Modeling of Chip Seal Performance on Kansas Highways

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ABSTRACT

Due to traffic loading and weathering, highway pavements deteriorate starting immediately after construction. Many rehabilitation methods are available to bring deteriorated pavements back to an appropriate level of service for road users. One of these methods, chip seal, has been widely used in many states, including Kansas. This study evaluated the performance of chip seal treatments in Kansas. The study used pavement condition data from the Pavement Management Information System (PMIS) database. The data include detailed distress information of most chip seal rehabilitation projects on Kansas highways from the last two decades. The multiple linear regression method was used to develop linear models that can predict distress progression and variation in performance of chip-sealed pavement. The effect of age of pavements and traffic loading on the performance of chip seals was also evaluated. Appropriate models for predicting roughness and rutting have been developed and validated. Models for transverse and fatigue cracking are not encouraging.

Key words: chip seal—distress progression—PMIS
INTRODUCTION

Timely preventive maintenance (PM) can preserve pavements above minimum acceptance serviceability level. The National Cooperative Highway Research Program (NCHRP) defines PM as “a program strategy intended to arrest light deterioration, retard progressive failures, and reduce the need for routine maintenance and service activities” (Gransberg and James 2005). Chip seal is one of the PM techniques that can play an important role in deferring the need for major rehabilitation (Abdul-Malak, Fowler & Meyer 1993).

In Kansas, the PM treatments adopted by the Kansas Department of Transportation (KDOT) include thin overlay, ultra-thin bonded bituminous surface (Novachip), chip seal, and slurry seal. The better the pavement condition when these treatments are applied, the longer the treatments will last, and the more cost-effective these treatments are. Chip seal is a relatively cost-effective preventive maintenance technique compared to other thin surface treatments since the cost of chip seal is about one-fifth to one-half the cost of a 2-in. overlay (Chen, Lin, and Luo 2005).

PROBLEM STATEMENT

Estimating the effectiveness of PM techniques is useful for PM purposes. By modeling the performance of a treatment, it is possible to determine the timing at which subsequent activities would be necessary. To achieve that, a long-term, continuous monitoring of distresses, such as roughness and cracking, is needed to determine relative effects of certain external factors and to predict future pavement performance. Performance models for flexible PM treatments, chip seal, flush seal, and sand seal treatments had been developed in the past (Sebaaly, Lani, and Hand 1995), but because of the localized nature of the materials, the models are not transferable.

Pavement design engineers can use these models to check the validity of their design procedures and the appropriateness of various assumptions that are made during design processes. Material engineers can verify whether a given type of material is appropriate for anticipated traffic and environmental conditions. As a result, design and construction practices can be altered to produce longer-lasting pavements. Pavement management engineers will gain the most from such studies because they are usually responsible for recommending various maintenance alternatives for specific applications.

KDOT maintains a comprehensive Pavement Management Information System (PMIS) database that contains detailed information related to section characteristics, historical distress data, performance estimation data, and traffic-related data. The PMIS database is generated from the information collected during the annual pavement condition survey conducted by KDOT staff. These condition survey data for the highway sections that have been treated with chip seal were extracted from the PMIS database for performance modeling in this study. The test sections in this study are consistent with respect to the distribution of age, pavement structure, pavement conditions prior to treatment, traffic loading, and environmental conditions. A total of 280 chip seal projects, distributed among the six administrative districts of KDOT, were identified and studied.
OBJECTIVE

The objective of this research project was to develop models capable of predicting progression of important distresses that have significant effects on the performance of chip seal-treated pavements. The distresses selected are roughness (International Roughness Index [IRI]), rutting, and cracking.

CHIP SEALS IN KANSAS

In Kansas during 1962 to 2006, at least 754 chip seal projects were completed, and 7,004 highway segments (1 mile length) have been maintained with chip seals. Many of these chip seal treatments had a 10-year design life as per the PMIS database. Because distress data on the chip seals before 1992 were not available in the database, only projects from 1992 to 2006 were studied in this research.

A total of 4,156 chip seal treatments were performed on 3,532 segments of 280 highways in Kansas from 1992 to 2006. About 16% of these segments were treated twice with chip seals, and 1% of them were treated three times, as can be seen in Figure 1.

![Figure 1. Proportion of segments by number of chip seal treatments](image)

CONDITION SURVEY IN KANSAS

The distresses that are surveyed during the annual condition survey of asphalt-surfaced pavements include roughness, rutting, transverse cracking, and fatigue cracking. Though block cracking is also surveyed, this distress was found to be quite negligible because the majority of test sections could be observed to have hardly any block cracking. Therefore, it was not considered in this study. The effect of chip seals on distress progression was examined for three classes of highways: Interstate highway, U.S. highway, and Kansas state highway.

Roughness

Road roughness is an important attribute in evaluating pavement condition because of its effect on ride quality and vehicle operating costs (Miller, Vedula, and Hossain 2004). Currently, KDOT employs a South Dakota-type profilometer equipped with laser sensors to collect roughness data in terms of IRI.
Since IRI values are computed on both wheel paths, the average value expressed in in./mile was taken in this study.

**Rutting**

Currently, most state highway agencies integrate the measurement of rut depth as a part of the condition survey of bituminous and composite pavements mostly using the profilometer. The measurement of rut depth can be automatically conducted with a rut bar mounted on a vehicle with three or five or more sensors that are capable of measuring the profile data of road surfaces (Miller, Vedula, and Hossain 2004). In Kansas, KDOT use a three-point system in which data are collected in each wheel path and at mid-lane. In that case, the rut depth is calculated as the difference in elevation between the mid-lane measurement and the wheel path measurement.

**Transverse Cracking**

In the annual KDOT pavement condition survey, transverse cracks are manually measured by selecting three, 100 ft test sections from each 1-mile highway segment and counting the number of full lane-width cracks (centerline to edge on a two-lane road). The average crack number of the three, 100 ft sections is recorded as the extent of transverse cracking, which might be a one or two digit number, to the nearest 0.1 cracks. A transverse crack is judged and falls into one of the following four categories: T0, T1, T2, and T3, based on severity conditions that are coded as the following:

- **T0**: Sealed cracks with no roughness and sealant breaks less than 1 ft per lane
- **T1**: No roughness, 0.25 in. or wider with no secondary cracking; or any width with secondary cracking less than 4 ft per lane, or any width with a failed seal (1 or more ft per lane)
- **T2**: Any width with noticeable roughness due to depression or bump, also, cracks that have greater than 4 ft of secondary cracking but no roughness
- **T3**: Any width with significant roughness due to depression or bump, secondary cracking will be more severe than Code T2.

Transverse cracking for a segment then expressed as EqTCR, which is the equivalent number of “T3” cracks expected per 100 ft segment.

**Fatigue Cracking**

In Kansas, fatigue cracking is measured manually by observing the amount of fatigue cracking on three, 100 ft test sections for each 1 mile (normally) highway segment during annual pavement condition surveys. Alligator cracking is recorded in the unit of linear feet/100 ft, and the extent must exceed five feet to be counted. The average value is reported for each segment with one or more of the four severity levels (FC1, FC2, FC3, and FC4), which are coded as the following:

- **FC1**: Hairline alligator cracking, pieces not removable
- **FC2**: Alligator cracking, pieces not removable, cracks spalled
- **FC3**: Alligator cracking, pieces are loose and removable, pavement may pump
- **FC4**: Pavement has shoved forming a ridge of material adjacent to the wheel path

The fatigue cracking is then described as EqFCR, which is the equivalent number of “FC4” cracks per 100 ft segment.

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METHODOLOGY

The multiple linear regression method and the Statistical Analysis System (SAS) software were used in this research. Multiple linear regression is an extension of simple linear regression and can be used to account for the effects of several independent variables simultaneously. The general multiple linear regression model can be defined in terms of $X$ variables in the following form (Weisherb 2005):

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \ldots + \beta_pX_p,$$

where $Y$ = dependent variable; $\beta_0$ = equation constant; $\beta_1, \ldots, \beta_p$ = partial regression coefficients; and $X_1, \ldots, X_p$ = independent variables.

$R$ squared ($R^2$) value, which is the coefficient of determination in linear regression, gives the proportion of variability in $Y$ explained by regression on a set of explanatory variables. It can also be interpreted as the square of correlation between observed values of $Y$ versus fitted values. The value of $R^2$ is in a range of 0 to 1, with 1 indicating that a fitted model perfectly explains the response and 0 indicating that a fitted model cannot explain the response. The stepwise variable selection method was used in this study to eliminate those variables that did not meet the 10% significance level. In the regression process, outliers, defined as the data point that has students’ residuals over 3.0, were eliminated from the data set to make the fitted model more precise.

DATA

Data used for the multiple linear regression analysis was extracted from the PMIS database by selecting highway segments treated with chip seals. Traffic data corresponding to each highway segment were also obtained. The Pavement Management System (PMS) segments in Kansas (usually 1 mile) belonging to the same road were combined and average distress and traffic values were calculated. Data on a single road during different service years were treated as different records by pavement age. The distribution of chip seal projects by annual average daily traffic (AADT) was also calculated. Three categories were used to classify AADT: low ($\leq$400 veh/day), intermediate (between 400 and 4,000 veh/day), and high (>4000 veh/day). Ninety-five percent of the chip seal projects were done on low and intermediate volume roads.

RESULTS AND ANALYSIS

The variables used in the modeling process and their description are shown in Table 1. The models developed in this study were proposed to predict progression of distresses, not the initiation mostly caused by the problems from structural design and materials. Therefore, the first year distress data after chip-sealing were used as a variable.
Table 1. Description of variables used in linear regression

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRI</td>
<td>International roughness index, in./mile</td>
<td>Dependent variable</td>
</tr>
<tr>
<td>RD</td>
<td>Rut depth, in.</td>
<td>Dependent variable</td>
</tr>
<tr>
<td>EqTCR</td>
<td>Equivalent number of full-width transverse tracks per 100-ft highway segment</td>
<td>Dependent variable</td>
</tr>
<tr>
<td>EqFCR</td>
<td>Equivalent fatigue cracks per 100 ft highway segment, ft/100 ft</td>
<td>Dependent variable</td>
</tr>
<tr>
<td>InitIRI</td>
<td>The first year IRI value after chip-sealing</td>
<td>Independent variable</td>
</tr>
<tr>
<td>InitRD</td>
<td>The first year rut depth value after chip-sealing</td>
<td>Independent variable</td>
</tr>
<tr>
<td>InitTCR</td>
<td>The first year transverse crack value after chip-sealing</td>
<td>Independent variable</td>
</tr>
<tr>
<td>InitFCR</td>
<td>The first year fatigue crack value after chip-sealing</td>
<td>Independent variable</td>
</tr>
<tr>
<td>AGE</td>
<td>The service year of a chip seal treatment</td>
<td>Independent variable</td>
</tr>
<tr>
<td>AADT</td>
<td>Annual average daily traffic, vehs/day</td>
<td>Independent variable</td>
</tr>
<tr>
<td>ESAL</td>
<td>Cumulative equivalent 18 kip single axle loads</td>
<td>Independent variable</td>
</tr>
<tr>
<td>CLASS</td>
<td>Highway class, “1” for interstate highways, “2” for US highways, and “3” for “K” or state highways</td>
<td>Independent variable</td>
</tr>
</tbody>
</table>

Models

Roughness (IRI)

The fitted state-wide roughness model is shown in equation (1). InitIRI, age and class are the significant variables. The $R^2$ value is 0.867, indicating that 86.7% of the variation in the IRI values can be explained by these three variables in equation (1). Figure 2a displays the plot of the predicted IRI values against the measured IRI values.

$$IRI = 3.97091 + 0.89323 \text{(InitIRI)} + 2.87797 \text{(Age)} + 1.29244 \text{(Class)}$$

\[(n = 844; R^2 = 0.867)\]

Based on the parameter coefficients in equation (1), a one-year increment of chip seal age would probably cause about a 3 in. increase of roughness. Road class also has a direct relationship with roughness condition. For example, in the same year after chip sealing, a “K” or state highway is likely to become 1.29 in. rougher than a U.S. highway. The fitted model in equation (1) was validated using data from Districts 5 and 6, as shown in Figure 2b. An $R^2$ value of 0.624 was achieved, so 62.4% of the variability of IRI values in Districts 5 and 6 can be explained using equation (1). Data points are evenly distributed around the line of equality and fairly close to the equality line for the data values below 100 in./mile. The fitted model is adequate for predicting the IRI progression after chip sealing on highways in Kansas, but it should be used with caution for those roads where severe roughness problems are observed.
Rutting

The derived model for predicting progression of rut depth is illustrated in equation (2). There are two significant parameters, InitRD and Road Class, at a 10% level of significance. The equation shows that the rut depth of chip-seal–treated pavements is dependent on rutting at the time of chip seal but independent of pavement age and traffic loading. The $R^2$ value shows that 73.5% of the variations in rut depth of a project can be explained by the model in equation (2) if the first-year rut depth value and road class are known. Figure 3a shows the predicted and observed values.

$$RD = 0.03621 + 0.76501 \text{ (InitRD)} - 0.00404 \text{ (Class)}$$

(n = 848; $R^2 = 0.735$)

Again, the rut depth data from Districts 5 and 6 were used to validate the model in equation (2). Figure 3b illustrates the calculated and measured rut depth values. About 58% of the calculated values matched the observations in the database.
In order to predict the progression of rutting on chip seal-treated pavements more precisely, more factors, such as material type, pavement thickness, etc., need to be considered. This may also indicate that chip seal is not a very good treatment for mitigating rutting on asphalt-surfaced pavements.

**Transverse Cracking**

Equation (3) shows the prediction model for predicting development of transverse cracks (designated as EqTCR) after chip seal applications.

\[
\text{EqTCR} = -0.0765 + 0.7833 \text{ (InitTCR)} + 0.0175 \text{ (Age)} + 0.0561 \text{ (Class)}
\]

\( (n = 722; R^2 = 0.633) \)

Besides the first-year transverse cracking value, age and road class are also significant at a 10% level of significance. The \( R^2 \) value is 0.632. Thus, 63.2% of variations in the observed transverse cracking values can be explained by the first-year EqTCR value, age, and class of highways. The equation shows that transverse crack development has a direct relationship with the age of chip seal. Lower functional class highways tend to have more transverse cracks than higher class ones. The plot of predicted EqTCR values versus observed values is shown in Figure 4a. The trend line implies that the developed model is very likely to underpredict transverse cracking conditions when actual values are larger than 0.5.

Figure 4b shows the validation plot for equation (3) using data from Districts 5 and 6. A number of data points are far away from the line of equality, resulting in a very low \( R^2 \) value of 12.9%. Therefore, this model has a very limited ability for predicting progression of transverse cracks on chip-seal–treated pavements. This model needs to be used with caution, especially for highway segments with large first-year EqTCR values. More factors, such as material types, pavement thickness, and characteristics prior to chip-sealing, might need to be considered for developing a better prediction model for EqTCR.

![State Level EqTCR Model](image)

![Verification of EqTCR Model](image)

**Fatigue Cracking**

Equation (4) is the linear model for the other cracking distress variable in PMIS, fatigue cracking (designated as EqFCR).

\[
\text{EqFCR} = -0.24839 + 0.49664 \text{ (InitFCR)} + 0.00008 \text{ (ESAL)} + 0.15381 \text{ (Class)}
\]

\( (n = 804; R^2 = 0.527) \)
Besides the first-year fatigue cracking value, equivalent single axle loads (ESAL) and highway class are the significant variables to predict fatigue cracking deterioration after chip sealing. Age is not significant. This may imply that fatigue cracking is more dependent on traffic loading than time. An $R^2$ value of 0.527 was obtained for this model. Figure 5a shows the plot of predicted EqFCR values versus observed values. A somewhat large scatter of data can be observed.

Figure 5b displays the predicted EqFCR values versus observed values for Districts 5 and 6. As can be seen, a very low $R^2$ value of 6.9% was obtained, suggesting a lack of applicability of this model to fit the whole data set. A number of roadways had no or very slight fatigue crack deterioration after chip-sealing, while some roadways had very significant fatigue crack development. This caused difficulties in modeling progression of fatigue cracking for chip seal-treated pavements. Again, these results may indicate that chip seal is not an appropriate treatment for fatigue-cracked pavements.

**CONCLUSIONS**

Multiple linear regression models were developed for predicting distress progression on chip-sealed pavements using data available in the PMIS database. The models were validated by data not used in the regression process. The IRI and rutting models appear to be reasonable. More variables need to be included in the transverse cracking and fatigue cracking models for better prediction. Chip seal does not appear to be a viable treatment for pavements with extensive transverse and fatigue cracking.
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