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FINAL REPORT

DETERMINATION OF THE APPROPRIATE USE OF PAVEMENT SURFACE HISTORY IN THE KDOT LIFE-CYCLE ANALYSIS PROCESS

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16 Abstract
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An analysis using KDOT's databases demonstrated that they could be used to estimate performance of new or reconstructed pavement lives for use in the LCCA process. For the predominant pavement types used in Kansas, full-depth asphalt concrete (FDAC) and doweled, jointed plain concrete (JPC-D), service lives were estimated to be 12 years and 20 years, respectively. These compare with 10 years and 20 years currently being used.

The impact of modifying the service lives for FDAC and JPC-D pavements was evaluated using the LCCA's of 12 recent KDOT construction/reconstruction projects. The LCCA's were obtained and re-computed using life-cycle models formulated from results of the performance analyses conducted for FDAC and JPC-D pavements and for maintenance and rehabilitation (M&R) treatments applied to them. The resulting life-cycle costs were then compared with those computed by KDOT. It was found that modified performance lives resulted in only a negligible change in the overall NPV for both pavement types on the 12 projects evaluated.

Three alternative methods for computing future rehabilitation costs for use in LCCA were presented and evaluated. One method, which utilizes a cost-to-own approach, warrants further evaluation and development. The advantage of the cost-to-own approach is that it does not require modeling of the service lives of the pavement being studied. It appears the cost data to perform this type of analysis are available in the KDOT data base.

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Life-Cycle Cost Analysis (LCCA), Pavement Performance, Maintenance, Rehabilitation, Agency Costs

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Final Report

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ABSTRACT

The primary objective of this study was to evaluate KDOT's pavement surfacing history and recommend whether or not the department's life-cycle cost analysis (LCCA) procedure should include a surfacing history component, and, if so, how the LCCA process should be revised/ updated to incorporate surfacing history.

An analysis using KDOT's databases demonstrated that they could be used to estimate performance of new or reconstructed pavement lives for use in the LCCA process. For the predominant pavement types used in Kansas, full-depth asphalt concrete (FDAC) and doweled, jointed plain concrete (JPC-D), service lives were estimated to be 12 years and 20 years, respectively. These compare with 10 years and 20 years currently being used.

The impact of modifying the service lives for FDAC and JPC-D pavements was evaluated using the LCCA's of 12 recent KDOT construction/reconstruction projects. The LCCA's were obtained and re-computed using life-cycle models formulated from results of the performance analyses conducted for FDAC and JPC-D pavements and for maintenance and rehabilitation (M&R) treatments applied to them. The resulting life-cycle costs were then compared with those computed by KDOT. It was found that modified performance lives resulted in only a negligible change in the overall NPV for both pavement types on the 12 projects evaluated.

Three alternative methods for computing future rehabilitation costs for use in LCCA were presented and evaluated. One method, which utilizes a cost-to-own approach, warrants further evaluation and development. The advantage of the cost-to-own approach is that it does not require modeling of the service lives of the pavement being studied. It appears the cost data to perform this type of analysis are available in the KDOT data base.

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This work was performed under the supervision of the KDOT 10159 Technical Panel, consisting of the following individuals:

- Andy Gisi–KDOT Bureau of Materials and Research
- Lon Ingram–KDOT Bureau of Materials and Research
- Rick Miller–KDOT Bureau of Materials and Research
- Roy Rissky–KDOT Bureau of Construction and Maintenance
- Dale Jost–KDOT Bureau of Fiscal Services
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- Kirk Fredrichs–FHWA, Kansas Division Office
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Asphalt Industry

- Jim Jones–Kansas Asphalt Pavement Association
- Larue Allen–APAC-Kansas, Shears Division
- Kip Spray–Venture Corp

Concrete Industry

- Matt Ross–Missouri-Kansas Chapter of American Concrete Pavement Association
- David Howard–Koss Construction Co.

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- Lon Ingram–KDOT Bureau of Materials and Research
- Andy Gisi–KDOT Bureau of Materials and Research
- Rick Miller–KDOT Bureau of Materials and Research
- Greg Schieber–KDOT Bureau of Materials and Research

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 - INTRODUCTION

The selection of pavement materials for the construction and reconstruction of pavements is an important and challenging decision for highway administrators. Pavement type selection requires balancing short- and long-term performance with initial and long-term costs. Generally, the traveling public does not express strong feelings on the type of pavement constructed, as long as the pavement provides a reasonable level of service. However, a healthy and spirited level of competition exists between the asphalt and concrete pavement industries. Industry competition helps ensure that highway agencies select the most cost-effective pavement types and that sound, transparent, and unbiased procedures are used in doing so.

One of the tools used by highway administrators in making pavement type-selection decisions is life-cycle cost analysis (LCCA)—an engineering economic analysis tool that considers all costs of the various alternatives. LCCA considers both agency costs and user costs. Agency costs generally include initial construction, operations, and maintenance and rehabilitation (M&R). User costs may include vehicle operating costs, crash costs, delay costs related to construction and M&R activities, and increased costs due to circuitous routings caused by detours.

The techniques for performing an LCCA are well documented in *Life Cycle Cost Analysis in Pavement Design-Interim Technical Bulletin*, published by the Federal Highway Administration (FHWA) in 1998. While the mechanics of LCCA are fairly straightforward, its application presents a number of challenges. One of the larger challenges is estimating the service life of each alternative, along with the scope and magnitude of M&R interventions that will be required. Service lives are often estimated through the analysis of pavement management data to identify the age at which pavements have historically required M&R treatments. However, because pavement designs and materials are constantly being improved, the historical estimates may be supplemented with time series analysis of pavement condition data, such as International Roughness Index (IRI) and distress data, to estimate the time when M&R will be required for these newer designs. In addition, in the future it is expected that modeling techniques in the mechanistic-empirical (M-E) pavement analysis and design procedures will aid in estimating the service lives of new pavement designs.

BACKGROUND

The Kansas DOT (KDOT) utilizes two primary funding programs to address pavement needs—Major Modification and Substantial Maintenance. The Major Modification Program is used to preserve and improve the service and safety of the existing highway system through modernization projects. Major Modification projects may involve rehabilitation of existing pavement, reconstruction of pavement on an existing alignment or an offset alignment, or addition of extra lanes to an existing pavement. The Substantial Maintenance Program helps protect the investment the state has made in its road and bridge infrastructure by preserving the "as-built" condition of its highways to the best extent possible. Substantial Maintenance projects typically involve surface treatments, such as chip seals, micro-surfacing, diamond grinding, and thin overlays.

KDOT uses the 1993 American Association of State Highway and Transportation Officials (AASHTO) *Guide for Design of Pavement Structures* to design and rehabilitate its roadway structures selected for Major Modification projects. The design process includes a LCCA to determine what paving material, hot-mix asphalt (HMA) or Portland cement concrete (PCC), is most appropriate for use on the project. For each design alternative (HMA, PCC, or variations of either), a series of subsequent rehabilitation activities is established for maintaining the structural integrity of the pavement over a long time. The timing and scope of these actions are determined in part using the 1993 Guide, meaning that they are based on an anticipated structural need. KDOT neither plans nor sets aside funds to complete the subsequent rehabilitation actions used in the LCCA process. Rather, it uses its Pavement Management System (PMS) as the primary driver to select the timing and scope of M&R actions. These actions may be based on a structural need or a functional need, such as surface roughness. Thus, the actions taken in real life are not necessarily the same as those used in the LCCA process.

In Kansas, as well as in other states, reductions in capital improvements (i.e., major rehabilitation, reconstruction) have led to increased scrutiny of the decision-making processes used by highway agencies in the selection and design of construction and rehabilitation projects. In 2002, the Kansas Legislature's House Appropriations Committee requested a performance audit evaluating the process that KDOT follows in determining and comparing the life-cycle costs for road construction and reconstruction projects. In February 2003, the Legislative Division of Post Audit State of Kansas issued their audit report on the LCCA procedures used by KDOT. The audit report's findings presented a generally favorable view of the processes being followed by KDOT in performing LCCA and making pavement type selection decisions. The audit report included the following recommendations (Kansas Legislative Post Audit, 2003):

> Department should evaluate key factors regularly, not less often than every 2 years, to ensure they reflect realistic values and up-to-date methodologies. The results of this

evaluation and changes initiated as a result should be sent to the State Transportation Engineer. That evaluation should include, but not be limited to, these elements:

- the 2% discount rate and the various economic factors that should be considered when determining that rate.
- the timing and extent of rehabilitation actions.
- the factors used to estimate the strength of asphalt and concrete over time and how those materials deteriorate over time.

Of these three recommendations, the timing and extent of rehabilitation actions is of greatest concern. This is not only because of the differences in the sequences of M&R activities between what's modeled in the LCCA and what occurs in real life, but also because of the possible impacts that new technologies and pavement policy changes can have on both predicted and actual M&R interventions.

OBJECTIVES AND SCOPE

The primary objective of this study was to evaluate KDOT's pavement surfacing history, recommend whether the Department's LCCA procedure should include a surfacing history component, and, if so, recommend how the LCCA process should be revised/updated to incorporate surfacing history. Secondary objectives included (a) determining the appropriateness of using historical-based performance models in the LCCA when funding levels change and when paving technology advancements and (b) developing guidelines on how to appropriately implement the study recommendations.

To achieve the objectives of this study, the research team completed several individual tasks. To begin with, a kick-off meeting was held in Topeka with KDOT staff to get more detailed information on the Department's pavement/LCCA practices and experiences, and to discuss the team's approach for conducting the study. The kick-off meeting was immediately followed by separate face-to-face interviews with representatives of both the asphalt and concrete pavement industries, to obtain their perspectives and input on KDOT's pavement/LCCA practices.

Following the interviews, the team met on-site with key staff from KDOT's Bureau of Materials and Research to review and collect pertinent pavement data from various KDOT databases and physical files. Additional data and information was obtained electronically from these individuals in the months following the on-site visit.

The collected data were compiled and assembled into a project database for use in analyzing pavement performance. Based on an agreed plan for evaluating pavement performance throughout the state and the nature and quality of data in the project database, an analysis matrix was developed identifying the number of 1-mi (1.6-km) pavement sections available for performance analysis for a specific pavement type (new structures and rehabilitation treatments) subject to distinct traffic, climate, and other conditions.

Pavement survival analysis and performance modeling techniques were then used to estimate the performance of the various pavement types. Based on these results, life-cycle models were developed depicting the typical historical sequence of M&R treatments for newly constructed HMA and PCC pavements.

Next, life-cycle cost comparisons were made using KDOT's standard life-cycle models and the historical-based models derived in this study. Upon presentation of the draft project results to government and industry representatives, questions were raised about the extents/quantities and costs of forecasted M&R treatments. Through discussions with KDOT, it was determined that a cost history could be obtained for contract rehabilitation work performed on the sections used in the development of pavement service life estimates. Although a complete and reliable rehabilitation cost history data file could not be developed under this project, procedures were developed and recommendations made on the application of the cost history data in LCCA.

CHAPTER 2 - DATA AND INFORMATION GATHERING

The data and information needed to conduct the study were gathered in four primary ways—downloading of KDOT manuals and reports from the KDOT website, a project kick-off meeting, personal interviews with the respective Kansas pavement industries, and on-site and remote delivery of various relevant databases, records, and policy documents.

Among the key manuals, reports, and policy documents obtained were as follows:

- Kansas Rural Interstate Expenditure Study (Cross and Parsons, 2002).
- KDOT Response to Kansas Rural Interstate Expenditure report (Sick, 2001).
- Kansas Legislative Post Audit Report (2003).
- 2003 through 2006 KDOT PMS Condition Survey Reports.
- KDOT District boundaries map.
- Various Kansas climatology maps.
- 2007 KDOT Geotechnical Manual, Volumes I and II (Frantzen et al.).
- 1998 KDOT CANSYS Manual.
- Various KDOT policy/guideline documents on performance-graded binder selection, HMA mix type selection, Superpave mix designation, pavement drainage, and pavement rehabilitation.

These and various Kansas research reports were instrumental in guiding the research activities.

KDOT PAVEMENT AND LCCA PRACTICES

A project kick-off meeting was held on April 19, 2007 with key KDOT staff and other stakeholders (FHWA, Kansas asphalt and concrete pavement associations) at the Eisenhower State Office Building in Topeka. At this meeting, the research team presented its approach for conducting the study and sought feedback on improving the approach, based on the knowledge/information held by the various attendees and their perceptions of the study objectives.

Summarized below are some of the key aspects of KDOT's current and past practices relating to highway pavement design and pavement LCCA/type selection.

Pavement Design

KDOT uses the DARWin® computer program, based on the 1993 AASHTO Pavement Design Guide, to design its flexible and rigid pavement structures. The following summarizes KDOT's procedures and criteria for selecting input values for designing pavements.

Design Traffic

Flexible pavements are designed using a staged approach, where the initial design is for the traffic estimated over the initial 10 years. Future overlays are then designed for the expected 10-year traffic estimates at years 10, 20, and 30. The overlay designs are used in the LCCA. The actual timing and thickness of the future overlays are based on the needs identified by the PMS and the Priority Needs formula.

Rigid pavements are designed for the estimated traffic over 20 years. Rehabilitation actions are included for years 20 and 30. However, the timing and scope of the future rehabilitation action is based on the findings of the PMS and the Priority Needs formula.

Subgrade Soil Strength

Resilient Modulus

The resilient modulus (M_R) of the subgrade soils is one of the most critical factors in designing flexible pavements. KDOT policy limits the M_R value for design to a range of 2,000 to

5,000 psi (14 to 34 MPa). KDOT has developed a correlation between the lower liquid limit (LLL) of the soil and the M_R. The equation is:

$$M_R = 19.4 \times (19199.6 \times LLL - 1.329) \quad (M_R \text{ in psi}) \qquad \text{Equation 1a}$$

$$M_R = 0.134 \times (19199.6 \times LLL - 1.329) \quad (M_R \text{ in Mpa}) \qquad \text{Equation 1b}$$

If the California bearing ratio (CBR) is known, then the M_R can be approximated with the equation:

$$M_R = 800 \times CBR \quad (M_R \text{ in psi}) \qquad \text{Equation 2a}$$

$$M_R = 5.2 \times CBR \quad (M_R \text{ in Mpa}) \qquad \text{Equation 2b}$$

Modulus of Subgrade Reaction

The modulus of subgrade reaction (k) is used for the design of rigid pavements. The value of k can be determined from the M_R value using the equation:

$$k = M_R / 19.4 \quad (k \text{ in psi/in}, M_R \text{ in psi}) \qquad \text{Equation 3a}$$

$$k = M_R / 0.49 \quad (k \text{ in kPa/m}, M_R \text{ in Mpa}) \qquad \text{Equation 3b}$$

The modulus of subgrade reaction can also be calculated from falling weight deflectometer (FWD) data; however, the effects of the base under the concrete pavement must be considered. As a general rule, KDOT uses an average value of 285 psi/in (50 kPa/m) for unstabilized subgrade soil, and values as high as 625 psi/in (110 kPa/m) for bound bases on a lime-treated subgrade (LTSG).

Reliability

As seen in table 1, reliability is a function of highway classification and traffic.

Rigid Pavement Design

Rigid pavements in Kansas are currently designed as doweled, jointed plain concrete (JPC-D). The joint spacing is 15 ft (5.0 m) with 18-in (457-mm) dowel bars spaced at 12 in (305 mm). Tie bars, typically 30-in (762-mm) #5 bars spaced at 24 in (610 mm) are used in all longitudinal joints. The shoulder thickness matches the mainline thickness on all Interstate routes. On Non-Interstate routes, the shoulder thickness is 6 in (152 mm) for slab thicknesses of less than 10 in (254 mm), and 8 in (203 mm) for slab thicknesses greater than 10 in (254 mm).

Subbase type is a function of the 20-year design equivalent single-axle loads (ESALs). A granular subbase is used for less than 9,000,000 ESALs and either a cement-treated or bituminous-treated subbase is used for pavements with more than 9,000,000 ESALs. Drainable bases were used under rigid pavements in the 1990's, however their use was discontinued due to infiltration of the lime-treated subgrade into the base. The minimum slab thickness for PCC pavements is 8 in (203 mm).

Table 1: KDOT reliability levels.

Class	AADT, veh/day	Reliability
A (Urban)	> 20,000	98%
A (Urban)	< 20,000	95%
A (Rural)	> 10,000	95%
A (Rural)	< 10,000	90%
B (Urban)	>20,000	95%
B (Urban)	< 20,000	90%
B (Rural)	>10,000	90%
B (Rural)	< 10,000	85%
C (Urban)	> 5,000	90%
C (Urban)	< 5,000	85%
C (Rural)		75%
D (Urban)	> 5,000	90%
D (Urban)	< 5,000	85%
D (Rural)		60%
E (Urban)	> 5,000	90%
E (Urban)	< 5,000	85%
E(Rural)		50%

Design Equation Input Factors

The design input factors used for the AASHTO design procedure are given in table 2.

Flexible Pavement Design

Flexible pavements are currently designed as full depth asphalt concrete (FDAC). When the 20-year design lane ESALs are less than 3,000,000, an asphalt pavement with an aggregate base can also be considered. The design input factors used for the AASHTO design procedure are given in table 3.

The output of the 1993 AASHTO method of design is a structural number (SN). The structural number is made up of a combination of terms relating the thickness of the pavement layers, their relative stiffnesses, and their relative susceptibility to the environment. The structural number is computed using the following formula:

$$SN = a_l \times m_l \times d_l + a_2 \times m_2 \times d_2 + a_3 \times m_3 \times d_3 \qquad \text{Equation 4}$$

Where: m = drainage coefficient for the layer.

d = thickness of the layer.

a_i = structural layer coefficient

Structural layer coefficients (a_i) for the various paving material are given in table 4. The values listed in the first column are used for the initial design. When designing the overlays at 10 years and 20 years, the layer coefficient of the in-place materials are those given in the 10-year and 20-year columns, respectively. The reduction in layer coefficients assumes the degradation due to traffic and environment.

Table 2: Rigid pavement design factor input.

Load Transfer (j)	2.8 Tied concrete shoulders or 3-ft widened lane
	4.0 Maximum value used if poor transverse joint load transfer and no tied shoulders
Mean concrete modulus of rupture (S_c)	600 lb/in^2
Modulus of elasticity (E_c)	4,000,000 lb/in^2
Drainage coefficient (C_d)	1.2 Bound drainable base
	1.0 All other bases
The initial serviceability (p_i)	4.5
The terminal serviceability (p_t)	2.5 STP rating of other than "E"
	2.0 STP rating of "E"
Standard deviation (S_o)	0.35

1 ft = 0.305 m   1 lb/in^2 = 6.895 kPa

Table 3: Flexible pavement design factor inputs.

Drainage coefficient (C_d)	1.2 Bound drainable base
	1.0 All other bases
The initial serviceability (p_i)	4.2
The terminal serviceability (p_t)	2.5 STP rating of other than "E"
	2.0 STP rating of "E"
Standard deviation (S_o)	0.45

Table 4: Structural layer coefficients used in flexible pavement design.

	Structural Layer Coefficient, a_i		
Material	Initial	10 Years	20 Years
Surface Course	0.42	0.34	0.28
Base Course	0.34	0.28	0.20
Aggregate Base	0.14	0.11	0.08
Cold In-place Recycled (CIPR) Asphalt	0.25	0.18	0.11
Lime-Treated Subgrade (LTSG)	0.11	0.08	0
Rubblized PCC	0.2	0.16	0.12

LCCA Practices

KDOT analyzes alternative pavement designs developed for Major Modification projects using traditional LCCA techniques and a Microsoft® Excel spreadsheet template. For rehabilitation projects, a 30-year analysis period is used, whereas a 40-year analysis period is used for projects involving new construction or reconstruction. For both types of projects, only the agency costs associated with the roadway pavement structure are considered; user costs, such as delay costs and vehicle operating costs (VOCs), are not computed.

The LCCA process uses a deterministic approach, in that only the mean values of the various inputs (pavement performance/service life, pay item unit costs, discount rate, etc.) are used in the computation. Variability of the inputs is not considered. A 2 percent discount rate previously was used to convert future costs to present worth, but KDOT currently uses a 3 percent discount rate, as dictated now by the Transportation Secretary based on annual internal economic analyses.

Life-cycle cost computations for each design alternative are presented in terms of the net present worth (NPW) for the entire limits of a project. For rehabilitation projects using a 30-year analysis period, the following sequence of construction and M&R interventions are utilized on most projects:

<u>HMA or PCC Design Alternative</u>

- Year 0—Initial Rehabilitation Treatment
- Year 10—Subsequent M&R Treatment #1 (treatment type and extent [thickness/depth] defined by KDOT).
- Year 20—Subsequent M&R Treatment #2 (treatment type and extent defined by KDOT).

For new construction and reconstruction projects using a 40-year analysis period, the following sequence of construction and M&R interventions are utilized:

<u>HMA Design Alternative</u>

- Year 0—Initial Construction of Full-Depth HMA Pavement.
- Year 10—Subsequent M&R Treatment #1 (treatment type and extent defined by KDOT).
- Year 20—Subsequent M&R Treatment #2 (treatment type and extent defined by KDOT).
- Year 30—Subsequent M&R Treatment #3 (treatment type and extent defined by KDOT).

<u>PCC Design Alternative</u>

- Year 0—Initial Construction of 15-ft JPC-D Pavement.
- Year 20—Subsequent M&R Treatment #1 (treatment type and extent defined by KDOT).
- Year 30—Subsequent M&R Treatment #2 (treatment type and extent defined by KDOT).

For both rehabilitation projects and new construction/reconstruction projects, the salvage values of the individual design alternatives at the end of the analysis period (30 or 40 years) are assumed equal and assigned a value of zero.

The pavement type selection process takes into account several factors, the most important ones being initial cost and life-cycle cost. The process begins with a review by a committee of KDOT managers of the project, the alternative designs developed for the project, and the results of the LCCA. Each committee member develops their own recommendations as to which pavement type to use, and those recommendations are passed onto the State

Transportation Engineer, who makes the final decision. Unlike some states, KDOT doesn't have a rule that says if the life-cycle cost difference between competing alternatives is greater than some percentage (often, 5 or 10%), then the lower cost alternative is selected. Other factors (e.g., traffic, soils, construction considerations) such as those presented in Appendix B ("Pavement Type Selection Guidelines") of the 1993 AASHTO Design Guide, are considered.

Following the selection of pavement type for a particular project, KDOT sends the initial and life-cycle cost calculations, and the selection results, to both pavement industries.

INTERVIEWS WITH KANSAS PAVEMENT ASSOCIATIONS

As noted in chapter 1, the flexible and rigid pavement industries in Kansas have a vested interest in the LCCA process. Therefore, their perceptions of the current process as it relates to the timing and extent of M&R actions established in the LCCA are valuable for a comprehensive and fair evaluation.

Key members of the ARA research team met separately with representatives of the Missouri–Kansas Chapter of American Concrete Pavement Association (MO–KS ACPA) and the Kansas Asphalt Pavement Association (KAPA) on April 19, 2007, at the KDOT Materials and Research Office. Provided below is a summary of the discussions with each industry group.

Missouri–Kansas Chapter of American Concrete Pavement Association

The following were the key points raised during the meeting with Mr. Matt Ross, MO-KS ACPA, and Mr. David Howard, Koss Construction Co.:

- Current design is JPC-D on cement-treated base (CTB) or lean concrete base. A double application of wax-based curing compound is used to prevent bonding between the base and the slab.

- Construction traffic is not allowed on the base.
- Dowel baskets, as opposed to dowel implanters, are generally used.
- In the past, KDOT used jointed reinforced concrete (JRC) pavement with a 30-ft (9.2-m) joint spacing. Mid-panel cracking was experienced. Retrofit dowels have been successfully used to correct this problem.
- In the late 1970s and early 1980s, KDOT constructed non-doweled jointed concrete (JPC-ND) pavements. These pavements experienced severe joint faulting, which has been corrected using retrofit dowels and pavement grinding.
- During the 1990s, many pavements were constructed using drainable bases placed directly on lime-treated subgrades. Within 3 to 5 years, the subgrade began to infiltrate the drainable base causing pavement settlement and cracking.
- Classification of aggregates and quarries about 20 years ago helped greatly in delaying the onset of “D” cracking.
- In 1999, KDOT introduced a specification change that allowed contractors to design the mixes (quality assurance/quality control [QA/QC] specification).
- KDOT banned silicone joint seal use in 1993. Now it uses hot-pour in longitudinal joints and preformed compression seals in transverse joints. There is a year’s worth of projects in the mid-1990s where the preformed designs were too wide and joint problems occurred.
- From 1990 to 2000, there was a propensity for higher sand mixes, which increased cement content and lowered the entrained air content (higher entrapped air). This resulted in weakened paste and increased joint distress (spalling) in areas subject to

freeze-thaw cycles. KDOT now measures bubble spacing (spacing factor requirements). Optimized aggregates were introduced in 2000/2001 and air void analyzer in 2003.

- PCC pavements do not develop load-related cracking (i.e. longitudinal, transverse or corner cracking). No maintenance has been applied to the JPC-D projects (on non-drainable bases) that have been built within the past 15 years or so.
- A key issue is how to define failure, given the Network Optimization System (NOS) that KDOT uses. Kansas is rehabbing pavements that most other states wouldn't think about touching. MO-KS ACPA feels that the planners have a greater influence on the timing and selection of rehabilitation strategies than the pavement engineers.
- There are no concrete maintenance actions for flexible pavements included in the NOS. Whitetopping could be a viable alternative; the concrete industry would like to see it as one of the alternatives considered for asphalt pavements. Currently, milling on HMA is typically 2 to 2.5 in (50 to 65 mm) deep.
- KDOT's minimum thickness criterion of 8 in (200 mm) prevents the PCC industry from being competitive on low-volume projects.
- Sections analyzed in the Kansas Rural Interstate Expenditure Study (Cross and Parsons, 2002) are not representative of today's standards (air entraining issues, no separation layer on drainable base). Pavements with known and corrected defects should not be included in the historical performance analysis.

Kansas Asphalt Pavement Association

The following are the key points raised during the April 19, 2007 meeting with Mr. Jim Jones (KAPA), Mr. Kip Spray (Venture Corp.), and Mr. LaRue Allen (APAC-Kansas):

- Few asphalt pavements in Kansas have required total reconstruction due to pavement distress. The only distresses occurring are thermal cracking and some top-down cracking; no load-related distress (bottom-up alligator cracking).
- Thermal cracking has been experienced due to “mediocre” asphalt cement from west Texas. Better asphalt and placement on recycled base has resulted in better performance. Thermal cracking problems have been significantly reduced. Right now, KDOT is using the 0.375-in (9.5-mm) mixtures for a 1-in (25-mm) overlay, after milling the surface to correct surface deficiencies. Mill and fill is very common, as is 1- to 2-in (25- to 51-mm) deep heater scarification followed by a 1- to 2-in (25- to 51-mm) overlay.
- Kansas does experience some asphalt stripping. The severity depends on the location. KDOT introduced anti-stripping test/requirement. Generally, the Department has used 0.25 to 0.5 percent of anti-stripping additive in the HMA mixes.
- Rutting was an issue with the old Marshall mixes. In the late 1990s, KDOT went to Superpave and largely eliminated rutting problems. PG 70-22, PG 58-28 or PG 64-22 binders are the most commonly used.
- Superpave mixes are a little on the dry side, resulting in light stress cracks in the wheelpath. Profile grinding or chip sealing is a typical response to correct this distress.
- KAPA believes KDOT is applying the 1993 AASHTO Pavement Design Guide incorrectly. Asphalt pavement thickness went up tremendously with the use of the 1993 Guide, as a result of the subgrade resilient modulus (1,500 to 2,000 lb/in^2 are used in design, when in reality they should be more like 5,000 to 6,000 lb/in^2) and mix modulus (a value is 0.34 for lower layers and 0.42 for upper layers; reduces down to 0.28 and 0.34, respectively, after 10 years) numbers used in design.

- The thicknesses of overlays occurring at 10, 20, and 30 years are much less than those estimated during the initial design.
- During the 1990s, many pavements were constructed using drainable bases placed directly on lime-treated subgrades. Within 3 to 5 years, the subgrade began to infiltrate the base causing pavement distress.
- To determine the pavement life-cycle costs for pavements in Kansas, KAPA engaged Dr. Steve Cross (Professor at University of Kansas) to evaluate performance of rural interstate pavements. KDOT has disputed some of the findings in the report. Hopefully this project will resolve some of the issues.

DATA COLLECTION

Following the pavement industry interviews, the team met on-site with key staff from KDOT's Bureau of Materials and Research to review and collect pertinent pavement data from various KDOT databases and physical files. Additional data and information was obtained via e-mail and ftp downloads in the months following the meeting. The data files obtained included:

- KDOT PMS database (converted to Microsoft® Access from Oracle®) selected tables, including geometry, pavement roughness, flexible and rigid pavement distress, maintenance and rehabilitation, and traffic.
- Pavement Layer History file (converted to Microsoft® Excel from Oracle®) from CANSYS database.
- 1926 through 2007 Kansas State Highway System Traffic Flow Maps.
- Kansas I-70 Stage II Overlay Map containing historical information for I-70 construction projects.

- 2003 Kansas Drainable Base location map.
- 2005 EPMS Optimization Program Activity Criteria and Costs.

CHAPTER 3 - DATABASE DEVELOPMENT

INTRODUCTION

To satisfy the project objectives, an intensive data collection and processing effort was undertaken. This effort involved obtaining the latest KDOT highway pavement databases and hardcopy records, reviewing the accuracy and completeness of the data, and, cleaning the data assembled, as needed, for analysis.

This chapter describes in detail the data collection, assembly, and analysis database development process. Specifically, it describes the work performed in collecting the required data, merging the various KDOT data files into one overall project database, and reviewing and cleaning it for use in the study. It also presents a summary of the project data in terms of representation of different pavement types and structural cross-sections (both original construction and M&R treatments), physical locations (KDOT Districts, highway IDs, climatic regions), traffic levels, and age/construction year.

DATA ASSEMBLY

Several electronic data tables and various other data records from KDOT were used to build the project databases for analysis, including the following:

- KDOT PMIS database (in MS Access® form). The database contained several data tables, the most relevant of which were:
  - PMIS MASTERID, PMIS CAT, and PMIS REHAB. Together these tables contained information on over 11,800 approximately 1-mi long pavement segments on Kansas highways with original construction undertaken between 1919 and 2005.
  - KDOT's PMIS LAZFAULT, PMIS LAZRUT, PMIS FDIST, PMIS LAZROUGH, PMIS MANDIST, PMIS_RDIST, and PMIS ROUGH data tables provided HMA and

concrete pavement performance data. Key data fields included those below. For all of the distress types and roughness, data were available since the late 1980's.

- HMA pavement rutting (1986 through 2007).
- HMA pavement fatigue and transverse cracking (1986 through 2007).
- JPC and JRC pavement faulting (1986 through 2007).
- HMA, JPC, and JRC pavement roughness (1986 through 2007).

➢ KDOT's PMIS TRAFFIC data table provided traffic information for analysis. Key data fields included the following:

- Section ID.
- Annual average daily traffic (1987 through 2006).
- Equivalent 18-kip axle load (1987 through 2006).
- Daily number of heavy commercial vehicles (1987 through 2006).
- Design-Lane ADL that incorporates EAL and multilane factors (1987 through 2006).

- KDOT's PMS GL GLAYERS WITH ROUTE (Excel spreadsheet). This data table contained historical construction, M&R, and reconstruction information for most of the projects in the PMIS data tables (generated from CANSYS data).
- KDOT Traffic Maps (1958 through 2006) (hardcopy).
- KDOT maps indicating FDAC and JPC pavement sections constructed with drainable bases.

Key relevant data items contained in the KDOT PMIS data tables and the KDOT PMS GL GLAYERS WITH ROUTE spreadsheet are presented in table 5.

Table 5: Detailed description of relevant information/data elements gathered/assembled from KDOT PMIS database.

Table	Variable Name	Format	Comment
PMIS CAT	RDCAT	Decimal	Roadway category
	CLASS	Text	I: for interstate. O: for all others.
	PVMT	Text	• PCCP: Portland cement concrete pavement. • COMP: Composite pavement, PCC pavement or brick that has been overlaid with asphalt concrete. • FDBIT: Full design bituminous pavement, designed and constructed to carry expected traffic. • PDBIT: Partial design bituminous pavement, not designed or constructed to carry expected traffic
	WDT	Text	Roadway width
	ADLLO	Decimal	Lower end of Design Lane Equivalent Axle Loads. Expressed in daily equivalent 18 kip axle loads
	ADLHI	Decimal	Higher end of Design Lane Equivalent Axle Loads. Expressed in daily equivalent 18 kip axle loads
	PVMTGRP	Decimal	Pavement Group, 1 – PCCP, 2 – COMP, 3 – FDBit, 4 – PDBit
	CATDESC	Text	Roadway category description
PMIS COUNTIES	COUNTY	Decimal	001 to 105 Corresponding county name and county abbreviation
	CONAME	Text	Full County Names
	COSNAME	Text	2 Character County Abbreviations
	DIST	Decimal	District No. 1 through 6 (1=NE, 2=NC, 3=NW, 4=SE, 5=SC, & 6=SW)
PMIS LAZFAULT	ID	Text	Section ID
	LDIR	Text	Direction (E, W, N, S)
	LDATE	Date/Time	Measurement date
	LAZF	Decimal	Coded degree of faulting based on FSCORE
	LAZF1 through LAZF3	Decimal	Number of Code 1 through Code 3 faults per mile
	FSCORE	Decimal	$c1 \times F1 + c2 \times F2 + c3 \times F3$
	NOJTS	Decimal	Number of joints
	EQFAULT	Decimal	Equivalent number of Code 3 (>12.77 mm) faults per 30 m.
PMIS_LAZRUT	ID	Text	Section ID
	FDIR	Text	Direction (E, W, N, S)
	FDATE	Date/Time	Measurement date
	FTIME	Decimal	Measurement time
	RUT	Decimal	This is a 2-digit coded value for rutting. The first digit signifies the mean rut depth for a pavement segment and the second digit the maximum rut depth
	RUTVAL	Decimal	Average depth of rut in inches based on three-point measurement

Table 5: Detailed description of relevant information/data elements gathered/assembled from KDOT PMIS database (continued).

Table	Variable Name	Format	Comment
PMIS FDIST	COUNTY	Decimal	001 to 105 Corresponding county name and county abbreviation
	RTTY	Decimal	Route Type 1=Interstate, 2=US-Route and 3=K Route (character 4 of PMISID)
	RTNO	Decimal	Route Number
	IMPBEG	Decimal	Integer portion of the Segment Beginning Milepost (characters 9-10 of PMISID)
	IMPEND	Decimal	Integer portion of the Segment Ending Milepost (characters 11-12 of PMISID)
	LANE	Decimal	0=undivided, 1=west bound, 2=north bound, 3=east bound, & 4=south bound
	ID	Text	Section ID
	FDATE	Date & Time	Survey date (for flexible distresses)
	RUTVAL & RUT	Decimal	Estimate of rut depth
	FCR1 through FCR4	Decimal	Condition of fatigue cracking as number of wheelpath feet per 100 feet. Fatigue Cracking severity codes are: • FC1: Hairline alligator cracking, pieces not removable. • FC2: Alligator cracking, pieces not removable, cracks spalled. • FC3: Alligator cracking, pieces are loose and removable, pavement may pump. • FC4: Pavement has shoved forming a ridge of material adjacent to the wheelpath.
	TCR0 through TCR3	Decimal	Condition of transverse cracking as number of full pavement width cracks per 100 ft. The severity codes are: • T0: Sealed cracks with no roughness and sealant breaks less than 1 foot per lane. • T1: No roughness, 0.25 in or wider with no secondary cracking; or any width with secondary cracking less than 4 feet per lane; or any width with a failed seal (1 or more feet per lane). • T2: Any width with noticeable roughness due to depression or bump. Also cracks that have greater than 4 feet of secondary cracking but no roughness. • T3: Any width with significant roughness due to depression or bump. Secondary cracking will be more severe than Code 2. Only cracks that are a full lane width are counted (centerline to edge on a two lane road).
	EQTCR	Decimal	This is a aggregated transverse cracking value obtained by c1×TCR1 + c2×TCR2 + TCR3
	EQFCR	Decimal	This is an aggregated fatigue cracking value
PMIS LAZROUGH	ID	Text	Section ID
	IRIDIR	Text	Direction (E, W, N, S)
	IRIDATE	Date/Time	Measurement date
	IRITIME	Decimal	Measurement time
	IRIL	Decimal	IRI (left)
	IRIR	Decimal	IRI (right)

Table 5: Detailed description of relevant information/data elements gathered/assembled from KDOT PMIS database (continued).

Table	Variable Name	Format	Comment
PMIS MANDIST	ID	Text	Section ID
	MANDIR	Text	Direction (E, W, N, S)
	MANDATE	Date/Time	Date of manual distress date collection
	MANTIME	Decimal	Time
	MANVHCL	Decimal	Vehicle number used for manual distress data collection
	MANOPRTR	Decimal	Operator number for manual distress data collection
	FCR1 through FCR4	Decimal	average wheelpath feet of code 1 through code 4 fatigue cracking in a 100 foot sample section
	TCR1 through TCR3	Decimal	average number of code 1 through code 3 transverse cracks per 100 foot sample section
	BCR	Decimal	Severity code of block cracking in a sample section where at least 50% of the sample is cracked
	JD1 through JD4	Decimal	Average number of code 1 through code 4 distressed joints per 100 foot
	TCR0	Decimal	average number of code 0 (sealed) transverse cracks per 100 foot sample section
	EQTCR	Decimal	This is a aggregated Transverse cracking value obtained by c1×TCR1 + c2×TCR2 + TCR3
	EQJD	Decimal	This is an aggregated Joint Distress value
	JD0	Decimal	Average number of code 0 (non-D-cracking joint distress) distressed joints per 100 foot
	EQFCR	Decimal	This is an aggregated fatigue cracking value
PMIS MASTERID	COUNTY	Decimal	001 to 105 Corresponding county name and county abbreviation
	RTTY	Decimal	Route Type 1=Interstate, 2=US-Route and 3=K Route (character 4 of PMISID)
	RTNO	Decimal	Route Number
	CODE	Decimal	See PMIS web site and look for "suffix" (character 8 of PMISID)
	LANE	Decimal	0=undivided, 1=west bound, 2=north bound, 3=east bound, & 4=south bound
	ID	Text	Section ID
	MPBEG	Decimal	Begin Milepost
	MPEND	Decimal	End milepost
	HPMS	Decimal	Tie to HPMS database
	LONGBEG	Decimal	Longitude begin
	LATBEG	Decimal	Latitude begin
	LONGEND	Decimal	Longitude end
	LATEND	Decimal	Latitude end
	STMPBEG	Double	Begin Milepost using statewide route referencing
	STMPEND	Double	End Milepost using statewide route referencing
	DISTRICT	Decimal	District # 1 through 6 (1=NE, 2=NC, 3=NW, 4=SE, 5=SC, & 6=SW)
	LRS_KEY	Text	Agency standard linear referencing. Similar to PMISID

Table 5: Detailed description of relevant information/data elements gathered/assembled from KDOT PMIS database (continued).

Table	Variable Name	Format	Comment
Table: PMIS_RDIST	COUNTY	Decimal	001 to 105 Corresponding county name and county abbreviation
	RTTY	Decimal	Route Type 1=Interstate, 2=US-Route and 3=K Route (character 4 of PMISID)
	RTNO	Decimal	Route Number
	CODE	Decimal	See PMIS web site and look for "suffix" (character 8 of PMISID)
	IMPBEG	Decimal	Integer portion of the Segment Beginning Milepost (characters 9-10 of PMISID)
	IMPEND	Decimal	Integer portion of the Segment Ending Milepost (characters 11-12 of PMISID)
	LANE	Decimal	0=undivided, 1=west bound, 2=north bound, 3=east bound, & 4=south bound
	ID	Text	Section ID
	RDATE	Date/Time	Date of Rigid pavement distress data collection
	FAULT	Decimal	Coded degree of faulting based on FSCORE
	JD1 through JD4	Decimal	Average number of code 1 through 4 distressed joints per 100 foot
	FSCORE	Decimal	c1×F1 + c2×F2 + c3×F3
	F1PCT through F3PCT	Decimal	Percent of Code 1 through Code 3 faults per mile
	JDI	Decimal	old combined index for joint distress (not used)
	EQFAULT	Decimal	Equivalent number of Code 3 (>12.77mm) faults per 30 m.
	EQJD	Decimal	This is an aggregated Joint Distress value
	EQFAULTR	Decimal	Equivalent number of Code 3 (>12.77mm) faults per 30 m. (based on percents from history)
	JD0	Decimal	Average number of code 0 (non-D-cracking joint distress) distressed joints per 100 foot
PMIS REHAB	ACTION	Decimal	Action code
	SDESC	Text	Short English description of the action
	SDESCKM	Text	Short Metric description of the action
	LDESC	Text	Long English description of the action
	LDESCKM	Text	Long metric description of the action
	PCCP	Decimal	Index number for optimization system for appropriate actions for PCCP
	COMP	Decimal	Index number for optimization system for appropriate actions for COMP
	FDBIT	Decimal	Index number for optimization system for appropriate actions for FDBit
	PDBIT	Decimal	Index number for optimization system for appropriate actions for PDBit
	EQUTHICK	Decimal	Estimated equivalent thickness of action to asphalt
	ACTTYPE	Text	Non-structural, light, medium, or heavy action category

Table 5: Detailed description of relevant information/data elements gathered/assembled from KDOT PMIS database (continued).

Table	Variable Name	Format	Comment
PMIS ROUGH	COUNTY	Decimal	001 to 105 Corresponding county name and county abbreviation
	RTTY	Decimal	Route Type 1=Interstate, 2=US-Route and 3=K Route (character 4 of PMISID)
	RTNO	Decimal	Route Number
	CODE	Decimal	See PMIS web site and look for "suffix" (character 8 of PMISID)
	IMPBEG	Decimal	Integer portion of the Segment Beginning Milepost (characters 9-10 of PMISID)
	IMPEND	Decimal	Integer portion of the Segment Ending Milepost (characters 11-12 of PMISID)
	LANE	Decimal	0=undivided, 1=west bound, 2=north bound, 3=east bound, & 4=south bound
	ID	Text	Section ID
	IRIDATE	Date/Time	IRI date
	IRIL	Decimal	IRI (left)
	IRIR	Decimal	IRI (right)
PMIS TRAFFIC	ID	Text	Section ID
	TRAFDATE	Date/Time	Traffic date (typically only the year is meaningful)
	AADT	Decimal	Annual average daily traffic
	EAL	Decimal	Equivalent 18-kip axle load
	HVYCOMM	Decimal	Daily number of heavy commercial vehicles
	D ADL	Decimal	Design-Lane ADL that incorporates EAL and multilane factors
PMS GL GLAYERS WITH ROUTE	BOUND GROUP		This is the CANSYS section ID that is an expanded version of the LRS_KEY in MASTERID
	BEGIN COUNTY MP		Distance of the beginning or end point of the control section from the county line or route origin within the county. Distances are measured to thousandths of a mile. This is not updated automatically, but must be coded manually
	END COUNTY MP		
	BEGIN STATE MP		Distance along the main route of the beginning point of the control section from the state line or the origin of that route within the state.
	END STATE MP		
	NE LENGTH ALL		Segment length
	SECT NETWORK DIRECTION		Direction of travel
	SECT PREFIX		I – Interstate and Turnpike U – U.S. K – Kansas
	DIVIDED UNDIVIDED		D = divided, U = undivided
	LAYER NO		A top down sequence of layers with 1 being on top and higher numbers underneath (MJG is the bottom showing when the original dirt work was done)
	MATERIAL		Material Type
	DEPTH		Thickness
	LAYER YEAR		Year the layer was placed

DATABASE DEVELOPMENT

Two separate databases were developed using the assembled data. The first database, used for survival analysis, consisted mainly of project history information (project type, M&R history, traffic). The second, used for developing trends in performance, consisted of both project history information and performance data (e.g., IRI, faulting, and so on). Development of both databases entailed several steps, which are described in detail in the sections below.

Merging of Relevant Data Tables to Develop Project Database for Survival Analysis

Key information in relevant KDOT data tables was merged into a project database to be used for survival analysis. Merging of the KDOT data tables was done in Microsoft Access® using a number of queries developed specifically for the needs of this project. The queries linked key data from the relevant data tables using a unique reference identifier (PMIS ID, route type and number, direction, state beginning and ending milepost), that defined a unique KDOT PMS uniform or homogeneous pavement section.

The key data tables merged to create the survival analysis project file were as follows:

- KDOT's PMS GL LAYERS WITH ROUTE.
- PMIS MASTERID.
- PMIS CAT.
- PMIS REHAB.

From the data tables listed above, the following key data items were assembled:

- PMIS ID
- BEGIN_STATE_MP
- END_STATE_MP
- LAYER_NO

- Depth, in
- Pavement Type
- LAYER YEAR
- End Year
- Age
- Combined Binder Type
- ACTTYPE
- LRS KEY
- BOUND GROUP
- EQUTHICK
- NE LENGTH ALL
- SECT NETWORK DIRECTION
- SECT_PREFIX
- DIVIDED UNDIVIDED
- COUNTY
- RTTY
- RTNO
- LANE

After merging of the data tables (resulting in the creation of the survival analysis project database), the following steps were performed, which are described below:

1. Define pavement types and M&R activities.
2. Categorize M&R activities (i.e., KDOT action type).
3. Establish historical construction and M&R activity record.

4. Evaluate data records for completeness and perform remedial actions.
5. Perform QC checks of assembled data (evaluation of database for anomalies and possible error and cleaning out the assembled data).
6. Establish final project database for survival analysis.

Step 1—Define Pavement Types and M&R Activities

The data presented in the various databases do not clearly define original pavement type and M&R activities. They present, however, detailed information on layer types that make up the pavement structure, along with the placement times. For the purposes of this study, pavement type and M&R activities had to be carefully defined, since analysis to determine pavement service life depends very much on the pavement type, as well as design features and properties. Note that all things being equal, a full-depth asphalt pavement and a conventional asphalt pavement may have significantly different lives. Thus, the pavement types and M&R activities were defined as follows:

Pavement Types

- Conventional Asphalt Concrete (CAC)—Relatively thin AC layer placed on relatively thick untreated aggregate base course and prepared subgrade. The criteria used to define CAC pavements were that the total asphalt layer thickness had to be less than 7.5 in (190 mm) and could constitute no more than 40 percent of the total structure thickness (i.e., combined thickness of asphalt surface and aggregate base/subbase).
- Deep-Strength Asphalt Concrete (DSAC)—Relatively thick AC layer (surface and HMA- or asphalt-treated base) placed on untreated aggregate base and prepared subgrade. The criteria used to define DSAC pavements were that the total asphalt layer thickness had to be at least 4.5 in (115 mm) and could not constitute less than 40 percent of the

total structure thickness (i.e., combined thickness of asphalt surface and aggregate base/subbase).

- FDAC—Current flexible design standard consisting of thick AC layer (surface and HMA- or asphalt-treated base) placed on prepared or modified (cement-, lime, or other-treated) subgrade.
- JRC-D—Primarily steel mesh-reinforced concrete with dowels and 61.5-ft (18.8-m) joint spacing, placed on unbound aggregate and prepared subgrade. The dowel bars are used to enhance load transfer at transverse joints.
- JPC-ND—Non-doweled concrete pavement with 15-ft (4.6-m) skewed joint spacing, placed on cement- or asphalt-treated aggregate base and prepared subgrade.
- JPC-D—Current rigid design standard consisting primarily of doweled concrete with 15-ft (4.6-m) perpendicular joint spacing, placed on cement- or aggregate-treated base and prepared or modified subgrade.

<u>M&R Activities</u>

- Cold- or hot-in-place recycling (M&F)—This involves the cold milling or the removal of material from an asphalt pavement surface followed by hot or cold in-place remixing of the removed material with an emulsified asphalt or other additives, and relaying and compacting the material.
- Application of chip seals and micro surfacing.
- HMA overlay—An asphalt overlay of an asphalt or concrete pavement, placed to improve ride quality and/or surface friction, or placed for the purpose of substantially increasing structural capacity.
- M&F plus HMA overlay—Combination of the M&F and HMA overlay.

- Joint—joint repair activities for jointed concrete pavements ranging from joint sealing to partial- and full-depth repair of spalls. Does not include dowel retrofit.
- Joint retrofit—Installing retrofit dowels in the joints of undoweled JPC pavements and the mid-panel cracks of JRC pavements.

Note that both asphalt and concrete pavements were categorized as drained or undrained, depending on whether the surface layer was placed over a drainable base layer.

Step 2—Categorize M&R Activities

KDOT categorizes M&R activity as Non-structural, Light, or Heavy, based on the activity type and structural impact on existing pavement. The very thick HMA overlays and dowel bar retrofit of existing joints are typically categorized as Heavy treatments, while crack sealing and surface seals are categorized as Non-structural. Categorization of M&R treatments for this study was made using the action type descriptions and criteria contained in the PMIS database (REHAB table). The categories are listed and described below.

- Non-Structural (N)—maintenance treatments, such as chip seals, slurry seals, and crack sealing that add little if any structural capacity to the pavement. Essentially, these treatments are less than 1.5 in (38 mm) thick.
- Light (L)—Major maintenance or minor rehabilitation treatments, such as conventional or mill-and-fill overlays on flexible pavements and conventional overlays or minor CPR (limited patching with or without diamond grinding) on rigid pavements, that add some structure to the pavement and significantly improve the ride quality and other functional characteristics. With the exception of minor CPR, these treatments typically range in thickness between 1.5 and 3.0 in (38 and 75 mm).

- Heavy (H)—Major rehabilitation treatments, such as conventional or mill-and-fill overlays on flexible pavements and conventional overlays or major CPR (dowel bar retrofit or extensive patching, followed by diamond grinding) on concrete pavements, that add substantial structure to the pavement, while also improving functional characteristics. With the exception of major CPR, these treatments are essentially greater than 3.0 in (75 mm) thick.

Step 3—Establish Historical Construction and M&R Activities Record

A record of all M&R activities and pavement reconstruction since original construction was established for all the unique KDOT PMS uniform or homogeneous pavement sections (i.e., combination of PMIS ID, route type and number, direction, state beginning and ending milepost). This was done using information mainly from the KDOT PMS GL LAYERS WITH ROUTE data table.

An example of how the information presented in the table for PMIS ID 0012054018200 was used to establish construction and M&R records is presented below.

- Example of information contained in KDOT PMS GL LAYERS WITH ROUTE data table for KDOT PMIS ID 0012054018200.

Layer No.	Material Type	Thickness, in (mm)	Layer Placement Year	KDOT PMISID
1	SM95A	1.0 (25)	2005	0012054018200
2	SRECYL	1.0 (25)	2005	0012054018200
3	BM2D	2.0 (51)	1997	0012054018200
4	HM3	1.0 (25)	1967	0012054018200
5	ACB3	13.0 (330)	1967	0012054018200
6	MJG	0.0 (0)	1967	0012054018200

- Using the information presented above, the following is determined:
  - Pavement was constructed originally as a FDAC pavement (total asphalt thickness = 14.0 in [355 mm]) with a 1.0-in (25-mm) surface asphalt layer and a 13.0-in (330-mm) intermediate/base asphalt layer in 1967.
  - The original FDAC pavement was overlaid with a 2-in (50-mm) thick asphalt layer in 1997.
  - In 2005, 1 in (25 mm) of the existing surface was milled and recycled, followed by the placement of a 1-in (25-mm) thick Superpave HMA layer.

- Thus, for this unique section, construction and M&R activities was established as follows:

Pavement Type/M&R Activity	Thickness, in (mm)	Start Year	End Year	Age	Censored?	Asphalt Layer Type	KDOT Asphalt Code
FDAC	12.52 (318)	1967	1997	30	No	Conventional asphalt	ACB3
HMA/FDAC	2.01 (51)	1997	2005	8	No	Superpave	BM2D
M&F/FDAC	0.98 (25)	2005	2005	0	Yes	Superpave	SRECYL

Censored: Yes implies that the pavement or M&R activity was still in service at the time of analysis (2005).

Step 4—Evaluate Data Records for Completeness and Performing Remedial Actions

The record of construction and M&R activities was evaluated for completeness. This was done mainly by determining possible gaps in the data record. A gap was described as having an excessively long period for which no significant M&R maintenance activity or reconstruction was performed (i.e., questionable time intervals (too short or too long between events). An example is shown below for KDOT PMIS ID 0773117006070.

Layer No.	Material Type	Layer Thickness, in (mm)	Layer Placement Year	PMIS ID
1	SM125A	1.6 (40)	2002	0773117006070
2	SEAL	0 (0)	1999	0773117006070
3	BM2	0.75 (20)	1999	0773117006070
4	SRECYL	1.0 (25)	1995	0773117006070
5	BITCOV	0.5 (13)	1951	0773117006070
6	MJG	0 (0)	1937	0773117006070

Note: Table does not include actions stemming from KDOT Maintenance Policy (i.e., chip seal every 3 years) between ~1940 and ~1970.

The information presented above shows that following the placement of a 0.5-in (13-mm) bituminous layer in 1951, no significant M&R or reconstruction occurred for 44 years until 1995. A significant gap was thus established for the construction and M&R activity record for KDOT PMIS ID 0773117006070 and the record was deemed incomplete.

Prior to 1970, KDOT had a Maintenance Program where maintenance forces applied chip seals, slurry seals, and blade-laid overlays. The timing of the seals was 3 years. Examinations of pavement cores show thin layers of bituminous material that add about 1 in (25 mm) of thickness per 10 year of pavement service life. Pavement core information could be used to rectify incomplete records.

An incomplete record was rectified by any of the following methods:

- Obtaining additional data from other KDOT data tables if possible to fill the gaps identified.
- Using only the parts of the construction and M&R records that is deemed as completed (e.g., records for the period of 1995 through 2005).
- Completely removing the PMIS section from the analysis database due to incompleteness.

Step 5—Perform QC Checks of Assembled Data

Following the records completion review and rectification of anomalies, the database was thoroughly and meticulously reviewed to identify anomalous/erroneous data. Specific items looked for and addressed were pavement sections missing PMIS IDs, inconsistencies within a pavement section between the original pavement type and the sequence of M&R activities, and missing or clearly inaccurate layer type and thickness information.

Most of the data issues identified were attributed to (a) missing PMIS IDs, (b) missing KDOT action type information (i.e., N, L, M, or H), (c) erroneous thickness data (PCC thickness less than 7-in [180 mm]), (d) layer orders not consistent with layer number or layer year was in reverse order (e.g., subbase layer was placed after the PCC layer), and (e) extrapolation errors that occurred during the merging of the two databases. Efforts were made to either obtain the appropriate data from KDOT or to use sound engineering judgment to develop reasonable estimates of the missing/erroneous data. Where neither approach was deemed adequate, the subject pavement section was removed from the database.

Sections not having matching PMIS IDs in the relevant tables were not used in the analysis. A review of sections with action types was made to determine KDOT procedures and then these procedures were used to assign missing action types to sections. If a portion of the construction data for sections with erroneous thickness data could be salvaged, the data were used in the analysis and the remaining data were removed from the analysis. Any layers that were clearly out of order were moved to the appropriate position in the construction history.

With regard to errors arising from merging information from several KDOT data tables, a detailed review was made of the event sequence and time-series performance data for all sections. Where clear discrepancies existed, either the data were replaced with the correct data or the section was removed from the database.

Step 6—Establish Final Database for Survival Analysis

Following steps 1 through 5, a cleaned-up project database for performing survival analysis was established. A full description of the database for the relevant pavements of interest is presented in the following sections.

FDAC and JPC-D Original Construction

As previously stated, the combination of PMIS ID, route type and number, direction, state beginning and ending milepost defined a unique KDOT PMS uniform or homogeneous pavement section. After combining relevant KDOT tables, a total of approximately 13,600 unique pavement sections were defined by PMIS ID, direction, and beginning and ending state milepost. Once the database was filtered of incomplete and erroneous data, there were approximately 11,200 unique sections representing a variety of pavement types.

Figures 1 and 2 show the distributions of FDAC and JPC-D (undrained) with uniform or homogeneous pavement section included in the final project database. The information presented shows a total of 5,385 and 1,745 unique FDAC and JPC-D pavement sections. Of the 1,745 JPC-D pavement sections, 500 had a drainable base. Construction dates for FDAC pavements ranged from the 1920’s to the 2000’s, while for JPC-D pavements they ranged from 1985 to 2000.

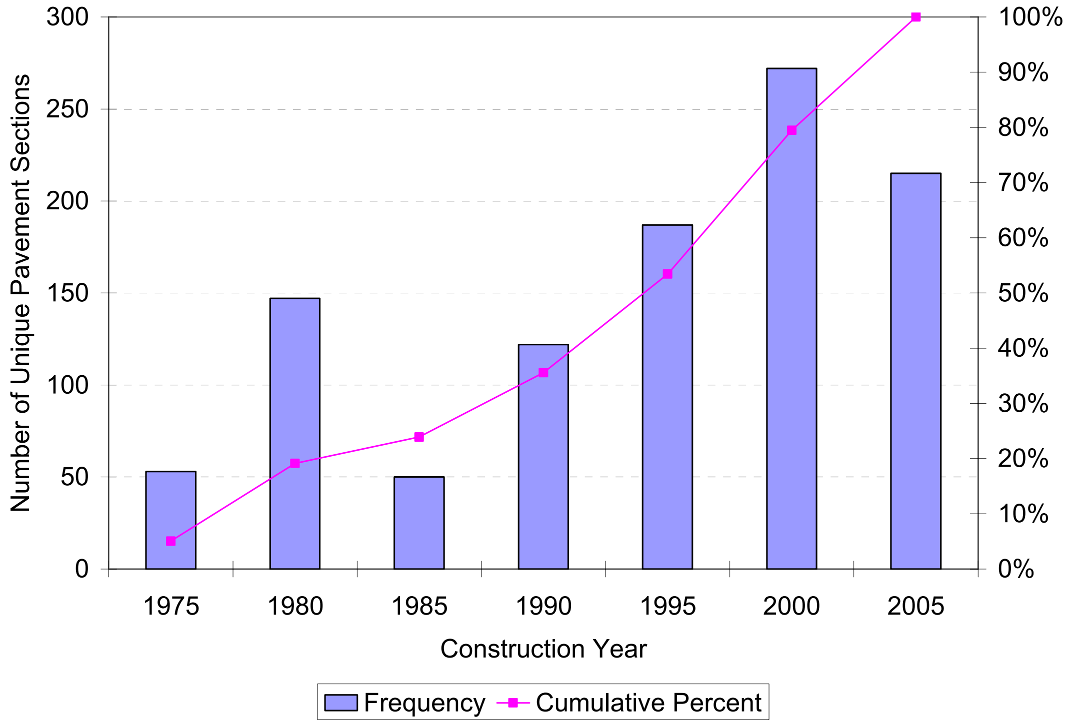

Figure 1: Distribution of FDAC with uniform or homogeneous pavement sections included in the final project database.

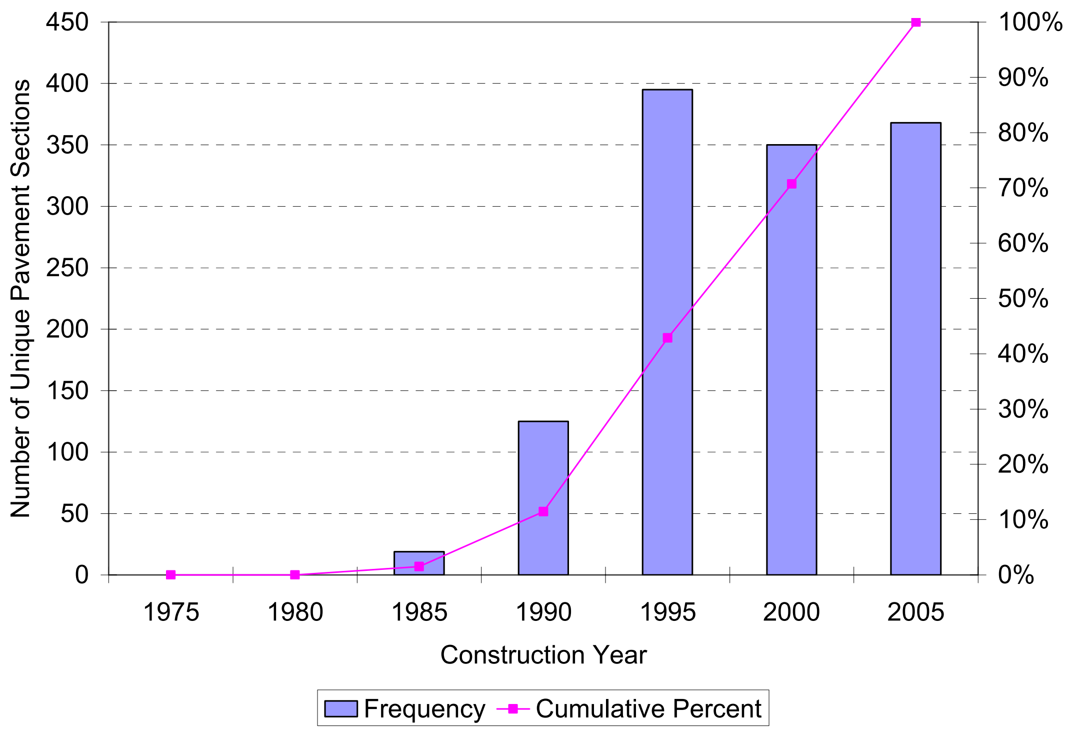

Figure 2:Distribution of JPC-D (undrained) with uniform or homogeneous pavement sections included in the final project database.

Of the unique FDAC and JPC-D pavement sections presented in figures 1 and 2, only pavements constructed after 1974 were included in the analysis. In the first place, there were no JPC-D pavements constructed before this time. And, secondly, an evaluation of the FDAC pavements showed unusually long performance lives of pavements built prior to 1974. In review, it appeared that this was caused by two reasons: (a) the M&R treatments did not appear to be incorporated into the history database and, (b) KDOT's maintenance policy between about 1940 and 1970 entailed application of chip seals on a 3-year basis, which negated the need for major rehabilitations. Thus, a total of 1,034 FDAC pavement sections and 1,257 undrained JPC-D pavement sections were available for analysis. Figure 3 shows the locations of these sections.

FDAC and JPC-D Pavements Subjected to M&R

Several rounds of M&R activities were performed on the FDAC pavements. None of the JPC-D pavements have been overlaid to date, although some have been subjected to joint repairs. All relevant M&R (i.e., HMA overlay, M&F, and M&F plus HMA overlay) activities performed after 1974 on all FDAC (regardless of original construction date) were included in the project database. A breakdown of the activities for FDAC is as follows:

- HMA overlay: 5,234 activities.
- M&F alone: 844 activities.
- M&F plus HMA overlay: 2,627 activities.

The locations of the M&R activities for FDAC are presented in figure 4.

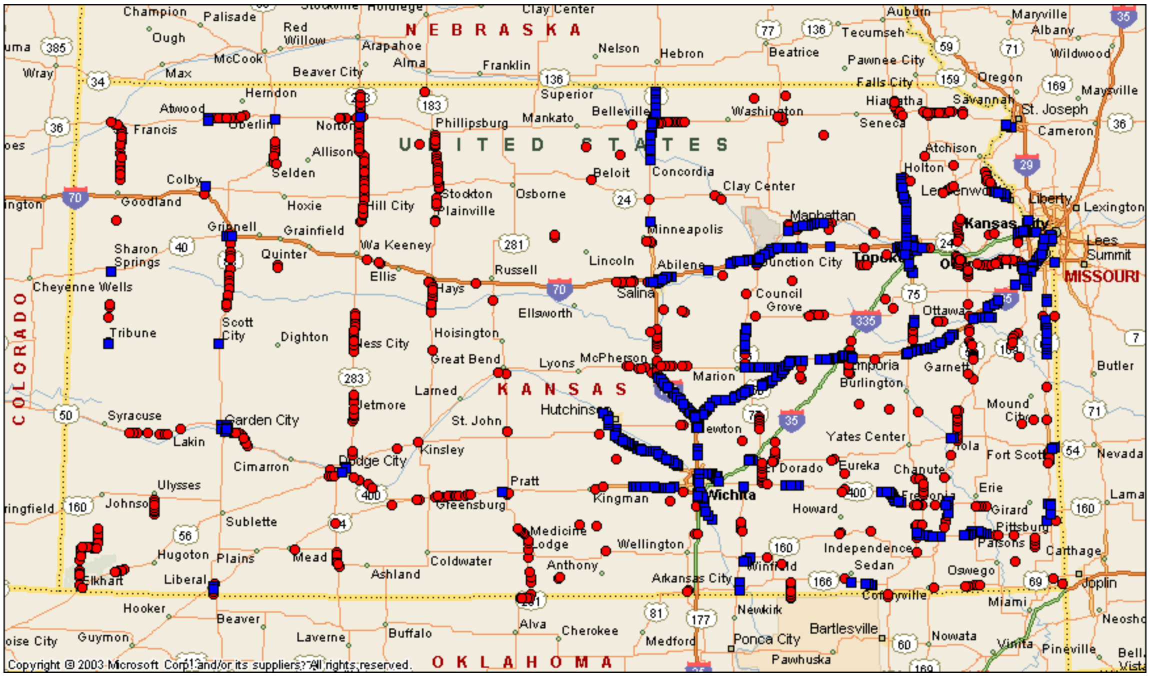

Figure 3: Locations of the FDAC and undrained JPC-D pavements sections used in analysis (red=FDAC, blue=JPC-D).

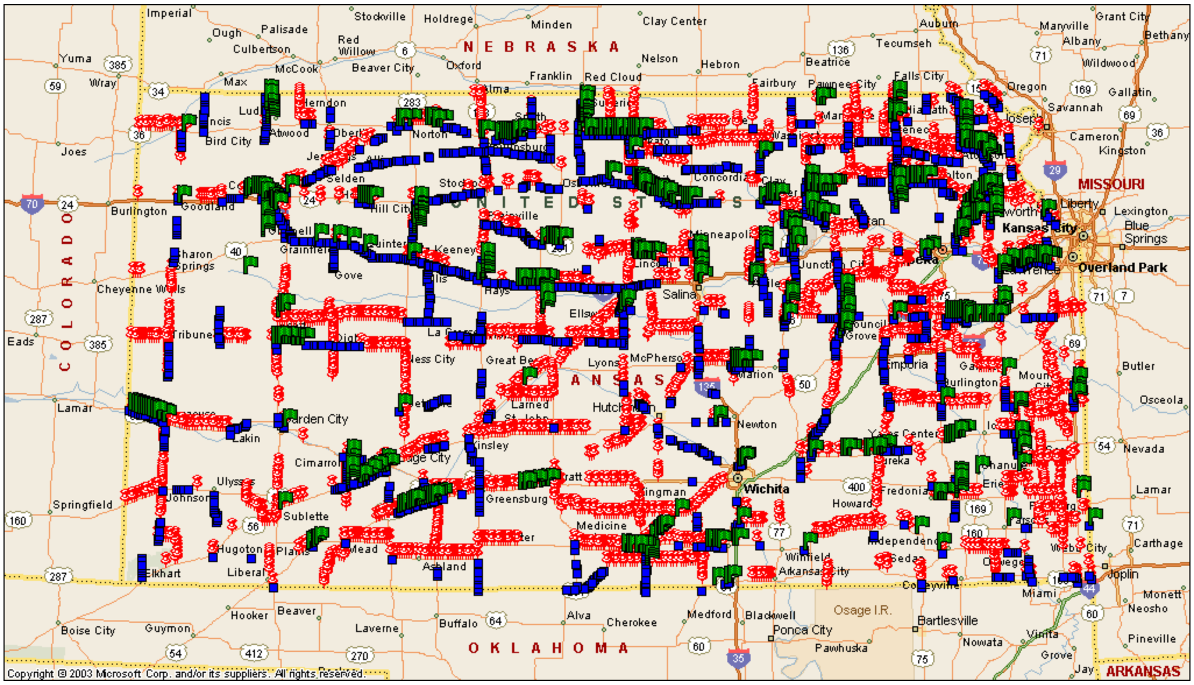

Figure 4: Locations of the FDAC pavements subjected to M&R and used in analysis (HMA overlay=red, M&F=green, M&F and HMA overlay=blue).

Pavement layer thicknesses for all the FDAC and JPC-D along with M&R activities thicknesses are summarized in table 6.

Table 6: Pavement layer thicknesses for all the FDAC and JPC-D pavement sections, and thicknesses of corresponding M&R activities.

Pavement Type	Pavement Thickness, in		
	Min	Max	Mean
FDAC	6.0	27.2	10.5
HMA/FDAC (L)	1.0	3.0	1.9
HMA/FDAC (H)	3.0	17.5	7.2
JPCP-D	7.0	13.4	10.1

1 in = 25.4 mm

Merging of Relevant Data Tables to Develop Project Database for Performance Analysis

Key distresses and IRI information in relevant KDOT data tables were merged into a survival analysis project database to establish the performance analysis database. Merging of the KDOT data tables was done in Microsoft Access© using a number of queries developed in

Microsoft Access© specifically for the needs of this project. The queries linked key data from the relevant distress/IRI data tables using a unique reference identifier (PMIS ID, route type and number, direction, state beginning and ending milepost) that defined a unique KDOT PMS uniform or homogeneous pavement section. Details of the database development process are summarized as follows:

- For FDAC, cracking, rutting, and IRI data were used in developing the performance database.
- Data were available for only the late 1980s and after. Thus, pavement sections constructed or subjected to M&R before 1985 were excluded from analysis.
- As distress data were reported for the entire KDOT PMIS section, PMIS sections that were not predominantly of a given pavement type with similar designs (e.g., layer thicknesses) were excluded from analysis (e.g., 50 percent FDAC and 50 percent JPC-D).
- The data assembled were reviewed for anomalies by plotting trends of distress/IRI versus age. Outliers and erroneous data (represented by unexplainable significant increases or decreases in distress/IRI) were identified and removed from the database.
- For JPC-D, faulting and IRI data were used in developing the performance database.

The final assembled database was a subset of the survival analysis database and thus contained fewer sections and M&R activities.

Addition of Traffic Data to Both Survival Analysis and Performance Databases

Estimates of traffic, characterized as equivalent axle load (EAL), were developed for all the relevant pavement sections. Traffic was estimated using data available in the KDOT PMIS traffic data table. For all cases, traffic data were available back to 1989. Thus, pre-1989 traffic was determined through backcasting using appropriate linear and non-linear models determined by developing plots of EAL versus pavement age for each unique pavement section. These plots were used to (1) select appropriate model forms for curve-fitting and (2) determine model coefficients for the model forms selected to relate EAL to age. Using the models developed, EAL estimates up till 1975 were backcasted.

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CHAPTER 4 - PAVEMENT PERFORMANCE ANALYSIS

INTRODUCTION

Pavement service life was defined in this study as follows:

- The life of a pavement structure or M&R treatment is from the time it is completed for use until application of the first maintenance action, significant rehabilitation treatment, or reconstruction (it is important to note that this would be the first significant cost expenditure for the pavement also).
- The life of a pavement structure or M&R treatment is from the time it is completed for use until actual or projected distress reaches a terminal or critical value that triggers M&R.

Survival analysis and performance trend analysis methods were used to analyze and develop estimates of (a) the service lives of newly constructed or reconstructed flexible and rigid pavements, and (b) the performance of M&R treatments, as delineated by KDOT action type. The combined analysis consisted of the following steps:

1. Formulation of initial analysis cells based on factors known to affect pavement life (these factors were determined based on engineering judgment).
2. Revision of initial analysis cells, based on check of the factors that significantly impact new pavement and M&R treatment performance/life.
3. Performing survival analyses.
    a. Develop survival functions and determine estimated service lives for newly constructed or reconstructed flexible and rigid pavements for each of the revised analysis cells established.

b. Develop survival functions and determine service lives for M&R treatments placed on original flexible and rigid pavements, in accordance with the revised analysis cells.

4. Performing performance trend analyses.
5. Determination of best estimates of new pavement and M&R service life.

Detailed descriptions of each step and the corresponding results are presented throughout this chapter. They are preceded by the following overview on pavement survival analysis techniques.

Pavement Survival Analysis

Survival analysis techniques have been applied widely and successfully in social sciences, economics, and engineering (reliability and failure time analysis). Specifically, for pavement engineering, survival analysis has been used for studying the effect of factors such as site conditions, design features, construction techniques, maintenance treatments, and rehabilitation activities on pavement service life.

The pavement sections that contain only partial performance information, either because they were still in-service at the time data were last collected or because data collection ceased while they were still in-service, are called censored observations. Censored observations arise whenever the dependent variable of interest (i.e., pavement life) represents the time to a terminal event, yet failure has not occurred.

Therefore, although survival analysis addresses the same research questions as many of the other statistical procedures or techniques, its main advantage is that it establishes the 50^{th} percentile pavement life when major rehabilitation or reconstruction work that have major cost consequences occur. This time can then be directly used in LCCA. Another advantage of this procedure is that it can include censored data.

Survival Analysis Procedures

Although there are several survival analysis procedures available for use, the two most commonly applied are the parametric and non-parametric procedures. The non-parametric procedure computes non-parametric estimates of a survival distribution function using the product-limit (Kaplan-Meier) or the life table (actuarial) estimate of a survival life distribution. The parametric procedure fits parametric accelerated failure time models to survival life data that may be left, right, or interval censored. The baseline distribution of the error term need not be defined or known for the non-parametric procedure, whereas for the accelerated failure time models of the parametric procedure it can be specified as one of several possible distributions, including, but not limited to, the normal, log normal, log logistic, and Weibull distributions.

In survival analysis, data associated with the time (measured in terms of pavement age or millions of truck traffic applications) until a major cost event occurs, is used. Often, this event is associated with a failure (for this study, it is the occurrence of a major rehabilitation event to restore pavement functionality or structural adequacy, which requires significant cost). Where no event or activity occurs (i.e., failure has not taken place), the time to which the latest data are available is utilized. This kind of time data is described as “censored.”

The probability distribution of such times to failure or censoring can be represented by different functions (e.g., probability distribution function, cumulative distribution function, survival function, hazard function, and so on). The relevant function for this research study is the survival function, which represents the probability that the event or activity that defines failure and major cost has not yet occurred and thus is used to determine service life.

Therefore, for both the non-parametric and parametric procedures, the first step in determining expected pavement service life is defining the survival function. The survival function, conventionally denoted by *S*, is defined as follows:

$$S(t) = Pr(T>t) \quad \text{Equation 5}$$

where: *t* = Time or age of pavement (or cumulative number of truck loadings).

T = Time or age of pavement at failure (or cumulative number of truck loadings at failure).

Pr = Probability.

Hence, the survival function is the probability that pavement time to failure (measured in terms of age [years] or cumulative traffic [number of truck applications]) is greater than some specified age or truck application level. For continuous probability distribution functions, equation 5 is modified and the survival function is defined as follows:

$$s(t) = \int_t^\infty f(T)dT = 1 - F(t) \quad \text{Equation 6}$$

where: *f(t)* = Probability distribution function (pdf).

F(t) = Cumulative density function (cdf) of the given distribution (e.g., normal, log logistic, Wiebull).

The survival function has the following characteristics:

1. It assumes that $S(0) = 1$ (although it could be less than 1 if there is the possibility of immediate pavement failure due to construction error).
2. Survival probability decreases with increasing life (i.e., $S(u) < S(t)$ if $u > t$). This expresses the notion that survival is only less probable as the pavement ages or as more trucks are applied to the pavement.
3. Survival probability is usually assumed to approach zero as pavement age or traffic applications increases without bound (i.e., $S(t) \rightarrow 0$ as t [measured as pavement age of the number of truck applications] $\rightarrow \infty$).

Both the parametric and non-parametric procedures were applied in this study for estimating pavement service life. Brief descriptions of the two procedures are presented in the sections below.

Non-Parametric Procedure (LIFETEST)

The most straightforward survival analysis procedure is the non-parametric procedure. In this procedure, life tables are used to calculate various types of time-to-failure distributions, such as the survival function, hazard functions, and so on. These life tables can be thought of as “enhanced” frequency distribution tables. The distribution of survival times is divided into a given number of intervals. For each interval, the following items are computed:

- The number and proportion of pavements that entered the respective interval in “good condition.”
- The number and proportion of pavements that failed in the respective interval (i.e., number of terminal events, or number of pavements that were “subjected to major rehabilitation or reconstruction”.

- The number of pavements with no data (unfailed) available (i.e., censored in the respective interval).

Using the computations listed above, a life table like the one shown in table 7 can be populated. Information contained in a life table is as follows:

- Number of pavements at risk (pavements yet to fail).
- Proportion of pavements that have failed.
- Proportion of pavements that have survived.
- Cumulative proportion surviving or failing (survival function).

The life table can then be used to develop a cumulative survival function, such as the one shown in figure 5. The statistics form the basis for determining the service life at which the cumulative survival function is equal to a given percentile (e.g., 25th, 50th, and 75th percentile). It should be noted that the 50th percentile, or median, for the cumulative survival function is usually not the same as the point in time up to which 50 percent of the sample survived. This would only be the case if there were no censored observations prior to this time.

Life tables are developed based on the following assumptions:

- For a given population of pavements, the exact service life of each pavement is independent and identically distributed. (Note that since the life table procedure is a non-parametric procedure, knowledge of the specific failure time distribution [e.g., normal, Weibull] is not required. However, it is essential that all the survival functions follow the same distribution.)
- The pavement sections are a random sample from the population of interest; thus, they are independent of each other and unbiased.

- If any pavement sections are censored, they must be randomly censored, and the distribution of censoring times is independent of the exact survival times. Also, the service lives of pavement sections that happen to be censored must come from the same time-to-failure distribution as those that are not censored.

Table 7: Example of life table computed using the product limit or Kaplan–Meier method.

Pavement Age, years	Cumulative No. of Failed Pavements	Cumulative No. of Censored Pavements[a]	Number of Pavements Left in Study	Proportion of Pavements Failed	Proportion of Pavements Surviving
0	0	0	57	0.000	1.000
3	0	3	54	0.000	1.000
5	0	8	49	0.000	1.000
8	0	14	43	0.000	1.000
9	0	16	41	0.000	1.000
13	8	16	33	0.195	0.805
14	13	16	28	0.317	0.683
15	15	16	26	0.366	0.634
18	19	16	22	0.463	0.537
19	24	16	17	0.585	0.415
22	32	16	9	0.780	0.220
23	41	16	0	1.000	0.000

[a] Censored pavements are those that are still in-service at time of analysis.

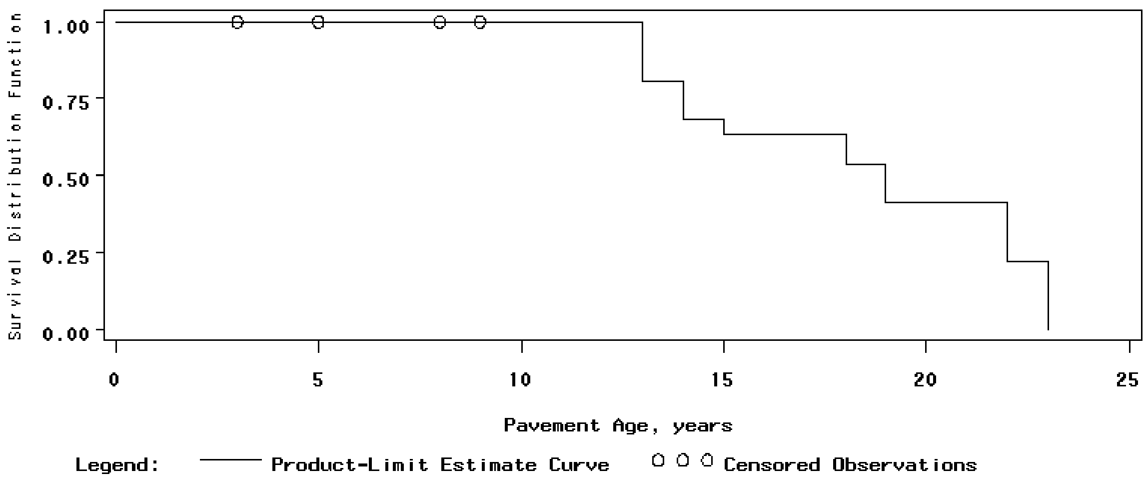

Figure 5: Example plot of product limit curve produced using the product limit or Kaplan–Meier method.

- The time during which the pavement sections are observed is partitioned into intervals (usually equal intervals, such as years). The probability of survival remains constant throughout a given interval.
- Pavement sections that survive to the beginning of an interval are considered exposed “at risk” throughout the time interval.

For this study, the LIFETEST procedure in SAS (Version 8.0) was used to compute non-parametric estimates of the survival function and thus service life. The log-rank test and the Wilcoxin test were used to test the equality of survival distributions across strata.

Parametric Procedure (LIFEREG)

Parametric procedures are suitable for situations where the distribution of the time-to-failure data are known or can be reasonably assumed, and the service life needs to be predicted using models. The major distributions that have been used to successfully model time to failure are the normal, log-normal, exponential (and linear exponential), and Weibull distributions.

For this study, the normal distribution was selected and used for modeling pavement survival because (a) it has been used successfully to fit time-to-failure data for pavements in several previous studies and (b) it obeys the central limit theorem, which basically states that as the sample size (N) becomes large (N > 30), the following occurs:

- The sampling distribution of the mean becomes approximately normal, regardless of the distribution of the original variable.
- The sampling distribution of the mean is centered at the population mean, μ, of the original variable. In addition, the standard deviation of the sampling distribution of the mean approaches $\frac{\sigma}{\sqrt{N}}$.

For analysis based on limited amounts of data without knowing the underlying distribution of the time-to-failure data, the ability to assume normality when *N* > 30 is key to obtaining reasonable results. The general formula for the normal probability distribution function is as follows:

$$F(x) = \frac{e^{-\frac{(X-\mu)^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}} \qquad \text{Equation 7}$$

where is the mean (also called the location parameter) and is the standard deviation (also called the scale parameter). The case where = 0 and = 1 is called the standard normal distribution.

The equation for the standard normal distribution is as follows:

$$F(x) = \frac{e^{-\frac{(X)^2}{2}}}{\sqrt{2\pi}} \qquad \text{Equation 8}$$

where the model parameters are as already defined.

The normal probability distribution function satisfies the following properties:

The probability that x is between two points *a* and *b* is: $p[a \le x \le b] = \int_a^b f(x)dx$

- *f(x)* is non-negative for all real *x*.
- The integral of the probability function $\int_{-\infty}^{\infty} f(x)dx$ is 1.

STEP 1—FORMULATION OF INITIAL ANALYSIS MATRIX

The analysis matrix is a key element in any network-level investigation of pavement performance. The original work plan for this study utilized KDOT's Road Categories as a basis for a preliminary analysis matrix. As illustrated in table 8, these Road Categories are defined by functional class (Interstate, non-Interstate), pavement type (partial- and full-design bituminous, composite, and concrete), roadway width (<32 ft or ≥32 ft [<9.8 m or ≥9.8 m]), and traffic range (design lane equivalent axle loads/day). Stratifying the network further by including climate and subgrade, the preliminary analysis matrix shown in table 9 was developed for consideration at the project kick-off meeting. Depending on the number of pavement sections (1-mi nominal sections) with available performance data, a pavement survival analysis and/or performance model regression would be conducted for each cell for both the original pavement structure and the various types of M&R treatments applied to the original structure.

At the project kick-off meeting, it was determined that certain refinements to the preliminary analysis matrix were needed. These refinements included the following:

- Elimination of roadway width as a factor (okay to combine like categories having different widths). For instance, Categories 12 and 15 could be combined.
- Elimination of fine and coarse subgrade as a factor, due to the lack of data in the database to distinguish subgrade.
- Climate zone breakout should capture north-south temperature differential, which is important from an asphalt grading standpoint. The breakout is best represented by US 50 extending across the lower one-third of the state. Most of the PG binder used above US 50 is −28 grade, whereas south of US 50 the predominant binder is −22 grade.

Table 8: KDOT Road Categories (KDOT, 2006).

Roadway Category	Functional Class	Pavement Type	Roadway Width, ft	Average Daily Traffic in Design Lane	
				Low	High
1	Interstate	PCCP	ANY	0	749
2	Interstate	PCCP	ANY	750	9999
3	Interstate	COMP	ANY	0	749
4	Interstate	COMP	ANY	750	9999
5	Interstate	FDBIT	ANY	0	9999
6	Other	PCCP	ANY	0	87
7	Other	PCCP	ANY	88	162
8	Other	PCCP	ANY	163	9999
9	Other	COMP	ANY	0	87
10	Other	COMP	ANY	88	162
11	Other	COMP	ANY	163	9999
12	Other	FDBIT		0	22
13	Other	FDBIT		23	50
14	Other	FDBIT		51	9999
15	Other	FDBIT	>32	0	22
16	Other	FDBIT	>32	23	50
17	Other	FDBIT	>32	51	9999
18	Other	PDBIT		0	22
19	Other	PDBIT		23	50
20	Other	PDBIT		51	9999
21	Other	PDBIT	>32	0	22
22	Other	PDBIT	>32	23	50
23	Other	PDBIT	>32	51	9999

Table 9: Preliminary analysis matrix (adapted after KDOT highway network road categories).

Road Category No.	Functional Class	Pavement Type	Roadway Width, ft	Design Lane ADL (Range in Equivalent 18-kip/day)	Climate Zone A		Climate Zone B	
					Fine Subgrade	Coarse Subgrade	Fine Subgrade	Coarse Subgrade
					Proposed Analysis Cells			
1	Interstate	PCC	All	0-749	1	2	3	4
2	"	"	"	750-9999	5	6	7	8
3	"	Composite	"	0-749	9	10	11	12
4	"	"	"	750-9999	13	14	15	16
5	"	Full Design Bit.	"	0-9999	17	18	19	20
6	Other	PCC	"	0-87	21	22	23	24
7	"	"	"	88-162	25	26	27	28
8	"	"	"	163-9999	29	30	31	32
9	"	Composite	"	0-87	33	34	35	36
10	"	"	"	88-162	37	38	39	40
11	"	"	"	163-9999	41	42	43	44
12	"	Full Design Bit.	<32	0-22	45	46	47	48
13	"	"	"	23-50	49	50	51	52
14	"	"	"	51-9999	53	54	55	56
15	"	"	≥32	0-22	57	58	59	60
16	"	"	"	23-50	61	62	63	64
17	"	"	"	51-9999	65	66	67	68
18	"	Partial Design Bit.	<32	0-22	69	70	71	72
19	"	"	"	23-50	73	74	75	76
20	"	"	"	51-9999	77	78	79	80
21	"	"	≥32	0-22	81	82	83	84
22	"	"	"	23-50	85	86	87	88
23	"	"	"	51-9999	89	90	91	92

- A factor for aggregate type/quality should be included. In general, Districts 1 and 4 (northeast and southeast part of the state) use crushed limestone, Districts 2 and 5 (north central and south central) use a blend of crushed limestone and crushed gravel, and Districts 3 and 6 (northwest and southwest) use crushed gravel.

During the database development stage, other refinements to the analysis matrix became apparent, based on the contents of the different databases and a better understanding of the types of pavements built and the types of M&R treatments utilized.

Based on the refinements suggested at the kick-off meeting and those identified during database development, a revised initial analysis matrix was established for both original pavement structures and M&R treatments. These matrices are shown in tables 10 and 11. It should be noted that, although traffic was removed as a factor in these matrices, it was accounted for later in the performance analyses. Also, where data were sufficient for individual cells, multiple levels of analysis addressing the effects of different paving mixtures and asphalt binders (i.e., Marshall vs. Superpave, −28 vs. −22 grade) were performed.

Table 10: Initial analysis matrix for original pavement structures (i.e., new construction or reconstruction).

<table>
<tr><th rowspan="3">Functional Class</th><th rowspan="3">Pavement Type</th><th>District 1</th><th>District 4 North</th><th>District 4 South</th><th>District 2</th><th>District 5 North</th><th>District 5 South</th><th>District 3</th><th>District 6 North</th><th>District 6 South</th></tr>
<tr><td colspan="3">Crushed Limestone Agg</td><td colspan="3">Blended Agg</td><td colspan="3">Crushed Gravel Agg</td></tr>
<tr><td>PG##−28</td><td>PG##−28</td><td>PG##−22</td><td>PG##−28</td><td>PG##−28</td><td>PG##−22</td><td>PG##−28</td><td>PG##−28</td><td>PG##−22</td></tr>
<tr><td rowspan="6">Interstates</td><td>JPC-ND</td><td>√</td><td colspan="2">√</td><td>√</td><td colspan="2">√</td><td>√</td><td colspan="2">√</td></tr>
<tr><td>JRC-D</td><td>√</td><td colspan="2">√</td><td>√</td><td colspan="2">√</td><td>√</td><td colspan="2">√</td></tr>
<tr><td>JPC-D</td><td>√</td><td colspan="2">√</td><td>√</td><td colspan="2">√</td><td>√</td><td colspan="2">√</td></tr>
<tr><td>CAC</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td></td><td>√</td></tr>
<tr><td>FDAC</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td></tr>
<tr><td>DSAC</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td></td><td>√</td><td>√</td><td>√</td></tr>
<tr><td rowspan="6">Non-Interstates</td><td>JPC-ND</td><td>√</td><td colspan="2">√</td><td>√</td><td colspan="2">√</td><td>√</td><td colspan="2">√</td></tr>
<tr><td>JRC-D</td><td>√</td><td colspan="2">√</td><td>√</td><td colspan="2">√</td><td>√</td><td colspan="2">√</td></tr>
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<tr><td>CAC</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td></tr>
<tr><td>FDAC</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td><td>√</td></tr>
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Table 11: Initial analysis matrix for M&R treatments (light and heavy categories only).

Functional Class	Pavement Type	District 1	District 4 North	District 4 South	District 2	District 5 North	District 5 South	District 3	District 6 North	District 6 South
		Crushed Limestone Agg			Blended Agg			Crushed Gravel Agg		
		PG##−28	PG##−28	PG##−22	PG##−28	PG##−28	PG##−22	PG##−28	PG##−28	PG##−22
Interstates	HMA/JPC-ND (L)	√	√		√	√		√	√	
	HMA/JPC-ND (H)	√	√		√	√		√	√	
	HMA/JRC-D (L)	√	√		√	√		√	√	
	HMA/JRC-D (H)	√	√	√	√	√	√	√	√	√
	HMA/JPC-D (L)	√	√	√	√	√	√	√	√	√
	HMA/JPC-D (H)	√	√	√	√	√	√	√	√	√
	HMA/CAC (L)	√	√	√	√	√	√	√	√	√
	HMA/CAC (H)	√	√	√	√	√	√	√	√	√
	HMA/FDAC (L)	√	√	√	√	√	√	√	√	√
	HMA/FDAC (H)	√	√	√	√	√	√	√	√	√
	HMA/DSAC (L)	√	√	√	√	√	√	√	√	√
	HMA/DSAC (H)	√	√	√	√	√	√	√		√
Non-Interstates	HMA/JPC-ND (L)	√	√		√	√		√	√	
	HMA/JPC-ND (H)	√	√		√	√		√	√	
	HMA/JRC-D (L)	√	√		√	√		√	√	
	HMA/JRC-D (H)	√	√	√	√	√	√	√	√	√
	HMA/JPC-D (L)	√	√	√	√	√	√	√	√	√
	HMA/JPC-D (H)	√	√	√	√	√	√	√	√	√
	HMA/CAC (L)	√	√	√	√	√	√	√	√	√
	HMA/CAC (H)	√	√	√	√	√	√	√	√	√
	HMA/FDAC (L)	√	√	√	√	√	√	√	√	√
	HMA/FDAC (H)	√	√	√	√	√	√	√	√	√
	HMA/DSAC (L)	√	√	√	√	√	√	√	√	√
	HMA/DSAC (H)	√	√	√	√	√	√	√	√	√

STEP 2—DEVELOP REVISED ANALYSIS MATRIX

The second step in pavement performance analysis was to check the assumptions on which the initial analysis cells were based (i.e., pavement performance is significantly influenced by climate within the state and district in which the pavement is located, and the functional class). The assumptions were checked for the two primary pavements of interest, FDAC and JPC-D (without drainable base). FDAC represented flexible pavements, while undrained JPC-D represented rigid pavements.

Evaluation of the assumptions was done as follows:

A. Develop survival functions for each level within a given factor used in defining the analysis matrix:

Factor	Level
Climate	North
	South
District	1
	2
	3
	4
	5
	6
Functional class	Interstate
	Non-Interstate

Perform a Log-rank test to determine if the survival functions are significantly different at a 5 percent level of significance. Log rank test is a form of Chi-square test. It calculates a test statistic for estimating p-value used for determining if the null hypothesis that the survival curves are the same for all groups (e.g., District 1 through 6). A p-value greater than 0.05 for this study was assumed to indicate that there was no significant difference in survival curves. Note that this test will only yield reliable results with fairly large samples sizes as the small sample "behavior" is not well understood.

B. Analyze results and revise analysis matrix as needed.

Evaluation Results

Results of the log-rank tests for FDAC and JPC-D (without drainable base) are presented in table 12. Figures 6 through 10 show the plots of the survival functions developed and used for statistical comparisons (Log-rank test).

Table 12: Results of the Log-rank tests for FDAC and JPC-D (without drainable base).

Pavement Type	Factor	Test Statistic	p-Value	N	Significant Difference?
FDAC	Climate	Log-Rank	0.5605	North = 796 South = 238	No
	District	Log-Rank	0.0001	District 1 = 249 District 2= 151 District 3= 180 District 4= 155 District 5= 150 District 6= 149	Yes
	Functional class	Log-Rank	<0.0001	Interstate = 69* Other = 965	Yes
JPC-D (without drainable base)	Climate	Log-Rank	<0.0001	North = 996 South = 261	Yes
	District	Log-Rank	<0.0001	District 1 = 401** District 2= 290 District 3= 21 District 4= 195 District 5= 310 District 6= 40	Yes
	Functional class	Log-Rank	0.0048	Interstate = 490 Other = 767	Yes

* Insufficient data, results not used in further analysis.

** A visual review of the survival functions show that District 1 appears to be significantly different from the remaining

Districts 2 through 6 (see figure 8).

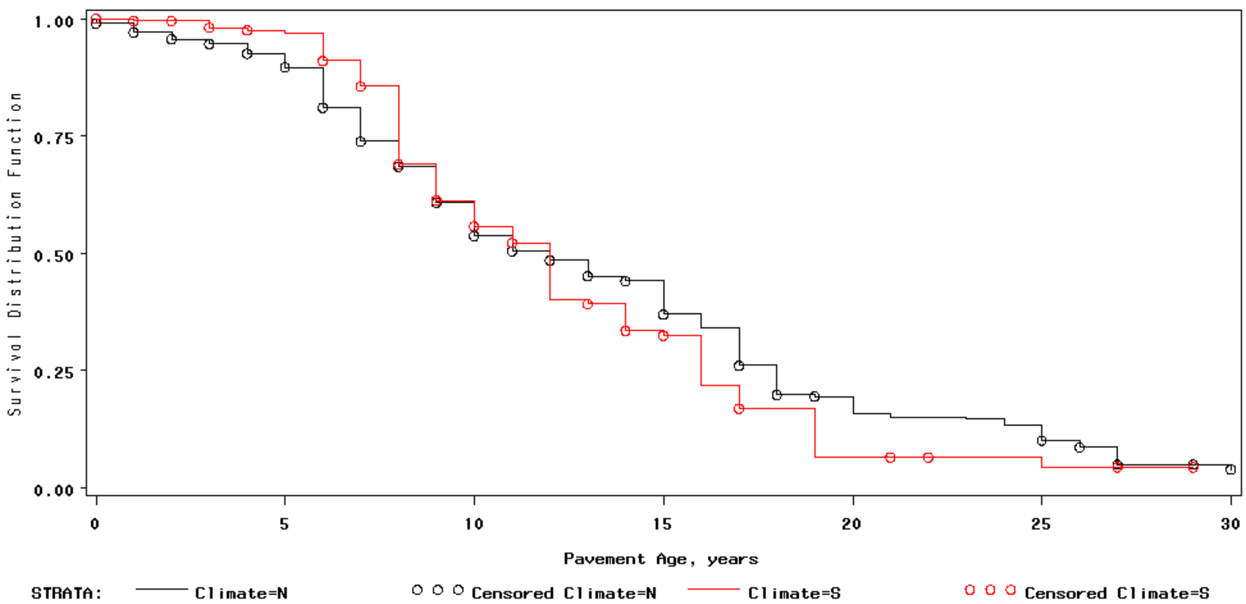


Figure 6: Survival functions showing effect of climate on FDAC failure times.

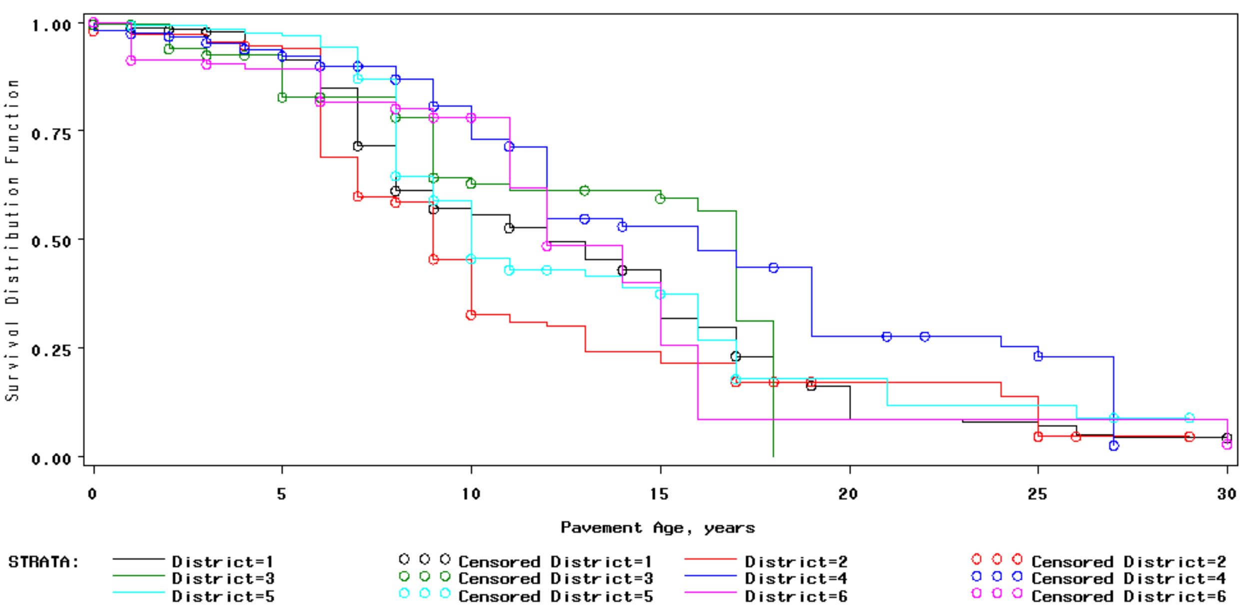


Figure 7: Survival functions showing effect of KDOT District on FDAC failure times.

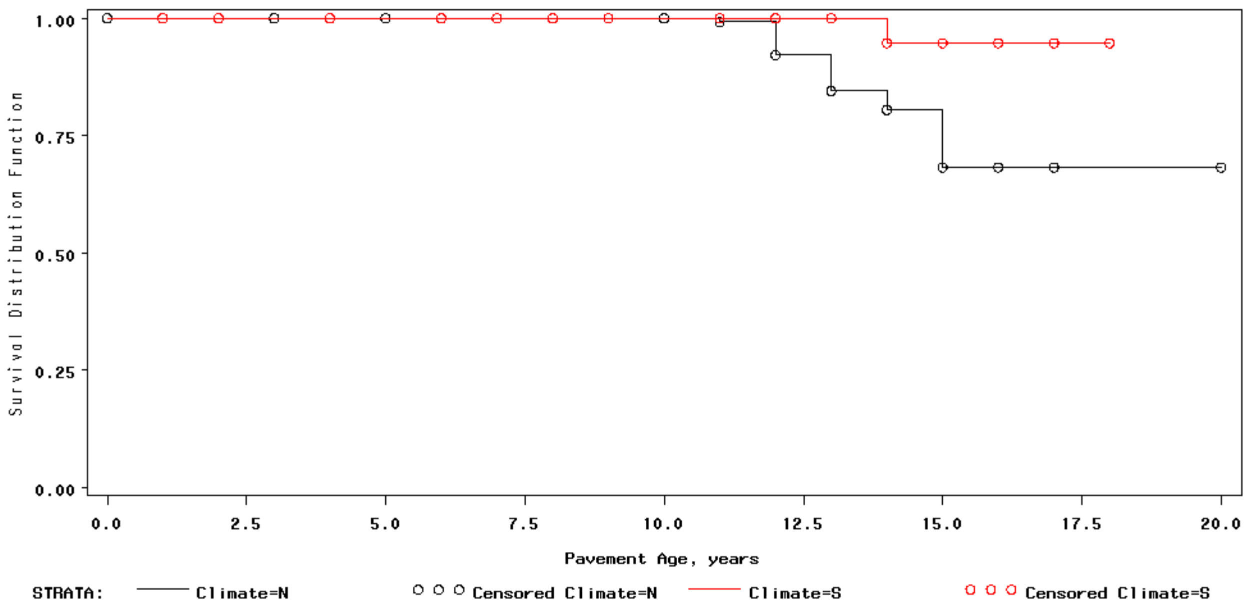


Figure 8: Survival functions showing effect of climate on JPC-D (without drainable base) failure times.

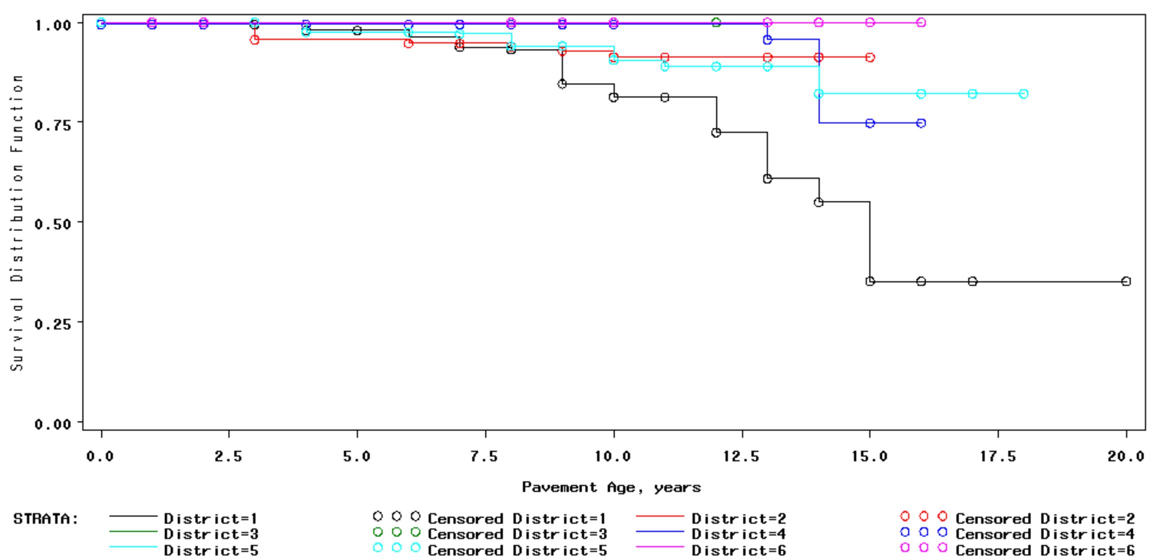


Figure 9: Survival functions showing effect of District on JPC-D (without drainable base) failure times.

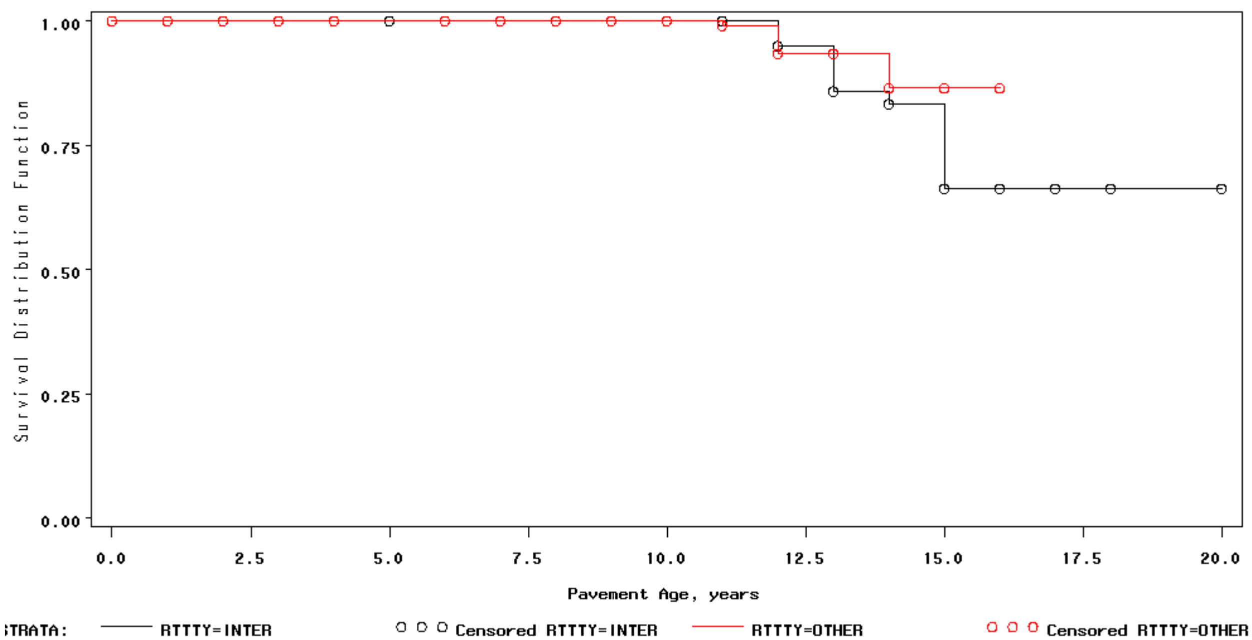


Figure 10: Survival functions showing effect of functional class on JPC-D (without drainable base) failure times.

The outcome of the statistical analysis performed to determine the reasonableness of factors used in developing analysis matrix, can be summarized as follows:

- FDAC.
  - Climate did not significantly influence performance.
  - There was insufficient data to test the influence of functional class, as most of the pavements were located on Non-Interstate routes (only 6.6 percent of the pavement sections were located on Interstate routes).
  - District did have a significant impact on performance.
- JPC-D (without drainable base).
  - Functional class did influence performance. The level of influence was somewhat smaller than the other factors used in defining analysis matrix.
  - Climate did influence performance.

➢ District did influence performance.

Based on the results presented above, the following were recommended for revising the analysis matrix:

- FDAC—The analysis matrix can be revised to consider only the impact of District, as District was the only factor that could be shown to influence performance. By considering District, however, several secondary factors not explicitly stated, such as subgrade, traffic, materials, design and construction practices, are also being considered.
- JPC-D (without drainable base)—Although overall, District did impact performance for JPC-D, a review of the survival functions presented in figure 8 indicates that District 1 JPC-D pavements performed somewhat differently from the JPC-D pavements located in the other five Districts. Further statistical analysis was thus needed to verify this observation. The results of the additional analysis are presented in figures 11 through 14 and table 13.

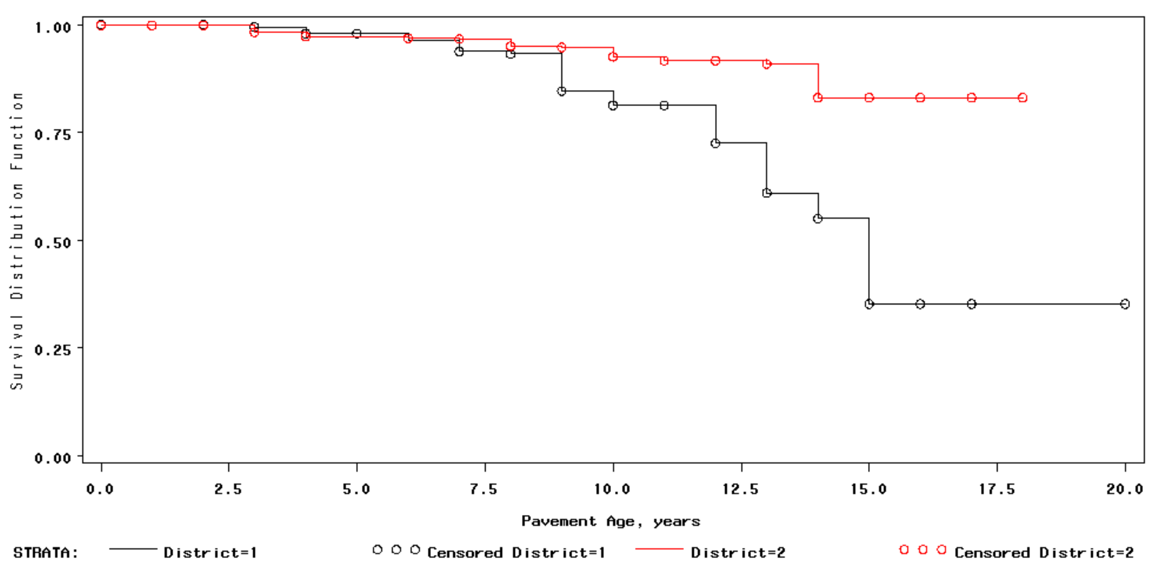


Figure 11. Comparison of survival functions between District 1 and Districts 2 through 6 combined (denoted in legend as District 2) for JPC-D (without drainable base).

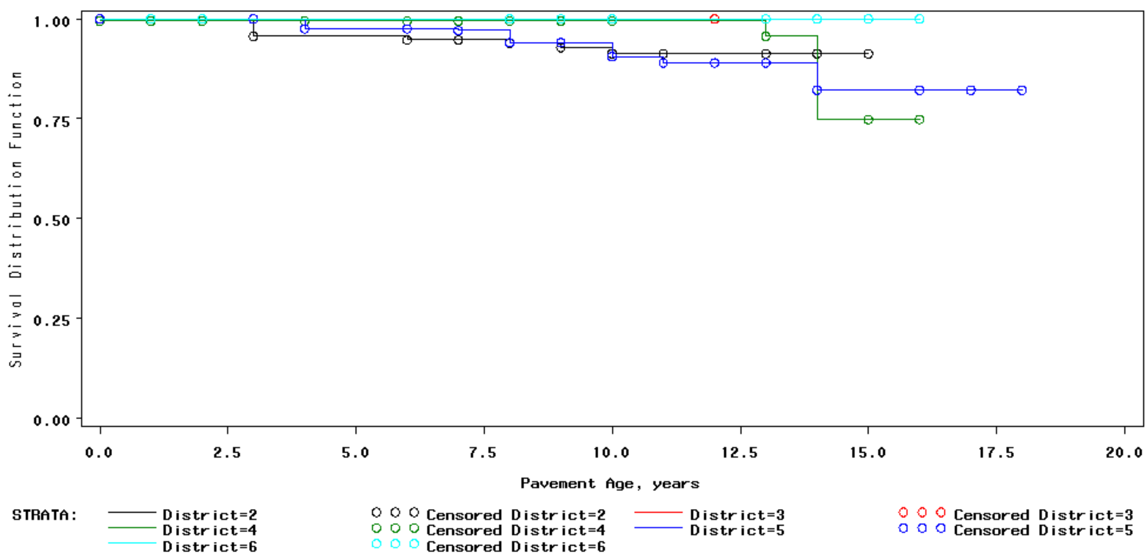


Figure 12: Survival functions for JPC-D (without drainable base) for Districts 2 through 6 only.

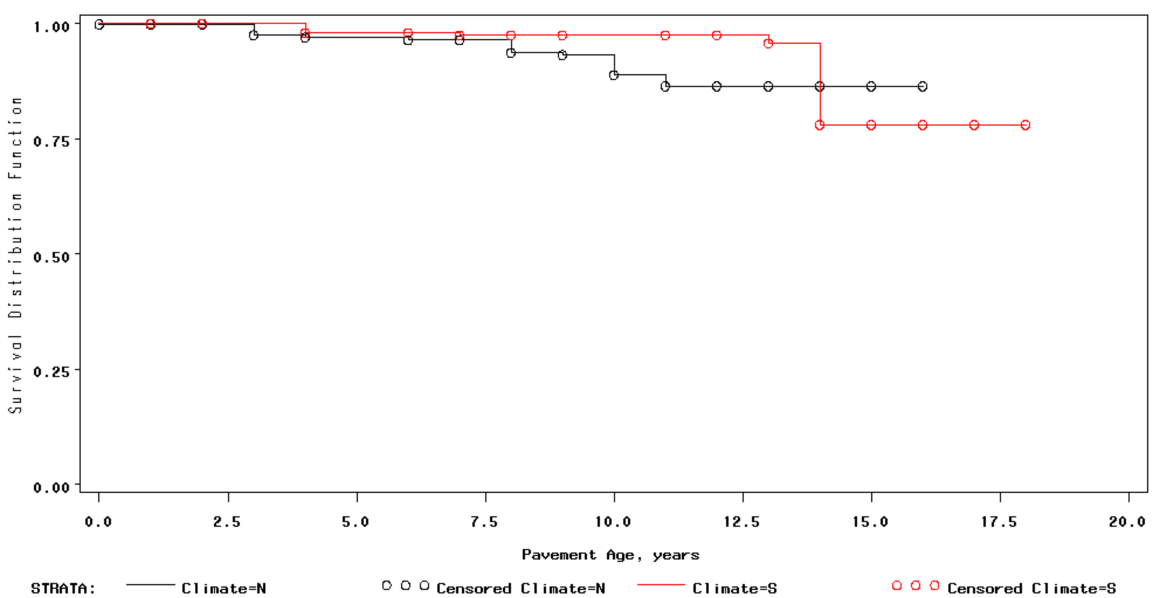
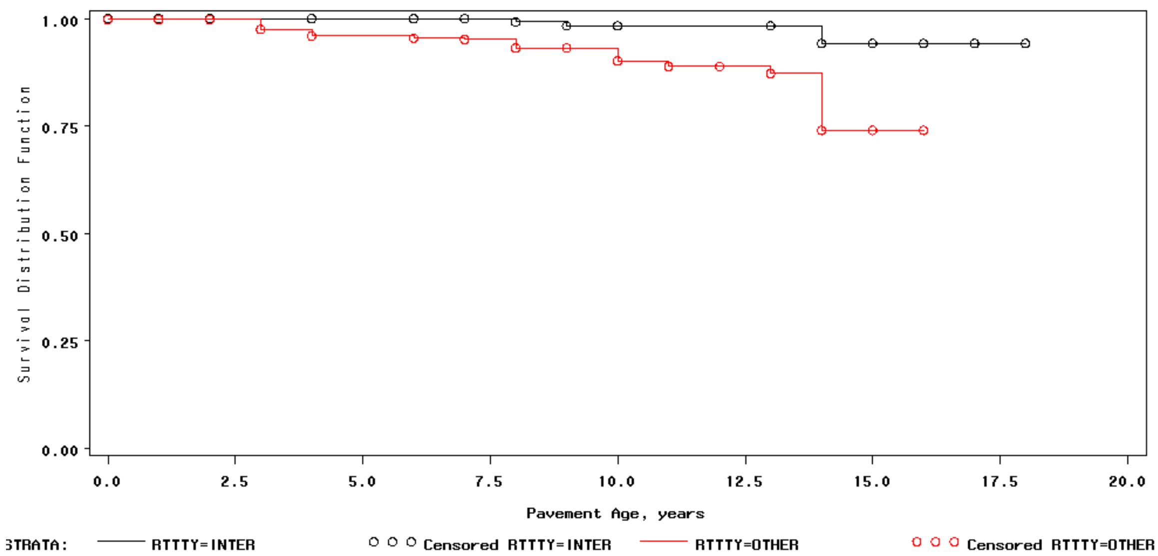


Figure 13: Survival functions for JPC-D (without drainable base) for climate (Districts 2 through 6 only).



(Districts 2 through 6 only).

Figure 14: Survival functions for JPC-D (without drainable base) for functional class

Table 13: Results of additional log-rank tests for JPC-D (without drainable base).

Pavement Type	**Factor**	**Test Statistic**	**p-Value**	**N**	**Significant Difference?**
JPC-D (without drainable base)	District (all)	Log-Rank	<0.0001	District 1 = 401 District 2 through 6 = 856	Yes
	Districts 2-6	Log-Rank	0.2844	District 2= 290 District 3= 21 District 4= 195 District 5= 310 District 6= 40	No
	Climate (Districts 2-6 only)	Log-Rank	0.1188	North = 796 South = 238	No
	Functional class (Districts 2-6 only)	Log-Rank	0.0001	Interstate = 286 Other = 570	Yes

The information presented in figures 11 through 14 and in table 13 indicates the following:

- District does influence the performance of JPC-D (without drainable bases). The Districts, however, can be grouped into two categories, namely District 1 and Districts 2 through 6.
- Although the reason for the difference in performance for JPC-D located in District 1 versus 2 through 6 is not certain, the interviews with KDOT and concrete industry representatives suggested that significant PCC material-related distresses (high sand contents resulting in paste issues) were observed in this pavement type soon after construction, for those pavements built during the 1990s. It is possible that a significantly high proportion of the JPC-D pavement that experienced early distress are located in District 1. The reasons for this could include the fact that a majority of this pavement type was constructed in this District or the problematic material or mix design was obtained from this District. Having the majority of early failure in District 1 does have a disproportionate impact on service life estimates for JPC-D pavements located within this District. Assuming that the causes of early material-related distresses have been resolved, including data from District 1 will unnecessarily impact negatively on future JPC-D pavement constructed without this problem. Thus, service life estimates of JPC-D pavements located in Districts 2 through 6 (mostly free of the early failures) were considered to be more representative of current and future KDOT JPC-D design and construction practices and thus performance.
- Climate did not influence performance among Districts 2 through 6.

- Although functional class did show some influence on performance statistically, further statistical analysis of the influence of functional class within each District showed the following:

District	Breakdown of JPC-D Pavements by Functional Class	Significant Difference
2	Interstate = 150 Non-Interstate = 140	Yes
3	Interstate = 0 Non-Interstate = 21	N/A
4	Interstate = 46 Non-Interstate = 149	No
5	Interstate = 90 Non-Interstate = 220	Yes (borderline)
6	Interstate = 0 Non-Interstate = 40	N/A

This shows that, with the exception of District 2, functional class is not a factor that significantly impacts pavement performance. Thus, there is no need to include functional class in the revised analysis matrix. Adjustment factors for the effect of functional class for pavements in each District can be developed and applied as needed.

Thus, the revised analysis matrix for FDAC and JPC-D (without drainable base) pavements, representing changes due to the influence of climate, District, and functional class on performance, is as presented in table 14.

Table 14: Final analysis matrix for new and rehabilitated FDAC and undrained JPC-D pavement structures.

<table>
<tr><th>Functional Class</th><th>Pavement Type</th><th>District 1</th><th>District 4 North</th><th>District 4 South</th><th>District 2</th><th>District 5 North</th><th>District 5 South</th><th>District 3</th><th>District 6 North</th><th>District 6 South</th></tr>
<tr><td rowspan="2">Interstates & Non-Interstates</td><td>JPC-D</td><td>√</td><td colspan="8">√</td></tr>
<tr><td>FDAC</td><td>√</td><td colspan="2">√</td><td>√</td><td colspan="2">√</td><td>√</td><td colspan="2">√</td></tr>
</table>

STEP 3—SURVIVAL ANALYSES

As discussed at the beginning of this chapter, two approaches were used in determining pavement service lives, depending primarily on data availability. For the pavement types or M&R treatments that had been in-service for relatively long periods and had been subjected to multiple applications of M&R (e.g., FDAC pavements), service life was determined largely by performing survival analysis using the historical records available documenting pavement and M&R treatment life. For pavement types that have been in service for only a relatively short period of time and have experienced few or no failures and corresponding M&R treatments (e.g., undrained JPC-D), pavement service life was primarily determined by projecting performance-based trends using pavement performance indicators, such as IRI. Detailed descriptions and results of the survival analyses performed are presented below.

Survival Analysis Results

Estimates of flexible and rigid pavement service life computed using survival analysis techniques are presented in tables 15 through 20. The information presented in these tables indicates the following:

- There were sufficient data for analysis of new FDAC. The cells seem to produce very similar estimates of pavement service life (mean = 12.7 years, standard deviation = 1.3 to 3.2 depending on the analysis method used).

- There were sufficient data for analysis of light category HMA overlays placed on FDAC. The cells seem to produce very similar estimates of pavement service life (mean ranges from 10.3 to 12.5 years and standard deviation ranges from 1.4 to 3.0 depending on the analysis method used).
- Most of the Districts did not have sufficient data for analysis of heavy category HMA overlays placed on FDAC. The estimates of service provided in table 17 are thus not reliable.
- There were sufficient data for analysis of new JPC-D (without drainable base) in Districts 2 through 6, where representative JPC-D projects were located. Estimated service life was 23.0 years.
- Service life estimates for light and heavy category HMA overlays placed on undrained JPC-D were 9.7 and 7.3 years, respectively. Note that these estimates are based on very limited data.

For the purpose of the analysis required for this study, the service life estimates presented according to Districts are adequate. Although statistically there may be variations in survival functions for different Districts for flexible and rigid pavements, practically, there is the need to obtain estimates of service life estimates that can be used statewide for life-cycle cost and other types of analyses.

Table 15: Service life estimates for original (i.e., new construction/reconstruction) flexible pavement structures, based on survival analysis.

Pavement Type	Analysis Type	Service Life Estimates by KDOT District, yrs						Mean, yrs	Std Dev, yrs
		1	2	3	4	5	6		
CAC	**N**	**19**	**45**	**62**	**41**	**28**	**21**		
	LifeTest	8.5	11.0	11.0	7.0	7.0	16.0	10.1	3.4
	LifeReg	10.1	11.0	11.7	10.1	10.2	14.9	11.3	1.9
FDAC	**N**	**249**	**151**	**180**	**155**	**150**	**149**		
	LifeTest	12.0	9.0	17.0	16.0	10.0	12.0	12.7	3.2
	LifeReg	12.5	11.0	12.8	15.1	12.5	12.4	12.7	1.3
DSAC	**N**	**11**	**15**		**17**	**15**			
	LifeTest				15.0			15.0	
	LifeReg	9.5	14.5		12.6			12.2	2.5

Table 16: Service life estimates for light-category HMA overlays on flexible pavement structures, based on survival analysis.

Pavement Type	Analysis Type	Service Life Estimates by KDOT District, yrs						Mean, yrs	Std Dev, yrs
		1	2	3	4	5	6		
HMA/CAC	**N**	**13**	**12**	**5**	**14**	**15**	**6**		
	LifeTest	7.0				8.0		7.5	0.7
	LifeReg	8.1				10.9	13.1	10.7	2.5
HMA/FDAC	**N**	**263**	**98**	**69**	**77**	**105**	**59**		
	LifeTest	9.0	15.0	9.0	13.0	9.0	7.0	10.3	3.0
	LifeReg	11.7	13.6	13.7	12.9	13.0	10.1	12.5	1.4
HMA/DSAC	**N**								
	LifeTest								
	LifeReg								

Table 17: Service life estimates for heavy-category HMA overlays on flexible pavement structures, based on survival analysis.

Pavement Type	Analysis Type	Service Life Estimates per KDOT District, yrs[1]						Mean, yrs	Std Dev, yrs
		1	2	3	4	5	6		
HMA/CAC	**N**	---	**3**	**34**	---	---	**10**	---	---
	LifeTest	---	---	12.0	---	---	---	12.0	---
	LifeReg	---	---	17.0	---	---	---	17.0	---
HMA/FDAC	**N**	**28**	**51**	**20**	**23**	**22**	**5**	---	---
	LifeTest	---	---	16.0	10.0		---	13.0	4.2
	LifeReg	---	---	18.0	7..3	19.1	---	18.6	0.8
HMA/DSAC	**N**	---	---	---	---	---	---	---	---
	LifeTest	---	---	---	---	---	---	---	---
	LifeReg	---	---	---	---	---	---	---	---

[1] Includes deep cold-recycle-and-overlay projects.

Table 18: Service life estimates for original (i.e., new construction/reconstruction) rigid pavement structures, based on survival analysis.

Pavement Type	Analysis Type		N	Percent Censored
	LifeTest	LifeReg		
JPC-ND	14.0	15.6	231	16.5
JPC-D (without drainable base)	---	23.0	856	94.8
JRC-D	20.0	19.6	321	44.2

Table 19: Service life estimates for light-category HMA overlays on rigid pavement structures, based on survival analysis.

Pavement Type	Analysis Type		N	Percent Censored
	LifeTest	LifeReg		
HMA/JPC-ND	6.0	8.7	33	66.7
HMA/JPC-D (without drainable base)	---	9.7	49	89.8
HMA/JRC-D	13.0	10.1	55	60.0

Table 20. Service life estimates for heavy-category HMA overlays on rigid pavement structures, based on survival analysis.

Pavement Type	Analysis Type		N	Percent Censored
	LifeTest	LifeReg		
HMA/JPC-ND	---	13.1	46	97.8
HMA/JPC-D (without drainable base)	---	7.3	16	87.5
HMA/JRC-D	---	14.5	50	94.0

For the rigid pavements, the service life estimates obtained from Districts 2 through 6 are representative of overall statewide conditions. For flexible pavements, however, additional analyses were performed to obtain statewide estimates of service life. New FDAC and HMA-overlaid FDAC survival functions developed and used to determine estimates of pavement service lives are presented in figures 15 through 17. Estimates of service life are presented in table 21.

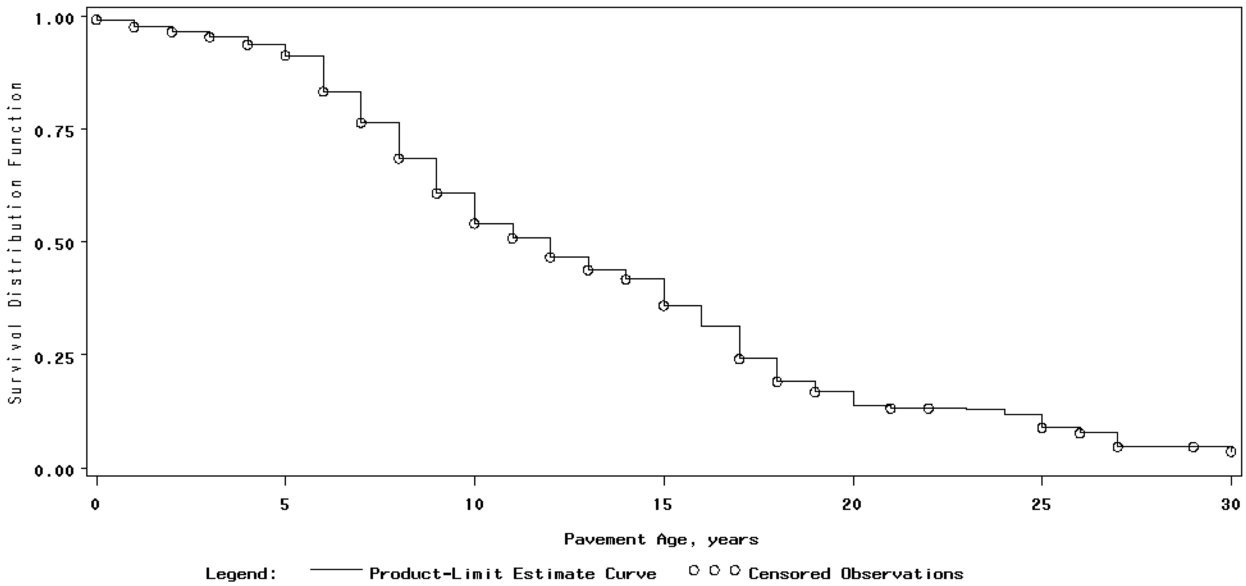


Figure 15: Plot showing statewide survival function for FDAC.

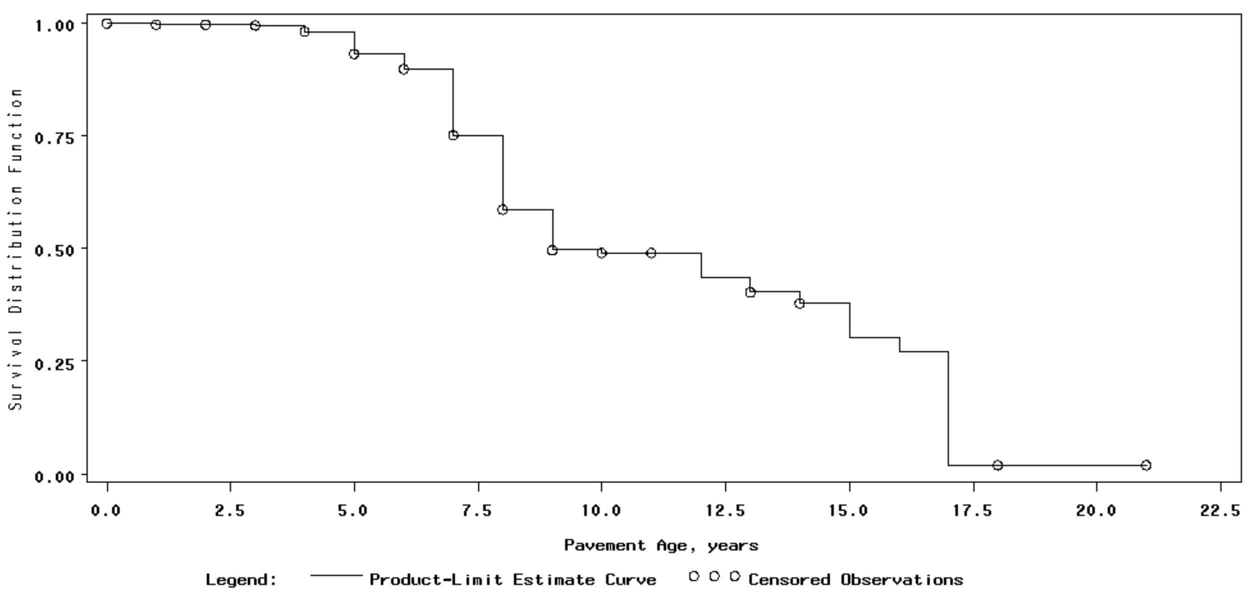


Figure 16: Plot showing statewide survival function for light-category HMA/FDAC.

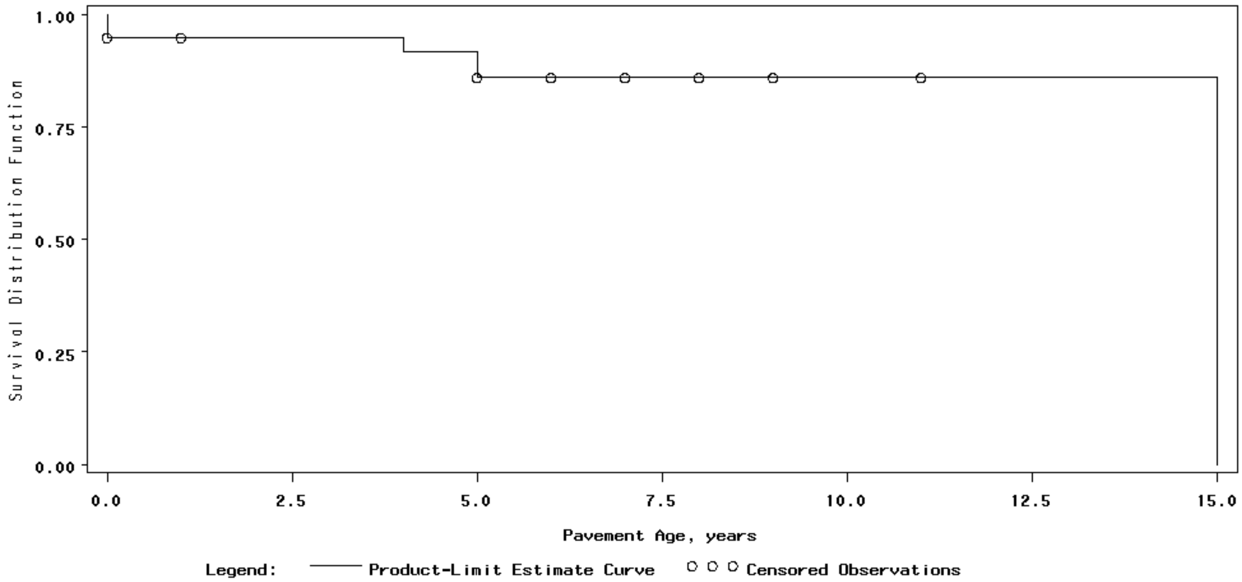


Figure 17: Plot showing statewide survival function for heavy-category HMA/FDAC.

Table 21: Statewide service life estimates for newly constructed/reconstructed flexible and rigid pavements and light- and heavy-category HMA overlays placed on original flexible and rigid pavements.

Pavement Type	Service Life Estimates			
	Survival Analysis			
	LifeTest	LifeReg	N	Percent Censored
CAC	11.0	11.3	216	17.1
DSAC		12.8	58	88
FDAC	12.0	12.7	1034	47.5
HMA/CAC (L)	9.0	12.2	65	83
HMA/CAC (H)				
HMA/DSAC (L)				
HMA/DSAC (H)				
HMA/FDAC (L)	9.0	12.4	671	72
HMA/FDAC (H)	16.0	13.8	149	89.9
JPC-ND	14.0	15.6	231	16.5
JPC-D (no drainable base)	---	23.0	856	94.8
JRC-D	20.0	19.6	321	44.2
HMA/JPC-ND (L)	6.0	8.7	33	66.7
HMA/JPC-D (no drainable base) (L)	---	9.7	49	89.8
HMA/JRC-D (L)	13.0	10.1	55	60.0
HMA/JPC-ND (H)	---	13.1	46	97.8
HMA/JPC-D (no drainable base) (H)	---	7.3	16	87.5
HMA/JRC-D (H)	---	14.5	50	94.0

STEP 4—PERFORMANCE TREND ANALYSES

Performance trend analysis consisted of the following steps:

A. Group unique PMIS sections according to new pavement type or rehabilitation type and KDOT action type.

B. Determine IRI thresholds corresponding to application of M&R treatments to flexible and rigid pavements.

C. Create time-series plots of pavement performance and develop performance models for each unique PMIS section.

D. Use the performance models/trends and IRI-based pavement performance thresholds to estimate service life of each unique PMIS section.

Step A—Group Unique PMIS Sections for Analysis

PMIS sections with performance data (IRI, rutting, faulting, and cracking) were grouped into the analysis cells presented in the final revised analysis matrix. In some cases, unique PMIS sections were placed in two or more analysis cells (e.g., FDAC and HMA/FDAC(L)), depending on the initial construction and subsequent M&R events for that given section. In evaluating the performance database, the issue of coded distress data surfaced. These coded data represent a range of distress rather than solid numerical data. Although an attempt was made to model these data, the results in terms of being able to forecast future performance were unsatisfactory. Thus, only IRI was used in the modeling effort of performance.

Step B—Determine IRI Thresholds for Each Group

Mean IRI thresholds were determined for both flexible and rigid pavements. The mean (50^{th} percentile) IRI threshold values were defined as the IRI value at which light or heavy M&R treatments occurred. As illustrated by the histogram in figure 18, a distribution of terminal IRI values for a particular pavement type was prepared, from which the mean IRI threshold could be estimated.

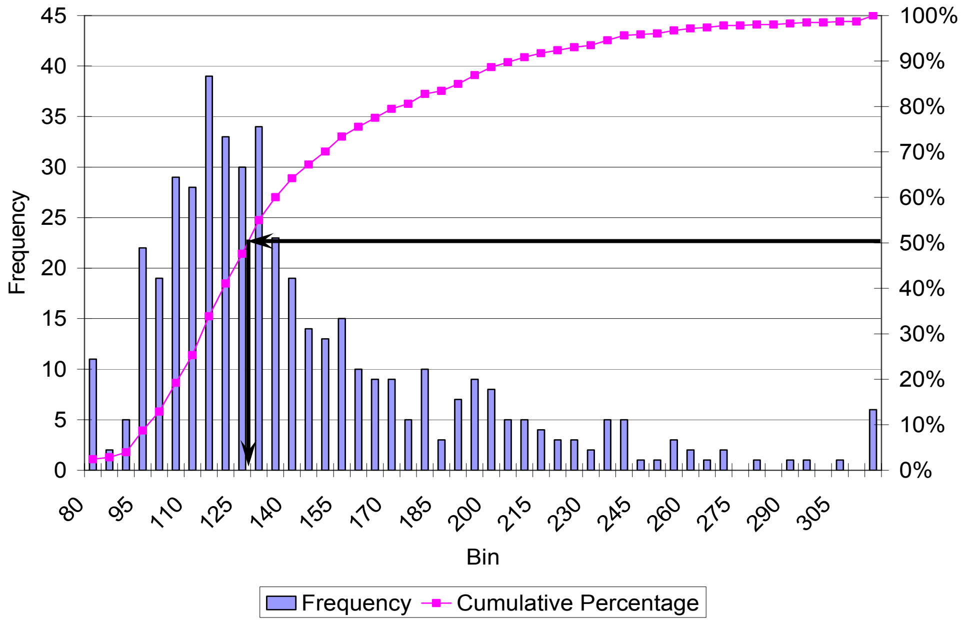


Figure 18: Example illustration of distribution of terminal IRI values.

The mean threshold values presented in table 22 represent the effect of typical KDOT practice. The information presented indicates that a threshold IRI value of 125 in/mi (1,973 mm/km) is reasonable for both FDAC and JPC-D.

Table 22: Threshold IRI values for various pavement types.

Pavement Type	IRI Mean Threshold Value, in/mi
CAC	125
DSAC	114
FDAC	123
JPC	126
JPC-D	124
JRC	115
JRC-D	142

1 in/mi = 15.78 mm/km

Step C—Create Time-Series Plots of Pavement Performance and Develop Performance Models

Plots of IRI versus pavement age were developed for each unique PMIS section. These plots were used to (1) select appropriate model forms for curve fitting and (2) determine model coefficients for the model forms selected to relate IRI to age. Different model types were considered for this study, but a simple non-linear model was found to be as accurate as the more complicated power law models. The non-linear model used and their coefficients are listed below:

$$IRI = INI\_IRI * e^{GR*AGE} \qquad \text{Equation 9}$$

where:

IRI	= International Roughness Index, in/mi.
INI_IRI	= Initial IRI (after construction or M&R) value (obtained through regression)
Age	= Pavement age, years.
GR	= growth rate (obtained through regression)
e	= 2.718

An example plot of IRI versus age and corresponding model for forecasting IRI is presented in figure 19 for PMIS ID 653027030310. Figures 20 shows a plot of predicted versus measured IRI for all the unique PMIS sections analyzed.

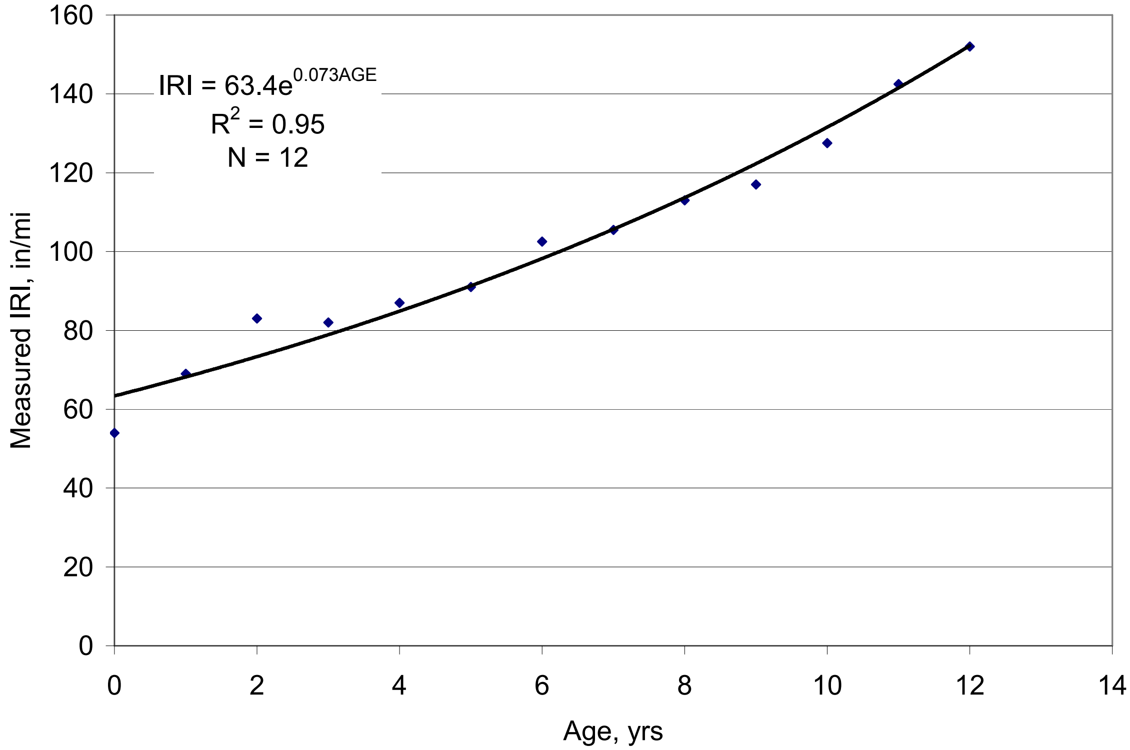


Figure 19: Plot of IRI versus age for KDOT PMIS ID 653027030310.

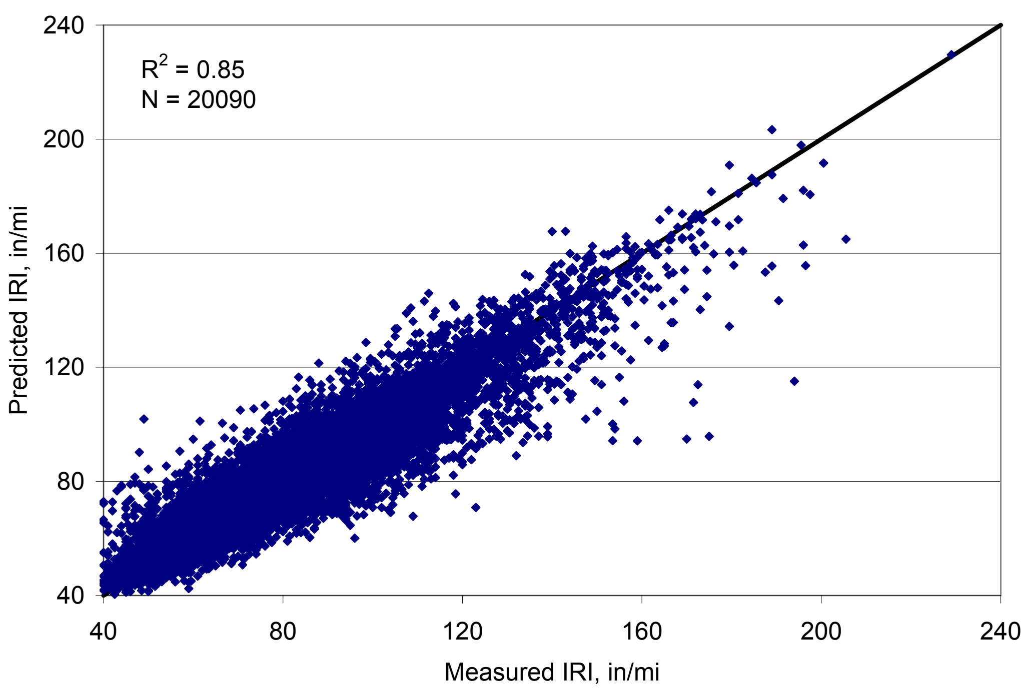


Figure 20: Plot of predicted versus measured IRI (for all KDOT unique PMIS sections analyzed).

Step D—Estimate Service Life

The service life of each PMIS section was determined as follows:

- For pavement sections where the IRI threshold values were exceeded, the service life was determined as the age when the terminal IRI value was reached. Linear interpolation was used to determine the specific age.
- For pavement sections where the IRI threshold values were not reached, the service life was determined through forecasting using section specific models to forecast or extrapolate future performance. The predicted performance was used to estimate the age at which the terminal IRI value is exceeded.

Using as inputs for survival analysis the database of estimates of unique pavement section life grouped according to the final revised analysis matrix, estimates of pavement and M&R service life were determined. The results are summarized in table 23.

Table 23: Estimates of pavement and M&R service life based on performance trend analysis.

Pavement Type	Service Life Estimate based on Performance Models[1]	N
FDAC	13.3	142
HMA/FDAC (L)	11.1	1395
HMA/FDAC (H)	20.6	96
JPC-D	19.4	246
HMA/JPC-D (L)	---	---
HMA/JPC-D (H)	---	---

[1] Threshold IRI for FDAC and JPC-D=125 in/mi (1,973 mm/km),

BEST ESTIMATES OF NEW PAVEMENT AND M&R SERVICE LIFE

As described throughout this chapter, different statistical modeling techniques were utilized to estimate new pavement and M&R treatment service life. All the techniques utilized have their strengths and weaknesses and thus may be more suitable for one given situation over another. For example, the LIFETEST procedure is most appropriate for situations where there is a large population of pavement projects with relatively few censored data. The LIFEREG procedure is more appropriate where there are sufficiently high numbers of censored data to make LIFETEST ineffective, but the number of censored data is not too large to make it impossible to model the survival function accurately. Performance trend analysis is most appropriate where it is not possible to obtain reasonable estimates from either LIFETEST or LIFEREG procedures.

The estimates of service life from all the techniques utilized in this study are summarized in table 24. Best estimates of pavement and M&R treatment service life, based on the appropriateness of each modeling technique, are presented in table 25. For FDAC, the LIFETEST was considered the strongest estimator of service life and 12 years was the recommended service life. Because of the large percentage of censored data in the survival analysis for JPC-D, the performance trend analysis estimate received a heavier weighting. Thus, the recommended service life for JPC-D is 20 years.

Table 24: Estimates of pavement and M&R service life from all modeling techniques used in this study.

Pavement or M&R Treatment Type	Service Life Estimates				
	Performance Trend Analysis	Survival Analysis			
		LIFETEST	LIFEREG	N	Percent Censored
CAC		11.0	11.3	216	17.1
DSAC			12.8	58	88
FDAC	13.3	12.0	12.7	1034	47.5
HMA/CAC (L)		9.0	12.2	65	83
HMA/CAC (H)					
HMA/DSAC (L)					
HMA/DSAC (H)					
HMA/FDAC (L)	11.1	9.0	12.4	671	72
HMA/FDAC (H)	20.6	16.0	13.8	149	89.9
JPC-ND		14.0	15.6	231	16.5
JPC-D (no drainable base)	19.4	---	23.0	856	94.8
JRC-D		20.0	19.6	321	44.2
HMA/JPC-ND (L)		6.0	8.7	33	66.7
HMA/JPC-D (no drainable base) (L)		---	9.7	49	89.8
HMA/JRC-D (L)		13.0	10.1	55	60.0
HMA/JPC-ND (H)		---	13.1	46	97.8
HMA/JPC-D (no drainable base) (H)		---	7.3	16	87.5
HMA/JRC-D (H)		---	14.5	50	94.0

Table 25: Best estimates of service life for new flexible and rigid pavements and light- and heavy-category HMA overlays.

Pavement Type	Service Life Estimate, yrs
CAC	11.0
DSAC	12.8
FDAC	12.0
HMA/CAC (L)	9.0
HMA/CAC (H)	---
HMA/DSAC (L)	---
HMA/DSAC (H)	---
HMA/FDAC (L)	9.0
HMA/FDAC (H)	13.8
JPC-ND	15.1
JPC-D	20.0
JRC-D	18
HMA/JPC-ND (L)	6.0
HMA/JPC-ND (H)	13.1
HMA/JPC-D (L)	9.7
HMA/JPC-D (H)	7.3
HMA/JRC-D (L)	10.1
HMA/JRC-D (H)	14.5

CHAPTER 5 - LIFE-CYCLE COST ANALYSIS

INTRODUCTION

Chapter 4 presented estimates of the timing from original construction to significant rehabilitation actions for plain jointed doweled concrete (JPC-D) and full depth asphalt concrete pavements (FDAC). These estimates, along with historical-based projections of the extents of future rehabilitation treatments (e.g., milling/recycling depths, overlay thicknesses, patching amounts), were used in the life-cycle cost analyses (LCCAs) of several recently completed KDOT projects, to assess the appropriateness of KDOT's JPC-D and FDAC life-cycle models. However, upon presentation of those LCCA results to government and industry representatives, questions were raised about the adequacy of the projected treatment extents and the resulting forecasted costs.

Subsequent to the presentation, it was determined that cost history data were available in the KDOT data base for contract rehabilitation work performed on the sections used in the development of the estimates of pavement performance lives. A process for utilizing these data to better estimate life-cycle costs was conceptualized and then attempted. This chapter briefly describes the process and presents the results of an initial attempt to extract and analyze the cost data from the KDOT database.

DISCUSSION OF THE PROCESS

Cost Factors for M&R Treatments

As discussed in chapter 3, KDOT categorizes M&R activities as Non-Structural, Light, or Heavy, based on the activity type and structural impact on existing pavement. The very thick HMA overlays and dowel bar retrofit of existing joints are typically categorized as Heavy treatments, while crack sealing and surface seals are categorized as Non-structural.

Categorization of M&R treatments for this study was made using the action type descriptions and criteria contained in the PMIS database (REHAB table). The categories are listed and described below.

- Non-structural (N)—maintenance treatments, such as chip seals, slurry seals, and crack sealing that add little if any structural capacity to the pavement. Essentially, these treatments are less than 1.5 in (38 mm) thick.
- Light (L)—Major maintenance or minor rehabilitation treatments, such as conventional or mill-and-fill overlays on flexible pavements and conventional overlays or minor CPR (limited patching with or without diamond grinding) on rigid pavements), that add some structure to the pavement and significantly improve the ride quality and other functional characteristics. With the exception of minor CPR, these treatments typically range in thickness between 1.5 and 3.0 in (38 and 75 mm).
- Heavy (H)—Major rehabilitation treatments, such as conventional or mill-and-fill overlays on flexible pavements and conventional overlays or major CPR (dowel bar retrofit or extensive patching, followed by diamond grinding) on concrete pavements, that add substantial structure to the pavement, while also improving functional characteristics. With the exception of major CPR, these treatments are essentially greater than 3.0 in (75 mm) thick.

Using various data extraction and manipulation techniques, a database was developed for JPC-D and FDAC containing the rehabilitation cost by year, control section, and rehabilitation category for each pavement type. Cost data were available for JPC-D pavements constructed since 1985 and FDAC pavements constructed since 1975. Review of the data indicated that weighted average 5-year cost data gave the most consistent results. The use of the 5-year weighted average tended to even out year-to-year variations in program funding and priorities. All of the costs are on a 2 lane per mile basis, adjusted for inflation to 2007 costs.

ANALYSIS PROCEDURE

Net present value (NPV) procedures were used for calculating the life-cycle rehabilitation costs for FDAC and JPC-D pavements. Three different analysis methods were used for estimating the life-cycle rehabilitation costs. They are briefly described below.

Method 1

This method follows the typical LCCA approach. It utilizes the timing for structural rehabilitation treatments (L and H) presented in chapter 4. In addition, the timing of the non-structural treatments (N) are estimated and included in the analysis. An example of Method 1 is illustrated in figure 21. The cost of each structural rehabilitation treatment is based on the relative percentage of the L and H treatments, by pavement type, during the 5-year period used to develop the cost values, and are referred to as $M\&R_{struc}$. $M\&R_{struc}$ values for FDAC and JPC-D were calculated as follows:

$$\$M\&R_{struc} = (L/(L+H))\times\$L + (L/(L+H))\times\$H \qquad \text{Equation 10}$$

Where: L = Number of L treatments.

H = Number of H treatments.

$L = Average cost of category L treatments.

$H = Average cost of category H treatments.

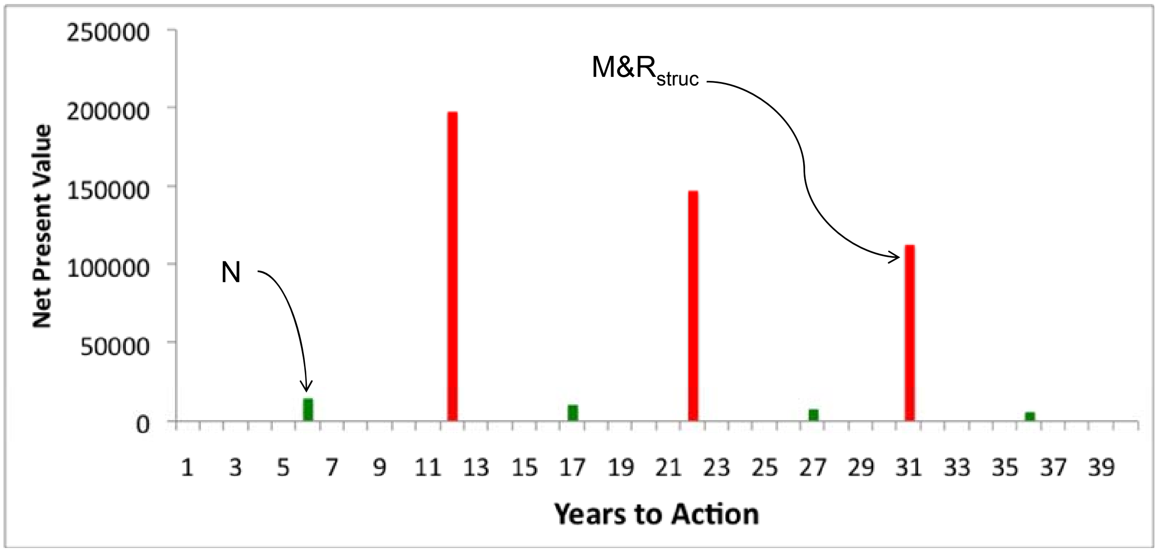


Figure 21: Example illustration of cost analysis Method 1.

Method 2

This method follows the same procedures as method 1 except that rather than using the estimated time and cost for individual N projects, the assumed average annual cost for N treatments per mile are used. To determine the average per mile N treatment cost, the total amount spent on N projects each year, by pavement type, are divided by the total number of miles of that pavement type. An example of Method 2 is illustrated in figure 22.

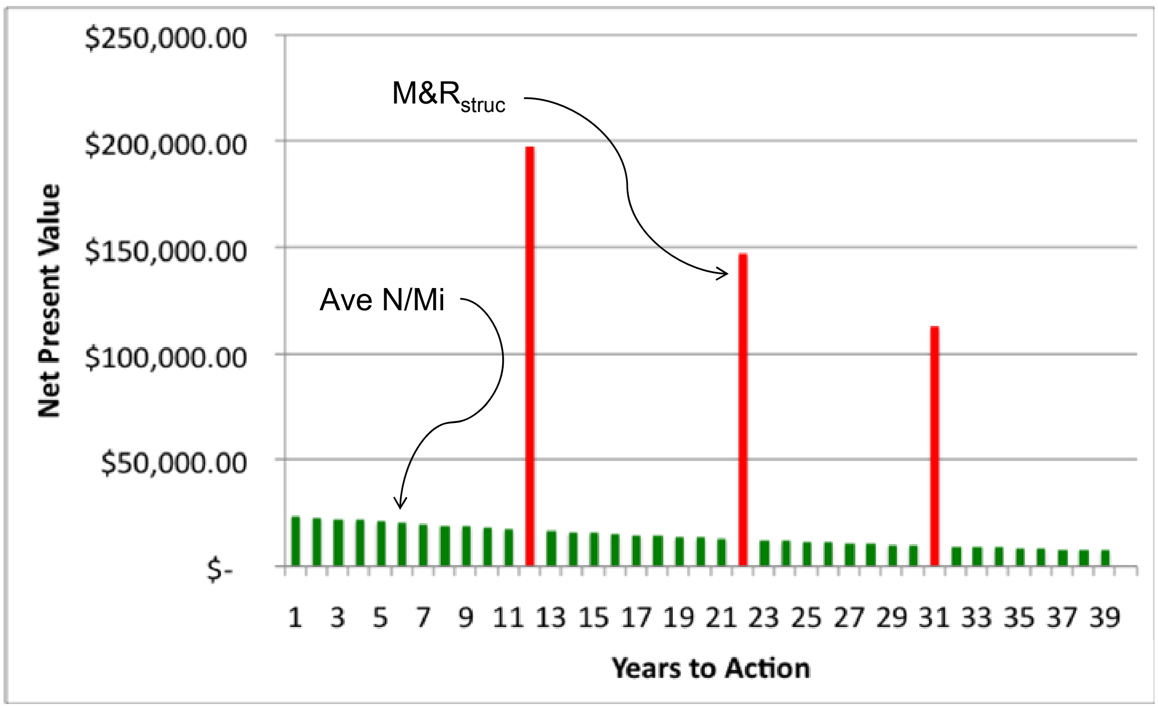


Figure 22: Example illustration of cost analysis Method 2.

Method 3

This method uses an average cost of ownership approach to determine total rehabilitation costs for each pavement type. In this approach, the total annual rehabilitation expenditures for each pavement type were determined. These total expenditures were then divided by the total miles of that pavement type to arrive at an average annual cost per mile.

This cost was then applied annually over the analysis period and a NPV calculated. An example of Method 3 is illustrated in figure 23.

Results

Cost data extracted from the KDOT databases were furnished in an Excel® workbook. Using various data querying, sorting, and processing techniques, spreadsheets were developed for JPC-D and FDAC that gave the rehabilitation cost by year and control section for each pavement type. The database utilized to develop the cost factors for N, L and H treatments consisted of the control sections representing the JPC-D pavements constructed since 1985 and the FDAC pavements constructed since 1974. Pavements constructed on drainable bases were excluded from the analysis, since this type of pavement is no longer built in Kansas.

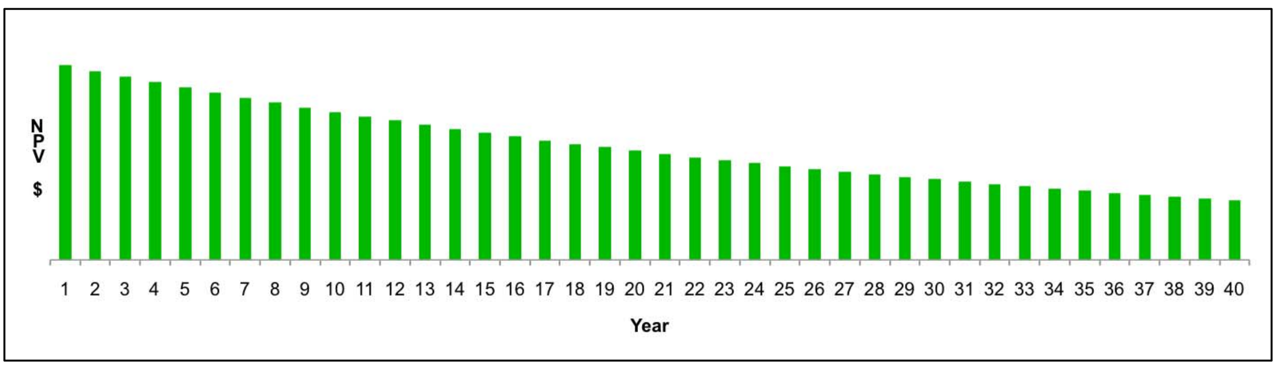


Figure 23: Example illustration of cost analysis Method 3.

The average cost values are based on project M&R project costs for projects performed during the 5-year period of 2001 through 2005. All of the costs were converted to a 2007 cost basis. Costs are on a 2 lane per mile basis and included costs per project by M&R type as well as overall average annual per mile M&R expenditures. The results are given in table 26. However, as discussed in the following paragraphs, the values shown in this table have serious deficiencies and are not suitable estimates of the life-cycle costs of JPC-D and FDAC pavements.

Table 26: Five-year average costs (ARA estimate).

	FDAC	JPC-D
Average per mile project costs		
Non-structural (N)	$17,077.87	$17,743.83
Light (L)	$60,925.65	$142,808.03
Heavy (H)	$441,664.34	$673,600.18
Average annual expenditure per mile of pavement		
Non-structural (N)	$4.90	$1,634.85
Combined N, L, and H	$25,432.06	$13,935.29

Upon reviewing the results shown in table 26, there was concern about the reasonableness of the average cost values, particularly as related to the cost and numbers of non-structural rehabilitation projects. In addition, there appeared to be inconsistencies in the coding of the light and heavy treatments.

Because of concern about the accuracy of the computed average rehabilitation costs, KDOT undertook an independent analysis of the cost data. The results of their analysis are presented in table 27. However, as discussed in the following paragraphs, the values shown in table 27 have serious deficiencies and are not suitable estimates of the life-cycle costs of JPC-D and FDAC pavements.

The inconsistency of results between the ARA and KDOT analysis to generate cost data for LCCA using historic data, showed weaknesses in the connectivity between the KDOT cost figures and the project history. Better ties between these data sources and significant cleansing of the data are needed before the historical cost data can be used for analyses. These include matching the year that costs are entered into the cost data base with the year entered in the history data base that describes the rehabilitation type (N, L, or H), and ensuring that the rehabilitation types are properly coded into the database.

Table 27: Five-year average costs (KDOT estimate).

	FDAC	***FDAC***	JPCP	JPCP-D	***JPCP***	***JRCP***
Average per mile project costs						
Non-structural (N)	$27,285	$26,222	$235,016	$263,893	$79,221	$83,652
Light (L)	$99,674	$83,947	$91,920	$81,794	$113,268	$140,395
Heavy (H)	$623,044	$223,732	$235,016	$2,196,205	$2,202,262	$752,347
Average Annual Expenditure per mile of pavement						
Non-Structural	$1,617	$1,880	$13,056	$743	$2,731	$4,334
Combined N, L, H	$9,171	$9,986	$21,912	$37,414	$46,702	$32,994

Labels with * * mean that any pavement type was used that included what is between the stars. Therefore, an HMA/JPCP-D will appear in the ***JPCP*** column but will not appear in the JPCP-D column.

Because satisfactory cost data could not be developed within the time and scope of this project, no attempt was made to perform the LCCA using the analysis methods described earlier. However, appendix A contains a more complete demonstration of the Analysis Methods 1, 2, and 3. The application of analysis method 3 would eliminate the need for performance modeling and future cost assumptions in the LCCA process. Before any of these methods can be formally utilized on project LCCAs, further development will be required. As noted in table A-16 of appendix A, there is a wide variation in the computed NPV of the rehabilitation costs using the current KDOT LCCA procedure. This is believed to be the result of variations in pavement width, traffic variation, and performance variations from district to district. Further analysis is recommended to develop regional average rehabilitation NPV values for low and high volume routes. In addition, correction factors may need to be developed for pavement width and other factors that impact rehabilitation costs.

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CHAPTER 6 - INCORPORATING TECHNOLOGICAL ADVANCES AND POLICY CHANGES

Pavement designs and materials being considered for projects today are subjected to higher demands than in the past. Consequently pavement design practices, materials selection and design, and construction practices are in a state of flux. AC mixture design has moved from the Marshall or Hveem procedures to the Superpave mixture design process. Asphalt mixtures now utilize polymers and special gradations to significantly delay the onset of cracking or rutting. PCC pavements in Kansas have incorporated more durable aggregates and have evolved from jointed reinforced doweled pavement to short jointed non-reinforced pavements, first non-doweled and now doweled. In addition, base types for the pavement have evolved from non-drainable bases to drainable bases and now to erosion-resistant non-drainable bases. As shown in the analysis in chapter 4, the various types of pavements have different performance lives.

Because of the constant evolution in pavement characteristics, it is important that the analysis of pavement performance be an integral part of the pavement management process. Continually updating pavement performance models will not only provide needed data for LCCA, it will also identify pavement performance issues. Examples of pavement performance results that may warrant follow-up are the survival functions for FDAC pavements by District. As shown in table 15, the survival analysis estimated a range of service lives of 9 years in District 2 to 17 years in District 3. These variations may be a function of materials or construction variations, traffic conditions, or a combination of these and other factors.

As part of this ongoing analysis process, we recommend that the databases described in chapter 3 be updated and expanded as necessary. On this project, two separate databases were developed using the assembled data. The first database, used for survival analysis, consisted mainly of project history information (project type, M&R history, traffic). The second, used for developing trends in performance, consisted of both project history information and performance data (e.g., IRI, faulting, and so on). The database for survival analysis is fairly straightforward, consisting primarily of project history data. The second database, which includes performance data, could be enhanced to make it more effective. The PMIS database has solid numerical IRI data, however distresses such as faulting, cracking, and rutting have severity codes that represent a range of distresses rather than a finite value. Faulting, cracking, and rutting are distresses considered in mechanistic-empirical (ME) design. It would be beneficial if numerical measurements were included in the database to allow the development of performance trends and the recalibration of the ME design procedure.

On this project, we used IRI data as a surrogate for distress data to estimate performance. Pavement distresses will result in an increase in IRI. In the MEPDG, it was shown that IRI can be modeled using key pavement distress types. For flexible pavements, these distress types include rutting, fatigue cracking, block cracking and longitudinal cracking, and for JPC pavements, transverse cracking, joint spalling, and joint faulting. On this project, the IRI at the time the various pavements were rehabilitated was determined. These “terminal” IRI values were used to estimate the performance lives of pavements that are still in service. This process was illustrated in chapter 4.

A major problem with using IRI as a surrogate is that certain early distress modes may be missed in the analysis. An example may be the early concrete joint deterioration that occurred on pavements constructed in District 1. This type of distress does not have a significant impact on IRI and could be overlooked in an IRI performance analysis.

On this project, we did not identify sufficient data to analyze specific new technologies. A suggested approach would be to determine what specific performance issue(s) a new technique addresses. Based on testing information, another State's experience, or the MEPDG, an estimate of the percentage increase in service life of the pavement could be made. An LCCA could then be performed to determine if the new technique was cost-effective. Once a new technique is implemented, performance and survivability data should be gathered to verify the initial assumption.

CHAPTER 7 - CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this study was to evaluate KDOT's pavement surfacing history and recommend whether or not the Department's LCCA procedure should include a surfacing history component, and, if so, how the LCCA process should be revised/updated to incorporate surfacing history.

To satisfy the project objectives, an intensive data collection and processing effort was undertaken. This effort involved obtaining the latest KDOT highway pavement databases and hardcopy records, reviewing the accuracy and completeness of the data, and, cleaning the data assembled, as needed, for analysis. The database created was used to perform survival analysis and performance trend analysis to develop estimates of (a) the service lives of newly constructed or reconstructed flexible and rigid pavements, and (b) the performance of M&R treatments, as delineated by KDOT action type.

The following conclusions and recommendations are based on the analysis of KDOT's data:

1. An analysis using KDOT's databases demonstrated that they could be used to estimate the service lives of new or reconstructed pavements, for use in the LCCA process.

   It is recommended that KDOT incorporate a process for performing survival and performance analysis of their in-service pavements as part of their pavement management process. With ongoing improvements in pavement design and materials, we would expect the performance lives to increase. This analysis is also a useful tool in identifying performance anomalies in specific regions of the state.

2. For the predominant pavement types used in Kansas, full depth asphalt concrete (FDAC) pavements and doweled, jointed plain concrete (JPC-D) pavements, service

lives were estimated to be 12 years and 20 years, respectively. These compare with 10 years and 20 years currently being used.

It is recommended that the LCCA procedure be modified to use estimated initial service lives of 12 years and 20 years for FDAC and JCP-D, respectively.

3. Only marginal success was achieved using the databases to estimate the types and service lives of the subsequent M&R treatments that are applied over the analysis period. However, the analysis indicates that the current estimates are reasonable.

   We recommend that the performance lives of M&R treatments continue to be monitored. Analysis results would be improved if there was greater definition of the treatments in the database, particularly as it relates to milling/recycle depths and overlay thicknesses.

4. The PMIS database has solid numerical IRI data, however, distresses such as faulting, cracking, and rutting have severity codes that represent a range of distress rather than a finite value. An example would be the following for faulting of rigid pavements:

   There are three faulting severity codes:

   F1: >0.125 in and <0.25 in (>3.2 mm and <6.4 mm)

   F2: 0.25 in to 0.5 in (6.4 mm to 12.7 mm)

   F3: >0.5 in (>12.7 mm)

   An attempt was made to model performance using the distress severity code, but the results were not satisfactory.

   The severity codes meet the needs of the pavement rehabilitation optimization program. However, the numerical measurements are needed to model performance or allow recalibration of the MEPDG design procedure. These measurements are currently being made and we understand they are included in the FDIST and RDIST databases.

We recommend that the state consider modifying their PMIS database to include the numerical measurements of pavement distresses that are predicted using the MEPDG. This will aid in the forecasting of pavement performance lives of in-service pavements and also permit an ongoing recalibration process of the MEPDG.

5. The impact of modifying the service lives for FDAC and JPC-D (on non-drainable base) was evaluated using the LCCA's of 12 recent KDOT construction/reconstruction projects. The LCCA's were obtained and re-computed using life-cycle models formulated from results of the performance analyses conducted for FDAC and JPC-D pavements and for the M&R treatments applied to them. It was found that the modified performances lives resulted in only a negligible change in the overall NPV for both pavement types on the 12 pavement projects evaluated.
6. The original intent when evaluating the life-cycle cost models was to define the make-up of each M&R treatment projected for FDAC and JPC-D pavement structures. However, the data in the database were deficient in the following regards:
    - The combination of mill-and-overlay or recycle-and overlay, according to the descriptions, did not match the absolute thickness.
    - The descriptions did not match the event (e.g., "Recy Cold 4", Overlay 1.5" for a PCC pavement).
    - Missing data.

Thus, while mean thicknesses were computed for light and heavy treatments, their reliability was unknown. Given these findings, it was decided to utilize the M&R treatments included in the KDOT analysis of the 12 recent LCCA's evaluated.

We recommend that, if KDOT continues to use traditional LCCA procedures, data be developed that better defines the cost and scope of the actual M&R treatments performed.

7. Subsequent to presentation of the draft final report, KDOT staff and industry expressed concerns that the analysis addressed historical timings of actions, but only tangentially included cost history. KDOT then provided historical project cost data in the hopes that it could be appropriately folded into the analysis. Three methodologies were developed to incorporate the historical cost data into the LCCA analysis and were presented in chapter 5.

   The three methodologies to incorporate historical cost data with the historical timing of action findings show promise. However, within the time and scope of this project, these costs could not be satisfactorily integrated. If such costs are obtained and appropriately integrated with the other sources of data, alternative methods of LCCA such as those explored in chapter 5 should produce an objective means of LCCA with fewer contentious external input demands. Work is needed to develop the systematic linkages to generate the inputs, but the methodologies are straightforward and sound.

   It is recommended that KDOT develop systematic, electronic, historical cost data tied to pavement projects and integrated with the other LCCA data sources to allow further pursuit of the alternative methods presented in chapter 5. Additional data may be needed such as a database to track pavement cores, which could be very useful in *determining if there are significant changes occurring in the structures of the pavements that is not addressed using the "average" analysis.*

8. The three alternative methods treat some costs as point-in-time and others as annualized costs. While all three alternative methods have merit, method 3 is particularly attractive because it moves away from needing prediction models to determine when or what will be needed for future M&R, and instead uses history to generate a cost of ownership for various pavement types.

   It is recommended that KDOT develop all three alternative methodologies and present these findings to KDOT executives and industry, such that a choice can be made between these alternatives and the current KDOT LCCA procedure. As part of this exercise, the sets of assumptions and ties to other key elements of the analysis for each of the three methods, including the need to track timings of actions and action type costs for methods 1 and 2, should be clearly listed.

9. KDOTs current LCCA methodology is reasonable and may be adjusted as stated in recommendations 1 through 6. Note that these adjustments to the current KDOT process are fairly small and the change in the timings of future actions had almost no impact on the LCCA outcomes. However, huge benefit can come from recommendations 7 and 8.

   It is recommended that KDOT modify the existing LCCA procedure to incorporate the revised timings of service lives of pavements (recommendation 2) while vigorously pursuing systematic historical cost data so that the method 3 cost analysis described in chapter 5 can be further explored and eventually employed. With method 3, *recommendations 1, 2, 3, 4, and 6 become moot and many of the contentious issues in LCCA become irrelevant.*

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APPENDIX A. DEMONSTRATION OF COST ANALYSIS METHODS

INTRODUCTION

Chapter 5 presented alternative methods for performing life-cycle cost analysis (LCCA). However, attempts to generate cost estimates using historic data could not be successfully developed within the time and scope of this project. The purpose of this appendix is to demonstrate the proposed alternative methods of LCCA using assumed cost data.

COST FACTORS FOR M&R TREATMENTS

The assumed 2-lane per mile project costs by M&R type, as well as overall average annual per mile M&R expenditures are given in table A-1.

Table A-1: Assumed 2-lane-mile average costs.

	FDAC Pavement	JPC-D Pavement
Average per mile project costs		
Non-structural (N)	$15,000	$20,000
Light (L)	$100,000	$85,000
Heavy (H)	$600,000	$2,000,000
Average annual expenditure per mile of pavement		
Non-structural (N)	$1200	$600
Combined N, L, and H	$27,500	$27,500

DEMONSTRATION ANALYSIS PROCEDURE

Net present value (NPV) procedures were calculated for the life-cycle rehabilitation costs for FDAC and JPC-D pavements. The assumed average costs shown in table A-1 were used in the demonstration analysis. Three different analysis methods were used to estimate the life-cycle rehabilitation costs.

Method 1

This method followed the typical LCCA approach. It utilized the timing for structural rehabilitation treatments (L and H) presented in chapter 4. In addition, the timings of the N treatments were estimated and included in the analysis. The cost of each structural rehabilitation treatment was based on the relative percentage of the L and H treatments during the 5-year period used to develop the cost values in table A-1, and are referred to as $M\&R_{struc}$. $M\&R_{struc}$ values for FDAC and JPC-D were calculated as follows:

FDAC (assumes the mix of structural rehabilitation types was 42% Light and 58% Heavy)

$$M\&R_{struc} = 0.42(L) + 0.58(H) = 0.42(100{,}000) + 0.58(600{,}000) = \$390{,}000$$

JPC-D (assumes the mix of structural rehabilitation types was 66% Light and 34% Heavy)

$$M\&R_{struc} = 0.66(L) + 0.34(H) = 0.66(85{,}000) + 0.34(2{,}000{,}000) = \$736{,}100$$

Method 2

This method followed the same procedures as Method 1 except that rather than using the estimated time and cost for individual N projects, the assumed average annual cost per mile for N treatments was used. The average per mile N treatment cost was determined by taking the total amount spent each year on N projects by pavement type and dividing it by the total number of miles of that pavement type.

Method 3

This method used an average cost of ownership approach to determine total rehabilitation costs for each pavement type. In this approach, the total annual rehabilitation expenditures for each pavement type were determined. These total expenditures were then divided by the total miles of that pavement type to arrive at an average annual cost per mile. This cost was then applied annually over the analysis period, from which NPV was then calculated.

RESULTS OF THE DEMONSTRATION ANALYSIS FOR FDAC PAVEMENTS

Tables A-2 through A-7 illustrate the approaches and results of the demonstration analyses for FDAC pavements. Both 30- and 40-year analysis periods were used with each of the three analysis methods.

Table A-2: FDAC life-cycle costs using Method 1 and 30-year analysis period.

Year	Treatment	Cost (Constant 2007 Dollars)	NPV (3% discount rate)
6	Non-structural	$15,000	$12,495
12	$M\&R_{struc}$	$390,000	$270,599
17	Non-structural	$15,000	$8937
22	$M\&R_{struc}$	$390,000	$199,546
27	Non-structural	$15,000	$6591
TOTAL			$498,167

Table A-3: FDAC life-cycle costs using Method 1 and 40-year analysis period.

Year	Treatment	Cost (Constant 2007 Dollars)	NPV (3% discount rate)
6	Non-structural	$15,000	$12,495
12	$M\&R_{struc}$	$390,000	$270,599
17	Non-structural	$15,000	$8937
22	$M\&R_{struc}$	$390,000	$199,546
27	Non-structural	$15,000	$6591
31	$M\&R_{struc}$	$390,000	$151,701
36	Non-structural	$15,000	$5010
TOTAL			$654,878

Table A-4: FDAC life-cycle costs using Method 2 and 30-year analysis period.

Year	Treatment	Cost (Constant 2007 Dollars)	NPV (3% discount rate)
1	Ave. annual per Mile N cost	$1200	$1164
2	Ave. annual per Mile N cost	$1200	$1129
3	Ave. annual per Mile N cost	$1200	$1095
4	Ave. annual per Mile N cost	$1200	$1062
5	Ave. annual per Mile N cost	$1200	$1030
6	Ave. annual per Mile N cost	$1200	$1000
7	Ave. annual per Mile N cost	$1200	$970
8	Ave. annual per Mile N cost	$1200	$940
9	Ave. annual per Mile N cost	$1200	$912
10	Ave. annual per Mile N cost	$1200	$885
11	Ave. annual per Mile N cost	$1200	$858
12	$M\&R_{struc}$	$390,000	$270,599
13	Ave. annual per Mile N cost	$1200	$808
14	Ave. annual per Mile N cost	$1200	$783
15	Ave. annual per Mile N cost	$1200	$760
16	Ave. annual per Mile N cost	$1200	$737
17	Ave. annual per Mile N cost	$1200	$715
18	Ave. annual per Mile N cost	$1200	$694
19	Ave. annual per Mile N cost	$1200	$673
20	Ave. annual per Mile N cost	$1200	$653
21	Ave. annual per Mile N cost	$1200	$633
22	$M\&R_{struc}$	$390,000	$199,546
23	Ave. annual per Mile N cost	$1200	$596
24	Ave. annual per Mile N cost	$1200	$578
25	Ave. annual per Mile N cost	$1200	$560
26	Ave. annual per Mile N cost	$1200	$544
27	Ave. annual per Mile N cost	$1200	$527
28	Ave. annual per Mile N cost	$1200	$511
29	Ave. annual per Mile N cost	$1200	$496
Total			$491,458

Table A-5: FDAC life-cycle costs using Method 2 and 40-year analysis period.

Year	Treatment	Cost (Constant 2007 Dollars)	NPV (3% discount rate)
1	Ave. annual per Mile N cost	$1200	$1164
2	Ave. annual per Mile N cost	$1200	$1129
3	Ave. annual per Mile N cost	$1200	$1095
4	Ave. annual per Mile N cost	$1200	$1062
5	Ave. annual per Mile N cost	$1200	$1030
6	Ave. annual per Mile N cost	$1200	$1000
7	Ave. annual per Mile N cost	$1200	$970
8	Ave. annual per Mile N cost	$1200	$940
9	Ave. annual per Mile N cost	$1200	$912
10	Ave. annual per Mile N cost	$1200	$885
11	Ave. annual per Mile N cost	$1200	$858
12	$M\&R_{struc}$	$390,000	$270,599
13	Ave. annual per Mile N cost	$1200	$808
14	Ave. annual per Mile N cost	$1200	$783
15	Ave. annual per Mile N cost	$1200	$760
16	Ave. annual per Mile N cost	$1200	$737
17	Ave. annual per Mile N cost	$1200	$715
18	Ave. annual per Mile N cost	$1200	$694
19	Ave. annual per Mile N cost	$1200	$673
20	Ave. annual per Mile N cost	$1200	$653
21	Ave. annual per Mile N cost	$1200	$633
22	$M\&R_{struc}$	$390,000	$199,546
23	Ave. annual per Mile N cost	$1200	$596
24	Ave. annual per Mile N cost	$1200	$578
25	Ave. annual per Mile N cost	$1200	$560
26	Ave. annual per Mile N cost	$1200	$544
27	Ave. annual per Mile N cost	$1200	$527
28	Ave. annual per Mile N cost	$1200	$511
29	Ave. annual per Mile N cost	$1200	$496
30	$M\&R_{struc}$	$390,000	$156,393
31	Ave. annual per Mile N cost	$1200	$467
32	Ave. annual per Mile N cost	$1200	$453
33	Ave. annual per Mile N cost	$1200	$439
34	Ave. annual per Mile N cost	$1200	$426
35	Ave. annual per Mile N cost	$1200	$413
36	Ave. annual per Mile N cost	$1200	$401
37	Ave. annual per Mile N cost	$1200	$389
38	Ave. annual per Mile N cost	$1200	$377
39	Ave. annual per Mile N cost	$1200	$366
Total			$651,581

Table A-6: FDAC life-cycle costs using Method 3 and 30-year analysis period.

Year	Treatment	Cost (Constant 2007 Dollars)	NPV (3% discount rate)
1	Ave. annual per Mile M&R cost	$27,500	$26,675
2	Ave. annual per Mile M&R cost	$27,500	$25,875
3	Ave. annual per Mile M&R cost	$27,500	$25,099
4	Ave. annual per Mile M&R cost	$27,500	$24,346
5	Ave. annual per Mile M&R cost	$27,500	$23,615
6	Ave. annual per Mile M&R cost	$27,500	$22,907
7	Ave. annual per Mile M&R cost	$27,500	$22,220
8	Ave. annual per Mile M&R cost	$27,500	$21,553
9	Ave. annual per Mile M&R cost	$27,500	$20,906
10	Ave. annual per Mile M&R cost	$27,500	$20,279
11	Ave. annual per Mile M&R cost	$27,500	$19,671
12	Ave. annual per Mile M&R cost	$27,500	$19,081
13	Ave. annual per Mile M&R cost	$27,500	$18,508
14	Ave. annual per Mile M&R cost	$27,500	$17,953
15	Ave. annual per Mile M&R cost	$27,500	$17,414
16	Ave. annual per Mile M&R cost	$27,500	$16,892
17	Ave. annual per Mile M&R cost	$27,500	$16,385
18	Ave. annual per Mile M&R cost	$27,500	$15,894
19	Ave. annual per Mile M&R cost	$27,500	$15,417
20	Ave. annual per Mile M&R cost	$27,500	$14,954
21	Ave. annual per Mile M&R cost	$27,500	$14,506
22	Ave. annual per Mile M&R cost	$27,500	$14,071
23	Ave. annual per Mile M&R cost	$27,500	$13,648
24	Ave. annual per Mile M&R cost	$27,500	$13,239
25	Ave. annual per Mile M&R cost	$27,500	$12,842
26	Ave. annual per Mile M&R cost	$27,500	$12,457
27	Ave. annual per Mile M&R cost	$27,500	$12,083
28	Ave. annual per Mile M&R cost	$27,500	$11,720
29	Ave. annual per Mile M&R cost	$27,500	$11,369
Total			$521,577

Table A-7: FDAC life-cycle costs using Method 3 and 40-year analysis period.

Year	Treatment	Cost (Constant 2007 Dollars)	NPV (3% discount rate)
1	Ave. annual per Mile M&R cost	$27,500	$26,675
2	Ave. annual per Mile M&R cost	$27,500	$25,875
3	Ave. annual per Mile M&R cost	$27,500	$25,099
4	Ave. annual per Mile M&R cost	$27,500	$24,346
5	Ave. annual per Mile M&R cost	$27,500	$23,615
6	Ave. annual per Mile M&R cost	$27,500	$22,907
7	Ave. annual per Mile M&R cost	$27,500	$22,220
8	Ave. annual per Mile M&R cost	$27,500	$21,553
9	Ave. annual per Mile M&R cost	$27,500	$20,906
10	Ave. annual per Mile M&R cost	$27,500	$20,279
11	Ave. annual per Mile M&R cost	$27,500	$19,671
12	Ave. annual per Mile M&R cost	$27,500	$19,081
13	Ave. annual per Mile M&R cost	$27,500	$18,508
14	Ave. annual per Mile M&R cost	$27,500	$17,953
15	Ave. annual per Mile M&R cost	$27,500	$17,414
16	Ave. annual per Mile M&R cost	$27,500	$16,892
17	Ave. annual per Mile M&R cost	$27,500	$16,385
18	Ave. annual per Mile M&R cost	$27,500	$15,894
19	Ave. annual per Mile M&R cost	$27,500	$15,417
20	Ave. annual per Mile M&R cost	$27,500	$14,954
21	Ave. annual per Mile M&R cost	$27,500	$14,506
22	Ave. annual per Mile M&R cost	$27,500	$14,071
23	Ave. annual per Mile M&R cost	$27,500	$13,648
24	Ave. annual per Mile M&R cost	$27,500	$13,239
25	Ave. annual per Mile M&R cost	$27,500	$12,842
26	Ave. annual per Mile M&R cost	$27,500	$12,457
27	Ave. annual per Mile M&R cost	$27,500	$12,083
28	Ave. annual per Mile M&R cost	$27,500	$11,720
29	Ave. annual per Mile M&R cost	$27,500	$11,369
30	Ave. annual per Mile M&R cost	$27,500	$11,028
31	Ave. annual per Mile M&R cost	$27,500	$10,697
32	Ave. annual per Mile M&R cost	$27,500	$10,376
33	Ave. annual per Mile M&R cost	$27,500	$10,065
34	Ave. annual per Mile M&R cost	$27,500	$9763
35	Ave. annual per Mile M&R cost	$27,500	$9470
36	Ave. annual per Mile M&R cost	$27,500	$9186
37	Ave. annual per Mile M&R cost	$27,500	$8910
38	Ave. annual per Mile M&R cost	$27,500	$8643
39	Ave. annual per Mile M&R cost	$27,500	$8384
Total			$618,097

RESULTS OF THE DEMONSTRATION ANALYSIS FOR JPC-D PAVEMENTS

Tables A-8 through A-13 illustrate the approaches and results of the demonstration analyses for JCP-D pavements. Again, both 30- and 40-year analysis periods were used with each of the three analysis methods.

Table A-8: JPC-D life-cycle costs using Method 1 and 30-year analysis period.

Year	Treatment	Cost (Constant 2007 Dollars)	NPV (3% discount rate)
8	Non-structural	$20,000	$15,675
15	Non-structural	$20,000	$12,665
20	$M\&R_{struc}$	$736,100	$400,287
25	Non-structural	$20,000	$9339
Total			$437,966

Table A-9: JPC-D life-cycle costs using Method 1 and 40-year analysis period.

Year	Treatment	Cost (Constant 2007 Dollars)	NPV (3% discount rate)
8	Non-structural	$20,000	$15,675
15	Non-structural	$20,000	$12,665
20	$M\&R_{struc}$	$736,100	$400,287
25	Non-structural	$20,000	$9339
30	$M\&R_{struc}$	$736,100	$295,181
35	Non-structural	$20,000	$6887
Total			$740,035

Table A-10: JPC-D life-cycle costs using Method 2 and 30-year analysis period.

Year	Treatment	Cost (Constant 2007 Dollars)	NPV (3% discount rate)
1	Ave. annual per Mile N cost	$600	$582
2	Ave. annual per Mile N cost	$600	$564
3	Ave. annual per Mile N cost	$600	$548
4	Ave. annual per Mile N cost	$600	$531
5	Ave. annual per Mile N cost	$600	$515
6	Ave. annual per Mile N cost	$600	$500
7	Ave. annual per Mile N cost	$600	$485
8	Ave. annual per Mile N cost	$600	$470
9	Ave. annual per Mile N cost	$600	$456
10	Ave. annual per Mile N cost	$600	$442
11	Ave. annual per Mile N cost	$600	$429
12	Ave. annual per Mile N cost	$600	$416
13	Ave. annual per Mile N cost	$600	$404
14	Ave. annual per Mile N cost	$600	$392
15	Ave. annual per Mile N cost	$600	$380
16	Ave. annual per Mile N cost	$600	$369
17	Ave. annual per Mile N cost	$600	$357
18	Ave. annual per Mile N cost	$600	$347
19	Ave. annual per Mile N cost	$600	$336
20	$M\&R_{struc}$	$736,100	$400,287
21	Ave. annual per Mile N cost	$600	$316
22	Ave. annual per Mile N cost	$600	$307
23	Ave. annual per Mile N cost	$600	$298
24	Ave. annual per Mile N cost	$600	$289
25	Ave. annual per Mile N cost	$600	$280
26	Ave. annual per Mile N cost	$600	$272
27	Ave. annual per Mile N cost	$600	$264
28	Ave. annual per Mile N cost	$600	$256
29	Ave. annual per Mile N cost	$600	$248
Total			$411,341

Table A-11: JPC-D life-cycle costs using Method 2 and 40-year analysis period.

Year	Treatment	Cost (Constant 2007 Dollars)	NPV (3% discount rate)
1	Ave. annual per Mile N cost	$600	$582
2	Ave. annual per Mile N cost	$600	$564
3	Ave. annual per Mile N cost	$600	$548
4	Ave. annual per Mile N cost	$600	$531
5	Ave. annual per Mile N cost	$600	$515
6	Ave. annual per Mile N cost	$600	$500
7	Ave. annual per Mile N cost	$600	$485
8	Ave. annual per Mile N cost	$600	$470
9	Ave. annual per Mile N cost	$600	$456
10	Ave. annual per Mile N cost	$600	$442
11	Ave. annual per Mile N cost	$600	$429
12	Ave. annual per Mile N cost	$600	$416
13	Ave. annual per Mile N cost	$600	$404
14	Ave. annual per Mile N cost	$600	$392
15	Ave. annual per Mile N cost	$600	$380
16	Ave. annual per Mile N cost	$600	$369
17	Ave. annual per Mile N cost	$600	$357
18	Ave. annual per Mile N cost	$600	$347
19	Ave. annual per Mile N cost	$600	$336
20	$M\&R_{struc}$	$736,100	$400,287
21	Ave. annual per Mile N cost	$600	$316
22	Ave. annual per Mile N cost	$600	$307
23	Ave. annual per Mile N cost	$600	$298
24	Ave. annual per Mile N cost	$600	$289
25	Ave. annual per Mile N cost	$600	$280
26	Ave. annual per Mile N cost	$600	$272
27	Ave. annual per Mile N cost	$600	$264
28	Ave. annual per Mile N cost	$600	$256
29	Ave. annual per Mile N cost	$600	$248
30	$M\&R_{struc}$	$736,100	$295,181
31	Ave. annual per Mile N cost	$600	$233
32	Ave. annual per Mile N cost	$600	$226
33	Ave. annual per Mile N cost	$600	$220
34	Ave. annual per Mile N cost	$600	$213
35	Ave. annual per Mile N cost	$600	$207
36	Ave. annual per Mile N cost	$600	$200
37	Ave. annual per Mile N cost	$600	$194
38	Ave. annual per Mile N cost	$600	$189
39	Ave. annual per Mile N cost	$600	$183
Total			$708,387

Table A-12: JPC-D life-cycle costs using Method 3 and 30-year analysis period.

Year	Treatment	Cost (Constant 2007 Dollars)	NPV (3% discount rate)
1	Ave. annual per Mile M&R cost	$27,500	$26,675
2	Ave. annual per Mile M&R cost	$27,500	$25,875
3	Ave. annual per Mile M&R cost	$27,500	$25,099
4	Ave. annual per Mile M&R cost	$27,500	$24,346
5	Ave. annual per Mile M&R cost	$27,500	$23,615
6	Ave. annual per Mile M&R cost	$27,500	$22,907
7	Ave. annual per Mile M&R cost	$27,500	$22,220
8	Ave. annual per Mile M&R cost	$27,500	$21,553
9	Ave. annual per Mile M&R cost	$27,500	$20,906
10	Ave. annual per Mile M&R cost	$27,500	$20,279
11	Ave. annual per Mile M&R cost	$27,500	$19,671
12	Ave. annual per Mile M&R cost	$27,500	$19,081
13	Ave. annual per Mile M&R cost	$27,500	$18,508
14	Ave. annual per Mile M&R cost	$27,500	$17,953
15	Ave. annual per Mile M&R cost	$27,500	$17,414
16	Ave. annual per Mile M&R cost	$27,500	$16,892
17	Ave. annual per Mile M&R cost	$27,500	$16,385
18	Ave. annual per Mile M&R cost	$27,500	$15,894
19	Ave. annual per Mile M&R cost	$27,500	$15,417
20	Ave. annual per Mile M&R cost	$27,500	$14,954
21	Ave. annual per Mile M&R cost	$27,500	$14,506
22	Ave. annual per Mile M&R cost	$27,500	$14,071
23	Ave. annual per Mile M&R cost	$27,500	$13,648
24	Ave. annual per Mile M&R cost	$27,500	$13,239
25	Ave. annual per Mile M&R cost	$27,500	$12,842
26	Ave. annual per Mile M&R cost	$27,500	$12,457
27	Ave. annual per Mile M&R cost	$27,500	$12,083
28	Ave. annual per Mile M&R cost	$27,500	$11,720
29	Ave. annual per Mile M&R cost	$27,500	$11,369
Total			$521,577

Table A-13: JPC-D life-cycle costs using Method 3 and 40-year analysis period.

Year	Treatment	Cost (Constant 2007 Dollars)	NPV (3% discount rate)
1	Ave. annual per Mile M&R cost	$27,500	$26,675
2	Ave. annual per Mile M&R cost	$27,500	$25,875
3	Ave. annual per Mile M&R cost	$27,500	$25,099
4	Ave. annual per Mile M&R cost	$27,500	$24,346
5	Ave. annual per Mile M&R cost	$27,500	$23,615
6	Ave. annual per Mile M&R cost	$27,500	$22,907
7	Ave. annual per Mile M&R cost	$27,500	$22,220
8	Ave. annual per Mile M&R cost	$27,500	$21,553
9	Ave. annual per Mile M&R cost	$27,500	$20,906
10	Ave. annual per Mile M&R cost	$27,500	$20,279
11	Ave. annual per Mile M&R cost	$27,500	$19,671
12	Ave. annual per Mile M&R cost	$27,500	$19,081
13	Ave. annual per Mile M&R cost	$27,500	$18,508
14	Ave. annual per Mile M&R cost	$27,500	$17,953
15	Ave. annual per Mile M&R cost	$27,500	$17,414
16	Ave. annual per Mile M&R cost	$27,500	$16,892
17	Ave. annual per Mile M&R cost	$27,500	$16,385
18	Ave. annual per Mile M&R cost	$27,500	$15,894
19	Ave. annual per Mile M&R cost	$27,500	$15,417
20	Ave. annual per Mile M&R cost	$27,500	$14,954
21	Ave. annual per Mile M&R cost	$27,500	$14,506
22	Ave. annual per Mile M&R cost	$27,500	$14,071
23	Ave. annual per Mile M&R cost	$27,500	$13,648
24	Ave. annual per Mile M&R cost	$27,500	$13,239
25	Ave. annual per Mile M&R cost	$27,500	$12,842
26	Ave. annual per Mile M&R cost	$27,500	$12,457
27	Ave. annual per Mile M&R cost	$27,500	$12,083
28	Ave. annual per Mile M&R cost	$27,500	$11,720
29	Ave. annual per Mile M&R cost	$27,500	$11,369
30	Ave. annual per Mile M&R cost	$27,500	$11,028
31	Ave. annual per Mile M&R cost	$27,500	$10,697
32	Ave. annual per Mile M&R cost	$27,500	$10,376
33	Ave. annual per Mile M&R cost	$27,500	$10,065
34	Ave. annual per Mile M&R cost	$27,500	$9763
35	Ave. annual per Mile M&R cost	$27,500	$9470
36	Ave. annual per Mile M&R cost	$27,500	$9186
37	Ave. annual per Mile M&R cost	$27,500	$8910
38	Ave. annual per Mile M&R cost	$27,500	$8643
39	Ave. annual per Mile M&R cost	$27,500	$8384
Total			$618,097

EVALUATION OF RESULTS

The results of the demonstration analyses (based on assumed costs) were used to evaluate current KDOT procedures. To assist in the evaluation, KDOT supplied the LCCA results for twelve pavement projects throughout Kansas. The locations of these projects can be seen in figure A-1. The projects consisted of new construction/reconstruction projects, located mostly on 2- or 4-lane US routes, with a couple located on Interstates. Brief descriptions of the projects are given below.

1. US 50 Reno County (50-78 K-7409-02)—Reconstruction of 2.89 mi (4.65 km) of 4-lane divided highway (2-way ADT=5,000+, %Trucks≈30%). Two design alternatives consisting of 17-in (430-mm) FDAC or 11-in (280-mm) JPC-D placed on 4-in (100-mm) CTB. A 30-year analysis period was utilized in the LCCA.
2. US 54 Kingman County (54-48 K-8244-01)—Reconstruction of 5.82 mi (9.37 km) of 4-lane divided highway (2-way ADT≈5,400, %Trucks≈25%). Three design alternatives consisting of 15.75-in (400-mm) FDAC, 18-in (460-mm) FDAC, or 9.5-in (240-mm) JPC-D placed on 4-in (100-mm) CTB. A 30-year analysis period was utilized in the LCCA.
3. US 50 Finney County (50-28 K-8246-01)—Reconstruction of 8.40 mi (13.52 km) of 4-lane divided highway (2-way ADT≈5,200, %Trucks≈23%). Two design alternatives consisting of 17-in (430-mm) FDAC or 10-in (250-mm) JPC-D placed on 4-in (100-mm) CTB. A 40-year analysis period was utilized in the LCCA.
4. US 169 Montgomery County (169-63 K-8241-01)—Reconstruction of 7.55 mi (12.16 km) of 4-lane divided highway (2-way ADT≈5,100, %Trucks≈30%). Two design alternatives consisting of 13.5-in (340-mm) FDAC or 9.5-in (240-mm) JPC-D placed on 4-in (100-mm) CTB. A 30-year analysis period was utilized in the LCCA.

5. US 54 Meade County (54-60 K-7410-01)—Reconstruction of 1.15 mi (1.85 km) of 2-lane and 4-lane undivided highway (2-way ADT≈3,700, %Trucks≈16%). Two design alternatives consisting of 17.5-in (440-mm) FDAC or 10-in (260-mm) JPC-D placed on 4-in (100-mm) CTB. A 30-year analysis period was utilized in the LCCA.
6. US 59 Franklin County (59-30 K-7889-02)—Reconstruction of 7.60 mi (12.24 km) of 4-lane divided highway (2-way ADT≈5,500, %Trucks≈10%). Two design alternatives consisting of 13-in (330-mm) FDAC or 8.5-in (215-mm) JPC-D placed on 4-in (100-mm) granular base. A 30-year analysis period was utilized in the LCCA.
7. US 400 Ford County (400-29 K-8237-01)—Reconstruction of 2.54 mi (4.09 km) of 2-lane highway (2-way ADT≈3,000, %Trucks≈27%). Two design alternatives consisting of 17-in (430-mm) FDAC or 10-in (260-mm) JPC-D placed on 4-in (100-mm) CTB. A 40-year analysis period was utilized in the LCCA.
8. I-435 Johnson County (435-46 K-7451-01)—Reconstruction of 3.90 mi (6.28 km) of 4-lane interstate highway (2-way ADT=75,500+, %Trucks=??). Two design alternatives consisting of 22-in (560-mm) FDAC or 14-in (360-mm) JPC-D placed on 4-in (100-mm) CTB. A 30-year analysis period was utilized in the LCCA.
9. KS 27 Sherman County (27-91 K-7406-01)—Reconstruction of 6.09 mi (9.80 km) of 2-lane highway (2-way ADT≈1,200, %Trucks≈30%). Two design alternatives consisting of 13.5-in (340-mm) FDAC or 8-in (200-mm) JPC-D placed on 4-in (100-mm) CTB. A 30-year analysis period was utilized in the LCCA.
10. KS 104 Saline County (104-85 K-7403-01)—Reconstruction of 4.47 mi (7.20 km) of 2-lane highway (2-way ADT≈2,300, %Trucks≈8%). Two design alternatives consisting of

9.5-in (240-mm) FDAC or 8-in (200-mm) JPC-D placed on 4-in (100-mm) CTB. A 30-year analysis period was utilized in the LCCA.

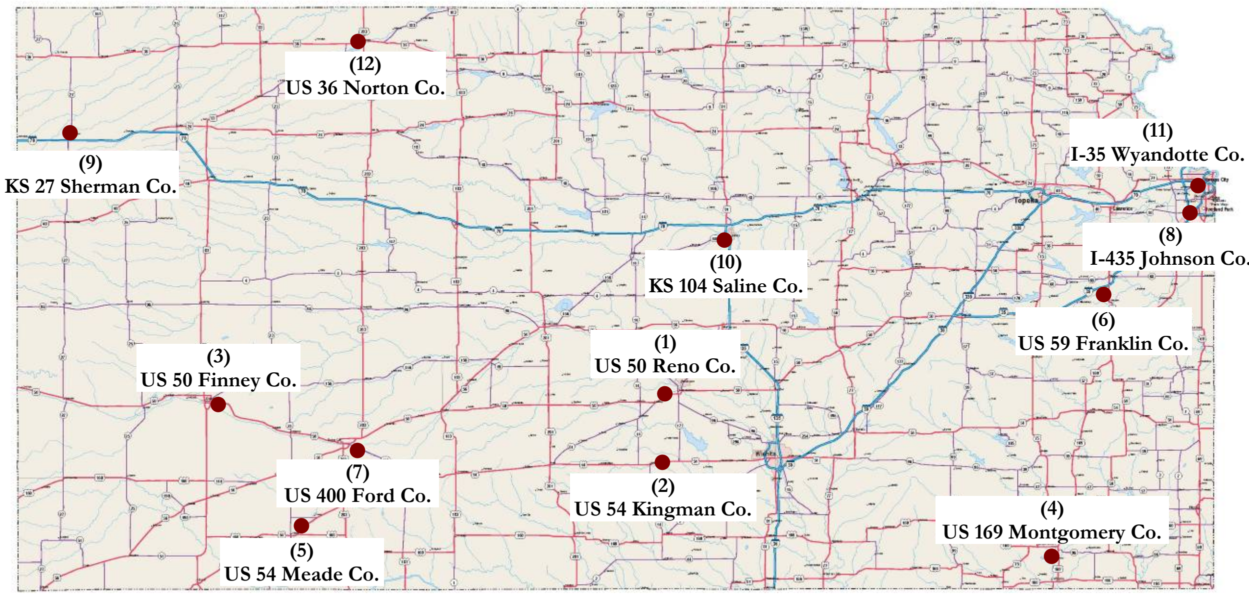

Figure A-1: Locations of projects used in LCCA comparisons.

11. I-35 Wyandotte County (35-105 K-6391-01)—Reconstruction of 1.93 mi (3.1 km) of 4-lane interstate highway (2-way ADT=83,000+, %Trucks=??). Two design alternatives consisting of 21.25-in (540-mm) FDAC or 13.5-in (340-mm) JPC-D placed on 4-in (100-mm) CTB. A 30-year analysis period was utilized in the LCCA.
12. US 36 Norton County (36-69 K-6373-01)—Reconstruction of 9.50 mi (15.30 km) of 2-lane highway (2-way ADT≈2,500, %Trucks≈22%). Two design alternatives consisting of 12-in (300-mm) FDAC or 8-in (200-mm) JPC-D placed on 4-in (100-mm) granular base. A 30-year analysis period was utilized in the LCCA.

Table A-14 shows the life-cycle models used by KDOT in performing the LCCAs for the 12 pavement projects. As can be seen, rehabilitation actions for the FDAC alternatives on each project were scheduled every 10 years over the course of the selected analysis period. Projected treatments varied somewhat, with the first rehabilitation consisting of either an L or H application, and the second rehabilitation (and third rehabilitation, in the case of projects 3 and 7) consisting of an H application. All projected treatments consisted of a combination of either surface recycle-and-overlay or mill-and-overlay.

Rehabilitation actions for the JPC-D alternatives on each project were scheduled at year 20 for projects that used 30-year analysis periods, and at years 20 and 30 for projects that used 40-year analysis periods. Most of the projected rehabilitation treatments were H applications, comprised of a certain percentage (5 typically) of full-depth patching followed by a thick HMA overlay. In one case, a CPR treatment was projected, consisting of full-depth patching, joint resealing, and some diamond grinding.

Table A-15 shows the estimated rehabilitation costs used by KDOT in their analysis.

For each of the 12 projects, the NPV of the estimated rehabilitation for each alternative were calculated using a 3 percent discount rate. The results of this analysis are presented in table A-16.

Table A-14: KDOT's life-cycle models for LCCA projects.

Project No. & Location (District)	Design Alternative	Original Structure	Rehab #1 (Year 10)	Rehab #2 (Year 20)	Rehab #3 (Year 30)
1 US 50 Reno Co. (District 5)	FDAC	17-in FDAC	1-in Surf Recycle, 3-in HMA OL	1-in Surf Recycle, 4.5-in HMA OL	
	JPC-D ☆	11-in JPC-D/ 4-in CTB	—	5% FD Patch, 3-in HMA OL	
2 US 54 Kingman Co. (District 5)	**FDAC #1 ☆**	15.75-in FDAC	1-in Surf Recycle, 3-in HMA OL	1-in Surf Recycle, 4-in HMA OL	
	FDAC #2	18-in FDAC	1-in Surf Recycle, 1.5-in HMA OL	1-in Surf Recycle, 4-in HMA OL	
	JPC-D	9.5-in JPC-D/ 4-in CTB	—	5% FD Patch, 3.5-in HMA OL	
3 US 50 Finney Co. (District 6)	FDAC	17-in FDAC	1-in Surf Recycle, 2.5-in HMA OL	1-in Surf Recycle, 3.5-in HMA OL	1-in Surf Recycle, 3.5-in HMA OL
	JPC-D ☆	10-in JPC-D/ 4-in CTB	—	5% FD Patch, 4-in HMA OL	5% FD Patch, 4-in HMA OL
4 US 169 Montgomery Co. (District 4)	**FDAC ☆**	13.5-in FDAC	1-in Surf Recycle, 3-in HMA OL	1-in Surf Recycle, 5-in HMA OL	
	JPC-D	9.5-in JPC-D/ 4-in CTB	—	3% FD Patch, 3-in HMA OL	
5 US 54 Meade Co. (District 6)	**FDAC ☆**	17.5-in FDAC	1.5-in Mill, 1.5-in HMA OL	1-in Surf Recycle, 3.5-in HMA OL	
	JPC-D	10-in JPC-D/ 4-in CTB	—	2% FD Patch, 3-in HMA OL	
6 US 59 Franklin Co. (District 4)	FDAC	13-in FDAC	1-in Surf Recycle, 3-in HMA OL	1-in Surf Recycle, 4.5-in HMA OL	
	JPC-D ☆	8.5-in JPC-D/ 4-in Agg Base	—	5% FD Patch, 3.5-in HMA OL	
7 US 400 Ford Co. (District 6)	FDAC	17-in FDAC	1-in Surf Recycle, 3-in HMA OL	1-in Surf Recycle, 4-in HMA OL	1-in Surf Recycle, 4.5-in HMA OL
	JPC-D ☆	10-in JPC-D/ 4-in CTB	—	5% FD Patch, 3-in HMA OL	5% FD Patch, 4-in HMA OL
8 I-435 Johnson Co. (District 1)	FDAC	22-in FDAC	1-in Surf Recycle, 3.75-in HMA OL	1-in Surf Recycle, 7-in HMA OL	
	JPC-D ☆	14-in JPC-D/ 4-in CTB	—	5% FD Patch, 3.5-in HMA OL	
9 KS 27 Sherman Co. (District 3)	**FDAC ☆**	13.5-in FDAC	1-in Surf Recycle, 3-in HMA OL	1-in Surf Recycle, 3-in HMA OL	
	JPC-D	8-in JPC-D/ 4-in CTB	—	5% FD Patch, 1.5-in HMA OL	
10 KS 104 Saline Co. (District 2)	**FDAC ☆**	9.5-in FDAC	1-in Surf Recycle, 2.5-in HMA OL	1-in Surf Recycle, 3.5-in HMA OL	
	JPC-D	8-in JPC-D/ 4-in CTB	—	2% FD Patch, 3-in HMA OL	
11 I-35 Wyandotte Co. (District 1)	FDAC	21.25-in FDAC	2-in Mill, 5.5-in HMA OL	3-in Mill, 9.5-in HMA OL	
	JPC-D ☆	13.5-in JPC-D/ 4-in CTB	—	5% FD Patch, 4-in HMA OL	
12 US 36 Norton Co. (District 3)	**FDAC ☆**	12-in FDAC	2-in Mill, 4-in HMA OL	3-in Mill, 5.5-in HMA OL	
	JPC-D	8-in JPC-D/ 4-in Agg Base	—	CPR (5% FD Patch, Joint Seal, 20% Grind)	

☆ Alternative with lowest computed life-cycle cost. 1 in = 25.4 mm

Table A-15: LCCA results for 12 pavement projects using KDOT life-cycle models.

LCCA Project No.	KDOT District	KDOT Const. Project	Design Alternative	Initial Structure	Initial Structure Cost	Rehab #1	Rehab #1 Year	Rehab #1 Cost	Rehab #2	Rehab #2 Year	Rehab #2 Cost	Rehab #3	Rehab #3 Year	Rehab #3 Cost	Salvage Type	Salvage Year	Salvage Amount	Discount Rate	NPV Life-Cycle Cost
1	5	US 50	FDAC	17-in HMA	$5,701,866	1-in Surf Recycle, 3-in HMA OL	10	$1,271,839	1-in Surf Recycle, 4.5-in HMA OL	20	$1,866,805				None	30	$0	3%	$7,681,838
		Reno Co.	JPC-D	11-in JPC-D/ 4-in CTB	$4,330,407	5% FD Patch, 3-in HMA OL	20	$1,377,143							None	30	$0	3%	$5,092,898
2	5	US 54	FDAC #1	15.75-in HMA	$7,336,236	1-in Surf Recycle, 3-in HMA OL	10	$1,719,628	1-in Surf Recycle, 4-in HMA OL	20	$2,176,846				None	30	$0	3%	$9,821,068
		Kingman Co.	FDAC #2	18-in HMA	$8,290,376	1-in Surf Recycle, 1.5-in HMA OL	10	$1,034,092	1-in Surf Recycle, 4-in HMA OL	20	$2,135,561				None	30	$0	3%	$10,242,246
			JPC-D	11-in JPC-D/ 4-in CTB	$8,595,981	5% FD Patch, 3.5-in HMA OL	20	$2,279,046							None	30	$0	3%	$9,857,834
3	6	US 50	FDAC	17-in HMA	$15,639,249	1-in Surf Recycle, 2.5-in HMA OL	10	$3,308,454	1-in Surf Recycle, 3.5-in HMA OL	20	$4,133,138	1-in Surf Recycle, 3.5-in HMA OL	30	$4,133,138	None	40	$0	3%	$22,092,266
		Finney Co.	JPC-D	10-in JPC-D/ 4-in CTB	$15,394,835	5% FD Patch, 4-in HMA OL	20	$5,711,898	5% FD Patch, 4-in HMA OL	30	$5,961,422				None	40	$0	3%	$21,013,401
4	4	US 169	FDAC	13.5-in HMA	$4,767,329	1-in Surf Recycle, 3-in HMA OL	10	$1,243,811	1-in Surf Recycle, 5-in HMA OL	20	$2,048,602				None	30	$0	2%	$7,166,338
		Montgomery Co.	JPC-D	9.5-in JPC-D/ 4-in CTB	$6,814,950	3% FD Patch, 3-in HMA OL	20	$1,425,253							None	30	$0	2%	$7,774,104
5	6	US 54	FDAC	17.5-in HMA	$688,130	1.5-in Mill, 1.5-in HMA OL	10	$82,828	1-in Surf Recycle, 3.5-in HMA OL	20	$184,379				None	30	$0	2%	$880,160
		Meade Co.	JPC-D	10-in JPC-D/ 4-in CTB	$934,235	2% FD Patch, 3-in HMA OL	20	$167,926							None	30	$0	2%	$1,047,244
6	4	US 59	FDAC	13-in HMA	$11,897,051	1-in Surf Recycle, 3-in HMA OL	10	$3,576,985	1-in Surf Recycle, 4.5-in HMA OL	20	$5,618,107				None	30	$0	3%	$17,669,273
		Franklin Co.	JPC-D	8.5-in JPC-D/ 4-in Agg	$11,925,631	5% FD Patch, 3.5-in HMA OL	20	$4,245,581							None	30	$0	3%	$14,276,306
7	6	US 400	FDAC	17-in HMA	$2,848,316	1-in Surf Recycle, 3-in HMA OL	10	$772,356	1-in Surf Recycle, 4-in HMA OL	20	$917,886	1-in Surf Recycle, 4.5-in HMA OL	30	$1,013,215	None	40	$0	3%	$4,348,664
		Ford Co.	JPC-D	10-in JPC-D/ 4-in CTB	$2,765,304	5% FD Patch, 3-in HMA OL	20	$958,777	5% FD Patch, 4-in HMA OL	30	$1,178,059				None	40	$0	3%	$3,781,500
8	1	I-435	FDAC	22-in HMA	$8,369,343	1-in Surf Recycle, 3.75-in HMA OL	10	$1,836,410	1-in Surf Recycle, 7-in HMA OL	20	$3,098,801				None	30	$0	2%	$11,961,243
		Johnson Co.	JPC-D	14-in JPC-D/ 4-in CTB	$9,136,076	5% FD Patch, 3.5-in HMA OL	20	$2,088,112							None	30	$0	2%	$10,541,316
9	3	KS 27	FDAC	13.5-in HMA	$2,804,745	1-in Surf Recycle, 3-in HMA OL	10	$771,748	1-in Surf Recycle, 3-in HMA OL	20	$771,748				Rem Life (2/10)	30	$86,906	2%	$3,909,233
		Sherman Co.	JPC-D	8-in JPC-D/ 4-in CTB	$3,859,167	5% FD Patch, 1.5-in HMA OL	20	$590,878							Rem Life (6/10)	30	$101,348	2%	$4,200,860
10	2	KS 104	FDAC	9.5-in HMA	$1,501,576	1-in Surf Recycle, 2.5-in HMA OL	10	$415,229	1-in Surf Recycle, 3.5-in HMA OL	20	$562,835				None	30	$0	2%	$2,220,980
		Saline Co.	JPC-D	8-in JPC-D/ 4-in CTB	$2,414,470	2% FD Patch, 3-in HMA OL	20	$470,763							None	30	$0	2%	$2,731,280
11	1	I-35	FDAC	21.25-in HMA	$4,938,005	2-in Mill, 5.5-in HMA OL	10	$1,341,367	3-in Mill, 9.5-in HMA OL	20	$2,195,077				Recycle 50% HMA	30	$2,056,119	2%	$6,380,494
		Wyandotte Co.	JPC-D	13.5-in JPC-D/ 4-in CTB	$5,366,323	5% FD Patch, 4-in HMA OL	20	$1,406,556							Recycle 50% HMA & PCC	30	$458,440	2%	$6,059,803
12	3	US 36	FDAC	12-in HMA	$3,884,037	2-in Mill, 4-in HMA OL	10	$1,406,430	3-in Mill, 5.5-in HMA OL	20	$1,888,775				Recycle 50% HMA	30	$1,428,036	2%	$5,520,514
		Norton Co.	JPC-D	8-in JPC-D/ 4-in Agg	$6,896,995	CPR (5% FD Patch, Jt. Seal, 20% grind)	20	$901,112							Recycle 50% PCC	30	$309,508	2%	$7,332,547

Table A-16: Net Present Value of Rehabilitation.

LCCA Project No.	Length, mi	No. Lanes	NPV of FDAC Rehabilitation, Per 2-lane-mi		NPV of JPC-D Rehabilitation. Per 2-lane-mi	
			30-year Analysis Period	40-year Analysis Period	30-year analysis period	40-year analysis period
1	2.89	4	$342,555.77		$131,918.80	
2 (FDAC Alt. 1)	5.82	4	$213,473.50		$108,406.57	
2 (FDAC Alt. 2)	5.82	4	$167,686.42		$108,406.57	
3	8.40	4		$384,108.15		$334,438.47
4	7.55	4	$136,408.84		$52,260.13	
5	1.15	2	$142,363.47		$80,849.18	
6	7.60	4	$379,751.47		$154,649.69	
7	2.54	2		$590,683.75		$400,120.88
8	3.90	4	$395,152.88		$148,222.69	
9	6.09	2	$164,458.32		$53,720.00	
10	4.47	2	$138,847.77		$58,310.98	
11	1.93	4	$573,436.25		$201,755.43	
12	9.50	2	$220,240.52		$52,518.30	
Average NPV of Rehabilitation, Per 2-lane-mi			$261,306.84	$487,395.95	$104,261.18	$367,279.67

Table A-17 provides a summary of the results obtained by the various methods used to calculate the average NPV values. Recall that the three demonstration methods are contrived and not based on actual historical data. This table demonstrates a comparative process that could be followed once suitable cost data are developed to perform the three analysis procedures.

Table A-17: Summary of the average NPV values calculated by various methods.

Method of Calculation	Average NPV of Rehabilitation, Per 2-lane-mi			
	FDAC		JPC-D	
	30-Year Analysis Period	40-Year Analysis Period	30-Year Analysis Period	40-Year Analysis Period
KDOT Estimated Costs and Timing	$261,307	$487,396	$104,261	$367,280
Analysis Method 1 (Demo)	$498,167	$654,878	$437,966	$740,035
Analysis Method 2 (Demo)	$491,458	$651,581	$411,341	$708,387
Analysis Method 3 (Demo)	$521,577	$618,097	$521,577	$618,097

Table A-18 shows the wide variety of results KDOT currently obtains from 30-year versus 40-year LCCAs for the two primary pavement types. It also shows that the alternative methods presented in this study may warrant an effort to develop history-based cost inputs.

Table A-18: Difference in average rehabilitation NPV values for FDAC and JPC-D pavements.

Method of Calculation	Difference in NPV of Rehabilitation Costs	
	30-Year Analysis Period	40-Year Analysis Period
KDOT Estimated Costs and Timing	$157,046	$120,116
Analysis Method 1 (Demo)	$60,201	$85,156
Analysis Method 2 (Demo)	$80,117	$56,806
Analysis Method 3 (Demo)	$0	$0

Analysis Method 3 has significant appeal for further development. This approach uses the actual cost of ownership for a particular type of pavement. A significant advantage is that it does not require performance models to be utilized.

As noted in table A-16, there are wide variations in expected rehabilitation costs from project to project. This results from variations in pavement width, traffic variation, and performance variations from district to district. Further analysis is recommended to develop regional average rehabilitation NPV values for low and high volume routes. In addition, correction factors should be developed for pavement width and other factors that impact rehabilitation costs.

DEPARTMENT OF TRANSPORTATION

AD ASTRA PER ASPERA

KANSAS