Pavement Performance Prediction for the Illinois Tollway System

Laxmikanth Premkumar
(Corresponding Author)
Project Engineer
100 Trade Centre Drive, Suite 200
Champaign, Illinois, 61820
Tel: (217)-356-4500, Fax: (217) 356-3088
E-mail: lpremkumar@ara.com

William R. Vavrik, Ph.D., P.E.
Vice President and Principal Engineer
100 Trade Centre Drive, Suite 200
Champaign, Illinois, 61820
Tel: (217)-356-4500, Fax: (217) 356-3088
E-mail: wvavrik@ara.com

Submitted for Presentation at the 2015 TRB Annual Meeting and Publication in the Journal of the Transportation Research Board

Word Count: 5645 (2895 text, 3 figures, and 8 tables)

August 2014
ABSTRACT

Accurate pavement performance prediction represents an important role in prioritizing future maintenance and rehabilitation needs, and predicting future pavement condition in a pavement management system. The Illinois State Toll Highway Authority (Tollway) with over 2000 lane miles of pavement utilizes the condition rating system (CRS) methodology to rate pavement performance. Pavement performance models developed in the past for the Illinois Department of Transportation (IDOT) are used by the Tollway to predict the future condition of its network. The model projects future CRS ratings based on pavement type, thickness, traffic, pavement age and current CRS rating. However, with time and inclusion of newer pavement types there was a need to calibrate the existing pavement performance models, as well as, develop models for newer pavement types.

This study presents the results of calibrating and developing new models for the various pavement types in the Illinois Tollway network. The predicted future condition of the pavements is used in estimating its remaining service life to failure, which is of immediate use in recommending future maintenance and rehabilitation requirements for the network.

Keywords: pavement performance models, remaining life, pavement management

BACKGROUND

The Illinois State Toll Highway Authority’s (Tollway) network provides heavily used key interstate highway routes in the Chicago area, the State of Illinois, and the Midwest. Commuters, freight haulers, and the overall traveling public rely on the Tollway each day to provide safe, reliable, and cost-effective highway transportation and have done so since the 1950’s. In fulfilling this mission, the Tollway has been faced with an aging highway network that requires substantial maintenance and rehabilitation to provide continued satisfactory service. By the beginning of the 21st century, components of many of the existing pavements were over 40 years in age and in need of major rehabilitation. In addition, at that time funding uncertainties precluded efforts to rehabilitate (or reconstruct) major portions of the network.

To address its pavement concerns, the Tollway implemented a comprehensive pavement management system and continues to update the system on a yearly basis. The Tollway’s pavement management system warehouses a comprehensive database of pavement-related information, and it allows the Tollway to quickly identify current pavement conditions, project future pavement performance, identify future pavement maintenance and rehabilitation needs, and generate multi-year pavement repair plans.

The Tollway uses the condition rating survey (CRS), a subjective pavement rating system developed by the Illinois Department of Transportation (IDOT) in the early 1980’s (1), to rate the condition of its roads. The CRS provides an overall pavement condition rating on a 1-to-9 scale, with 9 representing a newly constructed or resurfaced pavement and 1 representing a completely failed pavement. CRS ratings are based on the type, amount, and severity of the evident pavement distresses, as well as the overall roughness of the pavement surface, level of wheel path rutting, and magnitude of transverse joint faulting. Summaries of the CRS ratings and corresponding pavement conditions for the Tollway are provided in Table 1. The CRS surveys are performed in each direction of traffic, and the resulting CRS ratings represent the entire roadway width for a given traffic direction (2).
### TABLE 1: Summary of CRS Pavement Condition Ratings

<table>
<thead>
<tr>
<th>CRS rating</th>
<th>General pavement condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5 to 9.0</td>
<td>Excellent</td>
</tr>
<tr>
<td>6.5 to 7.4</td>
<td>Acceptable</td>
</tr>
<tr>
<td>6.0 to 6.4</td>
<td>Transitional</td>
</tr>
<tr>
<td>4.5 to 5.9</td>
<td>Fair</td>
</tr>
<tr>
<td>1.0 to 4.4</td>
<td>Poor</td>
</tr>
</tbody>
</table>

Annual updates of the Tollway pavement management system begin with updating current construction history, traffic, cost, and pavement condition data to optimize the effectiveness of its pavements. Future pavement condition is projected based on current year CRS values and the latest performance models.

CRS prediction models involve identifying individual pavement sections and modeling the expected future CRS value. The rate of change or slope of CRS over time is calculated for each pavement section by dividing the change in CRS by change in age. The average slope for each individual pavement type is used for the prediction model. The model uses a two-slope method for predicting CRS with age, with different slopes above and below a CRS value of 6.5 (1). However, these models only predict future CRS based on age and do not consider other variables that affect pavement performance like traffic and structure. The model form is shown below in equations 1 and 2:

\[
\text{If current CRS} \geq \text{BP, Future CRS} = \text{Current CRS} - \text{slope}_{9.0-\text{BP}} \times \text{years of prediction} \quad \text{Eq. 1}
\]

\[
\text{If current CRS} < \text{BP, Future CRS} = \text{Current CRS} - \text{slope}_{\text{BP}-1.0} \times \text{years of prediction} \quad \text{Eq. 2}
\]

where:
- current CRS = CRS value from most recent survey
- BP = break point
- slope\(_{9.0-\text{BP}} = \) model slope value from a CRS of 9.0 to the break point
- slope\(_{\text{BP}-1.0} = \) model slope value from a break point to CRS of 1.0
- Years of prediction = number of years into the future the prediction is desired

The Tollway pavement performance prediction models project future CRS ratings based on pavement type, thickness, pavement age, traffic and current CRS, unlike the traditional model. The models were developed originally for the IDOT Interstate highway network, and customized for the Illinois Tollway using the Tollway CRS data collected from 1997 to 2002 (2). The pavement performance models were developed to predict future pavement conditions, trigger various rehabilitation activities, and evaluate the impact that various rehabilitation programs have on pavement conditions.

Due to addition of new pavement types in the network, there was a need to develop new performance models and re-calibrate the existing performance models using updated Tollway CRS data. As part of the calibration effort, performance models for the following seven pavement types were considered, with new models developed for SMA-JPCP and JPCP with 15-ft joint spacing.
• Continuously reinforced concrete pavement (CRCP)
• Jointed plain concrete pavement, with 20-ft joint spacing (JPCP-20)
• Jointed plain concrete pavement, with 15-ft joint spacing (JPCP-15)
• Asphalt-overlaid JPCP with 20-ft joint spacing (HMA-JPCP-20)
• Full Depth Asphalt Pavement (HMAC)
• SMA-overlaid JPCP (SMA-JPCP)
• Asphalt-overlaid JPCP with no dowel (D-Crack)

These seven pavement types generally represent the pavement structure located within the Tollway network. The models presented in this study are specific to pavement types in the Tollway network and input data obtained from the Tollway pavement management database.

CRS CALIBRATION METHODOLOGY
The steps involved in calibration of the CRS performance models are shown in Figure 1. Detailed description of the individual steps is shown in subsequent sections.

Data Mining and Assembly
The first step in CRS model calibration was data mining and assembling data in the required format. The following information was required to calibrate the performance models:

• Calculated CRS values
• Traffic equivalent single axle load (ESAL) data
• Age and construction information of pavement sections evaluated
• Thickness information

Data mentioned above was mined from the Tollway pavement management system database. Sections of the Tollway routes with similar pavement types were grouped together for the analysis. The CRS data used in the model calibration were weighted according to the number of 1.0-mi units that they represent to reduce any bias based on section length.

To increase the working database set, CRS prediction for optimization analysis was performed on progressive sets of data within an individual section. For example if year 2000 through 2005 CRS data was available for a particular pavement type, the optimization analysis included CRS prediction of year 2005 using data from 2000 through 2004. This method was especially useful for pavement types with limited data.
The original IDOT CRS performance models utilized the following set of CRS prediction equations, with each pavement type incorporating different model constants \((2, 3, \text{ and } 4)\).

\[
CRS = 9 - 2 \cdot a \cdot (THICK \cdot TAF)^b \cdot (C_1 + \Delta \text{YEAR})^c \cdot (C_2 + \Delta \text{ESAL})^d
\]

Eq. 3

\[
C_1 = \frac{(9 - CRS_i)}{(2 \cdot a \cdot (THICK \cdot TAF)^b \cdot CESAL^d)^{1/(c + d)}}
\]

Eq. 4

\[
C_2 = C_1 \cdot CESAL
\]

Eq. 5

where:
- \(CRS\) = Condition survey rating (1 to 9).
- \(TAF\) = Thickness adjustment factor.
- \(THICK\) = Slab thickness, HMAC thickness, or AC overlay thickness.
- \(\Delta \text{YEAR}\) = Change in the age of the pavement, years.
- \(\Delta \text{ESAL}\) = Accumulated ESALs in millions over the time period \(\Delta \text{YEAR}\).
- \(CESAL\) = Current annual ESALs.
- \(C_1\) and \(C_2\) = Calibration coefficients.
- \(a, b, c, d\) = Constants for each pavement type.

Thickness adjustment factors \((TAFs)\) are used in the model to increase the effect of the thickness of the AC surface in reducing the rate of CRS deterioration \((2)\). The thickness of the AC surface is multiplied by the \(TAFs\) as follows:

- HMAC
If HMAC thickness is less than 4 in, $TAF = 2.0$.
If HMAC thickness is greater than or equal to 4 in and less than 8 in, $TAF = 1.75$.
If HMAC thickness is greater than or equal to 8 in, $TAF = 1.0$.

• AC overlay of JPCP
  If AC overlay thickness is less than 4 in, $TAF = 1.0$.
  If AC overlay thickness is greater than 4 in and less than 6 in, $TAF = 6.0$.

The thickness adjustment factors shown above for AC overlay of JPCP represent a stepwise function leading to potential aberration in CRS values at the interface between thickness intervals. To circumvent this, a continuous function was developed using available historical thickness data, and the TAF intervals were revised (2). The continuous equation used to obtain TAF is shown below in equation 6.

$$TAF_{\text{continuous}} = \frac{0.048 \times H^4 - 1.234 \times H^3 + 10.88 \times H^2 - 29.75 \times H + 26.28}{H} \quad \text{Eq. 6}$$

where: $H =$ Pavement thickness in inches.

The SMA-JPCP thickness data was not used in development of the continuous TAF equation. However for consistency sake, the continuous TAFs were used to develop the SMA-JPCP CRS prediction model. Future work will involve development of a revised TAF equation to incorporate SMA-JPCP thickness values.

Statistical Analysis

The calibration process focused on optimizing the original CRS model coefficients to derive a new set of the model constants ($a$, $b$, $c$, and $d$), by minimizing the difference between the actual and predicted CRS. Mathematical simulations were performed whereby the model constants were allowed to vary until a combination was reached that resulted in the lowest error sum of squares (SSE) for the many pairs of actual versus predicted CRS.

Hypothesis testing was performed to determine if the predicted and measured CRS values represent the same population. A paired t-test with a significance level, $\alpha$, of 0.05 was performed as follows:

1. Assume the following null and alternative hypothesis:
   a. $H_0$: Mean measured CRS = mean predicted CRS
   b. $H_A$: Mean measured CRS $\neq$ mean predicted CRS
2. Compute test p-value.
3. Compare computed p-value to predetermined level of significance for this test.

The null hypothesis $H_0$ is rejected if the p-value < 0.05. Rejection of $H_0$ implies that the predicted and calculated CRS values are essentially from different populations at the 5 percent
significance level. Some of the pavement type data sets were reduced in size for hypothesis testing, to conduct tests on independent samples and obtain meaningful results.

In addition, sensitivity of the predicted CRS values to thickness and traffic ESALs was evaluated for each pavement type. Various acceptable ranges of traffic and thickness data within each pavement type data set were used to evaluate the CRS prediction model. Measured CRS data from each pavement type dataset were used to validate the future predicted CRS values.

**CRS CALIBRATION RESULTS**

Seven different pavement types, as listed in previous sections were evaluated as part of the pavement performance model calibration process. As an example, detailed results for the JPCP-20 section are shown below. Similar analysis was performed for calibrating the pavement performance models for other pavement types.

The plot of CRS predicted using the performance model and calculated CRS values for the JPCP-20 model are shown below in Figure 2. The descriptive statistics and hypothesis testing results shown in Table 2 indicate good correlation between measured and predicted CRS values with an $R^2$ value of 0.93 and p-value greater than 0.05.

![Figure 2: Predicted vs. Measured CRS for JPCP-20 Pavement Type](image)

<table>
<thead>
<tr>
<th>Statistics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>0.932</td>
</tr>
<tr>
<td>$P(T&lt;=t)$ two-tail</td>
<td>0.11</td>
</tr>
<tr>
<td>Observations</td>
<td>940</td>
</tr>
</tbody>
</table>

A comparison of CRS values predicted over time using both the original and calibrated CRS models is shown below in Figure 3. From the figure below, it is observed that the calibrated model is less conservative and predicts a terminal CRS value of 6.5 in 15 years. The
Calibrated model results are based on a 12.3-in JPCP-20 pavement section, with initial traffic of 2.75 million ESALs, annual growth rate of 3%, and an initial CRS value of 8.9.

Sensitivity analysis was performed to predict variation in CRS with change in thickness and traffic ESALs. Thickness sensitivity analysis was performed by holding initial traffic, growth rate and initial CRS constant, and changing the thickness values. Similar analysis was performed for traffic by holding thickness constant. The range of thickness and traffic ESALs for sensitivity analysis was based on minimum and maximum thickness/ESALs values from the Tollway pavement management database for a particular pavement type. From the results shown below in Table 3 and Table 4, on an average the change in predicted service life to obtain a terminal serviceability of 6.5 is 1.8 years, for every 1.0-in change in pavement thickness or 0.5 years, for every 1.5 MESALs change in traffic ESALs. This analysis was performed to identify potential aberrant changes in predicted service life with change in thickness or traffic.

**Table 3: Thickness Sensitivity Analysis for JPCP-20 Performance Model**

<table>
<thead>
<tr>
<th>Thickness (in)</th>
<th>Initial Traffic (MESALs)</th>
<th>Traffic Growth Rate (%)</th>
<th>CRS (initial)</th>
<th>Predicted Service Life (years) Based on Terminal CRS Value of 6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>2.8</td>
<td>3</td>
<td>8.9</td>
<td>12.5</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td>14.5</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18</td>
</tr>
</tbody>
</table>
TABLE 4: Traffic Sensitivity Analysis for JPCP-20 Performance Model

<table>
<thead>
<tr>
<th>Initial Traffic (MESALs)</th>
<th>Thickness (in)</th>
<th>Traffic Growth Rate (%)</th>
<th>CRS (initial)</th>
<th>Predicted Service Life (years) Based on Terminal CRS Value of 6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>3</td>
<td>8.9</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
<td>13.5</td>
</tr>
<tr>
<td>6.5</td>
<td></td>
<td></td>
<td></td>
<td>13</td>
</tr>
</tbody>
</table>

To validate the predicted CRS results obtained from the JPCP-20 performance model, predicted and measured values were compared for actual pavement sections from the Tollway pavement management database. As shown in Table 5, there is good correlation between predicted and observed values with an average difference of 3%. Table 6 represents the predicted service life based on a terminal CRS of 6.5 for the individual routes, based on average thickness and traffic within each route. On an average, the JPCP-20 performance model predicts 15 years of service life to reach a terminal CRS value of 6.5.

TABLE 5: Validation of JPCP-20 Performance Model

<table>
<thead>
<tr>
<th>Section</th>
<th>Thickness (in)</th>
<th>Initial MESALs (growth rate)</th>
<th>Initial CRS (year)</th>
<th>Final Measured CRS (year)</th>
<th>Final Predicted CRS (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>1.5 (3.5%)</td>
<td>8.4 (2000)</td>
<td>6.7 (2012)</td>
<td>6.7 (2012)</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>5.5 (2.7%)</td>
<td>8.4 (2000)</td>
<td>6.0 (2012)</td>
<td>6.3 (2012)</td>
</tr>
<tr>
<td>4</td>
<td>12.3</td>
<td>1.5 (4.5%)</td>
<td>7.7 (2000)</td>
<td>6.6 (2009)</td>
<td>6.5 (2009)</td>
</tr>
</tbody>
</table>

TABLE 6: Predicted Service Life based on Terminal CRS of 6.5 for Individual Routes

<table>
<thead>
<tr>
<th>Route</th>
<th>Thickness</th>
<th>Initial MESALs (growth rate)</th>
<th>Initial CRS</th>
<th>Predicted Service Life (years) Based on Terminal CRS Value of 6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>1.7 (2.9%)</td>
<td>8.9</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>12.1</td>
<td>5.9 (2.6%)</td>
<td>8.9</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>12.4</td>
<td>4.9 (2.3%)</td>
<td>8.9</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>12.3</td>
<td>1.6 (3.5%)</td>
<td>8.9</td>
<td>16</td>
</tr>
<tr>
<td>Average</td>
<td>12.3</td>
<td>2.75 (3.0%)</td>
<td>8.9</td>
<td>15</td>
</tr>
</tbody>
</table>

The predicted service life based on a terminal CRS value of 6.5 for all Tollway pavement types evaluated are shown in Table 7. Results are based on initial traffic of 4.0 million ESAL’s, traffic growth rate of 4%, and initial CRS value of 8.9. The calibrated model coefficients for
existing pavement types, and model coefficients developed for new pavement types on the
Tollway are shown in Table 8.

Based on the results, CRCP pavements are the best performing with a service life of 29
years. The service life of JPCP with 15-foot joint spacing is nearly twice the service life of JPCP
with 20-foot joint spacing, demonstrating the increase in service life provided by reduced joint
spacing.

Similarly, pavement sections with SMA overlay perform better than HMA overlays,
providing two years and four years more service life than HMA-JPCP-20 and D-Crack sections,
respectively. Full depth HMAC sections have a service life of 15 years to reach terminal CRS
value of 6.5. Predicting service life of the pavement provides valuable input on future
performance of the pavement network, and assists in planning future maintenance and
rehabilitation activities.

Table 7: Predicted Service Life based on Terminal CRS of 6.5 using Pavement Performance Models

<table>
<thead>
<tr>
<th>Pavement Type</th>
<th>Initial Traffic (MESALs)</th>
<th>Thickness (in)</th>
<th>Traffic Growth Rate (%)</th>
<th>CRS (initial)</th>
<th>Predicted Service Life (years) Based on Terminal CRS Value of 6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRC</td>
<td>4.0</td>
<td>12.0</td>
<td></td>
<td>3.0</td>
<td>8.9</td>
</tr>
<tr>
<td>JPCP-20</td>
<td>4.0</td>
<td>12.0</td>
<td></td>
<td>3.0</td>
<td>8.9</td>
</tr>
<tr>
<td>JPCP-15</td>
<td>4.0</td>
<td>12.0</td>
<td></td>
<td>3.0</td>
<td>8.9</td>
</tr>
<tr>
<td>HMA-JPCP-20</td>
<td>4.0</td>
<td>4.0</td>
<td></td>
<td>3.0</td>
<td>8.9</td>
</tr>
<tr>
<td>HMA</td>
<td>4.0</td>
<td>12.0</td>
<td></td>
<td>3.0</td>
<td>8.9</td>
</tr>
<tr>
<td>SMA-JPCP</td>
<td>4.0</td>
<td>4.0</td>
<td></td>
<td>3.0</td>
<td>8.9</td>
</tr>
<tr>
<td>D-Crack</td>
<td>4.0</td>
<td>4.0</td>
<td></td>
<td>3.0</td>
<td>8.9</td>
</tr>
</tbody>
</table>

Table 8: Tollway Performance Model Coefficients

<table>
<thead>
<tr>
<th>Pavement Type</th>
<th>Calibration Coefficients</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRCP</td>
<td>6.7202</td>
<td>-2.0020</td>
<td>0.7256</td>
<td>0.1608</td>
<td></td>
</tr>
<tr>
<td>HMAC</td>
<td>0.1922</td>
<td>-0.863</td>
<td>0.6289</td>
<td>0.5140</td>
<td></td>
</tr>
<tr>
<td>JPCP-20</td>
<td>2.9848</td>
<td>-1.3646</td>
<td>0.7669</td>
<td>0.1161</td>
<td></td>
</tr>
<tr>
<td>SMA-JPCP</td>
<td>0.2441</td>
<td>-0.088</td>
<td>0.5872</td>
<td>0.0778</td>
<td></td>
</tr>
<tr>
<td>D-Crack</td>
<td>0.1935</td>
<td>-0.1558</td>
<td>0.4994</td>
<td>0.2965</td>
<td></td>
</tr>
<tr>
<td>HMA-JPCP-20</td>
<td>0.2995</td>
<td>-0.1550</td>
<td>0.5012</td>
<td>0.1350</td>
<td></td>
</tr>
<tr>
<td>JPCP-15</td>
<td>3.9334</td>
<td>-1.0911</td>
<td>0.2678</td>
<td>0.1377</td>
<td></td>
</tr>
</tbody>
</table>

SUMMARY AND CONCLUSIONS

Reliable and accurate pavement performance models are required to predict future
condition, trigger various rehabilitation activities, and evaluate the impact that various
rehabilitation programs have on pavement conditions. In this study, existing pavement
performance models for five different pavement types in the Tollway network were calibrated. In addition, new models were developed for SMA-JPCP and JPCP-15 pavement types. The models were utilized to predict the service life of the pavements, based on a terminal CRS value of 6.5.

Based on the results, the JPCP model with 15-foot joint spacing predicts nearly twice the service life of JPCP pavement sections with 20-foot joint spacing. This demonstrates the positive effects of reducing joint spacing in concrete pavements to improve performance. Pavements sections with SMA overlays in the Tollway network are demonstrating better performance when compared to pavements with HMA overlays.

These models will be validated continuously on a yearly basis using future CRS data to ensure accurate prediction of future conditions. Though the pavement performance model coefficients shown in this study are specific to the data collected on the Tollway, this methodology can be extended to other agencies for predicting pavement performance, and prioritizing rehabilitation projects.

Acknowledgements

This study is based on work supported by the Illinois State Highway Toll Authority. The authors would like to thanks Steven Gillen of the Tollway for his technical support, and providing good suggestions on this study.

REFERENCES