SINGLE POINT PROBABALISTIC ESTIMATION OF REMAINING SERVICE LIFE FOR PAVEMENTS USING LTPP DATA

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ABSTRACT

In order to provide safe and efficient surface transportation under ever increasing budgetary constraints, modern pavement planning methods emphasize an established and regularly utilized pavement management system (PMS) for state highway agencies (SHAs). Through long term record keeping it becomes possible to forecast future pavement conditions and distresses to effectively plan future projects and budgets. However, not all SHAs maintain a PMS database with sufficient records to forecast pavement behavior. This paper details a probabilistic method of forecasting the remaining service life (RSL) based on International Roughness Index (IRI) when limited time series data are available. The paper is based on data from the FHWA Long-Term Pavement Preservation (LTPP) program Special Pavement Study (SPS)-1.

The method, described herein as Single Record Pavement Life Estimate (SRPLE), is a promising means for SHAs to estimate RSL of specific pavement sections or for the pavement network when pavement condition and distress sampling has not yet occurred or if records are too few to perform pavement condition forecasting. Further, this method may be applicable for local highway agencies who do not regularly collect condition and distress data or do not have capabilities to model time series data. Once calibrated to local practices and environment, the established method will help pavement managers to better estimate pavement RSL with limited data points.

Keywords: Pavement management, RSL, pavement condition and distress, LTPP, network planning, IRI, asset management, SPS-1

INTRODUCTION

In order to provide safe and efficient surface transportation under ever increasing budgetary constraints, modern pavement planning methods emphasize an established and regularly utilized pavement management system (PMS) for state highway agencies (SHAs). Through long term record keeping it becomes possible to forecast pavement condition and distress progression over time to effectively plan future projects and budgets. Methodologies for projecting these actual conditions (roughness) and distresses vary between SHAs and local pavement managers with increasing emphasis on the remaining service life (RSL) method.

These forecasting methods fit recorded condition and distress data to a best fit line model along a time series, resulting in the ability to forward predict the time required to reach a pre-specified condition or distress threshold, the point where RSL is equal to zero. However, the difficulty of these methods are in the typical need for a minimum of three recorded time series data points to fit the model. Depending on the pavement condition monitoring frequency and budget, these three records may be collected between less than three years to greater than six years based on Federal Highway Administration (FHWA) Long-Term Pavement Preservation (LTPP) program data. This delay in the ability to estimate RSL may result in late applications of pavement treatments which become more expensive and less effective.

This paper presents an innovative method, herein referred to as Single Record Pavement Life Estimate (SRPLE), of predicting RSL values based on IRI for pavement sections using a single condition or distress record. This is accomplished by utilizing probabilistic curves for
pavement performance Condition States and RSL values, as outlined by Musunuru et al. [1]. For this study probability functions were fitted to time series IRI data of newly constructed flexible pavement test sections from the FHWA LTPP Special Pavement Study (SPS)-1 data and performed for all available climatic regions.

PROBABALISTIC ESTIMATION PROCEDURES

The development of proper SRPLE curves is dependent on several factors:

- Selection of significant number of pavement sections with sufficient time series condition and distress data to support modeling;
- Environmental and design similarity between selected pavement sections and sections which SRPLE curves will be administered or a wide range of design factors for generalized curves;
- Time-distress model selection;
- Probability density functions (PDFs) model selection and fitting; and
- Proper application and understanding of SRPLE limitations.

The aim of this study was to create a proof of concept SRPLE curve series inclusive to many pavement factors; allowing a generalized performance forecast based on pavement sections grouped by these pavement factors To accomplish this, LTPP SPS-1 was selected for analysis due to its aim to examine the effects of pavements sections with different structured factors for [2]:

- The effects of climatic region;
- Subgrade soil (fine- and coarse-grained); and
- Traffic rate (as a covariate).

While considering structural factors, again used for analysis grouping, including [2]:

- Drainage (presence or lack of it);
- Asphalt concrete (AC) thickness (102 mm and 178 mm);
- Base type (dense-graded untreated aggregate and/or dense-graded asphalt-treated); and
- Base thickness (203 mm and 305 mm for undrained sections and 203 mm, 305 mm and 406 mm for drained sections).

SPS-1 was also selected because the flexible pavement test sections were all constructed around the same period (in the early 1990s) and a relatively high number of pavement sections passed the modeling criteria outlined by Musunuru et al. [1], totaling 58 in all.
Selected pavement sections for this paper were re-modeled following established mathematical models. [1,3,4]. For IRI, the selected model is an exponential function (see Equation 1) form that fit the data using least squares regression. The analyses were conducted using Mathworks Matlab 2015a and the statistical parameters of the exponential function (alpha and beta) were obtained for each test section. Fitting evaluation of $R^2$ values found typical $R^2$ values from .40 to 1.00 with an average fit of .87 for before treatment modeling and values from .20 to 1.00 with an average fit of .81 for after treatment modeling. Further, for selected sections service lives fell within a typical range for most roadway owners of 17 and 8 years for IRI from roadway construction and first treatment, respectively. Equations one (1) and two (2) express the time “t” for the IRI to reach certain specified value.

$$IRI = \alpha e^{\beta t}$$  
Equation (1)

$$t = \frac{\ln{\text{Desired IRI value}}}{\alpha/\beta}$$  
Equation (2)

Where, $IRI = \text{calculated International Roughness Index}$ for a set alpha, beta, and time

$\alpha = \text{alpha, typically the first recorded or the y-intercept calculated through least squares regression (if the first record is not near the first year of service)}$;

$e = e, \text{exponential function}$

$\beta = \text{beta, rate of growth factor for the exponential function based on least squares regression}$

$t = \text{time, year or exact date from pavement construction or resurfacing to calculate IRI}$

$\ln = \text{natural log}$

For each pavement section, the parameters alpha and beta values were calculated, paired and stored for further analysis. Also, for each pavement section, a time series was constructed starting at year zero (the year when the pre-specified threshold is reached, RSL=0) where the IRI threshold was evaluated as 2.7 meters per kilometer (m/km) [1]. Back calculation for each section occurred on a yearly basis until one of two criteria were met:

1. $IRI$ evaluated at year $t$ was equal to alpha (first recorded data point).
2. The maximum year range was met. The maximum year range was set as 50 years for this study allowing for the full low IRI to be sampled for sections with slow condition (IRI) change (slower than a typical 20 year design life).
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Figure 1 displays a visual example of the results of this back calculation for three separate pavement sections and the combination of the three sections. Each individual pavement section displays its own growth behaviors and when combined can be seen as a series of distributed values. When sufficient values are available a probability distribution function or similar probability function can be created for a selected time period.

**FIGURE 1** Example backpropagation of IRI data for SHRP ID 26_0116, 19_0102, and 19_0103, individual pavement sections from SPS-1 and a combination thereof.

For this study, the RSL was divided into five ranges or five condition states (CS) developed by Musunuru et al. [1]. The ranges for the five CSs are:

- CS1 for 0 to less than 2 years,
- CS2 for 2 to less than 4 years,
- CS3 for 4 to less than 8 years,
- CS4 for 8 to less than 13 years, and
- CS5 for greater than or equal to 13 years.

Probability density function (PDF) modeling was completed using an Epanechnikov Kernel. Epanechnikov Kernels provided the closest fit to the observed data while providing secondary benefits of visual identification of possible sub-probability groups or divergent behaviors within larger generalized sample (SPS-1). Divergent or bimodal behaviors may be indicative of construction issues or premature failure of multiple sections otherwise experiencing similar condition or distress growth. Although this modeling method was selected, any PDF or Kernel method may be appropriate after evaluation of the goodness of fit.
With each PDF fit, SRPLE generation splits into two evaluation methods which may be used independently or in conjecture. The first method, SRPLE tables, are created with selected ranges of condition or distress and their average probabilities; these tables are easy to read and to utilize for quick estimation of a pavement CS. The second method, SRPLE plots, utilizes visualized data and confidence intervals to create a graphic representation which can also be used to estimate the current CS of a pavement section.

For SRPLE plots, directly after PDF generation each CS PDF is evaluated based on preferred confidence intervals (CIs). For this study CIs were evaluated for inner 50 percentile (25 percent at each tail was ignored), inner 90 percentile (5 percent along each tail was ignored), and at the PDF median prediction. These values are used to calculate CI ranges graphically overlain by PDF curves as shown in Figure 2 for all modeled SPS-1 pavement sections.

SRPLE tables utilize the CS groups and previously generated PDFs to create an easy to use table. For each analysis grouping (i.e. SPS-1 all climates) the total experienced condition or distress range is identified and subdivided into sub-distress ranges (.25 internals for this study case of IRI). Each of the sub-distress values has its probability recorded from the previously created PDFs for each of the five CSs. These PDF probabilities, for each sub-distress range (ie .25-.50), are then averaged and entered into a preliminary SRPLE table. This preliminary table is then finished by weighting the probabilities for each sub-distress across all five CS columns. This final step results in a cumulative 100 percent probability for each sub-distress row and helps to emphasize the differences in raw CS probabilities. For example, for CS5 PDF the IRI range of 0.25 to 0.50 m/km may have a 24 percent and 30 percent probability, respectively. The average probability for the 0.25 to .50 range is thus the average of 24 and 30 percent, 27 percent. If it is assumed that for the remains CS groups their respective percent probabilities are 20, 12, 8, and 1 percent for CS4, CS3, CS2, and CS1, respectively, the weighted probabilities can be found. Weighted probabilities are calculated for each CS as the averaged probability of the selected CS divided by the summation of all CSs for the sub-distress range. For this example the weighted values are 40, 29, 18, 12, and 1 percent probability for CS5, CS4, CS3, CS2, and CS1, respectively. It can then be best estimated that for an IRI value between 0.25 and 0.50 m/km the pavement has the greatest chance of being in CS5 with an RSL greater than or equal to 13 years.

Table 1 provides the matching SRPLE table for Figure 2 composed of all accepted SPS-1 test sections for all climatic regions. For visibility of the best fit CS shading is used with lighter colors referencing higher relative probability. Both SRPLE plots and tables can be made generic using an entire pavement network’s data for a pavement type or generated for specific climates, practices, designs, or other variables which would generally affect pavement performance. As an example, Figures 3 and 4 and Tables 2 and 3 show examples based on the analyses of SPS-1 test sections located in the dry-non-freeze and wet-freeze climatic regions, respectively.
FIGURE 2 SRPLE plot for SPS-1 sections for all climatic regions.

TABLE 1 SRPLE Table for SPS-1 Sections for all Climatic Regions

<table>
<thead>
<tr>
<th>IRI Range</th>
<th>1</th>
<th>2 to &lt; 4</th>
<th>4 to &lt; 8</th>
<th>8 to &lt; 13</th>
<th>≥ 13</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSL (years)</td>
<td>&lt; 2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>CS 1</td>
<td>0%</td>
<td>0%</td>
<td>1%</td>
<td>21%</td>
<td>78%</td>
</tr>
<tr>
<td>CS 2</td>
<td>2%</td>
<td>1%</td>
<td>5%</td>
<td>17%</td>
<td>76%</td>
</tr>
<tr>
<td>CS 3</td>
<td>5%</td>
<td>5%</td>
<td>9%</td>
<td>18%</td>
<td>63%</td>
</tr>
<tr>
<td>CS 4</td>
<td>9%</td>
<td>10%</td>
<td>14%</td>
<td>23%</td>
<td>44%</td>
</tr>
<tr>
<td>CS 5</td>
<td>15%</td>
<td>16%</td>
<td>21%</td>
<td>33%</td>
<td>15%</td>
</tr>
<tr>
<td>CS 6</td>
<td>18%</td>
<td>20%</td>
<td>29%</td>
<td>28%</td>
<td>4%</td>
</tr>
<tr>
<td>CS 7</td>
<td>23%</td>
<td>28%</td>
<td>33%</td>
<td>15%</td>
<td>1%</td>
</tr>
<tr>
<td>CS 8</td>
<td>33%</td>
<td>41%</td>
<td>20%</td>
<td>5%</td>
<td>0%</td>
</tr>
<tr>
<td>CS 9</td>
<td>59%</td>
<td>30%</td>
<td>9%</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>CS 10</td>
<td>77%</td>
<td>19%</td>
<td>3%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>
FIGURE 3 SRPLE plot for SPS-1 sections for the dry-non-freeze climatic region.

FIGURE 4 SRPLE plot for SPS-1 sections for the wet-freeze climatic region.
TABLE 2 SRPLE Table for SPS-1 Sections for the Dry-non-freeze Climatic Region

<table>
<thead>
<tr>
<th>IRI Range</th>
<th>CS 1</th>
<th>CS 2</th>
<th>CS 3</th>
<th>CS 4</th>
<th>CS 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSL (years)</td>
<td>&lt;2</td>
<td>2 to &lt;4</td>
<td>4 to &lt;8</td>
<td>8 to &lt;13</td>
<td>≥13</td>
</tr>
<tr>
<td>.25-.50</td>
<td>4%</td>
<td>0%</td>
<td>2%</td>
<td>12%</td>
<td>81%</td>
</tr>
<tr>
<td>.50-.75</td>
<td>9%</td>
<td>7%</td>
<td>9%</td>
<td>15%</td>
<td>60%</td>
</tr>
<tr>
<td>.75-1.00</td>
<td>10%</td>
<td>10%</td>
<td>12%</td>
<td>16%</td>
<td>52%</td>
</tr>
<tr>
<td>1.00-1.25</td>
<td>13%</td>
<td>13%</td>
<td>15%</td>
<td>18%</td>
<td>41%</td>
</tr>
<tr>
<td>1.25-1.50</td>
<td>18%</td>
<td>19%</td>
<td>21%</td>
<td>25%</td>
<td>17%</td>
</tr>
<tr>
<td>1.50-1.75</td>
<td>21%</td>
<td>22%</td>
<td>24%</td>
<td>29%</td>
<td>5%</td>
</tr>
<tr>
<td>1.75-2.00</td>
<td>26%</td>
<td>27%</td>
<td>29%</td>
<td>17%</td>
<td>1%</td>
</tr>
<tr>
<td>2.00-2.25</td>
<td>36%</td>
<td>33%</td>
<td>22%</td>
<td>9%</td>
<td>0%</td>
</tr>
<tr>
<td>2.25-2.50</td>
<td>46%</td>
<td>34%</td>
<td>17%</td>
<td>4%</td>
<td>0%</td>
</tr>
<tr>
<td>2.50-2.70</td>
<td>59%</td>
<td>32%</td>
<td>9%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

TABLE 3 SRPLE Table for SPS-1 Sections for the Wet-freeze Climatic Region

<table>
<thead>
<tr>
<th>IRI Range</th>
<th>CS 1</th>
<th>CS 2</th>
<th>CS 3</th>
<th>CS 4</th>
<th>CS 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSL (years)</td>
<td>&lt;2</td>
<td>2 to &lt;4</td>
<td>4 to &lt;8</td>
<td>8 to &lt;13</td>
<td>≥13</td>
</tr>
<tr>
<td>.25-.50</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>17%</td>
<td>83%</td>
</tr>
<tr>
<td>.50-.75</td>
<td>0%</td>
<td>0%</td>
<td>2%</td>
<td>21%</td>
<td>77%</td>
</tr>
<tr>
<td>.75-1.00</td>
<td>2%</td>
<td>2%</td>
<td>6%</td>
<td>22%</td>
<td>68%</td>
</tr>
<tr>
<td>1.00-1.25</td>
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<td>5%</td>
<td>10%</td>
<td>26%</td>
<td>54%</td>
</tr>
<tr>
<td>1.25-1.50</td>
<td>8%</td>
<td>8%</td>
<td>18%</td>
<td>42%</td>
<td>24%</td>
</tr>
<tr>
<td>1.50-1.75</td>
<td>9%</td>
<td>12%</td>
<td>30%</td>
<td>41%</td>
<td>9%</td>
</tr>
<tr>
<td>1.75-2.00</td>
<td>11%</td>
<td>20%</td>
<td>48%</td>
<td>19%</td>
<td>2%</td>
</tr>
<tr>
<td>2.00-2.25</td>
<td>21%</td>
<td>45%</td>
<td>27%</td>
<td>7%</td>
<td>0%</td>
</tr>
<tr>
<td>2.25-2.50</td>
<td>53%</td>
<td>36%</td>
<td>9%</td>
<td>2%</td>
<td>0%</td>
</tr>
<tr>
<td>2.50-2.70</td>
<td>83%</td>
<td>15%</td>
<td>2%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

INTERPRETING AND USING SRPLE ANALYSIS METHODS

SRPLE plots and tables can easily be used for qualitative analysis between design factors or environmental factors such as climatic region. The performance difference between typical wet-freeze and dry-non-freeze regions is visually clear in both SRPLE plots and tables for SPS-1.
pavement sections. One can also observe that wet-freeze conditions exhibit a more uniform
g failure for all pavement sections analyzed as both the 90 and 50 percentile CIs are shown as
being more compact compared to those of dry-non-freeze. Further, one can see both Figure 2, all
c climatic regions, and Figure 3, dry-non-freeze region, exhibit bimodal PDF behavior, indicating
that there may be a sub-group of data or design variables which should be examined further.

SRPLE plots and tables can also be used for a specific pavement section. Figure 3 and
Table 2 have been reproduced below as Figure 5 and Table 4 to examine a theoretical pavement
section having a previously recorded IRI value of 1.15 m/km. For the SRPLE plot (Figure 5) a
line from the recorded IRI value is drawn horizontally from the y-axis across the entire figure.
Where the horizontal line passes through the highest probability, 90 percentile range, 50
percentile range, and median probable values are examined and the value closest to the median
probable value is identified. A vertical line is then drawn from the horizontal IRI line (1.15
m/km), closest to the median probable value or range, directly down to the x-axis. The CS which
lies closest to this vertical line holds the greatest probability of being the current CS for the
recorded condition or distress. For this example an IRI value of 1.15 m/km is most likely to
belong to CS5, having a RSL of greater than or equal to 13 years. It also has a smaller
probability of belonging to CSs 4, 3, 2, or 1, where the horizontal line lies within the outer 50
and 90 percentile probable range.

![SRPLE plot for SPS-1 sections for the dry-non-freeze climatic region; highlighted for example identification of a theoretical pavement section.](image)

Similar analysis can be done using the SRPLE tables (see Table 4). First, select the IRI
range and associated row to be examined, again this example will utilize an IRI of 1.15 m/km.
Using the selected row, move horizontally to the right until the highest percentile value is found. This highest percentile range is the most likely CS for the recorded IRI. The results are the same as those found with the SRPLE plot; with a 41 percent relative probability an IRI value of 1.15 m/km, for a dry-non-freeze climate, is a member of CS5 with an RSL of greater than or equal to 13 years. This same IRI range has relative probabilities of 18 percent, 15 percent, 13 percent, and 13 percent, respectively for CSs 4, 3, 2, and 1.

It is important to note that the SRPLE method does not take into account the current age of the pavement and should be used as an advisory tool, not a standalone decision making tool. When additional information is known about the age of the pavement and the typical anticipated service life of the pavement in a network, that information should also be considered. Ideally, a model would be fit to the time series pavement condition and distress data of each pavement section. However, the method does provide a ‘best guess’ for the RSL of a pavement section based on limited condition data.

**TABLE 4 SRPLE table for SPS1 sections for all dry, non-freeze climatic sections; highlighted for example identification of theoretical pavement section.**

<table>
<thead>
<tr>
<th>IRI Range</th>
<th>Relative probability section condition state (CS)/ remaining service life (RSL) for selected IRI ranges.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CS 1 2 3 4 5</td>
</tr>
<tr>
<td>RSL (years)</td>
<td>&lt; 2 2 to &lt; 4 4 to &lt; 8 8 to &lt; 13 ≥ 13</td>
</tr>
<tr>
<td>.25-.50</td>
<td>4% 0% 2% 12% 81%</td>
</tr>
<tr>
<td>.50-.75</td>
<td>9% 7% 9% 15% 60%</td>
</tr>
<tr>
<td>.75-1.00</td>
<td>10% 10% 12% 16% 52%</td>
</tr>
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<td>1.00-1.25</td>
<td>12% 13% 15% 18% 41%</td>
</tr>
<tr>
<td>1.25-1.50</td>
<td>18% 19% 21% 25% 17%</td>
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<tr>
<td>1.50-1.75</td>
<td>21% 22% 24% 29% 5%</td>
</tr>
<tr>
<td>1.75-2.00</td>
<td>26% 27% 29% 17% 1%</td>
</tr>
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<td>2.00-2.25</td>
<td>36% 33% 22% 9% 0%</td>
</tr>
<tr>
<td>2.25-2.50</td>
<td>46% 34% 17% 4% 0%</td>
</tr>
<tr>
<td>2.50-2.70</td>
<td>59% 32% 9% 0% 0%</td>
</tr>
</tbody>
</table>

**SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS**

This paper presents a probabilistic method, SRPLE, of projecting RSL, based on IRI, using data from the FHWA LTPP SPS-1 experiment, for pavement sections limited to a single condition or distress record. Two separate SRPLE methods, figures and tables, are presented and an example of each considered. The following conclusions and recommendations were drawn:

- When limited pavement condition or distress records are available for a pavement section, SRPLE analysis is an appropriate method of approximating RSL for planning and analysis.
• SRPLE analysis results will improve with increased data volume for analysis and with secondary sub-SRPLE analyses taking into account different designs, environments, and pavement uses.

• SRPLE does not directly take into account the current age of a pavement when evaluating a pavement section likely CS. This may be beneficial by preventing bias towards performing treatments on roads which may be beyond the design or expected service life but still in good health.

• SPS-1 consists only of newly constructed pavements which have not received any maintenance or rehabilitation treatments. A more complex SRPLE may develop when considering the wide range of failures which may occur once maintenance and rehabilitation treatments are completed. SRPLE analysis needs to be expanded to verify if these changes will occur and how to best improve the SRPLE method to compensate for these changes.

ACKNOWLEDGEMENT

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REFERENCES


2. FHWA, “LTPP Specific Pavement Studies” last modified April 13, 2014
