the original one might be developed that could relate the spectral characteristics of road profile as measured by the new and better digital profilers to how the traveling public perceives ride in today's more modern vehicles. A similar analysis was also made of the data from the second session held in 2000 in the DFW area, focusing on concrete pavements

The original model had several problems. First, when using the Fast Fourier Transform (FFT) to computer the frequency components, the center frequencies were tied directly to the number of points and the sampling interval. Since the current profile estimates obtained from the Texas Profilers are related to the distance sensor on the profiler, this interval can vary depending on vehicle type and tire sizes. The center frequencies of the spectral estimates would hence be different for each vehicle, using a similar type model and would require interpolation or other similar adjustments when using the model. The sample interval of the original analog KJ Law Profiler and the later digital version used a fixed 0.5-foot interval. Secondly, the section length was fixed for 0.2 mile. PMIS currently uses 0.1 mile sections. Thus, it was decided that any new model should address these limitations.

The computation of the power spectral components for the 2000 rating session data was combined with the 1999 session and the results illustrated in Figures 5.1 and 5.2 for both 32 and 64 band computations. As noted in this figure, the power estimates for the PSR groups are distinguishable. Since the sampling interval was different, that is different profilers were used for the first and second sessions, the frequency bands were made identical by increasing the data file lengths by adding zeros to the next power of two, in conjunction with interpolation of the spectral estimates to account for the differences. Note that the more bands used, the lower the fundamental frequency and hence the longer the wavelength and the fewer the degrees of freedom for each spectral estimate.

MODEL DEVELOPMENT

The first approach used for developing a model was to simply repeat the process used in the original model described in Chapter 1, where the independent variables would be the power at the various bands and the dependent variable, PSR. In the original model, the power estimates for each wheel path, along with the cross spectral components were considered. This led eventually to the rather complicated model given in Chapter 1. The approach used for developing this model was to try and find a simpler, less complicated procedure. However, using the spectral estimates seemed attractive as it would be useful to relate the effects of certain frequencies on ride. A number of variations of variables and models were attempted but never resulted in satisfactory estimates any better than those found with the current IRI model.

Wavelength vs Power Spectral Rating 64 Bands for Combined Sessions

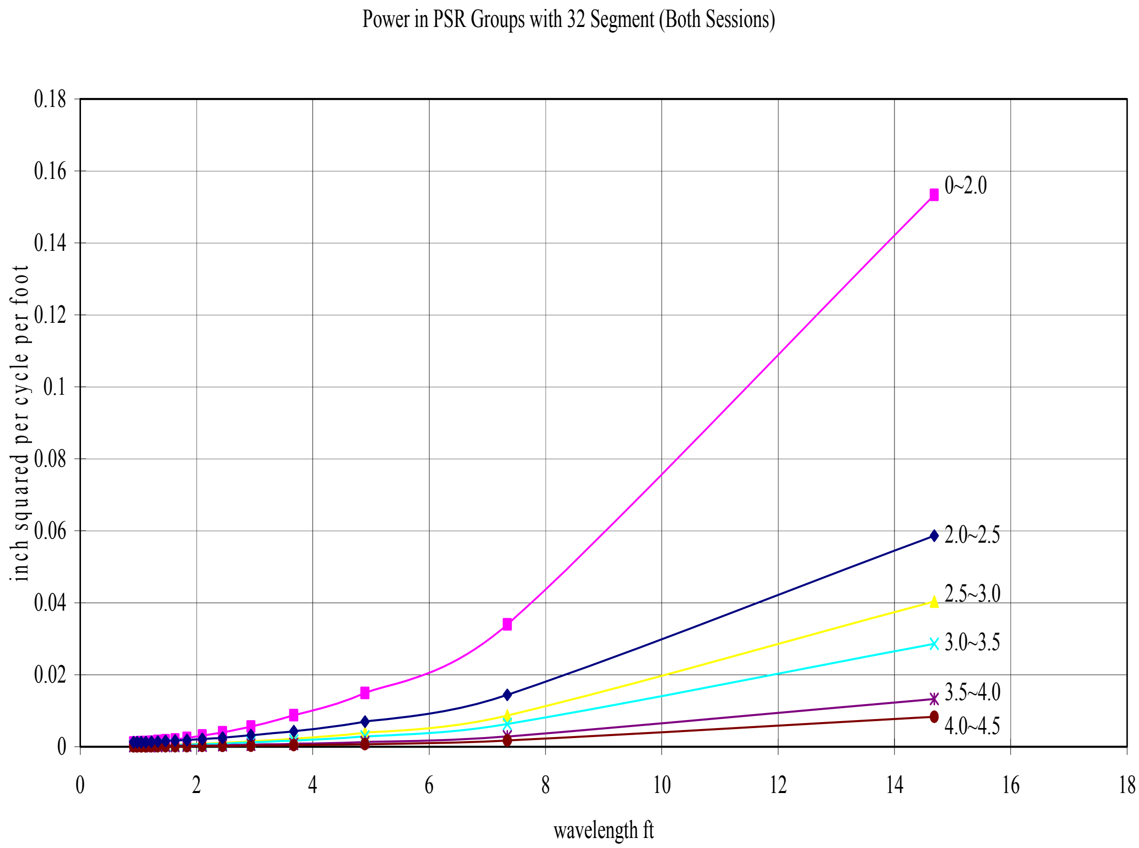


Figure 5.1 Wavelength vs Power Spectral Rating 64 Bands for Combined Sessions

Wavelength vs Power Spectral Rating 32 Bands for Combined Sessions

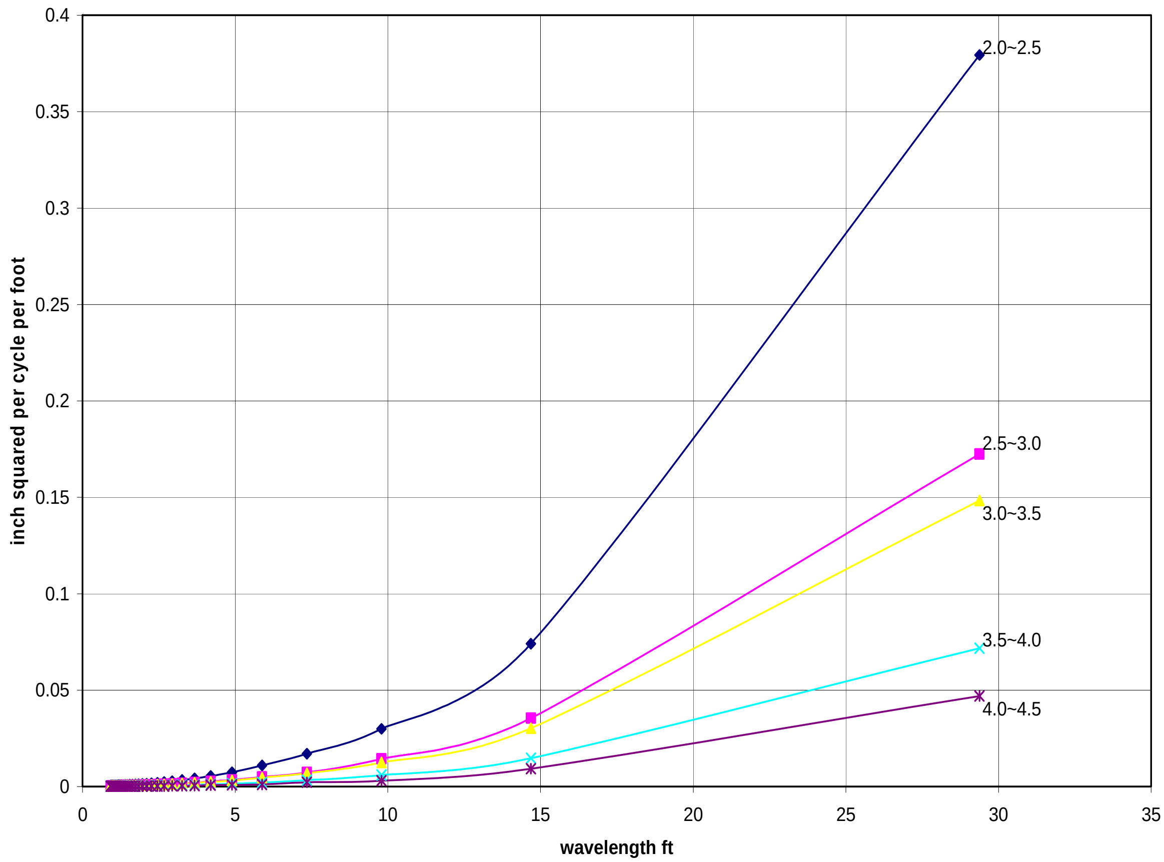


Figure 5.2 Wavelength vs Power Spectral Rating 32 Bands for Combined Sessions

After reviewing the correlations of the various frequency bands, it was decided to select the frequencies associated with a set of fixed, equally spaced wavelength bands, one to eight meters.

This set of frequencies would cover those that are affected by the ASTM ride number, as well as the profilograph. For these frequencies, the longest wavelength is 8 meter or about 26 feet.

The independent variables, the power spectral estimate for each run, are calculated and then averaged over the same section. These estimates for each of the eight frequencies are computed directly from the Discrete Fourier Transform (DFT) in accordance with the equation 5.1:

$$X(f) = \sum_{k=0}^{N-1} x_k e^{-j2*pi*k*f*t} \quad , 0 \le f \le 0.5/T \qquad (5.1)$$

where N = 64, f = 1/8, 2/8, .. 1 cycles/meter frequencies, and X(t) is the spectral component associated with the frequency.

The final model selected is of the form:

$$\text{PSI} = 5\, e^{-\sqrt{\alpha P}} \qquad (5.2)$$

where: PSI denotes the predicted PSR and αP can be described as follows.

$$\alpha P = \alpha_1 P_1 + \alpha_2 P_2 + ... + \alpha_8 P_8$$

and where each P term represents a power spectrum for each frequency component. The set of "α" coefficients are derived from the regression analysis.

Table 5.1 provides the PSR readings along with the predicted PSI values from the new (equation 5.2), and current models. The standard deviation of the residuals for the new model is 0.21. The advantage of computing the direct form of the DFT components as opposed to the FFT by this procedure is that equation 5.1 can be used to compute any set of DFT components of the profile, whether or not the frequencies are equally spaced in the frequency domain. Also, only eight spectral components need to be computed. The power of these complex X(t) frequency components are then computed by and averaged over the 0.1 mile data set.

MATLAB was used to perform the analysis. To determine the eight coefficients, a regression analysis is performed on the eight power spectral components with PSR values as the independent variable. The MATLAB script, “regress.m” is used to produce several statistics including the coefficients for the model and R^2 of the analysis. The regression analysis is performed with 95% confidence for the coefficients. In order to use the multiple linear regression procedures, it was necessary to transform the PSR variable before regression to:

$$PSR' = \left[-\ln\left(\frac{PSR}{5}\right) \right]^2 . \tag{5.3}$$

For the regression, a subset of the combined 1999 and 2000 profile data sets were selected. A subset was selected as indicated in Table 5.1 so that the remaining sections could be used to determine how well the model would work on data not used in the model development. The R square of the regression was found to be 0.87. The eight, α, coefficients found, beginning with the first frequency, 0.125 cycles per meter are as follows:

-2.36E+06
6.15 E+06
-5.80E+06
2.42E+06
-4.48E+05
3.36E+04
-5.80E+06
-6.79E+01

Figure 5.3 graphically displays the values in Table 5.1 for each of the sections used in the combined rating session for the model development. Figure 5.4 provides a plot of the regression residuals also shown in Table 5.1. As noted in Figure 5.3, the new model more closely follows the panel ratings than does the IRI to PSI model currently implemented by TxDOT.

PSR vs PSI NEW and CURRENT MODEL

Section	PSR	New Model	Current PSI
2	3.15	3.11	3.34
3	2.92	3.05	3.14
4	3.61	3.50	3.84
5	3.53	3.12	4.20
6	3.14	3.22	3.58
7	2.68	2.89	2.38
8	2.84	3.22	3.00
9	2.27	2.28	1.96
10	3.18	3.25	3.20
11	3.22	3.14	2.98
12	2.34	2.66	2.18
13	2.22	2.18	1.74
14	3.58	3.27	3.28
15	3.52	3.28	3.10
16	3.34	3.27	2.84
17	2.78	2.71	2.26
18	3.55	3.52	3.34
19	2.38	2.39	2.16
20	3.48	3.56	3.32
21	3.44	3.45	3.50
22	3.57	3.60	3.56
23	3.50	3.47	3.58
24	3.13	3.21	3.12
25	3.04	2.98	2.97
26	3.06	2.94	3.22
27	3.31	3.08	3.20
28	2.64	2.84	3.18
29	3.52	4.02	3.72
30	3.45	3.45	3.44
31	3.90	3.84	4.30
32	3.47	3.39	3.76
33	2.47	2.27	2.06
34	2.21	2.52	2.14
39	3.73	3.67	4.10
40	3.65	3.44	4.30
41	3.77	3.68	4.14
42	3.81	3.78	4.24
44	4.05	3.98	4.36
45	3.93	3.87	4.40

46	3.90	3.86	4.30
47	3.39	3.26	3.50
48	3.69	3.82	4.20
49	3.51	3.39	3.64
50	3.85	3.58	4.12
51	3.97	3.85	4.22
52	3.90	3.96	4.52
53	3.28	3.16	3.06
54	3.64	3.33	3.56
55	3.36	3.30	3.20
56	3.79	3.32	3.56
57	3.50	3.36	3.31
58	3.03	2.95	2.98
61	4.04	3.69	4.06
62	3.32	3.12	3.16
63	3.42	3.28	3.36
64	3.53	3.68	3.30
65	3.59	3.55	3.44
66	3.11	3.17	2.48
67	3.39	3.28	3.60
68	3.09	3.28	3.28
69	3.53	3.93	3.54
70	3.48	3.43	3.72
71	3.53	3.87	4.00
72	2.57	2.51	2.82
73	3.51	3.77	4.22
74	3.38	3.23	3.50
75	2.94	2.77	2.82
76	3.59	3.28	3.84
77	3.13	3.23	3.48
78	2.55	2.65	2.74
79	3.46	3.83	4.18
80	2.68	2.62	3.00
81	3.52	3.15	3.12
82	1.92	1.93	1.62
83	3.91	3.82	4.40
84	3.85	3.78	4.14
85	2.87	3.15	3.55
86	2.84	3.33	3.44
90	3.57	3.55	3.77
98	2.86	2.85	2.84

99	3.52	3.78	4.23
100	3.63	3.77	4.13
101	2.54	3.06	3.22
102	2.04	2.08	2.98
103	2.84	2.95	3.47
104	3.75	3.72	4.15
105	3.53	3.24	4.28
106	3.11	2.68	3.14
107	3.43	3.11	3.30

Table 5.1 PSR vs PSI New and Current Model

The two models differ the greatest on the upper and lower ends of the PSR ratings, i.e., the newer model rates the smoother roads rougher and the rougher roads smoother than does the current model. Note, however, that this is also the case when comparing the panel ratings to the current model. That is, the current model predicts readings for smooth roads greater and rough roads rougher than the panel ratings.

PSR vs. PSI of Two Models

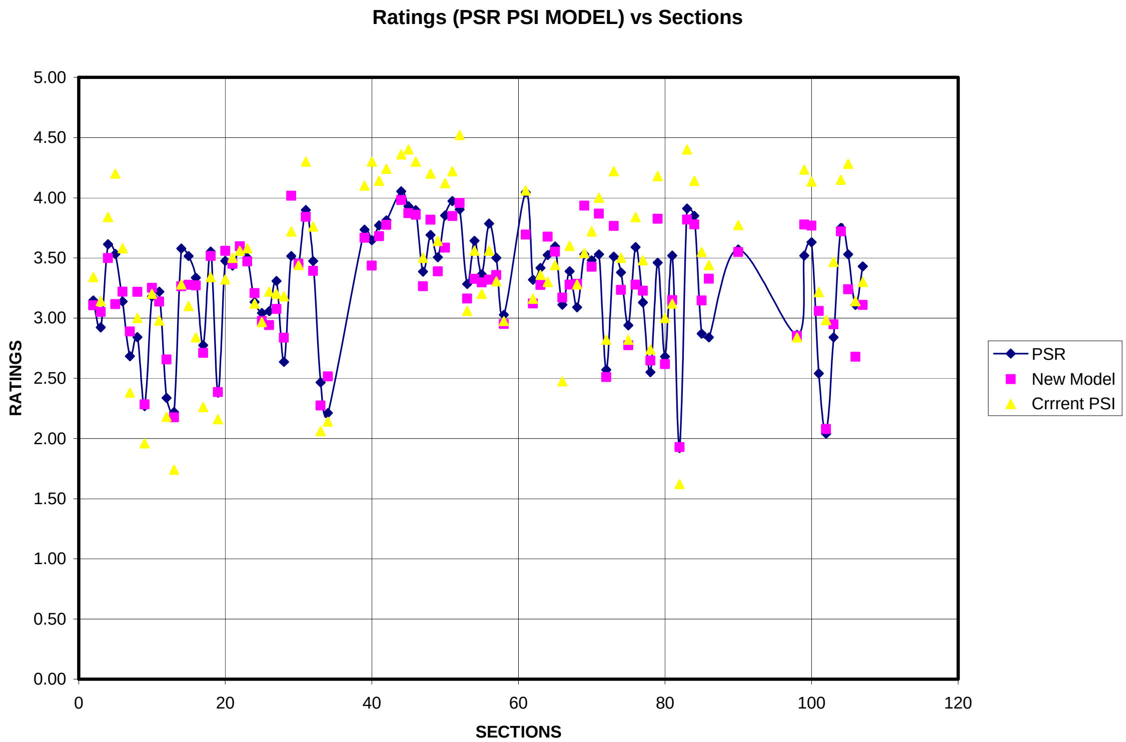


Figure 5.3 PSR vs. PSI of Two Models

Residuals of Two Models

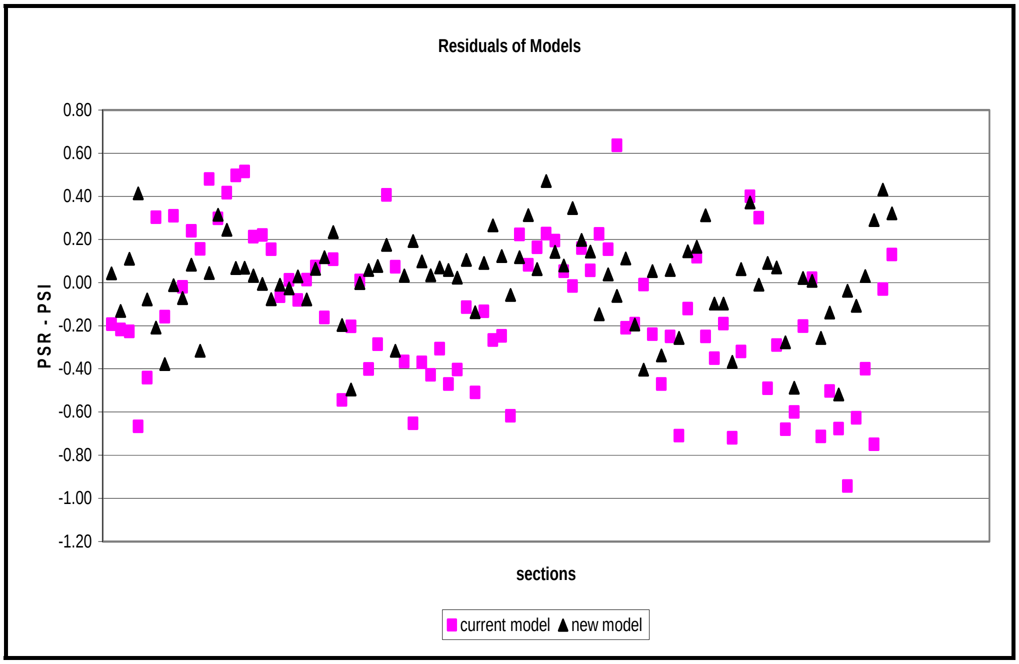


Figure 5.4 Residual of two models

PSI COMPUTATION PROCEDURES

MATLAB was used for the regression and also used to compute the power spectral estimates and PSI for each of the eight frequency components in accordance with the following steps:

1. The vector freq is set to the 8 frequencies

freq = [1/8 1/7 1/6 1/5 1/4 1/3 1/2 1];

2. The rectangular window is selected for the transformation (note: little differences were found between this, the Blackman, Hanning or Hamming windows). The power values are averaged over 64 points with non-overlapping intervals.

```
iwindo = 1;  %rectangular
overlap = 0; %no overlap
```

3. The profile data file is obtained and placed into the left and right wheel path arrays, x, and y for the, num, number of points, where delta is the sample interval and num = 528 / delta. For the TTI and DFW profile data sets, the script is executed each time because the interval lengths of these two data sets are different: 0.1269 m for TTI and 0.1399 m for DFW.

```
fid=fopen(num2str(str2num(fin)));

[a,count]=fscanf(fid,'%g %g',[2,inf]);


for i=1 : num
  x(i)=a(1,i)*0.001;    %rightside
  y(i)=a(2,i)*0.001;    %left side
end;
```

4. The differences between adjacent points are computed (derivative of x and y with respect to distance) to help offset non-stationary effects of the profile data. The average left and right profile values are obtained and placed in the array temp.

```
for i=1: num-1
  diff_x(i) = x(i) - x(i+1);
  diff_y(i) = y(i) - y(i+1);
end;

temp = (diff_x+diff_y) / 2;
```

5. The number of non-overlapping intervals (isegmts) are determined, the data are windowed, the spectral components are computed (temp4) in accordance with equation 5.2, and the average power values are computed and placed in the pds array.

```
for isegmt=0:nsgmts-1
temp2=temp((nshift*isegmt+1):(nshift*isegmt+NDFT));
[temp3,tsv]=spmask(temp2(1:NDFT),iwindo);
temp4 = spcomp(temp3(1:NDFT), freq*delta);
pds=pds+temp4(1:8).*conj(temp4(1:8))/(tsv*nsgmts);
end
```

where,

nsgmts are the number of non-overlapping segments,
NDFT is the number of spectral components (8),
delta is the distance between successive samples or sample interval,
tsv is the window correction factor,
spcomp is the function routine to compute equation 5.2, and
conj the complex conjugate function routine for the power computation.

6. The 8 coefficients are placed into the array coef and the PSI computed in accordance with equation 5.4.

```
temp_X = psd*coef;
PSI = 5*exp(-temp_X .^ 0.5)
```

MODEL VERIFICATION

As noted above, several sections from the 1999 and 2000 rating sessions were not used for model development. Instead, these were used to determine how well the model works on other profile sections. The four asphalt control sections 35 to 38 from the 1999 session and the asphalt and concrete sections 22 to 31 from the 2000 sessions were selected for the verifications. For each section, researchers determined the PSI from the current model and used the procedures described above to compute the PSI for the new model. The results are indicated in Table 5.2 and graphically illustrated in Figures 5.5 and 5.6. As can be noted from both the figures and table, the new model matched the PSR of the raters better than did the current model. A second set of profile data (Austin Control Sections) was collected with a different profiler having a 0.1207 m sample interval in Austin on July 12th, 2001. Figure 5.7 shows the result of the computation based on the two models for the Austin data. Although no PSR readings were available, it is noted that the same trend existed, where the smoother sections are rated higher, and the rougher sections lower by the current model than the new model.

Model Verification Runs

Session	Section	PSR	New Model	Old Model	New Model Res.	Old Model Res.
2000	22	3.57	3.50	3.56	0.07	0.01
2000	23	2.78	3.12	2.84	-0.34	-0.06
2000	24	3.57	3.48	3.77	0.09	-0.20
2000	25	3.3	3.90	3.79	-0.60	-0.49
2000	26	3.35	3.00	3.13	0.35	0.22
2000	27	3.33	3.09	3.30	0.24	0.03
2000	28	2.94	2.74	3.20	0.20	-0.26
2000	29	2.82	3.04	3.06	-0.22	-0.24
2000	30	2.36	2.49	2.64	-0.13	-0.28
2000	31	1.89	2.03	1.80	-0.14	0.09
1999	35	3.4	3.16	2.90	0.24	0.50
1999	36	2.7	2.28	2.10	0.42	0.60
1999	37	3.66	3.60	3.40	0.06	0.26
1999	38	4.03	4.34	3.95	-0.31	0.08
				mean	0.00	0.02
				std err	0.29	0.31

Table 5.2   Model Verification Runs

Comparisons of Current and New Model to Verification Section

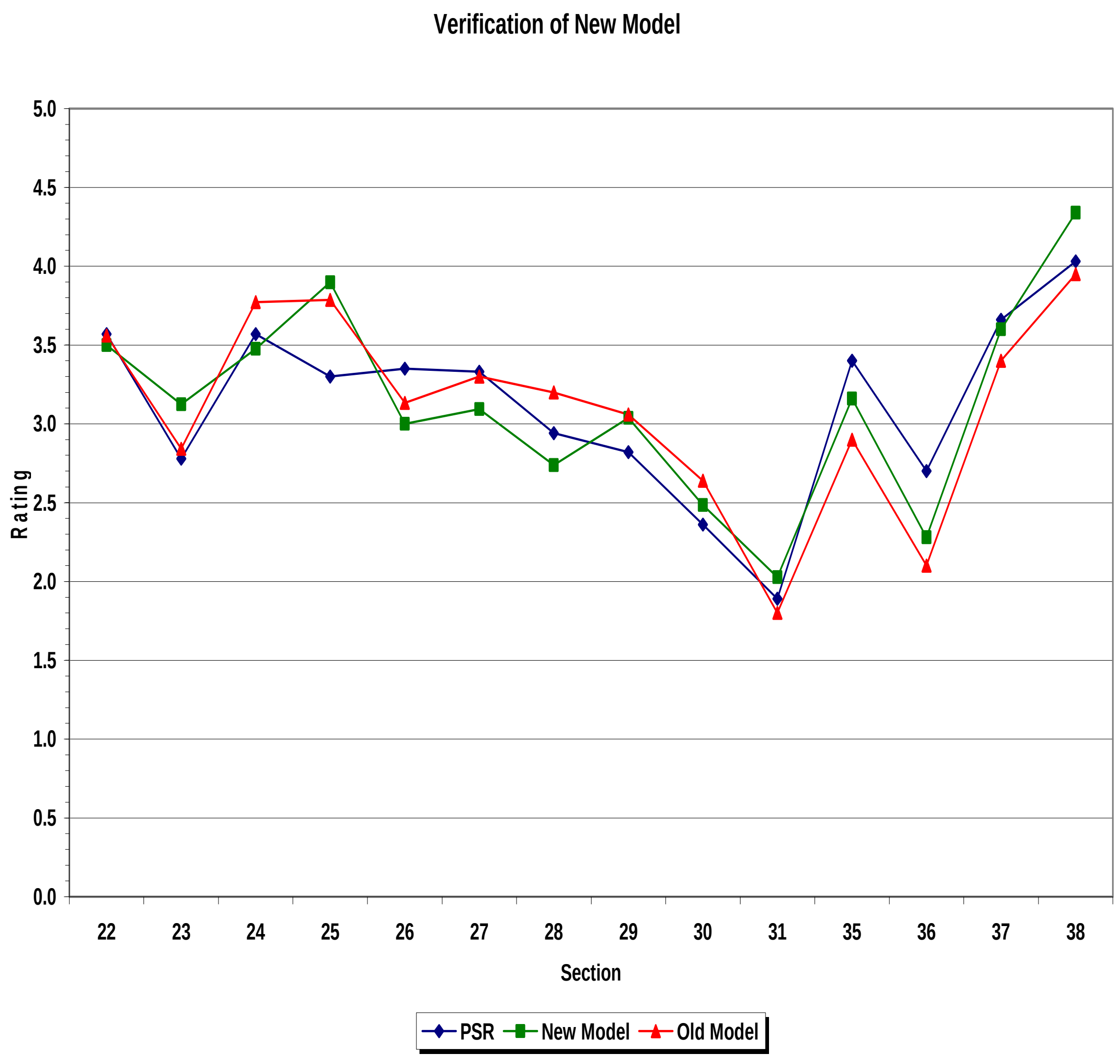


Figure 5.5 Comparisons of Current and New Model to Verification Sections

Comparisons of Residuals for Current and New Model for Verification Sections

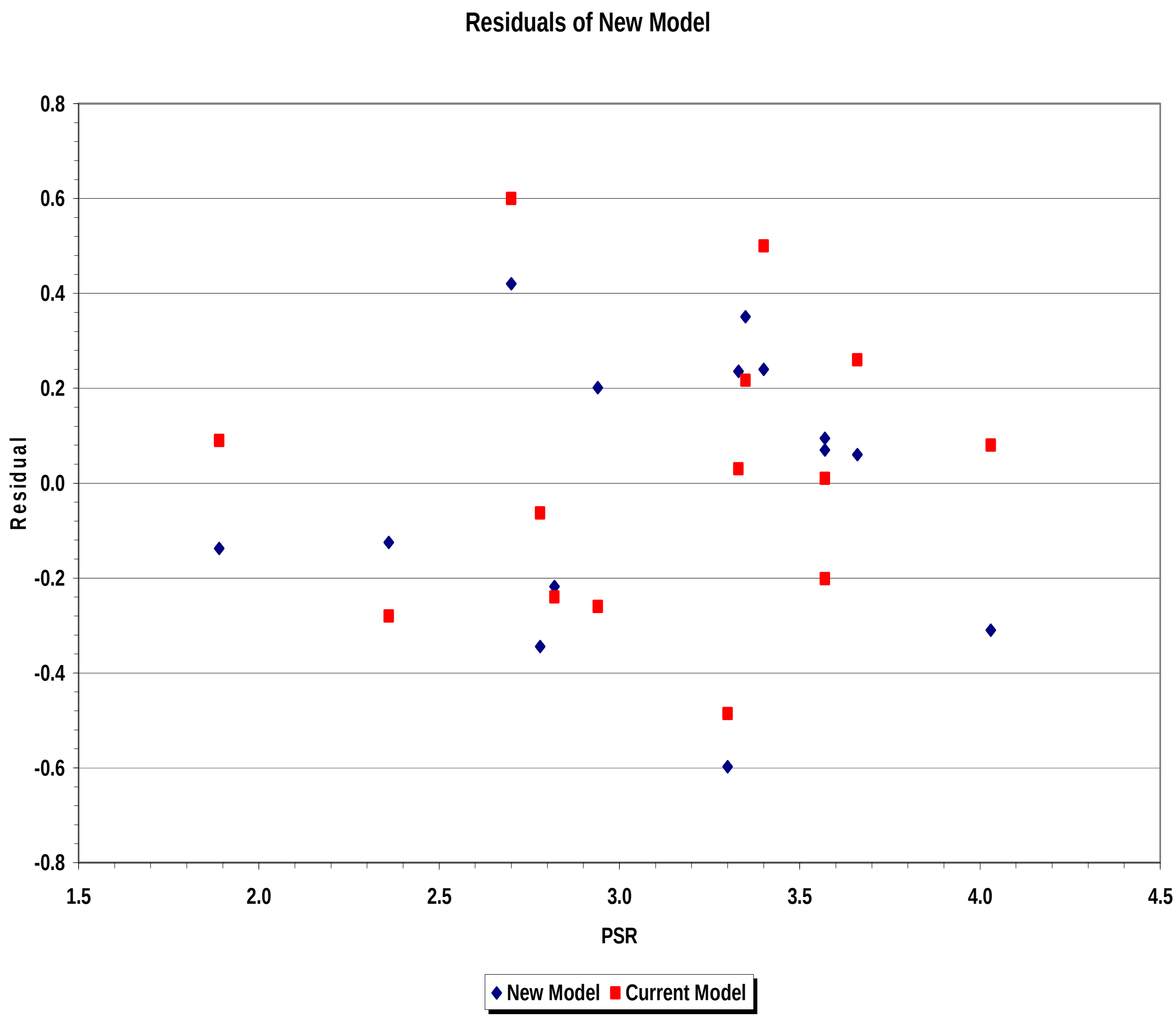


Figure 5.6 Comparisons of Residuals for Current and New Model for Verification Sections

Comparisons of PSI for Current and New Model for Austin Test Sections

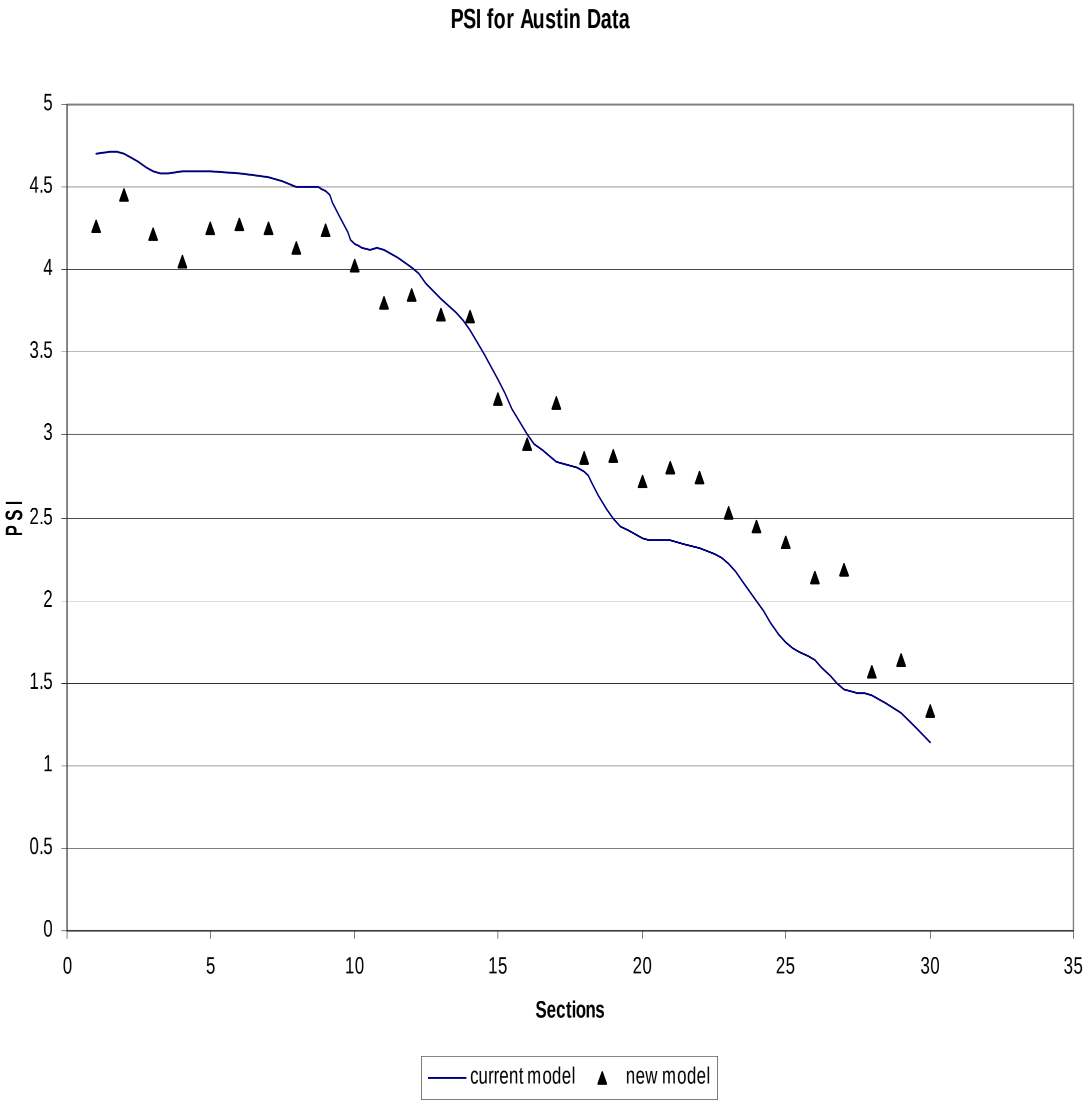


Figure 5.7 Comparisons of PSI for Current and New Model for Austin Test Sections

CHAPTER 6

SUMMARY AND CONCLUSIONS

SUMMARY

TxDOT funded a research project with the University of Texas at Arlington (UTA) and the Texas Transportation Institute (TTI) to investigate the adequacy of the current ride equation to estimate ride quality under present-day conditions. The existing equation for determining PSI from measured profile is based on ride measurements obtained from a rating session conducted in the late 1960s. Since its original development over 30 years ago, a number of changes have occurred that required a re-evaluation of the current equation.

To accomplish this objective, the researchers and project monitoring committee conducted two ride surveys on asphalt and Portland cement concrete pavements for the purpose of collecting user opinions of ride quality with which to evaluate the existing equation. This report describes the research that was performed to evaluate the current ride equation to determine if it is still suitable for today's usage. A historical overview of ride equation developments in Texas was discussed in Chapter I. Chapters II and III provided details and results of two ride surveys conducted in 1999 and 2000. Data collection and processing procedures were described in Chapter IV. The development of a new ride equation was then provided in Chapter V. The current ride equation relates ride directly to the International Roughness Index and actually has nothing to do with how the traveling public views pavement rideability. However, the two are closely related. The ride equation described in Chapter V directly relates the panel ratings to the physical characteristics of the road profile.

CONSIDERATION OF FUTURE APPLICATION OF NEW RIDE STATISTIC IN TXDOT'S SMOOTHNESS SPECIFICATION

The Texas Department of Transportation intends to replace the existing profilograph-based smoothness specification with one that is based on surface profiles beginning in 2003. A draft of the new ride specification has been approved by TxDOT's specification committee, and forwarded to the paving industry for its review. Under the proposed specification, initial surface smoothness shall be evaluated using the International Roughness Index determined from profiles measured with inertial profilers. The specification stipulates that the average of the IRIs determined on both wheel paths shall be used to evaluate the initial smoothness of each 0.l-mile section. Bonuses or penalties are then assessed based on the average IRIs. Figure 6.1 shows the pay adjustment schedules in the proposed ride specification. The engineer specifies in the plans the schedule to be used on a given project.

With the development of the new ride equation presented in this report, it is of interest to examine the application of the Present Serviceability Index for evaluating initial surface smoothness. To convert the pay adjustment schedules shown in Figure 6.1 and establish equivalent schedules based on PSI, researchers examined the relationship between PSI and IRI using the profile data collected from the 1999 and 2000 ride surveys. Figure 6.2 plots the average PSIs and IRIs for the sections used to develop the new ride equation. Researchers used the following model to fit the data points shown in the figure:

$$PSI = 5\, e^{-(\alpha\, IRI)^{\beta}} \tag{6.1}$$

Note that the equation is of the same form as the model used to predict PSI from frequency components of the surface profile. Using regression, the coefficients of Eq. (6.1) were determined to be:

- $\alpha = 0.003051$, and
- $\beta = 0.827981$

with the average IRI expressed in units of inches per mile. Figure 6.2 shows the fitted curve to the PSI and IRI data based on Eq. (6.1). The root-mean-square-error associated with the predicted PSIs is 0.213. The equation fits the data quite reasonably, as may be observed from

Figure 6.2. Researchers used Eq. (6.1) to determine equivalent pay adjustment schedules based on PSI. The resulting schedules are given in Figure 6.3. This figure may be used in an alternative smoothness specification based on PSI. Researchers recommend that TxDOT consider using the new ride statistic to evaluate initial surface smoothness.

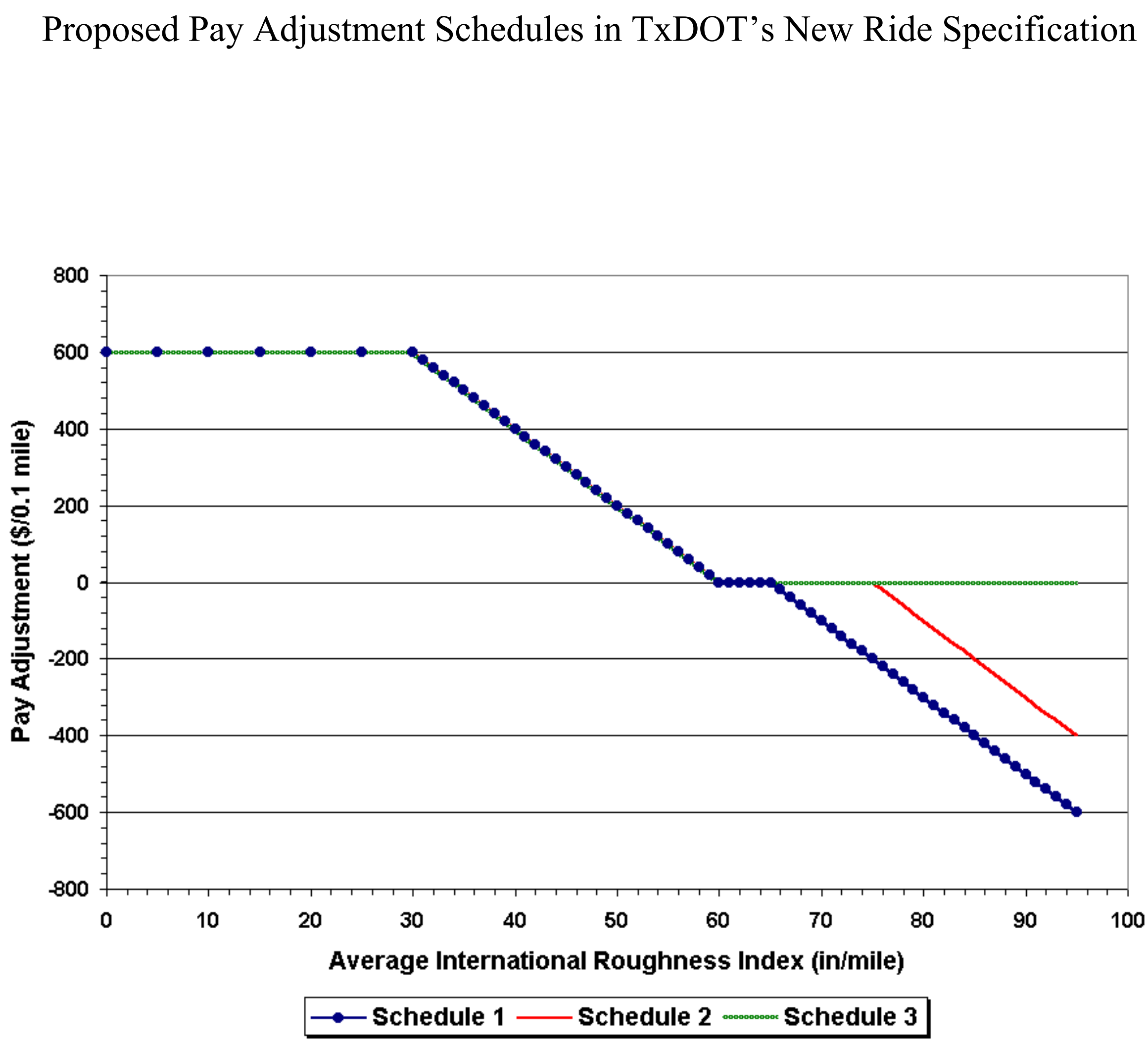


Figure 6.1 Proposed Pay Adjustment Schedules in TxDOT's New Ride Specification.

Relationship between PSI from New Model and IRI

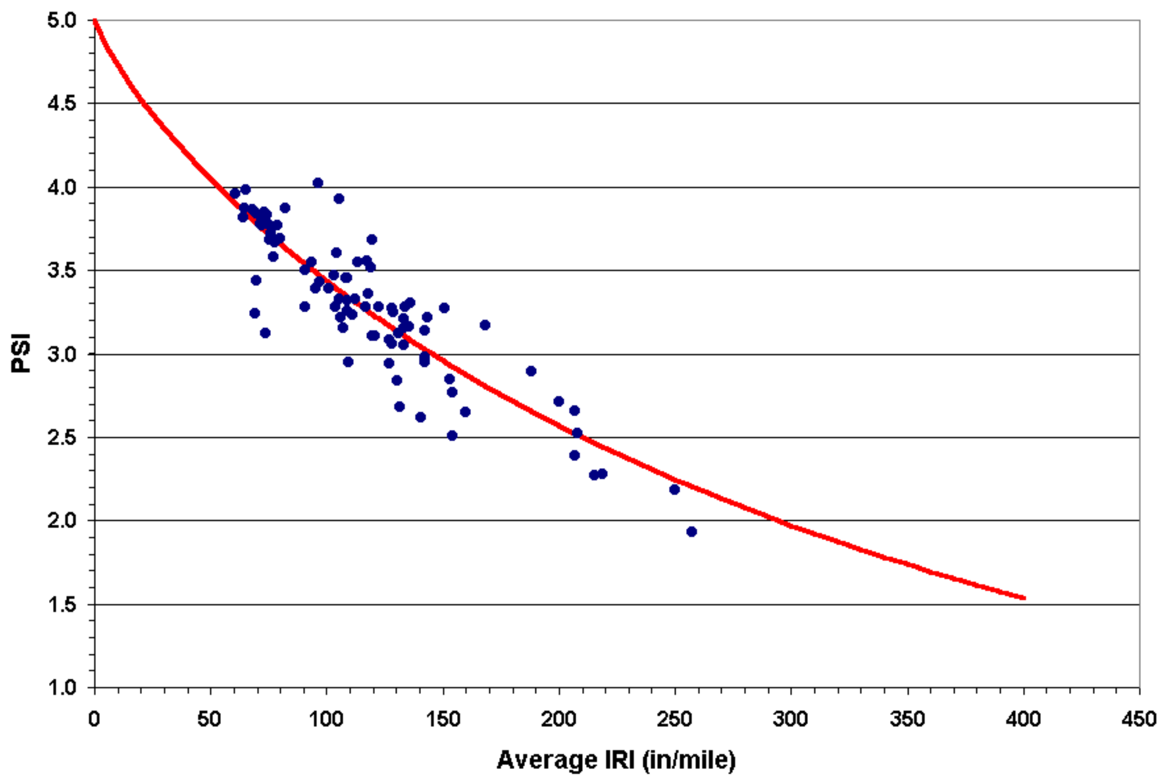


Figure 6.2 Relationship between PSI from New Model and IRI.

Alternative Pay Adjustment Schedule Based on PSI

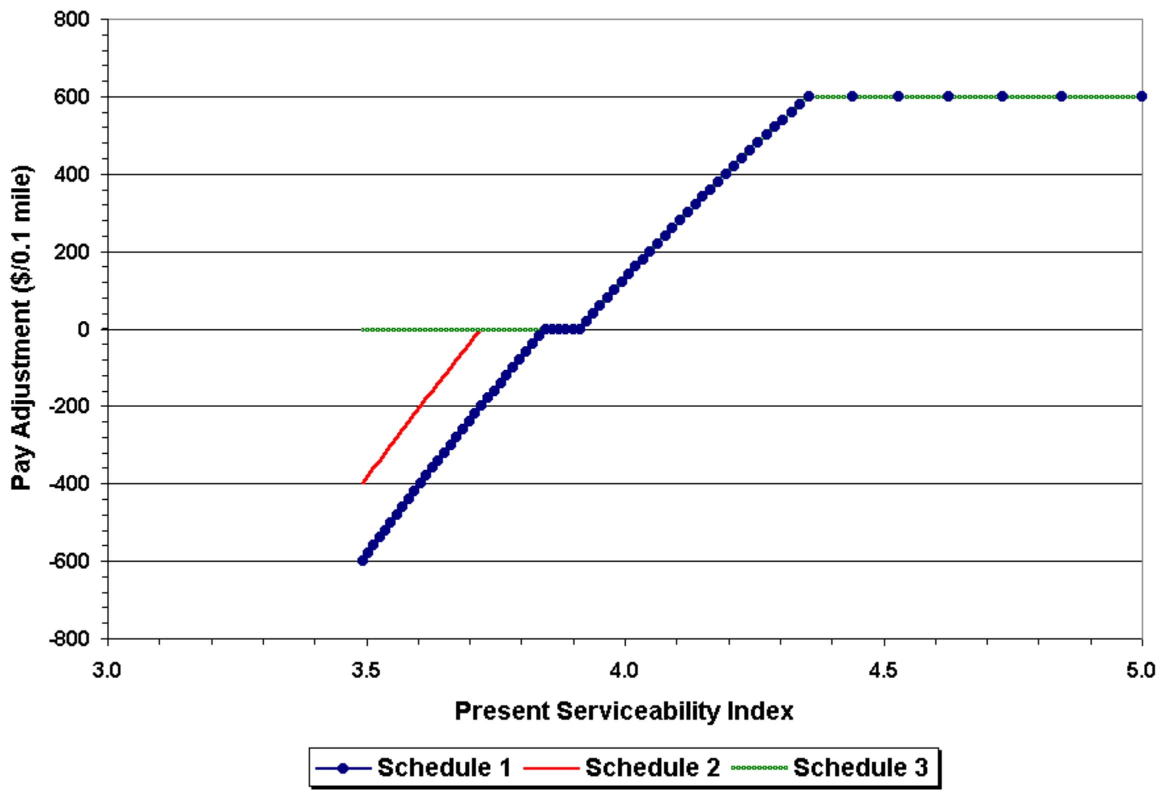


Figure 6.3 Alternative Pay Adjustment Schedule Based on PSI

CONCLUSIONS

Following is a summary of the findings and conclusions from this research.

1. The panel ratings from both the 1999 and 2000 surveys appear to be spatially independent even though the sections were rated in a certain sequence. In view of this finding, the evaluation of main effects and interactions between the study variables was accomplished using the usual *F*-tests and *t*-tests that are based on the assumption of a linear model.

2. The effects of the following factors on subjective ratings of ride quality were found to be significant at a confidence level of 95 percent or higher:

   a. Section roughness, which showed a noticeable correlation with the panel ride ratings;
   b. Vehicle type;
   c. The individual rater.

3. Using the data from both surveys, there was inconclusive evidence to support the need to include a blocking factor for pavement type in the ride equation.

4. The ratings from both surveys indicate that the existing ride equation tends to overestimate user opinions of ride quality. This finding points to the need for calibrating or revising the existing ride equation to improve the agreement with the panel ratings from the surveys conducted.

5. The current equation that directly relates ride to IRI is as good as or better than models found in two other independent studies in other states.

6. A ride model was developed that was more closely related to panel ratings and that related panel ratings directly to the physical or spectral characteristics of road profile. The model is ready for field evaluation.

REFERENCES

Al-Omari, B., and M.I. Darter, *Relationships Between International Roughness Index and Present Serviceability Rating,* Transportation Research Record 1435, Transportation Board, Washington, D.C., 1994, pp 130-136.

Clark, C. T., and L. L. Schkade. *Statistical Analysis for Administrative Decisions*. South-Western Publishing Co., Cincinnati, Ohio, 1979.

Gulen, S., R. Woods, J. Weaver, *Correlation of Present Serviceability Ratings with International Roughness Index,* Transportation Research Record 1435, Transportation Research Board, Washington, D. C., 1994, pp 27-37.

Ifeachor, Emmanuel C., Jervis, Barrie W., *Digital Signal Processing: A Practical Approach*, Addison-Wesley, New York, NY, April, 1993.

Least Squares Linear Regression, Department of Chemical Engineering MATLAB Tutorial, Website accessed on July 6th, 2001.

Mason, R. L., R. F. Gunst, and J. L. Hess. *Statistical Design and Analysis of Experiments With Applications to Engineering and Science*. John Wiley & Sons, Inc., New York, 1989.

Mays Ride Meter Booklet, Rainhart Company, Austin,Texas, 1972.

McKenzie, David W., W. Ronald Hudson, and C. E. Lee, *The Use of Road Profile Statistics for Maysmeter Calibration*, Research Report 251-1, Center for Transportation Research, The University of Texas at Austin, August 1982.

Nair, S. K., W. R. Hudson, and C. E. Lee. *Realistic Pavement Serviceability Equations Using the 690D Surface Dynamics Profilometer*. Research Report 354-1F, Center for Transportation Research, The University of Texas at Austin, Austin, Texas, 1985.

Roberts, F. L., and W. R. Hudson. *Pavement Serviceability Equations Using the Surface Dynamics Profilometer*. Research Report 73-3, Center for Highway Research, The University of Texas at Austin, Austin, Texas, 1970.

SAS/STAT User's Guide - Release 6.03 Edition. SAS Institute Inc., SAS Campus Drive, Cary, North Carolina, 1988.

Stearns, Samuel D., David, Ruth A., *Signal Processing Algorithms in MATLAB*, Prentice Hall, Upper Saddle River, NJ, 1996.

The AASHO Road Test: Report 5 – Pavement Research, HRB Special Report 61-E, Highway Research Board, National Academy of Sciences, Washington, D. C., 1962.

Walker, R.S. and W. Ronald Hudson, *The Use of Spectral Estimates for Pavement Characterization*, Research Report 156-2, Center for Highway Research, The University of Texas at Austin, August 1973.

Walker, Roger S., and W. R. Hudson, *A Correlation Study of the Mays Road Meter with the Surface Dynamics Profilometer*, Research Report 156-1, Center for Highway Research, The University of Texas at Austin, February 1973.

Walker, Roger S., Freddy L. Roberts, and W. R. Hudson, *A Profile Measuring, Recording, and Processing System,* Research Report 73-2, Center for Highway Research, The University of Texas at

APPENDIX A

DRIVER BRIEFING NOTEBOOK USED IN 1999 RIDE SURVEY

TEST SITES

Table A1. List of Test Sites Where Rating Sections Were Established.

Highway	Lane	Direction	Number of Sections	Milepost Limits	Posted Speed Limit (mph)	Surface Type
SH47	R1	Southbound to College Station	4[A]	413.2 to 414.5	70	Asphaltic Concrete
	L1	Northbound to Caldwell	4[B]	414.2 to 412.9	70	Asphaltic Concrete
FM2154	K1	Southbound to Navasota	20	622.6 to 637.4	Varies from 55 to 70	Asphaltic Concrete
SH30	K1	Eastbound to Huntsville	9	629.1 to 632.9	70	Asphaltic Concrete
IH45	R1	Northbound to Dallas	9	147.5 to 151.6	70	Asphaltic Concrete
	L1	Southbound to Houston	5	150.4 to 148.1	70	Asphaltic Concrete
Loop 336	K6	Eastbound to IH45 junction	6	677.7 to 674.3	55	Portland Cement Concrete
	K1	Westbound to SH105 junction	6	674.3 to 677.9	55	Portland Cement Concrete
Total number of sections			63			

[A] Sections to be rated at the start and end of the field ratings
[B] Control sections for rater training school

Table A2. List of Test Sections for Ride Surveys.

Section Number	County	Highway	Begin MP	End MP	Lane	Direction	Posted Speed Limit (mph)	LWP IRI (mm/m)	RWP IRI (mm/m)	Avg. IRI (mm/m)	PSI
2	Brazos	FM2154	622.6	622.7	K1	Southbound to Navasota	65	1.78	1.50	1.64	3.6
3	Brazos	FM2154	622.9	623.0	K1			1.89	1.32	1.61	3.6
4	Brazos	FM2154	623.5	623.6	K1			1.06	1.10	1.08	4.3
5	Brazos	FM2154	623.9	624.0	K1			0.92	1.18	1.05	4.4
6	Brazos	FM2154	624.2	624.3	K1			1.44	1.70	1.57	3.7
7	Brazos	FM2154	628.5	628.6	K1		70	2.08	3.83	2.96	2.4
8	Brazos	FM2154	628.8	628.9	K1			1.34	2.96	2.15	3.1
9	Brazos	FM2154	629.2	629.3	K1			2.29	5.10	3.70	1.9
10	Brazos	FM2154	629.6	629.7	K1			1.77	2.24	2.01	3.2
11	Brazos	FM2154	629.9	630.0	K1			1.97	1.89	1.93	3.3
12	Brazos	FM2154	632.5	632.6	K1			2.73	3.98	3.36	2.1
13	Brazos	FM2154	633.0	633.1	K1			2.93	4.25	3.59	1.9
14	Brazos	FM2154	633.3	633.4	K1			1.24	2.26	1.75	3.5
15	Brazos	FM2154	635.1	635.2	K1			1.77	1.91	1.84	3.4
16	Brazos	FM2154	635.5	635.6	K1			2.15	2.16	2.16	3.1
17	Brazos	FM2154	635.8	635.9	K1			2.41	3.08	2.75	2.6
18	Brazos	FM2154	636.1	636.2	K1			1.49	1.81	1.65	3.6
19	Brazos	FM2154	636.6	636.7	K1			2.78	3.48	3.13	2.3
20	Brazos	FM2154	636.9	637.0	K1			1.58	1.91	1.75	3.5
21	Brazos	FM2154	637.3	637.4	K1			1.56	1.56	1.56	3.7
22	Brazos	SH30	629.1	629.2	K1	Eastbound to Huntsville	70	1.41	1.69	1.55	3.7
23	Brazos	SH30	629.4	629.5	K1			1.38	1.50	1.44	3.8
24	Brazos	SH30	629.8	629.9	K1			1.41	2.14	1.78	3.4
25	Brazos	SH30	630.3	630.4	K1			1.98	2.47	2.23	3.0
26	Brazos	SH30	630.7	630.8	K1			1.59	1.89	1.74	3.5
27	Brazos	SH30	631.0	631.1	K1			1.75	1.81	1.78	3.4
28	Brazos	SH30	631.6	631.7	K1			2.06	1.88	1.97	3.2
29	Brazos	SH30	632.2	632.3	K1			1.02	1.25	1.14	4.2
30	Brazos	SH30	632.8	632.9	K1			1.36	1.55	1.46	3.8

Table A2. List of Test Sections for Ride Surveys.

Section Number	County	Highway	Begin MP	End MP	Lane	Direction	Posted Speed Limit (mph)	LWP IRI (mm/m)	RWP IRI (mm/m)	Avg. IRI (mm/m)	PSI
31	Brazos	SH47	413.2	413.3	R1	Southbound to College Station	70	1.14	0.93	1.04	4.4
32	Brazos	SH47	413.5	413.6	R1			1.36	1.37	1.37	3.9
33	Brazos	SH47	414.0	414.1	R1			2.74	2.70	2.72	2.6
34	Brazos	SH47	414.4	414.5	R1			3.00	3.24	3.12	2.3
35	Brazos	SH47	414.2	414.1	L1	Northbound to Caldwell	70	2.26	1.75	2.01	3.2
36	Brazos	SH47	413.9	413.8	L1			2.63	3.14	2.89	2.4
37	Brazos	SH47	413.5	413.4	L1			1.62	1.56	1.59	3.6
38	Brazos	SH47	413.0	412.9	L1			0.99	0.83	0.91	4.6
39	Madison	IH45	150.4	150.3	L1	Southbound to Houston	70	1.04	1.22	1.13	4.2
40	Madison	IH45	150.0	149.9	L1			0.82	0.95	0.89	4.6
41	Madison	IH45	149.3	149.2	L1			0.89	1.08	0.99	4.5
42	Madison	IH45	149.0	148.9	L1			0.98	0.98	0.98	4.5
43	Madison	IH45	148.2	148.1	L1			0.81	0.88	0.85	4.7
44	Madison	IH45	147.5	147.6	R1	Northbound to Dallas	70	0.69	1.05	0.87	4.6
45	Madison	IH45	147.9	148.0	R1			0.74	0.94	0.84	4.7
46	Madison	IH45	148.2	148.3	R1			0.88	0.87	0.88	4.6
47	Madison	IH45	148.5	148.6	R1			1.63	1.52	1.58	3.7
48	Madison	IH45	148.9	149.0	R1			0.98	1.11	1.05	4.4
49	Madison	IH45	149.2	149.3	R1			1.26	1.75	1.51	3.7
50	Madison	IH45	149.9	150.0	R1			1.02	1.14	1.08	4.3
51	Madison	IH45	151.2	151.3	R1			0.85	1.03	0.94	4.5
52	Madison	IH45	151.5	151.6	R1			0.80	1.05	0.93	4.5
53	Montgomery	SL336	674.3	674.4	K1	Westbound to SH105	55	2.02	2.02	2.02	3.2
54	Montgomery	SL336	675.1	675.2	K1			1.41	1.84	1.63	3.6
55	Montgomery	SL336	676.2	676.3	K1			2.02	1.86	1.94	3.3
56	Montgomery	SL336	676.8	676.9	K1			1.97	1.98	1.98	3.2
57	Montgomery	SL336	677.3	677.4	K1			1.93	1.97	1.95	3.3
58	Montgomery	SL336	677.8	677.9	K1			2.04	2.73	2.39	2.9

Table A2. List of Test Sections for Ride Surveys.

Section Number	County	Highway	Begin MP	End MP	Lane	Direction	Posted Speed Limit (mph)	LWP IRI (mm/m)	RWP IRI (mm/m)	Avg. IRI (mm/m)	PSI
61	Montgomery	SL336	677.7	677.6	K6	Eastbound to IH45	55	1.16	1.16	1.16	4.2
62	Montgomery	SL336	677.4	677.3	K6			1.95	1.68	1.82	3.4
63	Montgomery	SL336	676.7	676.6	K6			1.70	1.59	1.65	3.6
64	Montgomery	SL336	675.5	675.4	K6			1.73	1.75	1.74	3.5
65	Montgomery	SL336	675.2	675.1	K6			1.62	1.82	1.72	3.5
66	Montgomery	SL336	674.4	674.3	K6			2.21	2.25	2.23	3.0

SH47 SECTIONS

Table A3. Locations of SH47 Northbound (L1) Control Sections.

Section	Distance of start of section (miles) from reference[1]	Comments
35	0.9	Posted speed limit is 70 mph
36	1.2	
37	1.6	
38	2.1	Ends at intersection of SH47 and Goodson Bend Road

[1] The reference is at beginning of guardrail just north of Leonard Road or FM 1688 where a stake with red flagging tape has been placed on the shoulder (Figure A1).

Table A4. Locations of SH47 Southbound (R1) Test Sections.

Section	Distance of start of section (miles) from reference[2]	Comments
31	0.0	Starts after bridge. Posted speed limit is 70 mph.
32	0.3	
33	0.8	
34	1.2	

[2] Located about 0.6 miles south of the Fifth Street entrance to the Riverside Campus where a sign for College Station and Texas A&M University is located (Figure A2).

Figure A1. Reference for SH47 Northbound (L1) Control Sections at Start of Guardrail North of Leonard Road (FM 1688).

Figure A2. Reference for SH47 Southbound (R1) Sections at Sign for College Station and Texas A&M University.

FM2154 SECTIONS

Table A5. Locations of FM 2154 Test Sections.

Section	Distance of start of section (miles) from				Comments
	RM 622 on K1 shoulder	RM 628 on K6 shoulder	RM 632 on K6 shoulder	RM 636 on K6 shoulder	
2	0.6				Posted speed limit is 65 mph
3	0.9				
4	1.5				
5	1.9				
6	2.2				Posted speed limit becomes 55 mph after this section and changes to 70 mph after Wellborn
7		0.5			Starts after a hill
8		0.8			
9		1.2			
10		1.6			
11		1.9			
12			0.5		After section ends, slow down for STOP sign 0.2 miles ahead at FM 159 junction at Millican.
13			1.0		You have 0.2 miles to get up to test speed after STOP sign. End stake is on K6 shoulder.
14			1.3		
15			3.1		Start stake is on K6 shoulder.
16			3.5		
17			3.8		
18				0.1	
19				0.6	
20				0.9	
21				1.3	

SH30 SECTIONS

Table A6. Locations of SH 30 Test Sections.

Section	Distance of start of section (miles) from RM 628 on K6 shoulder	Comments
22	1.1	Posted speed limit is 70 mph
23	1.4	
24	1.8	
25	2.3	
26	2.7	Start stake on K6 shoulder and also at driveway edge on K1 shoulder
27	3.0	
28	3.6	
29	4.2	
30	4.8	

LOOP 336 SECTIONS

Table A7. Locations of Loop 336 K6 Test Sections.

Section	Distance of start of section from RM 678[4]	Comments
61	0.3	Posted speed limit is 55 mph.
62	0.6	
63	1.3	
64	2.5	
65	2.8	
66	3.6	You need to move up the curb to stop within this section (Figure A4). Take turnaround near IH45 interchange to get to the K1 sections.

[4] Coming from SH105, RM 678 is just east of the bridge over FM 2854 on K1 shoulder (Figure A3).

Table A8. Locations of Loop 336 K1 Test Sections.

Section	Distance of start of section (miles) from RM 674[5]	Comments
53	0.3	Posted speed limit is 55 mph.
54	1.1	Start is at guardrail post with green flagging tape (no stake)
55	2.2	
56	2.8	Start stake is at end of guardrail just past bridge
57	3.3	
58	3.8	

[5] RM 674 is on K1 shoulder just west of IH45 interchange (Figure A5).

Figure A3. Photo of K6 Lane Along Loop 336 in Conroe.

Figure A4. Photo of Curb Showing Absence of Shoulders Along K6 Lane Near the IH45 Junction.

Figure A5. Photo Showing Reference Marker for Loop 336 K1 Sections Just West of IH45 Junction.

IH45 SECTIONS

Table A9. Locations of IH45 Northbound (R1) Test Sections.

Section	Distance of start of section (miles) from RM 147 [3]	Comments
44	0.5	Posted speed limit is 70 mph.
45	0.9	
46	1.2	
47	1.5	
48	1.9	
49	2.2	
50	2.9	
51	4.2	
52	4.5	Take Normangee exit 152 to get to the IH45 southbound sections.

[3] RM 147 is located just north of the SH75 interchange

Table A10. Locations of IH45 Southbound (L1) Test Sections.

Section	Distance of start of section from RM 151	Comments
39	0.6	Posted speed limit is 70 mph.
40	1.0	Starts at RM 150 with green flagging tape
41	1.7	
42	2.0	Starts at RM 149 with green flagging tape
43	2.8	Take exit 146 for SH75 if you want to go back to the IH45 northbound sections

GUIDELINES FOR DRIVERS

FIELD GUIDELINES FOR DRIVERS

1. You are in charge. Follow safe driving practices at all times. Have all passengers and yourself buckle up for safety. Remain alert.

2. Maintain constant test speed while driving over a section to be rated unless you are forced to alter test speed and/or direction for safety reasons.

3. Familiarize yourself with the driver briefing notebook, particularly the information given for locating the test sections at a given site. Remember these simple guidelines to help you locate the test sections:

   a. Go to the page in your briefing notebook where the starting locations of sections at a site are given. Do this before you get to the site.
   b. Reset your vehicle's trip meter at the prescribed reference marker(s). To identify these markers from which distances are referenced, light red flagging tape has been wrapped at each marker. Read the starting location of a given section and monitor your trip meter so you know when a section is coming up.
   c. Watch for the section markers. The pavement surface at the starting location has been painted with a white stripe, and the section number (Figure A6). In addition, you will find a wooden stake with yellow green flagging tape at the beginning of a section. The ending locations have been marked with white paint stripes and wooden stakes with light red flagging tape (Figure A7).

4. Prepare the raters by having them fill up the rating forms with their names, section IDs, vehicle IDs, and date on the way to a given site. Have them arrange the forms in the sequence the sections are to be driven.

5. Give raters advance warning as you approach a given section. Mention the ID of the section to be rated. For example, you may say, "Section 7 coming up...one...two...START." At the end of a section, say, "STOP". For your information, consecutive sections at a given site are at least 0.2 miles apart. If you are driving at 65 mph, it will take about 11 seconds to cover 0.2 miles.

6. For documenting the time of rating on the form provided, it is not necessary to have the raters write the precise time at which the rating on a given section started or ended. Simply tell the raters the time at which ratings on all sections at a given site were completed, and have them write this time on each of their rating forms for the given site.

7. If you have to re-run a section, use your judgment as to when it is best to do so, and remember to follow safe driving practices in making your turnaround. Consider the option of finishing the remaining sections before re-running one that has previously been rated.

8. **After finishing a site, have the raters check their forms for completeness. Ask them if they are ready to proceed to the next site. In addition, ask if anyone needs to stop at a convenience store or rest area along the way for personal necessities.**

9. **You will be given forms, clipboards, and pens for the raters to use. At the end of the day, collect the rating forms and clipboards. Thank your passengers for their participation and remind them to check their personal belongings before getting out of the vehicle.**

10. **At any time during the field surveys, there should be no conversations regarding the ratings made, about the sections rated, or anything related to pavement roughness. On your way to a site, you can keep your passengers busy for part of the trip by asking them to prepare the forms for the next set of ratings.**

Figure A6. Illustration of Markers Placed at the Start of Each Test Section.

Figure A7. Illustration of Markers Placed at the End of Each Test Section.

GUIDELINES FOR TRAINING RATERS

1. **The following sections at the Ride/Rut Facility will be used to familiarize raters with the zero to five serviceability scale used by TxDOT (see Figures A8 to A10):**

Section ID	Average SI	Direction of Run
RR1	4.7	Southbound
RR2	3.5	Southbound
RR3	3.1	Northbound

2. **Each rater will be driven over sections RR1 to RR3 one at a time for at least three repeat runs. You will give advance warning of the approach of a section. For example, you might say, "Section RR1 coming up...one...two...START." At the end of the section, say, "STOP." Since the purpose of these runs is to orient the raters with the serviceability scale, we will inform them of the SI of each section. Make additional runs as necessary if requested by one or more raters. They need to develop a feel for different levels of roughness.**

3. **Steer the vehicle to track the wheelpath markings when driving over the sections and maintain a speed of 50 mph within a section. In making your turnarounds to make repeat runs, do not drive over the rut calibration bumps or on the unpaved shoulder as your tires will pick up dirt and debris which may affect the ride.**

4. **The control sections are located on the L1 lane of SH47 between Fifth Street and Leonard Road (FM 1688). These sections will be rated during the training school with each participant rating each section on each of the test vehicles provided. This will be conducted following the guidelines given for the field ratings. Our staging area will be in front of the Research Annex gate.**

Figure A8. Photo of Section RR1 at Ride/Rut Facility.

Figure A9. Start of Section RR2 at Ride/Rut Facility (Rut Calibration Bumps at Right of Photo).

Figure A10. Start of Section RR3 at Ride/Rut Facility.

RIDE RATING FORM

Rater ____________________ **Section ID** ____________

Vehicle _______________ **Date** ________ **Time** ________

5

Very Good

4

Good

3

Fair **Rating** ________

2

Poor

1

Very Poor

0

Rating Scale

Comments:

____

____

____

____

____

Figure A11. Rating Form Used in the Ride Surveys.

Table A11. Test Vehicles.

Vehicle ID	Description
C-1	1996 four-door Ford Taurus (4687 lbs GVWR)
C-2	1997 four-door Chevy Lumina (4322 lbs GVWR)
C-3	1993 four-door Chevy Lumina (4322 lbs GVWR)
T-1	1995 GMC Extended Cab 1500 Series Pickup (6200 lbs GVWR)
V-1	1998 Chevrolet 2500 Series Van (8600 lbs GVWR)
V-2	1995 Chevrolet Astro Van (5950 lbs GVWR)

Table A12. Schedule of Ride Panel Ratings.

Date	Activity
May 24	Driver orientation
May 25 (morning)	Driver orientation
May 25 (afternoon)	Rater training class
May 26	Field ratings
May 27 (morning)	Driver briefing (as necessary)
May 27 (afternoon)	Rater training class
May 28	Field ratings
June 2 (afternoon)	Rater training class
June 3	Field ratings

MAPS

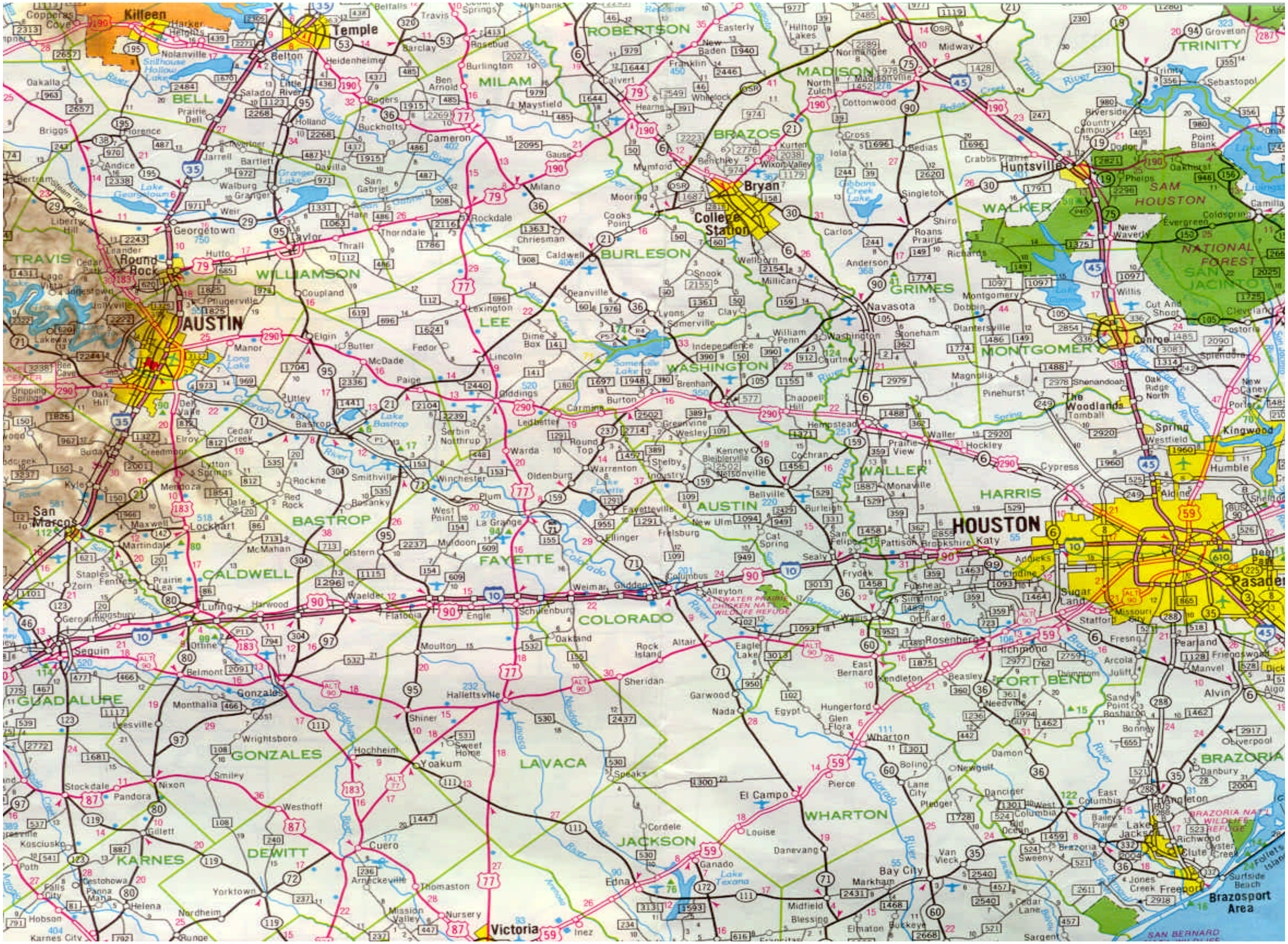


Figure A12. Map of Cities where Test Sections are Located (Bryan/College Station, IH45 North of Madisonville, and Conroe).

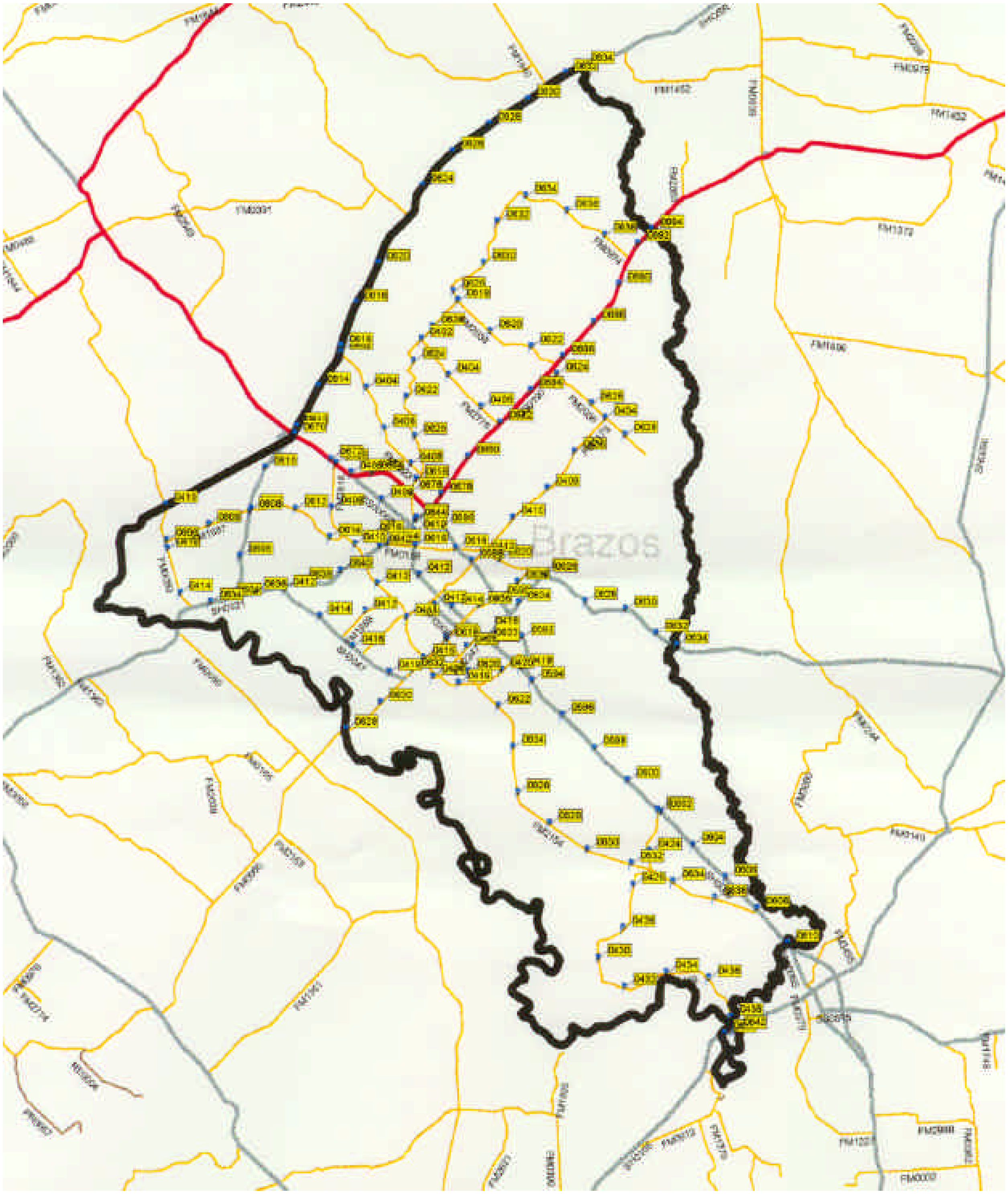


Figure A13. Map of Reference Markers in Brazos County.

Figure A14. Map Showing Locations of Test Sections along FM2154 and SH30 in Brazos County.

Figure A15. Map Showing where Test Sections along Loop 336 in Conroe are Located.

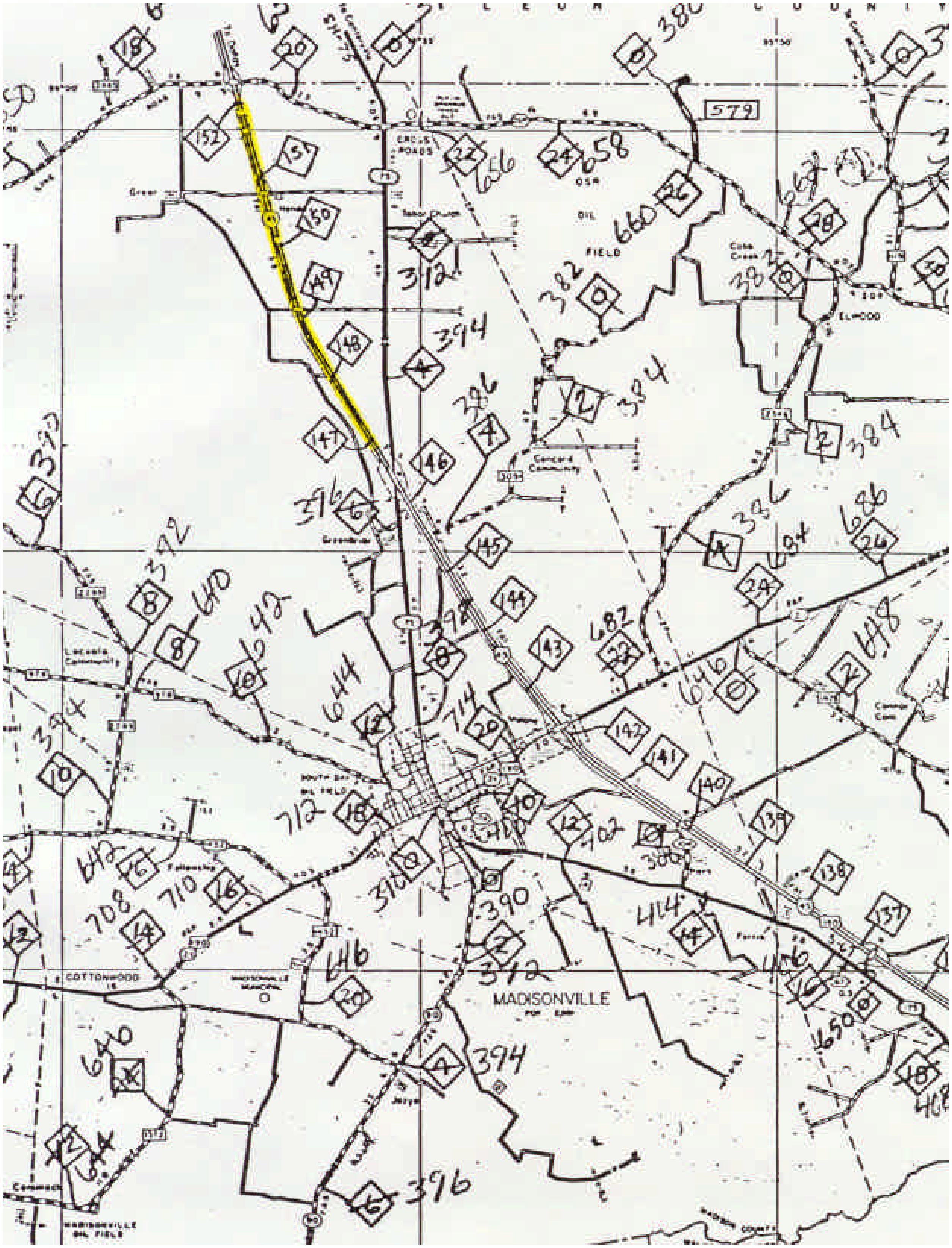


Figure A16. Map of Test Sections along IH45 North of Madisonville.