Georgia Institute of Technology

School of Civil and Environmental Engineering

Georgia Concrete Pavement Performance and Longevity

Final Report

Prepared for:
Office of Materials and Research
Georgia Department of Transportation

GDOT Research Project No. 10-10
Task Order No. 02-74

Prepared by:
Dr. James (Yichang) Tsai, P.E.
Yiching Wu
Chieh (Ross) Wang

February 2012

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III. Executive Summary

The Georgia Department of Transportation (GDOT) has effectively utilized its pavement management system (PMS) to make informed, data-driven pavement maintenance decisions, including project selection, project prioritization, and funding allocation. Currently, due to funding shortages and the increasing reconstruction needs of its aging road network, GDOT is seeking to enhance its life-cycle cost analysis (LCCA) in pavement design to make the best investment in the pavements. A key question to address in conducting a reliable LCCA in pavement design is how long the pavements last. This question can be addressed by analyzing pavement condition data in the PMS. A previous study, entitled "Improving GDOT's Highway Pavement Preservation," analyzed the service life of asphalt pavements in Georgia. The objective of this project is to study the longevity of concrete pavements in Georgia using historical concrete pavement condition data. Also, this study provides a better understanding of the actual performance of various designs of concrete pavement.

GDOT has conducted an annual concrete pavement survey of its jointed plain concrete pavements (JPCP) since 1971. In this study, the data between 1971 and 2009, in both electronic and paper format, were used for determining concrete pavement service life. For the purposes of analyzing concrete pavement performance by its design, data, such as pavement design, construction time, and traffic, were obtained from GDOT. A systematic procedure was established to determine the service life of concrete pavements based on the data acquired. First, the data were screened for consistency and accuracy. Second, historical concrete pavement condition data were processed and grouped based on pavement design. Based on key design features, four design categories were considered: 1) non-doweled JPCP on a soil or soil cement base constructed in the 1960s, 2) non-doweled JPCP on an improved base (e.g., graded aggregate base, GAB) for addressing faulting issues, constructed in the early 1970s, 3) doweled JPCP on an improved base (e.g., GAB) constructed in the late 1970s and 1980s, and 4) doweled pavements with a 15-ft joint spacing and a 13-ft wide lane on top of a GAB base and a 3-inch hot mix asphalt (HMA) interlayer constructed since the 1990s. Third, three types of events, including an asphalt concrete (AC) overlay, a major rehabilitation (i.e., diamond grinding in conjunction with slab replacement and joint reseal), and a faulting index of 15 were defined as the timings for the

end of the service life. Fourth, rules were established for identifying the end of the service life based on concrete pavement condition data. A total of 258 centerline miles of overlaid JPCP were used for analyzing the service life based on an AC overlay and 839 surveyed miles of in-service JPCP on interstate highways with good data quality were used for the analysis of the other two types of service life. Out of the 839 surveyed miles, 541 miles had reached a major rehabilitation; these pavements are referred to as the rehabilitated projects. A statistical analysis based the rehabilitated projects, a survival analysis based on all projects (i.e., 839 survey miles), and a project-level analysis on six selected projects were conducted to study pavement service life by design and to explore the performance in terms of age and equivalent single axle loads (ESALs). The major findings are summarized as follows:

1. For the 258 centerline miles of JPCP overlaid with AC, the average time to the first AC overlay was 13 years. It is noted that most of the AC overlay was applied on JPCP in the late 1970s as part of interstate widening (adding lanes) projects. The decision for an AC overlay was based not only on pavement condition but also on other factors such as adding lane(s), funding availability, agency policy, etc. Because the actual causes of an AC overlay were not available, the 13-year span cannot be interpreted as the effective service life based on the first AC overlay.
2. For the rehabilitated projects (541 surveyed miles), based on the time needed to reach a major rehabilitation the average service life of the original pavements was found to be approximately 17 years; service life for the first major rehabilitation was 14 years; service life for a second major rehabilitation was 8 years, as shown in Table IV.1. It is noted that the rehabilitated projects are non-doweled JPCP, both Categories 1 and 2 pavements. The service life based on the time to reach a faulting index of 15 was close to those based on the time to reach a major rehabilitation. This indicates the pavements had been rehabilitated when they were close to a faulting index of 15.

Table III.1 Concrete Pavement Service Lives

	Original Pavement	First Major Rehabilitation	Second Major Rehabilitation
All Rehabilitated Projects	17*/17**	14/13	8/6
Category 1	17/14	14/13	8/6
Category 2	21/26	17/17	-
Category 3***	>25	-	-
Category 4***	-	-	-

*Based on the time to reach a major rehabilitation
**Based on the time to reach a faulting index of 15
*** None has reached a major rehabilitation
****Not studied due to limited data

3. An analysis by design category shows pavement service life has been improved through changes in design features. On average, the service life of the original pavements based on major rehabilitation in Category 1 was found to be 17 years; and, Category 2 was 21 years, which is 23% more than that of Category 1. Although none of the pavements in Category 3 have reached a major rehabilitation, the average service life is expected to be longer than its average age of 25 years, which is 45% more than that of Category 1.
4. Survival analysis was conducted based on all projects (839 surveyed miles) to develop an estimate of the expected pavement service life. The average, expected service life (at the 50^{th} percentile) of the original pavement for all projects is approximately 21 years, which is about the 20-year design, and that of the first major rehabilitation is slightly shorter at about 19 years. An analysis by design category shows the expected service life (at the 50^{th} percentile) for Category 2 is about 27 years, which is nearly twice that of Category 1 (15 years). At age of 25, less than 10% pavements in Category 1 survive.
5. A project-level analysis on six projects (two in each design category) was conducted to study the pavement performance in terms of ESALs and critical distresses. The results of this analysis are not considered conclusive due to the small sample size but provide an understanding of the performance in detail. The major findings are summarized as follows:
    a) All six projects in Categories 1, 2 and 3 outperform the designed ESALs. These projects carried 17-30 million ESALs, which is 2-4 times the designed ESALs, before the first major rehabilitation. The two projects in Category 1 carried 20

million ESALs in 23 years; the projects in Category 2 carried more than 17 million ESALs; the projects in Category 3 carried more than 30 million in 30 years.

b) The pavements actually have carried similar traffic loads (20-36 million ESALs or approximately 3 times the designed ESLAs) after the first major rehabilitation. This means the pavements have carried similar truck loads within a shorter time span as the traffic increased. The results also indicate that with proper concrete pavement restoration strategy, including timing and treatment methods, the load carrying capability can be restored.

c) The two projects in Category 1 had the first major rehabilitation in 23 years with a deterioration rate in the faulting index of 0.9 per year (or 1.1 per million ESALs). Both projects exhibited increasing numbers of broken slabs and slabs with longitudinal cracks after 25 years. On average, there were 10-30 broken and replaced slabs and less than 10 slabs with longitudinal cracks.

d) The two projects in Category 2 carried 1.7-2.6 times the designed ESALs over 19 to 26 years before they were rehabilitated at a faulting index around 10. Both projects exhibited a fairly low deterioration rate of the faulting index (0.4-0.6 per year or 0.2-0.7 per million ESALs) but significant numbers of broken slabs, replaced slabs, and slabs with longitudinal cracks. The number slabs with longitudinal cracks were about 20 and 10 slabs per mile, more than the number of broken slabs. These two projects are comparable if not better than projects in Category1.

e) The two projects in Category 3 have not reached a major rehabilitation in 30 years with a low deterioration rate in the faulting index (approximately 0.3 per year or 0.3 per million ESALs) and very minimum numbers of broken slabs, replaced slabs, and slabs with longitudinal cracks (less than 5 slabs per mile) after 30 years.

The findings in this study can be used to support LCCA in pavement design and to evaluate the cost-effectiveness of second and subsequent rehabilitations. In addition, the project-level analysis provided the insight on the pavement performance in terms of the load carrying capability compared to the designed ESALs.

Further research is recommended as follows:

1. At the time of this study, no sufficient data was available to support an analysis of Category 4 pavements because they were constructed in more recent years. A follow-up study is recommended to analyze the performance of the current design when more data are collected by GDOT.
2. Limited by the scope of this study, the performance of AC overlaid pavements was not studied. The LCCA of AC overlay and other concrete pavement restoration methods (e.g., grinding) could be studied to evaluate the long-term benefit-cost of different rehabilitation strategies.
3. Limited by resources and traffic, a manual survey can only collect sampled faulting data, i.e., on every 8th joint and limited crack information. According to GDOT's concrete pavement condition evaluation system (CPACES), the number of broken slabs is recorded for each mile, but detailed information, such as crack length and location, is not measured. With the advances in laser technology, a mobile 3D laser sensing system can now collect faulting on all joints at highway speeds. Automated data collection using a mobile 3D laser sensing system is recommended to improve the data collection productivity, to have full-lane-width coverage, and to enhance the data quality in terms of accuracy and consistency.
4. Using a 3D laser sensing system for monitoring newly constructed or reconstructed pavements with the latest design (Category 4) to better understand the behavior of these pavements (e.g., curling and warping) is, also, recommended.

1 Introduction

1.1 Background

In response to increasing reconstruction needs of its aging road network and funding shortages, the Georgia Department of Transportation (GDOT) has become more interested in enhancing its life-cycle cost analysis (LCCA) of pavement design. Pavement longevity, i.e., the service lives of original and rehabilitated pavements, is essential information for conducting a reliable LCCA of pavement design. Since pavement longevity varies widely depending on design, construction quality, environment (e.g., weather and moisture), rehabilitation strategy, etc., analyzing pavement service life based on actual pavement condition data is necessary. The service life of asphalt pavements in Georgia has been analyzed in a previous study, entitled "Improving GDOT's Highway Pavement Preservation" [1]. Currently, the longevity of concrete pavements in Georgia has not been thoroughly studied. Better understanding of concrete pavement performance and longevity will improve the capability of making important data-driven pavement management decisions (e.g., pavement type selection).

GDOT currently maintains over 500 centerline miles of concrete pavements on its interstate highways and state routes; most of them are jointed plain concrete pavements (JPCP). Constructed between 1958 and 1986, approximately 80% of JPCP are more than 30 years old. Many of them have been rehabilitated with an asphalt concrete (AC) overlay or a concrete pavement restoration (e.g., slab replacement and diamond grinding). GDOT has conducted an annual pavement survey, now called a concrete pavement condition evaluation system (CPACES) survey, of its JPCP since 1971. With the availability of extensive historical concrete pavement condition data, there is an opportunity to study the actual service life of JPCP in Georgia. In this project, more than 30 years of concrete pavement condition data were used to study concrete pavement service life in Georgia. Various data, including CPACES data, pavement design, construction information, and traffic, were acquired and processed to determine pavement service life. The service lives of original and rehabilitated pavements were first analyzed using the data for the pavements that had reached the end of service life, i.e., with a major rehabilitation performed on the pavement. Survival analysis was conducted to develop estimate(s) of the expected service life using all data, including data for pavements that have not yet reached the end of their service life. A project-level analysis on a few selected projects with different designs was also conducted to explore the performance in terms of equivalent single axle loads (ESALs) and critical distresses.

1.2 Significance of Research

This research will enhance GDOT's pavement management decisions, such as pavement type selection, through a better understanding of the actual longevity of concrete pavements in Georgia. The service life studied based on the actual concrete pavement data will enhance the reliability of LCCA in pavement design. Project-level analysis on selected projects provides a better understanding of the performance of JPCP by different designs. In addition, the data collected and the findings of this study can be used to support future studies of calibrating the models for JPCP in the Mechanistic-Empirical Pavement Design Guide (MEPDG).

1.3 Research Objectives and Scope

The objective of this project is to study the longevity of concrete pavements in Georgia by analyzing historical CPACES data. The CPACES was developed for identifying and measuring pavement defects on JPCP; therefore, the analysis is limited to JPCP. Other types of concrete pavements, such as continuous reinforced concrete pavement (CRCP), are not included in this study. This project consists of four specific work tasks:

- **Work Task 1. Acquire comprehensive historical data to support performance evaluation of different concrete pavement types in Georgia.**

  The objectives of this work task are 1) to acquire various data, including historical CPACES data, traffic data, and construction time information, to support the study of concrete pavement longevity; and 2) to review GDOT's practices on surveying concrete pavements and identify the changes in devices and distresses (e.g., severity level) that could result in inconsistency in the data.
- **Work Task 2. Quantitatively evaluate historical concrete pavement condition survey data and determine concrete pavement service life.**

The objectives of this work task are 1) to conduct a review on concrete pavement service life studies by other researchers and state DOTs to support the definition of concrete pavement service life; 2) to develop a systematic method to consistently and quantitatively evaluate historical CPACES data; and 3) to determine the service life of a concrete pavement with a confidence level (e.g., high, medium, or low).

- **Work Task 3. Analyze differences in concrete pavement service life based on design and traffic category.**

  The objectives of this work task are 1) to conduct a statistical analysis on the service lives of original and rehabilitated concrete pavements; and 2) to analyze the service lives of concrete pavements based on design category.

- **Work Task 4. Develop a preliminary network-level concrete pavement performance prediction model.**

  The objective of this work task is to develop estimate(s) of expected service life using historical CPACES data.

1.4 Organization of This Report

This report is organized into the following seven chapters:

1) Chapter 1 introduces the background, significance, objective, and work tasks of this project.
2) Chapter 2 describes the data used in this study, as well as the procedure for screening and processing the data. GDOT’s practices on concrete pavement design and survey were reviewed to categorize various designs and identify the change in devices used for collecting the distresses data.
3) Chapter 3 presents the work performed for determining concrete pavement service life, including reviewing the studies on the service life of concrete pavements, defining the events for the end of service life, the rules for determining service life with a confidence level, and a summary of the service life data considered.
4) Chapter 4 presents the analysis of concrete pavement service life, including a statewide analysis and an analysis based on design category.

5) Chapter 5 presents survival curves that were developed to estimate the expected service life, including data for pavements that have not yet reached the end of their service life.
6) Chapter 6 presents a project-level analysis on selected projects to explore the performance in terms of ESALs.
7) Chapter 7 summarizes the findings of this project and makes recommendations for future research.

2 Description of Data

Various data, including historical CPACES data, pavement design data, and traffic data, were acquired and processed in this study to support the study of concrete pavement longevity in Georgia. This chapter describes the data acquired from various sources and the work performed in preparing the data for use in this study. In addition, GDOT's practices on concrete pavement design and survey method were reviewed. JPCP designs were categorized for studying pavement service life corresponding to each design category. GDOT's concrete pavement survey practice was reviewed to identify changes in the devices and methods for collecting the distress data, any of which can lead to inconsistencies/discrepancies in the data. Data processing was performed to convert the data collected by different devices and to clean anomalous/erroneous values in the data. A summary of potential gaps caused by the data conversion is also presented.

2.1 Data Acquisition

Various data, including historical concrete pavement condition data, pavement design data, construction information, and traffic data, were acquired with assistance from the Office of Materials and Research, the Office of Information Technology Applications, the Office of Traffic Data, and the Office of Maintenance. In addition, information regarding past maintenance and rehabilitation strategies was provided by Mr. Wouter Gulden. A brief description of each data source is provided below:

- Concrete pavement condition evaluation data:

  Historical concrete pavement condition data were acquired from the following three sources:

  1) An electronic database containing CPACES data from 2000 to 2010 was provided by the Office of Information Technology Applications in a Microsoft Access format. This database includes distresses recorded for each mile of JPCP, as well as a rating computed based on the pavement deficiencies (distresses). Table 2.1 depicts the data structure.
  2) Another electronic database containing the data from 1980, 1985, 1991-1993, and 1996-1997, which was obtained through a previous research project [1]. As shown in

3) Table 2.2, the data items in this database are similar to the database described above; however, the data structure is slightly different. These two databases were merged for the analysis.
4) Hard copies of annual concrete pavement condition evaluation reports from 1971-1997 were provided by the Office of Materials and Research. This information was used for manually verifying the pavement condition when needed.

Table 2.1 Data Structure for CPACES Data Obtained from GDOT

Field Name	Data Type	Field Name	Data Type
Fiscal_Year	Text	Faulting_Measurement_6	Integer
InterstateRoute	Text	Faulting_Measurement_7	Integer
District	Text	Faulting_Measurement_8	Integer
County	Integer[1]	Faulting_Measurement_9	Integer
Route	Text	Faulting_Measurement_10	Integer
Direction	Text	Faulting_Measurement_11	Integer
Begin_Milepost	Single[2]	Faulting_Measurement_12	Integer
End_Milepost	Single	Faulting_Measurement_13	Integer
ProjectNumber	Text	Faulting_Measurement_14	Integer
Date_Collected	Date/Time	Faulting_Measurement_15	Integer
Rater	Text	Faulting_Measurement_16	Integer
Divided_Highway	Text	Faulting_Measurement_17	Integer
Project_Limits	Text	Faulting_Measurement_18	Integer
Broken_Slabs_Level_1	Integer	Faulting_Measurement_19	Integer
Broken_Slabs_Level_2	Integer	Faulting_Measurement_20	Integer
Long_Cracks_Level_1	Integer	Faulting_Measurement_21	Integer
Long_Cracks_Level_2	Integer	Faulting_Measurement_22	Integer
Replaced_Slabs	Integer	Faulting_Measurement_23	Integer
Failed_Replaced_Slabs	Integer	Faulting_Measurement_24	Integer
Spalled_Joints	Integer	Faulting_Measurement_25	Integer
Patched_Joints	Integer	Faulting_Measurement_26	Integer
Failed_Spall_Patches	Integer	Faulting_Measurement_27	Integer
Shld_Distress_Level_1	Integer	Faulting_Measurement_28	Integer
Shld_Distress_Level_2	Integer	Faulting_Measurement_29	Integer
Faulting_Index	Integer	Faulting_Measurement_30	Integer
Roughness	Integer	Faulting_Measurement_31	Integer
Comments	Text	Faulting_Measurement_32	Integer
Rating	Integer	Faulting_Measurement_33	Integer
Faulting_Measurement_1	Integer	Faulting_Measurement_34	Integer
Faulting_Measurement_2	Integer	Faulting_Measurement_35	Integer
Faulting_Measurement_3	Integer	LastModifiedDate	Date/Time
Faulting_Measurement_4	Integer	LastModifiedBy	Text
Faulting_Measurement_5	Integer		

Notes: 1. Integer: non-fraction numbers from –32,768 to 32,767.

2. Single: numbers from –3.402823E38 to –1.401298E–45 for negative values and from 1.401298E–45 to 3.402823E38 for positive values.

Table 2.2 Data structure for CPACES Data [1]

Field Name	Data Type	Field Name	Data Type	Field Name	Data Type
TripDate	Date/Time	FM_1	Integer[1]	FM_33	Integer
EnterDate	Date/Time	FM_2	Integer	FM_34	Integer
District	Text	FM_3	Integer	FM_35	Integer
CountyNO	Text	FM_4	Integer	FM_36	Integer
RouteNO	Text	FM_5	Integer	AADT	Integer
RouteSuffix	Text	FM_6	Integer	PaveWidth	Integer
RouteType	Text	FM_7	Integer	ShoulderType	Integer
MilepostFrom	Single[2]	FM_1	Integer	ShoulderWidth	Integer
MilePostTo	Single	FM_9	Integer	FailedReplacedSlabs	Integer
Highway_Divided	Text	FM_10	Integer	PercentShoulderJoint	Integer
Direction	Text	FM_11	Integer	FN	Integer
Rating	Integer	FM_12	Integer	PercentTruck	Integer
Rater	Text	FM_13	Integer	Treatment	Text
Status	Text	FM_14	Integer	Cost	Integer
TotalLane	Integer	FM_15	Integer	Fiscal_Year	Integer
SurveyLane	Integer	FM_16	Integer		
Broken_Slabs_1	Integer	FM_17	Integer		
Broken_Slabs_2	Integer	FM_18	Integer		
Broken_Slabs	Integer	FM_19	Integer		
Long_Cracks_1	Integer	FM_20	Integer		
Long_Cracks_2	Integer	FM_21	Integer		
Replaced_Slabs	Integer	FM_22	Integer		
Spalled_Joints	Integer	FM_23	Integer		
Patched_Joints	Integer	FM_24	Integer		
Failed_Spall_Patches	Integer	FM_25	Integer		
Percent_Failed_Patches	Integer	FM_26	Integer		
Shld_Distress_1	Integer	FM_27	Integer		
Shld_Distress_2	Integer	FM_28	Integer		
Faulting_Index	Integer	FM_29	Integer		
Smoothness	Integer	FM_30	Integer		
Smoothness_Date	Date/Time	FM_31	Integer		
Remark	Text	FM_32	Integer		

Notes: 1. Integer: non-fractions numbers from –32,768 to 32,767.

2. Single: numbers from –3.402823E38 to –1.401298E–45 for negative values and from 1.401298E–45 to 3.402823E38 for positive values.

Note that because of heavy traffic, a concrete pavement survey was not conducted on some routes (e.g., I-285). The concrete pavement survey practice, including distress types and severity levels, is reviewed in the subsequent section.

- Traffic Data

  Traffic data from 1990 to 2010 were provided by the Office of Traffic Data in a Microsoft Excel format. The information in this file includes average annual daily traffic (AADT), truck percentage, and traffic counter location (county, route number, and mile point). Note that traffic counter location is referenced using mile points instead of mile posts that are recorded during a concrete pavement survey. Additional effort was needed to match traffic data with concrete pavement condition data. Key fields in the file are as follows:
    - Year
    - RCLink (a unique identifier in GDOT's linear location referencing system)
    - County
    - Route number
    - Traffic counter number
    - Begin mile post
    - End mile post
    - AADT
    - Truck percentage
- Mile Point and Mile Post List

  A file that references each mile post on interstate highways to mile point was provided by the Office of Traffic Data in a Microsoft Excel format. This information is useful for locating traffic counter location based on mile post. Key fields in the file are as follows:
    - RCLink
    - County
    - Route number
    - Mile point
    - Mile post
    - Traffic counter number
- Interstate Project List

  A list of all projects on interstate highways was provided by the Office of Materials and Research in a Microsoft Excel format. Each project has the same design and was constructed at the same time. This file provides useful information for identifying a project and its construction time. Key fields in the file are as follows:

  - Project number
  - Beginning of construction
  - Completion of construction
  - Length
  - Project limit description

- Pavement Design Data

  A hard copy of pavement design features inventory (e.g., thickness and joint spacing) on interstate highways and a few state routes (e.g., SR 5, SR 400, SR 365) was provided by the Office of Materials and Research. This information was based on GDOT's pavement faulting study in 1971 [2]. Key fields in the summary are as follows:

  - Project number
  - Mile post
  - Joint spacing
  - Joint orientation
  - Thickness
  - Base
  - Shoulder
  - Drainage
  - Dowels
  - Project location description

- Concrete Pavement Rehabilitation

  A list of concrete paving let projects between 2000 and 2009 was provided by the Office of Materials and Research in a Microsoft Excel format. Key fields in the summary are as follows:

  - Let data
  - Project number
  - District
  - Area
  - Contractor
  - Quantity

- Unit Cost
- Cost

Although the maintenance and rehabilitation records prior to 2000 were not available at the time of this study, general information regarding rehabilitation strategies was gathered from GDOT and from Mr. Wouter Golden. The following items summarize GDOT's rehabilitation practices:

- Faulting has been a primary concern for JPCP, especially for pavements constructed in the 1960s and the 1970s without dowels.
- A faulting index of 20 was designed as a trigger point for rehabilitation. The measurement of faulting and the meaning of faulting index are described in Section 2.3.1 in this report. This value is equivalent to an average faulting of 1/8-inch that is used as a threshold in MEPDG. However, pavements may be rehabilitated before reaching a faulting index of 20 depending on rehabilitation strategy and funding availability.
- Diamond grinding in conjunction with slab replacement and joint resealing has been used for correcting the faulting. In addition to correcting the faulting, diamond grinding alone may be applied to restore rideability (smoothness) of the pavements, especially for pavements constructed without a smoothness requirement in earlier years. Dowel bar retrofitting has not been widely used in Georgia.

2.2 GDOT's Design for Joint Plain Concrete Pavement

GDOT has been actively enhancing its concrete pavement design to improve the performance and longevity of its pavements. Since 1970s, various designs of JPCP have been implemented through research and field observation. For example, the causes of faulting on Georgia's interstate highways and the improvements for load transfer in existing concrete pavement were studied by Gulden and Brown [2, 3]. Based on the findings in these studies, the design features of JPCP in Georgia have evolved through the years. Various designs of JPCP were categorized by key design features, including load transfer (doweled vs. non-doweled), base type, and edge support, which also reflect major improvements in GDOT's concrete pavement design. Four categories were considered as follows:

- Category 1 includes the non-doweled JPCP with no edge support on a soil or soil cement base, which were considered as the state-of-art JPCP design in the 1960s. These designs often had a 9 or 10-in thickness, a 30-ft joint spacing, and an asphalt shoulder. Edge support, which was not used in this design category, can be tied concrete shoulders or a wide lane (greater than 12-ft).
- Category 2 includes the non-doweled JPCP with no edge support on an improved base, which were introduced in the early 1970s to address such issues as faulting and base erosion observed in the field [2]. Graded aggregate base (GAB) or cement stabilized GAB in conjunction with an asphalt interlayer was used to provide a non-erodible base and good support. Along with the improvements in the base, a variation of joint spacing (e.g. random) and joint orientation (e.g. skewed) was used to address the faulting issue. An asphalt shoulder was still in use.
- Category 3 includes doweled-JPCP with edge support (e.g., tied concrete shoulder) on an improved base (e.g., GAB). A study conducted by GDOT [3] found the use of dowel bar in the transverse joints is effective for addressing faulting on non-doweled JPCP. Doweled JPCP was first constructed in Georgia in the mid-1970s and has become a standard in the concrete pavement design since the 1980s.
- Category 4 refers to the latest concrete pavement design, which consists of doweled-JPCP, a short joint spacing (15-ft), edge support (a 13-ft wide lane), and an asphalt interlayer and a GAB base. The “13-ft wide lane” makes up a 12-ft outside lane (as marked by the edge traffic stripe) plus 1-ft of the same slab as part of the shoulder. It is noted that no sufficient data was available to support an analysis of long-term performance for Category 4 pavements. Therefore, the performance of JPCP in Category 4 was not discussed in this report.

2.3 GDOT’s Practice on Concrete Pavement Condition Evaluation

GDOT first conducted statewide faulting measurement of its interstate highways in 1971 as part of the data collection effort for a research project to study concrete pavement faulting [2]. Since then, GDOT has been conducting an annual survey on its JPCP. In 1996, CPACES was developed to standardize concrete pavement survey in terms of distress types and severity level.

A rating index based on pavement distresses was also developed to provide an overall assessment of concrete pavement condition and to associate it with the maintenance and rehabilitation treatments. This section presents a review of GDOT's CPACES and summarizes the changes in terms of the types of distresses collected and the devices used to collect distress data.

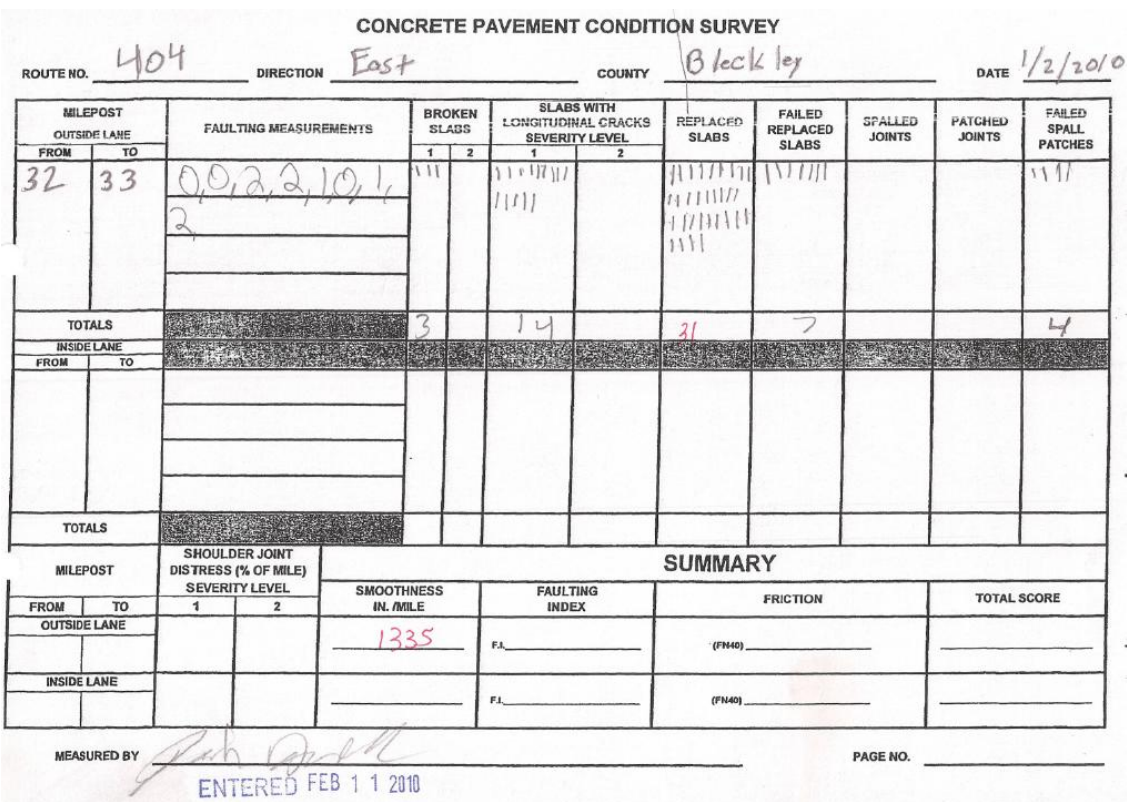
2.3.1 Concrete Pavement Condition Evaluation System (CPACES)

GDOT has conducted an annual survey of its JPCP according to CPACES since 1996. This annual survey consists of measuring joint faulting and counting pavement defect occurrences in outside lanes for each mile of JPCP in Georgia [4]. The faulting of every eighth joint is measured to obtain representative samples of each mile of JPCP using a Georgia Fault Meter, which was developed and built by the Office of Materials and Research [5]. The fault meter measures the faulting down to 1/32 inches. The rest of the survey consists of a visual tally of horizontally broken slabs, longitudinal cracks, replaced slabs, spalled joints, patched joints, failed spall patches, and shoulder deterioration. Table 2.3 summarizes the distresses included in CPACES. Data is recorded for each mile in the outside lanes using the Concrete Survey Form, as shown in Figure 2.1. This data is then entered in the office and summarized in an annual report, as shown in Figure 2.2. For each mile, the faulting index is computed as five times the average fault meter readings, which is the sum of all fault meter readings divided by the number of readings [5]. Therefore, instead of an average faulting, a faulting index that represents the total faulting of a hypothetical five joints in each mile is reported. A faulting index of 15 is equivalent to an average faulting of 3/32 inches in one mile. Note that pavement roughness values, i.e., international roughness index (IRI), are also included in this report, although the values are collected by a different unit. A rating index is computed for each mile based on pavement distresses. Table 2.3 shows the types of distresses and severity levels specified in CPACES.

Table 2.3 Types of Distresses in CPACES

Distress Type	Sample Location	Severity	Report Unit
Faulting	Every 8th joint	-	Faulting Index
Broken slab	One mile	Level 1	# of slabs
		Level 2	
Longitudinal crack (Slabs with longitudinal crack)	One mile	Level 1	# of slabs
		Level 2	
Replaced slab	One mile	-	# of slabs
Failed replaced slab	One mile	-	# of slabs
Joint with spalls	One mile	-	# of joints
Joint with patched spalls	One mile	-	# of joints
Joint with failed spalls	One mile	-	# of joints
Shoulder joint distress	One mile	-	# of joints
Roughness (IRI)[1]	One mile	-	mm/km

1. Roughness is collected by Road Laser Profiler.



CONCRETE PAVEMENT CONDITION SURVEY

ROUTE NO. 404 DIRECTION East COUNTY Bleckley DATE 1/2/2010

MILEPOST OUTSIDE LANE FROM	TO	FAULTING MEASUREMENTS	BROKEN SLABS 1	2	SLABS WITH LONGITUDINAL CRACKS SEVERITY LEVEL 1	2	REPLACED SLABS	FAILED REPLACED SLABS	SPALLED JOINTS	PATCHED JOINTS	FAILED SPALL PATCHES
32	33	0,0,2,2,1,0,1, 2									
TOTALS			3		14		31	7			4
INSIDE LANE FROM	TO										
TOTALS											

SUMMARY

MILEPOST FROM	TO	SHOULDER JOINT DISTRESS (% OF MILE) SEVERITY LEVEL 1	2	SMOOTHNESS IN./MILE	FAULTING INDEX	FRICTION	TOTAL SCORE
OUTSIDE LANE				1335	F.I.	(FN40)	
INSIDE LANE					F.I.	(FN40)	

MEASURED BY [illegible] PAGE NO.

ENTERED FEB 1 1 2010

Figure 2.1 Concrete Pavement Condition Survey Form

Concrete Survey Report (All Routes)
From 10-01-2009 To 03-31-2010
040100

County	BMP	EMP	Direction	FI	Rough	BS1	BS2	LC1	LC2	RSlabs	SJoints	SD1	SD2	Rating
75 Cook	38.0	39.0	NORTH	1	1106	0	0	0	0	336	0	0	0	98
75 Cook	39.0	38.0	SOUTH	0	854	0	0	0	0	336	0	0	0	100
93 Dooly	106.0	107.0	NORTH	0	1288	31	12	1	1	64	5	0	0	67
93 Dooly	107.0	106.0	SOUTH	0	1346	20	4	1	1	52	10	0	0	77
93 Dooly	107.0	108.0	NORTH	0	1715	11	15	0	0	60	5	0	0	60
93 Dooly	108.0	107.0	SOUTH	0	1432	18	2	0	1	70	16	0	0	77
93 Dooly	108.0	109.0	NORTH	0	1331	28	12	1	0	48	5	0	0	68
93 Dooly	109.0	108.0	SOUTH	0	1372	15	4	0	0	68	10	0	0	80
93 Dooly	109.0	110.0	NORTH	0	1447	36	20	0	1	47	9	0	0	60
93 Dooly	110.0	109.0	SOUTH	0	1565	24	9	0	1	100	3	0	0	65
93 Dooly	110.0	111.0	NORTH	0	1740	38	31	3	1	85	6	0	0	60
93 Dooly	111.0	110.0	SOUTH	0	1972	23	3	2	0	53	6	0	0	51
93 Dooly	111.0	112.0	NORTH	0	1638	23	22	2	1	80	3	0	0	52
93 Dooly	112.0	111.0	SOUTH	0	1367	7	3	1	0	28	7	0	0	86
93 Dooly	112.0	113.0	NORTH	0	1766	14	6	0	2	103	8	0	0	64

June 4, 2010 page 32

Figure 2.2 Annual Concrete Survey Report

2.3.2 Changes in GDOT's Concrete Pavement Survey

Prior to the development of CPACES in 1996, several changes were made in the annual concrete pavement survey, and they may have led to inconsistencies/discrepancies in the data. Table 2.4 summarizes the changes in devices and distress types discussed below:

- Only faulting index was collected between 1971 and 1976.
- The survey has been conducted in the outside lanes since 1971. Only between 1981 and 1994 were inside lanes also surveyed.
- Roughness was first measured in 1977, and it has been measured using different devices. Prior to 1995, roughness was measured using the Mays Ride Meter in inches per mile; after that, roughness has been measured by a Road Laser Profiler in millimeters per kilometer.
- Broken slabs and slabs with longitudinal cracks have been counted separately since 1995. Prior to that, only cracked slabs were recorded without differentiating types of cracks (e.g., longitudinal crack and transverse crack).

- Spalled joints and shoulder distress have been included since 1996.
- A CPACES rating has been computed since 1996.

Table 2.4 Changes in Devices and Recorded Distresses

Year	Distress												Lane	
													Outside Lane	Inside Lane
1971-1976	FI												X	
1977	FI	Cracked Slab	Replaced Slab	Slab Under seal									X	
1978-1979	FI	Cracked Slab	Replaced Slab		Roughness (Unknown device)								X	
1980-1981	FI	Cracked Slab	Replaced Slab		Roughness (Mays)								X	
1982-1985	FI	Cracked Slab	Replaced Slab		Roughness (Mays)								X	X
1986-1988	FI	Cracked Slab	Replaced Slab		Roughness (Mays)	Skid							X	X
1989-1994	FI	Cracked Slab	Replaced Slab		Roughness (Mays)		Fn						X	X
1995	FI		Replaced Slab		Roughness (Mays)		Fn	Broken Slab	Long Crack	Spalled Joint	SHLD Joint		X	
1996-	FI		Replaced Slab		Roughness (RP)		Fn	Broken Slab (1&2)	Long Crack (1&2)	Spalled Joint	SHLD Joint (1&2)	Rating	X	

2.4 Data Processing

This section briefly describes the data processing steps as follows:

1. Converting data

   Data conversion was conducted to ensure consistency in the data for the aforementioned changes and is summarized as follows:

a) Roughness has been measured by two devices: the Mays Ride Meter between 1980 and 1995 and the Road Profiler since 1996. Roughness measured by the Mays Ride Meter was converted using the conversion equation (Equation 2.1) that was provided by GDOT. The equation was based on a side-by-side test of the two devices conducted by GDOT.

(Equation 2.1)

b) The number of cracked slabs and replaced slabs prior to 1996 were split into severity levels 1 and 2 based on criteria established in consultation with GDOT.

- If # Broken Slabs < 8, they are all considered as Level 1;
- If 8 = < # Broken Slabs <= 15, 1/2 of them are considered as Level 1 and the remaining are considered as Level 2;
- If # Broken Slabs > 15, 1/3 of them are consider as Level 1 and 2/3 of them are Level 2.

c) Some abrupt decreases or increases in CPACES ratings were observed in some years, as shown in Figure 2.3. After discussion with GDOT, the CPACES rating was re-computed based on the deduct values described in Appendix I.

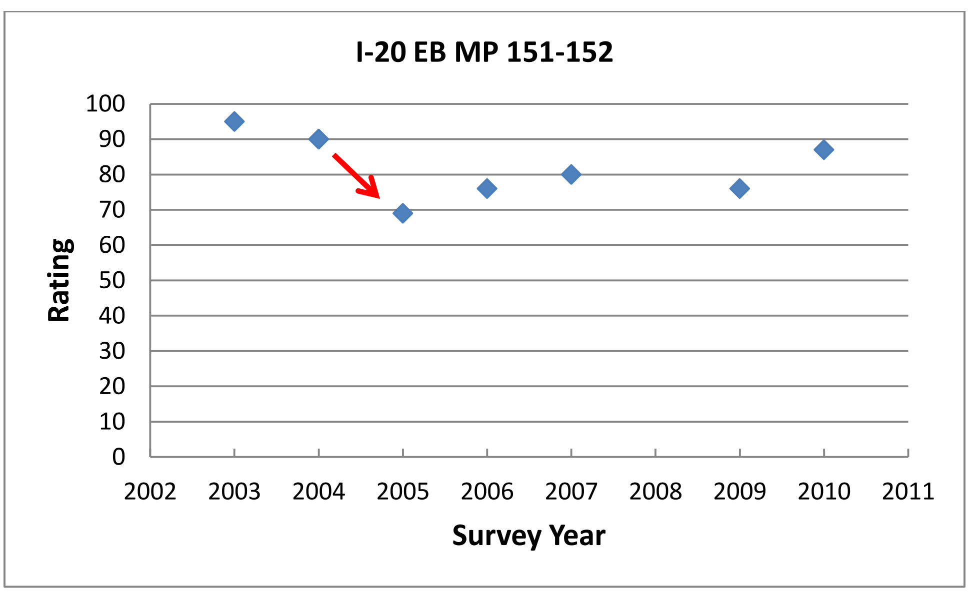


Figure 2.3 Variations in CPACES Ratings

2. Screening and cleaning data

   The data were carefully reviewed to identify anomalous values, such as a negative faulting index, a negative number of broken slabs, and an IRI value less than 200 mm/km. These values were cleaned to enhance the quality of the data. The CPACES rating was recomputed after cleaning anomalous values.

2.5 Summary

GDOT has been conducting concrete pavement surveys of its JPCP since 1971, and CPACES has been developed and implemented since 1996 to standardize the concrete pavement survey in terms of distress types and severity levels. The concrete pavement survey data are available in either a hard copy or an electronic database format. With the availability of extensive historical concrete pavement condition data, there was an opportunity to study the actual service life of JPCP in Georgia. In addition, various data, including traffic data and pavement design, was acquired to support the analysis of concrete pavement service life. Each data source was briefly described in this chapter. For the purpose of studying pavement service life by its design, various concrete pavement designs were categorized based on key design features and construction time. Four categories are 1) non-doweled JPCP on a soil or soil cement base, 2) non-doweled JPCP on an improved base, 3) doweled JPCP on an improved base, and 4) doweled JPCP with a short joint spacing (15-ft), with edge support (13-ft wide lane) on top of GAB and an asphalt interlayer. In addition, changes in concrete pavement survey practices, such as the devices used for measuring roughness and rating computation, were identified through a review of survey practices. CPACES data in two electronic databases were merged and processed for this study. The following summarizes the items that one should be aware of when reviewing the processed data:

- While the faulting index has been consistently measured since 1971, there have been changes in other distresses, such as the devices used to measure roughness and the severity level for broken slabs.
- While a rating was reconstructed for all records based on CPACES, there may be gaps in the rating trend by year due to the changes in distresses collected over the years. This should be considered when analyzing the rating data.

- While roughness measured by the Mays Ride Meter was converted, there seems to be a gap between the values converted and values directly measured by the Road Profiler. This gap should be considered when analyzing roughness trend by year.
- There has been no concrete pavement condition survey conducted on I-285 since 1975 because of heavy traffic.

3 Determining Service Life

This chapter presents the work performed in determining the service life of concrete pavements using historical CPACES data collected by GDOT. First, a review of state DOTs' studies on pavement service life was conducted with a focus on the definition of concrete pavement service life. Second, the steps involved in determining the service life, including selecting performance indicator(s), defining the service life, preparing project data, and determining the service life, were performed.

3.1 Literature Review

There have been various efforts to determine actual service life of pavements in support of LCCA in evaluating alternative pavement designs (e.g., pavement type selection) and assessing rehabilitation strategies (e.g., rehabilitation timing and method). However, there are limited reports that describe the determination of actual service life in detail [6]. This section presents a brief review of the surveys conducted by the South Carolina Department of Transportation (SCDOT) [6] and the Wisconsin Department of Transportation (WisDOT) [7], as well as studies by three other state DOTs on pavement service life [8, 9, 10], focusing on the definition of the service life of concrete pavements.

State DOTs have identified the determination of appropriate pavement service life (timing of future rehabilitation) as a concern in performing LCCA for pavement type selection [6]. The methods to determine the service life include the use of historical pavement condition data and/or rehabilitation records, performance prediction models, and engineers' judgment. The selection of the methods depends on the availability of the data and the resources available at the time. A general definition of the service life is the time to failure, whereas failure can be a major rehabilitation, a reconstruction, or reached a certain predefined serviceability threshold value [7]. Most state DOTs define the service life of concrete pavements as the time from initial construction to the first rehabilitation or from one rehabilitation to the next [7]. However, the activities included in the rehabilitation vary widely among state DOTs from a joint repair to an AC overlay [6, 7]. Several state DOTs apply a series of activities within the analysis period.

According to the survey conducted by the South Carolina Department of Transportation (SCDOT) [6], the service life of original pavements (initial service life) ranges from 15 to 35 years. Some state DOTs indicated the use of a shorter service life of rehabilitated pavements compared to initial service life, while the others reported the same values for both service lives. A summary of the service life of asphalt and concrete pavements compiled by SCDOT [6] is listed in Appendix II.

The Illinois Department of Transportation (IDOT) has periodically conducted pavement longevity studies since 1987 [8, 11, 12, 13, 14] based on the Illinois Pavement Feedback System (IPFS) database. The termination of pavement service life is defined as a major rehabilitation [8], which refers to an AC overlay. It was pointed out that while overlays are placed on pavements in poor condition in terms of roughness and distress, this level may vary from section to section based on funding availability and other factors [8]. Survival analysis was conducted to develop estimate(s) of the expected service lives of jointed reinforced concrete pavement (JRCP) and CRCP. On average, 10-in JRCP carried 10 million ESALs over 17.5 years and 10-in CRCP carried 90 million ESALs over 23 years at the 50th percentile. The Minnesota Department of Transportation (MnDOT) developed a sequence of rehabilitation activities based on pavement type for conducting LCCA in pavement type selection [9]. A panel of experts determined a logical sequence of rehabilitation activities, and the typical timing of applying these activities was queried based on the pavement management database. Joint repair was specified as the rehabilitation activity for concrete pavements at years of 18, 26, and 36. In another report [15], the service life was defined as the time to reach subsequent major rehabilitation (joint repair or diamond grinding), and the results shows half of the concrete pavement received some type of major rehabilitation by year of 20. The Missouri Department of Transportation (MoDOT) defines rehabilitation as the construction work necessary to return an existing roadway, including shoulders, to a condition of structural or functional adequacy [10]. Diamond grinding in conjunction with 2% full depth repair was indicated as major rehabilitation for JPCP at year of 25. The review of the state DOTs' studies on the service life of concrete pavements is summarized as follows:

- The service life is commonly defined as the time to reach major rehabilitation. In practice, few state DOTs express the service life in ESALs, although it is noted that ESALs directly relate to concrete pavement performance.
- The service life of the original concrete pavements reported by state DOTs ranges from 15 to 35 years, while the activities included in major rehabilitation vary among state DOTs.
- The activities included in a major rehabilitation vary among states DOTs. An AC Overlay was used to define the end of service life by several state DOTs, although it is noted that the decision on the AC overlay depends on pavement condition, as well as funding availability and other factors.
- Other activities included in major rehabilitation are joint repair, slab replacement, and diamond grinding. Diamond grinding is often included as part of the major rehabilitation.

3.2 Determination of Service Life

The process for determining pavement service life using historical concrete pavement condition data in this study involved four key steps, described as follows:

- Selecting performance indicator(s) that can be used to identify the service life cycle, i.e., the end of the service life;
- Defining pavement service life in terms of the events that indicate the end of the service life;
- Preparing project data;
- Determining the service life using a manual evaluation.

A discussion of each step is presented in subsequent sections.

3.2.1 Step 1: Selecting Performance Indicator(s)

Several performance indicators recorded in the CPACES database were reviewed in order to select an appropriate indicator for identifying the end of pavement service life. An indicator that has been measured consistently with a decent trend is preferred. A review of four performance indictors is presented as follows:

- Rating

  A rating index based on pavement conditions for each one-mile pavement has been computed each year to represent overall concrete pavement condition since 1996. For the data prior to 1996 and in the electronic database, a rating was reconstructed based on CPACES. However, there are inconsistencies in the rating due to the changes in the distresses collected. For example, longitudinal cracks were not collected before 1996. Therefore, the rating prior to 1996 has a zero deduct for longitudinal cracks. This rating may be higher than the actual rating if longitudinal crack(s) had been presented at that time. Therefore, the rating was not recommended as the primary performance indicator in this study.

- Roughness

  An IRI has been collected using the Road Profiler to measure rideability since 1990. Although the roughness measured by the Mays Ride Meter before 1990 was converted to IRI, a gap in the time-series IRI was observed in some projects. Therefore, IRI in conjunction with the faulting index and crack-related distresses was used for determining service life.

- Cracking-related distresses (e.g., broken slabs)

  The numbers of cracked and replaced slabs are manually counted and recorded for each mile based on CPACES. Compared to the distress measured using a device, such as faulting and roughness, the data collected by a manual count could be less accurate. In addition, there have been changes in the types of cracks collected and the severity levels, which cause inconsistencies in the data. A review of the numbers of broken and replaced slabs reveals a variation in the crack data, as show in Figure 3.1. In addition, the relationship between broken and replaced slabs is not clear. The number of broken slabs decreased in 2004; however, there was no corresponding replacement of slabs recorded in 2003. Therefore, cracking-related distresses, as a category, in conjunction with the faulting index and roughness were used for determining service life.

  .

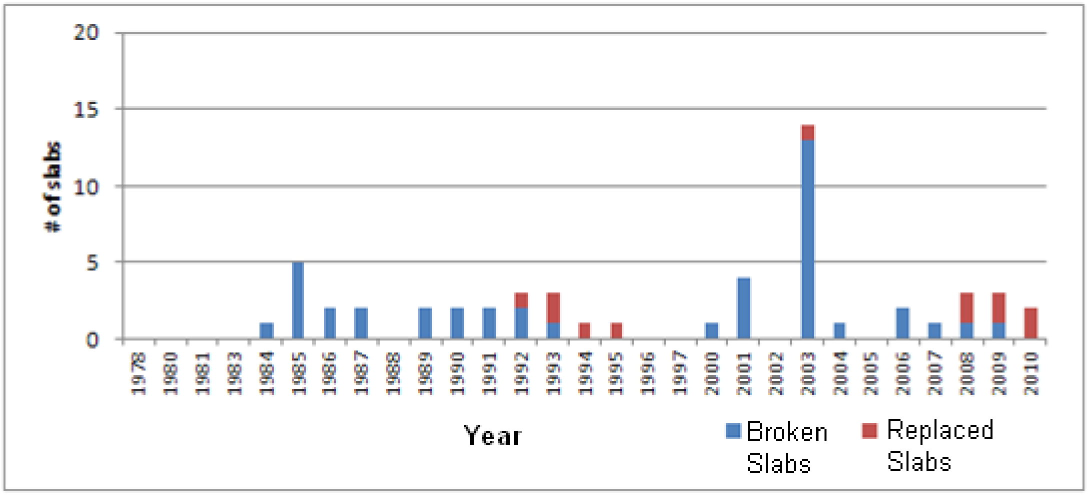


Figure 3.1 Broken and Replaced Slabs versus Year

- Faulting Index

  Faulting has been consistently measured since 1971, and the faulting index is reported for each mile to represent the faulting condition. A faulting index is defined as the total faulting of five joints in 1/32 of an inch increment. A review of the faulting index reveals a reasonable trend, as shown in Figure 3.2. A variation in the faulting index from year to year was expected because the faulting was measured on different sample locations (i.e., different joints) under different environments (e.g., temperatures and moisture). Note that a faulting index of 5 is equivalent to an average faulting of 1/32 inch for each joint. A five-point difference in the faulting index is within a reasonable range. The faulting index in conjunction with roughness and cracking-related distresses were recommended as the primary performance indicators for identifying the end of service life.

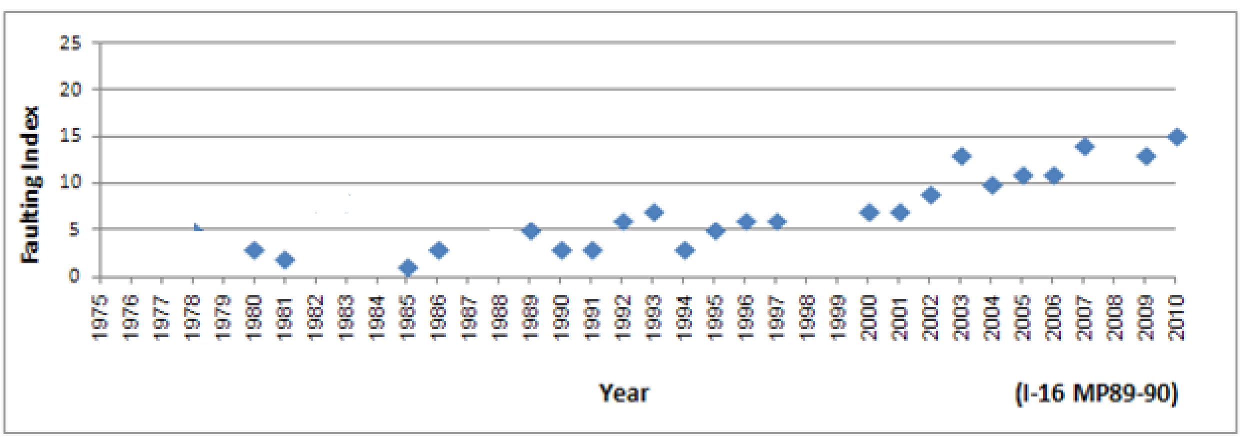


Figure 3.2 Faulting Index versus Year

3.2.2 Step 2: Defining Service Life

After discussion with GDOT, three types of events were selected to define the service life of concrete pavements, as follows:

- First AC Overlay

  The AC overlay was considered as a major rehabilitation for concrete pavements; therefore, the time from initial construction to the first AC overlay was studied. Note that pavement performance after the first AC overlay was not in the scope of this study.
- Major Rehabilitation

  Major rehabilitation was defined as diamond grinding in conjunction with a necessary concrete pavement restoration (e.g., slab replacement) and a joint reseal to restore the functional capacity of concrete pavements. Note that diamond grinding, alone, can be conducted to address pavement surface issue (roughness) when the faulting is in fair or good condition. However, this type of action is not considered as a major rehabilitation, as the pavement is not in poor condition in terms of the faulting index.
- Faulting Index of 15

  The time a major rehabilitation is applied to pavements varies based on pavement condition, funding availability, and other factors (e.g., adding lane(s)). Therefore, a faulting index threshold was defined to provide an objective comparison of the service life. A faulting index of 15 was selected for two reasons. First, a faulting index of 15 is considered as a trigger for rehabilitation. Second, the average faulting index before rehabilitation was found to be around 15, as discussed in Chapter 4.

3.2.3 Step 3: Preparing Project Data

The determination of the service life was performed at the project-level. Each project was constructed with the same design at the same time. To prepare historical CPACES data at the project-level, three tasks, including grouping CPACES data by design project, identifying outlier(s) in each project, and aggregating distress data, were performed.

- First, historical CPACES data were queried and grouped based on project limits in terms of mile post. Note that the beginning and ending mile that consists of more than one design are excluded to ensure a uniform design within a project. Figure 3.3 shows an example of the grouped CPACES data for a project on I-16 (MP 47- MP 57.5). The series represents the faulting index for each mile in the project. Note that the faulting index varies within the project in one year.

- Second, a manual review was conducted to identify the outlier(s). MP 56 and a faulting index of 2 in 2004 were identified as outliers in Figure 3.3. However, this manual review is subjective, based on individual observation. To enhance this process, the coefficient of variation (CV) was introduced as an indicator. The coefficient of variation expresses the standard deviation as a percentage of the sample mean. This is particularly useful when the size of variation is relative to the sample mean, which is the case of the variation in the faulting index. As the average faulting index increases, the variation within the project increases. The CVs are computed for each year, as shown in Table 3.1. A careful review of the CVs reveals a CV of 0.5 may indicate potential outlier(s). As shown in Table 3.1, the CVs in 1989, 1991, and 2004 are greater than 0.5. A manual review was then undertaken to identify and remove the outliers. Note that the CVs were not used as a restrict rule but as an indication of large variation in the faulting index. Figure 3.4 shows the faulting index after removing the outliers.
- Third, the distress data was averaged to represent the performance at the project-level. Figure 3.5 shows the average faulting index for the project.

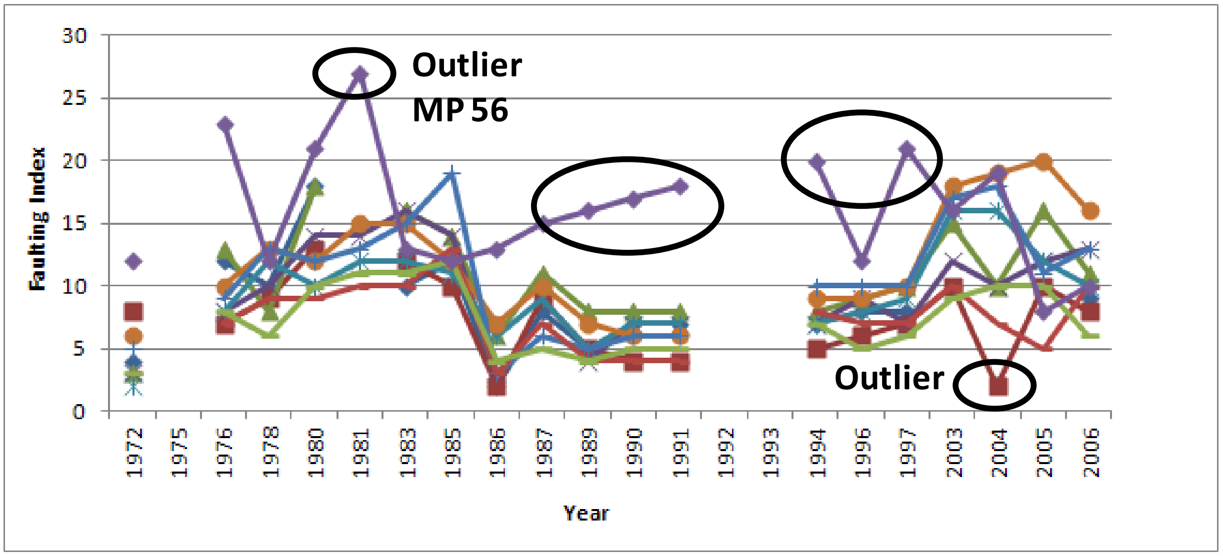


Figure 3.3 Faulting Index for a 10-mile Project (with Outliers)

Table 3.1 Coefficient of Variation for Each Year

1972	1975	1976	1978	1980	1981	1983	1985	1986	1987	1989	1990	1991	1992	1993	1994	1996	1997	2003	2004	2005	2006
0.6	-	0.5	0.2	0.3	0.4	0.2	0.2	0.7	0.3	0.6	0.5	0.6	-	-	0.5	0.2	0.5	0.3	0.5	0.4	0.3
0.5	-	0.2	0.2	0.3	0.1	0.2	0.2	0.5	0.2	0.3	0.2	0.2	-	-	0.2	0.2	0.2	0.3	0.4	0.4	0.3

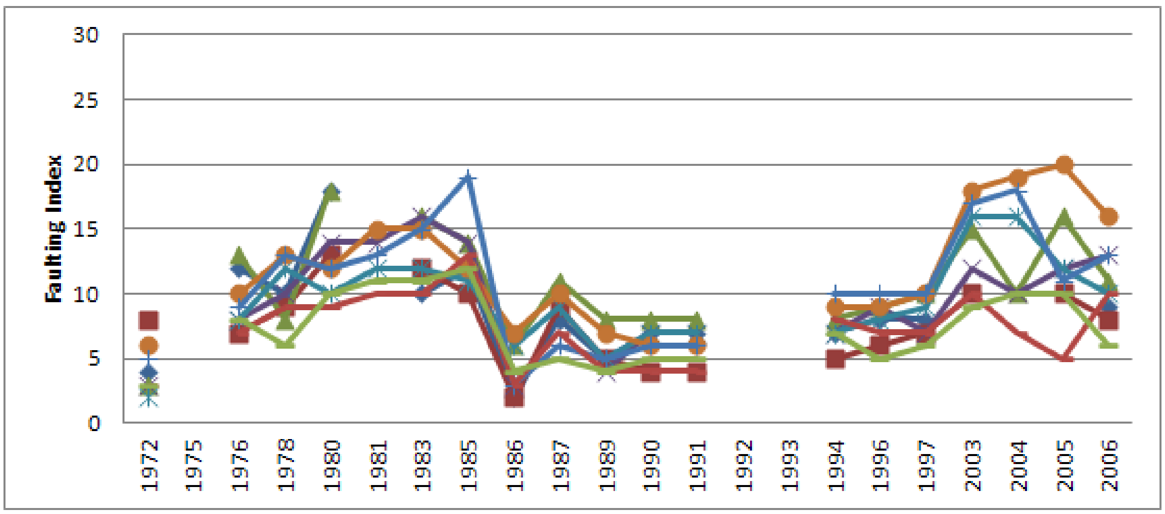


Figure 3.4 Faulting Index for a 10-mile Project (without Outliers)

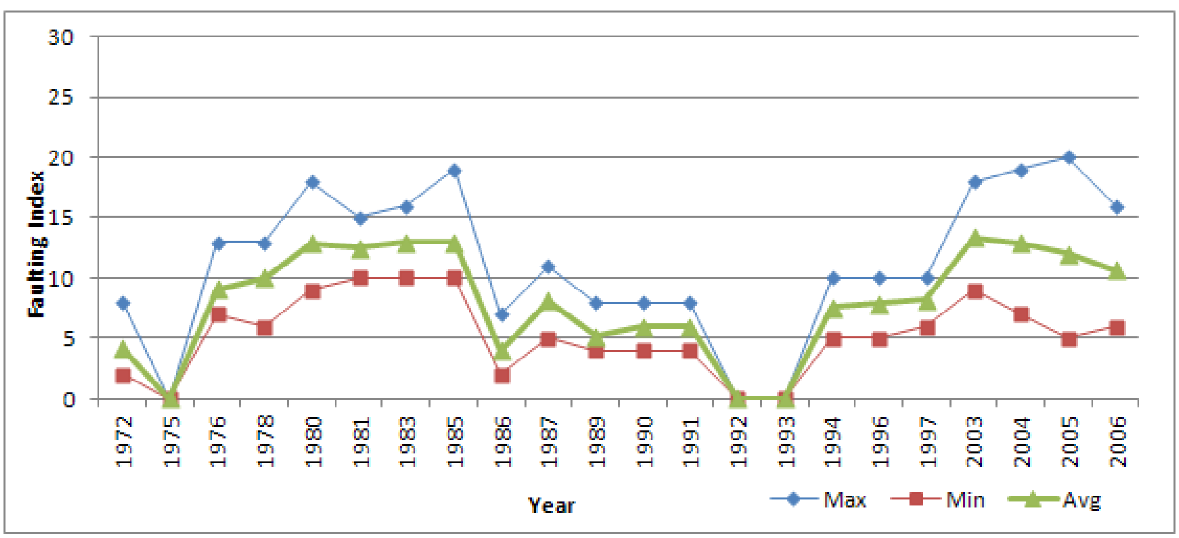


Figure 3.5 Average, Maximum, and Minimum Faulting Index for a 10-mile Project (without Outliers)

3.2.4 Determining Pavement Service Life

This section presents the rules used to determine pavement service life based on three events: the first AC overlay, a major rehabilitation, and a faulting index of 15, with a focus on the last two events. The service life based on the first AC overlay was identified by cross-checking various data sources. The type of the original and existing pavements was used to determine if a project was overlaid. A manual check of historical CPACES data was then conducted on the overlaid projects to find when the AC overlay was conducted.

Pavement service life based on a major rehabilitation and a faulting index of 15 was determined using historical concrete pavement condition data, mainly the faulting index. A careful review of the faulting index data was conducted to identify the rules for determining the occurrence of a major rehabilitation. Figure 3.6 shows the faulting index over time for a typical project. The JPCP constructed in 1972 started with a low faulting index (less than 5). The faulting index continued to increase as the faulting was developed with traffic loads. At a certain point, a major rehabilitation would be needed to restore the functional capacity of the pavements. A major rehabilitation (diamond grinding in conjunction with slab replacement and joint reseal) can be identified by a significant improvement (drop) in the faulting index. As shown in Figure 6, a major rehabilitation was conducted in 1986 and resulted in a drop of the faulting index. This indicates the end of the service life of the original pavements (from initial construction to the first major rehabilitation) and the beginning of the service life of the first major rehabilitation. The faulting index continues to increase after the first major rehabilitation.

To establish a systematic approach for determining pavement service life, three variables were developed to describe the characteristics of the service life. These variables are as follows:

- YR-S (Year Start) represents the beginning of the service life. For the original pavements, YR-S refers to the year when the construction was completed, which is available in the construction information. For rehabilitated pavements, YR-S refers to the year after the major rehabilitation was conducted. YR-S can be identified by a significant drop of the faulting index.
- YR-E (Year End) represents the end of the service life, which is immediately before YR-S. YR-E can be identified by a significant drop of the faulting index.

- TM (Trend in the Middle) represents the trend of the faulting index. The trend is classified by the number of observations (faulting index) and the variation.
- YR-FI15 (Year to Faulting Index of 15) represents the year to reach a faulting index of 15. YR-FI15 can be an actual observed year if the faulting had reached 15 or a predicted year if the faulting index has not reached 15.

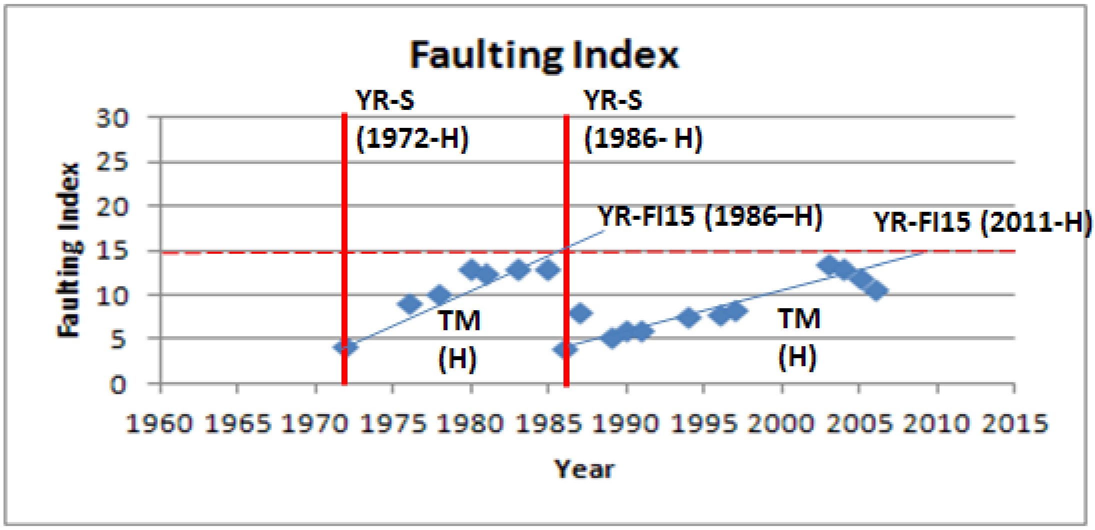


Figure 3.6 Faulting Index for a Typical Project

The rules for determining these variables were established by a review of the faulting index data. The value of these variables was determined along with a confidence level that describes the quality of the value. The rules are presented in Table 3.2. The variables used in the rules are described as follows:

- FI-BR (Faulting Index Before Rehabilitation) is the faulting index before a major rehabilitation was conducted.
- FI-AR (Faulting Index After Rehabilitation) is the faulting index after a major rehabilitation was conducted.
- CL (Confidence Level) represents the quality of the values. It is categorized into high (H), medium (M), low (L), and incomplete (I).

Table 3.2 Rules for Determining the Service Life

Item	CL	Description
YR-S	H	1 Initial construction year 2 Rehabilitation: - Rehabilitation activities recorded in CPACES - Clear drop in the faulting index (FI-BR - FI-AR ≥ 5) (FI-BR ≥ 13 and YR-E – YR-S ≤ 5); OR (8≤FI-BR<13 and # of replaced slabs ≥ 5×total miles×50% and YR-E – YR-S ≤ 5)
	M	Clear drop in the faulting index (FI-BR - FI-AR ≥ 5) (FI-BR ≥ 13 and YR-E – YR-S ≤ 5); OR (8≤FI-BR<13 and (# of replaced slabs ≥ 5×total miles×50% or YR-E – YR-S ≤ 5))
	L	Cannot find a clear drop in the faulting index (FI-BR - FI-AR ≥ 5) FI-BR < 8
YR-E	H	- Rehabilitation activities recorded in CPACES - Clear drop in the faulting index (FI-BR - FI-AR ≥ 5) (FI-BR ≥ 13 and YR-E – YR-S ≤ 5); OR (8≤FI-BR<13 and # of replaced slabs ≥ 5×total miles×50% and YR-E – YR-S ≤ 5)
	M	Clear drop in the faulting index (FI-BR - FI-AR ≥ 5) (FI-BR ≥ 13 and YR-E – YR-S ≤ 5); OR (8≤FI-BR<13 and (# of replaced slabs ≥ 5×total miles×50% or YR-E – YR-S ≤ 5))
	L	Cannot find a clear drop in the faulting index (FI-BR - FI-AR ≥ 5) FI-BR < 8
	I	The pavement is still in-service
TM	H	Reasonable trend and sufficient data ≥ 40% of the data points between the **YR-S** and **YR-E** point. The trend must look reasonable in the selected life cycle.
	M	Reasonable trend and sufficient data 30%-40% of the data points between the **YR-S** and **YR-E** point. The trend looks reasonable in the selected life cycle.
	L	Cannot identity a reasonable trend or sufficient data
YR-FI15	H^+	FI-BR≥15
	H	FI-BR<15 and FI reaches 15 < 10 years
	M	FI-BR<15 and FI reaches 15 ≥ 10 years and ≤ 15 years
	L	FI-BR<15 and FI reaches 15 > 15 years

Based on the design project list, a total of 336 projects in both directions were reviewed. Among them, 87 projects (839 surveyed-miles) have a high confidence level. These 87 projects are listed in Appendix IV.

3.3 Summary of Service Life Data

After processing the data, a total of 839 surveyed miles of JPCP on interstate highways that have service life data at a high confidence level were used in this study. It is noted that these pavements have not been AC overlaid. In addition to the 839 survey miles, 258 centerline miles of AC overlaid JPCP were identified for studying the service life based on an AC overlay. The data on state routes were also processed. Most of the state routes have not reached a major rehabilitation, and sufficient data regarding the service life, including construction time and pavement design, were not available. Therefore, only the 839 surveyed miles of interstate highways were analyzed further in the following chapters. Figure 3.7 shows the age distribution of these JPCP. About 95% of them are now 30 or years old or older. This provides an opportunity to study the long-term performance of in-service JPCP.

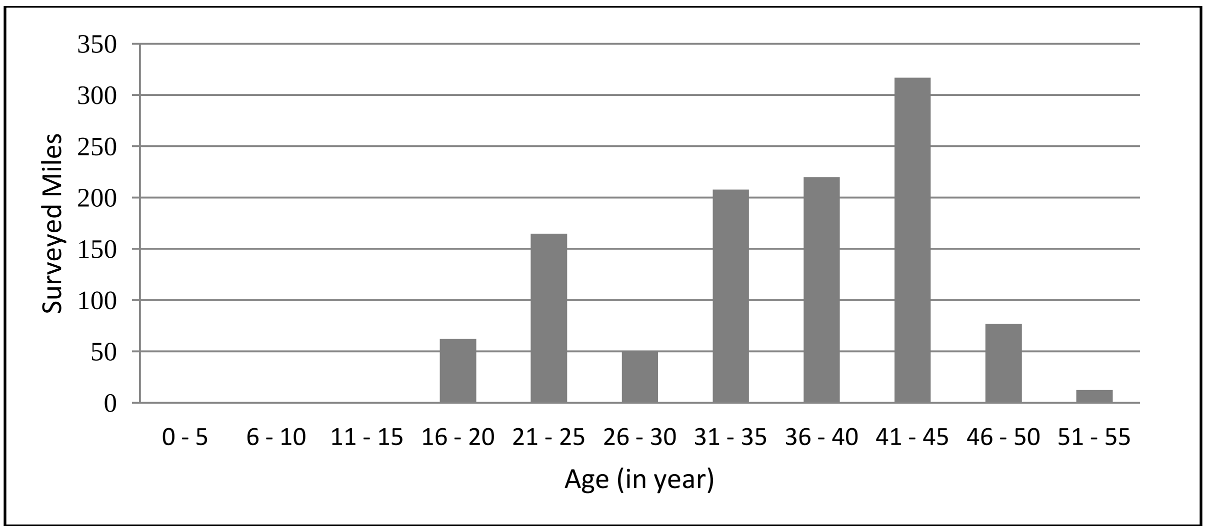


Figure 3.7 Age Distribution of JPCP

As shown in Figure 3.8, among the 839 surveyed miles, 35% have not reached a major rehabilitation and 65% of them have had at least one major rehabilitation, in which 32% have had one major rehabilitation; 22% have had two major rehabilitation; and 11% have had three major rehabilitation . The percentage in surveyed miles for each design category is shown in Figure 3.9. Among the 839 surveyed miles, more than half (54%) are in Category 1; 22% are in Category 2; 24% are in Category 3; and none are in Category 4.

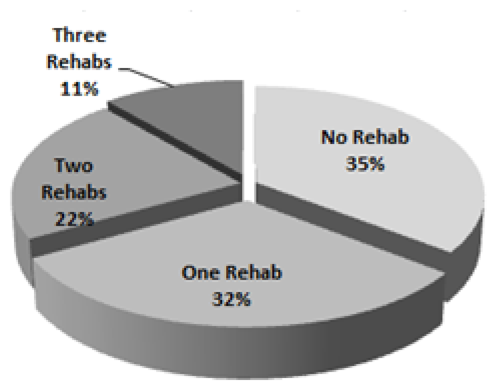


Figure 3.8 Percent Miles of Number of Major Rehabilitations

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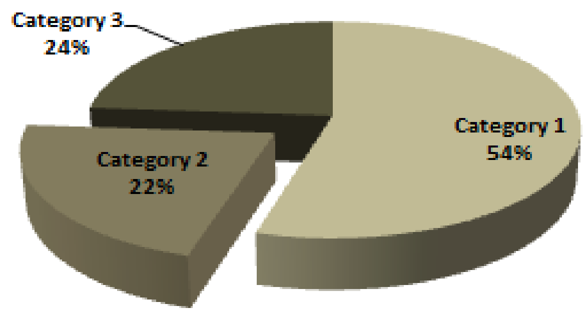

Figure 3.9 Percent Miles for Each Design Category

4 Analysis of Service Life

This chapter presents analysis of service life defined by different events. Three types of events, including an AC overlay, a major rehabilitation (i.e., diamond grinding in conjunction with slab replacement and joint reseal), and a faulting index of 15 were defined as the timings for the end of the service life. Pavement service life based on an AC overlay is first summarized using the 258 centerline miles of overlaid JPCP. A statistical analysis of pavement service life based on a major rehabilitation and a faulting index of 15 was conducted using the rehabilitated projects (541 surveyed miles) that have reached at least one major rehabilitation. Finally, a summary of the major findings is presented.

4.1 Service Life Based on AC Overlay

Of the 258 centerline miles of overlaid JPCP, the average time to the first AC overlay is 13 years. The AC overlay was applied on the Category 1 pavements constructed in the 1960s. The majority of the AC overlay was applied in the late 1970s (1977–1980) on I-75 and I-85 as part of the interstate widening (i.e., adding lane) project. The decision for an AC overlay was based not only on pavement condition but also on other factors, such as adding lane(s), funding availability, agency policy, etc. Because the causes of an AC overlay were not available, the 13-year span cannot be interpreted as the effective service life for the first AC overlay. Analysis of pavement performance after the AC overlay is not in the scope of this project.

4.2 Service Life Based on Major Rehabilitation

Based on the time needed to reach a major rehabilitation, the pavement service life of the rehabilitated projects (541 surveyed miles) that have had at least one major rehabilitation was analyzed. It is noted that all 541 surveyed miles are non-doweled JPCP (Categories 1 and 2). Doweled JPCP has not yet reached a major rehabilitation as of 2010. Among the 541 surveyed miles of JPCP, 49% have had their first major rehabilitation, 34% have had their second major rehabilitation, and a few sections (17%) have had their third major rehabilitation. The percentage of JPCP categorized by the number of major rehabilitations is shown in Figure 4.1. The service lives of the original and rehabilitated pavements are summarized in Table 4.1.

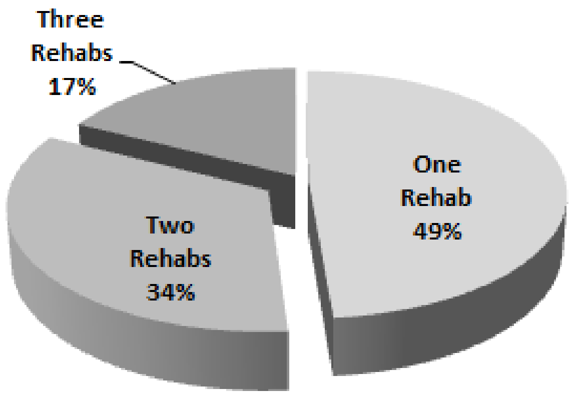

Figure 4.1 Percent Miles of Number of Major Rehabilitations

Table 4.1 Service Lives of based on Major Rehabilitation

Description		Original Pavement	First Major Rehabilitation	Second Major Rehabilitation
Time to Major Rehabilitation	Average	17	14	8
	Minimum	10	8	7
	Maximum	29	20	9
Average Faulting Index before Major Rehabilitation		16.5	14.6	17.3

- Service Life of Original Pavement

  On average, the non-doweled pavement service life of the original pavements, i.e., the time needed from initial construction to the first rehabilitation, was 17 years, as shown in Table 4.1. The average faulting index before the first major rehabilitation was 16.5. The distributions of the service life by year versus the faulting index and the corresponding miles before rehabilitation are shown in Figure 4.2. It shows a broad service life ranging from 10 years to 29 years, as is inferred in Table 4.1. Approximately 48% of the pavements had a major rehabilitation in 20 years. The faulting index before the rehabilitation also varies from 9 to 24 without a particular pattern. This indicates the timing of rehabilitation depends not only on pavement condition but also other factors, such as funding availability.

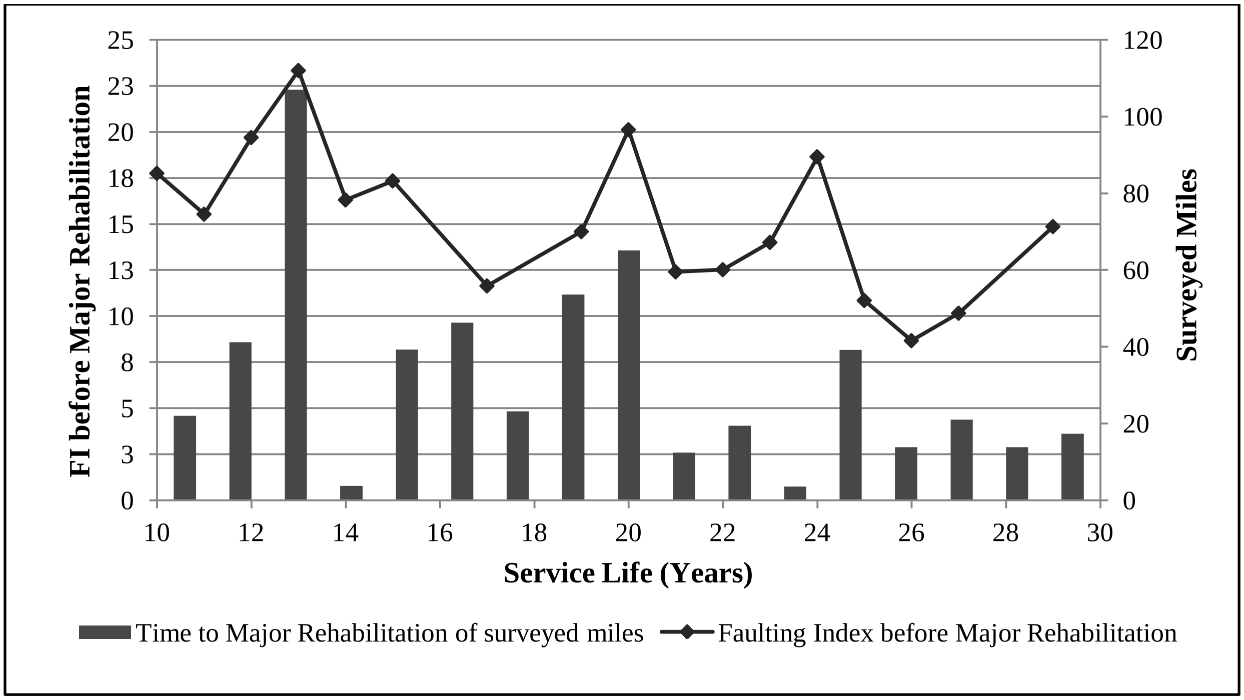

Figure 4.2 Distribution of Faulting Index and Surveyed Miles for Original Pavements

- Service Life of First Major Rehabilitation

  The pavement service life of the first major rehabilitation is the time from the first rehabilitation to a second major rehabilitation. Table 4.1 shows the average service life of the first major rehabilitation was 14 years, which is shorter (18% less) than the service life of original pavements. Note that the average service life of 14 years does not take into account the pavements that have reached their first major rehabilitation but have not yet had a second rehabilitation. The average faulting index before rehabilitation was 14.6, which is lower than the original pavement. Figure 4.3 shows the distribution of the service life by year. Pavement service life of the first major rehabilitation ranges from 8 to 20 years. About 166 surveyed miles were rehabilitated in the first 15 years.

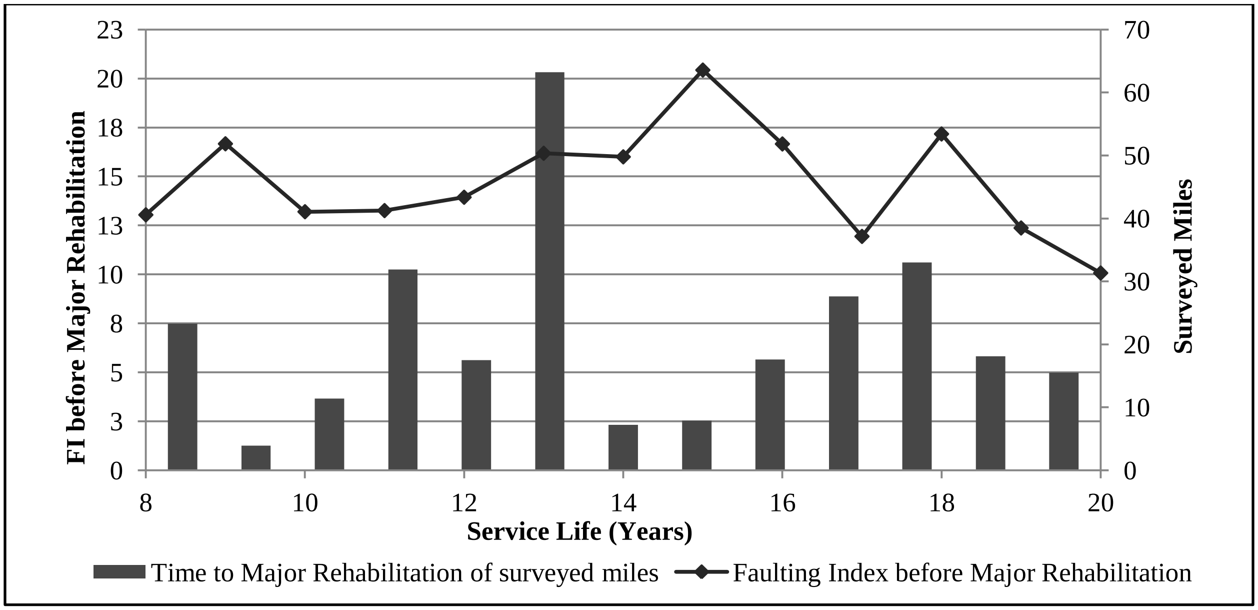

Figure 4.3 Distribution of Faulting Index and Surveyed Miles for First Rehabilitation

- Service Life of Second Major Rehabilitation

  The pavement service life of a second major rehabilitation is the time from the second major rehabilitation to a third major rehabilitation. Of the 541 surveyed miles of JPCP analyzed, only 17% (95 surveyed miles) have the service life of a second major rehabilitation, i.e., have reached a third major rehabilitation. As shown in Table 4.1, on average, the service life of a second major rehabilitation was 8 years, which is much shorter than the service life of the original pavements (17 years) and the first rehabilitation (14 years). In addition, the faulting index before the rehabilitation was 17.3, which is higher than that of two previous major rehabilitations. While the service life of a second major rehabilitation is based on a limited number of projects, this information can be used to evaluate the cost-effectiveness of second and subsequent rehabilitations.

4.3 Service Life Based on Faulting Index of 15

The time a major rehabilitation is applied to the pavements varies based on pavement condition and other factors, such as funding availability, adding lane(s), etc. Therefore, the time to reach a faulting index of 15 was also used in this study to provide a more objective comparison among projects. In this section, the pavement service life of the 541 surveyed miles of in-service JPCP is presented based on the time to reach a faulting index of 15. Table 4.2 shows the service lives of original and rehabilitated pavements based on a faulting index of 15.

Table 4.2 Service Lives based on a Faulting Index of 15

Description		Original Pavement	First Major Rehabilitation	Second Major Rehabilitation
Time to reach Faulting Index of 15	Average	17	12	6
	Minimum	4	6	5
	Maximum	38	28	7

- Service Life of Original Pavement

  The service life of original pavements based on a faulting index of 15, i.e., the time needed from initial construction to reach a faulting index of 15, ranges from 4 years to 38 years with an average of 17 years, as shown in Table 4.2. The average service life is the same as the pavement service life based on a major rehabilitation. This is because the faulting index before rehabilitation is 16.5, which is close to 15.
- Service Life of First Major Rehabilitation

  The service life of the first major rehabilitation based on a faulting index of 15 is the time taken to reach a faulting index of 15 after the first major rehabilitation. Table 4.2 shows that the service life of the first major rehabilitation has an average of 12 years, which is slightly shorter than the service life of the original pavements. The distribution of the service life shows a range of 6 years to a maximum of 28 years.
- Service Life of Second Major Rehabilitation

  The service life of the second major rehabilitation based on a faulting index of 15 is the time taken to reach a faulting index of 15 after a second major rehabilitation. Of the 541 surveyed miles of JPCP, only 17% (95 surveyed miles) reached the end of a second major rehabilitation, i.e., had a third rehabilitation. As shown in Table 4.2, on average, the service life of a second major rehabilitation based on a faulting index of 15 is 6 years, which is much shorter than the other two service lives (17 years for the original pavements and 14 year for the first rehabilitation). Again, this information can be used to evaluate the cost-effectiveness of second and subsequent rehabilitations.

4.4 Service Life by Pavement Design

GDOT has continuously made improvements in its concrete pavement design for better performance through research and field observation. As a result, various concrete pavement designs, including different bases, joint spacing, joint orientation, etc., have been constructed in Georgia. These designs were categorized in order to study the performance of the different designs. This section first presents the pavement design categories, and then presents an analysis of the service life by design category.

4.4.1 Service Life of Category 1

Among the 541 survey miles of JPCP that have had at least one rehabilitation, 440 surveyed miles are Category 1 pavements. Among them, 42% have had a first major rehabilitation; 37% have had a second major rehabilitation; and 21% have had a third major rehabilitation. Figure 4.4 shows the percent miles by number of major rehabilitations.

The service life for the pavement in Category 1 is summarized in Table 4.3. The average service lives of the original pavement, first major rehabilitation, and second major rehabilitation are 17, 14, and 8 years, respectively. It is noted that the service life of a second major rehabilitation is reduced to less than half of the first rehabilitation. This is the same as the result shown in statewide analysis because the pavement that has had a second major rehabilitation is all in Category 1. Out of the 261 surveyed miles that had a second major rehabilitation, only 36% had reached the end of their service life, i.e., had a third major rehabilitation. The remaining 64% are still in service as of 2010. The service lives presented in Table 4.3 can be used to assess the cost-effectiveness of major rehabilitation for the pavements in Category 1.

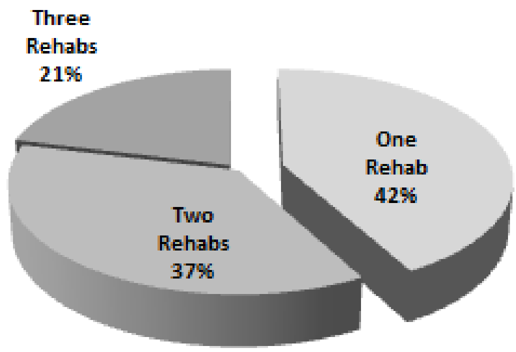

Figure 4.4 Percent Miles of Number of Major Rehabilitations (Design Category 1)

Table 4.3 Distribution of Service Lives for Design Category 1

Description		Original Pavement	First Major Rehabilitation	Second Major Rehabilitation
Time to Major Rehabilitation	Average	17	14	8
	Minimum	10	8	7
	Maximum	29	20	9
Average Faulting Index before Major Rehabilitation		16.8	14.9	17.3
Time to reach Faulting Index of 15	Average	14	14	6
	Minimum	4	6	5
	Maximum	35	35	7

4.4.2 Service Life of Category 2

A total of 102 surveyed miles of JPCP that had at least one major rehabilitation was used to study the service life for pavements in Category 2. Among the 102 surveyed miles, 83% have had the first major rehabilitation; 17% have had a second major rehabilitation; and none have had a third major rehabilitation. Figure 4.7 shows the percent mileage by number of major rehabilitations. The service life for the pavement in Category 2 is summarized in Table 4.4. It is noted that 81 surveyed miles of JPCP in Category 2, which have had no major rehabilitation, are excluded in the analysis of the service life.

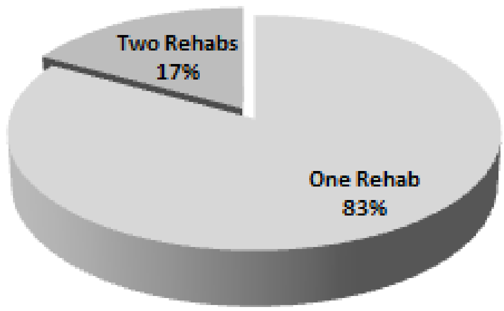

Figure 4.5 Percent Miles of Number of Major Rehabilitations (Design Category 2)

Table 4.4 Distribution of Service Lives based on Design Category 2

Description		Original Pavement	First Major Rehabilitation
Time to Major Rehabilitation	Average	21	17
	Minimum	14	17
	Maximum	29	17
Average Faulting Index before Major Rehabilitation		11.7	-
Time to reach Faulting Index of 15	Average	26	17
	Minimum	12	17
	Maximum	38	17

The average service lives of the original pavement and the first major rehabilitation are 21 and 17 years, respectively. It is noted that pavement service life of Category 2 is longer than the corresponding service life of Category 1. Also, the pavement in Category 2 was treated at a faulting index of 11.7, rather than 15. This indicates a longer service life based on a faulting index of 15 can be expected. As shown in Table 4.4, the average service life of an original pavement based on a faulting index of 15 is 26 years. This information provides a better understanding of the pavement in Category 2 and can be used to evaluate the cost-effectiveness of a major rehabilitation. The service life of the first major rehabilitation is also shown in Table 4.4. It is important to note that the service life of the first major rehabilitation is based on limited data (17 surveyed miles) that had a second major rehabilitation. A majority of the pavements that have had their first major rehabilitation have not yet reached the end of their service life, i.e., a second major rehabilitation.

4.4.3 Service Life of Category 3

Of the 214 surveyed miles of JPCP belonging in Category 3, none have had any major rehabilitation based on the CPACES data. Therefore, pavement service life of Category 3 was not available. The pavements in Category 3 were constructed in the late 1970s through the early 1980s with ages ranging from 25 to 33 years. Therefore, the average service life of the original pavements is expected to be longer than 25 years.

4.5 Summary

Pavement service life of interstate highways was analyzed based on three types of events, including an AC overlay, a major rehabilitation, and a faulting index of 15, and the results are summarized as follows:

- Of the 258 centerline miles of overlaid JPCP, the average time to the first AC overlay is 13years. However, it is noted that a majority of the AC overlays were performed between a short period of time (1977 and 1980) as part of interstate widening (adding lane) project. This indicates the decisions for an AC overlay were affected not only by pavement condition but also factors, such as funding availability, agency policy, adding lane(s), etc. Therefore, the 13-year span cannot be interpreted as the effective service life based only on the first AC overlay. Evaluation of pavement performance after the AC overlay is not in the scope of this project.
- A total of 541 surveyed miles of in-service, non-doweled JPCP was used to analyze pavement service life based on the time to reach a major rehabilitation and the time to reach a faulting index of 15. Service lives of original and rehabilitated pavements based on these two events are shown in Figure 4.6. The service life decreases as the pavement undergoes major rehabilitations. Based on a major rehabilitation, the service lives of the original pavement, the first rehabilitation, and the second rehabilitation are 17, 14, and 8 years, respectively. It is noted that the service life of a second major rehabilitation is much less than the service life before that. According to the concrete pavement rehabilitation guide for diamond grinding [16], "a typical concrete pavement may be ground up to three times without compromising its fatigue life based on fatigue analysis." While the service life of a second major rehabilitation is based on a limited number of

projects, this information can be used to evaluate the cost-effectiveness of second and third major rehabilitations. The service life based on a faulting index of 15 shows a trend similar to the service life based on a major rehabilitation, as shown in Figure 4.6.

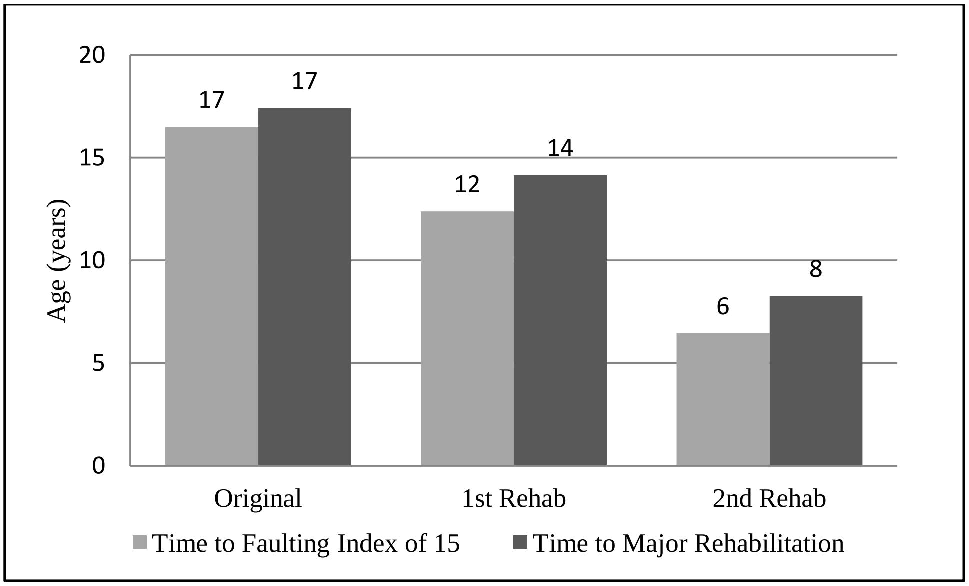

Figure 4.6 Comparison of Service Lives based on Faulting Index and Major Rehabilitation

- The analysis of the service life for each design category reveals a significant improvement in the service life of the pavements in Category 2 compared to the service life in Category 1. Figure 4.7 shows the service lives in each category. Overall, the service lives in Category 2 are three years longer than the corresponding service lives in Category 1. For example, the service life of the original pavement in Category 2 is 21 years, which is longer than the service life in Category 1 (17 years). It is noted that none of the pavements in Category 3 have had any major rehabilitation. With an age ranging from 25 to 33 years, pavement service life of Category 3 is expected to be longer than 25 years.

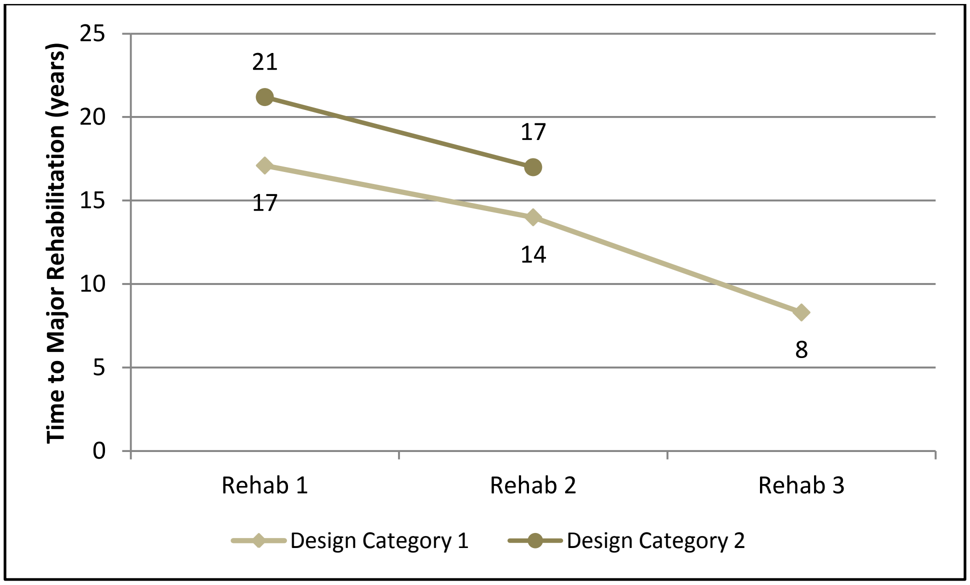

Figure 4.7 Distribution of Service Life based on Design Category

5 Survival Analysis

The statistical analysis presented in Chapter 4 is based only on the data for pavements that had reached the end of their service life. In this chapter, a survival analysis was conducted to develop an estimate of the expected service life using all the data from the 839 surveyed miles of interstate highways. This set of data takes into account 1) the pavements that have not had any major rehabilitation since initial construction and 2) the pavements that had reached major rehabilitation(s) but are still in service, i.e., in their current life. First, survival analysis is briefly described. Second, the survival curves of the original and rehabilitated pavements and the survival curves for different design categories are presented. Finally, a summary of the findings is presented.

5.1 Survival Analysis

Survival analysis is a statistical method widely used in social science, economics, biology, and engineering for determining the probability of survival. Mathematical models have been developed and used to predict the probability of survival as a function of time or other factors. Survival analysis has also been applied to study the longevity of pavements [12, 17]. Survival analysis was conducted to compare the longevity of jointed reinforced concrete pavement (JRCP), CRC and hot mixed asphalt concrete (HMAC) pavement with different pavement thicknesses in different climate zones in Illinois [12]. The Arizona Department of Transportation (ADOT) conducted survival analysis to evaluate the service life of different rehabilitation methods. The information was used to support the evaluation of the cost-effectiveness of rehabilitation methods (e.g., preservation versus reconstruction) [17]. LIFETEST procedure in SAS software package was used in both studies for estimating the survival functions [12, 17].

In this study, the Gompertz Growth Curve is used to model the probability of pavements being rehabilitated as a function of pavement age. The survival curve of a pavement is then computed by subtracting the Gompertz Growth Curve from 100%, as shown in Equation 5.1 [18]:

$$Survival = 100\% - A \times \exp\left[-\exp\left(\frac{\mu \times \exp(1)}{A}(\lambda - t) + 1 \right) \right] \times 100\% \qquad \text{(Equation 5.1)}$$

Where

t	= pavement age in years,
A	= the maximum of the growth curve,
	= the maximum slope of the growth curve, and
	= the lag phase, which indicates how long the growth curve remained 0%.

The R language, a free software environment for statistical computing and graphics, was chosen for the survival curve fitting. The "grofit" package [18] in R is used to generate the aforementioned coefficients for survival curves based on the pavement data.

5.2 Statewide Survival Analysis

A survival analysis was conducted to estimate the service lives of the original and rehabilitated pavements on interstate highways in Georgia. Pavement service life of a second major rehabilitation was not analyzed because most of the pavements that had a second rehabilitation are still in-service. Survival curves based on the time to a major rehabilitation and the time to a faulting index of 15 are presented in this section.

5.2.1 Survival based on the Time to Major Rehabilitation

Survival curves for non-doweled pavements, combined Categories 1 and 2, were developed to depict the survival of the original pavements and the first major rehabilitation based on the time to reach a major rehabilitation. The coefficients of survival curves were generated using the "grofit" package in R. The survival curves are shown in Figure 5.1. The curves follow a typical survival shape. The service life of the original pavements ranges widely from 10 to 29 years because the pavements were constructed with different designs and at different times. However, there were few original pavements that failed (rehabilitated) in the first 10 years. The corresponding ages for survival rates of 75% and 50% are 14 and 21 years, respectively. It should be noted that approximately 35% of the original pavements are still in-service, i.e., have not reached their first rehabilitation. The current age of these projects ranges from 25 to 41 years with an average of 31 years. As of 2010, the average faulting index of these pavements is roughly 9, which indicates that these projects are still in acceptable condition and are expected to last for several more years.

The survival curve of the first major rehabilitation, shown in Figure 5.1, is very close to the survival curve for the original pavements. The pavements that had the first major rehabilitation failed in as early as 8 years. The corresponding ages for survival rates of 75% and 50% are about 13 and 20 years, which are slightly shorter than those of the original pavement. It should be noted that approximately 49% of these pavements that are still in service. The age of these projects ranges from 6 to 33 years with an average of 20 years. The average faulting index of these in-service pavements was about 11 in 2010. However, a review of these projects shows several projects have a faulting index higher than 15. A follow-up study is recommended to update the survival curve for the first major rehabilitation when these projects are rehabilitated.

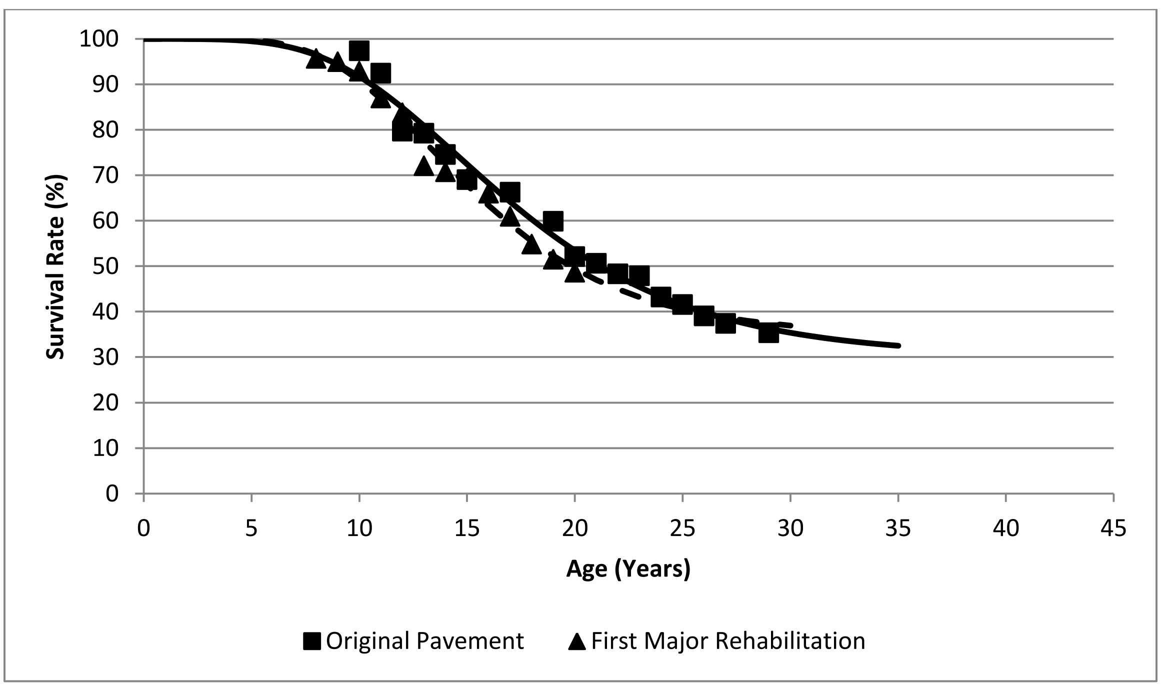

Figure 5.1 Survival Curves based on Time to Major Rehabilitation

5.2.2 Survival based on the Time to Faulting Index of 15

Survival curves for non-doweled pavements for both Categories 1 and 2 pavements were also developed to depict the survival of the original and rehabilitated pavements based on the time to reach a faulting index of 15. The survival curves of original and rehabilitated pavements are very close, as shown in Figure 5.2. The corresponding ages for survival rates of 75% and 50% are roughly 12 and 23 years, respectively. Currently, there are still 35% of original pavements that have not reached their first rehabilitation and 49% of rehabilitated pavements that have not reached their second rehabilitation. Again, a follow-up study is recommended to update the survival curve for the first major rehabilitation when these projects are rehabilitated.

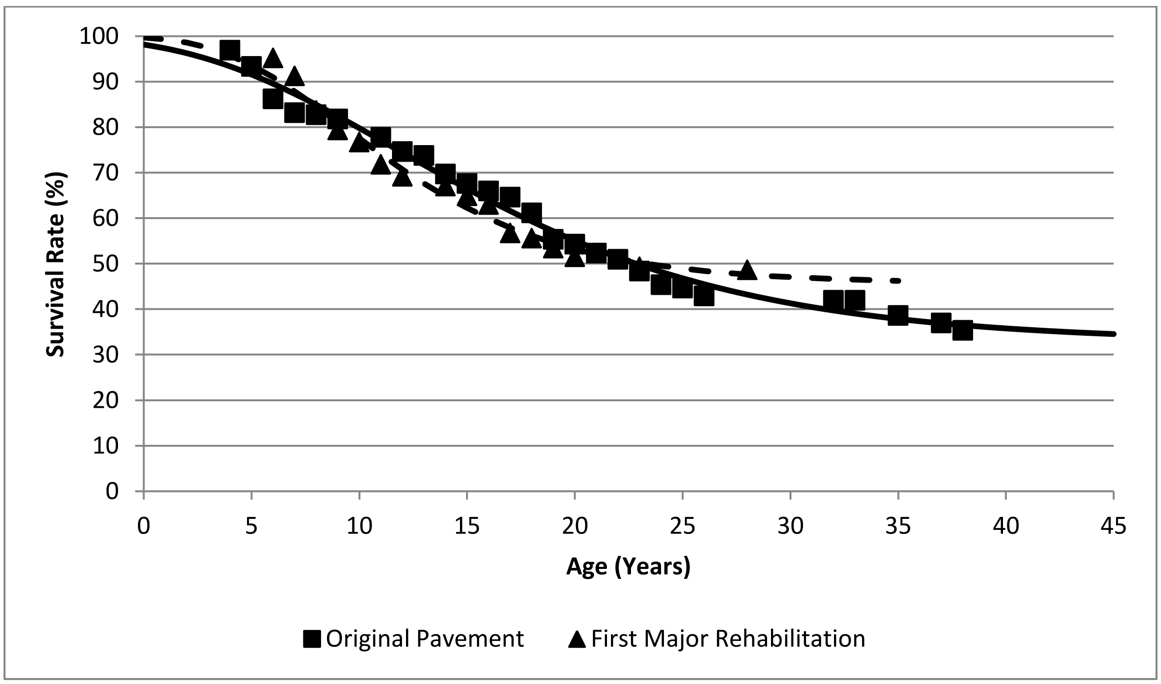

Figure 5.2 Survival Curves based on Time to Faulting Index of 15

5.3 Survival Analysis by Design Category

In this section, survival analysis was conducted to develop an estimate of the service life for pavements under different design categories. The survival curves of the original pavements in Categories 1 and 2 were developed. The survival curve for Category 3 was not developed because none of them has had any major rehabilitation. Figure 5.3 and Figure 5.4 show the survival curves based on the actual time to major rehabilitation and the time to a faulting index of 15. Figure 5.3 shows a significant difference in the survival curves for Categories 1 and 2. Given a survival rate of 75%, pavement service lives for Categories 1 and 2 are 12 and 19 years, respectively. At an age of 20 years, the survival rates for Categories 1 and 2 are 25% and 75%, respectively. It is noted that more than 95% of the original pavements in Category 1 had been rehabilitated as of 2010, while only 55% in Category 2 had been rehabilitated.

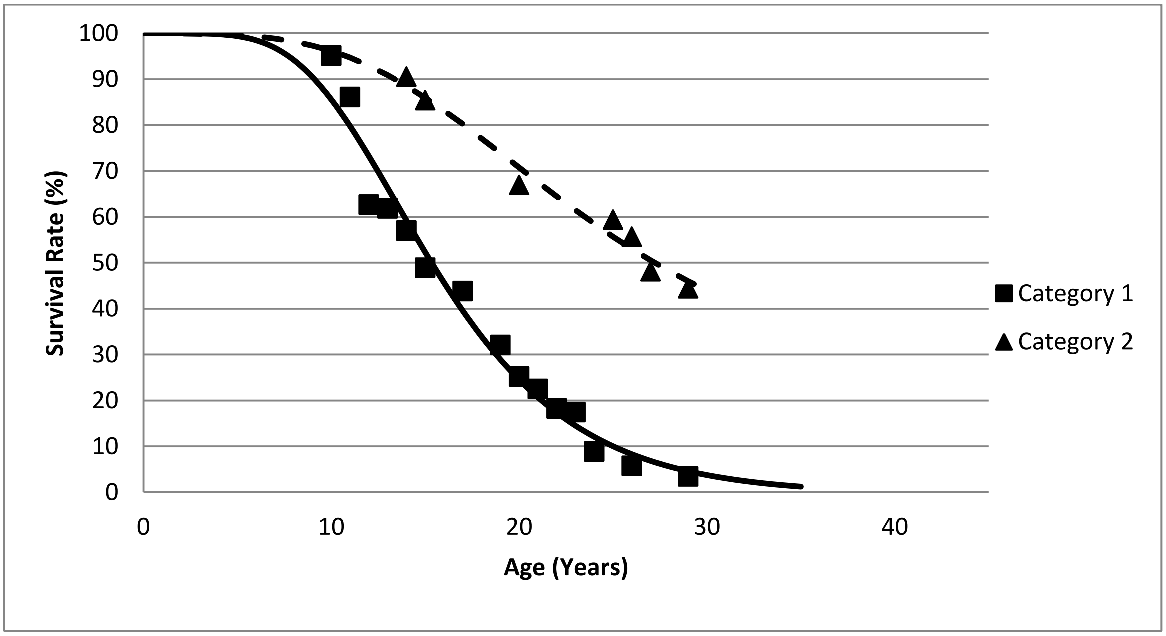

Figure 5.3 Survival Curves of Original Pavements based on Time to Major Rehabilitation

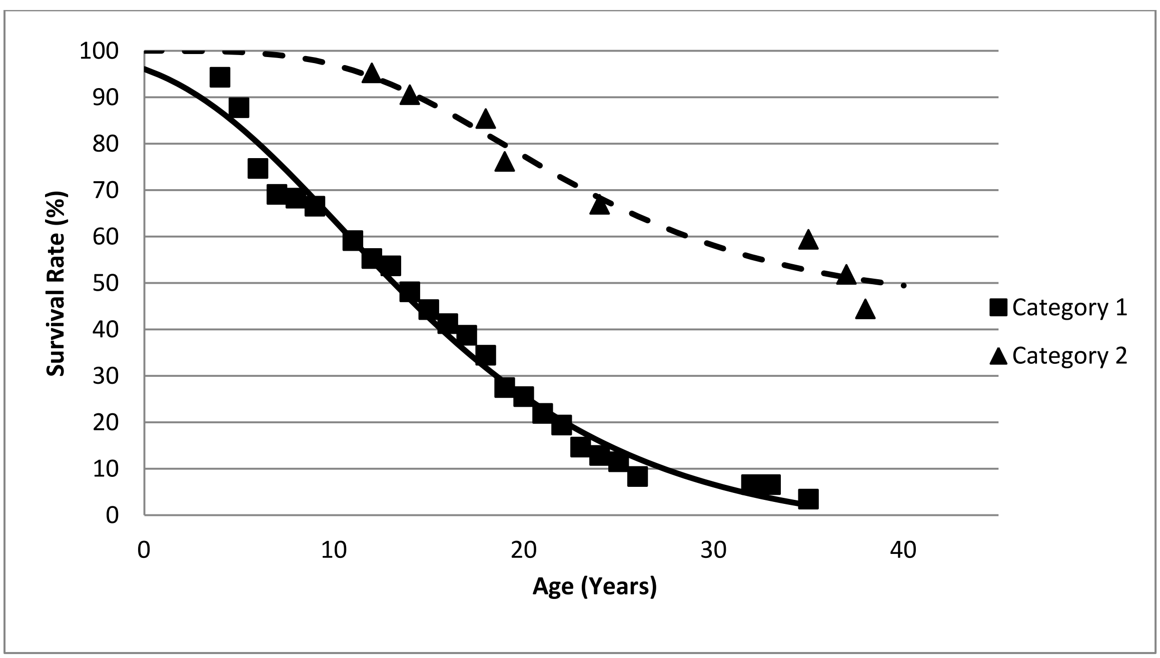

Figure 5.4 Survival Curves of Original Pavements based on Time to Faulting Index of 15

5.4 Summary

In this chapter, survival analysis was conducted to estimate the distribution of pavement service life based on all data from the 839 surveyed miles of interstate highways. The pavements in their current life, i.e., pavements that have not had any major rehabilitation since initial construction and the pavements that reached their first major rehabilitation but not their second, were considered in the analysis. Major findings are summarized below:

a) The service life of the original pavements with all designs varies widely from 10 to 29 years. Based on the time to a major rehabilitation, the corresponding ages for survival rates of 75% and 50% are 14 and 21 years. The survival curves of original and rehabilitated pavements are close.

b) The survival curves based on different design categories show the survival rate of Category 2 is higher than that of Category 1. Based on the time to major rehabilitation at the age of 20, which is the design year in Georgia, the survival rates of Categories 1 and 2 are 25% and 70%, respectively.

c) Survival analysis could be conducted periodically to develop complete estimates of pavement service lives. A follow-up study is recommended for updating the survival curves for Categories 2 and 3 as more pavements in these categories are rehabilitated.

6 Project-Level Analysis

This chapter presents the results of a project-level analysis of six selected projects, two each in three design categories (1, 2, and 3). In support of the analysis, detailed information, including pavement design, distress data, and ESALs, was obtained for each project. Pavement performance was studied using different performance indicators, such as the faulting index and cracking-related distresses (e.g. broken slabs and slabs with longitudinal cracks), in time (year) and ESALs. While the results of this analysis are not considered conclusive because of the small sample size, the information can provide a better understanding of the actual performance of in-service JPCP with different designs, which is useful for improving pavement design.

6.1 Project Description

Six projects, two each in Categories 1, 2, and 3, were selected for the project-level analysis through a careful review of their service lives and data availability. All six projects have a service life within a reasonable range of the expected service life for their design category, not extremely long or short. Detailed design information, including pavement thickness, load transfer design, joint spacing, base type, and design ESALs, was obtained for each project. Table 6.1 summarizes the design information for each project. All six projects have a 20-year design following GDOT's pavement design practice. Projects 167 and 168 in Category 1 were designed to carry approximately 5 million ESALs in 20 years with a 9-inch, random joint spacing, non-doweled JPCP on a 6-inch soil cement base. Constructed in 1972, these two projects have lasted 38 years as of 2010 with only one major rehabilitation each. Projects 128 and 129 in Category 2 were designed to carry 7.3 million and 10 million ESALs, respectively. Both projects were designed with a 10-inch, non-doweled JPCP on a 6-inch cement stabilized GAB base. Constructed in 1971 and 1973, these two projects also have lasted 38 years with only one major rehabilitation each. Projects 160 and 161 in Category 3 were constructed in the late 1970s (1977 and 1979). These two projects were designed to carry 13 million and 10 million ESALs with a10-inch, doweled JPCP on a 5-inch soil cement base plus a 1-inch hot mix asphalt (HMA) interlayer. There has been no major rehabilitation applied on these two projects.

Table 6.1 Summary of Selected Projects for Project-Level Analysis

Project ID	Design Period (Years)	Design ESALs (Million)	Pavement Thickness	Base Type	Dowels	Joint Spacing	Shoulder Types
167*	20	4.8	9"	6" Soil Cement	No	random/sk**	HMA
168	20	5.2	9"	6" Soil Cement	No	random/sk	HMA
128	20	7.3	10"	6" Cement Stabilized GAB	No	sk	HMA
129	20	10.3	10"	6" Cement Stabilized GAB	No	20', 30', sk, sq***	HMA
160	20	13.4	10"	5" Soil Cement + 1" HMA	Yes	20' sq	Tied PCC
161	20	10.4	10"	5" Soil Cement + 1" HMA	Yes	20' sq	Tied PCC

* Unique identified assigned by research team.
**Skewed Joint (angle to driving direction).
***Squared Joint (perpendicular to driving direction).

In addition to the design information, the annual ESALs for each project was reconstructed based on the traffic data between 1990 and 2010. After discussion with GDOT, a linear growth of AADT was assumed to estimate the traffic from initial construction year to 1990, for which the traffic data was not available. Annual ESALs were then computed using the equation below:

(Equation 6.1)

Where

AADT = the total annual average daily traffic of a segment in both directions.

TP = truck percentage.

LD = lane distribution factor, which was set to be 0.9 for 4-lane divided highways and 0.7 for 6-lane divided highways.

DD = direction distribution factor, 0.5 in general.

TC = transfer coefficient for truck loading. A value of 2.2 was used in this study.

6.2 Performance Analysis

The performance of the six selected projects was analyzed using different performance indicators (the faulting index and the number of broken/replaced slabs) in time (year) and ESALs. The results are presented in subsequent sections.

6.2.1 Projects in Category 1

Projects 167 and 168 in Category 1 have lasted 38 years with one major rehabilitation each. Both projects reached a faulting index of 20 and carried approximately 20 million ESALs, which are 3 times the designed ESALs, in the first 23 years before the major rehabilitation. The deterioration in the faulting index in terms of time and ESALs is summarized in Table 6.2. Both projects, in their original pavements, have a deterioration rate in the faulting index of 0.9 per year or 1.1 per million ESALs. Although both projects have not reached a second major rehabilitation, they have carried approximately 20 million ESLAs in 14 years, which is more than the ESLAs carried before the rehabilitation. As of 2010, the faulting index was about 18. Compared to the original pavements, the deterioration rate in faulting index after the first major rehabilitation is higher in time (1.2 per year); however, it is lower in ESALs (0.8 per million ESALs). Distress information for these two projects was retrieved to explore the performance in detail. Figures 6.1 to 6.2 show the plots of the faulting index versus time and cumulative ESALs. A drop of the faulting index (from 20 to approximately 3) indicates the projects were rehabilitated at the age of 24 years, as shown in Figure 6.1. The faulting index has increased more rapidly, in time, after the rehabilitation compared to the original pavements. However, Figure 6.2 shows the rate of increase in the faulting index is higher for the original pavements. Figure 6.3 and Figure 6.4 show the cracking-related distresses, including broken slabs, replaced slabs, and slabs with longitudinal cracks per mile, for these two projects. As shown in the figures, broken slabs developed after 5 years from initial construction. It is noted that slabs with longitudinal cracks were not recorded in CPACES until 1995. Prior to that all cracked slabs were considered as broken slabs. Fewer broken slabs, replaced slabs, and longitudinal cracks (less than 15 per mile) were observed on Project 168, than on Project 167, which exhibited a large number of broken slabs and replaced slabs. This indicates a potential base issue for Project 167. Overall, these two projects carried 3 to 4 times the designed ESALs each in their original pavements and the first major rehabilitation. Both projects also show a relatively higher faulting index compared to other projects discussed in subsequent sections.

Table 6.2 Service Life and Deterioration Rate Comparison for Category 1 Projects

	Project Number	Age (years)	ESALs (10^6)	Faulting Index	ESALs/ Design ESALs	Deterioration Rate by Year (FI/Year)	Deterioration Rate by ESALs (FI/10^6 ESAL)
Life of Original Pavement	167	23	18.9	20.9	3.94	0.91	1.10
	168	23	17.1	20.4	3.29	0.89	1.19
Life of First Rehabilitation*	**Project Number**	**Age (years)**	**ESALs (10^6)**	**Faulting Index**	**ESALs/ Design ESALs**	**Deterioration Rate by Year (FI/Year)**	**Deterioration Rate by ESALs (FI/10^6 ESAL)**
	167	13	20.5	16.3	4.27	1.25	0.79
	168	15	22.1	18.0	4.25	1.20	0.81

* For Projects 167 and 168, service life of the first rehabilitation has not finished.

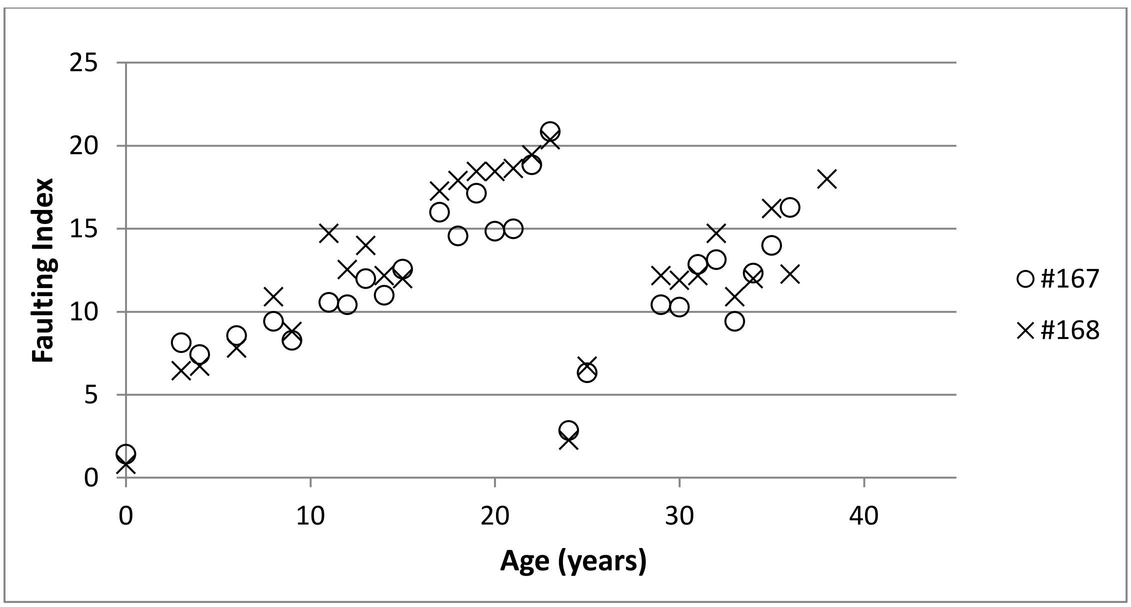

Figure 6.1 Faulting Index based on Age for Category 1 Projects

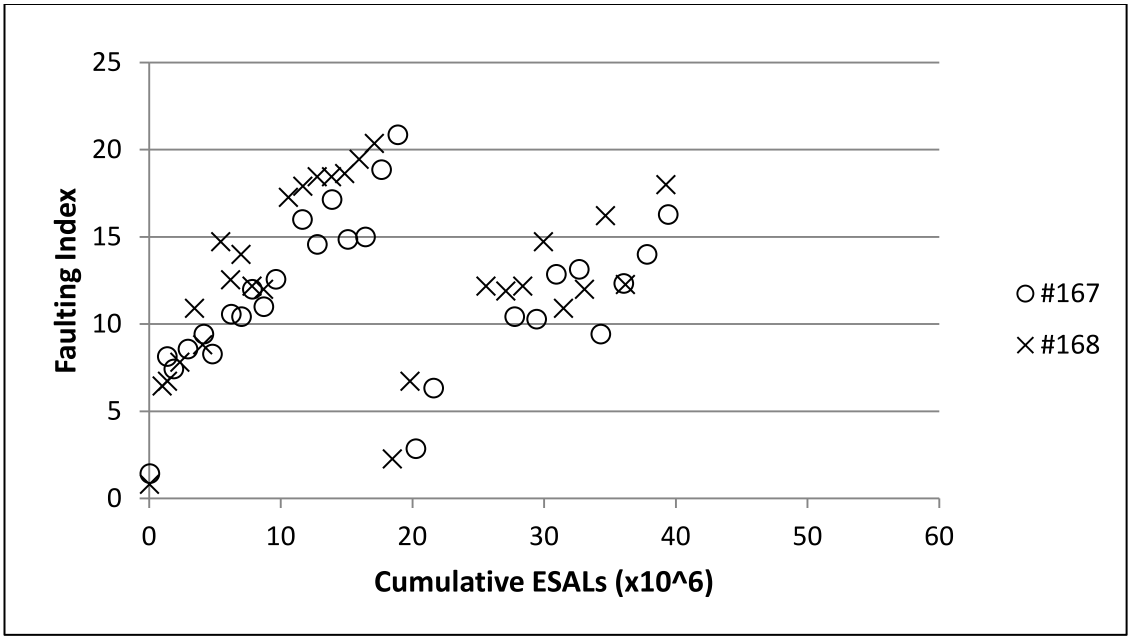

Figure 6.2 Faulting Index based on ESALs for Category 1 Projects

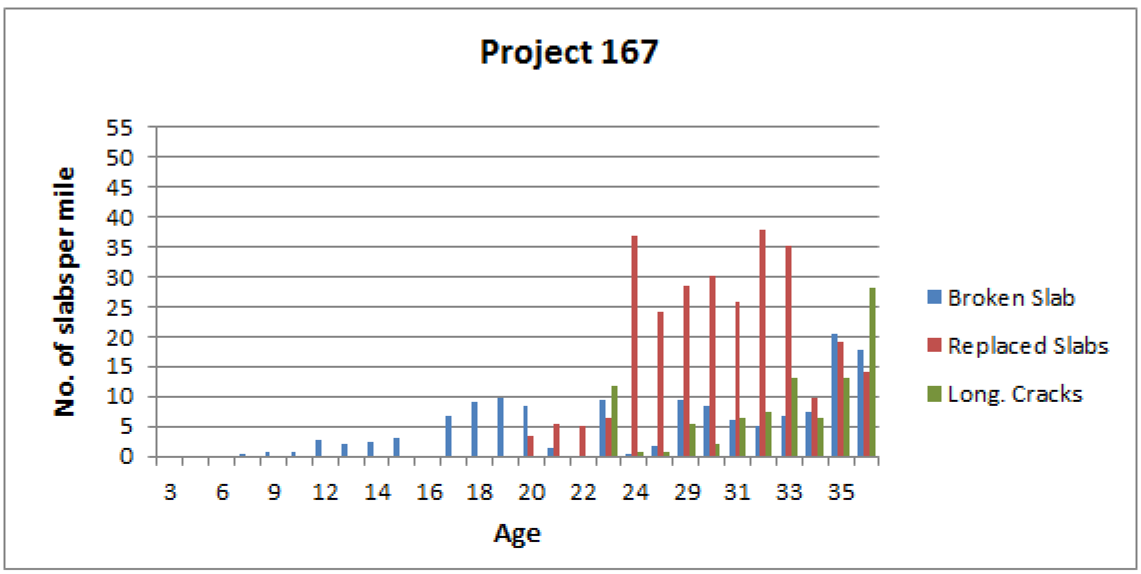

Figure 6.3 Cracking-related Distresses for Project 167

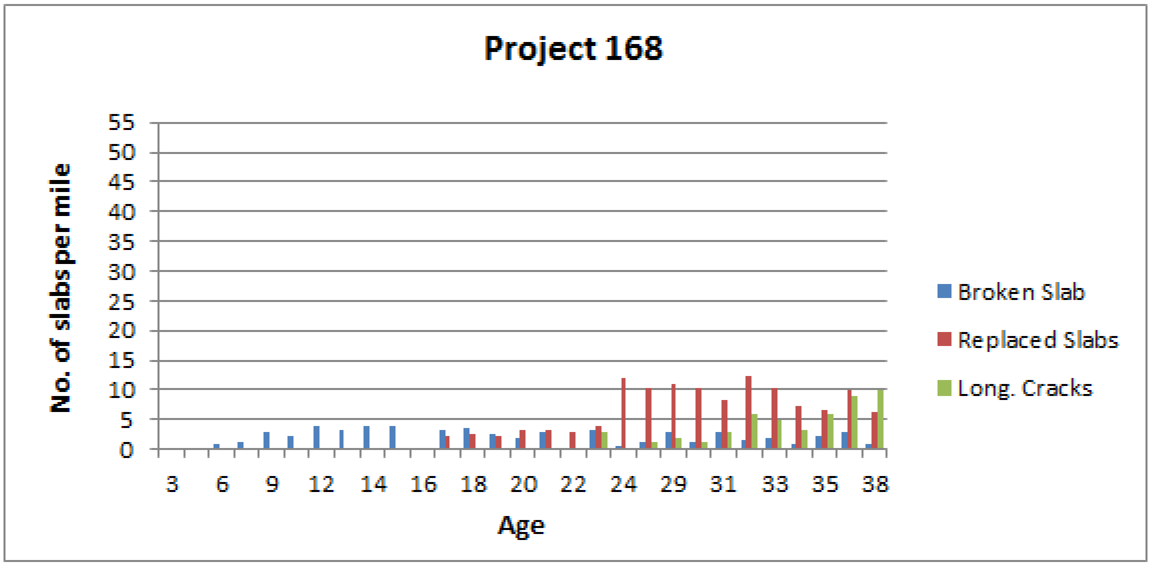

Figure 6.4 Cracking-related Distresses for Project 168

6.2.2 Projects in Category 2

Projects 128 and 129 in Category 2 have also lasted 38 years with one major rehabilitation each. However, the major rehabilitation was conducted when the faulting index was roughly 10. Project 128 carried 26 million ESALs (3.5 times the designed ESALs) over 26 years; Project 129 carried 19 million ESALs (1.6 times the designed ESALs) in 17 years. Table 6.3 summarizes the performance in terms of the faulting index before and after the major rehabilitation in time and ESALs. Both projects, in their original pavements, have a deterioration rate in the faulting index of less than 0.6 per year or 0.7 per million ESALs. Although both projects have not reached a second major rehabilitation, they have carried more ESLAs after the rehabilitation than in their original pavements. Project 128 has carried 25 million ESALs in 26 years; Project 129 has carried 36 million ESALs in 20 years. Still, both projects show a relatively small faulting index (4 and 7). A lower deterioration rate in the faulting index was observed for both projects after the rehabilitation, compared to their original pavement. Figure 6.5 and Figure 6.6 show the faulting index deteriorates at a very slow rate in both time and ESALs, especially for Project 128. Also, the two projects show better performance in terms of the faulting index after the rehabilitation. Detailed rehabilitation information was not available at this time. Further study is recommended to investigate the performance of rehabilitation. Figure 6.7 and Figure 6.8 show both projects have little cracking-related distresses, fewer than 5 cracked slabs per mile, in the first 25 years.

However, an increase in the numbers of broken slabs, replaced slabs, and slabs with longitudinal cracks was observed after 25 years. It is noted that a significant number of slabs with longitudinal cracks was observed, higher than the number of broken slabs. Overall, these two projects show a lower deterioration rate in the faulting index and more severe cracking-related distresses, especially slabs with longitudinal cracks, compared to the projects in Category 1.

Table 6.3 Service Life and Deterioration Rate Comparison for Category 2 Projects

	Project Number	Age (years)	ESALs (10^6)	Faulting Index	ESALs/ Design ESALs	Deterioration Rate by Year (FI/Year)	Deterioration Rate by ESALs (FI/10^6 ESAL)
Life of Original Pavement	128	26	26.6	10.2	3.64	0.39	0.38
	129	19	17.0	11.3	1.65	0.59	0.66
Life of First Rehabilitation*	**Project Number**	**Age (years)**	**ESALs (10^6)**	**Faulting Index**	**ESALs/ Design ESALs**	**Deterioration Rate by Year (FI/Year)**	**Deterioration Rate by ESALs (FI/10^6 ESAL)**
	128	11	24.7	3.8	3.38	0.34	0.15
	129	20	36.0	7.8	3.50	0.39	0.22

* For Projects 128 and 129, service life of the first rehabilitation has not finished.

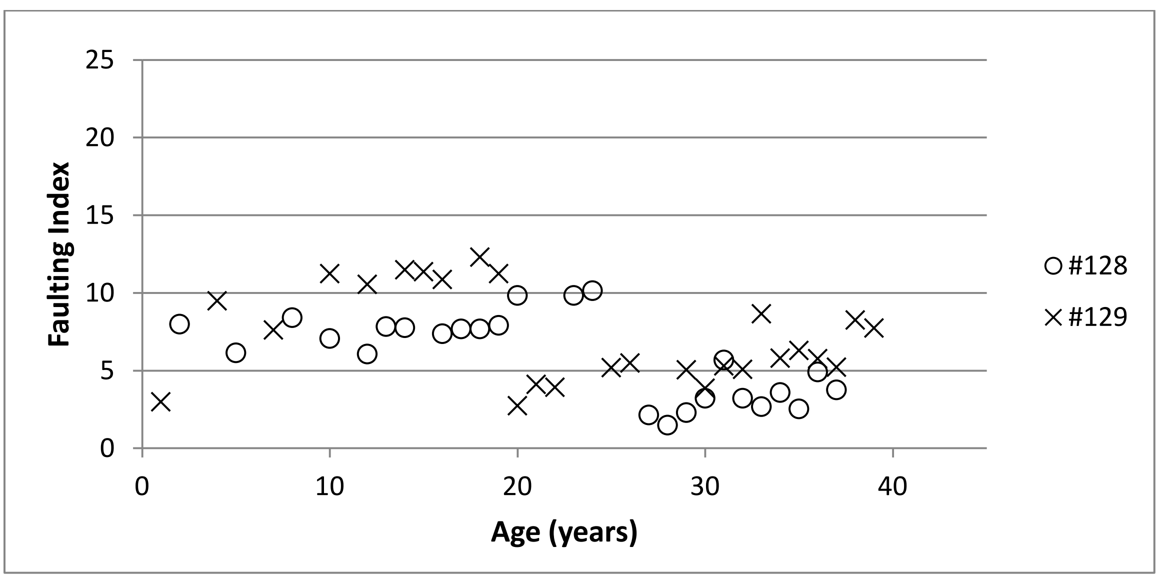

Figure 6.5 Faulting Index based on Age for Category 2 Projects

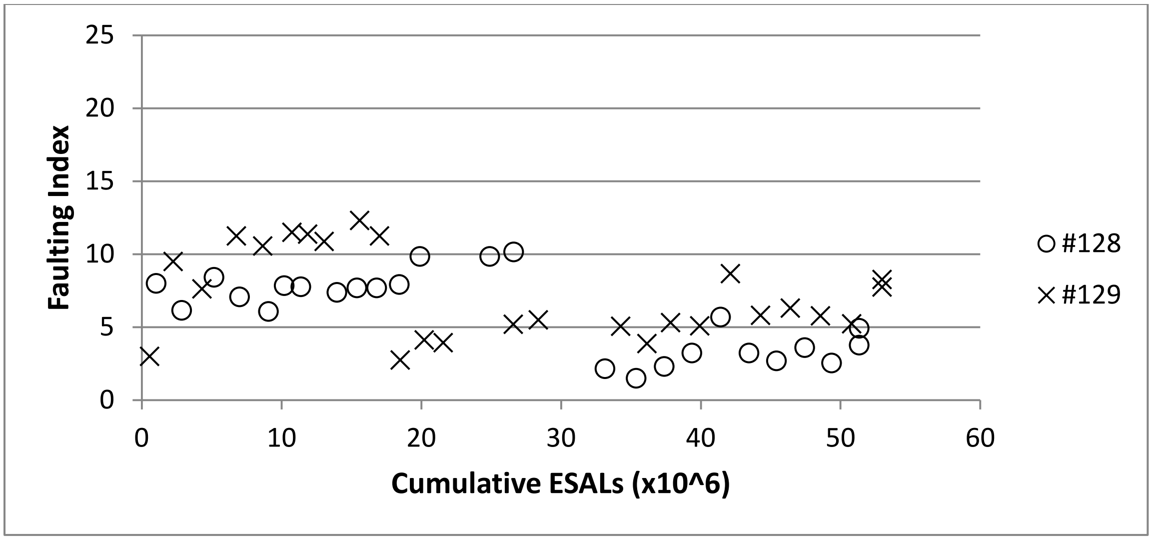

Figure 6.6 Faulting Index based on ESALs for Category 2 Projects

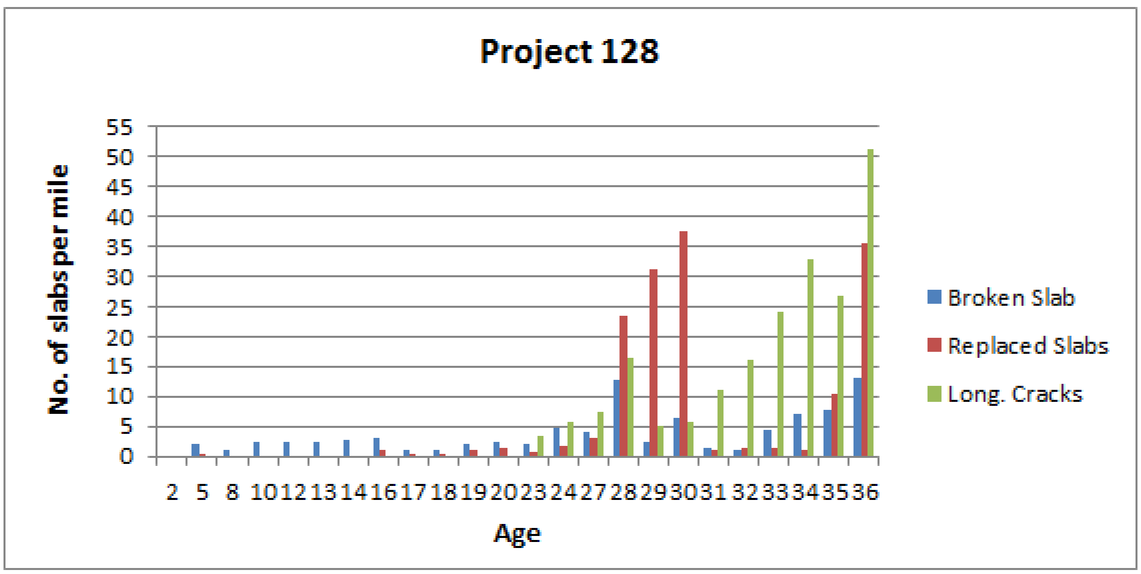

Figure 6.7 Cracking-related Distresses for Project 128

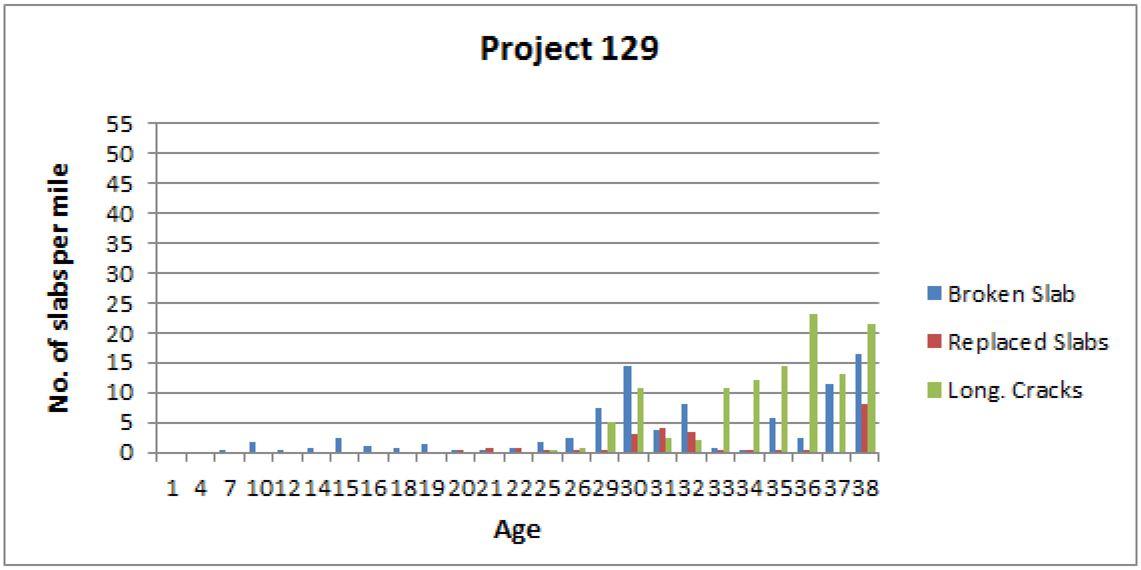

Figure 6.8 Cracking-related Distresses for Project 127

6.2.3 Projects in Category 3

Projects 160 and 161 in Category 3 were constructed in the late 1970s with dowels and edge support (tied PCC shoulder). Both projects have carried more than 30 million ESALs, which is about 3 times the designed ESALs, over 30 years without a major rehabilitation. They are still in fairly good condition with their faulting index around 10. Table 6.4 summarizes the performance in term of the faulting index in time and ESALs. These two projects have a steady, low deterioration rate in the faulting index of 0.3 per year or 0.3 per million ESALs. Figure 6.9 and Figure 6.10 show a consistent deterioration in the faulting index. Compared to the projects in Categories 1 and 2, these two projects have many fewer broken slabs, replaced slabs, and slabs with longitudinal cracks, fewer than 5 per mile after 30 years, as shown in Figures 6.11 and 6.12. Overall, these two projects have lasted 30 years with a relatively low faulting index and minor cracking-related distresses. The service lives of these two projects are expected to be more than30 years, 40 years if a faulting index of 15 is used as the end of service life.

Table 6.4 Service Life and Deterioration Rate Comparison for Category 3 Projects

	Project Number	Age (years)	ESALs (10^6)	Faulting Index	ESALs/ Design ESALs	Deterioration Rate by Year (FI/Year)	Deterioration Rate by ESALs (FI/10^6 ESAL)
Life of Original Pavement	160	33	30.4	9.7	2.27	0.29	0.32
	161	31	33.6	10.5	3.23	0.34	0.31

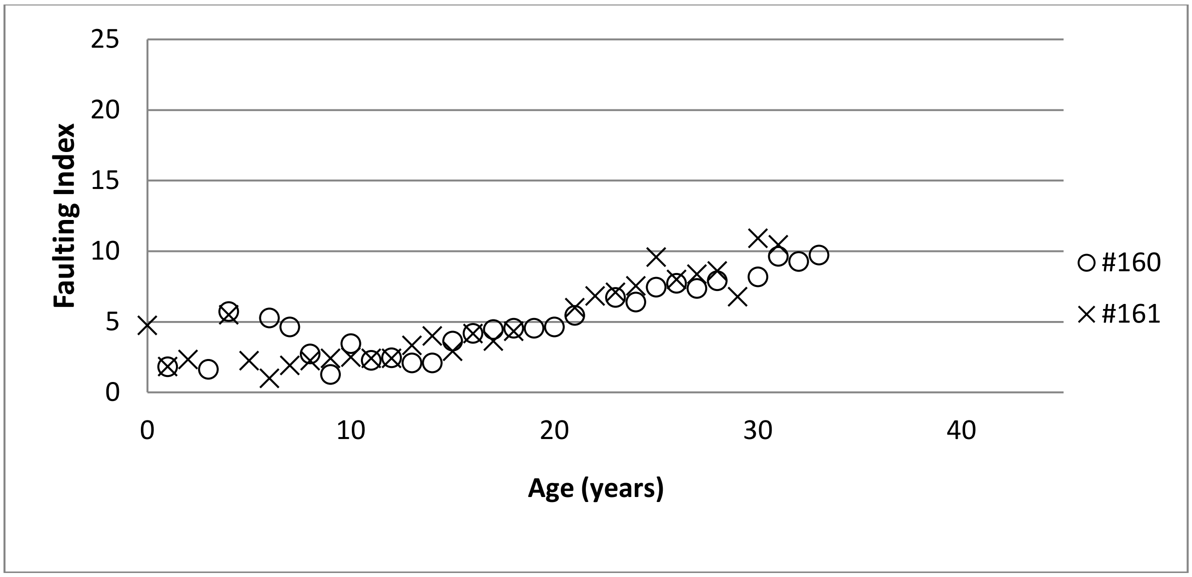

Figure 6.9 Faulting Index based on Age for Category 3 Projects

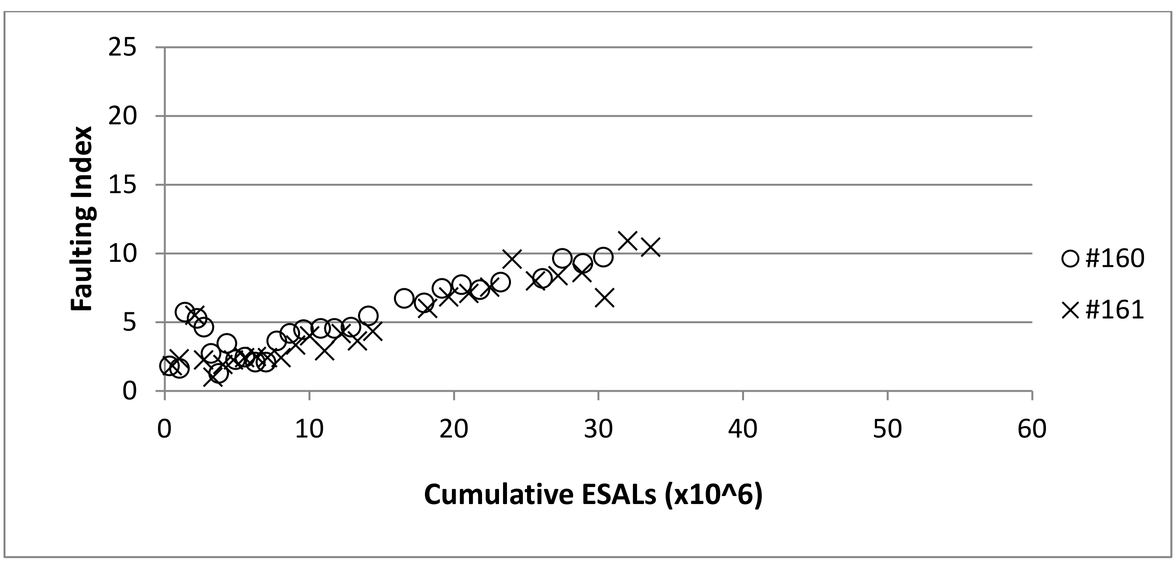

Figure 6.10 Faulting Index based on ESALs for Category 3 Projects

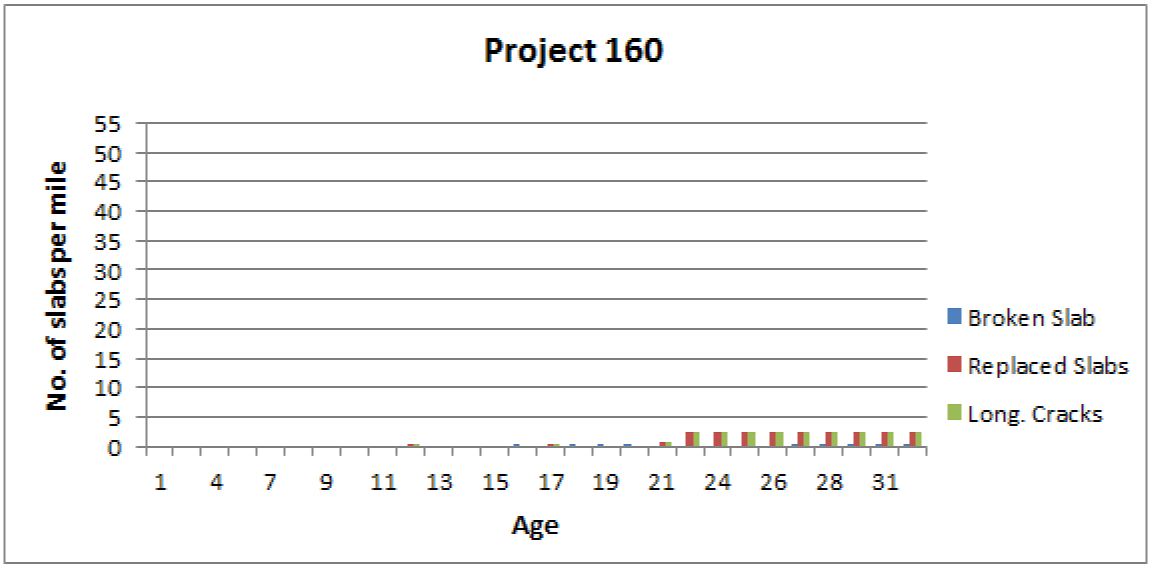

Figure 6.11 Cracking-related Distresses for Project 160

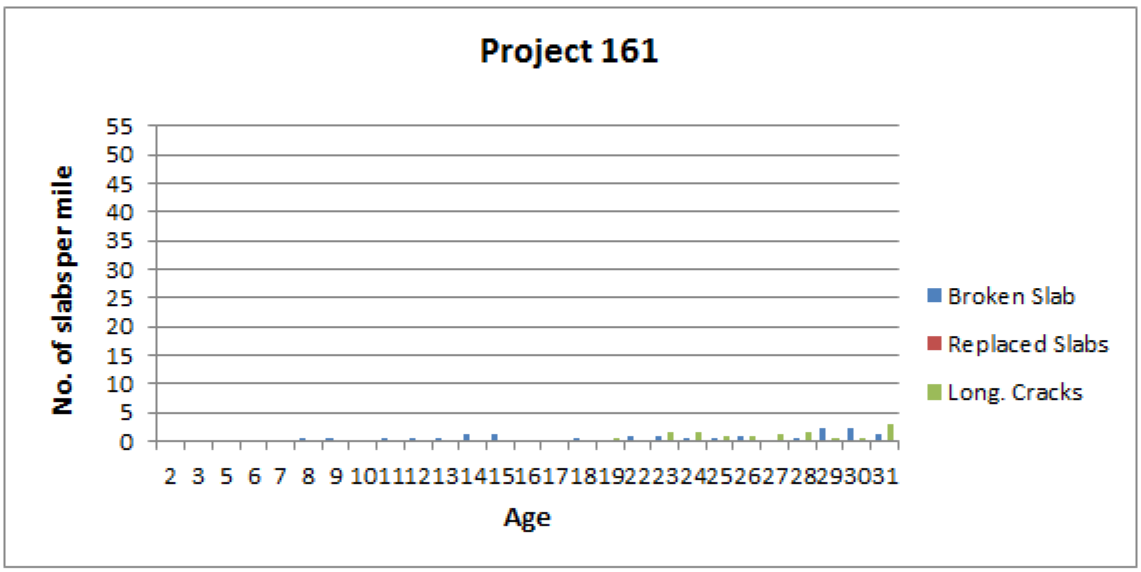

Figure 6.12 Cracking-related Distresses for Project 128

6.3 Identification of Projects with Extreme Performance

During the course of selecting projects for a project-level analysis, several projects with abnormal performance, i.e., with extremely long life or with poor performance, were identified. These projects can be further studied to explore the factors contributing to long-life pavements or poor performance, and they are discussed in this section.

Projects 131 and 132 on I-20 were identified as potential long-life pavements. Figure 6.13 and Figure 6.14 show the performance of the original pavement of five projects in Category 2, including Projects 131 and 132. Figure 6.13 shows Projects 131 and 132 have a relatively low faulting index compared to the other projects within the same design category. The faulting index maintains less than 8 over 35 years with a relatively flat trend. Figure 6.14 shows both projects have carried over 50 million ESALs.

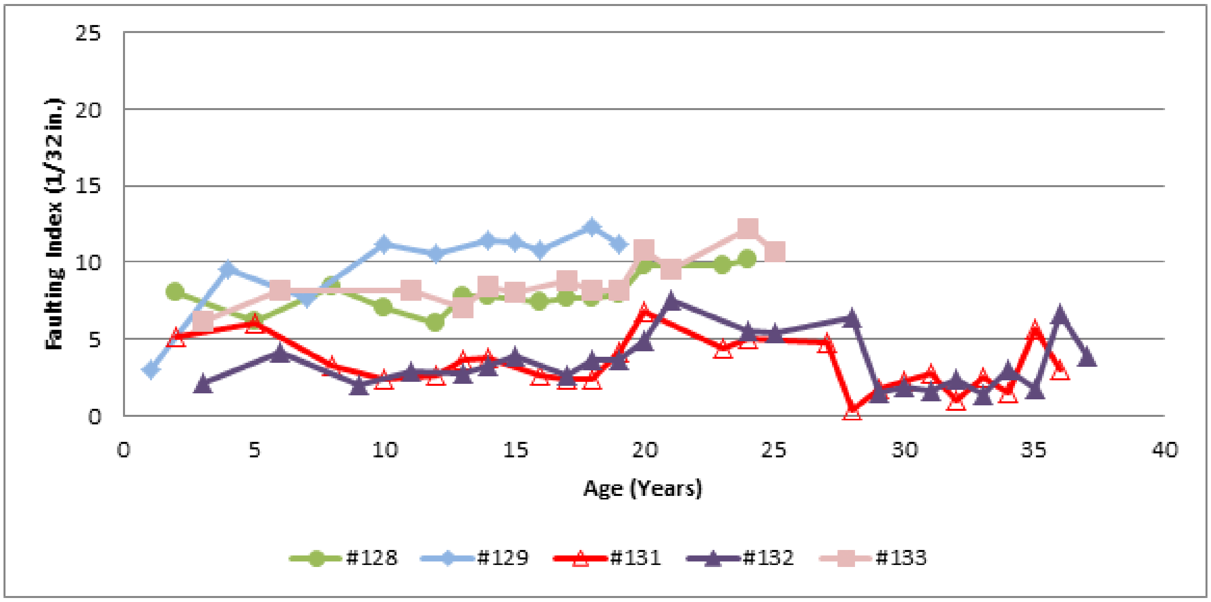

Figure 6.13 Category 2 Project Performance by Age

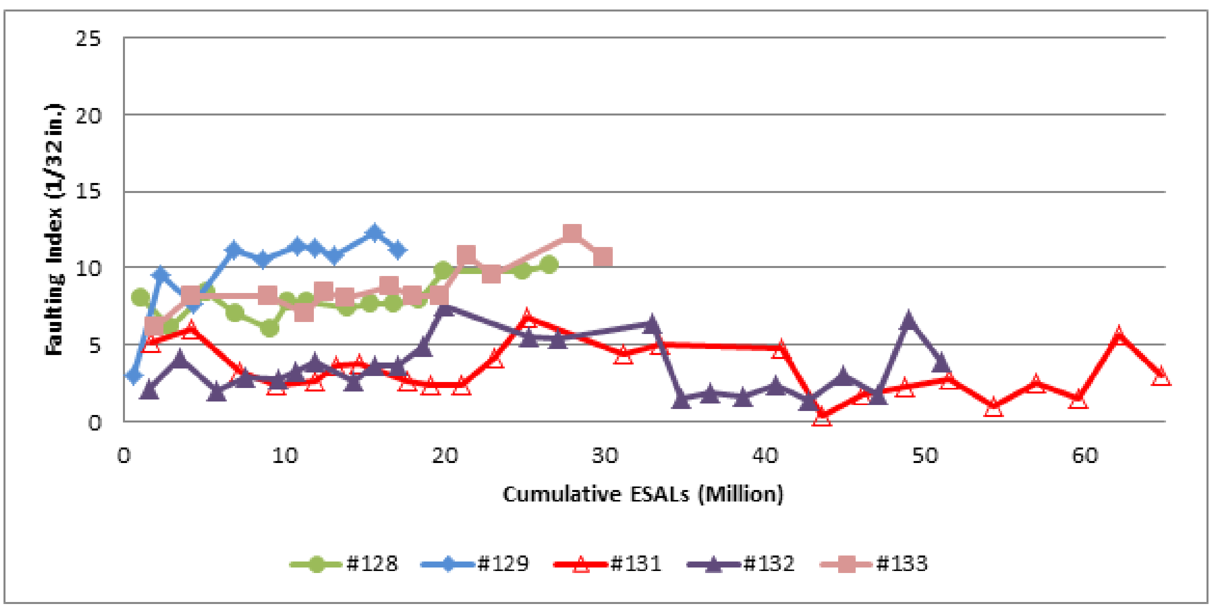

Figure 6.14 Category 2 Project Performance by Cumulative ESALs

Project 158 in Category 3 was identified for its relatively poor performance compared to the other projects in the same design category. Figure 6.15 and Figure 6.16**Error! Reference source not found.** show the faulting index versus time and ESALs for four projects in Category 3. Project 158 has a higher faulting index compared to the other projects, especially as shown in Figure 5.8. Further study is recommended to investigate the projects (131, 132, and 158) that have potential long-life or relatively poor performance.

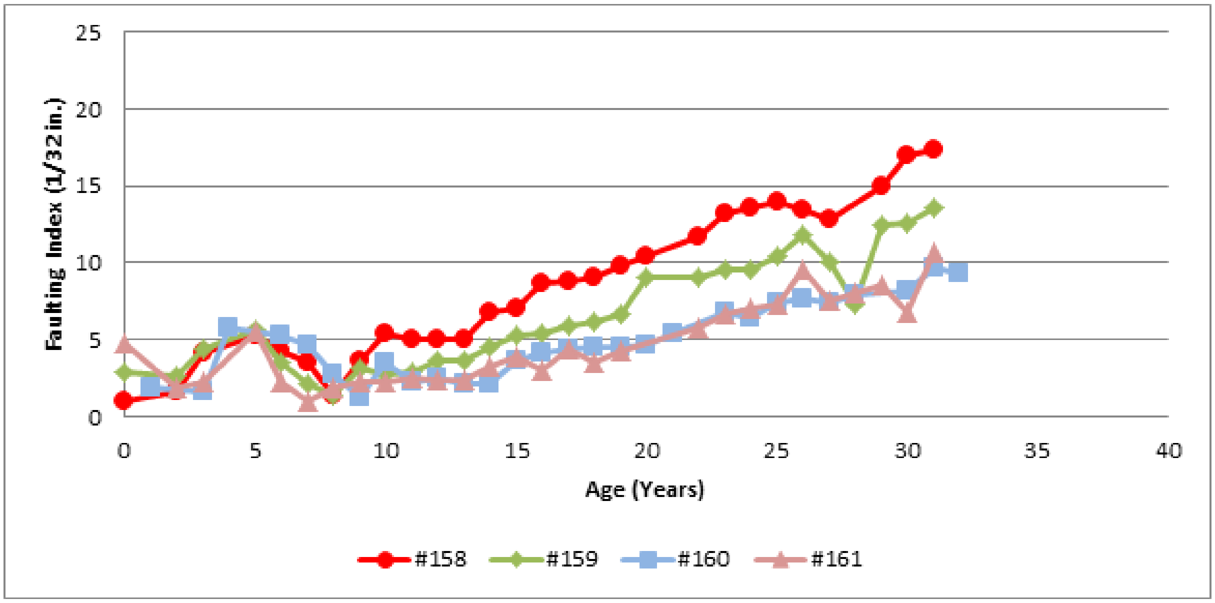

Figure 6.15 Category 3 Project Performance by Age

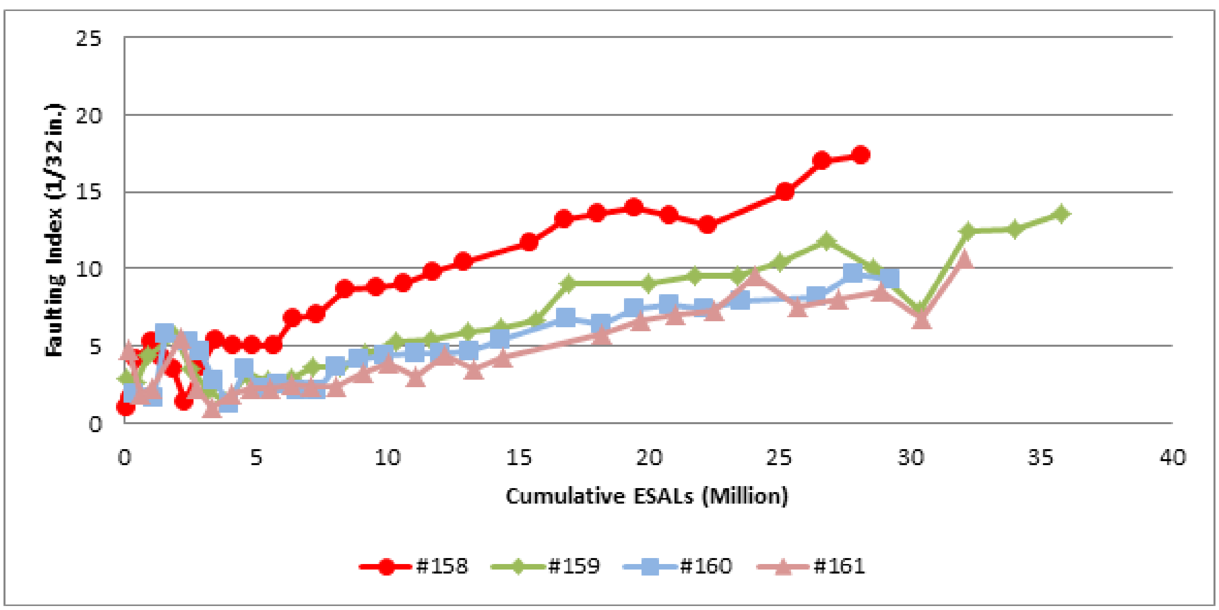

Figure 6.16 Category 3 Project Performance by Cumulative ESALs

6.4 Summary

A project-level analysis was conducted on six selected projects, two each in Categories 1, 2, and 3, to evaluate pavement performance in detail. The age of these projects ranges from 31 to 38 years, which provides an opportunity to study long-term, in-service JPCP performance. Although the results of this analysis are not to be considered conclusive due to the small sample size, this information can provide a better understanding of the actual performance of in-service JPCP with different designs. Figure 6.17 and Figure 6.18 show the plots of the faulting index versus time and ESALs for all six projects.

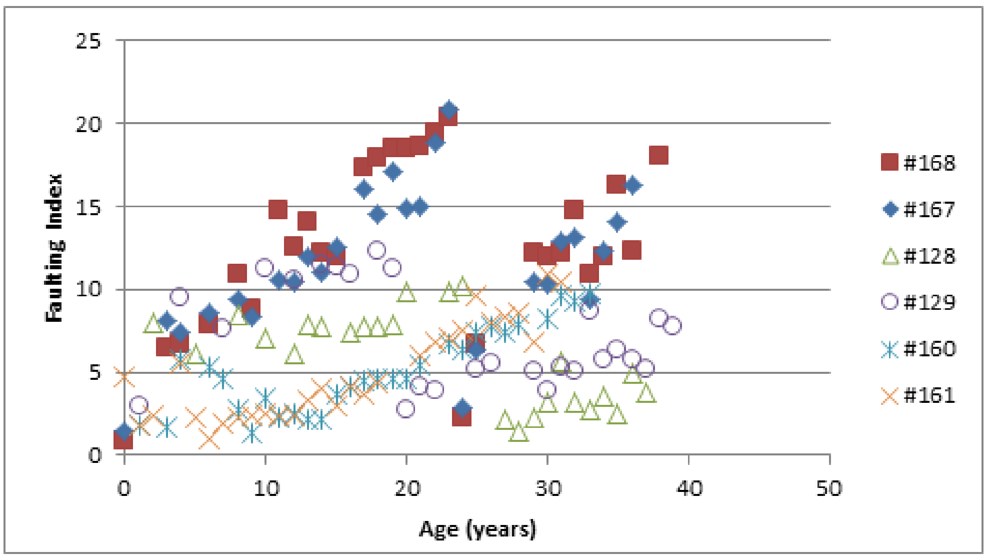

Figure 6.17 Faulting Index based on Age for Selected Projects

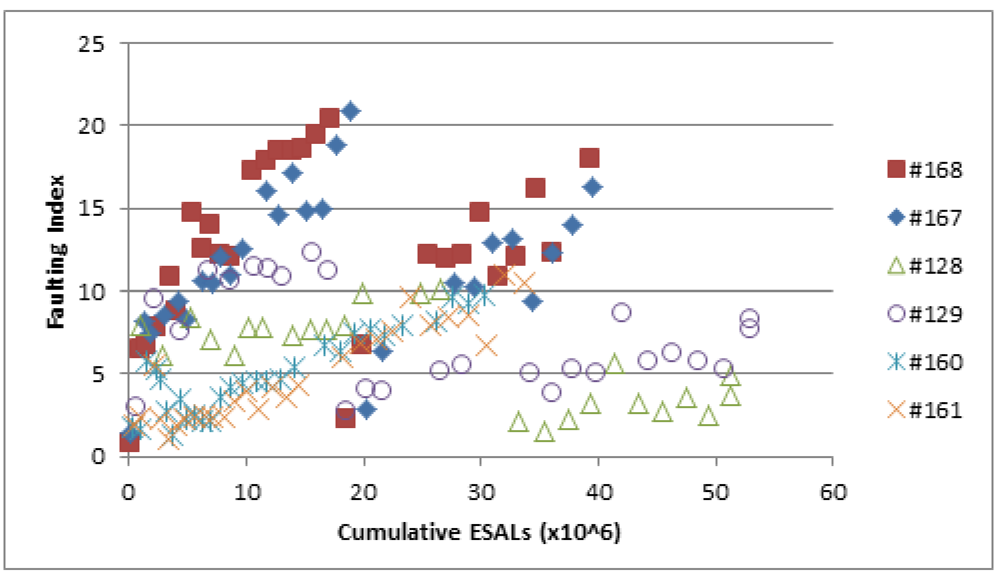

Figure 6.18 Faulting Index based on ESALs for Selected Projects

Major findings of the project-level analysis are summarized as follows:

- Projects 167 and 168 in Category 1 carried 18 million ESALs (3 times the designed ESALs) in 23 years in their original pavements with a deterioration rate in the faulting index of 0.9 per year or 1 per million ESALs. Both projects had a faulting index of around 20 before the rehabilitation. After the rehabilitation, both projects have carried more ESALs within a shorter time span compared to their original pavements.
- Projects 128 and 129 in Category 2 carried 17 to 26 million ESALs (1.6 to 3.5 times the designed ESALs) in more than 19 years in their original pavements. Compared to the original pavements, a lower deterioration rate of the faulting index was observed after the first rehabilitation. Both projects exhibited a fairly low deterioration rate of the faulting index and high numbers of broken slabs, replaced slabs, and slabs with longitudinal cracks. In both projects, slabs with longitudinal cracks were more than broken slabs, and an increase in the number of slabs with longitudinal cracks was observed after 25 years.
- Projects 160 and 161 in Category 3 have carried more than 30 million ESALs (3 times the designed ESALs) in 30 years without a major rehabilitation. Both projects have relatively low deterioration rates in the faulting index (approximately 0.3 per year or 0.3 per million ESALs) and very minimum numbers of broken slabs, replaced slabs, and slabs with longitudinal cracks, less than 5 slabs per mile after 30 years.
- Further study could be conducted to investigate the projects (131, 132, and 158) that have a long-life or relatively poor performance to enhance the pavement design toward long-life and better performance.

In addition, as presented in Appendix III, a preliminary study was conducted to assess the predictive capability of the faulting model in the MEPDG using the data collected on these six projects and Level 3 inputs. The results show the faulting model in the MEPDG can reasonably predict the faulting index for the two doweled projects in Category 3. However, the use of a 1.5-inch dowel bar diameter in current pavement design needs to be further investigated.

7 Conclusions and Recommendations

Due to funding shortages and the increasing reconstruction needs of its aging road network, GDOT has become increasingly interested in conducting LCCA on pavement type selection to make the best investment in the pavements. To support a reliable LCCA on pavement design, the number-one question to address is how long the pavements in Georgia last. Pavement longevity varies widely depending on the design, construction quality, environment (e.g., weather, and moisture), rehabilitation strategies, etc. Therefore, actual pavement longevity can be best studied by carefully evaluating the historical pavement condition data. The objective of this project was to analyze the longevity of concrete pavements in Georgia using more than 30 years of concrete pavement condition data collected by GDOT. To accomplish the goal, the following tasks were performed:

- Various data, including historical CPACES data, pavement design, construction time, and traffic data, were acquired and processed for data consistency and accuracy. The changes in GDOT's concrete pavement surveys were reviewed to identify potential inconsistencies in the data.
- A set of rules was established and applied to the data to systematically determine the service life based on three types of events: first AC overlay, major rehabilitation, and a faulting index of 15 for each project.
- A statistical analysis was conducted to study concrete pavement service life based on the data from the pavements that had reached their end of service life.
- Survival analysis was conducted to develop an estimate of the expected service life based all available data, including those pavements that have not yet reached the end of their service life.
- A project-level analysis on six selected projects, two each in three design categories, was conducted to explore their performance in detail. Cumulative ESALs for these projects were reconstructed based on traffic data between 1990 and 2010 to analyze the performance in terms of age and ESALs.

The data collected and the results generated in this study can support an informed, data-driven decision for pavement type selection and can provide a better understanding of the actual performance of concrete pavements by designs. The major findings are summarized as follows:

1. For the 258 centerline miles of JPCP overlaid with AC, the average time to the first AC overlay was 13 years. It is noted that most of the AC overlay was applied on JPCP in the late 1970s as part of interstate widening (adding lanes) projects. The decision for an AC overlay was based on not only pavement condition but also factors such as adding lane(s), funding availability, agency policy, etc. Because the actual causes of an AC overlay were not available, the 13-year span cannot be interpreted as the effective service life based on the first AC overlay.
2. Concrete pavement service life was analyzed using the data for the rehabilitated projects (541 surveyed miles) that had reached the end of their service life. None of the pavements in Category 3 have reached a major rehabilitation; therefore, the 541 surveyed miles of pavements are non-doweled JPCP in Categories 1 and 2. The following items summarize the results:
    a) Based on actual time to reach a major rehabilitation for all rehabilitated, non-doweled projects, the average service life for the original pavements was 17 years; service life for the first rehabilitation was 14 years; service life for the second rehabilitation was 8 years. The service life decreases as more major rehabilitation applied to the pavements. This information can be used to evaluate the cost-effectiveness of second and subsequent rehabilitations.
    b) Based on the time to reach a faulting index of 15, for all rehabilitated, non-doweled projects, the service lives were found to be close to those based on time to reach a major rehabilitation. The average service life for the original pavements was 17 years; service life for the first rehabilitation was 13 years; service life for the second rehabilitation was 6 years.
    c) The results of pavement service life by design category show the improvements in design features were corresponding to a longer service life. The average service life of the original pavements for Category 1 was 17 years; service life for Category 2 was 21 years. While none of the pavements in Category 3 has had a

major rehabilitation, the service life for Category 3 is expected to be longer than 25 years, which is 45% more than that of Category 1.

3. Survival analysis was conducted to estimate the expected service life using the data for all projects, including data from those pavements that have not yet reached their end-of-service-life. The following items summarize the results:
    a) Based on actual time to reach a major rehabilitation, the expected service life (at the 50^{th} percentile) of the original pavement was about 21 years; service life for the first rehabilitation was 19 years.
    b) Based on the time to reach a faulting index of 15, the expected service life (at the 50th percentile) of the original pavement was about 35 years; service life for the first rehabilitation was 23 years.
    c) The expected service life of the original pavements for Category 1 was found to be 15 years; service life for Category 2 was 27 years, which is approximately twice that of Category 1(15 years).
4. A project-level analysis of six non-extreme projects, two from each design category, was conducted to explore pavement performance in detail. The results of this analysis are not to be considered conclusive because of the small sample size. However, the analysis provided information about the deterioration in terms of different distresses and the ESALs carried by each project. The following items summarize the results:
    a) All six projects in three design categories carried 17 to 30 million ESALs, which is 2-4 times the designed ESALs, before reaching a major rehabilitation. The projects in Categories 1 and 2 have carried similar traffic loads after the major rehabilitation in a shorter time span.
    b) The two projects in Category 1 carried 18 million ESALs (3 times the designed ESALs) in 23 years before they were rehabilitated at a faulting index of 20. After the rehabilitation, both projects have carried more than 20 million ESALs in 13-15 years. The number of broken slabs and slabs with longitudinal cracks has slightly increased after the rehabilitation.
    c) The two projects in Category 2 carried 17 to 26 million ESALs (1.6 to 3.5 times the designed ESALs) in more than 19 years before they were rehabilitated at a faulting index of 10. Both projects have also carried more traffic loads (24 to 26

million ESALs) after the major rehabilitation. Significant numbers of broken slabs, replaced slabs, and slabs with longitudinal cracks were observed after 25 years. Especially, more slabs with longitudinal cracks than broken slabs were observed. Overall, these two projects show a lower deterioration in the faulting index and more severe cracking-related distresses, especially longitudinal cracks.

d) The two projects in Category 3 have carried more than 30 million ESALs (3 times the designed ESALs) in 30 years without a major rehabilitation. Both projects have a deterioration rate in the faulting index of 0.3 per year (or 0.3 per million ESALs) and small numbers of broken slabs, replaced slabs, and slabs with longitudinal cracks, fewer than 5 slabs per mile after 30 years. Compared to the projects in Categories 1 and 2, these two projects have a relatively low deterioration rate in the faulting index and very minimum number of cracking-related distresses.

e) A preliminary study shows the faulting index can be reasonably predicted using the MEPDG model with Level 3 inputs for the two projects in Category 3. Sensitivity analysis shows an increase in dowel diameter (e.g., 1.5 inches) can result in a significant drop in the predicted faulting, which needs to be further validated.

Further research is recommended as follows:

1. At the time of this study, sufficient data was not available to support an analysis of the pavements in Category 4 because they were constructed in recent years. A follow-up study is recommended to understand actual performance of the current design when more data is collected by GDOT.
2. Limited by the scope of this study, the performance of AC overlaid pavements was not studied. The LCCA of AC overlay and other concrete pavement restoration methods (e.g., grinding) could be further studied to evaluate the long-term benefit-cost of different rehabilitation strategies.
3. Limited by the resources and hazard imposed by the traffic, a manual survey can only collect sampled faulting data, i.e., on every 8th joint and limited crack information. According to CPACES, the number of broken slabs is recorded for each mile, but

detailed information, such as length, is not measured. With the advances in laser technology, a mobile 3D laser sensing system, such as the one developed by Georgia Tech, can now collect faulting on all joints at highway speeds. Automated data collection using a mobile 3D laser sensing system is recommended for use to improve the data collection productivity, to have full lane coverage, and to enhance the data quality in terms of accuracy and consistency.

4. It is also recommended that a 3D laser sensing system be used for monitoring newly constructed or reconstructed pavements with the latest design (Category 4) to better understand the behavior of these pavements (e.g., curling and warping).

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Appendix I. GDOT Concrete Pavement Rating Calculation

Pavement Rating Calculation
The pavement rating may be calculated from the following formula:

(A1)

Where, DFI= Deduct value for faulting index
DSM= Deduct value for smoothness
DBL= Deduct value for broken slabs
D_{BL} = #Broken Slab Level1 / 2 + #Broken Slab Level2
If #Broken Slab Level1 / 2 > 15 Then #Broken Slab Level1 / 2 = 15
If #Broken Slab Level2 > 30 Then #Broken Slab Level2 = 30
If D_{BL} > 30 Then D_{BL} = 30
DLC= Deduct value for Longitudinal Cracks
D_{LC} = 0.25 * #Longitudinal Cracks Slabs Level1 + 0.5 * #Longitudinal Cracks Slabs Level 2
If D_{LC} > 20 Then D_{LC} = 20
DSD= Deduct value for Shoulder Distress
D_{SD} = 0.1 * Percentage of Shoulder Distress Level1 (%) + 0.2 * Percentage of Shoulder Distress Level2 (%)
If D_{SD} > 10 Then D_{SD} = 10
DSP= Deduct value for Spalls
D_{SP}=0.25 * #Spalled Joints

Note 1:
Failed Spalled Joints are counted along with Spalls.

Note 2:
For some historical data, Broken Slabs are not considered as level 1 and level 2. In this case, Concrete Paces uses the following criteria to separate them:

- If # Broken Slabs<8, they are all considered as level 1;
- If 8 =< # Broken Slabs <= 15, 1/2 of them are considered as level1 and the left are considered as level 2;
- If # Broken Slabs > 15, 1/3 of them are consider as level 1 and 2/3 of them are level 2.

Note 3:
If you input smoothness in the MAYS profilergraph, Concrete PACES will convert it to LASER profilergraph using the following formula:

(A2)

Table A.1 Deduct Value Table (All values are based on 1 mile)

Faulting Index 1/32 in.		Smoothness mm/km		Broken Slabs				Longitudinal Cracks				Shoulder Distress (%)				Spalls	
				Level 1		Level 2		Level 1		Level 2		Level 1		Level2			
1	0	450	0	1	1	1	1	1	0	1	1	5	1	5	1	1	0
2	0	500	0	2	1	2	2	2	1	2	1	10	1	10	2	2	1
3	0	600	0	3	2	3	3	3	1	3	2	15	2	15	3	3	1
4	0	700	0	4	2	4	4	4	1	4	2	20	2	20	4	4	1
5	0	800	0	5	3	5	5	5	1	5	3	25	3	25	5	5	1
6	1	900	0	6	3	6	6	6	2	6	3	30	3	30	6	6	2
7	3	1000	1	7	4	7	7	7	2	7	4	35	4	35	7	7	2
8	4	1100	2	8	4	8	8	8	2	8	4	40	4	40	8	8	2
9	5	1200	3	9	5	9	9	9	2	9	5	45	5	45	9	9	2
10	6	1300	4	10	5	10	10	10	3	10	5	50	5	50	10	10	3
11	8	1400	6	11	6	11	11	11	3	11	6					11	3
12	9	1500	9	12	6	12	12	12	3	12	6					12	3
13	10	1600	13	13	7	13	13	13	3	13	7					13	3
14	11	1700	17	14	7	14	14	14	4	14	7					14	4
15	13	1800	22	15	8	15	15	15	4	15	8					15	4
16	14	1900	27	16	8	16	16	16	4	16	8					16	4
17	15	2000	32	17	9	17	17	17	4	17	9					17	4
18	16	2100	37	18	9	18	18	18	5	18	9					18	5
19	18	2160	40	19	10	19	19	19	5	19	10					19	5
20	19			20	10	20	20	20	5	20	10					20	5
21	20			21	11	21	21	21	5	21	11					21	5
22	21			22	11	22	22	22	6	22	11					22	6
23	23			23	12	23	23	23	6	23	12					23	6
24	24			24	12	24	24	24	6	24	12					24	6
25	25			25	13	25	25	25	6	25	13					25	6
				26	13	26	26	26	7	26	13					26	7
				27	14	27	27	27	7	27	14					27	7
				28	14	28	28	28	7	28	14					28	7
				29	15	29	29	29	7	29	15					29	7
				30	15	30	30	30	8	30	15					30	8
								31	8	31	16					31	8
								32	8	32	16					32	8
								33	8	33	17					33	8
								34	9	34	17					34	9
								35	9	35	18					35	9
								36	9	36	18					36	9
								37	9	37	19					37	9
								38	10	38	19					38	10
								39	10	39	20					39	10
								40	10	40	20					40	10

Examples

The following are some examples for calculating the pavement rating. Refer to Table A.1 for deduct values.

Table A.2 Example for rating calculation (1 mile)

		Value	Deduct
Faulting Index (1/32 in.)		14	11
Smoothness (mm/km)		1300	4
Broken Slabs	Level 1	2	1
	Level 2	1	1
Long Cracks	Level 1	5	1
	Level 2	3	2
Shoulder Distress	Level 1	10	1
	Level 2	28	6
Spalls		6	2
Rating		100-11-4-1-1-1-2-1-6-2=71	

Table A.3 Example for rating calculation (0.8 mile)

		Value	Deduct
Faulting Index (1/32 in.)*		14	11
Smoothness (mm/km)*		1300	4
Broken Slabs	Level 1	2 / 0.8 = 3	2
	Level 2	1 / 0.8 = 1	1
Long Cracks	Level 1	5 / 0.8 = 6	2
	Level 2	3 / 0.8 = 4	2
Shoulder Distress *	Level 1	10	1
	Level 2	28	6
Spalls		6 / 0.8 = 7.5	2
Rating		100-11-4-2-1-2-2-1-6-2 = 69	

* The effect of segment length has been considered in the values of Faulting Index, Smoothness and Shoulder Distress

Faulting Index Calculation

The Faulting Index (FI) may be calculated from the following formula:

(A3)

where, n=Total Number of Fault Meter Readings

Si=Fault Meter Reading (if Si < 0 then Si = 0)

5=Calculated Constant

The final answer is always rounded to the nearest integer (Example: 5.09 = 5, 5.49 = 5, 5.50 = 6, and 5.74 = 6).

The Si is measured on every 8^{th} slab, regardless of the slab length. If the slab length is 30 feet (assume all slab lengths are equal), there will be 22 measurements per mile.

$$5280 \text{ FT} / (30 \text{ FT} \times 8) = 22$$

Similarly, if the slab length is 20 feet (assume all slab lengths are equal) the Si count (n) will be 33. If the slab length varies the Si count (n) will be also different.

If the slab lengths are different within a mile, the Si count (n) will be different.

Example

The following is an example for calculating the Faulting Index:

Fault meter readings are as follows in a mile where the slab length is 30 feet long:
1, 1, 0, 2, -2, 0, 4, 2, 3, 5, 3, 0, 0, 2, -1, 1, 1, 3, 2, 2, -1, and 0

Then, from the FI formula:

n = number of measurements taken = 22
Sum(Si) = meter readings greater than 0 = 32 (ignore negative numbers)

Therefore, FI = (32 × 5) / 22 = 7.27 = 7 (rounded to the nearest number).

Appendix II. SCDOT Pavement Service Life Survey

Table A.4 Analysis Period and Rehabilitation Timings

State DOT	Analysis Period	Time to first rehabilitation		Rehabilitation Service Life	
		Flexible Pavements :	Rigid Pavements:	Flexible Pavements :	Rigid Pavements:
AL	28 yrs	12 yrs	20 Yrs, type not a consideration	8 yrs	8yrs
CA	Varies, from 20 to 55 years,	18-20 yrs Preventive maintenance before	JPCP 20-40 Yrs Preventive maintenance before	10 yrs	At least 10 yrs
CO	40 yrs	10 yrs	JPCP, 22 Yrs	10 yrs	18 yrs
GA	40 yrs	10 yrs	CRC - 25 years, JPCP - 20 years	10 yrs	20 yrs
IL	40 yrs	Depends on traffic	CPR of JPCP at 20 yrs CRCP: constructed for high-volume traffic routes and no LCCA is done.	Depends on the traffic factor	20 yrs
IN	40 yrs	25 yrs	JPCP, 30 Yrs	15 yrs	12 yrs
KS	30 yrs, but moving to 40 yrs	10 yrs	JPCP, 20 Yrs	Approximately 10 yrs	7-10 yrs
MD	40 yrs	15 yrs	JPCP, 20 yrs based on a 25 –yr initial structural life	12 yrs	Varies depending on which rehabilitation cycle
MI	Depends on the pavement/fix type	26 yrs	JPCP, 26 Yrs	10-15 yrs	21 yrs for unbonded overlay, 20 yrs for rubblizing & overlay
MN	50 yrs	For 7 million ESAL or less, route and seal cracks at year 6, for high ESAL do a crack fill at year 7.	JPCP, 17 Yrs	Depends on traffic	1st rehab:Joint reseal and minor CPR that lasts 10 yrs 2nd rehab: partial and some full depth repairs to last 13 yrs 3rd rehab:major CPR to last 15 yrs (which gives a 33% residual life at the end of the analysis period)
MS	40 yrs	12 yrs	JPCP, 1st rehab @ year 16	9 yrs	16 yrs
MO	45 yrs	20 yrs	25 Yrs	13 yrs for first mill and overlay, 12 yrs for 2nd mill & overlay	20 yrs
MT	35 yrs	19 yrs	JPCP, 20 yrs	12 yrs	20 yrs
NE	50 yrs	15-20	overlay at 35 Yrs unless performing exceptional	4" overlay for 12-15 yrs, then additional 4" overlay to give a total life of 50 Yrs	15 yrs for a total life of 50 Yrs

Source: Life Cycle Cost Analysis for Pavement Type Selection, SC DOT, 2008

Table A.4 Analysis Period and Rehabilitation Timings

State DOT	Analysis Period	Time to first rehabilitation		Rehabilitation Service Life	
		Flexible Pavements :	Rigid Pavements:	Flexible Pavements :	Rigid Pavements:
NC	20 yrs for SN<6.0 and 30 years for SN>6.0., looking at 40 yrs for SN>6.0	Typically 12-15 yrs	JPCP, 15 Yrs	12 Yrs	10 Yrs
SC	30 yrs	12 yrs for conventional mixes, 15 yrs for polymer-modified	JPCP, 20 Yrs	10 Yrs for conventional, 15 Yrs for polymer-modified	10 Yrs
UT	-	12-15 yrs	JPCP, 10 yrs for minor, 20 Yrs for major	OGSC* is at 7 to 8 yrs, rest is variable	Varies
VT	-	Varies	20 Yrs	10-12 yrs	10-15 yrs
WA	50 yrs	10-17 yrs	JPCP 20-30 yrs	10-17 yrs	Diamond grind 15-20 yrs, DBR** 15 yrs
WI	50 yrs	18 yrs over dense graded bse and 23 yrs over open-graded base	25 Yrs (undrained base) if placed over dense graded base and 31 Yrs if over open-graded base	Mill and overlay to give 12 yrs of service life	8 yrs if the initial rehab is repair 15 yrs if the initial rehab is an HMA overlay
Ontario	50 yrs	19 yrs for dense friction course, 21 yrs for SMA	JPCP, 18 yrs to first rehab, which is minor CPR and diamond grinding	13 yrs, then 12 yrs, then 11 yrs, then 10 yrs	10 yrs

*Dowel Bar Retrofit, **Open Graded Surface Course

Source: Life Cycle Cost Analysis for Pavement Type Selection, SC DOT, 2008

Appendix III. Project List

ProjectID	Project number	RouteNo	Direction	From	To
98	I-75-1(17)	401	P	21.2	31.3
98	I-75-1(17)	401	N	21.2	31.3
99	I-75-1(15)	401	P	42.2	52.5
99	I-75-1(15)	401	N	42.2	52.5
101	I-75-1(13)	401	P	52.5	58.7
101	I-75-1(13)	401	N	52.5	58.7
102	I-75-1(10)	401	P	63.9	71.1
102	I-75-1(10)	401	N	63.9	71.1
95	I-75-1(21)	401	P	109.4	115.8
95	I-75-1(21)	401	N	109.4	115.8
85	I-75-1(30)	401	P	136.5	146.3
82	I-75-1(31)	401	P	146.3	155.2
79	I-75-1(59)	401	N	156.6	162.9
80	I-75-1(43)	401	P	162.9	165.9
80	I-75-1(43)	401	N	162.9	165.9
74	I-75-2(26)	401	P	165.9	169.6
71	I-75-2(27)	401	P	169.6	179.4
69	I-75-2(31)	401	P	189.6	199.7
69	I-75-2(31)	401	N	189.6	199.7
68	I-75-2(33)	401	P	199.7	210.7
68	I-75-2(33)	401	N	199.7	210.7
NA	I-75-3(37)258	401	N	250	255
154	I-20-1(23)	402	P	0	11.7
154	I-20-1(23)	402	N	0	11.7
153	I-20-1(27)	402	N	11.7	23.7
129	I-20-2(47)	402	P	115.4	132.3
129	I-20-2(47)	402	N	115.4	132.3
128	I-20-2(48)	402	P	132.2	146.1
128	I-20-2(48)	402	N	132.2	146.1
133	I-20-2(30)	402	P	146.1	152.9
133	I-20-2(30)	402	N	146.1	152.9
132	I-20-2(32)	402	P	152.9	165.1
132	I-20-2(32)	402	N	152.9	165.1
131	I-20-2(34)	402	P	165.1	171.8
131	I-20-2(34)	402	N	165.1	171.8

ProjectID	Project number	RouteNo	Direction	From	To
137	I-20-2(23)	402	P	171.8	179.6
137	I-20-2(23)	402	N	171.8	179.6
41	I-85-1(39)	403	P	46.6	56
169	I-16-1(18)	404	P	1.5	11.9
169	I-16-1(18)	404	N	1.5	11.9
168	I-16-1(20)	404	P	11.9	23.3
168	I-16-1(20)	404	N	11.9	23.3
167	I-16-1(22)	404	P	23.3	31.5
167	I-16-1(22)	404	N	23.3	31.5
164	I-16-1(24)	404	P	31.5	36.8
164	I-16-1(24)	404	N	31.5	36.8
177	I-16-1(10)	404	P	38.6	50.2
177	I-16-1(10)	404	N	38.6	50.2
156	I-16-1(8)	404	P	50.2	67.7
162	I-16-1(34)	404	P	67.7	77.87
162	I-16-1(34)	404	N	67.7	77.87
161	I-16-1(36)	404	P	77.9	90.2
161	I-16-1(36)	404	N	77.9	90.2
159	I-16-1(67)	404	P	90.2	103.4
159	I-16-1(67)	404	N	90.2	103.4
158	I-16-1(69)	404	N	103.4	115.7
158	I-16-1(69)	404	P	103.4	115.7
160	I-16-1(38)	404	P	115.7	126.1
160	I-16-1(38)	404	N	115.7	126.1
163	I-16-1(32)	404	P	126.1	137.7
163	I-16-1(32)	404	N	126.1	137.7
172	I-16-1(16)	404	N	137.7	148.2
173	I-16-1(15)	404	P	148.2	159.6
173	I-16-1(15)	404	N	148.2	159.6
175	I-16-1(14)	404	P	159.6	166.3
175	I-16-1(14)	404	N	159.6	166.3
107	I-475-1(38)	408	N	0	7.4
107	I-475-1(38)	408	P	0	7.4
108	I-475-1(39)	408	N	7.4	14.8
108	I-475-1(39)	408	P	7.4	14.8
212	U-106-1 (2) CT1	411	N	0	4

ProjectID	Project number	RouteNo	Direction	From	To
212	U-106-1 (2) CT1	411	P	0	4
213	U-106-1 (3) CT1	411	N	4	8
213	U-106-1 (3) CT1	411	P	4	8
211	I-ID-675-1(137)	413	N	0	11
211	I-ID-675-1(137)	413	P	0	11
197	I-520-1(1) ct4	415	N	1.5	5.4
198	I-ID-520-1(1)	415	N	5.4	9
203	ID-575-1(21)	417	N	19.6	30
203	ID-575-1(21)	417	P	19.6	30
191	F-013-1(8) I-985/SR365	419	N	0	3.8
191	F-013-1(8) I-985/SR365	419	P	0	3.8
192	F-013-1(21) I-985/SR365	419	N	3.8	15.5
192	F-013-1(21) I-985/SR365	419	P	3.8	15.5
194	F-013-1(17) CT1	419	N	15.5	24.7
194	F-013-1(17) CT1	419	P	15.5	24.7

Appendix IV. A Preliminary Study on Joint Faulting Model in the MEPDG

In Mechanistic-Empirical Pavement Design Guide (MEPDG), the performance indicators for jointed plain concrete pavement include transverse joint faulting, transverse (fatigue) cracking, and IRI. A preliminary study was conducted to assess the prediction capability of the faulting model in the MEPDG using GDOT's concrete pavement condition data and to conduct preliminary sensitivity studies on two input parameters, AADT and dowel bar diameter. Six projects analyzed in Chapter 6 were used to evaluate the reasonableness of the faulting model using Level 3 inputs. The input parameters, the prediction results, and the sensitivity analysis are presented.

Project Information

Six projects analyzed in Chapter 6 were used in this preliminary study as listed below:

- Projects 167 and 168 in Category 1 were constructed with a 9-inch, non-doweled, random and skewed joint pavements on a 6-inch soil cement base. Both projects are on I-16 with a 5-million design ESALs.
- Projects 128 and 129 in Category 2 were constructed with a 10-inch, non-doweled, skewed joint pavements on a 6-inch cement stabilized graded aggregate base (GAB). Both projects are on I-20 with a higher design ESALs (7 and 10 million).
- Projects 160 and 161 in Category 3 were constructed with a 10-inch, doweled, 20-ft joint spacing pavements on a 1-inch HMA on top of a 5-inch soil cement base. Both projects are on I-16 with a 10-million design ESALs.

Input Parameters

As-built pavement structure and traffic data were obtained for each project. For traffic data, an initial AADT and compound growth factor were estimated based on traffic data collected between 1990 and 2010. A linear growth of AADT is assumed to estimate AADT from initial construction to the end of analysis period. The average vehicle distribution on Georgia's interstate highways was used for all six projects. A brief summary of the input parameters used in this study is presented in Table A.5.

Table A.5 Input Parameters

Traffic Modules	
Traffic Volume Adjustment Factors	
Monthly Adjustment	MEPDG Level-3 default values
Vehicle Class Distribution	Interstate Average
Hourly Truck Distribution	MEPDG Level-3 default values
Traffic Growth Factors	Specific site
Axle Load Distribution Factors	MEPDG Level-3 default values
General Traffic Inputs	
Number Axles/Truck	MEPDG default values
Lateral Traffic Wander	MEPDG default values
Axle Configuration	MEPDG default values
Wheelbase	MEPDG default values
Material Modules	
Dowel and slab info	
Dowel bar spacing (in)	12
Dowel bar diameter(in)	1.25
Long-term LTE (%)	default
Loss of full friction (age in months)	240-360 for asphalt base, default for others
Concrete material	
Unit weight (pcf)	150
Poisson's	0.2
Coefficient of thermal expansion	4.8
Thermal conductivity	1.25
Heat capacity (BTU/lb-F_o)	0.28
Cementitious material content (lb/yd^3)	500
Water/cement ratio	0.45
Aggregate Type	Granite
28-day PCC compressive strength	4,200
28-day PCC elastic modulus (psi)	3,600,000
Cement material	
Strength Properties	2,000,000
Asphalt material	
Aggregate Gradation	
Cumulative % retained 3/4 inch	0
Cumulative % retained 3/8 inch	5%
Cumulative % retained #4	25%
% Passing #200 sieve	7%
Asphalt Binder	AC20
Poisson's	0.35
Air voids	8.5
Total unit weight	148
Thermal conductivity	0.67
Heat capacity asphalt (BTU/lb-F)	0.23
Subgrade	
A-2-4	MEPDG Level-3 default values

Results for Six Projects

Figure A.1 shows the measured and predicted faulting index for the two projects in Category 1 (non-doweled, erodible base, no edge support). The results show the measured faulting index is always 5 to 10 points higher than the predicted values. Therefore, further study could be conducted to investigate the bias.

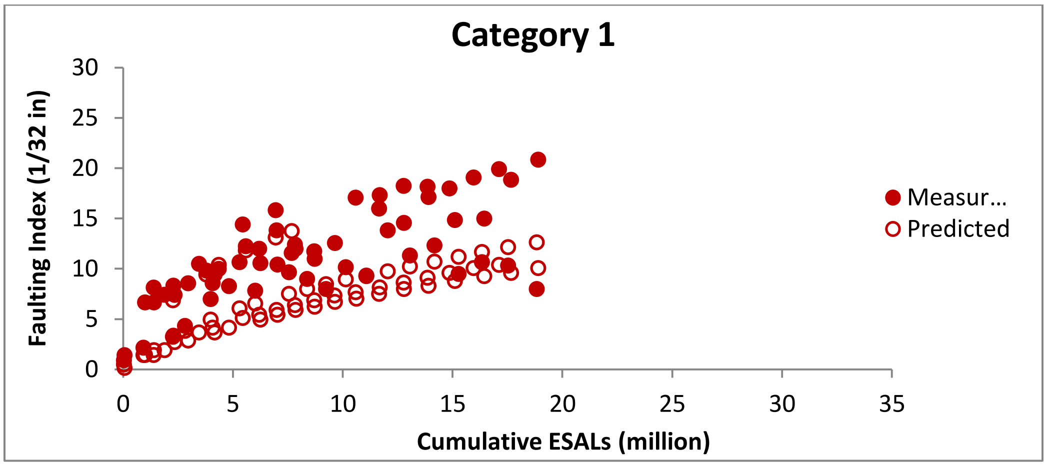

Figure A.1 Measured and Predicted Faulting Index versus ESALs (Category 1)

Figure A.2 shows the measured and predicted faulting index for the two projects in Category 2 (non-doweled, non-erodible base, no edge support). A smooth growth in the faulting index was predicted by the faulting model, while the measured faulting index shows a rapid increase in the first 5 million ESALs. The predicted and measured values became close after 10 million ESALs. Both measured and predicted values show a faulting index of 10 after 25 million ESALs.

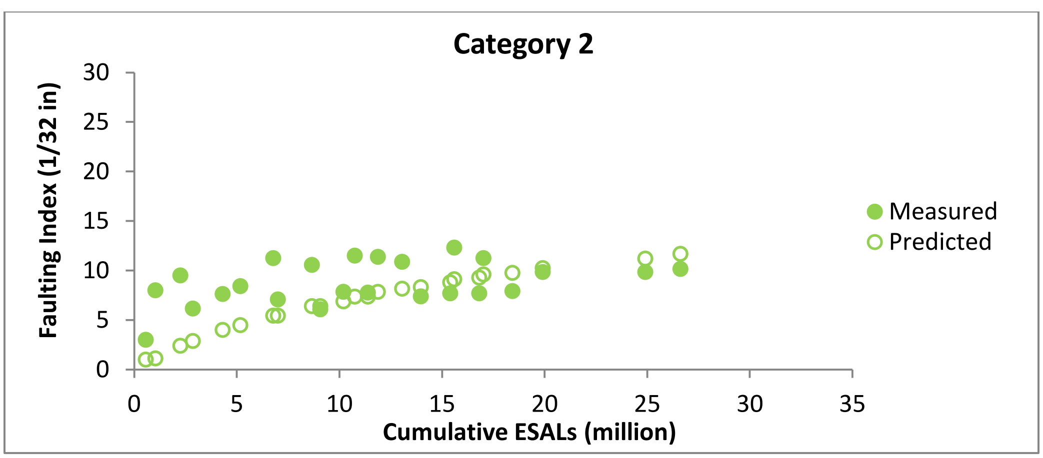

Figure A.2 Measured and Predicted Faulting Index versus ESALs (Category 2)

Figure A.3 shows the measured and predicted faulting index for the two projects in Category 3 (doweled, non-erodible base, edge support). The results show the predicted faulting index is fairly reasonable. Both measured and predicted values show a faulting index less than 10 after 30 million ESALs.

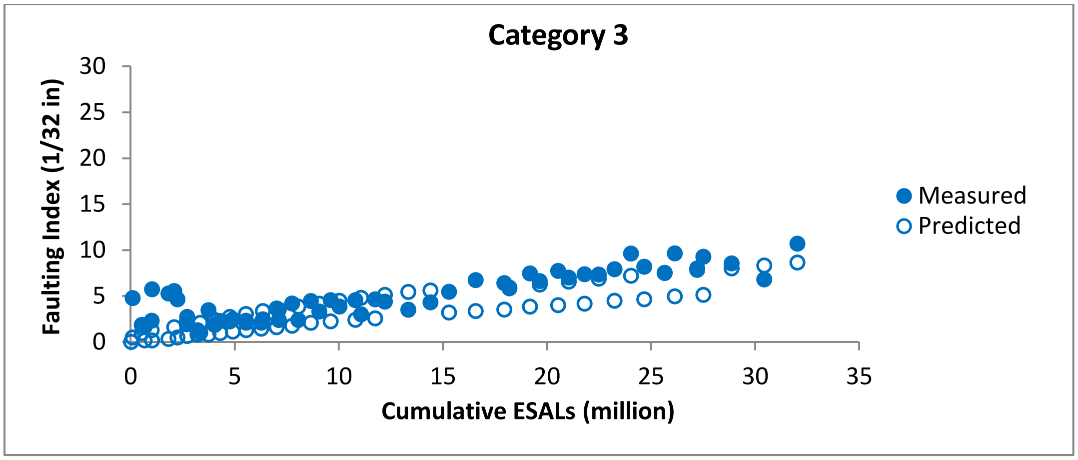

Figure A.3 Measured and Predicted Faulting Index versus ESALs (Category 3)

Sensitivity Analysis

- Dowel Bar Diameter

  The diameter of dowel bar is often determined as one eighth of concrete pavement thickness. For example, a 1.25-inch dowel bar is used for a 10-inch thick pavement. With the use of 11-inch or 12-inch thickness in current design, a 1.5-inch dowel bar is used in most new JPCP. Therefore, the dowel bar was increased from 1.25-inch to 1.5-inch on a 10-inch thick JPCP to study the impact of dowel bar diameter on predicted faulting index. Figure A.4 presents the measured and predicted faulting index for two dowel bar diameters, 1.25-inch and 1.5-inch. The results show the dowel bar diameter has a great impact on the predicted faulting index. With a 1.5-in dowel bar, the MEPDG predicts a very minimum faulting index, less than 5 after 30 million ESALs. Further study could be conducted to investigate the effect of dowel bar diameter in detail.

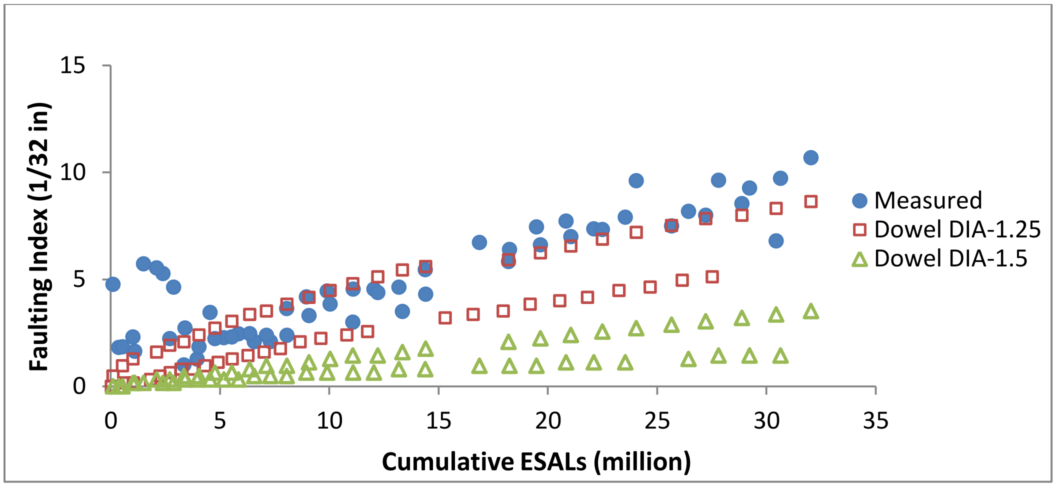

Figure A.4 Effect of Dowel Bar Diameter

Table A.6 Changes in Growth Rate

	Cumulative ESALs for 25 years
AADTT 4952, Growth rate 1.5%	24.45
AADTT 4952, Growth rate 2.5%	27.81
AADTT 4952, Growth rate 3.5% (baseline)	31.7
AADTT 4952, Growth rate 4.5%	36.27
AADTT 4952, Growth rate 5.5%	41.63

- Traffic Growth Rate

  AADT growth rate was varied from 1.5% to 5.5%, as shown in Table A.6, on Project 132 (Category 2) to evaluate the impact on the predicted faulting index. Figure A.5 shows there is no significant impact on the predicted faulting index given the traffic data.

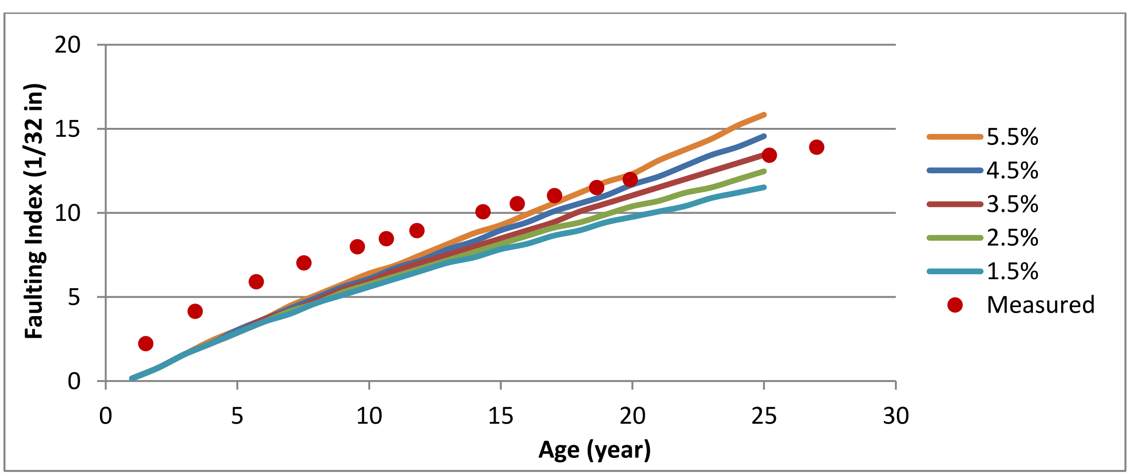

Figure A.5 Effect of Traffic Growth Rate

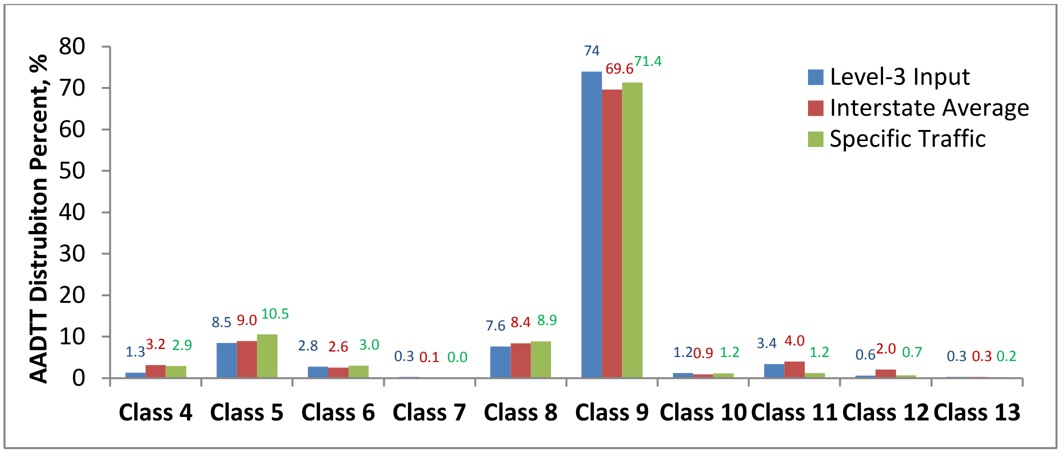

Figure A.6 Vehicle Distribution

- Vehicle Distribution

  An attempt was made to evaluate the impact of vehicle distribution on the predicted faulting. However, due to the similarity in the three sets of vehicle distribution (MEPDG Level 3, average on Georgia's interstate highways, and automatic traffic recorder) as show in Figure A.6, there is no significant difference in the prediction. Figure A.7 shows the predicted faulting index using three sets of vehicle distribution.

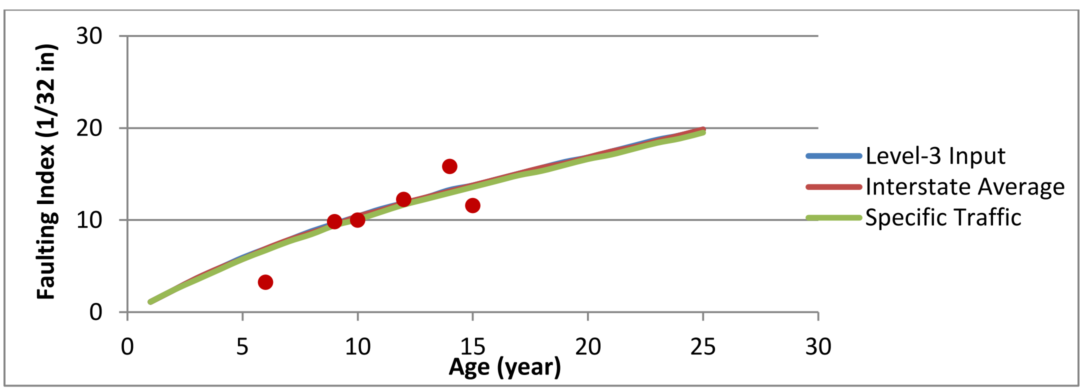

Figure A.7 Effect of Vehicle Distribution