NCAT Report 18-02

REVIEW OF INITIAL SERVICE LIFE DETERMINATION IN LIFE CYCLE COST ANALYSIS (LCCA) PROCEDURES AND IN PRACTICE

By

Dr. Mary Robbins

Dr. Nam Tran, PE, MBA

July 2018

National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY

277 Technology Parkway ■ Auburn, AL 36830

Review of Initial Service Life Determination in LCCA Procedures and in Practice

Dr. Mary Robbins
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, P.E., LEED GA, MBA
Research Professor
National Center for Asphalt Technology

Sponsored by
National Asphalt Pavement Association
State Asphalt Pavement Associations

July 2018

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

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

State departments of transportation (DOTs) use life cycle cost analysis (LCCA) to choose the most cost-effective project alternatives when planning new construction or reconstruction of their roadways. LCCA takes into account all anticipated costs over the life of each pavement alternative.

In LCCA, it is assumed that the two alternatives provide the same level of performance or benefits to the project's users. Therefore, the alternatives can be compared solely on the basis of cost. Two types of performance periods are typically considered in LCCA, initial performance period and rehabilitation performance period. Initial performance period represents the average time in years for a newly constructed or reconstructed pavement to reach an agency's threshold for first rehabilitation. Rehabilitation performance period is the length of time for a rehabilitated pavement to reach an agency's rehabilitation threshold.

The initial performance period (also known as initial service life) can be significantly different for competing alternatives, and it affects the timing of future maintenance and rehabilitation (M&R) activities, in turn, affecting the life cycle cost of each pavement alternative (*1*). Since initial service life plays such a critical role in LCCA, the following questions arise: what is the actual initial service life for each pavement type, and is the accurate initial service life being used in LCCA?

To address these questions, the following objectives were established for this study:

- Document methods DOTs currently use to determine initial service life for use in LCCA for both asphalt and concrete pavements;
- Document actual service lives, at the age of the pavement at first rehabilitation, for asphalt and concrete pavements based on historical data; and
- Provide recommendations on determining initial service life for LCCA.

A literature search and a survey of DOTs were conducted to gather information about pavement service life and rehabilitation activities considered in LCCA for both asphalt concrete (AC) and Portland cement concrete (PCC) pavements. Analyses of Long-term Pavement Performance (LTPP) program data were conducted to determine the actual timing of first rehabilitation of asphalt and concrete pavements, the ride quality based on International Roughness Index (IRI) at the first rehabilitation, and the progression of ride quality prior to the first rehabilitation for pavement sections in the U.S. and Canada. The key findings of this investigation are summarized herein.

Based on DOTs responses to the questionnaire issued in this study, it was found that procedures for determining initial pavement service life for use in LCCA vary by DOTs and tend to be multi-faceted. However, agencies commonly reported using historical data from their pavement management system (PMS). Other methods reported included using expert opinion or engineering judgement, distress or condition indices, and the pavement design life.

Based on the review of DOTs practices for determining the actual timing of the first rehabilitation for both AC and PCC pavements, it was found that procedures are unique to each agency and often include various types of condition indices as well as other factors. The individual distresses generally utilized in the indices reported were cracking, IRI, and rutting for flexible pavements, and cracking, IRI, and faulting for rigid pavements. While cracking was commonly reported for both pavement types, cracking is not the same across all pavement types and therefore cannot be compared directly. Given the difference in distress types and cracking definitions for each pavement, condition indices and associated thresholds are not comparable between unlike pavement types. Therefore, actual practices and criteria for determining time of rehabilitation do not appear to be based on achieving equal levels of performance.

It was also found that IRI is widely used in some aspect of the decision-making process for determining the actual timing of rehabilitation. While some agencies have threshold values associated with IRI, they vary widely by agency. Furthermore, there does not appear to be a nationwide consensus among DOTs on IRI values that indicate the need for rehabilitation.

The timing of the first rehabilitation events for AC and PCC pavements were documented for the pavements in the LTPP experiments. The actual timing of the first rehabilitation for AC and PCC pavements was summarized by pavement type and climatic zone as well as LTPP experiment (type of AC or PCC pavement) for pavements across the United States and Canada. Rehabilitation activities were defined based on the results of the questionnaire issued to DOTs in which the treatments for major rehabilitation of their AC and PCC pavements are considered in their LCCA procedures. The initial pavement service life was calculated based on the dates of the first rehabilitation activity and the original construction reported in the LTPP database.

For the investigation of pavement age at the time of the first rehabilitation, AC and PCC pavements in General Pavement Study (GPS) experiments and in the Specific Pavement Study (SPS) experiments were considered. GPS and SPS experiments selected for the study included existing in-place pavements that should have distresses typical of that agency and be representative of actual timing of rehabilitation. Only pavement sections that had not yet received a rehabilitation activity, as reported to LTPP, were utilized.

Specifically, pavements in the following LTPP GPS experiments were included:

- GPS-1 (AC on granular base);
- GPS-2 (AC on bound base);
- GPS-3 (JPCP);
- GPS-4 (JRCP); and
- GPS-5 (CRCP).

The SPS experiments used for this part of the study were limited to those that utilized existing, in-place pavement sections. For these SPS experiments, multiple sections at an experiment site of the existing pavement received variations of study rehabilitation treatments. Since the various rehabilitation treatments were often all applied within a short timeframe of one another, the average time to first rehabilitation for a site was determined. The following LTPP SPS experiments were included:

- SPS-5 (rehabilitation of AC pavements);

- SPS-6 (rehabilitation of JPCP);
- SPS-7 (bonded PCC overlay on concrete);
- SPS-9C (AC overlay on CRCP);
- SPS-9J (AC overlay on JPCP); and
- SPS-9O (AC overlay on AC pavement).

Based on the analysis of the initial performance periods for AC pavements in the LTPP program, the average asphalt pavement age at time of first rehabilitation was found to be approximately 18 years (Table E.1). However, based on previous surveys of DOTs, initial performance periods frequently used in LCCA for asphalt pavements are between 10 and 15 years. For concrete pavements, previous surveys showed most initial performance periods used in LCCA are between 20 and 25 years, whereas the average concrete pavement age at the time of first rehabilitation in the LTPP program is about 24 years (Table E.1). This suggests that initial performance period values used for LCCA do not adequately represent the actual age of asphalt pavements at time of first rehabilitation. However, initial performance periods used in LCCA for PCC pavements are generally representative of actual concrete pavement age at time of first rehabilitation.

Table E.1 Summary of Middle 90% of Pavement Ages at Time of First Rehabilitation

Pavement Type	No. of Sections	Average	Minimum	Maximum	Standard Deviation
AC	206	17.68	7.09	28.93	5.51
PCC	121	23.84	12.88	35.44	5.79

Initial performance periods in the LTPP program were also evaluated based on the experiment type and climatic zone. It was found that differences in pavement age at the first rehabilitation of JPCP, JRCP, and CRCP pavements were small. It should be noted the most common rehabilitation activity differed among these pavements types, with grinding common for JPCP pavements while JRCP and CRCP most frequently received an AC overlay in the first rehabilitation. Evaluation of initial performance periods by climatic zone indicated that climate likely has an impact on the timing of the first rehabilitation for asphalt pavements, however, it was not definitive for each climatic zone.

The last mean roughness index (MRI) values (the average of the left and right wheelpath IRI measurements) measured prior to the first rehabilitation were investigated using LTPP pavement sections. Pavement types included in the investigation were AC pavements on granular base (GPS-1) and AC pavements on bound base (GPS-2), and PCC pavement sections in the JPCP (GPS-3), JRCP (GPS-4), and CRCP (GPS-5). The MRI values for the pavement sections were compared with the FHWA categories for ride quality associated with IRI measurements (very good, good, fair, poor, and very poor), as shown in Table E.2. It was found that in general, AC pavements were smoother than PCC pavements at the time of rehabilitation. AC pavements were most often rehabilitated while in good or fair condition, while PCC pavements were rehabilitated in fair or poor condition. For AC and PCC pavements, more than 85% of the sections were rehabilitated before reaching the threshold of 170 in/mile for the very poor category. Given this high percentage, it can be concluded that 170 in/mi is too high to be used as a rehabilitation trigger for MRI.

Table E.2 Ride Quality (MRI) Prior to Rehabilitation

	Percent of Total Pavement Sections				
Pavement Type	**Very Good** < 60 in/mi**	**Good 60 – 94 in/mi**	**Fair 95 – 119 in/mi**	**Poor 120 – 170 in/mi**	**Very Poor > 170 in/mi**
AC Pavements	9.6%	34.3%	24.1%	17.5%	14.5%
PCC Pavements*	1.1%	23.3%	26.7%	34.4%	14.4%

*Sum is not 100% due to rounding **FHWA Categories for Ride Quality (*32*).

While AC pavements tended to be smoother than PCC pavements at the first rehabilitation, MRI values amongst these two pavement types did intersect. As shown in Table E.3, the 95% confidence interval about the mean for both pavements overlap between 119 in/mi and 121 in/mi, which corresponds well with the early FHWA threshold of 120 in/mi for pavements going from good to fair ride quality. This is based on average MRI values from LTPP pavement sections across the United States and Canada, therefore, MRI values may differ for individual DOTs.

Table E.3 Summary of Last MRI Value Before First Rehabilitation 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

Pavement roughness, expressed as IRI or MRI, is the only performance measure that is presently common to both AC and PCC. Therefore, it is necessary to understand the rate at which MRI progresses with time to enable more estimates of initial service life in LCCA. An investigation of the data revealed that relationships between pavement roughness (expressed as MRI) and pavement age vary by pavement section. It was found that AC pavements are more likely to have a linear relationship between pavement age and MRI than PCC pavements. PCC pavement tended to have pavement roughness values that remained stable over time; whereas, MRI on AC pavements increased at a faster rate in the years prior to the first rehabilitation (MRI data were not available for the entire first cycle for either AC or PCC pavements) than PCC pavements. Additionally, it was found that the rate pavement roughness progresses with age varies by climatic conditions for both AC and PCC pavements. Differences in pavement roughness with age were noted for the two types of AC pavements, indicating that the type of base (granular or bound) may have an influence on the rate MRI increases over time on AC pavements.

1 INTRODUCTION

1.1 Background

State departments of transportation (DOTs) often use life cycle cost analysis (LCCA) to choose the most cost-effective project alternatives, especially when planning new construction or reconstruction of their roadways. By comparing net present values (NPVs) of two potentially very dissimilar investments, such as asphalt concrete (AC) or Portland cement concrete (PCC) pavement, LCCA considers all of the anticipated costs over the life of the pavement including initial costs and discounted future costs.

An LCCA can be conducted in four main steps for a project. First, all potential expenditures and estimated cycles at which the future expenditures will be incurred are determined for each alternative, as illustrated in Figure 1.1. Each cost component in Figure 1.1 may include both agency and relevant user costs. Second, the expenditures are discounted back to their present values using a discount rate. If an alternative has any value remaining at the end of the analysis period, a salvage value is also discounted back to its present value. Third, the NPV of each competing alternative is determined as the sum of the initial construction cost, discounted costs for future maintenance and rehabilitation (M&R), and discounted salvage value (Equation 1.1). Alternatives with lower NPVs are considered cost-effective options for the project.

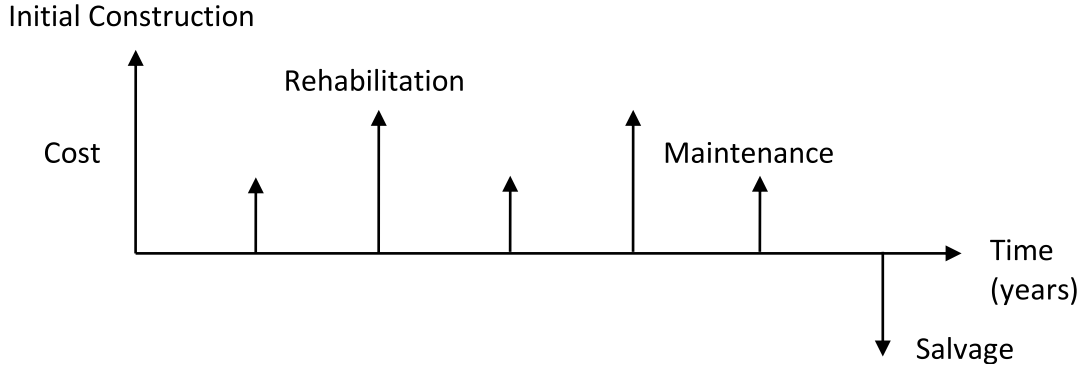


Figure 1.1 Stream of Expenditures for Determining NPV in LCCA

$$NPV = Initial\ Const.Cost + \sum_{k=1}^{N} Future\ Cost_k \left[\frac{1}{(1+i)^{n_k}}\right] - Salvage\ Value \left[\frac{1}{(1+i)^{n_e}}\right] \quad (1.1)$$

where

N = number of future costs incurred over the analysis period;
i = discount rate;
n_k = number of years from the initial construction to the k^{th} expenditure; and
n_e = analysis period, years.

As described, the calculation of NPV is straightforward in LCCA; however, the accurate determination of the inputs can be complicated, especially estimating future costs of M&R activities and their timing throughout the course of each pavement alternative's life span.

Figure 1.2 shows the ideal (textbook) life cycles of two competing alternatives under consideration in an LCCA. It is assumed in LCCA that the two alternatives will provide the same level of performance or benefits to the project's users; thus, the alternatives can be compared solely on the basis of cost.

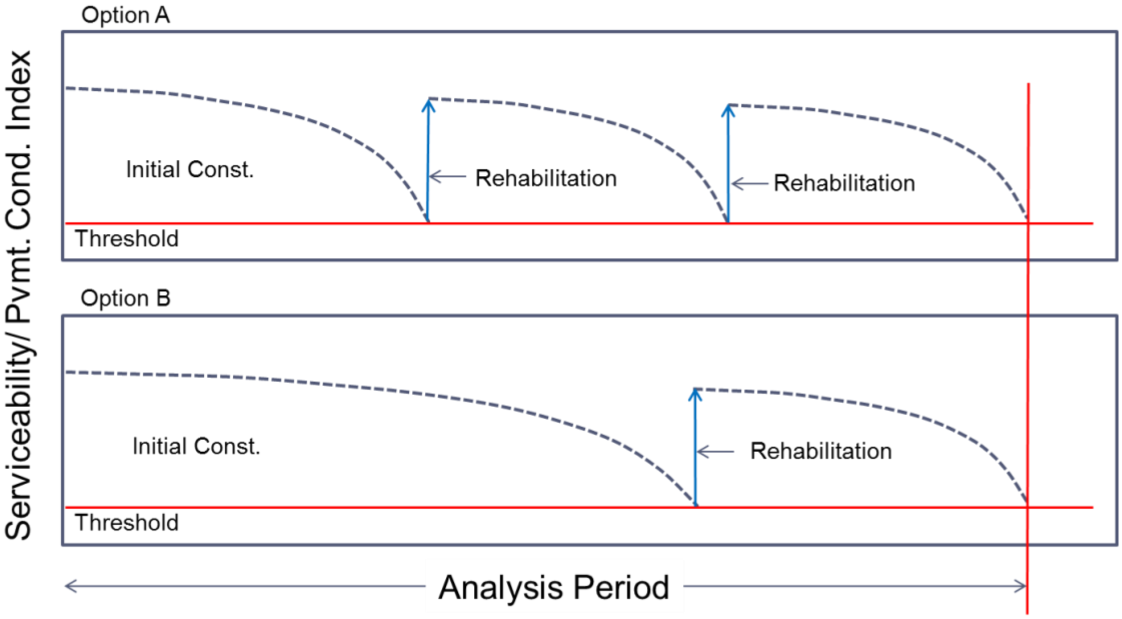


Figure 1.2 Ideal Life Cycle Diagrams of Two Hypothetical Pavement Alternates (*1*)

Two performance periods, Initial Performance Period (also known as Initial Service Life) and Rehabilitation Performance Period, are commonly considered in LCCA. Initial Performance Period represents the average time in years for a newly constructed or reconstructed pavement to reach an agency's criteria for rehabilitation (*1*). The Rehabilitation Performance Period is similar to the Initial Performance Period in that it is the length of time to reach an agency's rehabilitation thresholds or criteria; however, it is only relevant for the next rehabilitation (*1*). Generally, different Initial Performance Periods are considered for AC and PCC pavements. However, the Initial Performance Period "has a major impact on LCCA results" as it directly impacts the number of interventions (i.e. subsequent M&R activities), which ultimately affects the costs (*2*), and it can be assumed it will also impact the resulting NPV. Since Initial Performance Period plays such a critical role in LCCA, the following questions arise: How is the Initial Performance Period, also referred to as initial pavement service life, determined for each pavement type? What is the actual initial performance period for each pavement type and is the accurate initial performance period being used in LCCA?

First, it is important to understand how the procedure for determining initial pavement service life in LCCA differs from determining the actual time to the first rehabilitation, referred to as actual service life in this report. Initial service life in LCCA and actual service life in practice may not be the same. While LCCA is meant to be representative of actual practices, the values used are not directly associated with the pavement segment or project in question since the analysis is being conducted prior to construction. On the other hand, actual service life refers to the time at which an in-service pavement receives the first rehabilitation. Actual service life typically takes into account the age and condition of the existing pavement, among other factors.

For comparisons of alternatives in LCCA to be of benefit, the assumption that all alternatives provide equal performance should hold true. Thus, the performance measures used to evaluate the level of service and to establish the timing of the rehabilitation in LCCA should be common to each alternative, AC and PCC. Therefore, an investigation into the types of performance measures used to establish initial service life of AC and PCC pavements for LCCA is warranted. While LCCA should represent actual practices for determining time to first rehabilitation, initial service life in LCCA and actual service life may not be the same. Therefore, it is also necessary to understand what performance measures are used in practice to trigger rehabilitation for each pavement type.

DOTs are required to report on the condition of their pavement network to the Federal Highway Administration (FHWA). This would be a natural place to start, as each DOT is required to report the same set of performance measures. Specifically, each DOT reports Present Serviceability Rating (PSR) or International Roughness Index (IRI), depending on the functional classification and posted speed limit, as well as rutting or faulting, and cracking percent to the Highway Performance Monitoring System (HPMS) (*3*). IRI is the predominant measure for roughness and is required for all routes on the National Highway System (NHS) except where the posted speed limit is less than 40 mph, in which case, PSR may be reported instead of IRI. Rutting is required for AC pavements while faulting is to be reported for jointed concrete pavements (JCP). While in general the percent of cracking is required for all surface types, the measurements and calculations for this parameter are dependent on the pavement type. For AC pavements, agencies are required to report the percentage of the lane that has fatigue cracking in the wheelpath, whereas for continuously reinforced concrete pavement (CRCP), the areas reported should include the area of the section encompassed by punchouts, longitudinal cracking, and/or patching; transverse cracking is not considered for CRCP. Lastly, for jointed plain concrete pavement (JPCP) and jointed reinforced concrete pavement (JRCP) (together referred to as jointed concrete pavements (JCP)), the area reported is actually the number of slabs that have transverse cracking, taken as a percentage of the total number of slabs in the pavement section (*3*).

As part of the Moving Ahead for Progress in the 21st Century Act (MAP-21), DOTs are required to establish performance targets and report progress in achieving those targets. MAP-21 rulemaking, first proposed in 2015 and made final in 2017, lays out performance measures that will be the basis for the targets each DOT must establish (*4*). The performance measures, shown in Table 1.1, include the percentage of roadways in good, fair, or poor condition based on four metrics, dependent on surface type: PSR, IRI, cracking, rutting, and faulting. MAP-21 performance measures are calculated using performance metric data submitted by DOTs as part of the HPMS.

Table 1.1 MAP-21 Performance Measures (*4*)

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

While cracking percent is required for each pavement type, as noted previously, cracking percent required for HPMS and MAP-21 is not defined the same for each pavement type. As identified in the HPMS field manual, cracking encompasses longitudinal cracking, patching and punchouts for CRCP, the number of slabs with transverse cracking for JPCP and JRCP, and fatigue cracking in the wheel paths for AC pavements (*3*). The thresholds are therefore, unique to the pavement type. It should be noted that according to the MAP-21 final rulemaking, data needed to determine cracking for all pavement types except CRCP can be collected with manual, semi-automated, or fully automated methods according to the HPMS field guide (*4*). Although semi- and fully-automated crack detection methods are becoming increasingly more popular among DOTs, crack measurements are not uniform among automated methods. There is an ongoing research effort, NCHRP Project 01-57A, that aims "to develop standard, discrete definitions for common cracking types in flexible, rigid, and composite pavements" (*5*).

IRI, is required for all pavement types and the method of measurement is consistent across all pavement types. Therefore, the concept of IRI as a common performance measure for use in LCCA is further explored in this study.

1.2 Objectives and Scope

The objectives of this report are as follows:

- To document the methods DOTs are currently using to determine initial service life for use in LCCA for both asphalt and concrete pavements;
- To document actual service lives at the age of the pavement at first rehabilitation of both asphalt and concrete pavements based on historical data; and
- To provide recommendations on determining initial service life for LCCA.

To meet the objectives of this report, a questionnaire was issued to DOTs to better understand procedures and rehabilitation activities considered in LCCA for both asphalt and concrete pavements. Additionally, data from the Strategic Highway Research Program (SHRP) Long-Term Pavement Performance Program (LTPP) standard data release (SDR) 28 was utilized for analyses pertaining to actual service lives.

2 DETERMINING INITIAL SERVICE LIFE IN LCCA

In a 2007 Mississippi DOT initiated survey of members of AASHTO's Research Advisory Committee (RAC), participants were asked to respond to eight questions pertaining to LCCA procedures for pavement type selection (*6*). Of the twenty-one agencies (which included three Canadian provinces) that responded, sixteen stated that they use LCCA for determining pavement type selection. Four agencies stated that they do not use LCCA for pavement type selection, and one, the province of British Columbia, indicated no concrete pavements in their province. Similarly, in a survey conducted from 2005-2006 as part of a report published in 2008 for South Carolina DOT, 94% of participants indicated that LCCA is used as part of the decision-making process for pavement type selection (*7*). As indicated by these surveys, LCCA is widely used and is a critical component in the pavement type selection process.

As addressed earlier, the initial performance period, or initial service life, is a key parameter in LCCA and is defined as the time it takes to reach rehabilitation criteria or thresholds. To gain insight into how agencies determine the initial service life, it is helpful to understand which types of activities are considered rehabilitation. This information was sought in previous surveys as well as the questionnaire issued for this study in which agencies were asked to report the rehabilitation activities considered in LCCA. Those rehabilitation activities reported in previous surveys and in the recent questionnaire are discussed in this section.

To further understand the initial service lives considered for AC and PCC pavements, a review of previous survey responses and current practices was conducted. To support this effort, a questionnaire was issued to DOTs across the country in March 2014 as part of this study. The questions specifically pertained to the procedures used to identify the initial service life for AC and PCC pavements in LCCA as well as the parameters used to determine the actual time of first rehabilitation. The full list of questions issued is listed in Appendix A, and the responses are tabulated in subsequent appendices.

2.1 Rehabilitation Techniques Considered in LCCA

In the 2007 Mississippi DOT survey, participants were asked to report the timing and treatments considered for AC and PCC pavements used in their LCCA procedures (*6*). No two responses were the same, indicating that pavement strategies are unique to each agency. Some agencies included activities that would traditionally be considered maintenance or preservation, while others provided only rehabilitation activities. For example, New Jersey DOT indicated that crack sealing is the first activity considered for rigid pavements, and it is not until year 30 when something more substantial is considered, such as diamond grinding and 5% slab replacement. It is not clear if this combination or any one of these activities is considered a rehabilitation activity in New Jersey. On the other hand, Colorado DOT explicitly stated that rehabilitation for PCC pavement occurs 22 years after construction and consists of "0.5% full-depth slab replacement, ¼" diamond grinding for half the travel lanes, and replacement of all longitudinal and transverse joint sealant."

Authors of the 2008 report for South Carolina DOT specifically asked survey participants to identify the treatments they consider maintenance and those that are considered rehabilitation (*7)*. As was the case in the 2007 Mississippi DOT survey (*6*), the difference between the two actions was not clear and definitions of rehabilitation were unique to each agency. It was noted that the rehabilitation activities most commonly listed included concrete pavement rehabilitation (CPR), diamond grinding, and joint repair for rigid pavements, and milling with structural overlay, hot-in-place recycling, and cold-in-place recycling for flexible pavements (*7)*.

While the Mississippi DOT survey and surveys conducted for the South Carolina DOT-sponsored study were comprehensive, they were conducted between 2005 and 2007, and several agencies indicated that their LCCA procedures were under revision. Therefore, to gain an understanding of current LCCA practices, a questionnaire was issued to DOTs across the country as part of this study. DOTs were asked to indicate the major rehabilitation treatments for asphalt and concrete pavements considered for LCCA. As expected, based on previous nationwide surveys, responses varied and included a range of treatments for each pavement type.

The question, "What treatments does your agency consider in your existing LCCA for major rehabilitation of asphalt pavements? And of rigid pavements?" was intended to gain insight into the types of major rehabilitation treatments considered in LCCA procedures, not necessarily whether LCCA was used to identify the rehabilitation alternatives. However, one DOT indicated that no major rehabilitation is considered in their LCCA, although it was mentioned that rehabilitation strategies considered for flexible pavements included milling and resurfacing of the surface or the base and surface lifts, which are activities commonly reported as rehabilitation. Although one DOT indicated previously that an LCCA procedure is not currently used, a response was provided for the major rehabilitation treatment types considered for each pavement type. This response was excluded from the following summary as focus was placed on LCCA. With that being said, many DOTs utilize common rehabilitation types regardless of their use of LCCA.

Major rehabilitation treatments are summarized in Appendix K and are grouped by like treatment type; full responses are reported in Appendix D. As expected, the exact specifications and details associated with each treatment type vary by DOT. Specifics such as amount of milling or overlay thickness are listed where details have been provided.

2.2 Initial Service Life Values

The previous surveys conducted on the topic of LCCA asked agencies to report information related to initial service life. In the 2007 Mississippi DOT survey, agencies were asked to report the year each rehabilitation treatment is accounted for in their LCCA (*6*). As noted earlier, some agencies include both M&R activities in their pavement strategies used for LCCA. In looking at the timing of activities reported in the 2007 Mississippi DOT survey, the first intervention scheduled is not always a rehabilitation activity; rather, it may be a maintenance or pavement preservation activity. Therefore, to summarize the initial service life values previously reported, information regarding reported rehabilitation techniques used by DOTs (summarized in Appendix K) along with engineering judgment was used to identify the activity or activities reported in the

2007 Mississippi DOT survey that most likely represent rehabilitation. The timing associated with the perceived rehabilitation activity was then summarized for each state agency in Table 2.1.

Two surveys within the context of LCCA procedures were issued for the study conducted by Rangaraju, Amirkhanian, and Guven for South Carolina DOT published in 2008 (*7*). In the first "preliminary" survey issued in 2005, agencies were asked, "What is the initial performance period assigned for flexible pavements and rigid pavements?" (*7*). In the second "final" survey issued in 2006, the question was phrased as, "What is the time to first rehabilitation?" (*7*). While both surveys were put in the context of LCCA, neither question explicitly asked for the value used in the agency's LCCA procedure. A review of the responses showed that although the "final" survey had ten fewer responses than the "preliminary" survey, for the agencies that responded to both surveys, the responses for each were the same or generally very similar. The values summarized in the table below come from the "final" survey. Although Ontario responded to the 2006 final survey for the South Carolina DOT-sponsored study, it was reported in the later (2007) Mississippi DOT survey that their LCCA procedures were undergoing revisions; therefore, their results have been excluded from the table below (*6, 7*). Although Washington State DOT responded to the Mississippi DOT survey issued in 2007 and the survey issued in 2006 as part of the study conducted for South Carolina DOT, responses between the two varied slightly for flexible pavements; therefore, responses for each survey are shown in the table below. Where indicated with an "X" in Table 2.1, the associated State Asphalt Pavement Association (SAPA) has provided an updated value for the years to first rehabilitation or confirmed the value listed in previous surveys is accurate.

Table 2.1 Previous Survey Findings on Years to First Rehabilitation in LCCA (*6, 7*)

State	Flexible Pavements Years to First Rehabilitation	Rigid Pavements Years to First Rehabilitation	Survey		
			Mississippi DOT, 2007	South Carolina DOT, 2008	SAPA, 2016
AL	12	20	X	X	X
AR	12-15	15			X
CA	18-20	20-40 for JPCP		X	
CO	10	22	X	X	
FL	16: Overlay 32: Overlay	23: CPR 33: CPR			X
GA	10	CRC: 25, JPCP: 20		X	
IL	15 (HMA Overlay)	30 (HMA Overlay)			X
IN	25	JPCP: 30	X	X	
IA	20	JPCP: 40		X	
KS	10 (Overlay)	20 (3% Patching)	X	X	X
KY	10: Interstate 15: Other routes	15: Interstate 25: Other routes			X
MD	15	20		X	
MI	26	26		X	
MN	20 (Overlay)	20 (CPR)			X

State	Flexible Pavements Years to First Rehabilitation	Rigid Pavements Years to First Rehabilitation	Survey		
			Mississippi DOT, 2007	**South Carolina DOT, 2008**	**SAPA, 2016**
MS	12	16		X	
MO	20 (Overlay)	25 (Grinding and patching 1.5%)	X	X	X
MT	19	20	X	X	
NE	15-20	35		X	
NJ	15	30	X		
NC	12-15	15		X	
OH	14 (Overlay)	22 (Grinding)			X
PA	15	15 (2% Patching, 50% Grinding) 25 (4% Patching, 100% Grinding)			X
SC	Superpave/polymer modified surfaces: 15 Conventional surfaces: 12	20	X	X	X
TN	10	15			X
UT	12-15	JPCP: 10 Minor, 20 Grinding		X	X
VT	Varies	20		X	
WA	15	20	X	X	X
WI	18 (HMA Overlay)	25 (CPR or HMA Overlay)		X	X
WY	20	20	X		

The reported initial service lives shown in Table 2.1 ranged between 6 and 26 years for flexible pavements with the majority of agencies reporting values between 10 and 15 years. For rigid pavements, reported service life ranged from 10 to 35 years with the majority of agencies reporting a value of 20 to 25 years. These wide ranges in initial service life reported among the participating DOTs could in part be due to the rehabilitation activities considered in LCCA. As noted in section 2.1, the activities that agencies consider as part of their LCCA procedures vary from agency to agency, and it is not always clear whether an activity or combination of activities is considered rehabilitation or maintenance.

2.3 Review of Agency Practices for Determining Initial Service Life in LCCA

While the initial service life values used in LCCA for each pavement type are important, the method at which agencies arrive at that value is of most concern. Using LCCA to compare different pavement types requires both alternatives to provide the same level of performance or benefits to the user. As part of the final survey for the South Carolina report, agencies were asked to provide information on their basis for the time to first rehabilitation reported (*7*). Responses varied between historical data, a distress or pavement condition index, and a combination of visual inspection and available funding. The 2007 survey initiated by Mississippi DOT asked agencies to indicate whether the type and frequency of the treatments considered in LCCA were based on historical or theoretical data (*6*). The majority of DOTs indicated that historical data was used to determine the type and frequency of treatments, although some agencies indicated a combination of historical data and modeling or engineering judgment.

After reviewing DOTs' practices for LCCA procedures, authors of the 2008 report to South Carolina DOT proposed the use of a probabilistic-based LCCA approach. This approach uses a statistical analysis of historical information, including the location, type, and timing of past rehabilitation and maintenance activities to develop initial service life (*7*). However, the authors cautioned that using historical data "may not accurately reflect the life of a future rehabilitation" due to the significant changes in both materials and pavement design. This could be inferred to also apply to the life of new pavements. For this reason, and due to the lack of comprehensive historical data, researchers proposed that for LCCA, initial service life and subsequent performance periods are representative of actual practice (and it could be assumed to also mean current practice) and incorporate expert opinion. As a result, initial service lives were recommended for AC and PCC pavements, as shown below. It should be noted that the initial service lives shown in Table 2.2 were meant for use in their proposed probabilistic LCCA approach and were meant to act as seed values for initial evaluations to be refined as the process is used. The proposed probabilistic approach used a triangular probability distribution, such that the minimum and maximum boundaries of the distribution are at 75% and 125% of the mean value, respectively, as shown in Table 2.2 (*7*).

Table 2.2 Proposed Service Life Values for LCCA (*7*)

	Initial Service Life (Years)		
	Flexible: Conventional HMA	**Flexible: Polymer-modified HMA**	**Rigid**
Minimum	8	12	18
Most Likely	11	15	24
Maximum	14	18	30

2.3.1 Current Practices for Determining Initial Service Life in LCCA

To meet the objectives of this study, information regarding the process used to determine initial service life was of primary interest. To gain understanding about the current methods agencies are using, the questionnaire issued for this study asked agencies to report on the method utilized to determine initial service life used in LCCA procedures. Specifically, the following question was asked: "How does your agency determine the time to first major rehabilitation for flexible and rigid pavements in your existing LCCA procedure?" Additionally, respondents were asked to indicate what performance parameters, if any, were used in establishing the initial service life.

Thirty-four DOTs responded to the survey. Four agencies (Arkansas, Arizona, New Mexico, and Oklahoma DOTs) indicated that LCCA is not currently used or is under development. Michigan

DOT indicated that the time to first rehabilitation has not yet been determined, and Colorado DOT indicated that the time to first rehabilitation has been determined for rigid pavements but is under development for flexible pavements. Responses from the remaining states are summarized below.

- While it is generally assumed that initial service life is a fixed value for each pavement type, two agencies indicated that initial service life is determined on a project-by-project basis.
    - Montana DOT stated that initial service life is determined after reviewing "localized project history."
    - Oregon DOT stated that the "rehabilitation strategy is evaluated on a project-specific basis."
- Fifteen of the thirty states indicated that they use LCCA and determine the initial service life based on historical performance or pavement management system (PMS) records. For two of those states, initial service life determined in this way applied to only part of their network.
    - Ohio DOT indicated that historical performance data in terms of their Pavement Condition Rating (PCR) and historical time between rehabilitations were used to determine initial service life for flexible pavements only.
    - Kentucky DOT indicated that actual PMS data were utilized for establishing life cycles for interstates and parkways.
- The next most common method of determining initial service life for LCCA utilizes engineering judgment or experience. This includes committee consensus and/or basing the decision on state, regional, or national practice.
    - Although Ohio DOT utilized historical performance data to determine time to first rehabilitation for flexible pavements, an initial service life was estimated and compared with that used in surrounding states for rigid pavements. Similarly, California utilized maintenance decision trees and statewide and national practices to develop their initial service life for use in LCCA.
    - Louisiana, Kentucky, and South Carolina DOTs reported that expert consensus led to initial service life. Louisiana and Kentucky DOTs both stated that the initial service life was determined through the use of committees and industry input. In Kentucky, the service life determined in this fashion was considered only for routes other than interstates and parkways.
    - Pennsylvania and Tennessee DOTs utilized past experience to arrive at their initial service life. Pennsylvania DOT used experience on the timing of activities (routine and preventive maintenance as well as reconstruction) in conjunction with industry input. Tennessee DOT leaned on their past experience with age, roughness, and levels of distress to determine service life.
    - In Montana, engineering judgment was used to establish initial service life by considering the "localized project history" along with pavement design life and performance measures such as ride quality, rutting, and cracking.
- Several state agencies considered various distresses or condition indices to establish initial service life for LCCA.

    - Alaska DOT only uses flexible pavements, so LCCA is not used for pavement type selection but to compare alternative designs for asphalt pavements. Initial service life was determined based on performance parameters, including Present Serviceability Rating (PSR) as a function of rut depth and International Roughness Index (IRI).
    - North Carolina and New Jersey DOTs also utilized condition indices for establishing their service lives. North Carolina DOT reported that the pavement condition rating (PCR) for flexible pavements is "heavily weighted to cracking and rutting," and that for jointed concrete pavements, the PCR considers faulting, patching, and broken slabs. New Jersey DOT based their initial service life on their surface distress index (SDI), which considers the type, extent, and severity of each distress.
    - Colorado and Florida DOTs both considered pavement distresses; however, Colorado DOT has only done so for rigid pavements. Distresses considered by Colorado DOT include longitudinal and transverse cracking, corner breaks, IRI, and rutting. Florida DOT used thresholds for cracking, rutting, and ride ratings to determine initial service life for LCCA.
    - In Oregon, the selection of a rehabilitation strategy was based on various performance parameters and was done on a "project-specific basis." The parameters considered for flexible pavements include top-down cracking, studded tire wear rates, and miscellaneous environmental factors. Factors considered for rigid pavements include studded tire wear rates, punch-outs, and de-icer surface deterioration.
- Two states reported that they considered pavement design life when establishing initial service life for LCCA.
    - Connecticut DOT indicated that the time to first major rehabilitation in their LCCA procedure is dependent on the pavement design life. For flexible pavement design, initial service life is set as "twelve years before the design life of the structure or 18 years, whichever is later." For rigid pavements, it is set at 12 years prior to reaching the design life of the structure.
    - Although Montana DOT indicated that engineering judgment was employed to establish initial service life, it was also stated that timing of major rehabilitation is assumed to occur "after the pavement served its full design life."
- Nevada DOT indicated that initial service life was based on pavement age.
- Hawaii DOT indicated that initial service life was based only on assumed years to first rehabilitation.

DOTs were asked if their procedure for determining initial service life had been validated. Eight agencies indicated that their procedure had been validated, while three indicated that the validation had been completed to some degree. Eight DOTs indicated that a validation of their existing procedure had not been completed. In general, those that had validated their procedure had done so with PMS data. Full responses are listed in Appendix C.

The most common method for determining initial service life in LCCA was to base it on historical performance. It is typically understood that this is the process of identifying the historical average time to first rehabilitation for each pavement type or category. This procedure of basing initial service life in LCCA on the average time to first rehabilitation from PMS data is not new. The 2004

Wisconsin Transportation Synthesis report found that the majority of studies related to actual service life were (at that time) actually aimed at determining average times to first rehabilitation for LCCA (*8*). As noted here, many agencies are still using this method. However, advancements have been made in the pavement engineering field, particularly in the area of flexible pavements. These advancements, such as improvements in pavement design from empirical design systems to mechanistic-empirical design, use of resource-responsible materials, and improvements in construction equipment and practices, will likely have an impact on service life. With many of these advancements leading to longer service lives, average time to first rehabilitation from historical records may not accurately represent future life of new or reconstructed pavements. South Carolina DOT, as shown in Table 2.1, indicated different service lives for pavements with materials other than conventional asphalt mixes, but many agencies have not taken these changes into account.

Another limitation of historic-based initial service life is that the time rehabilitation actually occurs may not represent the time at which a pavement has reached performance thresholds indicating the need for rehabilitation. Rehabilitation may or may not occur when a pavement has reached performance thresholds for a number of reasons. There is typically a lag between the time when the need for rehabilitation is recognized and when the project is actually let and built. Budget constraints may delay a rehabilitation project. Political issues can also shift the timing of a rehabilitation project by moving rehabilitation up (prior to reaching established threshold values), which can indirectly affect other potential projects by diverting funds from one project to another. In summary, the time to first rehabilitation in PMS data is very dependent on an agency's practices and rehabilitation triggers (if used).

3 DETERMINING ACTUAL SERVICE LIFE

Initial service life in LCCA is defined as the time it takes to reach rehabilitation criteria or thresholds. In practice, service life is not always clearly defined, as was found in the 2004 Wisconsin DOT survey of AASHTO RAC members (*8*). The survey sought to understand how agencies defined or understood "pavement service life" and the pavement type categories for which it is defined or tracked. Fourteen states as well as one Canadian Province responded to their survey, and the most common definition was the time from initial construction to the first rehabilitation work or from the last completed rehabilitation to the next. Other definitions included service life based on serviceability indices and service life based on years to failure (as defined by either a threshold value or the need for major rehabilitation or full reconstruction). A recent Colorado DOT report on the life of their Superpave HMA pavements defined zero remaining service life as the point in time that the measured distresses exceed an acceptable condition (*9*). Von Quintus et al. defined service life in their investigation of expected service life of HMA pavements in LTPP as the "time in years from construction to the first major rehabilitation or to an unacceptable condition of the pavement surface" (*10*).

Previous efforts have been conducted to determine actual service life based on historical data alone. In a 2004 report, Minnesota DOT utilized historical PMS data to determine the average and median age of asphalt pavements and concrete pavements at the time of the first rehabilitation (*11*). Combining historical values with results from other efforts within the state and engineering experience, recommendations were then made for initial service life for LCCA. In a similar manner, researchers utilized the timing of the first major rehabilitation to determine historical service life of JPCP pavements in Georgia (*12*).

As noted earlier, basing service life on historic data alone may not capture advances in design and construction. For this reason, Von Quintus et al. chose to use levels of pavement condition (low, moderate, and excessive) to develop expected service life estimates for asphalt pavements in LTPP (*10*). Pavement service life was estimated for six performance measures: fatigue cracking, longitudinal cracking in the wheelpaths, longitudinal cracking outside of the wheelpaths, transverse cracking, rutting, and roughness. A recent report published by Colorado DOT considered the same performance measures (although no distinction was made for longitudinal cracking as in or outside of wheelpath) in their estimation of service life for pavements constructed with Superpave hot-mix asphalt (HMA) using thresholds from their mechanistic-empirical pavement design procedure (*9*).

Other research efforts have looked at the time to reach just one threshold. In addition to determining service life of Georgia's concrete pavements by time to the first major rehabilitation, Tsai et al. also conducted an analysis to determine service life based on a predetermined threshold value for faulting index (*12*). In a 2008 study, researchers utilized a common IRI value to estimate service life for both asphalt and concrete pavements in Kansas (*13)*. It is important to understand both aspects of the definition of pavement service life: historical time to the first major rehabilitation and the performance measures used to define unacceptable condition (which necessitates rehabilitation). Therefore, a review of agency practices for determining the actual time of first major rehabilitation of in-service asphalt and concrete roadways is necessary.

3.1 Review of Agency Practices for Determining Actual Service Life

As part of the questionnaire issued for this study, DOTs were polled about the decision-making process utilized to determine the actual timing of a major rehabilitation of their interstates. Thirty-four DOTs answered with a variety of responses as summarized below. Full responses can be viewed in Appendix F. From the responses, it can be surmised that each DOT utilizes a process that is unique to their state and dependent on a number of factors. Generally, DOTs indicated that their decision-making process consisted of reviewing pavement condition data from annual surveys. In many cases, the process also incorporated other factors such as funding and/or functional classification of the roadways. While each DOT's process was unique, there were commonalities in terms of the types of processes used to arrive at the actual time to the first rehabilitation. Similar processes were grouped together, but many aspects of the reported methods overlap. Responses are summarized as follows.

- The majority of agencies that responded indicated that their decision-making process for the actual timing of rehabilitation for interstate pavements was based mainly on pavement condition data or pavement condition indices. Additionally, several agencies indicated that a condition index or condition data trigger rehabilitation.

- Several agencies responded that a combination of pavement condition data and other factors were used to determine actual timing. Other factors included cost and benefit of rehabilitation, construction history, traffic, field observations/visual distress, or need for capacity.
    - Two agencies, Alabama and Maryland, noted that there was no formal or uniform process for arriving at the timing for rehabilitation. However, both agencies indicated that several factors were considered, including both objective information, such as PMS optimization results, rehabilitation history, or falling weight deflectometer (FWD) testing, and subjective information, such as perceived rehabilitation needs from district or regional offices or political considerations.
    - Several DOTs, such as Kansas, Kentucky, West Virginia and Utah DOTs, indicated that analysis of PMS data or optimization conducted within the PMS itself was used to help identify candidates for rehabilitation. In some cases, this consisted of predicting future condition and considering available funding. One agency indicated that trigger values were used as part of the PMS analysis. Another agency, West Virginia, noted that PMS identifies rehabilitation candidates, although other candidates were also identified subjectively, and both were evaluated as part of the annual resurfacing program.
    - Some agencies that used PMS to help identify candidates for rehabilitation, such as Missouri, South Carolina, and Utah, noted that they conducted a review of those candidates before approval.
- One agency, Hawaii DOT, stated that no trigger value was currently being used; however, the process for decision-making was not described in its response.
- One agency, Louisiana DOT, indicated that timing was based on experience; however, it was inferred in other DOTs' responses that experience was also factored into their processes.
- One agency, North Carolina, stated that a 10-year plan was being developed for managing their interstate pavements. Similarly, California has also implemented a ten-year plan and also has a five-year plan for maintenance projects.
- Based on the summary of responses, it is evident that the primary factors considered in arriving at the actual timing of rehabilitation for interstate pavements is pavement condition or pavement condition indices, PMS analyses, and threshold values for performance or condition.

3.2 Performance Measures Considered for Actual Service Life (Rehabilitation Triggers)

Based on the variety of methods reported for determining actual timing of interstate rehabilitation, there is a need to investigate the types of performance measures that trigger rehabilitation activities among each pavement type.

3.2.1 Previously Reported Performance Measures Used in Practice

In the 2009 Pavement Scores Synthesis report, DOTs were surveyed to summarize their pavement scores and rating methods utilized across the country (*14*). Agencies were also asked to note if those scores were used in identifying pavement maintenance or rehabilitation activities. However, agencies were not asked to differentiate the scores or methods between asphalt and concrete pavements. While the methods for computing pavement scores or ratings varied widely, 23 DOTs associated their pavement scores with recommended pavement maintenance or rehabilitation activities and 5 DOTs used decision trees to identify M&R activities. Table 3.1 summarizes the pavement scale and M&R action reported in the 2009 synthesis (*14*). Some agencies provided more detail than others on the M&R action. It is evident from this table that those indices used to identify M&R actions are unique to each agency.

While agencies also reported the distresses included in their condition surveys, it is difficult to discern from the report (*14*) specifically what parameters were used to compute the scores listed in Table 3.1 and how those parameters differ by pavement type. Papagiannakis also asked DOTs what index is being used to drive "network-level pavement repair decisions" (*14*). Of the ten DOTs that responded, nine indicated that one or a combination of indices is used. Only one agency, Arkansas DOT, indicated that their PMS does not drive network level pavement repair decisions. Although the index itself may not be consistent among the nine DOTs, there are some commonalities. Roughness or ride was reported as a component of the index or indices used to trigger network level pavement repair for five of the nine DOTs and was the main component used by Arizona DOT. Other performance measures considered included cracking, reported by five DOTs, and rutting, reported by four DOTs.

Table 3.1 Pavement Scores and Recommended M&R Actions (after *14*)

State	Survey/Score Name	Score/Scale	Description	M&R Action
AL	None	0-100	N/A	Overlay at 55
CA	Pavement Condition Survey (PCS)	1	Excellent	Preventive maint.
		2	Good	Preventive maint.
		3	Fair	Major rehab or replacement
		4	Poor	Major rehab or replacement
		5	Very Poor	Major rehab or replacement
CO	Remaining Service Life (RSL) (in years)	RSL > 11	Good	None
		6 – 10	Fair	None
		1 – 5	Poor	None
		0	Due	Need rehab
DE	Overall Pavement Condition (OPC)	4 – 5	Very Good	Routine maint.
		3 – 4	Good	Preventive maint.
		2.5 – 3	Fair	Preventive maint.
		2 – 2.5	Poor	Rehab
		< 2	Very Poor	Reconstruction
FL	Pavement Condition Rating (PCR)	10	Best	Preventive maint
		6.4	Sound condition	Preventive maint
		6	Not considered to be deficient when speed limit is < 50 mph	Major rehab or replacement
		0	Worst	Major rehab or replacement
GA	Pavement Condition Evaluation System (PACES)	100 – 75	Excellent/Good	
		70 – 75	Fair	Rehab
		<70	Poor/Bad	Resurfacing
IL	Pavement Condition Survey (CRS)	7.6 – 9	Excellent	Preventive maint.
		6.1 – 7.5	Good	Acceptable condition
		4.6 – 6.0	Fair	Repair in the short term
		0 – 4.5	Poor	Immediate major rehab

State	Survey/Score Name	Score/Scale	Description			M&R Action
IA	Pavement Condition Index (PCI)	80 – 100	Excellent			Preventive maint.
		60 – 80	Good			Preventive maint.
		40 – 60	Fair			Major rehab
		0 – 39	Poor			Reconstruction
KS	Performance Level (PL)	1	Smooth/no distress			Smooth/no distress
		2	Require routine maint.			Require routine maint.
		3	Require rehab			Require rehab
MI	Sufficiency Rating (SR) Distress Index (DI) Remaining Service Life (RSL) Ride Quality Index (RQI)	SR: 1.0 – 2.5	Good pavement			Preventive maint.
		SR: 3.0 – 3.5	Fair pavement			Major rehab or replacement
		SR: 4.0 – 5.0	Poor pavement			Major rehab or replacement
MO	Present Serviceability Rating (PSR)		NHS	Arter	Coll	
		Acceptable PSR	≥32	≥31	≥30	Preventive maint.
		Marginal PSR	29-32	29-31	29-30	Asphalt surface treatments
		Unacceptable PSR	<29	<29	<29	Rehab as per RTD 02-013/RI00-008
NY	Pavement Condition Index (PCI)	9 – 10	Excellent/No distress			Treatment Selection Report (PETSR)
		7 – 8	Good/Distress begins to show			
		6	Fair/Distress clearly visible			
		1 – 5	Poor/Distress freq/severe			
NC	Pavement Condition Rating (PCR) plus individual distress indices		Good: PCR>80			Rehab triggered by individual distress indices rather than PCR
OH	Pavement Condition Rating (PCR)	90 – 100	Very good			Preventive maint.
		75 – 90	Good			Preventive maint.
		65 – 75	Fair			Major rehab or replacement
		55 – 65	Fair to poor			Major rehab or replacement
		40 – 55	Poor			Major rehab or replacement
		0 – 40	Very poor			Major rehab or replacement

State	Survey/Score Name	Score/Scale	Description	M&R Action
OR (NHS)	Pavement Condition Surveys	100 – 98.1	Very Good	Preventive maint.
		98.0 – 75.1	Good	Preventive maint.
		75.0 – 45.1	Fair	Minor level of repair
		45.0 – 10.1	Poor	Major rehab or replacement
		10.0 – 0.0	Very poor	Major rehab or replacement
OR (non-NHS)	Visual survey and subjective rating	1.0 – 1.9	Very Good	Preventive maint.
		2.0 – 2.9	Good	Preventive maint.
		3.0 – 3.9	Fair	Minor level of repair
		4.0 – 4.9	Poor	Major rehab or replacement
		5	Very poor	Major rehab or replacement
SC	Pavement Quality Index (PQI)	4.1 – 5.0	Very good	Preventive maint.
		3.4 – 4.0	Good	Preventive maint.
		2.7 – 3.3	Fair	Minor level of repair
		2.0 – 2.6	Poor	Major rehab or replacement
		0.0 – 1.9	Very poor	Major rehab or replacement
SD	Pavement Serviceability Rating (PSR)	5	Best	Detailed method. In general, principal arterial resurfacing for (2.6<PSR<3.0) and reconstruction for (PSR<2.6). For other functional classes reconstruction for (PSR<2.6).
		3		
		2.6		
		0	Worst	
TN	Pavement Quality Index (PQI)	4.0 – 5.0	Very good	Do nothing
		3.5 – 4.0	Good	Routine and/or preventive maint.
		2.5 – 3.5	Fair	Eligible for resurfacing program
		1.0 – 2.5	Poor	Added to resurfacing program
		0 – 1	Very poor	Mandatory field review performed

State	Survey/Score Name	Score/Scale	Description	M&R Action
VT	PCI	100 – 40	Acceptable	None
		< 40	Unacceptable	Rehabilitation or reconstruction
VA	Critical Condition Index (CCI)	>90	Excellent	Decision trees; in general, CCI < 60 triggers rehab
		70 – 89	Good	
		60 – 69	Fair	
		50 – 59	Poor	
		<49	Very poor	
WA	Pavement Structural Condition (PSC)	100	Excellent	None
		100 – 50	Good	None
		50	Fair	Due
		<50	Poor	Rehabilitation or reconstruction
WV		5	Excellent	
		4	Good	
		3	Fair	
		2	Poor	Rehab at 2.5
		1	Very poor	
WI	Pavement Distress Index	0 – 19	Very good	Preventive maint.
		20 – 39	Good	Preventive maint.
		40 – 59	Fair	Major rehab or replacement
		60 – 79	Poor	Major rehab or replacement
		80 or more	Very poor	Major rehab or replacement

[1] Error in cited document, table presented here reflects values reported in the following source document: Missouri DOT, Missouri Guide for Pavement Rehabilitation, *Report No. RDT 02-013/RI00-008*, Missouri DOT, Jefferson City, MO, 2002.

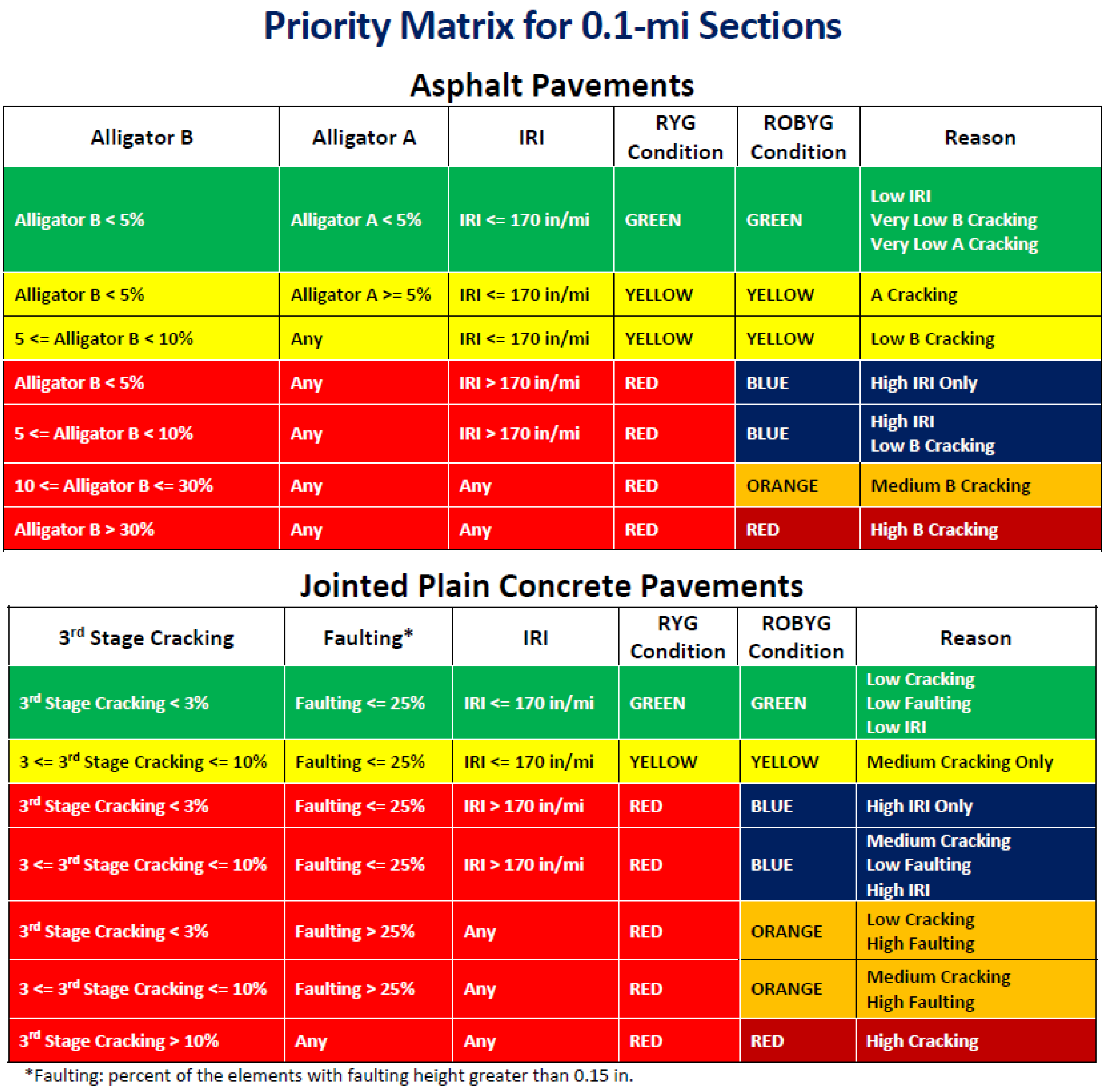
3.2.2 Performance Measures Used for Determining Actual Service Life – Current Practices

Although the Pavement Scores Synthesis report (*14*) provides insights into the performance measures considered for recommending M&R activities, the report was published in 2009 and several DOTs indicated that they were in the process of changing their process for rating or scoring their pavements. To gain an understanding of current practices, questions regarding condition or performance indices used in recommendations of M&R activities were also included in the questionnaire conducted for this study. Full responses to the questions below are listed in Appendix H and I, respectively. Specifically, agencies were asked:

- If some form of a condition or performance index is used to monitor the performance of your pavements, how is the index determined and what are the thresholds used to trigger overlay or rehabilitation?
- If not an index, then what method or measurements are used to monitor pavement performance and what are the thresholds used to trigger overlay or rehabilitation?

The majority of the agencies that responded stated that some form of a condition or performance index (or indices) was used to monitor the performance of their pavements. Minnesota stated that decision trees are utilized and provided a link to the supporting documents. They also indicated that thresholds are irrelevant as more pavements fail established performance targets than can be funded. Although various indices, including Ride Quality Index (RQI), Surface Rating (SR), Pavement Quality Index (PQI), and Remaining Service Life (RSL), and associated thresholds were included in Minnesota's decision trees, other factors were also included to identify the necessary treatment. These factors varied by pavement type and included severity and extent of cracking specific to the pavement type, as well as pavement age, last rehabilitation type, traffic, and functional classification. Arizona DOT also indicated that decision trees are used, and that rather than using an index, individual performance indicators such as IRI, cracking, and rutting, as well as cost-effectiveness analyses, served as triggers. Specifically, two triggers were provided: IRI greater than 105 in/mi and cracking greater than 15%. It was not stated how the decision trees in Arizona differ by pavement type.

California (Caltrans) indicated that pavements have traditionally been rated and placed into one of five categories, each color coded to reflect the type of project and cost. These five categories were consolidated in their previous State of the Pavement Reports into three conditions: good, fair, or poor. Good (corresponding to pavements rated green) and fair pavements (those rated yellow) were addressed with Highway Maintenance (HM) projects, while poor pavements (rated either blue, orange, or red) warranted State Highway Operation and Protection Program (SHOPP) projects. Beginning with their 2017 ten-year plan and moving forward, Caltrans has adopted the MAP-21 performance measures of cracking, ride, faulting, and rutting. Each performance measure is evaluated independently and rated as good, fair, or poor. The overall pavement is then rated as good, fair, or poor based on the combination of ratings for each performance measure. If all performance measures are considered good, the overall rating for the pavement is also good; if at least two of the performance measures are rated as poor, the overall rating is considered poor. A pavement receives an overall rating of fair if it does not fall into either good or poor categories. The priority matrices provided by Caltrans are shown for each asphalt and jointed plain concrete pavements in the figure below. The thresholds for each performance measure for good (green), fair (yellow) and poor (red) are also shown in Figure 3.1.



Priority Matrix for 0.1-mi Sections

Asphalt Pavements

Alligator B	Alligator A	IRI	RYG Condition	ROBYG Condition	Reason
Alligator B < 5%	Alligator A < 5%	IRI <= 170 in/mi	GREEN	GREEN	Low IRI Very Low B Cracking Very Low A Cracking
Alligator B < 5%	Alligator A >= 5%	IRI <= 170 in/mi	YELLOW	YELLOW	A Cracking
5 <= Alligator B < 10%	Any	IRI <= 170 in/mi	YELLOW	YELLOW	Low B Cracking
Alligator B < 5%	Any	IRI > 170 in/mi	RED	BLUE	High IRI Only
5 <= Alligator B < 10%	Any	IRI > 170 in/mi	RED	BLUE	High IRI Low B Cracking
10 <= Alligator B <= 30%	Any	Any	RED	ORANGE	Medium B Cracking
Alligator B > 30%	Any	Any	RED	RED	High B Cracking

Jointed Plain Concrete Pavements

3rd Stage Cracking	Faulting*	IRI	RYG Condition	ROBYG Condition	Reason
3rd Stage Cracking < 3%	Faulting <= 25%	IRI <= 170 in/mi	GREEN	GREEN	Low Cracking Low Faulting Low IRI
3 <= 3rd Stage Cracking <= 10%	Faulting <= 25%	IRI <= 170 in/mi	YELLOW	YELLOW	Medium Cracking Only
3rd Stage Cracking < 3%	Faulting <= 25%	IRI > 170 in/mi	RED	BLUE	High IRI Only
3 <= 3rd Stage Cracking <= 10%	Faulting <= 25%	IRI > 170 in/mi	RED	BLUE	Medium Cracking Low Faulting High IRI
3rd Stage Cracking < 3%	Faulting > 25%	Any	RED	ORANGE	Low Cracking High Faulting
3 <= 3rd Stage Cracking <= 10%	Faulting > 25%	Any	RED	ORANGE	Medium Cracking High Faulting
3rd Stage Cracking > 10%	Any	Any	RED	RED	High Cracking

*Faulting: percent of the elements with faulting height greater than 0.15 in.

Figure 3.1 Caltrans Priority Matrix

Seventeen agencies—a little over half of the agencies that responded—indicated that an index is used to trigger an overlay or rehabilitation. Each agency’s responses to the questions included under Question 2 (Appendices F – I) were used to compile the information in Table 3.2. Some agencies indicated the index, parameters it is a function of, or the trigger values themselves differ by pavement type; therefore, where provided, this information has been included in the table.

Not all of the triggers were provided in some cases, but rather subsets, or examples, were stated, which are noted where applicable. Additionally, details on the index itself as well as the components of the indices are summarized based on the information provided or other references an agency specifically listed or provided.

The indices and triggers varied from agency to agency. With the exception of Arizona and Washington DOTs, triggers are based on indices, which combine more than one condition indicator or measured distress. In the case of these two agencies, IRI, rutting, or cracking are stand-alone triggers. Other agencies consider these distresses by embedding them in the calculation of the condition or performance indices. While the indices themselves are often calculated for distresses specific to the pavement type, the trigger values may remain the same. This is the case for Arkansas, in which the trigger values for the pavement condition index (PCI), are the same. However, PCI is based solely on IRI for rigid pavements and is a composite index encompassing IRI, rutting, and cracking for flexible pavements. In some cases, such as Connecticut, Utah, and West Virginia DOTs, trigger values were specific to the type of pavement.

It is clear from the table that the methods and specific threshold values used to arrive at the actual timing of rehabilitation are unique to each agency. There are several distresses that are common to each agency's indices. The indices were mainly comprised of cracking, roughness (IRI), and rutting for flexible pavements and faulting for rigid pavements.

Table 3.2 Indices Used to Trigger Rehabilitation

State	Index	Function of	Trigger Values for Rehabilitation
AK	Present Serviceability Rating (PSR) 0 (poor) – 5.0 (very good)	Flexible: Rut Depth and IRI	PSR< 3.0
AL	Pavement Condition Rating (PCR)	Composite index based on semi-automated distress survey	PCR < 55
AR	Pavement Condition Index (PCI) 0 (Good) – 100 (Poor)	Flexible: IRI, Rutting and Cracking Rigid: IRI	PCI ≥ 65
CT	Scale: 0 – 10		Examples Provided Structural Rehab (Composite): 3.5 < Ride Index < 5.0 OR 3.0 < Environmental Index < 5.25 OR 3.5 < Structural Index < 5.0 Structural Rehab (Flexible): 3.0 < Structural Index < 5.0 Structural Overlay + Joint Repair (Rigid): 4.0 < Ride Index < 7.0 Structural Overlay + Joint Repair (Composite): 3.0 < Ride Index < 4.5 OR 2.0 < Environmental Index < 4.0 OR 3.0 < Structural Index < 4.5
	Environmental Cracking Index	Flexible: transverse and non-wheelpath cracking Composite: non-joint related cracking	
	Ride Index	IRI transformed to 0-10 scale	
	Structural Cracking Index	Flexible: wheelpath and some non-wheelpath longitudinal (at right edge) cracking Composite: transverse cracking in excess of expected single reflection crack, plus wheelpath and right edge longitudinal cracking	

State	Index	Function of	Trigger Values for Rehabilitation
FL	Scale: 0 – 10		Crack Index ≤ 6.5 OR Ride Index ≤ 6.5 OR Rut Index ≤ 6.5
	Rut	Rutting (Flexible)	
	Crack	Not provided (Flexible and Rigid)	
	Ride	IRI (Flexible and Rigid)	
IA	PCI	Pavement type, individual distress types	“Generally” PCI < 60
KS	Performance Level (PL) based on three-digit distress state	<u>Distress state</u> Flexible: First digit: Indicator of roughness based on IRI in right wheelpath Second digit: Indicator of transverse cracking Third digit: Indicator of rutting Rigid: First digit: Indicator of roughness based on IRI in right wheelpath Second digit: Indicator of joint distress Third digit: Indicator of faulting	PL = 3 Any of the following distress states is equivalent to PL = 3: 312, 313, 321-323, 331-333 Individual values that define distress states are based on optimization and therefore vary from year to year
MI	Distress Index (DI) and Remaining Service Life (RSL)	DI: Level of surface distress, project history, and projected growth of pavement surface distress. RSL: Estimated number of years from a specified date in time, until a pavement section is projected to reach a DI of 50	RSL ≤ 2 (at DI = 50)
MT	Ride	IRI	<u>Examples Provided</u> Overlay: Ride = 69.9
	Rut	Rutting	

State	Index	Function of	Trigger Values for Rehabilitation
	Alligator Cracking Index (ACI)	Alligator cracking	Minor Rehab: Ride = 57 Major Rehab: Ride = 30 Overlay or Minor Rehab: 65 < ACI < 80
	Miscellaneous Cracking Index (MCI)	Transverse/longitudinal cracking	
NC	Composite PCR	Includes cracking, both wheelpath and environmental, rutting, ride, raveling, bleeding for flexible	Unclear
NJ	SDI Scale: 0 – 5 (5 = distress-free pavement)	Severity and extent of distress; IRI not used	For minor rehab of asphalt & concrete pavements: 1.0 ≤ SDI ≤ 2.5 For major rehab of asphalt & concrete pavements: SDI < 1.0
NV	Point Rating Index (PRI) Pavement Age	IRI, friction, rutting, fatigue and block cracking, non-wheelpath cracking, patching, flushing, raveling	Overlay: 400-699 Major rehabilitation: > 699
OR	Condition Index Scale: 0 – 100	Detailed condition assessment completed every two years, including distress, rut, roughness, and friction	Distress and rut are primary triggers. Triggers adjusted to the appropriate rehabilitation type commensurate with where they are on the Pavement Management Curve. “Generally,” rutting = ¾” triggers an action, and widespread low fatigue or intermittent moderate fatigue would likely trigger action on the interstate
UT	RIDE	Roughness based on IRI	Concrete Grinding: RIDE or FALT ≤ 75 and CONK ≥ 80 and FALT ≥ 50 Concrete Minor Rehab: RIDE, FALT, CONK or JTSP ≤ 75 and CONC ≥ 60 Concrete Major Rehab: CONK ≤ 50 Low, Medium, or High Seal: RIDE, RUT and ENVCK ≥ 70 and WPCK ≥ 75
	CONK	Structural cracking from corner breaks and cracked slabs	
	FALT	Faulting (difference in slab elevation)	
	JONT	Joint index from spalling and asphalt patching	
	JTSP	Joint spall index	
	RUT	Rutting	

State	Index	Function of	Trigger Values for Rehabilitation
	ENVCK	Environmental cracking (transverse, longitudinal, block cracking)	Functional Repair – Interstate & Level 1: RIDE, RUT, or ENVCK < 70 and RIDE, RUT, and ENVCK > 50 and WPCK ≥ 70 Functional Repair – Level 2: RIDE, RUT, or ENVCK < 70 and RIDE, RUT & ENVCK > 50 Asphalt Minor Rehab: RIDE, RUT, or ENVCK < 60 or WPCK < 75 and WPCK ≥ 60 Asphalt Major Rehab: WPCK ≤ 55
	WPCK	Wheel-path cracking (cracking due to fatigue)	
WA	Pavement Structure Condition (PSC)	Cracking	45 < PSC < 60
	Pavement Rutting Condition	Rutting	Rut > .50 inches
	Pavement Profile Condition	IRI	IRI > 220 inches
WV	Composite Condition Index (CCI)	Flexible: Minimum of PSI, SCI, ECI, and RDI Rigid: Minimum of PSI, JCI, CSI	Thick Overlay: CCI: 1 – 2.5 Major CPR, Diamond Grind: CCI: 2.5 – 3.25 Reconstruction: CCI: 0 – 1
	PSI	IRI	
	Flexible Pavements:		
	Rutting Depth Index (RDI)	Rutting	
	Structural Cracking Index (SCI)	Fatigue cracking and longitudinal cracking	
	Environmental Cracking Index (ECI)	Transverse cracking and block cracking	
	Net Cracking Index (NCI)	Index is a function of a combined ECI and SCI	
	Rigid Pavements:		
	Joint Condition Index (JCI)	Faulting and Joint Distress	
	Slab Condition Index (SCI)	Transverse and Longitudinal slab cracking	

3.2.3 Use of IRI in Determining Actual Service Life

As noted in the previous section, condition indices and associated threshold values that trigger rehabilitation are unique to each agency and are, in part, dependent on pavement type. However, some common performance measures are used for each pavement type, such as various types of cracking and rutting for flexible pavements and cracking, faulting, and joint distress for rigid pavements. Pavement roughness, often characterized by IRI, was commonly reported as part of the condition indices used to trigger rehabilitation. Unlike cracking, which is classified into various types (such as longitudinal, transverse, slab, wheelpath, etc.) for each pavement type, pavement roughness was commonly characterized by the same parameter, IRI, regardless of pavement type. Given that this is the only performance measure common to both pavement types, the role of IRI in determining the actual time of rehabilitation was investigated further, as it may be a good candidate for basis of achieving equal performance or user benefits in LCCA. As part of the questionnaire issued for this study, agencies were asked how roughness (in terms of IRI) factors into the decision-making process to determine the actual time of rehabilitation of their asphalt and concrete roadways. Responses generally fell into five different categories and are summarized below (full responses are listed in Appendix G).

- IRI is part of an index or PMS model used to make the decision.
  - Nine agencies stated that IRI is part of their condition rating or indices. Two of those agencies indicated that IRI plays a significant role in their decision-making process. Arkansas DOT stated that IRI accounts for 50% of the overall condition index, PCI, for flexible pavements. Kansas stated that although it is one of the variables making up the condition index, it is a significant component of their condition assessment and decision-making process.
- IRI is one factor considered.
  - IRI was one of the triggers in seven agencies; three of those agencies indicated that IRI was more of a secondary trigger. Washington stated that IRI serves as a trigger with a threshold value of 220 in/mi and IRI is generally a lagging indicator, meaning pavements generally reach the threshold values for the other two indicators, PSC and rutting, before reaching the IRI threshold. Similarly, Alaska reported that although the FHWA criterion of 170 in/mi is considered, IRI is not the sole performance measure that can trigger action. Oregon DOT reported similar use of IRI, as it is used as a secondary trigger rather than a stand-alone trigger. Colorado DOT also indicated that it is one performance indicator that could trigger rehabilitation. Tennessee DOT's response indicated that IRI, in addition to distress, could also be used to identify possible candidates for rehabilitation. Connecticut DOT indicated that IRI is considered when IRI values have exceeded established thresholds. For composite pavements, Connecticut DOT considered IRI as a major indicator of structural distress and monitored its progression to identify potential structural deficiencies.
  - Arizona DOT indicated that decision trees are used, in which IRI is considered among other factors. A threshold value of 105 in/mi is used, a value much lower than those reported by Alaska and Washington.
  - Five agencies indicated that IRI is simply one of the factors considered in their decision-making process. Two of the five agencies also stated that IRI is used to

    communicate pavement performance. One agency reports IRI to the public, and the other reports IRI to the state's legislature and transportation commission.
  - IRI is the primary parameter considered.
    - In Arkansas, IRI is part of the condition index, PCI, used to monitor performance and trigger rehabilitation in flexible pavements, and it is the only component that makes up PCI for rigid pavements. Rehabilitation is triggered when PCI is in the poor category.
    - Minnesota indicated that IRI is the primary driver for their PMS and performance measures.
- IRI is not used to trigger rehabilitation.
    - Three agencies indicated that IRI is not used in the decision-making process. Another agency stated that it is generally not a dominant performance measure, and it is not currently used in their LCCA procedure.
    - Michigan DOT indicated that although IRI is not used directly in the decision-making process, it could be used if values are large enough to trigger complaints or lead to other issues.
    - New Jersey DOT does not use IRI to identify pavements in need of rehabilitation but does utilize IRI in combination with other condition indices to prioritize projects.
- Other:
    - Two agencies indicated that IRI is used to trigger maintenance activities. In California, corrective maintenance is considered for pavements with IRI greater than 170 in/mi. In Pennsylvania, pavements with fair or poor IRI (greater than 100 in/mi) are candidates for preventive maintenance treatments, at the least.

Although it was not specifically sought, responses to the question, "How is IRI used in the decision-making process?" (reported in Appendix G) revealed IRI threshold values used in the decision-making process for arriving at the actual time of rehabilitation. The reported values have a broad range. At the high end, Washington uses 220 in/mi as a trigger, although it was identified as a lagging indicator. Alaska considers an IRI threshold value of 170 in/mi, among other factors, in arriving at the actual service life. Alaska's IRI threshold is consistent with the FHWA threshold for poor IRI defined as greater than 170 in/mi under the MAP-21 performance measures (*4*). In Arkansas, rehabilitation is triggered when PCI reaches a level of poor (PCI of 65 or greater), and it was stated that for rigid pavements, PCI is based on IRI alone. Prior to calculating PCI, Arkansas DOT reported that IRI values are transformed to a 0 to 100 scale as part of the PCI calculation, so it is difficult to discern exactly the IRI values for rigid pavements that correspond to a PCI of 65 or greater. Although not provided, it could be assumed that poor PCI likely corresponds with poor categories for the IRI values. IRI categories were reported, such that values greater than 220 in/mi are considered poor, and values between 170 in/mi and 220 in/mi are mediocre.

Nevada DOT reported that a number of distresses including IRI are used to determine their point rating index, PRI, which is then used to trigger rehabilitation activities. The provided supporting document, Nevada DOT's Pavement Management System Overview, provides IRI categories as part of the PRI calculation for flexible pavements (*15*). Categorized as "smooth," "medium," or "rough," IRI values for each roadway classification are summarized in Table 3.3. The IRI values used to categorize flexible pavements as rough in Nevada are on the low end of the spectrum and are much lower, especially for interstates, than those used for Washington and Arkansas. In Nevada DOT's procedure, points are assigned or calculated based on the level of distress and roughness with the sum of the points representing the PRI. As shown in Table 3.3, higher points indicate poorer pavement condition and trigger rehabilitation. Points are assigned to each grouping of IRI values as listed in Table 3.3 with the highest points assigned to IRI values falling into the roughest category (e.g. greater than 115 in/mi for Interstates). PRI is a combination of several distresses and IRI, and values between 400 and 699 points trigger an overlay, while values greater than 699 trigger major rehabilitation. Based on the points assigned to IRI, it appears that IRI is a significant factor in the decision to rehabilitate flexible pavements. According to Nevada DOT's Pavement Management System Overview, rough pavements account for at least 400 points, the minimum value needed to trigger an overlay. Details on the IRI values, distresses, and associated points for concrete pavements were not listed in Nevada DOT's Pavement Management System Overview, nor were any distinctions made between pavement types in their responses; therefore, it is unclear if the same IRI values listed in Table 3.3 also apply to rigid pavements. This is likely due to the proportion of flexible pavements relative to the total lane miles Nevada DOT maintains.

Table 3.3 Nevada DOT's IRI Categories for Flexible Pavements (*15*)

Ride Indicator	**Interstates**		**Non-Interstates, NHS, Surface Transportation Program (STP)**		**All Other Routes (Low-volume roads)**	
	IRI in/mi	PMS Points	IRI in/mi	PMS Points	IRI in/mi	PMS Points
Smooth	0 – 40 41 – 70	0 100	0 – 80 81 – 100	0 100	0 – 90 91 – 130	0 100
Medium	71 – 90 91 – 105	200 300	101 – 115 116 – 130	200 300	131 – 150 151 – 170	200 300
Rough	106 – 115 > 115	400 500	131 – 160 > 160	400 500	171 – 200 > 200	400 500

Utah DOT considers IRI for their RIDE index, which is in part used to trigger minor rehabilitation for asphalt and concrete, functional repairs, concrete grinding, and asphalt "seals" (surface treatments and thin AC overlays) (*16*). RIDE index values of 50 represent the boundary between fair and poor condition, and a value of 50 correlates to 170 in/mi for asphalt pavements and 190 in/mi for concrete pavements. As shown in Table 3.4, Utah has assigned categories of good, fair, and poor to asphalt and concrete pavements such that concrete IRI values are shifted up by 20 in/mi at each category.

Table 3.4 Utah DOT IRI Categories (*16*)

Ride	**Asphalt IRI (in/mi)**	**Concrete IRI (in/mi)**
Good	< 95	< 115
Fair	95 – 170	115 – 190
Poor	> 170	> 190

Pennsylvania was less specific in their trigger values for rehabilitation, stating only that roadways with fair or poor IRI were candidates for at least preventive maintenance treatments, with poor being defined by IRI greater than 150 in/mi (*17*).

3.3 Summary

The goal of LCCA is to determine the most cost-effective alternative by evaluating the anticipated costs over the life of the pavement. Costs include those of construction and M&R activities over the life of the pavement, and they are combined with the timing of these activities to compute the net present value of each alternative. In LCCA, it is assumed that all the alternatives provide the same level of performance or benefits to the project's users, thus, the timing of the activities should be determined based on the same set of performance thresholds. However, many agencies utilize historical performance data that may not be determined based on the same performance criteria to determine the timing of the first rehabilitation activity used in LCCA. This chapter reviewed current practices employed by state agencies to arrive at the actual timing of rehabilitation activities for existing, in-service pavements.

In a questionnaire issued for this study, DOTs were asked to provide information on the decision-making process to determine the actual time of rehabilitation of in-service pavements. Responses indicate that the methods vary from agency to agency and include a number of factors. Despite their uniqueness, the methods largely consist of the use of pavement condition data. Half of the DOTs responding to the questionnaire indicated that rehabilitation triggers, typically some type of indices, are used as part of the decision-making process.

In looking at a synthesis conducted in 2009 on pavement scores used by DOTs across the country, it was found that just as the decision-making process for identifying the time of rehabilitation is unique to each agency, so are the indices that serve as rehabilitation triggers (*14*). Although the indices are unique to each agency, the performance measures that make up the indices generally consisted of roughness, cracking, and/or rutting, with roughness being the most frequently reported measure. Results of the questionnaire issued for this study were similar to the 2009 synthesis in that current rehabilitation triggers commonly consist of indices that combine one or more performance measures. The weight that an agency places on an individual performance measure and the manner in which they are combined to compute the indices are unique to each agency and each pavement type, making it difficult to draw direct comparisons among the threshold values provided.

Various performance measures are considered in DOTs' rehabilitation triggers for identifying the actual time of rehabilitation for AC and PCC pavements, and as noted earlier, not all performance measures apply to both pavement types. Unlike cracking or faulting, IRI is determined in the same manner regardless of the pavement type. IRI is a calculated value and serves as an objective measurement of the longitudinal profile of a pavement. Therefore, DOTs were also asked to report on the use of IRI in the decision-making process for pavement rehabilitation. Responses to the questionnaire indicate that most agencies utilize IRI in the decision-making process, and it generally is utilized as part of an index or in combination with other factors.

Some agencies reported qualitative categories assigned to IRI values, providing an indication of the IRI values that may contribute to a rehabilitation activity being triggered. On one extreme, Washington considers an IRI of 220 in/mi as a rehabilitation trigger, although it is recognized that it is often a lagging indicator behind the other two trigger indices used. Similarly, IRI values, which account for 100% of the trigger index (PCI) used in Arkansas for rigid pavements and 50% of the index for flexible pavements, are considered poor when greater than 220 in/mi. On the other end, Nevada DOT considers interstate pavements with IRI as low as 106 in/mi as poor, and this IRI value contributes 400 of the 700 points necessary to trigger major rehabilitation of their asphalt roadways based on their point rating index (PRI). In Utah, IRI is used in one of their indices that, in combination with other indices, may trigger minor rehabilitation, functional repairs, concrete grinding, and asphalt "seals." IRI values are assigned good, fair, and poor categories for asphalt and concrete, with IRI values in each category 20 in/mile greater for concrete than asphalt pavements. This indicates that a rougher ride is tolerated on concrete pavements, and criterion for this particular index (RIDE) is not based on achieving equal levels of performance between asphalt and concrete.

4 DOCUMENTING ACTUAL REHABILITATION CYCLES: SUMMARY OF LTPP DATA

The initial performance period is an important input in LCCA, and it should represent the actual time pavements are in need of rehabilitation. As shown in Section 3, the criteria for rehabilitation vary from agency to agency, making it difficult to assess when a pavement has reached a particular set of criteria or a single performance threshold. Therefore, the timing of the first rehabilitation will first be determined. Then, an analysis of the pavement condition at the time of rehabilitation will be conducted. An analysis to determine the actual time to first rehabilitation can be conducted utilizing a pavement management dataset documenting rehabilitation activities, pavement performance measures, and dates of original construction and rehabilitation activities. Several state agencies already collect pavement management data that are sufficient for such an analysis, as evidence from the results of previous surveys and the questionnaire issued for this study.

An analysis to determine the actual time to first rehabilitation was conducted in this study utilizing the databases established for the Long-Term Pavement Performance (LTPP) program. Data gathered under the LTPP program created the most expansive and consistent datasets available to researchers on pavement performance and was pointed out in the 1998 FHWA publication on LCCA in pavement design as a potential source for determining performance periods and activity timing for LCCA (*2*).

The LTPP program covers performance of both flexible and rigid pavements and spans all 50 states and several Canadian provinces (*18*). The Long-Term Pavement Performance (LTPP) program was initiated in 1987 as part of SHRP. It was initially aimed at collecting and storing pavement performance data of in-service highways. The data could then be analyzed to understand how pavement performance relates to pavement design, construction, rehabilitation, maintenance, preservation and management.

As part of LTPP, four geographic regions were established based roughly on climatic conditions: "North Atlantic," "North Central," "Southern," and "Western" regions (*19*). Four climatic zones were also established: "wet, freeze"; "wet, non-freeze"; "dry, freeze"; and "wet, non-freeze." The regional contractors are responsible for collecting test and monitoring data, such as pavement distress, deflection, profile, and environmental conditions. Data pertaining to the inventory, maintenance, rehabilitation, and traffic associated with each pavement section in the LTPP database are collected at the state level and sent to the regional centers. Established guidelines ensure consistency among data collection. Regional centers rely on DOTs and Canadian provinces participating in the program to report information such as original construction date, location, previous rehabilitation activities, time and type of rehabilitation since induction into LTPP, as well as traffic data (*19*). Although this process presents the potential for errors in reporting, misreporting, or failure to report data, the LTPP dataset remains the most comprehensive, and consistent database for the performance of in-service pavements. Thus, for this analysis, data from the standard data release (SDR) 28 was utilized.

Under the LTPP program, there are two classifications of experiments: the General Pavement Studies (GPS) and the Specific Pavement Studies (SPS). The GPS consist of a series of studies on existing pavements, whereas SPS include studies specifically designed to examine parameters related to construction, maintenance treatments, and rehabilitation activities (*20*). According to the User Guide, close to 800 existing in-service pavement sections were utilized for studies under the GPS classification, and nearly 1,700 pavement sections were constructed under the SPS classification. Each section is 500 feet in length and one lane wide. GPS sections were constructed and were in-service prior to the LTPP program, whereas SPS sections were constructed on existing routes as part of the LTPP program with specific objectives in mind. Therefore, there was more control over the features of AC and PCC pavements under the SPS program (*20*).

The experiments under the classification of GPS are listed in Table 4.1. GPS experiments were based on a factorial design to incorporate the effect of environment, loading, and pavement factors; however, not all of the combinations of factors were represented due to the use of existing pavements (*20*). Pavement sections included in GPS-1 through GPS-5 experiments were existing in-service pavement sections constructed prior to acceptance into LTPP. The remaining GPS experiments included pavements that were either overlaid prior to entering the LTPP program or rehabilitated after being in the program and reclassified to a new GPS experiment. It is not directly stated, but it is inferred from the data collection guide for M&R that decisions regarding the timing of rehabilitation activities of the existing pavements were left to the DOTs and provinces, although agencies were required to report activities (*21*). Additionally, pavements included in the GPS experiments were restricted to pavement structures in common use across the U.S. and incorporated materials and pavement design representative of good engineering practices (*20*). Therefore, the actual service lives determined for the GPS experiments should be representative of practices across the United States and Canada.

Table 4.1 GPS Experiments (*20*)

Experiment	Experiment Title
GPS-1	Asphalt Concrete (AC) Pavement on Granular Base
GPS-2	AC Pavement on Bound Base
GPS-3	Jointed Plain Concrete Pavement (JPCP)
GPS-4	Jointed Reinforced Concrete Pavement (JRCP)
GPS-5	Continuously Reinforced Concrete Pavement (CRCP)
GPS-6	AC Overlay on AC Pavement
GPS-6A	Existing AC Overlay of AC Pavement (at the start of the program)
GPS-6B	AC Overlay Using Conventional Asphalt of AC Pavement – No Milling
GPS-6C	AC Overlay Using Modified Asphalt of AC Pavement – No Milling
GPS-6D	AC Overlay on Previously Overlaid AC pavement Using Conventional Asphalt
GPS-6S	AC Overlay of Milled AC Pavement Using Conventional or Modified Asphalt
GPS-7	AC Overlay on PCC Pavement
GPS-7A	Existing AC Overlay on PCC Pavement
GPS-7B	AC Overlay Using Conventional Asphalt on PCC Pavement
GPS-7C	AC Overlay Using Modified Asphalt on PCC Pavement
GPS-7D	AC Overlay on Previously Overlaid PCC Pavement Using Conventional Asphalt
GPS-7F	AC Overlay Using Conventional or Modified Asphalt on Fractured PCC Pavement
GPS-7R	Concrete Pavement Restoration Treatments with No Overlay
GPS-7S	Second AC Overlay, Which Includes Milling or Geotextile Application, on PCC Pavement with Previous AC Overlay
GPS-9	Unbonded PCC Overlay on PCC Pavement

Table 4.2 lists SPS Experiments. These experiments were developed using factorial design, and there was more control over the experimental factors in the SPS experiments as either new pavements were constructed or specific maintenance or rehabilitation treatments were applied (*20*). To incorporate the different combinations of factors, SPS experiments required construction of multiple test sections at each site, unlike the GPS experiments. As shown in Table 4.2, the SPS experiments aimed to address structural factors, preventive maintenance treatments, rehabilitation treatments, environmental effects, and Superpave mix design and specifications.

Table 4.2 SPS Experiments (*20*)

Category	Experiment	Experiment Title
Pavement Structural Factors	SPS-1	Strategic Study of Structural Factors for Flexible Pavements
	SPS-2	Strategic Study of Structural Factors for Rigid Pavements
Pavement Maintenance	SPS-3	Preventive Maintenance Effectiveness of Flexible Pavements
	SPS-4	Preventive Maintenance Effectiveness of Rigid Pavements
Pavement Rehabilitation	SPS-5	Rehabilitation of AC Pavements
	SPS-6	Rehabilitation of Jointed Portland Cement Concrete (JPCC)*
	SPS-7	Bonded PCC Overlays of Concrete Pavements
Environmental Effects	SPS-8	Study of Environmental Effects in the Absence of Heavy Loads
Asphalt Aggregate Mixture Specifications	SPS-9P	Validation and Refinements of Superpave Asphalt Specifications and Mix Design Process
	SPS-9A	Superpave Asphalt Binder Study
	SPS-9C	AC Overlay on CRCP
	SPS-9J	AC Overlay on JPCC
	SPS-9N	New AC Pavement Construction
	SPS-9O	AC Overlay on AC Pavement

*Also referred to as Jointed Plain Concrete Pavement (JPCP)

New pavement sections were constructed for the SPS-1 and SPS-2 experiments, designed to investigate structural factors associated with each pavement type. Both new and existing pavement sections were included in the SPS-8 experiment. With the exception of SPS-9N, the remaining experiments utilized existing pavements. The condition of existing pavement sections was taken into consideration to select pavements that fit the objectives of each experiment. As part of the SPS-5, 6, and 7 experiments focusing on rehabilitation, the intention was to include existing pavements in their first performance period with no previous rehabilitation that met an agency's rehabilitation requirements, or as stated in the nomination guidelines for each, were "part of an agency's planned rehabilitation program" (*22-24*). Although not explicitly stated in the SPS-9A nomination guidelines, it is believed that pavements for which rehabilitation was already planned were also sought for the SPS-9A experiments, which aimed to study AC overlays on existing CRCP, JPCC, or AC pavements. Another condition for nomination to these six SPS studies was that the existing pavements exhibited pavement distress typical of the distresses experienced in that agency (*22-25*). Therefore, the timing at which the first rehabilitation was applied should be representative of typical distresses and agency practices.

4.1 Types of Rehabilitation Activities Considered

Once the data source was identified, the next step was to identify the types of rehabilitation activities to be considered for determining the actual initial service lives of flexible and rigid pavements. The LTPP Information Management System User Guide identifies the types of improvement activities considered and whether they are categorized as maintenance or rehabilitation activities (*20*). Maintenance activities are included in the maintenance module and include improvement activities that cause "no significant pavement structure change." According to the document, major improvements such as overlay, shoulder replacement, joint repair, resurfacing, reconstruction, and the addition of lanes are included in the rehabilitation module. The types of improvements that may be contained in the rehabilitation module are listed in Table 4.3.

Table 4.3 Rehabilitation Activities Assigned in LTPP Database (*20*)

Code	Type of Improvement
8	PCC Shoulder Restoration
9	PCC Shoulder Replacement
10	AC Shoulder Restoration
11	AC Shoulder Replacement
14	Pressure Grout Subsealing
16	Asphalt Subsealing
19	Asphalt Concrete Overlay
20	Portland Cement Concrete Overlay
38	Longitudinal Subdrainage
39	Transverse Subdrainage
40	Drainage Blankets
41	Well System
42	Drainage Blankets with Longitudinal Drains
43	Hot-Mix Recycled AC
44	Cold-Mix Recycled AC
45	Heater Scarification, Surface Recycled Asphalt Concrete
46	Crack-and-Seat PCC Pavement + AC Surface
47	Crack-and-Seat PCC Pavement + PCC Surface
48	Recycled PCC
49	Pressure Relief Joints in PCC Pavements
50	Joint Load-Transfer Restoration in PCC
51	Mill Off AC and Overlay with AC
52	Mill Off AC and Overlay with PCC
53	Other
55	Mill Existing Pavement and Overlay with Hot-Mix AC
56	Mill Existing Pavement and Overlay with Cold-Mix AC

Using the information obtained through previous surveys, the questionnaire issued for this study regarding the types of major rehabilitation activities considered in DOT LCCA procedures, and the rehabilitation activities listed in the LTPP Information Management System User Guide (*20*), a list of rehabilitation activities was developed for use in this investigation. Listed in Table 4.4 is the LTPP code for improvement type, a description of the activity, and the pavement type to which it is applied. Table 4.3 was used as a basis for creating a list of rehabilitation activities to be considered; however, activities pertaining to the shoulder, such as restoration or replacement, were removed to maintain focus on rehabilitation of the mainline. Activities related to drainage as well as "Pressure Relief Joints in PCC Pavements" were not identified in the rehabilitation activities listed by DOTs in their previous survey responses and the questionnaire summarized in this report; therefore, activities 38 through 41 and 49 were not included in the list for this investigation. Lastly, improvement type code 53, described by "other," was not included in the list, as it is unclear what activity was conducted, and this code represented a very small portion of the entire database. Two activities, slab replacement, and diamond grinding, were commonly mentioned in DOT responses for the types of rehabilitation considered for rigid pavements. Although these activities are listed as maintenance activities in the LTPP database, they are included here as rehabilitation activities based on DOT responses to the NCAT-issued questionnaire. While activity code 12 can be applied to either pavement type (flexible or rigid), care was taken to identify grinding on PCC pavements only, to be consistent with the practices reported by DOTs.

Table 4.4 LTPP Rehabilitation Types Considered for Time to First Rehabilitation

Code	Rehabilitation Type	Existing Pavement Type
7	PCC Slab Replacement (sq. yards)	PCC
12	Grinding surface (sq. yards)	PCC
14	Pressure Grout Subsealing (no. of holes)	PCC
16	Asphalt Subsealing (no. of holes)	AC
19	Asphalt Concrete Overlay (sq. yards)	AC/PCC
20	Portland Cement Concrete Overlay (sq. yards)	AC/PCC
43	Hot-Mix Recycled Asphalt Concrete (overlay) (sq. yards)	AC/PCC
44	Cold-Mix Recycled Asphalt Concrete (overlay) (sq. yards)	AC/PCC
45	Heater Scarification, Surface Recycled Asphalt Concrete (sq. yards)	AC
46	Fracture Treatment (crack-and-seat) of PCC Pavement as Base for New AC Surface (sq. yards)	PCC
47	Fracture Treatment (crack-and-seat) of PCC Pavement as Base for New PCC Surface (sq. yards)	PCC
48	Recycled Portland Cement Concrete (overlay) (sq. yards)	PCC
50	Joint Load Transfer Restoration in PCC Pavements (linear feet)	PCC
51	Mill Off AC and Overlay with AC (sq. yards)	AC
52	Mill Off AC and Overlay with PCC (sq. yards)	AC
55	Mill Existing Pavement and Overlay with Hot-Mix Recycled AC	AC/PCC
56	Mill Existing Pavement and Overlay with Cold-Mix Recycled AC	AC/PCC

For this analysis, pavement sections included in LTPP experiments across the U.S. (including Puerto Rico) and Canada were utilized. Using the rehabilitation activities listed above, the date associated with the first occurrence of one or more of the above rehabilitation activities was identified. At the time of inception of the LTPP program, the GPS pavements sections were already in-service; therefore, it is important to consider the date of original construction rather than the date it was assigned to the LTPP program. Using the data compilation view module, the original construction date was identified from the SECTION_STRUCTURE_HISTORY table. This table provides a timeline of activities for each pavement section and pulls information from various sources. In doing so, the construction dates for new pavements constructed as part of the Specific Pavement Studies (SPS) experiments are also included. Although some sections were newly constructed after their acceptance into LTPP, many were already in-service; therefore, it is also important to identify any sections that previously received rehabilitation. The INV_MAJOR_IMP table from the inventory module was utilized to identify pavement sections that had received one of the rehabilitation activities listed in Table 4.4 prior to acceptance into the LTPP program and the date of that activity. Since the age of the pavement at the time of the first rehabilitation was sought, any pavement sections that had received rehabilitation prior to being accepted into the LTPP program were removed from the dataset. Once removed, the age of the pavement at the time of the first rehabilitation was determined from the original construction date and date of the first rehabilitation. While every effort was made to work with unbiased, accurate data, information including types and dates of previous rehabilitation activities were reported by DOTs and Canadian provinces to the LTPP regional centers. While this process creates the potential that activities were not reported, or mis-reported, this type of error can exist in any dataset.

The following subsections explore the actual time to first rehabilitation for each pavement type as well as specific experiments conducted as part of the LTPP program, region, and climatic zone.

4.2 Determining Time to First Major Rehabilitation by LTPP Experiment

To better understand the experiments that are useful in meeting the objectives of this study, it is necessary to understand how events are tracked and how these events relate to the experiment numbers to which they are assigned. Once an experiment is entered into the LTPP program, it is assigned a construction number (CN) of 1. The CN serves to account for each event occurring on a section during the time it is in the program. The CN is increased incrementally with each event, and an event is the occurrence of a maintenance or rehabilitation activity or combination of activities. Depending on the type of activity, such an event can result in an experiment being reclassified under another study. For example, a pavement section that entered the program in the GPS-1 experiment (AC Pavement on Granular Base) could be reclassified as a section in the GPS-6B experiment (AC Overlay Using Conventional Asphalt of AC Pavement – No Milling) once the pavement has been rehabilitated with a conventional AC overlay with no milling (*26*). A pavement originally assigned to an SPS experiment can also be reclassified to a GPS experiment depending on the type of event that initiated the change in the CN. GPS-6B, GPS-6C, GPS-6D, GPS-6S, as well as GPS-7B, GPS-7C, GPS-7D, GPS-7F, GPS-7R, and GPS-7S are experiments that were initially entered into the program under a different experiment and were reclassified after receiving some type of overlay or concrete pavement restoration treatment.

For SPS experiments, which study maintenance and rehabilitation treatments (such as SPS-3, SPS-4, SPS-5, SPS-6, SPS-7, or SPS-9C, SPS-9J, or SPS-9O), pavement sections are first entered into the LTPP program, at which point they are assigned a CN of 1. Then, when the study treatment is applied, a new CN is assigned without reclassification of the experiment. For this study, the original experiment to which a pavement section was first assigned is of interest.

4.2.1 Actual Initial Service Life of GPS Experiments

Experiments GPS-6A, GPS-7A, and GPS-9 feature pavements that had received an overlay prior to the start of the experiment, and therefore, had already received a rehabilitation treatment. For that reason, only experiments GPS-1 through GPS-5 were explored for this study. As noted earlier, pavements considered in the GPS experiments were restricted to pavement structures in common use and representative of good engineering practices in terms of pavement design and pavement materials (*20*). The time of rehabilitation was decided upon by the agency itself, so the calculated time to first rehabilitation should also be representative of actual practices; by including pavements from across the U.S. and Canada, bias to one method is minimized.

The activities listed in Table 4.4 were used to determine the timing of the first rehabilitation. In some cases, one or more of those activities were constructed as part of the first rehabilitation. Additionally, maintenance activities were commonly performed in conjunction with the rehabilitation activities. For AC pavements in the GPS-1 (on granular base) experiment, the types of activities included in the first rehabilitation were AC overlay (code 19), hot-mix recycled AC overlay (code 43), mill existing AC and overlay with AC (code 51), and mill existing AC and overlay with hot-mix recycled AC (code 55). For pavements in the GPS-2 experiment, AC atop bound base stabilized with bituminous or non-bituminous (pozzolans, PCC, lime, etc.) binders (*20*), the same rehabilitation activities applied to AC pavements in the GPS-1 experiment were also used for GPS-2 pavements. The first rehabilitation activities associated with JPCP in the GPS-3 experiment included PCC slab replacement (code 7), grinding surface (code 12), AC overlay, hot-mix recycled AC overlay, fracture treatment (crack-and-seat) of PCC pavement as base for new AC surface (code 46), and joint load restoration (code 50). The same rehabilitation activities were also associated with JRCP and CRCP pavements in the first rehabilitation activity, with the exception of fracture treatments on JRCP. Although surface grinding was the most common first rehabilitation activity for JPCP pavements, AC overlays were the most common for JRCP and CRCP pavements.

The average, minimum, maximum, standard deviation, and coefficient of variation of the time to first rehabilitation was determined for each GPS experiment, as tabulated in Table 4.5. Experiments GPS-1 and GPS-2 pertain to AC pavements and the corresponding experiments for PCC pavements are experiments GPS-3, GPS-4, and GPS-5.

Table 4.5 Summary of Actual Service Life of LTPP Sections

Exp No.	Pavement Type	No.	Age at First Rehabilitation, Yrs				Coefficient of Variation
			Avg	Min	Max	Std Dev	
Surface Type: AC							
GPS-1	AC on Granular Base	122	18.0	0.1	31.9	6.47	36.0%
GPS-2	AC on Bound Base	83	16.9	5.3	41.1	6.90	40.8%
Surface Type: PCC							
GPS-3	JPCP	46	23.7	6.9	38.5	7.35	31.1%
GPS-4	JRCP	28	23.1	1.1	35.4	7.04	30.5%
GPS-5	CRCP	30	23.7	2.2	42.4	7.93	33.5%

There is a notable difference between the average age at first rehabilitation for GPS AC experiments and GPS PCC experiments. The average service life for AC pavements on granular base (GPS-1) and AC pavements on bound base (GPS-2) are 18.0 and 16.9 years, respectively. The average service life for JPCP (GPS-3), JRCP (GPS-4), and CRCP (GPS-5) pavements range between 23 and 23.7 years. Although differences are observed between AC and PCC pavements, little difference was observed among the pavement categories within each pavement type. The average time to first rehabilitation for AC pavements on granular base (GPS-1) and AC pavements on bound base (GPS-2) differ by only one year. Similarly, the average time to first rehabilitation for JPCP, JRCP, and CRCP pavements differed by less than a year. The average initial service lives for the AC pavements on granular base (GPS-1) and AC pavements on bound base (GPS-2) experiments are greater than the 10 to 15 years for AC pavements, which agencies most frequently reported for the initial service life considered in LCCA, as shown in Table 2.1 (*6, 7*). However, the actual initial service life for the JPCP (GPS-3), JRCP (GPS-4), and CRCP pavements (GPS-5) fall within the range of 20 to 25 years for initial service life of PCC pavements used in LCCA, also shown in Table 2.1.

The minimum time to first rehabilitation was found to be 0.1 years, or just less than one month. Minimum values for JRCP (GPS-4) and CRCP (GPS-5) pavements were only slightly larger, at 1.1 and 2.2 years. These values are likely outliers. As discussed previously, there are limitations in the data for experiments that used existing pavement sections, as the date of original construction (or last reconstruction) and any previous rehabilitation activities were left to the DOTs to report to the regional LTPP contractors. While the data were filtered to exclude sections that reported rehabilitation dates earlier than the reported original construction dates, it is difficult to sort out erroneous data from accurate data. Additional evaluations completed in this study and documented later in this report will attempt to account for and remove possible outliers such as these.

On the other end of the spectrum, the maximum times to first rehabilitation observed in these GPS experiments were all greater than thirty years. The highest service lives were found to be 41 and 42 years for AC pavements with a bound base (GPS-2) and CRCP (GPS-5) pavements, respectively. These values could also be outliers.

The coefficients of variation, calculated as the ratio of the standard deviation to the mean, were found to be greater than 30% for all of the experiments. The most variable experiment in terms of time to first rehabilitation was the experiment for AC pavements on bound base with a calculated coefficient of variation of 40.8%. Some variation is expected, as these data included the time to first rehabilitation for pavements from across the U.S. and Canada, which includes all four climatic regions, various functional classifications, and agency-specific materials.

4.2.2 Actual Initial Service Life of SPS Experiments

SPS experiments required multiple 500-foot test sections at a site to enable the investigation of the various combinations of factors. The number of test sections included in the core experiment ranged from as few as two to as many as twelve at a site. DOTs and some Canadian provinces built additional sections, referred to as supplemental sections, to investigate other factors specific to their agency. Table 4.6 lists the number of sites with pavement sections that met the criteria for this analysis (i.e., no prior rehabilitation and first rehabilitation defined by activities in Table 4.4). The number of rehabilitated sections that were part of the core experiment and those that were considered supplemental are also listed in the table. No pavements included in the SPS-8 experiment (study of environmental effects in the absence of heavy loads) met the criteria established in this report; and therefore, Experiment SPS-8 is excluded from the analysis conducted herein.

SPS-3 and SPS-4 experiments were designed to evaluate the performance of various preventive maintenance treatments on existing AC and PCC pavement sections (respectively). Although some SPS-3 pavement sections received an overlay, the overlay was a thin overlay, which was considered a preventive maintenance treatment as part of the experimental design. Therefore, SPS-3 sections were excluded from this analysis. The complement to this experiment, SPS-4 preventive maintenance for rigid pavements, was also excluded.

Table 4.6 Number of Rehabilitated Sections, SPS Experiments

Exp No.	Surface Type	Existing/New Pavement Sections	No. of Sites with Rehabilitation	No. of Rehabilitated Sections		
				Total	Core	Supplemental
SPS-1	AC	New	7	71	69	2
SPS-5	AC	Existing	17	186	139	47
SPS-9O	AC	Existing	7	36	20	16
SPS-9N	AC	New	3	8	8	0
SPS-2	PCC	New	8	18	14	4
SPS-6	PCC	Existing	14	158	101	57
SPS-7	PCC	Existing	4	36	32	4
SPS-9C	PCC	Existing	2	7	5	2
SPS-9J	PCC	Existing	6	38	18	20

Strategic studies of structural factors for flexible (SPS-1) and rigid (SPS-2) pavements included new construction, where structural factors such as layer thickness, base type, base thickness, and the use of drainage layers were varied (*20*). Four rehabilitation treatments were associated with the AC pavements in the SPS-1 experiment, which included two types of AC overlay, conventional and hot-mix recycled AC overlay, and mill and overlay with either AC or hot-mix recycled AC overlay, represented by activity codes 19, 43, 51, and 55. Only two rehabilitation treatments, PCC slab replacement and grinding surface, activity codes 7 and 12, respectively, were associated with the pavement sections in the SPS-2 experiment. The age of the pavements at the time of the first application of these rehabilitation treatments was determined for each pavement section within each experiment.

Histograms and cumulative distributions of the initial service lives for pavement sections in the SPS-1 (AC pavements) and SPS-2 (PCC pavements) experiments are plotted in Figures 4.1 and 4.2, respectively. PCC pavements were most frequently rehabilitated between three and six years. The majority of the AC pavement sections constructed were in service for three to twelve years before the first rehabilitation treatment was applied. These values are lower than the most commonly reported values used for service life in LCCA from earlier surveys of 10 to 15 years for AC pavements and 20 to 25 years for rigid pavements, as shown in Table 2.1 (*6, 7*). More surprising is the frequency of pavement sections that were rehabilitated less than three years after construction.

The differences in actual initial service life of the SPS-1 and SPS-2 experiments compared to initial service life commonly used by agencies could be attributed to the experimental design, age of the pavements, and the rehabilitation types. AC pavements included in the SPS-1 and PCC pavements included in the SPS-2 experiments were newly constructed or reconstructed to explore a number of structural factors, and as such, it is expected that varying structural factors will impact performance on either end of the spectrum, as some of the sections may feature pavement designs that are not adequate to accommodate traffic loadings, leading to early failures, while others may be overdesigned, resulting in extended service lives. Because the rehabilitation treatment is driven by performance, the experimental design would also impact the timing and treatment an agency chose to apply. Moreover, the construction date for pavement sections in SPS-1 (AC pavements) ranged from 1992 to 1998 and 1992 to as late as 2000 for SPS-2 (PCC pavements). Therefore, it is possible that the younger pavement sections have not yet needed rehabilitation.

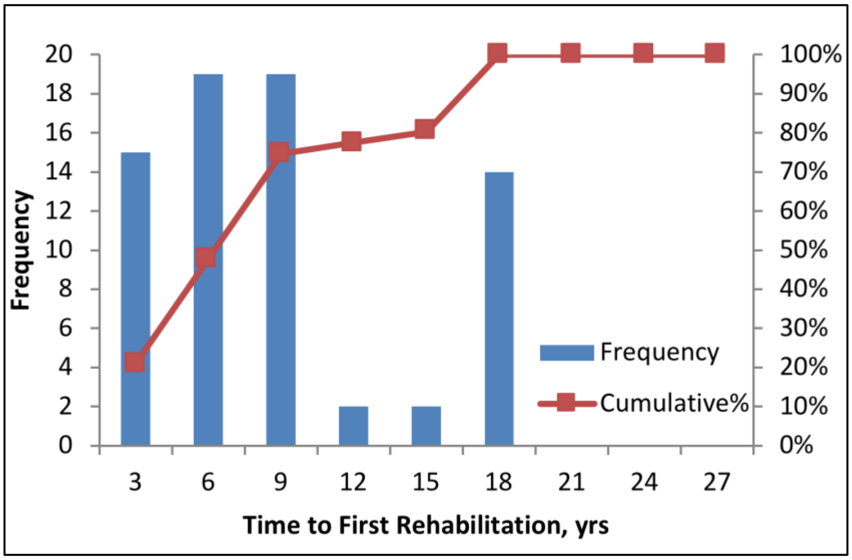


Figure 4.1 Distribution of Time to First Rehabilitation for AC Pavements in SPS-1 Experiment

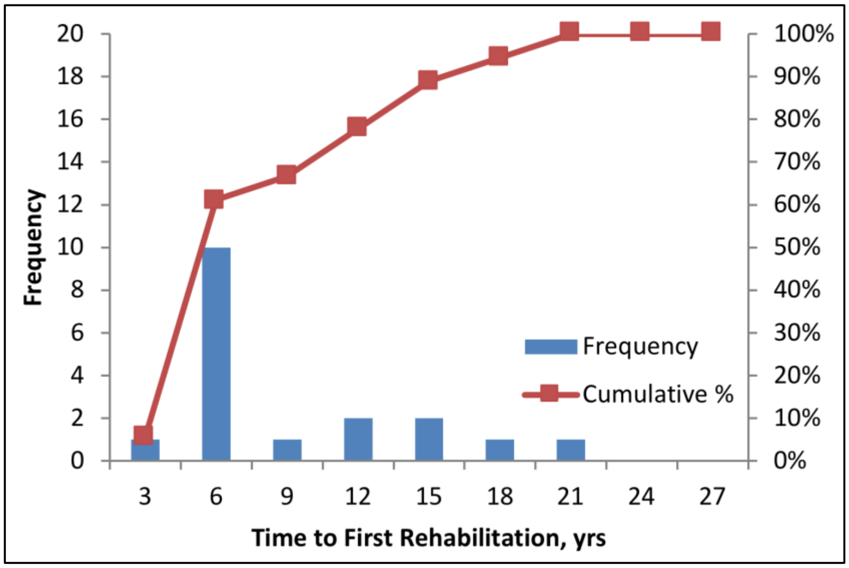


Figure 4.2 Distribution of Time to First Rehabilitation for PCC Pavements in SPS-2 Experiment

Given the large number (71) of AC pavement sections rehabilitated in the SPS-1 experiment, it would be expected that the distribution of actual service life would be normal. However, as shown in Figure 4.1, this is not the case. As noted above, multiple sections that varied by one or more structural factors were constructed at a site. The timing of rehabilitation was at the discretion of the agency. Therefore, it is likely that when one 500-foot section along the route required rehabilitation, all sections at the site were addressed for ease of construction. To explore this notion, the average time to first rehabilitation was determined for each site.

Tables 4.7 and 4.8 summarize the actual initial service life among the pavement sections at each site, described by the Site ID (the state code and first two digits of the SHRP ID), for the SPS-1 and SPS-2 experiments, respectively. Although there were 71 AC pavement sections in the SPS-1 experiment that received rehabilitation, these sections represent just 7 sites. Far fewer PCC pavement sections in the SPS-2 experiment were rehabilitated: only 18 sections at 8 sites.

Reading across the table reveals the average, minimum, maximum, and standard deviation for the time to first rehabilitation among the pavement sections at one site. Where the standard deviation is zero, or the minimum and maximum are equivalent to the average, all pavement sections at that site were rehabilitated at the same time. For example, Site 20-01 consisted of ten pavement sections that were rehabilitated. The same date of rehabilitation was reported for all ten pavement sections, as evident by the equivalent minimum and maximum values and standard deviation of zero. For site 48-01, the average time to first rehabilitation for the 20 sections at that site was 5.10 years, the earliest a section was rehabilitated was 4.8 years, the latest was 9.8 years, and the standard deviation for all 20 sections at this site was just 1.1 years. At the bottom of the table, the average, minimum, maximum, and standard deviation of the time to first rehabilitation was determined from the average time to rehabilitation for each site.

Table 4.7 Summary Statistics of Time to First Rehabilitation for AC Pavements in SPS-1 Experiment

Site ID	Statistics for Time to First Rehabilitation (Years) of Sections				
	No. of Sections	Average	Minimum	Maximum	Std Dev
10-01	14	0.4	0.4	0.4	0
19-01	1	1.0	N/A	N/A	N/A
20-01	10	7.9	7.9	7.9	0
26-01	9	7.2	7.2	7.2	0
39-01	5	14.9	11.6	16.6	2.05
48-01	20	5.1	4.8	9.8	1.10
51-01	12	15.7	15.7	15.7	0
Summary for Sites	7	7.5	0.4	15.7	6.05

Table 4.8 Summary of Time to First Rehabilitation for PCC Pavements in SPS-2 Experiment

Site ID	Statistics for Time to First Rehabilitation (Years) of Sections				
	No. of Sections	Average	Minimum	Maximum	Std Dev
10-02	8	4.1	4.1	4.1	0
19-02	1	10.8	N/A	N/A	N/A
20-02	2	11.1	3.4	18.9	N/A
26-02	1	8.6	N/A	N/A	N/A
38-02	2	15.7	14.8	16.5	N/A
4-02	1	14.4	14.4	14.4	N/A
55-02	2	6.1	2.6	9.6	N/A
6-02	1	4.0	N/A	N/A	N/A
Summary for Sites	8	9.4	4.0	15.7	4.44

As shown in Table 4.7, AC pavement sections at more than half of the SPS-1 sites were rehabilitated at the same time despite the varying structural factors associated with each section. Some of these sections were rehabilitated very early in their life. For example, all fourteen of the SPS-1 AC pavement sections that received rehabilitation at a site in Delaware (Site ID 10-01) were done so at the same time, just months after construction was completed. Although site 48-01 has a standard deviation of 1.1 years for the 20 AC pavement sections, all but one section was rehabilitated 4.8 years after construction. Only at one site in the SPS-1 experiment, Site 39-01, were all pavement sections at a site rehabilitated at different times. Determining the average time to first rehabilitation based on each pavement section is biased toward sites with the most sections. It is difficult to tell from the pavement distress information available on infopave.com (the online database application program for the LTPP program) how many sections at one site exhibited early distresses that truly necessitated rehabilitation. Based on the number of sections at each site in the SPS-1 experiment that received rehabilitation at the same time despite varying AC pavement cross-sections, it can be concluded that the timing of rehabilitation of these sections is not representative of the performance of these AC pavements or of agency practices.

In contrast, rehabilitations of PCC pavement sections in the SPS-2 experiment were mostly conducted for individual sections rather than multiple sections at a site. As shown in Table 4.8, those sites for which more than one section was rehabilitated were done so at different times (evident by the minimum and maximum values), with the exception of site 10-02. This could be due to the rehabilitation treatments selected. Slab replacement and grinding were the only rehabilitation treatments applied for the SPS-2 sections, which are more conducive to short sections as opposed to AC overlays. The time to first rehabilitation for these PCC pavement sections ranged from 2.6 to 18.9 years. At one site alone, the time to first rehabilitation among the PCC pavement sections ranged from 3.4 to 18.9 years. This wide range accounts for the variation in structural factors investigated as part of the SPS-2 experiment. As discussed previously, layer thickness, base type, base thickness, and the use of drainage layers were varied among the sections at each site. Therefore, it is expected that the performance, and thus, the need (and timing) for rehabilitation would vary as well. Based on the rehabilitation of individual PCC pavement sections, the timing to first rehabilitation of sections in the SPS-2 experiment is more representative of actual practices. However, the average time to first rehabilitation for the 18 pavement sections listed in Table 4.8 is biased toward site 10-02, in which 8 pavement sections with varying structural factors were rehabilitated at the same time. In the interest of understanding the time of first rehabilitation, these 8 sections represent the timing to first rehabilitation for only one pavement. In evaluating it in this manner, the average time to first rehabilitation for the 11 PCC pavement sections in the SPS-2 experiment was 9.8 years. Although the timing at which these pavements were rehabilitated may be representative of actual practices, the pavement cross-sections themselves may not have been representative of typical PCC designs, as structural factors were varied among the multiple sections at each site. This also holds true for the SPS-1 AC pavements, which also explored variations in structural factors. For these reasons, experiments SPS-1 and SPS-2 were excluded from further analysis.

Existing AC and PCC pavement sections were utilized in the SPS-5 and SPS-6 experiments, respectively, which evaluated rehabilitation treatments and combination of treatments. Existing jointed PCC pavements included in the SPS-7 experiment (bonded PCC overlay of concrete pavements) received one of eight combinations of bonded concrete treatments (*20*). Experiments SPS-9C, SPS-9J, and SPS-9O evaluated AC overlays on existing CRCP, JPCC, and AC pavements, respectively. Based on the nomination criteria, the timing at which the first rehabilitation was applied in the LTPP dataset should be representative of agencies' practices and typical distresses associated with rehabilitation.

AC pavements included in the SPS-9N experiment were newly constructed or reconstructed to examine aspects of implementing Superpave mix design. It is unclear how much mix designs were varied and the possible impact on performance, and therefore, timing of rehabilitation. For this reason, SPS-9N was excluded from further analysis.

Although strategic studies of structural factors for flexible (SPS-1) and rigid (SPS-2) pavements were excluded, they served to illustrate the importance of evaluating SPS experiments by pavement site rather than individual pavement sections. This is especially important when conducting the analysis for actual service life of existing pavements that were included in the rehabilitation experiments (SPS-5, SPS-6, and SPS-7) and Superpave overlay experiments, SPS-9O, SPS-9C, and SPS-9J. These experiments featured various sites across the country. Although each site consisted of multiple existing pavement sections, those sections consisted of the same pavement, and therefore, had equal or similar cross-sections (minor geospatial variations due to construction are expected), distress, and construction history. While the multiple sections at a site were used to evaluate various rehabilitation treatments, the intent of this study is to understand the time at which the first rehabilitation was applied. Given that these multiple test sections at a site are the same roadway and cross-section, considering the actual service life of these sections would create bias towards sites with more sections, as they were typically rehabilitated at the same time or within the same timeframe. Therefore, the average time to first rehabilitation was determined for a site. Table 4.9 shows the average time among the sites within an experiment. The minimum, maximum, and standard deviation of the time to first rehabilitation among the sites in each experiment are also reported in Table 4.9. The time to first rehabilitation among the pavement sections at each site within each experiment, as shown for SPS-1 and SPS-2 experiments earlier, are tabulated in Appendix J.

Table 4.9 Summary of Time to First Rehabilitation, SPS Experiments with Existing Pavements

Exp. No.	Surface Type	No. of Sites	Age at First Rehabilitation, Years			
			Avg	Min	Max	Std. Dev.
SPS-5	AC	17	19.6	9.0	31.3	5.48
SPS-9O	AC	7	25.0	6.0	33.2	10.01
SPS-6	PCC	14	24.8	17.2	32.0	5.55
SPS-7	PCC	4	23.2	12.9	34.8	9.20
SPS-9C	PCC	2	22.9	21.8	22.8	N/A
SPS-9J	PCC	6	28.2	23.0	39.6	6.41

The average time to the first rehabilitation was slightly higher for the AC pavements in the SPS-5 (rehabilitation of AC pavements) and SPS-9O (AC overlay on AC pavement) experiments than results found in the GPS-1 (AC on granular base) and GPS-2 (AC on bound base) experiments, as shown in Table 4.5. The highest average time to first rehabilitation was approximately 25 years for pavement sites in the SPS-9O experiment, a service life that extends seven years beyond the average service life for the GPS-1 experiment (AC pavement on granular base). It should be noted that there are much fewer data from which the average time to first rehabilitation was determined for the AC and PCC pavements in the SPS experiments, as shown in Table 4.9. On the other hand, the average time to the first rehabilitation for PCC pavements in SPS experiments conducted on existing pavement sections was more consistent with the times for the GPS-3 (JPCP), GPS-4 (JRCP), and GPS-5 (CRCP) experiments, as shown in Table 4.5.

4.3 Determining Time to First Major Rehabilitation by Pavement Type

To examine the time to first rehabilitation based on the original surface type, experiments with like surface type were combined based on the evaluation completed above for each experiment. Given the limitations associated with newly constructed pavements as part of LTPP, only the experiments conducted on existing pavements were included. For AC pavements, the times to first rehabilitation for the pavement sections from GPS-1 (on granular base) and GPS-2 (on bound base) experiments were combined with the times to first rehabilitation for AC pavement sites from the SPS-5 (rehabilitation of AC pavements) and SPS-9O (AC overlay on AC pavement) experiments. Similarly, for PCC pavements, the times to first rehabilitation for the pavement sections from GPS-3 (JPCP), GPS-4 (JRCP), and GPS-5 (CRCP) experiments were combined with the times to the first rehabilitation for pavement sites from the SPS-6 (rehabilitation of JPCP), SPS-7 (bonded PCC overlay of concrete pavements), SPS-9C (AC overlay on CRCP), and SPS-9J (AC overlay on JPCP) experiments. The distribution of the time to first rehabilitation was plotted for each pavement type in Figures 4.3 and 4.4. Distributions for both AC and PCC pavements, as shown in Figures 4.3 and 4.4, respectively, appear to be normal. The distributions represent the time to first rehabilitation for existing pavements across the U.S. and Canada. As such, the distributions include varying state and provincial practices, mix designs, and materials; varying climatic regions; and functional classifications. Therefore, it is expected that some distribution of the data would exist. The largest number of AC pavements (48 of 229) indicate a period between 15 and 18 years to first rehabilitation. The distribution of the PCC pavements was fairly uniform between 15 and 30 years, and does not display a definitive peak. The 50th percentile of the cumulative distribution is at a time of rehabilitation between 21 and 24 years, which is the center of this uniform period.

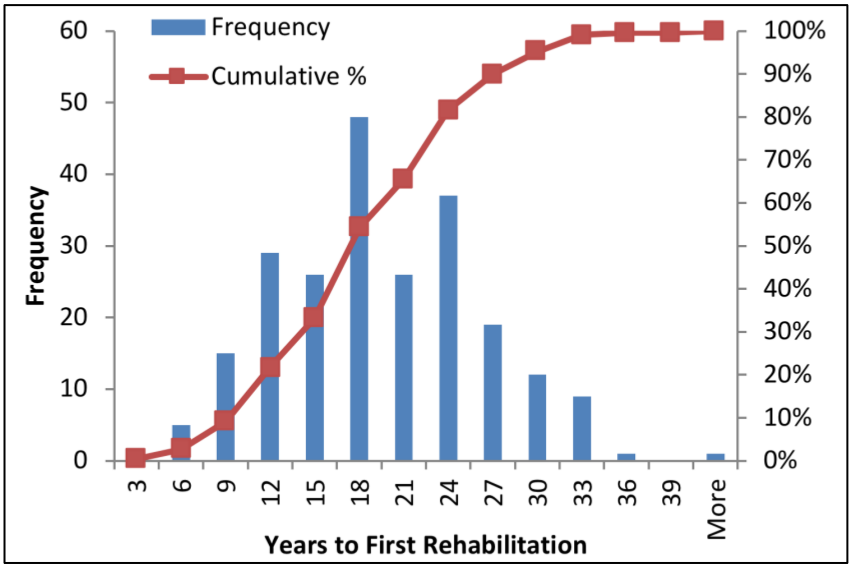


Figure 4.3 AC Pavements, Distribution of Time to First Rehabilitation

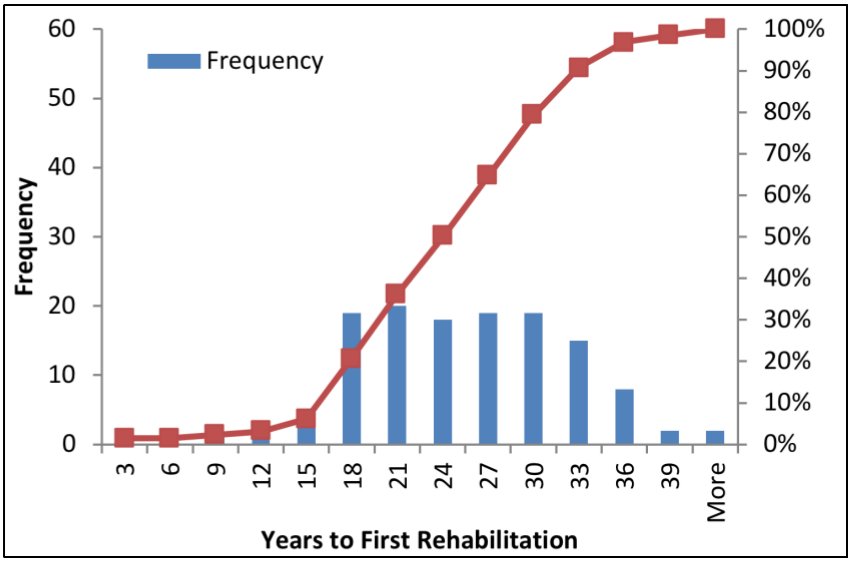


Figure 4.4 PCC Pavements, Distribution of Time to First Rehabilitation

Table 4.10 summarizes the statistics computed by Microsoft Excel for the time to first rehabilitation (actual initial service life) for each pavement type. The average time to first rehabilitation for AC pavements was found to be 17.93 years, with 95% confidence that the mean falls between 17.05 and 18.82 years. On average, the time to first rehabilitation for PCC pavements was found to be 23.84 years. The time to first rehabilitation for PCC pavements was slightly more variable, resulting in a wider 95% confidence interval of 22.60 to 25.08 years. The actual initial service life for AC pavements is slightly positively skewed; as such, the median value of 17.14 years is less than the mean. Opposite of this, the PCC pavements had a median time to first rehabilitation of 23.90 years, slightly larger than the mean time, and therefore had a negative skew. The minimum and maximum values were very similar among the two pavement types; however, as noted previously, the minimum values are unrealistic and are likely outliers. The coefficient of variation computed as the ratio of the standard deviation to the mean was higher for AC pavements (37.9%) than for PCC pavements (30.0%).

Table 4.10 Descriptive Stastitics for Time to First Rehabilitation

Statistic	**AC**	**PCC**
Mean	17.93	23.84
Standard Error	0.45	0.63
Median	17.14	23.90
Mode	21.22	21.91
Standard Deviation	6.80	7.16
Sample Variance	46.21	51.20
Kurtosis (Excess)	-0.15	0.44
Skewness	0.24	-0.21
Range	41.04	41.32
Minimum	0.07	1.12
Maximum	41.11	42.44
Sum	4106.07	3099.06
Confidence Level (95%)	0.89	1.24
Count	229	130

As noted previously, reporting errors may exist by using LTPP experiments conducted on existing pavements. This may account, in part, for the wide ranges in the time to first rehabilitation and the very short service lives, which are the minimum values found for each pavement. Despite the wide ranges, there are not a significant number of pavement sections on either end of the distribution, as evident in Figures 4.3 and 4.4. To guard against possible erroneous values, the data could be limited to the middle 90% of the distribution. Assuming a normal distribution for each pavement type, the upper and lower boundaries for the middle 90% are determined by the equations below, where σ is the standard deviation and μ is the mean. This results in lower and upper boundaries of 6.71 and 29.15 years for AC pavements and 12.03 years and 35.64 years for the PCC pavements. The data outside of these boundaries were removed and the average, minimum, and maximum pavement ages at the time of first rehabilitation were determined for the data in the middle 90% of each pavement type. These values are summarized in Table 4.11. While (in theory) the mean value remains the same, as the normal distribution is assumed to be symmetrical about the mean, in practice, the mean may shift slightly depending on how much the distribution is skewed positive or negative. In the case of the AC pavements, the mean time to first rehabilitation decreased slightly to 17.68 years; however, the mean remained the same for PCC pavements.

$$\text{Lower Boundary} = -1.65\sigma + \mu$$

$$\text{Upper Boundary} = 1.65\sigma + \mu$$

Table 4.11 Summary of Middle 90% of Pavement Ages at Time of First Rehabilitation

Pavement Type	No.	Avg	Min	Max	Std Dev
AC	206	17.7	7.1	28.9	5.51
PCC	121	23.8	12.9	35.4	5.79

Although pavement sections as part of the LTPP experiments considered herein included the U.S. and Canada, the majority of the pavements (188 of 206 AC pavements and 117 of 121 PCC pavements) were in the U.S. Therefore, it is reasonable to consider the values shown in Table 4.11 as those representative of practices across the U.S. However, because DOT practices can vary, the national averages for time of first rehabilitation may not reflect the averages in a particular state. Previous studies have examined the historical time to first rehabilitation for individual states. Minnesota DOT completed a study in 2003 in which their pavement management database was used to determine the average and median ages of AC pavements at the first overlay and of jointed concrete pavements at the first joint repair (*11*). Both the average and median ages reported for AC pavements were 19 years, slightly longer than the average and median times found here for pavements all across the U.S. and parts of Canada. Minnesota DOT reported that joint repairs historically occurred, on average, at 18 years, while the median age was 15 years. Researchers examined the age that non-doweled concrete pavements were historically rehabilitated in Georgia, reporting an average age of 17 years and minimum and maximums of 10 and 29 years, respectively (*12*). Ages when PCC pavements have been historically rehabilitated in both Minnesota and Georgia are much lower than the mean and median ages for the PCC pavements in the LTPP experiments evaluated here. However, these values for Georgia and Minnesota are just two examples of historical pavement age at the time of first rehabilitation for AC and PCC pavements.

The 2003 Minnesota DOT study determined the historical time of first rehabilitation as a basis for developing estimates for initial service life in LCCA (*11*). As reported in Section 2, many agencies have or continue to use historical values to estimate initial service life estimates for LCCA. In comparing earlier responses to the 2007 Mississippi DOT survey and surveys issued for the study conducted for South Carolina DOT shown in Table 2.1 (*6, 7*), the majority of DOTs reported a value for initial service life in LCCA between 10 and 15 years (or the range of 10 to 15 years) for AC pavements. Those values are between three and eight years sooner than the national average (17.7 years) for first rehabilitation of AC pavements. For PCC pavements, the majority of DOTs were using an initial service life of 20 to 25 years, as indicated by the survey responses (*6, 7*) and summarized in Table 2.1. These values are well aligned with the average age of 23.8 years found in the LTPP experiments investigated in this study.

To determine if there were trends associated with pavement type, region, climatic zone, or functional classification, the times to first rehabilitation were further examined for each parameter and each pavement type, which are discussed in the subsections below. For the following evaluations, the middle 90% of the distribution was utilized for AC and PCC pavements as described in Table 4.11.

4.3.1 By Pavement Type

The average, minimum, maximum, and standard deviation for the time to the first rehabilitation were summarized for LTPP experiment analyzed, as shown in Table 4.12, to reflect the middle 90% of the distribution for each AC and PCC pavement. For the AC and PCC pavements in the GPS experiments, the average pavement age at the first rehabilitation did not vary much from the values shown in Table 4.5 for 100% of the distribution. AC pavements on granular base had an average pavement age of 17.9 years, just slightly more than one year longer than AC pavements on bound base. The three PCC pavements in the GPS experiments, JPCP, JRCP, and CRCP, were rehabilitated when the pavement was between 23.4 and 23.9 years, on average. As was the case with 100% of the distribution, AC pavements in the SPS experiment were left in service longer than those in the GPS experiment, on average. This was also true for two of the SPS experiments for PCC pavements: SPS-6 and SPS-9J.

Table 4.12 Statistics for Time to First Rehabilitation by AC and PCC Pavement Types

Exp No.	Pavement Type	No. of Sections	Age at First Rehabilitation, Years			
			Avg	Min	Max	Std Dev
GPS-1	AC on Granular base	111	17.9	7.1	28.2	5.36
GPS-2	AC on Bound base	76	16.8	7.8	28.9	5.70
GPS-3	JPCP	41	23.4	14.7	34.7	5.98
GPS-4	JRCP	27	23.9	15.1	35.4	5.68
GPS-5	CRCP	28	23.8	14.8	33.7	6.11
SPS Experiments – Based on Averages at Pavement Sites						
Exp No.	**Pavement Type**	**No. of Sites**	**Avg**	**Min**	**Max**	**Std Dev**
SPS-5	AC	16	18.9	9.0	25.8	4.74
SPS-9O	AC	3	24.0	16.9	28.2	6.20
SPS-6	PCC	14	24.8	17.2	32.0	5.55
SPS-7	PCC	4	23.2	12.9	34.8	9.20
SPS-9C	CRCP	2	22.3	21.8	22.8	N/A
SPS-9J	JPCC	5	25.9	23.0	30.3	3.51

4.3.2 By Region

Four regions were established at the onset of the LTPP program: the North Atlantic, North Central, Southern, and Western regions, as shown in Figure 4.5. Statistics for the time to first rehabilitation for each pavement type are presented for each region below in Table 4.13. Data were not evenly distributed geographically for either pavement type. In the case of AC pavements, only 11% were located in the North Central region, while the remaining regions, North Atlantic, Southern, and Western, accounted for 30%, 31%, and 28%, respectively, of the total 206 AC pavements. The opposite was true for PCC pavements. The highest number was in the North Central region, accounting for nearly 57% of the 121 PCC pavements.

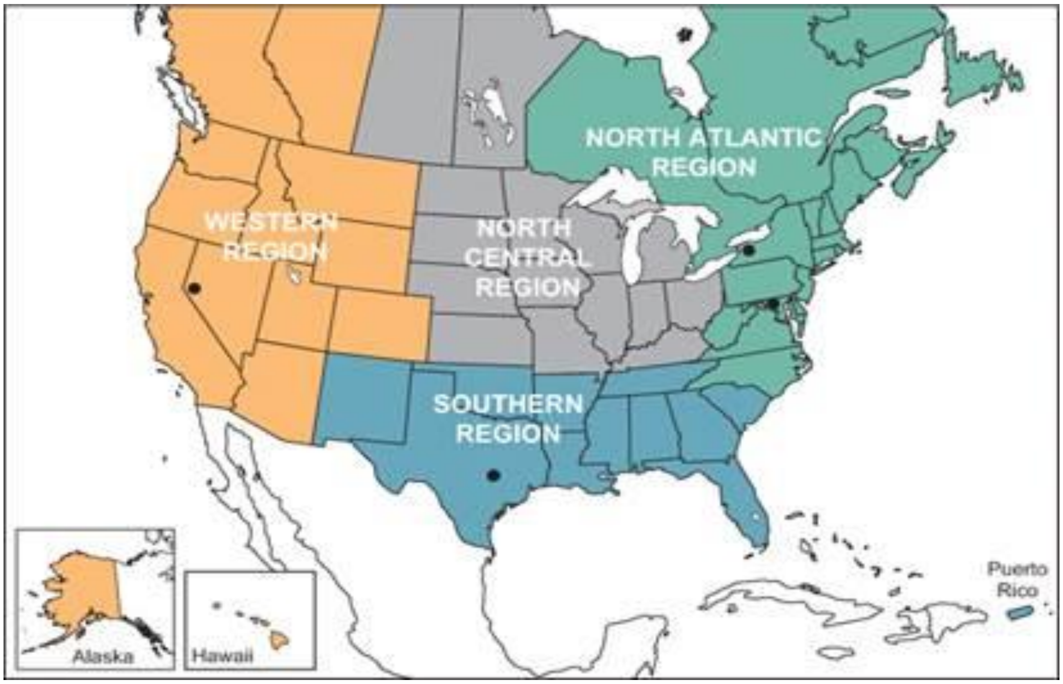


Figure 4.5 Map of LTPP Regions (*19*)

Table 4.13 Statistics for Time to First Rehabilitation by Pavement Type and LTPP Region

	AC Pavements					
Region	**No.**	**Avg**	**Min**	**Max**	**Std. Dev.**	**Coefficient of Variation**
North Atlantic	61	17.9	8.0	28.2	6.25	34.9%
North Central	23	19.4	10.7	26.5	4.44	22.9%
Southern	64	16.9	7.8	28.8	5.21	30.9%
Western	58	17.6	7.1	28.9	5.34	30.3%
	PCC Pavements					
Region	**No.**	**Avg**	**Min**	**Max**	**Std. Dev.**	**Coefficient of Variation**
North Atlantic	19	22.0	15.0	33.1	6.33	28.4%
North Central	69	23.7	14.7	35.4	5.74	24.1%
Southern	16	26.0	12.9	33.1	5.94	22.9%
Western	17	24.2	17.1	31.3	5.23	21.6%

AC pavements in the North Central region remained in service longer than in the other regions, at 19.34 years on average before receiving the first rehabilitation. Data from this region were also the least variable. The average time to first rehabilitation for AC pavements in the remaining regions were closer to the overall average of 17.7 years. PCC pavements were left in-service the longest, on average, in the Southern region at 26.0 years before receiving the first rehabilitation. The average time to first rehabilitation for PCC pavements in the North Central region most closely matched the overall average of 23.8 years.

4.3.3 By Climatic Zone

Although four geographic regions were identified based roughly on climatic conditions, the geographic regions were not delineated solely on the basis of climate. Therefore, four climatic zones were also established, as shown in the map in Figure 4.6. The climatic zones group areas together based on moisture or rainfall (wet or dry) and temperature (freeze or non-freeze). These climatic zones are wet, freeze; wet, non-freeze; dry, freeze; and wet, non-freeze. The times to first rehabilitation for each climatic zone are summarized for AC and PCC pavements in Table 4.14. The vast majority of the AC pavements were located in the wet, non-freeze climatic zone, representing 53% of the AC pavements included in the investigation. For the PCC pavements, 66% were located in the wet-freeze climatic zone.

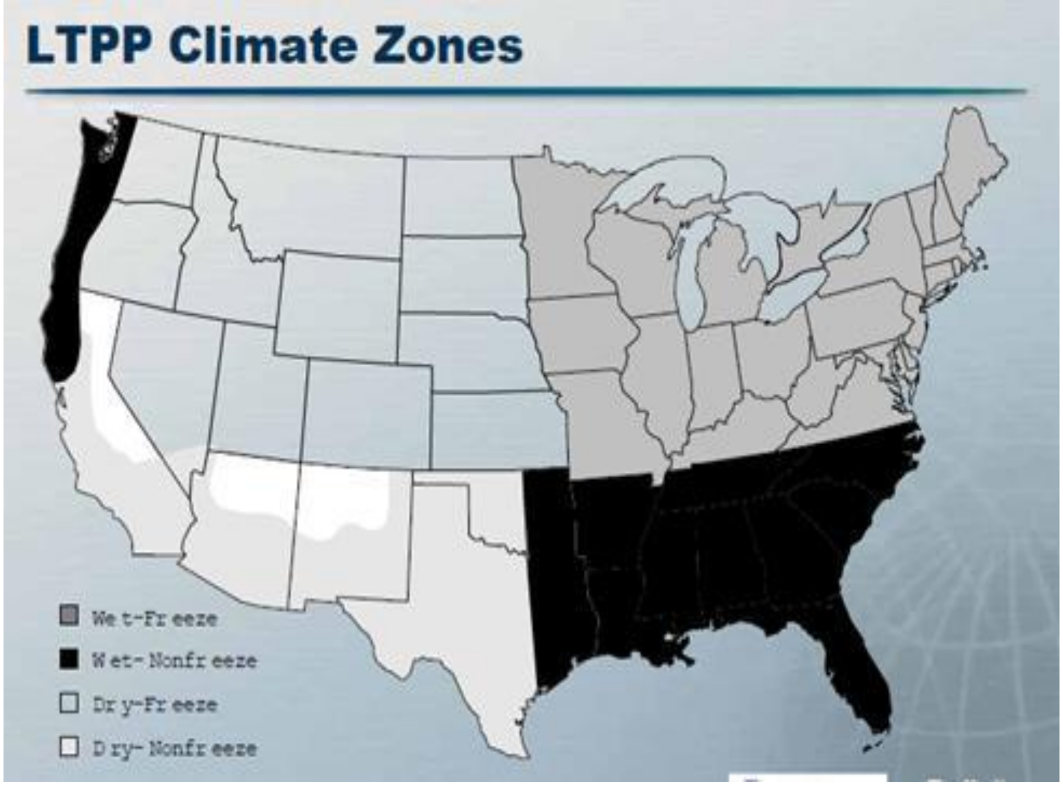


Figure 4.6 Map of LTPP Climate Zones (*27*)

Table 4.14 Statistics for Time to First Rehabilitation by Pavement Type and Climatic Zone

	AC Pavements					
Climatic Zone	**No.**	**Avg**	**Min**	**Max**	**Std. Dev.**	**Coefficient of Variation**
Dry, Freeze	24	15.0	7.1	26.3	5.11	34.0%
Dry, Non-freeze	23	19.7	7.8	27.0	4.63	23.5%
Wet, Freeze	50	20.0	8.8	28.2	5.46	27.3%
Wet, Non-freeze	109	16.8	7.8	28.9	5.33	31.8%
	PCC Pavements					
Climatic Zone	**No.**	**Avg**	**Min**	**Max**	**Std. Dev.**	**Coefficient of Variation**
Dry, Freeze	10	23.8	15.8	31.3	5.83	28.4%
Dry, Non-freeze	6	24.5	17.1	30.3	5.81	23.7%
Wet, Freeze	80	23.5	14.7	35.4	5.79	24.7%
Wet, Non-freeze	25	24.9	12.9	33.7	5.98	24.0%

The average time to first rehabilitation for PCC pavements did not vary much among the four climatic zones, with the shortest average pavement age at 23.5 in the wet, freeze zone and the longest at 24.5 in the dry, non-freeze zone. The number of pavements within each zone makes it difficult to draw any conclusions regarding the actual time to first rehabilitation for PCC pavements, particularly for those in the dry climate zones.

There was much more variability between climatic zones for the AC pavements, such that pavement age at the time of the first rehabilitation ranged from 15.0 to 20.0 years among the four zones. The dry, freeze zone accounted for the shortest average time to first rehabilitation of AC pavements while the wet, freeze zone accounted for the longest average time. For AC pavements in dry climates, pavements remained in-service 4.7 years longer on average in the warmer, non-freeze climate than in the freeze climate. The opposite was true for AC pavements in wet climates with pavements in the wet, freeze zone left in-service on average 3.2 years longer than in the wet, non-freeze zone.

4.3.4 By Functional Classification

The AC pavements included in this investigation were further examined by the functional classification of the routes for which they were placed. Table 4.15 summarizes the time to first rehabilitation for AC pavements. The vast majority of the AC pavements were located on rural routes. The highest number of AC pavements, 52% of the 206, were located on routes classified as “rural principal arterial – other.” The second and third most frequent routes were “rural principal arterial – interstate,” and “rural minor arterial,” respectively. Each remaining route classification represents a small portion of the total dataset. Among the three most frequent functional classifications, the average time of first rehabilitation ranged from 17.4 to 18.1 years. Due to the limited data available for other rural routes and urban routes, it is difficult to draw conclusions regarding average time to first rehabilitation based on the functional classification of the route.

Table 4.15 Summary of Time to First Rehabilitation for AC Pavements by Functional Classification

Functional Classification	No.	Avg	Min	Max	Std. Dev.
Rural Major Collector	4	12.6	8.9	15.7	3.32
Rural Minor Arterial	26	17.8	7.8	28.8	6.44
Rural Minor Collector	2	14.0	12.2	15.8	N/A
Rural Principal Arterial - Interstate	49	18.1	7.8	28.2	5.00
Rural Principal Arterial - Other	107	17.4	7.1	28.9	5.45
Urban Minor Arterial	1	24.4	24.4	24.4	N/A
Urban Other Principal Arterial	5	19.3	8.8	26.1	7.50
Urban Principal Arterial - Interstate	7	19.6	9.3	26.9	6.64
Urban Principal Arterial - Other Freeways or Expressways	5	19.4	15.9	24.3	3.95

The data for the time to first rehabilitation of PCC pavements are summarized by functional classification in Table 4.16. Fewer PCC pavements were available than AC pavements, and this is also reflected in the number of different functional classifications represented. Only six different functional classifications accounted for the 121 PCC pavements. As was the case with AC pavements, the majority of the PCC pavements were also on rural routes. The highest frequency of PCC pavements were on rural interstates, and the second highest were on “rural principal arterial – other.” Approximately 14% of the total were on urban interstates. There were too few PCC pavements on the remaining three functional classifications to draw comparisons. In looking at the three most frequent classifications, on average, the shortest time to first rehabilitation occurred on urban interstates, while the longest time occurred on “rural principal arterial – other.”

Table 4.16 Summary of Time to First Rehabilitation for PCC Pavements by Functional Classification

Functional Classification	No.	Avg	Min	Max	Std. Dev.
Rural Minor Arterial	5	28.9	23.4	32.8	3.69
Rural Principal Arterial - Interstate	60	23.5	12.9	32.3	5.31
Rural Principal Arterial - Other	33	24.4	14.7	32.3	6.48
Urban Other Principal Arterial	4	21.9	15.5	34.8	8.79
Urban Principal Arterial - Interstate	17	23.0	15.1	35.4	5.78
Urban Principal Arterial - Other Freeways or Expressways	2	22.7	19.3	26.0	N/A

4.4 Summary

The LTPP database was utilized to examine the actual time at which rehabilitation was conducted for AC and PCC pavements across the country. The LTPP program encompassed a number of experiments for each pavement type falling into either the General Pavement Studies (GPS) or the Specific Pavement Studies (SPS). As the name implies, the SPS experiments had very specific objectives while the GPS experiments were broader and focused on the performance of different types of AC and PCC pavements.

For this study, focus was placed on the experiment to which a pavement was first assigned. Under GPS, pavement sections were first assigned to one of five experiments based on the pavement type. These pavement sections were 500 feet in length and consisted of existing in-service pavements across the U.S. and parts of Canada. After entry to the LTPP program, pavement sections (GPS or SPS) could be reassigned based on maintenance and rehabilitation activities and objectives of other LTPP experiments. SPS experiments may consist of existing in-service pavements or newly constructed pavements. Unlike the GPS experiments, SPS experiments consisted of multiple 500-foot pavement sections at a project site along the same route. Project sites across the U.S. and Canada were selected based on specific objectives of the SPS experiment. For those SPS experiments consisting of newly constructed pavements, pavement sections at a project site were varied based on the experimental design. In SPS-1 and SPS-2 experiments, pavement sections varied by structural factors such as thickness and the presence or absence of a drainage layer. For those SPS experiments utilizing existing in-service pavements, pavement sections at a site varied by the type of preventive maintenance activities, rehabilitation activities, or overlays.

For this study, the time at which the first rehabilitation was conducted in a pavement's life was of interest; therefore, experiments utilizing only existing in-service pavements were selected. These experiments included GPS experiments one through five. Also included were SPS experiments that focused on rehabilitation techniques on existing pavements. As noted, SPS experiments conducted on existing in-service pavements consisted of multiple pavement sections at a site. These existing pavement sections were along the same route and thus, were subjected to the same or very similar traffic and roughly shared the same pavement structure. Although different rehabilitation activities were applied, they were often applied at approximately the same time. Therefore, the average pavement age at the time of the first rehabilitation for the pavement sections at a site was utilized to represent one pavement to reduce bias due to the multiple pavement sections.

Like pavement types (AC or PCC) were combined to determine the average time to first rehabilitation. The average timing of the first rehabilitation for AC pavements was found to be 17.93 years with 95% certainty that the mean was between 17.05 and 18.82 years. The median of the 229 AC pavements was 17.14 years. PCC pavements were rehabilitated later in their life, with an average time of first rehabilitation of 23.84 years and a 95% confidence interval for the mean of 22.60 to 25.08 years. The median for the 130 PCC pavements was 23.90 years.

To guard against possible erroneous values (such as the very short time to first rehabilitation found in each AC and PCC pavement dataset and shown as the minimum values in Table 4.5), the data could be limited to the middle 90% of the distribution. Assuming a normal distribution for each pavement type, the upper and lower boundaries for the middle 90% were determined, resulting in lower and upper boundaries of 6.71 and 29.15 years for AC pavements, and 12.03 years and 35.64 years for the PCC pavements. The middle 90% of the distribution for AC pavements included 206 pavement sections, and 121 sections were included in the middle 90% of the distribution of PCC pavements. Using these boundaries, the datasets were further examined by pavement type, geographic region, climatic zone, and functional classification of the roadways.

The timing of the first rehabilitation was summarized for each GPS and SPS experiment, as shown in Table 4.12. On average, AC pavements on granular bases were rehabilitated approximately one year later than AC pavements on bound bases. AC pavements included in the SPS experiments examined here were rehabilitated later than the AC pavements utilized in GPS experiments, with an average timing of first rehabilitation at 19.6 and 25.0 years. On average, PCC pavements in the GPS experiments were rehabilitated within less than one year of one another with pavement ages ranging from 23.4 to 23.9 years. For PCC pavements in the SPS experiments, CRCP pavements were rehabilitated the earliest, on average, while JPCC pavements were left in-service the longest prior to the first rehabilitation, on average.

It was found that the North Central region was associated with the longest average time to first rehabilitation for AC pavements at 19.4 years, while the Southern region was associated with the longest average time for PCC pavements at 26.0 years. The North Atlantic region was found to be the most variable for both pavement types.

As might be expected, due to the known influence moisture and low temperatures have on pavement damage, the dry, non-freeze climate was associated with the longest time to first rehabilitation for AC pavements. For AC pavements in climatic zones with wet conditions, longer times to first rehabilitation were shown in freeze areas as opposed to non-freeze, on average. Differences in the average pavement age at the time of first rehabilitation of PCC pavements in the four climatic zones were not prominent, with the largest difference in average pavement age amounting to just 1.4 years.

The majority of the AC and PCC pavements included in the LTPP experiments that were investigated for this study were under rural principal arterials classifications. While too few pavements were associated with many of the functional classifications for the AC pavements, the pavement ages at the time of first rehabilitation among the three most frequent functional classifications were within one year of each other. Pavement ages for three functional classifications (“rural principal arterial – other,” “rural principal arterial – interstate,” and “rural minor arterial”) ranged from 17.4 to 18.1 years. For PCC pavements on “rural principal arterial – other’” and “rural principal arterial – interstate,” the time to first rehabilitation was longer with average pavement ages of 24.4 and 23.5, respectively. The third most frequent functional classification for PCC pavements, “urban principal arterial – interstate,” had the shortest time to first rehabilitation with an average pavement age of 23.0 years.

By compiling this LTPP data from across the U.S. and Canada, it allows insight into whether the initial service life used in LCCA is representative of the actual timing of the first rehabilitation for AC and PCC pavements. Looking back at the earlier responses to the 2007 Mississippi DOT survey and surveys issued for the study conducted for South Carolina DOT shown in Table 2.1 (*6, 7*), the majority of DOTs reported a value between 10 and 15 years (or the range of 10 to 15 years).

These initial service lives used in LCCA are between three and eight years sooner than the national average, as shown in Table 4.11 as 17.68 years. As indicated by the survey responses summarized in Table 2.1 (*6, 7*), the majority of DOTs were using an initial service life of 20 to 25 years for PCC pavements, which aligns well with the average age of 23.84 years that PCC pavements were found to be rehabilitated in the LTPP experiments investigated here. While the results found in this study may not affect LCC for PCC pavements (i.e., the longer average time to first rehabilitation), they may have an impact on LCC for AC pavements.

5 PAVEMENT CONDITION DETERIORATION

Agencies often determine the initial pavement service life for use in LCCA by considering historical averages of pavement age at the time of first rehabilitation. However, not all pavements are rehabilitated when their performance measures reach the rehabilitation thresholds for various reasons. Thus, the initial service life of AC and PCC pavements should ideally be determined based only on a subset of historical data of pavements that have been rehabilitated based on common performance thresholds.

The previous section sought to determine national averages for AC and PCC pavements in the LTPP experiments GPS-1 through GPS-5 and SPS-5 through SPS-7, and SPS-9O for the actual timing of the first rehabilitation. Those averages were compared with agencies' responses to the questionnaire presented in Section 3. While some agencies utilize thresholds for pavement condition or condition indices as criteria for rehabilitation, the pavement condition indicators as well as the thresholds varied by agency and for each pavement type. LCCA is most often used to compare two competing alternatives, and in doing so, one important assumption should hold true—the alternatives provide the same level of benefit to the users. For DOTs, these two competing alternatives are AC and PCC pavements. As such, the indicator for user benefit or pavement performance and associated threshold should be equivalent between the two pavements, and it is the time it takes to reach that threshold that determines the initial service life.

Agencies are required to report the condition and performance of their roadways annually as part of HPMS (*3*). Specifically, the data requirements for the 11 surfaces considered in HPMS are shown in Table 5.1. Shown in Table 5.1 are the performance metric data required for each surface type, indicated by the unit of measure for IRI, the range of values for PSR, and the precision for rutting and faulting. The HPMS field manual also provides brief descriptions for the cracking percent to be reported for each pavement type. Only two types of pavement condition indicators are common to both AC and PCC pavements: cracking and roughness. Although cracking is required for almost all surface types, the type of cracking (fatigue, punchouts, longitudinal, cracked slabs, etc.) and actual measurements (area of fatigue cracking, number of slabs cracked as a percentage of total slabs, etc.) varies by pavement type, as shown in Table 5.1. Pavement roughness is reported through either PSR or IRI. PSR is a subjective composite rating of pavement performance that includes roughness on a scale of 0.1 to 5.0, where 0.1 represents a pavement that is extremely deteriorated or failed and has significant ride discomfort, and 5.0 represents a new pavement or newly resurfaced pavement with no distress and a very smooth ride. PSR can be reported rather than IRI for routes on NHS where the posted speed limit is less than 40 mph.

Table 5.1 Required HPMS Data by Surface Type (*3*)

Pavement Type	IRI	PSR	Rutting	Faulting	Cracking %
Unpaved					
Bituminous	in/mi	0.1 – 5.0	0.1 in		Fatigue % area
JPCP	in/mi	0.1 – 5.0		0.1 in	% cracked slabs
JRCP	in/mi	0.1 – 5.0		0.1 in	% cracked slabs
CRCP	in/mi	0.1 – 5.0			Punchout/long./ patch % area
AC Overlay on AC	in/mi	0.1 – 5.0	0.1 in		Fatigue % area
AC Overlay on JCP	in/mi	0.1 – 5.0	0.1 in		Fatigue % area
AC Overlay on CRCP	in/mi	0.1 – 5.0	0.1 in		Fatigue % area
Unbonded JCP Overlay on PCC	in/mi	0.1 – 5.0		0.1 in	% cracked slabs
Bonded PCC Overlay on PCC	in/mi	0.1 – 5.0		0.1 in	% cracked slabs
Other (e.g. brick)	in/mi	0.1 – 5.0			

Prior to the publication of proposed performance measures for MAP-21, a study was published in 2012 aimed at defining “a consistent and reliable method of assessing infrastructure health with a focus on bridges and pavements on Interstate Highway System” (*28*). As part of that study, researchers were tasked with developing a consistent approach for categorizing pavements as good, fair, or poor. A pilot study was conducted consisting of data from three DOTs to explore the use of various parameters for evaluating pavement condition: 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 was any correlation among the data sets. Among the condition measures evaluated (IRI, cracking percentage, cracking length, rutting, and faulting), a high level of confidence in the data was found only for IRI. It was also reported that IRI does not fully represent the condition of the pavement, particularly the ability of the pavement structure to withstand traffic loadings. However, based on the findings, it was recommended that IRI be used as a good/fair/poor indicator at the national level (*28*).

As part of MAP-21, DOTs are required to establish targets and report progress in the near future for four performance measures dependent on pavement type, including IRI, cracking, rutting for

AC pavements, and faulting for PCC pavements (*4*). Although IRI and cracking are required for both AC and PCC pavements, cracking types and the associated MAP-21 thresholds differ by pavement type.

As pointed out in the FHWA report, "Study of LTPP Distress Data Variability, Volume I," there is substantial variability associated with manual crack ratings (*29*). As a result, automated crack data collection methods as outlined in the AASHTO Automated Cracking Data Standards for Collection and Analysis and AASHTO Standards PP67-14 and PP68-14 have become increasingly popular among DOTs. However, different automated methods for crack detection and data collection exist. There is a nationally recognized need to unify data reporting and standardize pavement crack definitions. In response, NCHRP Project 01-57A (previously NCHRP Project 01-57) was initiated and is currently in progress to "develop standard, discrete definitions for common cracking types in flexible, rigid, and composite pavements" (*5*). It is anticipated that the results of the NCHRP study will aid DOTs in sharing information as well as reporting for federal requirements and "setting national, state, and local performance goals" (*5*).

While different parameters exist to evaluate ride quality, pavement roughness is defined and measured in the same manner regardless of pavement type. PSR is a subjective rating of pavement performance that includes roughness; however, IRI is an objective and repeatable measure of roughness defined in ASTM E 867 as the amount a longitudinal profile deviates from a true planar surface. 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 (*30, 31*). Qualitative categories for IRI were published in 2000 to help agencies translate between the perceived pavement roughness rated with PSR and the measured IRI values, as shown in Table 5.2 for Interstates. As part of the national performance measures for MAP-21, good, fair, and poor IRI were defined by the FHWA in 2017, also shown in Table 5.2 (*4*).

Table 5.2 FHWA IRI Categories (*4*, *32*)

	IRI Categories of Roughness (in/mi)				
Agency	**Very Good**	**Good**	**Fair**	**Poor**	**Very Poor**
FHWA (2000)	< 60	60 – 94	95 – 119	120 – 170	> 170
FHWA (2017)		< 95	95 – 170	> 170	

Although cracking may provide an understanding of how a pavement is degrading, pavement roughness is often "considered the pavement condition indicator that best reflects the publics' perception of the overall condition of a pavement section" (*33*). Given the importance of pavement roughness to the traveling public and the unified definition and measurement across all pavement types, pavement roughness measured by IRI enables the best comparison of level of performance between pavement types.

5.1 Importance of IRI in Determining Initial Service Life

It was found in Section 3 that although the use of IRI varies among DOTs, it is commonly utilized in the decision-making process for rehabilitation. Whether IRI is used directly, as a rehabilitation trigger, or indirectly as part of a condition index, it was found to play a role in the determination of actual service life. As discussed previously, initial service life utilized in LCCA should also reflect current practice. Previous research demonstrates that IRI can be used in estimating initial service life.

In the 2005 study of service life of HMA pavements in LTPP experiments, researchers estimated the expected time for pavements not yet rehabilitated to reach low, moderate, or excessive levels of distress (*10*). The expected service life was determined based on the probability of occurrence for each of the following six distresses: fatigue cracking, longitudinal cracking in the wheelpath, rutting, longitudinal cracking outside the wheelpath, transverse cracking, and roughness. According to the researchers, moderate level of roughness, 2.1 m/km to 2.5 m/km (133.1 in/mi to 158.4 in/mi), "is the amount of roughness that typically will trigger some type of rehabilitation activity." Similarly, moderate levels for the other five distresses signified the amount of distress that would typically trigger some type of rehabilitation. The time for AC pavements to reach this level of roughness was estimated at 22 years. This value was the same time for AC pavements to reach moderate levels of each rutting, longitudinal cracking outside the wheelpath, and transverse cracking (*10*). Of the six distresses investigated, these four distresses marked the shortest estimated time for AC pavements to reach a moderate level of distress.

The importance of IRI in the estimation of initial service life was evident in the 2008 study conducted for Kansas DOT (*13*). Although survival analyses were conducted to estimate service life based on age, a performance analysis was also conducted to determine the service life of AC and PCC pavements based on a performance threshold for IRI alone. The threshold was determined by identifying the mean IRI values at the time of light or heavy maintenance and rehabilitation from which a common threshold value was established. Using PMS data, the relationship between IRI and age was modeled, which was in turn used to determine the age at which the pavement had reached or would reach the IRI threshold (the expected service life) for each pavement type (*13*).

In a study aimed at evaluating the performance and life cycles of concrete pavements in Georgia, "faulting index in conjunction with roughness and cracking-related distresses were recommended as the primary performance indicators for identifying the end of service" (*12*). However, the authors ultimately determined service life separately for historical times of major rehabilitation (or AC overlay) and for the time needed to reach a faulting index threshold.

A more recent study was conducted to determine the time to rehabilitation for Superpave asphalt pavements in Colorado (*9*). Similar to the 2005 study on LTPP HMA pavements, the expected time to first rehabilitation was estimated based on individual distresses (roughness, permanent deformation, fatigue cracking, transverse cracking, and longitudinal cracking). The rate of change of each distress was determined for each pavement section. Using the average rate of change in distress, the average distress for the last year of available data, and threshold values from the Colorado DOT 2015 M-E Pavement Design Manual, the time to reach each threshold was estimated. This was completed for each functional classification as well as a statewide average. Based on the statewide averages, it was concluded that rehabilitation/reconstruction was triggered first by IRI, with an estimated time to reach the IRI threshold of 160 in/mi on interstate pavements of 13 years. The estimated time on all other routes statewide to reach 200 in/mi was reported as 19 years (*9*).

As noted above, previous research has been conducted to estimate expected service life at the national level using LTPP data (*10*); however, the estimates were limited to AC pavements and were based on a survivability analysis of pavements not yet rehabilitated. Moreover, service life was estimated using predetermined thresholds for individual distresses (including IRI); however, the threshold values were not validated based on actual distress values at the time of rehabilitation. Although other researchers identified a common IRI threshold for AC and PCC pavements based on mean IRI values at the time of rehabilitation, the value was limited to roadways in Kansas (*13*). IRI bridges the performance criteria between AC and PCC pavements, enabling it to be used for evaluating equal levels of performance in unlike pavement types. Therefore, there is a need to understand IRI values at the time of first rehabilitation and to determine the rate at which IRI progresses, or in other words, the rate at which ride quality deteriorates. The remaining subsections delve into the LTPP pavement sections to determine IRI values just prior to their first rehabilitation as well as the IRI values over time leading up to the first rehabilitation to understand the increase in pavement roughness with pavement age.

5.2 Roughness at First Rehabilitation

Due to the limited IRI data available for SPS pavement sections prior to rehabilitation as well as the issues discussed in Section 4.2.2 regarding the early rehabilitation of pavement sections at project sites, SPS data was excluded entirely from the evaluation of the deterioration of the pavements with respect to IRI over time. Therefore, only pavement sections that had not received rehabilitation prior to entry into the LTPP program and were initially entered into the program in one of the following GPS experiments were utilized: GPS-1 (AC on granular base), GPS-2 (AC on bound base), GPS-3 (JPCP), GPS-4 (JRCP), or GPS-5 (CRCP).

As noted in Section 4.3, the middle 90% of the AC and PCC distributions can be used to guard against erroneously reported times of first rehabilitation or values not representative of typical pavement performance or practices. The middle 90% was determined for age at first rehabilitation of each pavement type using the combination of SPS sites and GPS sections, as described in section 4.3. The lower and upper boundaries of the middle 90% for each pavement type are listed below.

- AC pavements
    - Lower boundary: 6.7 years
    - Upper boundary: 29.2 years
- PCC pavements
    - Lower boundary: 12.0 years
    - Upper boundary: 35.6 years

The upper and lower boundaries from the middle 90% were applied to the aforementioned GPS experiments. In doing so, the data were filtered to include only pavement sections that were rehabilitated for the first time between the boundaries listed above for the respective pavement type.

Using this dataset, the IRI data were obtained for the GPS pavement sections prior to the first rehabilitation. Although the middle 90% of the AC pavements included 206 pavement sections and the middle 90% of the PCC pavements included 121 pavement sections, roughness measurements (using inertial profilers to obtain IRI values) were not made on every pavement section prior to rehabilitation. As a result, the available pavement sections in the U.S. and Canada with time of first rehabilitation within the upper and lower boundaries and those including IRI value(s) prior to rehabilitation included 166 AC pavement sections and 90 PCC pavement sections.

The IRI at the time of rehabilitation is of interest to better understand the performance of each pavement type at the time the first rehabilitation was perceived necessary. Therefore, an analysis of the last IRI value measured prior to the application of the first rehabilitation activity is presented first. Further analysis is presented later in this section to examine the deterioration of the pavements with respect to roughness over time. Although the most complete and consistent dataset (LTPP) was used for this analysis, there are limitations with the data that should be noted. First, the last IRI measurement may have been obtained as much as four years prior to the first rehabilitation. Additionally, detailed measurements on pavement sections in the GPS experiment are not available prior to acceptance into the LTPP program. Therefore, the available IRI measurements in the LTPP database often do not span the entire life of the pavement. IRI is reported for each wheelpath and the average of the two wheelpaths, referred to as mean IRI or MRI. To remain consistent with the reporting requirements for HPMS and MAP-21, MRI was used for these evaluations. When IRI was measured for the LTPP projects, replicate measurements were generally made with the inertial profiler on a given day in which IRI was measured in the left and right wheelpaths. For each run, MRI was calculated and stored in the LTPP database as the mean IRI of the two wheelpaths. Averages of the replicate MRI values for each date were calculated and utilized in the analyses presented in the following subsections.

5.2.1 Roughness Prior to First Rehabilitation by Pavement type

Roughness measured prior to the first rehabilitation was examined by pavement type to gain an understanding of the approximate MRI at the time of rehabilitation. The number of GPS sections as well as the average, median, minimum, maximum, standard deviation, and 95% confidence interval for the last replicate MRI values before the first rehabilitation for each pavement type are listed in Table 5.3. On average, AC pavements were smoother than PCC pavements at the time of rehabilitation. However, based on the standard deviation, AC pavements were much more variable. The average MRI for both AC and PCC pavements were approximately equidistant from 120 in/mi, an early value used to delineate between fair and poor roughness and utilized by the FHWA in 2000 to translate PSR to IRI (*32*). The average MRI values just prior to the first rehabilitation for both AC and PCC pavements contrast sharply with the thresholds agencies use to categorize ride quality of their pavements as “rough” or “poor.” As discussed in Section 3.2.3, four agencies reported values of 170 in/mi or greater, and one agency, Pennsylvania, indicated a value of 150 in/mi as the boundary between fair and poor ride quality, all of which are much greater than the average MRI found for either AC or PCC pavements just prior to rehabilitation. Only one agency, Nevada DOT, reported an IRI value classifying interstate pavements as "rough" in tune with the average MRI value found here. Nevada DOT's value of 115 in/mile falls between the average MRI for AC and PCC pavements, as shown in Table 5.3.

Table 5.3 Summary of Last MRI Value before First Rehabilitation 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

The maximum MRI value prior to rehabilitation was exceptionally high for both pavement types, with maximum MRI values much greater than the 170 in/mi considered unacceptable in FHWA's categories for MAP-21 shown in Table 5.2 (*4*). Additionally, both AC and PCC pavements had minimum values representative of very smooth pavements.

The median MRI values were less than the average MRI by approximately 10 in/mi and 13 in/mi for PCC and AC pavements, respectively. The median MRI values fell within FHWA's fair category of 96 in/mi to 120 in/mi, as shown in Table 5.2, although the value for AC pavements was at the low end and the value for PCC pavements was at the high end of this range. Shown in Figures 5.1 and 5.2 are the distributions of MRI values for AC and PCC pavements. Median values less than the average MRI values are likely due to the long right tails of the distributions.

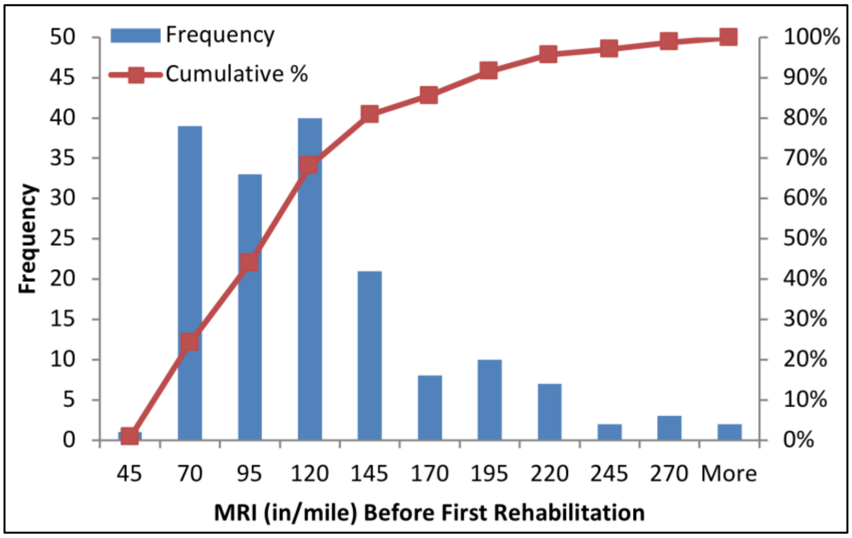


Figure 5.1 Distribution of MRI Prior to First Rehabilitation for AC Pavements

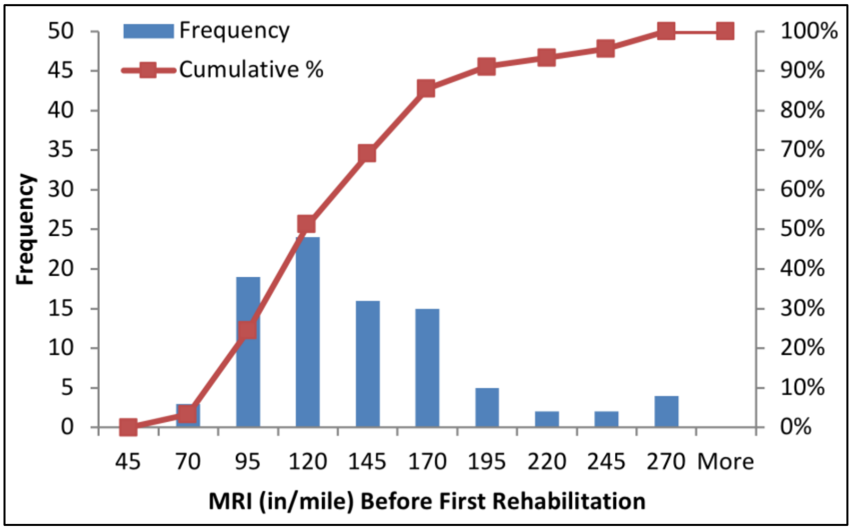


Figure 5.2 Distribution of MRI Prior to First Rehabilitation for PCC Pavements

The distribution in Figure 5.2 for PCC pavements shows a clear peak for MRI prior to rehabilitation at greater than 95 in/mi and less than or equal to 120 in/mi. Although the distribution for AC pavements shares the same peak, pavements with MRI values greater than 45 in/mi and less than or equal to 70 in/mi occurred almost as frequently, indicating that AC pavements with good or very good ride quality were rehabilitated almost as frequently as AC pavements with fair ride quality. To explore this in more detail, the IRI categories shown in Table 5.2 were applied to the distributions shown above.

The percentage of the total pavement sections for which the average MRI prior to rehabilitation falls into each FHWA category is listed in Table 5.4 While the frequencies of pavements are grouped in Figures 5.1 and 5.2 at even intervals for MRI, the categories defined by the FHWA are not at even intervals. As a result, the data show that AC pavements with good ride quality based on the last available average MRI value prior to rehabilitation were rehabilitated more frequently than pavements in any other ride quality category. The pattern for PCC pavements was opposite to this with more pavements having poor ride quality prior to rehabilitation than any other ride quality category. Unacceptable ride quality was defined by the FHWA in the 1998 National Strategic Plan as an IRI greater than 170 in/mi (*34*). As shown in Table 5.4, the percentage of total pavement sections with MRI values prior to rehabilitation in this category was nearly equivalent for both AC and PCC pavements at just over 14%. The data presented in Table 5.4 suggests that rehabilitation occurs on AC pavements well before reaching unacceptable levels and that AC pavements are more likely to have good ride quality prior to rehabilitation, while PCC pavements are more likely to reach poor ride quality before rehabilitation occurs.

Table 5.4 Ride Quality (IRI) Prior to Rehabilitation

Pavement Type	Percentage of Total Pavement Sections				
	Very Good** < 60	Good 60 – 94	Fair 95 – 119	Poor 120 – 170	Very Poor > 170
AC Pavements	9.6%	34.3%	24.1%	17.5%	14.5%
PCC Pavements*	1.1%	23.3%	26.7%	34.4%	14.4%

*Sum is not 100% due to rounding **Categories after *(32)*

The last MRI values measured prior to the first rehabilitation were further broken down by experiment type to evaluate if there were any notable differences. As shown in Table 5.5, AC pavements with a granular base were rougher on average than AC pavements on a bound base just prior to the first rehabilitation. However, both fell into the fair category (95 – 119 in/mi) on FHWA's scale (see Table 5.2). For PCC pavements, CRCPs were much smoother on average than JPCP and JRCPs just prior to receiving the first rehabilitation activity. Both JPCP and JRCPs had an average MRI prior to rehabilitation greater than 120 in/mi, the early threshold used by the FHWA to describe pavements with poor roughness. The minimum MRI values for these PCC pavement types were also notably greater than CRCP. Although the minimum values would both be considered good, the shift indicates that JPCP and JRCPs were consistently rougher than CRCPs prior to rehabilitation.

Table 5.5 Summary of Last MRI Value before First Rehabilitation by Experiment

Exp. No.	Pavement Type	No.	Avg MRI (in/mi)	Min MRI (in/mi)	Max MRI (in/mi)	Std. Dev.	Coefficient of Variation
	AC Pavements						
GPS-1	AC on Granular base	101	119.1	30.2	359.0	58.9	49.42%
GPS-2	AC on bound base	65	102.0	49.9	260.4	43.8	42.89%
	PCC Pavements						
GPS-3	JPCP	41	138.9	81.3	260.7	50.3	36.20%
GPS-4	JRCP	22	130.9	86.0	229.2	32.9	25.10%
GPS-5	CRCP	27	112.4	48.3	257.9	45.7	40.65%

5.2.2 Roughness Prior to First Rehabilitation by Climatic Zone

Differences also existed for AC and PCC pavements among the four climatic regions, as shown in Table 5.6. The majority of the AC pavements (52% of the pavement sections) were located in the wet, non-freeze climate, where the average MRI just prior to the first rehabilitation was approximately 106 in/mi with a fairly high coefficient of variation (approximately 44%). Using the categories established by the FHWA, as shown in Table 5.2, the average MRI values for AC pavements prior to first rehabilitation in the "dry, non-freeze" zone fell into the very good ride quality category. AC pavements in the "dry, freeze" and "wet, non-freeze" zones fell into the fair category, while the average MRI values for the "wet, freeze" zone were within the poor ride quality category.

Table 5.6 Summary of Last MRI Value before First Rehabilitation by Climatic Zone

Climatic Zone	No.	Avg MRI (in/mi)	Min MRI (in/mi)	Max MRI (in/mi)	Std. Dev.	Coefficient of Variation
	AC Pavements					
Dry, Freeze	21	116.4	47.4	214.4	40.1	34.43%
Dry, Non-freeze	20	81.7	46.5	136.6	24.2	29.57%
Wet, Freeze	39	139.6	60.0	359.0	72.6	52.02%
Wet, Non-freeze	86	106.2	30.2	260.4	46.7	43.97%
	PCC Pavements					
Dry, Freeze	9	117.7	72.5	228.4	47.3	40.20%
Dry, Non-freeze	6	102.2	75.1	154.0	29.8	29.18%
Wet, Freeze	56	138.7	48.3	260.7	45.8	33.01%
Wet, Non-freeze	19	114.1	64.7	257.9	45.2	39.66%

Nearly 62% of the 90 PCC pavements were located in the wet, freeze climatic region. The average MRI prior to rehabilitation for PCC pavements in this climatic region fell into the poor category for ride quality using the FHWA categories presented in Table 5.2. PCC pavements representing the other three climatic regions had average MRI values in the fair category prior to rehabilitation.

It is expected that the freeze/thaw cycles that pavements in the wet, freeze climates are subjected to would result in rougher pavements, while dry, non-freeze climates would result in smoother pavements. This was the case for both AC and PCC pavements. Pavements in the wet, freeze climate were the roughest AC pavements, on average. PCC pavements in the wet, freeze climate were also the roughest PCC pavements among the four climatic regions, where the average MRI prior to rehabilitation was nearly identical to that of AC pavements (approximately 140 in/mi). AC pavements in this climatic region were also the most variable, having a coefficient of 52% and the largest range in roughness. While the PCC pavements in the wet, freeze climate were less variable than the AC pavements in the same climate, they also represented the largest span in pavement roughness for PCC pavements among the four climates. AC pavements in the dry, non-freeze climate were the smoothest pavements just prior to rehabilitation, falling into the FHWA category of good. PCC pavements in the dry, non-freeze climate were also the smoothest PCC pavements among the four climates. However, the average MRI prior to rehabilitation was 20 in/mi greater than AC pavements in the same climatic region. MRI prior to rehabilitation was very similar between AC and PCC pavements in the dry, freeze zone, and likewise, AC and PCC pavements in the wet, freeze climate were nearly equivalent. However, there were differences in MRI values among the non-freeze climatic zones.

5.3 Ride Quality Deterioration

An investigation into the deterioration of ride quality (also referred to as the progression of pavement roughness) was conducted for the same GPS experiments from the LTPP as discussed in the previous subsections. All average MRI values collected prior to the first rehabilitation were plotted against pavement age at the time of the IRI measurement for each pavement type in

Figure 5.3. As noted earlier, due to the nature of the LTPP GPS experiments, detailed data may not be available for the entire life of the pavement, especially during the early portion of a pavement's life. As a result, for some pavement sections, there were only one or two dates in which IRI measurements were taken prior to rehabilitation, while for other pavement sections, measurements were collected on a much more frequent interval. Although only one MRI value is plotted per date for a pavement section in Figure 5.3, a single value represents the average of several MRI values determined from the replicate IRI measurements taken on a given date.

As shown in the figure below, MRI values generally tend to increase with time, as would be expected; as pavements age and experience structural and functional distresses, they also become rougher. Attaching a linear trend line to the data for simplicity reveals that the progression in pavement roughness (or decrease in ride quality) with age, which is evident by a positive slope, appears to be more rapid for AC pavements than PCC pavements. Whereas, the PCC pavements tend to have a much flatter trend line associated with the data. Neither trend line indicates a strong relationship between pavement age and MRI, as coefficient of determination (R^2) values for the linear trend lines are both very low. Other functions such as exponential or power functions were explored and were not found to improve the fit of the data for either AC or PCC pavements. The data in the plot for AC pavements in Figure 5.3 includes two types of asphalt pavements, AC on granular base and AC on bound base. Similarly, the plot for PCC pavements includes three types of concrete pavements: JPCP, JRCP, and CRCP. Additionally, both plots in Figure 5.3 represent data from the U.S. and parts of Canada and include pavements in all four climatic regions. As was completed in previous sections, the degradation of ride quality was further investigated for climatic region as well as experiment type.

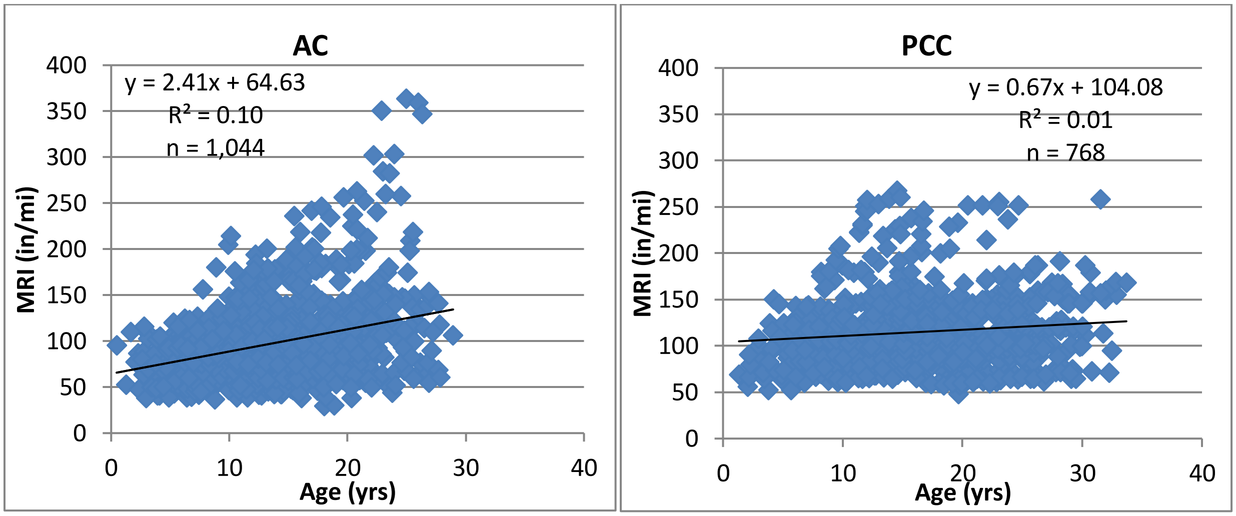


Figure 5.3 Pavement Roughness Progression by Pavement Type, LTPP GPS Pavement Sections

5.3.1 *By Experiment Type*

To explore if any trends exist among the types of AC and PCC pavements, the MRI values prior to rehabilitation were plotted against pavement age for the individual GPS experiments that represent different AC and PCC pavement types. As was conducted above, the mean IRI (MRI) values associated with the pavement sections in the middle 90% of the distribution for actual initial service life were utilized to explore the progression of pavement roughness up to the time of the first rehabilitation.

In Figure 5.4, pavement roughness with age is plotted separately for AC pavements on granular base (GPS-1 experiment) and AC pavements on bound base (GPS-2 experiment). Both plots are very similar to the plot for AC pavements shown in Figure 5.3 in that a positive trend in pavement roughness with pavement age is illustrated and that a linear trend line drawn through the data reveals that R^2 values are both low at less than 15%. The progression of pavement roughness was greater for AC pavements on granular base than AC pavements on bound base, as indicated by a slope of 2.77 inches per mile per year (in/mi/yr) for pavements in the GPS-1 experiment compared to 1.58 in/mi/yr for pavements in the GPS-2 experiment.

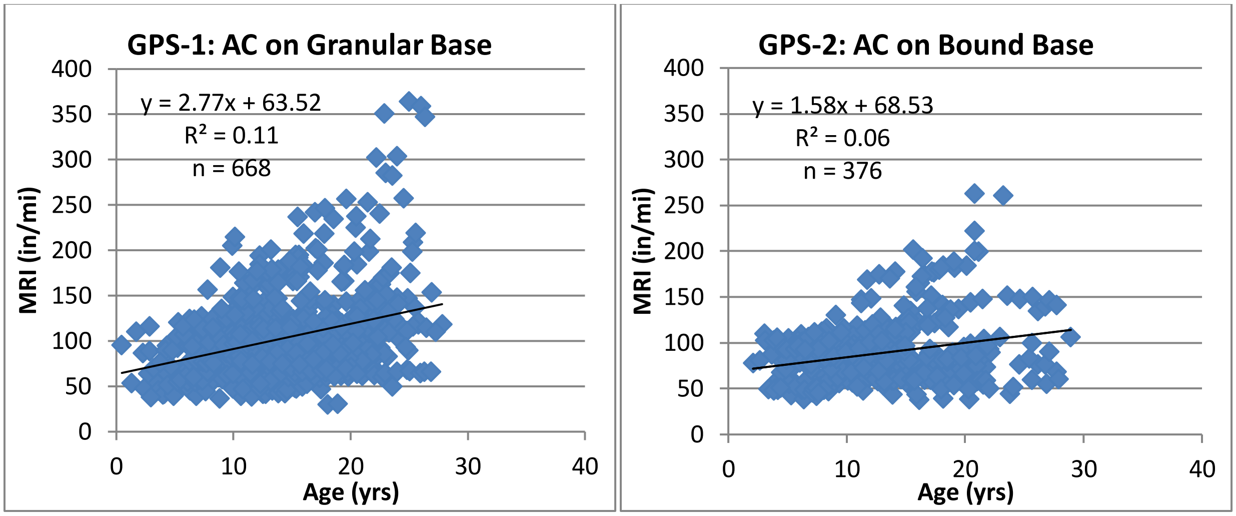


Figure 5.4 Pavement Roughness Progression for AC Pavements: GPS-1 and GPS-2 Experiments

As was done for the AC pavements, PCC pavements were plotted separately for each pavement type as denoted by the experiment number, JPCP (GPS-3), JRCP (GPS-4), and CRCP (GPS-5), in Figure 5.5. For only one PCC pavement type (i.e., JPCP), did the data indicate a positive trend in pavement roughness with age, as shown by a slope for the attached linear trend line of 1.72 in/mi/yr, which falls in between the rate of deterioration found in AC pavements on granular bases and AC pavements on bound bases. JPCP pavements also showed the strongest R^2 value for the linear relationship between pavement age and pavement roughness among the three PCC pavement types, albeit it was a rather poor value of 7%. The linear trend lines for the remaining PCC pavement types were nearly flat with slopes less than 0.25 in/mi/yr, and as such, the coefficients of determination were nearly zero.

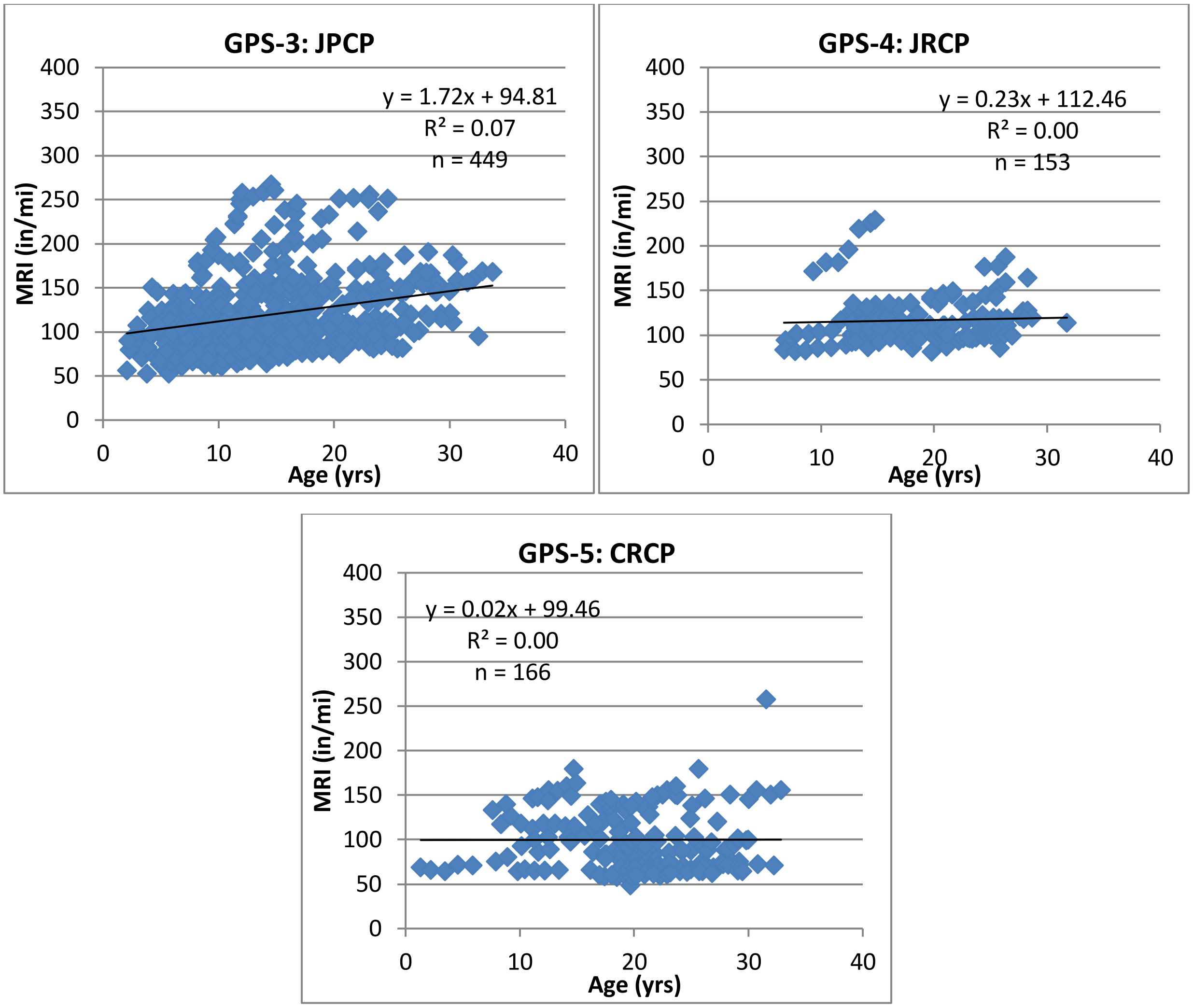


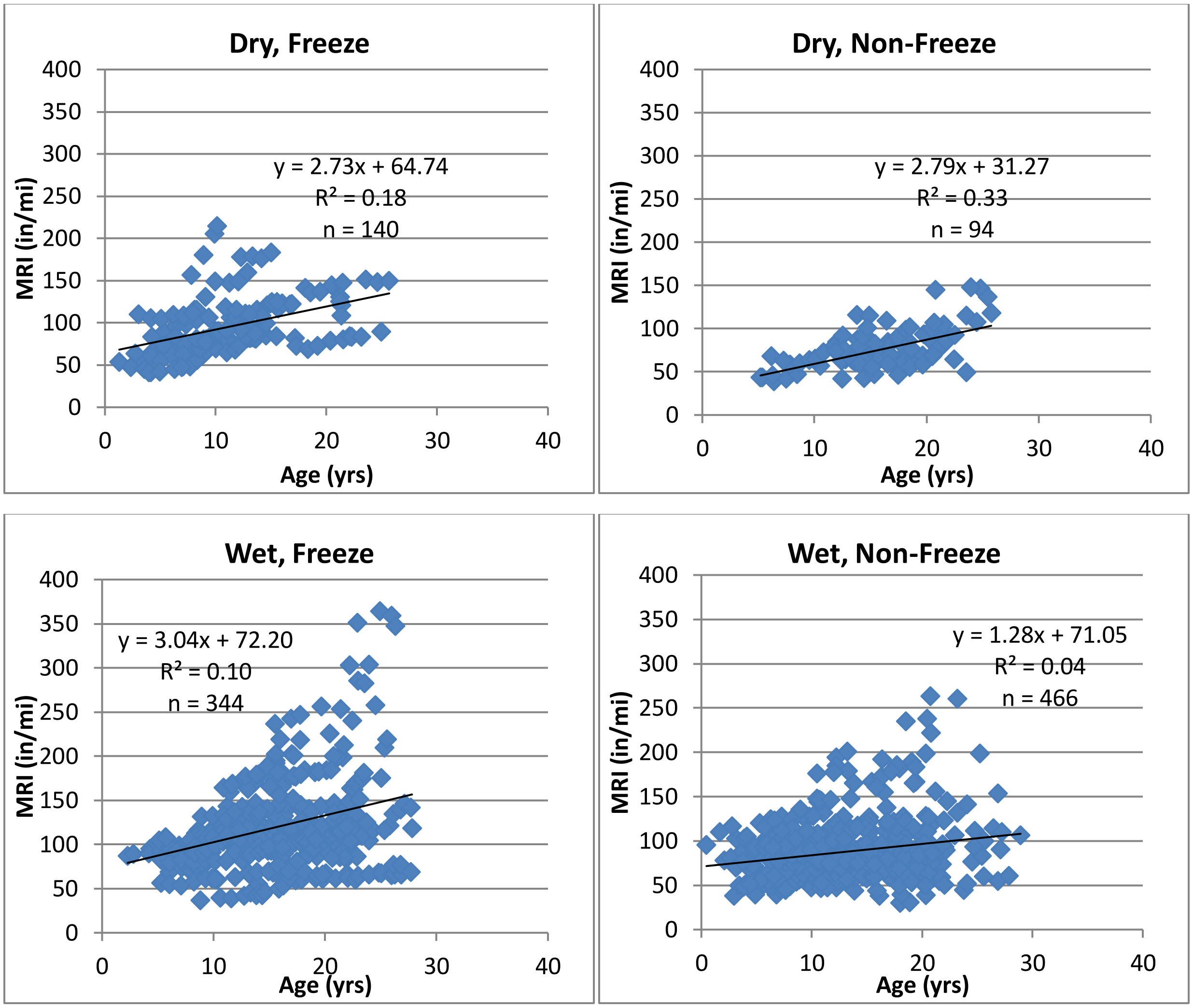
Figure 5.5 Pavement Roughness Progression for PCC Pavements: GPS-3, GPS-4, and GPS-5 Experiments

Although collectively, the data for each pavement type do not appear to have a strong relationship between pavement age and pavement roughness, AC pavements on granular base and JPCP indicate higher MRI values and general increases in pavement roughness with age. Furthermore, there are strings of data evident in each plot that show progression of pavement roughness over time. These strings of data are likely individual pavement sections, indicating that the rate at which pavement roughness develops is specific to the individual pavement itself. Therefore, the deterioration of pavement ride quality over time for individual pavement sections is further examined in a later subsection.

5.3.2 By Climatic Zone

As evident in previous subsections, the climatic zone impacts both the age at which rehabilitation is conducted and the pavement roughness just prior to rehabilitation. Therefore, the development of pavement roughness was also examined for AC and PCC pavements by climatic zone.

In Figure 5.6, MRI for AC pavements prior to rehabilitation are plotted against the age of the pavement at the time of the MRI measurement for each climatic zone. A linear trend line was also drawn for each plot to provide insight into the rate of deterioration of ride quality in each climatic zone. AC pavements in the dry climate showed the strongest linear relationship with 18% and 33% for the dry, freeze and dry, non-freeze climates, respectively. These two climatic regions also had very similar rates of deterioration of ride quality ranging from 2.73 in/mi/yr to 2.97 in/mi/yr. As expected, AC pavements in the wet, freeze climate tended to develop pavement roughness at a faster rate than the other three climatic zones, although the rate of deterioration was not much greater than that found for pavements in a dry climate. Additionally, pavements in wet conditions have greater scatter in the data with higher MRI values, as evident by the increased data points above 200 in/mi, especially for the older AC pavements.


Dry, Freeze

Dry, Non-Freeze

Wet, Freeze

Wet, Non-Freeze

Figure 5.6 Pavement Roughness Progression by Climatic Region, LTPP Flexible Pavement Experiments, GPS-1 and GPS-2

Pavement roughness in terms of MRI is plotted against pavement age for PCC pavements in each of the four climatic zones in Figure 5.7. Similar to AC pavements, PCC pavements in the dry, non-freeze climate appear to have the strongest linear relationship between pavement age and MRI with both having an R^2 of 33% for the linear regression. The dry, non-freeze climatic zone also represented the smallest subset of data for both pavement types. Unlike the AC pavements, PCC pavements in the wet, freeze climate tended to have the smallest rate of deterioration of ride quality. However, similar to AC pavements in the wet, freeze climate, there is a large amount of scatter in the data with MRI values exceeding 200 in/mi. Consistent with the previous plots for PCC pavements, the progression of pavement roughness tended to be relatively flat for most of the climatic zones.

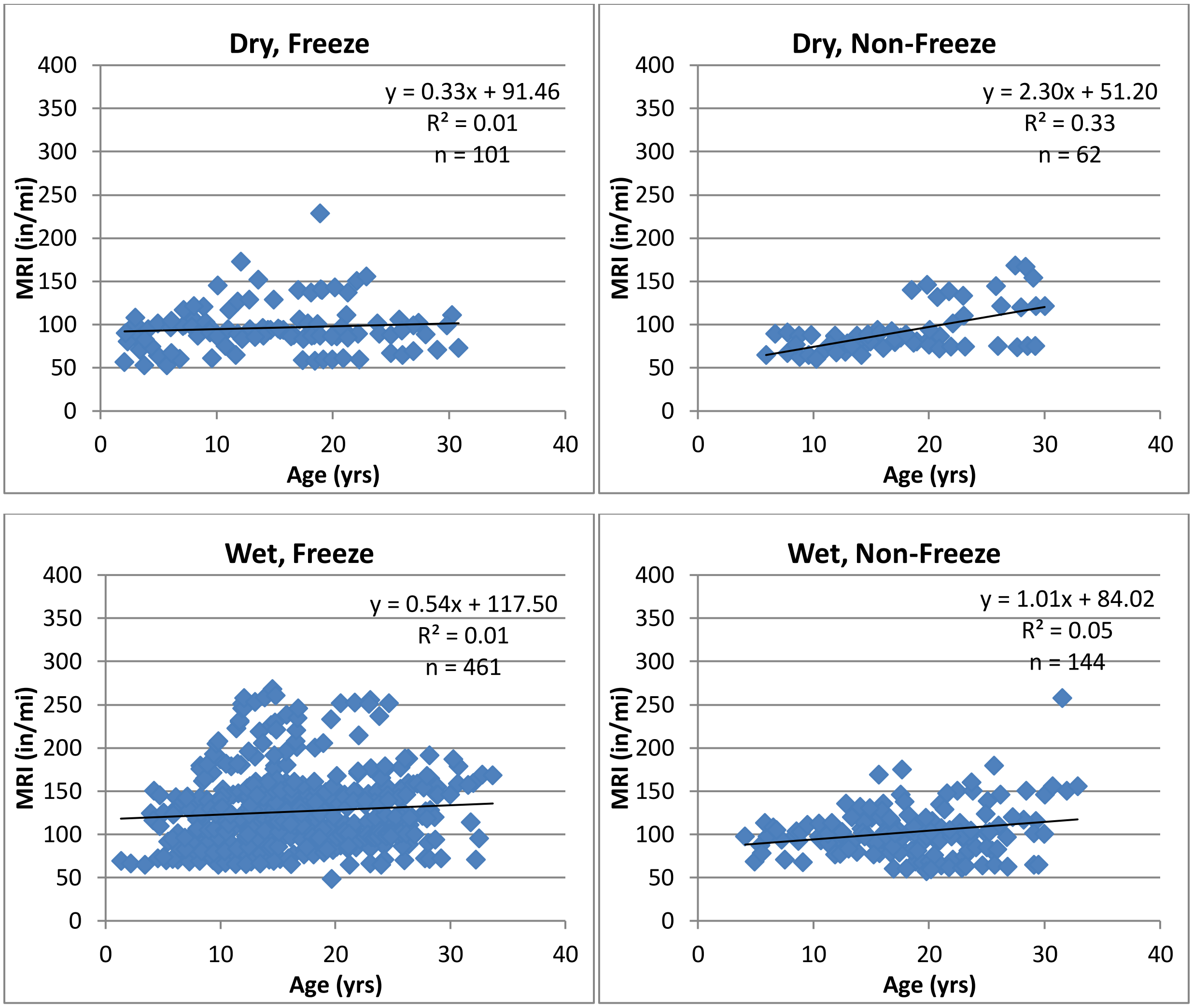


Figure 5.7 Pavement Roughness Progression by Climatic Region, LTPP Flexible Pavement Experiments, GPS-3, GPS-4 and GPS-5

5.3.3 Rate of Deterioration by Pavement Section

While there are general trends illustrated when MRI is plotted over time up to the first rehabilitation, there is substantial scatter in the data for both AC and PCC pavements. This scatter remains when the data are further examined for climatic zones and for individual pavement types (e.g. JRCP or CRCP). However, as was noted in Section 5.3.1, there are some trends among individual pavement sections that stand out in these plots. For example, in Figure 5.6 for AC pavements in the dry, freeze climate, there is a set of data that increases with time but is much lower than the linear trend line, starting at 17.28 years and 72.5 in/mi and continuing until 24.93 years and 89.3 in/mi. This string of data corresponds to all of the available MRI values prior to the first rehabilitation for pavement section 16-1007, where 16 indicates the state identifier code (Idaho) and 1007 is the identifying code for the pavement section. Similarly, in Figure 5.5 for PCC pavements in the GPS-4 experiment (JRCP pavements), there is an obvious string of data points that deviate from the flat progression of MRI over time for the remaining data points in the plot. This string of data points refers to MRI over time for pavement section 54-4004. It appears that although there is scatter (and low R^2 values) among the plots of MRI over time when looking at the data collectively for AC or PCC pavements, there may be much stronger relationships for individual pavement sections.

It should be kept in mind that the previous plots shown in subsections 5.3.1 and 5.3.2 present data for pavement sections that include several MRI values over time, prior to rehabilitation, as well as sections that have only one or two dates in which IRI measurements were made prior to the first rehabilitation. To determine if a linear relationship exists for the individual pavement sections, the dataset was limited to pavement sections with at least three dates for IRI measurements prior to rehabilitation. In doing so, the number of AC pavement sections that had no reported rehabilitation prior to entry into an LTPP experiment and an initial actual service life in the middle 90% for AC pavements was reduced to 142 pavement sections. Following the same restrictions (no previous rehabilitation and service life in the middle 90% for PCC pavements), the number of available PCC pavement sections was reduced to 73.

Linear regression was completed for each pavement section to determine the rate of deterioration of ride quality (slope), y-intercept, and the coefficient of determination. Linear regression has been used in previous research documenting the change in IRI with pavement age. It was used by Colorado DOT researchers in determining the rate of change in performance for each of five distresses (including IRI) in pursuit of service life estimates for their Superpave HMA pavements, although the y-intercept was assumed to be zero for all cases (*9)*. In the 1998 report on the progression of pavement roughness in LTPP sections, linear regression was utilized to document the progression of roughness for measured IRI; however, an exponential relationship between IRI and age was utilized to model and predict future IRI depending on the experiment (*35*). Similarly, linear regression analyses were conducted in a 2001 report to document pavement roughness progression for LTPP sections (*36*). An exponential relationship for IRI with age was also utilized in the 2008 study for Kansas DOT to predict future IRI values (*13*). A linear regression was chosen in this study for the simplicity of understanding the changes in documented MRI values over time.

The linear regression of individual pavement sections revealed that the linear relationship was very strong for some sections and poor for others, as indicated by low coefficients of determination. Poor relationships could be due, in part, to inconsistencies in the data. Inconsistencies in IRI data in LTPP sections were well documented in the 1998 report, "Investigation of Development of Pavement Roughness" (*35*). For example, IRI reported in one or both of the wheelpaths was either variable or showed a prominent spike (either increase or decrease in IRI), and there were also differences among IRI in each wheelpath. The authors attributed the inconsistencies in IRI data to variations in the actual path profiled (lateral variations of the wheelpath), temperature or seasonal effects, maintenance activities, or data collection activities (*35*).

Examples of cases in which an obviously strong linear relationship existed are provided in Figure 5.8 for Section 35-2118 (AC pavement) and Section 19-3055 (PCC pavement). In both examples, the coefficient of determination is very high, indicating that each linear regression model explains at least 98% of the variability in the data.

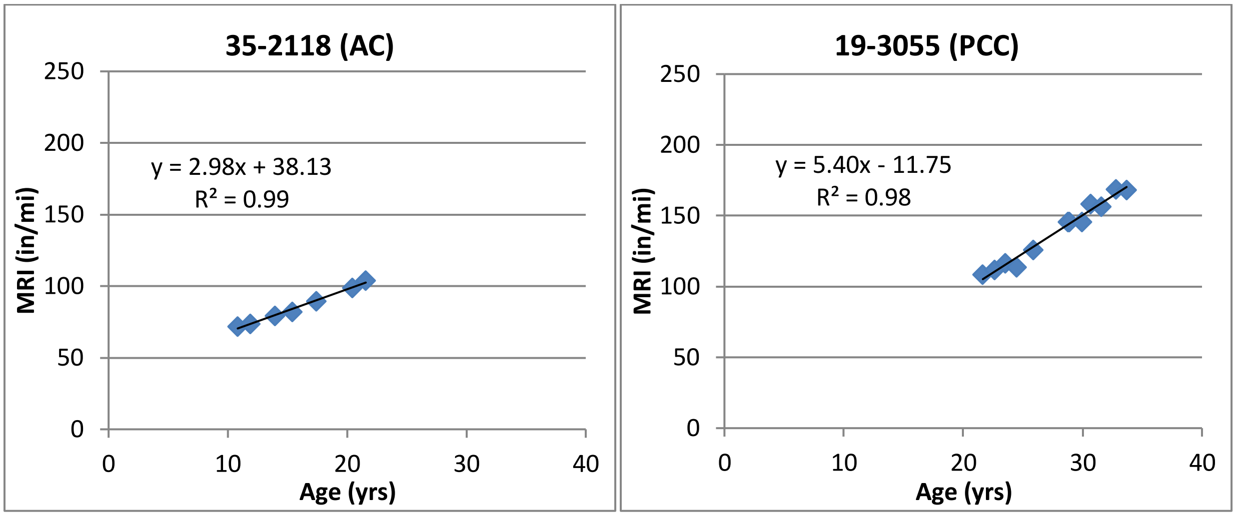


Figure 5.8 Examples of a Strong Linear Relationship between Age and MRI for Individual Pavement Sections

While the linear regression model explains the variability in the data very well for the examples above, MRI data for those sections were not available for the entire life cycle prior to the first rehabilitation. Therefore, the linear trend line, as shown in the above examples, may not be representative of the entire life cycle from initial construction (or reconstruction) to first rehabilitation. Thus, the slope and y-intercept only apply to the range of data available for each pavement section, meaning that in the examples above, the y-intercept does not represent the initial IRI value at the time of construction.

It is expected that the slope would be positive, indicating an increase in pavement roughness over time. While the majority of the pavement sections did have positive changes in pavement roughness with time, there were some cases in which the slope was negative, illustrating a reduction in MRI as the pavement aged. As shown in the percentage distribution of the rate of progression for pavement roughness in Table 5.7, negative rates were found for both AC and PCC pavements. It was found here that pavement sections with rates less than or equal to zero accounted for 10.6% and 8.2% of the total AC pavements and PCC pavement sections, respectively.

Table 5.7 Percentage Distribution of Rate of Pavement Roughness Progression

Rate of Change in MRI (in/mi/yr)	Percentage of Total Sections	
	AC Pavements	PCC Pavements
≤ 0	10.6%	8.2%
> 0 and ≤ 3	42.3%	60.3%
> 3 and ≤ 6	19.7%	21.9%
> 6 and ≤ 9	11.3%	5.5%
> 9 and ≤ 12	4.9%	2.7%
> 12 and ≤ 15	8.5%	0.0%
> 15	2.8%	1.4%

Negative slopes were also reported in the 1998 study of pavement roughness progression in LTPP experiments (*35*). However, in that study, negative slopes accounted for a higher percentage of the total sections for both AC and PCC pavements than were found herein. In GPS-1 and GPS-2 experiments, negative rates were found for 17% and 20%, respectively, of the total sections in each experiment. Even higher percentages of 30% to 47% of the total pavement sections in GPS-3 through GPS-5 experiments were reported for the PCC pavements. The previous report was published in 1998 and at that time, "profile data were generally available for 4 years in the database" (*35*).

An NCHRP study published in 2001 sought to investigate the effects of various factors on pavement roughness for LTPP pavement sections (*36*). In that study, similar results for rates of change based on linear regression of individual pavement sections were reported for GPS experiments in their first design phase. Pavement sections with a rate of progression less than zero represented 11% of the total sections in GPS-1 and represented 10% in the GPS-2 experiment. In the same study, the reported frequency of PCC pavement sections with negative rates of progression varied amongst the GPS-3, GPS-4, and GPS-5 experiments. In the GPS-3 experiment, rates of pavement roughness progression were presented by climatic zones and the presence or absence of dowels. The percentage of total pavement sections in each category with negative rates of roughness progression ranged from zero to as high as 31%. In the GPS-4 experiment, negative rates accounted for 9% of the total sections, while negative rates of progression were much more frequent among the GPS-5 experiments at 35% of the total pavement sections (*36*).

Although previous studies have been conducted to understand the progression of pavement roughness for LTPP pavements, these studies were conducted more than a decade ago (*35, 36*). Therefore, additional IRI measurements prior to the first rehabilitation were available for this study (specifically for those pavements that had not yet been rehabilitated at the time the NCHRP study was completed). Thus, a more complete investigation of the levels of pavement roughness leading up to the first rehabilitation could be conducted herein. The data from GPS-1 through GPS-5 experiments used for this study included only IRI measurements prior to the first rehabilitation (pavements reported as having been rehabilitated prior to entry to LTPP were excluded) that were within the middle 90% of the actual service life distribution to guard against erroneous data.

As shown in Table 5.7, rates of progression for pavement roughness were frequently rather small, with the highest percentage of AC or PCC sections falling between 0 and 3 in/mi/yr. Despite the additional years of data available for this study, the distributions of rates of change are very similar to the distributions of rates of change for GPS-1 through GPS-5 experiments reported in the 1998 study (*35*). In that study, the highest frequency of pavement sections for AC pavements (GPS-1 and GPS-2) had rates of change between 0 and 2 in/mi/yr. Aside from the GPS-3 experiment where the rate of change was most frequently less than zero, the PCC pavements in GPS-4 and GPS-5 also had the highest occurrence of rate of change between 0 and 2 in/mi. In the 2001 NCHRP report, the rates of change were similar to the 1998 study with the highest frequency falling between zero and 1.26 in/mi/yr (0.02 m/km/yr) for all five GPS experiments (*36*).

In looking at the distributions of the R^2 values for the linear regression of AC and PCC pavement sections presented in Table 5.8, AC pavement sections tended to have stronger linear relationships between pavement age and pavement roughness than PCC pavement sections. There is no obvious peak in the percentage distribution for PCC pavement sections; however, the highest frequency of R^2 occurrence for AC pavements was at values between 75% and 90%. The second highest frequency among the AC sections was at R^2 values greater than 90%, in which 21.8% of the 142 sections had linear regression resulting in very high coefficients of determination. The frequency of the R^2 values amongst AC and PCC pavement sections are again very similar to the results for the earlier study of pavement roughness progression (*35*) in that AC pavement sections (GPS-1 and GPS-2) had R^2 values greater than 75% more frequently than PCC sections (GPS-3, 4, and 5). However, in this study, the frequencies of occurrence at an R^2 of greater than 75% were higher for both AC and PCC pavements.

Table 5.8 Percentage Distribution of Coefficient of Determination for Linear Regression

Coefficient of Determination, R^2	**Percentage of Total Sections**	
	AC Pavements	**PCC Pavements**
≤ 15%	9.9%	15.1%
> 15% and ≤ 30%	4.2%	9.6%
> 30% and ≤ 45%	6.3%	13.7%
> 45% and ≤ 60%	9.9%	16.4%
> 60% and ≤ 75%	17.6%	12.3%
> 75% and ≤ 90%	30.3%	15.1%
> 90%	21.8%	17.8%

Based on the linear regression of the individual pavement sections, it is evident that linear relationships between pavement age and pavement roughness are dependent on the individual pavement section. As shown in Table 5.8, not all pavement sections have a strong linear relationship, and for a small percentage of AC and PCC sections, pavement roughness did not increase with time as expected. Negative rates of progression could be due to poor measurements as a result of debris or loose aggregate, raveling on the roadway, or due to recent patching or application of pavement preservation treatments. Patching and some preservation treatments can improve ride quality, and there are more options for pavement preservation treatments available for AC pavements than PCC pavements, which could explain the higher frequency of negative rates for AC pavement sections. By excluding pavements with negative rates of pavement roughness progression and limiting the dataset to pavement sections that show a fairly strong linear relationship between pavement roughness and age, the performance prior to rehabilitation of AC pavements and PCC pavements can be summarized collectively.

Each dataset was limited to pavement sections having IRI measurements made on at least three dates prior to rehabilitation with a rate of pavement roughness progression greater than zero and an R^2 value of 50% or better. In doing so, the number of pavement sections was reduced from 142 to 106 AC pavement sections and from 73 PCC pavement sections to 44. Using this data set, the average rate was determined for each AC and PCC pavement type and for each climatic zone. The average, minimum, and maximum rates of deterioration of ride quality (characterized by MRI) are tabulated for each AC and PCC pavement type as well as AC and PCC pavements as a whole in Table 5.9.

On average, pavement roughness progressed at a higher rate on AC pavements with a granular base than AC pavements with a bound base. As shown in Table 5.5, AC pavements on granular base were also rougher, on average, at the time of rehabilitation than AC pavements on bound base. Although rougher, AC pavements on granular base were found to be rehabilitated approximately one year later on average than AC pavements on bound base, as shown earlier in Table 4.12.

The average rate of pavement roughness progression for AC pavements was very similar to the rate determined by Colorado DOT in their investigation of the time to first rehabilitation for Superpave HMA pavements in which the statewide rate was found to be 6.60 in/mi/yr (*9*). In that study, the linear regression was conducted with an assumed y-intercept of zero.

Although the rates differed by a little more than 2 in/mi/yr for AC pavements, there was very little difference in the rate of ride quality deterioration among the three types of PCC pavements. On average, pavement roughness increased at a quicker rate for AC pavements than PCC pavements. This is consistent with pavement design theory in that AC pavements are typically designed to last for 15 to 20 years whereas the design life for PCC pavements is often as much as 30 to 40 years.

As shown in Table 5.7, the rate of progression for both pavement types was most frequently between 0 and 3 in/mi/yr. However, when the data were limited to sections with positive rates of progression and 50% or better R^2, as shown in Table 5.9, the rates of progression were greater, between 3 and 6 in/mi/yr, indicating that pavement sections with stronger positive linear relationships (as expressed by R^2) tend to have greater rates of pavement roughness progression.

Table 5.9 Rate of Pavement Roughness Progression by Experiment Type (Rate > 0 and $R^2 \geq 50\%$)

Exp. No.	Pavement Type	No.	Percent of Total	Mean Rate (in/mi/yr)	Min Rate (in/mi/yr)	Max Rate (in/mi/yr)
AC Pavements						
GPS-1	AC on Granular base	59	55.7%	6.8	0.6	24.5
GPS-2	AC on Bound base	47	44.3%	4.7	0.7	14.6
AC – Total		106	100.0%	5.8	0.6	24.5
PCC Pavements						
GPS-3	JPCP	24	54.5%	3.7	0.6	16.7
GPS-4	JRCP	11	25.0%	3.4	0.7	11.4
GPS-5	CRCP	9	20.5%	3.7	0.5	7.3
PCC – Total		44	100.0%	3.7	0.5	16.7

In Table 5.10, the average rate of pavement roughness progression is summarized for each pavement type and by climatic zone with the same restrictions applied as above (only positive rates and moderate or better coefficients of determination). In both AC and PCC pavements, roughness progressed more rapidly, on average, in wet, freeze climates. For PCC pavement sections, the remaining three climates had very similar rates of progression for pavement roughness; however, too few pavement sections represented these climatic zones to draw conclusions. Values for AC pavements in the remaining three climatic zones ranged from 4.28 in/mi/yr to 6.70 in/mi/yr. AC pavements in freeze climates had higher rates of pavement roughness progression than those in non-freeze climates. This agrees well with the previous analyses in Section 5.2.2, in which freeze conditions were associated with greater pavement roughness for both AC and PCC pavements.

Table 5.10 Rate of Pavement Roughness Progression by Climatic Zone (Rate > 0 and $R^2 \geq 50\%$)

Climatic Zone	No.	Percent of Total	Avg Rate (in/mi/yr)	Min Rate (in/mi/yr)	Max Rate (in/mi/yr)
AC Pavements					
Dry, Freeze	15	14.1%	6.7	0.9	24.0
Dry, Non-Freeze	13	12.3%	4.3	0.8	11.0
Wet, Freeze	21	19.8%	9.3	1.0	24.5
Wet, Non-Freeze	57	53.8%	4.7	0.6	14.6
PCC Pavements					
Dry, Freeze	5	11.4%	2.7	0.7	8.0
Dry, Non-Freeze	3	6.8%	2.6	2.2	2.9
Wet, Freeze	30	68.2%	4.2	0.6	16.7
Wet, Non-Freeze	6	13.6%	2.5	0.5	7.3

A quick summary of the pavement age and roughness prior to rehabilitation for only those sections that had moderate or better coefficient of determination for the positive linear regression is listed in Table 5.11. For both pavement types, the average pavement age at rehabilitation remains consistent with the average ages found in Section 4. Comparisons can be drawn between the values presented in Table 5.11 and the average MRI found in Table 5.3 for all 166 AC pavements and 90 PCC pavements. As shown in Table 5.11, PCC pavement sections that have a positive linear relationship between pavement age and pavement roughness have an average MRI of 146.51 in/mi just prior to rehabilitation. This is much greater than the average MRI prior to rehabilitation (128.97 in/mi) found for all PCC pavements regardless of the number of IRI measurements or strength of the relationship. Although not all PCC pavements show a strong relationship between age and pavement roughness, where this relationship does exist, PCC pavements tend to be rougher at the time of rehabilitation. The difference is relatively small between the average MRI shown in Table 5.3 for AC pavements (112.41 in/mi) and in Table 5.11 for sections with a positive and moderate or better linear relationship.

Table 5.11 Pavement Age and Roughness at Rehabilitation for Pavement Sections with Positive Linear Relationships (Rate > 0 and $R^2 \geq 50\%$)

Pavement Type	No.	Mean Pavement Age at Rehabilitation (yrs)	Mean MRI prior to Rehabilitation (in/mi)
AC	106	17.89	118.5
PCC	44	24.04	146.5

5.4 Summary

The historical first rehabilitation cycles were documented for pavement sections in the LTPP experiments in Section 4. Although historical times to first rehabilitation can be useful in LCCA, the performance level at the time of rehabilitation is critical in determining the initial service life in LCCA. One such performance parameter, pavement roughness, was found to be used frequently (either directly or indirectly) in determining the time of actual rehabilitation based on the questionnaire results presented in Section 3. IRI is a consistent and repeatable measure of pavement roughness. Furthermore, it has been reported that the public perceives pavement roughness as an indicator of performance. Therefore, this section sought to document the levels of pavement roughness in terms of IRI just prior to the first rehabilitation as well as the rate of progression of pavement roughness with pavement age leading up to the first rehabilitation.

Due to the bias identified relative to the time of rehabilitation in the SPS sections discussed in Section 4 of the report, data analyzed were limited to AC sections in the GPS-1 and GPS-2 experiments and the PCC sections in the GPS-3, 4, and 5 experiments. Additionally, the upper and lower bounds for the middle 90% of the actual service life distribution for each AC and PCC pavement were applied to each dataset to guard against errors in the LTPP database. This resulted in a combined 166 pavements from the GPS-1 and GPS-2 experiments and 90 PCC pavements from the GPS-3, 4, and 5 experiments. The last MRI (the average of the left and right wheelpath IRI measurements) measured prior to the first rehabilitation (based on rehabilitation activities identified in Section 4.1) was summarized for each pavement type, as well as for each experiment and climatic zone, to better understand the levels of pavement roughness at the time of the first rehabilitation.

Pavement roughness just prior to the first rehabilitation ranged widely for both AC and PCC pavements. Among the AC pavements, pavement roughness ranged from as smooth as 30 in/mi to as rough as 359 in/mi. The range for PCC pavements was a bit narrower with MRI ranging from 48 in/mi to 260 in/mi. Although AC pavements had a wider range for MRI prior to rehabilitation, the average among all 166 sections was only 112.41 in/mi. PCC pavements, on the other hand, were rougher with an average of the last MRI measured before rehabilitation of 128.97 in/mi. Using the earlier FHWA categories for ride quality (very good, good, fair, poor, and very poor) associated with IRI measurements (*32*), it was found that PCC pavements were more likely to reach poor ride quality before the first rehabilitation. MRI values for AC pavements most frequently fell into the good ride quality category, indicating that AC pavements were commonly much smoother than PCC pavements at the time of rehabilitation. Although the FHWA has established a threshold for unacceptable ride quality as greater than 170 in/mi (*34*), and some DOTs have adopted this threshold as part of their rehabilitation decisions as noted in Section 3, more than 85% of AC and PCC pavements were rehabilitated before reaching that level (Figures 5.1 and 5.2).

Differences in pavement roughness prior to the first rehabilitation as well as climatic conditions were noted for the GPS experiments. On average, AC pavements on granular base (GPS-1 experiment) were rougher prior to rehabilitation than AC pavements on bound base (GPS-2 experiment) and were the most variable amongst AC and PCC pavements investigated. AC pavements in the GPS-2 experiment represented the smoothest pavements at the time of the first rehabilitation with an average for the last MRI measurement prior to rehabilitation at 102 in/mi. JPCPs (GPS-3 experiment) were the roughest pavements among the five experiments prior to first rehabilitation at an average MRI of 139 in/mi. PCC pavements in the GPS-5 experiment (CRCP) represented the smoothest PCC pavements at the first rehabilitation with an average MRI less than that found for JPCPs by nearly 26 in/mi. Pavements in the dry, freeze climatic zone represented the smoothest AC and PCC pavements at the time of rehabilitation. AC and PCC pavements in the wet, freeze climatic zone experienced similar levels of pavement roughness prior to rehabilitation, with the average MRI for both pavement types approaching 140 in/mi, representing the roughest pavements among the four climatic zones for each AC and PCC pavements. The difference between AC and PCC pavements in the dry, freeze zone was stark, with average MRI for PCC pavements 20 in/mi greater than AC pavements.

The deterioration of ride quality was examined for each pavement type through the progression of MRI over time. First, all MRI values prior to the first rehabilitation were plotted against pavement age at the time of the measurement for each pavement type. Substantial scatter in the data existed for AC pavements and the linear trend line fitted to the data showed a very poor R^2 value. A linear trend line fitted to the data for PCC pavements also showed an increase in MRI for PCC pavements. However, the plot of MRI with pavement age shows the progression of MRI to be rather flat. The coefficient of determination associated with the linear trend line for PCC pavements was also very poor. As such, these plots were best for simply observing trends rather than drawing conclusions on rates of pavement roughness progression for each pavement type.

The data were further broken down to determine if the same or similar trends existed for each GPS experiment and climatic zone. While both GPS-1 and GPS-2 experiments had similar trends (an increase in MRI with pavement age), GPS-1 pavements tended to increase faster than GPS-2 AC pavements. Among the three experiments for PCC pavements, an increase in MRI with age was observed in only GPS-3 (JPCP) pavements. In the remaining two experiments, roughness appeared to remain steady with age. Again, coefficients of determination were poor as each plot represented numerous pavement sections across the U.S. and Canada. Similar trends existed for AC pavements among all four climatic zones with increases in MRI with pavement age observed. PCC pavements in the dry, non-freeze zone tended to increase with pavement age at a rate similar to those observed in the AC pavements. Little to no increase in roughness with time was observed for PCC pavements in the remaining climatic zones. Substantial scatter existed in each plot of AC and PCC pavements for the four climatic zones; however, the coefficients of determination for the linear trend line in the dry, freeze zone were reasonable at 33% for both AC and PCC pavements.

While trends were observed for AC pavements as a whole, and likewise for PCC pavements as a whole, further investigation of the data revealed that any existing relationships between MRI and pavement age varied by pavement section. Therefore, linear regression was completed for each pavement section with at least three MRI measurements prior to rehabilitation. The percent distribution of the rate of pavement roughness progression revealed that roughness on AC and PCC pavements most frequently increased at a rate between 0 and 3 in/mi/yr. A small percentage of AC and PCC pavement sections revealed negative rates of pavement roughness. Negative rates of roughness progression could be due to either inconsistent data or maintenance activities. While more than 30% of the AC pavement sections had R^2 values between 75% and 90% for the individual linear relationships, the coefficients of determination were more evenly distributed for PCC pavement sections. However, a similar percentage of the total number of pavement sections was found at R^2 values greater than 90%, with 21.8% of AC pavement sections and 17.8% of PCC pavement sections in this range.

Lastly, to better understand the rate of ride quality deterioration, the data were reduced again to include only pavement sections with positive rates of roughness progression and moderate or better linear relationships (R^2 greater than or equal to 50%). Approximately 75% of the AC pavement sections and 60% of the PCC pavement sections met these criteria. Rates for pavement roughness progression were summarized for each pavement type as well as experiment and climatic zone. It was found that the average rate among these individual AC pavement sections was 5.83 in/mi/yr. The average rate among individual PCC pavements was smaller at 3.65 in/mi/yr. While differences among the PCC experiments (GPS-3, 4, and 5) were negligible, the average rate of roughness progression was greater for AC pavement sections on granular base than AC pavement sections on bound base by more than 2 in/mi/yr. AC and PCC pavement sections in the wet, freeze zone showed the highest rates of roughness progression among each pavement type; however, the average rate for AC pavements was more than twice that for PCC pavements. While differences in the rate of progression among climatic zones existed for AC pavement sections, too few PCC pavement sections were represented in climates other than wet, freeze to draw comparisons. The average of the last MRI values prior to the first rehabilitation for pavement sections with positive and moderately strong or better linear relationships showed values greater than those identified in Section 5.2, especially for PCC pavement sections.

6 CONCLUSIONS

Initial pavement service life in LCCA is a very influential parameter in evaluating pavement type alternatives. In LCCA, initial pavement service life represents the average time in years for a newly constructed or reconstructed pavement to reach an agency's criteria for rehabilitation (*1*). LCCA enables the alternatives to be compared solely on the basis of cost by assuming the alternatives, AC or PCC pavement, provide the same level of performance or benefits to the users. Based on the assumptions of LCCA, the same criteria for rehabilitation would need to be applied to both AC and PCC pavements.

The objectives of this report were threefold. First, it discusses how DOTs determine the initial service life for AC and PCC pavements in LCCA and in practice. Second, it shows actual rehabilitation cycles using LTPP pavement sections to understand not only the timing of the first rehabilitation but also the deterioration of AC and PCC pavements leading up to the first rehabilitation. Based on the results of objectives one and two, the last objective is fulfilled with recommendations for determining initial service life for LCCA.

Based on the review of DOT practices in determining initial pavement service life for use in LCCA and determination of the actual timing of the first rehabilitation for both AC and PCC pavements, the following conclusions can be drawn:

- Procedures used to determine the initial service life for use in LCCA tend to be multi-layered and complex, especially those that are based on one or more condition or performance indices. Practices vary by DOT; therefore, direct comparisons could not be made. The following commonalities among practices for determining the initial service life for LCCA were noted.
- Most commonly, agencies utilize PMS data to estimate the initial service life. However, it is unclear if PMS data refers to historical pavement performance measures at the time of rehabilitation, the historical timing of rehabilitation, or a combination of both.
- The second most common method for determining initial service life for LCCA was through expert opinion or engineering judgment.
- Next, some agencies utilized distress or condition indices. Various indices were included in the responses provided, and in some cases the distresses used to compute the indices were also noted. Typically, these distresses were specific to a pavement type (e.g. faulting for jointed concrete pavements or rutting for asphalt pavements).
- While agencies indicated that historical data were used to estimate initial performance period for LCCA, it should be kept in mind that there are limitations associated with historical data, especially historical timing of rehabilitation. The time rehabilitation actually occurs may not represent the time at which a pavement has reached performance thresholds which indicate the need for rehabilitation.
- Actual practices and criteria for determining time of rehabilitation do not appear to be based on achieving equal levels of performance. DOTs decision-making process and

performance measures used to determine the actual timing of rehabilitation were reviewed. It was revealed that practices vary among agencies and often include various types of condition indices as rehabilitation triggers in addition to other factors. The condition indices generally included one or more distresses unique to a pavement type. Although cracking is a common distress to both AC and PCC pavements, cracking types and definitions are not equivalent, and as such, the condition indices and associated thresholds are not comparable between unlike pavement types.

- IRI is often not the sole performance measure used to trigger rehabilitation. However, it is widely used as part of the decision-making process for determining the time of actual rehabilitation and is an important parameter to consider when determining pavement service life.
- There is not a nationwide consensus among DOTs on IRI values that are indicative of pavements in need of rehabilitation. For those agencies that have assigned threshold values to IRI, the values were found to range widely by agency and in one case by pavement type.

The following conclusions are drawn based on the investigation of the initial performance periods for AC and PCC pavements in the LTPP program.

- The initial service life values used for LCCA do not adequately represent the actual pavement age of AC pavements at the time of first rehabilitation. In previous research, the initial service life used in LCCA for AC pavements was most frequently reported as a value between 10 and 15 years (*6, 7*). The results of the analyses conducted herein revealed the average pavement age at the time of the first rehabilitation for existing AC pavements in the LTPP program was found to be 17.7 years.
- The initial service life commonly used in LCCA for PCC pavements is generally representative of actual PCC pavement age at the time of the first rehabilitation. The initial service life used in LCCA for PCC pavements reported in previous literature was most frequently between 20 and 25 years (*6, 7*). This analysis showed an average pavement age of existing PCC pavements in the LTPP program of 23.8 years. However, it should be noted that the rehabilitation strategies used by DOTs differ from state to state and there is not a general consensus on which treatments (concrete pavement repair, overlay, etc.) make up a rehabilitation activity.
- Negligible differences exist for the pavement age at the first rehabilitation among JPCP, JRCP, and CRCP pavements. Although, the most common rehabilitation activity performed on JPCP pavements in the first rehabilitation was grinding the surface while JRCP and CRCP most frequently received an AC overlay in the first rehabilitation.
- The data showed climate most likely has an impact on rehabilitation timing for asphalt pavements, but was not definitive on the impact of climatic zones (i.e. wet vs. dry, freeze vs. non-freeze). Concrete pavements have minor variation in the timing of the first rehabilitation among the four climatic zones with concrete pavements in the freeze zones having a shorter performance period.

The following conclusions can be made regarding the ride quality at the time of rehabilitation based on the investigation of AC and PCC pavements in the LTPP program.

- Given that the majority (85%) of AC and PCC pavement sections were rehabilitated before reaching 170 in/mi, it can be concluded that an MRI of 170 in/mi is too high as a rehabilitation trigger. Although several agencies utilize 170 in/mi as a threshold for MRI, it is possible that threshold values for other distresses or condition indices are reached before the pavement roughness reaches this level.
- Generally, AC pavements are smoother than PCC pavements at the time of rehabilitation. AC pavements were first rehabilitated while in good or fair condition whereas PCC pavements were rehabilitated in fair or poor condition.
- Both AC and PCC pavements were smoothest prior to rehabilitation in the dry, non-freeze zone and the roughest in the wet, freeze zone, indicating that pavement roughness for both AC and PCC pavements is influenced similarly by climatic conditions.
- Although AC pavements tend to be smoother than PCC pavements at the time of rehabilitation, average MRI values for the two pavement types do overlap, indicating that an IRI threshold common to AC and PCC pavements could be estimated. The 95% confidence intervals for both pavement types overlap at approximately 120 in/mi and both AC and PCC pavements. Additionally, in the wet, freeze climatic zone, both pavements had MRI just prior to rehabilitation of approximately 140 in/mi.
- The average MRI values just prior to rehabilitation were based on LTPP pavement sections across the United States and parts of Canada; therefore, average values may differ for individual DOTs.

The following conclusions can be made regarding the deterioration of ride quality in the first pavement cycle based on the investigation of AC and PCC pavements in the LTPP program.

- Not all pavements have a linear relationship between pavement age and pavement roughness, expressed as mean IRI (in/mi). This was especially true for PCC pavements, which tended to have pavement roughness values that remained stable over time.
- AC pavements are more likely to have a linear relationship between pavement age and roughness than PCC pavements.
- Furthermore, AC pavements develop pavement roughness at a faster rate in the years prior to the first rehabilitation (MRI data were not available for the entire first cycle for either AC or PCC pavements) than PCC pavements.
- The rate at which pavement roughness progresses with age for AC and PCC pavements varies by climatic conditions.
- Differences in the rates of MRI progression associated with AC pavements on granular base and AC pavements on bound base were also found, indicating that the type of base may also influence rate of progression for AC pavements.
- Pavements that develop pavement roughness at a greater rate toward the end of the first pavement cycle are rougher at the time of rehabilitation.
- PCC pavement sections with a moderately strong or better (positive) linear relationship between pavement age and pavement roughness tend to be rougher at the time of

rehabilitation than those that do not have a moderately strong linear relationship between MRI and pavement age.

7 RECOMMENDATIONS FOR DETERMINING INITIAL PAVEMENT SERVICE LIFE FOR USE IN LCCA

Recommendations are made for determining the initial service life of AC and PCC pavements for use in LCCA. The recommendations are based on the analyses conducted on the initial performance periods for AC and PCC pavements in the LTPP program as well as the review of DOTs LCCA practices and rehabilitation triggers used for determining actual timing of the first major rehabilitation of AC and PCC pavements.

- While historical timing of rehabilitation has been used, it is recommended that agencies move toward the use of actual measured performance for determining initial service life for LCCA to ensure that consistent levels of performance are being compared among unlike pavement types. As was found in this study, practices for determining initial service life vary by agency. Therefore, efforts should be made to develop a standard practice of determining initial service life for LCCA.
- It is recommended that if used, historical timing should be combined with a performance measure and threshold common to all pavement types.
- The performance indicators and associated thresholds used to determine initial service life in LCCA should be indicative of when rehabilitation is truly necessitated and should strike a balance between structural and functional performance. Functional performance can be determined based on ride quality (IRI or MRI), while structural performance can be determined based on cracking and rutting for AC pavements and based on cracking and faulting for PCC pavements. Equivalent functional and structural performance thresholds can be used for determining initial service life for LCCA.
- Based on the findings of this report, it is recommended that a functional performance threshold (based on MRI) lower than 170 in/mile be used to trigger first rehabilitation. The MRI values of most pavements in the LTPP program were much lower than 170 in/mile when they were first rehabilitated. A threshold value of 120 in/mi is recommended, as it falls within the 95% confidence interval about the mean for both AC and PCC pavement prior to the first rehabilitation.
- In addition, it is recommended that an agency also conduct an evaluation of the rate at which pavement roughness progresses on their AC and PCC pavements leading up to the first rehabilitation. Determining this relationship between pavement age and MRI enables the estimate of functional performance, an indicator for determining initial service life in LCCA. The rate of progression should be determined for each unique climatic condition, AC pavement type, and PCC pavement type. There is also potential for rates to vary by traffic loading and volume. The rates from national-level data identified in this study can be used for comparison.
- Given the ongoing advancements in material characterization, pavement design, and construction, the pavement initial service life used in LCCA should be re-examined

periodically to capture the changes in pavement performance due to changes in design and materials.

8 REFERENCES

1. West, R., N. Tran, M. Musselman, J. Skolnik, and M. Brooks. *A Review of the Alabama Department of Transportation's Policies and Procedures for Life-Cycle Cost Analysis for Pavement Type Selection*. NCAT Report 13-06, National Center for Asphalt Technology at Auburn University, Auburn, Ala., 2013.
2. Walls III, J., and M. Smith. *Life-Cycle Cost Analysis in Pavement Design – Interim Technical Bulletin*. Report FHWA-SA-98-079. FHWA, U.S. Department of Transportation, 1998.
3. Office of Highway Policy Information. *Highway Performance Monitoring System Field Manual*. FHWA, U.S. Department of Transportation, 2014.
4. 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*, U.S. Department of Transportation, Washington, DC, 2017.
5. *NCHRP 01-57A: Developing Standard Definitions for Comparable Pavement Cracking Data*. Transportation Research Board of the National Academies, Washington, D.C., In progress. https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4276.
6. Mississippi Department of Transportation. *Life Cycle Cost Analysis for Pavement Type Selection*, *AASHTO RAC Member Survey Results*. AASHTO, Washington, D.C., 2007.
7. Rangaraju, P. R., S. Amirkhanian, and Z. Guven. *Life Cycle Cost Analysis for Pavement Type Selection*. Report FHWA-SC-08-01. South Carolina Department of Transportation, Columbia, S.C., 2008.
8. CTC & Associates, LLC. *Pavement Service Life - Rev. 2, Transportation Synthesis Report*. Wisconsin Department of Transportation, Madison, Wis., 2004. http://research.transportation.org/_layouts/15/AASHTORAC/RACSurveyResultDetail.aspx?SurveyID=91. Accessed February 3, 2014.
9. Goldbaum, J. E., and M. A. Perkins. *Years to First Rehabilitation of Superpave Hot Mix Asphalt*. Report CDOT-2014-10. Colorado Department of Transportation, Denver, Co., 2014.
10. Von Quintus, H., J. Mallela, and J. Jiang. *Expected Service Life and Performance Characteristics of HMA Pavements in LTPP*. Asphalt Pavement Alliance, Lexington, Ky., 2005.
11. Meade, J. N., and D. W. Janisch. *Pavement Type Determination Task Force Report*. Report MnDOT/OM-PM-2003-01. Minnesota Department of Transportation, St. Paul, Minn., 2003.
12. Tsai, J., Y. Wu and C. Wang. *Georgia Concrete Pavement Performance and Longevity*. Georgia Institute of Technology, Atlanta, Ga., 2012.
13. 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 KS-08-04. Kansas Department of Transportation, Topeka, Kans., 2008.
14. Papagiannakis, A., N. Gharaibeh, J. Weissmann, and A. Wimsatt. *Pavement Scores Synthesis*. Report FHWA/TX/-09/0-6386-1. Texas Department of Transportation, Austin, TX, 2009.
15. *Pavement Management System Overview*. Nevada Department of Transportation, Carson City, Nev., 2011.
16. Office of Asset Management. Pavement Condition Modeling with dTIMS. In *Pavement Preservation Manual - Part 4*, Utah Department of Transportation, Salt Lake City, Utah, 2009.

17. *Pavement Policy Manual*. Publication 242. Pennsylvania Department of Transportation, Harrisburg, Pa., 2010.
18. Turner-Fairbank Highway Research Center. *Long-Term Pavement Performance Program: Accomplishments and Benefits 1989-2009*. Report FHWA-HIF-10-071. FHWA, U.S. Department of Transportation, 2010.
19. Hadley, W. *SHRP-LTPP Overview: Five-Year Report*. Report SHRP-P-416. SHRP, National Research Council, Washington D.C., 1994.
20. Elkins, G. E., T. Thompson, B. Ostrom, A. Simpson, and B. Visintine. *Long-Term Pavement Performance Information Management System User Guide*. Report FHWA-RD-03-088 *(revision)*. FHWA, U.S. Department of Transportation, 2015.
21. Simpson, A., and T. Thompson. *Long-Term Pavement Performance Maintenance and Rehabilitation Data Collection Guide*. Report FHWA-HRT-06-068. FHWA, U.S. Department of Transportation, 2005.
22. Specific Pavement Studies Guidelines for Nomination and Evaluation of Candidate Projects for Experiment SPS-5 Rehabilitation of Asphalt Concrete Pavements. Operational Memorandum No. SHRP-LTPP-OM-006. SHRP, National Research Council, Washington, D.C., 1989.
23. Specific Pavement Studies Guidelines for Nomination and Evaluation of Candidate Projects for Experiment SPS-6 Rehabilitation of Jointed Portland Cement Concrete Pavements. Operational Memorandum No. SHRP-LTPP-OM-007. SHRP, National Research Council, Washington, D.C., 1989.
24. Specific Pavement Studies Guidelines for Nomination and Evaluation of Candidate Projects for Experiment SPS-7 Bonded Portland Cement Concrete Overlays. Operational Memorandum No. SHRP-LTPP-OM-011. SHRP, National Research Council, Washington, D.C., 1990.
25. Specific Pavement Studies Guidelines for Nomination and Evaluation of Candidate Projects for Experiment SPS-9A Superpave^{TM} Asphalt Binder Study. FHWA, U.S. Department of Transportation, 1995.
26. Long-Term Pavement Performance: Guidelines for Classification of Rehabilitation Test Sections. FHWA, U.S. Department of Transportation, 1998.
27. Hanna, A. N., S. D. Tayabji, and J. S. Miller. *SHRP Report SHRP-P-395: SHRP-LTPP Specific Pavement Studies: Five-Year Report*. SHRP, National Research Council, Washington D.C., 1994.
28. Guerre, J., J. Groeger, S. Van Hecke, A. Simpson, G. Rada, and B. Visintine. *Improving FHWA's Ability to Asses Highway Infrastructure Health*. Report FHWA-HIF-12-049. FHWA, U.S. Department of Transportation, 2012.
29. 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*. Report FHWA-RD-99-074. FHWA, U.S. Department of Transportation, 1999.
30. 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, Mi., 1998.
31. Shahin, M. Y. *Pavement Management for Airports, Roads, and Parking Lots*, 2nd ed. Springer Science, New York, N.Y., 2005.

32. 1999 Status of the Nation’s Highways, Bridges, and Transit: Conditions and Performance Report. U.S. Department of Transportation, 2000.
33. Flintsch, G., and K. K. McGhee. *NCHRP Synthesis of Highway Practice 401: Quality Management of Pavement Condition Data Collection*. Transportation Research Board of the National Academies, Washington, D.C., 2009.
34. *1998 National Strategic Plan*. FHWA, U.S. Department of Transportation, 1998.
35. Perera, R. W., C. Byrum, and S. D. Kohn. *Investigation of Development of Pavement Roughness*. Report FHWA-RD-97-147. FHWA, U.S. Department of Transportation, 1998.
36. Perera, R. W., and S. D. Kohn. *LTPP Data Analysis: Factors Affecting Pavement Smoothness.* NCHRP Web Document 40: Contractors Final Report. TRB, National Research Council, Washington, D.C., 2001. http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_w40-a.pdf.

9 APPENDIX A QUESTIONNAIRE ISSUED TO DEPARTMENTS OF TRANSPORTATION

Part 1

The first part of the questionnaire includes questions relating to the current LCCA procedures and the actual time to rehabilitation.

1. How does your agency determine the time to first major rehabilitation for flexible and rigid pavements in your existing LCCA procedure?
    a. If it is based on performance, specifically, what performance parameters are used to determine the time to first rehabilitation for each pavement type in your LCCA procedure?
    b. Has this method for determining time to first rehabilitation for LCCA been validated with existing PMS data? If so, is the document available for viewing?
    c. What treatments does your agency consider in your existing LCCA for major rehabilitation of asphalt pavements? And of rigid pavements?
    d. Is the LCCA procedure available on your agency's website? If so, could you please provide a link, and if not, may we have access to it? (Please provide any necessary contact information).
2. What is the decision making process that triggers the actual timing of the overlay (or other major rehabilitation process) on your Interstate System for flexible and rigid pavements? Is this information available on your website?
    a. How is IRI used in the decision making process?
    b. If some form of a condition or performance index is used to monitor the performance of your pavements, how is the index determined and what are the thresholds used to trigger overlay or rehabilitation?
    c. If not an index, then what method or measurements are used to monitor pavement performance and what are the thresholds used to trigger overlay or rehabilitation?

10 APPENDIX B DEPARTMENTS OF TRANSPORTATION RESPONSES TO QUESTION 1A

How does your agency determine the time to first major rehabilitation for flexible and rigid pavements in your existing LCCA procedure? If it is based on performance, specifically, what performance parameters are used to determine the time to first rehabilitation for each pavement type in your LCCA procedure?

No.	State	Response
1	AK	We only have flexible roadway pavements. LCCA is used to compare alternative designs for asphalt pavements. Performance parameters: Present Serviceability Rating (PSR) is often used. It is a function of rut depth and IRI. This report's page 81, details the PSR models used: http://www.dot.state.ak.us/stwddes/research/assets/pdf/fhwa_ak_rd_12_14.pdf
2	AL	The current ALDOT LCCA performance models seem to be based on the performance of Interstate pavements. There is no documentation regarding how the performance periods were determined. It is assumed that the performance periods are based on the time between initial construction and the first major rehabilitation activity. Under review but you should have the information for Alabama based on NCAT's current research in this area. Our current LCCA policy was set some years back and is one of the reasons we have implemented some research into our process.
3	AR	LCCA is currently under development
4	AZ	We have not formally used LCCA in our recent pavement design processes as pavement type selection has been a policy decision made within the Department. We design new pavements (flexible and rigid) for 20 years, however, total lane miles of these new pavements are very low when compared with total lane miles on our interstate system. Based on our experience with past projects, it is expected that the first major rehabilitation for these pavements will usually occur between 15 and 20 years after initial construction.
5	CA	Future Maintenance and Rehabilitation schedules were generated from Maintenance decision trees and statewide/national practice.
6	CO	CDOT is in the process of completing research on the time to the first major rehabilitation of HMA. The research is based on distress performance. We evaluated ride (IRI), rut depth, area of fatigue cracking, amount of transverse cracking and length of longitudinal cracking. This same research was completed on PCC. We monitored ride (IRI), rut depth, amount of transverse cracking, length of longitudinal cracking and the number of corner breaks.
7	CT	In our existing LCCA procedure, the first time to major rehabilitation depends on the design life of the original pavement. Flexible pavements (AASHTO 1993 Design Guide): 12 years before the design life of the structure or 18 years, whichever is later. Rigid pavements: 12 years before the design life of the structure.
8	DE	We only use LCCA on large scale projects; for the LCCA, we use existing pavement management data to determine rehabilitation times and strategies.

No.	State	Response
9	FL	Analysis of Pavement Management Data (performance). Rate each pavement on crack & ride, and for asphalt pavements, also rut. on a scale of 0 (worst) to 10 (best), 6.5 in any one of the 3 criteria triggers need for rehab.
10	HI	The time to first major rehabilitation for flexible and rigid pavments is assumed to be 10 and 30 years, respectively.
11	IA	Based on pavement management data.
12	IL	Time to first rehab comes from historical performance data. Condition rating survey (CRS) index is used to rate the condition of pavements and select candidates for rehab.
13	KS	Based on historical data from PMS of time to first rehab.
14	KY	Cycles for Interstates and Parkways were determined from actual PMS data. Cycles for other routes were determined by KYTC committee, including Pavement Management Staff.
15	LA	Arrived at by committee and discussed and agreed upon by industry
16	MD	It is based on historical average time until the first major rehab was performed for each pavement type, bumped up slightly to account for improvements in design, construction and materials.
17	MI	1. For our LCCA process, we haven't determined the time to the first major rehabilitation. We have determined the timing for each cycle of preventive maintenance (e.g. single course mill & resurface, various surface seals, patching, crack sealing, etc.). This is an average time, based on actual projects performed on each pavement type. Per State law, actual project data must be used when putting together these maintenance schedules for pavement type selection and provides network/system wide historical averages that may not be indicative of business practices on any particular project. [NOTE: other states generally use the term 'rehabilitation' where MDOT would use 'preventive maintenance'. MDOT's use of the term 'rehabilitation' generally refers to a fix that is more substantial than a maintenance project (e.g. multi-course HMA overlay, full-depth reclamation, unbonded concrete overlay, HMA over rubblized concrete).]
18	MN	Average roadway histories from pavement management system
19	MO	Initial assumptions for the time of first rehabilitation were based primarily on construction histories. In other words, at one point did a new pavement deteriorate enough to warrant repair. The observed distresses triggering rehab were typically some combination of cracking, rutting and raveling for asphalt and cracking, faulting and spalling for concrete.
20	MT	The time is established based on engineering judgment after reviewing localized project history. Generally, it is typically assumed that a major rehab will be required after the pavement served its full design life. For example, for a flexible pavement with a 20-year life, a major rehab might be required at year 30. This is achievable with a schedule of routine pavement preservation (chip seals) and minor rehabilitations (thin lift mill/fills). For rigid pavements, it is assumed that a minor rehab (diamond grinding & crack seal) might occur at 15-20 years, and a major

No.	State	Response
		rehab (crack & seat w/PMS overlay or unbonded concrete overlay) might occur at 40 years. General performance measures including ride, rut and cracking are reviewed for local pavements and used to determine the anticipated time periods.
21	NC	We use the pavement condition rating from our PMS to determine time to first rehabilitation. This PCR is heavily weighted to cracking and rutting of flexible pavements. Considers faulting, patching and broken slabs for PCC jointed pavements.
22	NJ	The time for first major rehab is based on a distress index called surface distress index (SDI). This index is measured on a 0 to 5 scale with 5 assigned to a distress-free pavement. SDI is based on a point deduction algorithm with distress weights and severity factors and extent factors assigned for each type of distress evident in a given pavement section.
23	NM	Currently, NMDOT does not have formalized LCCA procedures. State of New Mexico code does not require LCCA and therefore NMDOT has never used in the pavement type selection process and historically, major rehabilitation decisions have been based on visual distress surveys. That is changed now with FHWA-supported Alt Bid Process. In addition, we have a new support in our Pavement Mgmt System which included an entire new configuration. Within the PMS configuration are distress indices - structural index, environmental index and safety index, overall condition index (OCI), and pavement condition rating (PCR). The overall condition index is a function of the three distress indices. While this is a developing process for NMDOT, we are projecting to use all 3 distress indices and the OCI to make pavement type selection determination. B/c you mentioned first rehabilitation, my educated guess for when a first rehabilitation would be applied based on PMS data would be an OCI of 65.
24	NV	Pavement age.
25	OH	For flexible pavement we use performance history data. We look at our Pavement Condition Rating (PCR) and historic time between rehabilitations. For rigid pavements, we estimated the time and compared this to what our surrounding states use.
26	OK	Currently, we do not have a LCCA program in place.
27	OR	We design the structural components for a fixed structural service life. In Oregon, studded tire wear and environmental factors are majors factors causing minor to major rehabilitation within the structural service life. The rehabilitation strategy is evaluated on a project-specific basis. Performance Parameters for Asphalt: - ravelling, - top-down cracking, - studded tire wear rates, and - misc. environmental or other factors such as a history of moisture damage Performance Parameters for Concrete Pavement (Oregon primarily uses CRCP): - studded tire wear rates - punchouts - de-icer surface deterioration
28	PA	The Department has a standard maintenance schedule that is used for LCCA. The schedule was developed from Department past experience with the required timing of routine maintenance, preventative maintenance, and reconstruction, along with

No.	State	Response
		input from both the asphalt and concrete paving industries. Not applicable. Schedule is based on past experience.
29	SC	We use Expert Consensus.
30	TN	Based on past experience. Age, distress, roughness
31	UT	UDOT uses the annualized method for calculating LCCA. See Section 4.6 of our Pavement design Manual of Instruction (attached). To begin with it based on past history of each pavement type, see Table 4-2 & 4-3. See the attached Section 4 for UDOT's LCCA Process web link http://www.udot.utah.gov/main/f?p=100:pg:0:::1:T,V:1893,
32	WA	WSDOT used a comparison of similar pavement types located in the geographic location of a potential project. Cracking criteria is based on a condition index of 45 to 60, rutting is based on a rut depth of 0.50 inch and roughness is based on a IRI of 220 inches/mile.
33	WI	We use service life. We consider the service life to be that period of time to first major rehabilitation. Our service lives are based on the time it has historically taken before a major rehab was necessary.
34	WV	Our primary Design Directives for Pavement Design (DD 646), LCCA (DD 647) and use of an Alternate Design-Alternate Bid (ADAB) procedure (DD 648) were written and/or revised in 2010. A historical review of virtually all of our multi-lane highway sections of interstate and other major arterials was reviewed in order to develop these new directives. Based on our historical data, we have listed in DD 646 performance periods of 40-50 years for pavement design, and have included the rehab periods shown below: Flexible Pavements · Initial period-18 years (increased to 22 if the initial section has polymer in the top 4 inches or a combination of Superpave mixes and a 2 inch polymer surface lift) · Subsequent periods – ranges from 8 to 12 years and can be extended by 4 years if polymer is used in upper 4 inches Rigid Pavements · Initial Period - 22 years · Subsequent Periods – ranges from 10-14 years for CPR techniques. Ranges from 6-10 years if HMA overlay with same 4 year stipulation for use of polymer in rehab.

11 APPENDIX C DEPARTMENTS OF TRANSPORTATION RESPONSES TO QUESTION 1B

Has this method for determining time to first rehabilitation for LCCA been validated with existing PMS data? If so, is the document available for viewing?

No.	State	Response
1	AK	The PSR values are from the PMS database.
2	AL	Recently an analysis was performed on historic PMS data (pre 1989) and that analysis resulted in performance periods that are very close to the performance periods adopted in the early 1990s. The performance periods were based on the time between the initial construction and the first major rehabilitation activities.
3	AR	N/A
4	AZ	N/A
5	CA	No, but there are plans to validate in the future.
6	CO	CDOT used PMS data to develop the performance curves. Please contact me for the information.
7	CT	No.
8	DE	We use PMS data; there is not a specific document though.
9	FL	Yes. Yes.
10	HI	No
11	IA	See above.
12	IL	Yes, to a large extent (link to report below). https://apps.ict.illinois.edu/projects/getfile.asp?id=2931
13	KS	“Validation” occurs by reviewing representative projects that most closely reflect current practice. This has to be accomplished periodically as construction practices and materials change, so no formal validation document has been produced.
14	KY	Yes, an extensive study of Interstate and Parkway data was completed in the early 2000's. A summary is available on request.
15	LA	Somewhat. More problematic with newer mixes
16	MD	PMS data wasn't used to validate the time, it was used to generate the time. Not available for viewing, since it was a result of queries and spreadsheets.
17	MI	N/A
18	MN	That's what we do. No.
19	MO	The history based assumptions were corroborated with pavement condition scores collected with our ARAN data collection vehicle. No formal documentation is available.
20	MT	To my knowledge, no formal validation has occurred. No.
21	NC	The time has been validated by an independent study by SAS. I can make a copy of the document available upon request but it is not posted.
22	NJ	This method has been validated with distress date collected over many years Triggers are largely based on empirical observations. There is no document readily available for viewing.

No.	State	Response
23	NM	B/c this method has just been configured and is new, NO, the LCCA determination has not been validated. But, commitment is there to continue to validate and revise accordingly.
24	NV	Yes. Attached please find the PMS manual.
25	OH	Yes for flexible pavements.
26	OK	N/A
27	OR	PMS data is used in design to project future rehabilitation. Detailed PMS data is not readily available online, but is readily available to Agency personnel.
28	PA	The process has not been validated with the existing Roadway Management System (RMS); however, the Department is in the process of developing a new PMS to track pavement performance data.
29	SC	No, changes in pavement design and materials specification for both flexible and rigid lead us to believe that future performance may differ significantly from past performance.
30	TN	Not formally
31	UT	N/A
32	WA	Yes, the timing is determined on historical pavement performance taken from pavement management data. Since time to first rehabilitation is site specific, it is docmented in the LCCA documentation for the project.
33	WI	A review of our service lives was performed in approximately 2004. At that time, there was no compelling evidence to make changes. Our PMS data was used in that review. The document is not readily available.
34	WV	Not fully, but within the past 3-4 years we have aggressively started to use preservation treatments on HMA and also have begun to use CPR methods for existing concrete sections. The HMA preservation work has been perfomed mostly on lower levels of service (trunk line and feeder routes) but some interstate work has taken place. CPR strategies have been performed on several sections of existing PCC on our interstate and corridor system. Additionally, we have started reviewing some full-depth sections that were built within the past 10 years. We hope that after some additional seasons, we will have some new information that will allow us to re-evaluate our performance periods to either confirm or lead to revision.

12 APPENDIX D DEPARTMENTS OF TRANSPORTATION RESPONSES TO QUESTION 1C

What treatments does your agency consider in your existing LCCA for major rehabilitation of asphalt pavements? And of rigid pavements?

No.	State	Response
1	AK	See page 87, Figure 5-2 of this report: http://www.dot.state.ak.us/stwddes/research/assets/pdf/fhwa_ak_rd_12_14.pdf Major rehab may consist of full-depth reclamation using foamed-asphalt (or emulsion), covered with 2" to 4" HMA.
2	AL	PCC pavement major rehabilitation may include one or more of the following: removal and replacement of shattered slabs, under sealing, slab jacking, diamond grinding, joint and crack cleaning and re-sealing, HMA overlay. I believe ALDOT defines HMA major rehabilitation as pavement removal and replacement in excess of 5 inches or an overlay w/o milling in excess of 4 inches.
3	AR	N/A
4	AZ	N/A
5	CA	Asphalt Rehabilitation: Mill and overlay Rigid Rehabilitation: Lane replacement, concrete pavement over existing pavement, and crack, seat, and overlay.
6	CO	For HMA, CDOT considers full-depth reclamation, mill and fill, overlays, cold in-place recycling and three types of hot in-place recycling. For PCC, CDOT considers full and partial depth slab replacement, diamond grinding, sawing and sealing the cracks and re-sawing and resealing the joints.
7	CT	Asphalt (flexible) pavements: Structural overlay Rigid pavements: CPR and diamond grinding
8	DE	Asphalt - patching, overlay, crack sealing PCC - patching, sealing, joint stitching, diamond grinding
9	FL	Mill & resurface for asphalt pavements; CPR (full depth slab replacement) with joint clean & seal and grinding, or crack/seat/overlay for concrete.
10	HI	Mill and fill for asphalt pavements. Retexturing for rigid pavements.
11	IA	Flexible pavements : Mill and HMA overlay at year 20 Rigid pavements : No major rehab in the analysis period of 40 years
12	IL	Mill and fill with HMA. Patch and overlay with HMA.
13	KS	Asphalt pavements $\geq$ 1 mESALs: Mill and overlay based on historical actions at year 10, 20, and 30. Rigid pavements: 3% patching at year 20, and 5% patching + 3” mill and 3” overlay + saw and seal at year 30.
14	KY	No major rehabilitation is considered in LCCA in Kentucky. Rehab strategies for asphalt include milling and resurfacing (surface only or base+surface). Rehab strategies for concrete include concrete repair and diamond grinding.
15	LA	Asphalt - mill and overlay, or just overlay Concrete - clean and seal joints, patching, retexturing
16	MD	For asphalt, primarily patch, grind and overlay. For rigid, CPR at first, followed by asphalt overlay.

No.	State	Response
17	MI	c. Currently, our LCCA process only evaluates major rehabilitation projects for rigid and composite pavements (HMA over rubblized concrete is compared to an unbonded concrete overlay). Major rehabilitation projects are performed on flexible pavements, but those fixes are not currently evaluated in our LCCA process. Those fixes would include: full-depth reclamation (no new emulsion/AC added) followed by an HMA overlay, and multi-course HMA overlays (with milling when necessary).
18	MN	All anticipated treatments including crack sealing, seal coats, microsurfacing, overlays major CPR, minor CPR and remove and replace.
19	MO	New asphalt pavements have an assumed need for wearing course mil/fills at year 20 and 33 during a 45-year design period. New concrete pavements have an assumed need for diamond grinding and 1.5% full depth repair work at year 25 during a 45-year design period.
20	MT	Asphalt Pavements typically consider Full Depth Reclamation (FDR)/Pulverization, White-topping, engineered overlay and engineered mill and overlay. Cold in place recycle with thick structural overlay and Hot in place recycle with structural overlay might also be considered. A design life of 20 years is pursued for major rehabilitation. Rigid Pavement options consider dowel bar retrofit, diamond grinding, crack sealing, un-bonded overlay or crack and seat with PMS overlay.
21	NC	We have a variety of treatments in our PMS, but the first treatment in LCCA is to mill and replace surface mix in the travel lanes. For PCC, the initial treatment is diamond grinding with 1% patching and cleaning and resealing joints.
22	NJ	For asphalt pavements, most of the rehab is milling and paving of surface and intermediate layers. In some cases of reconstruction, the entire pavement box is excavated including the base layer and rebuilt. For concrete pavements, major rehab could involve rubblization of old concrete followed by thick asphalt overlays. In some instances, badly deteriorated concrete is removed and replaced with an asphalt pavement box. We seldom rebuild extensive areas of concrete pavement and do no new concrete pavement construction in NJ.
23	NM	Definitions from newly developed Pavement Management Manual Asphalt 1. Mill/inlay greater than 4" 2. Remixing HIPR greater than 4" 3. HIPR heater/scarification greater than 4" 4. Overlay greater than 4" 5. Process, Place and Compact w Overlay 6. Full Depth Reclamation OR Full Depth Recycling PCCP 1. Slab Stabilization 2. Slab replacement up to 15% 3. Unbonded concrete overlay (4"-11") 4. Crack and Seat and 6" HMA Overlay
24	NV	High Volume Asphalt Pavement: -2 ¾” mill and 2” dense grade and ¾” Open grade fill – At 10 and 20 years - 3 ¾” mill and 3” dense grade and ¾” Open grade fill – At 30 years High Volume Concrete Pavement: -Diamond grind, saw and seal weakened joints, spall repair, and 1% slab replacement – 15 years -Diamond grind, saw and seal weakened joints, spall repair, and 2% slab replacement – 30 years

No.	State	Response
25	OH	Replacement both rigid and flexible, rubblize and roll, unbonded concrete overlay, crack and seat with a flexible overlay
26	OK	N/A
27	OR	Asphalt: - Single-lift overlay or inlay due to wear, environmental factors, and top-down cracking - Overlays to maintain/increase structural number due to increase in traffic and/or degredation of existing materials - Ultimate deep inlay or thick overlay, typically beyond design service life due to increase in structure from thin overlay(s) Concrete (Oregon primarily uses CRCP): - Diamond Grinding to mitigate studded tire wear and/or de-icer surface deterioration - Non-structural overlay with HMAC to mitigate studded tire wear and/or de-icer surface deterioration - Localized structural repairs from punchouts - Structural overlay with HMAC at end of design service life
28	PA	Refer to PennDOT Publication 242, Chapter 11, Section 11.3 & 11.4. Click on the link below to access Publication 242. ftp://ftp.dot.state.pa.us/public/PubsForms/Publications/PUB%20242.pdf
29	SC	Asphalt; Mill 1 to 3 inches, and overlay 1 to 5 inches Rigid; CPR, asphalt overlay 5 inches
30	TN	Flexible: 1.25" mill & fill; 1.25" overlay; 1.25" mill and overlay 3.25". Rigid: full depth repair; partial depth repair; joint seal; slab stabilization; grinding; dowel bar retrofit; **each treatment is reviewed for necessity.
31	UT	N/A
32	WA	Asphalt: asphalt reconstruction, asphalt inlays or overlays, chip seal, cold in place recycle, CSOL, and preventive maintenance. Rigid: concrete reconstruction, dowel bar retrofit, diamond grinding, panel replacement, unbonded conrete overlay
33	WI	For first major rehab: Asphalt: overlay, mill and overlay Concrete: joint repair (with optional diamond grinding) Subsequent rehabilitations: Asphalt: mill and overlay Concrete: repair and overlay
34	WV	Flexible Pavements: · Milling if needed and use of multiple lift Overlays (common) · Concrete Overlays (although has not yet been performed in construction) Rigid Pavements: · Concrete joint repairs and Heavy multi-lift Overlays (common practice for decades) · Concrete Overlays (see above in flexible) · Rubbilization and HMA overlay – Three separate projects have been constructed over past 27 years – 16.75 miles of four-lane interstate)

13 APPENDIX E DEPARTMENTS OF TRANSPORTATION RESPONSES TO QUESTION 1D

Is the LCCA procedure available on your agency's website? If so, could you please provide a link, and if not, may we have access to it? (Please provide any necessary contact information).

No.	State	Response
1	AK	We have a draft LCCA chapter to be added to our "Alaska Flexible Pavement Design Manual". We're in the process of updating our software to accommodate the new LCCA module. Preliminary work is described here: http://www.dot.state.ak.us/stwddes/research/assets/pdf/fhwa_ak_rd_13_07.pdf
2	AL	The current LCCA procedure is available from Mr. Robert Shugart. P. E., Materials Engineer, 334-206-2309.
3	AR	N/A
4	AZ	N/A
5	CA	Yes. http://www.dot.ca.gov/hq/maint/Pavement/Offices/Pavement_Engineering/LCCA_index.html
6	CO	Please see chapter 10 in the following link. http://www.coloradodot.info/business/designsupport/materials-and-geotechnical/manuals/Complete%202014%20Pavement%20Design%20Manual%20Tables%20_6-25-2009_.pdf/view
7	CT	No.
8	DE	n/a; we do not have a defined procedure
9	FL	http://www.dot.state.fl.us/rddesign/PM/pcs/PTS-Manual.pdf
10	HI	The LCCA procedure is in Chapter 5 of our Pavement Design Manual. The link is as follows: http://hidot.hawaii.gov/highways/files/2013/01/hwy_l-HWY-Pavmenent-Design-Manual.pdf
11	IA	Previously, but not currently on our website.
12	IL	http://www.idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Split/Design-And-Environment/BDEManual/Chapter%2054%20Pavement%20Design.pdf
13	KS	No. KDOT does not have a current published document outlining LCCA procedure, since LCCA is only performed by a small group of pavement engineers internally.
14	KY	http://transportation.ky.gov/Highway-Design/Pavement%20Design/Appendix%20E.pdf
15	LA	No
16	MD	Not on the website, but available upon request. Contact info is in the first answer.
17	MI	d. Our LCCA process manual is available: http://www.michigan.gov/documents/mdot/MDOT_Pavement_Design_and_Selection_Manual_257723_7.pdf
18	MN	no
19	MO	The following link is to the actual alternate bid results for a project letting. The spreadsheet attached with the results shows the LCCA components. Keep in mind,

No.	State	Response
		pavement LCCAs are used to create an adjustment factor for alternate pavement bids, which are routine in Missouri, not to predetermine a pavement design for project development. http://epg.modot.mo.gov/files/d/df/AltPvmtJan07Results.pdf
20	MT	No formal procedure is currently available. Methods outlined in the 1993 AASHTO Design of Pavement Structures are used.
21	NC	Our LCCA is currently under review both within the agency and by the legislature. As a result, it is not available at this time.
22	NJ	The LCCA procedure is embedded in our pavement management software which is the dTIMS program supplied by Deighton Associates. As such it is not readily available.
23	NM	No
24	NV	LCCA Policy is not available on the website. The document is attached to this email. Contact person: Darin Tedford
25	OH	no but you can request it through the above contact.
26	OK	N/A
27	OR	Specific treatments and rehabilitation strategy for comparison are developed on a project specific basis based on PMS data. Design guidance is available in Chapter 9 of the ODOT Pavement Design Guide located at the following location: http://www.oregon.gov/ODOT/HWY/CONSTRUCTION/docs/pavement/pavement_design_guide.pdf
28	PA	Yes, it is available as an Excel spreadsheet. Please see the e-mail attachment.
29	SC	No
30	TN	No. The original procedure is over 20 years old and the update is in progress.
31	UT	N/A
32	WA	Yes, it is found in WSDOT's Pavement Policy: http://www.wsdot.wa.gov/NR/rdonlyres/D7971B81-5443-45B9-8B9B-BFC0D721F5A1/0/WSDOTPavementPolicyFinal71211.pdf
33	WI	Chapter 14 of our Facilities Development Manual (FDM) covers pavement design. See section 14-15-10 Life Cycle Cost Analysis (LCCA) Process http://roadwaystandards.dot.wi.gov/standards/fdm/
34	WV	Yes…see link below for access to our Design Directives. LCCA and other corresponding directives are within the Pavement Section…DD 641-660. http://www.transportation.wv.gov/highways/engineering/DD/2006DDManualMASTER.pdf

14 APPENDIX F DEPARTMENTS OF TRANSPORTATION RESPONSES TO QUESTION 2

What is the decision making process that triggers the actual timing of the overlay (or other major rehabilitation process) on your Interstate System for flexible and rigid pavements? Is this information available on your website?

No.	State	Response
1	AK	A combination of rut depth and IRI is used. The Pavement Serviceability Rating (PSR) [a scale ranging from 0 (poor) to 5 (very good)] is typically used to fund pavement projects. Values below 3.0 are considered mediocre.
2	AL	There is no formal decision making process that triggers major or minor rehabilitation. The Regional offices submit to the Central Office Maintenance Bureau their interstate maintenance priorities based on their own perceived needs. There is a Interstate Maintenance Committee (IMC) that makes site visits and reviews FWD data, rehab history, accident history etc. and the projects are prioritized and scoped based on this review.
3	AR	A pavement condition index (PCI) is used. When the PCI has fallen into the poor category, rehabilitation is triggered. PCI scale is below: 0 – 25 Good 25-50 Fair 50-65 Fair to Poor 65-100 Poor
4	AZ	Trigger values for performance indicators (IRI, Cracks, and Rutting etc.) and cost-effectiveness analyses. Not available on website
5	CA	From annual/bi-annual pavement condition summary. Recommendations are based from structural and functional distress data and validated by field review. Refer to the State of the Pavement Report http://www.dot.ca.gov/hq/maint/Pavement/Pavement_Program/PDF/2013_SOP_FINAL-Dec_2013-1-24-13.pdf
6	CO	A number of factors are used in CDOT's PMS to trigger a rehabilitation. Generally, the rehabilitation is based on the cost and benefit. The process is available from CDOT.
7	CT	Flexible Pavements: The agency's Pavement Management System generates an Environmental Cracking Index and a Structural Cracking Index. Coupled with roughness information (IRI), this information is used to generate a pavement strategy, which could include a major rehabilitation based on this condition. (Functional overlays and preservation treatments are triggered at higher condition levels, but the existing system contains many roads beyond preservation.) For rigid pavements, we use the IRI and slab and joint condition. There are only 5 segments of rigid pavement in the state highway network so the slab and joint condition are conducted through visual survey.
8	DE	Pavement condition data from PMS; n/a on website
9	FL	when a pavement section reaches "deficient" (< 6.5), the districts may program a project in the outer year of the 5 year work program. Our pavement management

No.	State	Response
		system provides tools for the districts which prioritize their pavements based on condition rating, & benefit to cost data (traffic, trucks, etc.)
10	HI	Presently, there is no trigger value used.
11	IA	We have an annual review of the Interstate system by a team of engineers representing Design, Materials, Construction, and the District offices. The entire system is driven each year to develop a list of candidate projects based on visual distress, material information and pavement management data.
12	IL	The condition rating survey (CRS) value is the primary trigger. It includes surface condition, IRI, rutting, and faulting.
13	KS	Maintenance is performed based on PMS data and district 1R tours. The PMS is an optimization system based on current condition, predicted future condition, feasible actions (including action predicted cost and performance), and available budget. Some is. Pavement condition data is available at http://www.ksdot.org/matreslab/pmis/.
14	KY	PMS system rates every interstate system routes annually. PMS makes recommendations for appropriate treatment and treatment year. This information is not available online.
15	LA	Experience within the Department No
16	MD	There is no uniform process. It is a combination of pavement management system optimization suggestions, district maintenance engineer suggestions, problem areas, political considerations, contract authority, and so on. Each of the 7 engineering districts decides using various combinations of these criteria.
17	MI	2. MDOT has an annual Call for Projects which adds the fifth year to a rolling five year plan. The Rehabilitation and Reconstruction (R&R) program includes major rehabilitation projects and reconstruction projects. The primary requirement for a project to be included in the Call is that the Remaining Service Life (RSL) at time of construction is projected to be 2 years or less. The regions utilize RSL data along with other pavement condition measures, their knowledge of the pavement and its history in terms of previous projects and maintenance issues. The regions work together, including van tours to conduct field reviews, to develop their recommended candidate list. The Scoping Manual incorporates quite a bit of information about the Call for Projects, and can be found at http://www.michigan.gov/mdot/0,4616,7-151-9622_11044_11367-243045--,00.html
18	MN	We are currently attempting to drive down the percent of poor pavements based upon IRI.
19	MO	The actual decision to perform rehabilitation is made by the District personnel having jurisdiction over the route of interest. They use a combination of PMS performance data and field observations. The PMS, however, does not blindly dictate rehab timing with no human judgement.
20	MT	Ride most often triggers an overlay. Alligator Cracking will also but ride is the usually distress. Major rehabilitation can be triggered by an individual distress that is severe

No.	State	Response
		like ride or ACI but usually it is a combination of lower distresses present, i.e. ride, rut and ACI.
21	NC	We have developed and have under review a 10 year plan for managing interstate pavements. This plan included preservation, light rehab, moderate rehab, heavy rehab and reconstruction. Not posted at this time.
22	NJ	N/A
23	NM	See earlier responses
24	NV	Nevada DOT pavement rehabilitation process is based on the proactive preservation principles. Age of the pavement triggers the timing of the overlay. PMS Overview manual contains this information. This manual is not available on the website.
25	OH	Pavement condition triggers an overlay. Major rehabilitation could be condition or capacity.
26	OK	N/A
27	OR	We do a detailed condition assessment every two years, including distress, rut, roughness, and friction. The distress and rut are the primary triggers. An overall score of 0-100 is assigned as a condition index. Experience has shown that interstates, in low fair to poor condition, require rehabilitation to address rutting and/or structural/materials problems. Generally speaking from a rutting standpoint, a rut of 3/4" triggers an action. Widespread low fatigue or intermittent moderate fatigue would likely trigger action on the interstate. Triggers are adjusted to the appropriate rehabilitation type commensurate with where they are on the Pavement Management Curve. As as side note, we have much open-graded mix, which when it experiences widespread raveling, becomes a rehabilitation trigger. The condition index may or may not pick this up. The condition inspection manual and report of date is available on website.
28	PA	Refer to PennDOT Publication 242, Appendix I and J. Link to Publication 242 provided above.
29	SC	PMS generates initial priority list. PMS list undergoes engineering review for final Rehab Candidate list. This is not available on our website.
30	TN	Skipped
31	UT	UDOT uses the dTIMS deterioration modeling software to identify pavement sections that should be prioritized for Preservation or Rehabilitation with the funding available. These recommendations then go to our Region pavement engineers to include in their decision making process for what projects to program and make the project level decisions on what specifically needs to be done. The Region recommendations then come back for review and commission approval. This link should provide a link for the Part 4 of our PM manual describing the model Index & Trigger formulas. https://www.udot.utah.gov/public/ucon/f?p=100:pg:0::::T,V:120
32	WA	The need for rehabilitation is triggered by Pavement Structure Condition (cracking), Pavement Rutting Condition (Rutting) and Pavement Profile Condition (IRI). Rehabilitation is desired at scores of 45-50, rutting is based on a rut depth of 0.50

No.	State	Response
		inch and roughness is based on a IRI of 220 inches/mile. Depending on funding the actual condition at the time of rehabilitation may be much lower.
33	WI	Condition and ride data are used. This information is not available on our website.
34	WV	Each year our resurfacing program is evaluated based on a combination of candidates selected from our PMS data base with those developed subjectively within the local districts or by central design staff. From these lists, attempts are also made to identify candidates for potential early preservation.

15 APPENDIX G DEPARTMENTS OF TRANSPORTATION RESPONSES TO QUESTION 2A

How is IRI used in the decision making process?

No.	State	Response
1	AK	IRI is not the sole performance measure that triggers action, even though FHWA's guideline of 170 in/mile gets considered sometimes. Some of our pavements suffer from studded-tire wear. Rut depth is often the criteria that triggers action (~0.75"). Pavements in other parts of the state suffer from embankment instability (due to thawing permafrost) before any traffic-related distress is evident.
2	AL	Current IRI data is made available to the IMC.
3	AR	Provided via powerpoint; Asphalt: PCI consists of IRI, Rutting and Cracking. IRI accounts for 50% of the overall PCI, and rutting and cracking each account for 25%. IRI is converted to a 0-100 scale; Rutting is on a 0-1” scale and cracking is converted to a uniform cracking index on a scale of 0-100, see scale below. Original IRI scale below also (based on standard categories in HPMS) IRI: 0-60: Very Good 60-95: Good 95-170: Fair 170-220: Mediocre >220: Poor Universal Cracking Index (UCI): 0-20: Good 20-50: Fair 50-80: Fair to Poor 80-100: Poor Concrete: PCI is determined by IRI alone
4	AZ	One of the factors in the decision trees and measure of cost-effectiveness.
5	CA	For all rehabilitation projects (minimum design life of 20 years), IRI must be 60 in/mile or smoother. For what Caltrans considers corrective maintenance projects (extending the service life for 5-10 years), the existing pavement must be corrected to 60 in/mile if the existing IRI is greater than 170 in/mile.
6	CO	IRI is one element that could trigger a rehabilitation.
7	CT	IRI is used when the values are above thresholds for various road classes, not before (since the correlation with structural condition is weaker at these lower levels). However, for composite pavements IRI is a major indicator of structural distress and is monitored at the project level by examining the progression of IRI since the last overlay in these cases to identify the potential for structural deficiency.
8	DE	n/a
9	FL	We use IRI for our ride rating.
10	HI	Not used.

No.	State	Response
11	IA	It is one of the data elements considered when addressing candidate pavement sections.
12	IL	IRI is included in determining the CRS value.
13	KS	IRI is one of the variables that makes up our condition index (called Distress State). The pavement smoothness is a significant component in the pavement condition assessment and subsequent decision process.
14	KY	IRI is a part of the formula to determine pavement condition along with other pavement distresses. Asphalt-cracking, rutting Concrete-cracking, faulting
15	LA	It is not. IRI is in the specifications
16	MD	It is just one of several factors.
17	MI	a. IRI is not typically used directly in the decision making process. It is used if the IRI is to a point where it triggers customer complaints or other issues. A project such as diamond grinding would most likely be directly related to IRI. Rutting and faulting may be used similarly in the project selection process.
18	MN	It is the primary driver of the pavement management system and our department's performance measures.
19	MO	IRI is the only pavement performance metric used for public state-of-the-system reporting. For example, if we publicize that 86 % of our major roads are in good condition, it merely means that percentage of major roads have an IRI less than or equal to 100 inches/mile. However, when it comes to project selection, it is only one factor used.
20	MT	IRI is used for triggering treatments and an overall index for in budgeting scenarios. It is the pavement performance measure used to communicate with the Transportation Commission and Legislature.
21	NC	It is not generally part of LCCA because ride quality is not our dominant performance issue.
22	NJ	IRI is not really used in the decision making process to determine when a pavement section is chosen for rehabilitation. This is mostly based on the distress index as described below. However, once pavement projects are selected, IRI is combined with SDI to determine project benefit and to prioritize individual projects.
23	NM	IRI has been included in pavement condition rating index. However, NMDOT is moving away from the using the IRI in the pavement type selection process.
24	NV	IRI values are used to validate and prioritize the rehabilitation projects.
25	OH	It is not used at all
26	OK	N/A
27	OR	IRI is rarely a stand-alone trigger. It is a secondary trigger, and is most commonly used to help assign smoothness specifications for the next rehabilitation.
28	PA	Pavements with IRI>100 in/mi (Fair or Poor) are candidates for at least preventative maintenance treatments.
29	SC	IRI is a component of the PMS model, which also includes various distresses.
30	TN	IRI and distress triggers are flagged in the Pavement Management Report. The regional resurfacing coordinator uses this to make a list of possible candidates. Field

No.	State	Response
		visits to all candidate sites are made and final list is compiled based on type of treatment required and funding availability.
31	UT	IRI is included in the Model, along with rutting, faulting, and various types of cracking data to trigger different treatments.
32	WA	IRI is used as a trigger for rehabilitation although it tends to be a lagging indicator. In 2012 IRI accounted for only 2.8 perent of all WSDOT lane miles (approx 18,500 lane miles, includes asphalt, chip seal and concrete) with scores above 220 inches/mile.
33	WI	It is one of the factors used.
34	WV	IRI is looked at individually sometimes, but is generally used within the triggers discussed below.

16 APPENDIX H DEPARTMENTS OF TRANSPORTATION RESPONSES TO QUESTION 2B

If some form of a condition or performance index is used to monitor the performance of your pavements, how is the index determined and what are the thresholds used to trigger overlay or rehabilitation?

No.	State	Response
1	AK	See answer to previous questions. PSR is used (scale 0 to 5).
2	AL	ALDOT generates an annual report that assigns a Pavement Condition Rating (PCR) to each overlay section. The PCR is a composite index based on semi-automated distress surveys. The following descriptions are used PCR > 70 Good (doesn't need treatment); 69 > PCR > 56 Fair (candidate for preventative maintenance); 55 > PCR Marginal (needs resurfacing).
3	AR	PCI is used, when it falls into Poor (65 or greater) rehabilitation is triggered, within budget limitations
4	AZ	No single composite index.
5	CA	N/A
6	CO	The index is based on the functional class of highway along with the severity and amount of distresses. CDOT uses a index value of 50 out of 100 to indicate a Driveable Life of zero.
7	CT	Connecticut DOT has an overall condition index that has been designed to mimic our legacy windshield index (scale of 1-9 from worst to "perfect.") This condition index comprises roughness, cracking, distortion (rutting), drainability, and disintegration (which is a proxy for pavement surface age). However, pavement treatments are triggered based on an Environmental Cracking Index and a Structural Index coupled with a ride index based on IRI. For each treatment in the PMS, there are ranges of condition in these indexes that are used to trigger the treatment. For flexible pavements, the Environmental Index is composed of transverse cracking and non-wheelpath cracking extents transformed to a 0-10 scale. The Structural Index is composed of wheelpath cracking and some non-wheelpath longitudinal cracking (at right edge) transformed to a 0-10 scale. The Ride Index is IRI transformed to a 0-10 scale. For composite pavements, the structural index is composed of transverse cracking in excess of the expected single reflection crack, plus wheelpath and right-edge longitudinal cracking. The environmental cracking is non-joint-related cracking. Once these three decision variables are determined, the pavement type is used to determine ranges of index values that would trigger rehabilitation. For instance, the structural rehabilitation trigger is: If pavement type is Composite Ride Index between 3.5 and 5.0 OR Environmental Index between 3.0 and 5.25 OR Structural Index between 3.5 and 5.0; For Flexible Pavement: Structural Index between 3.0 and 5.0 (environmental index is ignored for a structural overlay). A Structural overlay with joint repair is triggered for Rigid or Composite pavements, as follows: Rigid pavement: (Note: only 5 concrete pavement segments in state highway network) Ride Index between 4.0 and 7.0 Composite pavement: Ride Index between 3.0 and 4.5 OR Environmental Index between 2.0 and 4.0 OR Structural Index between 3.0

No.	State	Response
		and 4.5. Once a treatment is recommended, it is reviewed and fine-tuned at the project level.
8	DE	Our pavement data is collected on a two year cycle and analyzed. The data is then scored and pavement rated via field reviews. Based upon the reviews, pavements are submitted for funding.
9	FL	Rate each pavement on crack & ride, and for asphalt pavements, also rut. on a scale of 0 (worst) to 10 (best), 6.5 in any one of the 3 criteria triggers need for rehab.
10	HI	The Pavement Condition Index (PCI) generally following ASTM D6433 is used to monitor pavement performance. No trigger value is used.
11	IA	We use our PCI as part of the process. It is calculated based on pavement type and individual distress types. In general PCI less than 60 indicates a need for some type of rehabilitation.
12	IL	Computer program calculates a CRS value based on age, distresses, IRI, rut, and faulting, but a panel of experts reviews all interstate video images and adjusts the CRS values if necessary.
13	KS	See http://www.ksdot.org/matreslab/pmis/glossary.asp#DISTRESS_STATE and follow the embedded link to IRI Notes as an example of the components of the index. Note that because the system is an optimization, thresholds are not static from year to year.
14	KY	N/A
15	LA	Not at this time to govern activity timing in LCCA
16	MD	Several condition indexes are used to monitor performance, but no thresholds trigger any action. We monitor percent acceptable (e.g. % with IRI better than 170 in/mi); we monitor average index (convert condition data to 0-100 scale), and we also monitor remaining service life (0 years are the worst 2%, 50 years are the best 2%, and this is done for each roadway functional class).
17	MI	b. Distress Index (DI) quantifies the level of surface distress that exists on a pavement section based on 1/10 mile increments. The scale starts at zero and increases numerically as distress level increases (pavement condition worsens). DI is determined by recording surface distress from pavement images and assigning points to various distresses, their level and severity. Remaining Service Life (RSL) is the estimated number of years from a specified date in time, until a pavement section is projected to reach a DI of 50. RSL is a function of project history and projected growth of pavement surface distress. Major rehabilitations and reconstructions are typically performed on pavement with RSL of 2 years or less.
18	MN	This website contains our pavement management data and associated decision trees. The decision trees are NOT the final say on what gets done, just a means to sort potential repairs and associated costs: http://www.dot.state.mn.us/materials/pvmtmgmt.html
19	MO	The MoDOT PMS contains distress indices collected with the ARAN that comprise part of the overall pavement condition index score. These indices (rutting, cracking,

No.	State	Response
		faulting, etc.) are used qualitatively by our District designers and pavement specialists for scoping work, but do not have formal threshold triggers.
20	MT	All our indices can trigger treatments. The determined treatment is based on priority and exclusion from the previous treatment period. We have four indices Ride, Rut, ACI and MCI (transverse/longitudinal). For example Ride Index of 69.9 is an overlay; 57 is Minor Rehab and 30 is Major Rehab Alligator Cracking between 65 and 80 can trigger overlay or minor rehab depending on ESALs
21	NC	We currently use a composite PCR that includes cracking, both wheelpath and environmental, rutting, ride, ravelling, bleeding for flexible.
22	NJ	SDI is mainly used to trigger overlay or rehab treatments. The determination of SDI is described above and triggers are summarized below: • For minor rehab of asphalt & concrete pavements: 1.0 ≤ SDI ≤ 2.5 • For major rehab of asphalt & concrete pavements: SDI < 1.0
23	NM	See earlier responses
24	NV	NDOT uses a point rating index to monitor the pavement performance. This index is a function of IRI, friction, rutting, fatigue and block cracking, non-wheel path cracking, patching, flushing, and raveling. 400-699 points – Overlay >699 points - Major rehabilitation
25	OH	We use Pavement Condition Rating (PCR) http://www.dot.state.oh.us/Divisions/Planning/TechServ/TIM/Documents/PCRManual/2006PCRManual.pdf
26	OK	N/A
27	OR	See answers to previous questions for details.
28	PA	PennDOT uses an Overall Pavement Index (OPI), which ranges from 0 to 100, 100 being the best possible condition. The OPI formula includes cracking, edge deterioration, patching, raveling/weathering, and rutting for bituminous pavements and cracking, patching, faulting, broken slabs, and joint spalling for concrete. The collected distresses produce individual distress indices based on severity. These indices are weighted based on importance and added to produce the OPI. Currently, PennDOT does not use OPI to trigger a specific treatment but rather to measure health of the network or specific pavement.
29	SC	PMS uses a Pavement Quality Index (PQI) based on ride and distress correlated to expert panel rating. No specific threshold exists because the priorities are set based on current PQI and rate of change of PQI.
30	TN	Indices for roughness and distress are calculated within the Pavement Management System.Pavement Smoothness Index, uses direct conversion of IRI.Pavement Distress Index, subtracts deduct value for each distress from 5 (perfect - no distresses). Pavement Quality Index (PQI), PQI = distress^0.7*roughness^0.3
31	UT	IRI is the condition used for annual reporting for pavement condition. Preservation and Rehabilitation treatments are triggered using a combination of distress index

No.	State	Response
		values Refer to the model documentation info https://www.udot.utah.gov/public/ucon/f?p=100:pg:0::::T,V:120
32	WA	WSDOT uses the following: Cracking is based on a condition index of 45 to 60, rutting is based on a rut depth of 0.50 inch and roughness is based on a IRI of 220 inches/mile. The cracking condition index is called PSC (Pavement Structure Condition) and is documented int WA-RD 274.1 The WSPMS - A 1993 Update. htlp:www.wsdot.wa.gov/research/reports/fullreports/274.1.pdf
33	WI	WisDOT uses PCI, but it is not the only factor used. There is not a standard number.
34	WV	Our interstates are scanned annually using an automated road scan to develop continuous crack mapping, measure rutting, and measure IRI. IRI is converted to PSI for comparison to the following index values. From the scans, we then develop the additional condition indexes shown below. Flexible Pavements: · Rutting Depth Index (RDI) – basically measures rutting and determines max, min, and average per 0.1 segment · Structural Cracking Index (SCI) – includes fatigue cracking and longitudinal cracking within a travel lane per 0.1 mile segment · Environmental Cracking Index (ECI) – includes transverse cracking and block cracking within the travel lane per 0.1 mile segment · Net Cracking Index (NCI) – a cracking index that is a function of a combined ECI and SCI Rigid Pavements: · Joint Condition Index (JCI) – a function of faulting and Joint Distress per 0.1 mile segment. Slab Condition Index (SCI) – a function of Transvers and Longitudinal slab cracking An additional index is computed as a composite condition index (CCI). It is defined as equal to the lowest of the other indices. Distresses are compiled and index values established based on a scale from 0 to 5, with 5 being the upper limit or essentially representing no distress. Then trigger values can be set to call out different stages of rehab and develop rehab scenarios. The index values are then used in analysis using either the CCI only or with all the applicable indexes for the type of pavement being evaluated. The triggers are shown in the attached tables.

17 APPENDIX I DEPARTMENTS OF TRANSPORTATION RESPONSES TO QUESTION 2C

If not an index, then what method or measurements are used to monitor pavement performance and what are the thresholds used to trigger overlay or rehabilitation?

No.	State	Response
1	AK	N/A
2	AL	N/A
3	AR	An index is used, see above
4	AZ	IRI > 105, Crack > 15%
5	CA	The pavement condition date is mapped to three conditions states as detailed below. State 1: Preventive Maintenance project. Pavement in good/excellent condition with no or few potholes or cracks. This pavement requires a preventive maintenance pavement project. State 2: Corrective Maintenance project. Pavement is in fair condition with minor surface distress that only needs corrective maintenance. The types of minor surface distress include minor cracking, slab cracking, raveling and potholes. The repair is a corrective maintenance pavement project. State 3: Corrective Maintenance, Rehabilitation or Reconstruction project. Pavement includes major distress (pavement in poor condition with extensive cracks), minor distress (pavement in poor condition with significant cracks), and poor ride only. The severity of distressed pavement is defined by both the visual appearance of the pavement and the IRI. The ride quality is based on the FHWA standard that defines an acceptable IRI as 170 or less. The repair is a Pavement Rehabilitation or Reconstruction, lane replacement project or a Capital Preventive Maintenance (CAPM) project. Refer to the State of the Pavement Report for additional information: http://www.dot.ca.gov/hq/maint/Pavement/Pavement_Program/PDF/2013_SOP_FINAL-Dec_2013-1-24-13.pdf
6	CO	N/A
7	CT	N/A
8	DE	N/A
9	FL	N/A
10	HI	
11	IA	
12	IL	
13	KS	
14	KY	
15	LA	Working toward using PMS data more
16	MD	See previous question.
17	MI	N/A
18	MN	Thresholds are irrelevant since we cannot meet our performance targets. We have more roads that fail the thresholds than we can afford to fix.
19	MO	N/A

No.	State	Response
20	MT	N/A
21	NC	Use an index.
22	NJ	N/A
23	NM	N/A
24	NV	N/A
25	OH	N/A
26	OK	N/A
27	OR	An index is used.
28	PA	Several performance measures are used to monitor the condition of PennDOT's Interstate system, including IRI, OPI, and Treatment Cycles. Refer to PennDOT Publication 242, Appendix I and J for details.
29	SC	N/A
30	TN	an index is used
31	UT	N/A
32	WA	N/A
33	WI	N/A
34	WV	One additional parameter that has become a trigger subjectively over the past 10 years or more and has not been readily a part of our PMA triggers is longitudinal joint deterioration of asphalt pavements and overlays in composite sections. We have just now started to incorporate it into our PMS.

18 APPENDIX J ACTUAL SERVICE LIFE OF LTPP SPS EXPERIMENTS

Table J.1 Summary Statistics for Time to First Rehabilitation, SPS-5 Experiment (Rehabilitation of AC Pavements)

	Statistics for Time to First Rehabilitation (years) of Sections				
Site ID	No.	Avg	Min	Max	Std. Dev.
1-05	10	16.21	16.20	16.23	0.01
12-05	14	24.02	24.02	24.02	0
13-05	15	15.02	15.02	15.02	0
23-05	9	22.64	22.64	22.64	0
24-05	13	20.44	20.43	20.54	0.04
27-05	11	21.22	21.22	21.22	0
28-05	9	17.00	16.96	17.07	0.05
29-05	8	16.90	16.89	16.92	0.01
30-05	10	9.01	9.01	9.01	0
34-05	10	23.74	23.73	23.81	0.03
35-05	9	31.28	31.28	31.28	0
40-05	9	24.02	24.00	24.04	0.02
4-05	10	21.82	21.82	21.82	0
48-A5	8	14.26	14.15	14.39	0.11
6-05	22	25.75	25.75	25.75	0
8-05	11	17.00	17.00	17.00	0
81-05	8	13.34	13.34	13.34	0
Summary for Sites	17	19.63	9.01	31.28	5.48

Table J.2 Summary Statistics for Time to First Rehabilitation, SPS-6 Experiment (Rehabilitation of Jointed Portland Cement Concrete (JPCC))

Site ID	Statistics for Time to First Rehabilitation (years) of Sections				
	No.	Avg	Min	Max	Std. Dev.
1-06	10	31.93	31.86	32.17	0.13
17-06	14	27.54	25.86	37.02	4.02
18-06	21	18.51	18.45	18.56	0.05
19-06	9	24.76	23.72	31.68	2.63
26-06	7	31.98	31.98	32.02	0.02
29-06	15	17.19	16.84	20.37	0.88
29-A6	7	29.03	28.99	29.12	0.06
40-06	7	29.78	29.76	29.82	0.02
4-06	17	23.79	23.79	23.79	0
42-06	9	23.26	20.76	24.03	1.23
46-06	11	20.19	19.08	30.44	3.40
47-06	10	31.86	31.80	31.91	0.05
5-A6	8	18.71	17.84	24.69	2.42
6-06	13	18.54	18.52	18.55	0.01
Summary for Sites	14	24.79	17.19	31.98	5.55

Table J.3 Summary Statistics for Time to First Rehabilitation, SPS-7 Experiment (Bonded PCC Overlays of Concrete Pavements)

Site ID	Statistics for Time to First Rehabilitation (years) of Sections				
	No.	Avg	Min	Max	Std. Dev.
19-07	9	24.99	24.87	25.95	0.36
22-07	8	12.88	12.85	12.90	0.02
27-07	9	20.21	20.21	20.21	0
29-07	10	34.83	34.80	34.85	0.02
Summary for Sites	4	23.23	12.88	34.83	9.20

Table J.4 Summary Statistics for Time to First Rehabilitation, SPS-9C Experiment (AC Overlay on CRCP)

Site ID	Statistics for Time to First Rehabilitation (years) of Sections				
	No.	Avg	Min	Max	Std. Dev.
18-09	4	21.75	21.75	21.75	0.00
26-09	3	22.84	22.84	22.84	0.00
Summary for Sites	2	22.29	21.75	22.84	N/A

Table J.5 Summary Statistics for Time to First Rehabilitation, SPS-9J Experiment (AC Overlay on JPCC)

Site ID	Statistics for Time to First Rehabilitation (years) of Sections				
	No.	Avg	Min	Max	Std. Dev.
18-A9	6	29.07	29.07	29.07	0
27-09	5	39.56	39.51	39.58	0.03
29-09	9	30.27	30.27	30.27	0
55-09	6	24.05	24.02	24.05	0.02
55-A9	6	23.06	23.05	23.07	0.01
55-B9	6	22.97	22.97	22.97	0
Summary for Sites	6	28.16	22.97	39.56	6.41

Table J.6 Summary Statistics for Time to First Rehabilitation, SPS-9O Experiment (AC Overlay on AC Pavement)

Site ID	Statistics for Time to First Rehabilitation (years) of Sections				
	No.	Avg	Min	Max	Std. Dev.
12-09	4	33.17	33.17	33.17	0
24-09	6	6.01	6.01	6.02	0
28-09	3	32.70	32.70	32.70	0
34-09	6	28.16	28.16	28.16	0
35-09	4	30.90	30.88	30.93	0.02
4-B9	7	16.87	16.87	16.87	0
9-09	6	26.94	26.91	26.96	0.02
Summary for Sites	7	24.96	6.01	33.17	10.01

19 APPENDIX K SUMMARY OF REHABILITATION TREATMENTS INCLUDED IN DOT'S LCCA PROCEDURES

Rehabilitation Treatments for Flexible Pavements

The most common rehabilitation treatment for flexible pavement was to overlay the existing pavement. As shown in the list below, some agencies stated the various thicknesses that are considered, as well as the amount of milling considered. Within the category of overlays, subcategories were identified based on the responses. Generally, an overlay implies the addition of new flexible pavement material to the surface. One DOT specified the overlay as an "engineered overlay." An engineered overlay likely indicates that the overlay thickness is designed to meet necessary strength requirements for additional traffic or the remainder of pavement design life. Other DOTs indicated that the overlay was considered structural, which is often used to indicate when additional pavement is placed on the existing surface to replace or increase the structural capacity of the pavement. Other responses included "milling and filling," "mill and resurface," or "mill and inlay," which are assumed to generally be the same treatment in that a set thickness is removed and new material is placed at the same thickness. One DOT indicated that "milling and paving surface and intermediate layers" was used for rehabilitation of flexible pavements. It was not specified whether additional thickness is added as part of this process, therefore, it was assumed that this meant removal and replacement of the surface and intermediate layers, thereby falling into the "milling and filling" category. Lastly, one DOT indicated in their response that the rehabilitation treatments utilized include patch, grind and overlay. It is unclear from this response whether these are individual treatments or performed as part of the same activity. However, it is assumed that "grind" implies milling.

- Overlays/Inlays
    - Overlay
        - 1.25"
        - Greater than 2"
        - "Engineered overlay"
        - Structural Overlays
    - Inlays ("Milling and Filling")
        - 2 ¾" mill; Inlay with 2" dense graded and ¾" open graded asphalt
        - 3 ¾" mill; Inlay with 3" dense graded and ¾" open graded asphalt
        - 1.25"
        - Mill and fill of wearing course
        - Milling and paving surface and intermediate layers
        - Mill and resurface
    - Mill and Overlay
        - Mill 1-3" and overlay 1-5"
        - Mill 1.25" and overlay 3.25"
        - "Engineering mill and overlay"
        - "Patch, grind and overlay"

Three DOTs included full-depth reclamation (FDR) on their list of rehabilitation treatments for flexible pavements. Hot-in-place recycling was included on two DOT lists. The same two agencies, Colorado and Montana DOTs, in addition to Washington State DOT, also included cold-in-place recycling on their list of rehabilitation treatments for asphalt pavements considered in LCCA.

- Full Depth Reclamation (FDR)
  - Combined with 2-4" Hot-mix asphalt (HMA)
- Cold-in-place recycling
  - Combined with structural overlay
- Hot-in-place recycling
  - Combined with structural overlay

Other rehabilitation treatments mentioned in DOT responses included white-topping, full-depth patching, and reconstruction. One DOT stated that all anticipated treatments were considered, including crack sealing, seal coats, and micro surfacing. Crack sealing, seal coats, and micro surfacing are generally considered maintenance or preservation.

- White-topping
- Reconstruction
- Full-depth patching
- Crack sealing
- Seal coats, micro surfacing

Rehabilitation Treatments for Rigid Pavements

A range of rehabilitation treatments was included in DOT responses for rigid pavements in LCCA procedures. Concrete pavement rehabilitation or concrete pavement restoration (CPR), diamond grinding, and joint sealing or re-sealing were frequently reported. Within the category of CPR falls "major CPR" and "minor CPR," as well as full and partial depth repairs. Some agencies indicated slab replacement (including full or partial depth) was also a technique used. One DOT did indicate that a full depth slab replacement was considered CPR. Four DOTs stated patching or patching to some degree of PCC pavements was a rehabilitation activity considered in their LCCA procedures.

- Diamond grinding
  - "Retexturing"
  - Profiling
- Full and partial depth slab replacement
  - Removal and replacement of shattered slabs
  - Panel replacement
  - Slab replacement up to 15% of slabs
  - Slab replacement up to 1 or 2% of slabs
- Concrete pavement repair (CPR)
  - Major CPR
  - Minor CPR
  - Full depth slab replacement

    - 1.5% Full depth repair
    - Partial depth repair
- Patching
    - 1% patching
    - 3% patching
    - 5% patching

While two DOTs stated that joint repairs were considered for major rehabilitation of their PCC pavements, it can be assumed that joint stitching (reported by only one DOT), and dowel bar retrofitting would also be included in the category of joint repair. Several DOTs indicated specifically (cleaning and) sealing, re-sealing, re-sawing and re-sealing joints, or localized structural repairs as a rehabilitation treatment. Either slab stabilization or a specific type of stabilization, such as undersealing or slab jacking, was reported by three DOTs.

- Joint repair
    - Joint stitching
    - Dowel bar retrofit
- Joint and crack sealing
    - Re-sealing
    - Re-sawing and re-sealing joints
- Spall repair
- Slab stabilization
    - Under sealing
    - Slab jacking
- Localized structural repairs

Also, commonly reported among PCC rehabilitation treatments was some type of overlay. As shown in the list below, several DOTs indicated that asphalt overlays of various thicknesses, or, as some simply denoted, either structural or non-structural, were included in their list of rehabilitation options for rigid pavements. Three DOTs indicated that they consider unbonded concrete overlays for rehabilitation. More aggressive treatments such as rubblization of the existing concrete or cracking and seating of the concrete were also reported, and most agencies reporting one or both of these treatments also mentioned the inclusion of an asphalt overlay over the rubblized or cracked concrete. The most extensive rehabilitation treatments reported were lane replacement or full removal and replacement of the existing concrete pavement.

- HMA overlay
    - Non-structural overlay
    - Structural overlay
    - 3” overlay
    - 5” overlay
- Unbonded concrete overlay
    - 4 to 11” overlay
- Bonded concrete overlay

- Unbonded concrete overlay on crack and seat
- Rubblize and HMA overlay
- Crack, seat and HMA overlay
- Lane replacement
- Remove and replace
  - Replace with asphalt
  - Replace with concrete
- Reconstruction
  - Rubblize and seat, new concrete