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Roughness Progression Model on Kansas PCC Pavements

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ABSTRACT

Accurate prediction of pavement performance over longer time horizon represents a critical issue in the pavement surface type selection process by the Kansas Department of Transportation using the life-cycle-cost analysis. Prediction of roughness progression on the Portland Cement Concrete (PCC) pavements is very important since the current model used by Kansas Department of Transportation is based on the pavement serviceability (1993 *AASHTO Design Guide*). In this study, a statistical analysis approach was used to develop an accurate, time-dependent roughness prediction model for the newly constructed PCC pavements in Kansas. Data used in the model development process include construction and materials data as well as other inventory items, such as, traffic and climatic data. Using multiple regression analysis technique, a time-dependent roughness (International Roughness Index, IRI) prediction model was developed. The developed model produced output values that are very close to the actual (measured) IRI values ($R^2 = 0.73$). The 20-year and 30-year IRI values were also predicted. The results show that the PCC pavements with stabilized, non-drainable bases would likely outperform those with stabilized, drainable bases for majority of the projects. The sensitivity analysis conducted in this study quantified, to some degree, the impact of various key input parameters on the time-dependent PCC pavement roughness profile. Several other important conclusions were also drawn in this study.

Key words: life-cycle-cost analysis—portland cement concrete pavement—roughness progression model—sensitivity analysis

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INTRODUCTION

A significant portion of funds is spent on pavement reconstruction. The construction program for the jointed plain concrete pavements (JPCPs) in Kansas is in the range of $150 to $200 million (*1*). The pavement surface type selection process of the Kansas Department of Transportation (KDOT) uses life-cycle-cost (LCC) analysis. Performance prediction of JPCP over a longer analysis period (30 years as minimum) is required in order to compare the life cycle costs of competing surface types. Performance prediction models for JPCP are now lacking in Kansas since new construction practices (shorter slabs, dowel bars, etc.) started in the early 1990's. Identifying and selecting appropriate strategies that can potentially perform better than others would result in high benefit return (*2*).

In the past, many studies have been conducted in order to develop performance (i.e., pavement distress and roughness) prediction models for JPCP. Current performance prediction and analysis models involved in predicting PCC pavement distress indices are primarily an improvement over the models used in the prototype performance-related specifications (PRS) for JPCPs. Using version 2.0 of the PaveSpec PRS demonstration software, Yu et al. (*3*) established that the prototype PRS was improved. As a result, the PaveSpec PRS demonstration software was upgraded to Version 3.0. In the case of the development of Performance-Related Specifications for JPCP, the specific data elements required by distress indicator models were summarized. Depending on the required data elements, such models predicted the development of joint spalling, faulting, slab cracking, and pavement smoothness over time (*4*). Similarly, using local Microsoft Access database, Titus-Glover et al. (*5*) developed improved pavement distress and roughness prediction models that incorporate mechanistic principles but that are still practical for use by State highway agencies. Likewise, Yu et al. (*3*) used the ORACLE data base management system to evaluate the performance of 303 in-service concrete pavement sections located throughout North America. Current efforts should be concentrated on the development of enhanced and improved pavement models to predict the time-dependent pavement roughness profiles.

DATABASE DEVELOPMENT

Table 1 lists the 24 PCC projects, on state, US and Interstate routes in Kansas, selected in this study. The projects were constructed between 1993 and 1997. All pavement sections are JPCP with 4.6 m (15 ft.) joint spacing and doweled joints. The JPCP slab thickness varied from 229 mm (9 in.) to 292 mm (11.5 in.). The database developed for each section includes annual roughness values measured during each year after construction and a number of design, construction, and climatic variables. Longitudinal profile measurements were done on the right and left wheel paths with a South Dakota–type Profilometer. From these profile data, the International Roughness Index (IRI) values were calculated. Only the right wheel path IRI values were used in this study.

The data was categorized and assembled into an Excel spreadsheet for statistical analysis. Initially, 56 different potential independent variables were considered. However, after data cleansing and thorough examination, the database was limited to 26 practical input variables. The selected input variables include pavement profile (initial smoothness, represented by initial roughness IRI value), pavement section and layer data, time-series traffic, subgrade type and treatment, climatic conditions, shoulder type, concrete mixture design data and concrete materials test results. Pavement layer data included the PCC slab thickness and type of base, such as, portland cement treated base (PCTB) and bound drainable base (BDB). Time-series traffic data refers to the cumulative 80-kN (18-kip) equivalent single-axle loads (ESALs). Climatic information was included in order to develop a model that can directly account for the section-specific climatic conditions. The output variable was the time-series (i.e., annual) right wheel path IRI value, which is used to quantify the long-term pavement roughness performance.

TABLE 1. Selected PCC Projects in the Study

Project K Number	County	Lane	Route	Construction Date	Begin Milepost	End Milepost
K-2633-01	Lyon	East	I 35	1994	10.9	16.7
K-2633-01	Lyon	West	I 35	1994	10.9	16.7
K-3596-01	Franklin	East	I 35	1995	0	3.2
K-3596-02	Franklin	East	I 35	1995	3.2	9
K-4088-02	Johnson	East	I 35	1996	13	16
K-4088-02	Johnson	West	I 35	1996	13	16
K-2446-01	Shawnee	North	I 70	1993	11.7	15
K-3344-01	Shawnee	South	I 70	1993	9	10
K-2447-01	Wyandotte	North	I 70	1993	15.6	17.1
K-2447-01	Wyandotte	South	I 70	1993	15.6	17.1
K-3637-01	Johnson	West	I 435	1996	0	3.3
K-4058-03	Harvey	Undivided	US 50	1995	28.7	35.6
K-3216-02	Chase	Undivided	US 50	1997	0	9
K-3217-02	Chase	Undivided	US 50	1997	9	19
K-4422-02	Ford	Undivided	US 56	1996	12.2	16
K-3251-01	Jackson	East	US 75	1995	8	17.3
K-3251-01	Jackson	East	US 75	1995	12	17
K-3251-01	Jackson	West	US 75	1996	8	17.3
K-3251-01	Jackson	West	US 75	1996	12	17
K-4341-01	Shawnee	East	US 75	1996	20	22
K-4341-01	Shawnee	West	US 75	1996	20	22
K-3220-01	Marion	Undivided	US 77	1995	11.1	11.8
K-3684-01	Sedgwick	West	K 15	1997	0	5.7
K-4460-01	Sedgwick	North	K 96	1996	3.9	14.7

Table 2 lists the variables used in modeling into the following groups: (a) inventory, (b) construction, and (c) climate. The climatic data was obtained from the Kansas State University Weather Data Library. The historical roughness data was obtained from the KDOT PMIS database.

TABLE 2. Data Elements Selected as Independent Variables for PCC Pavements

Inventory	Construction	Climate
-County code -Route No. -Project No. -Begin milepost -End milepost -Project length -Cumulative AADT (year) -Cumulative truck factor (year) -Cumulative yearly ESAL values* -Initial right wheel path, IRI roughness (in./mile)* -IRI roughness value at age (n) year (in./mile)*	-Age of pavement (year)* -PCC slab thickness (in.)* -Base thickness (in.) -Plasticity index of natural subgrade soil material* -% Material passing No.4 sieve* -% Material passing No.200 sieve* -Subgrade treatment: *No treatment (N/A) (=0)** *6" lime treated subgrade (=1)** *Subgrade modification (=2)** -Unit weight (lbs./ft^3)* -Flexural strength (PSI) -Total width of outside shoulder (ft.) -Shoulder type (paved=1 or unpaved=0) -Shoulder thickness (in.) -Drainable base (=1) or non-drainable base (=0): (Base material/treatment type) *Cement Treated Drainable Base (CTDB)=1** *Bound Drainable Base (BDB)=1** *Edge drain=1** *Portland Cement Treated Base (PCTB)=0** *no edge drain=0** -Pavement cross-slope (1.6%) -Water-cement ratio -Slump (in.) -Air content (%) -Cement factor (lbs./yd^3)* -Weight percentage of coarse aggregate in mix -Weight percentage of fine aggregate in mix	-Cumulative annual total precipitation (in.) -Cumulative total no. of days below 32 ^{o}F/yr* -Cumulative total no. of days above 90 ^{o}F/yr* -Cumulative no. of wet days/year (more than 10 mm precipitation)* -Avg. no. of freeze-thaw cycles per year* -Mean annual temperature (^{o}C) -Max. annual temperature (^{o}C) -Minimum annual temperature (^{o}C)* -Depth of frost penetration (in.)

* independent variable used in models.

REGRESSION EQUATION METHOD

In order to develop roughness prediction equations for the PCC pavements in Kansas, linear regression analysis was used to find the best relationship between the independent variables and the dependent variable. The backward selection procedure in SAS (*6*) computer program was selected for multiple regression analysis. This method starts with a full model (all independent variables entered) and then eliminates one variable at a time until a reasonable good regression model is selected. The selected model contains the most significant independent variables.

The following model for predicting future IRI of the PCC pavements was obtained:

$$\begin{aligned} \text{IRI} = \; & 218.38 - 0.61*\text{FSI} - 0.07*\text{TSI} + 7.88*\text{MIAT} \qquad (R^2 = 0.73) \qquad (1) \\ & + 9.10*\text{SLTH} + 8.45*\text{BTY} + 1.64*\text{AP} + 0.78*\text{IIRI} \\ & - 0.01*\text{WET} - 1.673e - 7*\text{ESAL} + 11.97*\text{SUBTRT}\ , \end{aligned}$$

where

IRI = yearly right wheel path roughness IRI value
FSI = % subgrade materials passing No.4 sieve
TSI = % subgrade materials passing No. 200 sieve
MIAT = minimum annual temperature (^{o}C)
SLTH = PCC slab thickness (inch)
BTY = drainable base (=1) or non-drainable base (=0)
AP = age of pavement (year)
IIRI = initial right wheel path IRI (in./mile)
WET = cumulative no. of wet days per year (more than 10 mm precipitation)
ESAL = cumulative yearly ESAL values
SUBTRT = subgrade treatment:
  no treatment (N/A) (=0)
  6" lime treated subgrade (=1)
  Subgrade modification (=2)

The IRI prediction model yielded a coefficient of determination, R^2 of 0.73 as shown in Figure 1. The 20-year and 30-year IRI values were predicted, and the R^2 value for each project was also calculated. Table 3 shows the predicted IRI values. It appears that the projects with stabilized, non-drainable bases would likely outperform the projects with stabilized, drainable bases for majority of the projects.

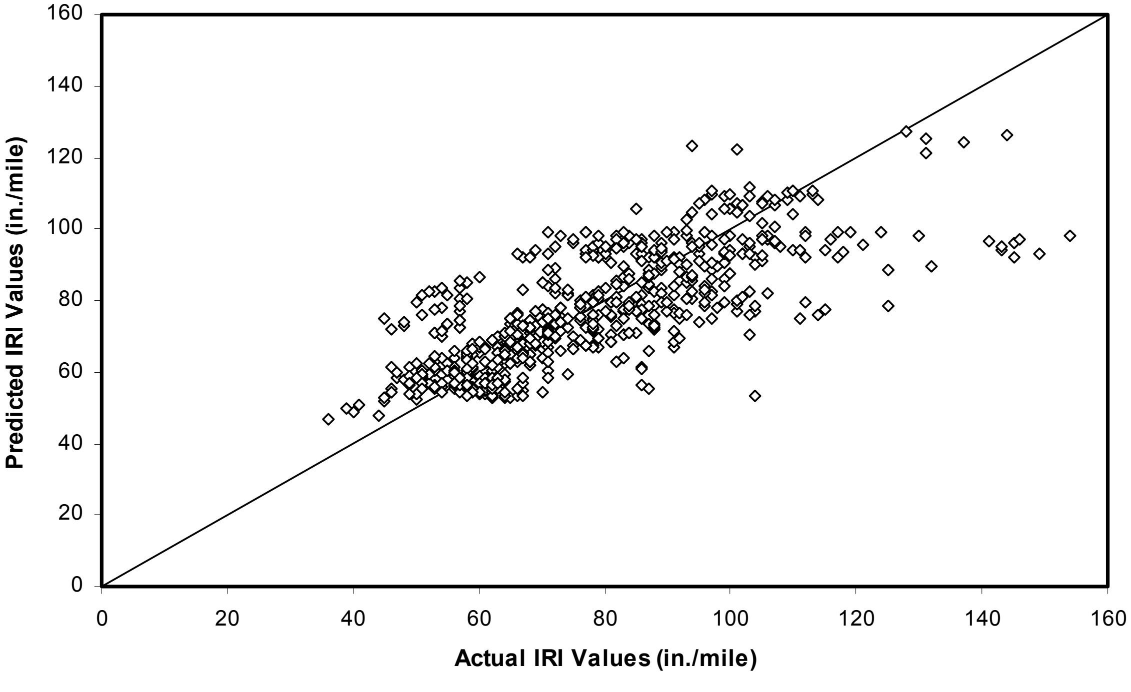

FIGURE 1. Comparison between Actual and Predicted IRI Values for the SAS-based Prediction Equation (R^2=0.73)

TABLE 3. Future 20-Year and 30-Year IRI Using SAS-Based Prediction Equation

Route	Lane	Initial IRI (in./mile)	20-Year IRI (in./mile)	30-Year IRI (in./mile)	R^2
I 35	East	52	96	106	0.07
I 35	East	90	100	110	0.35
I 35	East	97	92	101	1.00
I 35	West	100	123	132	1.00
I 35	East	84	111	121	0.99
I 35	West	99	111	121	0.99
I 70	North	46	76	86	0.95
I 70	South	36	66	76	0.98
I 70	North	110	120	129	0.99
I 70	South	97	120	129	0.99
I 435	West	80	92	101	1.00
US 50	Undivided	57	82	91	0.83
US 50	Undivided	71	93	102	0.51
US 50	Undivided	93	108	119	0.75
US 56	Undivided	97	113	125	0.03
US 75	East	71	87	95	0.89
US 75	West	67	87	95	0.89
US 75	East	71	87	96	0.85
US 75	West	68	83	92	0.89
US 75	East	68	90	100	0.38
US 75	West	85	92	103	0.61
US 77	Undivided	131	141	151	1.00
K15	West	50	74	84	1.00
K 96	North	67	73	83	1.00

* Drainable base: edge drain, cement treated drainable base (CTDB), bound drainable base (BDB).
** Non-drainable base: no edge drain, portland cement treated base (PCTB).

SENSITIVITY ANALYSIS

In order to assess the impact of each independent input variable on the time-dependent IRI profile, a sensitivity analysis was performed (Figure 2). To accomplish this objective, a PCCP section with average input values was chosen. The sensitivity analysis then determined the effects of three levels, minimum, median, and maximum, of each independent variable while keeping all other input variables stationary. As shown in Figure 2, the PCC slab thickness and the initial roughness have greater impact on the roughness profile than percent subgrade materials passing US No. 200 sieve and cumulative yearly ESAL values. PCC pavements with lower slab thickness tend to sustain the smoothness longer. After seven years of service, other things being constant, an increase in the PCC slab thickness by 2.5 in. (11.5 inches vs. 9 inches) will increase the predicted roughness by 23 in./mile. Similar observations have also been made by Siddique et al. (*7*) for some other Kansas PCC pavements and by Perera and Kohn (*8*) for the PCC pavements in the LTPP program. Also, PCC pavements built with lower IRI values tend to sustain smoothness longer, too. Subgrade soils with a high amount of materials passing the US No. 200 sieve tend to remain smoother. This may appear to defy common experience. However, it is to be noted that those soils will generally have higher plasticity. In that situation, KDOT usually would require some form of subgrade treatment/stabilization using lime or lime and fly ash to reduce volume change potential under varying moisture conditions. Thus, treated subgrade would be beneficial for sustaining smooth PCC pavements. Also, the developed model is not highly sensitive to the traffic loading parameter (ESAL).

CONCLUSIONS

Roughness prediction models were developed in this study for Jointed Plain Concrete Pavements (JPCP) in Kansas using historical roughness, traffic, inventory, and climatic data. Roughness predictions were done for 20-year and 30-year horizons with good coefficients of determination value in most cases. The results show that the projects with stabilized, non-drainable bases would likely outperform the projects with stabilized, drainable bases for most cases. Higher PCC slab thickness would result in higher future roughness values. The same would happen for higher initial (as constructed) roughness. The future predicted roughness did not appear to be very sensitive to the traffic.

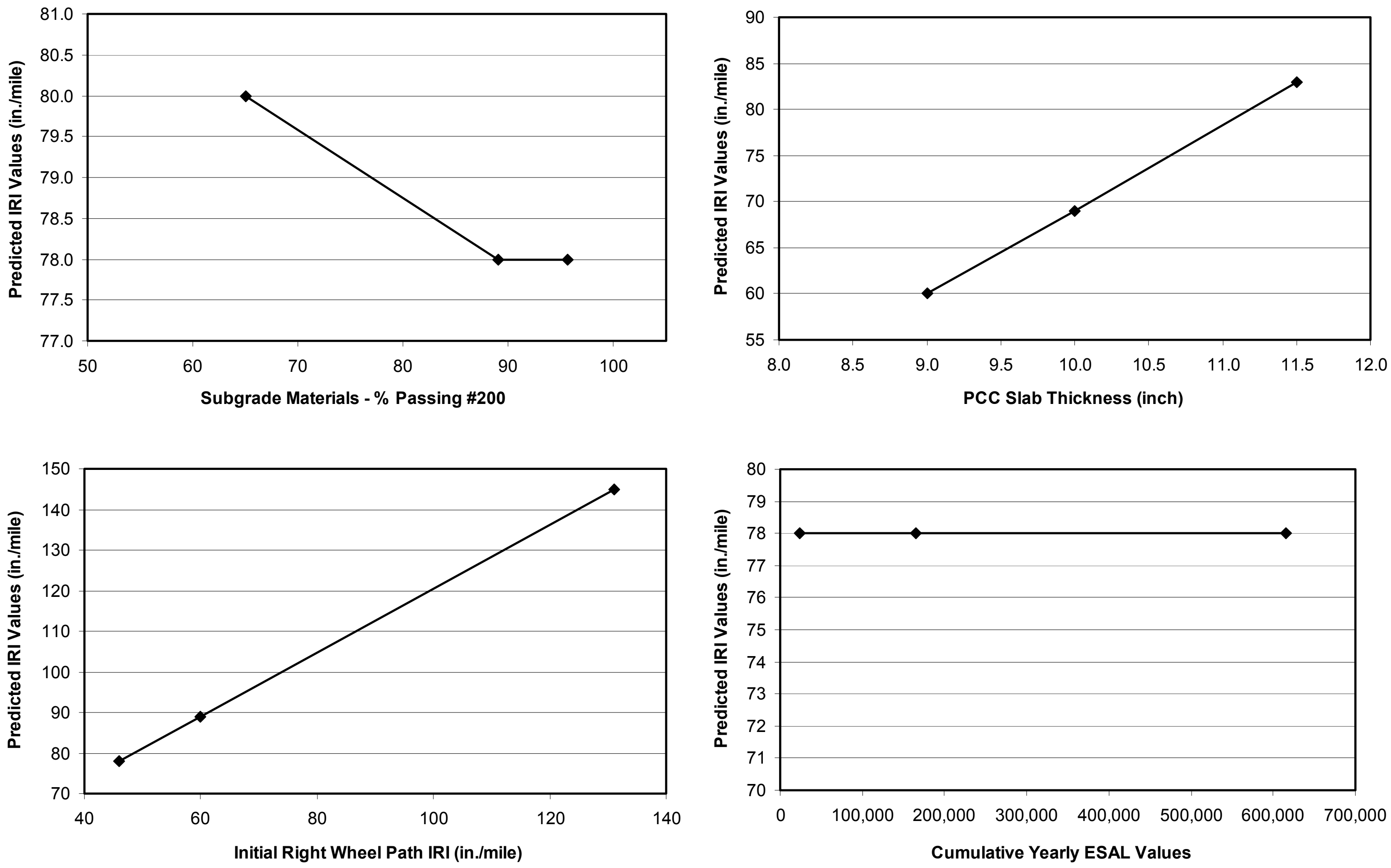

FIGURE 2. Sensitivity Analysis Results

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