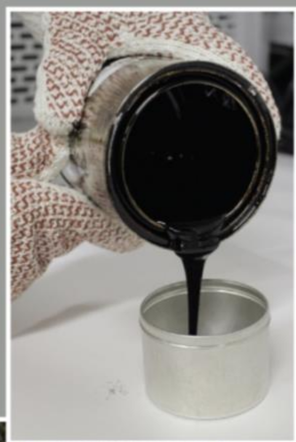
NCAT Report 19-06

DETERMINING INITIAL SERVICE LIFE FOR LCCA USING COMPARABLE IRI AS ONE OF THE CRITERIA



By
Mary Robbins
Nam Tran

August 2019

National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY

277 Technology Parkway ■ Auburn, AL 36830

Determining Initial Service Life for LCCA Using Comparable IRI as One of the Criteria

NCAT Report 19-06

By

Mary Robbins, PhD
Research Engineer
Ohio Research Institute for Transportation and the Environment at Ohio University
(Work completed while at National Center for Asphalt Technology)

Dr. Nam Tran, PhD, PE
Assistant Director and Research Professor
National Center for Asphalt Technology

Sponsored by
National Asphalt Pavement Association
State Asphalt Pavement Associations

August 2019

ACKNOWLEDGEMENTS

The authors wish to thank the National Asphalt Pavement Association and the State Asphalt Pavement Associations for sponsoring this research as part of the Determining Service Life Based on Comparable IRI research project and for providing technical review of this document.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the National Center for Asphalt Technology or Auburn University. This report does not constitute a standard, specification, or regulation. Comments contained in this paper related to specific testing equipment and materials should not be considered an endorsement of any commercial product or service; no such endorsement is intended or implied.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Pavement smoothness is important to the traveling public as rougher pavements can increase vehicle operating costs. Pavement smoothness can be quantified by International Roughness Index (IRI) and is used by state highway agencies (SHAs) as a functional performance measure in conjunction with other pavement structure-related performance measures, such as cracking, to assess the pavement conditions and select a pavement candidate for its first maintenance or rehabilitation.

While IRI is used in the evaluation process, a survey of SHAs conducted earlier in this study suggests that it is a lagging measure as a pavement is often selected for its first intervention based on other structure-related performance measures. In addition, the reported IRI threshold values used to select pavements for their first intervention vary significantly. For example, IRI values of 220 in/mile or greater were reported for two agencies while a value of 105 in/mile was reported for one agency. An IRI value greater than 170 in/mile is considered poor ride quality by the Federal Highway Administration (FHWA).

Since pavement smoothness is important to the traveling public, the question arises, why is pavement smoothness a lagging measure in the pavement evaluation process? To answer this question, data from long-term pavement performance (LTPP) general pavement studies (GPS) sections were evaluated to determine the mean international roughness index (MRI) (defined as the mean IRI of the left and right wheelpaths) of these sections at the time of first intervention. It was found that 85 percent of asphalt concrete (AC) pavements and 85 percent of Portland cement concrete (PCC) pavements in the GPS were intervened for the first time before reaching FHWA's poor ride quality IRI level of 170 in/mile. A threshold of 170 in/mile might be too rough for a first intervention trigger as most AC and PCC pavements were maintained or rehabilitated before reaching this level.

A further analysis of the LTPP data shows the 95 percent confidence interval of the mean for MRI was between 104 in/mile and 121 in/mile for AC pavements and 119 in/mile to 139 in/mile for PCC pavements at the time of first intervention. These two confidence intervals overlap between 119 in/mi and 121 in/mi. This intersection corresponds well with the FHWA's early (2000) value of 120 in/mi for pavements going from the "fair" pavement condition category to "mediocre" pavement condition. Based on this evaluation, an MRI threshold of 120 in/mile was considered more representative of the LTPP pavement roughness at the time of first intervention.

The LTPP data were then analyzed to determine the best method for using MRI data to estimate the pavement age at which surface smoothness is 120 in/mile for both AC and PCC pavements. Three methods were evaluated to determine the best approach for estimating initial service life using an MRI criterion. The most promising method was found to be that of linear interpolation. For pavement sections with MRI values greater than 120 in/mile measured at the time of first intervention, linear interpolation was utilized to identify the pavement age when MRI criterion was reached. This method resulted in more accurate estimates of pavement age when MRI is 120 in/mile as follows:

- AC pavements (based on data from 36 pavement sections):

    - Average: 14 years
    - 95-percent confidence intervals: 13 to 16 years
- PCC pavements (based on data from 20 pavement sections):
    - Average: 16 years
    - 95-percent confidence intervals: 13 to 19 years

In summary, pavement smoothness, as measured by IRI, is a functional performance measure that is important to the traveling public. While IRI is used as a functional performance measure in conjunction with other pavement structure-related performance measures, such as cracking, to select a pavement candidate for its first intervention, it is often a lagging parameter. An analysis of the LTPP data suggests that a maximum MRI threshold of 170 in/mile is too high to be used as a threshold for the first intervention because most AC and PCC pavements in the LTPP program were maintained or rehabilitated before reaching this level. An MRI threshold of 120 in/mile is found to be more representative of the pavement roughness at the time of first intervention in the LTPP database. The ages of AC and PCC pavements at which their smoothness reaches 120 in/mile are similar for AC and PCC pavements.

This study focused on pavement smoothness and the use of an MRI criterion for determining initial performance period. This criterion can be used with other performance measures when selecting pavement candidates for maintenance or rehabilitation.

1. INTRODUCTION

When planning for new construction or reconstruction of roadways, state highway agencies (SHAs) are tasked with selecting the most cost-effective alternative. The selection process can be conducted by employing life-cycle cost analysis (LCCA). LCCA considers the anticipated costs over the life of the pavement by incorporating initial costs and discounted future costs. The result, a net present value (NPV), enables a fair comparison between two potentially dissimilar investments, such as asphalt concrete (AC) and Portland cement concrete (PCC) pavements. In LCCA, it is assumed that the two alternatives provide the same level of performance or benefits to the project's users; thus, the alternatives can be compared on the basis of cost.

As part of a pavement's life-cycle, initial performance period (also referred to as initial service life) has a significant impact on LCCA results (*1*). Initial performance period is intended to represent the average time span in years for a newly constructed (or reconstructed) pavement to reach the agency's criteria (or thresholds) for first intervention.

Initial performance periods can be determined through analysis of pavement management data, historical experience and/or "based on the collective experience of their [SHAs] senior engineers" (*1*). While this may represent common practice, the use of historical work cycle data for determining the pavement life cycles may not represent true service lives, as some pavements may not reach or may far exceed the threshold at the time of intervention, possibly skewing LCCA results. Furthermore, this method may not satisfy one of the assumptions of LCCA that alternatives provide the same level of benefits to the user, which is necessary for alternatives to be fairly compared on the basis of cost. As such, a fair estimate of initial service life for each pavement type should be determined based on (1) pavement performance measures representing user benefits and common for both pavement alternatives; and (2) associated thresholds that reflect the condition at which pavements need intervention.

Several structural and functional performance measures are used for assessing asphalt and concrete pavements, as will be discussed later in this report. Structural performance, the ability of the pavement structure to withstand traffic loadings, may be measured by cracking and structural rutting. Functional performance is a measure of the pavement's ride quality and safety. One functional performance measure, pavement roughness, can be quantified by International Roughness Index (IRI) and is a measure of ride quality. Through state, regional, and nationwide surveys, it has been established that ride quality (or pavement smoothness, i.e. the absence of roughness) is important to the traveling public. While both asphalt and concrete pavements experience cracking, the mechanism for and the definition of cracking for asphalt and concrete pavements differ. However, IRI is determined by applying a mathematical model to the longitudinal profile of a pavement. As a result, the definition of IRI is consistent across all pavement types and is the only performance measure that is truly common to both pavement alternatives.

Although IRI is a functional performance measure and does not fully represent the structural performance of a pavement, it is important to the traveling public and is common to both pavement types. Therefore, there is motivation to determine initial service life when a common IRI criterion is considered. This study aims to evaluate IRI as one of the criteria that can be considered to provide a fair estimate of initial service life for both asphalt and concrete pavements. As such, it should be used in conjunction with other pavement performance measures.

2. OBJECTIVE AND SCOPE

The objective of this report is twofold: (1) to estimate initial service life for flexible and rigid pavements using a common IRI criterion, and (2) to provide recommendations for using IRI as one of the criteria to determine initial service life of each pavement type for LCCA.

Data from the Strategic Highway Research Program (SHRP) Long-Term Pavement Performance (LTPP) program standard data release (SDR) 28 were utilized for analyses. Specifically, IRI data, recorded maintenance and rehabilitation activities, and pavement age from pavement sections in LTPP General Pavement Studies (GPS) were employed.

3. BACKGROUND

In this section, performance measures and associated thresholds for asphalt concrete (AC) and Portland cement concrete (PCC) pavements are reviewed to select a common performance measure that can set the same level of user benefit at the time of intervention for both pavement types.

3.1. A Common Performance Measure for All Pavement Alternatives

A questionnaire documented in a previous report asked SHAs about their decision-making process for determining the timing of intervention for interstate pavements (*2*). The responses indicated that practices are unique to each agency. Half indicated that rehabilitation triggers, typically condition or performance indexes, are used as part of the decision-making process. The distress data that make up these indexes were found to vary by agency, as well as the number and type of indexes used. Common distresses, such as cracking, rutting, pavement roughness, and faulting, were reported as either part of an index or as a trigger for rehabilitation. For several SHAs, the performance measures were not the same for the two pavement types. This was especially true where cracking was utilized, as its definitions and measurements were different for AC and PCC pavements. It was observed that the current practices and criteria for determining the timing of intervention were developed independently for each pavement type; they were not developed to achieve equal levels of performance for the traveling public (*2*).

Several attempts have been made to develop common national performance measures for the two pavement types. During the initial LTPP program data analysis, a group of experts responsible for managing highways (consultants, state agency personnel, etc.) established levels of distress for classifying the performance of asphalt pavements (*3*). These distresses include smoothness measured by IRI, average rut depth, percentage of fatigue cracking, and the length of transverse cracking per mile. Using the previous distress levels established by Rauhut et al. (*3*) as a basis, Von Quintus (*4*) established performance categories for asphalt pavements for the purpose of determining service life of high traffic volume facilities, as are shown in Table 1.

Table 1 General Categories of Flexible Pavement Performance (*after 4*)

Performance Indicator	Performance Categories			
	Exceptional	Good	Fair	Poor
Smoothness (inches/mile)	< 95	≥ 95 and < 120	≥ 120 and ≤ 160	> 160
Average Rutting (inches)	< 0.35	≥ 0.35 and < 0.50	≥ 0.50 and ≤ 0.75	> 0.75
Fatigue Cracking (%)	< 5	≥ 5 and < 10	≥ 10 and ≤ 25	> 25
Transverse Cracks (ft/mile)	< 200	≥ 200 and < 500	≥ 500 and ≤ 1,500	> 1,500

More recently, legislation has resulted in the development of national performance measures to be used by all SHAs for both AC and PCC pavements. As part of Moving Ahead for Progress in the 21st Century (MAP-21), SHAs are also required to establish performance targets for their roadways and bridges (*5*). The MAP-21 performance measures and associated criteria for good, fair, and poor categories established by the Federal Highway Administration (FHWA) are shown in Table 2. In this table, IRI, reported as Mean Roughness Index (MRI, which is the average of the left and right wheelpath IRI measurements), and cracking are performance measures for all pavement types, while mean rutting is used for AC pavements only, and faulting is required for jointed concrete pavements (JCP). Present Serviceability Rating (PSR) may be reported as an alternative to IRI for routes with a posted speed limit less than 40 miles per hour (mph) (*5*). Although cracking is a performance measure for all pavement types, the categories for percent cracking vary due to the difference in the types of cracking specific to each pavement type.

MAP-21 performance measures are calculated using performance metric data submitted by SHAs as part of the Highway Performance Monitoring System (HPMS) (*5, 6*). As shown in Table 2, the thresholds for percent cracking vary depending on the cracking associated with each pavement type. Specifically, for asphalt pavements including AC overlays, cracking percent is the total area in which fatigue type cracking is exhibited in the wheelpath (*6*). For continuously reinforced concrete pavements (CRCP), the area of the section exhibiting longitudinal cracking, punchouts, and/or patching is the cracking percent, while for JCP, cracking percent is the percentage of slabs exhibiting transverse cracking (*6*).

Table 2 MAP-21 Performance Measures (*5*)

Performance Parameter	Good	Fair	Poor
PSR (All)*	≥ 4.0	> 2.0 and <4.0	≤ 2.0
IRI** (inches/mile)	< 95	95-170	> 170
Cracking (%) (AC)	< 5	5-20	> 20
Cracking (%) (JCP)	< 5	5-15	> 15
Cracking (%) (CRCP)	< 5	5-10	> 10
Rutting (inches)	< 0.20	0.20-0.40	> 0.40
Faulting (inches)	< 0.10	0.10-0.15	> 0.15

*on routes with posted speed limit < 40 mph
**Mean IRI (MRI) is used

Based on the performance measures listed in Tables 1 and 2, two performance measures are shared by asphalt and concrete pavements: pavement roughness (in terms of IRI), and cracking.

However, types of cracking and methods of measurement are not equivalent for asphalt and concrete pavements. For asphalt pavements (and AC overlays), types of cracking considered include fatigue type cracking (percent). Types of cracking considered for concrete pavement at the national level include cracked slabs (percent) for JCP, and punchouts, longitudinal cracking, and patched area (percent) for CRCP.

In addition to varying types of cracking associated with each pavement type, achieving accurate and reliable crack measurements can be difficult. Rada et al. found that substantial variability is associated with manual ratings (*7*). Although many agencies are now using automated crack data collection methods, different automated methods for crack detection and data collection exist. It has been recognized at the national level that there is a need to unify data reporting and standardize pavement crack definitions. The National Cooperative Highway Research Program (NCHRP) has initiated Project 01-57 and Project 01-57A to address this need and to "develop discrete definitions for common cracking types in flexible, rigid, and composite pavements" (*8*).

The other parameter identified at the national level as a functional performance measure for both asphalt and concrete pavements is IRI. IRI is an objective and repeatable measure of roughness where roughness is defined in ASTM E867 (2012) as "the deviation of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics and ride quality." A relative measure of the longitudinal profile is determined with an inertial profiler to which a mathematical model is applied to compute IRI as the suspension (vertical) displacement per unit of distance traveled (*9, 10*). According to the 2014 HPMS Field Manual, IRI "is a time-stable, reproducible, mathematical processing of the known profile" (*11*).

As part of a 2012 study aimed at defining "a consistent and reliable method of assessing infrastructure health with a focus on bridges and pavements on Interstate Highway System," researchers were tasked with developing a consistent approach for categorizing pavements as good, fair, or poor (*12*). Data from three SHAs were used to explore the use of various parameters for evaluating pavement condition. The evaluated parameters included IRI, pavement condition index, structural capacity based on deflections, selected distresses combined with IRI and/or structural capacity, and remaining service life. Comparisons were made amongst state PMS data, HPMS data (if available for the parameter), and field data to determine if there were any correlations among the data sets. It was found that among the condition measures evaluated (IRI, cracking percent, cracking length, rutting, and faulting), a high-level of confidence in the data was found for IRI only. Although it was also reported that IRI does not fully represent the structural performance of the pavement, which is the ability of the pavement structure to withstand traffic loadings, it was recommended that IRI be used as a measure to indicate the good/fair/poor functional performance of the pavement at the national level (*12*).

Moreover, pavement roughness is often "considered the pavement condition indicator that best reflects the publics' perception of the overall condition of a pavement section" (*13*). Public perception is likely to be influenced by increased vehicle operating costs due to rougher pavements as fuel consumption, tire wear, maintenance, and repair are all influenced by pavement roughness (*14*). The traveling public associates pavement roughness with the need for rehabilitation or resurfacing. In a 2001 report, respondents to a survey conducted in the Midwest “believed the resurfacing should only occur when the ride deteriorated” (*15*). A 2013 Edelman Berland survey revealed that more than two-thirds of participants would be “willing to accept periodic maintenance delays if it means they got to enjoy a smooth driving experience” (*16*).

Ideally, a common performance parameter for use in determining initial service life in LCCA is chosen such that it strikes a balance between structural and functional performance. Cracking may provide an understanding of how a pavement is degrading structurally. However, cracking types and measurements are not equivalent between asphalt and concrete pavements, making it difficult to determine the timing of intervention at which both pavement types are at the same level of performance and at a performance level that is important to the traveling public. Although pavement roughness is often considered a functional distress, given the unified definition and measurement across all pavement types and the importance to the traveling public, pavement roughness measured by IRI enables the best comparison of user benefits and performance between pavement types.

3.2. IRI Criteria

Prior to the development of MAP-21 performance measures, the FHWA indicated a long-term goal of achieving acceptable ride quality for over 93 percent of the national highway system (NHS) within 10 years as part of their 1998 National Strategic Plan. In doing so, acceptable ride quality was defined as an International Roughness Index (IRI) of less than 170 inches/mile (*17*).

While “acceptable” (IRI of 0 – 170 inches/mile) and “less than acceptable” (> 170 inches/mile) ride quality had been defined in the 1998 report, the FHWA defined overall pavement condition qualitatively in 2000 by categorizing pavements as very good, good, fair, mediocre, or poor (*18*). FHWA derived these categories to translate between Present Serviceability Rating (PSR) and IRI, as shown in Table 3.

Table 3 Relationship Between IRI and PSR (*18*)

Condition Term	PSR Rating		IRI Rating (inches/mile)		Interstate & NHS Ride Quality
Categories	Interstate	Other	Interstate	Other	
Very Good	≥ 4.0	≥ 4.0	< 60	< 60	Acceptable 0 - 170
Good	3.5-3.9	3.5-3.9	60-94	60-94	
Fair	3.1-3.4	2.6-3.4	95-119	95-170	
Mediocre	2.6-3.0	2.1-2.5	120-170	171-220	Less than Acceptable > 170
Poor	≤ 2.5	≤ 2.0	> 170	> 220	

Recently, a final ruling was announced on the performance measures for MAP-21, which included categories for good, fair, and poor IRI, as shown previously in Table 2 (*5*). MAP-21 categories differ from the previous FHWA categories in that good IRI is defined by an IRI less than 95 in/mile, while fair IRI is in a relatively wide range of 95 to 170 in/mile. Poor ride quality is defined by an IRI value of 170 in/mile, which is consistent with previous FHWA thresholds for poor ride quality.

The intention of this study is to determine a service life estimate for LCCA based on a criterion common to both asphalt and concrete pavements, and as noted earlier, the criterion should be associated with pavements in need of maintenance or rehabilitation. A previous report conducted as part of this study summarized SHA responses to a questionnaire regarding practices for determining the timing of intervention of their interstate pavements (*2*). The questionnaire revealed that for those agencies that reported IRI threshold values as part of their decision-making process, a wide spectrum of values is considered. For example, IRI values of 220 in/mile or greater were reported for two agencies, while a value of 105 in/mile was reported for one agency.

Despite the MAP-21 and FHWA definition for poor ride quality, it was found in this study that AC and PCC pavements frequently receive the first intervention prior to reaching that threshold (*2*). Using LTPP data, it was found that 85% of AC pavements and 85% of PCC pavements were intervened for the first time before reaching 170 in/mile. Furthermore, the average MRI values just prior to the first intervention were much lower than 170 in/mile (*2*). This suggests that a lower threshold value should be used for the first intervention.

In a 2008 study conducted for the Kansas Department of Transportation, researchers estimated pavement service life using three methods: parametric survival analysis, non-parametric survival analysis, and performance trend analysis (*19*). As part of the performance trend analysis, researchers identified the mean (50th percentile) IRI at the time a light or heavy maintenance and rehabilitation treatment occurred for each pavement type. In turn, a common IRI threshold of 125 in/mile was identified for both full-depth asphalt concrete and jointed plain concrete with dowels. The common IRI threshold was then used to estimate the age at which the IRI threshold was exceeded as an estimate of service life for each pavement type.

A similar approach for identifying a common IRI threshold was used for this study. Documented in an earlier report and summarized in a subsequent section herein, LTPP data were utilized to determine the MRI measured on asphalt and concrete pavements just before the first intervention (*2*). An MRI threshold common to both asphalt and concrete was identified as 120 in/mile, a value consistent with the FHWA IRI threshold for interstate pavements with mediocre ride quality, as shown in Table 3. LTPP data from across the United States and Canada were included in the study, resulting in an MRI threshold that represents actual practices and pavements in need of maintenance or rehabilitation across North America.

As noted previously, there is a need to determine the initial service life for use in LCCA that satisfies the assumption that both pavement alternatives provide equal levels of performance. Thus, service life should be estimated using a set of criteria that include at least a performance measure that is common to the two pavement alternatives and represents pavements in need of intervention. This report aims to estimate service life using a common criterion of 120 in/mile for MRI. This criterion can be used with other performance measures to determine initial pavement service life.

4. COMPARABLE IRI FOR LCCA

As part of this study and documented in a previous 2018 report, data from LTPP GPS sections were evaluated with the goal of determining a common criterion to be used to determine service life for LCCA (*2*). Use of LTPP data follows the recommendation made in the 1998 FHWA publication for LCCA, stating, "Current FHWA efforts to analyze pavement performance data collected as part of the LTPP should provide an additional valuable resource to SHAs" (*1*). Moreover, the LTPP dataset is one of the most comprehensive datasets available. The efforts documented in the 2018 report (*2*) are summarized in this section.

Based on an analysis of pavement age at the time of the first intervention using pavement sections in both the Specific Pavement Studies (SPS) and GPS, the distribution of pavement age was determined. Maintenance and rehabilitation activities used in this study are based on those provided by SHAs in their response to the issued questionnaire and based on those reported in the LTPP database, as documented in the previous report (*2*). The middle 90% of the distribution of pavement age at first intervention was determined separately for AC pavements and for PCC pavements. For AC pavements, the middle 90% of the distribution of pavement age at the first intervention was bound by 6.71 years and 29.15 years, while boundaries for PCC pavements were 12.03 years and 35.64 years. The limits of the middle 90% of each distribution were used to limit data for all analyses to minimize the use of erroneous data or pavements not representative of common practice.

To evaluate the condition of the pavement at the time of intervention, IRI at the time of the first intervention was examined for AC and PCC pavements. Only pavement sections with IRI measured prior to the first intervention and having a pavement age within the boundaries described above were utilized. Data from the following LTPP experiments were employed for the analysis:

- GPS-1: AC pavement on granular base
- GPS-2: AC pavements on bound base
- GPS-3: Jointed plain concrete pavements (JPCP)
- GPS-4: Jointed reinforced concrete pavements (JRCP)
- GPS-5: Continuously reinforced concrete pavements (CRCP)

MRI was chosen for the analysis to be consistent with the requirements for HPMS (and now MAP-21) in which MRI is reported rather than IRI in a designated wheelpath. In most cases, on a given day, multiple IRI measurements were taken from which multiple MRI values were computed. Therefore, the MRI values were averaged among the daily measurements. The last MRI values measured prior to the first intervention were summarized for each pavement type and experiment (GPS-1 through GPS-5) to better understand the levels of pavement roughness at the time of the first intervention. To evaluate each pavement type, data from the GPS experiments were grouped together by like pavement type. AC pavements on granular base (GPS-1) were combined with AC pavements on bound base (GPS-2) to represent AC pavements. Data for JPCP (GPS-3), JRCP (GPS-4) and CRCP (GPS-5) were combined to represent PCC pavements.

In general, AC pavements tended to be smoother than PCC pavements at the first intervention. However, in comparing the last MRI prior to intervention with the FHWA's 1998 criteria for unacceptable ride quality (IRI greater than 170 in/mi), it was found that more than 85% of each AC pavements and PCC pavements were rehabilitated before reaching that level. Based on this, it was concluded that a threshold of 170 in/mile is too rough for a maintenance or rehabilitation trigger as most AC and PCC pavements were rehabilitated before reaching this level.

The last average MRI values obtained prior to the first intervention are summarized for each pavement type in Table 4. Although the spread is wide for both pavement types, AC pavements had the largest range in values despite having the lowest average MRI. As shown below, the 95% confidence interval about the mean was between 104 in/mile and 121 in/mile for AC pavements and 119 in/mile to 139 in/mile for PCC pavements. Although there is a difference of more than 16 in/mile between the average MRI for AC pavements and PCC pavements, there is a small window where the confidence intervals overlap: between 119 in/mi and 121 in/mi. This intersection corresponds well with the FHWA's early (2000) value of 120 in/mi for pavements going from the fair pavement condition category to mediocre pavement condition. Based on this evaluation, a comparable IRI threshold of 120 in/mile was selected.

Table 4 Summary of Last MRI Value before First Intervention by Pavement Type

Type	No.	Avg MRI (in/mi)	Median MRI (in/mi)	Min MRI (in/mi)	Max MRI (in/mi)	Std. Dev. (in/mi)	95% Confidence Interval (in/mi)
AC	166	112.4	99.4	30.2	359.0	54.0	104.1 – 120.7
PCC	90	129.0	119.2	48.3	260.7	46.1	119.3 – 138.6

4.1. Progression of Pavement Roughness

As part of this study and documented previously, the progression of pavement roughness was also examined for each pavement type through the progression of MRI over time (*3*). First, all MRI values prior to the first intervention were plotted against pavement age at the time of the measurement for each pavement type. Substantial scatter in the data existed for both datasets, and the trend lines fitted to the data showed very poor coefficients of determination (R^2).

Further investigation of the data revealed that relationships between MRI and pavement age were evident when plotted for individual pavement sections. Therefore, linear regression was completed for each pavement section that had at least three MRI measurements made prior to the first intervention. The resulting linear trend lines were of the form shown in Equation 1. The results of the linear regression are reported in Appendix A for AC pavements and in Appendix B for PCC pavements.

$$MRI = m(Age) + b \tag{1}$$

where:

MRI = average of IRI in left and right wheelpaths (in/mile);
Age = pavement age, time from initial construction (yr);
m = slope (in/mile/yr); and
b = y-intercept (in/mile).

It should be noted that the y-intercept shown in Equation 1 represents the point at which the linear trend line crosses the y-axis, and it does not necessarily represent the initial MRI value immediately after construction. Likewise, the slope of the linear trend line may not represent the progression of pavement roughness for the entire period from construction to first intervention. The data that were available for linear regression generally represented only the latter part of the initial performance period. Therefore, using regression equations to project backwards to estimate smoothness earlier in the life or at initial construction may not be accurate.

5. METHODOLOGY

A comparable MRI criterion of 120 in/mile had been recommended in a previous report (*2*). To understand how this criterion can be used to determine initial service life for LCCA, the researchers looked at three different approaches for using the criterion and associated data to arrive at an initial service life estimate.

First, initial service life was predicted based on the linear relationship between pavement age and MRI. In the second approach, for those sections that had a range of recorded MRI values that encompassed the MRI threshold of 120 in/mile by the time they had been maintained or rehabilitated, linear interpolation was conducted to estimate the actual age at the threshold. For those sections where the threshold was not within the range of measured MRI values, exponential regression was conducted and then used to predict age at the MRI threshold. Lastly, only sections for which the threshold was within the range of MRI values were evaluated using linear interpolation.

To estimate the initial service life for AC and PCC pavements based on a comparable MRI value of 120 in/mile, the same data used to identify the common IRI criterion were used to estimate service life. The dataset included AC pavement sections in LTPP GPS-1 (AC on granular base) and GPS-2 (AC on bound base) and PCC pavement sections in LTPP GPS-3 (JPCP), GPS-4 (JRCP), and GPS-5 (CRCP). Only pavement sections in these GPS experiments that had IRI measurements made at least three times prior to intervention were included for this analysis. Additionally, data were limited to only pavement sections that fell into the middle 90% of the distribution of age at the time of first intervention for each pavement type. The middle 90% of age at first intervention was defined by lower and upper limits of 6.71 and 29.15, respectively, for AC pavements and 12.03 and 35.64 years, respectively, for PCC pavements. The resulting dataset included IRI measurements leading up to the first intervention for 142 AC pavement sections and 73 PCC pavement sections. For each pavement section, the pavement age when the MRI reached 120 in/mile was determined. Once determined, the pavement age at the threshold was summarized by pavement type and GPS experiment.

5.1. Linear Correlations to Estimate Initial Service Life at a Common MRI

The use of simple linear regression to predict the age at which each pavement section reached an MRI value of 120 in/mile was explored. It was found in the previous report that the rate at which the roughness progresses (and the associated initial MRI) was unique to each section (*2*). Therefore, the linear regression equation determined for each section was rearranged to determine the pavement age that corresponded to the target MRI value, resulting in Equation

2. Details for the linear regression equations (R^2, slope and y-intercept) are listed for each AC section in Appendix D and for each PCC section in Appendix E. The data for the analysis were limited to those sections that were reasonably represented by a linear relationship: sections with positive rates of roughness progression (slope greater than zero) and moderate or better linear relationships (R^2 greater than or equal to 50%).

$$Age = \frac{(120 - MRI_0)}{m} \tag{2}$$

where:

Age	=	pavement age, time from initial construction (yr);
MRI_0	=	y-intercept for linear regression (in/mile); and
m	=	rate of roughness progression (slope for linear regression) (in/mile/yr).

As shown in Appendices D and E, there are some pavement sections which have a negative MRI_0. While forcing the y-intercept to be positive may improve predictions, it does not accurately capture the roughness over time for each pavement section. Additionally, as noted previously, MRI data were not available for all sections throughout the entire initial performance period, rather, the MRI data were generally representative of the latter portions of the initial performance period. IRI or MRI may not change at the same rate throughout the entire initial performance period. Although GPS experiments that used existing in-service pavements that had not been rehabilitated prior to acceptance into the LTPP study were selected for this investigation, preservation activities may have been performed on these sections prior to the first intervention. Such activities can improve pavement roughness, seen as a decrease in MRI.

5.2. Combination of Linear Interpolation and Exponential Methods to Estimate Initial Service Life at a Common MRI

In this approach, two methods for estimating initial service life were used. First, those sections in which the threshold was within the range of measured MRI values were identified. Linear interpolation was then conducted between the first two MRI measurements closest to 120 in/mile. For those sections in which the MRI criterion was outside the range of measured MRI values, pavement age was estimated by using an exponential regression equation relating MRI and pavement age.

An earlier study on pavement smoothness on LTPP pavement sections found that for GPS-1 sections (AC on granular base) roughness progression followed an exponential trend for older pavements (10 years old or greater) and an exponential trend was also found for some pavement sections in the GPS-2, GPS-3, and GPS-4 experiments (*20*). Based on this finding, an exponential function of the form shown in Equation 3 was fit to the measured data for each pavement section for which 120 in/mile was outside of the range of measured values. It was found that the exponential function generally fit the measured data better than the linear regression based on observed increases in the coefficients of determination (R^2). The equation was then rearranged to estimate the pavement age at the MRI threshold of 120 in/mile. Only sections that were fit with an exponential regression equation that resulted in a coefficient of determination greater or equal to 50% were used for prediction of age at the MRI criterion. Additionally, for those sections fit with an exponential regression equation, only those with an increase in IRI over time (or a positive “b” value) were included to be consistent with the analysis described in the previous subsection using linear regression.

$$MRI = ce^{(bAge)} \tag{3}$$

where:

MRI	=	mean IRI (in/mile);
c, b	=	regression coefficients;
e	=	constant (2.718281); and
Age	=	pavement age, time from initial construction (yr).

5.3. Linear Interpolation to Estimate Initial Service Life at a Common MRI

The first two approaches included methods for predicting age based on MRI outside of the range of measured values. The third approach sought to evaluate only those pavement sections for which the threshold was within the range of MRI values. Therefore, only those pavement sections for which linear interpolation was conducted in the second approach were evaluated.

6. RESULTS AND DISCUSSION

One of the most influential parameters in LCCA is the initial service life, the time from initial construction or reconstruction until a pavement has reached a critical threshold, which delineates the time of the first intervention. In a previous report, it was found that many states rely on historical timing of intervention to determine initial service life for LCCA (*2*). Such an approach has many shortcomings, with the first being comparable performance. One of the primary assumptions in an LCCA, which is necessary for a fair comparison of the pavement alternatives, is that all alternatives provide the same level of performance or benefit to the users. This was the primary motivation for determining a comparable criterion that applies to both AC and PCC pavements. In an earlier report, this common criterion was identified as an MRI value of 120 in/mile, which represents the average roughness of both pavement types at the time of first intervention (*2*). As noted previously, this common MRI threshold was determined based on the average MRI at the time of first intervention. By using only pavement sections in the GPS in determining the threshold, this value should represent SHAs practices in terms of identifying pavements in need of intervention.

Although three approaches were used to estimate initial service life from the MRI threshold, only detailed results for the recommended procedure are provided in the body of this report. Results for the other two approaches are provided in Appendices C through H.

6.1. Results for Estimating Initial Service Life at a Common MRI using Linear Interpolation

In this approach (described in Section 5.3), only those sections for which the MRI threshold was included in the range of measured MRI values were evaluated. For those sections, linear interpolation was conducted to estimate the pavement age at 120 in/mile. Results are summarized in Table 5 and full results are compiled in Appendices A and B. The benefit of this approach is that the estimates are based only on pavement sections that have reached the MRI threshold prior to the first intervention, and therefore, no regression equations are necessary. The downfall, however, is that the sample size was greatly reduced.

Table 5 Summary of Estimated Age at MRI = 120 in/mile by Experiment, based on Linear Interpolation

Experiment	No.	Mean Age (yr)	Min Age (yr)	Max Age (yr)	Std Dev (yr)
AC Pavements					
AC on Granular Base	23	14.44	6.26	25.77	5.58
AC on Bound Base	13	13.97	8.52	17.74	2.66
AC Total	36	14.27	6.26	25.77	4.70
PCC Pavements					
JPCP	10	14.42	5.64	25.88	7.17
JRCP	6	18.63	13.42	27.03	5.57
CRCP	4	14.69	8.55	17.42	4.17
PCC Total	20	15.74	5.64	27.03	6.25

Overall, estimates made with linear interpolation alone had much lower variability, as indicated by the lower standard deviations for all five experiments. The average ages for AC pavements and for PCC pavements of 14.3 and 15.7 years, respectively, are also much lower than those estimates in which predictions were employed based on regression equations, as shown in Appendices C and F. The range of values is realistic due to the fact that actual pavement age and measured MRI values were used to estimate the time to reach the threshold as opposed to relying on regression equations. However, linear interpolation limits the analysis to sections in which MRI reached values greater than 120 in/mile before intervention, thereby excluding pavement sections which were smoother than 120 in/mile at the time of first intervention.

As shown in Table 6, all four climatic zones are represented in the data for both AC and PCC pavement sections, although some are better represented than others. Due to the few PCC pavement sections in climatic zones other than the wet, freeze zone and the few AC pavement sections in dry climate zones, conclusions cannot be drawn regarding the time to reach MRI of 120 in/mile relative to climate.

Table 6 Summary of Estimated Age at MRI = 120 in/mile by Climatic Zone based on Linear Interpolation

Climatic Zone	No.	Mean Age (yr)	Min Age (yr)	Max Age (yr)	Std Dev (yr)
AC Pavements					
Dry, Freeze	4	13.09	8.52	14.81	3.05
Dry, Non-freeze	2	19.95	17.83	22.08	N/A
Wet, Freeze	12	13.84	8.50	25.77	4.71
Wet, Non-freeze	18	14.18	6.26	25.67	4.97
AC Total	36	14.27	6.26	25.77	4.70
PCC Pavements					
Dry, Freeze	2	8.32	7.81	8.83	N/A
Dry, Non-freeze	1	25.88	25.88	25.88	N/A
Wet, Freeze	14	16.13	5.64	27.03	6.31
Wet, Non-freeze	3	15.46	13.38	17.42	2.02
PCC Total	20	15.74	5.64	27.03	6.25

6.2. Summary of Analysis Results

The LTPP SDR 28 database was utilized to identify AC and PCC pavements in the GPS-1 through GPS-5 experiments that had IRI measurements prior to the first intervention. Data analysis to determine a comparable IRI criterion for use in determining initial service life in LCCA was conducted and documented in a previous report (*2*). The IRI criterion was identified as an MRI threshold of 120 in/mile, which falls within the 95% confidence interval about the mean MRI for both AC and PCC pavement prior to the first intervention.

Three approaches were taken to estimate the time to reach an MRI threshold of 120 in/mile in order to estimate the initial service life of AC and PCC pavements for use in LCCA. The average time to reach the comparable IRI criterion of MRI = 120 in/mile as well as the median age and the 95% confidence interval about the mean are summarized in Table 7.

- For the first approach, simple linear regression was completed to determine the effect of MRI on pavement age. Once the linear regression equation was developed, the MRI threshold was applied to determine the time to reach 120 in/mile.
- The second approach consisted of conducting linear interpolation to determine the pavement age at the MRI threshold for those sections which the MRI threshold was within the range of measured MRI values prior to intervention. For those sections that the MRI threshold was outside of the measured MRI values, exponential regression was completed. The MRI threshold was then applied to the exponential regression equation to determine pavement age at 120 in/mile.
- Lastly, only those sections for which linear interpolation was conducted were evaluated.

Table 7 Summary of Estimates for Pavement Age at MRI Threshold

	Linear Regression	Linear Interpolation and Exponential Regression	Linear Interpolation
AC Pavements			
No. of Sections	106	116	36
Average Age (yrs) at MRI = 120 in/mile	27.55	22.68	14.27
Median Age (yrs) at MRI = 120 in/mile	21.49	18.41	14.32
95% Confidence Interval (yrs)	20.55–28.55	20.11 – 25.25	12.68–15.86
PCC Pavements			
No. of Sections	44	45	20
Average Age (yrs) at MRI = 120 in/mile	24.61	23.96	15.74
Median Age (yrs) at MRI = 120 in/mile	16.78	17.20	15.25
95% Confidence Interval (yrs)	15.83–33.39	17.57–30.35	12.82–18.66

Estimates for pavement age based on linear regression equations (detailed in Appendix C) resulted in the most variable estimates of initial service life (relative to standard deviations). As suggested earlier, this is likely because IRI or MRI does not change at the same rate throughout the entire initial performance period. Using linear interpolation and exponential regression equations improved the variability of the predictions. A limited number of sections were available for linear interpolation, although the estimates were the least variable and the most conservative. Therefore, for the dataset used in this research, linear interpolation is recommended for determining initial service life using a comparable MRI criterion of 120 in/mile.

Documented in the previous report (*2*), a literature review of earlier surveys identified typical values used for initial service life in LCCA. For AC pavements, SHAs commonly used an initial service life between 10 and 15 years, whereas values of 20 to 25 years were typically utilized for PCC pavements (*2*). The estimates from linear interpolation are in line with these values for AC pavements but are much lower for PCC pavements.

7. CONCLUSIONS AND RECOMMENDATIONS

The objectives of this report were to (1) estimate the initial service life for AC and PCC pavements to be used in LCCA using one IRI criterion common to both pavement alternatives; and (2) provide recommendations for using IRI as a criterion to determine initial service life of each pavement type for LCCA.

Based on the findings reported herein, the following conclusions and recommendations are made:

- A review of the common performance measures for AC and PCC pavements suggests that IRI enables the best comparison of user benefits and functional performance between pavement types due to its consistency in measurement among all pavement types. IRI alone may not fully represent the structural condition of the pavement.

Therefore, agencies may consider using IRI with other performance measures to capture both functional and structural performance in their LCCA practices.

- An analysis of IRI measurements, reported as MRI which is the average of the left and right wheelpath IRI measurements, prior to the first intervention in the LTPP database revealed that 85% of AC pavements and 85% of PCC pavements were first intervened prior to reaching an MRI of 170 in/mile, which is the threshold for poor ride quality defined by FHWA and for MAP-21 (*5, 18*). This suggests a lower IRI value should be used as a threshold for determining the timing of the first intervention. The FHWA and MAP-21 threshold of 170 in/mile for poor ride quality may be representative of pavements near the end of their life, i.e. those in need of reconstruction, instead of the smoothness condition of pavements at the first intervention.
- The analysis also showed that the 95% confidence interval for the mean was between 104 in/mile and 121 in/mile for AC pavements and 119 in/mile to 139 in/mile for PCC pavements. There is a small window where the confidence intervals for AC and PCC pavements overlap: between 119 in/mile and 121 in/mile. This intersection corresponds well with the early FHWA value of 120 in/mi for pavements going from the fair pavement condition category to mediocre pavement condition (*18*). Based on this evaluation, a comparable MRI threshold of 120 in/mile was selected. The selected threshold of 120 in/mile is very similar to a threshold of 125 in/mile previously identified in a Kansas study (*19*).
- Three approaches were taken for estimating pavement age at a comparable MRI criterion of 120 in/mile. Conclusions based on these three approaches are provided below:
    - Estimating pavement age at the comparable MRI criterion using linear regression results in variable estimates of initial service life. Given the large range of estimated pavement age at an MRI of 120 in/mile, linear regression may not be appropriate for estimating pavement age based on an MRI threshold outside the range of measured values.
    - Using linear interpolation and exponential regression allows for the inclusion of more pavement sections in the LTPP database. This approach resulted in less conservative, more variable estimates of initial service life estimates.
    - Estimates based on linear interpolation utilize only pavements that have measured MRI values in the range of the MRI threshold; therefore, estimates based on this approach are less variable and most accurate. However, this approach included only pavement sections for which MRI were greater than 120 in/mile while excluding the smoother pavement sections that were rehabilitated before reaching 120 in/mile. Linear interpolation resulted in the most conservative estimates of initial service life.
- The linear interpolation method was selected for determining initial service life for LCCA based on an MRI threshold of 120 in/mile for the dataset included in this study. Based on the results of this approach, initial service life estimates based on national level data from LTPP sections are as follows:
    - AC pavements (based on data from 36 pavement sections):
        - Average: 14 years

        - 95% confidence intervals: 13 to 16 years
    - PCC pavements (based on data from 20 pavement sections):
        - Average: 16 years
        - 95% confidence intervals: 13 to 19 years
- The initial service life estimates determined for an MRI criterion of 120 in/mile in this study are based on national level LTPP data. It is recommended that an agency evaluate the proposed MRI criterion relative to their own IRI data to first determine if that threshold is appropriate for their conditions and materials. Second, an agency should evaluate the approaches taken in this study to determine the most appropriate approach for estimating initial service life from a common MRI criterion for their conditions and materials.

In summary, this study shows that a common IRI threshold can be used in conjunction with other performance measures to determine the initial service life of AC and PCC pavements for LCCA, as it satisfies the assumption in LCCA that equal levels of functional performance or user benefits are achieved with each pavement alternative. An analysis of the LTPP data suggests that (1) a common MRI threshold of 120 in/mile can be used for this purpose; and (2) a performance measure threshold of 170 in/mile is too high to be used as a threshold for the first intervention because most AC and PCC pavements in the LTPP program were rehabilitated before reaching this level. The initial service lives determined based on the LTPP data using an MRI threshold of 120 in/mile are similar for AC and PCC pavements.

REFERENCES

1. Walls III, J. and M. Smith. *Life-Cycle Cost Analysis in Pavement Design – Interim Technical Bulletin.* FHWA-SA-98-079, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1998.
2. Robbins, M., and N. Tran. *Review of Initial Service Life Determination in Life Cycle Cost Analysis (LCCA) Procedures and In Practice*. NCAT Report 18-02, National Center for Asphalt Technology, Auburn, Ala., 2018.
3. Rauhut, J. B., H. L. Von Quintus, and A. Eltahan. *Performance of Rehabilitated Asphalt Concrete Pavements in the LTPP Experiments – Data Collected Through February 1997*. *FHWA-RD-99-00-029*, Federal Highway Administration, McLean, Va., 2000.
4. Von Quintus, H. Performance Characteristics of the Ideal Asphalt Pavement. In *Journal of the Association of Asphalt Paving Technologists*. Vol. 78, 2009, pp. 941-968.
5. U.S. Department of Transportation. *National Performance Management Measures; Assessing Condition for the National Highway Performance Program and Bridge Condition for the National Highway Performance Program*. Vol. 82, No. 11, 23 CFR Part 490, Washington, D.C., 2017.
6. FHWA. *Highway Performance Monitoring System Field Manual*. Office of Highway Policy Information, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2016.
7. Rada, G. R., C. L. Wu, R. K. Bhandari, A. R. Shekharan, G. E. Elkins, and J. S. Miller. *Study of LTPP Distress Data Variability, Volume I*. FHWA-RD-99-074, FHWA, McLean, Va., 1999.
8. Transportation Research Board. *Standard Definition for Comparable Pavement Cracking Data*. NCHRP 01-57, Transportation Research Board, Washington, D.C., In progress. http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3855. Accessed August, 2017
9. Sayers, M. W., and S.M. Karamihas. *The Little Book of Profiling: Basic Information about Measuring and Interpreting Road Profiles*. The Regent of the University of Michigan, Ann Arbor, Mich., 1998.
10. Shahin, M.Y. *Pavement Management for Airports, Roads, and Parking Lots*. 2nd edition, Springer Science, New York, NY, 2005.
11. FHWA. *Highway Performance Monitoring System Field Manual*. Office of Highway Policy Information, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2014.
12. Guerre, J., J. Groeger, S. Van Hecke, A. Simpson, G. Rada, and B. Visintine. *Improving FHWA's Ability to Asses Highway Infrastructure Healthy Pilot Study Report*. FHWA-HIF-12-049, FHWA, Washington, D.C., 2012.
13. Flintsch, G., and K. K. McGhee. *NCHRP Synthesis 401: Quality Management of Pavement Condition Data Collection*. Transportation Research Board of the National Academies, Washington, D.C., 2009.
14. Robbins, M., and N. Tran. *A Synthesis Report: Value of Pavement Smoothness and Ride Quality to Roadway Users and the Impact of Pavement Roughness on Vehicle Operating Costs*. NCAT Report 16-03, National Center for Asphalt Technology, Auburn, Ala., 2016.

15. Kuemmel, D., R. Robinson, R. Sonntag, R. Griffin, and J. Giese. Public Perceptions of the Midwest's Pavements: Policies and Thresholds for Pavement Improvement on Rural Two-Lane Highways. *Transportation Research Record: Journal of the Transportation Research Board, No. 1769*, TRB*,* National Research Council, Washington, D.C., 2001, pp. 11-19.
16. Asphalt Pavement Alliance. *Ahead of the Summer Driving Season, a New Survey from the Asphalt Pavement Alliance (APA) Finds U.S. Drivers Increasingly Frustrated with the State of U.S. Roads*. APA News. Lanham, Md., May 21, 2014. http://www.asphaltroads.org/news/post/national-driver-survey-reveals-need-focus-drivability/. Accessed August 1, 2014.
17. FHWA. *1998 National Strategic Plan*. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1998.
18. FHWA, *1999 Status of the Nation's Highways, Bridges and Transit: Conditions and Performance*. Report to Congress, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 2000.
19. Hallin, J. P., K. L. Smith, and L. Titus-Glover. *Determination of the Appropriate Use of Pavement Surface History in the KDOT Life-Cycle Analysis Process*. Report No. KS-08-04, Kansas Department of Transportation, Topeka, Kans., 2008.
20. Perera, R. W., and S. D. Kohn. *LTPP Data Analysis: Factors Affecting Pavement Smoothness*. NCHRP Web Document 40: Contractors Final Report, NCHRP, Washington, D.C., 2001.

APPENDIX A AC LINEAR INTERPOLATION RESULTS

STATE_CODE	SHRP_ID	Age at Rehab (yrs)	Est Age at 120 in/mile (yrs)
2	1002	13.73	10.69
4	1002	16.66	10.76
6	2002	18.84	17.30
6	2040	18.76	17.74
6	7454	27.85	21.44
12	1370	27.22	25.67
16	1001	26.93	25.77
18	1037	11.71	7.58
18	2008	14.42	10.01
23	1001	22.61	17.03
27	1023	16.48	10.63
27	6251	16.82	12.90
28	3087	13.88	12.60
28	3091	16.84	15.87
29	1010	17.90	14.34
34	1031	23.02	18.24
36	1643	18.39	15.72
37	1802	10.59	10.33
37	2825	24.35	12.22
42	1597	19.86	11.56
47	9025	15.69	14.86
48	1039	14.18	10.27
48	1111	26.97	22.08
48	3769	26.93	17.83
48	3835	8.57	6.26
48	9005	12.21	8.62
50	1004	16.88	8.50
51	1023	16.92	16.82
51	2004	16.53	14.31
56	2015	26.27	14.56
56	2017	16.90	14.81
56	2020	12.89	8.52
56	7775	15.73	14.47
83	6454	21.59	13.07
87	1622	22.13	17.82
89	1021	14.17	12.41

APPENDIX B PCC LINEAR INTERPOLATION RESULTS

STATE_CODE	SHRP_ID	Age at Rehab (yrs)	Est Age at 120 in/mile (yrs)
9	5001	15.10	8.55
16	3017	21.93	8.83
17	5843	19.08	17.20
19	3055	34.68	25.20
20	3013	19.55	16.36
20	4052	15.76	13.42
27	4034	35.44	27.03
28	5803	33.06	15.58
29	4036	20.18	18.39
29	5081	21.91	14.90
31	4019	26.88	14.37
37	3008	17.93	13.38
39	4018	28.29	23.67
48	5287	28.02	17.42
49	7086	19.15	7.81
53	7409	30.28	25.88
55	3010	14.68	11.79
55	3012	31.69	19.73
83	3802	15.01	5.64
89	3015	17.16	9.58

APPENDIX C RESULTS FOR ESTIMATING INITIAL SERVICE LIFE AT A COMMON MRI USING LINEAR CORRELATIONS

The results for each LTPP GPS experiment are shown in Table 8 below; full results for the estimated age to reach MRI of 120 in/mile are listed in Appendices B and C for each section. The data included in this analysis were limited to those sections with linear relationships having a positive slope and a coefficient of determination of 50% or better. Using this method, the mean estimated age to reach the common MRI threshold of 120 in/mile was 27.55 years and 24.61 years for AC pavements and PCC pavements, respectively. AC pavements in the AC on granular base experiment had a similar, although slightly shorter average age to 120 in/mile than those in the AC on bound base experiment. Of the three PCC GPS experiments, age to the MRI threshold were very similar among JPCP and JRCP with average values of approximately 20 years, while those in the CRCP experiment were estimated to take twice as long to reach 120 in/mile.

Table 8 Summary of Estimated Age at MRI = 120 in/mile based on Linear Regression ($R^2 \geq$ 0.50; Slope > 0) by Experiment

Experiment	No.	Mean Age (yr)	Min Age (yr)	Max Age (yr)	Std Dev (yr)
AC Pavements					
AC on Granular Base	59	25.85	3.62	126.09	21.43
AC on Bound Base	47	29.67	8.08	103.82	19.97
AC Total	106	27.55	3.62	126.09	20.78
PCC Pavements					
JPCP	24	20.13	-24.04	77.94	24.42
JRCP	11	20.88	5.23	51.62	12.91
CRCP	9	41.13	5.97	146.43	46.59
PCC Total	44	24.61	-24.04	146.43	28.87

The standard deviations are unreasonably large for both pavement types. As reported in the previous report, the standard deviations for the age at first intervention were in the range of approximately five to six years for both AC and PCC pavements in the same GPS experiments. The standard deviation for the estimate of age at 120 in/mile for PCC pavements was 28.87 years, which is larger than the mean age at the MRI threshold. Similarly, the standard deviation for AC pavements was found to be greater than the initial service life commonly used in practice, 10 to 15 years. Results for AC pavements are shown in Appendix D, and PCC sections results are tabulated in Appendix E.

Also of interest are the ranges of predicted values for each pavement type shown in Table 8. For AC pavements, age at an MRI of 120 in/mile ranged for the 106 sections from just less than 4 years to as high as 126 years. Likewise, the range for PCC pavements was exceptionally large, with a minimum value among the 44 sections of -24 years and a maximum value just greater than 146 years. If the negative ages predicted at the MRI threshold were removed for the PCC sections, the average among the 40 sections would be 28.17 years, the new minimum value would be 2.53 years while the maximum value would remain the same, and the standard deviation would decrease only slightly to 27.74 years.

Neither the high nor low end of these ranges are reasonable for the time a pavement would be in-service from the initial construction until the first intervention. While those sections may be exceptionally smooth and/or be able to maintain smoothness for an extended period of time, it is unlikely that such long service lives could be reached without failure by some performance measure (e.g. faulting, fatigue cracking, rutting). The negative age estimated for PCC sections and the wide ranges in both AC and PCC sections are likely due to the fact that the MRI threshold of 120 in/mile is outside of the measured data for some sections, and the linear trend line is not suitable for prediction of MRI outside of the range measured on those sections. As noted earlier, the dataset included 142 AC pavement sections and 73 PCC pavement sections. While nearly 75% of AC pavements had linear relationships between pavement age and MRI that were positive and moderately strong, only 60% of the PCC sections were positive and moderately strong.

The pavement age at the MRI threshold are summarized for AC and PCC pavements by climatic zone in Table 9. More than half of the AC pavements that had a moderately strong or better positive linear relationship between pavement age and MRI were in the wet, non-freeze climate. Similarly, over two-thirds of the PCC pavement sections were in the wet, freeze zone. The remaining climatic zones had small sample sizes for PCC pavements, making comparisons difficult.

As shown in Table 9, the estimated age of AC pavements at the MRI threshold varies by climatic zones. The longest time to reach the MRI threshold was in the dry, non-freeze zone for AC pavements at 35 years, well beyond typical values for initial service life in LCCA. The range of estimated age and the standard deviation among the AC pavements in each zone are rather large, as was evident in Table 9. The maximum age of 74 years for PCC pavements in the wet, freeze zone (the only zone with a reasonable sample size) was also too large to be realistic.

Table 9 Summary of Estimated Age at MRI = 120 in/mile based on Linear Regression ($R^2 \geq 0.50$; Slope > 0) by Climatic Zone

Climatic Zone	No.	Mean Age (yr)	Min Age (yr)	Max Age (yr)	Std Dev (yr)
AC Pavements					
Dry, Freeze	15	19.56	4.67	55.69	14.02
Dry, Non-freeze	13	35.11	14.94	81.93	21.71
Wet, Freeze	21	21.18	6.39	58.07	12.26
Wet, Non-freeze	57	30.27	3.62	126.09	23.51
AC Total	106	27.55	3.62	126.09	20.78
PCC Pavements					
Dry, Freeze	5	37.99	6.98	73.14	30.54
Dry, Non-freeze	3	24.98	13.40	32.91	10.26
Wet, Freeze	30	16.74	-24.04	73.80	19.59
Wet, Non-freeze	6	52.65	12.06	146.43	51.56
PCC Total	44	24.61	-24.04	146.43	28.87

APPENDIX D AC LINEAR REGRESSION RESULTS

STATE_CODE	SHRP_ID	Slope (in/mile/yr)	y-intercept (in/mile)	R^2	Predicted Age (yr) at 120 in/mile
1	1001	1.49	40.92	0.31	53.24
1	1019	3.09	73.29	0.87	15.09
1	4155	1.50	37.48	0.81	55.13
2	1002	-0.06	104.85	0.00	-257.71
4	1002	12.07	10.50	0.30	9.07
4	1006	6.88	-57.15	0.99	25.77
4	1007	11.00	-44.30	0.85	14.94
4	1015	-5.94	141.68	0.90	3.65
4	1016	6.10	-18.96	0.95	22.78
4	1017	2.56	35.91	0.70	32.84
4	1018	0.84	51.56	0.60	81.69
4	1021	0.93	65.04	0.17	59.08
4	1022	1.13	27.58	0.66	81.93
4	1024	2.31	26.66	0.50	40.33
4	1034	4.23	3.14	0.80	27.60
5	2042	14.63	-84.45	0.95	13.98
6	2002	3.59	50.31	0.73	19.41
6	2038	2.63	19.72	0.79	38.07
6	2040	7.68	-18.73	0.90	18.07
6	2041	5.88	-33.32	0.86	26.08
6	2051	1.20	49.78	0.59	58.53
6	7452	1.70	55.95	0.86	37.71
6	7454	0.18	108.74	0.02	63.78
6	8149	6.87	-73.84	0.86	28.20
6	8150	2.98	22.82	0.92	32.60
6	8153	4.54	24.35	0.80	21.05
8	1053	0.92	68.69	0.73	55.69
9	1803	0.79	94.91	0.21	31.77
10	1450	1.80	47.42	0.88	40.22
12	1370	5.84	-27.71	0.58	25.30
12	3997	2.52	28.18	0.71	36.42
12	4096	1.86	4.46	0.85	62.04
12	4100	1.28	24.67	0.86	74.59
12	4106	2.40	28.54	0.84	38.08
13	4096	0.50	55.23	0.23	130.21
13	4112	1.55	63.30	0.66	36.53
13	4113	2.64	18.94	0.98	38.27
16	1001	5.08	-32.24	0.59	29.97
16	1007	2.60	24.37	0.90	36.84

STATE_CODE	SHRP_ID	Slope (in/mile/yr)	y-intercept (in/mile)	R^2	Predicted Age (yr) at 120 in/mile
18	1028	3.56	22.66	0.68	27.33
18	1037	3.58	92.49	0.89	7.68
18	2008	14.64	-18.70	0.82	9.47
20	1009	1.15	115.86	0.60	3.62
21	1034	0.21	65.23	0.01	256.97
23	1001	-0.91	138.71	0.04	20.61
23	1009	-0.79	78.92	0.16	-52.32
23	1026	0.18	85.61	0.00	186.01
23	1028	-3.17	159.62	0.67	12.52
24	1632	1.75	43.94	0.85	43.57
24	1634	-0.73	73.31	0.52	-63.94
25	1004	-0.18	70.05	0.26	-274.51
27	1016	8.83	-7.91	0.81	14.48
27	1018	-4.72	230.40	0.08	23.41
27	1023	11.63	4.68	0.92	9.92
27	1028	9.05	-37.90	0.70	17.45
27	6251	13.03	-46.73	0.76	12.80
28	1001	5.90	24.60	0.93	16.18
28	2807	1.27	84.20	0.66	28.17
28	3081	3.88	22.18	0.90	25.19
28	3087	12.13	-37.73	0.85	13.00
28	3091	10.22	-39.99	0.94	15.65
29	1010	13.25	-61.25	0.95	13.68
30	7066	8.90	-16.99	0.91	15.39
30	7088	7.95	-9.14	0.94	16.24
30	8129	4.16	37.46	0.50	19.83
32	1020	4.79	17.87	0.98	21.30
32	1030	0.35	52.39	0.05	194.52
33	1001	5.13	-17.76	0.64	26.85
34	1003	-6.82	229.24	0.68	16.01
34	1011	2.27	56.58	0.81	27.88
34	1030	24.52	-268.51	0.90	15.84
34	1031	7.15	-11.92	0.73	18.44
34	1033	0.74	172.22	0.02	-70.22
35	2118	2.98	38.13	0.99	27.43
36	1011	2.17	55.87	0.54	29.61
36	1643	13.22	-72.98	0.69	14.60
36	1644	2.30	36.84	0.90	36.16
37	1006	0.64	39.79	0.77	126.09
37	1024	3.36	31.04	0.33	26.47

STATE_CODE	SHRP_ID	Slope (in/mile/yr)	y-intercept (in/mile)	R^2	Predicted Age (yr) at 120 in/mile
37	1028	1.21	43.78	0.81	63.06
37	1040	1.31	61.88	0.80	44.28
37	1645	2.55	38.74	0.87	31.88
37	1801	-0.29	70.76	0.03	-167.89
37	1802	12.62	-16.18	0.79	10.79
37	1817	2.86	38.44	0.38	28.51
37	2819	6.44	4.74	0.88	17.90
37	2824	1.48	38.00	0.08	55.39
37	2825	7.97	55.60	0.83	8.08
40	4087	0.76	65.26	0.65	71.95
40	4154	1.67	74.48	0.95	27.31
40	4163	0.72	45.63	0.54	103.82
40	4164	7.21	-24.18	0.72	20.01
41	2002	3.83	9.35	0.78	28.86
42	1597	14.01	-36.26	0.95	11.15
42	1599	0.95	88.25	0.62	33.50
42	1605	1.23	98.17	0.31	17.68
45	1025	12.32	22.42	0.75	7.92
47	1023	-0.23	55.17	0.05	-278.16
47	1028	2.25	64.23	0.75	24.83
47	1029	1.86	29.67	0.86	48.58
47	3101	3.94	25.87	0.58	23.87
47	9024	-2.09	119.89	0.84	-0.05
47	9025	5.77	33.34	0.94	15.01
48	1039	13.59	-35.34	0.65	11.43
48	1068	1.29	68.89	0.40	39.72
48	1092	6.20	30.87	0.84	14.37
48	1096	3.51	105.40	0.79	4.16
48	1111	4.43	18.64	0.64	22.90
48	2108	1.89	85.12	0.97	18.43
48	3669	1.65	70.66	0.60	29.91
48	3729	2.84	77.06	0.99	15.14
48	3769	4.60	32.89	0.83	18.95
48	3835	1.83	103.64	0.42	8.96
48	3855	1.70	62.82	0.81	33.70
48	9005	11.90	26.10	0.95	7.89
50	1004	0.16	112.10	0.00	47.96
50	1681	-5.39	218.49	0.84	18.29
50	1683	5.14	1.81	0.49	23.01
51	1023	2.08	79.43	0.36	19.55

STATE_CODE	SHRP_ID	Slope (in/mile/yr)	y-intercept (in/mile)	R^2	Predicted Age (yr) at 120 in/mile
51	1464	-0.40	80.45	0.13	-99.71
51	2004	11.58	-27.37	0.80	12.73
51	2021	3.47	73.35	0.72	13.43
53	1008	9.95	-46.48	0.97	16.73
56	2015	3.49	66.53	0.94	15.30
56	2017	5.44	32.90	0.94	16.00
56	2019	4.43	65.48	0.98	12.32
56	2020	12.18	10.49	0.97	8.99
56	7772	1.46	100.37	0.67	13.48
56	7775	6.48	24.49	0.92	14.73
81	1804	24.00	-31.18	0.99	6.30
81	1805	6.38	90.22	0.82	4.67
82	1005	2.15	32.00	0.96	40.93
83	6454	5.88	59.40	0.36	10.30
84	1684	1.77	69.07	0.67	28.74
87	1620	2.59	80.85	0.26	15.11
87	1622	3.74	38.87	0.59	21.67
87	1680	0.00	80.60	0.00	-9539.17
87	1806	1.25	47.70	0.58	58.07
89	1021	8.77	12.37	0.96	12.27
89	1125	18.99	-86.52	0.99	10.87
89	1127	8.96	62.73	0.52	6.39
90	6420	24.36	-295.17	0.65	17.05

APPENDIX E PCC LINEAR REGRESSION RESULTS

STATE_CODE	SHRP_ID	Slope (in/mile/yr)	y-intercept (in/mile)	R^2	Predicted Age (yr) at 120 in/mile
4	7614	2.21	47.28	0.71	32.91
6	3010	0.27	77.60	0.09	157.40
6	7455	-0.13	78.24	0.09	-319.11
6	7456	2.58	85.49	0.57	13.40
6	7493	0.17	86.92	0.09	197.04
8	3032	0.86	76.46	0.41	50.48
9	5001	-0.90	128.11	0.23	8.97
10	4002	-2.55	165.90	0.18	18.03
10	5005	1.25	42.79	0.37	61.79
13	3015	2.13	49.93	0.90	32.92
13	3017	0.28	73.68	0.17	164.30
13	3019	1.21	83.65	0.53	30.16
16	3017	1.58	96.03	0.41	15.14
16	3023	0.29	92.93	0.22	92.30
16	5025	2.38	95.40	0.53	10.35
17	5843	5.03	33.53	0.88	17.20
17	5849	0.11	86.52	0.01	306.01
17	5854	5.97	84.38	0.89	5.97
17	9267	0.13	67.42	0.16	394.16
17	9327	5.19	48.08	0.68	13.85
18	3003	1.77	78.67	0.23	23.36
18	5022	0.07	134.21	0.00	-189.66
18	5043	1.04	119.28	0.41	0.69
18	5518	4.84	-12.43	0.73	27.34
19	3006	7.32	68.79	0.89	7.00
19	3009	0.87	129.94	0.82	-11.49
19	3055	5.40	-11.75	0.98	24.38
20	3013	2.43	77.82	0.78	17.32
20	3015	0.73	65.58	0.33	74.10
20	4052	4.00	66.73	0.93	13.30
21	3016	0.26	92.50	0.11	107.20
27	4034	0.64	98.81	0.42	33.16
27	4050	0.41	77.97	0.08	102.42
28	5803	7.29	0.68	0.89	16.37
29	4036	3.20	56.05	0.93	20.01
29	5000	2.40	94.45	0.96	10.65
29	5058	1.07	85.93	0.81	31.99
29	5081	3.91	63.09	0.97	14.56
29	5091	1.67	75.13	0.92	26.86

STATE_CODE	SHRP_ID	Slope (in/mile/yr)	y-intercept (in/mile)	R^2	Predicted Age (yr) at 120 in/mile
31	3024	1.25	81.90	0.86	30.51
31	3028	1.08	58.46	0.63	57.01
31	4019	2.67	79.68	0.72	15.08
37	3008	3.01	83.73	0.81	12.06
37	5827	0.47	51.05	0.65	146.43
38	3006	1.78	53.31	0.40	37.52
39	3013	4.53	150.95	0.50	-6.84
39	4018	1.08	91.22	0.69	26.57
39	5003	-0.16	68.34	0.25	-326.90
40	4157	0.66	68.56	0.58	77.94
41	5006	0.73	71.99	0.60	65.46
41	5008	1.13	37.24	0.93	73.14
42	1606	0.74	82.00	0.59	51.62
42	1623	0.59	76.26	0.55	73.80
42	3044	-0.64	149.79	0.30	46.52
46	3010	3.02	104.94	0.46	4.99
46	3012	1.85	164.38	0.53	-24.04
46	6600	3.73	83.33	0.74	9.82
48	5154	0.05	98.73	0.01	461.10
48	5274	-0.06	105.31	0.00	-258.64
48	5287	0.23	116.98	0.06	13.17
49	3015	1.82	115.39	0.67	2.53
49	7083	1.49	69.20	0.54	34.01
49	7086	7.98	64.25	0.91	6.98
50	1682	5.09	16.98	0.33	20.24
53	7409	2.93	36.07	0.90	28.64
54	4004	11.37	60.57	0.94	5.23
54	5007	5.78	74.31	0.51	7.91
55	3010	11.57	-17.22	0.96	11.86
55	3012	4.26	41.72	0.94	18.39
55	3014	3.19	169.71	0.07	-15.59
83	3802	16.71	34.78	0.95	5.10
89	3001	2.26	122.76	0.88	-1.22
89	3015	7.05	43.34	0.38	10.88

APPENDIX F RESULTS FOR ESTIMATING INITIAL SERVICE LIFE AT A COMMON MRI USING A COMBINATION OF LINEAR INTERPOLATION AND EXPONENTIAL METHODS

Where the common MRI threshold, 120 in/mile, was within the range of measured MRI values for a given section, the pavement age was linearly interpolated between the two data points closest to the MRI threshold. Of the 142 AC pavement sections in the dataset, only 36 had measured MRI values inclusive of the MRI threshold. Similarly, the threshold was within measured MRI values for 20 of the 73 PCC pavement sections, and thus, linear interpolation was conducted. For the remaining 106 AC pavement sections and 53 PCC pavement sections, an exponential regression of form shown in Equation 3 was conducted. Once the exponential regression equation was determined, the threshold of 120 in/mile was used and the equation was solved for age.

For those sections that exponential regression was needed, only sections with an increase in MRI over time (represented by a positive "b" value) and an R^2 greater than or equal to 50% were included in this discussion to be consistent with the analysis conducted using linear regression. The results of the linear interpolation and exponential methods are summarized in Table 10; full results are reported in Appendices A and B for linear interpolation and Appendices G and H for exponential regression. This method was a slight improvement over predictions made with linear regression equations based on average ages that were more realistic and a reduction in standard deviation relative to those shown in Appendix C, Table 8. The average age for AC and PCC pavements as well as those found for each experiment were more in line with actual timing of first intervention as reported in the 2017 report: 18 and 17 years for AC on granular base and AC on bound base, respectively; 23, 24, and 24 years for JPCP, JRCP, and CRCP, respectively. However, the estimated age for AC pavements using a combination of linear interpolation and exponential regression were still greater than expected. The maximum age to reach 120 in/mile and the standard deviations generally decreased relative to the linear regression results reported in Appendix C, Table 8. Despite improvements, this combination of methods results in very high estimations of pavement age at the MRI threshold that are well beyond realistic values for initial service life.

Table 10 Summary of Estimated Age at MRI = 120 in/mile based on Linear Interpolation and Estimation from Exponential Regression ($R^2 \geq 0.50$; "b">0) by Experiment

Experiment	No.	Mean Age (yr)	Min Age (yr)	Max Age (yr)	Std Dev (yr)
AC Pavements					
AC on Granular Base	67	20.84	3.02	78.58	14.19
AC on Bound Base	49	25.20	8.52	69.89	13.37
AC Total	116	22.68	3.02	78.58	13.96
PCC Pavements					
JPCP	22	22.67	2.12	65.83	18.05
JRCP	12	20.19	3.40	48.11	11.94
CRCP	11	30.66	5.35	110.20	32.84
PCC Total	45	23.96	2.12	110.20	21.26

The estimated pavement age at the MRI threshold was also summarized for AC and PCC pavements by climatic zone in Table 11. Improvements in the pavement age estimates were also observed for each climatic zone. Similar to the results for linear regression, there were not enough PCC pavement sections in each climatic zone for comparisons. The majority of the PCC pavement sections were in the wet freeze climatic zone, which had an average of 19 years to reach the 120 in/mile threshold. The average actual age at first intervention for PCC pavement sections in the wet, freeze climatic zone was previously reported to be 23.5 years (*2*). Given that the PCC pavement sections were found to be rougher at the time of intervention than asphalt pavements, it is reasonable to expect a shorter time to reach the MRI threshold of 120 in/mile, a value nearly 20 in/mile less than the average MRI value (139 in/mile) at the time of intervention in the wet, freeze climatic zone (*2*). However, the standard deviation is still quite large at 15 years, indicating high variability among the estimates, as is the range of estimates. AC pavements in the wet, freeze climatic zone had a similar sample size, and similar average MRI at the time of intervention, reported as nearly 140 in/mile (*2*). Therefore, the shorter time to reach the threshold of 120 in/mile is reasonable relative to the actual time to first intervention of 20 years (*2*). Among the AC pavements in the four climatic zones, the wet, freeze also had the least variability.

Table 11 Summary of Estimated Age at MRI = 120 in/mile based on Linear Interpolation and Estimation from Exponential Regression ($R^2 \geq 0.50$; "b">0) by Climatic Zone

Climatic Zone	No.	Mean Age (yr)	Min Age (yr)	Max Age (yr)	Std Dev (yr)
AC Pavements					
Dry, Freeze	15	17.03	3.63	47.20	11.15
Dry, Non-freeze	13	29.32	14.87	63.30	14.15
Wet, Freeze	27	17.65	4.58	42.11	8.96
Wet, Non-freeze	61	24.88	3.02	78.58	15.36
AC Total	116	22.68	3.02	78.58	13.96
PCC Pavements					
Dry, Freeze	6	29.24	7.81	60.27	25.16
Dry, Non-freeze	3	22.30	12.26	28.77	8.81
Wet, Freeze	29	19.08	2.12	65.83	14.99
Wet, Non-freeze	7	40.36	13.38	110.20	35.44
PCC Total	45	23.96	2.12	110.20	21.26

APPENDIX G AC EXPONENTIONAL REGRESSION RESULTS

STATE_CODE	SHRP_ID	Age at Rehab (yrs)	c	b	R^2	Est Age at 120 in/mile (yrs)
1	1001	12.67	42.75	0.0265	0.33	39.01
1	1019	11.69	75.98	0.0180	0.89	25.44
1	4155	23.51	42.17	0.0234	0.81	44.60
4	1006	18.76	7.67	0.1202	1.00	22.88
4	1007	16.76	22.96	0.1112	0.85	14.87
4	1015	19.26	330.50	-0.1275	0.90	7.95
4	1016	17.96	19.08	0.0871	0.96	21.11
4	1017	20.79	44.62	0.0337	0.70	29.37
4	1018	21.35	52.72	0.0130	0.60	63.30
4	1021	18.52	66.08	0.0118	0.16	50.52
4	1022	18.29	30.28	0.0256	0.67	53.88
4	1024	21.76	37.85	0.0324	0.54	35.57
4	1034	26.10	32.82	0.0484	0.81	26.76
5	2042	20.85	48.55	0.0726	0.96	12.46
6	2038	28.93	38.62	0.0314	0.82	36.10
6	2041	24.68	22.91	0.0649	0.87	25.50
6	2051	15.93	50.87	0.0193	0.59	44.46
6	7452	27.10	62.34	0.0183	0.85	35.85
6	8149	21.44	6.81	0.1115	0.88	25.73
6	8150	14.84	28.94	0.0580	0.90	24.54
6	8153	18.07	44.13	0.0490	0.77	20.41
8	1053	17.41	69.31	0.0116	0.73	47.20
9	1803	14.98	94.95	0.0079	0.23	29.78
10	1450	22.42	53.13	0.0225	0.88	36.16
12	3997	20.70	40.20	0.0335	0.71	32.67
12	4096	28.83	18.77	0.0394	0.88	47.08
12	4100	26.09	29.84	0.0256	0.87	54.27
12	4106	16.30	31.55	0.0485	0.85	27.53
13	4096	15.84	55.37	0.0082	0.23	94.15
13	4112	21.27	66.16	0.0178	0.65	33.50
13	4113	21.27	31.25	0.0416	0.98	32.38
16	1007	25.20	39.29	0.0330	0.90	33.80
18	1028	20.49	40.38	0.0423	0.66	25.76
20	1009	10.65	116.10	0.0092	0.60	3.58
21	1034	20.56	65.16	0.0032	0.01	190.75
23	1009	22.99	80.93	-0.0124	0.16	-31.77
23	1026	23.22	86.07	0.0018	0.00	185.75
23	1028	21.86	185.16	-0.0328	0.66	13.22
24	1632	10.96	45.15	0.0307	0.84	31.79

STATE_CODE	SHRP_ID	Age at Rehab (yrs)	c	b	R^2	Est Age at 120 in/mile (yrs)
24	1634	21.94	74.65	-0.0120	0.52	-39.41
25	1004	26.94	70.10	-0.0027	0.26	-197.71
27	1016	22.72	53.36	0.0569	0.84	14.24
27	1018	16.48	96.19	0.0445	0.91	4.97
27	1028	25.58	48.68	0.0540	0.73	16.71
28	1001	11.44	34.77	0.0880	0.95	14.08
28	2807	11.18	84.81	0.0133	0.66	26.07
28	3081	11.86	30.53	0.0686	0.91	19.94
30	7066	9.04	14.51	0.1639	0.91	12.89
30	7088	10.27	19.73	0.1275	0.93	14.16
30	8129	15.01	48.71	0.0491	0.86	18.38
32	1020	16.29	30.42	0.0745	0.97	18.44
32	1030	17.14	52.65	0.0060	0.05	137.94
33	1001	22.68	15.71	0.0849	0.68	23.95
34	1003	20.36	316.87	-0.0609	0.66	15.95
34	1011	28.18	67.52	0.0207	0.80	27.76
34	1030	28.02	42.76	0.0835	0.89	12.36
34	1033	23.38	171.52	0.0043	0.02	-83.00
35	2118	22.29	49.08	0.0344	1.00	25.97
36	1011	9.29	57.63	0.0298	0.54	24.62
36	1644	15.89	42.52	0.0345	0.91	30.11
37	1006	12.28	40.13	0.0139	0.77	78.58
37	1024	11.78	38.64	0.0512	0.35	22.14
37	1028	20.35	45.77	0.0199	0.83	48.32
37	1040	16.81	63.73	0.0164	0.79	38.51
37	1645	13.63	41.93	0.0414	0.89	25.40
37	1801	22.40	71.32	-0.0048	0.03	-108.63
37	1817	11.97	43.50	0.0424	0.37	23.95
37	2819	10.86	26.20	0.0968	0.88	15.72
37	2824	7.97	39.29	0.0296	0.08	37.76
40	4087	11.47	65.46	0.0107	0.65	56.61
40	4154	11.63	75.00	0.0194	0.95	24.17
40	4163	12.39	45.92	0.0137	0.53	69.89
40	4164	16.33	18.73	0.1000	0.69	18.57
41	2002	22.25	36.12	0.0433	0.79	27.72
42	1599	23.68	88.39	0.0098	0.62	31.29
42	1605	23.80	100.98	0.0098	0.32	17.63
45	1025	13.59	68.47	0.0755	0.76	7.43
47	1023	22.25	55.22	-0.0045	0.05	-173.26
47	1028	15.96	66.20	0.0267	0.74	22.23

STATE_CODE	SHRP_ID	Age at Rehab (yrs)	c	b	R^2	Est Age at 120 in/mile (yrs)
47	1029	15.71	33.43	0.0362	0.87	35.26
47	3101	15.68	39.62	0.0507	0.61	21.86
47	9024	17.91	126.41	-0.0238	0.83	2.19
48	1068	13.68	69.22	0.0165	0.42	33.40
48	1092	15.05	44.95	0.0702	0.76	13.99
48	1096	20.15	112.05	0.0227	0.81	3.02
48	2108	17.88	86.67	0.0180	0.97	18.11
48	3669	17.39	71.75	0.0190	0.60	27.01
48	3729	16.26	80.85	0.0262	0.99	15.06
48	3855	19.22	66.19	0.0191	0.81	31.21
50	1681	28.04	544.83	-0.0745	0.84	20.32
50	1683	28.08	51.64	0.0371	0.50	22.75
51	1464	18.34	80.91	-0.0056	0.14	-70.78
51	2021	10.49	76.56	0.0345	0.72	13.04
53	1008	15.74	16.36	0.1240	0.97	16.06
56	2019	11.25	69.26	0.0469	0.97	11.72
56	7772	11.80	100.85	0.0130	0.66	13.36
81	1804	10.18	56.53	0.1308	1.00	5.76
81	1805	15.13	104.24	0.0388	0.81	3.63
82	1005	7.09	33.42	0.0489	0.97	26.12
84	1684	18.00	72.06	0.0188	0.66	27.07
87	1620	11.19	82.49	0.0258	0.27	14.55
87	1680	12.34	80.55	0.0000	0.00	-166930.58
87	1806	11.09	48.48	0.0215	0.57	42.11
89	1125	17.92	40.79	0.1037	0.99	10.41
89	1127	15.76	96.77	0.0470	0.56	4.58
90	6420	26.53	7.13	0.1617	0.73	17.46

APPENDIX H PCC EXPONENTIONAL REGRESSION RESULTS

STATE_CODE	SHRP_ID	Age at Rehab (yrs)	c	b	R^2	Est Age at 120 in/mile (yrs)
4	7614	19.10	51.39	0.0295	0.74	28.77
6	3010	22.18	77.63	0.0033	0.09	131.63
6	7455	29.38	78.16	-0.0017	0.08	-255.67
6	7456	29.21	97.23	0.0172	0.56	12.26
6	7493	17.10	86.96	0.0019	0.09	173.38
8	3032	31.19	78.74	0.0086	0.38	49.20
10	4002	16.42	172.39	-0.0201	0.18	18.02
10	5005	24.03	47.67	0.0176	0.35	52.51
13	3015	30.64	58.02	0.0229	0.90	31.78
13	3017	26.47	73.87	0.0035	0.17	137.23
13	3019	29.06	85.18	0.0117	0.54	29.39
16	3023	27.02	92.98	0.0030	0.22	85.33
16	5025	22.93	103.20	0.0162	0.52	9.29
17	5849	28.71	86.15	0.0014	0.01	239.32
17	5854	14.76	97.59	0.0387	0.91	5.35
17	9267	32.27	67.49	0.0019	0.16	305.28
17	9327	26.59	87.06	0.0286	0.68	11.23
18	3003	18.43	82.89	0.0159	0.21	23.26
18	5022	20.39	134.39	0.0005	0.00	-236.42
18	5043	33.69	121.33	0.0072	0.41	-1.53
18	5518	23.14	28.48	0.0544	0.74	26.46
19	3006	24.94	107.41	0.0343	0.90	3.23
19	3009	33.52	131.19	0.0058	0.82	-15.48
20	3015	18.62	65.91	0.0099	0.35	60.46
21	3016	24.60	92.43	0.0027	0.11	97.10
27	4050	26.98	78.28	0.0048	0.08	89.84
29	5000	21.91	100.11	0.0176	0.96	10.30
29	5058	21.91	87.51	0.0101	0.81	31.15
29	5091	22.24	78.77	0.0160	0.92	26.31
31	3024	27.52	83.43	0.0123	0.86	29.65
31	3028	24.28	60.26	0.0141	0.63	48.85
37	5827	30.02	51.92	0.0076	0.64	110.20
38	3006	20.93	54.07	0.0256	0.40	31.10
39	3013	23.35	165.95	0.0187	0.50	-17.32
39	5003	24.02	68.29	-0.0023	0.25	-241.82
40	4157	26.22	68.74	0.0086	0.57	64.78
41	5006	30.27	73.68	0.0081	0.60	60.27
41	5008	31.27	42.15	0.0175	0.93	59.70
42	1606	30.77	82.83	0.0077	0.60	48.11

STATE_CODE	SHRP_ID	Age at Rehab (yrs)	c	b	R^2	Est Age at 120 in/mile (yrs)
42	1623	24.85	76.80	0.0068	0.56	65.83
42	3044	15.01	149.89	-0.0045	0.31	49.71
46	3010	15.76	108.46	0.0215	0.45	4.70
46	3012	15.76	165.73	0.0098	0.52	-32.94
46	6600	25.27	99.01	0.0233	0.75	8.27
48	5154	29.97	98.68	0.0005	0.01	414.72
48	5274	27.34	105.12	-0.0005	0.00	-282.72
49	3015	21.01	116.68	0.0133	0.67	2.12
49	7083	17.10	69.65	0.0184	0.52	29.55
50	1682	28.02	61.84	0.0339	0.34	19.57
54	4004	15.07	98.90	0.0569	0.95	3.40
54	5007	15.08	91.40	0.0377	0.51	7.21
55	3014	16.68	175.02	0.0144	0.07	-26.23
89	3001	32.02	128.34	0.0133	0.88	-5.06