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A STUDY OF FACTORS AFFECTING ROUGHNESS PROGRESSION ON PORTLAND CEMENT CONCRETE PAVEMENTS IN KANSAS

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16 Abstract

Portland Cement Concrete Pavements (PCCP) with favorable as-constructed smoothness and lower rates of roughness progression are expected to have longer service lives. This study was done to estimate pavement damage due to dynamic wheel loads generated for various levels of roughness and also to quantify the effect of as-constructed smoothness and other design, construction, traffic, and climatic variables on the rate of roughness progression on concrete pavements in Kansas. Effect of concrete strength on estimated pavement damage was also studied. Selected inventory, construction, climatic, and annual roughness data were obtained for 21 PCCP projects constructed after 1992. From the annual roughness data in terms of International Roughness Index (IRI), collected by the South Dakota-type Profilometer, the rate of roughness progression was obtained through regression analysis. Multiple linear regression analysis was then done to find the functional relationships between the rate of IRI Roughness progression and the independent variables selected. The results show that the concrete modulus of rupture, subgrade material, number of wet days, and initial IRI roughness (roughness measured during the first year network-level survey after construction) significantly affect the rate of IRI roughness progression. Higher flexural strength tends to help retain as-constructed smoothness longer. Some pavements with high initial IRI roughness tend to become smoother as traffic passes over it presumably due to the “smoothening” of minor surface irregularities and stabilization of subgrade soil moisture during early years of pavement life. Permeable sub-base tends to decrease the rate of roughness progression. A trend analysis of annual IRI roughness data showed that the as constructed smoothness tends to “wear” out in about 3 to 5 years, and thus does not influence any future roughness development. The calculated dynamic wheel load has no definitive relationship with the roughness statistic, IRI. The dynamic wheel loads are rather functions of actual pavements profiles. The results of the damage analysis also indicate that neither pavement damage nor pavement life appeared to have any relationship with IRI. Concrete strength showed significant effect on pavement life. Higher strength concrete tends to have longer pavement life. Thus, use of high strength concrete is expected to result in PCC pavements with longer service life. Grinding reduces roughness on concrete pavements in the short term only. Grinding alone does not appear to be effective in lowering the rate of roughness progression in the long term

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Final Report

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THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

KANSAS STATE UNIVERSITY
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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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ABSTRACT

Portland Cement Concrete Pavements (PCCP) with favorable as-constructed smoothness and lower rates of roughness progression are expected to have longer service lives. This study was done to estimate pavement damage due to dynamic wheel loads generated for various levels of roughness and also to quantify the effect of as-constructed smoothness and other design, construction, traffic, and climatic variables on the rate of roughness progression on concrete pavements in Kansas. Effect of concrete strength on estimated pavement damage was also studied. Selected inventory, construction, climatic, and annual roughness data were obtained for 21 PCCP projects constructed after 1992. From the annual roughness data in terms of International Roughness Index (IRI), collected by the South Dakota-type Profilometer, the rate of roughness progression was obtained through regression analysis. Multiple linear regression analysis was then done to find the functional relationships between the rate of IRI roughness progression and the independent variables selected. The results show that the concrete modulus of rupture, subgrade material, number of wet days, and initial IRI roughness (roughness measured during the first year network-level survey after construction) significantly affect the rate of IRI roughness progression. Higher flexural strength tends to help retain as-constructed smoothness longer. Some pavements with high initial IRI roughness tend to become smoother as traffic passes over it presumably due to the "smoothening" of minor surface irregularities and stabilization of subgrade soil moisture during early years of pavement life. Permeable sub-base tends to decrease the rate of roughness progression. A trend analysis of annual IRI roughness data showed that the as-

constructed smoothness tends to "wear" out in about 3 to 5 years, and thus does not influence any future roughness development. The calculated dynamic wheel load has no definitive relationship with the roughness statistic, IRI. The dynamic wheel loads are rather functions of actual pavement profiles. The results of the damage analysis also indicate that neither pavement damage nor pavement life appeared to have any relationship with IRI. Concrete strength showed significant effect on pavement life. Higher strength concrete tends to have longer pavement life. Thus, use of high strength concrete is expected to result in PCC pavements with longer service life. Grinding reduces roughness on concrete pavements in the short term only. Grinding alone does not appear to be effective in lowering the rate of roughness progression in the long term

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Pavement smoothness is a lack of roughness. Pavement roughness can be described by the magnitude of longitudinal profile irregularities and their distribution over the measurement interval, and consists of random multi-frequency waves of many wavelengths and amplitudes. ASTM (ASTM 1998) defines roughness as "The deviations of a pavement surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads, and drainage, for example, longitudinal profile, transverse profile and cross slope." Pavement profiles and detailed recordings of surface elevations are frequently used to characterize smoothness. Different wavelengths will have different effects on ride quality depending upon vehicle characteristics and driving speed. Thus smoothness is an important indicator of pavement riding comfort and safety. From an auto driver's point of view, rough roads mean discomfort, decreased speed, potential vehicle damage, and increased operating cost. According to Hudson (Hudson 1981), the purposes of smoothness measurement are:

- To maintain construction quality control;
- To locate abnormal changes in the highway, such as drainage, subsurface problems, or extreme construction deficiencies;
- To establish a statewide basis for allocation of road maintenance resources; and
- To evaluate pavement serviceability-performance life histories for evaluation of alternate designs.

There is a growing push in the transportation industry for smoother and smoother pavements. The road surface smoothness of newly constructed Portland Cement Concrete Pavement (PCCP) is of major concern to the Kansas Department of Transportation (KDOT). The first PCCP with smoothness specifications was built by KDOT in 1985, and the first standard specifications for as-built smoothness were adopted in 1990.

1.2 BACKGROUND

In 1985, KDOT selected a 25ft. (7.63 m) California-type profilograph for determining as-constructed smoothness of concrete pavements. A 0.2in. (5.1 mm) blanking band was used for evaluation of the profilogram. Three PCCP projects were built using a provisional set of specifications at that time. Results indicated that the provisional smoothness specifications were achievable. In 1990, the specifications shown in Table 1.1 were adopted as standards for quality control of as-built PCCP smoothness in Kansas (Hossain and Parcells 1994).

Table 1.1 Schedule for Adjusted Payment for PCC Pavements (1990 Specification 502.06 - using 0.2in. blanking band)

PROFILE INDEX IN/MI PER 0.10MI SEGMENT	PRICE ADJUSTMENT PERCENT OF CONTRACT UNIT BID PRICE
3.0 or less	106
3.1 to 4.0	103
4.1 to 10.0	100
10.1 to 12.0	96
12.1 to 14.0	92
14.1 to 15.0	90
15.1 or more	88 (Corrective Work Required or Replace)

In 1990 there was a noticeable, high-frequency vibration on a PCCP reconstruction project on I-70. On a concurrent PCCP project on I-470, such a problem did not exist. Close examination of the profilograph traces revealed that on the I-70 project, a sine-wave oscillation of about 8 ft. (2.44 m) spacing with a 0.2in. amplitude was present. However, most of the surface deviations were covered up by the 0.2in. (5.1 mm) blanking band during the trace reduction process. On the I-470 project, the oscillation waves were spaced at about 30ft. (9.14 m) with an amplitude of 0.2in. (5.1 mm), which were again covered by the 0.2in. (5.1 mm) blanking band width (Hossain and Parcells 1994). The I-70 and I-470 projects of 1990 prompted KDOT to study the effects of the blanking band on trace reduction. It was decided to use a "zero" blanking band width or "null" blanking band. A null blanking band is nothing but a reference line placed at the center of the trace. In addition to the projects on I-70 and I-470, each of the 1990 projects was reanalyzed using the null blanking band. By replacing the 0.2in. (5.1 mm) blanking band with the null blanking band, results indicated that achieving bonus would be harder. The change in the blanking band resulted in a new set of specifications. The new specifications were incorporated in the 1992 construction projects (Hossain and Parcells 1994).

With the introduction of 90P-111-R1 in 1993, the maximum amount of bonus was increased from 6% of the unit bid price to 8% of the unit bid price, but the full pay range was narrowed to include slightly more rigid grind-back provisions. In 1994, 90P-111-R2 and 90P-111-R3 were intended to make pavements initially smoother by lowering the Profile Index (PI)/Profile Roughness Index (PRI) values required for the highest, 108%, incentive payment. In 1996, the percent unit bid item price incentives and disincentives were replaced with dollar values per section of pavement in 90P-111-R4. 90P-111-R4 made the concrete smoothness specifications similar to the asphalt smoothness specifications, which had always been based on dollar values per section of pavement. Further revisions include such changes as requiring ProScan automated profilogram reduction software, grinding provisions, a 0.30in. (7.62mm) bump template, and introduction of metric units. Currently KDOT is using specification 90P-111-R9, shown in Table 1.2 (Parcells 1999).

Table 1.2 Schedule for Adjusted Payment for PCC Pavements (90P-111-R9)

PROFILE INDEX IN/MI (0.10 MI SECTION)	PRICE ADJUSTMENT CONTRACT PRICE ADJUSTMENT
6.0 or less	+$1200.00
6.1 to 10.0	+$1000.00
10.1 to 15.0	+$750.00
15.1 to 18.0	$370.00
18.1 to 30.0	$0.00
30.1 to 40.0	$0.00 (grind back or replace)
40.1 or more	-$750.00 (grind back or replace)

Changes to the original specifications of 1990 are considered to have enhanced the quality of new concrete pavement construction in Kansas. Since 1990, there has been an increasing trend in the number of PCCP's constructed in the bonus range and a decreasing trend in the number of PCCP's produced in the penalty range as depicted in Figure 1.1. The most significant change to the specification, from percent based to dollar based, occurred between the years 1994 and 1995.

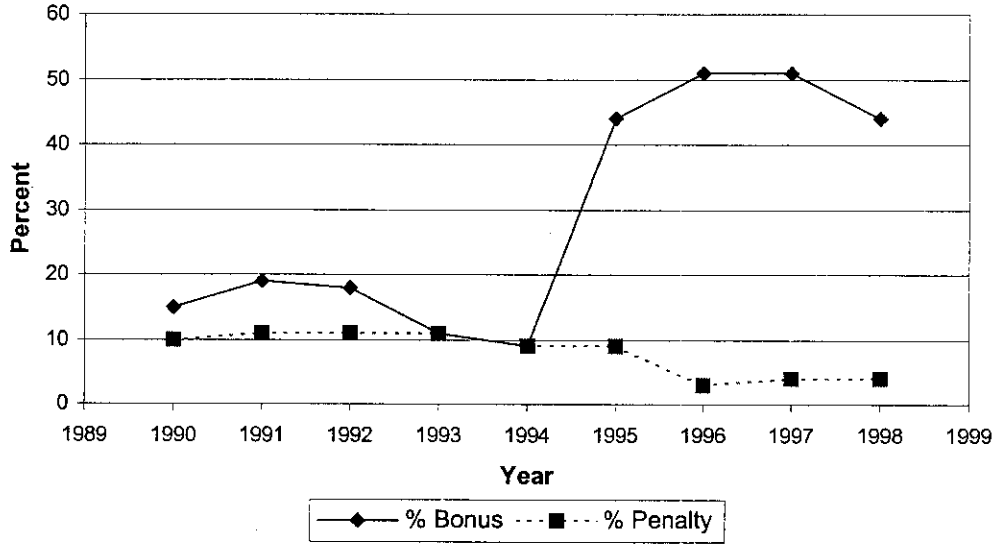


Figure 1.1 Specification Compliance on New PCC Pavements

1.3 PROBLEM STATEMENT

There is a growing interest in the concrete paving industry now for attaining smoother and smoother as-constructed PCCP's. Results from a 1992 NCHRP study show that of the 22 states reporting, 91% utilized smoothness criteria on new pavement construction (Scofield 1992). The incentive/disincentive values in the smoothness specifications typically ranges from 1% to 5% of the bid price with 31% of these states reporting allowable incentives up to 5%. The relatively high incentives now possible with many of the profilograph specifications indicate the need for closer look at the effects of these specifications on the end results, i.e. service lives of the pavements.

In general it is believed that the initial smoothness has a significant effect on the future smoothness of PCCP. NCHRP project 1-31 studied this issue (Smith et al. 1997). The study found that the initial smoothness did seem to have a positive effect on the future smoothness on 70% of the projects studied. However, the study did not identify the factors that are responsible for making initial smoothness not to be indicative of future smoothness on 30% of the projects. It is also recognized that apart from riding quality issue, rougher pavements tend to increase the magnitude of wheel loads applied on the pavements. NCHRP project 1-25(1) studied the PCCP damage due to dynamic wheel loads of heavy trucks (Gillespie et al. 1993). The mechanics of truck-pavement interaction were studied to identify the relationships between truck properties and pavement damage (fatigue and rutting). Table 1.3 shows the results of the rigid pavement fatigue interactions between pavement roughness, vehicle speed, tandem dynamics, joint load transfer, etc. The results showed the roughness in the road surface excites truck dynamic axle loads, thus increasing fatigue damage. Rough pavements (2.5 Present Serviceability Index, PSI) experience damage at a rate that is approximately 50 percent greater than that of the smooth roads (above 4 PSI) for most typical truck suspensions. With a walking-beam tandem suspension, however, rough roads may experience damage as much as three times greater than that of smooth roads. On the rougher roads, fatigue damage may increase by 200 percent to 400 percent depending on the type of road and truck properties (Gillespie et al. 1993).

In the 1980's and 1990's KDOT actively funded nearly 120-lane miles (200 lane km) of new PCCP's each construction season. The current specifications, 90P-111-R9, can potentially cost KDOT more than 1.5 million dollars in bonus payments each year (Parcells 1999). There is an apprehension that such a high emphasis on smooth PCCP may not be of any benefit to the overall life of the pavement. In general, the results from the KDOT annual pavement roughness surveys show that pavements with both high and low initial roughness tend to have a similar rate of roughness progression as shown in Figure 1.2.

Table 1.3 Rigid Pavement Fatigue Interactions (Gillespie et al 1993)

	Vehicle/Tire Factors	Axle loads	Gross weight	Axle spacing	Static load sharing	Speed	Single axle susp. type	Tandem dynamics	Maneuvering	Inflation pressure	Single, dual, wide-base	Ply type	Wheel path location	Pavement Factors	Roughness	Temperature gradient	Slab thickness	Base layer thickness	Subgrade strength	Slab length	Joint load transfer
Vehicle/Tire Factors																					
Axle loads		●							○	○	●	○				○					
Gross weight			●						○							○					
Axle spacing				●	●					○	○		○				○	○		○	○
Static load sharing				●	●												○	○			
Speed						●	○	●	○						●					○	○
Single axle susp. type						○	●		○		○				○					○	○
Tandem dynamics						●		●	○	○	○				●					○	○
Maneuvering		○	○			○	○	○	●												
Inflation pressure		○		○				○		●	●	●					○				
Single, dual, wide-base		●		○			○	○		●	●	○	○				○	○			
Ply type		○								●	○	●									
Wheel path location				○							○		●			○				○	○
Pavement Factors																					
Roughness						●	○	●							●	○				○	●
Temperature gradient		○	○										○		○	●	○	○		●	○
Slab thickness				○	○					○	○					○	●	●			○
Base layer thickness				○	○						○					○	●	●			○
Subgrade strength																			●		
Slab length				○		○	○	○					○		○	●				●	●
Joint load transfer				○		○	○	○					○		●	○	○	○		●	●

● = Strong interaction ○ = Weak interaction (blank) = No interaction

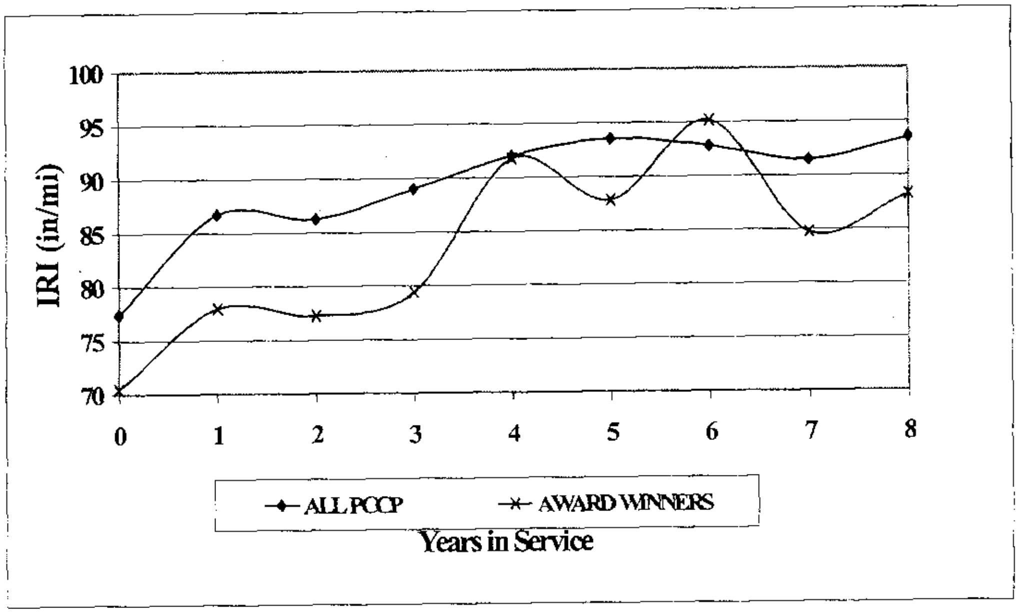


Figure 1.2 KDOT PCCP Roughness Progression

The "award winners" in the figure were those pavements that won awards for being ultra smooth in most of the cases. Both smoother and all other PCCP's reach a threshold roughness at about the same point in time. There is a suspicion that the bonus sections may not be outperforming the full-pay sections in terms of service life roughness (Hossain et al. 1997).

Analyzing the damage of PCCP due to combined effect of roughness and heavy truck and also identifying the factors responsible for the rapid rate of roughness progression could potentially increase the service life of PCCP and justify bonus payments. Roughness value is an important parameter for calculating pavement service life. Also, the pavement designers could use performance histories developed from the factors responsible for roughness and the rate of roughness progression.

1.4 OBJECTIVES

The primary objective of this study is to identify the factors responsible for rapid roughness progression on the PCCP projects built by KDOT after 1992. The year 1992 was chosen as the base year because KDOT started profile-based roughness measurements that year. The influence of initial roughness on the rate of roughness progression was also studied. Another objective was to estimate pavement damage resulting from higher dynamic forces generated by heavy vehicles due to various levels of PCCP roughness.

Lower rates of roughness progression will result in pavements that are smoother in the long term. In return we can expect less damage to vehicles, and lower pavement maintenance or rehabilitation cost. The study would be beneficial to both highway user and the owner, KDOT.

1.5 ORGANIZATION OF REPORT

This report is divided into six chapters. Chapter 1 is an introduction to the problem. Chapter 2 is a literature review of road roughness, causes of roughness, causes of pavement damage, and brief introduction of the software, RoadRuf, KENSLAB and TruckSim, used in this study. Chapter 3 identifies the projects used in the study. This chapter also describes the data collection process. Chapter 4 presents the correlation study to identify significant factors affecting roughness progression. This chapter also presents the results of multiple regression analysis. C hapter 5 presents the results of the damage analysis and also discusses the correlation of pavement damage with the roughness statistic. Finally, Chapter 6 offers some conclusions and recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 ROUGHNESS AND SERVICEABILITY

Roughness is an indicator of pavement serviceability. Serviceability is the perception the user has of the roadway. The American Association of State Highway Officials (AASHO) Road Test has indicated that the serviceability of pavement is affected by the unevenness of the longitudinal surface profile. Each driver has a different threshold of roughness that is directly correlated to vehicle speed, vehicle characteristics, and tolerance of the vehicle driver or passenger (Haas et al. 1994). Roughness is viewed as a distortion of the pavement surface. While a rough road may be viewed as structurally sound, its level of service due to roughness may be reaching the lowest level. However, the vice-versa may also hold true. The serviceability of a road can be determined by periodic measurements of riding quality. From a pavement manager's viewpoint, the pavement has to perform above a minimum level of acceptability during its design period, as shown in Figure 2.1. Engineers and users differ widely on their views of whether a pavement is acceptable or unacceptable. Many engineers based their evaluations on cracking distresses. Designs for the pavement thickness required that computed stresses and strains did not exceed specified values (Haas et al. 1994).

During the AASHO Road Test, a method of performance evaluation was needed to evaluate pavement based on user's perception. The result was the "serviceability-performance concept" developed by Carey and Irick in the early 60's. They concluded that serviceability should be defined in relation to the purpose of the pavement to provide a ride that is smooth, comfortable, and safe. It is also suggested that the measurement should directly correlate to the user, who is most influenced by the condition of the pavement (Haas et al. 1994).

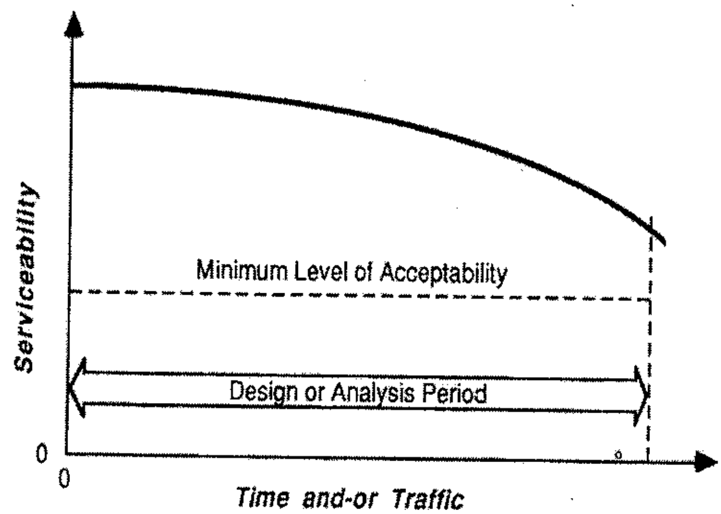


Figure 2.1 Deterioration of ride quality or serviceability over time (Haas et al. 1994)

The Present Serviceability Index (PSI) statistic is used as an indicator of roadway quality. The PSI statistic was developed at the AASHO road test. This equation has been modified many times in accordance with different measuring techniques developed (Haas et al. 1994). The original form of the PSI equation is:

$$PSI = C + (A_1R_1 + ...) + (B_1D_1 + B_2D_2 + ...) \pm e \qquad (2.1)$$

Where,

C = coefficient (5.03 flexible & 5.41 rigid);

A_1 = coefficient (-1.91 flexible & -1.80 rigid);

R_1 = log (1+SV), where SV= mean slope variance;

B_1 = coefficient (-1.38 flexible & 0 rigid);

D_1 = function of rut depth;

B_2 = coefficient (-0.01 flexible & -0.09 rigid);

D_2 = function of surface deterioration (C+P), cracking and patching; and

e = error term.

The PSI equation, developed in the early 60's, is often misunderstood and misused. It should be noted here that the PSI equation is not solely a function of roughness. The PSI equation also accounts for other pavement distresses such as cracking and patching. To truly isolate roughness as the sole factor responsible for serviceability is the most user-friendly approach. It should be kept in mind that it is the user that must traverse the profile. Therefore, terms such as patching and cracking have no influence on the user. The user will determine the road satisfactory if it is smooth, regardless of cracks and patches.

2.2 ROUGHNESS STATISTICS AND ROADRUF

Roughness causes a number of problems to the highway user, including poor ride quality, unsafe driving conditions, excitation of truck dynamics leading to further pavement deterioration, and damage to vehicles and cargo. The vast majority of highway users are most sensitive to ride quality; therefore, ride quality is the primary criterion in setting pavement rehabilitation priorities. Since it is not possible to build perfectly smooth pavements, paving specifications usually prescribe the maximum acceptable roughness. Two basic approaches to measure ride quality are currently used. One measures the effect of roughness on ride quality through rating panels or equipment correlated with rating panels. The second approach, called profiling, describes pavement surfaces independent of the measuring equipment. Road surface profiles present a "profile" or picture of the road described in terms of wavelengths and amplitudes. The road profile measurements can be accomplished by Response Type Road Roughness Measuring (RTRRM) systems, which measure the accumulated suspension deflections over the length of the test sections. The results are expressed as the ratio between suspension deflections in inches (or in meters) and the length of the test section in miles (or kilometers). This roughness index of in/mi (or m/km) has been in use for many years. The International Roughness Index (IRI) is now a widely accepted roughness statistic. Almost every automated road profiling system includes software to calculate this statistic. Since 1990, the Federal Highway Administration (FHWA) has required the states to report road roughness on the IRI scale for inclusion in the Highway Performance Monitoring System (HPMS) (Road Profiles 1997). KDOT has adopted IRI for reporting pavement roughness since 1992.

The IRI number indicates the vertical displacement of the pavement surface using the quarter-car simulation. The quarter car is a representation of one fourth, i.e., one wheel of a car. The concept of quarter car simulation as a method for analyzing pavement profile data was originally an attempt to simulate the output of the BPR roughometer (Hass et al. 1994). The quarter car simulation model, illustrated in Figure 2.2, has been adopted by the World Bank as the primary mean of roughness simulation. It consists of a sprung mass, suspension spring, damper, unsprung mass of the suspension, tire, and wheel, and tire spring constant. The quarter car model was first developed for the RTRRMS devices, in which the movement between the vehicle axle and body is measured. When a profilometer is used to measure the actual profile of the pavement the quarter car model measures the differences in velocities between the sprung and unsprung masses. This difference in the velocities is then integrated over time to produce the quarter car statistic (QCS). The QCS equation is shown below:

$$QCS = \frac{1}{C}\int_{0}^{T}\left|\dot{Z}_s - \dot{Z}_u\right| dt \tag{2.2}$$

Where,

C = section length;

$\dot{Z}_s$ = velocity of sprung mass;

$\dot{Z}_u$ = velocity of unsprung mass; and

T = total time required to traverse the section.

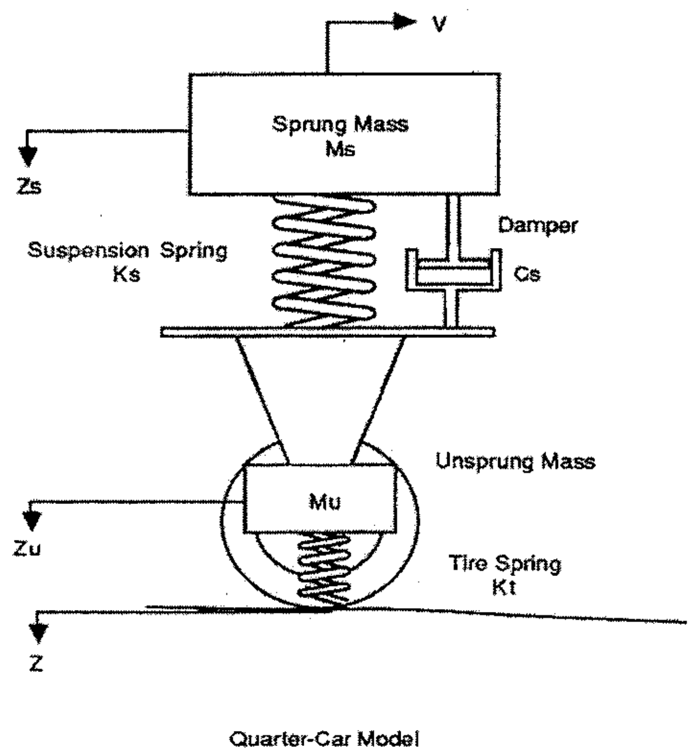


Figure 2.2 Quarter-car model (Haas et al. 1994)

The Highway Safety Research Institute (HSRI) created a set of vehicle parameters to be used when analyzing pavement profiles using the quarter car simulation model and QCS. The HSRI vehicle parameters were later adopted by the World Bank, which termed the QCS as the IRI (Haas et al. 1994). The resulting IRI statistic has units of slope. As a user, one can express the slope in any appropriate units. The most common choices are in/mi and m/km (1 m/km = 63.36 in/mi) (RoadRuf 1997). The IRI is linearly related to variations in profile, in the sense that if all of the elevation values in the profile are doubled, the resulting IRI will also be doubled. Two programs are available for the calculation of IRI. The first is a user-friendly, Windows-based software package called RoadRuf for interpreting longitudinal road roughness profile data, including the calculation of IRI. The second is a sample FORTRAN program for calculating IRI and RN (Ride Number). RoadRuf was used to calculate IRI for this study.

2.2.1 RoadRuf

RoadRuf is an integrated set of computer tools for interpreting longitudinal road profile data. It provides well-tested profile analyses in a user-friendly package. The algorithms used in the software are the same ones that have been published by the UMTRI researchers (Sayers, Karamihas, and Gillespie) in a variety of FHWA reports, TRB papers, and World Bank technical reports (RoadRuf 1997). The ASTM standards recently included the IRI and Ride Number (RN) algorithms for analyzing longitudinal profile. The software also includes a plotter with built-in filters. It also includes advanced analysis capabilities to support research activities in addition to computing standard roughness indices from profile measurements. These include a spectrum analyzer and customizable filters. All features can be operated interactively or in a batch-processing mode. RoadRuf was developed at the University of Michigan Transportation Research Institute (UMTRI) with funding from the Federal Highway Administration (FHWA) under a research project called "Interpretation of Road Roughness Profile Data." The software is in the public domain and available from the Internet (http://www.umtri.umich.edu/erd/roughness/rr_home.html).

The components of RoadRuf are shown graphically in Figure 2.3. The Analyses screen has buttons for using the plotter to view profiles (Plot Input Profiles button), analyzing profiles to obtain roughness indices and possibly output profiles (Run IRI/RN Filter button), using a text editor to view tables of roughness indices (View Tables of results button), and using the plotter to view outputs of the profile analyses (Plot Analyses Output button).

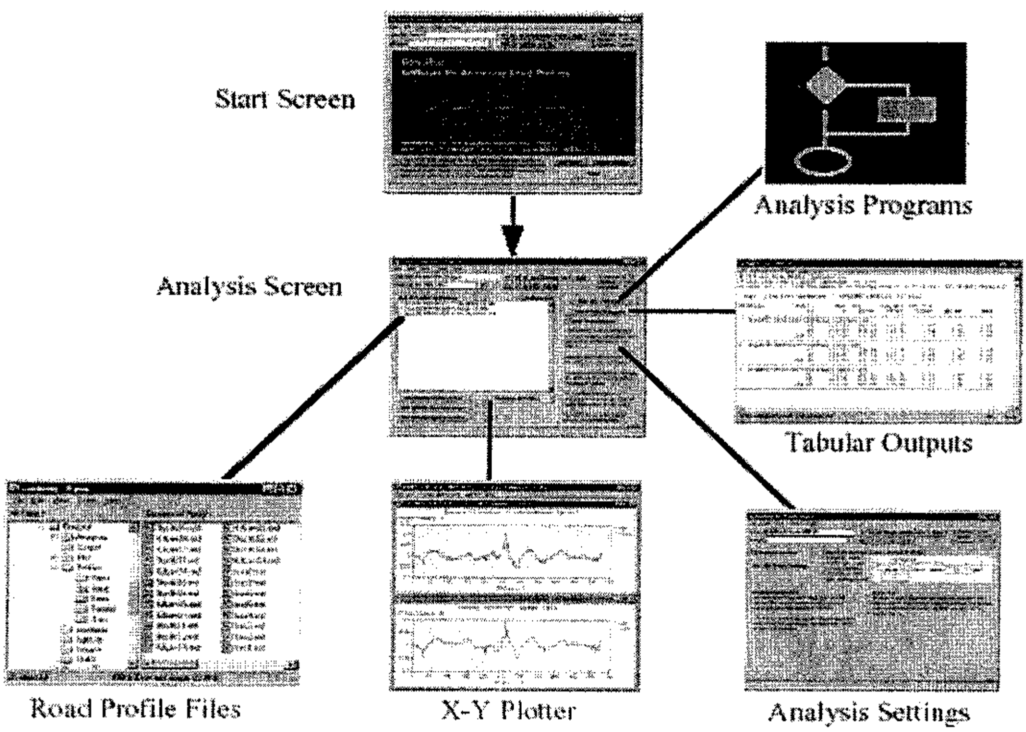


Figure 2.3 Components of RoadRuf (RoadRuf 1997)

RoadRuf involves four basic steps to generate tabulated results using Analyses screen. The steps are as follows:

- To select a list of files to process.
- To select an analysis type.
- To run the calculation.
- To view the tabulated results.

There are also two basic steps to see the plot using the screen – to select files to plot and to view the plot. RoadRuf has three types of filter – IRI/RN, Quarter-car filter, and Butterworth filter. It has some default values from UMTRI. The user can also modify the filter criteria. The filters also define the way the sections are split up for reporting summary indices into the table of analysis results. Figure 2.4 shows the screen that contains the settings that are needed to define the analyses. Starting Point field defines the starting point for splitting the profile into sub-sections. The first sub-section will begin at the position along the section of the entered Starting Point and end at the Starting Point plus the Print Interval. Print Interval field defines the length of each sub-section. Each sub-section starts at the end of the previous sub-section and has a length equal to the Print Interval.

RoadRuf requires files with a standard format (ERD Files). The ERD file format was developed within the Engineering Research Division (ERD) of the University of Michigan Transportation Research Institute (UMTRI) to facilitate automated plotting of simulation data, experimentally measured data, and data from various analysis programs. An ERD file contains two independent sections, the header, and the data. The header contains only text, and the data section contains numbers. The numbers can be written in

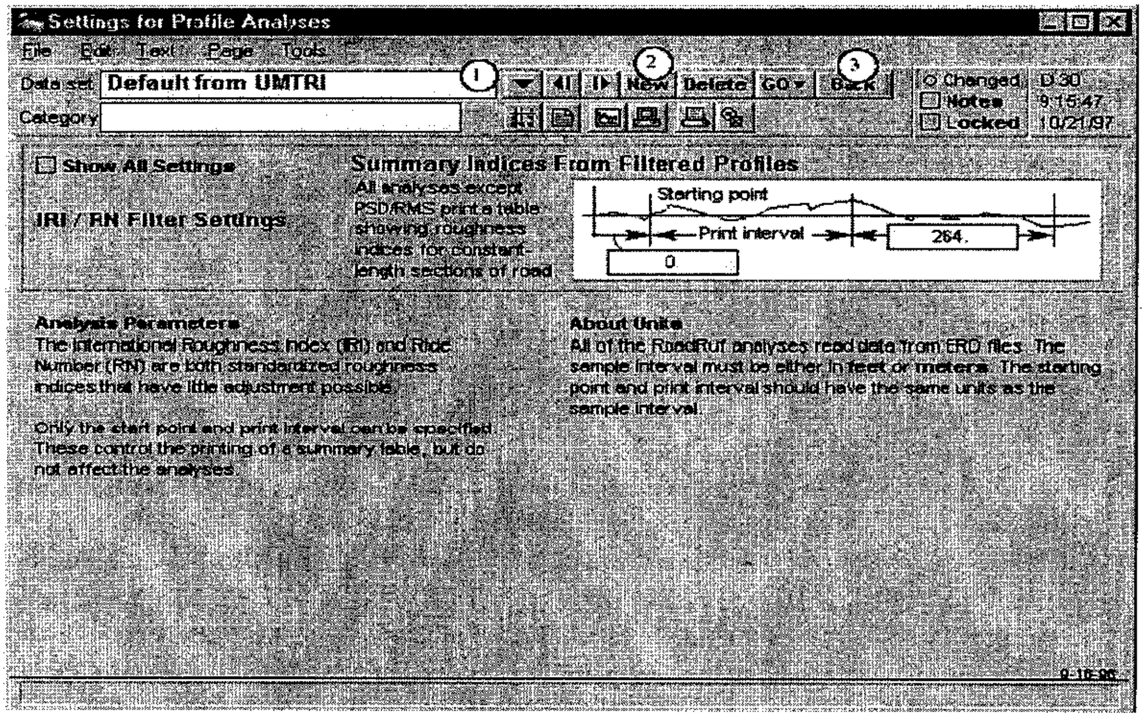


Figure 2.4 Basic Analysis Settings

```
ERDFILEV2.00
2, 529, 1,  4232,  1,  1.00000,  -1,
TITLE   1993 RPUG Study, Dipstick, Section 1, Measurement 1
SHORTNAMLElev.  RElev.
LONGNAMELeft Elevation                    Right Elevation
UNITSNAMft       ft
GENNAME Profile Elevation                 Profile Elevation
XLABEL  Distance
XUNITS  ft
FORMAT  (2G14.6)
PROFINSTDipstick
HISTORY Converted to ERD format at 23:46, Oct. 23, 1994
END
0.000000      0.000000
 0.416667E-03 -0.141667E-02
0.416667E-03  0.583333E-03
0.666667E-03  0.916667E-03
0.133333E-02  0.133333E-02
0.750000E-03 -0.166667E-02
-0.300000E-02 -0.458333E-02
-0.558333E-02 -0.500000E-02
-0.625000E-02 -0.658333E-02
-0.775000E-02 -0.825000E-02
```

Figure 2.5 Typical Header for an ERD File with Text Data

either text or binary form. The text form is convenient for viewing and editing data with a word processor, whereas the binary form provides more efficient access for automatic processing. If the data section is in text format then both the header and the data are kept in a single file. As a minimum, the header contains three lines of text. The first line identifies the file as following the ERD format. The second line describes the way that the numerical data are stored in the data section of the file. The third required line is an END statement, which indicates the end of the header portion. Any number of optional lines can be included between line 2 and the END line. Figure 2.5 shows a typical example of a header for a file with its data in text form. It is to be noted that the data entry begins immediately after the END line of the header. The first number in the second line indicates the number of column in the data section. The second number indicates the number of data in each column in the data section and the sixth number indicates the data interval. The data section of the ERD file contains nothing but numbers, organized into columns and rows. The only restriction on free format numbers is that adjacent numbers must be separated.

2.3 PAVEMENT DAMAGE AND KENSLAB

Pavements are classified as flexible or asphalt, composite, and rigid or concrete pavements. Rigid pavements can be further classified according to their jointing and use of temperature steel. Each of these road types has a number of characteristic failure mechanisms, and each failure mechanism is affected by many factors (Gillespie et al. 1993). NCHRP Report 353 shows that pavement "damage" was limited to three categories that are closely linked to the history of applied vehicle loads: (1) fatigue damage of rigid pavements, (2) fatigue damage of flexible pavements, and (3) permanent deformation (rutting) of flexible pavements. The wheel loads of heavy trucks contribute to various forms of pavement distress. Fatigue, which leads to cracking, is among the various types of damage that are of great importance and is the primary focus of this study. The fatigue damage can be expressed as a summation of damage ratios. Damage ratio is the ratio between predicted and allowable number of load repetitions. Damage occurs when the sum of the damage ratios reaches a value of 1. The allowable number of load repetitions is also related to the stress ratio. The stress ratio is the ratio between the flexural stress and the modulus of rupture. It is found that the concrete will not fail by fatigue if the stress ratio is smaller than 0.5, although no real limit was found up to 10-20 million load repetitions (Huang 1993).

Fatigue of concrete can cause both transverse cracking and longitudinal cracking. Transverse cracking initiates at the pavement edge midway between transverse joints, and longitudinal cracking initiates in the wheel paths at the transverse joints. Figure 2.6 shows the most critical loading and stress locations for fatigue damage development. Midslab edge loading and joint loading causes transverse and longitudinal cracking, respectively. Because of the lateral distribution of traffic, wheel loads are not applied to the same location. Only a fraction of the load repetition needs to be considered for fatigue damage. NCHRP Report 1-26 suggested the use of an equivalent damage ratio, EDR (Huang 1993). EDR is the ratio of the traffic applied at the same critical location to the total traffic distributed over all locations. Therefore, truckload placement must be carefully considered in the rigid pavement fatigue damage.

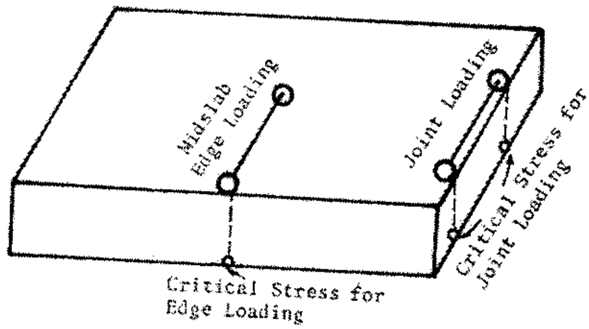


Figure 2.6 Critical Loading and Stress Locations for Fatigue Analysis (Huang 1993)

2.3.1 KENSLAB

KENSLAB is a computer program developed in 1985 by Dr. Yang H. Huang of the University of Kentucky. This program was written on FORTRAN 77 and uses the finite element method to analyze rigid pavement subjected to specific loading and environmental conditions. The finite element analysis method divides the pavement into rectangular finite elements that have a large number of nodes. These nodes are used to indicate the exact location of loads and to calculate the response of the pavement to those loads. All loads and reactions are considered vertical concentrated loads acting on each node. This program offers the possibility of assuming three different types of foundations for the analysis of pavements. They are: (1) Liquid Foundation, (2) Solid Foundation, and (3) Layer Foundation. The solid foundation is the most realistic one. The major advantage of this foundation model is that the effect of all the nodes of the structure is considered when analyzing any particular location. This type of foundation is also called Boussinesq's foundation because Boussinesq's equation for the surface deflection is used to determine the flexibility matrix of the structure. The flexibility matrix of the foundation is defined as the deflection at a given node due to the forces at all other nodes including the node itself. Once the matrix is formed, a five point Gaussian quadrature formula in both x and y directions is used to integrate the response of each node and then superimposed over all the adjoining elements. The stiffness matrix of the foundation can be obtained by inverting the flexibility matrix (Huang 1993).

Damage analysis is based on the fatigue cracking only. The damage is defined by the cracking Index (CI), which is the same as damage ratio.

$$D_r = \sum_{i=1}^{p}\sum_{j=1}^{m}\frac{n_{ij}}{Nij} \tag{2.3}$$

Where,

D_r = is the damage ratio;

n_{ij} = the predicted number of load repetition; and

N_{ij} = the allowable number of load repetition.

The allowable number of repetition can be expressed

$$\log N_f = f_1 - f_2\left(\frac{\sigma}{S_c}\right) \tag{2.4}$$

Where,

N_f = the allowable number of repetitions;

σ = the flexural stress in slab; and

S_c = the modulus rupture in concrete.

In the design of zero maintenance jointed plain concrete pavements, Darter and Barenberg (1977) recommended the use of f_1 = 16.61 and f_2 = 17.61 (Huang 1993). Portalnd Cement Association (PCA) recommends the following fatigue equations.

For $\frac{\sigma}{S_c} \geq 0.55$: $$\log N_f = 11.737 - 12.077\left(\frac{\sigma}{S_c}\right) \quad (2.5)$$

For $0.45 < \frac{\sigma}{S_c} < 0.55$: $$\log N_f = \left(\frac{4.2577}{\frac{\sigma}{S_c} - 0.4325}\right)^{3.268} \quad (2.6)$$

For $\frac{\sigma}{S_c} \leq 0.45$: $$N_f = \text{unlimited} \quad (2.7)$$

The PCA method assumes that one tandem axle load should be considered as one repetition. But in the zero-maintenance method, it is considered as two repetitions. Theoretically, the damage analysis is explained by Figure 2.7. The tensile stress caused by the passage of the first axle load is σ_a and that of the second axle load is $\sigma_a - \sigma_b$. If $\sigma_a - \sigma_b$ is much smaller than σ_a, the stress ratio due to second load is most probably smaller than 0.45. According to PCA method, if the stress ratio is less than 0.45, it has no effect on fatigue damage. Therefore, the assumption of one-tandem-axle load as one repetition is more reasonable. For the same reason, the passage of the set of tridem-axle loads should also be considered as one repetition.

Damage Analysis under KENSLAB can be performed by dividing each year into a maximum of 24 periods, each with maximum of 24 load groups. As only the properties of foundation vary with the season, a foundation seasonal adjustment factor (FSAF) is assigned to each period. The modulus of subgrade reaction of liquid foundation or the stiffness matrix of solid and layer foundation is multiplied by the FSAF to simulate the seasonal change in the stiffness of the foundation.

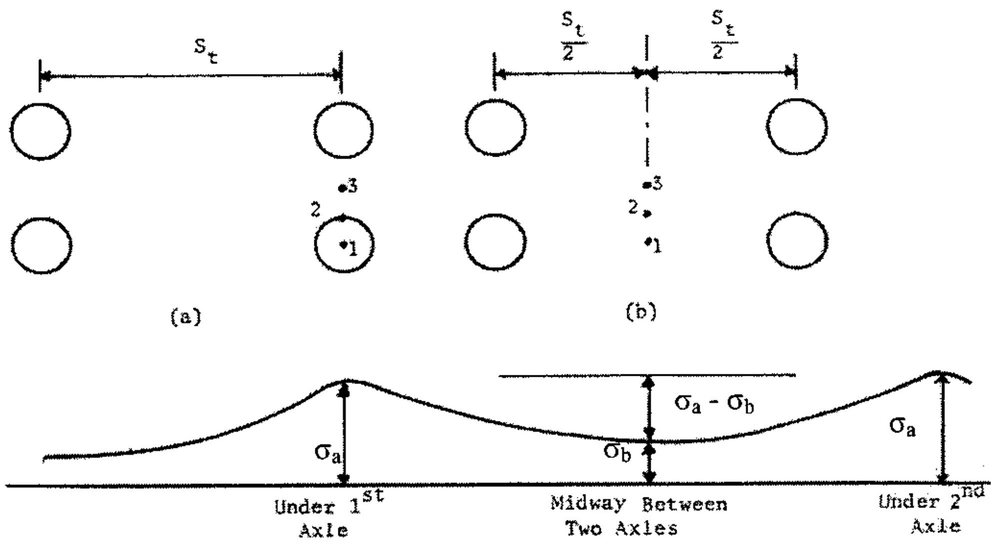


Figure 2.7 Damage Analysis of Tandem-axle Loads (Huang 1993)

2.4 DYNAMIC WHEEL LOADS AND TRUCKSIM

The wheel loads of heavy trucks contribute to various forms of pavement distress. Under NCHRP Project 1-25(1), the mechanics of truck-pavement interaction were studied to identify relationships between truck properties and the damage they cause (fatigue and rutting). Not all heavy trucks, however, will cause equal damage because of differences in wheel loads, number and location of axles, types of suspensions and tires, and other factors. Furthermore, the damage is specific to the properties of the pavement, operating conditions, and environmental factors. Roughness is the major cause of dynamic axle load variations in heavy trucks, thus increasing fatigue damage. In this study, the primary objective was to observe how various road profiles of roughness affect dynamic load variations from trucks and to calculate the dynamic wheel load for different road profiles of different roughness. The TruckSim was used for calculating dynamic wheel loads of a truck for various levels of PCCP roughness.

TruckSim is a software package for simulating and analyzing the behavior of heavy trucks, and combination vehicles in response to steering, braking, and acceleration inputs. TruckSim was developed at the University of Michigan Transportation Research Institute (UMTRI) with funding from the Motor Vehicle Manufacturers of America and the Great Lakes Center for Truck and Transit Research. It produces the same kind of outputs that might be measured with physical tests involving instrumented vehicles. The software version 3.2 was used in this study. The software presently includes two modules: (1) 2D Ride and Dynamic Pavement Load, and (2) 3D Handling and Roll. The 2D Ride module was used in this study. The 2D Ride/Loading module predicts vehicle vibrations due to road roughness and the dynamic pavement loads resulting from those vibrations. The following section introduces the TruckSim environment and some of its capabilities.

2.4.1 TruckSim

Detailed mathematical models for simulating automotive vehicle dynamics have been in use for decades. TruckSim includes a database that minimizes the time needed to build a vehicle description and set up run conditions. Vehicles, components, inputs, existing runs - are accessible easily. TruckSim combines information from the data screens with the vehicle dynamics programs to simulate vehicle behavior. TruckSim also links the simulation results with animation and plotting programs. The package is primarily made up of four tightly integrated software modules. The parts of TruckSim are shown in Figure 2.8. Data screens serve as primary interface to TruckSim. They contain vehicle model parameters, control inputs, and run settings. The data screens are part of a database that maintains libraries of related data sets.

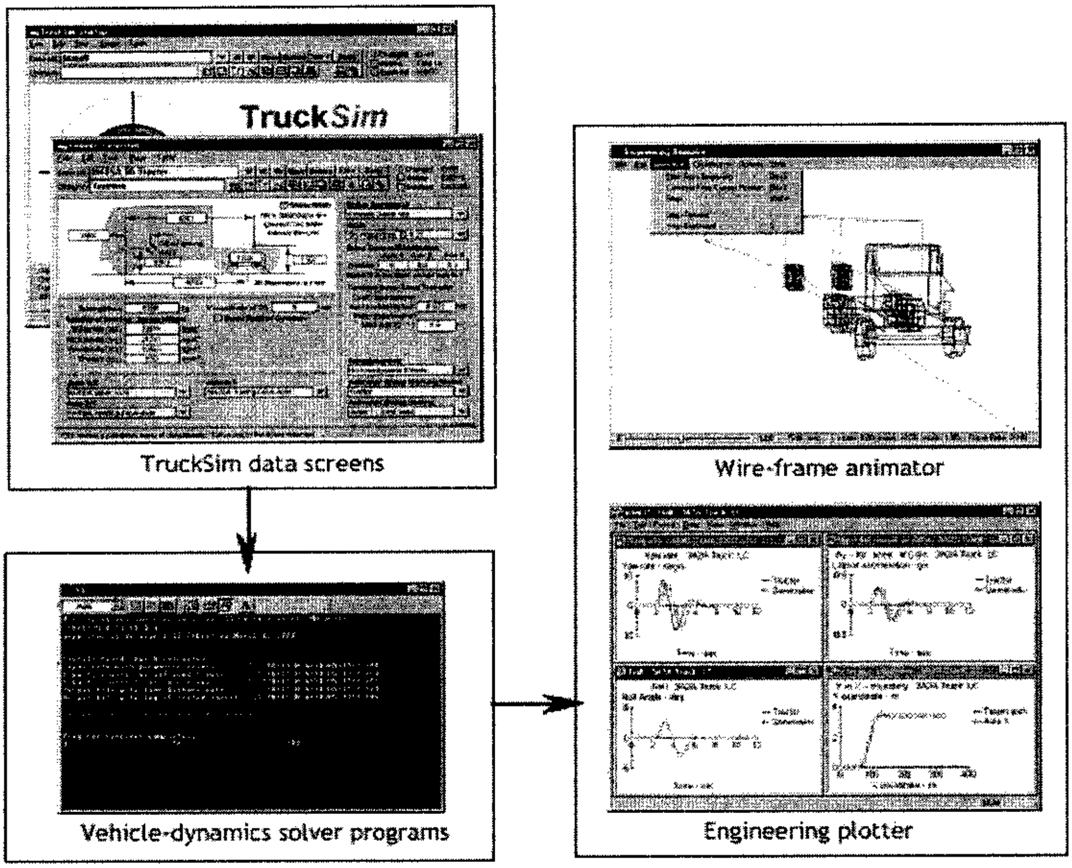


Figure 2.8 Four Parts of TruckSim

TruckSim includes about 60 libraries (each with multiple data sets) that are linked together to make up the database (TruckSim 1995). Vehicle dynamics solver programs use *equations of motion* in mathematical models to calculate output variables. The process of performing these calculations is called making a *simulation run* or simply a *run*. The Windows Engineering Plotter (WinEP) creates plots of vehicle variables as functions of time or as cross plots of output variables. This tool is used to view any of the hundreds of variables computed by the simulation models. Any combination of variables and vehicles can be plotted from different runs. The basic operation of TruckSim involves the sequence shown below:

1. Selection of a vehicle to run.
2. Specification of the control inputs for steering, braking, and throttle, pavement type, and profile input.
3. Running the simulation (as the run proceeds, TruckSim writes force and motion variables into an output file for later analysis).
4. Viewing animation of the simulated test to get an overall view of the vehicle behavior.
5. Viewing plots and analyzing the resultant behavior in more detail.

The motions of the various components in a vehicle are predicted mechanistically by solving the differential equations that describe their dynamics and kinematics. The assumption is made that the truck consists of a system of rigid bodies upon which forces and moments act. The bodies of tractor and semitrailer are the primary masses in the systems. These are supported at each axle by suspension systems, and designated as the *sprung masses*. The mass of axle, brakes, steering knuckle, wheels, and portion of the suspension linkage are denoted as *unsprung masses*. A typical tractor-semitrailer model, illustrated in Figure 2.9, includes two sprung masses (the tractor and semitrailer) and five unsprung masses (one for each axle). The trailer is attached to the tractor at the hitch point with a pin joint. The pin joint allows the semitrailer to rotate relative to the tractor. Each unsprung mass (axle mass) is translated vertically relative to sprung mass. Suspensions are modeled using UMTRI leaf springs. It defines the spring force as a function of displacement and the direction of the deflection. Shock absorbers are dampers that produce a force resisting motion in the suspension. The force is dependent on velocity, but may vary nonlinearly with velocity because of the orifices and blow-off valves used in shock absorbers. In TruckSim, shock absorbers are represented with a list of forces as a function of damper compression rate. These forces can represent linear or nonlinear dampers (Karamihas et al. 1995).

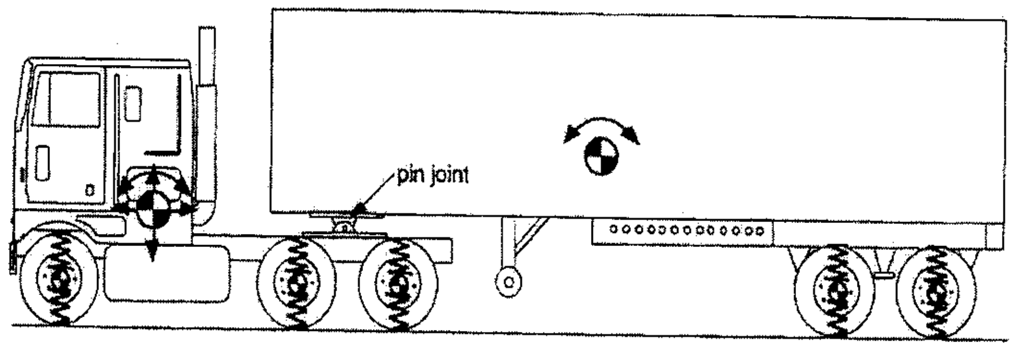


Figure 2.9 Typical Tractor-Semitrailer Model (Karamihas et al. 1995)

Heavy-truck leaf springs have a considerable amount of Coulomb friction. This is often the largest source of damping in a heavy vehicle. The Coulomb friction has a hysteretic behavior (TruckSim 2000). Figure 2.10 describes the force-jounce (suspension compression) behavior of the spring model used in TruckSim. As the spring is compressed and extended, the force of the spring alternatively approaches *compression* and *extension envelopes* (TruckSim 2000). The approaches are exponential in character. Load transfer in tandem suspensions has three components:

1. Static load distribution,
2. Dynamic load transfer due to vertical tire forces, and

3. Dynamic load transfer due to applied wheel spin torques.

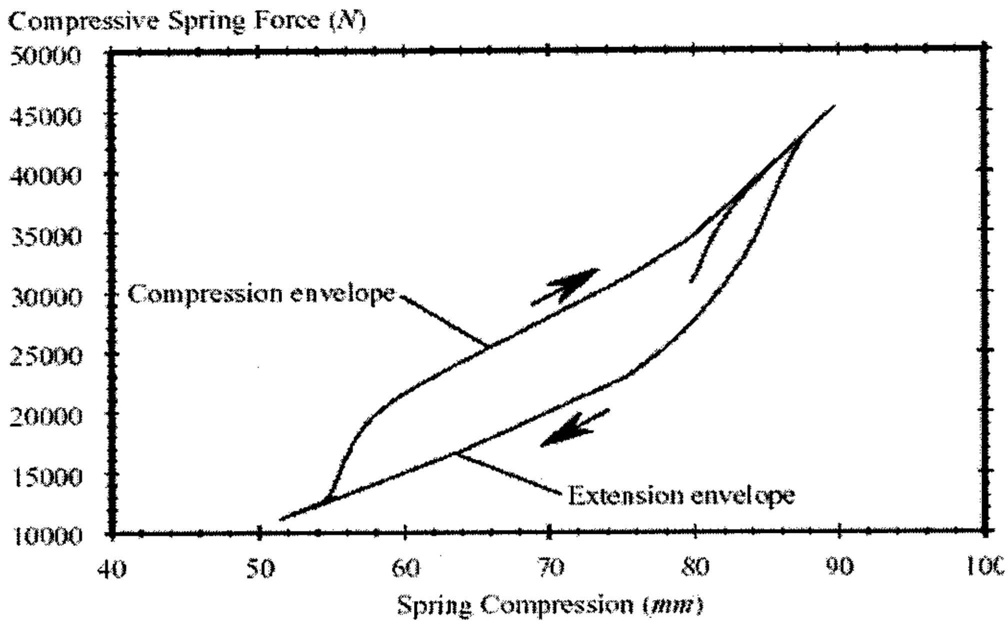


Figure 2.10 Hysteric Force-Jounce Behavior of a Heavy-truck Leaf Spring (TruckSim 2000)

The primary purpose of a tandem suspension with mechanical coupling between axles (e.g., a 4-spring or walking beam) is to equalize the vertical loads on the axles. However, tire forces, which stimulate this equalization, are primarily high frequency inputs to the system due to road roughness (TruckSim, 2000). A schematic of tandem suspension load sharing is shown in Figure 2.11. The springs in this figure are shown as leaf-springs.

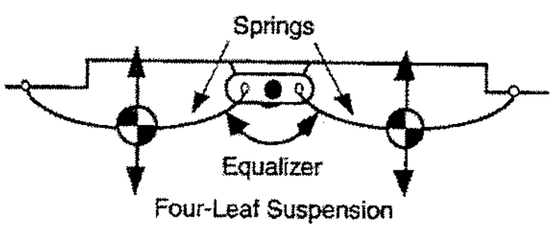


Figure 2.11 Tandem Suspension Load Sharing (Karamihas et al. 1995)

TruckSim can simulate different types of heavy vehicles/trucks. It has some default models for different types and combination of tractor-trailer such as 2-axle truck, 3-axle semi, 3-axle truck, and 5-axle semi, etc. The user can make modifications to the existing combination vehicle by changing the load on axles, distances between axles and tires, etc. The primary interface of TruckSim is the Runs screen. This allows users to move freely within TruckSim, and provides a link to any input screen. The data to be used in the run simulation may be viewed directly from the System field in the Simulation Input section of the Run screen. More detailed sketches of truck can be accessed from the menu. Computation Parameters located in the Simulation Input column controls the simulation and the format of the output data files. It is important that the data resulting from the simulation be stored in a text file. To obtain this format, the input box must contain a FORTRAN format statement, such as, (100G14.6) or (200G14.6). One of the Simulation Input parameters is the road profile, which is the main concern of this study. Since the objective of using TruckSim was to calculate the dynamic wheel load of trucks for various road profiles, creation of new road profile input parameter was of great concern. 'Road Bump' and several other actual road profiles files (IRI files) are currently available in TruckSim. The default, however, is 'no profile.' Detailed instructions for creating new road profile data sets in TruckSim are described below.

The first step to import data into TruckSim is to go to the Road Profile Input screen in TruckSim. While in this screen create a temporary road profile by clicking the NEW button, naming the profile, and inputting a couple of data points in the Profile Input field. The file needs to export for further modification. The exported file will be located in the c:\ TruckSim\ Input\ Prof_Tab\ directory. The exported temporary road profile now needs to be modified and is to be imported with the new road profile data. This can be done by opening the exported road profile with a text editor. An example of an exported file is shown in Figure 2.12. The data input format consists of the horizontal distance in feet followed by the vertical distance in inches separated by a comma. The name and category of the new road profile data need to be changed as well. Once these modifications have been made, the file is ready for import in TruckSim. The new road profile data will now be in TruckSim with the specified name and category. An example of an edited export file ready for importing is also shown in Figure 2.13 as well. In this example the new name is 'I80' and the category is 'Interstates'. Note the amount of data TruckSim can handle is limited. TruckSim can handle maximum of 450 data points. Any data exceeding TruckSim's limit will not be included in the new road profile.

TruckSim simulations generate many types of data related to the forces that exist as a truck travels over the pavements. The data needed in this study are the vertical forces of the left tires and the distances between the axles of each truck type. The results of a simulation may be viewed using a plotter called WinEP. For example, the user can view the vertical tire loads on the any truck simulation, by going to the Output section of the Runs screen. The Plot Setup field will lead to Tires and then to Fz (vertical forces--left side). Then the graph will appear as the data is gathered from the output file. The graph shows each wheel's vertical load. The x (time in seconds) and y (force in pounds) coordinates will appear in the screen. "FZ L1" indicates the vertical forces on the left tire of axle 1. The user can also view all the calculation parameters and the final position values for the simulation.

Exported File

```
exportSGUIFile v1.0
book "INPUT\PROF_TAB\PROFILE.TBK"
category "input,Profile"
page "Temporary"
RField "startend"
1,3,1,9
~endRField
RField "x1000"
~endRField
RField "PlotData"
1,1
2,4
3,9
~endRField
RField "notes"
Data for no tabular profile input.
~endRField
RField "subdir"
IRI25.0
~endRField
```

Figure 2.12 Example of an Exported Profile Input Data File (Bhatti et al. 1996)

Modified File for Importing

```
exportSGUIFile v1.0
book "INPUT\PROF_TAB\PROFILE.TBK"
category "input,Profile"
page "I80"
RField "startend"
1,3,1,9
~endRField
RField "x1000"
~endRField
RField "PlotData"
1,2
2,4
3,6
4,8
5,10
6,12
7,14
8,16
9,18
10,20
11,22
12,24
~endRField
RField "notes"
Data for no tabular profile input.
~endRField
RField "subdir"
Interstates
~endRField
endBook
```

Figure 2.13 Example of a Modified Exported Road Profile Input Data File (Bhatti et al. 1996)

CHAPTER 3

PROJECT IDENTIFICATION AND DATA COLLECTION

3.1 SELECTION OF PROJECTS

The projects selected for the roughness progression study are all jointed plain concrete pavements (JPCP) constructed after 1992. The year 1992 was chosen as the base year since KDOT started profile-based roughness measurements that year. Twenty-one projects were selected as shown in Table 3.1. The projects varied in length from 1 mile (1.6 km) to 10 miles (16 km). Most of the projects are on the Interstate and US routes in urban areas. The average equivalent single axle loads (ESAL's) per day ranged from 211 to 11,988. All projects had treated subgrades and subbases. Dense graded Portland Cement Treated Bases (PCTB) were used on some projects. For the last few years, KDOT has been using Bound Drainable Bases (BDB) with cement and cement-fly ash as binders. A drainable base is defined as the base with a minimum of 303 meter/day (1000 ft/day) permeability.

For damage analysis three projects, I-135 (McPherson County), US-75 (Jackson County), and K-7 (Johnson County), were selected randomly from the projects under roughness progression study. I-135 was built smoother than the other two. Table 3.2 shows the projects selected for damage analysis. The initial roughness in IRI indicates the roughness measured with the KDOT South Dakota-type profiler during network level pavement management system (PMS) survey in the first year after construction.

TABLE 3.1 Projects Selected for Roughness Progression Study

County	Route	Begin M.P.	End M.P.	Project #	Lane	Base Type	ESAL/day	Construction Date
Shawnee	70	9	10	K-3344-01	West	PCTB	11192	Oct-93
Shawnee	70	9	10	K-3344-01	East	PCTB	11192	Oct-93
Osage	75	13	15	K-3347-01		BDB	1713	Nov-93
Jackson	75	0	8	K-3250-01	North	PCTB	2656	Oct-94
Jackson	75	0	8	K-3250-01	South	PCTB	2656	Oct-94
Lyon	50	0	7	K-2853-01		PCTB	4710	Dec-94
Johnson	7	12	15	K-3382-01	North	PCTB	1567	Sep-95
Johnson	7	12	15	K-3382-01	South	PCTB	1567	Sep-95
Osage	35	6	11	K-5028-01		BDB	10996	Dec-95
Shawnee	75	20	22	K-4341-01	North	BDB	3735	Jun-96
Shawnee	75	20	22	K-4341-01	South	BDB	3735	Jun-96
Jackson	75	12	17	K-3251-01	North	BDB	1993	Aug-96
Jackson	75	12	17	K-3251-01	South	BDB	1993	Aug-96
Johnson	35	13	16	K-4088-02	North	BDB	11988	Sep-96
Johnson	35	13	16	K-4088-02	South	BDB	11988	Sep-96
Cowley	360	0	3	K-4432-02		PCTB	211	Sep-96
McPherson	135	6	14	K-4689-01	North	BDB	8272	Oct-96
McPherson	135	6	14	K-4689-01	South	BDB	8072	Oct-96
Shawnee	75	3	8	K-3371-03		BDB	696	Nov-97
Chase	50	0	9	K-3216-02		PCTB	4853	Dec-97
Chase	50	9	19	K-3217-02		PCTB	4980	Dec-97

TABLE 3.2 **Projects Selected for Damage Analysis**

County	Route	Begin M.P.	End M.P.	Const. Date	Lane	Layer Thicknesses		Initial IRI (in/mi)
						PCC Slab	Base	
Jackson	75	0	8	Oct-94	North	9in	4in	153
Jackson	75	0	8	Oct-94	South	9in	4in	78
Johnson	7	12	15	Sep-95	North	9in	4in	79
Johnson	7	12	15	Sep-95	South	9in	4in	81
McPherson	135	6	14	Oct-96	North	11in	4in	57
McPherson	135	6	14	Oct-96	South	11in	4in	71

3.2 SELECTION OF DATA ELEMENTS AND DATA COLLECTION

Data elements were selected based on availability and their potential influence on the roadway profile. Table 3.3 lists the data elements collected under three groups (inventory, construction and climate) for this study. Inventory and the majority of the construction data were derived from the KDOT's Construction Management System (CMS) database. The Kansas State University Weather Data Library provided nearly all of the climatic data. The historical roughness data was obtained from the KDOT PMS database. Several variables were discarded in the analysis process. For example, average annual daily traffic (AADT) was replaced by the equivalent single axle loads (ESAL) per day. By replacing AADT with ESAL/day, the possibility of inter-related variables was kept to minimum.

One problem encountered during data collection process was how to get as-constructed Profile Index (PI) values for the projects in this study. The PI values were generally available. However, matching the PI values from the construction station references with the county-route-mile post referencing system used for obtaining and logging roughness data in the KDOT PMS database was difficult at best. For this reason, as-constructed PI values were obtained for only ten projects.

TABLE 3.3 Data Elements Selected as Independent Variables in this Study

INVENTORY	CONSTRUCTION	CLIMATE
County Code	Construction Date	Annual Precipitation*
Route No.	Drainage Type*	Wet Days/Year*
Project No.	JRCP or JPCP	Mean Annual Temp.*
Begin Milepost	Conc. Comp. Strength*	Minimum Avg. Temp.*
End Milepost	Conc. Unit Wt.*	Maximum Avg. Temp.*
Project Length	Conc. Mod. of Rupture*	Days Below 0 C*
AADT	Conc. Water/Cement*	Days Above 32 C*
DHV	% Air*	Freeze-Thaw Cycles/Yr.*
Directional Distribution	% Fine Agg.*	
Percent Trucks*	% Coarse Agg.*	
Posted Speed Limit*	% Cement	
ESAL/Day*	% Water	
Annual IRI Roughness*	Transverse Joint Spacing*	
	Width of Outside Shoulder*	
	Subbase Thickness*	
	Subbase Stabilization*	
	Subgrade Treatment*	
	Permeable Subbase*	
	Subgrade Depth*	
	Subgrade Plasticity Index*	
	Subgrade Liquid Limit*	
	Subgrade % Pass #4*	
	Subgrade % Pass #200*	
	Dowels (y/n)*	
	Dowel Spacing*	
	PRI*	

* independent variable in statistical analysis

The rate of roughness progression was calculated using an exponential fit of the annual roughness data. The average IRI value for a project was calculated from the annual PMS data on individual mile segments. An exponential curve was fitted to the mean annual IRI data, and the rate of roughness progression was determined from the slope of this curve. Figure 3.1 shows a typical example of exponential curve fitted to the mean annual IRI data. Table 3.4 shows the results of this analysis. The exponential fit was judged to be good. The linear fit was also tried to calculate the roughness rate. An Example of a linear fit to the annual IRI data is also shown in Figure 3.2.

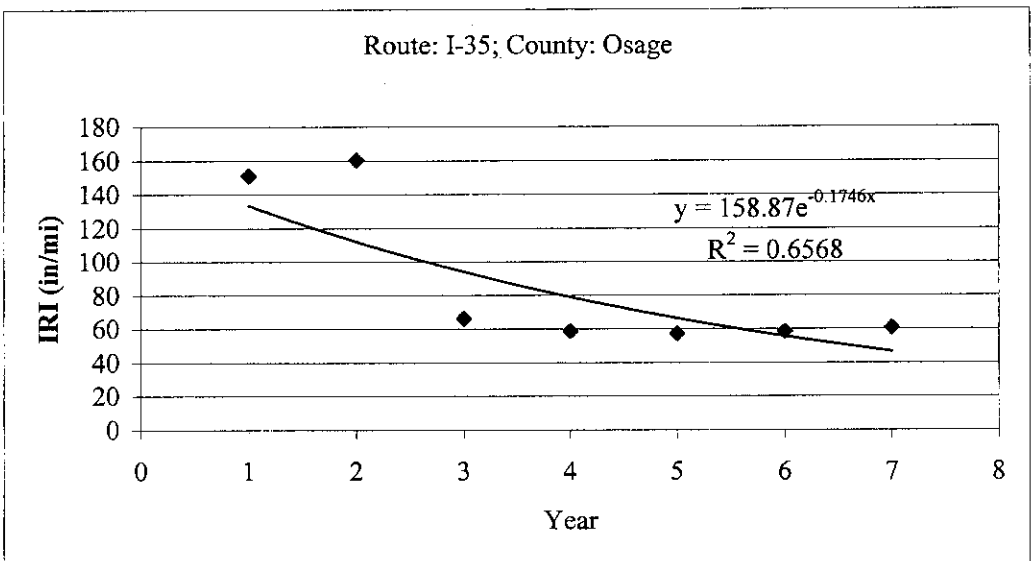


Figure 3.1 Example of an Exponential-fit Curve to the Mean Annual IRI Data

TABLE 3.4 Rates of IRI Roughness Progression

County	Route	Project No.	Construction Date	Equation - Exponential fit	Slope	R^2
Shawnee	70	K-3344-01(W)	10/15/93	$y=1.5331e^{(0.0088x)}$	0.0088	0.1334
Shawnee	70	K-3344-01(E)	10/15/93	$y=1.3371e^{(0.0186x)}$	0.0186	0.8064
Osage	75	K-3247-01	11/30/93	$y=1.4939e^{(0.0112x)}$	0.0112	0.1362
Jackson	75	K-3250-01(N)	10/21/94	$y=2.0344e^{(-0.0864x)}$	-0.0864	0.6091
Jackson	75	K-3250-01(S)	10/21/94	$y=1.1787e^{(-0.0167x)}$	-0.0167	0.3169
Lyon	50	K-2853-01	12/27/94	$y=1.287e^{(0.0016x)}$	0.0016	0.0125
Johnson	7	K-3382-01(N)	9/8/95	$y=1.2399e^{(0.0072x)}$	0.0072	0.3018
Johnson	7	K-3382-01(S)	9/8/95	$y=1.2879e^{(0.0023x)}$	0.0023	0.0813
Osage	35	K-5028-01	12/4/95	$y=2.5074e^{(-0.1746x)}$	-0.1746	0.6568
Shawnee	75	K-4341-01(N)	6/28/96	$y=1.0347e^{(0.0483x)}$	0.0483	0.6702
Shawnee	75	K-4341-01(S)	6/28/96	$y=1.3318e^{(0.0176x)}$	0.0176	0.4112
Jackson	75	K-3251-01(N)	8/13/96	$y=1.0641e^{(0.0263x)}$	0.0263	0.8998
Jackson	75	K-3251-01(S)	8/13/96	$y=1.018e^{(0.0279x)}$	0.0279	0.58
Johnson	35	K-4088-02(N)	9/1/96	$y=1.5141e^{(0.0057x)}$	0.0057	0.0691
Johnson	35	K-4088-02(S)	9/1/96	$y=1.5864e^{(0.0196x)}$	0.0196	0.3037
Cowley	360	K-4432-02	9/11/96	$y=1.6174e^{(-0.0211x)}$	-0.0211	0.8707
McPherson	135	K-4689-01(N)	10/15/96	$y=0.8971e^{(0.0192x)}$	0.0192	0.129
McPherson	135	K-4689-01(S)	10/15/96	$y=1.1004e^{(-0.0128x)}$	-0.0128	0.1924
Shawnee	75	K-3371-03	11/26/97	$y=1.0959e^{(-0.0373x)}$	-0.0373	0.8436
Chase	50	K-3216-02	12/4/97	$y=0.9455e^{(0.0381x)}$	0.0381	0.675
Chase	50	K-3217-02	12/4/97	$y=1.101e^{(0.0322x)}$	0.0322	0.3602

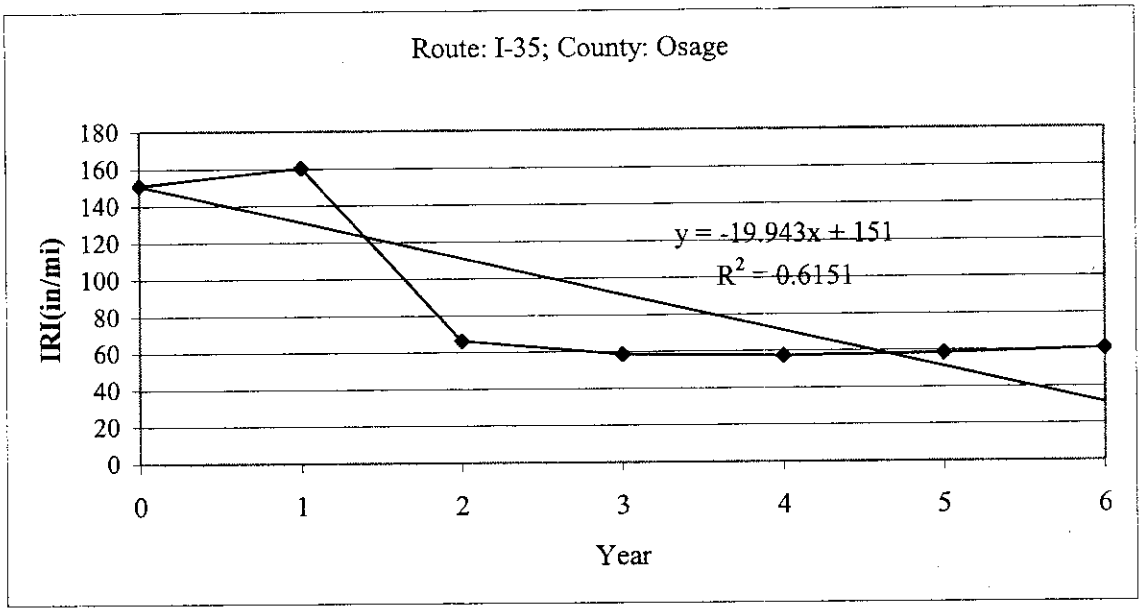


Figure 3.2 Example of a Linear-fit to the Mean Annual IRI Data

On average, exponential fit appeared to give higher coefficients of determination, R^2 values for most of the projects. Some of the newer projects were found to have negative slopes, indicating a decrease in roughness progression. However, most had increasing roughness with time. The occurrence of negative slope is not unusual for the concrete pavements in Kansas. Figure 3.3 shows the average SPS-2 project roughness measured by an LTPP 690DNC profiler up to 1997 and then by an LTPP K.J. Law 8300 profiler. The project showed a decrease in annual roughness initially.

The data was divided into several subgroups depending on the rate of the roughness progression and availability of as-constructed smoothness measurements. Division was also made based on the concrete strength variables. Figure 3.4 shows the subdivision of the database for statistical analysis. The largest database consists of 15 projects and the smallest one consists of six projects.

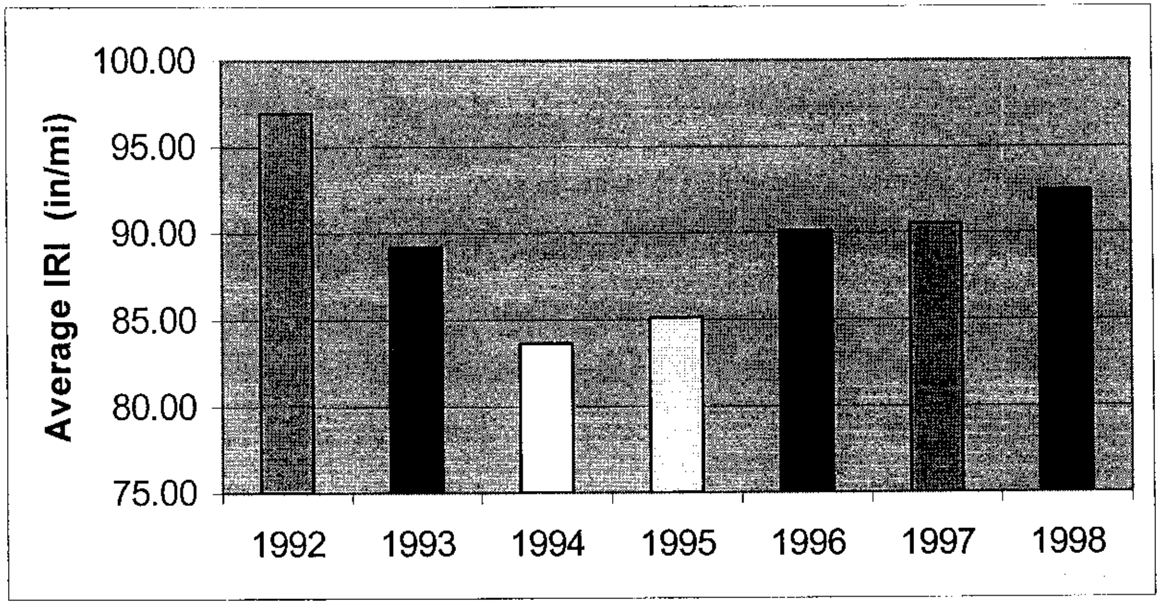


Figure 3.3 Kansas SPS-2 Project Roughness History (I-70, Geary County)

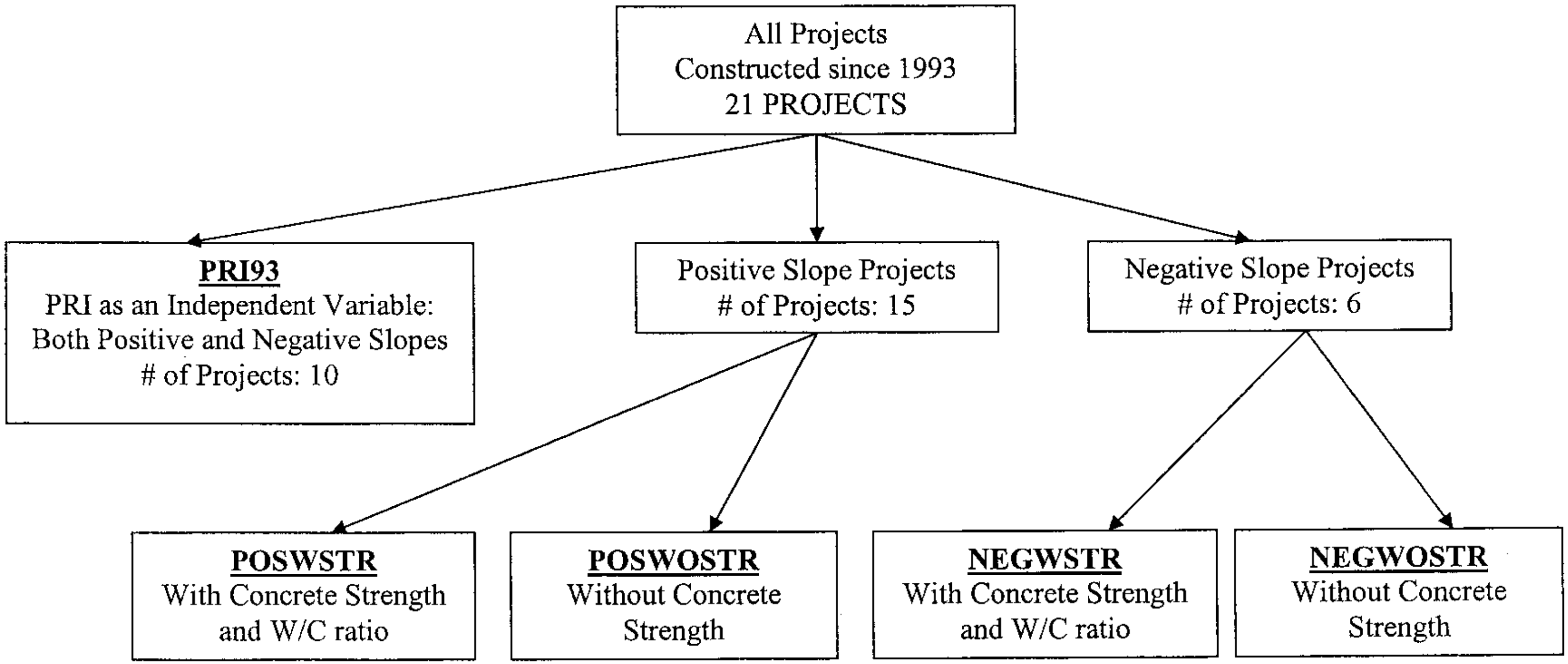


Figure 3.4 Division of Data

3.3 INPUT PARAMETERS FOR ROADRUF

As described in Chapter 2, the RoadRuf requires files in the ERD format. An ERD file contains two independent sections, the header and the data. The header contains only text, and the data section contains numbers. The numbers can be written in either text or binary form. If the data section is in text format then both the header and the data are kept in a single file. The format for the data section consists of vertical distance in feet. The only restriction on free format numbers is that adjacent numbers must be separated. The only input parameter in calculating IRI using RoadRuf was the road profile. The RoadRuf was used to calculate IRI for 0.02 mile (0.032 km) long segments.

3.4 INPUT PARAMETERS FOR TRUCKSIM

The computer software TruckSim was used to calculate the dynamic wheel load for a selected truck for different road profiles. The truck used in this study is shown in Figure 3.5. The figure also shows the spacing between axles and static loads on each axle. The axle and tire spacing is also shown in Figure 3.6.

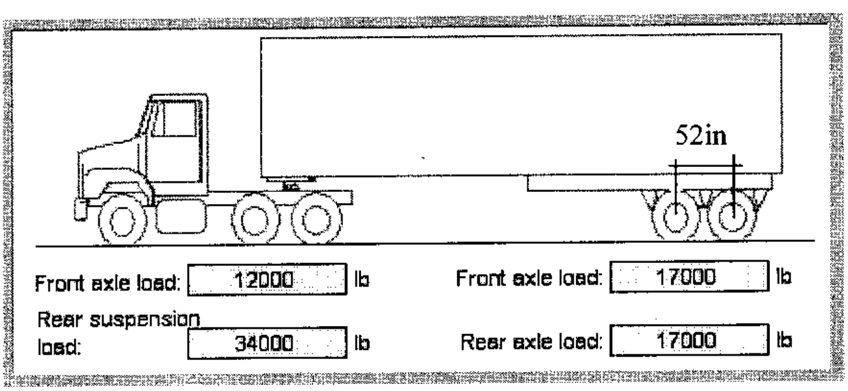


Figure 3.5 5-axle Tandem Truck and Loads on Axles

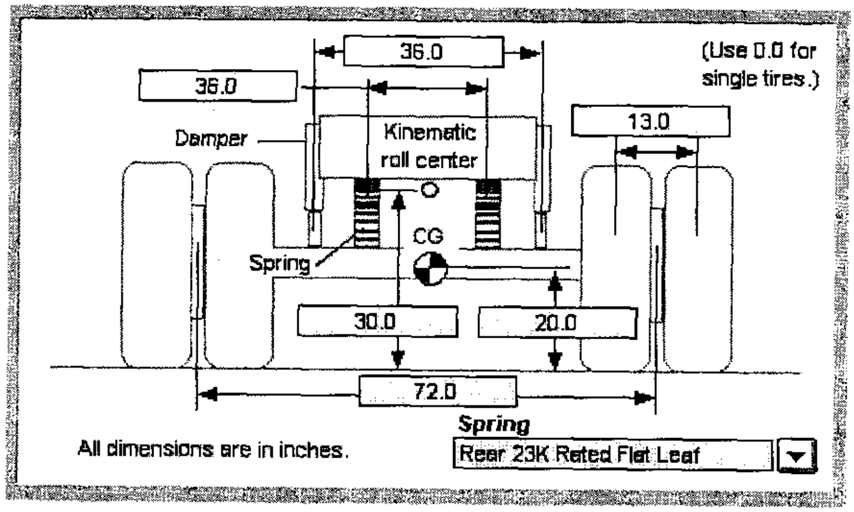


Figure 3.6 Distance between Tires

Another input parameter was the profile data for each run. The format for profile input consists of the horizontal distance in feet followed by the vertical distance in inches separated by a comma. As mentioned earlier, the amount of data TruckSim can handle is limited. TruckSim can handle maximum of 450 data points. KDOT collects profile data at 3 inch (76 mm) intervals. That is why a 0.02 mile (0.032 km) segment was chosen for each run. The simulation was run and dynamic wheel loads were calculated at 60 mph (97 km/hr).

3.5 INPUT PARAMETERS FOR KENSLAB

Input parameters for damage analysis using KENSLAB are listed in Table 3.5. Standard values for elastic modulus of elasticity of concrete, modulus of elasticity of steel, modulus of dowel support, co-efficient of thermal expansion of concrete, etc. were assumed. Number of load repetitions was calculated using the ESAL's and Equivalent Axle Load Factors (EALF) for the selected truck. EALF for the PCC pavements depends on the slab thickness. The EALF's for K-7, US-75, and I-135 were 4.016, 4.016 and

Table 3.5 Input Parameters for KENSLAB

Modulus of Elasticity of Concrete = $4X10^6$ psi(27.6 GPa)
Poisson's Ratio of Concrete = 0.15
Modulus of Elasticity of Steel = $29X10^6$ psi(200 GPa)
Poisson's Ratio of Steel = 0.3
Modulus of Dowel Support = $1.5X10^6$ pci($4.15X10^{10}$ kg/m^3)
Co-efficient of Thermal Expansion = $5.5X10^{-6}$ in/in/^{0}F($9.9X10^{-6}$ mm/mm/^{0}C)
Tire Pressure = 90psi(0.62MPa)

County	Route	Construction Date	PCC Thickness (in)	Modulus of Rupture (psi)	Subbase Thickness (in)	Subgrade Depth (in)	Dowel Spacing (in)	Joint Spacing (ft)	Joint Type
Jackson	US 75	10/21/1994	9	512	4	6	12	15	Contraction
Jackson	US 75	10/21/1994	9	512	4	6	12	15	Contraction
Johnson	K 7	9/8/1995	9	550	4	6	12	15	Contraction
Johnson	K 7	9/8/1995	9	550	4	6	12	15	Contraction
McPherson	I 135	10/15/1996	11	589	4	6	12	15	Contraction
McPherson	I 135	10/15/1996	11	589	4	6	12	15	Contraction

4.094, respectively. The loaded area for each tire was calculated using a tire pressure of 90psi (0.62MPa).

3.5.1 Placement of Wheels on PCC Slab

It was discussed earlier that truckload placement must be carefully considered in the rigid pavement fatigue damage analysis. According to the PCA method, if the stress ratio is less than 0.45, it has no effect on fatigue damage. The stress ratio is the ratio between the maximum flexural stress and the modulus of rupture. Proper wheel placement is necessary to calculate maximum stresses. Figure 3.7 shows the distance between the tandem axles modeled in this study. All three projects have 15 foot (4.5 m) long PCC slabs. The full length of the truck selected for this study does not fit on one slab. It was decided to split the truck in two parts - (1) combination of the first single axle and the first tandem axle, and (2) only second tandem axle. Two adjacent slabs were chosen to take into account the joint and load transfer capacity of dowels. Both combinations of wheels were used and the maximum stress for each one was calculated. It was observed that the second combination gives stresses larger than that of the first combination of wheels. Figure 3.8 shows the position of the second tandem axle on two slabs. It was also mentioned earlier that the most critical loading and stress locations for fatigue damage are mid-slab edge loading and joint loading. The position of wheels, shown in Figure 3.8, covers both mid-slab edge loading and joint loading locations. The dimension of wheels (input parameter for KENSLAB: loaded area) varies with different dynamic wheel loads and was calculated using a tire pressure of 90psi (0.62MPa).

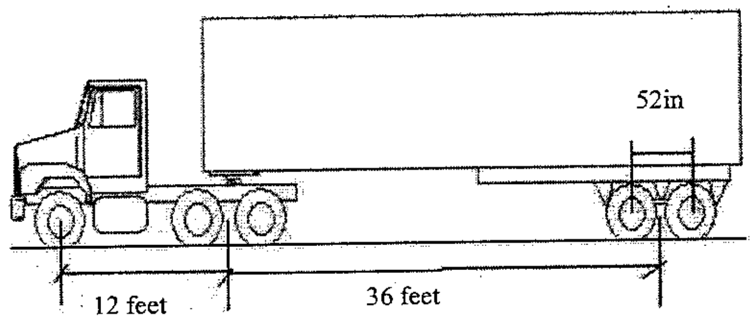


Figure 3.7 Axle Spacing for selected 5-axle Tractor-Semitrailer Model

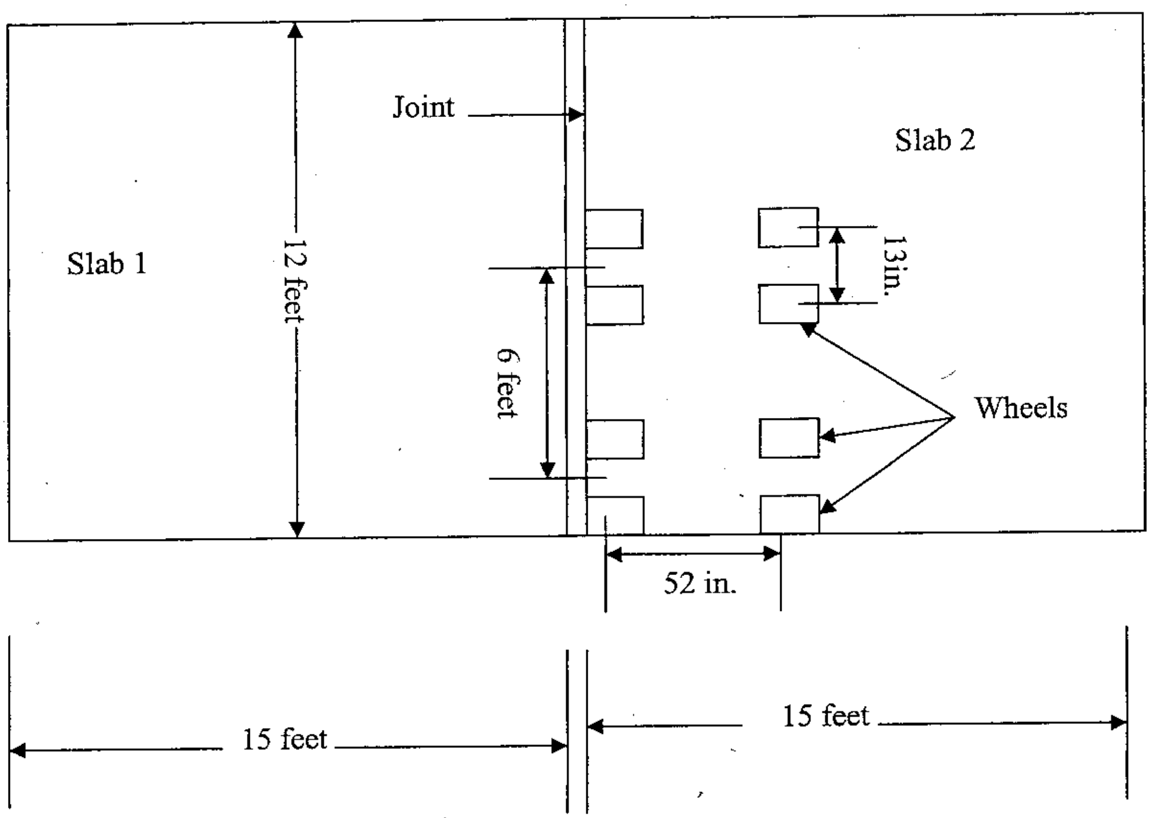


Figure 3.8 Placement of Third Axle Wheels on Slab (not to scale)

CHAPTER 4

FACTORS AFFECTING ROUGHNESS PROGRESSION

4.1 MULTIPLE REGRESSION ANALYSIS

4.1.1 Background

For this study, models were developed that would quantify key predictor variables, which influence the rate of roughness progression. Multiple regression analysis (MRA) is helpful for developing predictive equations of a dependent variable and various independent variables. MRA finds a correlation between the independent and dependent variables. Correlation between more than one independent variable and a dependent variable can be determined in multiple regression analysis. An equation, known as a "model," is the result of multiple regression analysis. The assumption was made that the rate of roughness progression satisfies the following relationship:

$$\text{Rate} = F\text{ (inventory data, construction data, and climatic data)}$$

The function F has partial derivatives with respect to the variables in the argument. The function reduces to an expression, which is linear in form:

$$\text{Rate} = a_0 + a_1X1 + a_2X2 + a_3X3 + \ldots$$

Where Rate is the dependent variable; X_1, X_2, and X_3 are the independent variables; and a_0, a_1, a_2, and a_3 are linear regression coefficients.

4.1.2 Model Selection Criteria

Models were selected based on a variety of statistical information. The following criteria were considered:

(1) R^2 Value: The selected model in this study usually was the model with the largest R^2 but with a minimum number of variables;

(2) *t-statistic:* Variables with a t-value less than two were considered as insignificant variables; and

(3) *Practicality*: Engineering judgment was used to interpret which models were practical and which were not.

4.1.3 Model Development

Statistical Analysis System (SAS) (SAS 1979) computer program was used for statistical analysis of data in this study. Several methods exist to determine which model best explains the data. The forward selection procedure in SAS was used to determine which independent variables most influence the dependent variable, the rate of roughness progression, in this study. This procedure in SAS first selects the variable that has the highest correlation with the dependent variable, rate of roughness progression. From this point additional variables, those that increase the R^2, are added to the model. With each addition of a variable, R^2, MSE, and the F-statistic are computed and reported in the output. The addition of variables is continued until all variables with five-percent significance level have been added to the model, and the model appeared to satisfy all other model selection criteria discussed earlier. The following models were derived:

1. *Model for the rate of roughness progression with as-constructed smoothness as one of the dependent variables (PRI93)*: In this model, projects with both positive and negative slopes and as-constructed smoothness values were included in analysis. There were 10 projects that had as-constructed smoothness values. Table 4.1 shows the model obtained. The as-constructed smoothness, PI, did not appear to be a significant factor in determining the rate of roughness progression.

2. *Model for increasing rate of roughness progression with the concrete strength as independent variables (POSWSTR)*: For this model, all projects with positive slopes (positive rate of roughness progression) were selected. There were 15 projects that showed positive roughness progression. Concrete strength (i.e. compressive strength and concrete modulus of rupture) was included as independent variables to identify their effect on roughness progression. Table 4.1 also shows the selected model. Neither of the concrete strength data types was selected in the model. However, the initial roughness, the roughness measured during the first year after construction, is a significant variable in this model.
3. *Model for increasing rate of roughness progression without concrete strength as independent variables (POSWOSTR)*: All projects with positive slope were analyzed without taking concrete strength data as independent variables. The model obtained in this case is the same as in *POSWSTR*.
4. *Model for decreasing rate of roughness progression with the concrete strength as independent variables (NEGWSTR)*: For this model, all projects with negative slope (negative rate of roughness progression) were considered. Six projects showed decreasing roughness progression. Concrete strength data was included to observe the effect on roughness progression. Table 4.1 also shows the selected model. The concrete modulus of rupture is a significant variable in this model. Initial roughness is the other significant variable.

TABLE 4.1 Models Derived with Exponential-fit Rate of Roughness Progression

Variable	Description	Coefficient	p -value	Model Statistics
PRI93 (10 Projects)				
Intercept	Y-intercept	0.4962	0.031	$R^2 = 0.6333$ SSE = 0.0011 MSE = 0.0002
MOR	Concrete Modulus of Rupture (MPa)	-0.0167	0.187	
PI	Subgrade Material Plasticity Index before treatment	0.002	0.276	
TUHUND	Subgrade Materials Passing 0.075 mm Sieve	-0.4977	0.0216	
POSWSTR (15 Projects)				
Intercept	Y-intercept	-0.3956	0.17	$R^2 = 0.8671$ SSE = 0.0003 MSE = 0.00005
CA	% Coarse Aggregate in Mix (Decimal Form)	0.0764	0.705	
WOS	Width of Outside Shoulder (m)	0.0117	0.613	
PI	Subgrade Material Plasticity Index before treatment	0.0051	0.009	
TUHUND	Subgrade Materials Passing 0.075mm Sieve	-0.147	0.05	
WD	Number of days with more than 10 mm of Precipitation	0.0050	0.21	
MINT	Average Low Temperature (0^oC)	-0.0079	0.02	
INI	Initial IRI (m/km)	-0.0739	0.004	
NEGWSTR (6 Projects)				
Intercept	Y-intercept	-0.4872	0.0043	$R^2 = 0.9999$ SSE = 0.0000 MSE = 0.0000
MOR	Concrete Modulus of Rupture (MPa)	0.1753	0.005	
LL	Subgrade Material Liquid Limit before treatment	-0.6620	0.009	
WD	Number of days with more than 10 mm of Precipitation	0.0016	0.03	
INI	Initial IRI (m/km)	0.0583	0.004	
NEGWOSTR (6 projects)				
Intercept	Y-intercept	-0.3559	0.08	$R^2 = 0.9969$ SSE = 0.0000 MSE = 0.0000
P	Permeable Subbase (1=Yes, 0=No)	0.0402	0.16	
ESAL	Equivalent Single Axle Load per Day	0.0000042	0.283	
AP	Mean Annual Precipitation (mm)	0.0031	0.12	
INI	Initial IRI (m/km)	0.0599	0.1	

5. *Model for decreasing rate of roughness progression without concrete strength as independent variables (NEGWOSTR)*: Concrete strength was excluded from the list of independent variables in this case, and all projects with negative slopes were analyzed. This model appeared to be very different from NEGWSTR. Traffic ESAL/day and the initial roughness are the significant variables as shown in Table 4.1.

The following models were derived with the linear-fit rate of roughness progression and by taking the initial roughness or as-constructed smoothness values as independent variables. Table 4.2 shows the model derived under this category.

1. *JPCPWINI*: Model for IRI roughness on JPCP=s constructed after 1992. Table 4.2 shows that the initial IRI values, measured during the first year after construction, significantly affect the rate of IRI roughness progression. Higher initial IRI may be due to surface irregularities resulting from construction or due to changes in moisture content of the subgrade soil before it reaches equilibrium.
2. *PRIVARI*: Model for IRI roughness progression on JRCP and JPCP with as-constructed PI as an independent variable. Water-cement ratio and equivalent single axle loads per day (ESAL's/day) influence the rate of IRI roughness progression the most as shown in Table 4.2.
3. *9597IRI*: Model for IRI Roughness on JPCP constructed between 1990 and 1994. Table 4.2 shows the effect of initial IRI on the rate of IRI roughness progression for very new projects (2 to 4 years). A decrease in the rate of IRI roughness progression was observed as the initial IRI value increases.

TABLE 4.2 Models Derived with Linear-fit Rate of Roughness Progression

Variable	Description	Coefficient	t-statistic
JPCPWINI			
Intercept	y-intercept	0.301	6.14
INI	Initial IRI	-0.228	-7.35
Model Statistics: $R^2 = 0.83$ MSE = 0.0035 F = 53.67 p = 0.0001 N = 13			
PRIVARI			
Intercept	y-intercept	-4.19	-1.87
WCR	Water-Cement Ratio	10.803	2.05
ESAL	Equivalent Single Axle Loads/Day	-0.000115	-3.48
Model Statistics: $R^2 = 0.70$ MSE = 0.0382 F = 5.93 p = 0.0479 N = 8			
9597IRI			
Intercept	y-intercept	0.294	5.44
IRI	Initial IRI	-0.230	6.76
Model Statistics: $R^2 = 0.85$ MSE = 0.0040 F = 46.80 p = 0.0001 N = 10			

4.2 SENSITIVITY ANALYSIS

The coefficient of determination (R^2) values only show the relative variation in the models obtained. For these models, the rate of roughness progression was plotted against several independent variables to study the sensitivity of the predicted variable, rate of roughness progression, toward different levels of significant independent variables. The sensitivity analysis determined the effects of three levels, minimum, median, and maximum, of each independent variable, if applicable. Sensitivity analysis was conducted on the models with exponential fits only since those models were judged to be superior to the models with the linear fit.

4.2.1 PRI93 Sensitivity Analysis

Table 4.1 shows that the concrete modulus of rupture, subgrade material plasticity index, and the subgrade material passing US No. 200 (0.075 mm) sieve are the factors that significantly effect the rate of roughness progression. Figure 4.1 shows the effects of these three factors on the rate of roughness progression. Other things being constant, an increase in concrete modulus of rupture by 1.5MPa will decrease the rate of roughness progression by 0.025. It appears that concrete pavements built with higher flexural strength tend to sustain the as-constructed smoothness longer. It should be mentioned here that the average age of the beam samples for calculating concrete modulus of rupture varied from 4 to 6 days. A seven-percent increase in subgrade material plasticity index will tend to increase the rate of roughness progression by 0.013. This indicates that subgrade treatment would be beneficial to sustain the as-constructed smoothness. An increase in the amount of subgrade material passing US No. 200 (0.075mm) sieve will decrease the rate of roughness progression. This finding is somewhat surprising. However, this indicates that subgrade treatment would be most beneficial as far as smoothness is concerned, when a large percentage of subgrade material consists of silt and clay.

4.2.2 POSWSTR Sensitivity Analysis

Table 4.1 also lists factors that significantly affect the rate of roughness progression on projects where roughness has been steadily increasing since construction. Figure 4.2 shows the effects of those factors on the rate of roughness progression. The effect of each factor was studied while keeping others constant. An increase in the percent coarse aggregate in the concrete mix will increase the rate of roughness progression. KDOT currently uses two types of mixture; 50% coarse and 50% sand and 30% coarse and 70% sand. The higher sand mixes tend to have lower rate of roughness progression. The same effect was also observed with the factors: width of outside shoulder, subgrade material

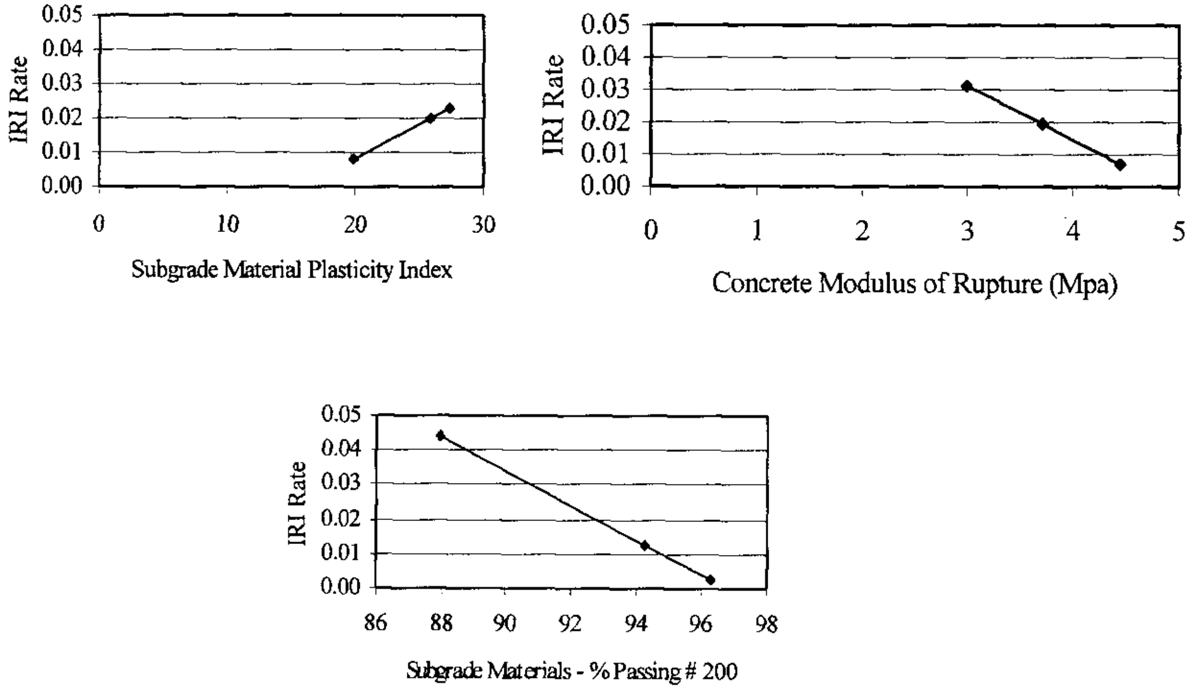


FIGURE 4.1 PRI93 Sensitivity Analysis

plasticity index, subgrade material passing US No. 200 (0.075mm) sieve and the number of wet days (with more than 10mm precipitation). The rate of roughness progression is more sensitive to the subgrade material plasticity index and the number of wet days than to the subgrade material passing US No. 200 (0.075 mm) sieve. The sensitivity of the IRI rate increase to the number of wet days is not surprising. More wetting and drying results in higher slab warping. The effect is opposite for the factors average low temperature and initial IRI. A 5^0C decrease in the average low temperature will decrease the rate of roughness progression by 0.039. Figure 4.2 also illustrates the influence of initial IRI on the rate of roughness progression. A decrease in the rate of IRI roughness progression of 0.05 was observed when the initial IRI was almost twice the minimum initial IRI roughness for the projects in this model. This demonstrates that although high initial roughness is encountered often for new PCCP's, some degree of pavement "smoothening" occurs when traffic passes over it. This also may happen due to stabilization of subgrade soil moisture during early years of pavement life. It is, however, accepted that eventually all pavements will have positive rates of roughness progression.

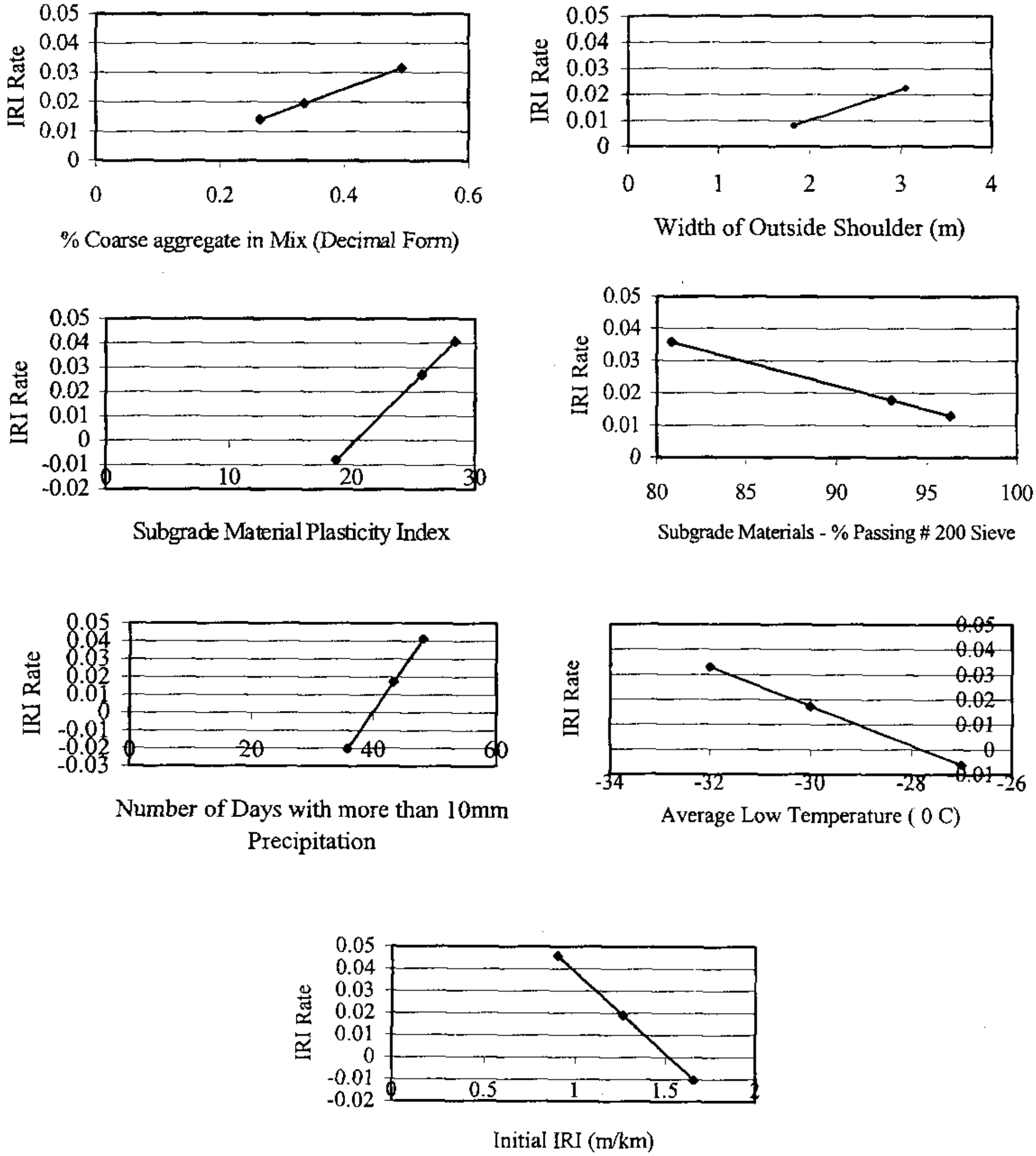


FIGURE 4.2 POSWSTR Sensitivity Analysis

4.2.3 NEGWSTR Sensitivity Analysis

Concrete modulus of rupture, subgrade material liquid limit, number of wet days (with more than 0.4in. precipitation), and initial IRI influence the negative rate of roughness progression in most of the projects in this model as shown in Table 4.1. Figure 4.3 illustrates the effect of these factors on the rate of roughness progression. A 145psi increase in the concrete modulus of rupture will increase the negative rate of roughness progression by about 0.16. This increased negative rate of roughness progression means pavements would become even smoother or in other words, would retain the as-constructed smoothness longer. The effect is the same as that had been discussed earlier. An increase in the subgrade material liquid limit by about 10% would decrease the negative rate of roughness progression by 0.08. Figure 4.3 also shows that the negative rate of roughness increases with the increase in number of wet days and initial IRI. Initial IRI values above 70in/mi produce pavements with decreasing rates of IRI roughness progression. High initial IRI values offer a large window of pavement "smoothening" to occur during early years of pavement lives.

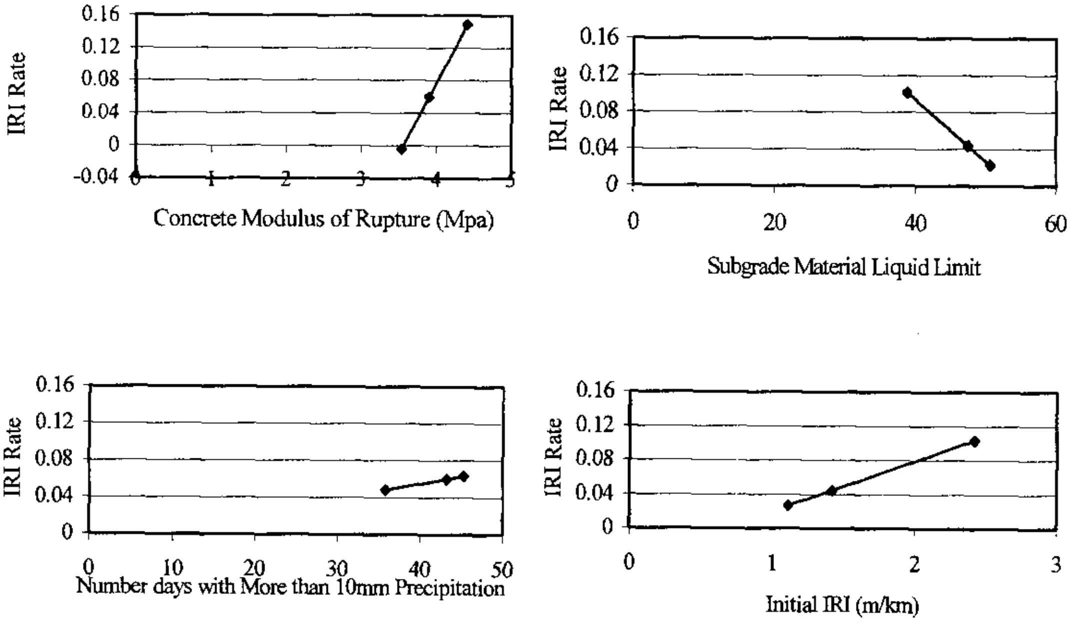


FIGURE 4.3 NEGWSTR Sensitivity Analysis

4.2.4 NEGWOSTR Sensitivity Analysis

Table 4.1 also lists the factors that affect the negative rate of roughness progression significantly. Figure 4.4 shows the effect of permeable sub-base on the negative rate of roughness progression. A permeable sub-base tends to help retain the as-constructed smoothness longer. As the project is opened to traffic, it "smoothens" the pavement and tends to slow IRI roughness progression. An increase in the amount of traffic by 7000 ESAL's/day will increase the negative rate of roughness progression by 0.03. Higher ESAL's/day tend to produce smoother pavements with time initially. The higher number of ESAL's/day may contribute to the "smoothening" of the surface irregularities of the pavements.

Figure 4.4 also demonstrates the influence of mean annual precipitation and initial IRI on the negative rate of roughness progression. The negative rate of roughness progression increases with the increase of the mean annual precipitation, which again means pavement "smoothening." It appears that more moisture tends to help PCCP retain the smoothness presumably due to stabilization of subgrade moisture. Again an increase in the negative rate of roughness progression was observed as the initial IRI value increased. This increase in the negative rate of roughness progression indicates pavement "smoothening" during initial years of the pavement life.

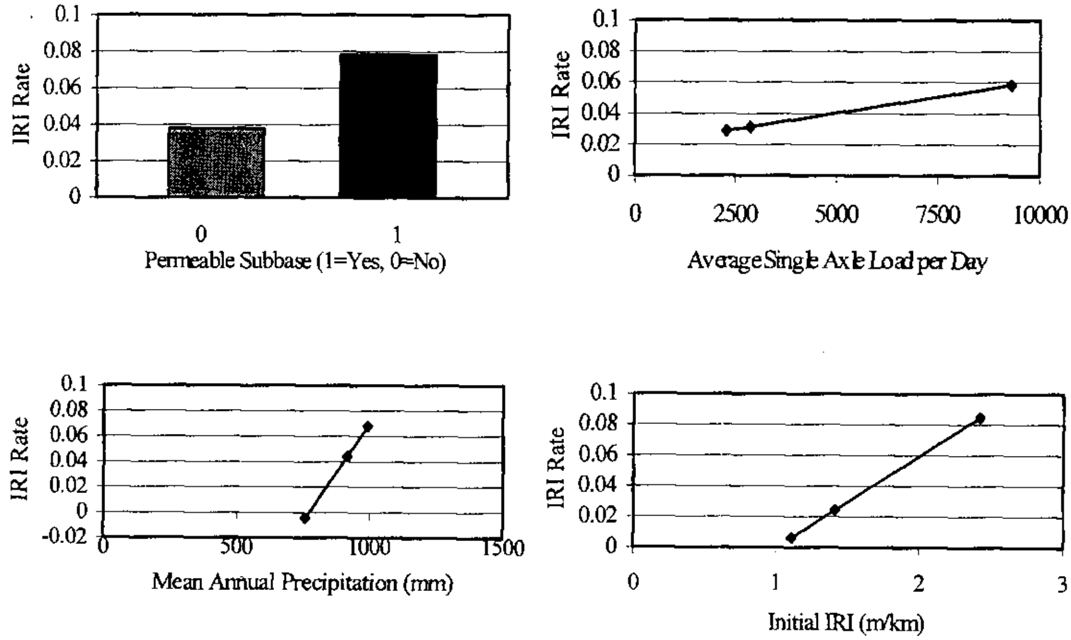


FIGURE 4.4 NEGWOSTR Sensitivity Analysis

4.3 INDEPENDENT CORRELATION ANALYSIS

In this part, independent variables were singled out, and correlation with the dependent variable was checked. Independent correlation between the independent variables and the rate of roughness progression showed which independent variables had the greatest impact on the rate of roughness progression. Table 4.2 displays the correlation between the four highest correlated variables and the rate of roughness progression for each data set, independent of models chosen. A correlation coefficient close to one, negative or positive, indicates a direct correlation. The rate of roughness progression can be either negatively or positively correlated with the independent variables. This means that the independent variables can either increase or decrease the rate of roughness progression.

4.3.1 PRI93 Independent Correlation

This analysis was done for the projects that have as-constructed smoothness values. The as-constructed smoothness values did not show any correlation with the rate of roughness progression. Subgrade material passing the US No. 200 sieve (0.075mm) influences the rate of roughness progression. Other variables, such as, days below 0^0C, freeze-thaw cycles per year, and the water-cement ratio, show weaker correlation. Water-cement ratio is negatively correlated (coefficient -0.52) with the rate of roughness. High water-cement ratios tend to produce slabs with "locked in" curvature, a physical phenomenon due to uneven shrinkage caused by non-uniform temperature rise and uneven curing. Thick slabs, with top faces exposed during curing, will generally curl up on the ends because of drying shrinkage. "Locked-in" curvature tends to increase the rate of IRI roughness progression (Byrum 2000).

TABLE 4.3 Correlation among Independent Variables and the Rate of Roughness Progression

Variables	Coefficients
PRI93	
% Subgrade Material Passing US No. 200 Sieve	-0.64
Number of days below 0 C/year	0.58
Number of Freeze Thaw Cycles per Year	0.53
Water Cement Ratio in Concrete Mix	-0.52
POSWSTR & POSWOSTR	
% Coarse Aggregate in Mix (Decimal Form)	0.63
% Fine Aggregate in Mix (Decimal Form)	-0.61
Initial IRI (m/km)	-0.58
Mean Annual Precipitation (mm)	-0.58
NEGWSTR & NEGWOSTR	
Initial IRI (m/km)	0.83
Mean Annual Precipitation (mm)	0.72
Equivalent Single Axle Load per Day	0.64
Average Low Temperature (C)	0.63

4.3.2 POSWSTR/POSWOSTR Independent Correlation

The projects with positive slopes for the IRI progression rates were analyzed in two different ways: with and without concrete strength variables. However, no strength variable was found to be significant. The percentage of coarse aggregate in the mix had the highest correlation with the rate of roughness progression, followed by the percentage of fine aggregates in the mix. Initial IRI and mean annual precipitation also influence the rate of roughness progression. These two are negatively correlated with the rate of roughness progression. Roughness decreases with the increase in initial IRI and mean annual precipitation.

4.3.3 NEGWSTR/NEGWOSTR Independent Correlation

Initial IRI greatly influences the negative rate of IRI roughness progression in this case. The correlation coefficient between the initial IRI and the negative rate of IRI roughness progression is 0.83. As these projects have negative slopes, positive correlation means the decrease in the rate of roughness progression with the increase in initial IRI. Higher initial roughness usually leads to "smoothening," thereby decreasing the rate of roughness progression. The negative rate of roughness progression increases with increase in mean annual precipitation. The ESAL's/day also is highly correlated with the rate of roughness progression. This may be attributed to the "smoothening" of pavement imperfections. An average low temperature also is correlated with the negative rate of roughness progression.

4.4 ROUGHNESS PROGRESSION AS FUNCTION OF AS-CONSTRUCTED SMOOTHNESS

As mentioned earlier, KDOT determines bonus or full-pay sections in terms of as-constructed smoothness of the 0.1 mile (0.16km) segments. In this part of the analysis, the bonus or full-pay sections were identified and the analysis was done with 1 mile (1.6 km) bonus and full-pay sections of selected projects to find the time when both sections would attain similar roughness in terms of IRI. In general, the annual IRI measurements show that the projects/sections with full-pay will have a lower rate of roughness progression, whereas the bonus projects/sections will have a higher rate of roughness progression. Figures 4.5 to 4.7 show the trends of roughness progression for three projects on I-135, US-75, and K-7, respectively. The project on I-135 in McPherson County was built rather smooth. It was a bonus project and all mile long sections in the project were bonus miles. On the other hand, the project on US-75 in Jackson County was a full-pay project with all full-pay miles. K-7 in Johnson County was also a full-pay project with all full pay miles. On I-135, although some bonus miles had higher initial IRI values, they got smoother rapidly, and most of the miles tend to converge at about the same roughness in approximately 3 to 4 years. On US-75, it was observed that some miles showed very high rates of roughness progression. K-7 is only a three-mile project. It was observed a mile was built with relatively high IRI (1.55 m/km) and showed high rate of roughness progression. For both US-75 and K-7, most of the miles converged at about the same IRI roughness in approximately 3 years. Similar trend was observed on other projects. The time taken by the individual mile long sections to reach similar IRI values was about 3 to 5 years. This analysis indicates two facts: (i) As-constructed PI and initial IRI values may not be correlated, and (ii) the as-constructed smoothness tends to "wear" out in about 3 to 5 years. These results also indicate that the as-constructed smoothness specifications based on IRI may help retain the smoothness somewhat better, since the initial IRI would be lower to start with.

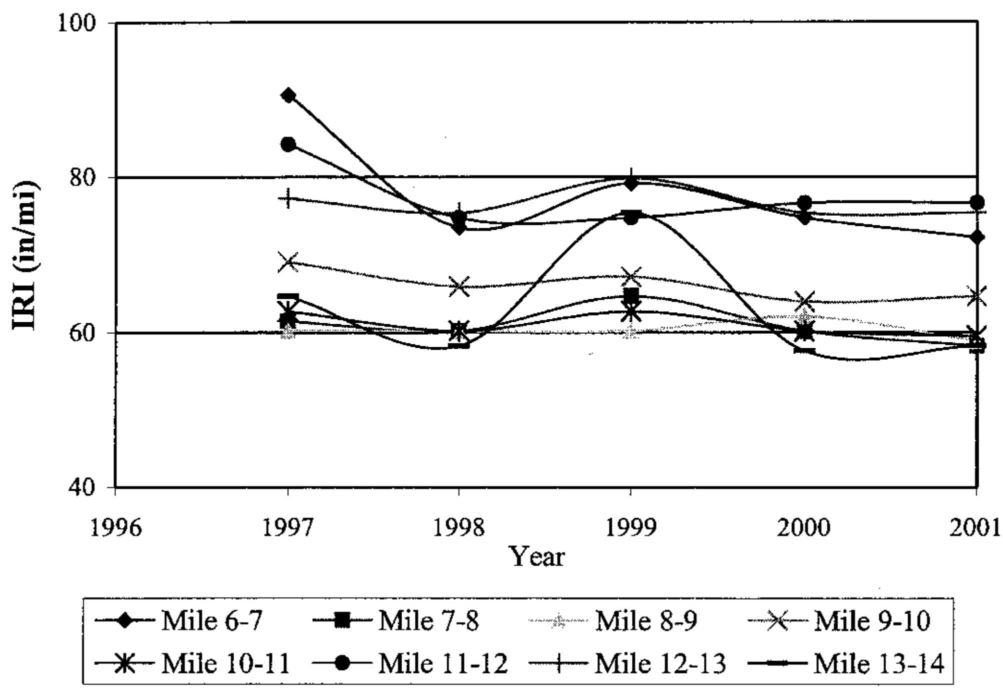


FIGURE 4.5 Roughness Progression of 1mile Sections of Project I-135 of McPherson County (All are bonus miles)

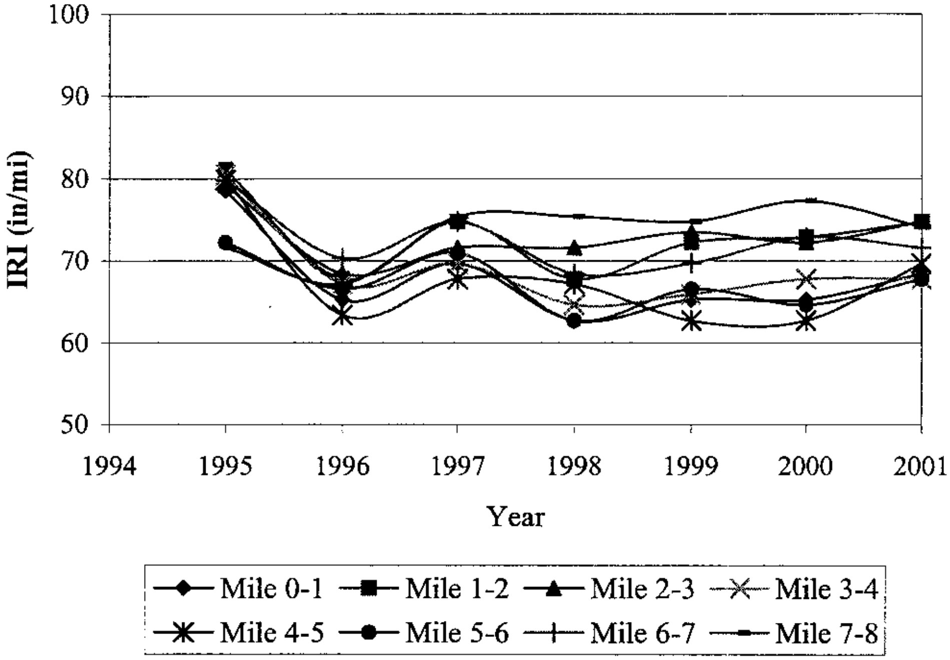


FIGURE 4.6 Roughness Progression of 1mile Sections of Project US-75 of Jackson County (All are full pay miles)

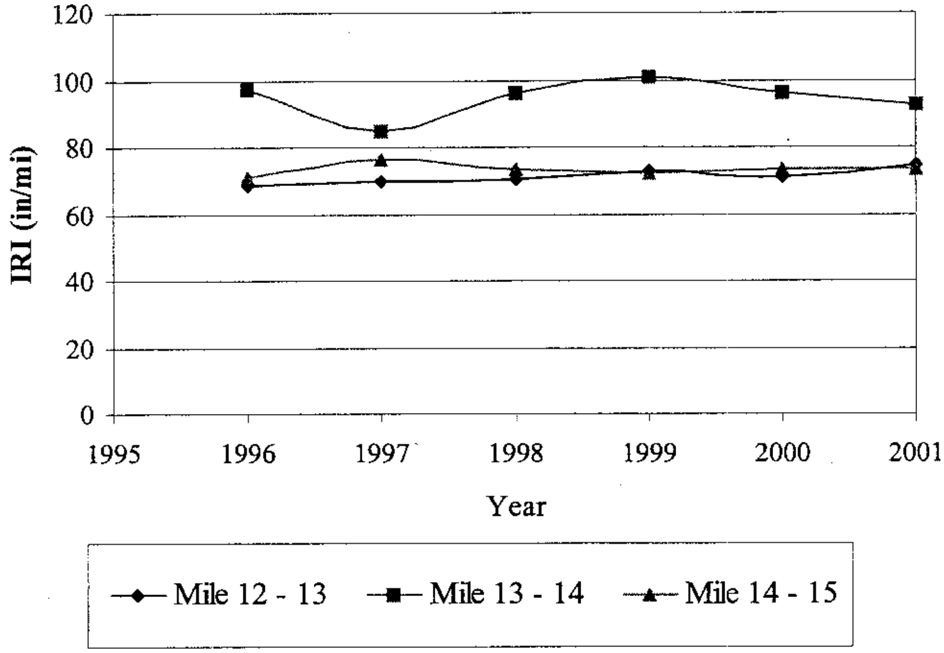


FIGURE 4.7 Roughness Progression of 1 mile Sections of Project K-7 of Johnson County (All are full pay miles)

CHAPTER 5

DAMAGE ANALYSIS

5.1 ROUGHNESS STATISTICS USING ROADRUF

RoadRuf was used to calculate the roughness statistic, IRI for damage analysis for the selected projects on I-135, US-75 and K-7. The primary objective of this research is to estimate damage of PCC pavements for a range of roughness. The roughness values for each mile segment of a project for a particular year was found from the KDOT Pavement Management System (PMS) database. The roughness statistic, IRI, was calculated using RoadRuf for different 0.02 mile (0.032 km) segments of the three projects selected for damage analysis. Figures 5.1 and 5.2 show the roughness variation of the segments during the year after construction and in 2001, respectively. Unusually high IRI values are observed on several segments of the I-135 project in McPherson County during the year after construction (1997). As mentioned earlier I-135 was built rather smooth compared to the other two projects. All miles of this project were bonus miles. The segments, which showed remarkably high roughness, are from Milepost 6 to 7. This one-mile long section showed highest roughness for this project. The roughness of the 0.1mile (0.16km) sections on that particular mile was calculated and the variation of roughness is shown in Figure 5.3. In 2001, there are some segments on K-7 in Johnson County that showed unusually high IRI values too (Figure 5.2).

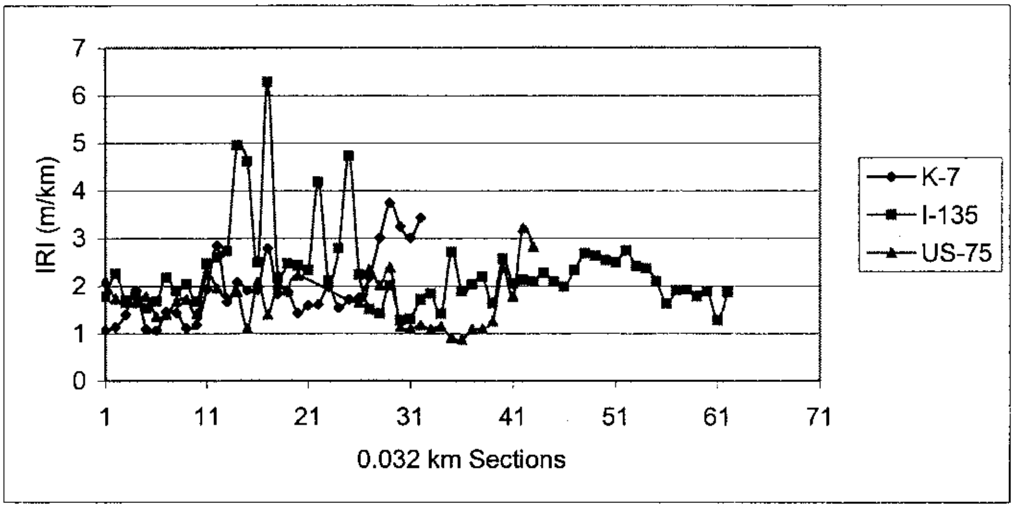


Figure 5.1 Variation of IRI of 0.02 mi. Sections during the year after Construction

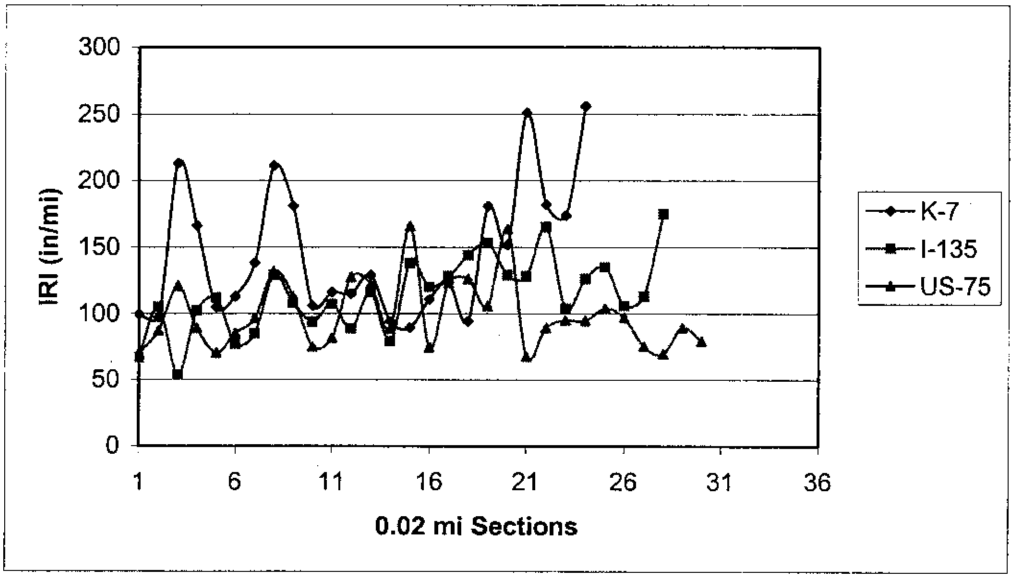


Figure 5.2 Variation of IRI of 0.02 mi Sections in 2001

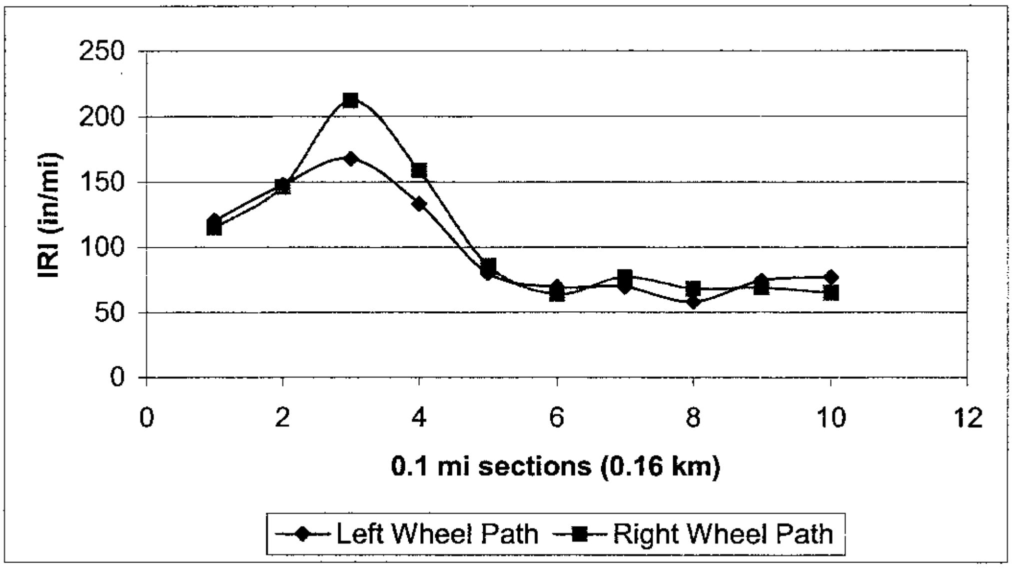


Figure 5.3 Variation of IRI of Route I-135 in McPherson County (Milepost: 6 - 7)

5.2 Dynamic Wheel Load (DWL) Calculation using TruckSim

As roads age and deteriorate from the effect of heavy truck traffic and weather, signs of distresses appear. Road roughness is one of the distresses and is detrimental to both pavement life and ride quality. It was also mentioned earlier that the effects of dynamic loads of heavy vehicles on pavement damage are closely related to road roughness and vehicle speed (Hegmon 1993). Roughness causes excitation of truck dynamics leading to further pavement deterioration. Dynamic wheel loads (DWL) of the selected truck (shown in Figure 3.3) were calculated using TruckSim. In order to calculate the DWL due to roughness, pavement profiles were fed as inputs. Figure 5.4 shows the variation of the DWL with respect to the roughness statistic values. It was observed that DWL has no definitive relationship with the roughness statistic, IRI. The IRI's shown in Figure 5.4 represent the roughness of selected 0.02mi (0.032 km) sections. The computed PSI values from the highway performance monitoring system (HPMS) equation vary from 4.0 (0.85 m/km) to 1 (6.3 m/km). It appears that it is the profile of the pavement, which affects the wheel loads, not the summary statistic. Although it is true that roughness is described by the longitudinal profile of the pavement surface, different wavelengths have different effects on the dynamic behavior of truck depending on its suspension type. Some profiles of the selected segments that produced high DWL are also illustrated by plot and shown in Figure 5.5. These profiles, selected from route I-135 and K-7, result in higher DWL but have relatively low IRI values. Some segments that produced low DWL but have higher roughness statistics, IRI values, are also shown in Figure 5.6. These results indicate that IRI potentially is not a good potential indicator of pavement damage due to truckloads.

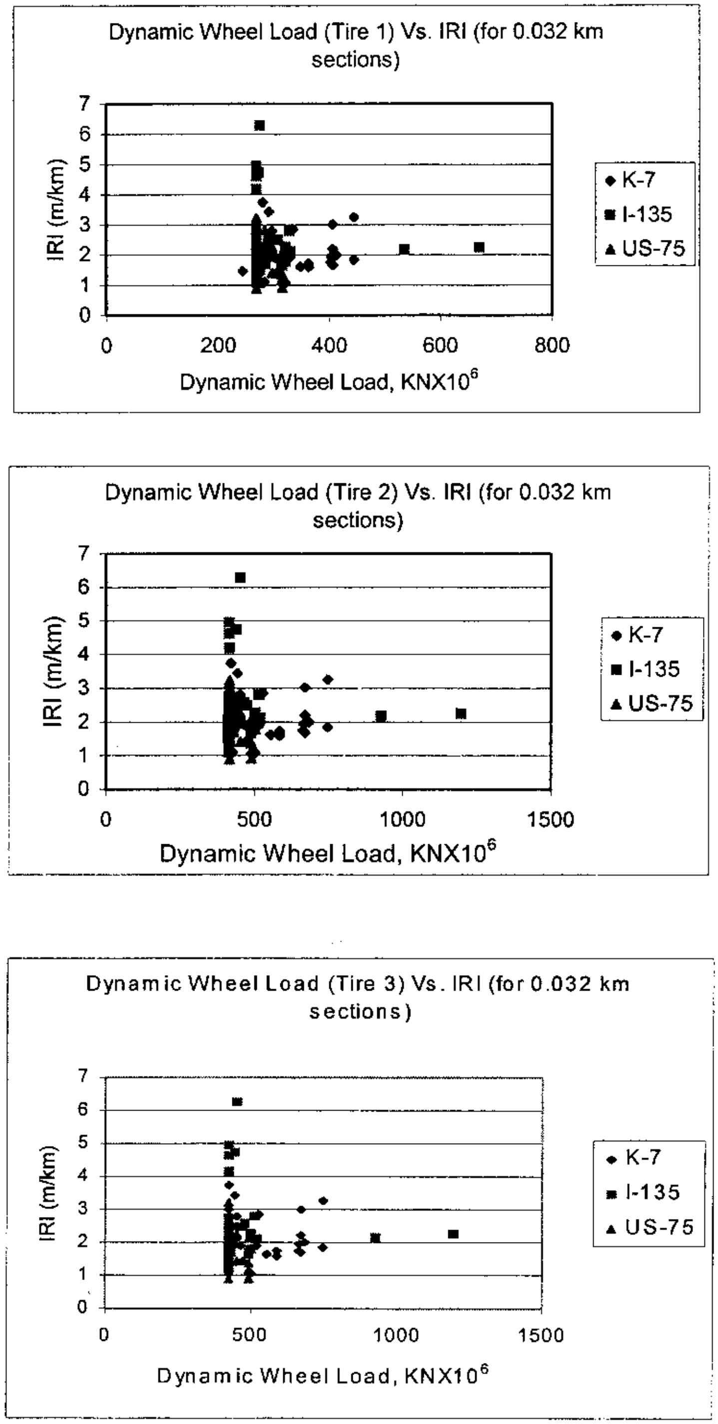
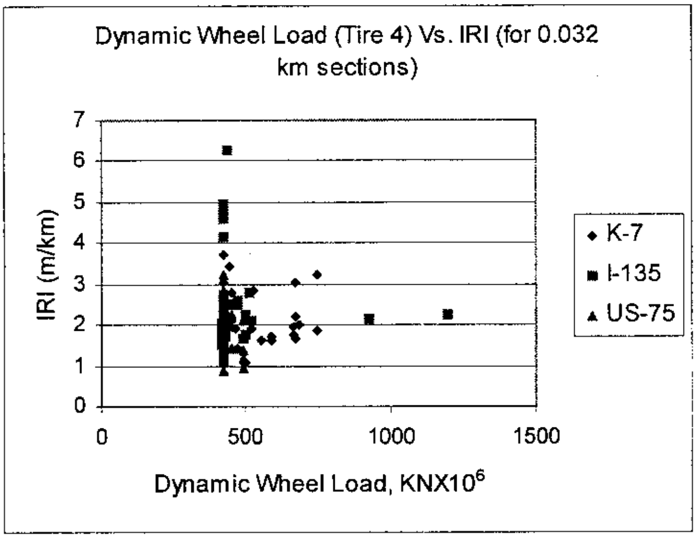


Figure 5.4 Variation of Dynamic Wheel Loads with respect to IRI



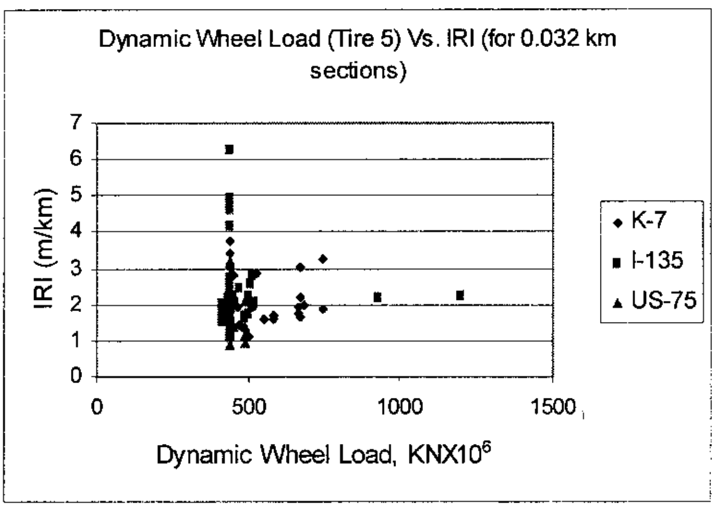


Figure 5.4 Variation of Dynamic Wheel Loads with respect to IRI (Contd.)

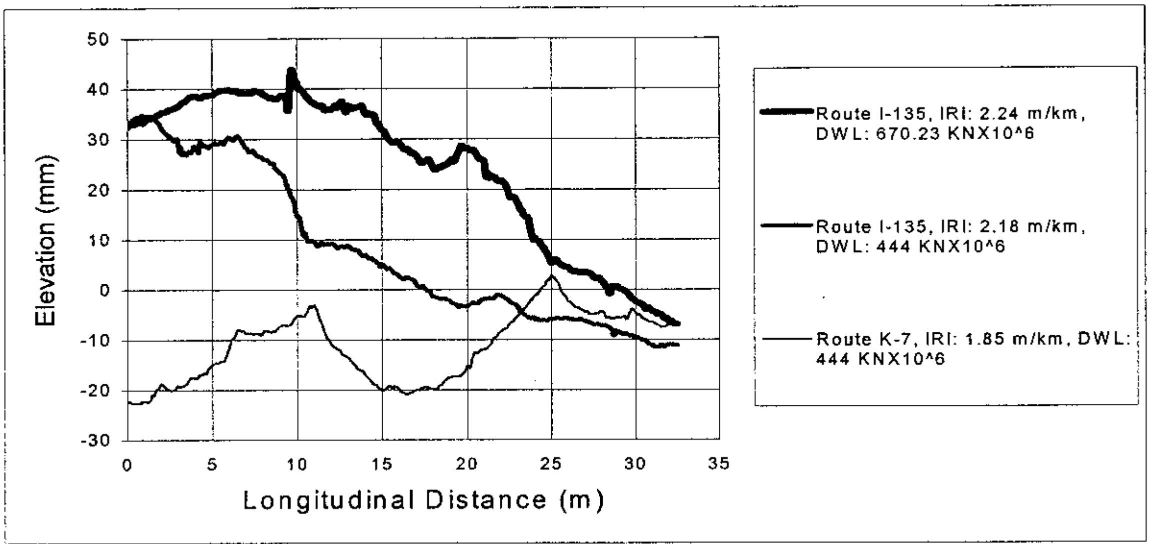


Figure 5.5 Relative Pavement Profiles of Some Selected 0.02 mile Sections with Lower IRI Values

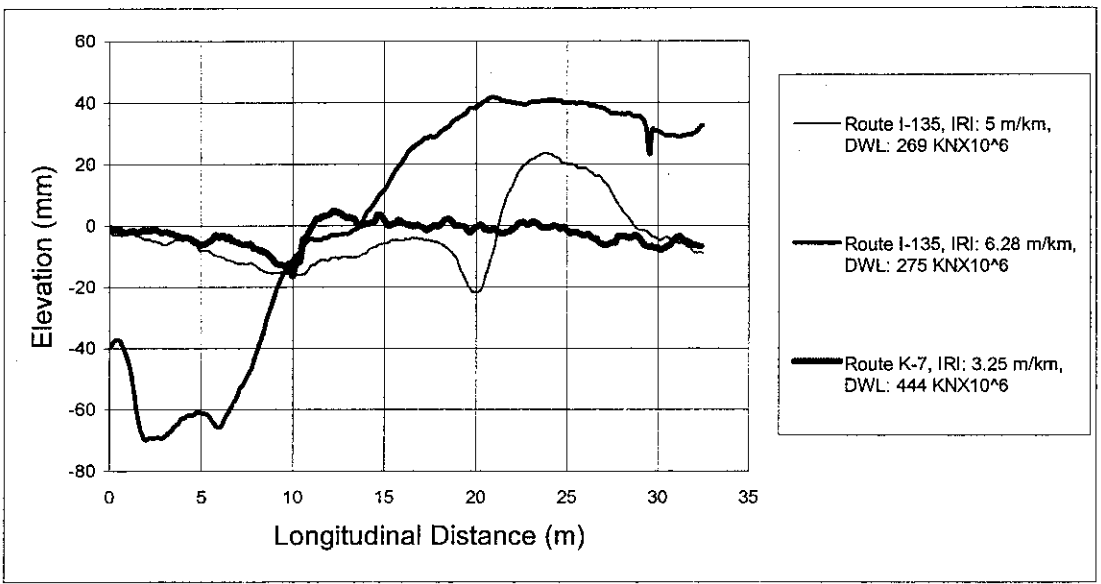


Figure 5.6 Relative Pavement Profiles of Some Selected 0.02 mile Sections with Higher IRI Values

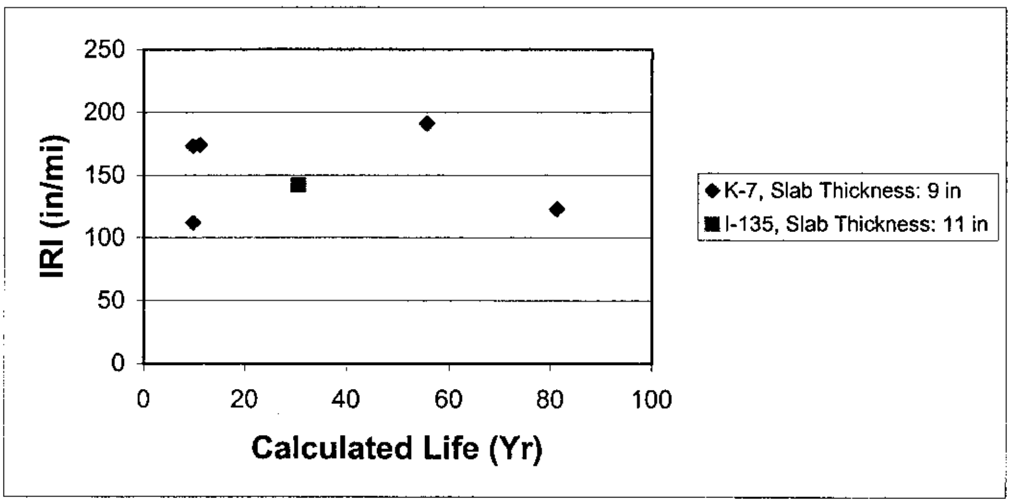
5.3 PCCP LIFE USING KENSLAB

PCCP life of the projects was calculated using KENSLAB for the calculated dynamic wheel loads for a specific segment. The Portland Cement Association (PCA) recommended method was used for life calculations. Tables 5.1 to 5.3 tabulate the PCCP lives of different segments with varying IRI. This comparison is also illustrated by Figure 5.7. For some pavement segments of the project on K-7, calculated lives varied from 10 to 11 years. On the other hand, I-135 and US-75 were found to have infinite load carrying capacity. It was observed that if the dynamic wheel loads are not high enough, the pavement segments, as constructed, are theoretically capable of carrying unlimited load repetitions. Neither pavement damage nor pavement life appeared to have any relationship with IRI. Damage calculations also depend on allowable and predicted number of load repetitions. Predicted numbers of load repetitions varied from 89,609 to 113,652 for I-135 for different mile-long segments. Predicted number of loads is lower in case of US-75 and K-7 (ranging from 30,265 to 51,714 and 21,358 to 66,074, respectively). K-7 in Johnson County has lower life when compared with US-75 in Jackson County even though they have the same PCC slab thickness (9 in.).

5.4 EFFECT OF CONCRETE STRENGTH ON ESTIMATED PAVEMENT DAMAGE AND LIFE

It was found earlier that the concrete modulus of rupture significantly affects the rate of roughness progression. The strength showed negative relationship with the rate of roughness progression: rate of roughness decreases with the increase in concrete modulus of rupture. Damage was also calculated varying the concrete modulus of rupture.

Variation of PCCP lives of various segments with varying concrete modulus of rupture is shown in Tables 5.1 to 5.3. A significant decrease in pavement life happens with the decrease in concrete modulus of rupture. High strength concrete tends to have longer life. The rate of roughness decreases and pavement life increases with the increase in concrete modulus of rupture. In other words, use of high strength concrete should result in pavements with longer service life.



(Note: US-75 was not included in this graph as it was found to capable of carrying unlimited load repetitions, i.e., have infinite life.)

Figure 5.7 Variation of PCCP Life with respect to Roughness

Table 5.1 Variation PCCP Life of Route I-135 of McPherson County

Year: 1997; Slab Thickness: 11in. (279 mm)					
M.P.	Lane	IRI (in/mi)	Mod. Of Rup. (psi)	Cracking Index	Life (Yr)
6.28	North	177	589*	N/A	N/A
			337	0.00424	235.85
			295	0.2922	3.42
6.32	North	142	589*	0.03265	30.63
			531	0.41521	2.41
			501	1.0413	0.96
			472	2.7649	0.36
6.18	South	158	589*	N/A	N/A
			343	0.0018768	532.83
			324	0.028306	35.33
			295	0.3152	3.17
Year: 2001					
6.66	North	108	589*	N/A	N/A
			283	0.00596	167.8
12.64	South	175	589*	N/A	N/A
			300	0.0035224	283.9

* As constructed Concrete Modulus of Rupture

Table 5.2 Variation of PCCP Life of Route US-75 of Jackson County

Year: 1995; Slab Thickness: 9in (229mm)					
M.P.	Lane	IRI (in/mi)	Mod. Of Rup. (psi)	Cracking Index	Life (Yr)
0	North	134	514*	N/A	N/A
			435	0.00126	794.92
			406	0.01823	54.85
			385	0.08616	11.61
			359	0.2904	3.44
			334	0.91802	1.09
1.82	South	128	514*	N/A	N/A
			380	0.00071	1414
			334	0.0753	13.27
			308	0.32664	3.06
Year: 2001					
5.64	North	132	514*	N/A	N/A
			380	0.00097	1029
			360	0.01504	66.47
			334	0.1065	9.65
			308	0.44901	2.23
1.66	South	92	514*	N/A	N/A
			380	0.00105	956
			360	0.01701	58.77
			334	0.11717	8.53
			308	0.50784	1.97

* As constructed Concrete Modulus of Rupture

Table 5.3 Variation of PCCP Life of Route K-7 of Johnson County

Year: 1996; Slab Thickness: 9in. (229 mm)					
M.P.	Lane	IRI (in/mi)	Mod. Of Rup. (psi)	Cracking Index	Life (Yr)
13.3	North	123	537*	0.0123	81.26
			383	0.1953	5.12
			457	0.5052	1.98
			431	1.326	0.75
			405	3.96	0.25
13.34	North	112	592	0.0046	216.86
			537*	0.1023	9.78
			383	0.6501	1.54
			457	1.637	0.61
			431	4.625	0.22
			405	15.004	0.07
13.62	South	173	592	0.0046	216.86
			537*	0.1023	9.78
			383	0.6501	1.54
			457	1.637	0.61
			431	4.625	0.22
			405	15.004	0.07
13.64	South	191	537*	0.018	55.67
			383	0.235	4.25
			457	0.592	1.69
			431	1.569	0.64
			405	4.736	0.21
Year: 2001					
13.32	North	174	592	0.00874	114.42
			537*	0.0893	11.2
			383	0.49	2.04
			457	1.277	0.78
			431	3.748	0.27
			405	12.7	0.08
12.98	South	92	537*	N/A	N/A
			511	0.0007	1436.54
			457	0.0409	24.44
			431	0.1297	7.77
			405	0.3467	2.88
			377	1.0924	0.92

* As constructed Concrete Modulus of Rupture

CHAPTER 6

EFFECT OF GRINDING

6.1 BACKGROUND

The KDOT PCCP smoothness specification contains provisions for grind back of pavements constructed in the penalty range of roughness. As part of this study the effectiveness of grinding was explored to determine if smoother pavements result from spot diamond grinding. Spot diamond grinding is fairly expensive. It also exposes aggregates, once covered by cement paste, to the elements of weather. It is known that once exposed to freeze-thaw, the aggregates tend to split and spall from the concrete surface. For these reasons, diamond grinding is studied here to determine if any benefits were obtained.

6.2 RESULT

Figure 5.1 shows the results of grinding on a KDOT PCC pavement constructed on US-81 in Saline County. US- 81 is a 4-lane highway with two lanes in the southbound direction and two lanes in the northbound direction. This data is for the southbound lanes only, for a distance of six miles south of the county line. The total distance is divided into sixty sections each of 0.1 miles in length. Generally the pavement was constructed in the full pay zone, between 18 and 30 in/mi. The project was constructed on 1996. However, approximately one year after construction a large portion of the pavement became rough. The graph shows that the traffic loading possibly caused the increase in roughness. The spikes in the profile at the time of construction and one year after construction indicate that bumps in the original profile enlarged due to dynamic loading. Due to public complaint, the pavement was ground back to well within the bonus range. Figure 6.2 shows the effect of grinding based on the year. The results indicate that grinding has made the pavement smoother in the short term.

After four years, IRI values on some sections have already approached the pre-ground level.

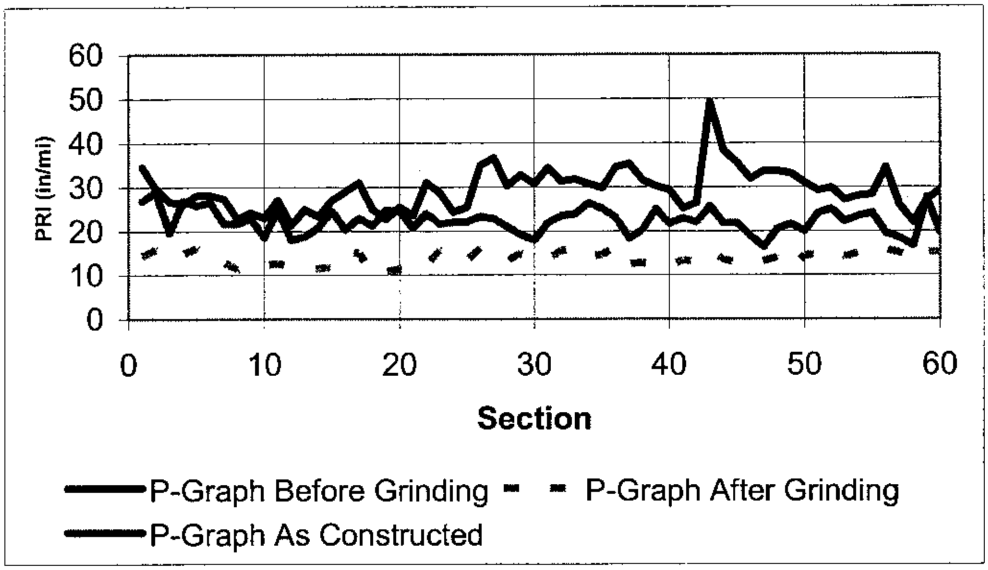


Figure 6.1 Short Term Effect of Grinding

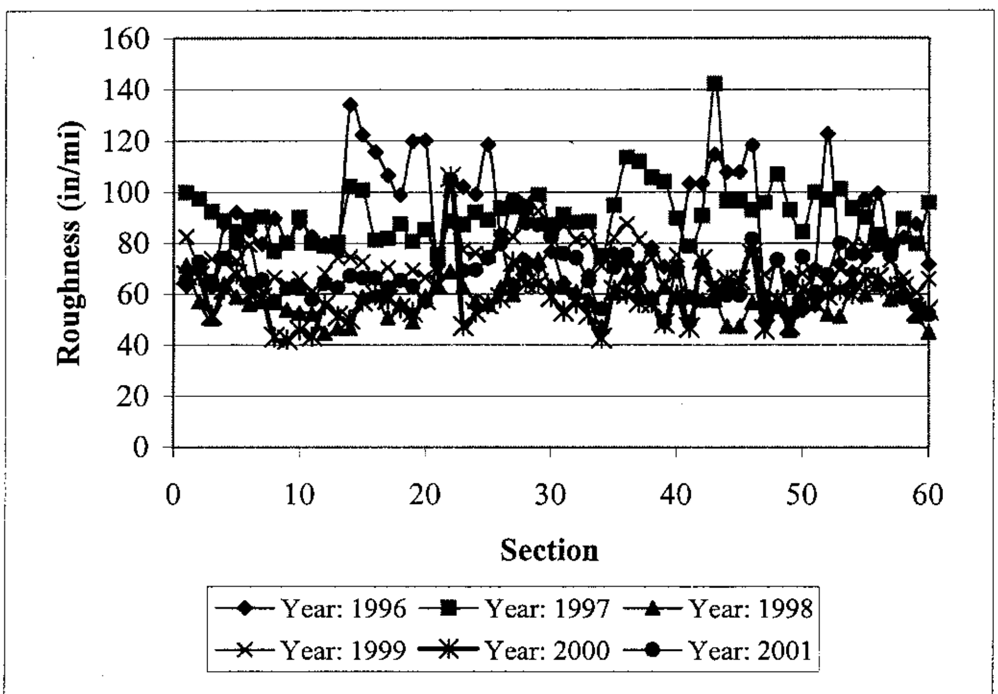


Figure 6.2 Long Term Effect of Grinding

Figure 6.3 shows roughness progression on the east and westbound lanes of a section of PCCP on I-70 in Geary and Dickinson counties. The roughness data used in this figure are for I-70 for the M.P. 9 to M.P. 10 in Dickinson County and M.P. 0 to M.P 7 in Geary County. This particular project was the first KDOT PCCP constructed with smoothness specifications. The pavement was reported as fairly smooth until 1989. The project was ground in 1989 due to public complaints. Part of the project was rehabilitated with dowel retrofit and grinding in early 90's. From 1990 to 2001 the roughness of this pavement has remained fairly constant with no significant increases in roughness progression. On this project, grinding (coupled with the dowel retrofit) appeared to have a longer lasting solution to the pavement roughness progression. These results may also appear to indicate that most of the roughness on PCCP's in Kansas is being derived from the joints or joint-related problems such as, faulting.

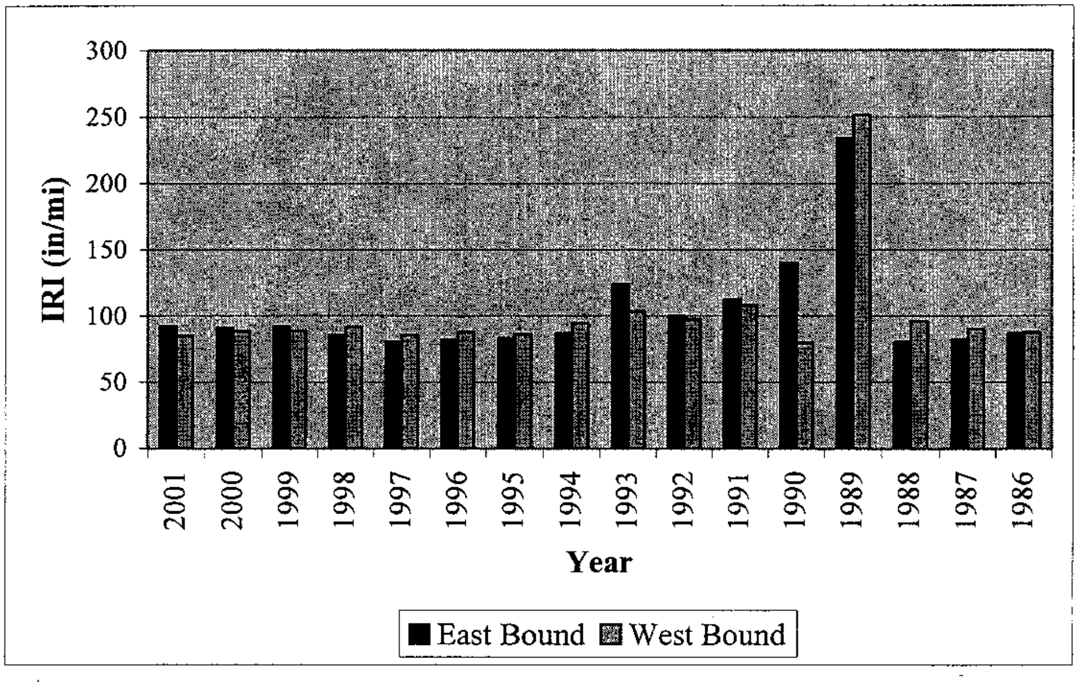


Figure 6.3 Long Term Effect of Grinding on I-70

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

This study was done to estimate pavement damage for various levels of roughness and also to quantify the effect of as-constructed smoothness and other design, construction, traffic, and climatic variables on the rate of roughness progression on concrete pavements in Kansas. Based on the results of this study the following conclusions may be drawn:

1. Good prediction equations were developed by the statistical analysis of all predictor variables isolated in this study from the inventory, construction, climatic and roughness database for the PCCP projects in Kansas.
2. The concrete modulus of rupture, subgrade material, number of wet days, and initial IRI roughness significantly affect the rate of IRI roughness progression.
3. Pavements with high initial IRI roughness (IRI measured during the first year after construction) tend to become smoother as traffic passes over it presumably due to "smoothening" of minor surface irregularities and stabilization of subgrade moisture.
4. The as-constructed smoothness tends to "wear" out in about 3 to 5 years. After that the as-constructed smoothness does not influence future roughness development. Also, as-constructed PI and initial IRI values are not correlated.
5. Permeable sub-base tends to decrease the rate of roughness progression.
6. Initial IRI and subgrade materials showed good correlation with the rate of roughness progression. The ESAL's per day also is highly correlated with the rate

of roughness progression. This may be attributed to the "smoothening" of pavement imperfections.

7. Water-cement ratio is well correlated with the rate of roughness. High water-cement ratios tend to produce slabs with "locked in" curvature. "Locked-in" curvature tends to increase the rate of IRI roughness progression.
8. Concrete flexural strength has a very significant effect on roughness progression as well as on pavement damage. Rate of roughness decreases and pavement life increases with the increase in concrete modulus of rupture. High strength concrete tends to have longer life. Higher flexural strength helps to retain the as-constructed smoothness longer.
9. Dynamic wheel load has no definitive relationship with the roughness statistic, IRI, within the range of IRI values studied. It is the profile of the pavements that appears to affect the wheel loads. IRI is potentially not a good indicator of pavement damage due to truckloads. Neither pavement damage nor pavement life appeared to have any relationship with IRI.
10. Grinding reduces roughness on concrete pavements in the short term only. Grinding alone does not appear to be effective in lowering the rate of roughness progression in the long term.

7.2 RECOMMENDATIONS

The pavement damage analysis was done for limited number of projects. To calculate the dynamic wheel loads for a selected truck, profile data is needed. Since the wheel loads vary with the suspension type, it would be useful to study the dynamic wheel loads generated for various types of truck combinations. Further research is needed to study the pavement damage due to dynamic wheel loads for various profile types.

REFERENCES

ASTM (American Society of Testing and Materials). *Standard Specification No. E867*, Annual Book of ASTM Standards, Section 4, Vol. 0.4.03, 1998.

Bhatti, M.A., B. Lin, P. Taylor, and L. Hart. *PAVESIM: Simulation of Pavement Damage due to Heavy Vehicles*, Public Policy Center, University of Iowa, Iowa City, IA, 1996.

Byrum, C.R. Analysis of LTPP JCP Slab Curvature Using High Speed Profiles. In *Transportation Research Record 1730*, Transportation Research Board, National Research Council, Washington D.C., January 2000.

Gillespie, T.D., S.M. Karamihas, M.W. Sayers, M.A. Nasim, W. Hansen, and N. Ehsan. *Effects of Heavy-Vehicle Characteristics on Pavement Response and Performance, NCHRP Report 353*, Transportation Research Board, National Research Council, Washington D.C., 1993.

Haas, R., R.W. Hudson and J. Zaniewski. *Modern Pavement Management*, Krieger Publishing Company, Malabar, FL, 1994.

Hegmon, R.R. A Close Look at Road Surface. Public Roads On-Line, summer 1993.

Hossain, M., R. Kaldate and W.H. Parcells Jr. *Smoothness for Newly Constructed Concrete Pavements - Specifications and End Results. Paper Prepared for Presentation at the 6th International Purdue Conference on Concrete Pavement.* West Lafayette, IN, November 18-21, 1997.

Huang, Y.H. *Pavement Analysis and Design*, Prentice Hall, Englewood Cliffs, New Jersey, 1993

Hudson, R.W. *Road Roughness: Its Elements and Measurement, Transportation Research Record 836*, Transportation Research Board, National Research Council, Washington D.C., 1981.

Janoff, M.S. *Pavement Roughness and Ridability*. NCHRP Report No. 275, Transportation Research Board, National Research Council, Washington D.C., 1985.

Karamihas, S.M. and T.D. Gillespie. *Guidelines for Longitudinal Pavement Profile Measurement, Final Report, NCHRP Project 10-47*, Transportation Research Board, National Research Council, Washington D.C., 1999.

Karamihas, S.M., T.D. Gillespie and S.M. Riley. *Axle Tramp Contribution to the Dynamic Wheel Loads of a Heavy Truck, Proceedings of the Fourth International Symposium on Heavy Vehicle Weights and Dimensions,* Road Transport Technology 4, Ann Arbor, Michigan, 1995, pp. 425-434.

Keever, D.B., K.E. Weiss and R.C. Quarles. *Moving Ahead: The American Public Speaks on Roadways and Transportation in Communities*. Final Report, No. FHWA-OP-01-017, Federal Highway Administration, Washington D.C., February 2001.

Ott, R.L. *An Introduction to Statistical Methods and Data Analysis. 1st Edition*, Duxbury Press, Belmont, CA, 1993.

Parcells, Jr., W.H. and Hossain, M. *Kansas Experience with Smoothness Specifications for Concrete Pavements*. In Transportation Research Record 1435, TRB, National Research Council, Washington D.C., 1994.

Parcells, W.H. Jr. *Control of Pavement Trueness in Kansas, Ninth Interim Report*, Kansas Department of Transportation 73-1, Topeka, KS, 1999.

RoadRuf User Manual, The University of Michigan Transportation Research Institute, MI, 1997.

SAS, *Statistical Analysis System*, The SAS Institute, Carey, North Carolina, 1979.

Sayers, M.W., and S.M. Karamihas. *The Little Book of Profiling: Basic Information about Measuring and Interpreting Road Profiles*. The University of Michigan Transportation Research Institute, MI, 1997.

Scofield, L.A. *Profilograph Limitations, Correlation, and Calibration Criteria for Effective Performance Based Specifications*. Final Report, NCHRP Project 20-7, Task 53, Transportation Research Board, National Research Council, Washington D.C., 1992.

Simpson, A.L., J.B. Rauhut, P.R. Jordhal, M.I. Owusu-Antwi, R. Ahamad, O.J. Pendleton and Y. Lee. *Sensitivity Analysis for Selected Pavement Distresses, SHRP-P-393*, Strategic Highway Research Program, National Research Council, Washington D.C. 1994.

Smith, K.L., K.D. Smith, L.D. Evans, T.E. Hoerner, M.I. Darter, and J.H. Woodstrom, *Smoothness Specifications for Pavements*. Final Report, *NCHRP Project 1-31*, Transportation Research Board, National Research Council, Washington D.C., March 1997.

Stoner, J.W., and M.A. Bhatti. Estimating Pavement Damage from Longer and Heavier Combination Vehicles, The Midwest Transportation Center, Iowa 1994.

TruckSim User Manual, Version 4.6, Mechanical Simulation Corporation, Ann Arbor, MI, 2000

TruckSim Vehicle Models and Solver Programs, Version 4.6, Mechanical Simulation Corporation, Ann Arbor, MI, 2000.

APPENDICES

APPENDIX A
Typical SAS Input and Output File

INPUT FILE

```
options ls=80 ps=60 nodate nonumber;
data JP93PRI;
infile 'JPCP93PRI.dat';
INPUT CS MOR WCR A CA FA WOS P PI LL FOUR TUHUND V ESAL AP WD
MEANT MINT MAXT DB DA FT IRIR PRI;
title1 'Roughness Progression on KDOT PCC Pavements';
title2 'JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV';

run;


proc reg;
model IRIR=CS MOR WCR A CA FA WOS P PI LL FOUR TUHUND V ESAL AP
WD MEANT MINT MAXT DB DA FT PRI/selection=f;
run;



proc reg;
model IRIR= CS MOR WCR A CA FA WOS P PI LL FOUR TUHUND V ESAL AP
WD MEANT MINT MAXT DB DA FT PRI/selection=RSQUARE;
run;


proc corr;
var IRIR CS MOR WCR A CA FA WOS P PI LL FOUR TUHUND V ESAL AP WD
MEANT MINT MAXT DB DA FT PRI;
run;



quit;
```

SAS - Output
OUTPUT FILES

Roughness Progression on KDOT PCC Pavements
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

Forward Selection Procedure for Dependent Variable IRIR

Step 1 Variable TUHUND Entered R-square = 0.41251250 C(p) = -1.17222085

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	1	0.00123353	0.00123353	5.62	0.0452
Error	8	0.00175675	0.00021959		
Total	9	0.00299028			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.36299671	0.14574796	0.00136214	6.20	0.0375
TUHUND	-0.37021672	0.15620387	0.00123353	5.62	0.0452

Bounds on condition number: 1, 1

Step 2 Variable MOR Entered R-square = 0.54543779 C(p) = -0.26455717

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	2	0.00163101	0.00081551	4.20	0.0633
Error	7	0.00135927	0.00019418		
Total	9	0.00299028			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.52865538	0.17941759	0.00168587	8.68	0.0215
MOR	-0.01656985	0.01158143	0.00039748	2.05	0.1956
TUHUND	-0.48024170	0.16580052	0.00162913	8.39	0.0231

Bounds on condition number: 1.274094, 5.096377

Step 3 Variable PI Entered R-square = 0.63333565 C(p) = 1.01312709

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	3	0.00189385	0.00063128	3.45	0.0917
Error	6	0.00109643	0.00018274		
Total	9	0.00299028			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
INTERCEP	0.49623134	0.17613806	0.00145041	7.94	0.0305
MOR	-0.01673081	0.01123581	0.00040519	2.22	0.1870
PI	0.00199099	0.00166012	0.00026284	1.44	0.2756
TUHUND	-0.49765404	0.16149503	0.00173527	9.50	0.0216

Bounds on condition number: 1.284476, 10.70412

No other variable met the 0.5000 significance level for entry into the model.
Roughness Progression on KDOT PCC Pavements
Page 1

SAS - Output
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

Summary of Forward Selection Procedure for Dependent Variable IRIR

Step	Variable Entered	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F
1	TUHUND	1	0.4125	0.4125	-1.1722	5.6173	0.0452
2	MOR	2	0.1329	0.5454	-0.2646	2.0470	0.1956
3	PI	3	0.0879	0.6333	1.0131	1.4383	0.2756

Roughness Progression on KDOT PCC Pavements
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

Near collinearity forces the use of a slow version of the leaps and bounds algorithm. The problem will require a large amount of computing time.
Subsets with tolerances less than 1.110223E-7 have been encountered and omitted.

Roughness Progression on KDOT PCC Pavements
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

N = 10 Regression Models for Dependent Variable: IRIR

In	R-square	Variables in Model
1	0.4125125	TUHUND
1	0.3352438	DB
1	0.2843462	FT
1	0.2714555	WCR
1	0.1934132	MINT
1	0.1934132	WOS
1	0.1934132	FOUR
1	0.1132320	MAXT
1	0.0776930	V
1	0.0740229	FA
1	0.0640790	ESAL
1	0.0633790	CS
1	0.0527310	PI
1	0.0486046	PRI
1	0.0482101	CA
1	0.0369289	MEANT
1	0.0108888	P
1	0.0052328	LL
1	0.0043112	AP
1	0.0022007	A
1	0.0016049	WD
1	0.0006301	MOR
1	0.0002041	DA
2	0.6128845	CA DB
2	0.6080821	FA DB
2	0.6079216	WD FT
2	0.6043928	AP FT
2	0.5962609	CA FA
2	0.5819575	DA FT
2	0.5454378	MOR TUHUND
2	0.5267915	WCR MEANT
2	0.5133941	TUHUND MAXT
2	0.5087025	WCR TUHUND
2	0.4978345	PI TUHUND
2	0.4960107	AP DB
2	0.4907089	TUHUND MINT
2	0.4907089	WOS TUHUND

2	0.4907089	FOUR TUHUND
2	0.4898313	TUHUND PRI
2	0.4857064	WD DB
2	0.4828550	WCR MAXT
2	0.4761623	WCR A
2	0.4747154	MOR MINT
2	0.4747154	MOR FOUR
2	0.4747154	MOR WOS
2	0.4714526	TUHUND FT
3	0.6339089	CA FA FT
3	0.6333621	WCR CA FA
3	0.6333357	MOR PI TUHUND

Roughness Progression on KDOT PCC Pavements
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

In	R-square	Variables in Model
3	0.6327266	PI LL FT
3	0.6315359	WCR A PI
3	0.6313111	A CA FA
3	0.6308064	MOR A MEANT
3	0.6305905	CA ESAL DB
3	0.6305607	CA FA DA
3	0.6303718	CA MAXT DA
3	0.6303289	CA FA MEANT
3	0.6303014	TUHUND DA FT
3	0.6302063	FA ESAL DB
3	0.6299636	CA FA MAXT
3	0.6297002	CA FA AP
3	0.6296284	CA FA WD
3	0.6294875	CA MEANT MAXT
3	0.6294811	CA WD MINT
3	0.6294811	CA FOUR WD
3	0.6294810	CA WOS WD
3	0.6294026	CA WOS AP
3	0.6294025	CA AP MINT
3	0.6294025	CA FOUR AP
4	0.6348658	CA P MINT DA
4	0.6348658	CA P FOUR DA
4	0.6348658	CA WOS P DA
4	0.6348657	MOR A ESAL MEANT
4	0.6348657	WCR CA FA FOUR
4	0.6348657	PI LL MEANT DB
4	0.6348657	WCR CA FA MINT
4	0.6348657	WCR CA FA WOS
4	0.6348656	CA FA PI MAXT
4	0.6348656	CA FA PI MEANT
4	0.6348654	CA FA MEANT MAXT
4	0.6348653	CA FA P TUHUND
4	0.6348649	A CA TUHUND DB
4	0.6348649	CA PI MEANT MAXT
4	0.6348649	WCR CA FA WD
4	0.6348646	WCR CA FA DA
4	0.6348646	WCR CA FA AP
4	0.6348641	MOR V MEANT MAXT
4	0.6348639	MOR FA AP MAXT
4	0.6348637	FA PI MEANT MAXT
4	0.6348631	WCR CA FA MEANT
4	0.6348630	WCR CA FA MAXT
4	0.6348628	WCR PI WD DA

5	0.6361793	MOR CA P AP MAXT
5	0.6353726	CS LL V MEANT DA
5	0.6353350	CS CA LL AP MEANT
5	0.6351769	P PI ESAL AP DA
5	0.6351538	CS MOR V ESAL DA
5	0.6350623	P FOUR V AP WD
5	0.6350609	MOR CA ESAL AP MAXT
5	0.6350583	MOR WCR CA WD MAXT
5	0.6350563	CS P FOUR AP WD

Roughness Progression on KDOT PCC Pavements
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

In	R-square	Variables in Model
5	0.6350439	CA V ESAL AP MEANT
5	0.6350340	CS FOUR V AP WD
5	0.6350297	FA TUHUND V AP WD
5	0.6350289	CS FOUR ESAL AP WD
5	0.6350284	CS CA ESAL AP MEANT
5	0.6350278	FOUR V ESAL AP WD
5	0.6350211	CS LL FOUR AP WD
5	0.6350168	LL FOUR V AP WD
5	0.6350150	CS CA V AP MEANT
5	0.6350068	CS PI FOUR AP WD
5	0.6349989	PI FOUR V AP WD
5	0.6349815	CA PI V AP MEANT
5	0.6349734	P V AP WD MINT
5	0.6349692	CS P AP WD MINT
6	0.6364212	MOR CA P AP MAXT PRI
6	0.6354286	CS LL V MEANT DA PRI
6	0.6353914	CS CA LL AP MEANT PRI
6	0.6352310	P PI ESAL AP DA PRI
6	0.6352137	CS MOR V ESAL DA PRI
6	0.6351529	MOR CA ESAL AP MAXT PRI
6	0.6351207	MOR WCR CA WD MAXT PRI
6	0.6351065	CA V ESAL AP MEANT PRI
6	0.6350914	CS CA ESAL AP MEANT PRI
6	0.6350801	LL FOUR V AP WD PRI
6	0.6350784	CS CA V AP MEANT PRI
6	0.6350706	CS PI FOUR AP WD PRI
6	0.6350632	PI FOUR V AP WD PRI
6	0.6350465	CA PI V AP MEANT PRI
6	0.6350142	LL V AP WD MINT PRI
6	0.6350127	CA P ESAL AP DA PRI
6	0.6350120	MOR LL FOUR AP WD PRI
6	0.6350106	MOR PI FOUR AP WD PRI
6	0.6350078	CS PI AP WD MINT PRI
6	0.6350042	PI V AP WD MINT PRI
6	0.6350038	CS A FA PI V PRI
6	0.6349964	MOR LL AP WD MINT PRI
6	0.6349952	CS CA P AP MEANT PRI

NOTE: Models of not full rank are not included.

Roughness Progression on KDOT PCC Pavements
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

Correlation Analysis

24 'VAR' Variables:					
IRIR	CS	MOR	WCR	A	CA
FA	WOS	P	PI	LL	FOUR

SAS - Output

TUHUND	V	ESAL	AP	WD	MEANT
MINT	MAXT	DB	DA	FT	PRI

Simple Statistics

Variable	N	Mean	Std Dev	Sum	Minimum	Maximum
IRIR	10	0.01774	0.01823	0.17740	-0.01280	0.04830
CS	10	39.12520	3.79659	391.25200	30.07000	43.13300
MOR	10	3.80520	0.45271	38.05200	2.99500	4.44600
WCR	10	0.45100	0.01595	4.51000	0.42000	0.47000
A	10	0.06430	0.00556	0.64300	0.06000	0.07100
CA	10	0.37640	0.10411	3.76400	0.26430	0.49190
FA	10	0.39176	0.09859	3.91760	0.28410	0.49820
WOS	10	2.80416	0.51406	28.04160	1.82880	3.04800
P	10	0.60000	0.51640	6.00000	0	1.00000
PI	10	24.74900	2.72686	247.49000	19.87500	27.33000
LL	10	0.46416	0.03139	4.64160	0.41630	0.50630
FOUR	10	0.99544	0.00961	9.95440	0.97720	1.00000
TUHUND	10	0.93258	0.03162	9.32580	0.87940	0.96250
V	10	111.04100	5.08810	1110	96.56000	112.65000
ESAL	10	5425	3069	54252	2409	10367
AP	10	905.45920	97.99755	9055	758.19000	1005
WD	10	43.28000	4.88007	432.80000	35.80000	48.10000
MEANT	10	12.78888	0.42778	127.88880	12.22220	13.33330
MINT	10	-30.40000	0.84327	-304.00000	-32.00000	-30.00000
MAXT	10	45.80000	1.54919	458.00000	43.00000	47.00000
DB	10	107.68000	5.46154	1077	101.80000	114.90000
DA	10	39.90000	12.66000	399.00000	28.40000	58.80000
FT	10	81.58000	6.61829	815.80000	74.10000	89.10000
PRI	10	0.33090	0.09609	3.30900	0.19100	0.45800

Roughness Progression on KDOT PCC Pavements
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

Correlation Analysis

Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 10

	IRIR	CS	MOR	WCR	A	CA
IRIR	1.00000 0.0	-0.25175 0.4829	-0.02510 0.9451	-0.52101 0.1225	0.04691 0.8976	0.21957 0.5422
CS	-0.25175 0.4829	1.00000 0.0	-0.01194 0.9739	0.73511 0.0154	-0.77400 0.0086	-0.44122 0.2018
MOR	-0.02510 0.9451	-0.01194 0.9739	1.00000 0.0	0.22492 0.5321	-0.20454 0.5708	0.67385 0.0326
WCR	-0.52101 0.1225	0.73511 0.0154	0.22492 0.5321	1.00000 0.0	-0.70549 0.0226	-0.43889 0.2045
A	0.04691 0.8976	-0.77400 0.0086	-0.20454 0.5708	-0.70549 0.0226	1.00000 0.0	0.48450 0.1559
CA	0.21957 0.5422	-0.44122 0.2018	0.67385 0.0326	-0.43889 0.2045	0.48450 0.1559	1.00000 0.0
FA	-0.27207 0.4470	0.44258 0.2002	-0.66793 0.0348	0.46352 0.1773	-0.46252 0.1783	-0.99743 0.0001
WOS	-0.43979	-0.11561	-0.74602	0.03304	0.40770	-0.53508

	0.2034	0.7505	0.0132	0.9278	0.2422	0.1110
P	-0.10435 0.7742	0.34179 0.3337	0.57642 0.0811	0.45862 0.1825	-0.14709 0.6851	0.45094 0.1909
PI	0.22963 0.5233	-0.41854 0.2287	-0.03362 0.9265	-0.31008 0.3832	0.59758 0.0681	0.45296 0.1886
LL	0.07234 0.8426	-0.56218 0.0907	0.13496 0.7101	-0.39761 0.2552	0.80021 0.0054	0.67727 0.0314
FOUR	-0.43979 0.2034	-0.11561 0.7505	-0.74602 0.0132	0.03304 0.9278	0.40770 0.2422	-0.53508 0.1110
TUHUND	-0.64227 0.0452	0.14287 0.6938	-0.46382 0.1769	0.36085 0.3056	0.27652 0.4393	-0.39799 0.2547
V	-0.27873 0.4355	0.83803 0.0025	0.15693 0.6650	0.46257 0.1783	-0.42350 0.2226	-0.00877 0.9808
ESAL	-0.25314 0.4804	0.27561 0.4408	-0.24574 0.4938	0.45123 0.1906	0.05673 0.8763	-0.20102 0.5776
AP	-0.06566 0.8570	0.62369 0.0540	-0.31723 0.3718	0.56893 0.0861	-0.83579 0.0026	-0.87058 0.0010
WD	-0.04006 0.9125	0.63190 0.0500	-0.27316 0.4451	0.56838 0.0865	-0.86154 0.0014	-0.84020 0.0023

Roughness Progression on KDOT PCC Pavements
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

Correlation Analysis

Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 10

	IRIR	CS	MOR	WCR	A	CA
MEANT	-0.19217 0.5948	-0.59644 0.0688	-0.39421 0.2596	-0.48130 0.1590	0.93038 0.0001	0.20832 0.5636
MINT	-0.43979 0.2034	-0.11561 0.7505	-0.74602 0.0132	0.03304 0.9278	0.40770 0.2422	-0.53508 0.1110
MAXT	-0.33650 0.3417	-0.34812 0.3243	-0.68751 0.0280	-0.21582 0.5493	0.66577 0.0356	-0.27913 0.4348
DB	0.57900 0.0794	-0.50741 0.1344	0.49418 0.1465	-0.66805 0.0347	0.35303 0.3170	0.85347 0.0017
DA	0.01429 0.9688	-0.68932 0.0274	0.07557 0.8356	-0.62174 0.0550	0.94827 0.0001	0.70973 0.0215
FT	0.53324 0.1125	-0.73058 0.0164	0.20396 0.5719	-0.86809 0.0011	0.67761 0.0313	0.79193 0.0063
PRI	-0.22046 0.5405	0.47309 0.1673	0.12040 0.7404	0.59958 0.0669	-0.78085 0.0077	-0.55755 0.0940

Roughness Progression on KDOT PCC Pavements
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

Correlation Analysis

SAS - Output

Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 10

	FA	WOS	P	PI	LL	FOUR
IRIR	-0.27207 0.4470	-0.43979 0.2034	-0.10435 0.7742	0.22963 0.5233	0.07234 0.8426	-0.43979 0.2034
CS	0.44258 0.2002	-0.11561 0.7505	0.34179 0.3337	-0.41854 0.2287	-0.56218 0.0907	-0.11561 0.7505
MOR	-0.66793 0.0348	-0.74602 0.0132	0.57642 0.0811	-0.03362 0.9265	0.13496 0.7101	-0.74602 0.0132
WCR	0.46352 0.1773	0.03304 0.9278	0.45862 0.1825	-0.31008 0.3832	-0.39761 0.2552	0.03304 0.9278
A	-0.46252 0.1783	0.40770 0.2422	-0.14709 0.6851	0.59758 0.0681	0.80021 0.0054	0.40770 0.2422
CA	-0.99743 0.0001	-0.53508 0.1110	0.45094 0.1909	0.45296 0.1886	0.67727 0.0314	-0.53508 0.1110
FA	1.00000 0.0	0.57555 0.0817	-0.44252 0.2003	-0.45945 0.1816	-0.66176 0.0371	0.57555 0.0817
WOS	0.57555 0.0817	1.00000 0.0	-0.40825 0.2415	0.04813 0.8950	0.09001 0.8047	1.00000 0.0001
P	-0.44252 0.2003	-0.40825 0.2415	1.00000 0.0	0.49364 0.1471	0.44724 0.1950	-0.40825 0.2415
PI	-0.45945 0.1816	0.04813 0.8950	0.49364 0.1471	1.00000 0.0	0.90268 0.0003	0.04813 0.8950
LL	-0.66176 0.0371	0.09001 0.8047	0.44724 0.1950	0.90268 0.0003	1.00000 0.0	0.09001 0.8047
FOUR	0.57555 0.0817	1.00000 0.0001	-0.40825 0.2415	0.04813 0.8950	0.09001 0.8047	1.00000 0.0
TUHUND	0.45454 0.1869	0.88634 0.0006	0.00626 0.9863	0.09519 0.7936	0.17641 0.6259	0.88634 0.0006
V	0.02623 0.9427	-0.16667 0.6454	0.40825 0.2415	-0.33257 0.3478	-0.27584 0.4405	-0.16667 0.6454
ESAL	0.21777 0.5456	0.38780 0.2682	0.58953 0.0729	0.61612 0.0579	0.42404 0.2220	0.38780 0.2682
AP	0.84892 0.0019	0.05710 0.8755	-0.25698 0.4735	-0.59120 0.0719	-0.86268 0.0013	0.05710 0.8755
WD	0.81613 0.0040	-0.00216 0.9953	-0.23280 0.5175	-0.59515 0.0695	-0.86945 0.0011	-0.00216 0.9953

Roughness Progression on KDOT PCC Pavements
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

Correlation Analysis

Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 10

FA	WOS	P	PI	LL	FOUR

MEANT	-0.17002 0.6386	0.69818 0.0247	-0.20123 0.5772	0.47855 0.1618	0.67835 0.0311	0.69818 0.0247
MINT	0.57555 0.0817	1.00000 0.0001	-0.40825 0.2415	0.04813 0.8950	0.09001 0.8047	1.00000 0.0001
MAXT	0.31887 0.3692	0.95258 0.0001	-0.38889 0.2667	0.23640 0.5108	0.33573 0.3429	0.95258 0.0001
DB	-0.88681 0.0006	-0.69674 0.0252	0.19383 0.5916	0.40262 0.2487	0.47511 0.1652	-0.69674 0.0252
DA	-0.68318 0.0294	0.19566 0.5880	0.09178 0.8009	0.60883 0.0618	0.86907 0.0011	0.19566 0.5880
FT	-0.81536 0.0040	-0.35199 0.3185	-0.00260 0.9943	0.54471 0.1035	0.64967 0.0420	-0.35199 0.3185
PRI	0.55512 0.0958	-0.11573 0.7502	-0.19347 0.5923	-0.74907 0.0126	-0.81789 0.0038	-0.11573 0.7502

Roughness Progression on KDOT PCC Pavements
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

Correlation Analysis

Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 10

	TUHUND	V	ESAL	AP	WD	MEANT
IRIR	-0.64227 0.0452	-0.27873 0.4355	-0.25314 0.4804	-0.06566 0.8570	-0.04006 0.9125	-0.19217 0.5948
CS	0.14287 0.6938	0.83803 0.0025	0.27561 0.4408	0.62369 0.0540	0.63190 0.0500	-0.59644 0.0688
MOR	-0.46382 0.1769	0.15693 0.6650	-0.24574 0.4938	-0.31723 0.3718	-0.27316 0.4451	-0.39421 0.2596
WCR	0.36085 0.3056	0.46257 0.1783	0.45123 0.1906	0.56893 0.0861	0.56838 0.0865	-0.48130 0.1590
A	0.27652 0.4393	-0.42350 0.2226	0.05673 0.8763	-0.83579 0.0026	-0.86154 0.0014	0.93038 0.0001
CA	-0.39799 0.2547	-0.00877 0.9808	-0.20102 0.5776	-0.87058 0.0010	-0.84020 0.0023	0.20832 0.5636
FA	0.45454 0.1869	0.02623 0.9427	0.21777 0.5456	0.84892 0.0019	0.81613 0.0040	-0.17002 0.6386
WOS	0.88634 0.0006	-0.16667 0.6454	0.38780 0.2682	0.05710 0.8755	-0.00216 0.9953	0.69818 0.0247
P	0.00626 0.9863	0.40825 0.2415	0.58953 0.0729	-0.25698 0.4735	-0.23280 0.5175	-0.20123 0.5772
PI	0.09519 0.7936	-0.33257 0.3478	0.61612 0.0579	-0.59120 0.0719	-0.59515 0.0695	0.47855 0.1618
LL	0.17641 0.6259	-0.27584 0.4405	0.42404 0.2220	-0.86268 0.0013	-0.86945 0.0011	0.67835 0.0311

FOUR	0.88634 0.0006	-0.16667 0.6454	0.38780 0.2682	0.05710 0.8755	-0.00216 0.9953	0.69818 0.0247
TUHUND	1.00000 0.0	0.14645 0.6864	0.60599 0.0633	-0.00538 0.9882	-0.05773 0.8741	0.59998 0.0667
V	0.14645 0.6864	1.00000 0.0	0.11256 0.7569	0.14644 0.6864	0.15696 0.6650	-0.31033 0.3828
ESAL	0.60599 0.0633	0.11256 0.7569	1.00000 0.0	0.02946 0.9356	0.00669 0.9854	0.22282 0.5361
AP	-0.00538 0.9882	0.14644 0.6864	0.02946 0.9356	1.00000 0.0	0.99824 0.0001	-0.66220 0.0370
WD	-0.05773 0.8741	0.15696 0.6650	0.00669 0.9854	0.99824 0.0001	1.00000 0.0	-0.70480 0.0228

Roughness Progression on KDOT PCC Pavements
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

Correlation Analysis

Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 10

	TUHUND	V	ESAL	AP	WD	MEANT
MEANT	0.59998 0.0667	-0.31033 0.3828	0.22282 0.5361	-0.66220 0.0370	-0.70480 0.0228	1.00000 0.0
MINT	0.88634 0.0006	-0.16667 0.6454	0.38780 0.2682	0.05710 0.8755	-0.00216 0.9953	0.69818 0.0247
MAXT	0.81233 0.0043	-0.27217 0.4468	0.33219 0.3484	-0.22873 0.5250	-0.28571 0.4236	0.87931 0.0008
DB	-0.75111 0.0123	-0.22002 0.5413	-0.39756 0.2552	-0.64348 0.0447	-0.60342 0.0647	-0.00940 0.9794
DA	0.18719 0.6046	-0.24423 0.4965	0.03864 0.9156	-0.96335 0.0001	-0.97659 0.0001	0.83571 0.0026
FT	-0.50370 0.1377	-0.39924 0.2531	-0.31429 0.3765	-0.78302 0.0074	-0.76374 0.0101	0.36422 0.3008
PRI	-0.08800 0.8090	0.15687 0.6652	-0.24458 0.4959	0.76065 0.0106	0.76893 0.0093	-0.65714 0.0390

Roughness Progression on KDOT PCC Pavements
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

Correlation Analysis

Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 10

	MINT	MAXT	DB	DA	FT	PRI
IRIR	-0.43979 0.2034	-0.33650 0.3417	0.57900 0.0794	0.01429 0.9688	0.53324 0.1125	-0.22046 0.5405
CS	-0.11561 0.7505	-0.34812 0.3243	-0.50741 0.1344	-0.68932 0.0274	-0.73058 0.0164	0.47309 0.1673
MOR	-0.74602	-0.68751	0.49418	0.07557	0.20396	0.12040

	0.0132	0.0280	0.1465	0.8356	0.5719	0.7404
WCR	0.03304 0.9278	-0.21582 0.5493	-0.66805 0.0347	-0.62174 0.0550	-0.86809 0.0011	0.59958 0.0669
A	0.40770 0.2422	0.66577 0.0356	0.35303 0.3170	0.94827 0.0001	0.67761 0.0313	-0.78085 0.0077
CA	-0.53508 0.1110	-0.27913 0.4348	0.85347 0.0017	0.70973 0.0215	0.79193 0.0063	-0.55755 0.0940
FA	0.57555 0.0817	0.31887 0.3692	-0.88681 0.0006	-0.68318 0.0294	-0.81536 0.0040	0.55512 0.0958
WOS	1.00000 0.0001	0.95258 0.0001	-0.69674 0.0252	0.19566 0.5880	-0.35199 0.3185	-0.11573 0.7502
P	-0.40825 0.2415	-0.38889 0.2667	0.19383 0.5916	0.09178 0.8009	-0.00260 0.9943	-0.19347 0.5923
PI	0.04813 0.8950	0.23640 0.5108	0.40262 0.2487	0.60883 0.0618	0.54471 0.1035	-0.74907 0.0126
LL	0.09001 0.8047	0.33573 0.3429	0.47511 0.1652	0.86907 0.0011	0.64967 0.0420	-0.81789 0.0038
FOUR	1.00000 0.0001	0.95258 0.0001	-0.69674 0.0252	0.19566 0.5880	-0.35199 0.3185	-0.11573 0.7502
TUHUND	0.88634 0.0006	0.81233 0.0043	-0.75111 0.0123	0.18719 0.6046	-0.50370 0.1377	-0.08800 0.8090
V	-0.16667 0.6454	-0.27217 0.4468	-0.22002 0.5413	-0.24423 0.4965	-0.39924 0.2531	0.15687 0.6652
ESAL	0.38780 0.2682	0.33219 0.3484	-0.39756 0.2552	0.03864 0.9156	-0.31429 0.3765	-0.24458 0.4959
AP	0.05710 0.8755	-0.22873 0.5250	-0.64348 0.0447	-0.96335 0.0001	-0.78302 0.0074	0.76065 0.0106
WD	-0.00216 0.9953	-0.28571 0.4236	-0.60342 0.0647	-0.97659 0.0001	-0.76374 0.0101	0.76893 0.0093

Roughness Progression on KDOT PCC Pavements
JPCP from 1993 to 1997 - This run has as-constructed smoothness,PRI as IV

Correlation Analysis

Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 10

	MINT	MAXT	DB	DA	FT	PRI
MEANT	0.69818 0.0247	0.87931 0.0008	-0.00940 0.9794	0.83571 0.0026	0.36422 0.3008	-0.65714 0.0390
MINT	1.00000 0.0	0.95258 0.0001	-0.69674 0.0252	0.19566 0.5880	-0.35199 0.3185	-0.11573 0.7502
MAXT	0.95258 0.0001	1.00000 0.0	-0.44965 0.1923	0.47361 0.1668	-0.05895 0.8715	-0.35768 0.3102
DB	-0.69674	-0.44965	1.00000	0.49035	0.91590	-0.48725

	0.0252	0.1923	0.0	0.1502	0.0002	0.1532
DA	0.19566 0.5880	0.47361 0.1668	0.49035 0.1502	1.00000 0.0	0.72808 0.0170	-0.79805 0.0057
FT	-0.35199 0.3185	-0.05895 0.8715	0.91590 0.0002	0.72808 0.0170	1.00000 0.0	-0.69105 0.0269
PRI	-0.11573 0.7502	-0.35768 0.3102	-0.48725 0.1532	-0.79805 0.0057	-0.69105 0.0269	1.00000 0.0

APPENDIX B
Typical KENSLAB Output File

damage analysis for k7 mile 13.3 8w

NUMBER OF PROBLEMS TO BE SOLVED (NPROB) = 1

****

*

* TWO SLABS ON SOLID FOUNDATION (DAMAGE ANALYSIS) ROUTE K-7 (NL-13.3) *

*

****

TYPE OF FOUNDATION (NFOUND)	=	1
TYPE OF DAMAGE ANALYSIS (NDAMA)	=	1
NUMBER OF PERIODS PER YEAR (NPY)	=	1
NUMBER OF LOAD GROUPS (NLG)	=	1
TOTAL NUMBER OF SLABS (NSLAB)	=	2
TOTAL NUMBER OF JOINTS (NJOINT)	=	1

ARRANGEMENT OF SLABS

SLAB NO.	NO. OF NODES (NX) IN X DIRECTION	NO. OF NODES (NY) IN Y DIRECTION	JOINT NO. AT FOUR SIDES (JONO) LEFT	RIGHT	BOTTOM	TOP
1	6	8	0	1	0	0
2	10	8	1	0	0	0

NUMBER OF LAYERS (NLAYER)------------------------------------= 1

NODAL NUMBER USED TO CHECK CONVERGENCE (NNCK)-----------------= 49

NUMBER OF NODES NOT IN CONTACT (NOTCON)-----------------------= 0

NUMBER OF GAPS (NGAP)---= 0

NUMBER OF POINTS FOR PRINTOUT (NPRINT)------------------------= 3

CODE FOR INPUT OF GAPS OR PRECOMPRESSIONS (INPUT)-------------= 0

BOND BETWEEN TWO LAYERS (NBOND)-------------------------------= 0

CONDITION OF WARPING (NTEMP)----------------------------------= 0

CODE INDICATING WHETHER SLAB WEIGHT IS CONSIDERED (NWT)-------= 0

MAX NO. OF CYCLES FOR CHECKING CONTACT (NCYCLE)---------------= 1

NUMBER OF ADDITIONAL THICKNESSES TO BE READ IN (NAT)
FOR LAYER 1 --= 0
FOR LAYER 2 --= 0

NUMBER OF POINTS ON X AXIS OF SYMMETRY (NSX)------------------= 0

NUMBER OF POINTS ON Y AXIS OF SYMMETRY (NSY)------------------= 0 damage analysis for k7 mile 13.3 8w

MORE DETAILED PRINTOUT FOR EACH CONTACT CYCLE (MDPO)----------= 0

DIFFERENCE IN TEMP. BETWEEN TOP AND BOTTOM OF SLAB (TEMP)-----= .00000

UNIT WEIGHT OF LAYER 1 (GAMA(1))-----------------------------= .00000

UNIT WEIGHT OF LAYER 2 (GAMA(2))-----------------------------= .00000

MODULUS OF RUPTURE OF LAYER 1 (PMR(1))-----------------------= 537.00000

MODULUS OF RUPTURE OF LAYER 2 (PMR(2))-----------------------= .00000

COEFFICIENT OF THERMAL EXPANSION (CT)------------------------= .500E-05

TOLERANCE FOR ITERATIONS (DEL)-------------------------------= .100E-02

MAXIMUM ALLOWABLE VERTICAL DISPLACEMENT (FMAX)---------------= 1.00000

FOR LAYER 1 FATIGUE COEFFICIENTS: F1 = .00000 F2 = .00000

FOR LAYER 2 FATIGUE COEFFICIENTS: F1 = .00000 F2 = .00000

FOR SLAB NO. 1 : X= .00000 45.00000 90.00000 135.00000 160.00000
180.00000
Y= .00000 16.00000 40.00000 75.00000 80.00000
95.00000 120.00000 144.00000

FOR SLAB NO. 2 : X= .00000 10.00000 22.00000 42.00000 52.00000
64.00000 70.00000 100.00000 140.00000 180.00000

Y= .00000 16.00000 40.00000 75.00000 80.00000
95.00000 120.00000 144.00000

LAYER NO.	THICKNESS (T)	POISSON'S RATIO (PR)	YOUNG'S MODULUS (YM)
1	9.00000	.15000	.400E+07

NUMBER OF LOADED AREAS (NUDL) FOR EACH LOAD GROUP ARE:
8

NUMBER OF CONCENTRATED NODAL FORCES (NCNF) FOR EACH LOAD GROUP ARE:
0

GROUP 1 LOADS ARE APPLIED ON THE SLAB NO.(LS) WITH COORDINATES (XL AND YL) AND INTENSITY(QQ) AS SHOWN:

2	.00000	11.52000	.00000	7.94000	90.00744
2	.00000	11.52000	13.00000	20.94000	90.00744
2	1.06500	10.45500	72.73500	79.20500	90.00744
2	1.06500	10.45500	85.73500	92.20500	90.00744
2	52.00000	63.52000	.00000	7.94000	90.00744
2	52.00000	63.52000	13.00000	20.94000	90.00744
2	53.18500	62.33500	72.82000	79.12000	90.00744
2	53.18500	62.33500	85.82000	92.12000	90.00744

```
NODAL NUMBERS FOR STRESS PRINTOUT (NP) ARE:
   81      89      97


FOUNDATION SEASONAL ADJUSTMENT FACTOR (FSAF) FOR EACH PERIOD ARE
   1.00000

YOUNG'S MODULUS OF FOUNDATION (YMS) =  .500E+04

POISSON'S RATIO OF FOUNDATION (PRS) =    .45000


YOUNG MODULUS OF DOWEL BAR (YMSB)   =  .290E+08
POISSON RATIO OF DOWEL BAR (PRSB)   =    .30000


     JOINT    SPRING  CONSTANT   MODULUS OF   DOWEL     DOWEL     JOINT       GAP
BETWEEN        NO. OF NODES
      NO.     SHEAR     MOMENT   DOWEL SUP.  DIAMETER  SPACING    WIDTH      DOWEL AND
CONC.     ALONG JOINT
           (SPCON1)  (SPCON2)    (SCKV)      (BD)      (BS)      (WJ)         (GDC)
          (NNAJ)
       1    .000E+00   .000E+00   .150E+07  1.00000  12.00000   .25000        .00000
           0


FOR PERIOD  1  TOTAL NO. OF LOAD REPETITIONS (TNLR) FOR EACH LOAD GROUP ARE:
     54350.00000


JOINT NO.     EQUIVALENT SPRING CONSTANT (SPCON)
   1                            .395E+05

HALF BAND WIDTH (NB) =   69


PERIOD  1  LOAD GROUP  1  AND CYCLE NO. 1
ITERATION NO. (IC) =  1 DIFFERENCE IN DEFLECTION (DF) =   .06094086
ITERATION NO. (IC) =  3 DIFFERENCE IN DEFLECTION (DF) =   .02342880
ITERATION NO. (IC) =  5 DIFFERENCE IN DEFLECTION (DF) =   .00574293
ITERATION NO. (IC) =  7 DIFFERENCE IN DEFLECTION (DF) =   .00155073
ITERATION NO. (IC) =  9 DIFFERENCE IN DEFLECTION (DF) =   .00042598
ITERATION NO. (IC) = 11 DIFFERENCE IN DEFLECTION (DF) =   .00011731
ITERATION NO. (IC) = 13 DIFFERENCE IN DEFLECTION (DF) =   .00003230

SUM OF APPLIED FORCES (FOSUM)=   54244.9     SUM OF TOTAL REACTIONS (SUBSUM)=
54219.5

ITERATION NO. (IC) = 15 DIFFERENCE IN DEFLECTION (DF) =   .00000891

SUM OF APPLIED FORCES (FOSUM)=   54244.9     SUM OF TOTAL REACTIONS (SUBSUM)=
54230.3


DEFLECTIONS OF SLABS (F) ARE: (DOWNWARD POSITIVE)
  1   .1175E-01   2   .1165E-01   3   .1149E-01   4   .1111E-01   5   .1105E-01   6
 .1084E-01   7   .1037E-01   8   .9783E-02
  9   .1661E-01  10   .1658E-01  11   .1636E-01  12   .1558E-01  13   .1542E-01  14
 .1486E-01  15   .1370E-01  16   .1236E-01
 17   .2599E-01  18   .2592E-01  19   .2540E-01  20   .2361E-01  21   .2324E-01  22
 .2198E-01  23   .1938E-01  24   .1647E-01
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25   .4656E-01  26   .4591E-01  27   .4411E-01  28   .3959E-01  29   .3874E-01  30
.3593E-01  31   .3053E-01  32   .2480E-01
33   .6556E-01  34   .6396E-01  35   .6043E-01  36   .5308E-01  37   .5182E-01  38
.4764E-01  39   .3992E-01  40   .3220E-01
41   .8420E-01  42   .8153E-01  43   .7585E-01  44   .6577E-01  45   .6408E-01  46
.5857E-01  47   .4861E-01  48   .3929E-01
49   .9225E-01  50   .8656E-01  51   .7776E-01  52   .6798E-01  53   .6633E-01  54
.6043E-01  55   .4907E-01  56   .3842E-01
57   .9033E-01  58   .8474E-01  59   .7622E-01  60   .6613E-01  61   .6447E-01  62
.5870E-01  63   .4763E-01  64   .3706E-01
65   .8754E-01  66   .8219E-01  67   .7412E-01  68   .6377E-01  69   .6211E-01  70
.5650E-01  71   .4584E-01  72   .3547E-01
73   .8262E-01  74   .7744E-01  75   .6967E-01  76   .5960E-01  77   .5800E-01  78
.5268E-01  79   .4265E-01  80   .3289E-01
81   .7958E-01  82   .7447E-01  83   .6678E-01  84   .5719E-01  85   .5566E-01  86
.5053E-01  87   .4087E-01  88   .3155E-01
89   .7434E-01  90   .6963E-01  91   .6256E-01  92   .5365E-01  93   .5224E-01  94
.4747E-01  95   .3850E-01  96   .2984E-01
97   .7101E-01  98   .6667E-01  99   .6012E-01 100   .5162E-01 101   .5026E-01 102
.4573E-01 103   .3721E-01 104   .2895E-01
105  .5224E-01 106   .5003E-01 107   .4640E-01 108   .4044E-01 109   .3944E-01 110
.3622E-01 111   .3022E-01 112   .2414E-01
113  .3234E-01 114   .3154E-01 115   .3004E-01 116   .2704E-01 117   .2650E-01 118
.2475E-01 119   .2137E-01 120   .1778E-01
121  .1859E-01 122   .1818E-01 123   .1757E-01 124   .1635E-01 125   .1614E-01 126
.1541E-01 127   .1380E-01 128   .1183E-01

   FOR JOINT NO. 1 SHEAR (FAJ1) AND MOMENT (FAJ2) AT THE NODES ARE:
   41    2542.239        .000        42   3972.862        .000        43    2234.304
    .000       44      1742.104       .000
   45     888.060        .000        46   1467.634        .000        47     443.748
    .000       48      -412.207       .000

   FOR JOINT NO. 1 SHEAR IN ONE DOWEL BAR (FAJPD) AT THE NODES IS:
   41    3813.358      42    2383.717      43     908.870      44    1045.262
45    1065.672      46     880.581
   47     217.346      48    -412.207

   FOR JOINT NO. 1 BEARING STRESS (BEARS) OF CONCRETE AND SHEAR STRESS (SHEARS) OF
DOWELS AT THE NODES ARE:
   41    5956.084     4855.309      42    3723.127     3035.037      43    1419.563
 1157.206      44     1632.595     1330.867
   45    1664.474     1356.854      46    1375.379     1121.188      47     339.473
  276.733      48     -643.826     -524.837

   NODAL NUMBER AND REACTIVE PRESSURE (SUBR) ARE: (COMPRESSION POSITIVE)
   1   -.69817     2   -.26687     3   -.38459    4   -.05408    5   -.32269    6
-.33854     7   -.29447     8   -.95259
   9   -.00732    10   -.06208    11   -.09635   12   -.01385   13   -.08457   14
-.09699    15   -.10056    16   -.50254
  17    .99505    18    .07847    19    .08303   20    .00835   21    .04828   22
.01184     23   -.05076    24   -.66060
  25   4.38894    26    .79044    27    .82197   28   -.01873   29    .98784   30
.49949     31    .29976    32   -.09665
  33   9.70022    34   2.20292    35   2.09092   36   3.02797   37  -2.61047   38
1.65252    39   1.02522    40   1.38692
  41  11.65426    42   3.37791    43   3.46795   44   1.81325   45    .71199   46
2.44278    47   2.00807    48   3.59265
  49  34.43555    50  10.06999    51   8.20636   52   5.29618   53   4.25485   54
6.08821    55   4.31929    56   6.04974
  57  17.75039    58   3.96248    59   2.20874   60   2.23740   61   1.76294   62
2.22325    63   1.17641    64   1.15230
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  65  17.58061    66    4.11614   67    3.44447    68    2.22062    69     .86415    70
2.29727    71   1.51763   72   1.62638
  73  15.41358    74    3.57954   75    2.70671    76    1.75235    77     .95472    78
1.85881    79   1.16430   80   1.02700
  81  14.96371    82    3.40670   83    2.75720    84    1.60768    85    1.22231    86
1.68066    87   1.01836   88    .74715
  89   9.85560    90    1.88470   91   -1.43946    92    1.13170    93    1.16860    94
.92709    95    .26050    96    .28570
  97   9.32594    98    2.39146   99    3.03663   100     .92084   101     .69797   102
1.14381   103    .80423   104   .47915
 105   7.62340   106    1.48806  107    1.41201   108     .03753   109    1.44184   110
.83857   111    .53355   112   .11456
 113   2.80545   114     .44321  115     .46809   116     .04442   117     .37336   118
.26875   119    .13957   120   -.35848
 121   -.26097   122    -.49676  123    -.68658   124    -.07875   125    -.63207   126
-.60339   127   -.62120   128  -2.38026

     NODE    LAYER   STRESS X          STRESS Y          STRESS XY            MAJOR
  MINOR                MAX.SHEAR
       81      1       .247172E+03     .000000E+00       .000000E+00       .000000E+00
.247172E+03        .123586E+03
       89      1       .253425E+03     .000000E+00       .000000E+00       .000000E+00
.253425E+03        .126712E+03
       97      1       .132364E+03     .000000E+00       .000000E+00       .000000E+00
.132364E+03        .661822E+02
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STRESS DIFFERENTIAL FOR MULTIPLE WHEELS IS   6.25229

MAXIMUM STRESS (SMAX) AT BOTTOM OF LAYER 1 IS 253.42470 AND OCCURS AT NODE 89

FOR PERIOD 1 LOAD GROUP 1 CRACKING INDEX (CI) FOR LAYER 1 IS .12306E-01
PRIMARY CRACKING INDEX IS .12306E-01 SECONDARY CRACKING INDEX IS .00000E+00

FOR LAYER 1, SUM OF CRACKING INDEX (SUMCI) OVER ALL PERIODS AND LOAD GROUPS =
.12306E-01

DESIGN LIFE (DL) IN YEARS =   81.26