Evaluation of the Cost Benefits of Continuous Pavement Preservation Design Strategies Versus Reconstruction

Final Report 491

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16. Abstract

The Arizona Department of Transportation (ADOT) has traditionally employed continuous pavement preservation (consisting of a myriad of treatment options that cost-effectively address existing pavement problems) as part of an overall design strategy to maintain the highest levels of service for highway users. However, with concern about the effects of continual weakening of substructure material layers on preservation treatment performance and cost, ADOT sponsored a study to determine the cost-effectiveness of the continuous preservation approach as compared to a reconstruction strategy. Another goal of the study was to determine the break-even point for the continuous preservation and reconstruction strategies (i.e., after how many rehabilitation treatments does reconstruction becomes equally cost-effective as continuous preservation).

Using inputs such as pavement performance/life estimated primarily through pavement survival analysis, best estimate unit costs derived from historical data, work zone-related user costs, and a specified analysis period and discount rate, the total life-cycle costs for each of four alternative strategies (one continuous preservation strategy, three reconstruction strategies) for each of 15 commonly occurring pavement scenarios in Arizona were determined and compared. The results of the analysis showed a consistent reduction in total life-cycle costs with a corresponding increase (from 0 to 2) in the number of rehabilitations between original construction and the first reconstruction event. Results also showed that for 9 of the 15 scenarios, total life-cycle costs associated with the third reconstruction alternative (i.e., two rehabilitations occurring prior to the first reconstruction event) were within 3 percent (sometimes higher, sometimes lower) of the total life-cycle costs of the continuous preservation strategy. Hence, the break-even point between the two strategies typically occurs after two to three cycles of rehabilitation

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APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	square millimeters	mm^2	mm^2	Square millimeters	0.0016	square inches	in^2
ft^2	square feet	0.093	square meters	m^2	m^2	Square meters	10.764	square feet	ft^2
yd^2	square yards	0.836	square meters	m^2	m^2	Square meters	1.195	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	square kilometers	km^2	km^2	Square kilometers	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	cubic meters	m^3	m^3	Cubic meters	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	cubic meters	m^3	m^3	Cubic meters	1.308	cubic yards	yd^3
	NOTE: Volumes greater than 1000L shall be shown in m^3.								
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000lb)	0.907	megagrams (or “metric ton”)	mg (or “t”)	Mg	megagrams (or “metric ton”)	1.102	short tons (2000lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C	°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION					**ILLUMINATION**		
fc	foot candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2	cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE AND PRESSURE OR STRESS					**FORCE AND PRESSURE OR STRESS**		
lbf	poundforce	4.45	newtons	N	N	newtons	0.225	poundforce	lbf
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380

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LIST OF TERMS AND ACRONYMS

TERMS

Analysis Period—Time period over which the initial and future costs are evaluated for different design alternatives.

Discount Rate—The rate used in economic analysis to represent the real value of money over time. It is a function of both the interest rate and inflation rate, and is used to convert future costs to present-day costs and/or present-day costs to annualized costs.

(Highway) Agency Costs—Costs incurred directly by an owner agency over the life of a highway project. Agency costs are generally subdivided into three groups: initial cost, future costs, and salvage value.

(Highway) User Costs—Costs incurred by the highway user over the life of a highway project. The user costs of concern are the differential or extra costs incurred by the traveling public as a result of one highway design being used instead of another. User cost categories typically include time delay costs, vehicle operating costs, accident costs, and discomfort costs associated with work zones or normal operating conditions.

Life-Cycle Cost Analysis—An economic technique that allows comparisons of investment alternatives having different cost streams. In the highway arena, it is a formal, systematic approach for considering most of the factors that go into making a pavement investment decision.

Life-Cycle Model—Depiction of the sequence of activities expected for a given pavement design alternative, from the initial structure to the final M&R treatment. In a life-cycle model, the type and timing of each anticipated activity is indicated, along with the expected quantities.

(Pavement) Preservation—The planned strategy of cost-effective pavement treatments to an existing roadway to extend the life or improve the serviceability of a pavement. It is a program strategy intended to arrest deterioration, retard progressive failure, and improve the functional or structural capacity of the pavement. It is a strategy for individual pavements and for optimizing the performance of a pavement network.

(Pavement) Service Life—The period of time over which no major cost events (i.e., rehabilitation, reconstruction) are required in providing a reasonable level of service to users.

(Pavement) Survival Analysis—A statistical analysis technique used to determine the expected service life of pavements and/or the performance of rehabilitation techniques. The procedure involves computing and graphing the probability of a pavement remaining without need of a rehabilitation or reconstruction event, based on historical pavement event data.

ACRONYMS

AC	Asphalt Concrete
ADT	Average Daily Traffic
CAC	Conventional Asphalt Concrete
CRC	Continuously Reinforced Concrete
DSAC	Deep-Strength Asphalt Concrete
FDAC	Full-Depth Asphalt Concrete
HMA OL	Hot-Mix Asphalt Overlay
JPC	Jointed Plain Concrete, Nondoweled
JPCD	Jointed Plain Concrete, Doweled
LCCA	Life-Cycle Cost Analysis
M&R	Maintenance and Rehabilitation
PCC	Portland Cement Concrete
PMS	Pavement Management System
RF	Regional Factor
VOC	Vehicle Operating Cost

EXECUTIVE SUMMARY

The Arizona Department of Transportation (ADOT) has a long and valuable history of highway pavement preservation. The Department has utilized and benefited greatly from the findings of past research concerning the cost-effectiveness of timely and appropriate forms of pavement preservation. Its current overall design strategy entails a continuous preservation approach, whereby one of a myriad of treatment options is selected based on its ability to cost-effectively address existing pavement conditions and future forecasted traffic loadings.

With concern about the effects of continual weakening of substructure material layers on preservation treatment performance and cost, this study was conducted to assess the appropriateness of the continuous preservation approach as compared to a total reconstruction approach. The evaluation was made in terms of total life-cycle costs, as determined by pavement service life and construction costs, M&R treatment performance and costs, user delay associated with work zones, and the discount rate. The study also sought to determine the break-even point for the two design strategies (i.e., the point at which reconstruction becomes equally cost-effective as continuous preservation), so as to better allocate the funding of construction and preservation activities.

To compute and compare the life-cycle costs of the two approaches, a detailed assessment of the key inputs of the life-cycle cost analysis (LCCA) process was made. First, using historical pavement project information and statewide pavement management data, the performance characteristics of six different pavement types—conventional asphalt concrete (CAC), deep-strength AC (DSAC), full-depth AC (FDAC), non-doweled jointed plain concrete (JPC), doweled JPC (JPCD), and continuously reinforced concrete (CRC) pavement—and numerous maintenance and rehabilitation (M&R) treatment types were analyzed. This analysis was done using pavement survival analysis techniques, supplemented by mechanistic-based performance modeling. The resulting information was then used to construct life-cycle models for 15 different scenarios representative of Arizona highway pavements and conditions.

Second, a detailed analysis of construction and M&R unit costs was performed using data from three separate cost sources. Best estimates of the unit costs were then made based on the availability and reliability of data and engineering judgment.

Lastly, a review of user cost components and models was made, with recommendations developed regarding the best practices for Arizona conditions.

All of the resulting information was entered into the FHWA LCCA spreadsheet program *RealCost*, whereby the probabilistic life-cycle costs of continuous preservation and reconstruction alternatives were computed for each of the 15 pavement scenarios using a 4 percent discount rate and 60-year analysis period. Results indicated a consistent reduction in total life-cycle costs corresponding to an increase (from 0 to 2) in the number of rehabilitations between initial construction and the first reconstruction. Moreover, for a majority of scenarios evaluated, it was found that the total life-cycle costs associated with the third reconstruction alternative (two rehabilitations prior to reconstruction) were within 5 percent (sometimes higher, sometimes lower) of the total life-cycle costs of the continuous preservation strategy. Thus, it was determined that the break-even point between the continuous preservation strategy and the reconstruction strategy typically occurs after two to three cycles of rehabilitation (i.e., reconstruction preceded by two to three sequential rehabilitation treatments).

CHAPTER 1. INTRODUCTION

BACKGROUND AND PROBLEM DESCRIPTION

The term "pavement preservation" has been in use in the transportation facilities field for many years. Although its meaning has varied over time and among pavement practitioners, it is still often viewed in the sense described by the American Association of State Highway and Transportation Officials (AASHTO):

> *The planned strategy of cost-effective pavement treatments to an existing roadway to extend the life or improve the serviceability of a pavement. It is a program strategy intended to arrest deterioration, retard progressive failure, and improve the functional or structural capacity of the pavement. It is a strategy for individual pavements and for optimizing the performance of a pavement network.*

Thus, pavement preservation represents an umbrella of activities, ranging from preventive maintenance treatments, such as slurry seals and chip seals, to minor rehabilitation treatments, like diamond grinding of Portland cement concrete (PCC) pavements and thin asphalt concrete (AC) overlays, to major rehabilitation treatments, such as extensive full-depth PCC repairs with or without diamond grinding and thick AC overlays with or without cold-milling.

The Arizona Department of Transportation (ADOT) has a long and valuable history of highway pavement preservation. Beginning in the early to mid-1970s, the Department began shifting its focus from extensive patching and crack filling (corrective measures designed to hold a pavement together until reconstruction) to resurfacing (a type of preservation) in the form of an AC overlay or milling followed by AC overlay. Preservation funding increased in the years thereafter, and the implementation of a pavement management system in the early 1980's helped researchers confirm the benefits of a preservation approach and evaluate the effectiveness of different preservation treatments (Way, 1983).

Today, the Department has a large arsenal of preservation treatments that are used on a continuous basis to keep highways facilities fully operational and in good serviceable condition. The treatments selected for use are based on an extensive evaluation of the functional and structural conditions of the existing pavement and the long-term traffic forecasted for the facility. The treatments are generally designed for a 10-year performance life and a heavy emphasis is placed on the re-use of materials.

The appropriateness of the continuous pavement preservation approach is a matter that the Department has recently deemed worthy of investigation. With rehabilitation activities taking place every 10 to 15 years, the direct costs of these activities add up quickly and could be undercut by the costs of a construct–reconstruct approach having longer periods between interventions. Such a reconstruct approach would also appear to provide benefit in the arena of user costs, in that fewer interventions could translate into less time delay for highway users.

This project investigates the legitimacy and cost practicality of the continuous preservation design philosophy, as compared to the construct–reconstruct approach. It involves a thorough evaluation of the performance and costs of ADOT pavement structures and rehabilitation treatments, followed by comprehensive life-cycle cost analyses (LCCAs) to determine the conditions or circumstances favorable to one approach over the other.

PROJECT OBJECTIVES AND SCOPE

The overall objective of this research project is to evaluate the cost benefit of continued pavement preservation design strategies, as compared to pavement reconstruction. The evaluation is to result in the identification of the best pavement design strategies available, based on total life cycle cost, and in the development of criteria for determining the break-even point between pavement preservation and reconstruction.

The original scope of the research project consisted of seven primary tasks, as listed below.

- Task 1—Review Pavement Design Strategies and Performance Characteristics.
- Task 2—Analyze ADOT's Construction Costs for Typical Design Strategies.
- Task 3—Evaluate Best Practices for User Costs.
- Task 4—Develop Life-Cycle Models and Conduct LCCA.
- Task 5—Develop Design Strategy and Selection Model Recommendations.
- Task 6—Prepare Final Report.
- Task 7—Prepare Research Note.

An eighth task, involving the performance evaluation of cold in-place recycling (CIR) projects, was subsequently added to the study. A separate report on this investigation was prepared and submitted to ADOT.

OVERVIEW OF REPORT

This report is presented in eight chapters. Chapter 1 is this introduction. Chapter 2 discusses the data collection and database development work. Descriptions of the pavement performance analyses conducted and the corresponding results are provided in chapter 3. Chapters 4 and 5 present the findings of the analysis of construction costs and user cost practices, respectively. Chapters 6 and 7 feature the life-cycle models and LCCA results for the alternative pavement design strategies (continuous pavement preservation versus reconstruction). Finally, an overall summary of the conclusions and recommendations regarding design strategies is discussed in chapter 8.

This report also includes one appendix. Appendix A contains survival curves for the various pavement structures and rehabilitation treatments examined in the study.

CHAPTER 2. DATA COLLECTION AND DATABASE DEVELOPMENT

INTRODUCTION

In order to satisfy the project objectives, an intensive data collection and processing effort was undertaken. This effort involved obtaining the latest highway pavement databases and hardcopy records from ADOT, manually and electronically uploading the data into Microsoft® Access 2002, reviewing the accuracy and completeness of the data, and, where possible, adding new or replacement data.

This chapter describes in detail the database development process leading to the establishment of datasets for pavement performance analysis. It describes the work performed in collecting the required data, building the project database, and reviewing and cleaning it for use in the study. It also presents a summary of the project data in terms of the types of pavements (new/reconstructed and rehabilitated) analyzed and their breakdowns by facility type, highway, ADOT District, construction year and age, traffic, and surface layer thickness.

DATA COLLECTION

Two electronic databases and various other data records from ADOT were used to build the project database. These information sources included the project history database, the pavement management system (PMS) database, the 2002 State highway log, the 1997 traffic composition table, a SuperPave asphalt mix design project list, and a project list for doweled, jointed plain concrete (JPCD) pavement. A brief description of each of these sources is provided in the sections below.

Project History Database

ADOT's project history database was provided as a Microsoft Access® database management file. The database included information on over 5,800 construction/rehabilitation projects undertaken on Arizona highways between 1928 and 2003. Key data fields included the following:

- ADOT construction project number.
- ADOT District.
- Highway number, direction, and lane.
- Project limits (begin and end mileposts).
- Activity/structure information, in terms of layer material types and thicknesses.

PMS Database

ADOT's PMS database was also provided as a Microsoft Access® database management file. Over 7,200, 1-mi long pavement sections covering all five interstate routes, 17 U.S. routes, and 82 State routes, were included in this database. Key data fields included the following:

- Highway number, type (e.g., alternate, business, spur), direction, and lane.
- Section beginning milepost (established on 1-mi intervals [e.g., 1.0, 2.0, 3.0]).
- ADOT District.
- Regional factor (RF).
- Average daily traffic (ADT) for years 1974 through 2002.
- Traffic growth factors for years 2000, 2001, and 2002.
- Year of most recent condition survey.
- Pavement cracking quantities for years 1979 through 2002.
- Smoothness measurements for years 1972 through 2002.
- Pavement rutting measurements for years 1986 through 2002.
- Pavement patching quantities for years 1979 through 2002.
- Pavement flushing quantities for years 1979 through 2002.
- Average maintenance costs for years 1979 through 2002.

2002 Highway Log

This electronic file provided useful general information about the 100+ Arizona highways. It included overall mileage (centerline miles and lane miles) information for each highway facility, as well as linear referencing (mile markers, mileposts), geometric (number of lanes, lane widths, shoulder widths) and surfacing (travel lane and shoulder surface types) data for specifically-defined segments of each route. Also available were ADT and truck percentages for individual traffic count segments for the years 1997 through 2001.

1997 Traffic Composition Table

Although the PMS database included extensive historical traffic data, the need existed for information on the number or percentage of trucks that pass over Arizona highways. Hence, ADOT provided in hardcopy form a detailed traffic table containing vehicle composition and equivalent single-axle load (ESAL) information for traffic count segments on all highways included in the PMS database.

Data from this table were manually entered into Microsoft Excel® for ultimate incorporation into the project database. The data fields entered included highway number and traffic section milepost limits, the percentage of trucks in the overall vehicle population, and the percentage of medium and heavy trucks (FHWA vehicle classes 4 through 13) in the overall truck population. Two-way annual traffic growth rates, derived from 1991 and 1997 ADT data, were also included.

Using the above information, the percentage of medium and heavy trucks in the overall vehicle population was computed. The resulting percentages were subsequently used in conjunction with the annual ADT values in the PMS database to yield annual numbers of trucks.

SuperPave Mix Design Project List

With the Department's expressed interest in the evaluation of its SuperPave asphalt mixes, the project database needed to specify the pavement sections containing a SuperPave mix. For this purpose, a listing of about 30 different SuperPave projects performed throughout Arizona between 1997 and 2001 was provided by ADOT. Although this list included detailed information about each mix design, the information of primary use was the ADOT construction project number, the project bid date, and the project location information (i.e., highway and milepost limits, benchmark/reference points). With these data and the activity/structure information given in the project history database, identification was made as to the rehabilitation projects that included a SuperPave mix.

JPCD Project List

Because the project history database did not list any JPCD projects, even though several such sections had been built between 1984 and 2001, a detailed list of JPCD projects was developed and provided by ADOT. This list contained general information, including ADOT construction project number, highway number and milepost limits, and completion dates, on about 25 projects constructed between 1984 and 2003. The information was used with the activity/structure information given in the project history database to indicate whether or not a 1-mi PMS section was built as JPCD.

DATABASE DEVELOPMENT

Development of the project database entailed seven key steps. These steps included the following:

1. Merging the ADOT project history and PMS databases.
2. Assigning event and pavement type codes to the pavement structures.
3. Adding important information on SuperPave and JPCD projects performed in recent years.
4. Incorporating key traffic data (ADT growth rates and percent trucks) into the database.
5. Performing detailed quality control (QC) checks of the data.

6. Assigning broad-based maintenance and rehabilitation (M&R) treatment codes to the thousands of recorded M&R activities.
7. Performing quality assurance (QA) checks of the data using statistical procedures.

A discussion of each step is provided in the sections below.

Step 1—Merging of Project History and PMS Databases

Merging of the project history and PMS databases was done in Microsoft Access® using a special querying function. The querying function linked key data from the two databases according to a unique reference identifier (unique ID) comprising facility type, highway number, direction, and PMS beginning milepost. Only information pertaining to the outer-most lane of a pavement section was included in the merge and, because of the mismatches in milepost limits between the two databases, projects were only linked to a given PMS section if they covered more than one-half of the section. An illustration of this criterion is provided in figure 1.

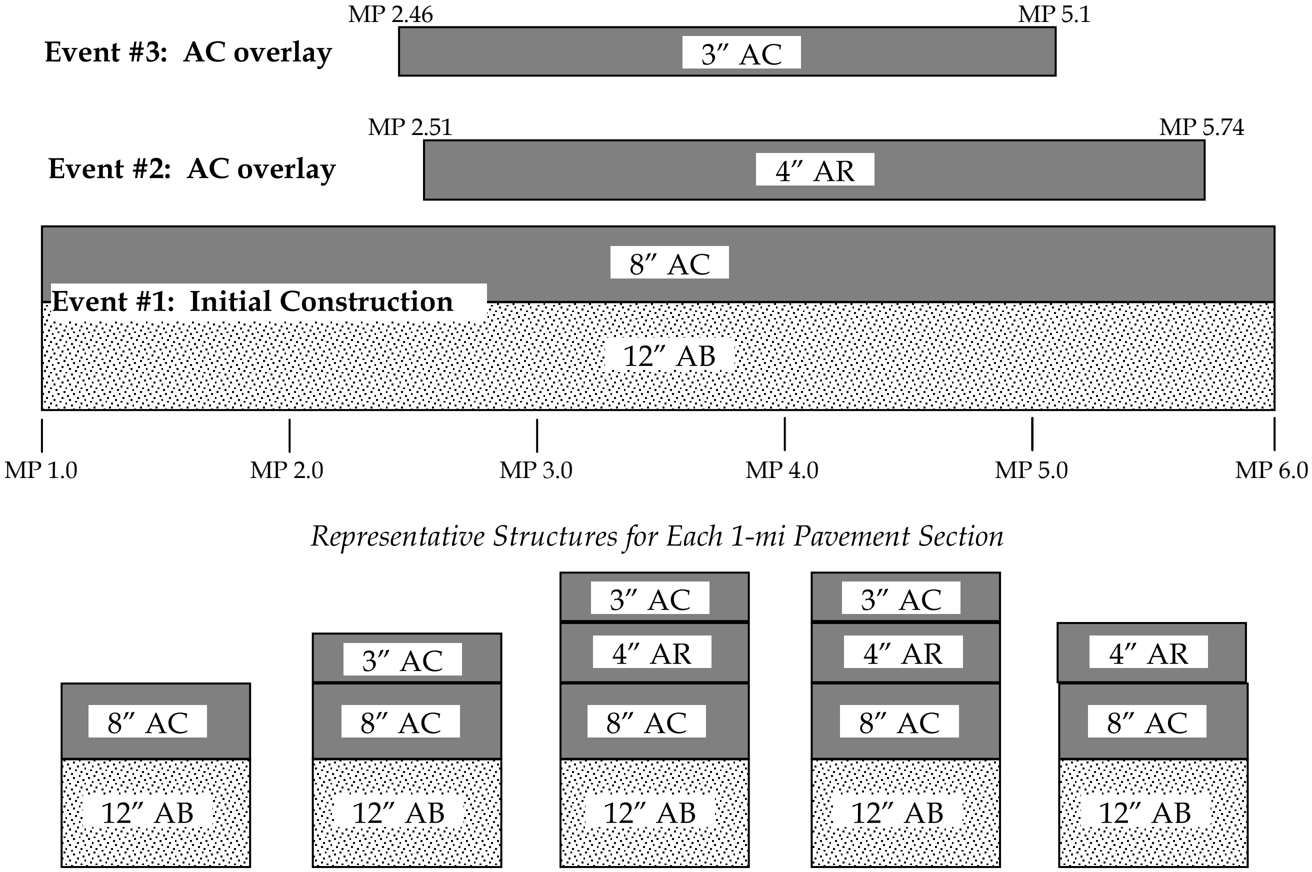


Figure 1. Establishment of activities/structures for 1-mi PMS pavement sections.

Step 2—Assigning Event and Pavement Type Codes

The first part of this step entailed assigning an event code to each individual event (i.e., construction, rehabilitation, maintenance) that took place over time on each 1-mi pavement section. These event codes aided the performance analysis process. New or reconstructed pavement structures were assigned the code “O” (“original” structure), rehabilitation treatments were assigned the code “R,” and maintenance treatments were assigned the code “M.” The “O” codes were subsequently expanded to “O1,” “O2,” “O3,” etc., to reflect the sequence number of each original structure that a pavement section received.

In the second part of this step, pavement type codes were assigned to each event, designating the basic type of pavement structure constructed or in existence at the time of an M&R treatment. A total of eight different pavement types were identified in the database, based on the following definitions:

- Conventional asphalt concrete (CAC)—Hot-mix asphalt (HMA) surface constructed over an untreated aggregate base/subbase course and prepared subgrade. The criterion used to define CAC pavements were that the total asphalt layer thickness had to be less than 7.5 in and could constitute no more than 40 percent of the total structure thickness (i.e., combined thickness of asphalt surface and aggregate base/subbase).
- Conventional asphalt concrete with treated base/subbase (CACT)—HMA surface constructed over a cement- or lime-treated aggregate base/subbase course and prepared subgrade.
- Deep-strength asphalt concrete (DSAC)—HMA surface constructed on HMA base and/or asphalt-treated base, an untreated aggregate base/subbase, and prepared subgrade. The criterion used to define DSAC pavements were that the total asphalt layer thickness had to be at least 4.5 in and could not constitute less than 40 percent of the total structure thickness (i.e., combined thickness of asphalt surface and aggregate base/subbase).
- Deep-strength asphalt concrete with treated base/subbase (DSACT)—HMA surface constructed on cement- or lime-treated aggregate base/subbase, and prepared subgrade.
- Full-depth asphalt concrete (FDAC)—HMA surface constructed on HMA base and/or asphalt-treated base (with variable percentage asphalt content) and prepared subgrade.
- Non-doweled jointed plain concrete (JPC)—Portland cement concrete (PCC) surface constructed over a treated or untreated base and prepared subgrade. The PCC can also be constructed directly over the subgrade. The PCC layer typically contains joints to control cracks expected in the concrete. For non-doweled JPC, dowel bars are not used to enhance load transfer at transverse joints. However, steel tie bars are generally used at longitudinal joints (lane-to-lane and lane-to-

PCC shoulder) to prevent excessive joint openings and to enhance longitudinal joint load transfer.

- Doweled jointed plain concrete (JPCD)—Similar to JPC with the exception that dowel bars are used to enhance load transfer at transverse contraction joints.
- Continuously reinforced concrete (CRC)—PCC surface with continuous longitudinal steel reinforcement and no intermediate transverse expansion or contraction joints constructed over a treated or untreated base and subgrade. The PCC can also be constructed directly over the subgrade.

Step 3—Designation of SuperPave and JPCD Projects

This step simply entailed changing the activity/material codes for pavement sections where SuperPave mixes were used in the asphalt overlay or where dowels were used in the new/reconstructed concrete pavement. For sections with SuperPave, the code "AC" was replaced with "AC*." For sections in which dowels were used, the code "PC" was changed to "PD."

Step 4—Addition of Traffic Composition and Growth Rate Data

In this step, the percentage of medium and heavy trucks in the overall vehicle population was added to the project database, along with the 2-way annual traffic growth rate. Because this information existed according to traffic count segments that varied in length and did not match the PMS section limits, a querying function was developed and used to extrapolate the traffic data across the 1-mi PMS sections.

Step 5—Performing QC Checks of Data

Following the completion of step 4, the database was thoroughly and meticulously reviewed to identify missing and anomalous/erroneous data. Specific items looked for and addressed were missing pavement sections, inconsistencies within a pavement section between the original pavement type and the sequence of M&R activities, missing or clearly inaccurate layer type and thickness information, and questionable time intervals (too short or too long) between events.

Most of the data issues identified were attributed to (a) missing or erroneous data in the project history and PMS databases and (b) extrapolation errors that occurred during the merging of the two databases. With regard to the former, efforts were made to either obtain the appropriate data from ADOT 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.

With regard to the latter, merging information from the two databases according to a common lane was sometimes problematic where multi-lane, urban highways were involved. This was because any time a lane was added as part of an event, the lane designation for the lane of interest (the outermost lane) changed. To rectify this situation, a detailed review was made of the event sequence and time-series performance data for all sections comprised by multiple lanes. Where clear discrepancies existed, either the data were replaced with the correct data or the section was removed from the database.

Step 6—Categorizing M&R Treatments

To identify the types of M&R treatments used by ADOT and evaluate the performance life of rehabilitation treatments, the entire project database was scanned and an M&R categorization scheme was developed. Well over 500 distinct M&R treatments were identified and categorized according to the following structure-related criteria:

- Removal Depth of Existing Pavement
  - none.
  - shallow ($\leq$ 4.0 in).
  - deep (>4.0 in).
- Treatment Application Thickness
  - none.
  - thin maintenance ($\leq$ 0.3 in).
  - thick maintenance (> 0.3 in and $\leq$ 1.5 in).
  - thin overlay (> 1.5 in and $\leq$ 4.0 in).
  - thick overlay (> 4.0 in).

For the many treatments involving the application of an asphalt layer(s), another level of categorization was given, based on the predominate type of asphalt mixture used in the treatment. The mixture types included the following:

- Asphalt Mixture Type
  - conventional asphalt.
  - asphalt rubber.
  - SuperPave asphalt.
  - recycled asphalt.

Using the pavement activity/material codes listed in table 1, the two M&R categorization tables shown in tables 2 and 3 were developed. The project database was then updated to reflect the category assigned to each individual M&R activity.

Table 1. Description of pavement preservation activity/material codes.

Code	Description	Code	Description
AB	Aggregate base	LB	Lime-treated base
AC	Asphalt concrete	LC	Leveling Coarse-AC AZMO
AR	AC with asphalt rubber binder	LS	Lime-treated subgrade
AS	ACSC—asphalt concrete surface coarse	MC	Mix and compact existing materials
BB	Bituminous-treated base	OA	Open-graded base material
BM	Base material-AB, SM	OB	Open-graded bituminous treated base
BS	Bituminous-treated surface	OC	Open-graded asphalt concrete
CB	Cement-treated base	PC	Portland cement concrete (PCC)
CF	Construction fabric	PD	PCC, doweled
CL	Lean concrete base	PP	PCC, pre-stressed
CS	Cement-treated subgrade	PR	PCC, continuously reinforced
DC	Double chip seal (2 emulsified asphalt applications)	PS	Plant mix seal coat
FB	Fly ash base	RC	Recycled AC-asphalt removed, rejuvenated, replaced
FC	ACFC, asphalt concrete friction course	RE	Remove existing material
FF	Filter fabric	RF	Rock fill
FL	Flush coat-fog seal	RM	Rubber. membrane (interlayer or seal coat)
FR	ACFC with asphalt rubber binder	RO	Recycled AC overlay
FS	Fly ash subgrade	SB	Aggregate subbase (similar to select material)
GR	Grind	SC	Seal coat cover material with emulsified asphalt
GV	Groove	SM	Select material
HS	Heater scarification	SR	Slurry seal
KS	Crack and seat PCC	SS	Subgrade seal

Table 2. Categorization of M&R treatments for asphalt pavements.

Asphalt Mix	**Preservation Treatment**	**Maintenance**		**Rehabilitation**					
		T≤0.25″	**0.25″<T≤1.5″**	**Straight Overlay**		**Shallow Removal (≤ 4.0″) & Overlay**		**Deep Removal (>4.0″) & Overlay**	
				1.5″<T≤4.0″	**T>4.0″**	**1.5″<T≤4.0″**	**T>4.0″**	**1.5″<T≤4.0″**	**T>4.0″**
Conventional	AC	M1A	M2A	R1A	R2A				
	AC+AC+SC								
	AC+AC+SC+SC								
	AC+FC								
	AC+FC+FL								
	AC+FL								
	AC+FL+SC								
	AC+SC								
	AC+SC+SC								
	AC+SC+SC+SC								
	AC+SR								
	AS								
	BS								
	BS+PS								
	BS+SC								
	FC								
	FC+FL								
	FC+RM+FC								
	FL								
	FL+LC+RM+FC+FL								
	FL+SC								
	GT+AC+SC								
	GT+AC+SC+SC								
	HS								
	HS+AC								
	HS+AC+FC								
	HS+AC+FL								
	HS+AC+FC+FL								
	HS+AC+SC								
	HS+AS								
	HS+FC								
	HS+FC+FL								
	HS+FC+FL+SC								
	HS+FL+AC+FC								
	HS+FL+AC+FL								
	HS+FL+FC								
	HS+LC+AC+FC								
	HS+LC+AC+FL								
	HS+SC								
	LC+AC								
	LC+AC+FC								
	LC+AC+SC								
	LC+AC+SC+FL								
	LC+AS+FC								
	LC+FC								

Table 2. Categorization of M&R treatments for asphalt pavements (continued).

Asphalt Mix	Preservation Treatment	Maintenance		Rehabilitation					
		T≤0.25″	0.25″<T≤1.5″	Straight Overlay		Shallow Removal (≤ 4.0″) & Overlay		Deep Removal (>4.0″) & Overlay	
				1.5″<T≤4.0″	T>4.0″	1.5″<T≤4.0″	T>4.0″	1.5″<T≤4.0″	T>4.0″
Conventional	LC+FC+FC	M1A	M2A	R1A	R2A	▨	▨	▨	▨
	LC+PS					▨	▨	▨	▨
	LC+RO					▨	▨	▨	▨
	MC+AC+FL					▨	▨	▨	▨
	PS					▨	▨	▨	▨
	RM+AC+FC					▨	▨	▨	▨
	RM+LC+AC+FC					▨	▨	▨	▨
	RM+SC					▨	▨	▨	▨
	RO					▨	▨	▨	▨
	RO+FC					▨	▨	▨	▨
	RO+SC					▨	▨	▨	▨
	SC					▨	▨	▨	▨
	SC+SC					▨	▨	▨	▨
	SC+FL					▨	▨	▨	▨
	SR					▨	▨	▨	▨
	SR+SR					▨	▨	▨	▨
	LC+RM+AC+FC					▨	▨	▨	▨
	RE+AC			▨	▨	R3A	R4A	R5A	R6A
	RE+AC+AC			▨	▨				
	RE+AC+AC+FC			▨	▨				
	RE+AC+AC+SC			▨	▨				
	RE+AC+AC+SC+SC			▨	▨				
	RE+AC+AS			▨	▨				
	RE+AC+FC			▨	▨				
	RE+AC+FL			▨	▨				
	RE+AC+RO+FC			▨	▨				
	RE+AC+SC			▨	▨				
	RE+AC+SC+SC			▨	▨				
	RE+FC			▨	▨				
	RE+FC+RM+FC			▨	▨				
	RE+FL+AC+FC			▨	▨				
	RE+GT+AC+FC			▨	▨				
	RE+GT+AC+SC			▨	▨				
	RE+HS+AS+FC			▨	▨				
	RE+RO+AC			▨	▨				
	RE+RO+AC+FC			▨	▨				
	RE+RO+AC+SC			▨	▨				
	RE+RO+FC			▨	▨				
	RE+RO+FL			▨	▨				
	RE+RO+SC			▨	▨				

Table 2. Categorization of M&R treatments for asphalt pavements (continued).

Asphalt Mix	Preservation Treatment	Maintenance		Rehabilitation					
		T≤0.25″	0.25″<T≤1.5″	Straight Overlay		Shallow Removal (≤ 4.0″) & Overlay		Deep Removal (>4.0″) & Overlay	
				1.5″<T≤4.0″	T>4.0″	1.5″<T≤4.0″	T>4.0″	1.5″<T≤4.0″	T>4.0″
Asphalt Rubber	AC+AR	M1B	M2B	R1B	R2B	▨	▨	▨	▨
	AC+AR+FR					▨	▨	▨	▨
	AC+FR					▨	▨	▨	▨
	AC+FR+FL					▨	▨	▨	▨
	AC+RM+AC+SC					▨	▨	▨	▨
	AR					▨	▨	▨	▨
	AR+FR					▨	▨	▨	▨
	FC+FR					▨	▨	▨	▨
	FC+RM					▨	▨	▨	▨
	FC+RM+FC					▨	▨	▨	▨
	FR					▨	▨	▨	▨
	HS+RM+FC					▨	▨	▨	▨
	LC+RM					▨	▨	▨	▨
	LC+RM+AC					▨	▨	▨	▨
	LC+RM+AC+SC					▨	▨	▨	▨
	LC+RM+AC+SC+FL					▨	▨	▨	▨
	LC+RM+AC+SC+SC					▨	▨	▨	▨
	RM					▨	▨	▨	▨
	RM+AC					▨	▨	▨	▨
	RM+AC+FC					▨	▨	▨	▨
	RM+AC+FL					▨	▨	▨	▨
	RM+AC+SC					▨	▨	▨	▨
	RM+AC+SC+SC+SC					▨	▨	▨	▨
	RM+FC					▨	▨	▨	▨
	RM+FL					▨	▨	▨	▨
	RM+SC					▨	▨	▨	▨
	RE+AC+AC+FR			▨	▨	R3B	R4B	R5B	R6B
	RE+AC+AR			▨	▨				
	RE+AC+AR+FC			▨	▨				
	RE+AC+AR+FR			▨	▨				
	RE+AC+FR			▨	▨				
	RE+AR			▨	▨				
	RE+AR+FR			▨	▨				
	RE+FR			▨	▨				
	RE+RM+RO+SC			▨	▨				
	RE+SP+FR			▨	▨				

Table 2. Categorization of M&R treatments for asphalt pavements (continued).

Asphalt Mix	**Preservation Treatment**	**Maintenance**		**Rehabilitation**					
				Straight Overlay		**Shallow Removal (≤ 4.0″) & Overlay**		**Deep Removal (>4.0″) & Overlay**	
		T≤0.25″	**0.25″<T≤1.5″**	**1.5″<T≤4.0″**	**T>4.0″**	**1.5″<T≤4.0″**	**T>4.0″**	**1.5″<T≤4.0″**	**T>4.0″**
SuperPave	RE+AC*+AR+FR					R3C	R4C	R5C	R6C
	RE+AC*+FR								
	RE+AC*+SC								
	RE+AC+AC*+FC								
	RE+AC+AC*+FR								
	RE+AC+AC+AC*+FR								
Recycled	RC					R3D	R4D	R5D	R6D
	RC+AC								
	RC+AC+FC								
	RC+AC+FL								
	RC+AC+FR								
	RC+AR+FC								
	RC+AS								
	RC+FC								
	RC+FR								
	RC+LC+AS+FC								
	RC+RM+RO+FC								
	RC+RM+SC								
	RC+SC								
	RC+RO+FC								
	RC+SC+SC								

Table 3. Categorization of M&R treatments for concrete pavements.

Asphalt Mix	Preservation Treatment	Maintenance		Rehabilitation of Original PCC							Rehabilitation of Overlaid PCC			
					Straight Overlay		Restoration & Overlay		Crack/Seat & Overlay		Shallow Removal (≤ 4.0″) & Overlay		Deep Removal (>4.0″) & Overlay	
		T≤0.25″	0.25″<T≤1.5″	Restoration	1.5″<T≤4.0″	T>4.0″	1.5″<T≤4.0″	T>4.0″	1.5″<T≤4.0″	T>4.0″	1.5″<T≤4.0″	T>4.0″	1.5″<T≤4.0″	T>4.0″
None	GV	M3												
	GR			R7										
	GR+GV													
Conventional	FL	M1A	M2A											
	SC													
	AC				R1A	R2A								
	AC+FC													
	AC+SC													
	FC													
	FC+RM+FC													
	FL+LC+RM+FC+FL													
	HS+AC													
	HS+AC+FC													
	HS+FC													
	RE+FC+RM+FC										R3A	R4A	R5A	R6A
	RE+GT+AC+FC													
	GR+AC						R10A	R11A						
	GR+AC+FC													
	GR+FC													
	KS+AC								R12A	R13A				
Asphalt Rubber	AC+AR+FR	M1B	M2B		R1B	R2B								
	AR+FR													
	FC+FR													
	FR													
	LC+RM													
	RM													
	RE+FR													
	RE+AC+FR										R3B	R4B	R5B	R6B
	RE+AR+FR													
	GR+AR						R10B	R11B						
	GR+AR+FR													
	GR+FR													
	KS+AC+ AR+FR								R12B	R13B				

Step 7—Performing QA Checks of Data

A final overall check of the data was made using a statistical procedure called univariate analysis. In this procedure, descriptive statistics, such as range, mean, and standard deviation, were computed for all numerical data fields (e.g., thickness, construction date, age, service life). The goal of this effort was to identify obvious anomalous data (e.g., thickness < 0.0 in, construction date of 2020). Anomalies were identified and flagged for further review. This review ranged from rechecking the value of the given data element by referencing the original data source to referring the suspect data to ADOT personnel for clarification. In cases where the anomalies could be rectified, the data for the pavement section in question was replaced. If not, the section was removed from the database.

During the QA checking process, some very short and very long service lives were observed for both original pavement structures and rehabilitation treatments. Sections with this phenomenon were subsequently investigated by comparing time-series performance (e.g., smoothness, cracking, rutting) plots and maintenance cost plots with the timing of reported M&R activities, as listed in the project history database. This process was ultimately carried out for all pavement sections that survived rehabilitation or reconstruction for 20 or more years.

Of the approximately 1,000 pavement sections evaluated, discrepancies between significant changes in performance/maintenance cost and the reported M&R were identified for approximately 200 pavement sections. A significant change in performance/maintenance cost was defined as follows:

- Smoothness performance indicator—An abrupt decrease in the International Roughness Index (IRI) of about 10 in/mi or a greater, with a sustained reduction in IRI of 5+ years.
- Cracking performance indicator—An abrupt decrease in cracking of about 10 percentage points or greater, with a sustained reduction in cracking of 5+ years.
- Rutting performance indicator—An abrupt decrease in rutting of about 0.1 in or greater, with a sustained reduction in rutting of 5+ years.
- Maintenance cost—Since maintenance costs did not always coincide with a potential special rehabilitation event (SRE) or documented rehabilitation events in the dataset, they were used only to validate the possibility of a SRE.

If a potential SRE was suspected from the plots of smoothness performance, cracking performance, or rutting performance, all plots were laid side-by-side to coordinate an evaluation of the suspected rehabilitation event. The rehabilitation events for previous and subsequent 1-mi sections to the suspected 1-mi section were also reviewed to validate the possibility of a SRE. The 5-year sustained IRI reduction after an abrupt drop in one of the indicators was used to discount maintenance activities.

This anomaly was rectified by checking the ADOT dataset for the possibility of identifying the reasons for the significant change in performance. Where no possible reason could be identified, the data was flagged by indicating the occurrence of a SRE at the date at which a significant change in performance occurred. Though the nature of the event was not known or recorded, it was important in determining the life of the pavement structure.

DATA SUMMARY

The assembled project database consisted of over 7,200 individual 1-mi sections of Interstate, U.S., and State highway pavement, as established by the ADOT PMS database. Approximately 28 years of traffic data and 20+ years of key distress (i.e., cracking, rutting, patching) data, smoothness data, and maintenance cost data were available for most of the 7,200+ sections. Moreover, for each 1-mi section, detailed information about the location, climate, original structure (construction year, material types and thicknesses), and types of maintenance and rehabilitation (M&R) treatments applied through 2002 were available.

A total of eight different original (i.e., new or reconstructed) pavement types were identified in the database. Of these eight original types, six were selected by ADOT for performance analysis. These were CAC, DSAC, FDAC, JPC, JPCD, and CRC.

As only sections with complete traffic records (i.e., original pavements built after 1973 and M&R treatments applied after 1973) were chosen for analysis, a total of 1,389 sections were available for analysis of initial pavement service life. These consisted of 471 CAC pavements, 637 DSAC pavements, 66 FDAC pavements, 145 JPC pavements, 58 JPCD pavements, and 12 CRC pavements. A summary of the number of pavement sections represented by facility type is presented in table 4.

Table 4. Summary of the number of pavement sections along with facility types.

Pavement Type	Facility Type	No. of Sections	Total
CAC	Interstates	121	471
	State Routes	274	
	U.S. Highways	76	
DSAC	Interstates	318	637
	State Routes	230	
	U.S. Highways	89	
FDAC	Interstates	52	66
	State Routes	14	
	U.S. Highways	0	
JPC	Interstates	25	145
	State Routes	72	
	U.S. Highways	48	
JPCD	Interstates	54	58
	State Routes	4	
	U.S. Highways	0	
CRC	Interstates	0	12
	State Routes	12	
	U.S. Highways	0	

Table 5 presents an overview of the ADOT Districts represented by the data used in analysis. For each District, the pavement sections were broken down by facility type (i.e., Interstate, U.S. highways, and State routes) and the following climatic zones, as defined by ADOT's regional factor (RF):

- Hot-dry ($RF \leq 1.5$).
- Moderate ($1.5 < RF \leq 3.0$).
- Cool-wet ($RF > 3.0$).

The number of pavement sections per District ranged from 45 to 287. Depending on the geographic location of the District, all or some of the three climate types in Arizona were represented.

Table 6 shows a breakdown of the pavement sections analyzed by highway. This table shows that the 1,389 pavement sections represent six different Interstates, eight different U.S. highways, and 38 different State routes. Although the State routes were well represented, their contribution in terms of actual pavement sections was limited, primarily because a high portion of them were originally constructed before 1973. A total of 570 pavement sections were located on Interstates, 606 were located on State routes, and the remaining 213 pavement sections were located on U.S. highways.

Table 5. Overview of the pavement sections used in analysis.

ADOT District	**Climate Zone**	**Facility Type**			**Total**
		Interstate	**State Routes**	**U.S. Highways**	
Phoenix	Hot-Dry	86	133	53	299
	Moderate	0	27	0	
	Cool-Wet	0	0	0	
Flagstaff	Hot-Dry	42	9	2	173
	Moderate	16	19	18	
	Cool-Wet	40	9	18	
Globe	Hot-Dry	0	0	0	93
	Moderate	0	25	9	
	Cool-Wet	0	31	28	
Holbrook	Hot-Dry	0	1	0	45
	Moderate	25	11	8	
	Cool-Wet	0	0	0	
Kingman	Hot-Dry	20	55	29	266
	Moderate	142	13	7	
	Cool-Wet	0	0	0	
Prescott	Hot-Dry	0	23	0	157
	Moderate	21	68	0	
	Cool-Wet	0	45	0	
Safford	Hot-Dry	0	0	0	86
	Moderate	32	35	19	
	Cool-Wet	0	0	0	
Tucson	Hot-Dry	0	44	0	134
	Moderate	41	45	4	
	Cool-Wet	0	0	0	
Yuma	Hot-Dry	105	13	18	136
	Moderate	0	0	0	
	Cool-Wet	0	0	0	

Table 6. Highway breakdown of pavement sections analyzed for initial service life.

Highway	No. of Pavement Sections	Highway	No. of Pavement Sections
I-10	214	SR 68	18
I-15	42	SR 69	33
I-17	59	SR 73	5
I-19	37	SR 74	25
I-40	205	SR 77	41
I-8	13	SR 78	7
SR 101	67	SR 80	17
SR 143	8	SR 84	3
SR 169	8	SR 85	8
SR 179	1	SR 86	12
SR 189	2	SR 87	78
SR 19	4	SR 88	17
SR 202	6	SR 89	8
SR 238	1	SR 90	6
SR 260	56	SR 92	5
SR 261	6	SR 95	48
SR 264	8	SR 96	5
SR 287	11	SR 99	1
SR 288	1	US 160	1
SR 303	13	US 163	1
SR 347	21	US 180	32
SR 387	8	US 191	20
SR 40	8	US 60	63
SR 51	8	US 89	42
SR 64	25	US 93	36
SR 66	7	US 95	18

Table 7 provides a listing of the number of pavement sections analyzed for initial service life, as well as the number of rehabilitation treatments analyzed for performance, according to the specified pavement type and facility type combinations.

As noted previously and seen in table 6, a total of 1,389 pavement sections were used in the analysis of initial service life. For the analysis of rehabilitation performance, approximately 3,500 pavement sections were used, which yielded 4,570 individual rehabilitation treatments for analysis. For both initial service life and rehabilitation performance life analysis, only sections with activities that occurred after 1973 were used, because of the availability of traffic data back to that time.

Table 7. Types of rehabilitation activities performed according to pavement and facility types.

		Original Construction/Reconstruction (O) and Rehabilitation (R) Groups										
		O	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R10**	**R12**	**R13**
Pavement Type	**Facility Type**	**Orig. Const. & Reconst.** [a]	**HMA OL (1.5″<T≤4.0″)** [b]	**HMA OL (T>4.0″)** [b]	**Shallow Mill (<4.0″) & HMA OL (1.5″<T≤4.0″)** [b]	**Shallow Mill (<4.0″) & HMA OL (T>4.0″)** [b]	**Deep Mill (>4.0″) & HMA OL (1.5″<T≤4.0″)** [b]	**Deep Mill (>4.0″) & HMA OL (T>4.0″)** [b]	**Diamond Grind**	**Restoration & HMA OL (1.5″<T≤4.0″)** [b]	**Crack/Seat & HMA OL (1.5″<T≤4.0″)** [b]	**Crack/Seat & HMA OL (T>4.0″)** [b]
CAC	Interstates	121	356	131	453	822	1	268	0	0	0	0
	State Routes	274	907	54	123	59	0	10	0	0	0	0
	U.S. Routes	76	686	36	133	99	0	7	0	0	0	0
DSAC	Interstates	318	3	4	82	78	7	75	0	0	0	0
	State Routes	230	43	0	19	0	0	2	0	0	0	0
	U.S. Routes	89	1	0	0	0	0	0	0	0	0	0
FDAC	Interstates	52	0	4	32	0	0	25	0	0	0	0
	State Routes	14	1	0	0	1	0	0	0	0	0	0
	U.S. Routes	0	0	0	0	0	0	0	0	0	0	0
JPC	Interstates	25	33	15	23	0	0	0	50	25	14	9
	State Routes	72	7	0	0	0	0	0	0	0	0	0
	U.S. Routes	48	0	0	0	0	0	0	0	0	0	0
JPCD	Interstates	54	0	0	0	0	0	0	0	0	0	0
	State Routes	4	0	0	0	0	0	0	0	0	0	0
	U.S. Routes	0	0	0	0	0	0	0	0	0	0	0
CRC	Interstates	0	0	0	0	0	0	0	0	0	0	0
	State Routes	12	0	0	0	0	0	0	0	0	0	0
	U.S. Routes	0	0	0	0	0	0	0	0	0	0	0
TOTAL		1,389	2,037	244	865	1,059	8	387	50	25	14	9

[a] Based on pavement sections originally constructed or reconstructed after 1973.

[b] Based on rehabilitation treatments that occurred after 1973.

T = Thickness.

OL = Overlay.

Descriptive Statistics for CAC Pavements

The project database contains a variety of data elements for 471 CAC pavement sections built (constructed or reconstructed) after 1973. A breakdown of the CAC pavement sections among the nine ADOT Districts and three climatic regions is provided in table 8. As can be seen, each District and climate is represented, though it should be noted that the distribution of climate zones within a District is limited by the geographic location of the District.

CAC Construction Year and Age

The histogram in figure 2 shows the distribution of construction dates for CAC pavements. It can be seen that most of the sections analyzed (218 out of 471) were built

Table 8. Location breakdown of CAC pavement sections.

ADOT District	Climate	Number of Pavement Sections
Phoenix	Hot-Dry	32
	Moderate	19
	Cool-Wet	0
Flagstaff	Hot-Dry	20
	Moderate	10
	Cool-Wet	16
Globe	Hot-Dry	0
	Moderate	20
	Cool-Wet	22
Holbrook	Hot-Dry	1
	Moderate	13
	Cool-Wet	0
Kingman	Hot-Dry	58
	Moderate	33
	Cool-Wet	0
Prescott	Hot-Dry	22
	Moderate	34
	Cool-Wet	26
Safford	Hot-Dry	0
	Moderate	23
	Cool-Wet	0
Tucson	Hot-Dry	34
	Moderate	15
	Cool-Wet	0
Yuma	Hot-Dry	72
	Moderate	0
	Cool-Wet	0

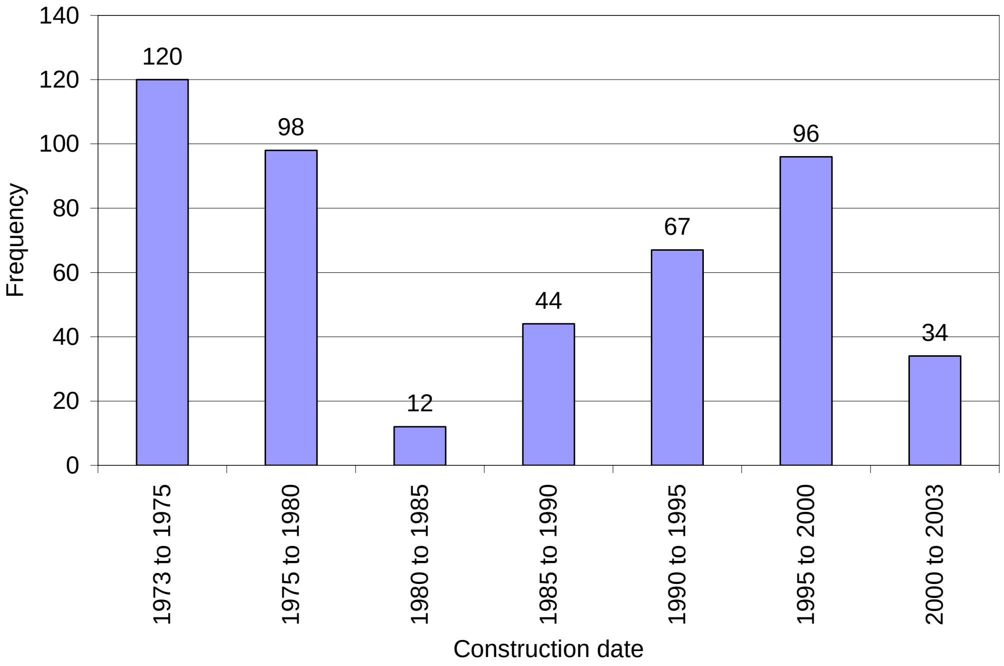


Figure 2. Construction date histogram for CAC pavement sections.

between 1973 and 1980, and that a substantial number of sections (130) were built after 1995. The resulting ages of CAC pavement sections vary from 1 to 30 years, with a mean of 13.8 years and a standard deviation of 8.1 years. The histogram of age for CAC pavement sections given in figure 3 shows that CAC ages were well distributed, with most of the 471 sections less than 20 years old.

CAC Pavement Traffic

Traffic was qualified in terms of the number of truck (vehicle class 4 though 15) applications per year. The CAC pavement sections showed a wide range of traffic loadings (0.005 to 2.04 million trucks/year), with a mean value of 0.46 million trucks/year and a standard deviation of 0.56 million trucks/year. A truck traffic histogram for CAC pavement sections is provided in figure 4.

CAC Cross-Section

The total pavement thickness (i.e., thickness of all layers above the subgrade) of original CAC pavements ranged from 4.5 to 32.5 in. Mean total thickness was 16.5 in, with a standard deviation of 5.4 in. The asphalt thickness in CAC pavements ranged from 2.5 to 7.5 in, with a mean of 5.0 in and a standard deviation of 1.4 in. As seen in the histogram in figure 5, most of the CAC pavements had asphalt thicknesses between 3.0 and 7.5 in.

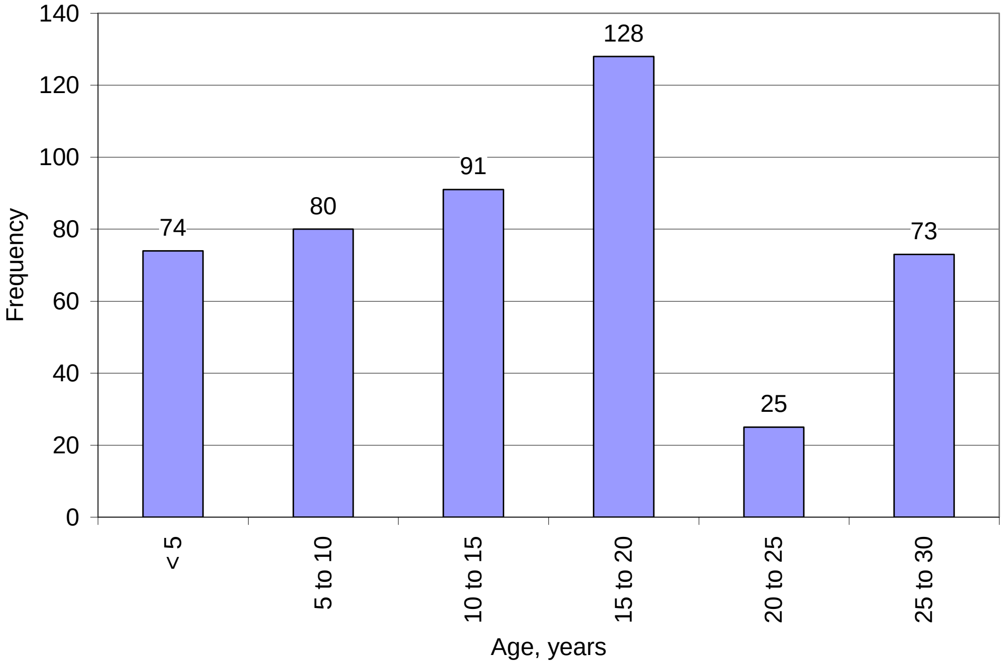


Figure 3. Age histogram for CAC pavement sections.

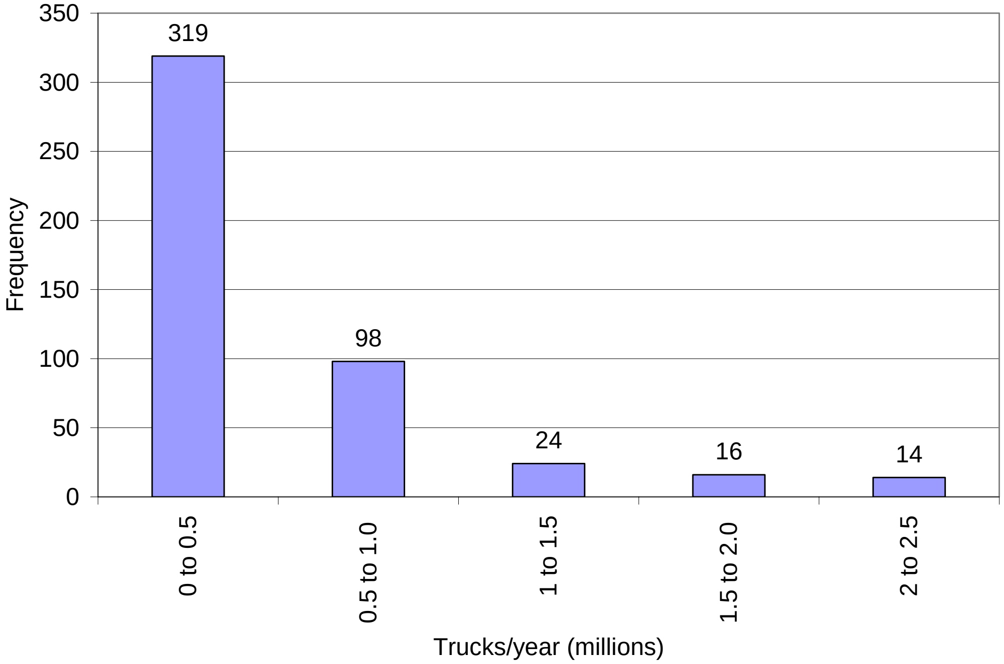


Figure 4. Traffic histogram for CAC pavement sections.

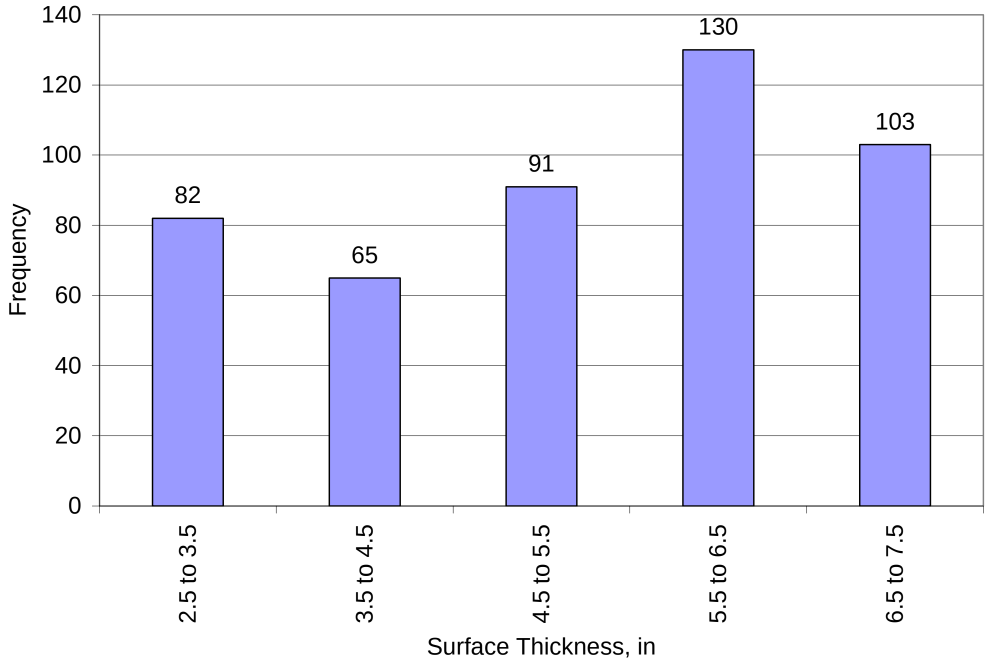


Figure 5. Asphalt thickness histogram for CAC pavement sections.

Descriptive Statistics for DSAC Pavements

The project database contains a variety of data elements for 637 DSAC pavement sections built (constructed or reconstructed) after 1973. As seen in table 9, all nine ADOT Districts and all three climatic zones were represented by DSAC pavements.

DSAC Construction Year and Age

The construction date histogram in figure 6 shows that 356 out of the 637 DSAC sections analyzed were constructed between 1973 and 1980, while 145 were constructed between 1990 and 1995. Forty-seven pavement sections were constructed between 1980 and 1985.

The resulting ages of DSAC pavement sections ranged from 1 to 30 years, with a mean of 16.0 years and a standard deviation of 6.7 years. As seen by the age histogram in figure 7, the DSAC pavement ages were well distributed with most of the 637 sections between 10 and 25 years old.

Table 9. Location breakdown of DSAC pavement sections.

ADOT District	Climate	Number of Pavement Sections
Phoenix	Hot-Dry	36
	Moderate	8
	Cool-Wet	0
Flagstaff	Hot-Dry	33
	Moderate	43
	Cool-Wet	24
Globe	Hot-Dry	0
	Moderate	14
	Cool-Wet	37
Holbrook	Hot-Dry	0
	Moderate	26
	Cool-Wet	0
Kingman	Hot-Dry	45
	Moderate	104
	Cool-Wet	0
Prescott	Hot-Dry	1
	Moderate	41
	Cool-Wet	18
Safford	Hot-Dry	0
	Moderate	63
	Cool-Wet	0
Tucson	Hot-Dry	9
	Moderate	71
	Cool-Wet	0
Yuma	Hot-Dry	64
	Moderate	0
	Cool-Wet	0

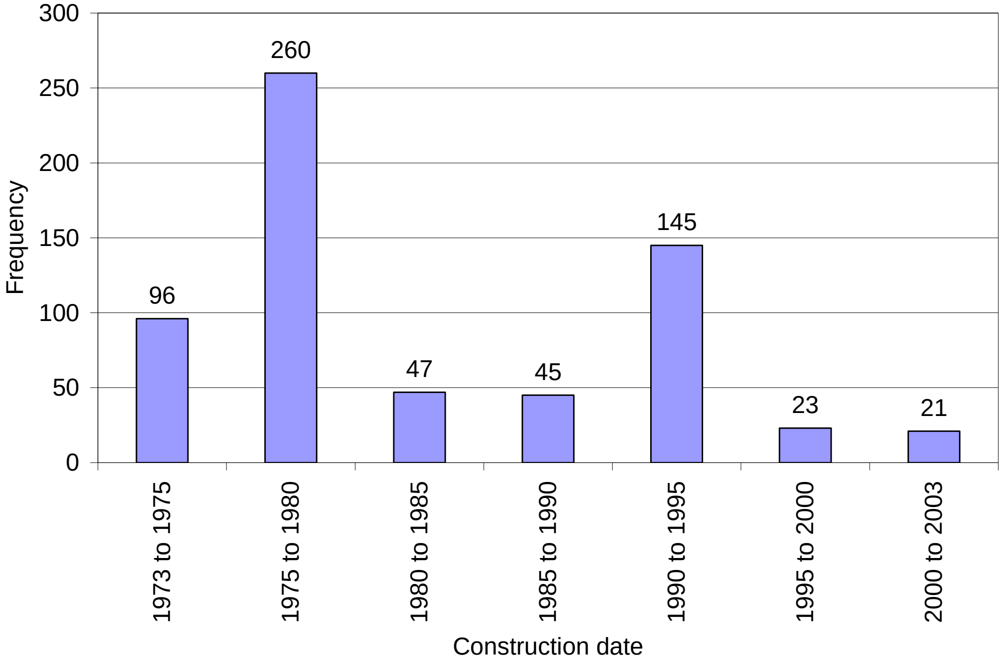


Figure 6. Construction date histogram for DSAC pavement sections.

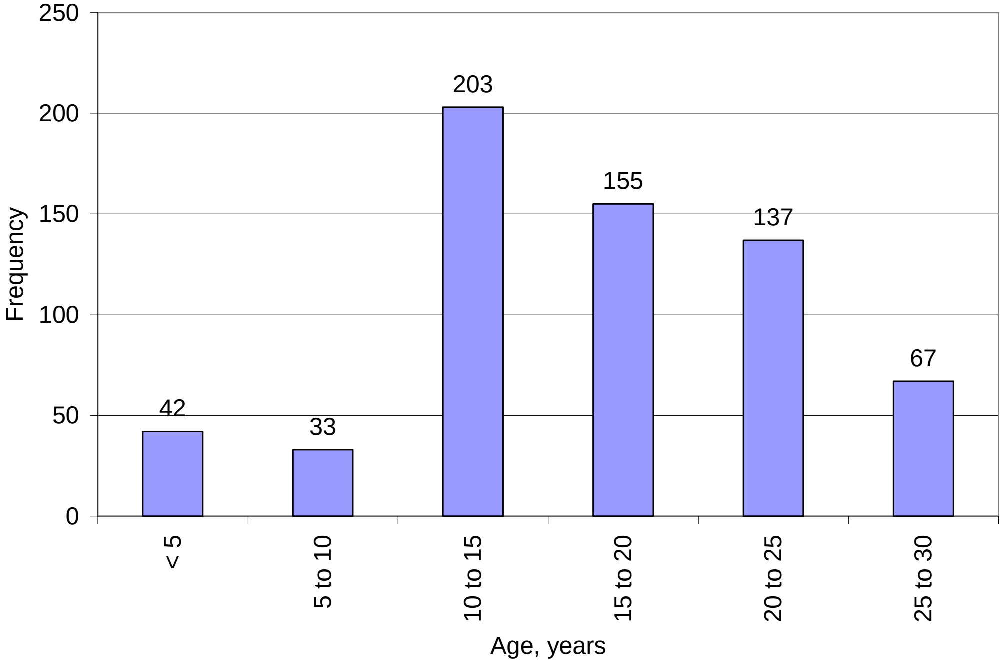


Figure 7. Age histogram for DSAC pavement sections.

DSAC Pavement Traffic

Traffic was qualified in terms of the number of truck (vehicle class 4 though 15) applications per year. The DSAC pavement sections showed a wide range of traffic loadings (0.006 to 4.55 million trucks per year), with a mean value of 0.61 million trucks/year and a standard deviation of 0.5 million trucks/year. A histogram of CAC pavement sections traffic is provided in figure 8.

DSAC Cross-Section

The total thickness (i.e., thickness of all layers above the subgrade) of original DSAC pavements ranged from 9.3 to 39.0 in. Mean total thickness was 16.3 in with a standard deviation of 6.1 in. Asphalt thickness in the DSAC pavements ranged from 4.5 to 15.0 in, with a mean of 8.5 in and a standard deviation of 2.8 in. Figure 9 presents a histogram of the distribution of asphalt thickness for the DSAC pavements analyzed.

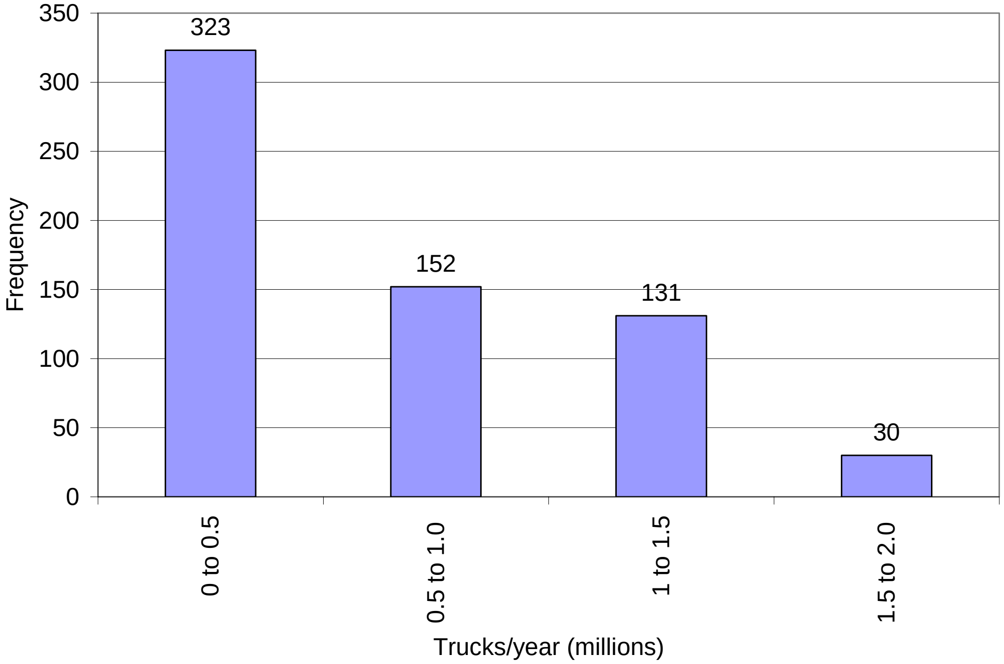


Figure 8. Traffic histogram for DSAC pavement sections.

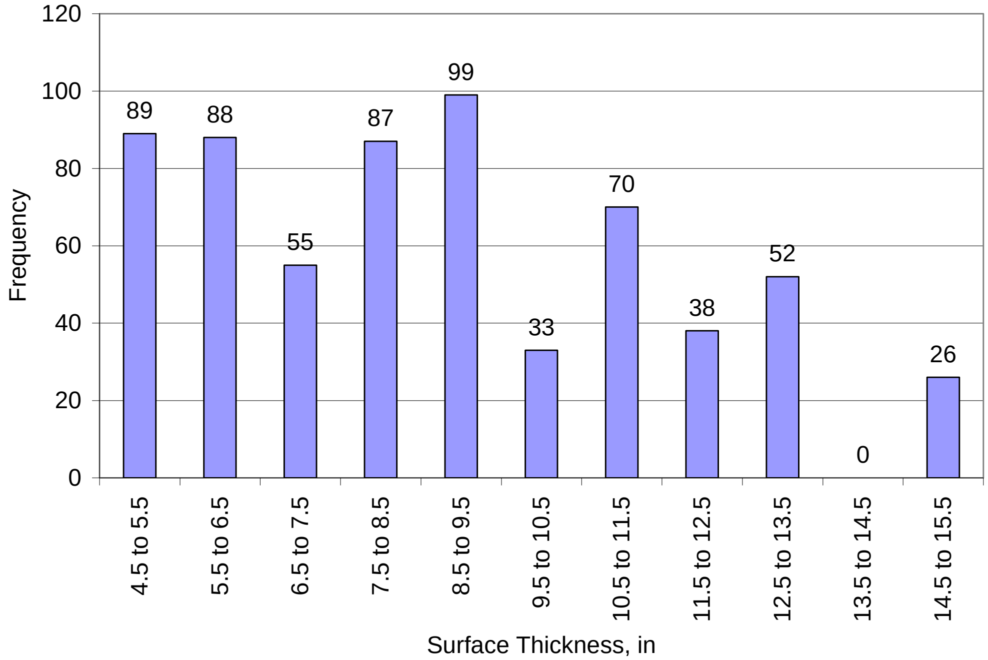


Figure 9. Asphalt thickness histogram for DSAC pavement sections.

Descriptive Statistics for FDAC Pavements

The project database contains a variety of data elements for 66 FDAC pavement sections constructed or reconstructed after 1973. Table 10 shows the breakdown of FDAC sections among the nine ADOT Districts and three climatic regions. As can be seen, four Districts and all three climates were represented, though most sections fell within the hot-dry and moderate climates.

FDAC Construction Year and Age

The construction date histogram in figure 10 shows that most of the FDAC sections analyzed (53 out of 66) were constructed between 1975 and 1980. Only four were built after 1985 and none were built after 1989.

The resulting ages of FDAC pavement sections ranged from 1 to 23 years, with a mean of 16.7 years and a standard deviation of 5.8 years. As seen in the age histogram in figure 11 the vast majority of sections were between 15 and 25 years old.

Table 10. Location breakdown of FDAC pavement sections.

ADOT District	Climate	Number of Pavement Sections
Phoenix	Hot-Dry	21
	Moderate	0
	Cool-Wet	0
Holbrook	Hot-Dry	0
	Moderate	5
	Cool-Wet	0
Kingman	Hot-Dry	0
	Moderate	25
	Cool-Wet	0
Prescott	Hot-Dry	0
	Moderate	14
	Cool-Wet	1

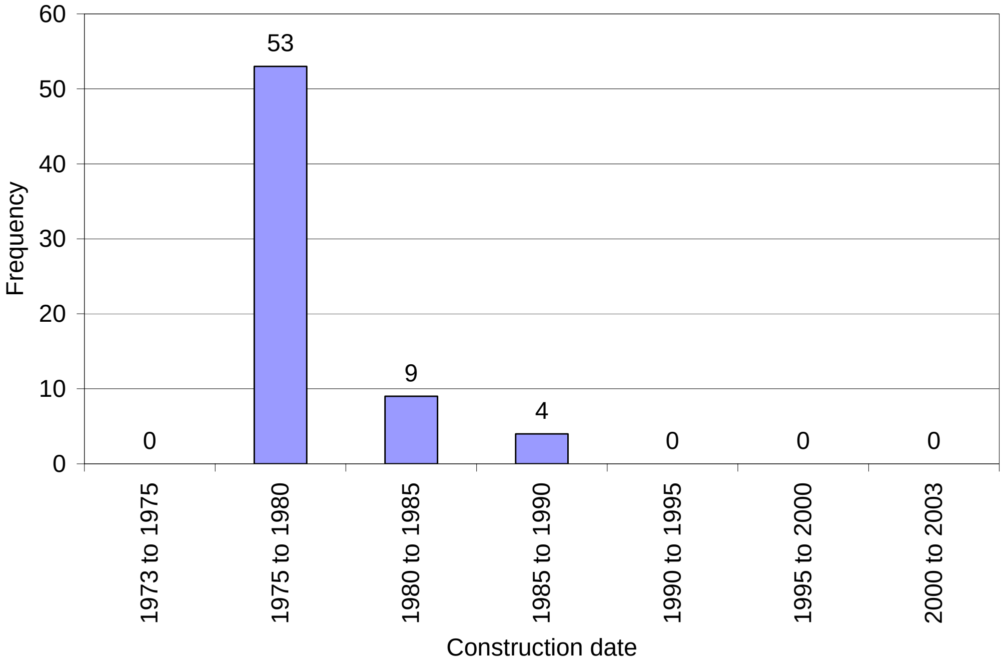


Figure 10. Construction date histogram for FDAC pavement sections.

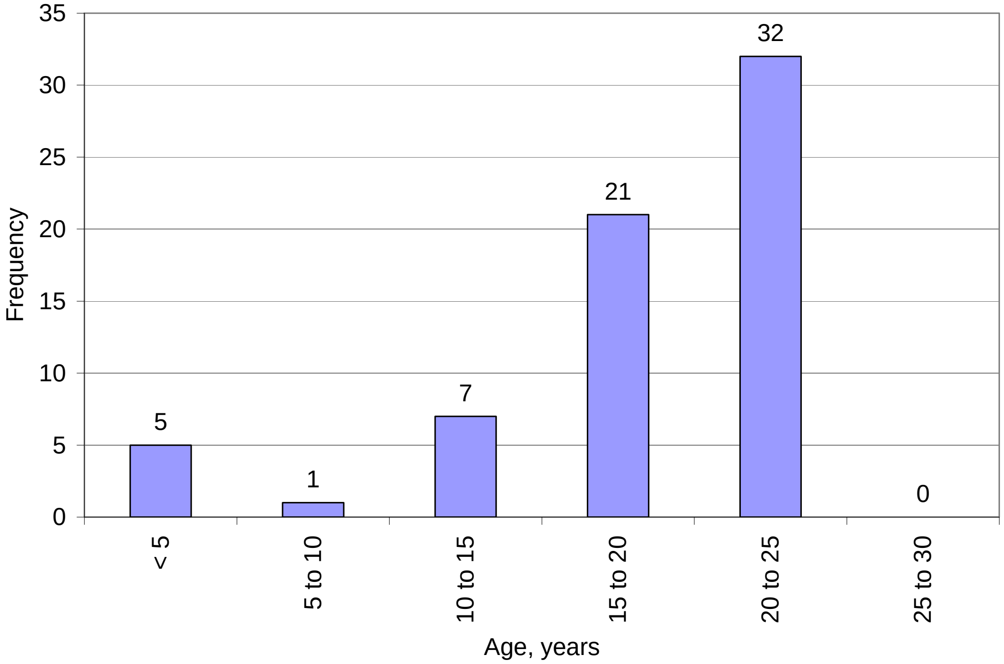


Figure 11. Age histogram for FDAC pavement sections.

FDAC Pavement Traffic

Traffic was qualified in terms of the number of truck (vehicle class 4 though 15) applications per year. The FDAC pavement sections showed a wide range of traffic loading (0.05 to 1.6 million trucks/year), with a mean value of 0.8 million trucks/year and a standard deviation of 0.4 million trucks/year. A histogram of truck traffic for FDAC pavements is provided in figure 12.

FDAC Cross-Section

The total thickness (i.e., thickness of all layers above the subgrade) of original FDAC pavements ranged from 8.5 to 24.5 in. Mean total thickness was 15.6 in, with a standard deviation of 5.9 in. The asphalt thickness of FDAC pavements ranged from 3.0 to 12.5 in, with a mean of 7.7 in and a standard deviation of 2.9 in. The histogram in figure 13 shows that most of the FDAC pavements had an asphalt thickness between 4.5 and 11.0 in.

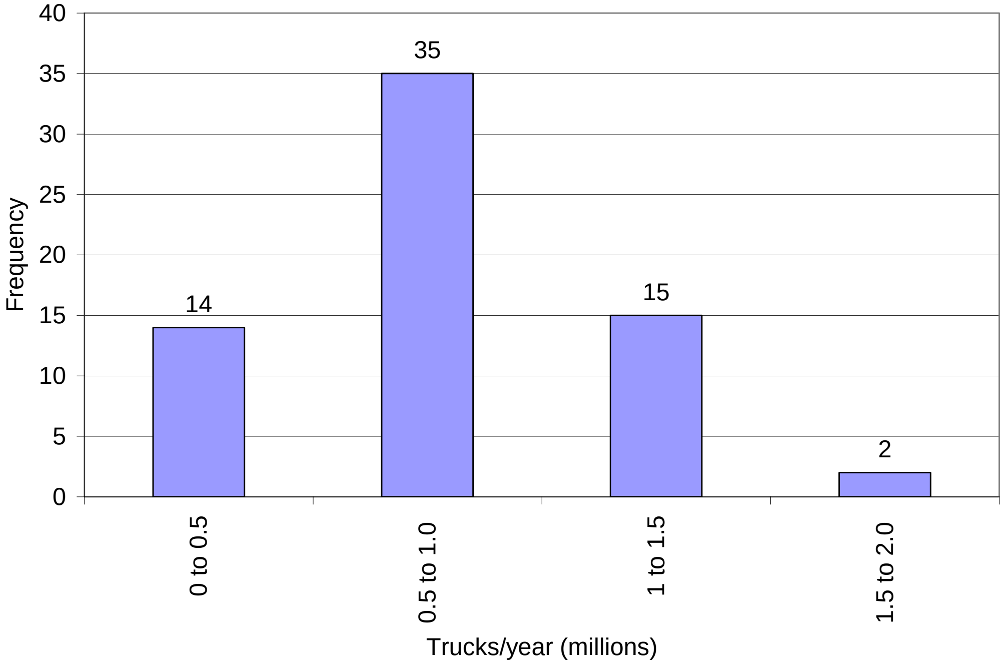


Figure 12. Traffic histogram for FDAC pavement sections.

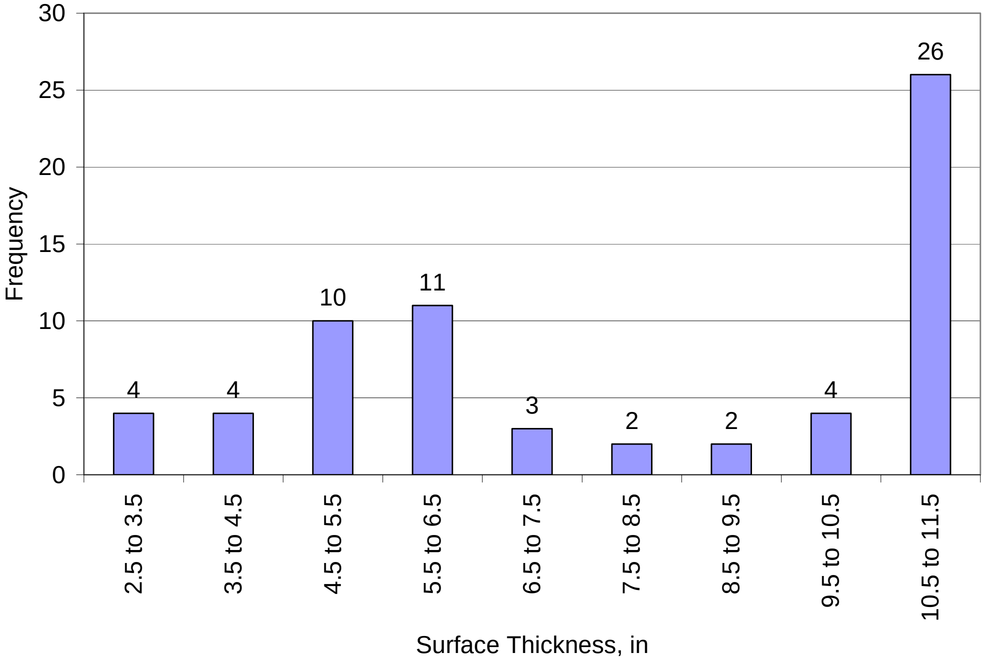


Figure 13. Asphalt thickness histogram for FDAC pavement sections.

Descriptive Statistics for JPC Pavements

The project database contains a variety of data elements for 145 JPC pavement sections constructed or reconstructed after 1973. As seen in table 11, the JPC pavement sections analyzed were located in four of the nine ADOT Districts and in the hot-dry and cool-wet climatic regions.

JPC Pavement Age

The histogram in figure 14 shows the distribution of construction dates for JPC pavements. Most of the sections in the 1973 to 1979 category were built in the Flagstaff District, whereas most of those built between 1995 and 2003 were located in the Phoenix District. The resulting ages of JPC pavement sections ranged from 1 to 28 years, with a mean of 11.4 years and a standard deviation of 7.3 years. The histogram in figure 15 shows more than half of the JPC sections used in analysis were less than 15 years old.

JPC Pavement Traffic

Traffic was qualified in terms of the number of truck (vehicle class 4 though 15) applications per year. The JPC pavement sections showed a wide range of traffic loading (0.05 to 2.6 million trucks/year), with a mean value of 0.87 million trucks/year and a standard deviation of 0.54 million trucks/year. A histogram showing the annual truck traffic for JPC pavements is provided in figure 16.

PCC Slab Thickness

The total pavement thickness (i.e., thickness of all layers above the subgrade) of original JPC pavement sections ranged from 10.0 to 20.0 in. Mean total thickness was 16.2 in, with a standard deviation of 2.3 in. PCC surface thickness for the JPC pavements ranged from 8.0 to 16.0 in, with a mean of 11.2 in and a standard deviation of 2.15 in. The histogram in figure 17 shows that most of the JPC pavements analyzed had slab thicknesses between 7.5 and 13.5 in.

Table 11. Location breakdown of JPC pavement sections.

ADOT District	Climate	Number of Pavement Sections
Phoenix	Hot-Dry	117
	Moderate	0
	Cool-Wet	0
Flagstaff	Hot-Dry	0
	Moderate	0
	Cool-Wet	27
Tucson	Hot-Dry	1
	Moderate	0
	Cool-Wet	0

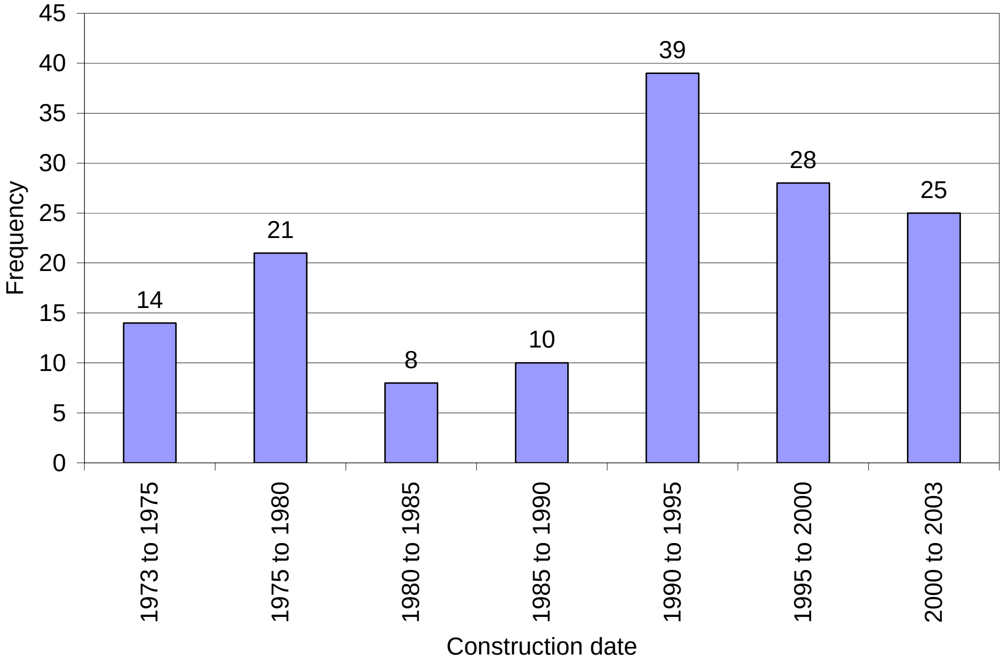


Figure 14. Construction date histogram for JPC pavements.

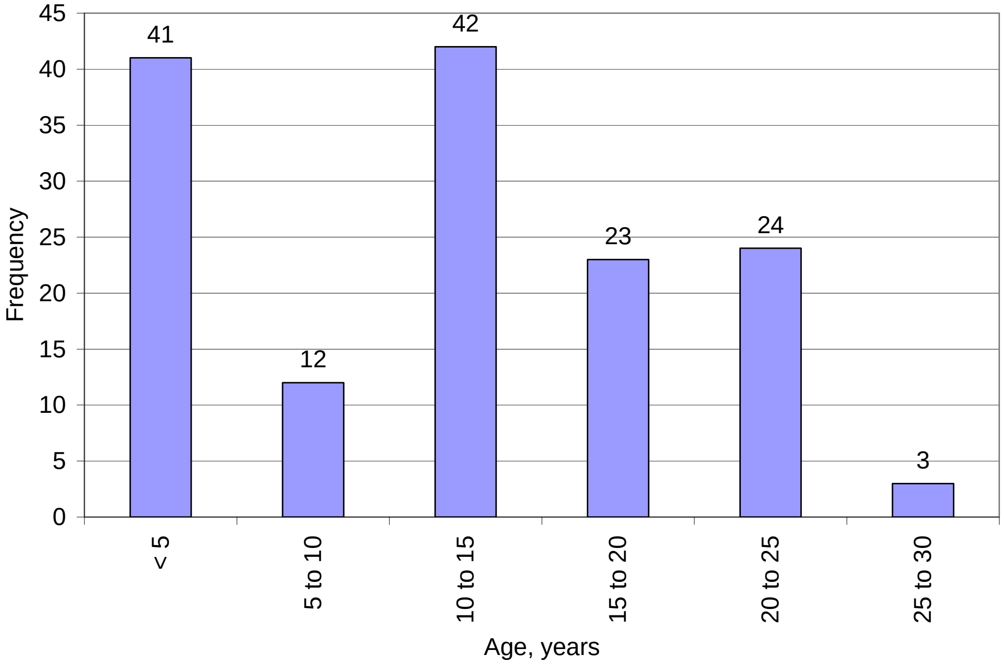


Figure 15. Age histogram for JPC pavement sections.

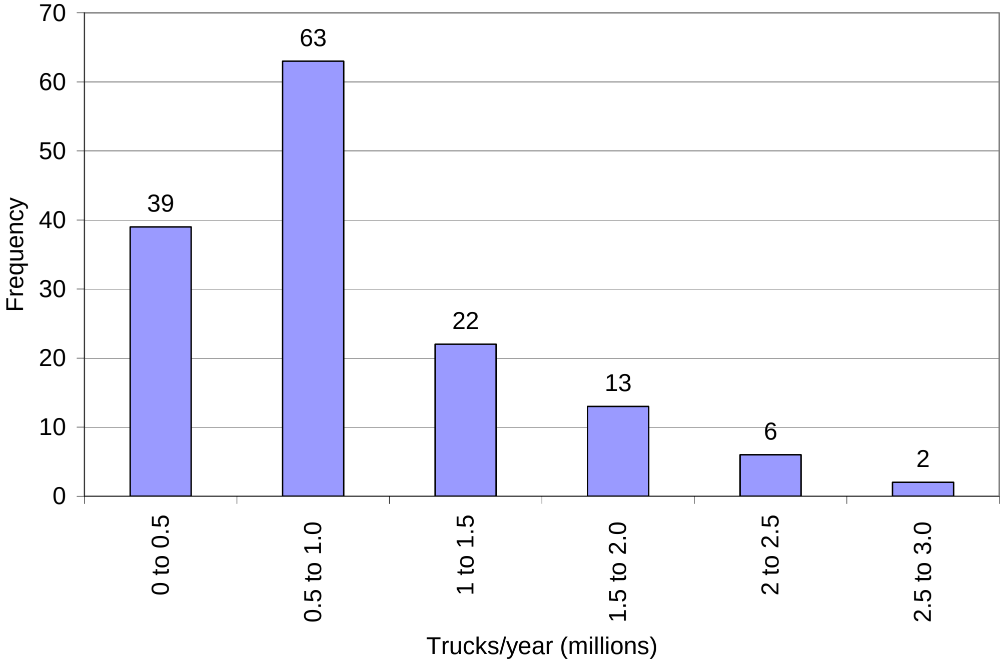


Figure 16. Traffic histogram for JPC pavement sections.

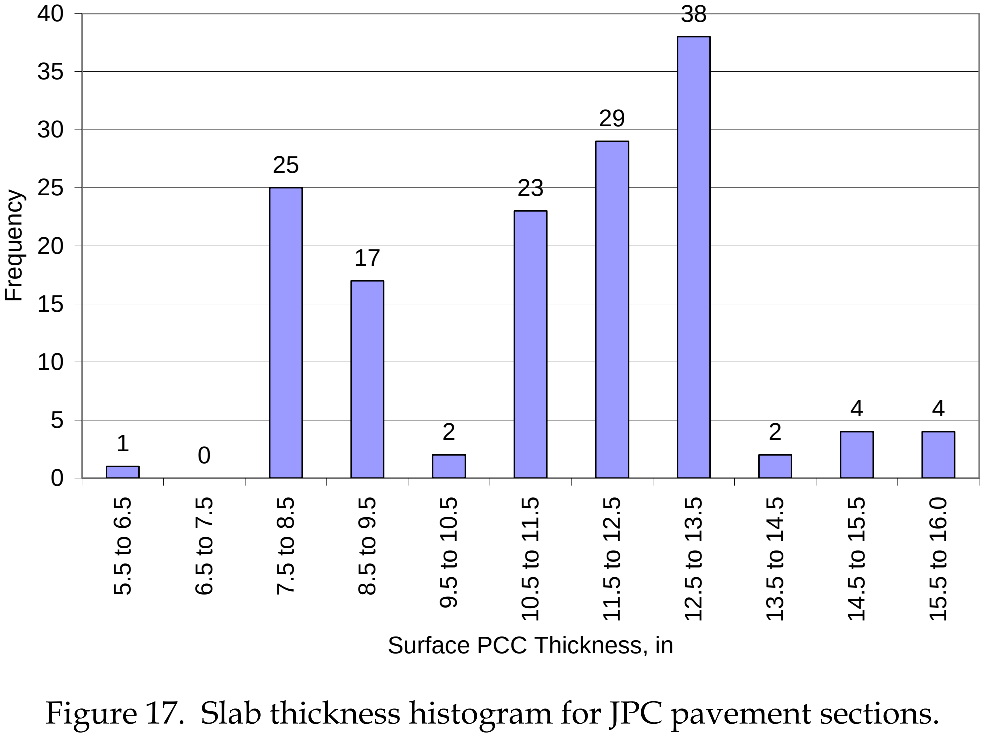


Figure 17. Slab thickness histogram for JPC pavement sections.

Descriptive Statistics for JPCD Pavements

The project database contains a variety of data elements for 58 JPCD pavement sections constructed or reconstructed after 1973. As table 12 shows, the JPCD pavement sections analyzed were located in the Phoenix and Tucson Districts and in the hot-dry and moderate climates.

JPCD Construction Year and Age

The histogram in figure 18 shows the distribution of construction dates for JPCD pavements. It can be seen in this figure that all of the sections analyzed were built after 1980. The resulting ages of JPCD pavement sections ranged from 2 to 19 years, with a mean of 12.9 years and a standard deviation of 5.5 years. The age histogram in figure 19 shows that most JPCD pavement sections were less than 20 years old.

JPCD Pavement Traffic

Traffic was qualified in terms of the number of truck (vehicle class 4 though 15) applications per year. The JPCD pavement sections showed a very wide range of traffic loadings (0.9 to 6.7 million trucks/year), with a mean value of 3.8 million trucks/year and a standard deviation of 1.7 million trucks/year. A traffic histogram of JPCD pavement sections is provided in figure 20.

PCC Slab Thickness

The total thickness (i.e., thickness of all layers above the subgrade) of original JPCD pavement sections ranged from 15.0 to 29.0 in. Mean total thickness was 16.5 in, with a standard deviation of 3.5 in. PCC surface thickness ranged from 10.0 to 15.0 in, with a mean of 11.3 in and a standard deviation of 1.71 in. The histogram in figure 21 shows the distribution of PCC thickness for the JPCD pavements analyzed.

Table 12. Location breakdown of JPCD pavement sections.

ADOT District	Climate	Number of Pavement Sections
Phoenix	Hot-Dry	54
	Moderate	0
	Cool-Wet	0
Tucson	Hot-Dry	0
	Moderate	4
	Cool-Wet	0

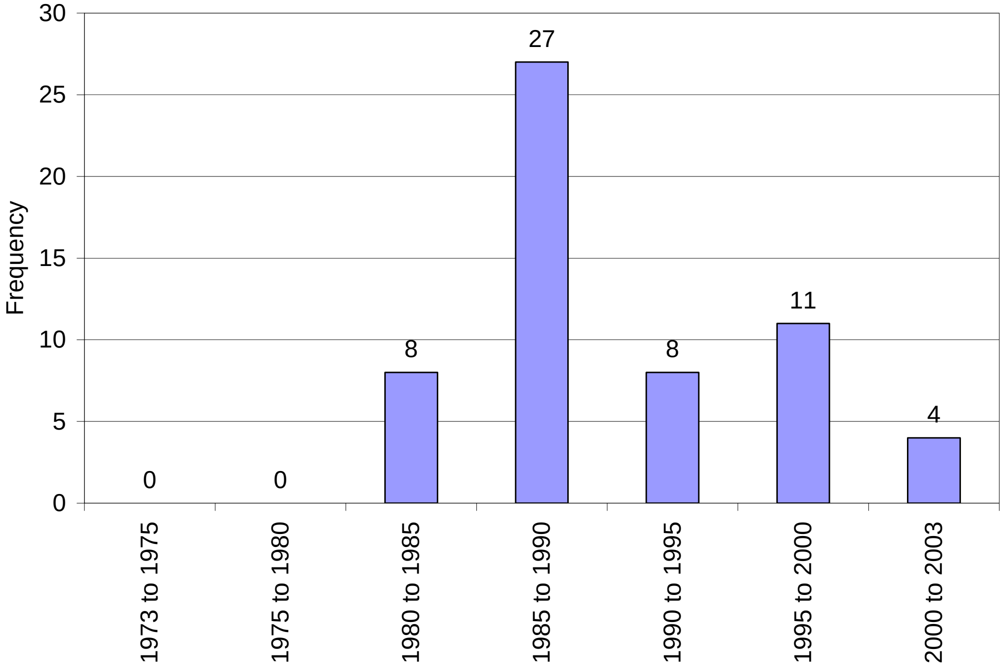


Figure 18. Construction date histogram for JPCD pavement sections.

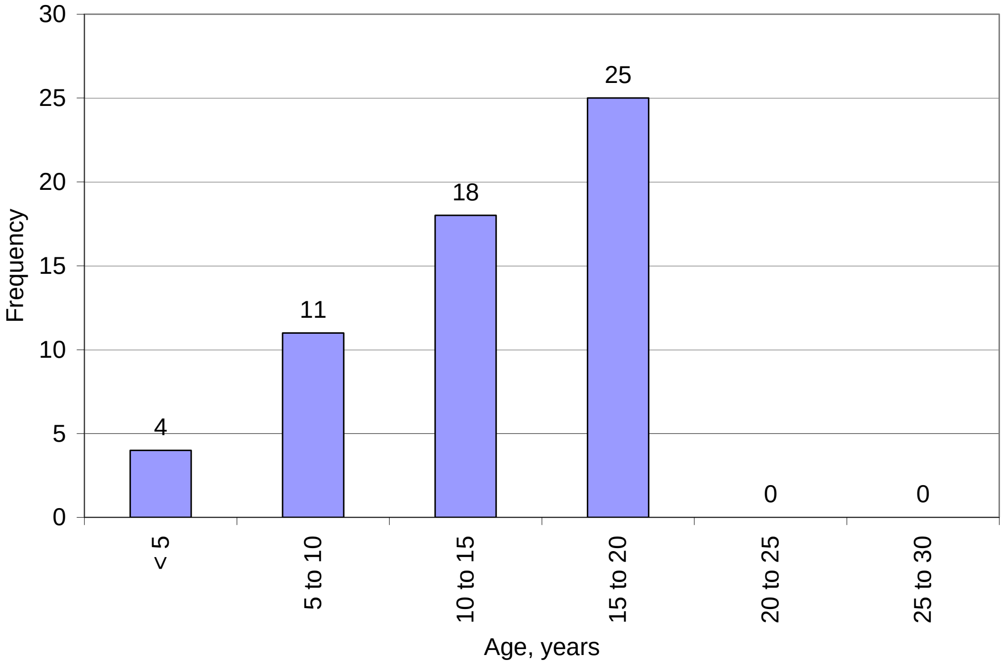


Figure 19. Age histogram for JPCD pavement sections.

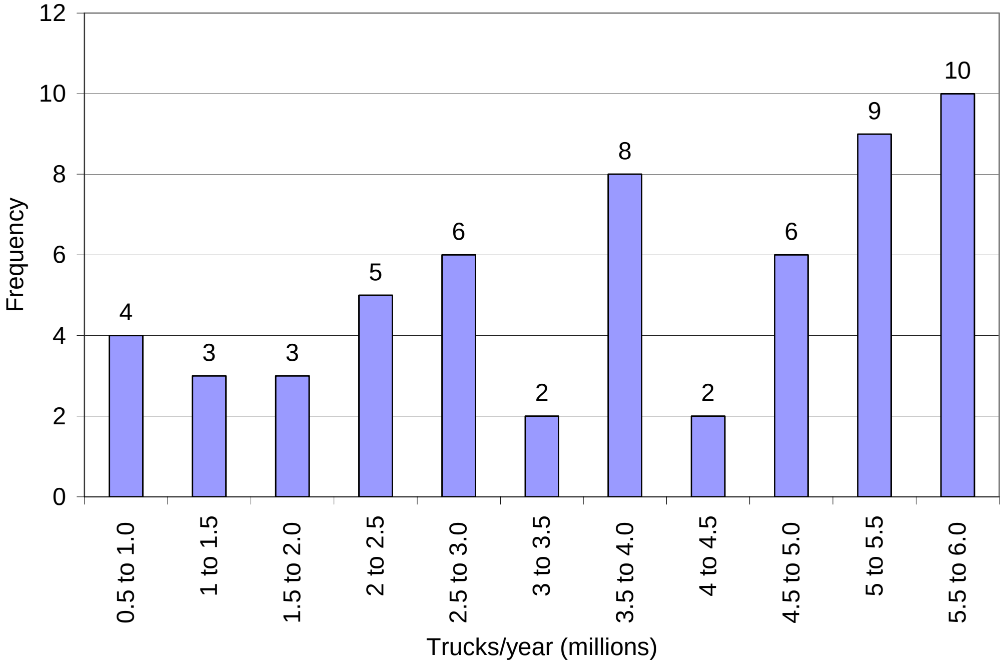


Figure 20. Traffic histogram for JPCD pavement sections.

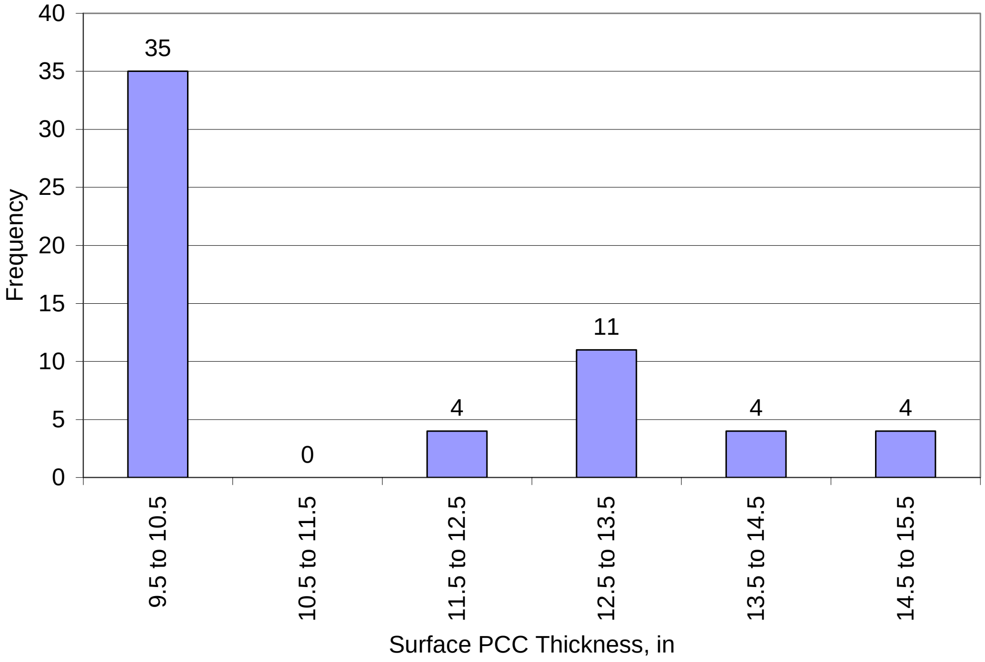


Figure 21. Slab thickness histogram for JPCD pavement sections.

Descriptive Statistics for CRC Pavements

The project database contains a variety of data elements for 12 CRC pavement sections constructed or reconstructed after 1973. As seen in table 13, the CRC pavement sections analyzed were located solely in the hot-dry climate of the Phoenix District.

CRC Construction Year and Age

The histogram in figure 22 shows that all 12 CRC sections were constructed in 1987, making their age at time of analysis 16 years (figure 23).

CRC Pavement Traffic

Traffic was qualified in terms of the number of truck (vehicle class 4 though 15) applications per year. The CRC pavement sections showed a narrow range of traffic loading (0.37 to 0.40 million trucks/year), with a mean value of 0.38 million trucks/year and a standard deviation of 0.01 million trucks/year. A traffic histogram for CRC pavement sections is provided in figure 24.

PCC Slab Thickness

The total thickness (i.e., thickness of all layers above the subgrade) of the original CRC pavement sections analyzed was 14.0 in. The PCC slab thickness was 9.0 in for all the pavement sections analyzed.

Table 13. Location breakdown of CRC pavement sections.

ADOT District	Climate	Number of Pavement Sections
Phoenix	Hot-Dry	12
	Moderate	0
	Cool-Wet	0

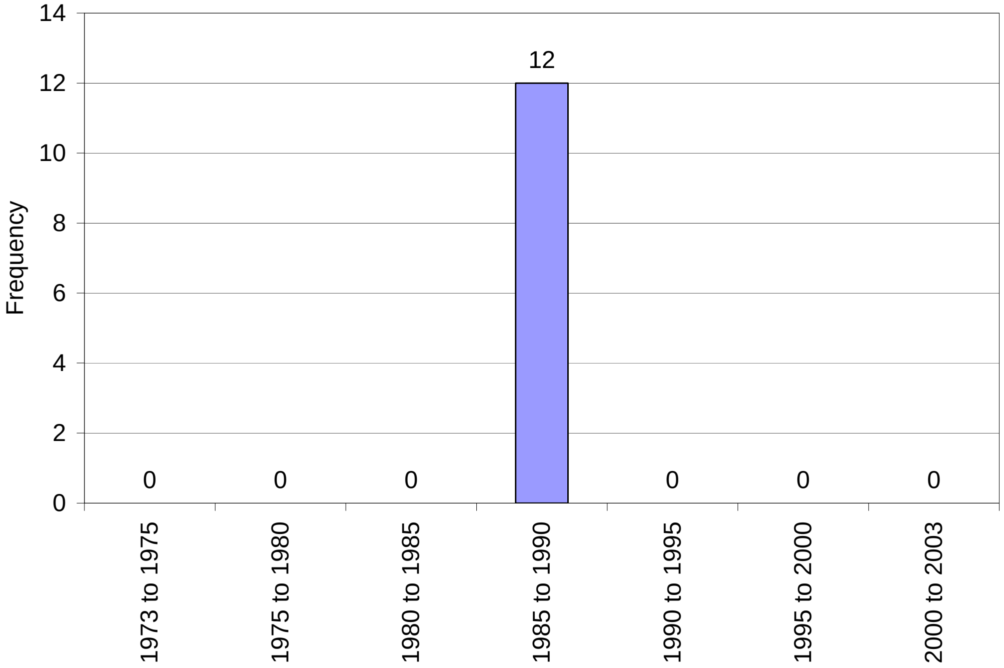


Figure 22. Construction date histogram for CRC pavement sections.

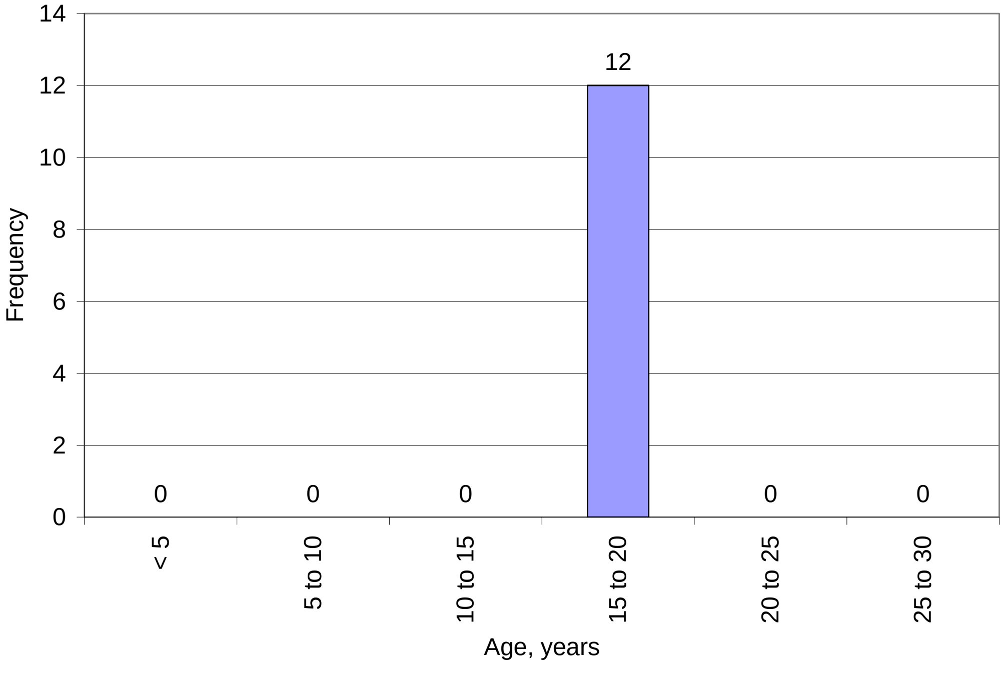


Figure 23. Age histogram for CRC pavement sections.

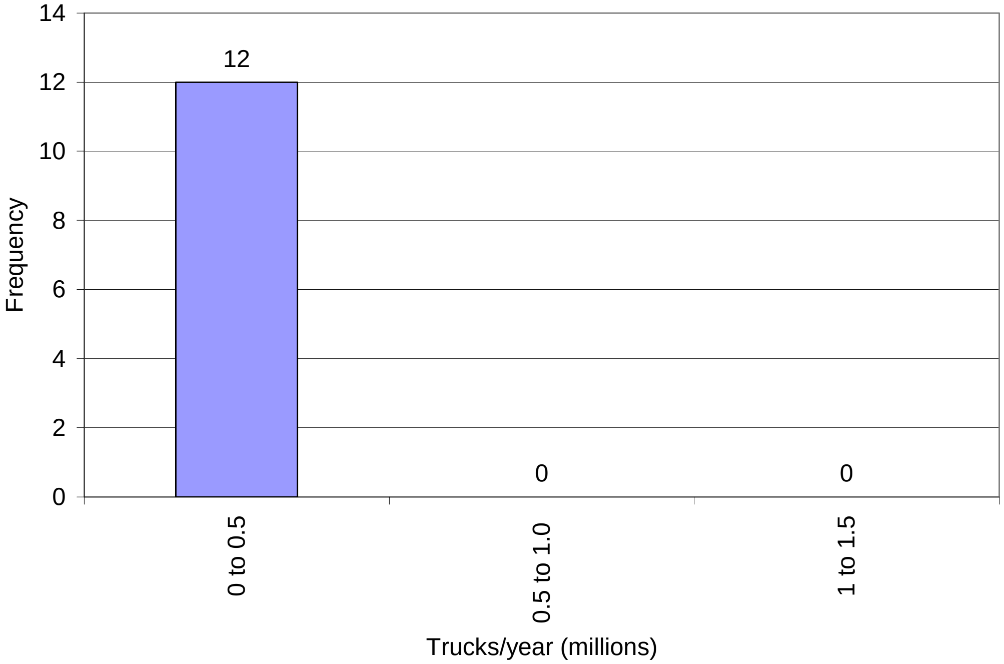


Figure 24. Traffic histogram for CRC pavement sections.

SUMMARY OF DATA USED IN PERFORMANCE ANALYSIS

The data assembled for performance analysis consisted of 1,389 original pavement sections built after 1973 and 4,698 pavement sections subjected to rehabilitation after 1973. Although eight different pavement types were included in the project database, only six—CAC, DSAC, FDAC, JPC, JPCD, and CRC—were selected for analysis by ADOT. With the exception of subgrade soil information, all relevant pavement properties, such as year of original construction, structural cross-section, and climate, as well as historical traffic, M&R, and performance (i.e., smoothness and distress data), were available for the sections used in analysis.

The overall quality of the pavement data was acceptable. For the pavement sections included in the assembled database, anomalies and erroneous data were identified and corrected. The most common anomalies identified were in the following fields:

1. Layer thicknesses (e.g., excessively high or low).
2. Original construction, reconstruction, and M&R dates (e.g., out of sequence).
3. Identification of M&R types/activities.

These anomalies were rectified by:

- Reviewing the ADOT database for additional information (construction history, M&R, and so on.
- Reviewing similar information available for adjacent pavement sections.
- Conducting interviews with or sending feedback information to relevant ADOT personnel.

Where the correct information could be found, the anomalous data were corrected or replaced. Otherwise, the section was removed from the database and not used in the analysis. Data points deemed to be outliers or erroneous were also removed from the database.

Over 7,200 pavement sections were available in the ADOT PMS database. Approximately 20 percent (1,389 of 7,200) were included in the analysis of new/reconstructed pavements, while approximately 65 percent (4,698 of 7,200) were included in the analysis of pavement rehabilitation. The pavement sections included adequately represented the data available in the ADOT database and the population of pavements available in Arizona. Pavement sections not included in the samples for analysis did not have all the required data available.

Table 14 presents a summary of the pavement section included in the databases for analysis. As can be seen, there was generally sufficient data available for analysis and decision-making for CAC, DSAC, and FDAC pavements. However, the data available for PCC pavements (JPC, JPCD, and CRC) was somewhat limited. There was no data available for the rehabilitation of JPCD and CRC, thereby limiting the ability to reasonably estimate the performance of rehabilitation treatments on these pavement types.

Table 14. Summary of pavement sections included in databases for analysis.

Pavement Type	**Total Number of Sections**	
	New and Reconstructed	**Rehabilitation**
CAC	471	4,145
DSAC and FDAC	703	377
JPC	145	176
JPCD	58	0
CRC	12	0

Summary Descriptive Statistics for Asphalt-Surfaced Pavements

A summary of the descriptive statistics for asphalt-surfaced pavements used in the analysis of initial pavement life is provided in figures 25 through 27. These figures show a good representation of current asphalt pavement design practices and the expected traffic loadings for each asphalt pavement type.

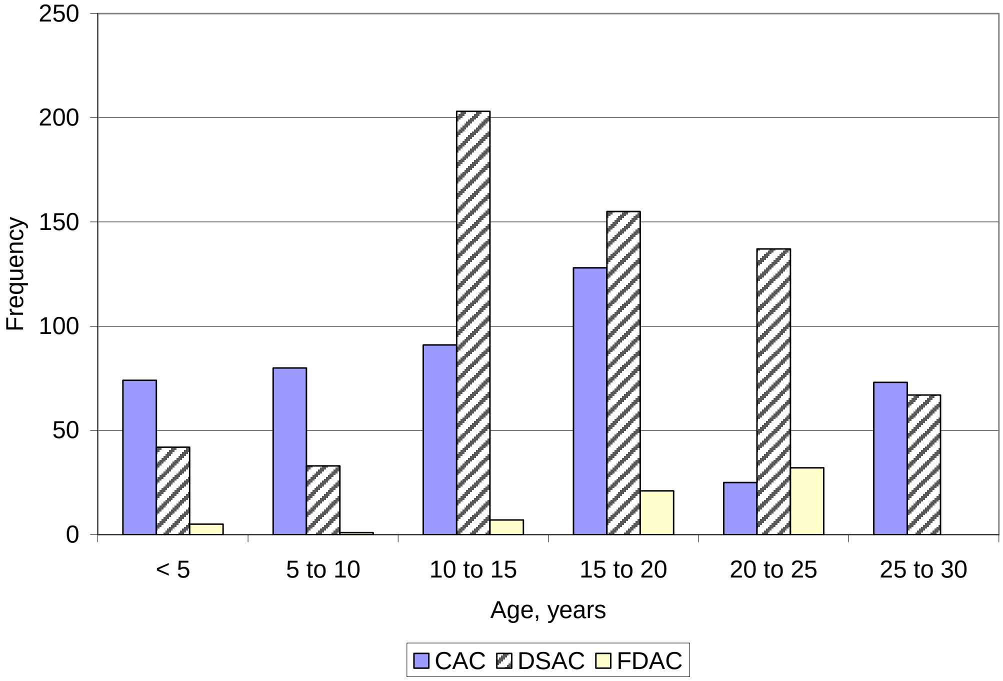


Figure 25. Age histogram for CAC, DSAC, and FDAC pavement sections.

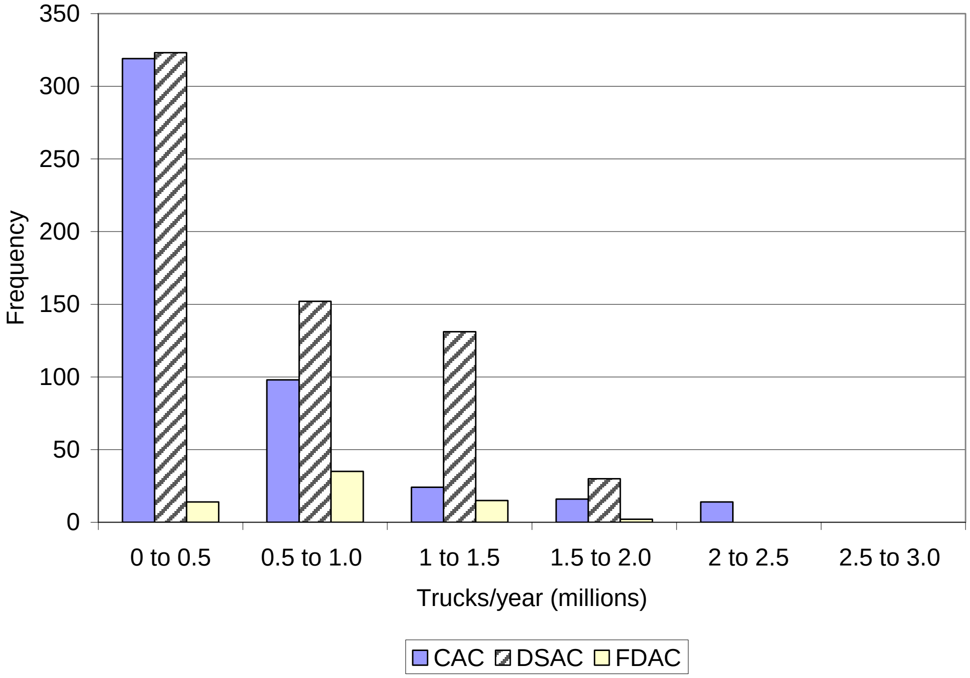


Figure 26. Traffic histogram for CAC, DSAC, and FDAC pavement sections.

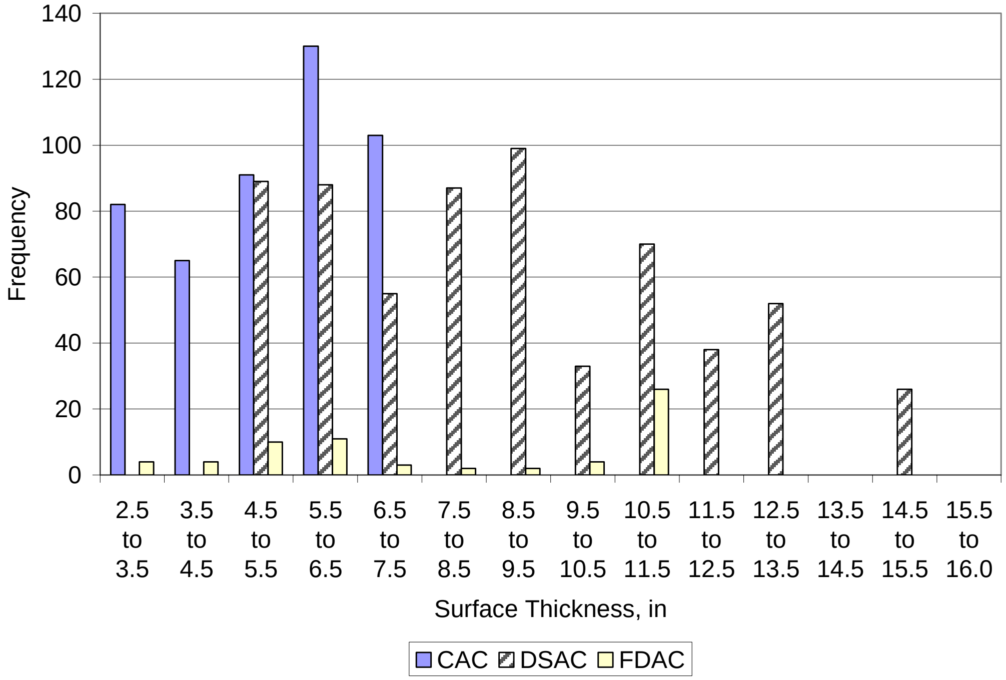


Figure 27. Asphalt thickness histogram for CAC, DSAC, and FDAC pavement sections.

Summary Descriptive Statistics for PCC-Surfaced Pavements

A summary of the descriptive statistics for PCC-surfaced pavements used in the analysis of initial pavement life is provided in figures 28 through 30. These figures show a good representation of current concrete pavement design practices and the expected traffic loadings for each type of PCC pavement.

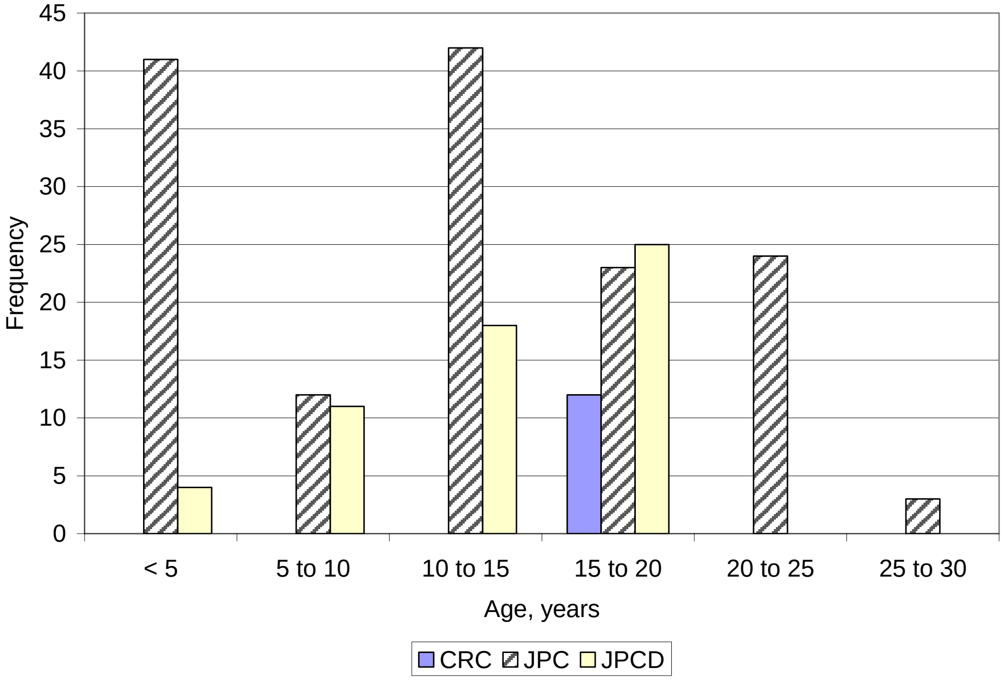


Figure 28. Age histogram for JPC, JPCD, and CRC pavement sections.

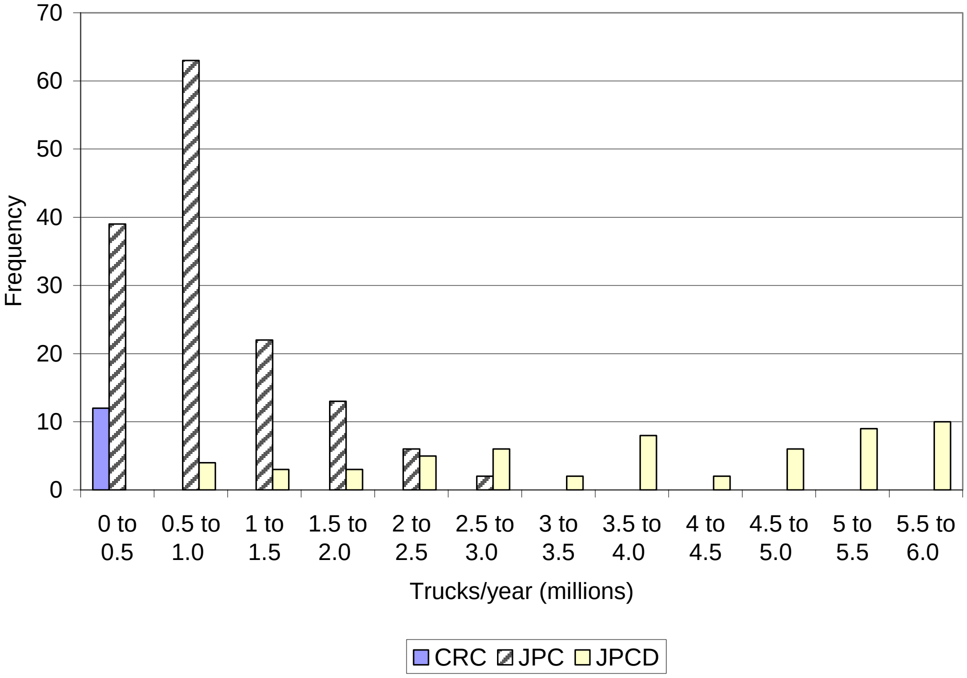


Figure 29. Traffic histogram for JPC, JPCD, and CRC pavement sections.

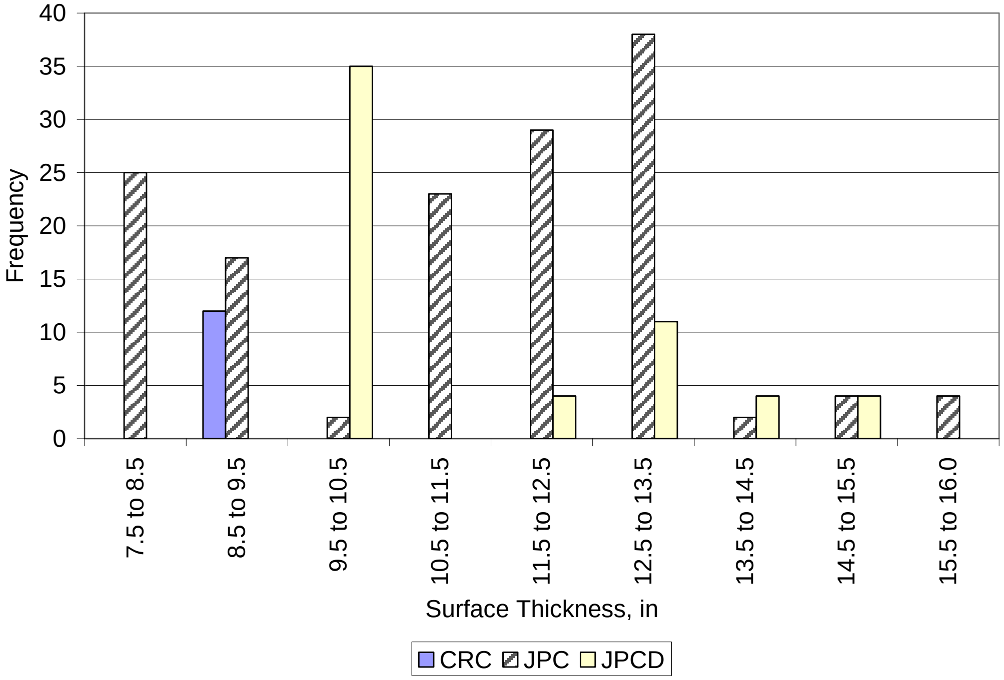


Figure 30. Slab thickness histogram for JPC, JPCD, and CRC pavement sections.

CHAPTER 3. PAVEMENT PERFORMANCE ANALYSIS

INTRODUCTION

Survival analysis and mechanistic-based performance evaluation 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 rehabilitation treatments, as delineated by the categories listed in tables 2 and 3 in chapter 2.

The pavement performance analysis consisted of the following steps:

1. Using the databases assembled as part of this study and described previously in chapter 2, establish analysis cells based on factors known to affect pavement life (these factors were determined based on engineering judgment).
2. Develop survival functions and determine estimated service lives for newly constructed or reconstructed flexible and rigid pavements for each of the analysis cells established.
3. Revise the analysis cells to reflect (a) data availability and (b) similarity in service life estimates.
4. Develop survival functions and determine service lives for rehabilitation treatments placed on original flexible and rigid pavements, in accordance with the revised analysis cells.
5. Conduct additional performance analyses using mechanistic–empirical (M–E) models developed as part of NCHRP Project 1-37A; the objective being to confirm original service life estimates from the survival analysis (for analysis cells with adequate or inadequate levels of data available) and/or to estimate initial life for analysis cells with no or very limited data.

PAVEMENT SURVIVAL ANALYSIS

The statistical tool used for determining the expected service life of pavements and the performance of rehabilitation treatments was survival analysis. Survival analysis techniques have been widely and successfully applied 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. Pavement service life is the period of time over which no major cost events (i.e., rehabilitation, reconstruction) are required in providing a reasonable level of service to users. It must be noted that level of service is not a technical term and depends on the users and/or owners expectations of performance and service. Thus, it may differ from the pavement's economic life, physical life, or design life.

Regardless of the level of service deemed adequate by the pavement users or owners, expected service life is highly correlated to pavement design features, construction quality, climate, traffic, subgrade type and strength, and maintenance practices applied. Even though standard statistical techniques, such as linear regression and analysis of variance (ANOVA), can be used for comparing the effect of these factors on pavement life, survival analysis allows for including pavements sections that are still in-service at the last time data are collected for analysis (for this study, data were last collected in 2002).

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.

Analysis Procedures

Survival analysis procedures can be grouped into three basic approaches—parametric, non-parametric, and semi-parametric. 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:

$$S(t) = Pr(T>t) \qquad \text{Eq. 1}$$

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 1 is modified and the survival function is defined as follows:

$$s(t) = \int_t^\infty f(T)dT = 1 - F(t) \qquad \text{Eq. 2}$$

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 an "enhanced" frequency distribution table. The distribution of survival times is divided into a given number of intervals. For each interval the following items are computed:

1. The number and proportion of pavements that entered the respective interval in "good condition."
2. 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").
3. The number of pavements with no data (unfailed) available (i.e., censored in the respective interval).

Using the computations listed above, a life table can be populated. Examples of information contained in a life table are 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).
- Median survival time and/or traffic.

These 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, and so on] 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 and 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.
- 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, as it was shown to provide the best fit of the project data and has been used successfully in previous studies (Hall et al., 1993; Gharaibeh et al., 1997). 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:

$$F(x) = \frac{e^{-\frac{(X-\mu)^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}} \qquad \text{Eq. 3}$$

where μ is the mean (also called the location parameter) and σ is the standard deviation (also called the scale parameter). The case where $\mu = 0$ and $\sigma = 1$ is called the standard normal distribution. The equation for the standard normal distribution is as follows:

$$F(x) = \frac{e^{-\frac{(X)^2}{2}}}{\sqrt{2\pi}} \qquad \text{Eq. 4}$$

where the model parameters are as already defined. Figure 31 is a plot of the standard normal distribution. 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.

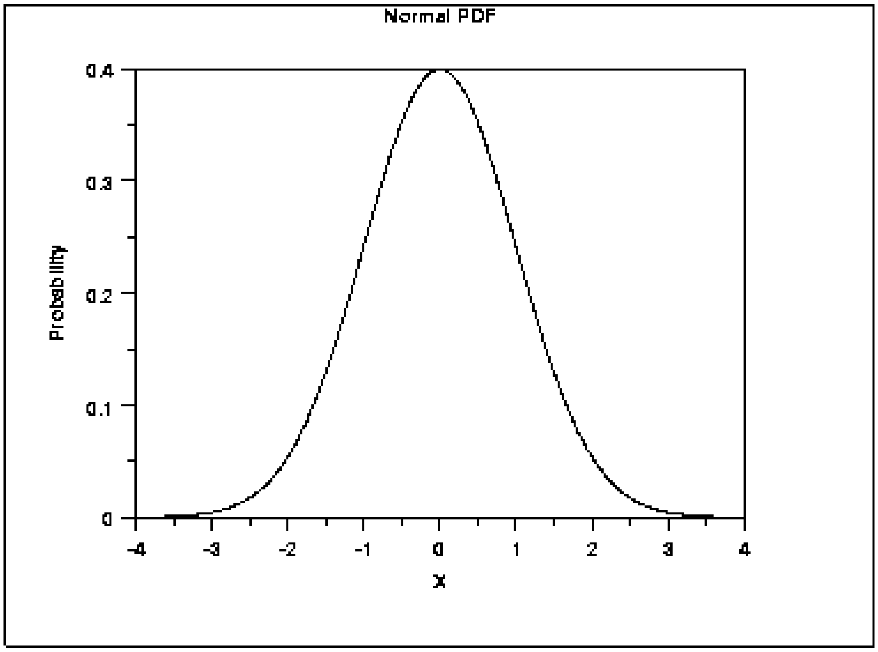


Figure 31. Plot of the standard normal distribution.

Normal Distribution Model Parameter Estimation

For survival analysis, a linear regression algorithm is mostly used to determine the probability distribution function parameters (this is true for the normal and other distributions). The use of linear regression is made possible by transforming the normal probability distribution function into a linear model using appropriate transformation procedures. Transformations are done in a manner that reduces the likelihood for the introduction of errors and biases into the transformed probability distribution model.

An example of a transformed linear model for the normal distribution (which is basically identical to the ordinary multiple regression model) is presented as follows:

$$t = a + b_1 * z_1 + b_2 * z_2 + \ldots + b_m * z_m \qquad \text{Eq. 5}$$

where t denotes the survival function, a and b_i are regression constants, and z is the standardized normal variable.

For this study, the LIFEREG procedure in SAS (version 8.0) was used to produce estimates of parametric regression models based on the normal distribution with right-censored survival data. Model optimization was done using the maximum likelihood optimization technique. The model form used in LIFEREG is similar to equation 5 and is presented as follows:

$$\log(T_i) = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_k x_{ik} + \sigma\varepsilon \qquad \text{Eq. 6}$$

where T_i denotes the survival function, ε is the random error term, and the βs and σ are parameters to be estimated. Equation 6 is transformed to estimate T_i as follows:

$$T_i = \exp(\beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_k x_{ik} + \sigma\varepsilon) \qquad \text{Eq. 7}$$

In a linear regression, it is typical to assume that β has a normal distribution with a mean and variance which is constant across observations, and that ε is independent across observations.

Determination of Expected Pavement Service Life

Criteria for Determining Expected Life

Pavement service life was defined in this study as the life of a pavement structure from the time it is completed for use until application of the first significant rehabilitation treatment or reconstruction (it is important to note that this would be the first significant cost expenditure for the pavement also). Thus, any occurrence of a reconstruction or one of the hundreds of rehabilitation treatments listed in tables 2 and 3 in chapter 2, signaled the end of a pavement's serviceable life and time to first significant cost expenditure.

Establishing the Performance Analysis Matrix

Initial Analysis Matrix

Table 15 shows the initial matrix used for pavement survival analysis. As can be seen, the 54 individual analysis cells in this table were defined according to combinations of initial pavement structure type, facility type, and climate. Traffic level was originally included in this table, but was removed in favor of conducting both age-based and traffic-based survival analyses.

Verification of Initial Analysis Matrix

The suitability of the initial analysis matrix (table 15) was evaluated by determining the sufficiency of data (i.e., 1-mi PMS sections with complete historical traffic data) in each analysis cell and by checking whether the factors used to define the cells were reasonable (i.e., were there significant differences in service life estimates across cells?). The goal in this process was to reduce the number of analysis cells and increase data availability within each cell. In situations where there were inadequate data and/or reasonably small differences in estimated life, engineering judgment was used to group or combine analysis cells.

Table 15. Initial pavement survival analysis matrix.

Pavement Type	Facility Type	Climate		
		Hot-Dry (RF $\leq$ 1.5)	**Moderate (1.5 < RF $\leq$ 3.0)**	**Cool-Wet (RF > 3.0)**
CAC	Interstates	1	2	3
	U.S. Highways	4	5	6
	State Routes	7	8	9
DSAC	Interstates	10	11	12
	U.S. Highways	13	14	15
	State Routes	16	17	18
FDAC	Interstates	19	20	21
	U.S. Highways	22	23	24
	State Routes	25	26	27
JPC	Interstates	28	29	30
	U.S. Highways	31	32	33
	State Routes	34	35	36
JPCD	Interstates	37	38	39
	U.S. Highways	40	41	42
	State Routes	43	44	45
CRC	Interstates	46	47	48
	U.S. Highways	49	50	51
	State Routes	52	53	54

Table 16 summarizes the estimated service life results (in terms of age) of the survival analyses performed for each analysis cell shown in table 15. The results are given in terms of the lives associated with 75%, 50%, and 25% survival probability. Both non-parametric (LIFETEST) and parametric (LIFEREG) results are provided, along with the number of 1-mi sections that comprised each analysis cell.

As seen in table 16, 24 of the initial 54 analysis cells had no data (N=0) available for analysis. Furthermore, 16 of the remaining 30 cells had results based on less than 30 data points (N<30), which is the minimum number recommended for analysis. It should also be noted that for some analysis cells, the service lives associated with 75%, 50%, and/or 25% survival probability could not be estimated because the survival rates remained too high for reasonable projection. In these instances, the term "NA" was given to indicate that an estimate was not available.

Revised Analysis Matrix

Based on the results of the initial survival analysis, the analysis matrix was carefully revised to the one given in table 17. The initial 54 analysis cells were reduced to 15 cells by eliminating cells with no data and combining others with limited data as follows:

Table 16. Age-based survival analysis results for original/reconstructed pavements (initial analysis matrix).

Pavement Type	Facility Type	Age based on 75%, 50%, and 25% Survival Probability— LIFETEST results, LIFEREG results, No. of Sections (N)		
		Hot-Dry (RF ≤ 1.5)	**Moderate (1.5 < RF ≤ 3.0)**	**Cool-Wet (RF > 3.0)**
CAC	Interstates	16.0 – 17.0 – 19.0 15.9 – 18.2 – 20.5 N=93	18.0 – 19.0 – 19.0 15.1 – 17.5 – 19.8 N=28	N=0
	U.S. Highways	12.0 – 15.0 – 15.0 13.0 – 14.1 – 15.2 N=25	23.0 – NA – NA 25.6 – 32.8 – 39.9 N=27	NA – NA – NA 17.1 – 28.8 – 40.6 N=24
	State Routes	18.0 – 24.0 – NA 17.6 – 22.6 – 27.6 N=122	14.0 – 25.0 – NA 19.4 – 25.3 – 31.2 N=112	11.0 – 12.0 – NA 8.3 – 12.3 – 16.2 N=40
DSAC	Interstates	15.0 – 18.0 – NA 14.9 – 17.3 – 19.7 N=94	15.0 – 19.0 – 22.0 15.4 – 18.7 – 22.0 N=209	10.0 – 11.0 – 21.0 10.0 – 13.2 – 16.4 N=15
	U.S. Highways	18.0 – 18.0 – NA 18.9 – 23.9 – 29.0 N=29	18.0 – NA – NA 21.9 – 28.6 – 35.3 N=38	28.0 – 28.0 – NA 20.2 – 30.9 – 41.7 N=22
	State Routes	NA – NA – NA 22.5 – 29.3 – 36.1 N=65	21.0 – 25.0 – NA 18.9 – 25.7 – 32.6 N=123	20.0 – 23.0 – 26.0 16.5 – 21.5 – 26.5 N=42
FDAC	Interstates	15.0 – 15.0 – 15.0 15.0 – 15.0 – 15.0 N=16	11.0 – 21.0 – 21.0 11.9 – 16.5 – 21.2 N=36	N=0
	U.S. Highways	N=0	N=0	N=0
	State Routes	19.0 – 22.0 – 22.0 13.1 – 17.8 – 22.5 N=5	NA – NA – NA NA – NA – NA N=8	23.0 – 23.0 – 23.0 23.0 – 23.0 – 23.0 N=1
JPC	Interstates	N=0	N=0	19.0 – 20.0 – 20.0 19.2 – 19.6 – 19.9 N=25
	U.S. Highways	NA – NA – NA NA – NA – NA N=48	N=0	N=0
	State Routes	NA – NA – NA NA – NA – NA N=70	N=0	NA – NA – NA NA – NA – NA N=2
JPCD	Interstates	NA – NA – NA NA – NA – NA N=50	NA – NA – NA NA – NA – NA N=4	N=0
	U.S. Highways	N=0	N=0	N=0
	State Routes	NA – NA – NA NA – NA – NA N=4	N=0	N=0
CRC	Interstates	N=0	N=0	N=0
	U.S. Highways	N=0	N=0	N=0
	State Routes	NA – NA – NA NA – NA – NA N=12	N=0	N=0

NA = Not available (e.g., insufficient failures occurred to allow determination or projection of pavement life).

Table 17. Revised pavement survival analysis matrix.

Pavement Type	**Facility Type**	**Climate**		
		Hot-Dry (RF ≤ 1.5)	**Moderate (1.5 < RF ≤ 3.0)**	**Cool-Wet (RF > 3.0)**
CAC	Interstates	1	2	
	Non-Interstates (U.S. Highways & State Routes)	3	4	5
DSAC & FDAC	Interstates	6	7	8
	Non-Interstates (U.S. Highways & State Routes)	9	10	11
JPC	Interstates	12		13
	Non-Interstates (U.S. Highways & State Routes)			
JPCD	Interstates	14		
	Non-Interstates (U.S. Highways & State Routes)			
CRC	Interstates	15		
	Non-Interstates (U.S. Highways & State Routes)			

- For all pavement types, U.S. Highways and State Routes were grouped together under the "Non-Interstates" label.
- For PCC pavements, Interstates and Non-Interstates were grouped together.
- FDAC pavements were grouped by climate with DSAC pavements. These two pavement types have similar structures and surface types, and their survival characteristics are similar.
- The four JPCD pavements in the moderate climate were grouped with JPCD pavements in the hot-dry climate. The regional factor (RF) of 1.7 for these four pavements barely fell outside the 1.5 limit for the hot-dry climate.

Service Life Estimates for Newly Constructed and Reconstructed Pavements

Using both non-parametric (LIFETEST) and parametric (LIFEREG) survival analysis procedures, service life estimates were developed for original pavements comprising the 15 revised analysis cells given in table 17. Figures A-1 through A-15 in appendix A show the non-parametric survival curves developed for each analysis cell. These curves show the percentages of section survival as a function of (a) age and (b) cumulative truck traffic. Some of the plots include censored data points, which as indicated previously represent the ages (or cumulative truck applications) of pavement sections that at the time of analysis (2003) had not failed.

Tables 18 and 19 summarize the age-based and truck traffic-based initial pavement service lives associated with 75%, 50%, and 25% survival probability. Both LIFETEST and LIFEREG results are listed, along with the number of sections that were included in the analysis.

As seen in these tables, limited data (less than 30 sections) existed for the following analysis cells:

- CAC Interstate pavements in moderate climate.
- DSAC/FDAC Interstate pavements in cool-wet climate.
- JPC pavements in cool-wet climate.
- CRC pavements in hot-dry climate.

Once again, for cells where reasonable service life projections could not be made due to high survival rates, an "NA" designation was given.

With a couple possible exceptions, the survival analysis results given in tables 18 and 19 appear to be reasonable. The item that needs to be kept in mind is that pavements located on Interstates carry far more truck traffic on average than those off Interstate. Of course, these pavements are designed to carry heavier truck traffic and thus have more substantial structural designs.

The median (50% survival probability) ages for the Interstate asphalt pavements are fairly typical for pavements located in the southwestern U.S. Moreover, given the much lower traffic levels of the Non-Interstate routes, the longer median ages for the asphalt pavements was largely expected.

With regard to the concrete designs, the 20-year median life for JPC (non-doweled) in the cool-wet climate was derived using sections mostly located on I-17. These sections were built in the mid 1970s and were diamond ground and overlaid (1-in asphalt rubber friction course [FR]) in 1994. Although similar JPC sections on I-40 built in the late 1960s were not included in the analysis because of incomplete traffic data, a review of the database indicated that many of those sections typically survived between 18 and 22 years.

Figures 32 and 33 are histograms showing side-by-side comparisons of the median service lives of asphalt and concrete pavements, measured in terms of pavement age and cumulative truck applications. These figures show the significance of design/traffic on the age of a pavement at time of first rehabilitation. For instance, while CAC Non-Interstate pavements lasted longer in terms of time than their Interstate counterparts, they also experienced substantially less truck traffic.

Table 18. Age-based survival analysis results for newly constructed and reconstructed pavements (revised analysis matrix).

Pavement Type	Facility Type	Age (years) based on 75%, 50%, and 25% Survival Probability—LIFETEST results, LIFEREG results, No. of Sections (N)		
		Hot-Dry (RF ≤ 1.5)	**Moderate (1.5 < RF ≤ 3.0)**	**Cool-Wet (RF > 3.0)**
CAC	Interstates	16.0 – 17.0 – 19.0 15.8 – 18.2 – 20.5 N=93	18.0 – 19.0 – 19.0 15.1 – 17.5 – 19.8 N=28	
	Non-Interstates	18.0 – 25.0 – 27.0 16.7 – 21.6 – 26.5 N=147	20.0 – 25.0 – NA 21.2 – 27.8 – 34.4 N=139	11.0 – 13.0 – NA 9.3 – 15.1 – 20.8 N=64
DSAC & FDAC	Interstates	15.0 – 18.0 – 19.0 14.7 – 16.9 – 19.2 N=110	15.0 – 21.0 – 22.0 14.8 – 18.4 – 21.9 N=245	10.0 – 11.0 – 21.0 10.0 – 13.2 – 16.4 N=15
	Non-Interstates	18.0 – 22.0 – NA 18.7 – 23.9 – 29.1 N=99	22.0 – 26.0 – NA 19.9 – 26.8 – 33.7 N=169	20.0 – 26.0 – 27.0 16.8 – 23.2 – 29.5 N=65
JPC	Interstates & Non-Interstates	NA – NA – NA 25.0 – 31.6 – 38.1 N=118		19.0 – 20.0 – 20.0 19.2 – 19.6 – 19.9 N=27
JPCD	Interstates & Non-Interstates	NA – NA – NA NA – NA – NA N=58		
CRC	Interstates	NA – NA – NA NA – NA – NA N=12		

NA = Not available (e.g., insufficient failures occurred to allow determination or projection of pavement life).

Table 19. Truck traffic-based survival analysis results for newly constructed and reconstructed pavements (revised analysis matrix).

Pavement Type	Facility Type	Cumulative Trucks (millions) based on 75%, 50%, and 25% Survival Probability—LIFETEST results, LIFEREG results, No. of Sections (N)		
		Hot-Dry (RF ≤ 1.5)	**Moderate (1.5 < RF ≤ 3.0)**	**Cool-Wet (RF > 3.0)**
CAC	Interstates	13.9 – 17.2 – 27.4 14.0 – 20.1 – 26.2 N=93	16.6 – 16.7 – 17.6 12.2 – 15.2 – 18.2 N=28	
	Non-Interstates	2.7 – 6.0 – 9.8 3.6 – 5.8 – 8.0 N=147	2.8 – 5.3 – 7.5 4.0 – 6.5 – 9.0 N=139	4.2 – 5.4 – 6.5 3.2 – 5.3 – 7.4 N=64
DSAC & FDAC	Interstates	14.1 – 19.5 – 26.9 14.7 – 19.4 – 24.1 N=110	8.2 – 17.5 – 20.7 10.8 – 16.2 – 21.6 N=245	10.6 – 17.0 – 18.3 9.5 – 13.1 – 16.8 N=15
	Non-Interstates	7.4 – 9.5 – NA 8.7 – 12.4 – 16.1 N=99	4.1 – 7.3 – NA 3.9 – 6.4 – 9.0 N=169	1.2 – 2.0 – 4.9 1.5 – 3.7 – 5.9 N=65
JPC	Interstates & Non-Interstates	47.9 – NA – NA 49.2 – 67.1 – 85.0 N=118		9.1 – 10.3 – 10.8 9.3 – 10.2 – 11.1 N=27
JPCD	Interstates & Non-Interstates	NA – NA – NA NA – NA – NA N=58		
CRC	Interstates	NA – NA – NA NA – NA – NA N=12		

NA = Not available (e.g., insufficient failures occurred to allow determination or projection of pavement life).

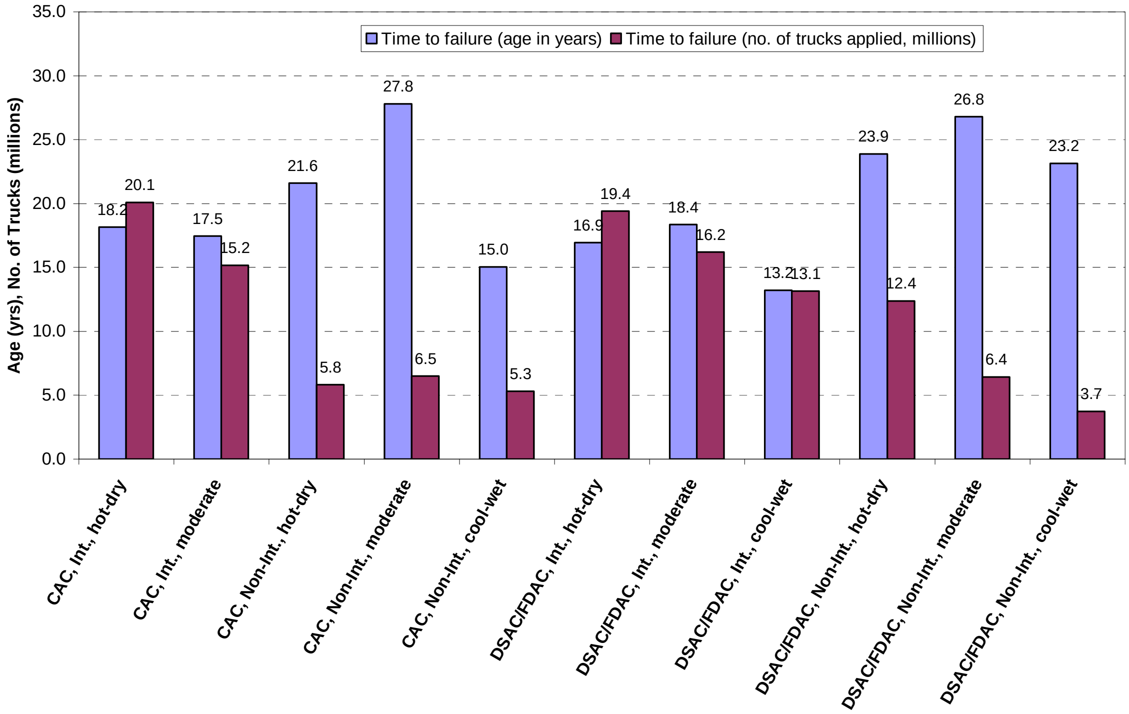


Figure 32. Comparison of median service life estimates (LIFEREG) for original asphalt pavements, based on age and cumulative truck applications.

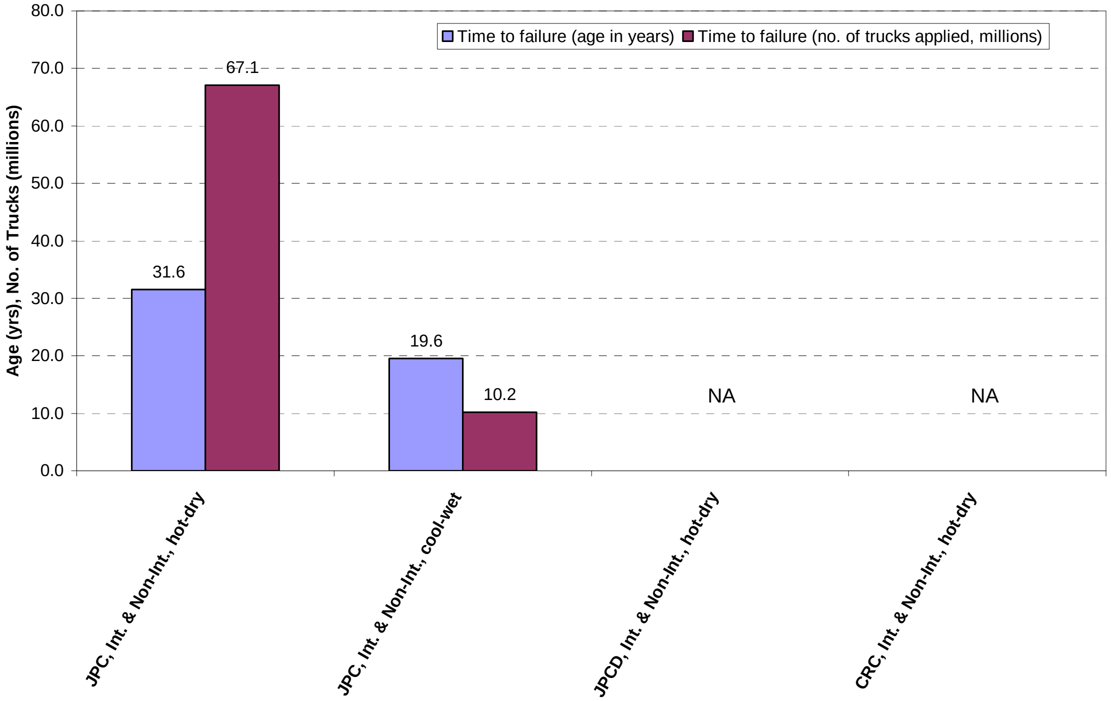


Figure 33. Comparison of median service life estimates (LIFEREG) for original concrete pavements, based on age and cumulative truck applications.

The same was true for DSAC/FDAC pavements. Also, it can be seen that, while CAC and DSAC/FDAC pavements had fairly similar median ages for a given facility type, the truck levels were typically higher for the DSAC/FDAC pavements. These data tend to show that even though higher type pavements are designed for heavier truck traffic over the same design period, they still do not show the same life until rehabilitation.

One possible reason is that the AASHTO structural design may not be considering all aspects of materials, and thus while a pavement may be thicker, the materials properties may not be sufficient to carry the heavier truck traffic. Much more study is needed to clarify the reasons for this finding in survival ages between Interstates and Non-Interstates for asphalt pavements.

Figure 33 shows that JPC has survived much longer in hot-dry climate than in a cool-wet climate (32 versus 20 years), even when subjected to far heavier truck traffic in the hot-dry climate (67 versus 10 million trucks). This difference may be explained through the common occurrence of joint faulting in non-doweled JPC, which throughout the U.S. is much greater in cold and wet climates (due to greater joint opening and loss of load transfer efficiency).

The survival of JPCD and CRC pavements could not be calculated due to fact that all of the sections are still in service. The ranges in age and cumulative truck traffic for JPCD pavements are 2 to 19 years and 4 to 71 million trucks, whereas the ranges for CRC pavements are 16 years and 6 to 6.5 million trucks. Actual median lives, in terms of age and cumulative truck applications, will be well in excess of these values, since all of the sections are still in service.

Figures 34 and 35 provide comparisons of the median initial pavement service life estimates obtained using non-parametric (LIFETEST) and parametric (LIFEREG) procedures. The comparisons show a good correlation between the two sets of estimates (R^2 equal to 83 percent in both cases). As such, the predicted lives from parametric procedures (based on the normal distribution) for this data set seems reasonable.

Performance Estimates for Rehabilitation Treatments

Because of the vast numbers of specific rehabilitation treatments applied over the years to Arizona highways, the analysis of rehabilitation treatment performance life was focused solely on the structure-defined rehabilitation categories (R1 through R13) and structure/mixture-defined categories (i.e., R1A through R13B) presented in tables 2 and 3 in chapter 2. Approximately 3,500 pavement sections, featuring some 4,570 specific treatments, were utilized in the analysis. As with the evaluation of initial pavement service life, only those pavement sections with rehabilitation activities that occurred after 1973 were used, because of the availability of traffic data back to that time.

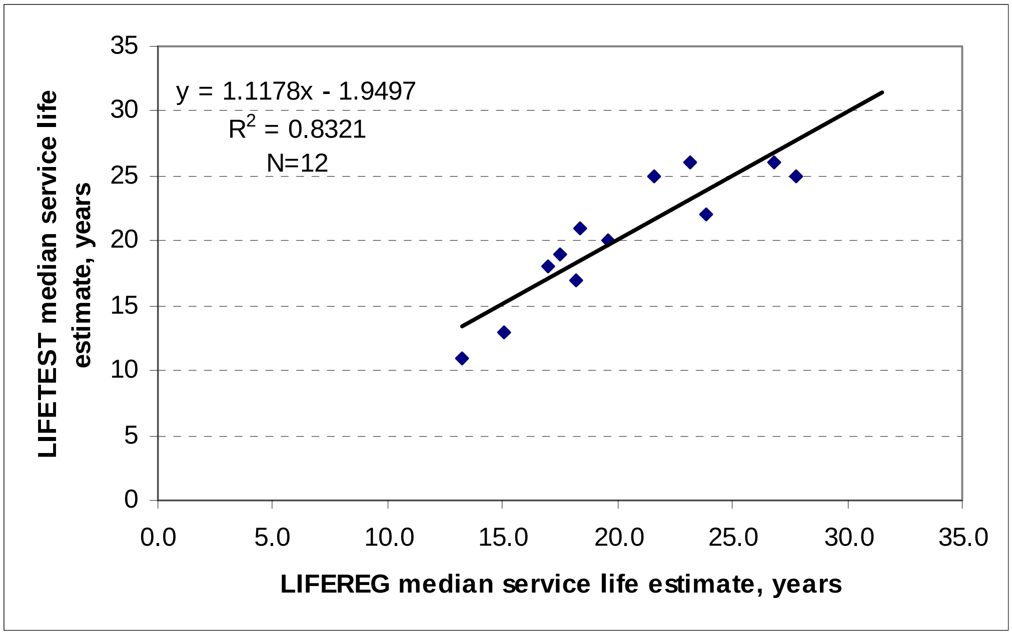


Figure 34. Comparison of median age-based initial service life estimates obtained using non-parametric (LIFETEST) and parametric (LIFEREG) procedures.

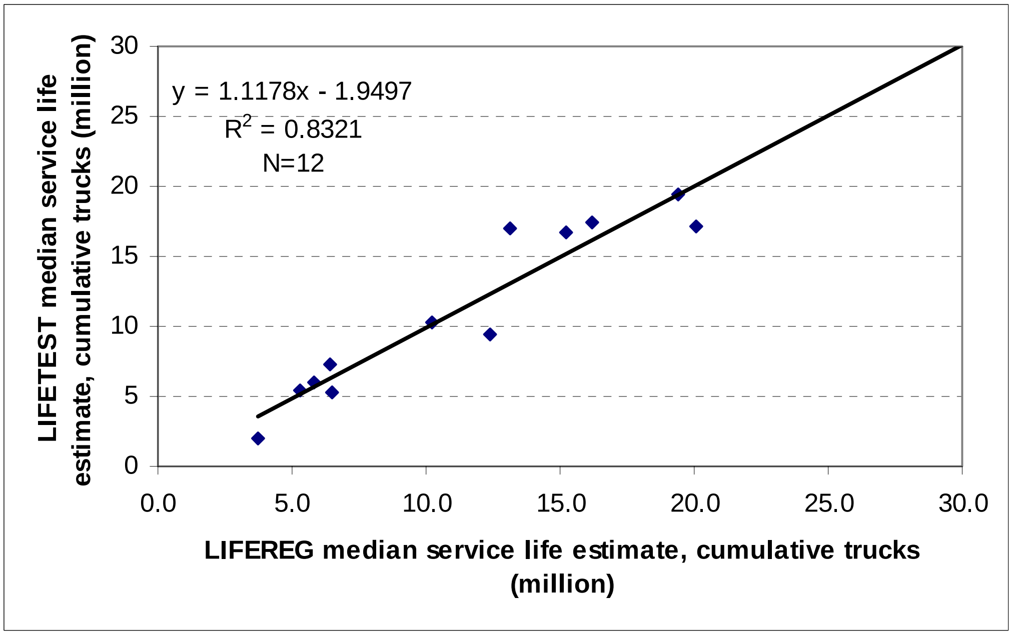


Figure 35. Comparison of median truck-based initial service life estimates obtained using non-parametric (LIFETEST) and parametric (LIFEREG) procedures.

Results of the survival analyses of structure-defined rehabilitation treatments are presented in tables 20 and 21. These tables list the age-based and truck traffic-based performance lives, corresponding to 75%, 50%, and 25% survival probabilities. Both non-parametric (LIFETEST) and parametric (LIFEREG) results are shown, along with the number of sections that were included in each analysis. As can be seen, there were a substantial number of rehabilitation treatments of asphalt pavements available for analysis and few treatments of concrete pavement available. The predominant treatments for asphalt pavement were thin conventional overlays (R1), shallow removal and thin overlays (R3), and shallow removal and thick overlays (R4). On Interstate pavements, many deep removal and thick overlay treatments (R6) were applied. The predominant treatments for concrete pavement were thin conventional overlays (R1) and diamond grinding (R7).

As with the service lives of original asphalt pavements, the lives of rehabilitation treatments applied to asphalt pavements were generally longer for Non-Interstate highways than for Interstate highways. The median age for treatments on U.S. and State routes ranged from 14 to 26 years, compared to a range of 13 to 16 years for treatments on Interstate routes. Tables 20 and 21 also show that the variation in lives (i.e., difference in lives associated with 75% and 25% survival probability) within cells often exceeded the variations observed for original structures. It is believed that the higher variations are partly the result of not separating out (a) the pavement type (e.g., CAC, DSAC, FDAC) on which the rehabilitation was done and (b) the mixture type.

Figures A-16 through A-98 in appendix A show the non-parametric survival curves developed for each structure/mixture-defined rehabilitation category for various combinations of facility type and climate. These curves show the percentages of rehabilitated section survival as a function of (a) age and (b) cumulative truck traffic. The rehabilitation categories include the following asphalt mixture types:

- Category A—Conventional asphalt mixes.
- Category B—Asphalt rubber mixes.
- Category C—SuperPave asphalt mixes.
- Category D—Recycled asphalt mixes.

Tables 22 and 23 summarize the performance lives of the structure/mixture-defined rehabilitation categories, derived using both non-parametric (LIFETEST) and parametric (LIFEREG) survival procedures. These tables show that there were a substantial number of rehabilitation treatments utilizing conventional asphalt, asphalt rubber, and recycled asphalt mixes, but much fewer using SuperPave mixes. This was expected since only about 30 SuperPave projects covering the years 1997 through 2001 were included in the database.

Table 20. Age-based survival results for structure-defined rehabilitation categories.

Pavement Type	Facility Type	Rehab Category	Age (years) based on 75%, 50%, and 25% Survival Probability—LIFETEST results, LIFEREG results, No. of Sections (N)		
			Hot-Dry (RF ≤ 1.5)	Moderate (1.5 < RF ≤ 3.0)	Cool-Wet (RF > 3.0)
CAC, DSAC, & FDAC	Interstates	R1	9.0 – 11.0 – 17.0 9.2 – 13.1 – 17.0 N=150	11.0 – 15.0 – 17.0 10.9 – 14.3 – 17.7 N=187	11.0 – NA – NA 14.0 – 20.7 – 27.3 N=22
		R2	11.0 – 16.0 – 20.0 10.9 – 14.6 – 18.3 N=11	10.0 – 12.0 – 18.0 11.1 – 15.1 – 19.2 N=78	1.0 – 3.0 – NA 4.6 – 16.1 – 27.7 N=50
		R3	10.0 – 13.0 – NA 10.7 – 14.0 – 17.3 N=293	10.0 – 13.0 – NA 10.2 – 13.4 – 16.6 N=261	11.0 – 11.0 – 11.0 10.5 – 12.3 – 14.1 N=13
		R4	14.0 – 17.0 – 17.0 11.7 – 15.4 – 19.1 N=430	11.0 – 15.0 – 18.0 11.6 – 14.9 – 18.1 N=470	N=0
		R5	N=0	NA – NA – NA NA – NA – NA N=8	N=0
		R6	14.0 – 14.0 – 21.0 12.5 – 15.4 – 18.3 N=189	10.0 – 17.0 – 17.0 11.4 – 14.2 – 16.9 N=173	NA – NA – NA NA – NA – NA N=6
	Non-Interstates	R1	16.0 – NA – NA 17.7 – 24.3 – 30.9 N=280	17.0 – 23.0 – NA 16.0 – 23.6 – 31.2 N=1,030	13.0 – 23.0 – NA 11.9 – 19.9 – 28.0 N=328
		R2	17.0 – NA – NA 17.9 – 26.4 – 34.9 N=20	15.0 – 23.0 – NA 18.8 – 24.9 – 33.0 N=63	NA – NA – NA NA – NA – NA N=7
		R3	10.0 – NA – NA 11.7 – 17.2 – 22.8 N=121	15.0 – 17.0 – 19.0 13.6 – 17.6 – 21.5 N=125	NA – NA – NA 14.1 – 18.5 – 22.9 N=29
		R4	14.0 – 15.0 – 16.0 13.9 – 16.2 – 18.5 N=54	NA – NA – NA 13.0 – 14.0 – 15.1 N=84	NA – NA – NA NA – NA – NA N=21
		R6	18.0 – NA – NA 19.0 – 21.3 – 23.7 N=4	3.0 – 19.0 – NA 9.1 – 16.7 – 24.3 N=12	9.0 – 9.0 – NA 9.0 – 9.9 – 10.8 N=3
JPC	Interstates & Non-Interstates	R1	N=0	2.0 – 10.0 – NA 5.4 – 13.5 – 21.7 N=8	10.0 – 10.0 – 14.0 9.7 – 11.4 – 13.1 N=32
		R2	N=0	NA – NA – NA NA – NA– NA N=6	NA – NA – NA NA – NA – NA N=9
		R3	N=0	NA – NA – NA NA – NA – NA N=1	NA – NA – NA NA – NA – NA N=22
		R5	N=0	11.0 – 11.0 – 11.0 11.0 – 11.0 – 11.0 N=1	11.0 – 11.0 – 11.0 11.0 – 11.0 – 11.0 N=6
		R7	14.0 – 15.0 – 16.0 13.3 – 15.4 – 17.5 N=22	10.0 – 12.0 – 12.0 10.6 – 11.4 – 12.3 N=29	N=0
		R10	N=0	N=0	NA – NA – NA NA – NA – NA N=25
		R12	N=0	N=0	9.0 – NA – NA 10.8 – 15.7 – 20.6 N=14
		R13	N=0	N=0	NA – NA – NA NA – NA – NA N=9
JPCD & CRC	Interstates & Non-Interstates	R7	NA – NA – NA NA – NA – NA N=4	N=0	N=0

NA = Not available (e.g., insufficient failures occurred to allow determination or projection of treatment life).

Table 21. Truck traffic-based survival results for structure-defined rehabilitation categories.

Pavement Type	Facility Type	Rehab Category	Cumulative Trucks (millions) based on 75%, 50%, and 25% Survival Probability—LIFETEST results, LIFEREG results, No. of Sections (N)		
			Hot-Dry (RF ≤ 1.5)	**Moderate (1.5 < RF ≤ 3.0)**	**Cool-Wet (RF > 3.0)**
CAC, DSAC, & FDAC	Interstates	R1	5.0 – 6.0 – 13.6 3.9 – 11.0 – 18.0 N=150	14.0 – 19.5 – 22.2 12.9 – 18.7 – 24.4 N=187	4.7 – NA – NA 13.5 – 32.6 – 51.8 N=22
		R2	7.9 – 16.1 – 16.1 7.7 – 15.7 – 23.7 N=11	13.8 – 17.4 – 30.9 13.7 – 20.7 – 27.7 N=78	0.9 – 2.6 – NA 5.5 – 24.6 – 43.7 N=50
		R3	16.1 – 20.1 – 37.7 15.6 – 23.2 – 30.7 N=293	11.3 – NA – NA 18.0 – 28.5 – 38.9 N=261	6.8 – 6.8 – 7.2 7.0 – 8.5 – 10.0 N=13
		R4	11.7 – 25.9 – NA 16.9 – 27.9 – 38.8 N=430	15.9 – 26.6 – NA 17.6 – 26.0 – 34.4 N=470	N=0
		R5	N=0	NA – NA – NA NA – NA – NA N=8	N=0
		R6	32.5 – 39.9 – 39.9 25.3 – 36.3 – 47.2 N=189	30.9 – 30.9 – 30.9 22.4 – 29.1 – 35.8 N=173	NA – NA – NA 9.0 – 15.7 – 22.4 N=6
	Non-Interstates	R1	3.0 – 6.3 – 18.5 4.5 – 6.8 – 9.1 N=280	1.5 – 3.5 – 7.4 2.0 – 3.5 – 5.1 N=1,030	0.7 – 2.4 – 6.8 1.4 – 3.0 – 4.5 N=328
		R2	5.4 – NA – NA 8.4 – 17.1 – 25.9 N=20	2.1 – 5.4 – NA 2.7 – 4.9 – 7.2 N=63	3.4 – NA – NA 8.8 – 13.9 – 19.0 N=7
		R3	3.7 – NA – NA 6.8 – 13.4 – 20.0 N=121	1.8 – 7.3 – 8.1 2.9 – 4.7 – 6.6 N=125	NA – NA – NA 7.9 – 13.1 – 18.4 N=29
		R4	2.0 – 3.6 – 11.1 3.5 – 5.6 – 7.6 N=54	NA – NA – NA 10.3 – 13.8 – 17.3 N=84	NA – NA – NA NA – NA – NA N=21
		R6	11.2 – 11.2 – 11.2 NA – NA – NA N=4	0.3 – 0.8 – 2.4 0.6 – 1.2 – 1.9 N=12	1.2 – 1.2 – NA 1.2 – 1.3 – 1.5 N=3
JPC	Interstates & Non-Interstates	R1	N=0	0.2 – 11.6 – 13.8 3.2 – 8.0 – 12.7 N=8	10.0 – 13.8 – 20.5 11.3 – 14.7 – 18.0 N=32
		R2	N=0	NA – NA – NA NA – NA– NA N=6	NA – NA – NA NA – NA – NA N=9
		R3	N=0	NA – NA – NA NA – NA – NA N=1	NA – NA – NA NA – NA – NA N=22
		R5	N=0	18.3 – 18.3 – 18.3 18.3 – 18.3 – 18.3 N=1	16.8 – 17.6 – 18.3 17.0 – 17.5 – 18.1 N=6
		R7	47.7 – 56.0 – 64.8 48.0 – 54.6 – 61.2 N=22	15.12 – 45.1 – 50.8 26.2 – 37.1 – 47.9 N=29	N=0
		R10	N=0	N=0	NA – NA – NA NA – NA – NA N=25
		R12	N=0	N=0	14.1 – NA – NA 17.1 – 26.1 – 35.0 N=14
		R13	N=0	N=0	NA – NA – NA NA – NA – NA N=9
JPCD & CRC	Interstates & Non-Interstates	R7	NA – NA – NA NA – NA – NA N=4	N=0	N=0

NA = Not available (e.g., insufficient failures occurred to allow determination or projection of treatment life).

Table 22. Age-based survival results for structure/mixture-defined rehabilitation categories.

Pavement Type	Facility Type	Rehab Category	Age (years) based on 75%, 50%, and 25% Survival Probability—LIFETEST results, LIFEREG results, No. of Sections (N)		
			Hot-Dry (RF ≤ 1.5)	Moderate (1.5 < RF ≤ 3.0)	Cool-Wet (RF > 3.0)
CAC, DSAC, & FDAC	Interstates	R1A	9.0 – 11.0 – 17.0 9.2 – 13.1 – 17.0 N=150	10.0 – 15.0 – 17.0 10.9 – 14.3 – 17.8 N=180	NA – NA – NA NA – NA – NA N=12
		R1B	N=0	14.0 – 14.0 – 14.0 14.0 – 14.0 – 14.0 N=7	11.0 – 11.0 – 11.0 11.0 – 11.0 – 11.0 N=10
		R2A	11.0 – 16.0 – 20.0 10.9 – 14.6 – 18.3 N=11	10.0 – 12.0 – 18.0 11.1 – 15.1 – 19.2 N=78	1.0 – 3.0 – NA 4.6 – 16.1 – 27.7 N=50
		R3A	9.0 – 11.0 – 13.0 9.2 – 10.9 – 12.6 N=77	8.0 – 11.0 – NA 9.0 – 12.6 – 16.3 N=112	N=0
		R3B	NA – NA – NA 12.4 – NA – NA N=183	11.0 – NA – NA 10.6 – NA – NA N=122	NA – NA – NA NA – NA – NA N=6
		R3C	N=0	NA – NA – NA NA – NA – NA N=6	N=0
		R3D	13.0 – NA – NA 14.9 – 21.9 – NA N=33	11.0 – 13.0 – NA 11.8 – 14.3 – 16.7 N=21	11.0 – 11.0 – 11.0 10.2 – 12.1 – 14.1 N=7
		R4A	NA – NA – NA NA – NA – NA N=56	NA – NA – NA 16.6 – NA – NA N=148	N=0
		R4B	NA – NA – NA 12.4 – NA – NA N=146	NA – NA – NA 11.0 – NA – NA N=94	N=0
		R4C	N=0	NA – NA – NA NA – NA – NA N=32	N=0
		R4D	14.0 – 16.0 – 17.0 11.7 – 15.1 – 18.5 N=228	10.0 – 14.0 – 18.0 11.5 – 13.9 – 16.4 N=196	N=0
		R5A	N=0	NA – NA – NA NA – NA – NA N=1	N=0
		R6A	NA – NA – NA NA – NA – NA N=21	10.0 – 10.0 – 17.0 9.9 – 11.4 – 12.8 N=14	N=0
		R6B	NA – NA – NA NA – NA – NA N=79	NA – NA – NA NA – NA – NA N=97	NA – NA – NA 9.8 – NA– NA N=6
		R6C	NA – NA – NA NA – NA – NA N=41	NA – NA – NA NA – NA – NA N=38	N=0
		R6D	8.0 – 14.0 – 14.0 10.4 – 13.5 – 16.7 N=48	NA – NA – NA NA – NA – NA N=24	N=0

NA = Not available (e.g., insufficient failures occurred to allow determination or projection of treatment life).

Table 22. Age-based survival results for structure/mixture-defined rehabilitation categories (continued).

Pavement Type	Facility Type	Rehab Category	Age (years) based on 75%, 50%, and 25% Survival Probability— LIFETEST results, LIFEREG results, No. of Sections (N)		
			Hot-Dry (RF ≤ 1.5)	Moderate (1.5 < RF ≤ 3.0)	Cool-Wet (RF > 3.0)
CAC, DSAC, & FDAC	Non-Interstates	R1A	16.0 – NA – NA 19.1 – 25.2 – NA N=235	17.0 – 22.0 – NA 16.6 – 24.0 – 31.4 N=750	13.0 – 23.0 – 25.0 13.3 – 21.3 – 29.3 N=217
		R1B	10.0 – 10.0 – 10.0 8.8 – 12.8 – 16.8 N=45	13.0 – 24.0 – NA 13.8 – 21.7 – 29.6 N=280	3.0 – 19.0 – NA 7.0 – 12.9 – 18.8 N=111
		R2A	11.0 – NA – NA 22.7 – 35.7 – NA N=15	12.0 – 23.0 – NA 16.5 – 24.9 – 33.2 N=56	19.0 – NA – NA 24.0 – 28.7 – NA N=7
		R3A	9.0 – NA – NA 11.7 – 17.1 – NA N=78	12.0 – 14.0 – NA 11.8 – 14.5 – 17.2 N=45	9.0 – NA – NA 11.6 – 15.3 – 19.0 N=10
		R3B	NA – NA – NA NA – NA – NA N=30	NA – NA – NA NA – NA – NA N=38	NA – NA – NA NA – NA – NA N=15
		R3C	NA – NA – NA NA – NA – NA N=7	NA – NA – NA NA – NA – NA N=7	N=0
		R3D	3.0 – 3.0 – 3.0 1.0 – 6.7 – 12.4 N=6	17.0 – 17.0 – 19.0 14.8 – 19.4 – 24.0 N=35	NA – NA – NA NA – NA – NA N=4
		R4A	15.0 – NA – NA 17.1 – 21.9 – NA N=7	NA – NA – NA NA – NA – NA N=42	NA – NA – NA NA – NA – NA N=3
		R4B	NA – NA – NA NA – NA – NA N=7	NA – NA – NA NA – NA – NA N=39	NA – NA – NA NA – NA – NA N=7
		R4C	NA – NA – NA NA – NA – NA N=22	N=0	N=0
		R4D	14.0 – 14.0 – 16.0 14.1 – 14.8 – 15.5 N=18	12.0 – NA – NA 12.5 – 13.7 – NA N=3	NA – NA – NA NA – NA – NA N=11
		R6A	18.0 – NA – NA 19.0 – 21.3 – NA N=4	3.0 – 19.0 – NA 9.0 – 16.7 – 24.3 N=12	9.0 – 9.0 – NA 9.0 – 9.9 – 10.8 N=3
JPC	Interstates & Non-Interstates	R1A	N=0	2.0 – 6.0 – NA 3.8 – 13.4 – 22.9 N=6	9.0 – 10.0 – 10.0 9.3 – 10.2 – 11.1 N=16
		R1B	N=0	12.0 – 12.0 – 12.0 12.0 – 12.0 – 12.0 N=2	14.0 – 14.0 – 14.0 11.3 – 13.2 – 15.0 N=16
		R2B (same as R2)	N=0	NA – NA – NA NA – NA – NA N=6	NA – NA – NA NA – NA – NA N=9
		R3B (same as R3)	N=0	NA – NA – NA NA – NA – NA N=1	NA – NA – NA NA – NA – NA N=22
		R5A (same as R5)	N=0	11.0 – 11.0 – 11.0 11.0 – 11.0 – 11.0 N=1	11.0 – 11.0 – 11.0 11.0 – 11.0 – 11.0 N=6
		R10B (same as R10)	N=0	N=0	NA – NA – NA NA – NA – NA N=25
		R12A (same as R12)	N=0	N=0	9.0 – NA – NA 10.8 – 15.7 – NA N=14
		R13B (same as R13)	N=0	N=0	NA – NA – NA NA – NA – NA N=9

NA = Not available (e.g., insufficient failures occurred to allow determination or projection of treatment life).

Table 23. Truck traffic-based survival results for structure/mixture-defined rehabilitation categories.

Pavement Type	Facility Type	Rehab Category	Cumulative Trucks (millions) based on 75%, 50%, and 25% Survival Probability—LIFETEST results, LIFEREG results, No. of Sections (N)		
			Hot-Dry (RF ≤ 1.5)	**Moderate (1.5 < RF ≤ 3.0)**	**Cool-Wet (RF > 3.0)**
CAC, DSAC, & FDAC	Interstates	R1A	5.0 – 6.0 – 13.6 3.9 – 11.0 – 18.0 N=150	15.2 – 19.5 – 23.0 13.0 – 18.8 – 24.6 N=180	NA – NA – NA NA – NA – NA N=12
		R1B	N=0	14.0 – 14.0 – 14.0 13.6 – 14.5 – 15.4 N=7	4.6 – 4.7 – 4.8 4.6 – 4.7 – 4.8 N=10
		R2A	7.9 – 16.1 – 16.1 7.7 – 15.7 – 23.7 N=11	13.8 – 17.4 – 30.9 13.6 – 20.7 – 27.7 N=78	0.9 – 2.6 – NA 5.5 – 24.6 – 43.7 N=50
		R3A	9.1 – 17.2 – 20.1 11.0 – 17.8 – 24.5 N=77	10.3 – 16.2 – NA 13.4 – 24.0 – 34.6 N=112	N=0
		R3B	NA – NA – NA 37.2 – NA – NA N=183	NA – NA – NA 23.1 – NA – NA N=122	NA – NA – NA NA – NA – NA N=6
		R3C	N=0	NA – NA – NA NA – NA – NA N=6	N=0
		R3D	13.1 – 13.7 – NA 10.3 – 14.8 – 19.4 N=33	7.2 – 14.0 – NA 13.3 – 28.3 – 43.4 N=21	6.8 – 6.8 – 7.2 6.2 – 7.9 – 9.5 N=7
		R4A	NA – NA – NA NA – NA – NA N=56	NA – NA – NA 28.8 – NA – NA N=148	N=0
		R4B	NA – NA – NA 15.9 – NA – NA N=146	NA – NA – NA 20.0 – NA – NA N=94	N=0
		R4C	N=0	NA – NA – NA 15.4 – NA – NA N=32	N=0
		R4D	11.7 – 16.2 – 32.5 13.5 – 24.7 – 35.9 N=228	14.3 – 16.2 – NA 13.7 – 21.2 – 28.7 N=196	N=0
		R5A	N=0	NA – NA – NA NA – NA – NA N=1	N=0
		R6A	NA – NA – NA NA – NA – NA N=21	16.1 – 16.1 – 30.9 16.9 – 22.1 – 27.4 N=14	N=0
		R6B	NA – NA – NA NA – NA – NA N=79	NA – NA – NA NA – NA – NA N=97	NA – NA – NA 9.0 – NA – NA N=6
		R6C	NA – NA – NA NA – NA – NA N=41	NA – NA – NA NA – NA – NA N=38	N=0
		R6D	12.7 – 13.7 – 40.0 12.6 – 20.6 – 28.6 N=48	NA – NA – NA NA – NA – NA N=24	N=0

NA = Not available (e.g., insufficient failures occurred to allow determination or projection of treatment life).

Table 23. Truck traffic-based survival results for structure/mixture-defined rehabilitation categories (continued).

Pavement Type	Facility Type	Rehab Category	Cumulative Trucks (millions) based on 75%, 50%, and 25% Survival Probability—LIFETEST results, LIFEREG results, No. of Sections (N)		
			Hot-Dry (RF ≤ 1.5)	Moderate (1.5 < RF ≤ 3.0)	Cool-Wet (RF > 3.0)
CAC, DSAC, & FDAC	Non-Interstates	R1A	3.0 – 6.3 – 18.5 4.6 – 7.0 – NA N=235	1.5 – 3.5 – 8.2 2.0 – 3.6 – 5.2 N=750	0.8 – 2.4 – 4.9 1.4 – 3.1– 4.7 N=217
		R1B	2.6 – 4.4 – 8.9 3.9 – 5.9 – 7.8 N=45	1.5 – 3.5 – 4.4 1.8 – 3.2 – 4.6 N=280	0.2 – NA – NA 1.0 – 2.3 – 3.6 N=111
		R2A	7.0 – NA – NA 14.3 – 24.6 – NA N=15	3.2 – 5.4 – NA 2.6 – 5.0 – 7.3 N=56	3.4 – NA – NA 8.8 – 13.9 – NA N=7
		R3A	2.7 – NA – NA 6.5 – 13.7 – NA N=78	1.8 – 7.3 – 8.1 3.2 – 5.2 – 7.3 N=45	1.2 – NA – NA 4.2 – 10.0 – NA N=10
		R3B	NA – NA – NA NA – NA – NA N=30	NA – NA – NA NA – NA – NA N=38	NA – NA – NA NA – NA – NA N=15
		R3C	NA – NA – NA NA – NA – NA N=7	NA – NA – NA NA – NA – NA N=7	N=0
		R3D	0.1 – 0.1 – 0.1 0.1 – 0.8 – 1.8 N=6	1.2 – NA – NA 1.7 – 3.1 – 4.4 N=35	NA – NA – NA NA – NA – NA N=4
		R4A	11.2 – 11.2 – 11.2 7.4 – 10.0 – 12.5 N=7	NA – NA – NA NA – NA – NA N=42	NA – NA – NA NA – NA – NA N=3
		R4B	NA – NA – NA NA – NA – NA N=7	NA – NA – NA NA – NA – NA N=39	NA – NA – NA NA – NA – NA N=7
		R4C	NA – NA – NA NA – NA – NA N=22	N=0	N=0
		R4D	1.6 – 1.6 – 2.0 2.5 – 2.6 – 2.6 N=18	1.6 – NA – NA 1.6 – 1.8 – NA N=3	NA – NA – NA NA – NA – NA N=11
		R6A	11.2 – 11.2 – 11.2 11.1 – 11.1 – 11.12 N=4	0.3 – 0.8 – 2.4 0.6 – 1.2 – 1.9 N=12	1.2 – 1.2 – NA 1.2 – 1.3 – 1.5 N=3
JPC	Interstates	R1A	N=0	0.2 – 7.0 – 13.8 1.2 – 5.1 – 9.0 N=6	8.5 – 10.0 – 12.3 9.4 – 10.8 – 12.2 N=16
		R1B	N=0	11.6 – NA – NA 11.8 – 12.4 – 13.1 N=2	15.2 – 20.5 – 21.8 15.8 – 18.9 – 22.0 N=16
		R2B (same as R2)	N=0	NA – NA – NA NA – NA – NA N=6	NA – NA – NA NA – NA – NA N=9
		R3B (same as R3)	N=0	NA – NA – NA NA – NA – NA N=1	NA – NA – NA NA – NA – NA N=22
		R5A (same as R5)	N=0	18.3 – 18.3 – 18.3 18.3 – 18.3 – 18.3 N=1	16.8 – 17.6 – 18.3 17.0 – 17.5 – 18.1 N=6
		R10B (same as R10)	N=0	N=0	NA – NA – NA NA – NA – NA N=25
		R12A (same as R12)	N=0	N=0	14.1 – NA – NA 17.1 – 26.1 – 35.0 N=14
		R13B (same as R13)	N=0	N=0	NA – NA – NA NA – NA – NA N=9

NA = Not available (e.g., insufficient failures occurred to allow determination or projection of treatment life).

Figures 36 and 37 show the median performance lives (parametric LIFEREG) of conventional asphalt mixes when used with different structure-defined rehabilitation categories (R1 through R6). It can generally be seen that, although the median ages remain similar across the categories—11 to 16 years on Interstates, 15 to 25 years on Non-Interstates—the median truck traffic increases corresponding to thicker rehabilitation treatments. Moreover, although the effect of climate on conventional asphalt mix performance was not as profound as expected, there did seem to be some impact on Non-Interstate routes, with performance being generally better in the hot-dry regions and worse in the cool-wet.

Figures 38 through 41 present side-by-side comparisons of the median performance lives (parametric LIFEREG) of asphalt pavement rehabilitation treatments, measured in terms of pavement age and cumulative truck applications. Each figure represents an individual structure category (e.g., R1=thin conventional overlay), and the performance of the four different asphalt mixtures for that category are displayed (where available), corresponding to facility type and climate.

A comparison of conventional asphalt mixes with asphalt rubber mixes yielded conflicting performance results. For thin conventional overlays (R1) placed on Non-Interstate asphalt pavements, better performance was experienced with conventional asphalt mix than with asphalt rubber (23 to 25 years versus 13 to 22 years) for fairly similar truck traffic levels. On the other hand, for shallow removal and thin overlays

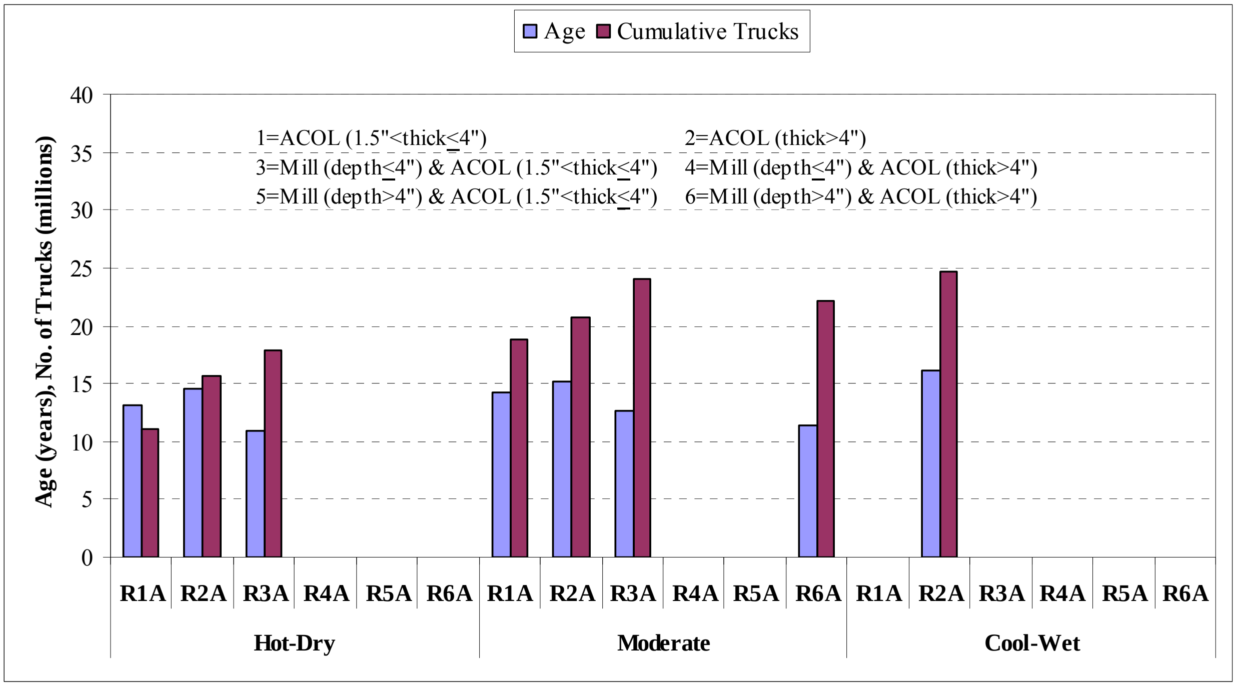


Figure 36. Performance life of conventional asphalt mix when used in different structure-defined rehabilitations applied to Interstate asphalt pavements.

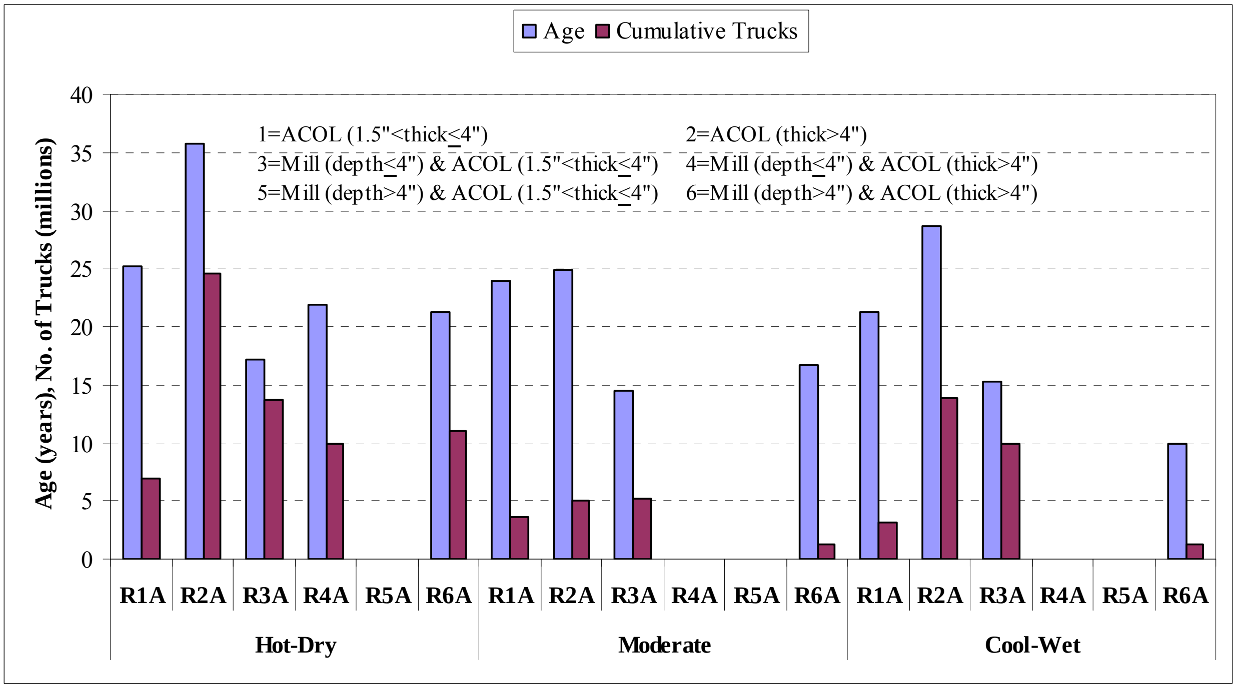


Figure 37. Performance life of conventional asphalt mix when used in different structure-defined rehabilitations applied to Non-Interstate asphalt pavements.

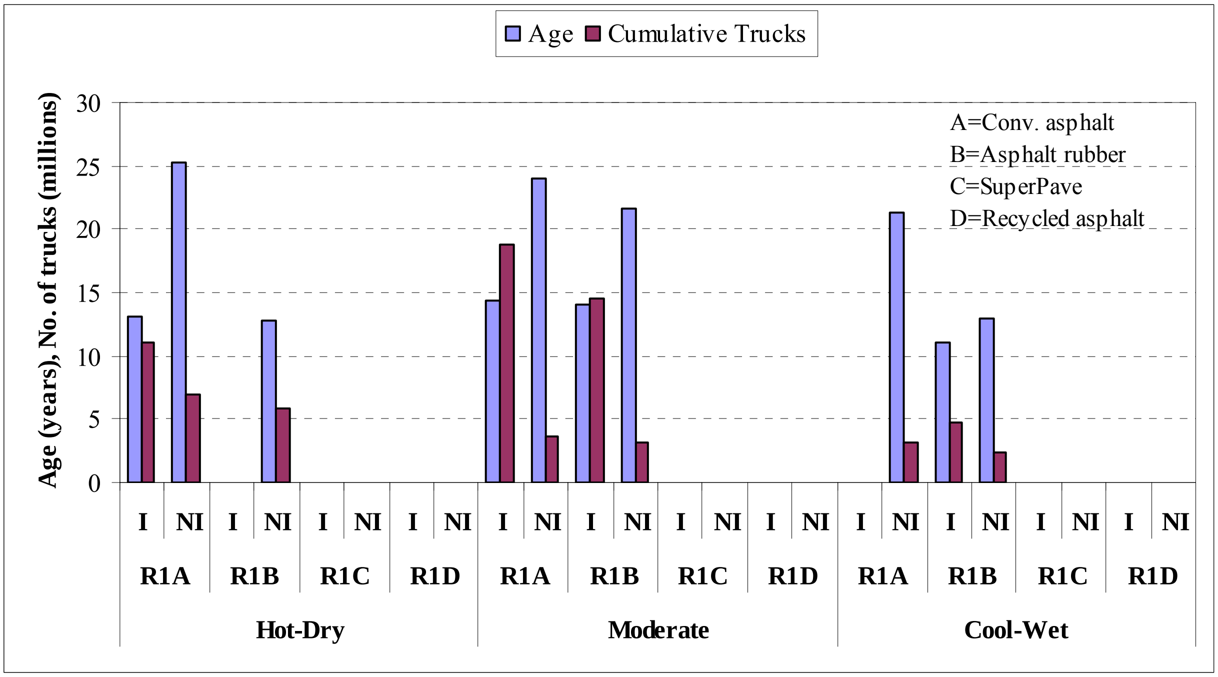


Figure 38. Performance life of thin conventional overlays (R1) on asphalt pavement using different asphalt mixture types.

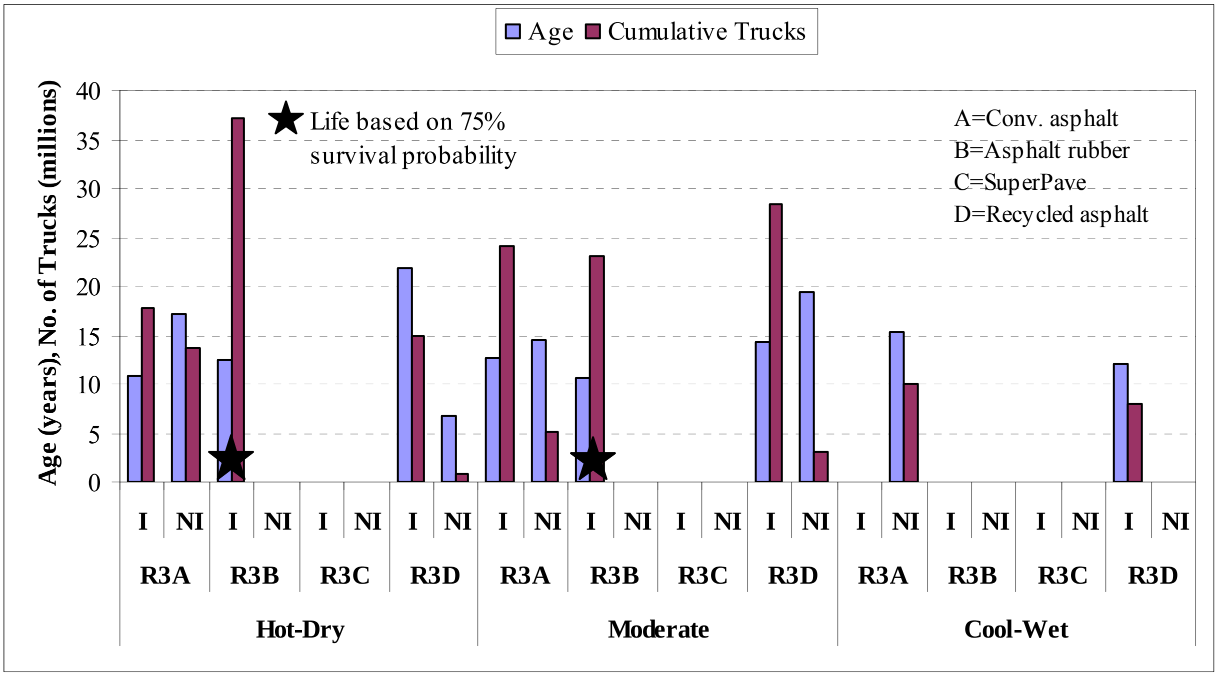


Figure 39. Performance life of shallow removal and thin overlays (R3) on asphalt pavement using different asphalt mixture types.

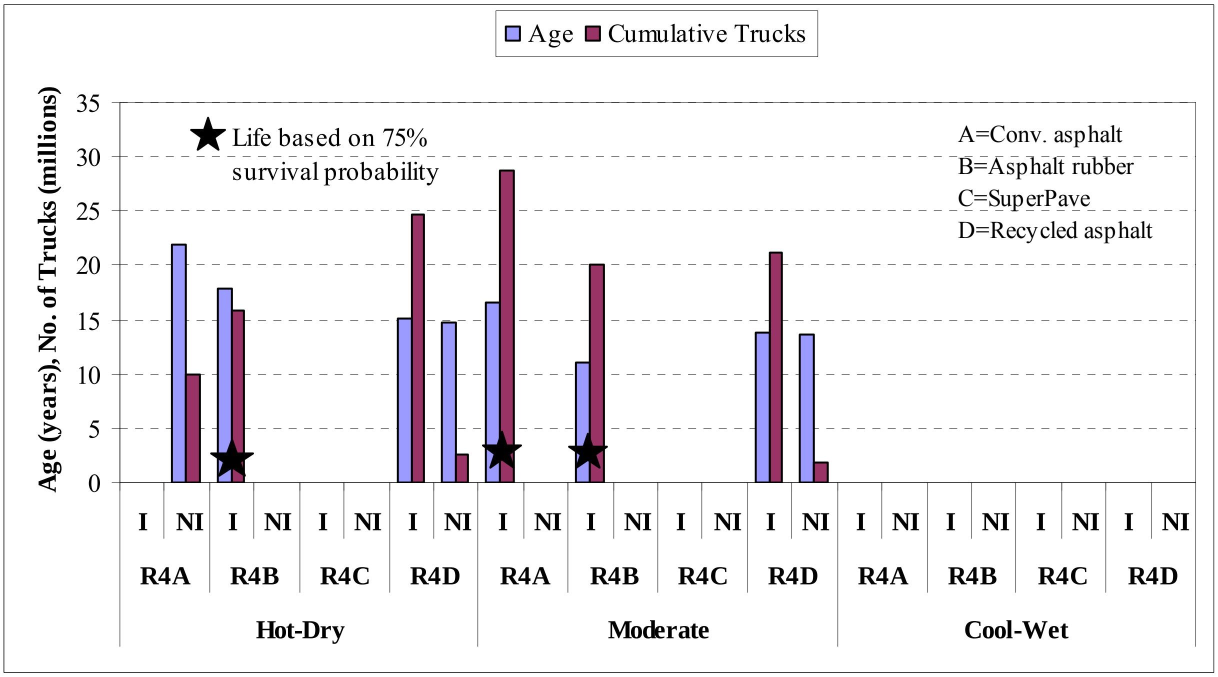


Figure 40. Performance life of shallow removal and thick overlays (R4) on asphalt pavement using different asphalt mixture types.

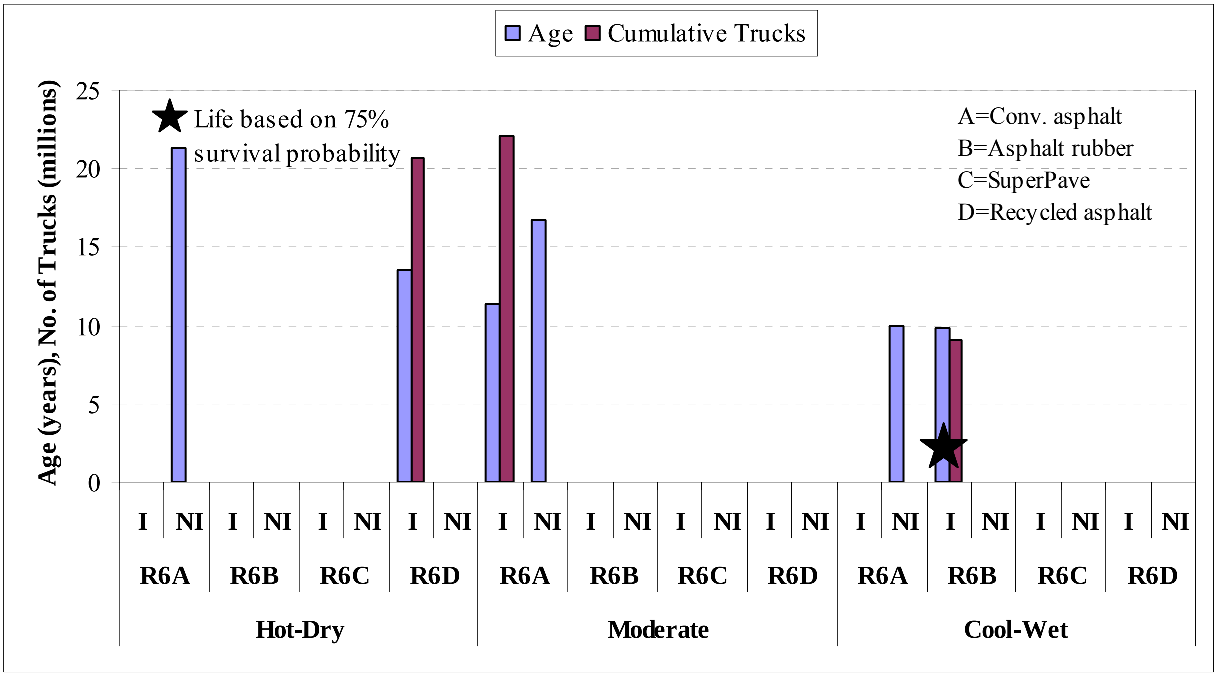


Figure 41. Performance life of deep removal and thick overlays (R6) on asphalt pavement using different asphalt mixture types.

(R3) placed on Interstate pavements, the asphalt rubber mix yielded better performance than the conventional mix (similar or longer lives for significantly higher levels of truck traffic).

With regard to other mix types, similar or better performance was experienced by some treatments (R3 on Interstate and Non-Interstate pavements) using recycled asphalt mixes, as compared to conventional asphalt mixes. A comparison of SuperPave mix performance could not be made, as all sections containing this mix type were relatively young (<6 years) and still in service.

Figure 42 shows the median lives of conventional asphalt and asphalt rubber mixes, when applied as part of a thin overlay on JPC pavements. Although based on a limited number of sections, it can be seen that the age survival of the two mixes are similar (10 to 13 years), but that the asphalt rubber treatments received significantly more truck traffic (about 7 million more trucks in each case).

Figures 43 and 44 provide comparisons of the median structure/mixture-defined rehabilitation life estimates obtained using non-parametric (LIFETEST) and parametric (LIFEREG) procedures. The comparisons show a fairly good correlation between the two sets of estimates (R^2 equal to about 0.63 in both cases). As such, the predicted lives from parametric procedures (based on the normal distribution) for this data set seem reasonable.

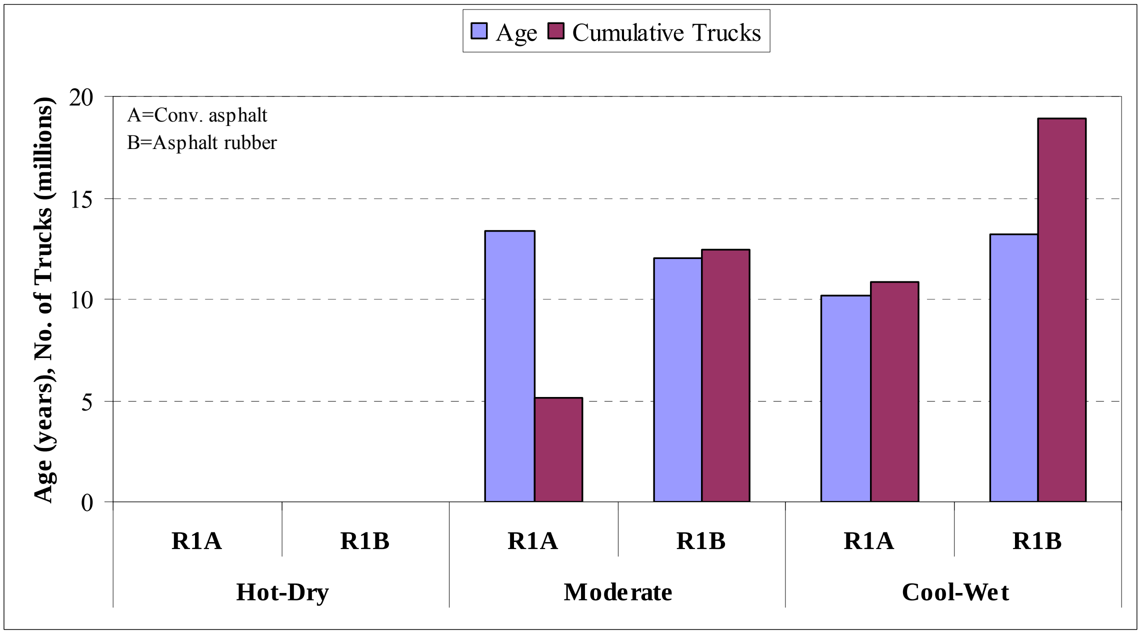


Figure 42. Performance life of conventional asphalt and asphalt rubber mixes when used in thin conventional overlay of JPC pavements.

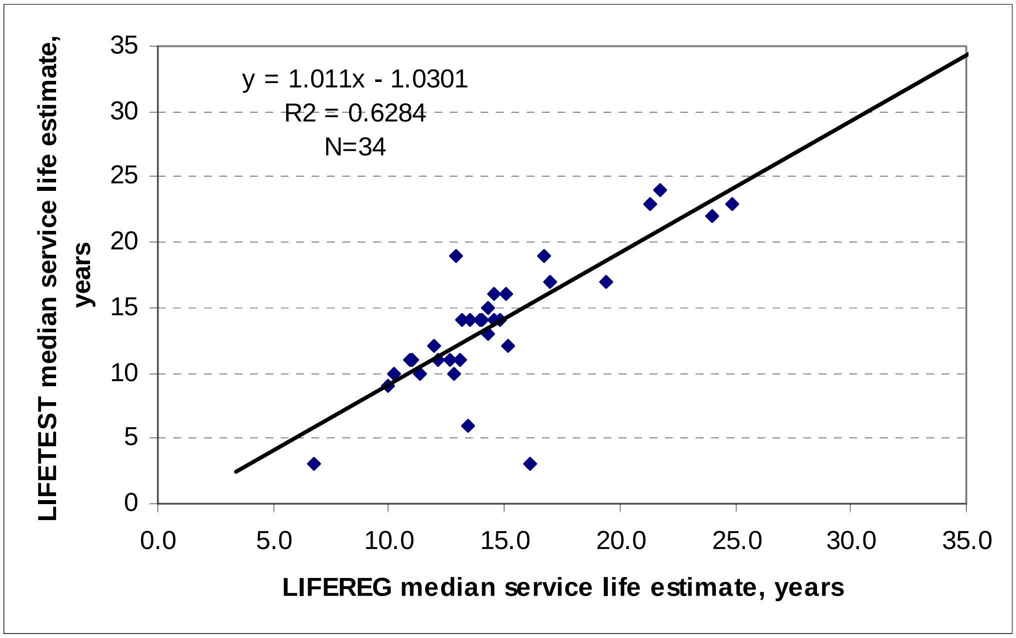


Figure 43. Comparison of median age-based rehabilitation performance life estimates obtained using non-parametric (LIFETEST) and parametric (LIFEREG) procedures.

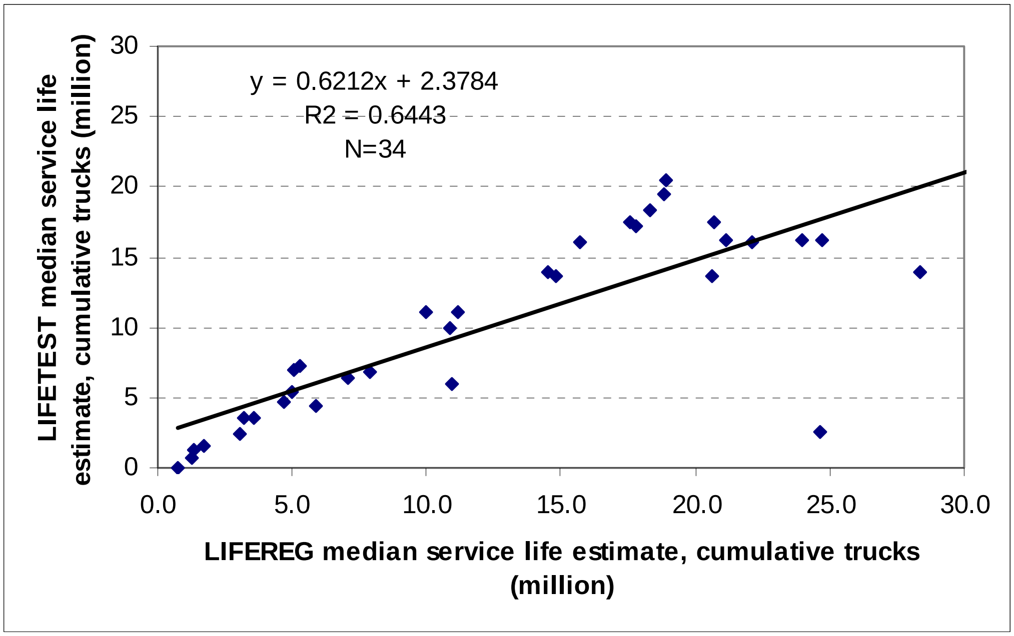


Figure 44. Comparison of median truck-based rehabilitation performance life estimates obtained using non-parametric (LIFETEST) and parametric (LIFEREG) procedures.

MECHANISTIC-BASED PERFORMANCE ANALYSIS

Mechanistic-based analysis was conducted to determine if the estimates of service life were comparable to the results from survival analyses in Arizona over a broad range of pavement types and climates. The pavement types considered were CAC, DSAC/FDAC, JPC, JPCD, and CRC.

The mechanistic analysis consisted of the following steps:

1. Determine representative locations for the three climate zones in Arizona—hot-dry, moderate, and cool-wet.
2. Establish typical ADOT designs for the five pavement types to be analyzed—CAC, DSAC/FDAC, JPC, JPCD, and CRC.
3. Verify the NCHRP 1-37A mechanistic-empirical (M-E) distress models using data from LTPP pavement sections located in Arizona.
4. Determine appropriate values of pavement characteristics and develop "virtual" pavements for analysis.
5. Perform M-E evaluation of typical pavements and determine pavement service life based on terminal values of key distress and smoothness.
6. Analyze the results obtained from the M-E analysis using survival analysis.

The steps listed along with the analysis performed are described in the following sections.

Determination of Representative Locations for Hot-Dry, Moderate, and Cool-Wet Climates in Arizona

Three locations representing the three climate zones in Arizona were identified for use in the mechanistic-based analysis. They were as follows:

- Hot-dry climate—Represented by the City of Phoenix.
  - longitude=112.017°; latitude=33.43°; elevation=1,117 ft
- Moderate climate—Represented by the Cities of Kingman and Seligman.
  - longitude=114.017° and 112.86°, respectively; latitude=35.2° and 35.32°, respectively; elevation=3,341 ft and 5,242 ft, respectively.
- Cool-wet climate—Represented by the City of Flagstaff.
  - longitude=111.667°; latitude=35.133°; elevation=6,899 ft

Establish Typical ADOT Designs for Pavement Types to be Analyzed

The design and site conditions of five LTPP pavement sections located in Arizona and representing each of the pavement types to be analyzed were used as the basis for developing virtual pavements for analysis. Additional information on pavement design properties was obtained from several other LTPP pavement sections located in Arizona. The list of pavements used to establish typical designs are presented in table 24 along with other LTPP pavement sections from which the additional information on pavement design features and material properties were obtained. Key pavement properties (of the five selected pavements) needed for mechanistic-based evaluations are presented in tables 25 through 28.

Verify NCHRP 1-37A Mechanistic-Empirical Models

The five LTPP sections representing the five pavement types listed in table 24 were evaluated using the NCHRP 1-37A M-E performance prediction models. Predicted distresses were compared to measured distresses obtained from both the LTPP database and ADOT PMS database. The comparisons of measured and predicted distress showed that the M-E models predicted distress with reasonable accuracy and thus are suitable for use in pavement evaluation in Arizona. Figures 45 and 46 present examples of predicted versus measured distress for CAC cracking and JPC faulting, respectively. Both plots show reasonable predictions of distress.

Determine Appropriate Values of Pavement Characteristics and Develop "Typical" Pavements for Analysis.

Using data from the ADOT PMS database and LTPP, typical pavement structures along with expected site conditions (i.e., traffic and climatic conditions) were developed that reflect the types of pavements that are constructed in Arizona for analysis.

Table 24. Description of the LTPP pavement sections used in developing the virtual pavements for analysis.

Pavement Type [a]	SHRP ID	Section Length, ft	County	Functional Class [b]	Facility [c]	Route No.	Direction of Travel	Mile Point	Elevation, ft	Latitude, °	Longitude, °	Subgrade (ASSHTO Soil Class)
CAC	041006	500	Maricopa	RPA	I	10	West	110.65	1,050	33.44	112.66	A-2-4
DSAC/ FDAC	041001	500	Maricopa	RPA	I	10	West	123.34	1,046	33.47	112.45	A-1-b/ A-2-6
JPC	047613	500	Maricopa	UPA	SR	360	West	7.42	1,190	33.42	111.81	A-7-6/ A-2-7
JPCD	047614	500	Maricopa	RPA	I	10	West	130.5	990	33.46	112.81	A-2-4
CRC	047079	500	Maricopa	UPA	SR	101	North	11.9	1,151	33.60	112.25	A-6
Other LTPP Pavement Sections	040600	500	Coconino	RPA	I	40	East	202.16	6,900	35.22	111.56	A-3
	041003	500	Maricopa	RPA	I	10	West	98.53	1,104	33.48	112.86	A-2-6
	041007	500	Maricopa	RPA	I	10	West	115.43	1,044	33.44	112.58	A-2-6 A-1-b
	041021	500	Mohave	RPA	I	40	West	72.87	3,574	35.16	113.68	A-2-4
	041024	500	Yavapai	RPA	I	40	East	106.95	5,456	35.28	113.13	A-2-6
	041025	500	Yavapai	RPA	I	40	West	113.03	5,460	35.30	113.03	A-1-a A-1-b

[a] Used as the basis for creating "virtual" pavements.
[b] RPA = Rural principal arterial, UPA = Urban principal arterial.
[c] I = Interstate, SR = State route.

Table 25. Key pavement properties required for mechanistic-based evaluation for typical CAC and DSAC/FDAC pavements located in Arizona.

Pavement Type	**Property**	**Value**
CAC (041006)	Traffic	Initial 2-way AADTT: 830 Number of lanes in design direction: 2 Percent of trucks in design direction (%): 50 Percent of trucks in design lane (%): 95 Operational speed (mi/hr): 60
	Climate	Latitude (degrees.minutes): 33.43 Longitude (degrees.minutes): -112.66 Elevation (ft): 1,050 Depth of water table (ft): 10
	Structure	Layer 1 -- Asphalt concrete Material type: Asphalt concrete Layer thickness (in): 8.7 Dynamic modulus (psi): 1.0 to 3.0 million (based on temp.) Layer 2 -- A-2-4 Unbound Material: A-2-4 Thickness (in): 8.5 Modulus (psi): 32,000 Layer 3 -- A-2-4 Unbound Material: A-2-4 Thickness (in): Semi-infinite Modulus (psi): 32,000
DSAC/FDAC (041001)	Traffic	Initial 2-way AADTT: 265 Number of lanes in design direction: 2 Percent of trucks in design direction (%): 50 Percent of trucks in design lane (%): 95 Operational speed (mi/hr): 60
	Climate	Latitude (degrees.minutes): 33.46 Longitude (degrees.minutes): -112.44 Elevation (ft): 1,046 Depth of water table (ft): 10
	Structure	Layer 1 -- Asphalt concrete Material type: Asphalt concrete Layer thickness (in): 12.5 Dynamic modulus (psi): 0.85 to 2.5 million (based on temp.) Layer 2 -- A-2-4 Unbound Material: A-2-4 Thickness (in): Semi-infinite Modulus (psi): 32,000

Table 26. Key pavement properties required for mechanistic-based evaluation for typical JPC pavements located in Arizona.

Pavement Type	Property	Value
JPC (047613)	Traffic	Initial 2-way AADTT: 1,895 Number of lanes in design direction: 2 Percent of trucks in design direction (%): 50 Percent of trucks in design lane (%): 95 Operational speed (mi/hr): 60
	Climate	Latitude (degrees.minutes): 33.38 Longitude (degrees.minutes): -111.83 Elevation (ft): 1,190 Depth of water table (ft): 10
	Structure	Layer 1 -- JPCP Material type: PCC Layer thickness (in): 13.0 28-day modulus of rupture (psi): 575 Layer 2 -- A-2-7 Unbound Material: A-2-7 Thickness (in): 6 Modulus (psi): 42,000 Layer 3 -- A-2-4 Unbound Material: A-7-6 Thickness (in): Semi-infinite Modulus (psi): 35,000
	Design	Joint Design Joint spacing (ft): 13, 17 (mean = 15) Sealant type: Liquid Dowel diameter (in): None Edge Support Tied PCC shoulder Long-term LTE (%): 40 Widened Slab (ft): None Base Properties Base type: Granular Erodibility index: Erosion Resistant (3) Base/slab friction coefficient: 0.85 PCC-Base Interface: Unbonded

Table 27. Key pavement properties required for mechanistic-based evaluation for typical JPCD pavements located in Arizona.

Pavement Type	Property	Value
JPCD (047614)	Traffic	Initial 2-way AADTT: 1,850 Number of lanes in design direction: 2 Percent of trucks in design direction (%): 50 Percent of trucks in design lane (%): 95 Operational speed (mi/hr): 60
	Climate	Latitude (degrees.minutes): 33.45 Longitude (degrees.minutes): -112.32 Elevation (ft): 990 Depth of water table (ft): 10
	Structure	Layer 1 -- JPCP Material type: PCC Layer thickness (in): 13.0 28-day MR (psi): 600 Layer 2 -- A-2-7 Unbound Material: A-2-7 Thickness (in): 6 Modulus (psi): 42,000 Layer 3 -- A-2-4 Unbound Material: A-7-6 Thickness (in): Semi-infinite Modulus (psi): 35,000
	Design	Joint Design Joint spacing (ft): 13, 17 (mean = 15) Sealant type: Liquid Dowel diameter (in): 1.25 Edge Support Tied PCC shoulder: None Widened Slab (ft): None Base Properties Base type: Cement-treated material Erodibility index: Very Erosion Resistant (2) Base/slab friction coefficient: 0.85 PCC-Base Interface: Bonded (for 60 months)

Table 28. Key pavement properties required for mechanistic-based evaluation for typical CRC pavements located in Arizona.

Pavement Type	**Property**	**Value**
CRC (047079)	Traffic	Initial 2-way AADTT: 1,770 Number of lanes in design direction: 2 Percent of trucks in design direction (%): 50 Percent of trucks in design lane (%): 77 Operational speed (mi/hr): 60
	Climate	Latitude (degrees.minutes): 33.6 Longitude (degrees.minutes): -112.25 Elevation (ft): 1,151 Depth of water table (ft): 10
	Structure	Layer 1 -- CRCP Material type: PCC Layer thickness (in): 9.0 28-day compressive strength (psi): 5,654 Layer 2 -- Asphalt Material: Asphalt Thickness (in): 4 Modulus (psi): 0.5 to 1.2 million (based on temp.) Layer 3 -- A-2-4 Unbound Material: A-6 Thickness (in): Semi-infinite Modulus (psi): 17,000
	Design	Steel Reinforcement Percent steel (%): 0.57 Bar diameter (in): 0.63 Steel depth (in): 4.5 Edge Support AC shoulder Base Properties Base type: Granular Erodibility index: Erosion Resistant (3) Base/slab friction coefficient: 7.6

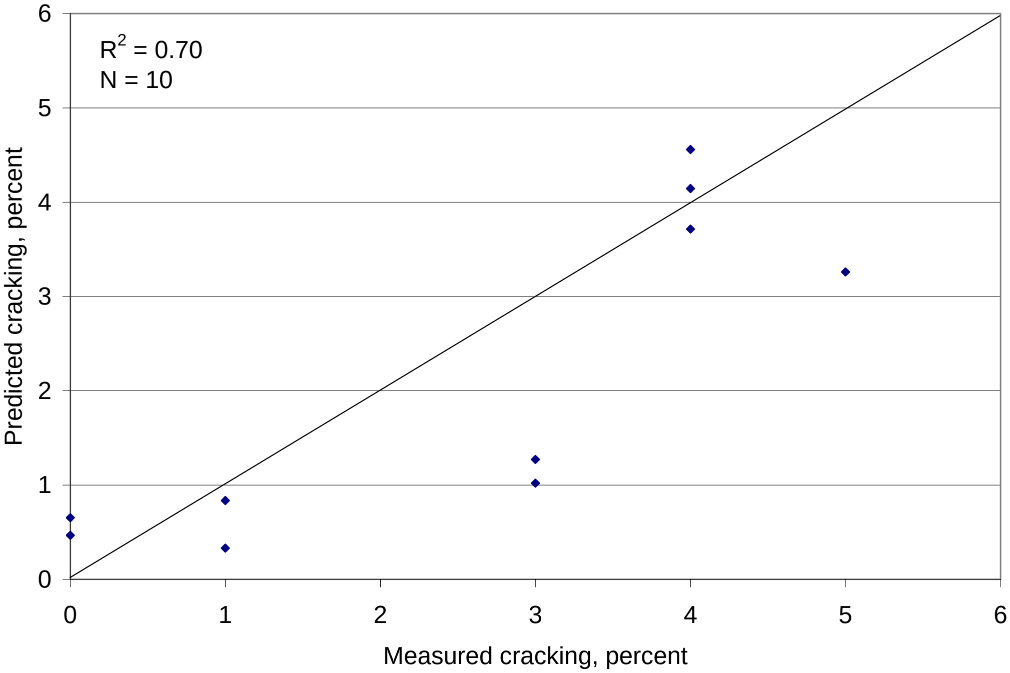


Figure 45. Predicted versus measured cracking (longitudinal and fatigue) for CAC at SHRP site 041006 (I-10, Maricopa County, MP 110.65).

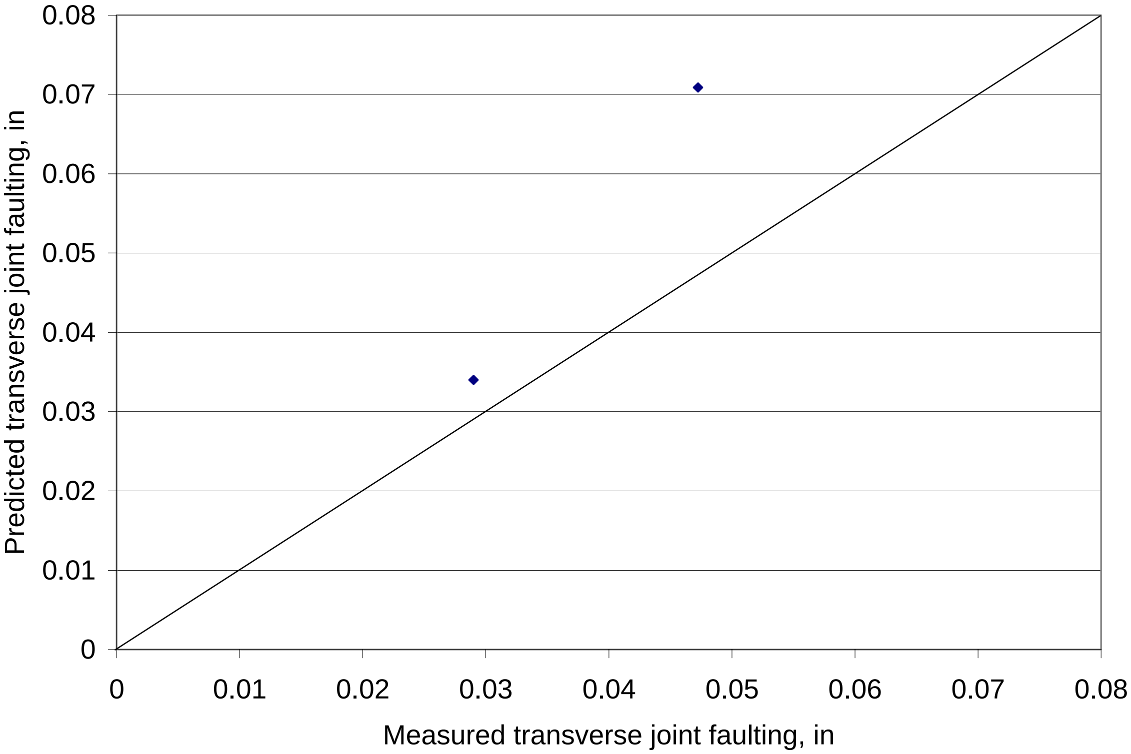


Figure 46. Predicted versus measured transverse joint faulting for JPC at SHRP site 047613 (SR 360, Maricopa County, MP 7.42).

The ranges of key pavement parameters (i.e., surface layer thickness, traffic, and subgrade properties) used in developing the "typical" pavements are presented in table 29. The information in this table was used to develop a typical sample of pavements that cover the range of traffic application, the range of pavement surface layer thickness, three climate zones, and a single subgrade type. The CAC and DSAC/FDAC pavements were evaluated over a 25-year period while JPC, JPCD, and CRC pavements were evaluated over a 35-year period. Performance indicators along with terminal values based on facility type (i.e., Interstate and Non-Interstates) used in analysis to determine service life are summarized in table 30. Pavements that did not experience terminal levels of distress or smoothness at the end of the evaluation period were censored as done typically in survival analyses.

Perform M-E Evaluation of "Typical" Pavements and Determine Pavement Service Life

Results of the mechanistic-based evaluations of the "typical" pavements are presented in tables 31 through 35.

M-E Performance Analysis Results

Survival analysis was performed using data obtained from the M-E evaluation of "typical" pavements. The survival analysis assumed that the sample of data (as provided in these tables) was generally typical of a subset of Arizona pavements in terms of design, climate, traffic, soils, and materials. The overall results of the M-E analysis are presented in table 36 and a comparison of survival life estimated in terms of pavement age in years are plotted in figures 47 and 48. With the exception of the JPCD and CRC life estimates, these figures show a reasonable comparison between actual and simulated estimates of survival life for both flexible and rigid pavements. The survival estimates shown in figure 48 for JPCD and CRC are minimum values; median life estimates were not available due to no failures with these pavements.

Table 29. Typical range of surface layer thickness, traffic, and subgrade properties used in developing "typical" pavements.

Pavement Type	Pavement Characteristic Variable	Range
CAC	Thickness, in	4 to 8
	Traffic, trucks applied per year, millions	0.25 to 1.0
	Subgrade, AASHTO soil class	A-2-4
DSAC/FDAC	Thickness, in	9 to 13
	Traffic, trucks applied per year, millions	0.25 to 1.05
	Subgrade, AASHTO soil class	A-2-4
JPC	Thickness, in	8 to 13
	Traffic, trucks applied per year, millions	0.5 to 1.5
	Subgrade, AASHTO soil class	A-7-6
JPCD	Thickness, in	10 to 13
	Traffic, trucks applied per year, millions	3.2 to 5.5
	Subgrade, AASHTO soil class	A-7-6
CRC	Thickness, in	8 to 13
	Traffic, trucks applied per year, millions	0.5 to 2.5
	Subgrade, AASHTO soil class	A-6

Table 30. Performance indicators along with terminal values based on facility type used in analysis.

Pavement Type	Performance Indicator	Facility Type	
		Interstate	Non-Interstate
CAC, DSAC/FDAC	Cracking (fatigue [alligator] and longitudinal cracking (percent area, all severities)	20	30
	Rutting, in	0.625	0.90
	Smoothness (IRI, in/mi)	150	200
JPC/JPCD	Mean transverse joint faulting, in	0.13	0.20
	Slab transverse cracking (percent slabs cracked, all severities)	15	25
	Smoothness (IRI, in/mi)	150	200
CRC	Punchouts, (no. per mile, all severities)	10	–
	Smoothness (IRI, in/mi)	150	200

.

Table 31. Predictions of time and traffic loadings to failure for original or reconstructed CAC pavements, determined using NCHRP Project 1-37A performance models.

AC Thickness, in	No. of Trucks, millions	Climate	Time to Failure, yrs						Traffic to Failure, cumulative trucks (millions)					
			Interstate[a]			Non-Interstate[b]			Interstate[a]			Non-Interstate[b]		
			Rutting	Fatigue Crack	IRI	Rutting	Fatigue Crack	IRI	Rutting	Fatigue Crack	IRI	Rutting	Fatigue Crack	IRI
4.5	0.25	Hot-Dry	18.29	23.79	25.00	25.00	25.00	25.00	4.03	5.90	6.34	6.34	6.34	6.34
		Moderate	18.29	23.79	25.00	25.00	25.00	25.00	4.03	5.90	6.34	6.34	6.34	6.34
		Cool-Wet	25.00	24.08	22.81	25.00	25.00	25.00	6.34	6.00	5.54	6.34	6.34	6.34
	0.5	Hot-Dry	10.70	14.58	25.00	24.92	19.85	25.00	3.90	5.88	12.69	12.63	9.05	12.69
		Moderate	10.70	14.58	25.00	24.92	19.85	25.00	3.90	5.88	12.69	12.63	9.05	12.69
		Cool-Wet	20.04	14.75	21.70	25.00	20.04	25.00	9.18	5.97	10.30	12.69	9.18	12.69
	0.75	Hot-Dry	7.77	10.58	25.00	18.88	14.76	25.00	3.91	5.77	19.04	12.64	8.97	19.04
		Moderate	7.77	10.58	25.00	18.88	14.76	25.00	3.91	5.77	19.04	12.64	8.97	19.04
		Cool-Wet	14.89	10.79	20.68	25.00	14.94	25.00	9.08	5.91	14.41	19.04	9.11	19.04
5.5	0.25	Hot-Dry	22.58	25.00	25.00	25.00	25.00	25.00	5.46	6.34	6.34	6.34	6.34	6.34
		Moderate	22.58	25.00	25.00	25.00	25.00	25.00	5.46	6.34	6.34	6.34	6.34	6.34
		Cool-Wet	25.00	25.00	23.56	25.00	25.00	25.00	6.34	6.34	5.81	6.34	6.34	6.34
	0.5	Hot-Dry	13.71	17.95	25.00	25.00	25.00	25.00	5.41	7.84	12.69	12.69	12.69	12.69
		Moderate	13.71	17.95	25.00	25.00	25.00	25.00	5.41	7.84	12.69	12.69	12.69	12.69
		Cool-Wet	25.00	18.94	23.08	25.00	25.00	25.00	12.69	8.46	11.28	12.69	12.69	12.69
	0.75	Hot-Dry	9.75	13.47	25.00	22.86	19.37	25.00	5.19	7.92	19.04	16.67	13.12	19.04
		Moderate	9.75	13.47	25.00	22.86	19.37	25.00	5.19	7.92	19.04	16.67	13.12	19.04
		Cool-Wet	19.83	14.09	22.65	25.00	20.54	25.00	13.56	8.42	16.45	19.04	14.27	19.04
6.5	0.25	Hot-Dry	25.00	25.00	25.00	25.00	25.00	25.00	6.34	6.34	6.34	6.34	6.34	6.34
		Moderate	25.00	25.00	25.00	25.00	25.00	25.00	6.34	6.34	6.34	6.34	6.34	6.34
		Cool-Wet	25.00	25.00	23.93	25.00	25.00	25.00	6.34	6.34	5.91	6.34	6.34	6.34
	0.5	Hot-Dry	15.72	24.81	25.00	25.00	25.00	25.00	6.52	12.55	12.69	12.69	12.69	12.69
		Moderate	15.72	24.81	25.00	25.00	25.00	25.00	6.52	12.55	12.69	12.69	12.69	12.69
		Cool-Wet	25.00	25.00	23.63	25.00	25.00	25.00	12.69	12.69	11.67	12.69	12.69	12.69
	0.75	Hot-Dry	11.70	18.74	25.00	25.00	25.00	25.00	6.57	12.51	19.04	19.04	19.04	19.04
		Moderate	11.70	18.74	25.00	25.00	25.00	25.00	6.57	12.51	19.04	19.04	19.04	19.04
		Cool-Wet	23.83	21.58	23.42	25.00	25.00	25.00	17.73	15.33	17.28	19.04	19.04	19.04

[a,b] Refer to table 30 for terminal values of distress/smoothness.

Table 32. Predictions of time and traffic loadings to failure for original or reconstructed DSAC/FDAC pavements, determined using NCHRP Project 1-37A performance models.

AC Thickness, in	No. of Trucks, millions	Climate	Time to Failure, yrs						Traffic to Failure, cumulative trucks (millions)					
			Interstate[a]			Non-Interstate[b]			Interstate[a]			Non-Interstate[b]		
			Rutting	Fatigue Crack	IRI	Rutting	Fatigue Crack	IRI	Rutting	Fatigue Crack	IRI	Rutting	Fatigue Crack	IRI
7	0.4	Hot-Dry	10.73	18.81	25.00	21.79	25.00	25.00	3.13	6.70	10.14	8.28	10.14	10.14
		Moderate	23.83	25.00	25.00	25.00	25.00	25.00	9.44	10.14	10.14	10.14	10.14	10.14
		Cool-Wet	23.83	25.00	25.00	25.00	25.00	25.00	9.44	10.14	10.14	10.14	10.14	10.14
	0.75	Hot-Dry	7.73	13.79	25.00	15.79	22.84	25.00	3.15	6.63	15.43	7.98	13.50	15.43
		Moderate	17.78	22.72	25.00	25.00	25.00	25.00	9.41	13.39	15.43	15.43	15.43	15.43
		Cool-Wet	17.78	22.72	25.00	25.00	25.00	25.00	9.41	13.39	15.43	15.43	15.43	15.43
	1.1	Hot-Dry	4.79	11.01	25.00	10.69	18.92	25.00	3.21	8.88	27.85	8.54	18.55	27.85
		Moderate	10.90	14.75	25.00	23.80	23.91	25.00	8.77	13.12	27.85	25.89	26.06	27.85
		Cool-Wet	10.90	14.75	25.00	23.80	23.91	25.00	8.77	13.12	27.85	25.89	26.06	27.85
8.5	0.4	Hot-Dry	13.25	25.00	25.00	25.00	25.00	25.00	4.13	10.14	10.14	10.14	10.14	10.14
		Moderate	25.00	25.00	25.00	25.00	25.00	25.00	10.14	10.14	10.14	10.14	10.14	10.14
		Cool-Wet	25.00	25.00	25.00	25.00	25.00	25.00	10.14	10.14	10.14	10.14	10.14	10.14
	0.75	Hot-Dry	7.83	24.52	25.00	15.95	25.00	25.00	3.94	18.49	19.04	9.98	19.04	19.04
		Moderate	21.78	25.00	25.00	25.00	25.00	25.00	15.54	19.04	19.04	19.04	19.04	19.04
		Cool-Wet	21.78	25.00	25.00	25.00	25.00	25.00	15.54	19.04	19.04	19.04	19.04	19.04
	1.1	Hot-Dry	5.68	10.11	25.00	11.84	25.00	25.00	3.91	5.92	27.85	9.77	27.85	27.85
		Moderate	16.70	25.00	25.00	25.00	25.00	25.00	15.56	27.85	27.85	27.85	27.85	27.85
		Cool-Wet	16.70	25.00	25.00	25.00	25.00	25.00	15.56	27.85	27.85	27.85	27.85	27.85
10	0.4	Hot-Dry	15.86	25.00	25.00	25.00	25.00	25.00	5.27	10.14	10.14	10.14	10.14	10.14
		Moderate	25.00	25.00	25.00	25.00	25.00	25.00	10.14	10.14	10.14	10.14	10.14	10.14
		Cool-Wet	25.00	25.00	25.00	25.00	25.00	25.00	10.14	10.14	10.14	10.14	10.14	10.14
	0.75	Hot-Dry	9.72	25.00	25.00	19.71	25.00	25.00	5.17	19.04	19.04	13.44	19.04	19.04
		Moderate	21.81	25.00	25.00	25.00	25.00	25.00	15.57	19.04	19.04	19.04	19.04	19.04
		Cool-Wet	21.81	25.00	25.00	25.00	25.00	25.00	15.57	19.04	19.04	19.04	19.04	19.04
	1.1	Hot-Dry	6.82	25.00	25.00	14.72	25.00	25.00	4.87	27.85	27.85	13.07	27.85	27.85
		Moderate	16.72	25.00	25.00	25.00	25.00	25.00	15.59	27.85	27.85	27.85	27.85	27.85
		Cool-Wet	16.72	25.00	25.00	25.00	25.00	25.00	15.59	27.85	27.85	27.85	27.85	27.85

[a,b] Refer to table 30 for terminal values of distress/smoothness.

Table 33. Predictions of time and traffic loadings to failure for original or reconstructed JPC pavements, determined using NCHRP Project 1-37A performance models.

PCC Thickness, in	No. of Trucks, millions	Climate	Time to Failure, yrs						Traffic to Failure, cumulative trucks (millions)					
			Interstate[a]			Non-Interstate[b]			Interstate[a]			Non-Interstate[b]		
			Crack	Fault	IRI	Crack	Fault	IRI	Crack	Fault	IRI	Crack	Fault	IRI
9	0.5	Hot-Dry	18.25	25.79	24.17	14.25	35.00	35.00	6.78	11.22	10.19	10.24	17.96	17.96
		Moderate	18.55	18.42	19.67	24.63	35.00	33.05	6.94	10.48	7.54	10.48	17.96	16.42
		Cool-Wet	16.08	34.46	19.54	21.58	35.00	29.14	5.68	17.52	7.47	8.63	17.96	13.51
	1.0	Hot-Dry	10.42	16.17	14.73	14.21	28.87	24.75	6.24	11.22	9.88	9.40	26.12	20.70
		Moderate	10.52	11.21	12.11	14.53	25.54	22.25	6.32	6.85	7.59	9.69	21.70	17.69
		Cool-Wet	8.86	22.21	14.26	12.51	35.00	21.46	5.08	17.64	9.45	7.93	35.23	16.79
	1.5	Hot-Dry	6.83	11.96	10.59	9.75	21.96	18.50	5.57	11.27	9.63	8.65	26.19	20.47
		Moderate	7.08	8.12	8.58	10.03	19.29	16.56	5.81	6.88	7.37	8.97	21.72	17.53
		Cool-Wet	5.95	16.54	10.88	8.56	35.00	17.95	4.71	17.49	9.96	7.35	53.18	19.61
11	0.5	Hot-Dry	35.00	35.00	35.00	35.00	35.00	35.00	17.96	17.96	17.96	17.96	17.96	17.96
		Moderate	35.00	35.00	35.00	35.00	35.00	35.00	17.96	17.96	17.96	17.96	17.96	17.96
		Cool-Wet	35.00	35.00	35.00	35.00	35.00	35.00	17.96	17.96	17.96	17.96	17.96	17.96
	1.0	Hot-Dry	35.00	29.71	35.00	35.00	35.00	35.00	35.23	27.29	35.23	35.23	35.23	35.23
		Moderate	35.00	24.50	31.08	35.00	35.00	35.00	35.23	20.40	29.27	35.23	35.23	35.23
		Cool-Wet	35.00	35.00	30.25	35.00	35.00	35.00	35.23	35.23	28.06	35.23	35.23	35.23
	1.5	Hot-Dry	35.00	22.58	28.55	35.00	35.00	35.00	53.18	27.30	38.79	53.18	53.18	53.18
		Moderate	35.00	35.00	35.00	35.00	35.00	35.00	53.18	53.18	53.18	53.18	53.18	53.18
		Cool-Wet												
13	0.5	Hot-Dry	35.00	35.00	35.00	35.00	35.00	35.00	17.96	17.96	17.96	17.96	17.96	17.96
		Moderate	35.00	35.00	35.00	35.00	35.00	35.00	17.96	17.96	17.96	17.96	17.96	17.96
		Cool-Wet	35.00	35.00	35.00	35.00	35.00	35.00	17.96	17.96	17.96	17.96	17.96	17.96
	1.0	Hot-Dry	35.00	35.00	35.00	35.00	35.00	35.00	35.23	35.23	35.23	35.23	35.23	35.23
		Moderate	35.00	35.00	35.00	35.00	35.00	35.00	35.23	35.23	35.23	35.23	35.23	35.23
		Cool-Wet	35.00	35.00	35.00	35.00	35.00	35.00	35.23	35.23	35.23	35.23	35.23	35.23
	1.5	Hot-Dry	35.00	35.00	35.00	35.00	35.00	35.00	53.18	53.18	53.18	53.18	53.18	53.18
		Moderate	35.00	35.00	35.00	35.00	35.00	35.00	53.18	53.18	53.18	53.18	53.18	53.18
		Cool-Wet	35.00	35.00	35.00	35.00	35.00	35.00	53.18	53.18	53.18	53.18	53.18	53.18

[a,b] Refer to table 30 for terminal values of distress/smoothness.

Table 34. Predictions of time and traffic loadings to failure for original or reconstructed JPCD pavements, determined using NCHRP Project 1-37A performance models.

PCC Thickness, in	No. of Trucks, millions	Climate	Time to Failure, yrs						Traffic to Failure, cumulative trucks (millions)					
			Interstate[a]			Non-Interstate[b]			Interstate[a]			Non-Interstate[b]		
			Crack	Fault	IRI	Crack	Fault	IRI	Crack	Fault	IRI	Crack	Fault	IRI
9.5	2.5	Hot-Dry	13.00	35.00	35.00	17.25	35.00	35.00	21.09	89.10	89.10	31.07	89.10	89.10
		Moderate	12.33	35.00	33.29	16.83	35.00	35.00	19.68	89.10	82.38	30.03	89.10	89.10
		Cool-Wet	9.22	35.00	23.15	12.75	35.00	35.00	13.51	89.10	47.43	20.56	89.10	89.10
	4.0	Hot-Dry	8.92	35.00	29.05	11.96	35.00	35.00	20.67	142.29	106.55	30.15	142.29	142.29
		Moderate	8.33	35.00	25.85	11.33	35.00	35.00	19.00	142.29	89.27	28.12	142.29	142.29
		Cool-Wet	6.20	35.00	19.42	8.50	35.00	32.50	13.25	142.29	58.68	19.48	142.29	126.70
	5.5	Hot-Dry	6.89	35.00	23.33	9.08	35.00	35.00	20.66	195.47	105.28	29.06	195.47	195.47
		Moderate	6.35	35.00	21.03	8.89	35.00	35.00	18.75	195.47	90.43	28.29	195.47	195.47
		Cool-Wet	4.92	35.00	17.07	6.50	35.00	28.75	13.85	195.47	67.17	19.27	195.47	144.03
11.0	2.5	Hot-Dry	26.96	35.00	35.00	35.00	35.00	35.00	59.53	89.10	89.10	89.10	89.10	89.10
		Moderate	25.67	35.00	35.00	34.03	35.00	35.00	55.30	89.10	89.10	85.24	89.10	89.10
		Cool-Wet	19.03	35.00	33.50	25.25	35.00	35.00	35.69	89.10	83.19	53.96	89.10	89.10
	4.0	Hot-Dry	18.42	35.00	35.00	25.04	35.00	35.00	54.42	142.29	142.29	85.10	142.29	142.29
		Moderate	17.92	35.00	35.00	24.00	35.00	35.00	52.33	142.29	142.29	79.88	142.29	142.29
		Cool-Wet	13.00	35.00	27.15	17.42	35.00	35.00	33.68	142.29	96.08	50.30	142.29	142.29
	5.5	Hot-Dry	14.25	35.00	35.00	19.39	35.00	35.00	52.38	195.47	195.47	80.44	195.47	195.47
		Moderate	13.62	35.00	32.06	18.54	35.00	35.00	49.30	195.47	170.44	75.48	195.47	195.47
		Cool-Wet	9.92	5.00	24.11	13.38	35.00	35.00	32.49	195.47	110.50	48.09	195.47	195.47
12.5	2.5	Hot-Dry	35.00	35.00	35.00	35.00	35.00	35.00	89.10	89.10	89.10	89.10	89.10	89.10
		Moderate	35.00	35.00	35.00	35.00	35.00	35.00	89.10	89.10	89.10	89.10	89.10	89.10
		Cool-Wet	35.00	35.00	35.00	35.00	35.00	35.00	89.10	89.10	89.10	89.10	89.10	89.10
	4.0	Hot-Dry	35.00	35.00	35.00	35.00	35.00	35.00	142.29	142.29	142.29	142.29	142.29	142.29
		Moderate	34.08	35.00	35.00	35.00	35.00	35.00	136.47	142.29	142.29	142.29	142.29	142.29
		Cool-Wet	28.04	35.00	35.00	35.00	35.00	35.00	100.93	142.29	142.29	142.29	142.29	142.29
	5.5	Hot-Dry	28.05	35.00	35.00	35.00	35.00	35.00	138.76	195.47	195.47	195.47	195.47	195.47
		Moderate	26.96	35.00	35.00	35.00	35.00	35.00	130.61	195.47	195.47	195.47	195.47	195.47
		Cool-Wet	22.00	35.00	31.75	29.17	35.00	35.00	96.54	195.47	167.84	147.24	195.47	195.47

[a,b] Refer to table 30 for terminal values of distress/smoothness.

Table 35. Predictions of time and traffic loadings to failure for original or reconstructed CRC pavements, determined using NCHRP Project 1-37A performance models.

PCC Thickness, in	No of Trucks, million	Climate	Time to Failure, yrs		Traffic to Failure, cumulative trucks (million)	
			Punchouts	IRI	Punchouts	IRI
9	0.5	Hot-Dry	35.00	35.00	17.20	17.20
		Moderate	35.00	35.00	17.20	17.20
		Cool-Wet	35.00	35.00	17.20	17.20
	1.0	Hot-Dry	28.47	35.00	24.96	34.41
		Moderate	29.06	35.00	25.76	34.41
		Cool-Wet	35.00	35.00	34.41	34.41
	1.5	Hot-Dry	22.69	35.00	26.62	51.61
		Moderate	23.30	35.00	27.69	61.61
		Cool-Wet	31.54	35.00	43.85	51.61
9.5	0.5	Hot-Dry	35.00	35.00	17.20	17.20
		Moderate	35.00	35.00	17.20	17.20
		Cool-Wet	35.00	35.00	17.20	17.20
	1.0	Hot-Dry	32.68	35.00	30.90	34.41
		Moderate	33.33	35.00	31.86	34.41
		Cool-Wet	35.00	35.00	34.41	34.41
	1.5	Hot-Dry	26.54	35.00	33.66	51.61
		Moderate	26.77	35.00	34.09	51.61
		Cool-Wet	35.0	35.00	51.61	51.61
10	0.5	Hot-Dry	35.00	35.00	17.20	17.20
		Moderate	35.00	35.00	17.20	17.20
		Cool-Wet	35.00	35.00	17.20	17.20
	1.0	Hot-Dry	35.00	35.00	34.41	34.41
		Moderate	35.00	35.00	34.41	34.41
		Cool-Wet	35.00	35.00	34.41	34.41
	1.5	Hot-Dry	29.70	35.00	39.95	51.61
		Moderate	30.55	35.00	41.74	51.61
		Cool-Wet	35.00	35.00	51.61	51.61

[a,b] Refer to table 30 for terminal values of distress/smoothness.

Table 36. Survival analysis results of service life data obtained from M-E evaluation of "typical" pavements.

Pavement Type	Facility Type	Climate	No.	50% Survival Age, yrs	50% Survival Life, No. of trucks (millions)
CAC	I	Cool-Wet	9	19.34	8.11
CAC	I	Hot-Dry	9	15.32	5.33
CAC	I	Moderate	9	15.32	5.33
CAC	NI	Cool-Wet	9	28.07	15.23
CAC	NI	Hot-Dry	9	28.18	15.00
CAC	NI	Moderate	9	28.18	15.00
DSAC/FDAC	I	Cool-Wet	9	20.64	21.18
DSAC/FDAC	I	Hot-Dry	9	9.16	6.50
DSAC/FDAC	I	Moderate	9	20.64	21.18
DSAC/FDAC	NI	Cool-Wet	9	27.53	28.61
DSAC/FDAC	NI	Hot-Dry	9	18.55	10.55
DSAC/FDAC	NI	Moderate	9	27.53	28.61
JPCD	I	Cool-Wet	9	16.35	104.68
JPCD	I	Hot-Dry	9	22.20	150.50
JPCD	I	Moderate	9	20.62	144.49
JPCD	NI	Cool-Wet	9	21.83	151.18
JPCD	NI	Hot-Dry	9	29.91	209.87
JPCD	NI	Moderate	9	27.29	238.36
JPC	I	Cool-Wet	9	33.21	53.28
JPC	I	Hot-Dry	9	30.81	56.34
JPC	I	Moderate	9	35.81	55.58
JPC	NI	Cool-Wet	9	40.52	54.39
JPC	NI	Hot-Dry	9	44.15	54.63
JPC	NI	Moderate	9	43.45	55.08
CRC	I	Cool-Wet	9	35.37	53.75
CRC	I	Hot-Dry	9	37.22	43.43
CRC	I	Moderate	9	37.04	42.34

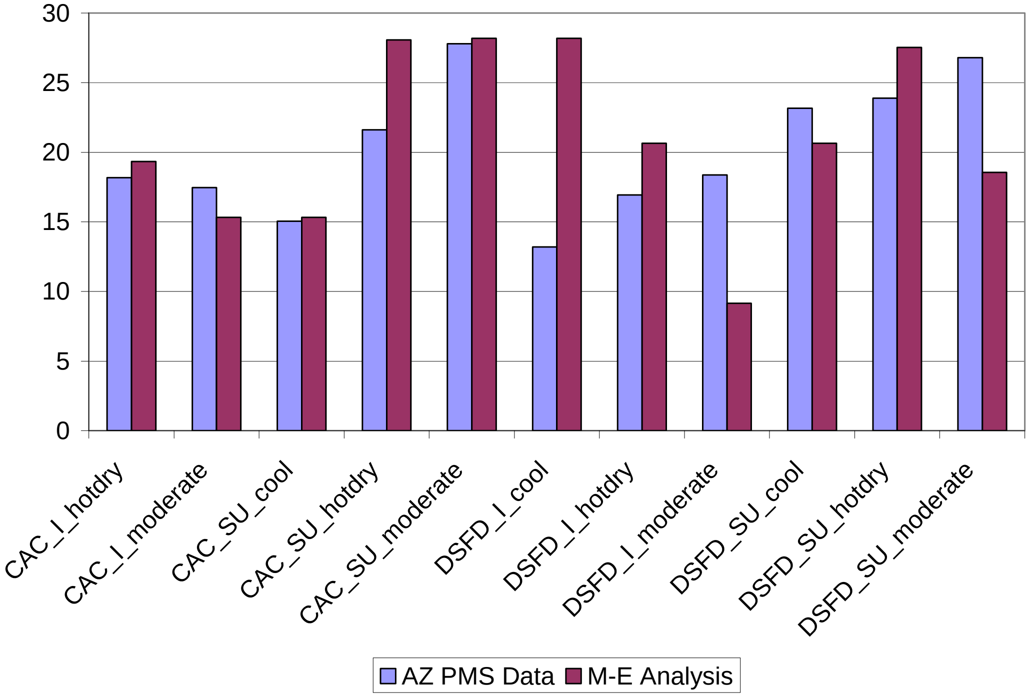


Figure 47. Histogram showing 50 percent survival life estimated from ADOT performance data and M-E evaluation of typical ADOT flexible pavements.

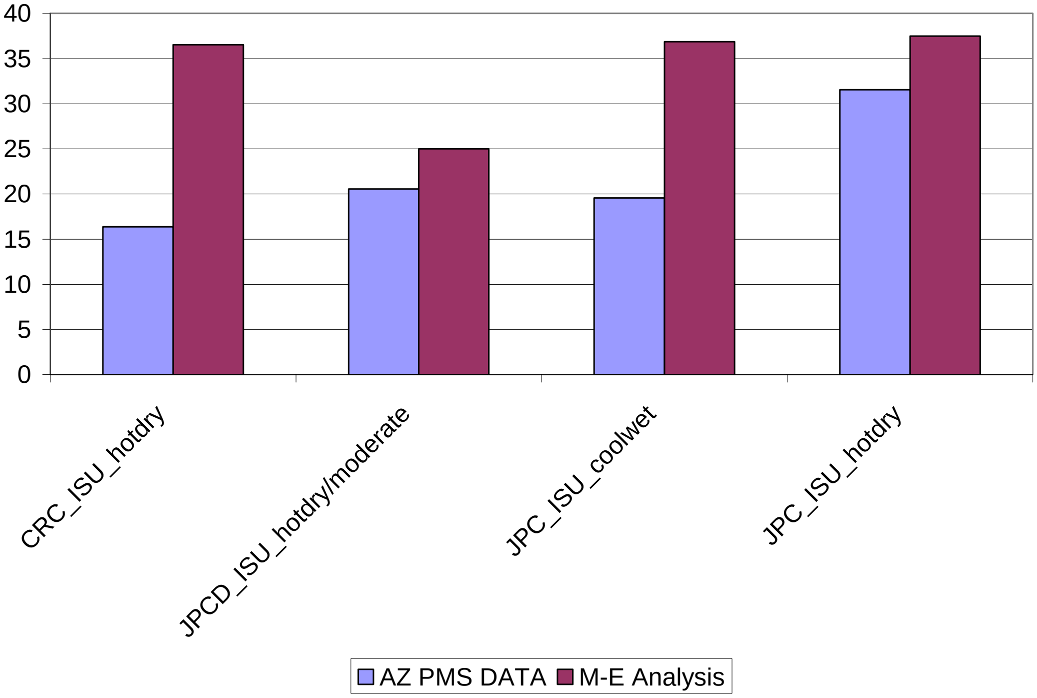


Figure 48. Histogram showing 50 percent survival life estimated from ADOT performance data and M-E evaluation of typical ADOT rigid pavements.

CHAPTER 4. ANALYSIS OF CONSTRUCTION COSTS

INTRODUCTION

One of the most critical aspects of LCCA is establishing the direct agency costs associated with building, maintaining, and rehabilitating the subject pavement types. Having the best unit price estimates possible for the various pay items associated with initial construction and periodic upkeep goes a long way toward ensuring a fair assessment of life cycle costs.

To conduct the pavement LCCAs in this study, unit cost data from multiple sources were collected and carefully analyzed. Best estimates were then developed covering a range of initial pavement structure types (e.g., CAC, JPCD) and M&R treatments. This chapter discusses the process used to assess unit costs and presents the resulting best estimates used later in the LCCAs.

DEVELOPMENT OF BEST ESTIMATES OF COSTS

Sources of Data

Three sources of unit cost data were tapped for the cost analysis. These sources are as follows:

- 1999 Construction Costs report prepared by the ADOT Contracts and Specifications Section.
- 2002 report "Arizona Asphalt Rubber Projects, 1988-2001" prepared by the ADOT Materials Group Pavement Design Section.
- ADOT 1999 Pavement Management Cost Estimate.

Since the sources of unit cost data were available only in hard copy form, the data were manually entered into a Microsoft® Excel spreadsheet for subsequent analysis. The entered costs were then carefully checked and corrected, as necessary, to ensure the highest level of confidence in the resulting best estimates.

Costs from the first source consisted of the three lowest contractor bid prices for pay items associated with projects put to bid in 1999. Data for over 100 different pavement-related pay items were extracted from this source and entered into a Microsoft® Excel spreadsheet for subsequent analysis. Table 37 provides a sample of the data collected and used in the study.

Table 37. Sample data obtained from Construction Costs report (ADOT, 1999).

Pay Item 2020085 Remove Bituminous Pavement (Milling, 3 in)

Quantity	3 Low Bidders-Unit Price			Route	County	MP	Project	Project Location
	No. 1	No. 2	No. 3					
5,530	$4.00	$3.00	$2.00	U 093	YV	172	H430601C	NB & SB climbing lanes, MP 173-176
7,000	$2.50	$3.44	$	S 089	CN	549	H421501C	Colorado River – State Line
3,627	$3.00	$3.00	$3.50	S 089A	YV	353	H434201C	Main Street Intersection, Cottonwood
4,890	$3.00	$2.50	$	S 080	CH	342	H4229C01	Jct. SR92 – Jct. Double Adobe Road
117,333	$0.82	$0.80	$1.25	I 015	MO	008	H4532C01	Littlefield – Virgin River
361	$1.80	$2.50	$1.00	I 040	AP	318	H4433C01	Pinta T I- McCarrell TI
1,222	$1.30	$0.75	$	I 010	PN	208	H4426C01	Picacho – Picacho Peak
181,529	$1.00	$1.00	$0.95	S 089	YV	338	H4541C01	Paulden – Hells Canyon
68,000	$0.80	$0.85	$1.10	S 066	MO	057	H4559C01	Thompson Avenue – AT Railway
17,100	$1.80	$1.80	$2.25	U 060	MA	160	H5405C01	US 60, Grand Avenue/27th Avenue

Costs from the second source consisted of first-bid mix and binder unit costs for asphalt rubber projects constructed between 1988 and 2001. The asphalt rubber projects included those that used dense-graded mixes (AR) or open-graded friction courses (FR) as part of the construction/resurfacing work. Table 38 provides a sample of the asphalt rubber cost data collected and used.

Costs from the third source consisted of average in-place estimates for a variety of pavement activities, such as milling, application of a chip seal coat, and application of an asphalt rubber friction course (FR). These costs are used by ADOT pavement managers in developing preliminary cost estimates for future projects.

Analysis of 1999 Construction Costs

To begin this analysis, the average unit price of the three lowest contractors' bids for each project for each pavement-related pay item were calculated. Next, the average costs were adjusted for inflation to 2003 prices using the following formula and a 2 percent inflation rate:

$$\$F = \$P * (1 + i)^{n} \qquad \text{Eq. 8}$$

where: $\$F$ = Current year (1999) cost adjusted for inflation, \$.
$\$P$ = Past year cost, \$.
i = Inflation rate, decimal (0.02)
n = Number of years between 2003 and 1999 (4 years).

Table 38. Sample data obtained from Asphalt Rubber Projects report (ADOT, 2002).

TRACS	Project Name	Route	Beginning MP	End MP	Ton Mix	First-Bid Mix, $/ton	Ton Binder	First-Bid Binder, $/ton
H453201C	Littlefield - Virgin River	015	7.94	13.12	26,770	$12.65	2,142	$230.50
H421201C	Coconino National Forest Boundary - Buffalo Range TI	040	217.85	224.70	19,228	$26.00	1,601	$230.00
H443301C	Pinta TI – McCarrel TI	040	318.80	330.60	62,698	$20.50	5,016	$210.00
H422801C	Andy Devine Avenue	040B	52.75	56.40	20,025	$24.00	1,602	$290.00
H455901C	Thompson Avenue – AT Railway	066	57.70	61.50	20,800	$23.00	1,665	$225.00
H453901C	Mendocino Drive – Walker Road	069	286.80	292.84	34,274	$20.47	2,742	$202.28
H422201C	Coyote Wash – East Boundary San Carlos	070	287.40	300.10	27,019	$18.00	2,162	$225.00
H422901C	Jct. SR 92 – Jct. Double Adobe Road	080	343.59	347.40	8,530	$29.75	683	$275.00
H455501C	Patagonia Lake Road – East Patagonia	082	12.30	20.60	21,470	$30.00	1,718	$270.00
H470501C	Lenox Park – Deadman Flat	089	218.60	230.20	8,521	$23.00	682	$250.00
H384501C	Long House Valley – Kayenta	160	372.50	389.50	38,985	$31.00	3,120	$250.00
H422601C	Jct. SR 69 – Jct. I-17	169	0.00	4.65	34,860	$15.00	2,790	$200.00
H444501C	Double Adobe – Elfrida	191	4.19	23.48	49,000	$18.00	3,920	$235.00
H456001C	Thompson Road – Sunizona	191	27.00	38.60	21,710	$22.00	1,737	$270.00
H396001C	Beaver Head Lodge – Jct. US 180	191	239.00	253.70	27,891	$29.00	2,231	$290.00

The average and standard deviation of the inflation-adjusted costs for each pay item were then calculated to give a preliminary indication of costs. These values are listed in table 39.

Average and standard deviation costs were also determined based on the quantity of an item used on a project. The statistics were calculated in this manner so that it could be determined whether the cost of an item changed based on the quantity required for the project. As expected, the average inflation-adjusted unit cost of a pay item generally decreased with increasing quantity. Some example histograms that show these trends for a couple pay items are illustrated in figures 49 and 50. Also, as expected, the variability of the data decreased as the quantity of the item increased. Therefore, consideration had to be given to the size of the project when developing best estimates for the mean and standard deviation cost of individual pay items.

Using selected minimum quantities for each pay item, small projects with higher-than usual costs were filtered out of analysis, allowing the average and standard deviation unit costs in table 39 to be recomputed. The resulting inflation-adjusted and quantity-filtered costs are provided in table 40.

Table 39. Inflation-adjusted unit costs for pay items in 1999 Construction Costs report (based on average of three lowest bid prices).

Material/ Activity Code	Pay Item No.	Pay Item Description	Unit	No.	2003 Unit Cost (inflated from 1999)	
					Average	Std. Deviation
RE	2020029	Removal of AC pavement	yd^2	38	$5.99	$4.98
	2020030	Removal of AC pavement	yd^2	20	$2.01	$1.87
	2020080	Remove bit. pvt. (milling, 0.5 in)	yd^2	5	$0.54	$0.16
	2020081	Remove bit. pvt. (milling, 1 in)	yd^2	2	$0.76	$0.00
	2020083	Remove bit. pvt. (milling, 2 in)	yd^2	12	$1.62	$1.03
	2020084	Remove bit. pvt. (milling, 2.5 in)	yd^2	7	$2.35	$1.88
	2020085	Remove bit. pvt. (milling, 3 in)	yd^2	10	$2.11	$1.03
	2020086	Remove bit. pvt. (milling, 3.5 in)	yd^2	1	$1.06	–
	2020087	Remove bit. pvt. (milling, 4 in)	yd^2	5	$2.20	$0.76
	2020088	Remove bit. pvt. (milling, 4.5 to 6 in)	yd^2	5	$1.42	$0.32
	2020089	Remove bit. pvt. (milling, 6 to 8 in)	yd^2	2	$2.72	$1.16
LS	3010001	Lime-treated subgrade	yd^2	2	$1.43	$0.33
	3010011	Hydrated lime for subgrade treat.	ton	1	$86.96	–
	3010012	Quicklime for subgrade treat.	ton	1	$105.72	–
CS	302????	Cement-treated subgrade	yd^2	0	–	–
	302????	Cement for subgrade treat.	ton	0	–	–
SM, SB	3030026	Aggregate subbase, class 6	yd^3	4	$23.84	$13.70
AB, OA	3030022	Aggregate base, class 2	yd^3	51	$35.70	$15.99
	3030023	Aggregate base, class 3	yd^3	12	$34.26	$17.05
CB	304????	Cement-treated base	ton	0	–	–
CL	305????	Lean concrete base	yd^2	0	–	–
PC, PD	4010010	PCC pavement (10 in)	yd^2	5	$31.70	$15.26
	4010012	PCC pavement (12 in)	yd^2	2	$20.88	$0.06
	4010013	PCC pavement (13 in)	yd^2	2	$51.60	$11.23
	4010015	PCC pavement (15 in)	yd^2	2	$63.86	$2.55
	4010016	PCC pavement (16 in)	yd^2	3	$74.74	$59.24
	4010301	Load transfer dowels	each	1	$19.12	–
PR	4010039	PCC pavement (reinforced, 9 in)	yd^2	1	$36.08	–
	4020060	Seal cracks in PCC pavement	ft	2	$2.43	$0.65
	4020061	Seal edge of PCC pavement	ft	2	$0.95	$0.09
GR	4020048	Grind existing PCC pavement	yd^2	2	$37.60	$36.68
GV	4020080	Groove PCC pavement	yd^2	1	$2.62	–
??	4020072	Repair PCC spalled areas	ft^2	3	$46.05	$49.22
??	4020090	PCC pavement slab repair	yd^2	2	$336.64	$182.16
FL	4040125	Fog coat	ton	37	$380.84	$273.23
	4040126	Fog coat (ERA-25)	ton	8	$333.24	$218.62
	4040163	Blotter material	ton	53	$48.43	$85.61
SC	4040074	Emulsified asphalt (CRS-2)	ton	12	$297.34	$347.38
	4040162	Cover material	yd^3	11	$78.38	$68.94
Prime Coat	4040101	Prime coat	ton	5	$293.15	$96.86
Tack Coat	4040111	Bituminous tack coat	ton	64	$172.37	$31.64
	4040116	Apply bituminous tack coat	hour	70	$121.69	$31.28

Table 39. Inflation-adjusted unit costs for pay items in 1999 Construction Costs report (based on average of three lowest bid prices) (continued).

Material/ Activity Code	**Pay Item No.**	**Pay Item Description**	**Unit**	**No.**	**2003 Unit Cost (inflated from 1999)**	
					Average	**Std. Deviation**
AC, LC, BB, OB	4040262	Asphalt binder (PG 64-16)	ton	14	$151.20	$8.95
	4040264	Asphalt binder (PG 64-22)	ton	10	$163.88	$12.70
	4040270	Asphalt binder (PG 70-10)	ton	11	$149.08	$8.43
	4040272	Asphalt binder (PG 70-16)	ton	4	$150.32	$7.76
	4040280	Asphalt binder (PG 76-10)	ton	8	$148.20	$8.03
	4040282	Asphalt binder (PG 76-16)	ton	4	$160.81	$31.90
	4060008	AC (0.75-in mix)	ton	3	$21.58	$2.53
	4060015	AC (0.5-in mix)	ton	2	$22.86	$1.96
	4060021	AC (base mix)	ton	1	$19.66	–
	4060024	Mineral admixture (for 0.5-in mix)	ton	2	$97.42	$0.00
	4060026	Mineral admixture (for 0.75-in mix)	ton	4	$97.42	$0.00
	4060027	Mineral admixture	ton	3	$97.42	$0.00
FC	4070001	AC friction course (FC) mix	ton	8	$34.99	$8.97
	4070006	AC friction course (FC) mix	ton	1	$33.19	–
	4070021	Mineral admixture (for FC mix)	ton	7	$97.42	$0.00
RC	4080011	cold recycling (bit. surface)	yd^2	1	$1.32	–
AR	4130040	Asphalt rubber AC mix (AR)	ton	14	$26.33	$5.65
	4130042	Asphalt rubber binder (for AR mix)	ton	14	$265.98	$27.26
	4130044	Mineral admixture (for AR mix)	ton	13	$97.42	$0.00
FR	4140040	Asphalt rubber friction course (FR) mix	ton	44	$32.71	$10.78
	4140042	Asphalt rubber binder (for FR mix)	ton	44	$300.85	$67.36
	4140044	Mineral admixture (for FR mix)	ton	42	$97.42	$0.00
AC (end product)	4160002	AC (0.75-in mix) (end product)	ton	16	$27.18	$7.46
	4160008	AC (base mix) (end product)	ton	3	$18.59	$0.52
	4160009	AC (end product)	ton	4	$21.32	$5.81
	4160031	Mineral admixture	ton	38	$97.42	$0.00

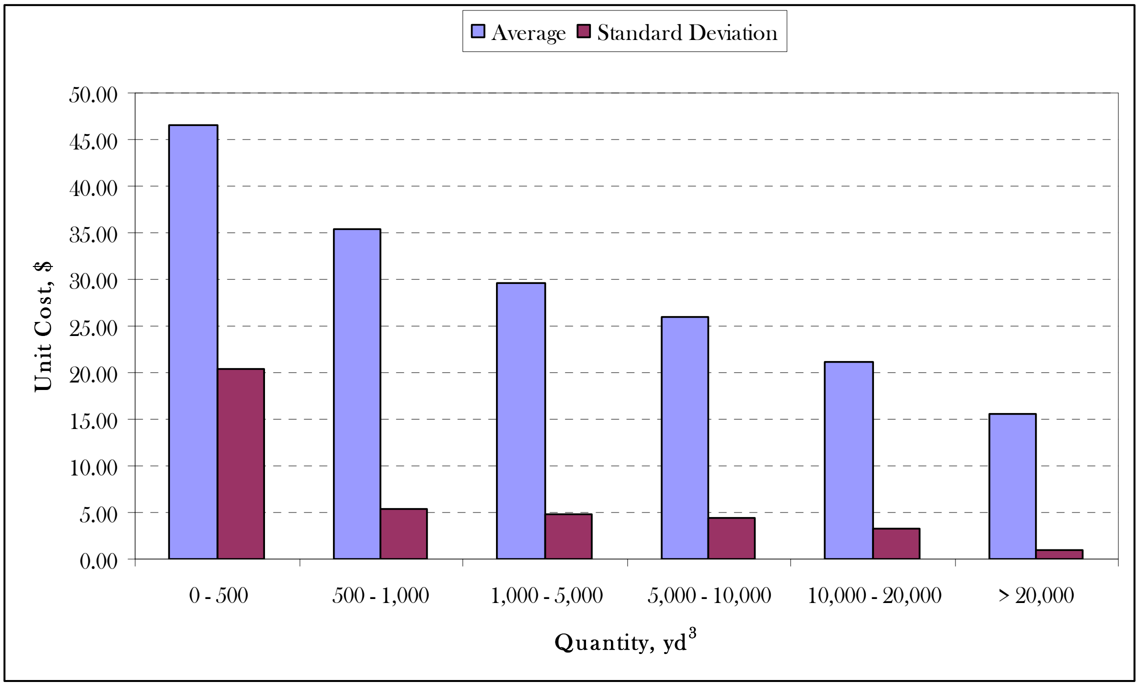


Figure 49. Unit cost histogram for pay item 3030022, class 2 aggregate base (AB) (based on 1999 Construction Costs report).

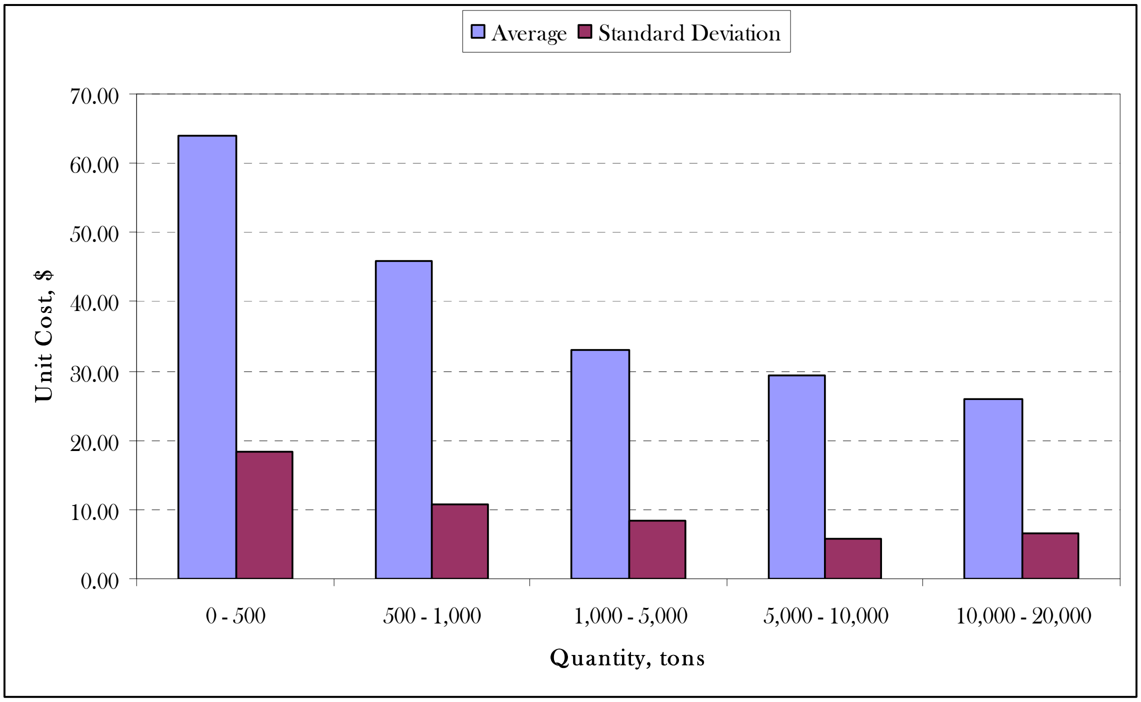


Figure 50. Unit cost histogram for pay item 4140040, asphalt rubber used in asphalt rubber friction course (FR) (based on data from 1999 Construction Costs report).

Table 40. Inflation-adjusted and quantity-filtered unit costs for pay items in 1999 Construction Costs report (based on average of three lowest bid prices).

Material/ Activity Code	Pay Item No.	Pay Item Description	Unit	Min. Quantity	No.	2003 Unit Cost (inflated from 1999 and filtered by quantity)	
						Average	Std. Deviation
RE	2020029	Removal of AC pavement	yd^2	10,000	6	$1.23	$0.33
	2020030	Removal of AC pavement	yd^2	10,000	15	$1.23	$0.66
	2020080	Remove bit. pvt. (milling, 0.5 in)	yd^2	10,000	5	$0.54	$0.16
	2020081	Remove bit. pvt. (milling, 1 in)	yd^2	10,000	1	$0.76	–
	2020083	Remove bit. pvt. (milling, 2 in)	yd^2	10,000	10	$1.23	$0.36
	2020084	Remove bit. pvt. (milling, 2.5 in)	yd^2	10,000	3	$1.25	$0.31
	2020085	Remove bit. pvt. (milling, 3 in)	yd^2	10,000	4	$1.30	$0.54
	2020086	Remove bit. pvt. (milling, 3.5 in)	yd^2	10,000	1	$1.06	–
	2020087	Remove bit. pvt. (milling, 4 in)	yd^2	10,000	2	$1.50	$0.18
	2020088	Remove bit. pvt. (milling, 4.5 to 6 in)	yd^2	10,000	5	$1.42	$0.32
	2020089	Remove bit. pvt. (milling, 6 to 8 in)	yd^2	10,000	1	$1.89	–
LS	3010001	Lime-treated subgrade	yd^2	10,000	2	$1.43	$0.33
	3010011	Hydrated lime for subgrade treat.	ton	250	1	$86.96	–
	3010012	Quicklime for subgrade treat.	ton	250	1	$105.72	–
CS	302????	Cement-treated subgrade	yd^2		0	–	–
	302????	Cement for subgrade treat.	ton		0	–	–
SM, SB	3030026	Aggregate subbase, class 6	yd^3	2,500	2	$17.32	$0.56
AB, OA	3030022	Aggregate base, class 2	yd^3	2,500	16	$23.64	$5.26
	3030023	Aggregate base, class 3	yd^3	2,500	6	$23.77	$5.01
CB	304????	Cement treated base	ton		0	–	–
CL	305????	Lean concrete base	yd^2		0	–	–
PC, PD	4010010	PCC pavement (10 in)	yd^2	10,000	3	$20.60	$0.70
	4010012	PCC pavement (12 in)	yd^2	10,000	2	$20.88	$0.06
	4010013	PCC pavement (13 in)	yd^2	10,000	0	–	–
	4010016	PCC pavement (16 in)	yd^2	10,000	1	$26.12	–
	4010301	Load transfer dowels	each	5,000	0	–	–
PR	4010039	PCC pavement (reinforced, 9 in)	yd^2	10,000	0	–	–
	4020060	Seal cracks in PCC pavement	ft	5,000	2	$2.43	$0.65
	4020061	Seal edge of PCC pavement	ft	10,000	2	$0.95	$0.09
GR	4020048	Grind existing PCC pavement	yd^2	10,000	1	$10.25	–
GV	4020080	Groove PCC pavement	yd^2	10,000	1	$2.62	–
	4020072	Repair PCC spalled areas	ft^2	1,000	1	$15.51	–
	4020090	PCC pavement slab repair	yd^2	1,000	1	$207.83	–
FL	4040125	Fog coat	ton	10	23	$209.28	$32.04
	4040126	Fog coat (ERA-25)	ton	10	5	$239.64	$26.22
	4040163	Blotter material	ton	50	31	$19.43	$7.77
SC	4040074	Emulsified asphalt (CRS-2)	ton	50	9	$180.37	$26.51
	4040162	Cover material	yd^3	500	6	$40.68	$7.58
Prime Coat	4040101	Prime coat	ton	50	3	$222.79	$14.09
Tack Coat	4040111	Bituminous tack coat	ton	50	39	$163.44	$20.38
	4040116	Apply bituminous tack coat	hour	50	53	$114.25	$24.50

Table 40. Inflation-adjusted and quantity-filtered unit costs for pay items in 1999 Construction Costs report (based on average of three lowest bid prices) (continued).

Material/ Activity Code	Pay Item No.	Pay Item Description	Unit	Min. Quantity	No.	2003 Unit Cost (inflated from 1999 and filtered by quantity)	
						Average	Std. Deviation
AC, LC, BB, OB	4040262	Asphalt binder (PG 64-16)	ton	500	7	$153.73	$9.61
	4040264	Asphalt binder (PG 64-22)	ton	500	9	$162.85	$13.02
	4040270	Asphalt binder (PG 70-10)	ton	500	10	$147.72	$7.50
	4040272	Asphalt binder (PG 70-16)	ton	500	4	$150.32	$7.76
	4040280	Asphalt binder (PG 76-10)	ton	500	7	$148.76	$8.51
	4040282	Asphalt binder (PG 76-16)	ton	500	2	$172.88	$47.79
	4060008	AC (0.75-in mix)	ton	1,000	3	$21.58	$2.53
	4060015	AC (0.5-in mix)	ton	1,000	2	$22.86	$1.96
	4060021	AC (base mix)	ton	2,500	1	$19.66	–
	4060024	Mineral admixture (for 0.5-in mix)	ton	25	1	$97.42	–
	4060026	Mineral admixture (for 0.75-in mix)	ton	25	4	$97.42	$0.00
	4060027	Mineral admixture	ton	100	3	$97.42	$0.00
FC	4070001	AC friction course (FC) mix	ton	2,500	3	$28.13	$3.65
	4070021	Mineral admixture (for FC mix)	ton	25	5	$97.42	$0.00
RC	4080011	cold recycling (bit. surface)	yd^2	10,000	1	$1.32	–
AR	4130040	Asphalt rubber AC mix (AR)	ton	10,000	12	$25.65	$5.21
	4130042	Asphalt rubber binder (for AR mix)	ton	1,000	12	$260.48	$20.94
	4130044	Mineral admixture (for AR mix)	ton	100	11	$97.42	$0.00
FR	4140040	Asphalt rubber friction course (FR) mix	ton	2,500	33	$29.44	$7.17
	4140042	Asphalt rubber binder (for FR mix)	ton	250	30	$274.99	$25.83
	4140044	Mineral admixture (for FR mix)	ton	25	33	$97.42	$0.00
AC (end product)	4160002	AC (0.75-in mix) (end product)	ton	1,000	16	$27.18	$7.46
	4160008	AC (base mix) (end product)	ton	10,000	3	$18.59	$0.52
	4160009	AC (end product)	ton	10,000	4	$21.32	$5.81
	4160031	Mineral admixture	ton	100	35	$97.42	$0.00

Analysis of Costs from Asphalt Rubber Projects Report

As discussed previously, the costs associated with only four pay items were included in the Asphalt Rubber Projects report. These included the first-bid mix costs for asphalt rubber asphalt concrete (AR) and asphalt rubber asphalt concrete friction course (FR), as well as the binder costs (asphalt and asphalt rubber) for these two mixes.

As with the 1999 construction costs, the costs from this source were inflated to 2003 prices using equation 8 at a 2 percent inflation rate. Similarly, the costs were subdivided by quantity to determine the effect of quantity on cost. Figures 51 through 54 are the resulting unit cost histograms for each pay item. They clearly show increased average costs and cost variations for small projects.

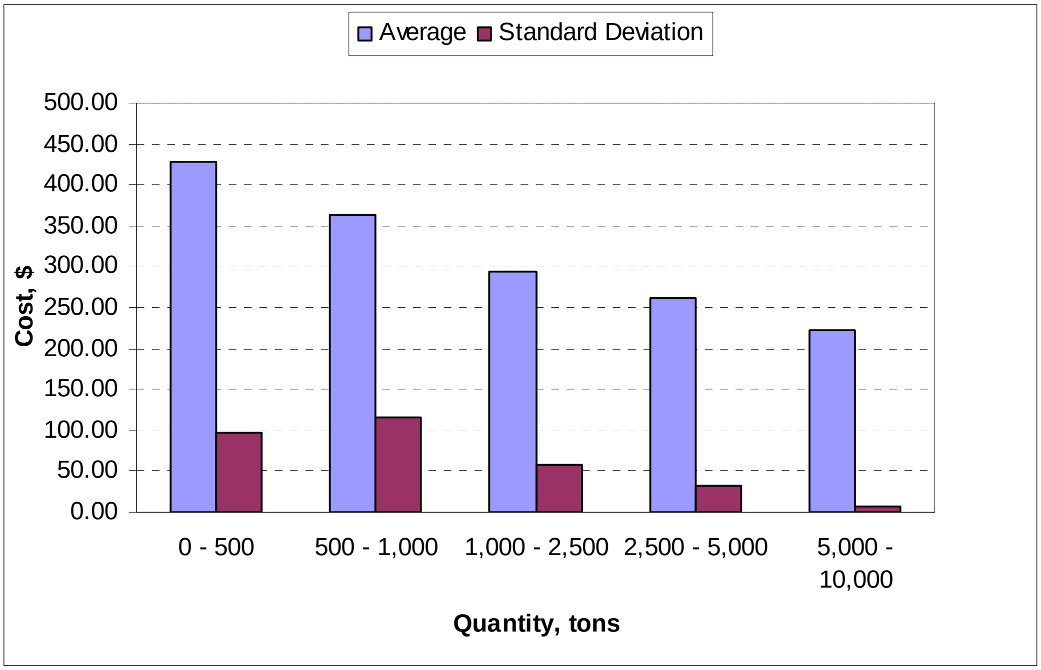


Figure 51. Unit cost histogram for asphalt rubber (AR) binder pay item (based on data from Asphalt Rubber Projects report).

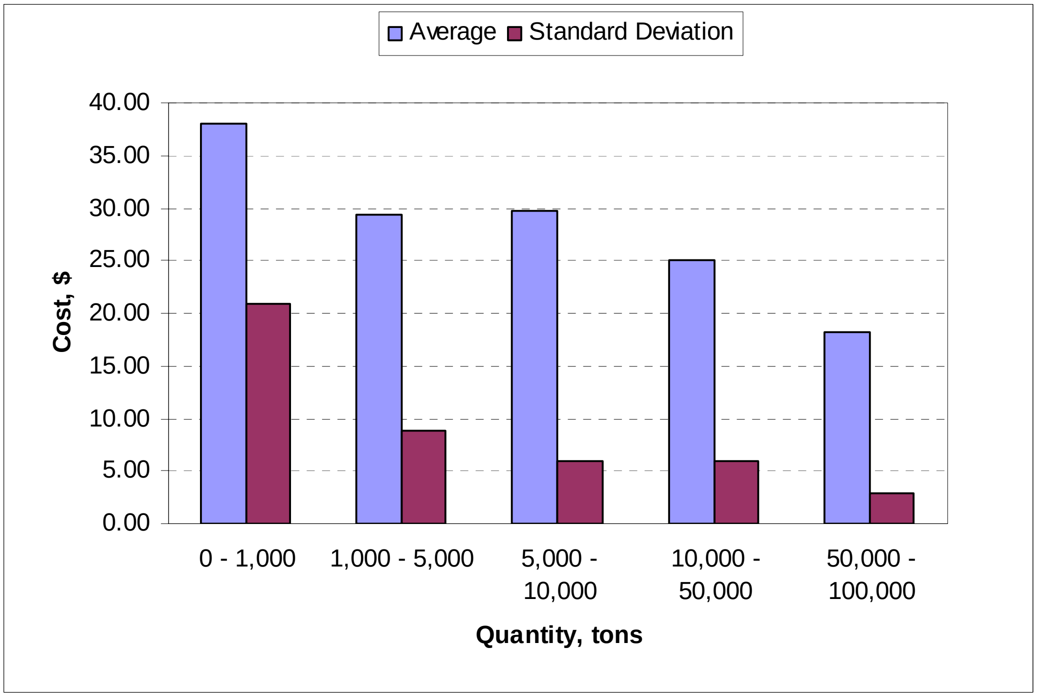


Figure 52. Unit cost histogram for asphalt rubber (AR) mixture pay item (based on data from Asphalt Rubber Projects report).

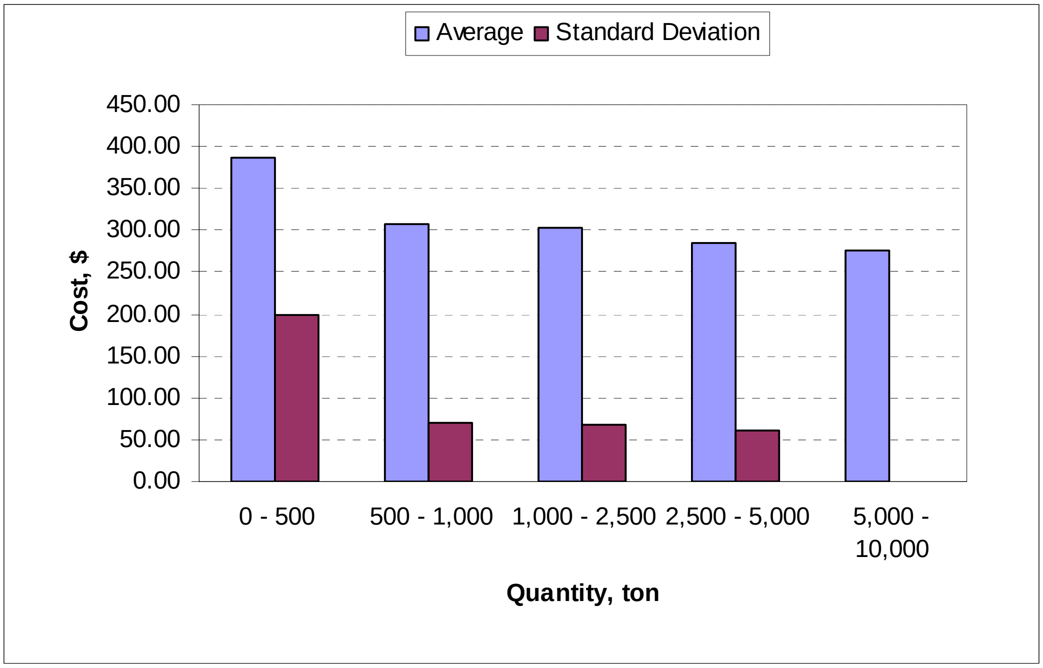


Figure 53. Unit cost histogram for asphalt rubber friction course (FR) binder pay item (based on data from Asphalt Rubber Projects report).

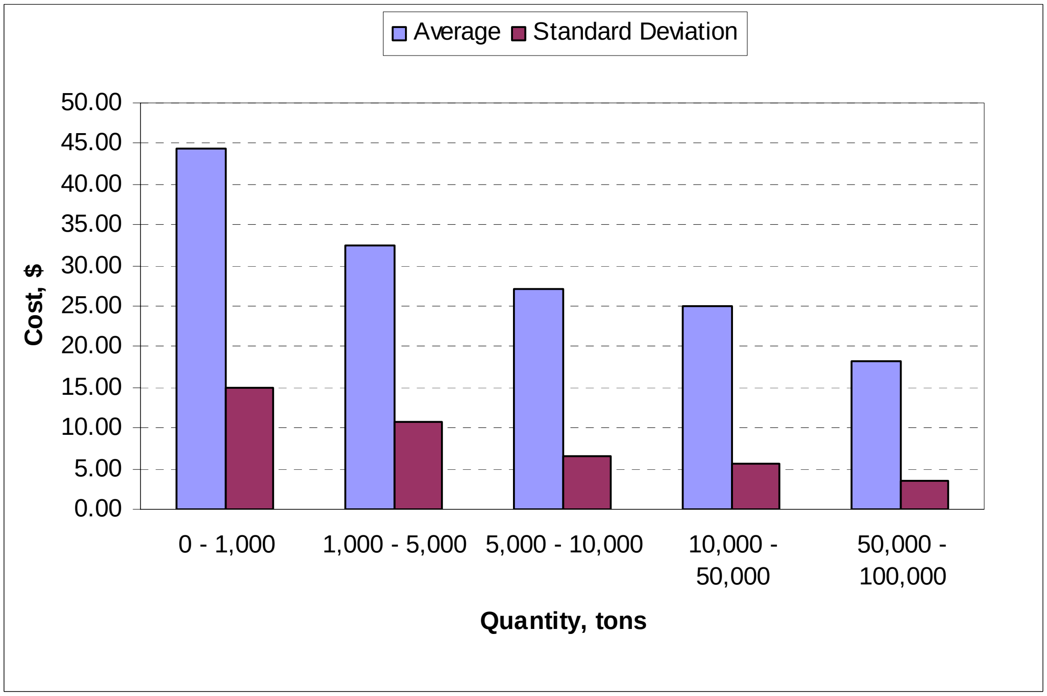


Figure 54. Unit cost histogram for asphalt rubber friction course (FR) mixture pay item (based on data from Asphalt Rubber Projects report).

Using the same minimum quantities chosen to filter small projects in the analysis of 1999 construction costs, the average and standard deviation unit costs for AR and FR were computed. The resulting inflation-adjusted and quantity-filtered costs are provided in table 41.

Analysis of Pavement Management Cost Estimates

Table 42 shows the inflation-adjusted, in-place unit costs derived from the ADOT Pavement Management Cost Estimate. The costs represent base costs (i.e., engineering, traffic control, and other add-on costs not included).

Summary of Unit Costs

Table 43 summarizes the pay item unit costs derived from the three data sources considered in this study. As can be seen, there was generally good agreement among the three sources. For only a few pay items were there significant disparities in the mean unit costs. A major reason for the disparities was the low number of cost values (i.e., lack of projects and/or sizeable projects) available for some pay items.

For the LCCAs conducted in chapter 7 of this report, pay item unit costs were assigned primarily using the inflation-adjusted and quantity-filtered costs from the 1999 Construction Costs report. If these costs were based on limited data (less than 5 data values) or were significantly different from the costs derived from the other data sources, then a best estimate was developed using the available information and engineering judgment. For pay items with no data available from any of the three sources, best estimates were developed solely using engineering judgment. A summary of the unit costs used in conducting the LCCAs is provided in chapter 7.

Table 41. Inflation-adjusted and quantity-filtered unit costs for pay items in Asphalt Rubber Projects report (based on first-bid prices).

Activity Pay Item Designation	Activity Pay Item Description	No.	Average	Standard Deviation
AR	Asphalt rubber (AR) mix	73	$24.61/ton	$5.95/ton
	Asphalt rubber binder (for AR)	66	$287.92/ton	$62.30/ton
FR	Asphalt rubber friction course	226	$27.78/ton	$8.27/ton
	Asphalt rubber binder (for FR)	220	$316.45/ton	$74.27/ton

Table 42. Inflation-adjusted, in-place unit costs of various pay items contained in ADOT Pavement Management Cost Estimate.

Activity Pay Item Designation	Activity Pay Item Description	2003 In-Place Unit Cost (inflated from 1999)		
		Overall	Interstate	Non-Interstate
SC	Chip seal coat	0.97/yd^2	–	0.97/yd^2
FC	AC friction course (0.5 in)	1.52/yd^2	1.19/yd^2	1.19/yd^2
RM	Stress-absorbing membrane interlayer (SAMI)	1.95/yd^2	–	–
AR	Asphalt rubber AC	2.71/yd^2	–	–
	Asphalt rubber AC (2 in)	1.10/yd^2	5.95/yd^2	5.95/yd^2
FR	Asphalt rubber AC friction course (0.625 in)	2.38/yd^2	1.95/yd^2	1.95/yd^2
RC	Cold-recycle AC	0.87/yd^2	–	–
	AC-recycled	1.41/yd^2	–	–
AC, BB	AC (0.75-in mix)	1.73/yd^2	–	–
	AC (base mix)	1.41/yd^2	–	–
RE	Milling (0.75 in)	0.81/yd^2	–	–
	Milling (1 in)	1.08/yd^2	–	–
	Milling (2 in)	1.24/yd^2	–	–
	Milling (3 in)	1.35/yd^2	–	–
	Milling (4 in)	1.46/yd^2	–	–
	Milling (5 in)	1.57/yd^2	–	–
GV	Grooving PCC	3.25/yd^2	–	–
GR	Grinding PCC	6.49/yd^2	–	–

Table 43. Comparison of inflation-adjusted and quantity-filtered unit costs derived from various cost data sources.

Activity Pay Item Designation	Activity Pay Item Description	Construction Costs Report				Asphalt Rubber Report				Pavement Management Cost Estimates
		No.	Mean	Std. Dev.	Mean In-Place	No.	Mean	Std. Dev.	Mean In-Place	
FL	Fog Coat	28	$\$214.70/\text{ton}$	32.84/ton	$\$0.32/\text{yd}^2$					
	Blotter	31	$\$19.43/\text{ton}$	$\$7.77/\text{ton}$						
GV	Grooving PCC	1	$\$2.62/\text{yd}^2$	–	$\$2.62/\text{yd}^2$					$\$3.25/\text{yd}^2$
GV	Grinding PCC	1	$\$10.25/\text{yd}^2$	–	$\$10.25/\text{yd}^2$					$\$6.49/\text{yd}^2$
	PCC crack sealing [a]	2	$\$2.43/\text{ft}$	$\$0.65/\text{ft}$	$\$2.43/\text{ft}$					
	PCC joint sealing (Long)	2	$\$0.95/\text{ft}$	$\$0.09/\text{ft}$	$\$0.95/\text{ft}$					
SC	Emulsified asphalt (CRS-2)	9	$\$180.37/\text{ton}$	$\$26.51/\text{ton}$	$\$0.49/\text{yd}^2$					$\$0.97/\text{yd}^2$
	Cover material	6	$\$40.68/\text{yd}^3$	$\$7.58/\text{yd}^3$						
	Repair PCC spalled areas	1	$\$15.51/\text{ft}^2$	–	$\$15.51/\text{ft}^2$					
	PCC pavement slab repair	1	$\$207.83/\text{yd}^2$	–	$\$207.83/\text{yd}^2$					
	Prime Coat	3	$\$222.79/\text{ton}$	$\$14.09/\text{ton}$	$\$0.09/\text{yd}^2$					
	Tack Coat	39	$\$163.44/\text{ton}$	$\$20.38/\text{ton}$	$\$0.10/\text{yd}^2$					
	Apply Bituminous Tack Coat	53	$\$114.25/\text{hr}$	$\$24.50/\text{hr}$						
FC	AC friction course (0.5 in)	3	$\$28.13/\text{ton}$	$\$3.65/\text{ton}$	$2.15/\text{yd}^2$					$\$1.52/\text{yd}^2$
	Asphalt binder (various grades)	39	$\$154.03/\text{ton}$	$\$13.93/\text{ton}$						
	Mineral admixture	5	$\$97.42/\text{ton}$	$\$0.00/\text{ton}$						
RM	Stress-absorbing membrane interlayer (SAMI)									$\$1.95/\text{yd}^2$
AR	Asphalt rubber (AR) mix	12	$\$25.65/\text{ton}$	$\$5.21/\text{ton}$	$2.48/\text{yd}^2$	73	$\$24.61/\text{ton}$	$\$5.95/\text{ton}$	$\$2.50/\text{yd}^2$	$\$2.71/\text{yd}^2$
	Asphalt rubber binder (for AR)	12	$\$260.48/\text{ton}$	$\$20.94/\text{ton}$		66	$\$287.92/\text{ton}$	$\$62.30/\text{ton}$		
	Mineral admixture	11	$\$97.42/\text{ton}$	$\$0.00/\text{ton}$						
FR	Asphalt rubber friction course (0.625 in)	33	$\$29.44/\text{ton}$	$\$7.17/\text{ton}$	$\$2.61/\text{yd}^2$	226	$\$27.78/\text{ton}$	$\$8.27/\text{ton}$	$\$2.70/\text{yd}^2$	$\$2.38/\text{yd}^2$
	Asphalt rubber binder (for FR)	30	$\$274.99/\text{ton}$	$\$25.83/\text{ton}$		220	$\$316.45/\text{ton}$	$\$74.27/\text{ton}$		
	Mineral admixture	33	$\$97.42/\text{ton}$	$\$0.00/\text{ton}$						
RC	Cold-recycle AC	1	$\$1.32/\text{yd}^2$	–	$\$1.32/\text{yd}^2$					$\$0.87/\text{yd}^2$
	AC-recycled									$\$1.41/\text{yd}^2$
AC	AC (0.5- and 0.75-in mixes)	5	$\$22.09/\text{ton}$	$\$2.16/\text{ton}$	$\$1.66/\text{yd}^2$					$\$1.73/\text{yd}^2$
	Asphalt binder (various grades)	39	$\$154.03/\text{ton}$	$\$13.93/\text{ton}$						
	Mineral admixture (for 0.5- and 0.75-in mixes)	5	$\$97.42/\text{ton}$	$\$0.00/\text{ton}$						

[a] Cost of this activity expected to be similar to cost of transverse PCC joint resealing.

Table 43. Comparison of inflation-adjusted and quantity-filtered unit costs derived from various cost data sources (continued).

Activity Pay Item Designation	Activity Pay Item Description	Construction Costs Report				Asphalt Rubber Report				Pavement Management Cost Estimates
		No.	Mean	Std. Dev.	Mean In-Place	No.	Mean	Std. Dev.	Mean In-Place	
BB	AC (base mix)	1	\$19.66/ton	–	\$1.48/yd^2					\$1.41/yd^2
	Asphalt binder (various grades)	39	\$154.03/ton	\$13.93/ton						
	Mineral admixture	3	\$97.42/ton	\$0.00/ton						
PC	PCC pavement (10 in)	3	\$20.60//yd^2	\$0.70/yd^2	\$20.60/yd^2					
	PCC pavement (12 in)	2	\$20.88/yd^2	\$0.06/yd^2	\$20.88/yd^2					
	PCC pavement (15 in)	1	\$62.06/yd^2	–	\$62.06/yd^2					
RE	AC pavement removal	21	\$1.23/yd^2	\$0.48/yd^2	\$1.23/yd^2					
	Milling (0.5 in)	5	\$0.54/yd^2	\$0.16/yd^2	\$0.54/yd^2					
	Milling (0.75 in)									\$0.81/yd^2
	Milling (1 in)	1	\$0.76/yd^2	–	\$0.76/yd^2					\$1.08/yd^2
	Milling (2 in)	10	\$1.23/yd^2	\$0.36/yd^2	\$1.23/yd^2					\$1.24/yd^2
	Milling (2.5 in)	3	\$1.25/yd^2	\$0.31/yd^2	\$1.25/yd^2					
	Milling (3 in)	4	\$1.30/yd^2	\$0.54/yd^2	\$1.30/yd^2					\$1.35/yd^2
	Milling (3.5 in)	1	\$1.06/yd^2	–	\$1.06/yd^2					
	Milling (4 in)	2	\$1.50/yd^2	\$0.18/yd^2	\$1.50/yd^2					\$1.46/yd^2
	Milling (4.5 to 6 in)	5	\$1.42/yd^2	\$0.32/yd^2	\$1.42/yd^2					\$1.57/yd^2

CHAPTER 5. USER COST BEST PRACTICES

INTRODUCTION

A review of current practices was made by the project team using information obtained through the Neutral Third Party (NTP) review of Ohio's pavement type selection process and through collected literature on the topic of user costs (ERES, 2003). The review indicated that the user cost components that are predominately evaluated are the user delay costs resulting from traffic slowdowns and disruptions that occur during construction and maintenance operations. A secondary cost that is evaluated is the increased vehicle operating cost (VOC) that results from decreased smoothness.

USER DELAY COSTS ASSOCIATED WITH WORK ZONES

The process favored for evaluation of user delay costs is one presented by the Federal Highway Administration (FHWA) in their Interim Technical Bulletin on Life Cycle Cost Analysis in Pavement Design (Walls and Smith, 1998). This process was thoroughly evaluated in NCHRP Project 1-37A and has been adopted for use in the 2002 Pavement Design Guide. Two published reports reviewing the FHWA process were examined by the team. These reports, prepared for the Kentucky Transportation Cabinet (KTC) (Rister and Graves, 2002) and the Louisiana Department of Transportation and Development (DOTD) (Aghazadeh et al., 2003), provided favorable reviews of the FHWA procedure.

The only other analysis approach that is currently being considered for use by State transportation agencies is the QuickZone User Delay Software developed by Mitretek for FHWA. QuickZone is a Microsoft® Excel spreadsheet application for estimating traffic delays that are the result of construction or maintenance operations. The QuickZone software is available from McTrans, which has reported the following capabilities of QuickZone:

- Quantifies corridor delay resulting from capacity decreases in work zones.
- Identifies delay impacts of alternative construction phasing plans.
- Supports trade-off analysis between construction costs and delay costs.
- Considers alternate phasing schedules, such as location along mainline, time-of-day (peak vs. off-peak), and season (summer vs. winter).
- Assesses impacts of delay mitigation strategies that include alternate route signal re-timing, traveler information (variable message signing [VMS], highway advisory radio [HAR] and pre-trip information), lane widening, ramp metering, and media campaign.
- Supports work completion incentives.

The University of Maryland has developed a version of QuickZone for the Maryland DOT. This version was developed to analyze both urban and rural roadways.

The Kentucky Transportation Center evaluated QuickZone and arrived at the following conclusions:

> “The QuickZone program ideally lends itself to urban work zone planning. It has the capability of quantifying corridor delay resulting from capacity decreases in work zones; identifying delay impacts of alternative project phasing plans; and supports tradeoff analyses between construction costs and delay costs! However, this program is more sophisticated than the other two programs that will be discussed below and will require the user to enter a great deal more of information concerning a particular project.
>
> To use the QuickZone program the user must first create a network of traffic facilities. Each network is built from a system of nodes that are linked to each other by user defined links. Nodes are the simplest element of a QuickZone network. Nodes generally represent a roadway intersection and determine the beginning and end of a road or link. Links are quoted in the QuickZone user's manual as being the heart of the network. Each link in a network is defined as either a mainline, detour, or a work zone. In addition, links include most of the attributes that are used within the QuickZone algorithm such as: number of lanes, free flow speed, capacity, jam density, length, direction, type and position. The QuickZone user's manual advises that approximately three hours may be needed to input information into the program to create a network. This does not account for the time needed to research/collect necessary traffic data.
>
> Once a network has been finalized and input into the program the next step is to run a simulation on the network to calculate backups on the mainline, alternate routes, and detours for different phases/scenarios of the construction process. This backup/queue estimating process is mathematically calculated in the program by comparing the expected travel demand against proposed capacity by facility on an hour-by-hour basis for the life of the project. Ultimately these calculated backups are used to calculate total user delay costs that in turn can be used in a life cycle cost analysis.
>
> Although the QuickZone program can be used to calculate many different attributes about work zone delays in a particular network, it should be mentioned that there may be several drawbacks to using this program to

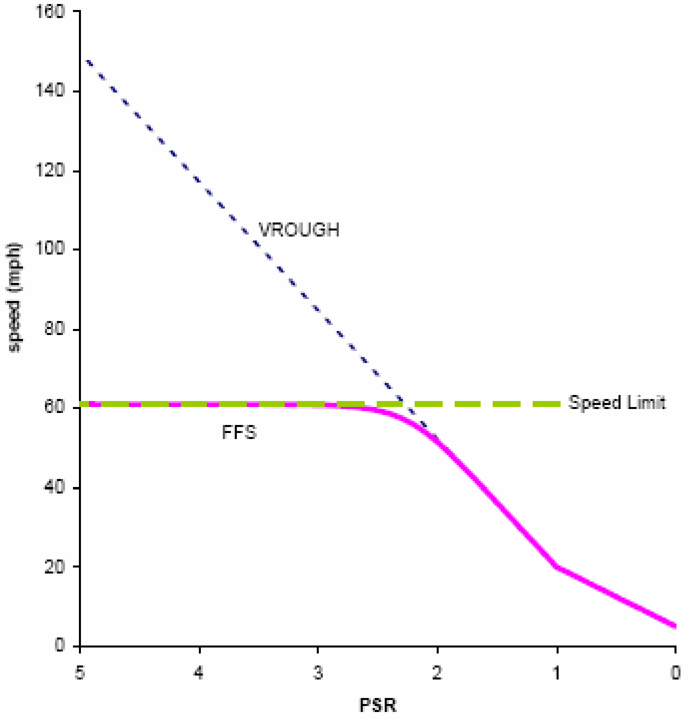
> determine road user costs. First, QuickZone does not calculate a reduced work zone capacity value. This is a much needed value that will be used to calculate the lengths or volumes of queued traffic. QuickZone recommends that the user refer to the 1994 Highway Capacity Manual (HCM) for defining work zone capacity reductions if the user is unaware of an appropriate value. Second, data entered to estimate user delay costs (i.e.: value of time) are based on a single vehicle per hour cost and a user defined inflation rate. QuickZone offers no distinction between user delay costs for that of passenger cars and trucks, and no directive as to defining an applicable inflation rate.
>
> Based on both the depth of traffic information that must be input to create a network, and that the user must have prior knowledge of the work zone capacity, it would appear that the QuickZone program does not adequately meet the objectives of this study. It also appears that this program may insufficiently address road user costs since the user is advised to only input a delay cost per vehicle hour and an inflation rate. In addition, the QuickZone program may not be as user friendly or as simplistic as the other two reviewed programs. However, if the overall impact of traffic delay was to be defined in an urban area, the QuickZone program is the only program reviewed in this study that addresses traffic impacts on multiple facilities to any great detail. It should also be mentioned that the QuickZone (version 0.99) reviewed in this study was a fourth generation beta testing version. A modified public version number (1.0) is to be released in early 2002."

Recommendation for User Delay

Since many of the pavements being investigated in this study are rural highways, it is believed the FHWA procedure will provide an adequate level of analysis. However, in cases where urban freeways or areas with detours or complete road closures are being evaluated, use of the QuickZone program will be considered by the project team.

VEHICLE OPERATING COSTS ASSOCIATED WITH PAVEMENT SMOOTHNESS

In its 1998 Technical Bulletin, the FHWA concluded that differences in vehicle operating costs are negligible for the range of smoothness generally encountered on high-volume highways in the U.S. This conclusion, based on work done in New Zealand, is generally supported by the FHWA (2002) Highway Economics Requirement System (HERS) model, which looks at the effect of road smoothness on speed, as shown in figure 55. This figure indicates that speed limit generally governs truck speed for pavements with a Present Serviceability Rating (PSR) above 2.5.



source: constructed from equations in FHWA (2002).

Figure 55. Impact of pavement smoothness on vehicle speed.

Minnesota also looked at the issue of the effect of pavement smoothness on vehicle operating costs (Barnes and Langworthy, 2003). Minnesota looked at current and past work in this area and general concluded that pavement smoothness has a minimal effect on well maintained pavements. Based on their review of the literature they developed adjustment factors which are multipliers to increase vehicle operating costs for pavements with a PSR of less than 3.0. These multipliers are shown in table 44.

Recommendation for Vehicle Operating Costs Associated with Pavement Smoothness

Regarding VOCs resulting from decreased pavement smoothness, the project team recommends the use of cost adjustment factors, such as those used by Minnesota, that are a function of serviceability and/or smoothness. These factors support FHWA conclusions that VOC differences for pavements that are fairly well maintained, such as those on interstate facilities, are negligible. Whereas, for lower maintained pavements, VOC differences become significant and must be properly addressed in LCCA.

Table 44. Effect of pavement serviceability/smoothness on vehicle operating costs.

Present Serviceability Rating (PSR)	International Roughness Index (IRI), in/mi (m/km)	VOC Adjustment Multiplier
2.0 and worse	170 (2.7)	1.25
2.5	140 (2.2)	1.15
3.0	105 (1.7)	1.05
3.5 and better	80 (1.2)	1.0

CHAPTER 6. DEVELOPMENT OF LIFE-CYCLE MODELS

INTRODUCTION

Life-cycle models reflect the types and sequence of M&R activities that can be expected to occur for a particular original pavement structure over the chosen analysis period. To evaluate the cost-benefit of continuous pavement preservation design strategies as compared to a reconstruction approach, a variety of scenarios were identified for which the life-cycle costs of the two approaches could be calculated and then compared.

Based on the revised performance analysis matrix presented in chapter 3 (table 17), various ADOT Districts were chosen to represent each of the 15 analysis cells, as defined by combinations of initial pavement type (CAC, DSAC, JPC, JPCD, and CRC), facility type (Interstate and Non-Interstate), and climatic region ($RF \leq 1.5$, $1.5 < RF \leq 3.0$, and $RF > 3.0$). Each of the 8 Districts—Globe, Holbrook, Kingman, Phoenix, Prescott, Safford, Tucson, and Yuma—is represented at least once and selections were based largely on the number of 1.0-mi highway sections in each District that fit the criteria of the analysis cell. For instance, in the case of DSAC interstate pavement built in the hot-dry climate ($RF \leq 1.5$), the Yuma District was chosen as it had 59 sections of this type, compared to 22 in Flagstaff and 12 in Kingman.

Table 45 shows the Districts selected for each analysis cell, along with the key highways that are representative of the cell. It also lists the typical cross-sections of the initial pavement structures on the key highways. In conducting an LCCA for each analysis cell, an initial pavement structure was defined according to the material type and thickness parameters provided in this table.

For each analysis cell, a continuous pavement preservation life-cycle model was established that largely represents the M&R strategies used by the selected Districts. A starting point for establishing the types and sequence of M&R treatments was the various treatments listed in table 46. These treatments are a reflection of what each District has done in the past in terms of upkeep for their key highways. Information from this table, combined with the pavement performance findings (both initial pavement service life and rehabilitation performance life) given in chapter 3, were used to develop specific, continuous preservation life-cycle models for each analysis cell.

Corresponding to each continuous preservation life-cycle model, three different reconstruction life-cycle models were developed. These reconstruction models included the same initial pavement structure, but differed in terms of the number of rehabilitation treatments applied before the reconstruction event. In addition, they each

Table 45. Typical initial pavement structures corresponding to 15 revised analysis cells.

Pavement Type	**Facility Type**	**Climatic Zone**		
		Hot-Dry (RF ≤ 1.5)	**Moderate (1.5 < RF ≤ 3.0)**	**Cool-Wet (RF > 3.0)**
CAC	Interstate	Yuma District (I-8, I-10) • 4.8″ to 6.5″ AC+FC • 4″ AB • 5″ to 20″ SM (9″ to 12″ most typical)	Safford District (I-10) • 4″ to 8.8″ AC+FC (4″ to 4.5″ common for ‘60s design, 8.8″ used on a few ‘70s sections) • 6″ AB or 4″ BB (6″ AB most common) • 12″ to 21″ SM (14″ to 15″ most typical)	
	Non-Interstate	Tucson District (SR 287, SR 347) • 4.5″ AC+FC (SR 347) or 4.3″ AC+SC (SR 287) • 8″ to 10″ AB	Holbrook District (US 180, SR 87, SR 264) • 3.3″ to 4.3″ AC+SC • 3″ to 6″ AB • 6″ to 12″ SM	Prescott District (SR 69 SR 260) • 4″ to 8.3″ AC or AC+FC • 6″ to 18″ AB (12″ to 16″ most common)
DSAC	Interstate	Yuma District (I-10) • 9″ to 13″ AC+FC • 5″ to 9″ SM or 4″ to 7″ AB or • 4.5″ AC+FC • 2.5″ to 5″ BB • 3″ to 5.5″ AB	Kingman District (I-40) • 6″ to 15″ AC+FC (11.5″ to 15″ common ‘70s design, 9″ to 11″ common ‘80s/‘90s design) • 6″ to 28″ AB (6″ AB used in ‘70s/’80s, 24″ to 28″ used in ‘90s) • 0″ to 8″ SM (5″ to 8″ used in ‘70s, 0″ used in ‘90s)	Flagstaff District (I-17, I-40) • 8″ to 11.5″ AC or AC+FC (10″ to 11.5″ used in ‘70s, 8″ to 11″ used in ‘80s) • 4″ to 5″ BB (‘80s designs only) • 6″ to 8″ AB (‘80s designs only) • 6″ to 12″ SM (‘70s designs only)
	Non-Interstate	Kingman District (US 93, SR 68, SR 95) • 7″ to 7.5″ AC+FC • 4″ to 6″ AB	Safford District (US 19, SR 90, SR 92) • 4.3″ to 9″ AC or AC+SC • 6″ to 14″ AB	Globe District (US 180, SR 260) • 7.3″ to 10.3″ AC or AC+SC • 6″ to 8″ AB
JPC	Interstate & Non-Interstate	Phoenix District (I-10, I-17, US 60, SR 101) • 9″ to 16″ PCC (9″ common ‘60’s design [I-10 and I-17], 11″ to 13″ common ‘90s/’00s design [US 60, SR 101]) • 4″ AB or CB • 5″ to 6″ SM (SM used only in ‘60s)		Flagstaff District (I-17, I-40) • 8″ to 10″ PCC (8″ common ‘70s design, 10″ used a couple times in early ‘90s) • 4″ to 6″ CB • 4″ to 6″ SS or SM
JPCD	Interstate & Non-Interstate	Phoenix Dist (I-10) • 10″ to 13.5″ PCC (9″ to 10″ common ‘80s design, 12″ to 13.5″ common ’90s design) • 5″ CL or 3″ to 4″ AC (LCB used in ‘80s, AC used in ‘90s)		
CRC	Interstate & Non-Interstate	Phoenix Dist (I-17, SR 101) • 9″ to 15″ PCC (9″ common ‘80s design [SR 101], 13″ common ’90 design [I-10], 15″ common ’00s design [SR 101]) • 5″ OA or 6″ AB (OA used in ‘80s and ’90, AB used in ‘00s)		

Table 46. Typical M&R treatments corresponding to 15 revised analysis cells.

Pavement Type	Facility Type	Climatic Zone		
		Hot-Dry (RF ≤ 1.5)	Moderate (1.5 < RF ≤ 3.0)	Cool-Wet (RF > 3.0)
CAC	Interstate	Yuma District (I-8, I-10) • 0 to 2 applications of FL or SR every 3 to 5 yrs (on initial structure) • RC+FC (2.5/3.0 to 5.0/5.5) • RC+FC (4.5/5.0) ⇒ RE+AC+FF (4.5/7.0) • RC+AC+FC (3.5/5.5 to 4.0/8.5) • RE+AC+FC (2.0/2.0) ⇒ RE+AR+FF (2.0/2.5 to 2.0/4.5) • RE+AC+FF (3.0/5.5 to 4.5/6.5) • RC+RO+FC (4.0/6.0) • RC+RO+FC (4.0/5.0) ⇒ RC+AC+FF (4.5/7.0)	Safford District (I-10) • 0 to 1 applications of FL every 8 yrs or 0 to 1 applications of SC or FC (0.5) every 5 to 14 yrs (on initial structure) • LC+AC+FC (2.5) • LC+AC+FC (2.8 to 3.8) ⇒ RE+AC+FC (3.0/3.0 to 4.0/8.0) • LC+AC+FC (2.8) ⇒ RC+AC+FC (3.0/5.5) ⇒ RE+AR+FR (2.5/2.5) • LC+AC+FC (4.8) ⇒ FL ⇒ RE+AC+FC (2.8/2.5) ⇒ RE+AC+FC (4.0/6.5) • LC+AS+FC (2.8) ⇒ FL ⇒ RC+AC+FC (4.5/6.5 to 6.0/9.5) • RC+AC+FC (2.5/5.5) • RC+AC+FC (2.0/4.5 to 4.0/7.5) ⇒ RE+AC+FR (4.0/4.5 to 6.5/6.5) • RC+LC+AS+FC (4.0/6.7) ⇒ RE+AC+FC (3.0/3.5)	
	Non-Interstate	Tucson District (SR 287, SR 347) • 0 to 1 applications of FC every 10 yrs (on initial structure) • RE+AC (2.5/2.5) • RE+RO+AC+SC (2.0/3.8) • HS+FC (0.0/0.5) ⇒ RE+AC (2.5/2.5) ⇒ AC+FR (4.6)	Holbrook District (US 180, SR 87, SR 264) • 0 to 1 applications of FL every 4 yrs or 0 to 2 applications of SC every 3 to 5 yrs (on initial structure) • AC+SC (2.3) • AC+SC (2.3) ⇒ SC ⇒ FR (0.8) • AC+SC (2.3) ⇒ FL+SC (0.3) ⇒ SC ⇒ AC+SC (1.8) • AC+SC+SC (3.0) ⇒ AC+SC+SC (3.0) • AC+SR (3.0)	Prescott District (SR 69 SR 260) • 0 to 1 applications of FL every 5 to 6 yrs followed by 0 to 2 applications of SC every 5 to 15 yrs (on initial structure) • AC+FC (2.0) ⇒ AC+FR (3.5) • AC+SC (1.8) ⇒ FR (0.5) • AC+SC (1.8) ⇒ SC+SC ⇒ FR (0.5) • RE+AR+FR (2.5/3.0)

Table 46. Typical M&R treatments corresponding to 15 revised analysis cells (continued).

Pavement Type	Facility Type	Climatic Zone		
		Hot-Dry (RF ≤ 1.5)	**Moderate (1.5 < RF ≤ 3.0)**	**Cool-Wet (RF > 3.0)**
DSAC	Interstate	Yuma District (I-10) • 0 to 2 applications of FL or SR every 3 to 5 years (initial structure) • RC+AC+FR (6.0/9.0) • RC+RO+FC (4.0/6.0) • RC+RO+FC (3.0/5.0) ⇒ RE+AC+FR (4.5/7.0 to 9.5/12.0) • RE+AC+FR (6.0/6.5) • RE+AC+FC (2.5/2.5) ⇒ RE+AR+FR (2.0/2.5)	Kingman District (I-40) • RE+FC (0.8/0.8) • RE+AC+FC (3.0/5.5 to 4.0/7.5) • RE+SuperPave+FR (5.5/5.5)	Flagstaff District (I-17, I-40) • RC+FC (2.0/2.5) ⇒ RE+AC+FR (5.0/5.5) • RE+FC (0.5) ⇒ RE+AC+FR (3.0/3.5) • RE+AR+FR (2.0/2.5)
	Non-Interstate	Kingman District (US 93, SR 68, SR 95) • None (no sections treated to date)	Safford District (US 19, SR 90, SR 92) • 0 to 1 applications of FL every 3 yrs or 0 to 1 applications of SC every 4 to 18 yrs (on initial structure) • AC+SC (2.3) • AR+FR (2.2 to 2.5) • FR (0.5) • RE+AC+FL (1.0/2.0) ⇒ RE+AC+SC (3.0/3.3) • SC+SC (0.5)	Globe District (US 180, SR 260) • 0 to 1 applications of SC every 5 to 6 yrs • AR (1.5)
JPC	Interstate & Non-Interstate	Phoenix District (I-10, I-17, US 60, SR 101) • GR ⇒ FR (1.0) • FC+RM+FC (1.3) ⇒ RE+FR (1.0/1.0) • RE+FR (1.0) * Based on I-10 & I-17 sections built in '60s		Flagstaff District (I-17, I-40) • AR (1.5) • AR+FR (2.5) ⇒ RE+AR+FR (2.0/2.5) • FR (1.0) ⇒ FR (0.5) • GR+FR (1.0) • KS+AC (4.0) ⇒ FR (1.0) • KS+AC (4.0) ⇒ RE+AC+FR (2.0/3.0) • KS+AC+AR+FR (5.5) • RM+AC+FC (2.8) ⇒ AC+AR+FR (5.5) • FL+LC+RM+FC+FL (1.8) ⇒ FR (1.0)
JPCD	Interstate & Non-Interstate	Phoenix Dist (I-10) • None (no sections treated to date)		
CRC	Interstate & Non-Interstate	Phoenix Dist (I-17, SR 101) • None (no sections treated to date)		

included the application of a thin functional overlay preceding the reconstruction event by 5 to 6 years.

Figure 56 illustrates the four conceptual design strategies. For simplicity, it was assumed that each reconstruction consisted of the same basic structure as the initial construction. However, to keep the same service life and account for the increased traffic, each successive reconstruction included a slightly thicker structure (1 in HMA for asphalt pavements, 0.5 in PCC for concrete pavements).

Discussions of the development of life-cycle models and a presentation of the final models are provided in the sections below, corresponding to the 15 analysis cells.

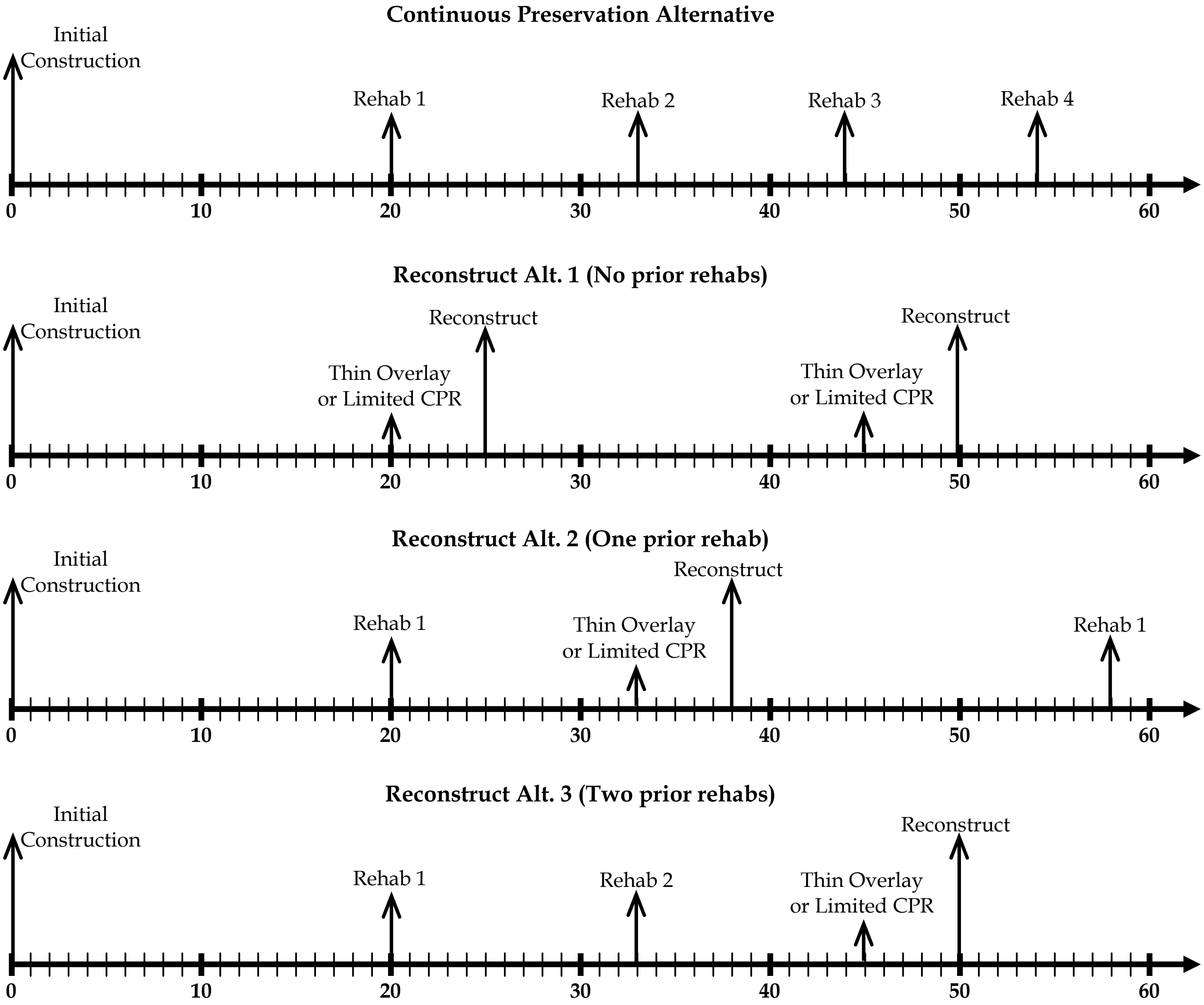


Figure 56. Conceptual illustration of continuous preservation and reconstruction design strategies.

ANALYSIS CELL 1

Figure 57 shows the alternative life-cycle models developed for analysis cell 1—CAC Interstate pavement located in a hot-dry climate. The representative pavement section is I-8, MP 40-41 in Yuma County, which is in the Yuma District. This section of highway is a 4-lane rural interstate, with 12-ft travel lanes and 10-ft outside and 4-ft inside shoulders. The section had a 2002 ADT (1-way) of approximately 10,000 vehicles/day, and the 13 percent trucks on this facility yields an estimated 0.45 million trucks/year (based on a lane distribution factor [LDF] of 0.9).

The cross-section established for the initial mainline structure consists of 6 in of AC on 16 in of aggregate base and subbase. Full-depth asphalt shoulders have been assumed to accompany the mainline structure.

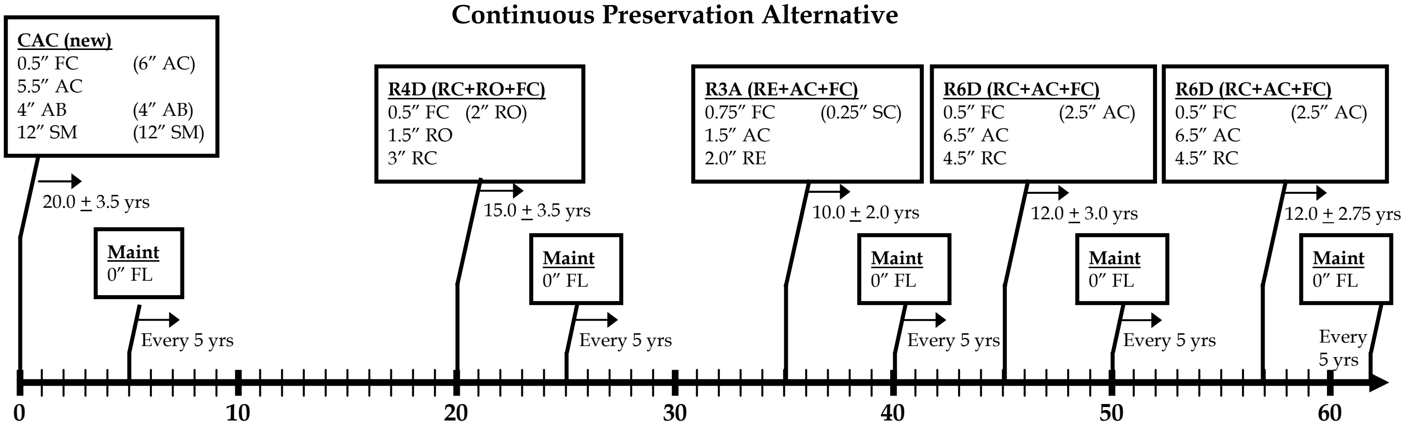
Survival analysis results indicated a median life of 18.2 years and 20.1 million trucks (tables 18 and 19 in chapter 3) for CAC interstate pavements in the hot-dry climate. This equates to about 1.1 million trucks/year, which is more than double the 0.45 million trucks/year estimated for 2002 for this section. To account for the lower annual truck traffic, the 18.2-year median service life was adjusted upward to 20 years. A standard deviation (1σ) of 3.5 years was applied, corresponding to about one-half the difference between the 75 percent and 25 percent survival probabilities (15.8 and 20.5 years) listed in table 18. (Note: a true standard deviation would be one-half the difference between the 83 percent and 17 percent survival probabilities).

Four sequential rehabilitation treatments—R4D, R3A, R6D, and R6D—were established for the continuous preservation alternative, corresponding to the types of treatments typically performed in the Yuma District in recent years. Performance lives were assigned in accordance with the survival analysis results provided in tables 22 and 23 in chapter 3. To account for traffic growth and deterioration of the underlying pavement layers over time, the life of each treatment was adjusted downward by 1 year for each rehabilitation cycle, starting with the second cycle (i.e., R3A). Also, for probabilistic LCCA purposes, the fourth treatment (R6D) was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 57 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 1-in asphalt friction course (FC) was used to delay each reconstruction event by 5 years. Hence the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Years 25 and 50.
- Reconstruct Alternative 2—Year 40.
- Reconstruct Alternative 3—Year 50.

Continuous Preservation Alternative



Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	Reconstruct Alt. #2	Reconstruct Alt. #3
20	M2A (FC) (5.0 ± 0.0 yrs) 1″ FC (1″ AC)	R4D (RC+RO+FC) (15.0 ± 3.5 yrs) 0.5″ FC (2″ RO) 1.5″ RO 3″ RC Maint: FL every 5 yrs	R4D (RC+RO+FC) (15.0 ± 3.5 yrs) 0.5″ FC (2″ RO) 1.5″ RO 3″ RC Maint: FL every 5 yrs
25	CAC (Reconstruct) (20.0 ± 3.5 yrs) 0.5″ FC (7″ AC) 6.5″ AC 4″ AB (4″ AB) 12″ SM (12″ SM) 23″ RE (23″ RE) Maint: FL every 5 yrs		
35		M2A (FC) (5.0 ± 0.0 yrs) 1″ FC (1″ AC)	R3A (RE+AC+FC) (10.0 ± 2.0 yrs) 0.75″ FC (0.25″ SC) 1.5″ AC 2.0″ RE Maint: FL every 5 yrs
40		CAC (Reconstruct) (20.0 ± 3.5 yrs) 0.5″ FC (8″ AC) 7.5″ AC 4″ AB (4″ AB) 12″ SM (12″ SM) 25″ RE (25″ RE) Maint: FL every 5 yrs	
45	M2A (FC) (5.0 ± 0.0 yrs) 1″ FC (1″ AC)		M2A (FC) (5.0 ± 0.0 yrs) 1″ FC (1″ AC)
50	CAC (Reconstruct) (20.0 ± 3.5 yrs) 0.5″ FC (8″ AC) 7.5″ AC 4″ AB (4″ AB) 12″ SM (12″ SM) 24″ RE (24″ RE) Maint: FL every 5 yrs		CAC (Reconstruct) (20.0 ± 3.5 yrs) 0.5″ FC (8″ AC) 7.5″ AC 4″ AB (4″ AB) 12″ SM (12″ SM) 25.5″ RE (25.5″ RE) Maint: FL every 5 yrs
60		R4D (RC+RO+FC) (12.0 ± 2.5 yrs) 0.5″ FC (2″ RO) 1.5″ RO 3″ RC	

Figure 57. Life-cycle models for analysis cell 1—CAC interstate pavement, hot-dry climate.

ANALYSIS CELL 2

Figure 58 shows the alternative life-cycle models developed for analysis cell 2—CAC Interstate pavement located in a moderate climate. The representative pavement section is I-10, MP 385-386 in Cochise County, which is in the Safford District. This section of highway is a 4-lane rural interstate, with 12-ft travel lanes and 10-ft outside and 4-ft inside shoulders. The section had a 2002 ADT (1-way) of approximately 19,500 vehicles/day, and the 18 percent trucks on this facility yields an estimated 1.2 million trucks/year (LDF=0.9).

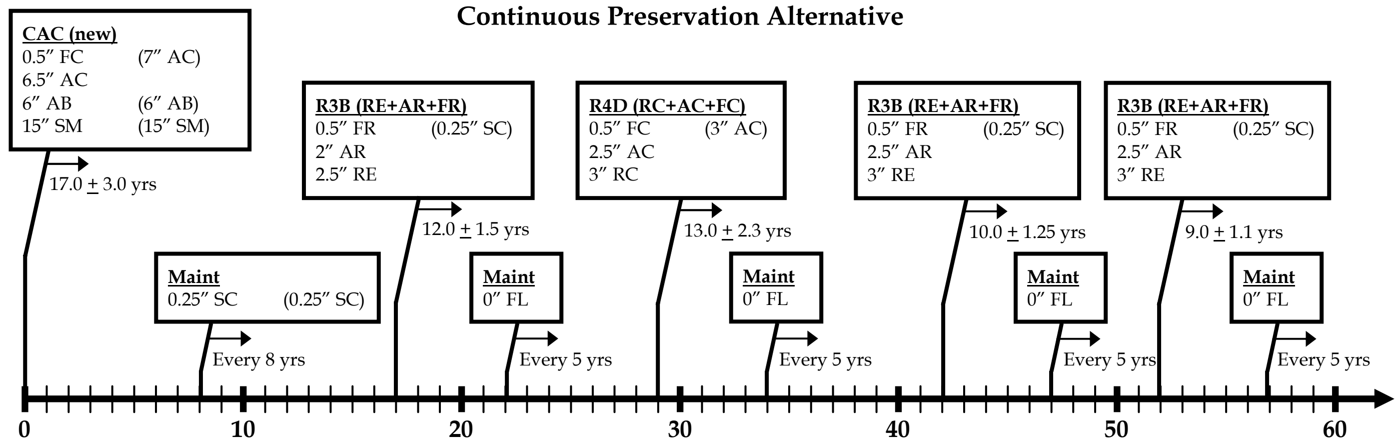
The cross-section established for the initial mainline structure consists of 7 in of AC on 21 in of aggregate base and subbase. Full-depth asphalt shoulders have been assumed to accompany the mainline structure.

Survival analysis results indicated a median life of 17.5 years and 15.2 million trucks (tables 18 and 19 in chapter 3) for CAC interstate pavements in the moderate climate. This equates to about 0.9 million trucks/year, which is somewhat less than the 1.2 million trucks/year estimated for 2002 for this section. To account for the higher annual truck traffic, the 17.5-year median service life was adjusted downward to 17 years. A standard deviation (1σ) of 3.0 years was applied, corresponding to about one-half the difference between the 75 percent and 25 percent survival probabilities (15.1 and 19.8 years) listed in table 18.

Four sequential rehabilitation treatments—R3B, R4D, R3B, and R3B—were established for the continuous preservation alternative, corresponding to the types of treatments typically performed in the Safford District in recent years. Performance lives were assigned in accordance with the survival analysis results provided in tables 22 and 23 in chapter 3. To account for traffic growth and deterioration of the pavement layers over time, the life of each treatment was adjusted downward by 1 year for each rehabilitation cycle, starting with the second cycle (i.e., R4D). Also, for probabilistic LCCA purposes, the fourth treatment (R3B) was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 58 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 1-in asphalt rubber friction course (FR) was used to delay each reconstruction event by 5 years. Hence the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Years 22 and 44.
- Reconstruct Alternative 2—Year 34.
- Reconstruct Alternative 3—Year 47.


Continuous Preservation Alternative

Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	Reconstruct Alt. #2	Reconstruct Alt. #3
17	M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC)	R3B (RE+AR+FR) (12.0 ± 1.5 yrs) 0.5″ FR (0.25″ SC) 2″ AR 2.5″ RE Maint: FL every 5 yrs	R3B (RE+AR+FR) (12.0 ± 1.5 yrs) 0.5″ FR (0.25″ SC) 2″ AR 2.5″ RE Maint: FL every 5 yrs
22	CAC (Reconstruct) (17.0 ± 3.0 yrs) 0.5″ FC (8″ AC) 7.5″ AC 6″ AB (6″ AB) 15″ SM (15″ SM) 29″ RE (29″ RE) Maint: SC every 8 yrs		
29		M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC)	R4D (RC+AC+FC) (13.0 ± 2.3 yrs) 0.5″ FC (3″ AC) 2.5″ AC 3″ RC Maint: FL every 5 yrs
34		CAC (Reconstruct) (17.0 ± 3.0 yrs) 0.5″ FC (8″ AC) 7.5″ AC 6″ AB (6″ AB) 15″ SM (15″ SM) 29″ RE (29″ RE) Maint: SC every 8 yrs	
39	M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC)		
42			M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC)
44	CAC (Reconstruct) (17.0 ± 3.0 yrs) 0.5″ FC (9″ AC) 8.5″ AC 6″ AB (6″ AB) 15″ SM (15″ SM) 30″ RE (30″ RE) Maint: SC every 8 yrs		
47			CAC (Reconstruct) (17.0 ± 3.0 yrs) 0.5″ FC (9″ AC) 8.5″ AC 6″ AB (6″ AB) 15″ SM (15″ SM) 32″ RE (32″ RE) Maint: SC every 8 yrs
51		R3B (RE+AR+FR) (12.0 ± 1.5 yrs) 0.5″ FR (0.25″ SC) 2″ AR 2.5″ RE Maint: FL every 5 yrs	

Figure 58. Life-cycle models for analysis cell 2—CAC interstate pavement, moderate climate.

ANALYSIS CELL 3

Figure 59 shows the alternative life-cycle models developed for analysis cell 3—CAC Non-Interstate pavement located in a hot-dry climate. The representative pavement section is SR 287, MP 115-116 in Pinal County, which is in the Tucson District. This section of highway is a 2-lane rural highway, with 12-ft travel lanes and 5-ft shoulders. The section had a 2002 ADT (1-way) of approximately 13,000 vehicles/day, and the 5 percent trucks on this facility yields an estimated 0.25 million trucks/year (LDF=1).

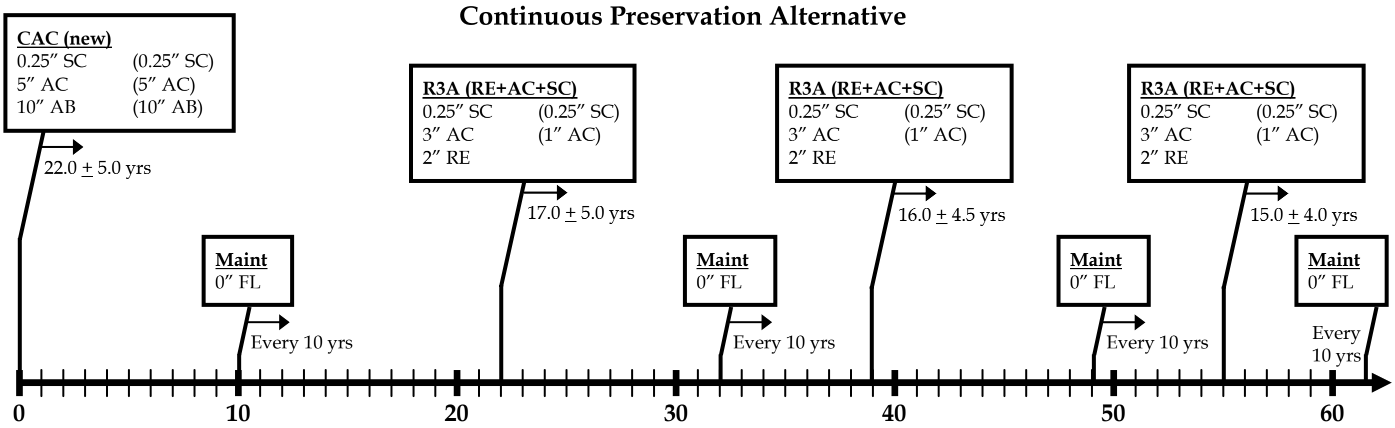
The cross-section established for the initial mainline structure consists of 5.25 in of AC on 10 in of aggregate base. Full-depth asphalt shoulders have been assumed to accompany the mainline structure.

Survival analysis results indicated a median life of 21.6 years and 5.8 million trucks (tables 18 and 19 in chapter 3) for CAC Non-Interstate pavements in the hot-dry climate. This equates to about 0.27 million trucks/year, which is slightly higher than the 0.25 million trucks/year estimated for 2002 for this section. For purposes of LCCA, the 21.6-year median service life was rounded upward to 22 years. A standard deviation (1σ) of 5.0 years was applied, corresponding to about one-half the difference between the 75 percent and 25 percent survival probabilities (16.7 and 26.5 years) listed in table 18.

Three sequential rehabilitation treatments—all R3A—were established for the continuous preservation alternative, corresponding to the types of treatments typically performed in the Tucson District in recent years. Performance lives were assigned in accordance with the survival analysis results provided in tables 22 and 23 in chapter 3. To account for traffic growth and deterioration of the pavement layers over time, the life of each treatment was adjusted downward by 1 year for each rehabilitation cycle, starting with the second cycle. Also, for probabilistic LCCA purposes, the R3A treatment was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 59 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 1-in asphalt friction course (FC) was used to delay each reconstruction event by 6 years. Hence the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Years 28 and 57.
- Reconstruct Alternative 2—Year 45.
- Reconstruct Alternative 3—Year 60.


Continuous Preservation Alternative

Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	Reconstruct Alt. #2	Reconstruct Alt. #3
22	M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)	R3A (RE+AC+SC) (17.0 ± 5.0 yrs) 0.25″ SC (0.25″ SC) 3″ AC (1″ AC) 2″ RE Maint: FL every 10 yrs	R3A (RE+AC+SC) (17.0 ± 5.0 yrs) 0.25″ SC (0.25″ SC) 3″ AC (1″ AC) 2″ RE Maint: FL every 10 yrs
28	CAC (Reconstruct) (22.0 ± 5.0 yrs) 0.25″ SC (0.25″ SC) 6″ AC (6″ AC) 10″ AB (10″ AB) 16.5″ RE (16.5″ RE) Maint: FL every 10 yrs		
39		M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)	R3A (RE+AC+SC) (16.0 ± 4.5 yrs) 0.25″ SC (0.25″ SC) 3″ AC (1″ AC) 2″ RE Maint: FL every 10 yrs
45		CAC (Reconstruct) (22.0 ± 5.0 yrs) 0.25″ SC (0.25″ SC) 7″ AC (7″ AC) 10″ AB (10″ AB) 17.5″ RE (17.5″ RE) Maint: FL every 10 yrs	
50	M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)		
54			M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)
57	CAC (Reconstruct) (22.0 ± 5.0 yrs) 0.25″ SC (0.25″ SC) 7″ AC (7″ AC) 10″ AB (10″ AB) 17.5″ RE (17.5″ RE) Maint: FL every 10 yrs		
60			CAC (Reconstruct) (22.0 ± 5.0 yrs) 0.25″ SC (0.25″ SC) 7″ AC (7″ AC) 10″ AB (10″ AB) 19″ RE (19″ RE) Maint: FL every 10 yrs

Figure 59. Life-cycle models for analysis cell 3—CAC non-interstate pavement, hot-dry climate.

ANALYSIS CELL 4

Figure 60 shows the alternative life-cycle models developed for analysis cell 4—CAC Non-Interstate pavement located in a moderate climate. The representative pavement section is SR 264, MP 475-476 in Apache County, which is in the Holbrook District. This section of highway is a 4-lane rural highway, with 12-ft travel lanes and 4-ft shoulders. The section had a 2002 ADT (1-way) of approximately 5,500 vehicles/day, and the 6 percent trucks on this facility yields an estimated 0.11 million trucks/year (LDF=0.9).

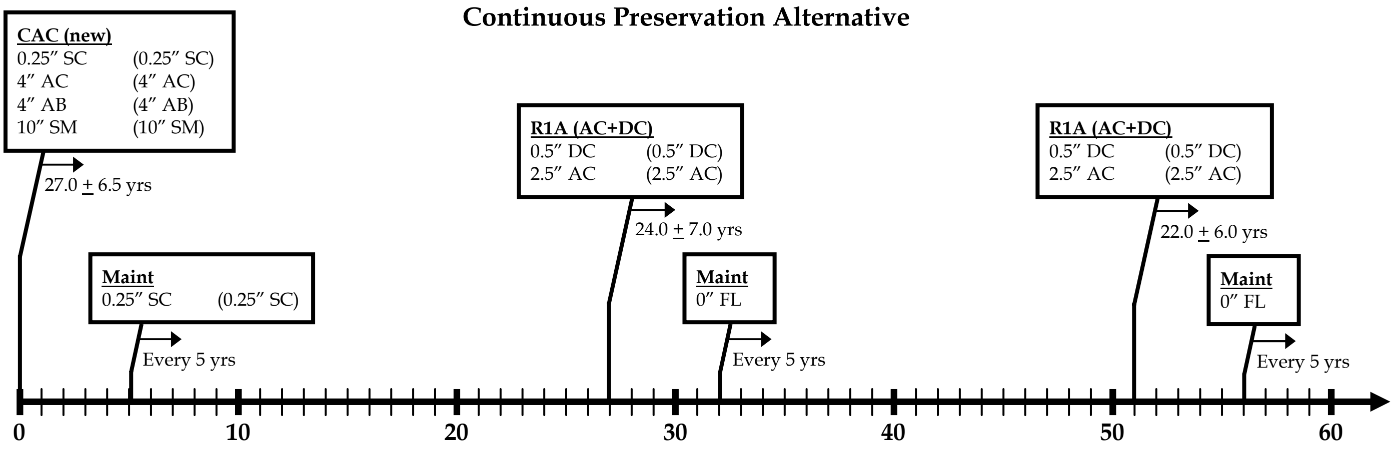
The cross-section established for the initial mainline structure consists of 4.25 in of AC on 14 in of aggregate base and subbase. Full-depth asphalt shoulders have been assumed to accompany the mainline structure.

Survival analysis results indicated a median life of 27.8 years and 6.5 million trucks (tables 18 and 19 in chapter 3) for CAC Non-Interstate pavements in the moderate climate. This equates to about 0.23 million trucks/year, which is higher than the 0.11 million trucks/year estimated for 2002 for this section. For purposes of LCCA, the 27.8-year median service life was rounded upward to 28 years. A standard deviation (1σ) of 6.75 years was applied, corresponding to about one-half the difference between the 75 percent and 25 percent survival probabilities (21.2 and 34.4 years) listed in table 18.

Two sequential rehabilitation treatments—both R1A—were established for the continuous preservation alternative, corresponding to the types of treatments typically performed in the Holbrook District in recent years. Performance lives were assigned in accordance with the survival analysis results provided in tables 22 and 23 in chapter 3. To account for traffic growth and deterioration of the pavement layers over time, the life of each treatment was adjusted downward by 2 years for each rehabilitation cycle, starting with the second cycle. Also, for probabilistic LCCA purposes, the R1A treatment was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 60 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 1-in asphalt friction course (FC) was used to delay each reconstruction event by 6 years. Hence, the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Year 33.
- Reconstruct Alternative 2—Year 57.
- Reconstruct Alternative 3—None. For the 60-year analysis period, the activity sequence for this alternative is the same as that for continuous preservation. However, the first event after the 60-year analysis period is different for the two alternatives. For the continuous preservation alternative, the next event is the R1A rehabilitation treatment, whereas for Alternative 3, the next event is M2A.



Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	**Reconstruct Alt. #2**	**Reconstruct Alt. #3**
27	M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)	R1A (AC+DC) (24.0 ± 7.0 yrs) 0.5″ DC (0.5″ DC) 2.5″ AC (2.5″ AC) Maint: FL every 5 yrs	R1A (AC+DC) (24.0 ± 7.0 yrs) 0.5″ DC (0.5″ DC) 2.5″ AC (2.5″ AC) Maint: FL every 5 yrs
33	CAC (Reconstruct) (27.0 ± 6.5 yrs) 0.25″ SC (0.25″ SC) 5″ AC (5″ AC) 4″ AB (4″ AB) 10″ SM (10″ SM) 16.5″ RE (16.5″ RE) Maint: SC every 5 yrs		
51		M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)	R1A (AC+DC) (22.0 ± 6.0 yrs) 0.5″ DC (0.5″ DC) 2.5″ AC (2.5″ AC) Maint: FL every 5 yrs
57		CAC (Reconstruct) (27.0 ± 6.5 yrs) 0.25″ SC (0.25″ SC) 6″ AC (6″ AC) 4″ AB (4″ AB) 10″ SM (10″ SM) 21.5″ RE (21.5″ RE) Maint: SC every 5 yrs	
60	M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)		

Figure 60. Life-cycle models for analysis cell 4—CAC non-interstate pavement, moderate climate.

ANALYSIS CELL 5

Figure 61 shows the alternative life-cycle models developed for analysis cell 5—CAC Non-Interstate pavement located in a cool-wet climate. The representative pavement section is SR 260, MP 290-291 in Gila County, which is in the Prescott District. This section of highway is a 4-lane rural highway, with 12-ft travel lanes and 4-ft inside and 10-ft outside shoulders. The section had a 2002 ADT (1-way) of approximately 5,000 vehicles/day, and the 10 percent trucks on this facility yields an estimated 0.17 million trucks/year (LDF=0.9).

The cross-section established for the initial mainline structure consists of 4.5 in of AC on 16 in of aggregate base. Full-depth asphalt shoulders have been assumed to accompany the mainline structure.

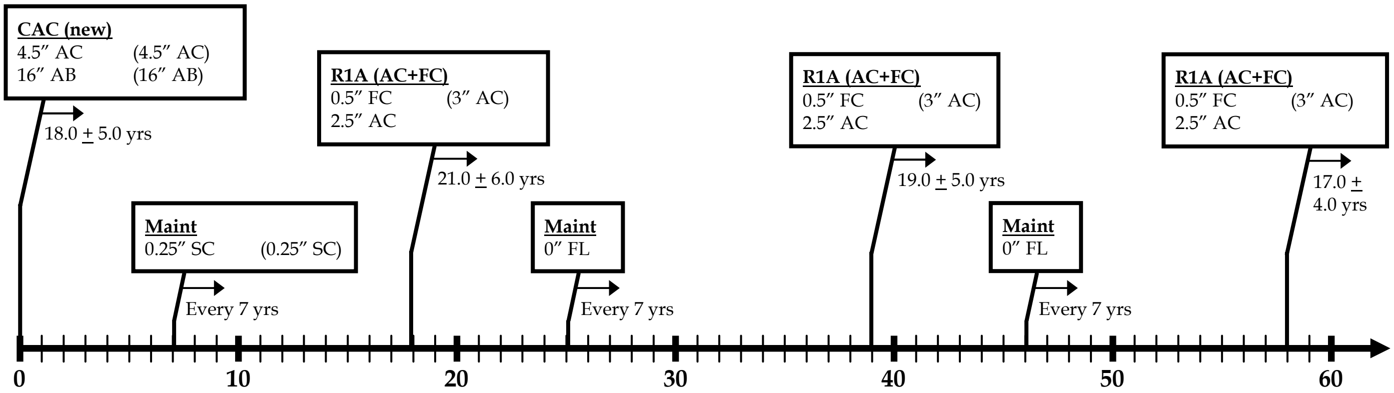
Survival analysis results indicated a median life of 15.1 years and 5.3 million trucks (tables 18 and 19 in chapter 3) for CAC Non-Interstate pavements in the cool-wet climate. This equates to about 0.35 million trucks/year, which is higher than the 0.17 million trucks/year estimated for 2002 for this section. For purposes of LCCA, the 15.1-year median service life was rounded upward to 18 years. A standard deviation (1σ) of 5.5 years was applied, corresponding to about one-half the difference between the 75 percent and 25 percent survival probabilities (9.8 and 20.8 years) listed in table 18.

Three sequential rehabilitation treatments—all R1A—were established for the continuous preservation alternative, corresponding to the types of treatments typically performed in the Prescott District in recent years. Performance lives were assigned in accordance with the survival analysis results provided in tables 22 and 23 in chapter 3. To account for traffic growth and deterioration of the pavement layers over time, the life of each treatment was adjusted downward by 2 years for each rehabilitation cycle, starting with the second cycle. Also, for probabilistic LCCA purposes, the R1A treatment was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 61 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 1-in asphalt friction course (FC) was used to delay each reconstruction event by 6 years. Hence, the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Years 24 and 48.
- Reconstruct Alternative 2—Year 45.
- Reconstruct Alternative 3—None.

Continuous Preservation Alternative



Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	**Reconstruct Alt. #2**	**Reconstruct Alt. #3**
18	M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)	R1A (AC+FC) (21.0 ± 6.0 yrs) 0.5″ FC (3″ AC) 2.5″ AC Maint: FL every 7 yrs	R1A (AC+FC) (21.0 ± 6.0 yrs) 0.5″ FC (3″ AC) 2.5″ AC Maint: FL every 7 yrs
24	CAC (Reconstruct) (18.0 ± 5.0 yrs) 5.5″ AC (5.5″ AC) 16″ AB (16″ AB) 22″ RE (22″ RE) Maint: SC every 7 yrs		
39		M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)	R1A (AC+FC) (19.0 ± 5.0 yrs) 0.5″ FC (3″ AC) 2.5″ AC Maint: FL every 7 yrs
42	M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)		
45		CAC (Reconstruct) (18.0 ± 5.0 yrs) 6.5″ AC (6.5″ AC) 16″ AB (16″ AB) 25″ RE (25″ RE) Maint: SC every 7 yrs	
48	CAC (Reconstruct) (18.0 ± 5.0 yrs) 6.5″ AC (6.5″ AC) 16″ AB (16″ AB) 23″ RE (23″ RE) Maint: SC every 7 yrs		
58			M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)

Figure 61. Life-cycle models for analysis cell 5—CAC non-interstate pavement, cool-wet climate.

ANALYSIS CELL 6

Figure 62 shows the alternative life-cycle models developed for analysis cell 6—DSAC Interstate pavement located in a hot-dry climate. The representative pavement section is I-10, MP 100-101 in Maricopa County, which is in the Yuma District. This section of highway is a 4-lane rural interstate, with 12-ft travel lanes and 4-ft inside and 10-ft outside shoulders. The section had a 2002 ADT (1-way) of approximately 22,000 vehicles/day, and the 18 percent trucks on this facility yields an estimated 1.3 million trucks/year (LDF=0.9).

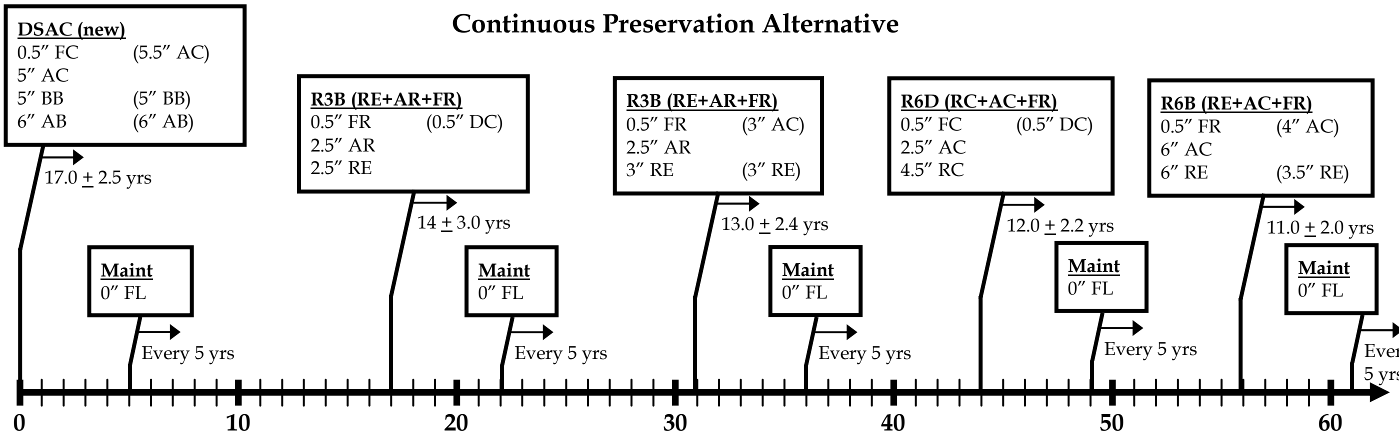
The cross-section established for the initial mainline structure consists of 10.5 in of asphalt (5.5 in AC, 5 in BB) on 6 in of aggregate base. Full-depth asphalt shoulders have been assumed to accompany the mainline structure.

Survival analysis results indicated a median life of 16.9 years and 19.4 million trucks (tables 18 and 19 in chapter 3) for DSAC Interstate pavements in the hot-dry climate. This equates to about 1.15 million trucks/year, which is a little less than the 1.3 million trucks/year estimated for 2002 for this section. For purposes of LCCA, the 16.9-year median service life was rounded downward to 17 years. A standard deviation (1σ) of 2.5 years was applied, corresponding to about one-half the difference between the 75 percent and 25 percent survival probabilities (14.7 and 19.2 years) listed in table 18.

Four sequential rehabilitation treatments—R3B, R3B, R6D, and R6B—were established for the continuous preservation alternative, corresponding to the types of treatments typically performed in the Yuma District in recent years. Performance lives were assigned in accordance with the survival analysis results provided in tables 22 and 23 in chapter 3. To account for traffic growth and deterioration of the pavement layers over time, the life of each treatment was adjusted downward by 1 year for each rehabilitation cycle, starting with the second cycle. Also, for probabilistic LCCA purposes, the fourth treatment (R6B) was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 62 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 1-in asphalt friction course (FC) was used to delay each reconstruction event by 5 years. Hence, the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Years 22 and 39.
- Reconstruct Alternative 2—Years 36 and 58.
- Reconstruct Alternative 3—Year 49.


Continuous Preservation Alternative

Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	Reconstruct Alt. #2	Reconstruct Alt. #3
17	M2A (FC) (5.0 ± 0.0 yrs) 1″ FC (1″ AC)	R3B (RE+AR+FR) (14.0 ± 3.0 yrs) 0.5″ FR (0.5″ DC) 2.5″ AR 2.5″ RE Maint: FL every 5 yrs	R3B (RE+AR+FR) (14.0 ± 3.0 yrs) 0.5″ FR (0.5″ DC) 2.5″ AR 2.5″ RE Maint: FL every 5 yrs
22	DSAC (Reconstruct) (17.0 ± 2.5 yrs) 0.5″ FC (6.5″ AC) 6″ AC 5″ BB (5″ BB) 6″ AB (6″ AB) 17.5″ RE (17.5″ RE) Maint: FL every 5 yrs		
31		M2A (FC) (5.0 ± 0.0 yrs) 1″ FC (1″ AC)	R3B (RE+AR+FR) (13.0 ± 2.4 yrs) 0.5″ FR (3″ AC) 2.5″ AR 3″ RE (3″ RE) Maint: FL every 5 yrs
34	M2A (FC) (5.0 ± 0.0 yrs) 1″ FC (1″ AC)		
36		DSAC (Reconstruct) (17.0 ± 2.5 yrs) 0.5″ FC (7.5″ AC) 7″ AC 5″ BB (5″ BB) 6″ AB (6″ AB) 18″ RE (18″ RE) Maint: FL every 5 yrs	
39	DSAC (Reconstruct) (17.0 ± 2.5 yrs) 0.5″ FC (7.5″ AC) 7″ AC 5″ BB (5″ BB) 6″ AB (6″ AB) 18.5″ RE (18.5″ RE) Maint: FL every 5 yrs		
44			M2A (FC) (5.0 ± 0.0 yrs) 1″ FC (1″ AC)

Figure 62. Life-cycle models for analysis cell 6—DSAC interstate pavement, hot-dry climate.

Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	Reconstruct Alt. #2	Reconstruct Alt. #3
49			DSAC (Reconstruct) (17.0 ± 2.5 yrs) 0.5″ FC (7.5″ AC) 8″ AC 5″ BB (5″ BB) 6″ AB (6″ AB) 18″ RE (18″ RE) Maint: FL every 5 yrs
53		M2A (FC) (5.0 ± 0.0 yrs) 1″ FC (1″ AC)	
56	M2A (FC) (5.0 ± 0.0 yrs) 1″ FC (1″ AC)		
58		DSAC (Reconstruct) (17.0 ± 2.5 yrs) 0.5″ FC (7.5″ AC) 8″ AC 5″ BB (5″ BB) 6″ AB (6″ AB) 18.5″ RE (18.5″ RE) Maint: FL every 5 yrs	

Figure 62. Life-cycle models for analysis cell 6—DSAC interstate pavement, hot-dry climate (continued).

ANALYSIS CELL 7

Figure 63 shows the alternative life-cycle models developed for analysis cell 7—DSAC Interstate pavement located in a moderate climate. The representative pavement section is I-40, MP 120-121 in Yapapai County, which is in the Kingman District. This section of highway is a 4-lane rural interstate, with 12-ft travel lanes and 4-ft inside and 10-ft outside shoulders. The section had a 2002 ADT (1-way) of approximately 17,000 vehicles/day, and the 24 percent trucks on this facility yields an estimated 1.3 million trucks/year (LDF=0.9).

The cross-section established for the initial mainline structure consists of 10 in of AC on 12 in of aggregate base. Full-depth asphalt shoulders have been assumed to accompany the mainline structure.

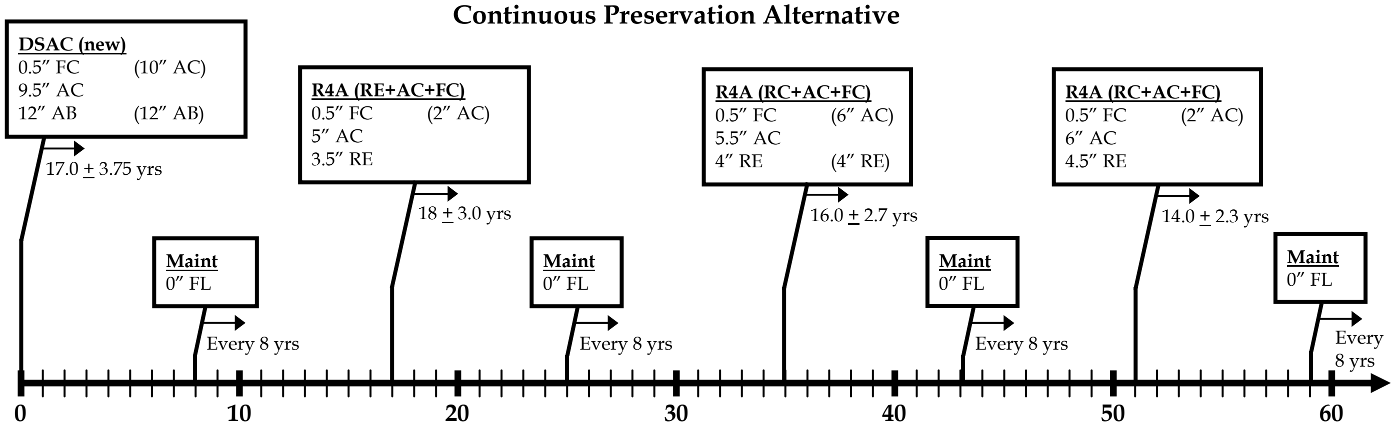
Survival analysis results indicated a median life of 18.4 years and 16.2 million trucks (tables 18 and 19 in chapter 3) for DSAC Interstate pavements in the hot-dry climate. This equates to about 0.88 million trucks/year, which is less than the 1.3 million trucks/year estimated for 2002 for this section. For purposes of LCCA, the 18.4-year median service life was adjusted downward to 17 years. A standard deviation (1σ) of 3.75 years was applied, corresponding to about one-half the difference between the 75 percent and 25 percent survival probabilities (14.8 and 21.9 years) listed in table 18.

Three sequential rehabilitation treatments—all R4A—were established for the continuous preservation alternative, corresponding to the types of treatments typically performed in the Kingman District in recent years. Performance lives were assigned in accordance with the survival analysis results provided in tables 22 and 23 in chapter 3. To account for traffic growth and deterioration of the pavement layers over time, the life of each treatment was adjusted downward by 2 years for each rehabilitation cycle, starting with the second cycle. Also, for probabilistic LCCA purposes, the R4A treatment was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 63 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 0.75-in mill-and-replacement with asphalt friction course (FC) was used to delay each reconstruction event by 5 years. Hence, the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Years 22 and 44.
- Reconstruct Alternative 2—Year 40.
- Reconstruct Alternative 3—Year 56.

Continuous Preservation Alternative



Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	Reconstruct Alt. #2	Reconstruct Alt. #3
17	M2A (RE+FC) (5.0 ± 0.0 yrs) 0.75″ FC 0.75″ RE	R4A (RE+AC+FC) (18.0 ± 3.0 yrs) 0.5″ FC (2″ AC) 5″ AC 3.5″ RE Maint: FL every 8 yrs	R4A (RE+AC+FC) (18.0 ± 3.0 yrs) 0.5″ FC (2″ AC) 5″ AC 3.5″ RE Maint: FL every 8 yrs
22	DSAC (Reconstruct) (17.0 ± 3.75 yrs) 0.5″ FC (11″ AC) 10.5″ AC 12″ AB (12″ AB) 22″ RE (22″ RE) Maint: FL every 8 yrs		
35		M2A (RE+FC) (5.0 ± 0.0 yrs) 0.75″ FC 0.75″ RE	R4A (RE+AC+FC) (16.0 ± 2.7 yrs) 0.5″ FC (6″ AC) 5.5″ AC 4″ RE (4″ RE) Maint: FL every 8 yrs
39	M2A (RE+FC) (5.0 ± 0.0 yrs) 0.75″ FC 0.75″ RE		
40		DSAC (Reconstruct) (17.0 ± 3.75 yrs) 0.5″ FC (12″ AC) 11.5″ AC 12″ AB (12″ AB) 24″ RE (24″ RE) Maint: FL every 8 yrs	
44	DSAC (Reconstruct) (17.0 ± 3.75 yrs) 0.5″ FC (12″ AC) 11.5″ AC 12″ AB (12″ AB) 23″ RE (23″ RE) Maint: FL every 8 yrs		
51			M2A (RE+FC) (5.0 ± 0.0 yrs) 0.75″ FC 0.75″ RE
56			DSAC (Reconstruct) (17.0 ± 3.75 yrs) 0.5″ FC (12″ AC) 11.5″ AC 12″ AB (12″ AB) 26″ RE (26″ RE) Maint: FL every 8 yrs
57		M2A (RE+FC) (5.0 ± 0.0 yrs) 0.75″ FC 0.75″ RE	

Figure 63. Life-cycle models for analysis cell 7—DSAC interstate pavement, moderate climate.

ANALYSIS CELL 8

Figure 64 shows the alternative life-cycle models developed for analysis cell 8—DSAC Interstate pavement located in a cool-wet climate. The representative pavement section is I-17, MP 311-312 in Coconino County, which is in the Flagstaff District. This section of highway is a 4-lane rural interstate, with 12-ft travel lanes and 4-ft inside and 8-ft outside shoulders. The section had a 2002 ADT (1-way) of approximately 23,000 vehicles/day, and the 15 percent trucks on this facility yields an estimated 1.1 million trucks/year (LDF=0.9).

The cross-section established for the initial mainline structure consists of 10.5 in of AC on 8 in of aggregate base. Full-depth asphalt shoulders have been assumed to accompany the mainline structure.

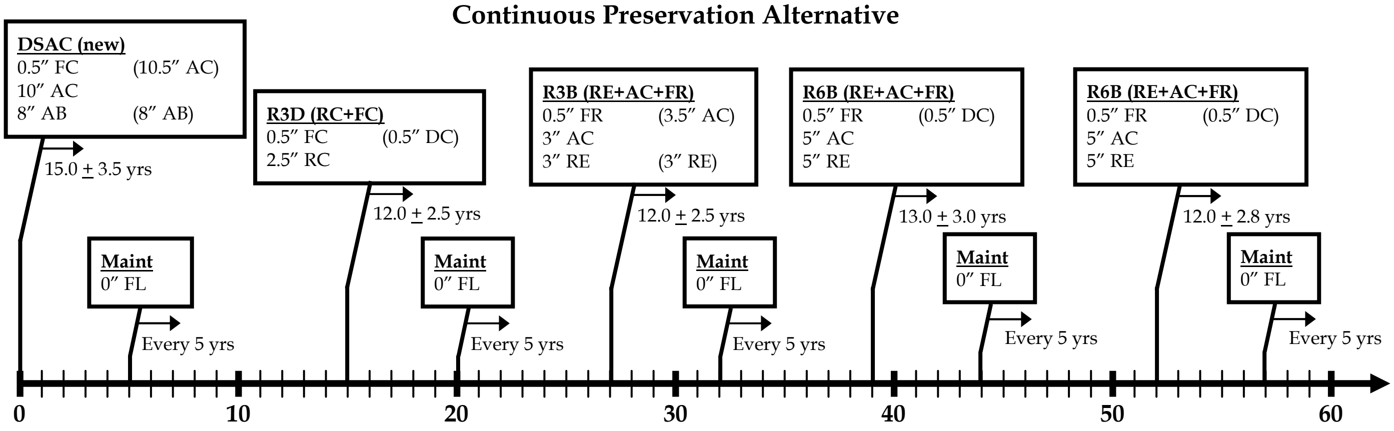
Survival analysis results indicated a median life of 13.2 years and 13.1 million trucks (tables 18 and 19 in chapter 3) for DSAC Interstate pavements in the cool-wet climate. This equates to about 1 million trucks/year, slightly lower than the 1.1 million trucks/year estimated for 2002 for this section. Because the 13.2-year median service life was derived from a limited number of observations (15 total pavement sections) and because mechanistic analysis indicated a service life greater than 20 years for this design, the service life was adjusted upward to 15 years. A standard deviation (1σ) of 3.5 years was applied, corresponding to about one-half the difference between the 75 percent and 25 percent survival probabilities (10.0 and 16.4 years) listed in table 18.

Four sequential rehabilitation treatments—R3D, R3B, R6B, and R6B—were established for the continuous preservation alternative, corresponding to the types of treatments typically performed in the Flagstaff District in recent years. Performance lives were assigned in accordance with the survival analysis results provided in tables 22 and 23 in chapter 3. To account for traffic growth and deterioration of the pavement layers over time, the life of each treatment was adjusted downward by 1 year for each rehabilitation cycle, starting with the second cycle. Also, for probabilistic LCCA purposes, the fourth treatment (R6B) was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 64 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 0.75-in mill-and-replacement with asphalt friction course (FC) was used to delay each reconstruction event by 5 years. Hence, the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Years 20, 40, and 60.
- Reconstruct Alternative 2—Year 32.
- Reconstruct Alternative 3—Year 44.

Continuous Preservation Alternative



Year	**Activity Sequence for Reconstruction Alternatives**		
	Reconstruct Alt. #1	**Reconstruct Alt. #2**	**Reconstruct Alt. #3**
15	M2A (RE+FC) (5.0 ± 0.0 yrs) 0.75″ FC 0.75″ RE	R3D (RC+FC) (12.0 ± 2.5 yrs) 0.5″ FC (0.5″ DC) 2.5″ RC Maint: FL every 5 yrs	R3D (RC+FC) (12.0 ± 2.5 yrs) 0.5″ FC (0.5″ DC) 2.5″ RC Maint: FL every 5 yrs
20	DSAC (Reconstruct) (15.0 ± 3.5 yrs) 0.5″ FC (11.5″ AC) 11″ AC 8″ AB (8″ AB) 18.5″ RE (18.5″ RE) Maint: FL every 5 yrs		
27		M2A (RE+FC) (5.0 ± 0.0 yrs) 0.75″ FC 0.75″ RE	R3B (RE+AC+FR) (12.0 ± 2.5 yrs) 0.5″ FR (3.5″ AC) 3″ AC 3″ RE (3″ RE) Maint: FL every 5 yrs
32		DSAC (Reconstruct) (15.0 ± 3.5 yrs) 0.5″ FC (11.5″ AC) 11″ AC 8″ AB (8″ AB) 19″ RE (19″ RE) Maint: FL every 5 yrs	
35	M2A (RE+FC) (5.0 ± 0.0 yrs) 0.75″ FC 0.75″ RE		
39			M2A (RE+FC) (5.0 ± 0.0 yrs) 0.75″ FC 0.75″ RE
40	DSAC (Reconstruct) (15.0 ± 3.5 yrs) 0.5″ FC (12.5″ AC) 12″ AC 8″ AB (8″ AB) 19.5″ RE (19.5″ RE) Maint: FL every 5 yrs		
44			DSAC (Reconstruct) (15.0 ± 3.5 yrs) 0.5″ FC (12.5″ AC) 12″ AC 8″ AB (8″ AB) 19.5″ RE (19.5″ RE) Maint: FL every 5 yrs
47		R3D (RC+FC) (11.0 ± 2.25 yrs) 0.5″ FC (0.5″ DC) 2.5″ RC Maint: FL every 5 yrs	

Figure 64. Life-cycle models for analysis cell 8—DSAC interstate pavement, cool-wet climate.

Year	**Activity Sequence for Reconstruction Alternatives**		
	Reconstruct Alt. #1	**Reconstruct Alt. #2**	**Reconstruct Alt. #3**
55	M2A (RE+FC) (5.0 ± 0.0 yrs) 0.75″ FC 0.75″ RE		
58		M2A (RE+FC) (5.0 ± 0.0 yrs) 0.75″ FC 0.75″ RE	
59			R3D (RC+FC) (10.0 ± 2.0 yrs) 0.5″ FC (0.5″ DC) 2.5″ RC Maint: FL every 5 yrs
60	DSAC (Reconstruct) (15.0 ± 3.5 yrs) 0.5″ FC (13.5″ AC) 13″ AC 8″ AB (8″ AB) 19.5″ RE (19.5″ RE) Maint: FL every 5 yrs		

Figure 64. Life-cycle models for analysis cell 8—DSAC interstate pavement, cool-wet climate (continued).

ANALYSIS CELL 9

Figure 65 shows the alternative life-cycle models developed for analysis cell 9—DSAC Non-Interstate pavement located in a hot-dry climate. The representative pavement section is US 93, MP 40-41 in Mohave County, which is in the Kingman District. This section of highway is a 4-lane rural interstate, with 12-ft travel lanes and 4-ft inside and 10-ft outside shoulders. The section had a 2002 ADT (1-way) of approximately 9,000 vehicles/day, and the 11 percent trucks on this facility yields an estimated 0.35 million trucks/year (LDF=0.9).

The cross-section established for the initial mainline structure consists of 7.5 in of AC on 4 in of aggregate base. Partial-depth asphalt shoulders have been assumed to accompany the mainline structure.

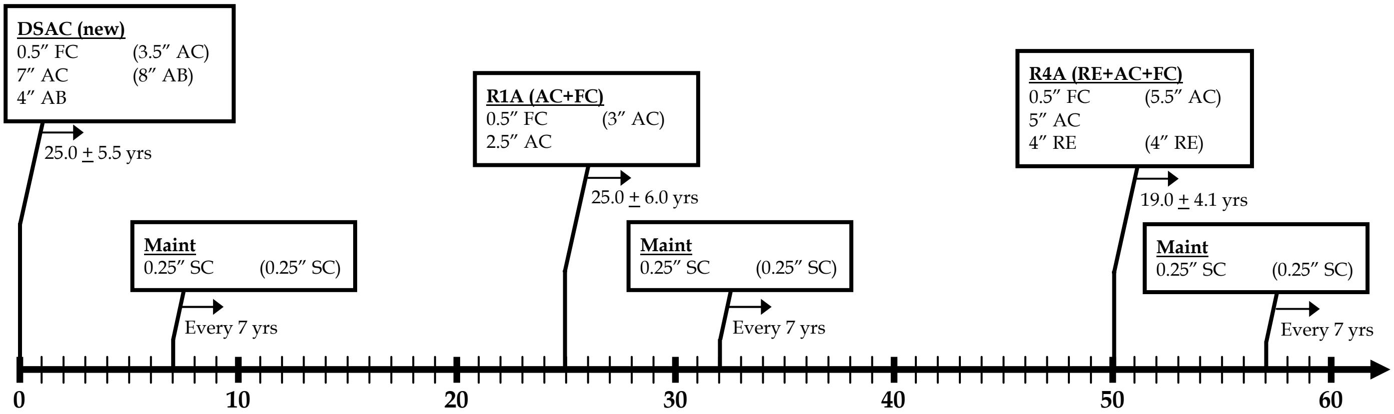
Survival analysis results indicated a median life of 23.9 years and 12.4 million trucks (tables 18 and 19 in chapter 3) for DSAC Non-Interstate pavements in the hot-dry climate. This equates to about 0.5 million trucks/year, a little higher than the 0.35 million trucks/year estimated for 2002 for this section. For purposes of LCCA, the 23.9-year median service life was adjusted upward to 25 years. A standard deviation (1σ) of 5.5 years was applied, corresponding to about one-half the difference between the 75 percent and 25 percent survival probabilities (18.7 and 29.1 years) listed in table 18.

Two sequential rehabilitation treatments—R1A and R4A—were established for the continuous preservation alternative, corresponding to the types of treatments typically performed in the Kingman District in recent years. Performance lives were assigned in accordance with the survival analysis results provided in tables 22 and 23 in chapter 3. To account for traffic growth and deterioration of the pavement layers over time, the life of each treatment was adjusted downward by 2 years for each rehabilitation cycle, starting with the second cycle. Also, for probabilistic LCCA purposes, the second treatment (R4A) was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 65 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 1-in asphalt friction course (FC) was used to delay each reconstruction event by 6 years. Hence, the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Year 31.
- Reconstruct Alternative 2—Year 56.
- Reconstruct Alternative 3—None. For the 60-year analysis period, the activity sequence for this alternative is the same as for continuous preservation. However, the first event after the 60-year analysis period is different for the two alternatives. For the continuous preservation alternative, the next event is the R4A rehabilitation treatment, whereas for Alternative 3, the next event is M2A

Continuous Preservation Alternative



Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	**Reconstruct Alt. #2**	**Reconstruct Alt. #3**
25	M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)	R1A (AC+FC) (25.0 ± 6.0 yrs) 0.5″ FC (3″ AC) 2.5″ AC Maint: SC every 7 yrs	R1A (AC+FC) (25.0 ± 6.0 yrs) 0.5″ FC (3″ AC) 2.5″ AC Maint: SC every 7 yrs
31	DSAC (Reconstruct) (25.0 ± 5.5 yrs) 0.5″ FC (4.5″ AC) 8″ AC (8″ AB) 4″ AB 13.5″ RE (13.5″ RE) Maint: SC every 7 yrs		
50		M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)	R4A (RE+AC+FC) (19.0 ± 4.1 yrs) 0.5″ FC (5.5″ AC) 5″ AC 4″ RE (4″ RE)
56	M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)	DSAC (Reconstruct) (25.0 ± 5.5 yrs) 0.5″ FC (5.5″ AC) 9″ AC (8″ AB) 4″ AB 16.5″ RE (16.5″ RE) Maint: SC every 7 yrs	

Figure 65. Life-cycle models for analysis cell 9—DSAC non-interstate pavement, hot-dry climate.

ANALYSIS CELL 10

Figure 66 shows the alternative life-cycle models developed for analysis cell 10—DSAC Non-Interstate pavement located in a moderate climate. The representative pavement section is SR 90, MP 320-321 in Cochise County, which is in the Safford District. This section of highway is a 2-lane rural highway, with 12-ft travel lanes and 4-ft shoulders. The section had a 2002 ADT (1-way) of approximately 14,000 vehicles/day, and the 10 percent trucks on this facility yields an estimated 0.5 million trucks/year (LDF=1.0).

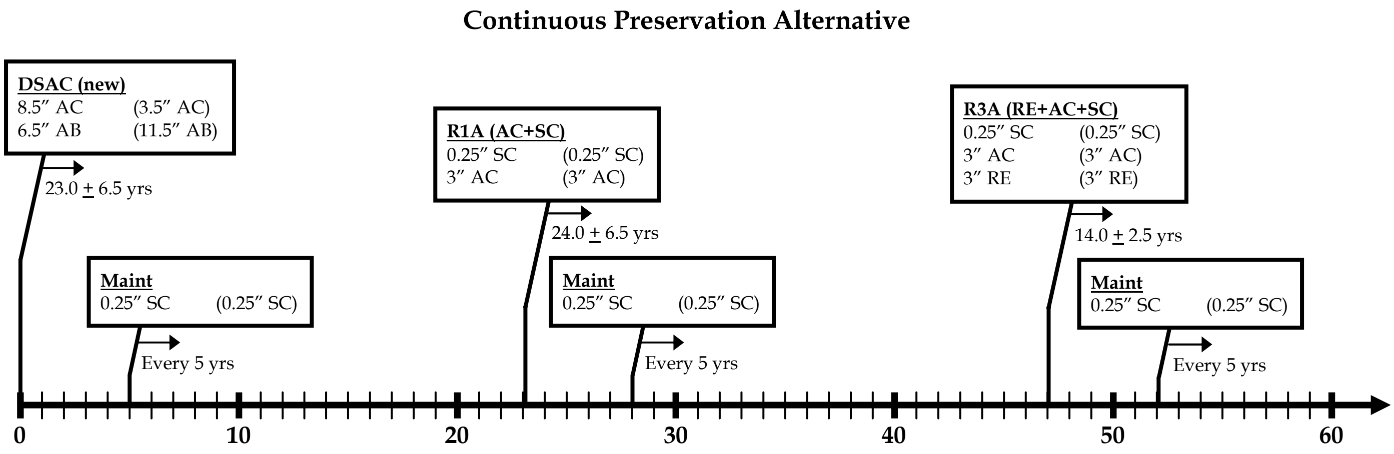
The cross-section established for the initial mainline structure consists of 8.5 in of AC on 6 in of aggregate base. Partial-depth asphalt shoulders have been assumed to accompany the mainline structure.

Survival analysis results indicated a median life of 26.8 years and 6.4 million trucks (tables 18 and 19 in chapter 3) for DSAC Non-Interstate pavements in the moderate climate. This equates to about 0.25 million trucks/year, which is one-half the 0.5 million trucks/year estimated for 2002 for this section. For purposes of LCCA, the 26.8-year median service life was adjusted downward to 23 years. A standard deviation (1σ) of 6.5 years was applied, corresponding to about one-half the difference between the 75 percent and 25 percent survival probabilities (19.9 and 33.7 years) listed in table 18.

Two sequential rehabilitation treatments—R1A and R3A—were established for the continuous preservation alternative, corresponding to the types of treatments typically performed in the Safford District in recent years. Performance lives were assigned in accordance with the survival analysis results provided in tables 22 and 23 in chapter 3. To account for traffic growth and deterioration of the pavement layers over time, the life of each treatment was adjusted downward by 2 years for each rehabilitation cycle, starting with the second cycle. Also, for probabilistic LCCA purposes, the second treatment (R3A) was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 66 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 1-in asphalt friction course (FC) was used to delay each reconstruction event by 6 years. Hence, the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Years 29 and 58.
- Reconstruct Alternative 2—Year 53.
- Reconstruct Alternative 3—None. For the 60-year analysis period, the activity sequence for this alternative is the same as for continuous preservation. However, the first event after the 60-year analysis period is different for the two alternatives. For the continuous preservation alternative, the next event is the R3A rehabilitation treatment, whereas for Alternative 3, the next event is M2A.



Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	Reconstruct Alt. #2	Reconstruct Alt. #3
23	M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)	R1A (AC+SC) (24.0 ± 6.5 yrs) 0.25″ SC (0.25″ SC) 3″ AC (3″ AC) Maint: SC every 5 yrs	R1A (AC+SC) (24.0 ± 6.5 yrs) 0.25″ SC (0.25″ SC) 3″ AC (3″ AC) Maint: SC every 5 yrs
29	DSAC (Reconstruct) (23.0 ± 6.5 yrs) 9.5″ AC (4.5″ AC) 6.5″ AB (11.5″ AB) 17″ RE (17″ RE) Maint: SC every 5 yrs		
47		M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)	R3A (RE+AC+SC) (14.0 ± 2.5 yrs) 0.25″ SC (0.25″ SC) 3″ AC (3″ AC) 3″ RE (3″ RE)
52	M2A (FC) (6.0 ± 0.0 yrs) 1″ FC (1″ AC)		
53		DSAC (Reconstruct) (23.0 ± 6.5 yrs) 10.5″ AC (5.5″ AC) 6.5″ AB (11.5″ AB) 20.5″ RE (20.5″ RE) Maint: SC every 5 yrs	
58	DSAC (Reconstruct) (23.0 ± 6.5 yrs) 10.5″ AC (5.5″ AC) 6.5″ AB (11.5″ AB) 18″ RE (18″ RE) Maint: SC every 5 yrs		

Figure 66. Life-cycle models for analysis cell 10—DSAC non-interstate pavement, moderate climate.

ANALYSIS CELL 11

Figure 67 shows the alternative life-cycle models developed for analysis cell 11—DSAC Non-Interstate pavement located in a cool-wet climate. The representative pavement section is US 180, MP 405-406 in Apache County, which is in the Globe District. This section of highway is a 2-lane rural highway, with 12-ft travel lanes and 5-ft shoulders. The section had a 2002 ADT (1-way) of approximately 1,400 vehicles/day, and the 7 percent trucks on this facility yields an estimated 0.04 million trucks/year (LDF=1.0).

The cross-section established for the initial mainline structure consists of 9.25 in of AC on 6 in of aggregate base. Partial-depth asphalt shoulders have been assumed to accompany the mainline structure.

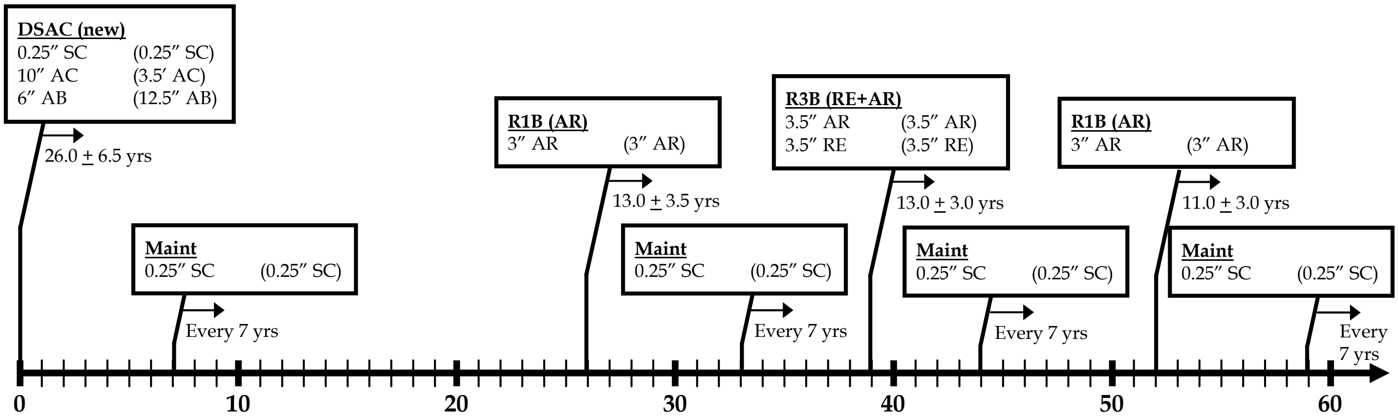
Survival analysis results indicated a median life of 23.2 years and 3.7 million trucks (tables 18 and 19 in chapter 3) for DSAC Non-Interstate pavements in the cool-wet climate. This equates to about 0.16 million trucks/year, which is triple the 0.04 million trucks/year estimated for 2002 for this section. For purposes of LCCA, the 23.2-year median service life was adjusted upward to 26 years. A standard deviation (1σ) of 6.5 years was applied, corresponding to about one-half the difference between the 75 percent and 25 percent survival probabilities (16.8 and 29.5 years) listed in table 18.

Three sequential rehabilitation treatments—R1B, R3B, and R1B—were established for the continuous preservation alternative, corresponding to the types of treatments typically performed in the Globe District in recent years. Performance lives were assigned in accordance with the survival analysis results provided in tables 22 and 23 in chapter 3. To account for traffic growth and deterioration of the pavement layers over time, the life of each treatment was adjusted downward by 1 year for each rehabilitation cycle, starting with the second cycle. Also, for probabilistic LCCA purposes, the third treatment (R1B) was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 67 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 1-in asphalt rubber (AR) overlay was used to delay each reconstruction event by 6 years. Hence, the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Year 32.
- Reconstruct Alternative 2—Year 45.
- Reconstruct Alternative 3—Year 58.

Continuous Preservation Alternative



Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	Reconstruct Alt. #2	Reconstruct Alt. #3
26	M2B (AR) (6.0 ± 0.0 yrs) 1″ AR (1″ AR)	R1B (AR) (13.0 ± 3.5 yrs) 3″ AR (3″ AR) Maint: SC every 7 yrs	R1B (AR) (13.0 ± 3.5 yrs) 3″ AR (3″ AR) Maint: SC every 7 yrs
32	DSAC (Reconstruct) (26.0 ± 6.5 yrs) 0.25″ SC (0.25″ SC) 11″ AC (4.5″ AC) 6″ AB (12.5″ AB) 18″ RE (18″ RE) Maint: SC every 7 yrs		
39		M2B (AR) (6.0 ± 0.0 yrs) 1″ AR (1″ AR)	R3B (RE+AR) (13.0 ± 3.0 yrs) 3.5″ AR (3.5″ AR) 3.5″ RE (3.5″ RE) Maint: SC every 7 yrs
45		DSAC (Reconstruct) (26.0 ± 6.5 yrs) 0.25″ SC (0.25″ SC) 11″ AC (4.5″ AC) 6″ AB (12.5″ AB) 21″ RE (21″ RE) Maint: SC every 7 yrs	
52			M2B (AR) (6.0 ± 0.0 yrs) 1″ AR (1″ AR)
58	M2B (AR) (6.0 ± 0.0 yrs) 1″ AR (1″ AR)		DSAC (Reconstruct) (26.0 ± 6.5 yrs) 0.25″ SC (0.25″ SC) 11″ AC (4.5″ AC) 6″ AB (12.5″ AB) 22″ RE (22″ RE) Maint: SC every 7 yrs

Figure 67. Life-cycle models for analysis cell 11—DSAC non-interstate pavement, cool-wet climate.

ANALYSIS CELL 12

Figure 68 shows the alternative life-cycle models developed for analysis cell 12—JPC pavement located in a hot-dry climate. The representative pavement section is US 60, MP 190-191 in Maricopa County, which is in the Phoenix District. This section of highway is a 6-lane urban freeway, with 12-ft travel lanes and 8-ft inside and 11-ft outside shoulders. The section had a 2002 ADT (1-way) of approximately 80,000 vehicles/day, and the 5 percent trucks on this facility yields an estimated 1.2 million trucks/year (LDF=0.8).

The cross-section established for the initial mainline structure consists of 13 in of PCC on 4 in of aggregate base. Tied concrete shoulders have been assumed to accompany the mainline structure.

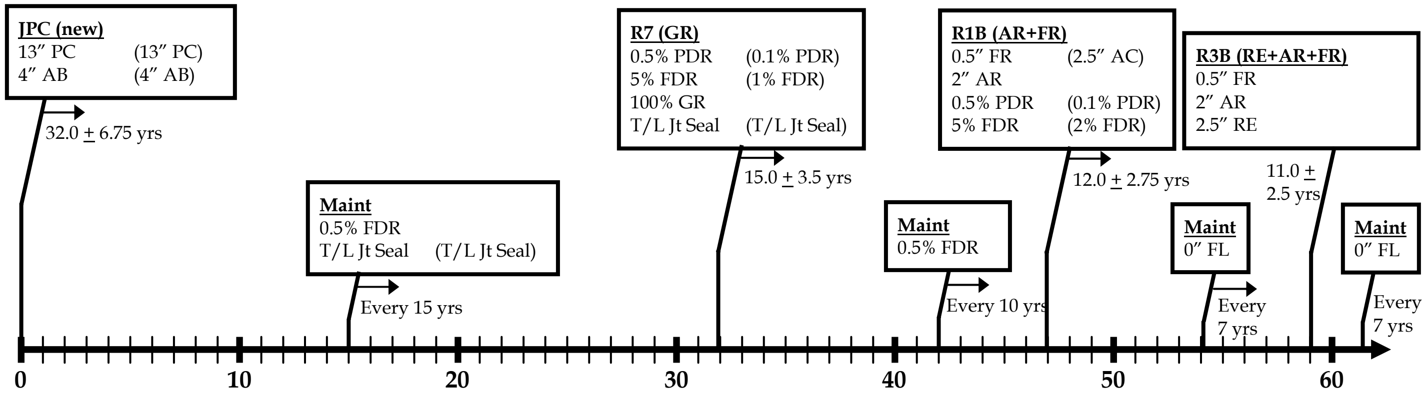
Survival analysis results indicated a median life of 31.6 years and 67.1 million trucks (tables 18 and 19 in chapter 3) for JPC pavements in the hot-dry climate. This equates to about 2.1 million trucks/year, which is considerably higher than the 1.2 million trucks/year estimated for 2002 for this section. For purposes of LCCA, the 31.6-year median service life was adjusted upward slightly to 32 years. A standard deviation (1σ) of 6.75 years was applied, corresponding to about one-half the difference between the 75 percent and 25 percent survival probabilities (25.0 and 38.1 years) listed in table 18.

Three sequential rehabilitation treatments—R7, R1B, and R3B—were established for the continuous preservation alternative. Although the results of survival analysis indicated a median life of 24 years, this value was based on limited data (21 sections) and was deemed to be too high. For this reason, a more conservative estimate of 15 years was used. Because the R1B and R3B treatments had no sections available for analysis in the hot-dry climate, best estimates of their service lives were developed by examining their performance in other climate zones and their performance on AC pavements. Median values of 13 years for each treatment were used, however, to account for traffic growth and deterioration of the pavement layers over time, these values were adjusted downward by 1 year for each rehabilitation cycle, starting with the second cycle. Also, for probabilistic LCCA purposes, the third treatment (R3B) was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 68 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 1-in asphalt rubber friction course (FR) (with limited patching when placed on exposed concrete) was used to delay each reconstruction event by 5 years. Hence, the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Year 32.
- Reconstruct Alternative 2—Year 45.
- Reconstruct Alternative 3—Year 58.

Continuous Preservation Alternative



Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	Reconstruct Alt. #2	Reconstruct Alt. #3
32	M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC) 1% PDR (AC) (0.2% PDR (AC)) 1% FDR (0.2% FDR)	R7 (GR) (15.0 ± 3.5 yrs) 0.5% PDR (0.1% PDR) 5% FDR (1% FDR) 100% GR T/L Jt Seal (T/L Jt Seal)	R7 (GR) (16.0 ± 3.5 yrs) 0.5% PDR (0.1% PDR) 5% FDR (1% FDR) 100% GR T/L Jt Seal (T/L Jt Seal)
37	JPC (Reconstruct) (32.0 ± 6.75 yrs) 13.5″ PC (13.5″ PC) 4″ AB (4″ AB) 18″ RE (18″ RE)		
47		M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC)	R1B (AR+FR) (12.0 ± 2.75 yrs) 0.5″ FR (2.5″ AC) 2″ AR 0.5% PDR (0.1% PDR) 5% FDR (2% FDR)
52		JPC (Reconstruct) (32.0 ± 6.75 yrs) 14″ PC (14″ PC) 4″ AB (4″ AB) 18″ RE (18″ RE)	
59			M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC)

Figure 68. Life-cycle models for analysis cell 12—JPC pavement, hot-dry climate.

ANALYSIS CELL 13

Figure 69 shows the alternative life-cycle models developed for analysis cell 13—JPC pavement located in a cool-wet climate. The representative pavement section is I-17, MP 330-331 in Coconino County, which is in the Flagstaff District. This section of highway is a 4-lane rural interstate, with 12-ft travel lanes and 4-ft inside and 10-ft outside shoulders. The section had a 2002 ADT (1-way) of approximately 25,000 vehicles/day, and the 15 percent trucks on this facility yields an estimated 1.2 million trucks/year (LDF=0.9).

The cross-section established for the initial mainline structure consists of 11 in of PCC on 6 in of aggregate base. Tied concrete shoulders have been assumed to accompany the mainline structure.

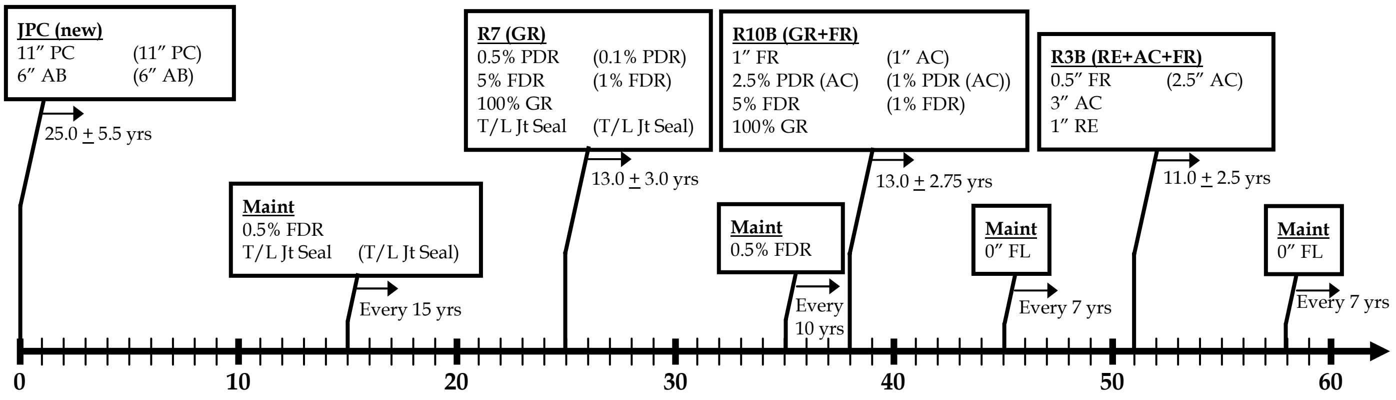
Survival analysis results indicated a median life of 19.6 years and 10.2 million trucks (tables 18 and 19 in chapter 3) for mostly 8-in JPC pavements in the cool-wet climate. Although based on a limited number of pavement sections (27), this equates to about 0.6 million trucks/year, which is about one-half the 1.2 million trucks/year estimated for 2002 for this section. Because this heavier truck traffic would be more than offset by the thicker slab (11 in instead of 8 in), the 19.6-year median service life was adjusted upward to 25 years. A standard deviation (1σ) of 5.5 years was applied as a more reasonable estimate than what would be given by the difference in the 75 percent and 25 percent survival probabilities (19.2 and 19.9 years) listed in table 18.

Three sequential rehabilitation treatments—R7, R10B, and R3B—were established for the continuous preservation alternative. Because no performance estimates for these treatments were available from the survival analysis, best estimates were developed by examining the raw performance data and the performance estimates of similar applications. To account for traffic growth and deterioration of the pavement layers over time, the best estimate values were adjusted downward by 1 year for each rehabilitation cycle, starting with the second cycle. Also, for probabilistic LCCA purposes, the third treatment (R3B) was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 69 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 1-in asphalt rubber friction course (FR) (with limited patching when placed on exposed concrete) was used to delay each reconstruction event by 5 years. Hence, the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Year 32.
- Reconstruct Alternative 2—Year 45.
- Reconstruct Alternative 3—Year 58.

Continuous Preservation Alternative



Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	**Reconstruct Alt. #2**	**Reconstruct Alt. #3**
25	M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC) 1% PDR (AC) (0.2% PDR (AC)) 1% FDR (0.2% FDR)	R7 (GR) (13.0 ± 3.0 yrs) 0.5% PDR (0.1% PDR) 5% FDR (1% FDR) 100% GR T/L Jt Seal (T/L Jt Seal)	R7 (GR) (13.0 ± 3.0 yrs) 0.5% PDR (0.1% PDR) 5% FDR (1% FDR) 100% GR T/L Jt Seal (T/L Jt Seal)
30	JPC (Reconstruct) (25.0 ± 5.5 yrs) 11.5″ PC (11.5″ PC) 6″ AB (6″ AB) 18″ RE (18″ RE)		
38		M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC) 1% PDR (AC) (0.2% PDR (AC)) 1% FDR (0.2% FDR)	R10B (GR+FR) (13.0 ± 2.75 yrs) 1″ FR (1″ AC) 2.5% PDR (AC) (1% PDR (AC)) 5% FDR (1% FDR) 100% GR
43		JPC (Reconstruct) (25.0 ± 5.5 yrs) 11.5″ PC (11.5″ PC) 6″ AB (6″ AB) 18″ RE (18″ RE)	
51			M2B (RE+FR) (5.0 ± 0.0 yrs) 1″ FR 1″ RE
55	M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC) 1% PDR (AC) (0.2% PDR (AC)) 1% FDR (0.2% FDR)		
56			JPC (Reconstruct) (25.0 ± 5.5 yrs) 12″ PC (12″ PC) 6″ AB (6″ AB) 18″ RE (18″ RE)
60	JPC (Reconstruct) (25.0 ± 5.5 yrs) 12″ PC (12″ PC) 6″ AB (6″ AB) 18.5″ RE (18.5″ RE)		

Figure 69. Life-cycle models for analysis cell 13—JPC pavement, cool-wet climate.

ANALYSIS CELL 14

Figure 70 shows the alternative life-cycle models developed for analysis cell 14—JPCD pavement located in a hot-dry climate. The representative pavement section is I-10, MP 154-155 in Maricopa County, which is in the Phoenix District. This section of highway is a 10-lane urban freeway, with 12-ft travel lanes and 13-ft inside and 12-ft outside shoulders. The section had a 2002 ADT (1-way) of approximately 240,000 vehicles/day, and the 9 percent trucks on this facility yields an estimated 4.7 million trucks/year (LDF=0.6).

The cross-section established for the initial mainline structure consists of 12.5 in of PCC on a 4-in AC base. Tied concrete shoulders have been assumed to accompany the mainline structure.

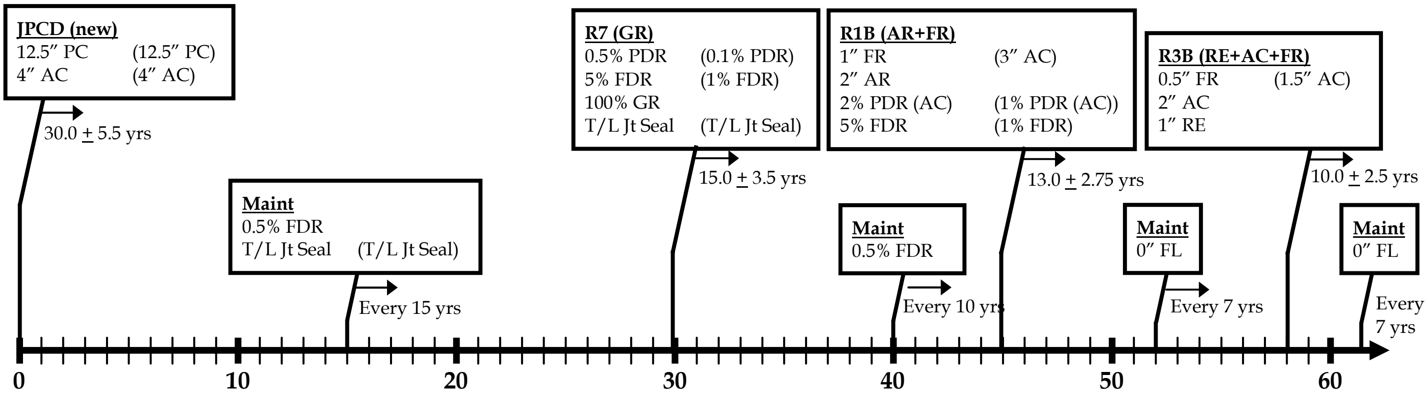
Because service life estimates for JPCD were not available from the survival analysis, a best estimate of 30 years was made for the median service life. Also, a standard deviation of service life of 5.5 years was selected.

Three sequential rehabilitation treatments—R7, R10B, and R3B—were established for the continuous preservation alternative. Because no performance estimates for these treatments were available from the survival analysis, best estimates were developed by examining the raw performance data and the performance estimates of similar applications. To account for traffic growth and deterioration of the pavement layers over time, the best estimate values were adjusted downward by 1 year for each rehabilitation cycle, starting with the second cycle. Also, for probabilistic LCCA purposes, the third treatment (R3B) was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 70 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 1-in asphalt rubber friction course (FR) (with limited patching when placed on exposed concrete) was used to delay each reconstruction event by 5 years. Hence, the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Year 30.
- Reconstruct Alternative 2—Year 50.
- Reconstruct Alternative 3—None.

Continuous Preservation Alternative



Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	Reconstruct Alt. #2	Reconstruct Alt. #3
30	M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC) 1% PDR (AC) (0.2% PDR (AC)) 1% FDR (0.2% FDR)	R7 (GR) (15.0 ± 3.5 yrs) 0.5% PDR (0.1% PDR) 5% FDR (1% FDR) 100% GR T/L Jt Seal (T/L Jt Seal)	R7 (GR) (15.0 ± 3.5 yrs) 0.5% PDR (0.1% PDR) 5% FDR (1% FDR) 100% GR T/L Jt Seal (T/L Jt Seal)
30	JPCD (Reconstruct) (30.0 ± 5.5 yrs) 13″ PC (13″ PC) 4″ AC (4″ AC) 17.5″ RE (17.5″ RE)		
45		M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC) 1% PDR (AC) (0.2% PDR (AC)) 1% FDR (0.2% FDR)	R1B (AR+FR) (13.0 ± 2.75 yrs) 1″ FR (3″ AC) 2″ AR 2% PDR (AC) (1% PDR (AC)) 5% FDR (1% FDR)
50		JPCD (Reconstruct) (30.0 ± 5.5 yrs) 13.5″ PC (13.5″ PC) 4″ AC (4″ AC) 17.5″ RE (17.5″ RE)	
58			M2B (RE+FR) (5.0 ± 0.0 yrs) 1″ FR 1″ RE
60	M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC) 1% PDR (AC) (0.2% PDR (AC)) 1% FDR (0.2% FDR)		

Figure 70. Life-cycle models for analysis cell 14—JPCD pavement, hot-dry climate.

ANALYSIS CELL 15

Figure 71 shows the alternative life-cycle models developed for analysis cell 15—CRC pavement located in a hot-dry climate. The representative pavement section is SR 101L, MP 11-12 in Maricopa County, which is in the Phoenix District. This section of highway is a 6-lane urban freeway, with 12-ft travel lanes and 8-ft inside and 10-ft outside shoulders. The section had a 2002 ADT (1-way) of approximately 75,000 vehicles/day, and the 4 percent trucks on this facility yields an estimated 0.9 million trucks/year (LDF=0.8).

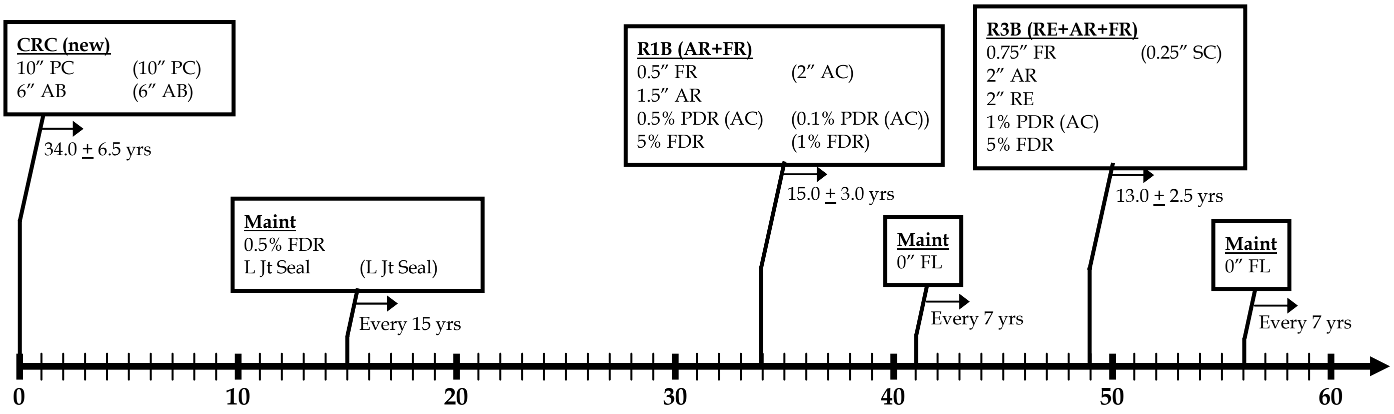
The cross-section established for the initial mainline structure consists of 10 in of PCC on a 6-in aggregate base. Tied concrete shoulders have been assumed to accompany the mainline structure.

Because service life estimates for CRC were not available from the survival analysis, a best estimate of 34 years was made for the median service life. Also, a standard deviation of service life of 6.5 years was selected.

Two sequential rehabilitation treatments—R1B and R3B—were established for the continuous preservation alternative. Because no performance estimates for these treatments were available from the survival analysis, best estimates were developed by examining the raw performance data and the performance estimates of similar applications. To account for traffic growth and deterioration of the pavement layers over time, the best estimate values were adjusted downward by 1 year for each rehabilitation cycle, starting with the second cycle. Also, for probabilistic LCCA purposes, the third treatment (R3B) was repeated, as necessary, beyond the 60-year analysis period.

The bottom part of figure 71 shows the sequence of M&R activities for each reconstruction alternative over the 60-year analysis period. As can be seen, a 1-in asphalt rubber friction course (FR) (with limited patching when placed on exposed concrete) was used to delay each reconstruction event by 5 years. Hence, the timings of reconstruction for each alternative were as follows:

- Reconstruct Alternative 1—Year 39.
- Reconstruct Alternative 2—Year 54.
- Reconstruct Alternative 3—None.



Continuous Preservation Alternative

Year	Activity Sequence for Reconstruction Alternatives		
	Reconstruct Alt. #1	Reconstruct Alt. #2	Reconstruct Alt. #3
34	M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC) 1% PDR (AC) (0.2% PDR (AC)) 1% FDR (0.2% FDR)	R1B (AR+FR) (15.0 ± 3.0 yrs) 0.5% FR (2″ AC) 1.5″ AR 0.5% PDR (AC) (0.1% PDR (AC)) 5% FDR (1% FDR)	R1B (AR+FR) (15.0 ± 3.0 yrs) 0.5% FR (2″ AC) 1.5″ AR 0.5% PDR (AC) (0.1% PDR (AC)) 5% FDR (1% FDR)
39	CRC (Reconstruct) (34.0 ± 5.5 yrs) 10.5″ PC (10.5″ PC) 6″ AB (6″ AB) 17″ RE (17″ RE)		
49		M2B (FR) (5.0 ± 0.0 yrs) 1″ FR (1″ AC) 1% PDR (AC) (0.2% PDR (AC)) 1% FDR (0.2% FDR)	R3B (RE+AR=FR) (13.0 ± 2.5 yrs) 0.75″ FR (0.25″ SC) 2″ AR 2″ RE 1% PDR (AC) 5% FDR
54		CRC (Reconstruct) (34.0 ± 6.5 yrs) 11″ PC (11″ PC) 6″ AB (6″ AB) 19″ RE (19″ RE)	

Figure 71. Life-cycle models for analysis cell 15—CRC pavement, hot-dry climate.

CHAPTER 7. LIFE-CYCLE COST ANALYSIS

INTRODUCTION

This chapter provides a discussion of the life-cycle cost analyses (LCCAs) performed to determine the cost-effectiveness of continuous pavement preservation and the break-even point between the continuous preservation and reconstruction strategies. The discussion covers the LCCA approach and software used to compute life-cycle costs for the alternative strategies, the various LCCA inputs (e.g., project details, analysis options, traffic data, value of user time) utilized in the analyses, and the subsequent results.

LCCA APPROACH AND SOFTWARE

For the economic analyses required by this study, a probabilistic approach was taken using the FHWA's LCCA spreadsheet program, *RealCost* Version 2.1 (FHWA, 2004). Probabilistic LCCA is a simulation technique that accounts for the real-world variability and/or uncertainty associated with the various input parameters (e.g., costs, performance) that are used to compute life-cycle costs. The process entails defining individual input parameters by a frequency (or probability) distribution (rather than by discrete values, as is done in deterministic LCCA) and computing an array of life-cycle costs through iterative sampling of the pre-defined frequency distributions of each input variable. The resulting array of life-cycle costs form a unique probability distribution, which can then be examined and compared with the cost distribution of a competing design alternative.

RealCost was developed by the FHWA in 2002/2003 to support the application of LCCA in the pavement project-level decision-making process. This Microsoft® Excel-based program is built on the principles and best practices outlined in the FHWA's Interim Technical Bulletin on LCCA (Walls and Smith, 1998) and it utilizes the Visual Basic programming functions available within Excel. The program can perform both deterministic and probabilistic modeling and can compute both agency and user (work zone-related) life-cycle costs. The life-cycle costs are in the form of net present value (NPV), which is computed as follows:

$$NPV = Initial\ Cost + \sum Future\ Cost * \left[\frac{1}{(1+i)^n} \right] \qquad \text{Eq. 9}$$

where: NPV = Net present value, \$.
i = Discount rate, percent.
n = Time of future cost, years.

The simulation technique utilized by *RealCost* for probability simulation is the Monte Carlo simulation. As illustrated in figure 72, the Monte Carlo simulation draws values from the probability distributions for each uncertain input variable, and uses these values to compute a single NPV output value. Note that a single iteration of the simulation process represents one possible scenario or outcome. The process of sampling from a probability distribution is repeated until the specified number of iterations is completed or until the simulation process converges. The simulation converges at the point where additional iterations do not significantly change the output distribution (Walls and Smith, 1998).

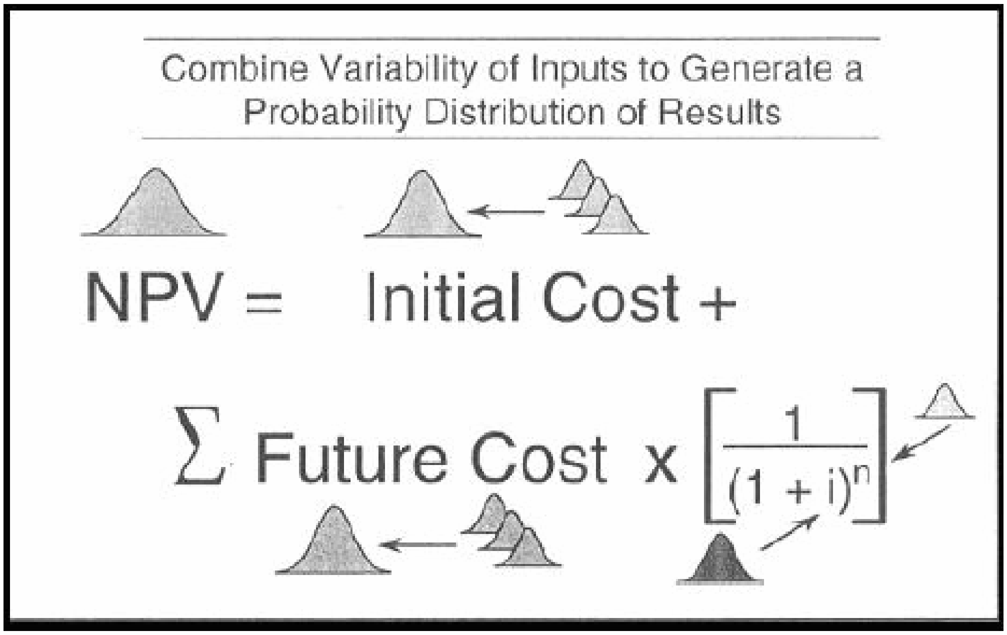


Figure 72. NPV distribution generation (Walls and Smith, 1998).

LCCA INPUTS

Well-developed inputs for the *RealCost* LCCA spreadsheet program are necessary to predict accurate life-cycle costs for pavement alternatives (pavement preservation design or reconstruction approach strategies as discussed in chapter 6) using a probabilistic-based analysis. Provided in the sections below are presentations of the input values used in performing the LCCAs and discussions of how they were derived.

For this study, a normal probability distribution was used for all probabilistic inputs. Moreover, a total of 1,000 simulations were performed for each LCCA. Only two alternatives per LCCA could be considered due to the makeup and structure of the *RealCost* program. For each LCCA, the resulting life-cycle cost distributions for each alternative were compared to determine the more economical alternative.

Project Details

The following inputs were entered into the Project Detail module of *RealCost* to accurately define the projects and design alternatives presented in chapter 6:

- State Route.
- Project Name.
- Region (ADOT District).
- County.
- Analyzed By.
- Begin Milepost.
- End Milepost.
- Lane Width.
- Shoulder Width.

Analysis Options

The following inputs and selections were made as part of the Analysis Options module of *RealCost*:

- Analysis Period—The analysis period is defined as the time period over which the initial and future costs are evaluated for different design alternatives. For the primary assessment of life-cycle costs, a uniform analysis period of 60 years was used, since examinations of up to three reconstruction events were considered. Shorter analysis periods of 40 and 50 years were used for a couple scenarios to examine the impact of analysis period on the life-cycle costs of continuous preservation and reconstruction.
- Discount Rate—The discount rate is very important because it can significantly influence the results of the analysis. The discount rate is a function of both the interest rate and inflation rate. For the primary assessment of life-cycle costs, a discount rate of 4 percent with a standard deviation of 0.4 percent was used to best represent the time value of money. For sensitivity analysis purposes, discount rates of 0, 4, and 8 were used in a couple scenarios.
- Beginning of Analysis Period—The current year (2004) was defined as the beginning of the analysis period.
- Include Agency Cost Residual Value—This option was selected to include salvage value representing the remaining serviceable life of an alternative at the end of the analysis period. The salvage value is calculated as the percentage of the design life remaining at the end of the analysis period multiplied by the cost of the last rehabilitation of the alternative.
- Include User Costs in Analysis—This option was selected to include work zone-related user costs in the analysis.

- User Cost Computation Method—"Calculated" was selected to allow the work zone related user cost to be computed by the LCCA2002 program. "Specified" can be selected so that manually computed user costs can be entered in Alternative 1 and/or Alternative 2 modules.
- Traffic Direction—"Both" was selected to include analysis of rehabilitation of both directions of the project section. "Inbound" can be selected to analyze the inbound direction or "Outbound" can be selected to analyze the outbound direction of the project section.
- Include User Costs Residual Value—This option, which is a new concept, allows the user to indicate whether the residual value of the user cost associated with the last rehabilitation of an alternative should be accounted for when the last rehabilitation is expected to last beyond the analysis period. User cost residual value is calculated as the total user cost during the last rehabilitation multiplied by the percentage of the remaining life of the last rehabilitation. This option was not selected due to unfamiliarity with its consequences on life-cycle costs.

Table 47 summarizes the selections made in the Analysis Options module.

Table 47. Summary of the selections made for the Analysis Options module.

Input Variable	Value
Analysis period, yrs	60 (40 and 50 also examined)
Include User Costs in Analysis	Yes
Include User Cost Remaining Service Life Value	No
Use Differential User Costs	Yes
User Cost Computation Method	Calculated
Include Agency Cost Remaining Service Life Value	Yes
Traffic Direction	Both
Beginning of Analysis Period	2004
Discount Rate, percent	4 (0 and 8 also examined)

Traffic Data

The following inputs define the traffic data for both the continuous preservation and reconstruction pavement strategies.

- AADT (Both Directions) Construction Year—Annual average daily traffic for both directions of roadway corresponding to the initial construction year. Each AADT value entered was for the specific roadway section selected for the analysis cell.

- Single Trucks as Percentage of AADT Year—Number of single-unit trucks as a percentage of AADT for both directions of the roadway. Each percentage of single trucks entered was for the specific roadway section selected for the analysis cell.
- Combo Unit Trucks as Percentage of AADT Year—Number of combination-unit trucks as a percentage of AADT for both directions of the roadway. Each percentage of combination unit trucks entered was for the specific roadway section selected for the analysis cell.
- Annual Growth of Traffic—Annual growth rate of traffic in percent. A 2.5 percent average growth rate with a standard deviation 0.4 percent was entered for each analysis cell.
- Speed Limit Under Normal Conditions—Speed limit (in miles per hour [mi/hr]) under normal conditions or when a work zone is not in place. The current Arizona State maximum speed limit of 75 mi/hr for rural freeways and 55 mi/hr for divided highway, undivided highway, and urban freeway was entered for the normal condition speed limit.
- Lanes Open in Each Direction Under Normal Operation Year—Number of lanes open during normal operations. The maximum number of lanes was entered for the specific roadway section selected for the analysis cell.
- Free Flow Capacity—Free flow capacity is the maximum capacity, in vehicles per hour per lane (vphpl) a facility can handle under free flow conditions. Free flow capacity was used in calculating user costs when there was no work zone in place or queue. Free flow capacity is a function of number of factors, including number and width of lanes, shoulder widths, terrain of the roadway and traffic composition.
- Queue Dissipation Capacity—Queue dissipation capacity is the capacity of the roadway, in vehicles per hour per lane (vphpl), when a queue has been formed and is dissipating. Queue dissipation capacity was less than the free flow capacity, even though all lanes were available for traffic. Queue dissipation capacity is used in calculating user costs whenever a queue has been formed and is dissipating.
- Maximum AADT (Both Directions)—When existing traffic and expected growth rate are high, calculated future traffic that is determined from existing AADT compounded by AADT growth rate, could exceed the capacity of the roadway over a 24-hour period. This is not practically possible and is a limitation of the assumptions made regarding the growth rate, future traffic behavior or capacity improvements. The maximum AADT can be used to cap the future AADT at some reasonable levels. It should be less than the 24-hour capacity of the roadway. If this is higher than the 24-hour capacity, future AADT will be capped using an estimated 24-hour capacity in the analysis.
- Maximum Queue Length—Practical maximum length of queue in miles (mi). User costs are calculated on an hourly basis and when the demand (traffic volume) exceeds capacity, queue begins to form. As long as this condition prevails, the queue will continue to grow and may results in calculated or

theoretical queue lengths that are quite large and not practical. When queue length becomes significantly long, what is a long queue varies based on network level traffic condition and other factors, some redistribution of traffic will occur. In these cases, the maximum queue length is intended to account for this in an approximate manner. The maximum queue length could be one or two exits prior to the work zone or an exit that leads to a reasonable alternate route. Calculated queue length is capped at the maximum queue length.
- Rural/Urban Year—Specifies whether the project section is located in a rural or urban area. The entry for this field was specific to the roadway section selected for the analysis cell.

The traffic information used in the analyses was specific to the project being evaluated. A summary of the selected inputs is presented in table 48.

Value of User Time

The following inputs define the value of user time for both the continuous preservation and reconstruction pavement strategies:

- Value of Time for Passenger Cars—Economic value of time for passenger cars, expressed in $/hour, reflects the added cost to passenger cars due to time lost in traveling through work zone. Recommended range for value of time for passenger cars is $10 to $13/hour (Walls and Smith, 1998).
- Value of Time for Single-Unit Trucks—Economic value of time for single-unit trucks, expressed in $/hour, reflects the added cost to single unit trucks due to time lost in traveling through work zone. Recommended range for value of time for single unit trucks is $17 to $20/hour (Walls and Smith, 1998).
- Value of Time for Combination Unit Trucks—Economic value of time for combination trucks, expressed in $/hour, reflects the added cost to combination trucks due to time lost in traveling through work zone. Recommended range for value of time for combination trucks is $21 to $24/hour (Walls and Smith, 1998).

Traffic Hourly Distribution

Since directional hourly traffic distribution data were not available for each of the projects analyzed, the default hourly distributions for various roadway types in urban and rural settings from MicroBenCost was used in this module (NCHRP 1995). The default hourly distribution used is shown in figure 73 for rural and urban project site locations.

Table 48. Summary of traffic information used in LCCA.

Project ID	AADT, veh/day [a]	Cars as Percentage of AADT, %	Percent Single Trucks [b]	Percent Combo Unit Trucks [b]	Annual Growth of Traffic, %	Speed Limit, mi/hr	Lanes Open [c]	Free Flow Capacity, vphpl	Rural or Urban?[d]	Queue Dissipation Capacity, vphpl	Maximum AADT, veh/day [e]	Maximum Queue Length, mi
Cell 1	10,000	77	13	10	2.5	70	2	2,200	Rural	1,800	100,000	4
Cell 2	18,000	72	18	10	2.5	70	2	2,200	Rural	1,800	100,000	4
Cell 3	13,000	85	5	10	2.5	55	1	2,200	Rural	1,800	100,000	4
Cell 4	6,000	84	6	10	2.5	55	2	2,200	Rural	1,800	100,000	4
Cell 5	7,500	83	7	10	2.5	55	2	2,200	Rural	1,800	100,000	4
Cell 6	17,000	66	24	10	2.5	70	2	2,200	Rural	1,800	100,000	4
Cell 7	23,000	75	15	10	2.5	70	2	2,200	Rural	1,800	100,000	4
Cell 8	9,000	79	11	10	2.5	55	2	2,200	Rural	1,800	100,000	4
Cell 9	14,000	80	10	10	2.5	55	1	2,200	Rural	1,800	100,000	4
Cell 10	1,400	83	7	10	2.5	55	1	2,200	Rural	1,800	100,000	4
Cell 11	17,000	66	24	10	2.5	70	2	2,200	Rural	1,800	100,000	4
Cell 12	80,000	85	5	10	2.5	55	3	2,200	Urban	1,800	100,000	4
Cell 13	25,000	75	15	10	2.5	70	2	2,200	Rural	1,800	100,000	4
Cell 14	240,000	81	9	10	2.5	55	5	2,200	Urban	1,800	100,000	4
Cell 15	75,000	86	4	10	2.5	55	3	2,200	Urban	1,800	100,000	4

[a] Both directions, construction year.
[b] Percentage of AADT.
[c] In each direction under normal operation.
[d] Hourly traffic distribution.
[e] Total for both directions.

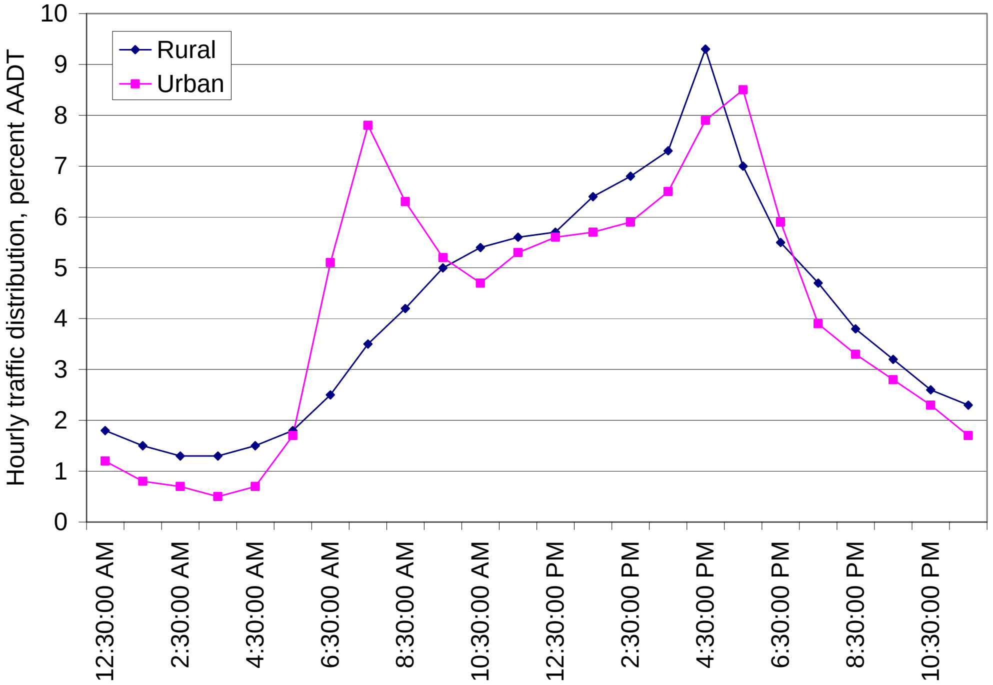


Figure 73. Default hourly distribution used in analysis (for rural and urban project site locations).

Added Vehicle Time and Cost

The default added time and vehicle running cost per 1000 stops and idling costs were used for this module. The costs were escalated to the year 2003 using the built-in function.

Alternative-Level Inputs

The following inputs describe each of the pavement alternatives compared in the LCCAs. Each alternative included an initial construction and six rehabilitation/ reconstruction events/activities.

Alternative Description

The alternative description identifies the pavement alternative (continuous preservation, reconstruction with no prior rehabilitations, reconstruction with 1 prior rehabilitation, reconstruction with 2 prior rehabilitations), pavement type (CAC, DSAC/FDAC, JPC, JPCD, and CRC), county in which the project is located, route name, begin and end milepost, and climate type (hot-dry, moderate, and cool-wet).

Activity Description

The activity description identifies the construction or rehabilitation activity. The activity description defines whether the activity is new construction or a preservation activity. The activity description also includes the cross-section of the pavement.

Agency Construction Costs

The agency construction costs are the individual costs (in $1,000) of the initial pavement structure and each of the subsequent rehabilitation/reconstruction events/activities. These costs were computed using the estimated pay item unit costs listed in table 49 (derived from the analyses of unit costs discussed in chapter 4) and the pay item quantities projected for each event/activity. For the probabilistic LCCA, a standard deviation of 12 percent was applied to each event/activity cost. Additional cost items used in the LCCAs were as follows:

- Traffic control costs—Average daily cost of traffic control, including Traffic Control Labor (4 people, 10 hr days), Sequential Arrow Sign, and Traffic Control Supervisor. A daily cost of $1,080 was used.
- Mobilization—An average mobilization cost of 5 percent of the project total cost was used.
- Sales Tax—An average sales tax of 7.6 percent of the project total cost was used.
- Engineering and Contingencies—An average engineering and contingency cost of 15 percent of the project total cost was used.
- Preliminary engineering costs—An average preliminary engineering cost of 10 percent of the total construction cost was used.

Activity Service Life

The activity service life represents the expected life of the initial pavement structure or the rehabilitated/reconstructed pavement. For this investigation, the service life values used were those defined in the life-cycle models developed and presented in chapter 6. The values were derived from the results of the comprehensive pavement performance analyses described in chapter 3.

User Work Zone Costs

The user work zone costs is the total user cost (in $1,000) of the initial or rehabilitation activities, when "Specified" option is selected for User Cost Computation in the Analysis Options module. This input is disabled when "Calculated" option is selected for User Cost Computation. The User Cost Computation was specified as “Calculated” for all analysis in this study. Table 50 presents a summary of the user work zone unit costs used in the LCCAs.

Table 49. Summary of pay item unit costs used to estimate event/activity costs.

Bid Item	Unit	Description Bid Item Components	Unit Price	Quantity Per Day
Asphalt Concrete Friction Course (FC)	ton	Asphalt Concrete Friction Course	\$28.13	2,000
	ton	Asphalt Cement for ACFC	\$154.03	
	ton	Mineral Admixture for ACFC	\$97.42	
Asphalt Rubber AC Friction Course (FR)	ton	Asphalt Rubber AC Friction Course	\$29.44	2,000
	ton	Asphalt Cement for AR-ACFC	\$274.99	
	ton	Mineral Admixture for AR-ACFC	\$97.42	
Asphalt Concrete (AC)	ton	Asphalt Concrete (3/4" Mix)	\$22.09	2,000
	ton	Asphalt Cement for AC (3/4" Mix)	\$154.03	
	ton	Mineral Admixture for AC (3/4" Mix)	\$97.42	
Asphalt Rubber AC (AR)	ton	Asphalt Rubber AC	\$25.65	2,000
	ton	Asphalt Cement for AR-AC	\$260.48	
	ton	Mineral Admixture for AR-AC	\$97.42	
Asphalt Concrete (Base Mix)	ton	Asphalt Concrete (Base Mix)	\$19.66	2,000
	ton	Asphalt Cement for AC (Base Mix)	\$154.03	
	ton	Mineral Admixture for AC (Base Mix)	\$97.42	
Recycled AC (RO)	ton	Recycled AC	\$18.00	2,000
	ton	Asphalt Cement for Recycled AC	\$158.17	
	ton	Mineral Admixture for Recycled AC	\$97.42	
Seal Coat (SC)	ton	Emulsified Asphalt (CRS-2)	\$180.37	40
	yd^3	Cover Material	\$40.68	800
Tack Coat	ton	Asphalt for Tack Coat	\$163.44	–
	hr	Apply Tack Coat	\$114.25	
Prime Coat	ton	Asphalt for Prime Coat	\$222.79	–
Concrete pavement repair (CPR)	ft^2	Partially Depth Repairs	\$15.51	–
	yd^2	Full Depth Repairs	\$207.83	–
	yd^2	Grind Existing PCC Pavement	\$10.25	–
	ft	Longitudinal Joint Seal	\$0.95	–
	ft	Transverse Joint Seal	\$2.43	–
Aggregate Base (AB), Class 2	yd^3	Aggregate Base, Class 2	\$23.70	2,500
Aggregate Subbase (SM, SB), Class 6	yd^3	Aggregate Subbase, Class 6	\$17.32	2,500

Table 49. Summary of pay item unit costs used to estimate event/activity costs (continued).

Bid Item	Unit	Description Bid Item Components	Unit Price	Quantity Per Day
Bituminous Pavement (milling)	yd^2	Milling depth = 0.5"	\$0.54	20,000
	yd^2	Milling depth = 1.0"	\$0.76	18,000
	yd^2	Milling depth = 2.0"	\$1.10	16,000
	yd^2	Milling depth = 2.5"	\$1.25	15,000
	yd^2	Milling depth = 3.0"	\$1.35	14,000
	yd^2	Milling depth = 3.5"	\$1.40	13,500
	yd^2	Milling depth = 4.0"	\$1.50	13,000
	yd^2	Milling depth = 4.5"	\$1.60	12,500
	yd^2	Milling depth = 5.0"	\$1.70	12,000
JPC (nondoweled PCC)	yd^2	11.0-in PCC	\$27.00	2,500
	yd^2	11.5-in PCC	\$28.00	
	yd^2	12.0-in PCC	\$29.00	
	yd^2	12.5-in PCC	\$30.00	
	yd^2	13.0-in PCC	\$31.00	
	yd^2	13.5-in PCC	\$32.00	
	yd^2	14.0-in PCC	\$33.00	
JPCD (doweled PCC)	yd^2	12.5-in PCC (incl. dowels)	\$33.00	2,200
	yd^2	13.0-in PCC (incl. dowels)	\$34.10	
	yd^2	13.5-in PCC (incl. dowels)	\$35.20	
CRC	yd^2	10.0-in PCC (incl. reinforcing steel)	\$32.50	2,000
	yd^2	10.5-in PCC (incl. reinforcing steel)	\$33.80	
	yd^2	11.0-in PCC (incl. reinforcing steel)	\$35.10	
Pavement Removal	yd^2-in	Removal of Aggregate Base	\$0.20	5,000
	yd^2-in	Removal of AC Pavement	\$0.30	4,000
	yd^2-in	Removal of Non-Reinforced PCC Pavement	\$0.50	3,000
	yd^2-in	Removal of Reinforced PCC Pavement	\$0.60	2,000

Table 50. Summary of user work zone unit costs.

Parameter	Cost
Value of Time for Passenger Cars ($/hour)	$3.08
Value of Time for Single Unit Trucks ($/hour)	$20.95
Value of Time for Combination Trucks ($/hour)	$25.21

Maintenance Frequency

The maintenance frequency is the interval (in years) between routine maintenance activities. A zero is entered when no routine maintenance is included with an initial construction or rehabilitation. The maintenance frequency entered for all analysis cells' alternatives was specific for each initial construction or rehabilitation.

Agency Maintenance Costs

Agency maintenance costs are the routine maintenance costs (in $1,000) for the initial or rehabilitation activities. The agency maintenance costs are applied at the interval specified in the maintenance frequency for the duration of particular activity's life. The agency maintenance costs were calculated in Microsoft® Excel spreadsheets outside of the *RealCost* program using bid items, unit costs, and mainline and shoulder widths for the specific design section selected for each analysis cell. An example maintenance calculation for a JPCD design section with 1% full-depth repairs (FDR), 100% diamond grinding (GR), and longitudinal joint sealing is shown table 51.

Table 51. Example calculation of agency maintenance costs.

<table>
<tr><th colspan="7">Mainline Maintenance Activity - 1% Full Depth Repair</th></tr>
<tr><th>Length (ft)</th><th>Width (ft)</th><th>Area (yd^2)</th><th>Percent</th><th>Unit Cost ($/yd^2)</th><th>Average Cost ($)</th><th>Std. Dev. Cost ($)</th></tr>
<tr><td>5,280</td><td>72</td><td>42,240</td><td>1</td><td>207.83</td><td>$87,787</td><td></td></tr>
<tr><td>5,280</td><td>72</td><td>42,240</td><td>1</td><td>---</td><td></td><td>---</td></tr>
<tr><td colspan="7"></td></tr>
<tr><th colspan="7">Mainline Maintenance Activity - 100% Groove Existing JPCD Pavement</th></tr>
<tr><th>Length (ft)</th><th>Width (ft)</th><th>Area (yd^2)</th><th>Percent</th><th>Unit Cost ($/yd^2)</th><th>Average Cost ($)</th><th>Std. Dev. Cost ($)</th></tr>
<tr><td>5,280</td><td>72</td><td>42,240</td><td>100</td><td>2.62</td><td>$110,669</td><td></td></tr>
<tr><td>5,280</td><td>72</td><td>42,240</td><td>100</td><td>---</td><td></td><td>---</td></tr>
<tr><td colspan="7"></td></tr>
<tr><th colspan="7">Mainline Maintenance Activity - Longitudinal Joint Seal</th></tr>
<tr><th>Length (ft)</th><th>Width (ft)</th><th>Length (LF)</th><th>Percent</th><th>Unit Cost ($/ft)</th><th>Average Cost ($)</th><th>Std. Dev. Cost ($)</th></tr>
<tr><td>5,280</td><td>72</td><td>42,240</td><td>100</td><td>0.95</td><td>$40,128</td><td></td></tr>
<tr><td>5,280</td><td>72</td><td>42,240</td><td>100</td><td>0.09</td><td></td><td>$3,802</td></tr>
<tr><td colspan="5">Total Maintenance Cost</td><td>$238,584</td><td></td></tr>
</table>

Work Zone Length

The work zone is the length of section (in miles [mi]) where the work zone is in place. When large sections of roadway are rehabilitated, construction proceeds in sequence and the work zone is in place only for only a portion of the project. For all analyses, a work zone length of 1 mi was used.

Work Zone Duration

The work zone duration is the total number of days the work zone will be in place to complete the initial or rehabilitation activity for the entire project length. The work zone duration includes all days that the work zone will be in place (restricted travel conditions) and is not limited to the days of construction activity. The work zone duration is the summation of the estimated individual duration of each pay item for the project. The work zone duration was calculated for both alternatives for each analysis cell in an Alternative Agency Cost worksheet.

Work Zone Speed Limit

The work zone speed limit is the speed limit (in miles per hour [mi/hr]) during work zone. The work zone speed limit must be less than the speed limit under normal operating conditions. A work zone speed limit of 45 mi/hr was used for all analysis cells.

Number of Lanes Open in Each Direction During Work Zone

The number of lanes open in each direction during work zone is used to calculate the capacity of the roadway when a work zone is in place and cannot be higher than the number of lanes in each direction of the roadway. The number of lanes open in each direction is 1 less than the total number of lanes in each direction for all analysis cells.

Period of Lane Closure

Three different periods of work zone hours can be specified for each inbound and outbound direction of the roadway. If only one direction of the roadway is being analyzed, then only the number of hours related to that direction needs to be provided. The number of hours needs to be entered using a 24-hour clock. For example, if a work zone is put in place from 10 PM to 5 AM the next day, then this should be entered using two periods as follow: Period 1: 0 hours to 5 hours and Period 2: 22 hours to 24 hours. For all the cells analyzed, the period of lane closure was 9 AM to 5 PM.

SUMMARY OF LCCA RESULTS

A detailed summary of the results of the LCCA is presented for all 15 cells in table 52. This table shows the NPV for each alternative (see chapter 6) at both the mean (50 percent) and 90 percent probability. Figures 74 through 88 provide plots of agency and user costs for each iteration within a given analysis cell.

Sensitivity Analysis

A sensitivity analysis was done by varying the value of critical parameters to determine their impact on cost. This was done at two levels: (1) the impact of critical parameters on estimated cost (NPV) and (2) the impact of critical parameters on optimal timing of reconstruction. At the first level, the critical parameters evaluated included:

- Initial construction cost.
- Initial construction life.
- Initial construction work zone duration.
- Queue dissipation capacity.
- Rehabilitation construction cost.
- Rehabilitation construction life.
- Rehabilitation construction work zone duration.

A summary of the four most significant parameters for analysis cell 3 (2-lane, CAC) and analysis cell 12 (6-lane, JPC) were (1) initial construction cost, (2) initial construction life, (3) discount rate, and (4) value of time for passenger cars.

For the second level of sensitivity analysis the effect of two critical parameters, namely discount rate and analysis period, on costs and, hence the optimal timing of reconstruction, was evaluated. The ranges of the critical parameters evaluated are as follows:

- Discount rate—0, 4, and 8 percent.
- Analysis period—40-, 50-, and 60-years.

The results of the evaluation are presented in figures 89 and 90.

Table 52. Summary of NPV at mean (50 percent) and 90 percent probability.

Project ID	Analysis Type	Alt.	Estimated Cost @ 50 percent Probability, $1,000			Std. Dev., $1,000		Estimated Cost @ 90 percent Probability, $1,000			Mean Cost, $1,000	Difference in Cont. Pres. and Reconst. Alt. Cost, %[1]
			Total	Agency	User	Agency	User	Total	Agency	User		
Cell 1 (CAC)	Cont. Pres.	1	1,815.87	1,768.56	47.31	216.59	18.44	2,203.67	2,125.93	77.74	2,195.19	–
		2	1,833.14	1,783.21	49.93	215.29	19.39	2,220.36	2,138.44	81.92		
		3	1,769.01	1,720.69	48.32	219.4	18.5	2,161.55	2,082.70	78.85		
	Reconst.	1	2,294.65	2,231.20	63.45	284.59	29.33	2,812.62	2,700.77	111.84	2,812.62	+28.13
		2	1,970.10	1,925.41	44.69	234.54	10.62	2,374.61	2,312.40	62.21	2,374.61	+8.17
		3	1,815.01	1,762.14	52.87	220.95	24.43	2,219.89	2,126.71	93.18	2,219.89	+1.13
Cell 2 (CAC)	Cont. Pres.	1	2,332.58	2,068.78	263.80	217.96	85.18	2,832.76	2,428.41	404.35	2,825.20	–
		2	2,336.04	2,079.38	256.66	205.81	82.29	2,811.41	2,418.97	392.44		
		3	2,344.62	2,078.63	265.99	215.35	79.68	2,831.42	2,433.96	397.46		
	Reconst.	1	3,563.12	3,016.95	546.17	359.74	223.68	4,525.76	3,610.52	915.24	4,525.76	+60.19
		2	2,721.32	2,422.70	298.62	257.22	143.24	3,382.08	2,847.11	534.97	3,382.08	+19.71
		3	2,847.53	2,295.65	551.88	261.04	184.04	3,581.91	2,726.37	855.55	3,581.91	+26.78
Cell 3 (CAC)	Cont. Pres.	1	1,457.49	1,188.50	268.99	139.81	60.08	1,787.31	1,419.19	368.12	1,794.64	–
		2	1,469.81	1,197.35	272.46	136.03	63.70	1,799.36	1,421.80	377.57		
		3	1,465.77	1,195.18	270.59	140.49	60.41	1,797.26	1,426.99	370.27		
	Reconst.	1	2,027.30	1,527.84	499.46	221.81	136.86	2,619.11	1,893.83	725.28	2,619.11	+45.94
		2	1,728.11	1,331.65	396.46	192.44	90.95	2,195.70	1,649.18	546.53	2,195.70	+22.34
		3	1,508.28	1,204.61	303.67	156.53	115.41	1,956.98	1,462.88	494.10	1,956.98	+9.05
Cell 4 (CAC)	Cont. Pres.	1	1,021.50	1,017.44	4.06	115.60	0.42	1,212.93	1,208.18	4.75	1,212.36	–
		2	1,024.53	1,020.46	4.07	107.64	0.44	1,202.86	1,198.07	4.80		
		3	1,028.70	1,024.62	4.08	116.28	0.43	1,221.27	1,216.48	4.79		
	Reconst.	1	1,281.70	1,275.72	5.98	182.88	1.19	1,585.42	1,577.47	7.94	1,585.42	+30.77
		2	1,073.38	1,068.45	4.93	151.81	1.22	1,325.88	1,318.94	6.94	1,325.88	+9.36
		3	1,019.72	1,015.65	4.07	115.18	0.51	1,210.61	1,205.70	4.91	1,210.61	-0.14

[1] Positive value means continuous preservation is less expensive alternative. Negative value means reconstruction is less expensive alternative.

Table 52. Summary of NPV at mean (50 percent) and 90 percent probability (continued).

Project ID	Analysis Type	Alt.	Estimated Cost @ 50 percent Probability, $1,000			Std. Dev., $1,000		Estimated Cost @ 90 percent Probability, $1,000			Mean Cost, $1,000	Difference in Cont. Pres. and Reconst. Alt. Cost, %[1]
			Total	Agency	User	Agency	User	Total	Agency	User		
Cell 5 (CAC)	Cont. Pres.	1	1,551.11	1,544.46	6.65	172.97	0.96	1,838.09	1,829.86	8.23	1,833.84	–
		2	1,553.48	1,546.89	6.59	159.69	0.83	1,818.34	1,810.38	7.96		
		3	1,559.91	1,553.28	6.63	172.02	0.82	1,845.10	1,837.11	7.98		
	Reconst.	1	2,274.14	2,260.99	13.15	329.44	3.55	2,823.57	2,804.57	19.01	2,823.57	+53.97
		2	1,794.58	1,785.12	9.46	253.37	2.02	2,215.97	2,203.18	12.79	2,215.97	+20.84
		3	1,569.90	1,562.57	7.33	189.25	2.72	1,886.65	1,874.83	11.82	1,886.65	+2.88
Cell 6 (DSAC)	Cont. Pres.	1	3,001.77	2,409.70	592.07	266.00	176.65	3,732.14	2,848.60	883.54	3,739.32	–
		2	3,001.77	2,409.70	592.07	266.00	176.65	3,732.14	2,848.60	883.54		
		3	3,024.55	2,423.54	601.01	262.55	179.35	3,753.69	2,856.75	896.94		
	Reconst.	1	4,003.26	3,172.20	831.06	340.19	220.44	4,928.30	3,733.51	1,194.79	4,928.30	+31.79
		2	3,651.11	2,734.17	916.94	313.35	323.78	4,702.37	3,251.20	1,451.18	4,702.37	+25.75
		3	3,341.92	2,514.24	827.68	286.92	201.55	4,147.90	2,987.66	1,160.24	4,147.90	+10.92
Cell 7 (DSAC)	Cont. Pres.	1	2,592.61	2,318.62	273.99	257.13	105.07	3,190.24	2,742.88	447.36	3,196.08	–
		2	2,613.58	2,334.88	278.70	250.09	102.79	3,195.83	2,747.53	448.30		
		3	2,612.37	2,332.00	280.37	257.49	99.97	3,202.18	2,756.86	445.32		
	Reconst.	1	3,699.72	3,155.28	544.44	413.44	249.74	4,793.97	3,837.46	956.51	4,793.97	+49.99
		2	2,974.58	2,568.03	406.55	304.08	180.08	3,773.44	3,069.76	703.68	3,773.44	+18.06
		3	2,924.18	2,371.08	553.10	293.38	272.71	3,858.23	2,855.16	1,003.07	3,858.23	+20.71
Cell 8 (DSAC)	Cont. Pres.	1	2,615.76	2,086.16	529.60	231.85	116.80	3,191.03	2,468.71	722.32	3,198.52	–
		2	2,619.30	2,091.21	528.09	229.03	115.70	3,188.10	2,469.11	719.00		
		3	2,633.43	2,101.87	531.56	229.81	123.51	3,216.41	2,481.06	735.35		
	Reconst.	1	1,551.11	1,544.46	6.65	172.97	0.96	1,838.09	1,829.86	8.23	1,829.86	-42.79
		2	1,553.48	1,546.89	6.59	159.69	0.83	1,818.34	1,810.38	7.96	1,810.38	-43.40
		3	1,559.91	1,553.28	6.63	172.02	0.82	1,845.10	1,837.11	7.98	1,837.11	-42.56

[1] Positive value means continuous preservation is less expensive alternative. Negative value means reconstruction is less expensive alternative.

Table 52. Summary of NPV at mean (50 percent) and 90 percent probability (continued).

Project ID	**Analysis Type**	**Alt.**	**Estimated Cost @ 50 percent Probability, $1,000**			**Std. Dev., $1,000**		**Estimated Cost @ 90 percent Probability, $1,000**			**Mean Cost, $1,000**	**Difference in Cont. Pres. and Reconst. Alt. Cost, %[1]**
			Total	**Agency**	**User**	**Agency**	**User**	**Total**	**Agency**	**User**		
Cell 9 (DSAC)	Cont. Pres.	1	1,252.82	1,242.46	10.36	156.02	7.07	1,521.92	1,499.89	22.03	1,520.60	–
		2	1,255.40	1,245.45	9.95	148.67	5.40	1,509.62	1,490.76	18.86		
		3	1,264.32	1,253.83	10.49	154.19	6.99	1,530.27	1,508.24	22.02		
	Reconst.	1	1,505.14	1,492.40	12.74	202.47	10.05	1,855.80	1,826.48	29.32	1,855.80	+22.04
		2	1,256.53	1,245.25	11.28	170.21	8.35	1,551.15	1,526.10	25.06	1,551.15	+2.01
		3	1,243.12	1,233.34	9.78	155.69	6.79	1,511.21	1,490.23	20.98	1,511.21	-0.62
Cell 10 (DSAC)	Cont. Pres.	1	1,549.74	1,260.26	289.48	152.37	85.42	1,942.09	1,511.67	430.42	1,949.26	–
		2	1,549.74	1,260.26	289.48	152.37	85.42	1,942.09	1,511.67	430.42		
		3	1,565.18	1,269.14	296.04	154.72	86.75	1,963.61	1,524.43	439.18		
	Reconst.	1	2,174.70	1,614.18	560.52	247.07	165.52	2,855.47	2,021.85	833.63	2,855.47	+46.49
		2	1,675.63	1,322.47	353.16	193.93	130.18	2,210.41	1,642.45	567.96	2,210.41	+13.40
		3	1,554.68	1,261.33	293.35	158.38	117.53	2,009.93	1,522.66	487.27	2,009.93	+3.11
Cell 11 (DSAC)	Cont. Pres.	1	1,586.12	1,578.52	7.60	202.14	0.93	1,921.19	1,912.05	9.13	1,926.33	–
		2	1,592.04	1,584.43	7.61	195.26	0.96	1,915.80	1,906.61	9.19		
		3	1,597.01	1,589.36	7.65	208.11	0.97	1,941.99	1,932.74	9.25		
	Reconst.	1	1,774.13	1,763.97	10.16	259.09	2.15	2,205.18	2,191.47	13.71	2,205.18	+14.48
		2	1,659.92	1,650.75	9.17	240.90	1.31	2,059.57	2,048.24	11.33	2,059.57	+6.92
		3	1,599.73	1,590.82	8.91	220.85	2.12	1,967.63	1,955.22	12.41	1,967.63	+2.14
Cell 12 (JPC)	Cont. Pres.	1	4,428.11	4,058.91	369.20	463.21	49.44	5,273.98	4,823.21	450.78	5,293.32	–
		2	4,460.92	4,086.95	373.97	449.80	55.55	5,294.75	4,829.12	465.63		
		3	4,455.12	4,082.88	372.24	465.73	53.13	5,311.24	4,851.33	459.90		
	Reconst.	1	5,144.27	4,413.90	730.37	576.74	171.19	6,378.35	5,365.52	1,012.83	6,378.35	+20.50
		2	4,693.80	4,151.43	542.37	547.78	137.24	5,824.08	5,055.27	768.82	5,824.08	+10.03
		3	4,300.65	3,895.98	404.67	493.15	119.48	5,311.49	4,709.68	601.81	5,311.49	+0.34

[1] Positive value means continuous preservation is less expensive alternative. Negative value means reconstruction is less expensive alternative.

Table 52. Summary of NPV at mean (50 percent) and 90 percent probability (continued).

Project ID	Analysis Type	Alt.	Estimated Cost @ 50 percent Probability, $1,000			Std. Dev., $1,000		Estimated Cost @ 90 percent Probability, $1,000			Mean Cost, $1,000	Difference in Cont. Pres. and Reconst. Alt. Cost, %[1]
			Total	Agency	User	Agency	User	Total	Agency	User		
Cell 13 (JPC)	Cont. Pres.	1	3,281.61	2,881.80	399.81	323.43	129.12	4,028.32	3,415.46	612.86	4,053.42	–
		2	3,313.82	2,903.76	410.06	323.82	135.62	4,071.90	3,438.06	633.83		
		3	3,303.22	2,898.99	404.23	329.41	129.27	4,060.04	3,442.52	617.53		
	Reconst.	1	4,338.91	3,175.99	1,162.92	423.92	416.88	5,726.23	3,875.46	1850.77	5,726.23	+41.27
		2	4,130.17	3,044.28	1,085.89	404.06	247.03	5,204.47	3,710.98	1493.49	5,204.47	+28.40
		3	3,757.22	2,951.77	805.45	374.07	419.94	5,067.34	3,568.99	1498.35	5,067.34	+25.01
Cell 14 (JPCD)	Cont. Pres.	1	7,719.74	7,455.96	263.78	828.04	11.92	9,105.67	8,822.23	283.45	9,111.77	–
		2	7,774.01	7,510.21	263.80	800.52	12.09	9,114.82	8,831.07	283.75		
		3	7,774.01	7,510.21	263.80	800.52	12.09	9,114.82	8,831.07	283.75		
	Reconst.	1	8,579.06	8,247.65	331.41	997.04	29.02	10,272.06	9,892.77	379.29	10,272.06	+12.73
		2	8,040.19	7,743.37	296.82	971.01	21.98	9,678.62	9,345.54	333.09	9,678.62	+6.22
		3	7,723.34	7,460.93	262.41	833.09	11.74	9,117.31	8,835.53	281.78	9,117.31	+0.06
Cell 15 (CRC)	Cont. Pres.	1	4,269.59	3,973.21	296.38	471.05	49.24	5,128.07	4,750.44	377.63	5,130.22	–
		2	4,303.37	4,001.42	301.95	453.18	54.07	5,140.33	4,749.17	391.17		
		3	4,255.63	3,958.13	297.50	472.52	52.71	5,122.26	4,737.79	384.47		
	Reconst.	1	4,961.45	4,384.74	576.71	565.76	129.09	6,107.95	5,318.24	789.71	6,107.95	+19.06
		2	4,496.98	4,071.44	425.54	528.17	127.92	5,579.53	4,942.92	636.61	5,579.53	+8.76
		3	4,280.52	3,985.23	295.29	458.56	50.82	5,121.00	4,741.85	379.14	5,121.00	-0.18

[1] Positive value means continuous preservation is less expensive alternative. Negative value means reconstruction is less expensive alternative.

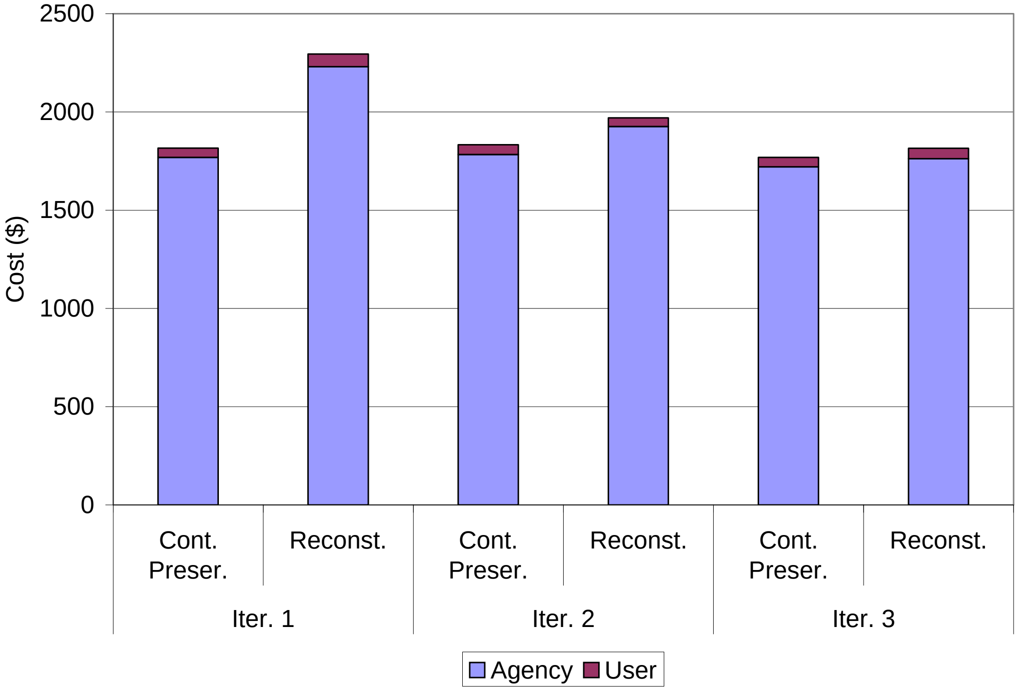


Figure 74. Agency and user costs (50% probability level) for each iteration for analysis cell 1.

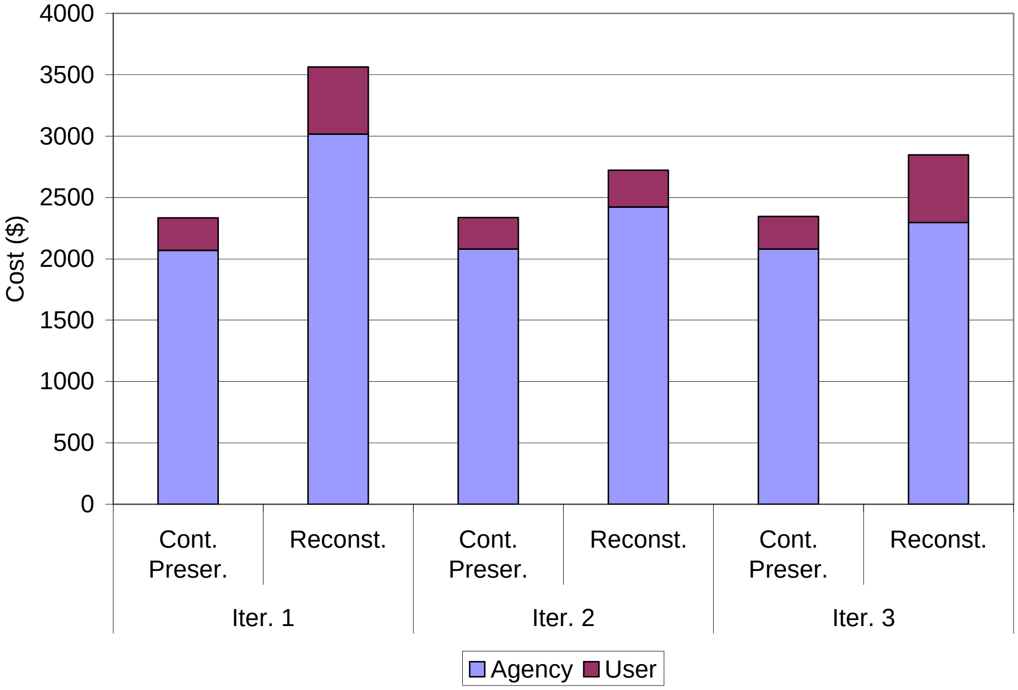


Figure 75. Agency and user costs (50% probability level) for each iteration for analysis cell 2.

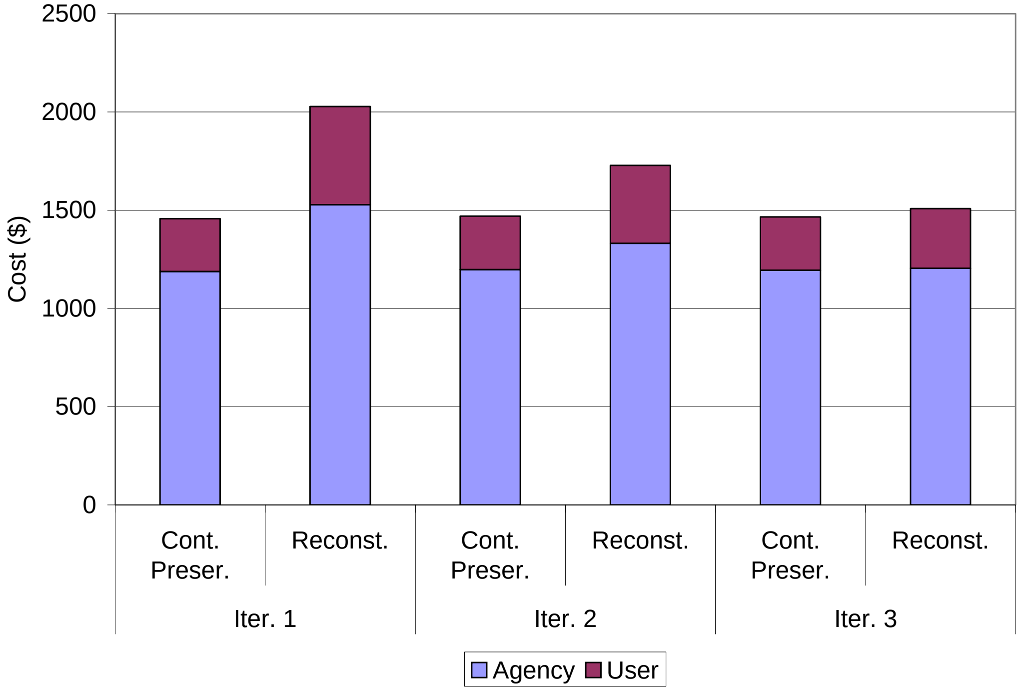


Figure 76. Agency and user costs (50% probability level) for each iteration for analysis cell 3.

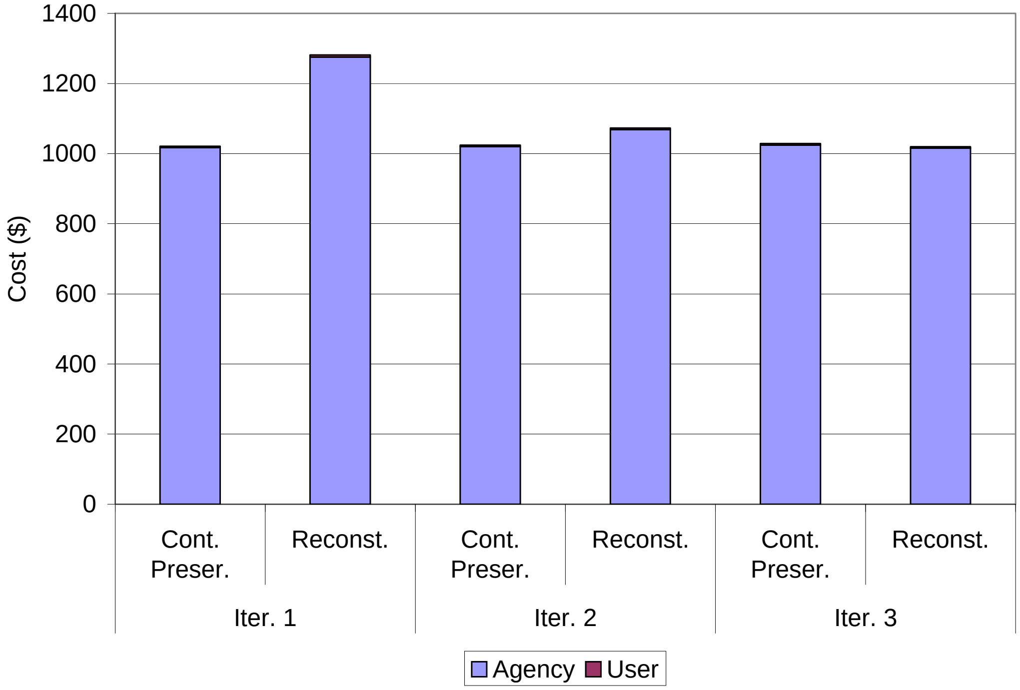


Figure 77. Agency and user costs (50% probability level) for each iteration for analysis cell 4.

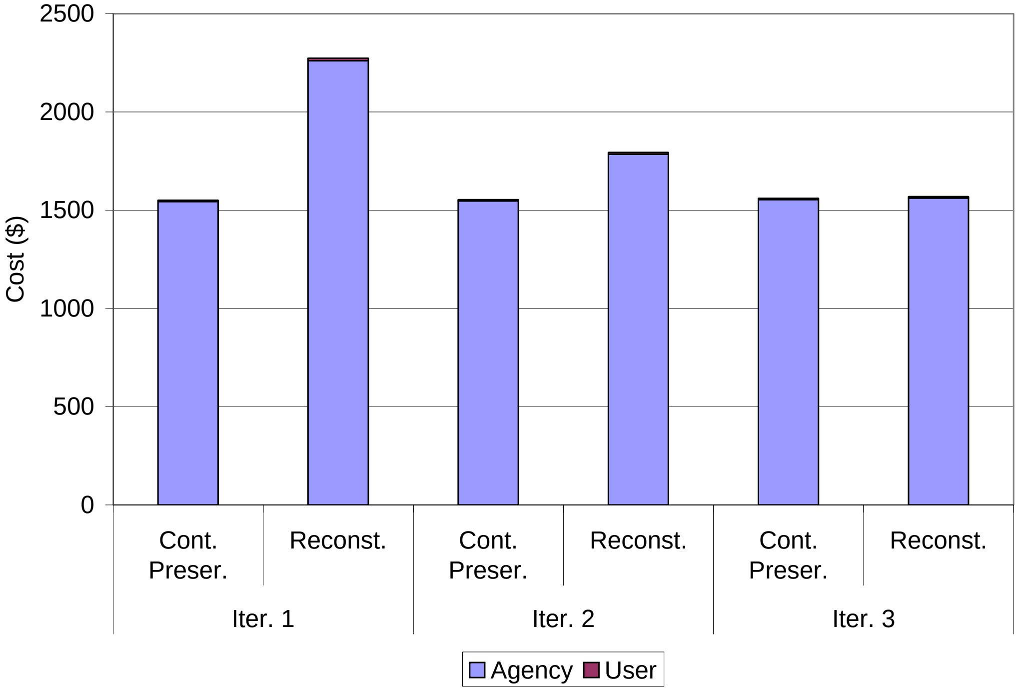


Figure 78. Agency and user costs (50% probability level) for each iteration for analysis cell 5.

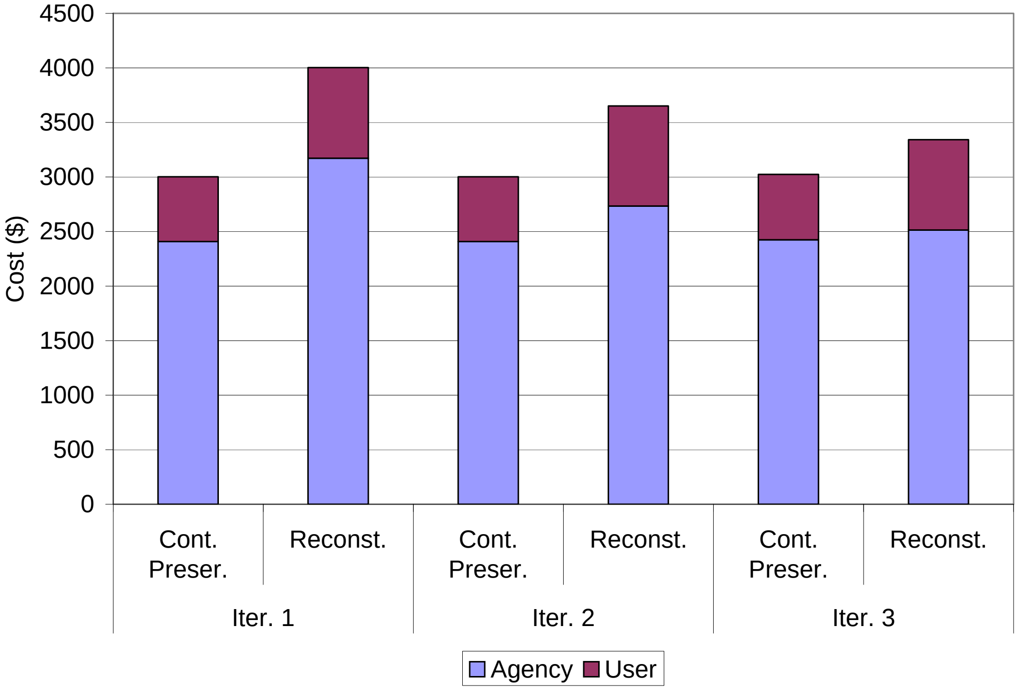


Figure 79. Agency and user costs (50% probability level) for each iteration for analysis cell 6.

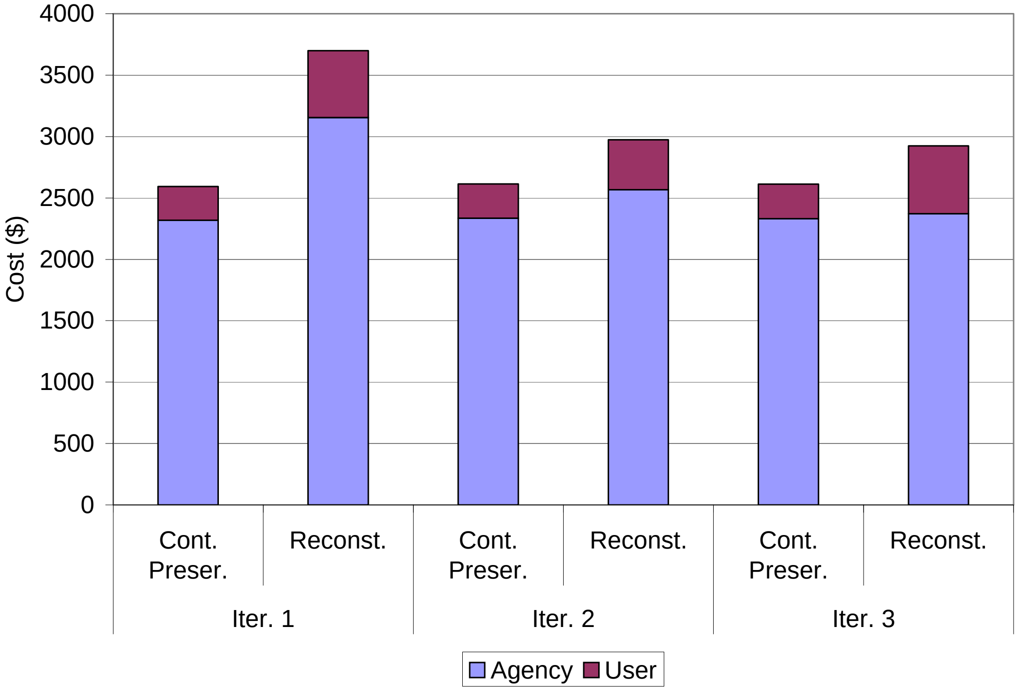


Figure 80. Agency and user costs (50% probability level) for each iteration for analysis cell 7.

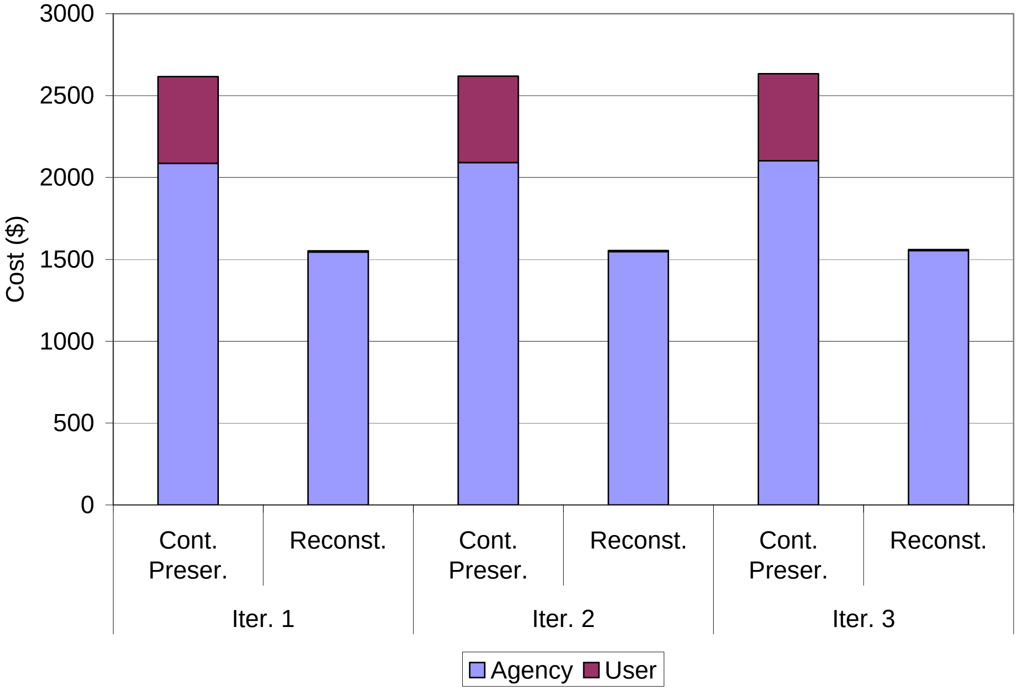


Figure 81. Agency and user costs (50% probability level) for each iteration for analysis cell 8.

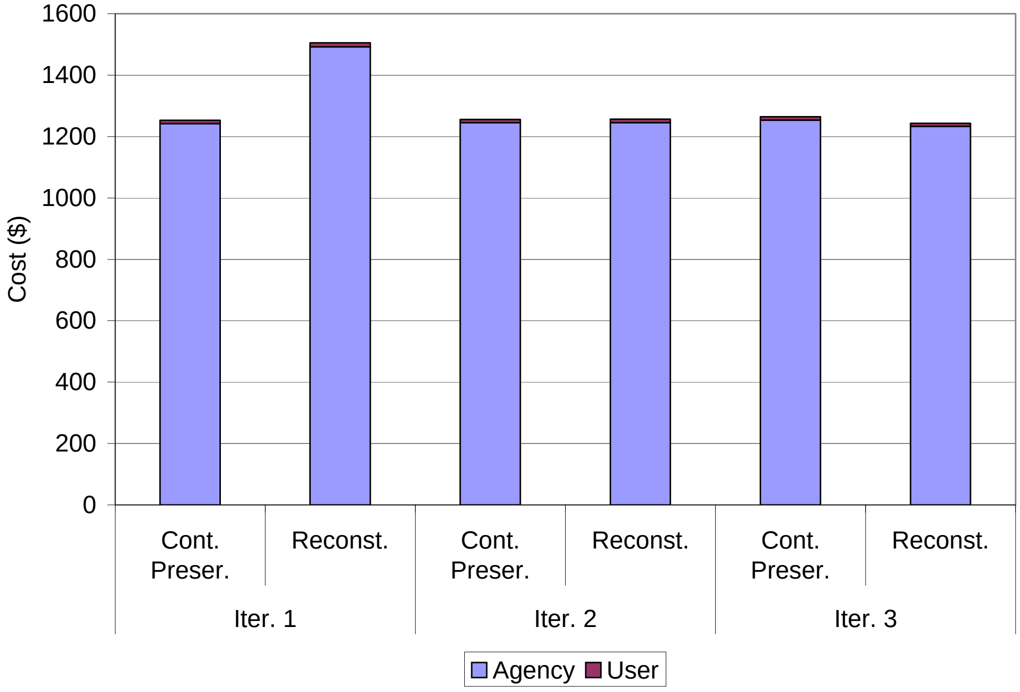


Figure 82. Agency and user costs (50% probability level) for each iteration for analysis cell 9.

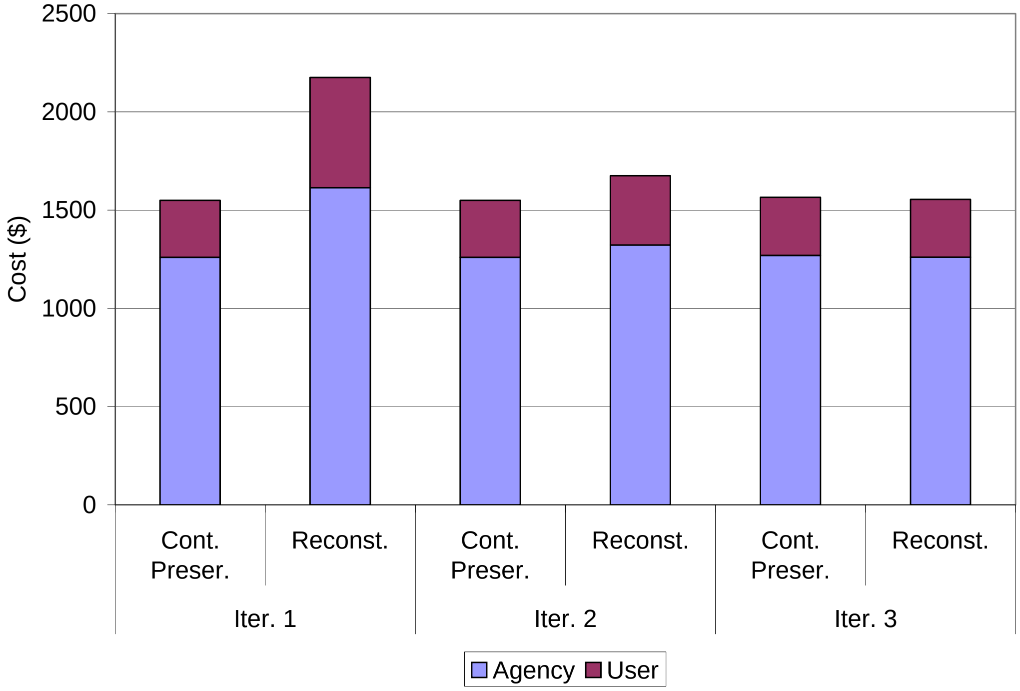


Figure 83. Agency and user costs (50% probability level) for each iteration for analysis cell 10.

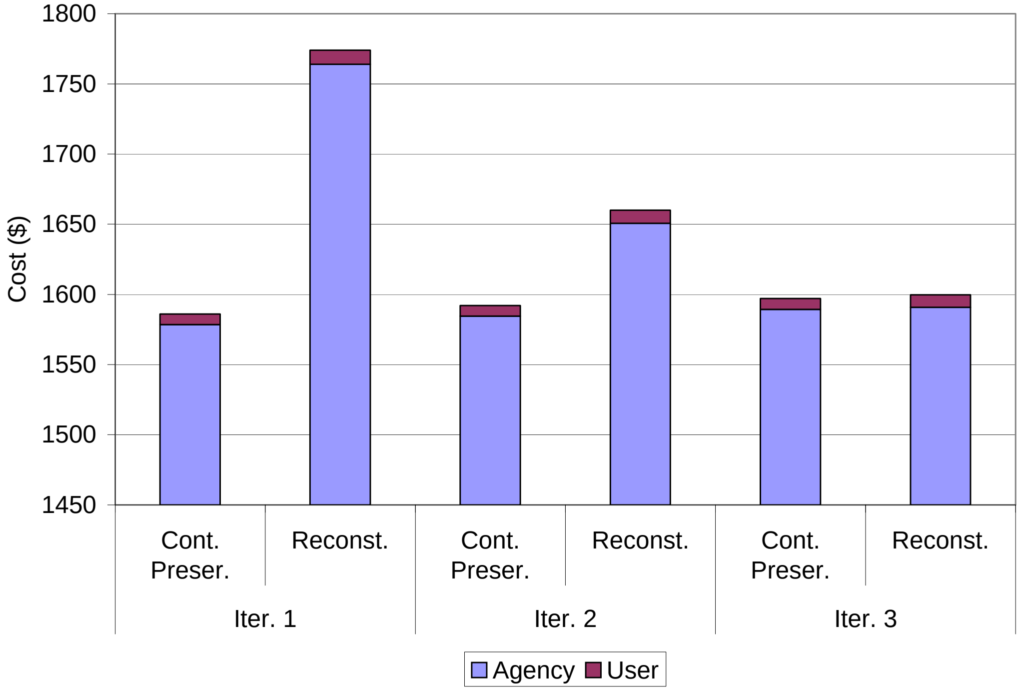


Figure 84. Agency and user costs (50% probability level) for each iteration for analysis cell 11.

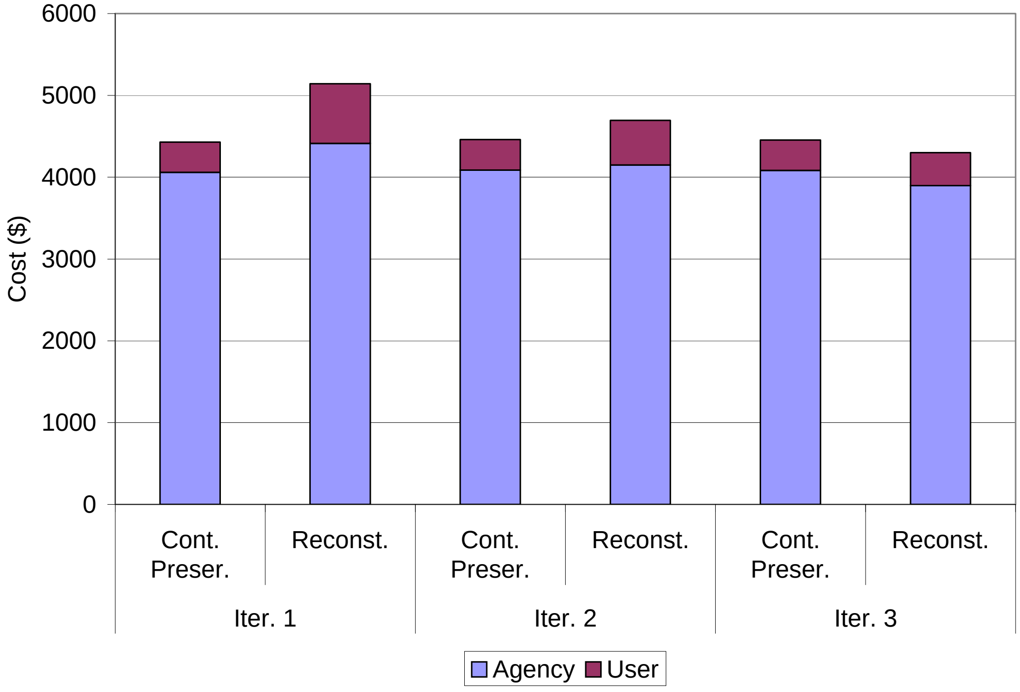


Figure 85. Agency and user costs (50% probability level) for each iteration for analysis cell 12.

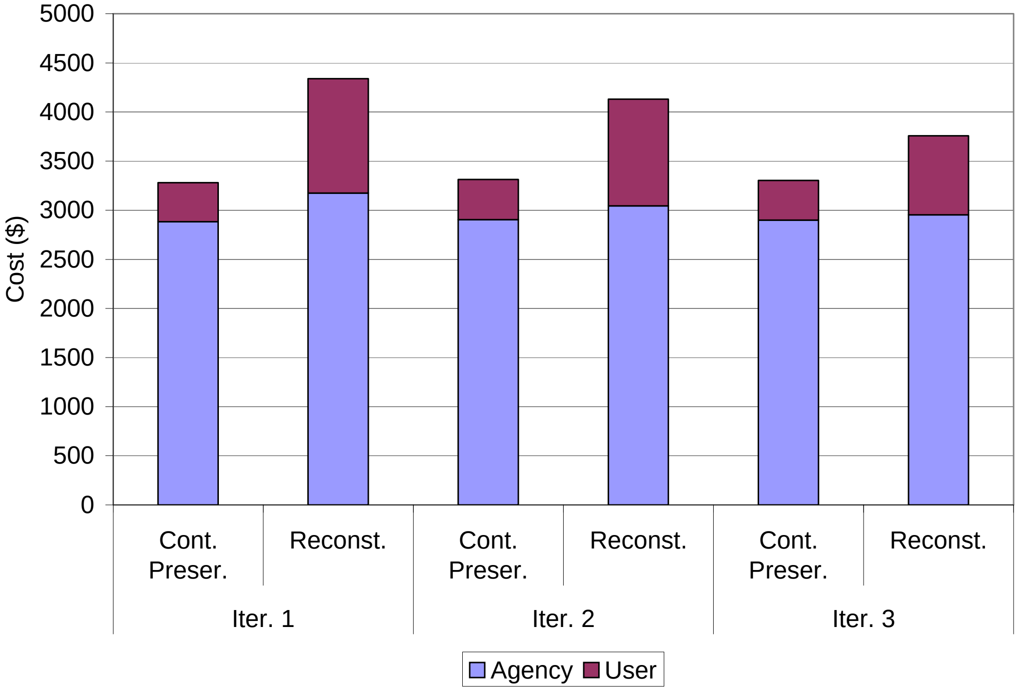


Figure 86. Agency and user costs (50% probability level) for each iteration for analysis cell 13.

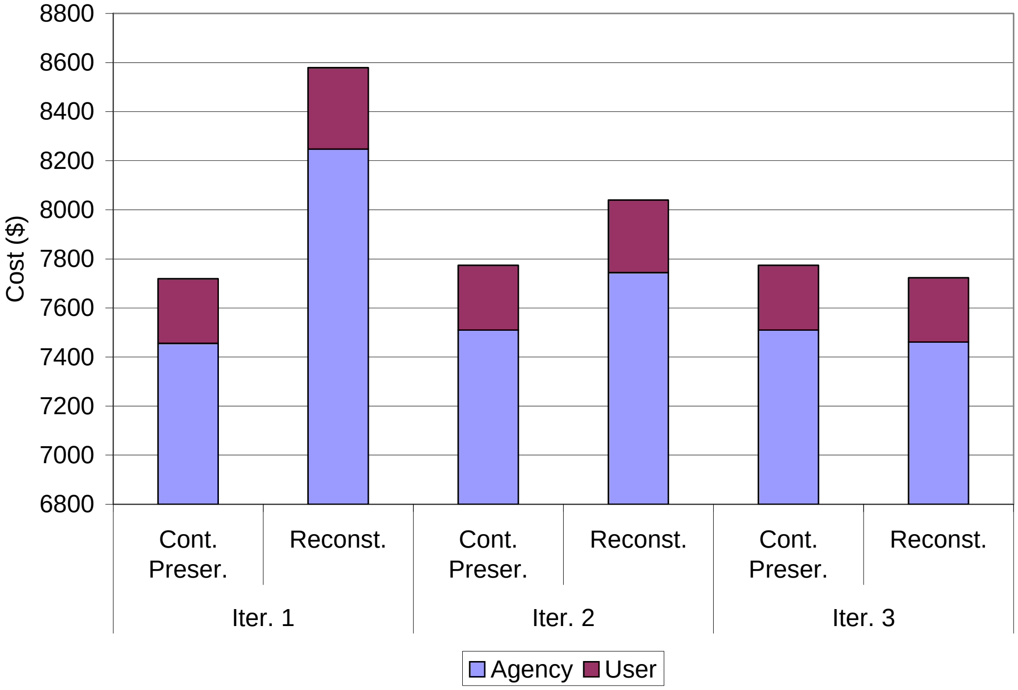


Figure 87. Agency and user costs (50% probability level) for each iteration for analysis cell 14.

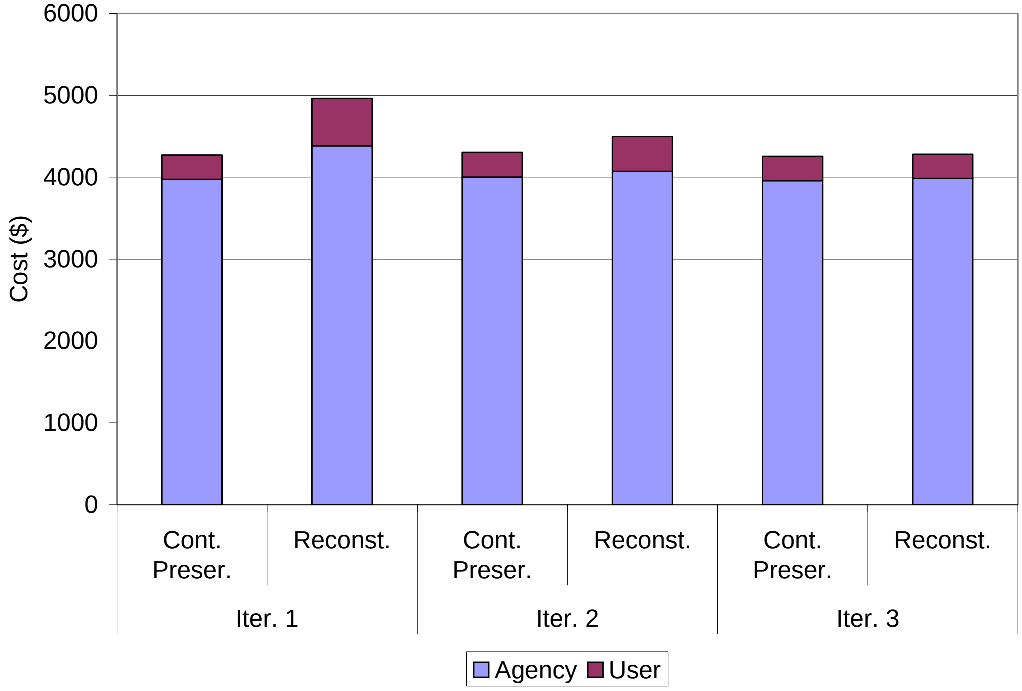


Figure 88. Agency and user costs (50% probability level) for each iteration for analysis cell 15.

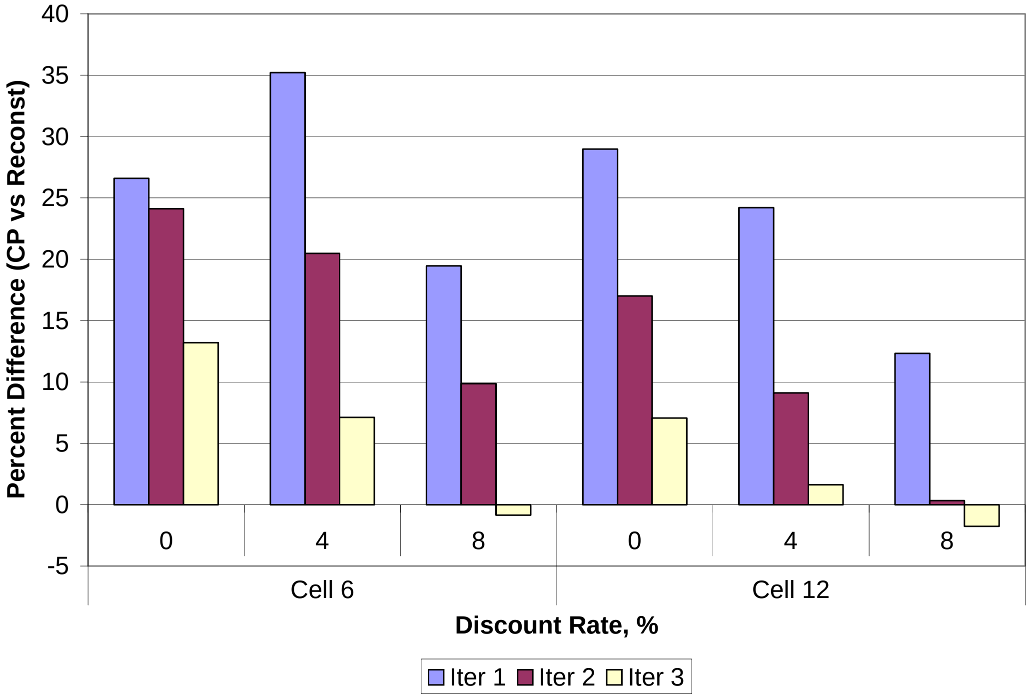


Figure 89. Effect of discount rate on cost difference between continuous preservation and reconstruction alternatives.

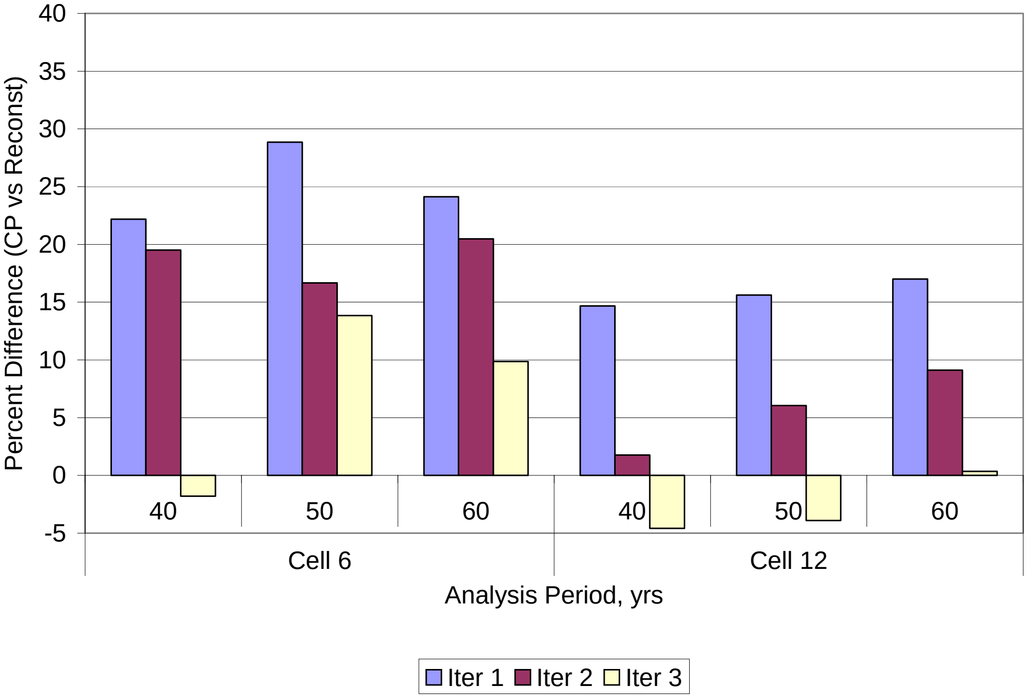


Figure 90. Effect of analysis period on cost difference between continuous preservation and reconstruction alternatives.

The information presented in the figures show the following:

- For both analysis cell 6 and 12, the discount rate does influence the cost difference between continuous preservation and reconstruction alternatives.
- The difference in continuous preservation and reconstruction alternatives cost decreases significantly (i.e., 13 to -1 percent for cell 3 alternative 3 and 7 to -2 percent for cell 12 alternative 3) as the discount rate increases.
- The timing of reconstruction (i.e., after how many rehabilitation events) is influenced by the discount rate, with the number of rehabilitation events required prior to reconstruction decreasing as the discount rate increases.
- For both analysis cells 6 and 12, analysis period had some effect on the cost difference between continuous preservation and reconstruction alternatives.
- The effect of analysis period on cost tended to be project specific. However, in general, a decrease in analysis period resulted in a decrease in the cost difference between continuous preservation and reconstruction alternatives.

The results of the sensitivity analysis summarized above shows that the timing of pavement reconstruction could be affected by the overall strategy applied for pavement rehabilitation and reconstruction. That is, for multilane highways, if reconstruction is staggered and performed only when required for a given lane, overall NPV for that alternative will be reduced. A reduction in NPV for the given reconstruction alternative would result in a forward shift in the timing of reconstruction or a reduction in the number of rehabilitation required prior to reconstruction.

Summary

Transportation agencies responsible for providing and maintaining highways and other related infrastructure are always faced with budgetary constraints. Such constraints typically lead to an implementation of cost-cutting measures leading to a haphazard implementation of developmental plans not in the interest of the user public.

To avoid this situation, ADOT initiated this study to evaluate in-service pavement design, performance, maintenance and rehabilitation, and cost data to determine the cost-effectiveness of commonly applied pavement maintenance, rehabilitation, and reconstruction strategies. The specific goal was to determine the optimum timing of reconstruction after initial construction (i.e., at what point after initial construction and subjecting a pavement to typical M&R strategies will reconstruction be a more cost-effective solution?). The answer to this question is very important since the trade-off between the cost of continuous preservation activities and reconstruction are important to all highway agencies.

All the main elements of highway cost, namely initial capital cost, future maintenance cost, future rehabilitation cost, reconstruction cost, salvage cost at the end of the analysis period, and user cost (traffic delay cost and so on), were considered in the LCCA that was conducted in this study. Results have been presented throughout this chapter.

As per the goal of this study, table 52 gives a summary of the mean cost of pursuing the continuous preservation strategy along with three alternate reconstruction strategies. The reconstruction strategies were typically a combination of minor and major rehabilitation activities at different intensities and frequency prior to reconstruction. The alternate reconstruction strategies can be summarized as follows:

- Alternative 1—Reconstruction immediately after initial construction and a minor rehabilitation activity.
- Alternative 2—Reconstruction after both a minor and major rehabilitation activity.
- Alternative 3—Reconstruction after a minor and two major rehabilitation activities.

Detailed descriptions of all the activities within these alternative strategies have been presented and described in chapter 6.

To fulfill the goals of this study, a comparison of NPV of each alternative reconstruction strategy was done with the continuous preservation strategy to determine when reconstruction was becomes a more cost-effective strategy in a pavement's life. The general trend observed for all the 15 cells analyzed showed that in all cases there was a decrease in NPV as the number of rehabilitation activities prior to reconstruction increased. Specifically, the following was observed:

- Nine of the 15 cells analyzed (60 percent) reported a NPV for reconstruction (alternative 3), less than 3 percent that estimated for continuous preservation. Three of the 15 cell reported NPV for reconstruction (alternative 3), less than that estimated for continuous preservation.
- Two of the 15 cells analyzed, reported a NPV for reconstruction (alternative 3), between 3 to 10 percent of the continuous preservation NPV.
- The remaining 4 cells analyzed, reported a NPV for reconstruction (alternative 3), greater than 10 percent of the continuous preservation NPV.

Figure 91 shows the decline in NPV for as the number of rehabilitation events prior to reconstruction (alternative 1 through alternative 3) increases. The information presented in the plot also shows that mean percentage change in NPV dropped significantly from 25.63 percent for reconstruction alternative 1 to 6.9 percent for rehabilitation alternative 3. With this trend it is reasonable to conclude that reconstruction becomes a feasible cost-effective option only after a minor and 2 major rehabilitation events have been performed.

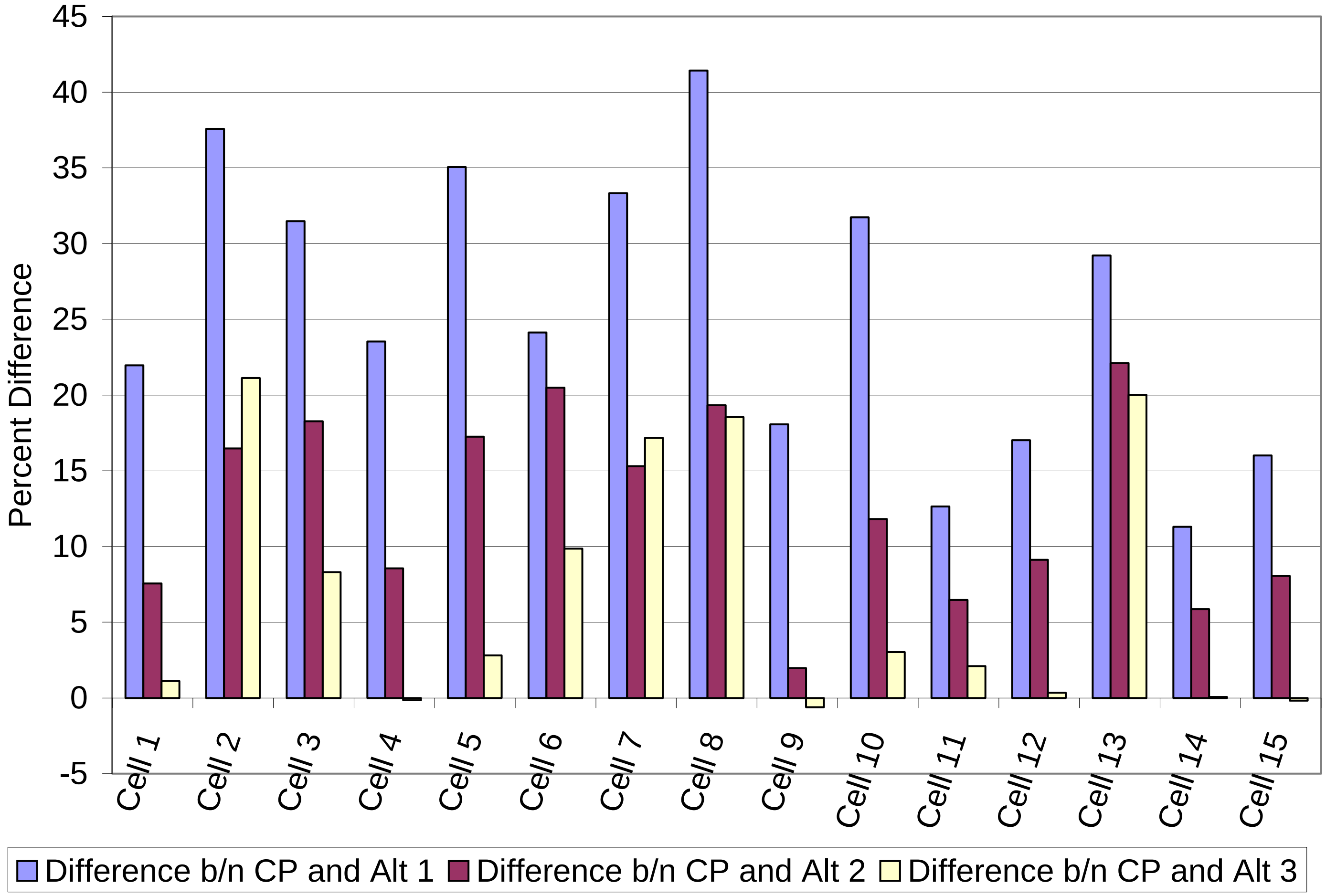


Figure 91. Percent change in NPV between continuous preservation and reconstruction for all analysis cells (alternatives 1 through 3).

CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS

This study examined the performance and costs of asphalt and concrete pavements used on Arizona highways. Both the initial pavement structure type and the series of M&R treatments applied to each structure type over a long time period were evaluated in an effort to determine the cost-effectiveness of the continuous pavement preservation design strategy, as compared to reconstruction.

The pavement types considered in the investigation included conventional asphalt concrete (CAC), deep-strength AC (DSAC), full-depth AC (FDAC), non-doweled jointed plain concrete (JPC), doweled JPC (JPCD), and continuously reinforced concrete (CRC) pavement. Hundreds of M&R treatment types applied to these pavement structures were also considered, but under several broad categories defined by (a) depth of removal (i.e., milling) of existing pavement, (b) treatment application thickness, and (c) type of asphalt mixture used in the treatment.

Pavement life and M&R treatment performance for both asphalt and concrete pavements were evaluated using survival analysis techniques, supplemented by mechanistic–empirical (M–E) performance analysis. The evaluations covered 15 different scenarios defined by key variables of interest and the availability of historical pavement data. These 15 scenarios included the following:

- CAC Pavement
  - Interstate highways in hot-dry and moderate climates.
  - Non-Interstate highways in hot-dry, moderate, and cool-wet climates.
- DSAC and FDAC Pavement
  - Interstate highways in hot-dry, moderate, and cool-wet climates.
  - Non-Interstate highways in hot-dry, moderate, and cool-wet climates.
- JPC Pavement
  - All highways in hot-dry and cool-wet climates.
- JPCD Pavement
  - All highways in hot-dry climate.
- CRC Pavement
  - All highways in hot-dry climate.

Unit costs of initial construction and M&R pay items were analyzed to develop best estimates for use in the LCCA process. Three sources of data were utilized in this analysis—the 1999 Construction Costs report, the 2002 Asphalt Rubber Projects report, and the 1999 Engineer's Estimate.

Also investigated in the study were user cost practices. Both user cost components and user cost models were examined to determine the practices most suitable for use in the LCCA process.

Using the results the various pavement performance analyses, pay item unit costs analyses, and user cost practices evaluation, a comprehensive set of comparative LCCAs were performed. For each of the 15 scenarios described above, a representative section of highway was chosen to serve as a design project, for which the life-cycle costs of continuous preservation and reconstruction approaches could be determined and compared. Customized life-cycle models were developed for each of the following four alternatives for each project:

- Continuous preservation (i.e., continuous stream of rehabilitation treatments).
- Reconstruction with no prior rehabilitation treatments.
- Reconstruction with one prior rehabilitation treatment.
- Reconstruction with two prior rehabilitation treatments.

The established models, along with the best estimates of unit costs and work zone-related user cost inputs, were then entered into the FHWA probabilistic LCCA spreadsheet program, *RealCost*, whereupon life-cycle costs were computed using a 60-year analysis period and 4 percent discount rate. Sensitivity analysis was performed by computing life-cycle costs for a couple projects using variations of the discount rate (0, 4, and 8) and analysis period (40, 50, and 60 years).

CONCLUSIONS

Based on the results of the various analyses performed in this study, the following conclusions are drawn:

Initial Pavement Service Life

- On average, throughout the entire State of Arizona, CAC pavements on Interstate routes in the hot-dry and moderate climates have lasted 15 to 18 years (and carried 15 to 20 million trucks) without significant rehabilitation (defined as receiving a 2-in or greater AC overlay [with or without milling]). On Non-Interstate routes, an average life of between 15 and 27 years (carrying 5 to 7 million trucks) has occurred, with the lower end being most representative of life in the cool-wet environment.
- On average, DSAC/FDAC pavements on Interstate routes have lasted 13 to 19 years (and carried 13 to 20 million trucks) without the need for significant rehabilitation. On Non-Interstate routes, an average life between 23 and 27 years (4 to 12 million trucks) was determined.
- JPC (non-doweled) pavements, mostly 11 to 13 in thick and located on freeways in the hot-dry climate can be expected to last about 31 years (and carry 67 million

trucks), on average, before the need for significant rehabilitation. On average, 8- to 9-in thick JPC (non-doweled) pavements located on freeways in the cool-wet climate have lasted 18 to 20 years (and carried 9 to 11 million trucks).

- Due to no failures, a formal survival analysis of JPCD pavements could not be conducted. However, based on the existing lives and traffic of JPCD pavements and a mechanistic-based performance analysis, 10- to 13-in JPCD pavements located on freeways in the hot-dry climate can be expected to last at least 20 years (and carry at least 100 million trucks) before significant rehabilitation is needed.
- Due to no failures, a formal survival analysis of CRC pavements could not be conducted. However, based on the existing lives and traffic of CRC pavements and a mechanistic-based performance analysis, 9-in CRC pavements located on freeways in the hot-dry climate can be expected to last at least 30 years (and carry at least 25 million trucks) before significant rehabilitation is needed.

M&R Treatment Performance

- The predominant rehabilitation treatments for asphalt pavements in Arizona have been thin conventional overlays (R1), shallow removal and thin overlays (R3), and shallow removal and thick overlays (R4). On Interstate pavements, many deep removal and thick overlay treatments (R6) have also been applied. Although the average lives of these treatments on Interstate routes have been fairly similar (12 to 16 years), the levels of truck traffic have generally corresponded to the scope/size (mill depth and overlay thickness) of the treatment (e.g., 11 to 18 million trucks for R1 treatment, 29 to 36 million trucks for R6 treatment). On Non-Interstate pavements, much longer average service lives have been provided by the R1 treatments as compared to the R3 and R4 treatments (20 to 24 years versus 14 to 18 years); however, lower truck traffic levels have been experienced (3 to 6 million trucks versus 5 to 14 million trucks).
- The predominant treatments for concrete pavements in Arizona have been thin conventional overlays (R1) and diamond grinding (R7). Based on limited data, the average lives and truck traffic for these treatments have been 11 to 14 years and 8 to 15 million cumulative trucks for R1 and 11 to 15 years and 37 to 55 million cumulative trucks for R7.
- The effect of asphalt mixture on rehabilitation treatment life is only partly discernable due to insufficient performance data to date. Current results indicate better performance by asphalt rubber mixes compared to conventional asphalt mixes when used with some treatments (thin conventional overlays [R1] on Non-interstate pavements) and worse performance when used with others (shallow removal and thin overlays [R3] placed on Interstate pavements). Moreover, similar or better performance has been experienced by some treatments (R3 on Interstate and Non-Interstate pavements) using recycled asphalt mixes, as compared to conventional asphalt mixes. The performance of treatments using SuperPave asphalt mixes was not evaluated due to the lack of performance data.

Climatic Effects

- The effect of climate on initial pavement life and rehabilitation treatment performance was most significant for the cool-wet climatic zone. Although some differences in asphalt pavement performance existed between the hot-dry and moderate climates, substantial reductions in life were consistently observed for pavements in the cool-wet climate. The effect of climate on rigid pavements was not evaluated due to insufficient data.

Construction and M&R Pay Item Unit Costs

- With the exception of various concrete pavement-related pay items, sufficient data were available to develop best estimates of unit costs for use in the LCCAs conducted in this study. All original cost data were inflated to 2003 values and, where appropriate, were reprocessed to filter out the effects of projects having small quantities.
- Generally good agreement was found between the unit cost estimates derived from the three data sources used—the 1999 Construction Costs report, the 2002 Asphalt Rubber Projects report, and the 1999 Pavement Management Cost Estimate.
- For pay items with limited or no cost data, best estimates were developed using all available cost information and engineering judgment.

User Cost Practices

- User cost components that are predominately evaluated by highway agencies are the user delay costs resulting from traffic slowdowns and disruption that occur during construction and M&R operations. A secondary cost that is evaluated is the increased vehicle operating cost (VOC) that results from decreased pavement smoothness.
- The process favored for evaluation of user delay costs is the procedure outlined in the FHWA *Interim Technical Bulletin on Life Cycle Cost Analysis in Pavement Design* (Walls and Smith, 1998).

Life-Cycle Costs

- For all 15 projects investigated using a 4 percent discount rate and 60-year analysis period, a consistent reduction in total life-cycle costs was observed corresponding to an increase (from 0 to 2) in the number of rehabilitations between initial construction and the first reconstruction. Thus, there is economic value in performing at least one or two sequential rehabilitation treatments prior to reconstruction.
- For 9 of the 15 scenarios investigated, the total life-cycle costs associated with the third reconstruction alternative (two rehabilitations prior to reconstruction) were within 3 percent (sometimes higher, sometimes lower) of the total life-cycle costs of the continuous preservation strategy. Hence, based on a 4 percent discount rate and 60-year analysis period, the break-even point between the continuous preservation strategy and the reconstruction strategy typically occurs after two to

three cycles of rehabilitation (i.e., reconstruction preceded by two to three sequential rehabilitation treatments). The exact timing of the break-even point, in terms of years, is largely dependent upon the pavement design and the conditions in which it is used.
- An increase in the discount rate results in a corresponding decrease in the life-cycle cost differences between the continuous preservation and reconstruction alternatives. Thus, use of a higher discount rate favors a reduction in the number of rehabilitation events prior to reconstruction. Conversely, a lower discount rate favors a continuous preservation strategy.
- A decrease in analysis period from 60 to 40 years results in a decrease in the life-cycle cost differences between continuous preservation and reconstruction. The rate of decrease is case specific.

RECOMMENDATIONS

The following recommendations are offered as related to the pavement strategies currently used by ADOT:

- Pavement survival analyses should be routinely (perhaps biennially) performed to develop more complete and accurate estimates of initial pavement life and rehabilitation performance. Specifically, an improved database with few errors is greatly needed for all pavements of interest and better forecasting is needed for a variety of designs/materials: SuperPave mixes, JPCD pavements (the current Arizona design), concrete pavement rehabilitation treatments, and asphalt pavement rehabilitation treatments utilizing different asphalt mixtures.
- A comprehensive economic analysis, using reasonably accurate estimates of pavement life and traffic loadings, should be performed for all major pavement projects to determine not only the type of pavement to use, but the optimal timing of reconstruction. For most of the conditions prevailing in Arizona, a reasonable estimate of the optimal timing for reconstruction is after the sequential application of two to three rehabilitation activities.
- The practice of programming pavements for improvement and performing detailed evaluations and testing to determine the best improvement strategy should continue, but the history of the pavement should be reviewed to determine if reconstruction should be considered as an option. If records show that the existing pavement has been rehabilitated at least twice since original construction, then an economic analysis should be performed to determine whether the pavement should undergo another rehabilitation or be reconstructed.
- User costs stemming from the time delay associated with work zones should be evaluated as part of the pavement LCCA. The FHWA process (*RealCost*) is the preferred method for determining these costs; however, use of the QuickZone

user cost program should be considered in cases where urban freeways or areas with detours or complete road closures are being evaluated.

- The evaluation of VOCs resulting from decreased pavement smoothness should be considered in pavement LCCA. Moreover, the use of cost adjustment factors, such as those used by the Minnesota DOT, should be considered, particularly for pavements maintained at a lower serviceability level.

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APPENDIX A. PAVEMENT SURVIVAL CURVES

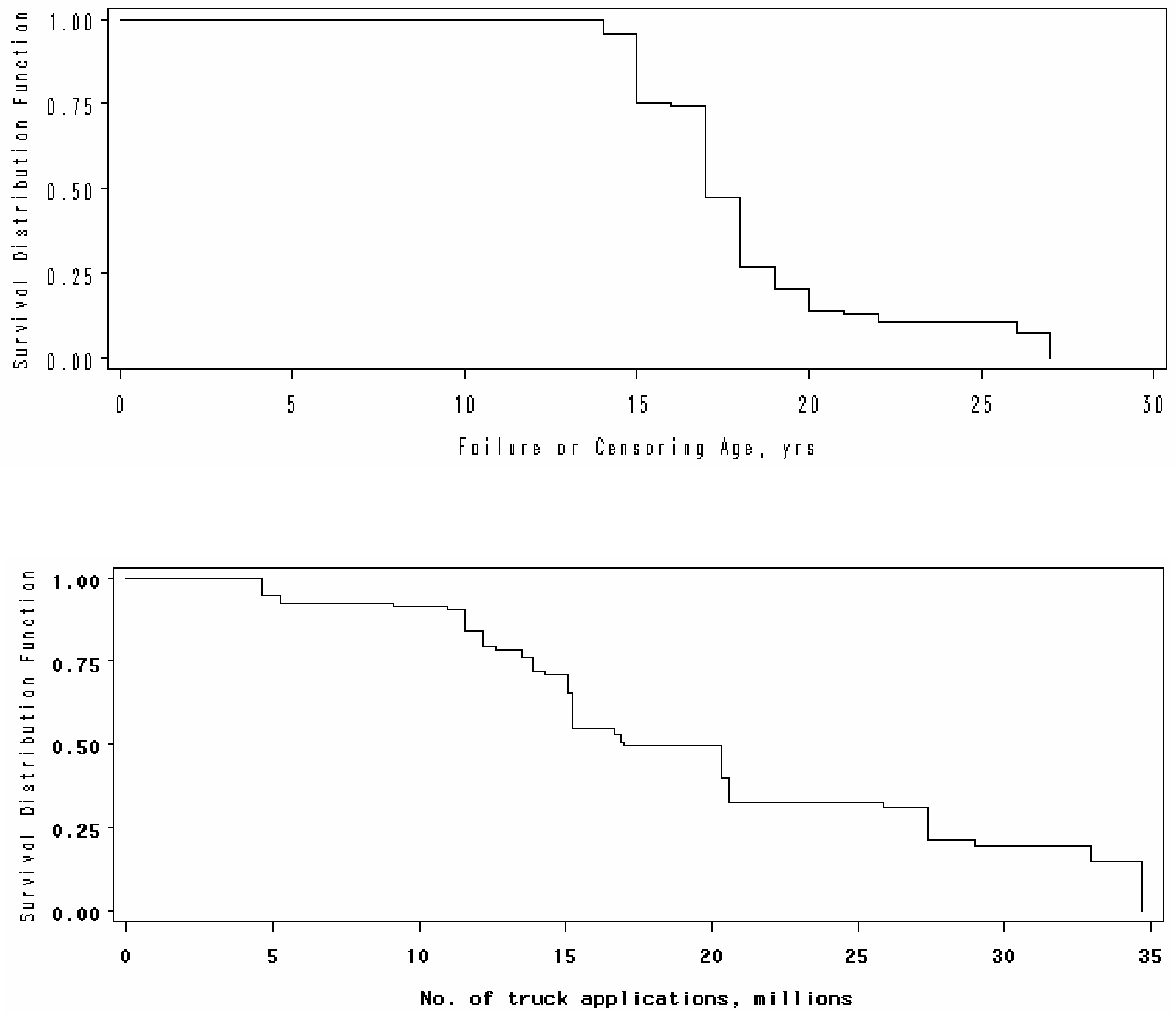
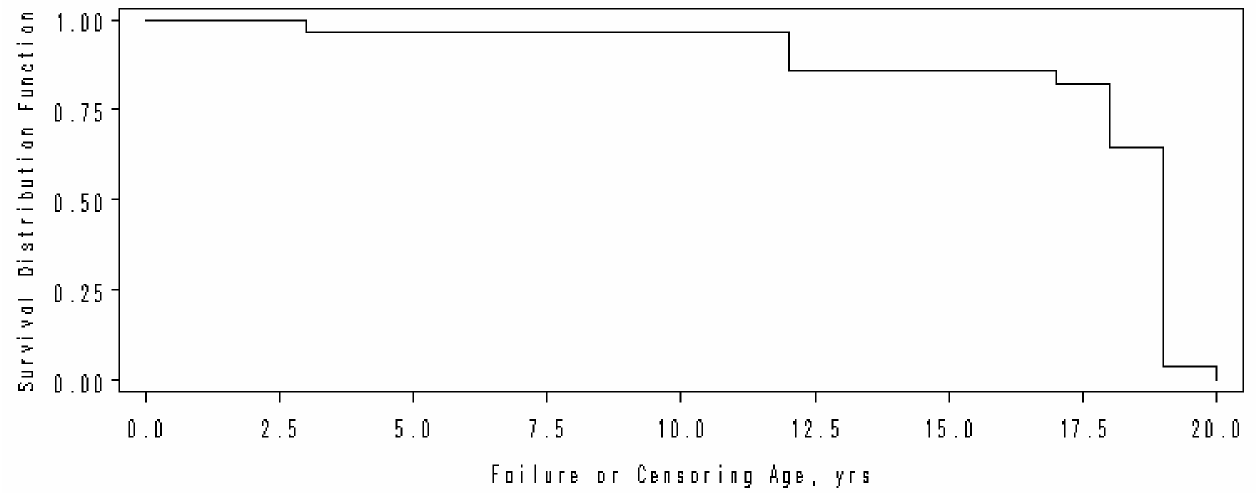


Figure A-1. Age- and truck traffic-based survival plots for CAC Interstate pavements located in hot-dry climate (analysis cell 1).



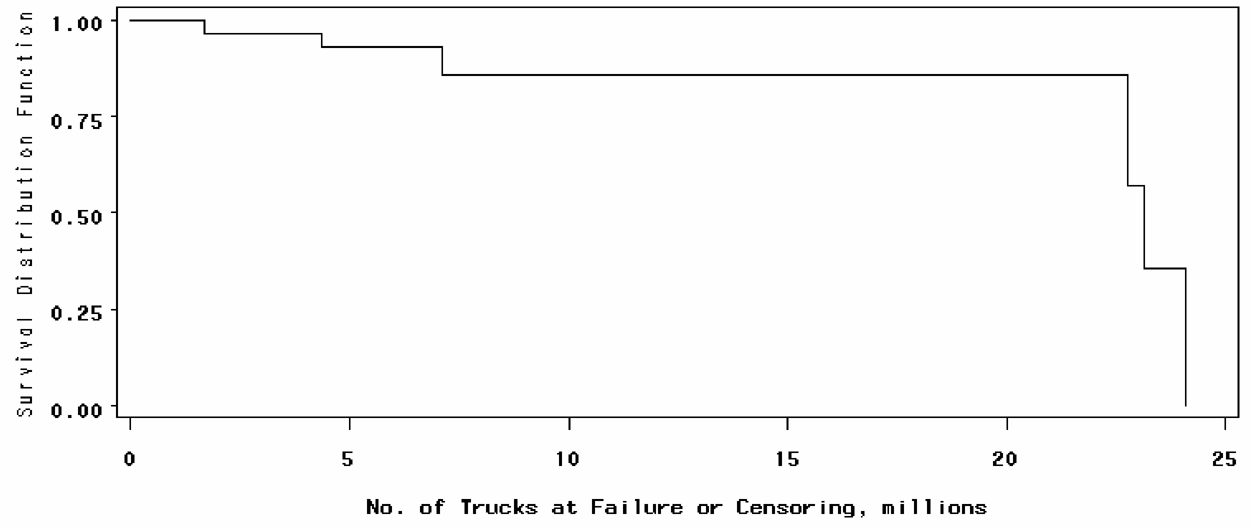
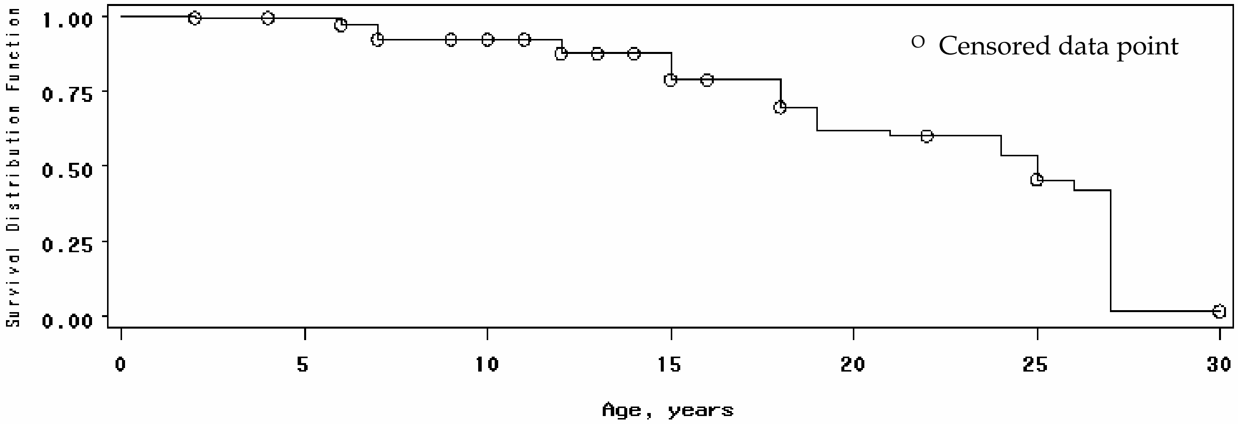


Figure A-2. Age- and truck traffic-based survival plots for CAC Interstate pavements located in moderate climate (analysis cell 2).



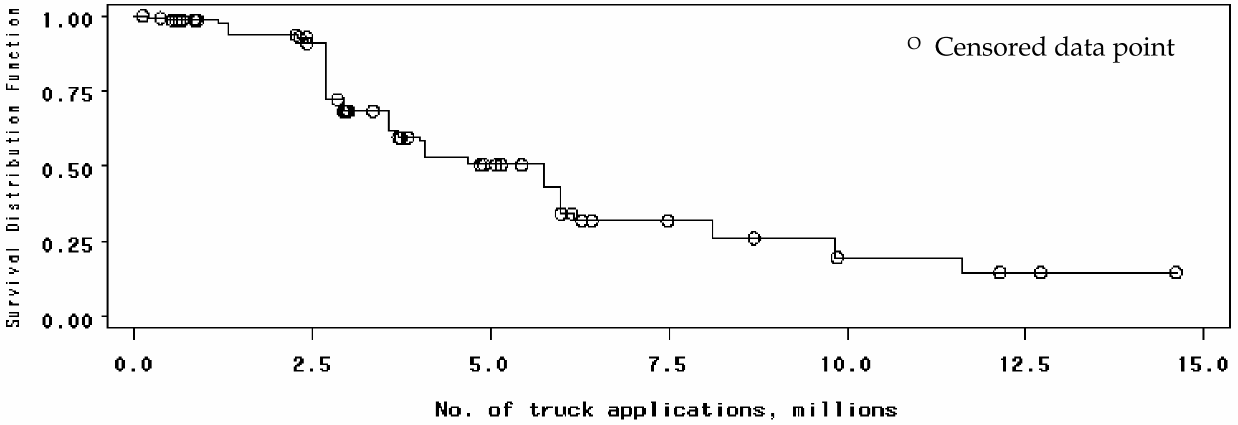
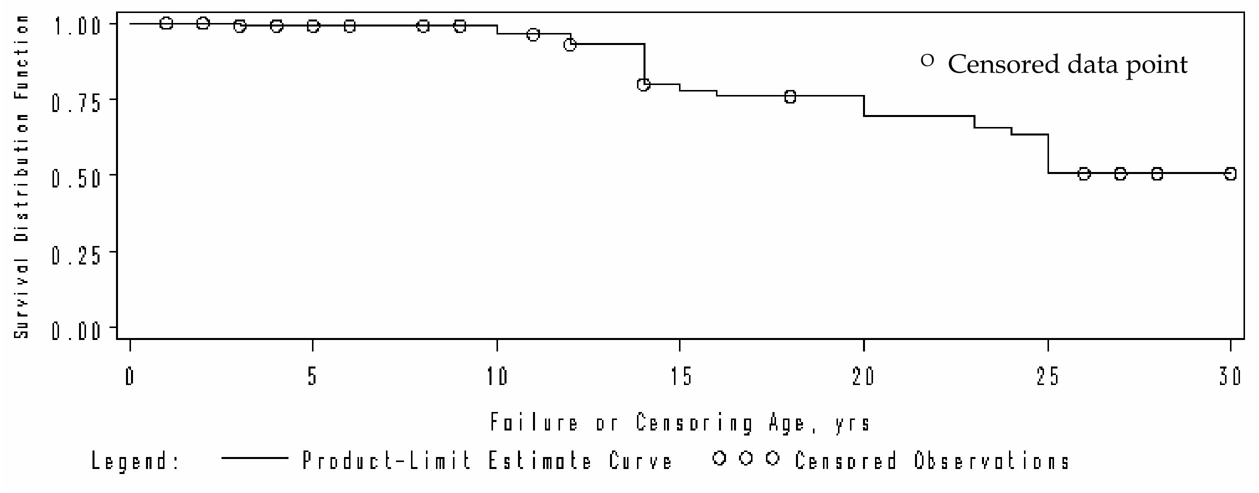


Figure A-3. Age- and truck traffic-based survival plots for CAC Non-Interstate pavements located in hot-dry climate (analysis cell 3).



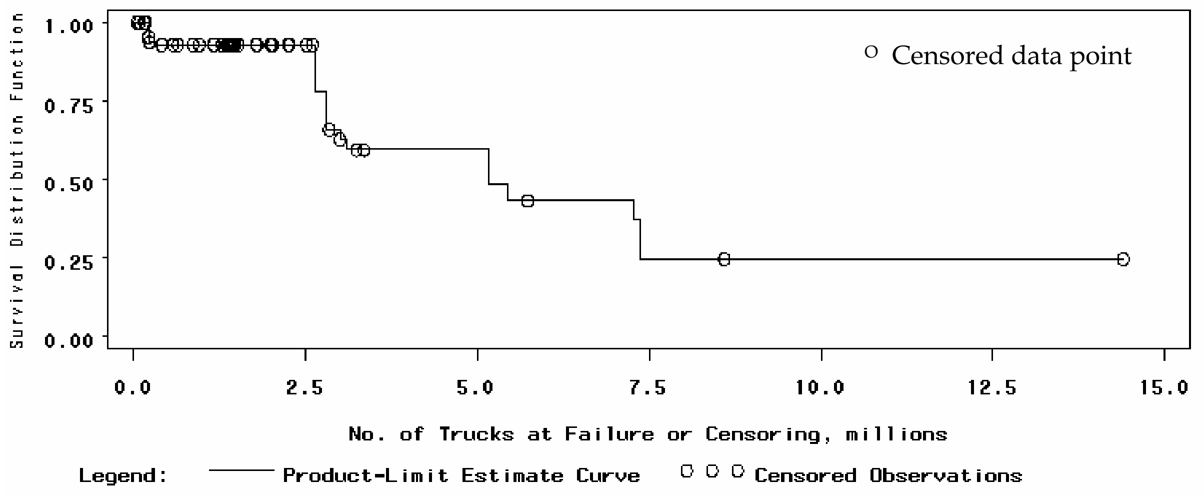
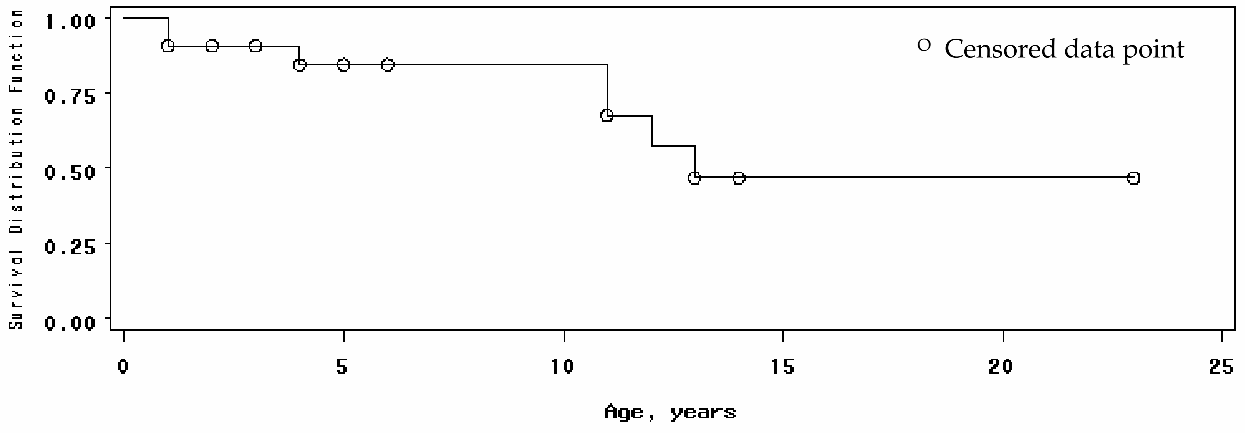


Figure A-4. Age- and truck traffic-based survival plots for CAC Non-Interstate pavements located in moderate climate (analysis cell 4).



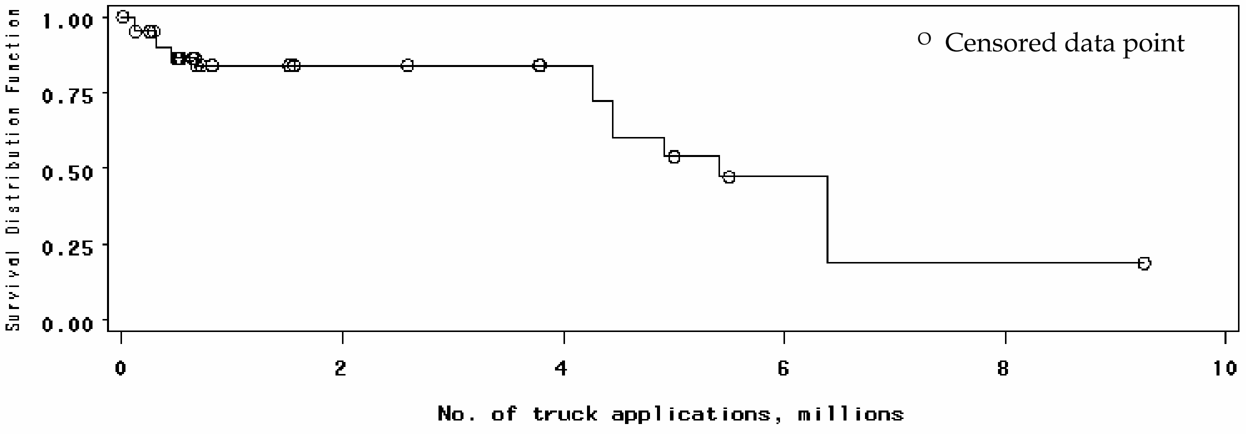
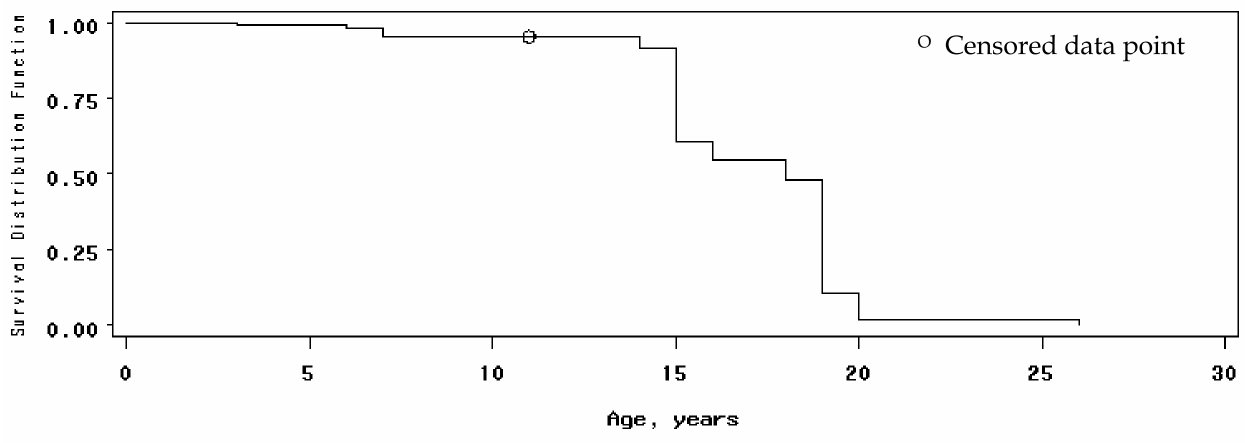


Figure A-5. Age- and truck traffic-based survival plots for CAC Non-Interstate pavements located in cool-wet climate (analysis cell 5).



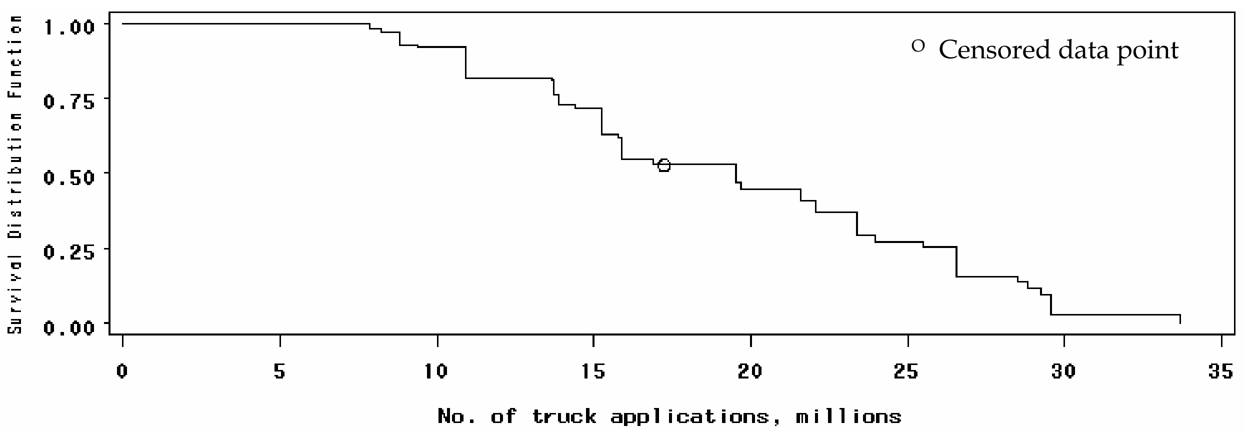
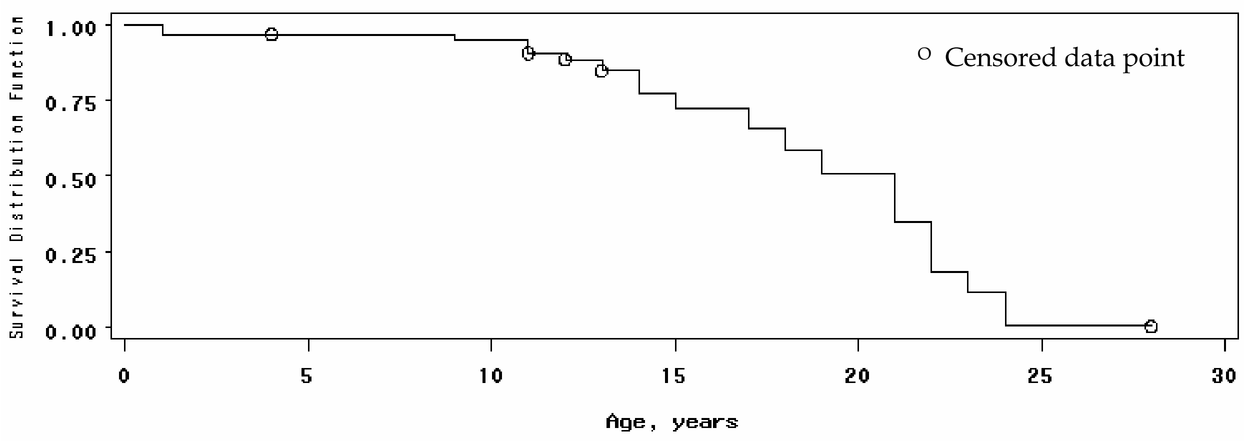


Figure A-6. Age- and truck traffic-based survival plots for DSAC/FDAC Interstate pavements located in hot-dry climate (analysis cell 6).



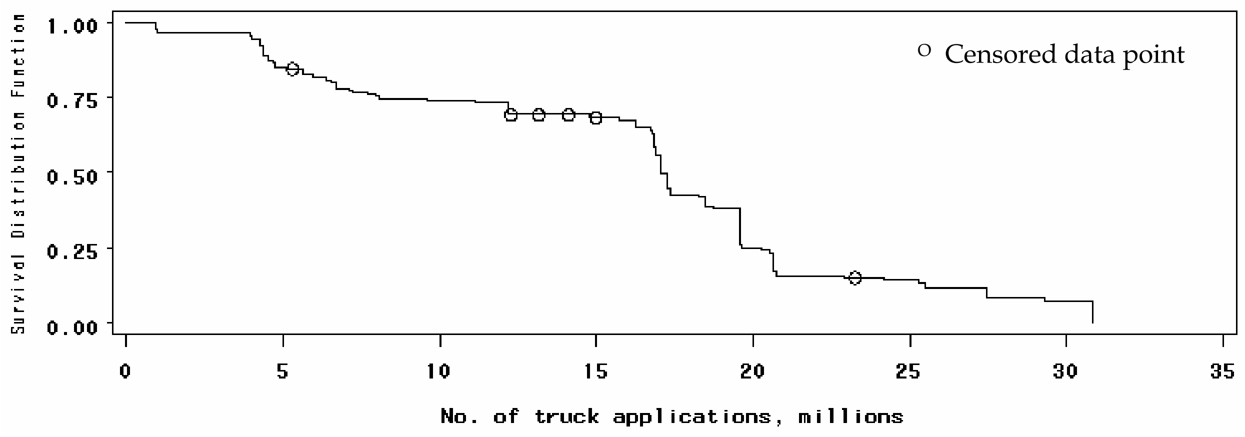
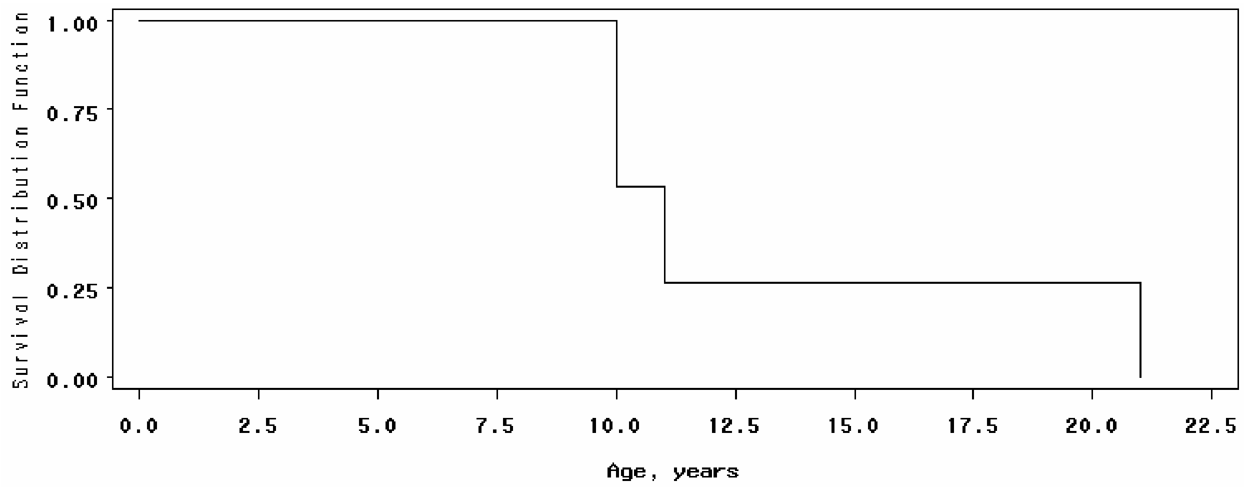


Figure A-7. Age- and truck traffic-based survival plots for DSAC/FDAC Interstate pavements located in moderate climate (analysis cell 7).



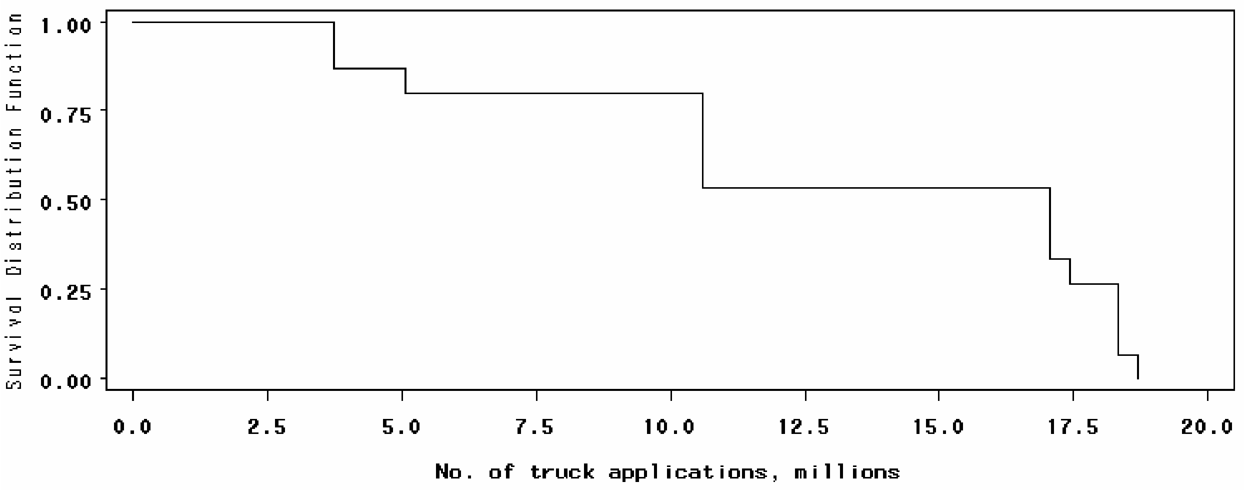
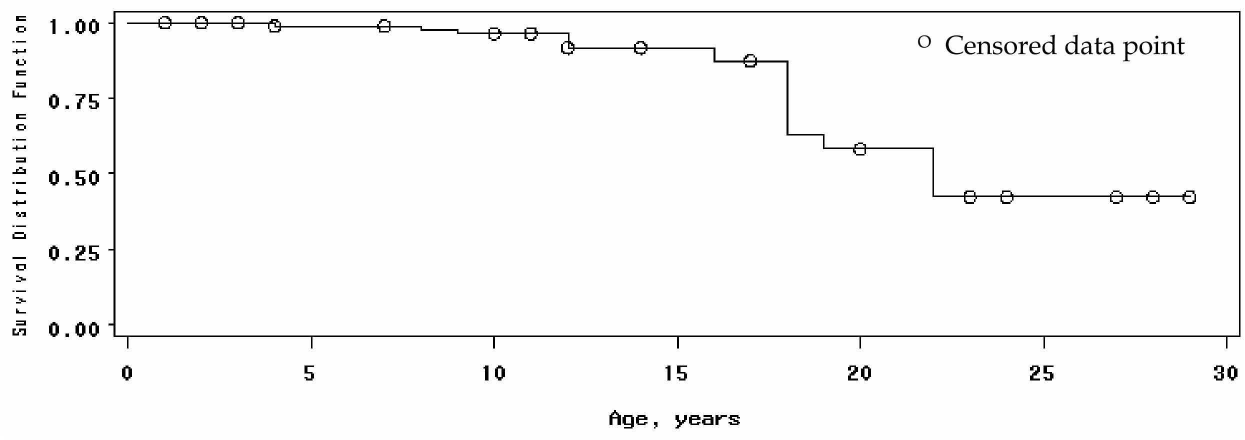


Figure A-8. Age- and truck traffic-based survival plots for DSAC/FDAC Interstate pavements located in cool-wet climate (analysis cell 8).



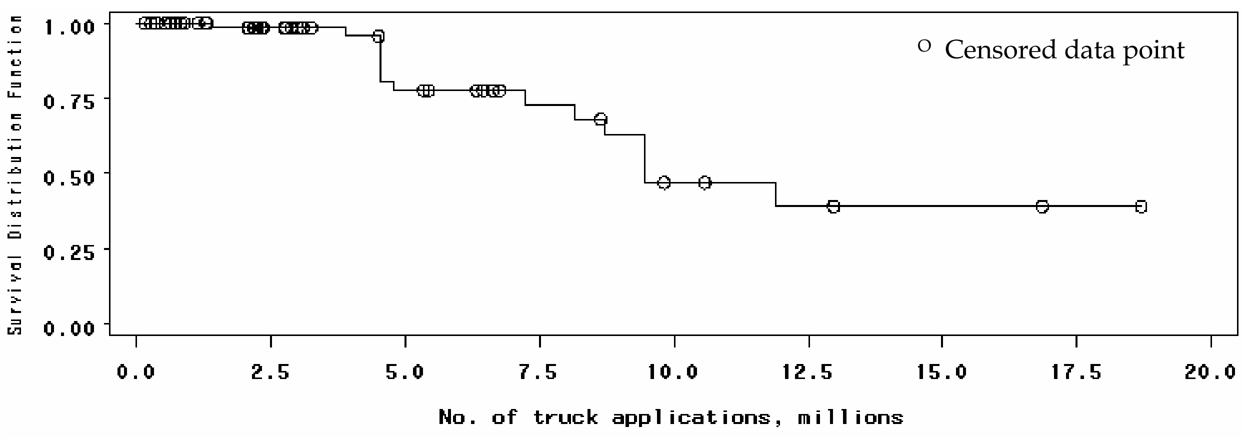
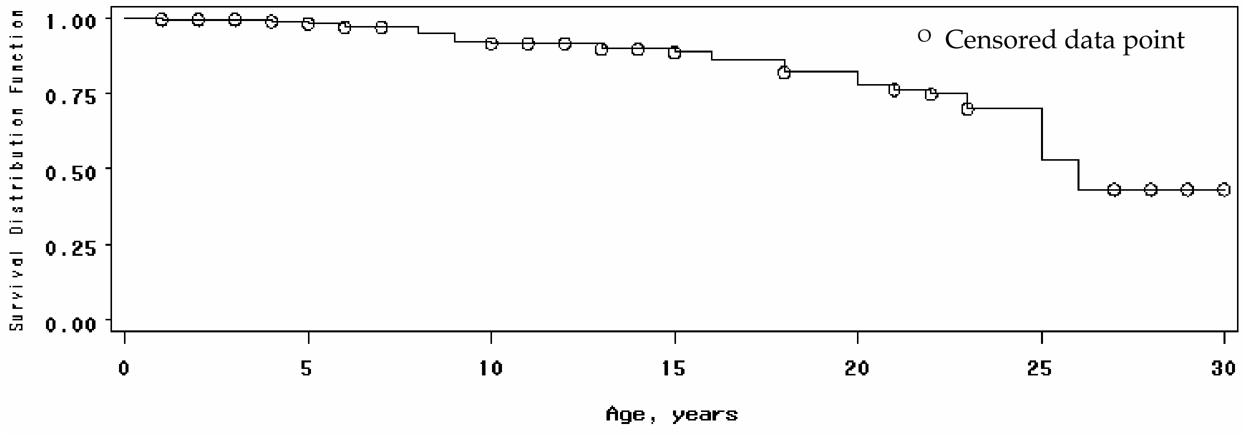


Figure A-9. Age- and truck traffic-based survival plots for DSAC/FDAC Non-Interstate pavements located in hot-dry climate (analysis cell 9).



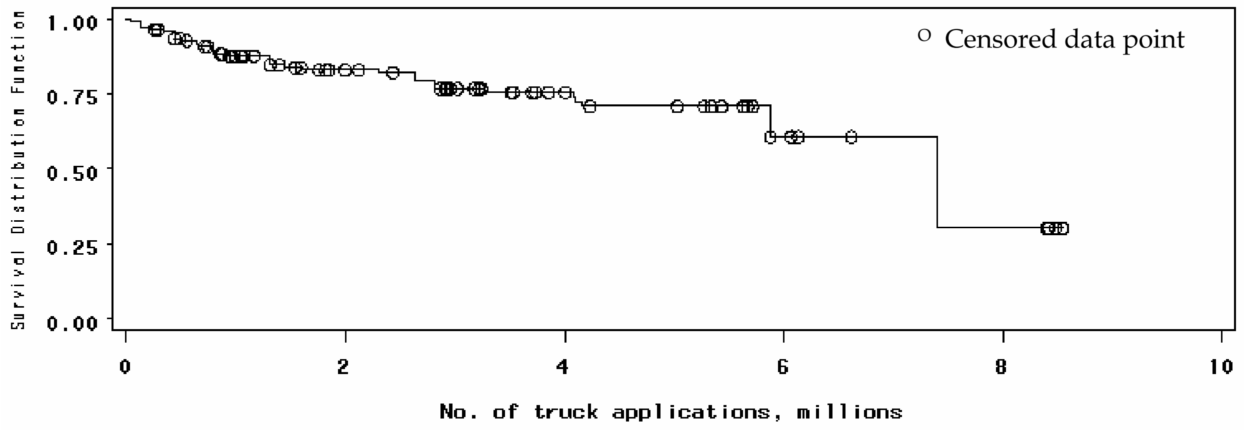


Figure A-10. Age- and truck traffic-based survival plots for DSAC/FDAC Non-Interstate pavements located in moderate climate (analysis cell 10).

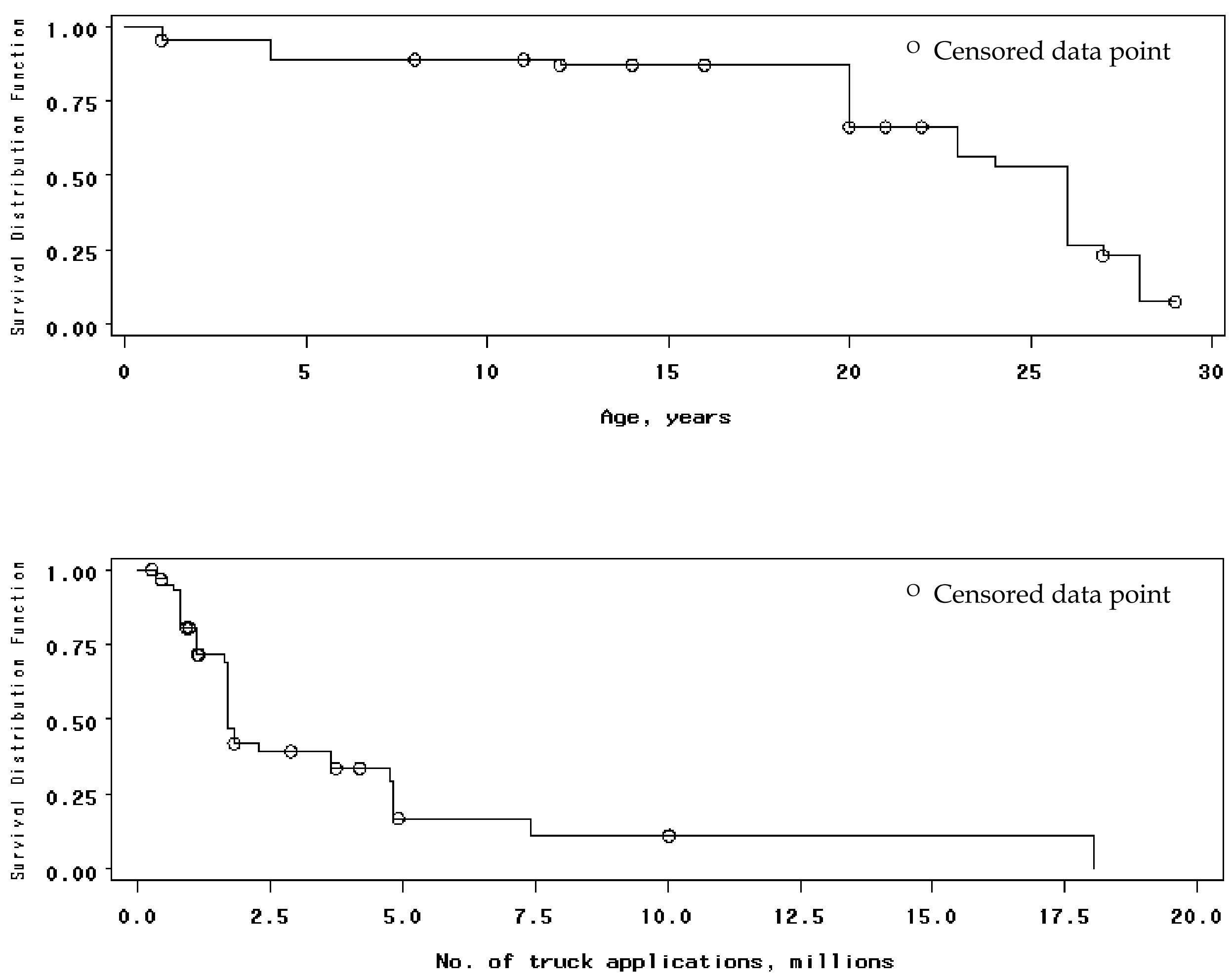
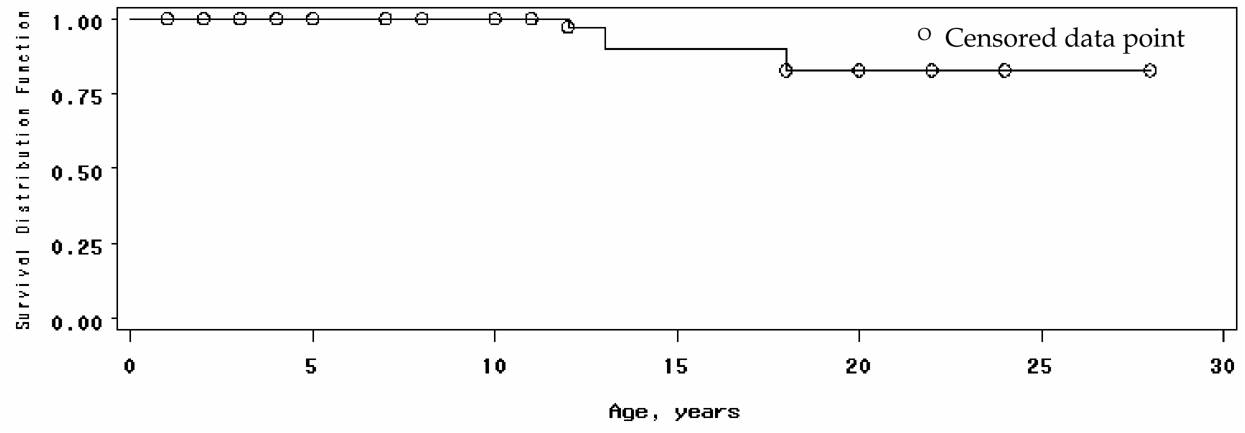


Figure A-11. Age- and truck traffic-based survival plots for DSAC/FDAC Non-Interstate pavements located in cool-wet climate (analysis cell 11).



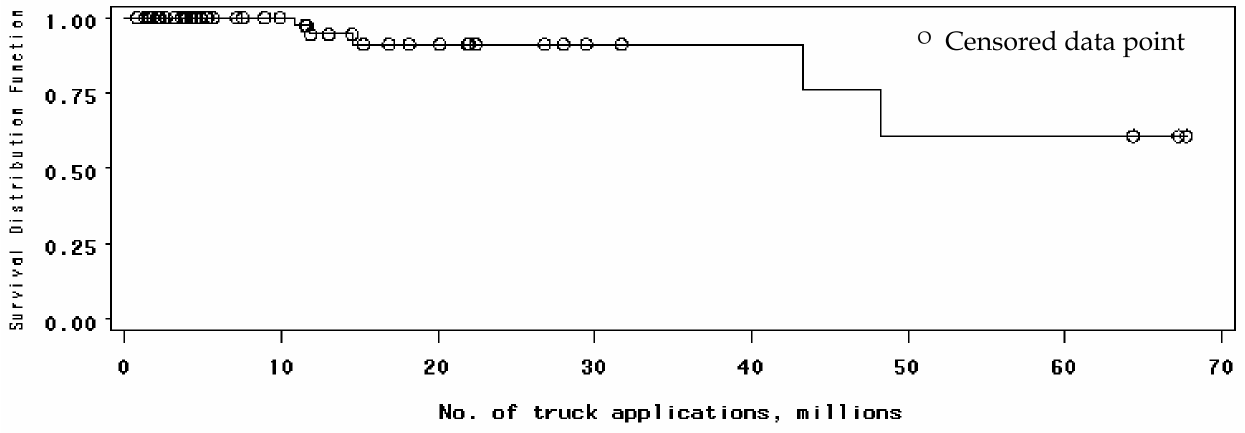


Figure A-12. Age- and truck traffic-based survival plots for JPC pavements located in hot-dry climate (analysis cell 12).

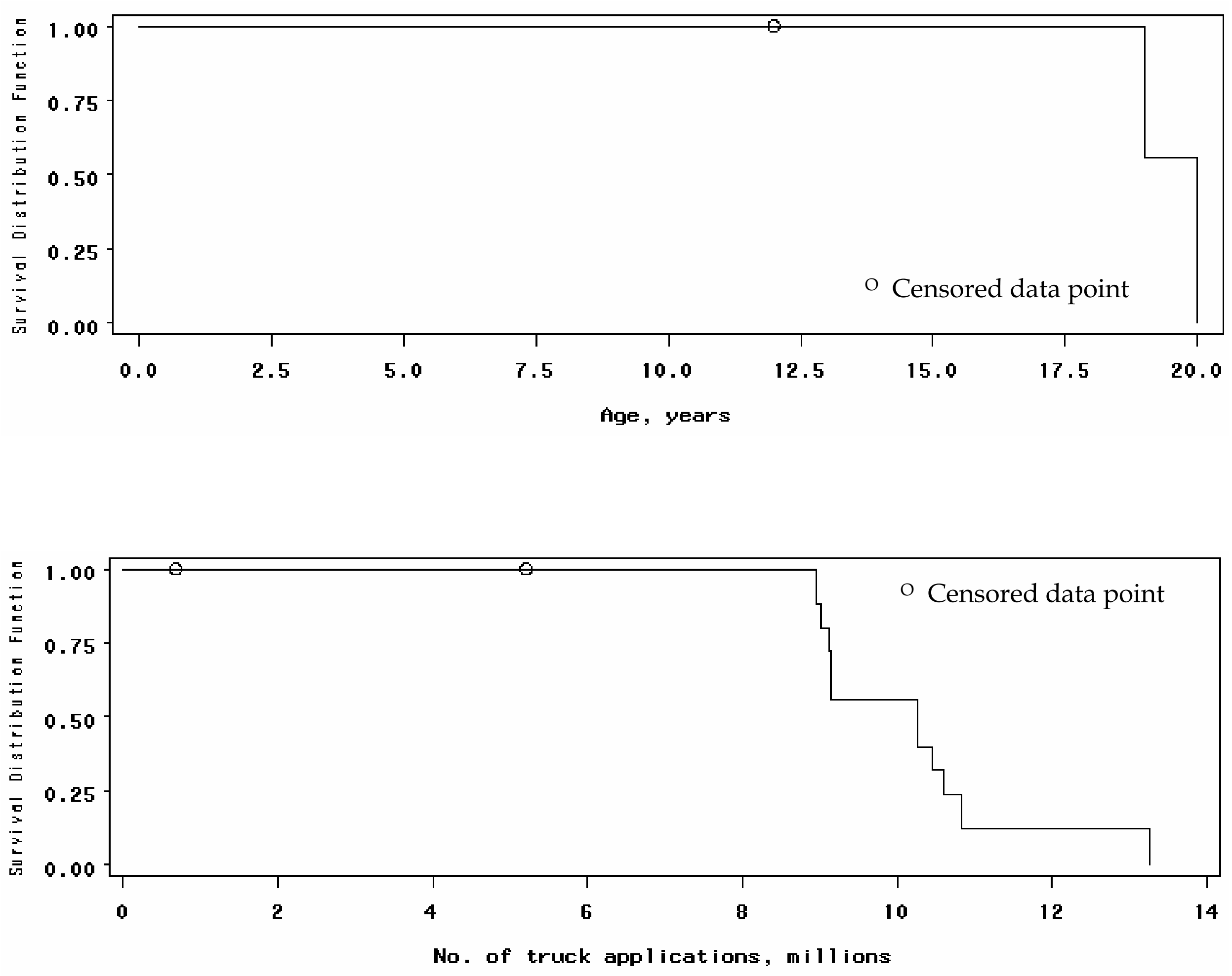
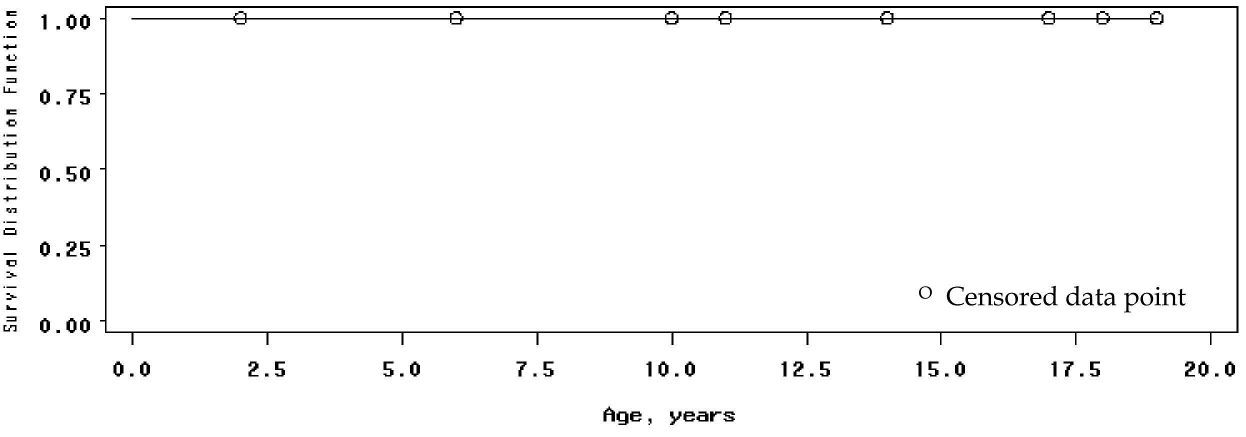


Figure A-13. Age- and truck traffic-based survival plots for JPC pavements located in cool-wet climate (analysis cell 13).



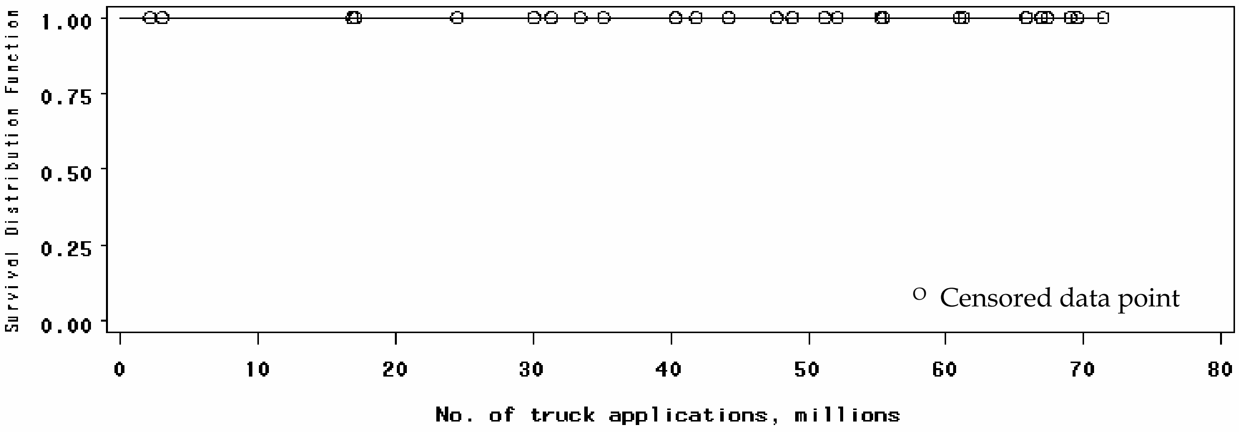


Figure A-14. Age- and truck traffic-based survival plots for JPCD pavements located in hot-dry climate (analysis cell 14).

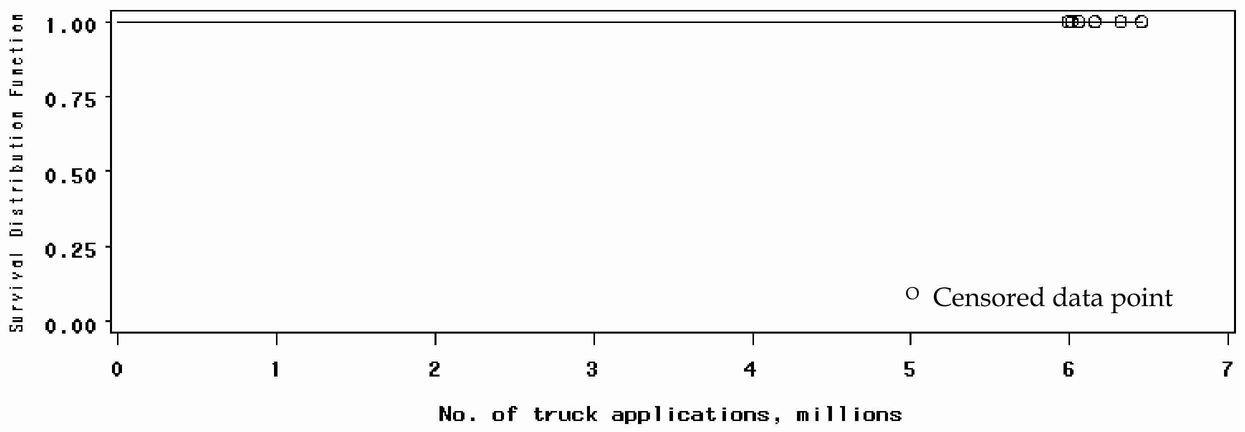
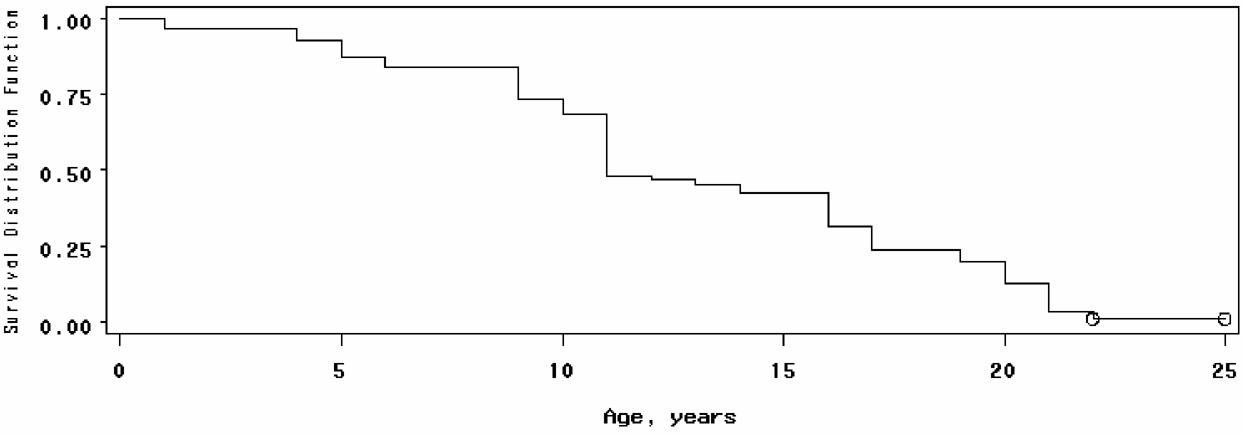


Figure A-15. Age- and truck traffic-based survival plots for CRC pavements located in hot-dry climate (analysis cell 15).



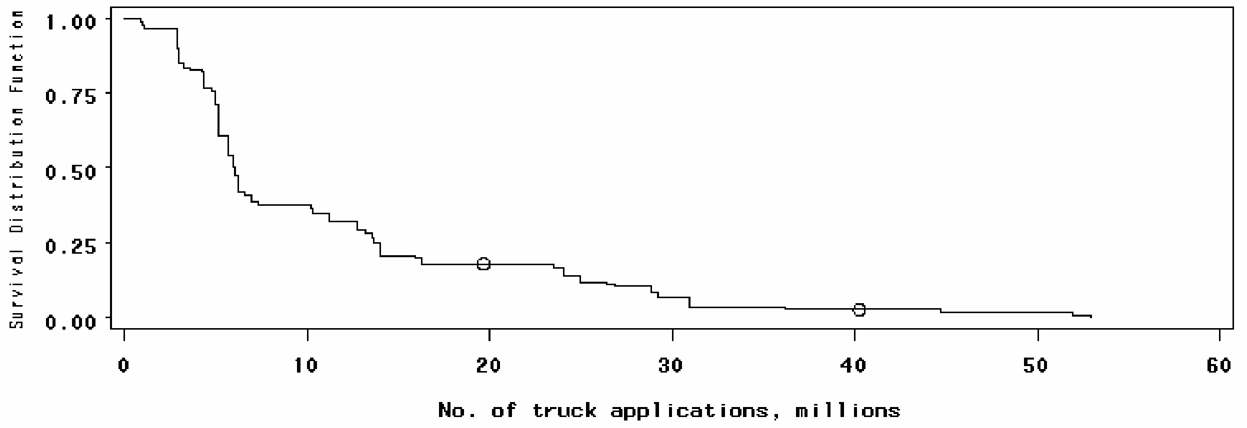
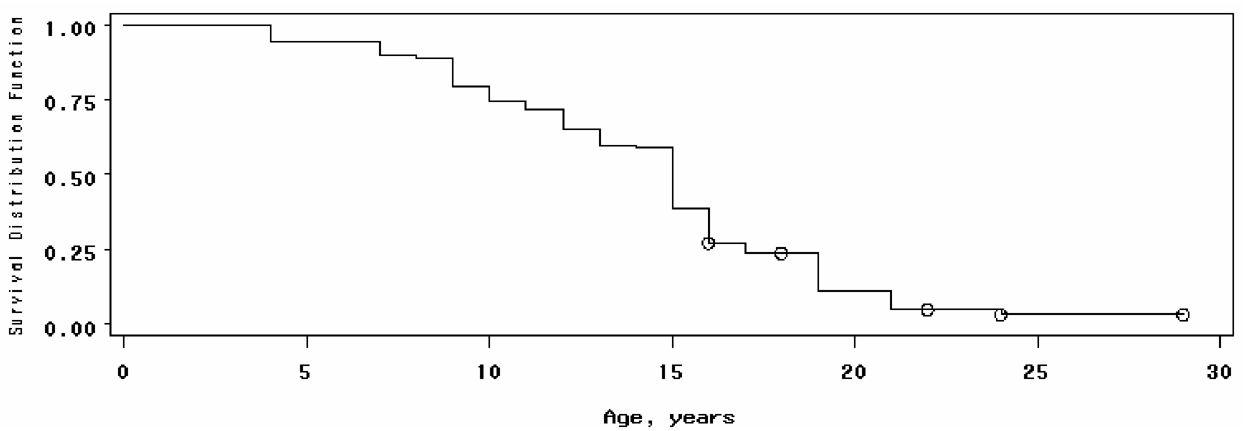


Figure A-16. Age- and truck traffic-based survival plots for R1A rehabilitation treatments applied to asphalt Interstate pavements located in hot-dry climate.



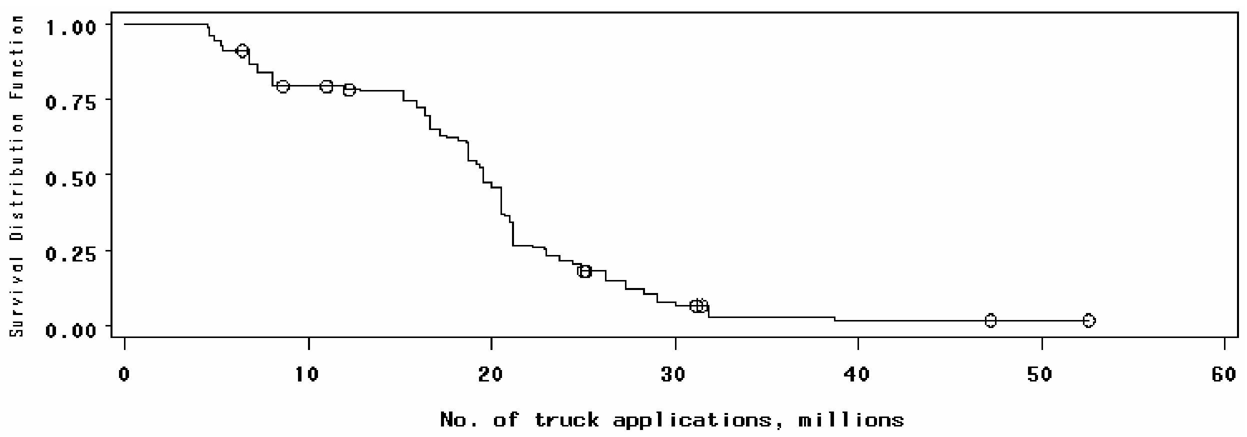
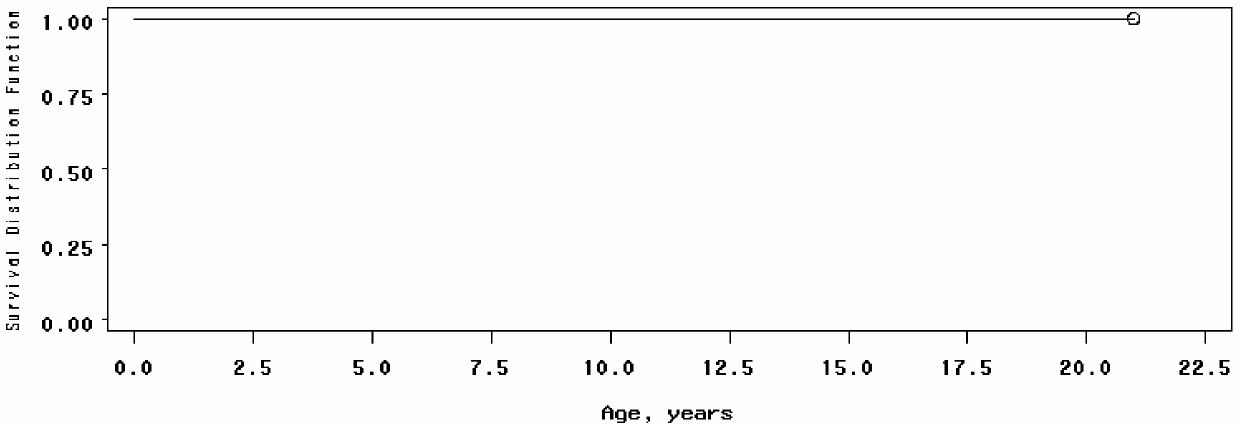
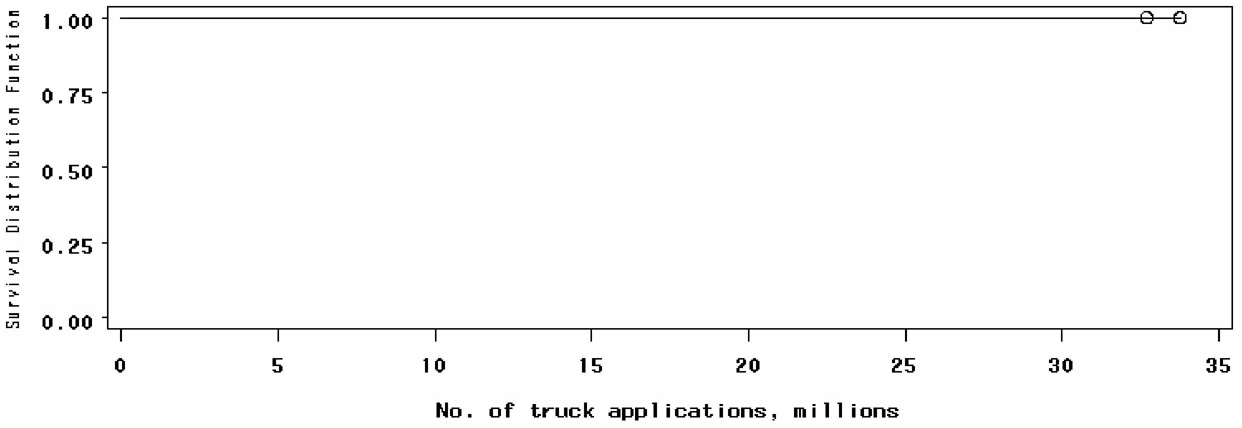


Figure A-17. Age- and truck traffic-based survival plots for R1A rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.





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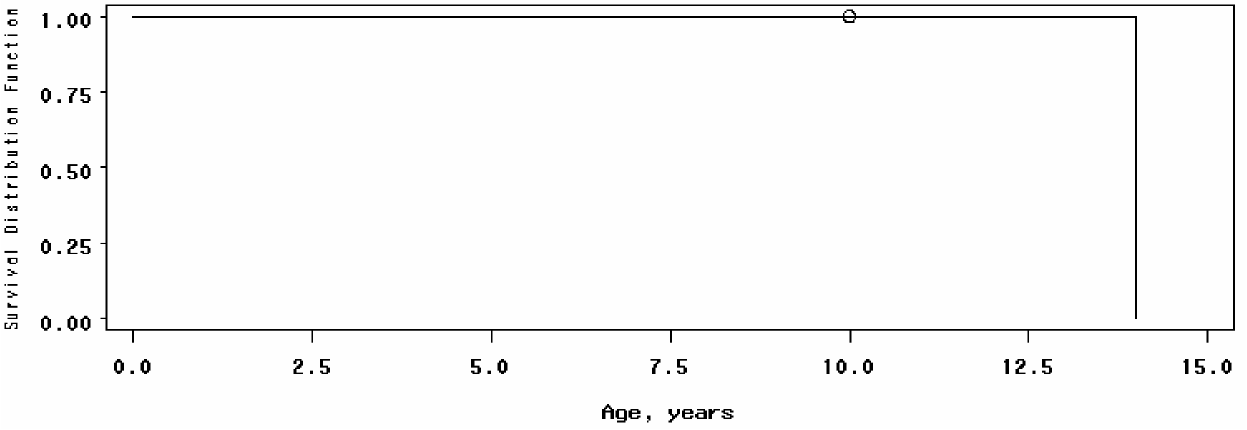


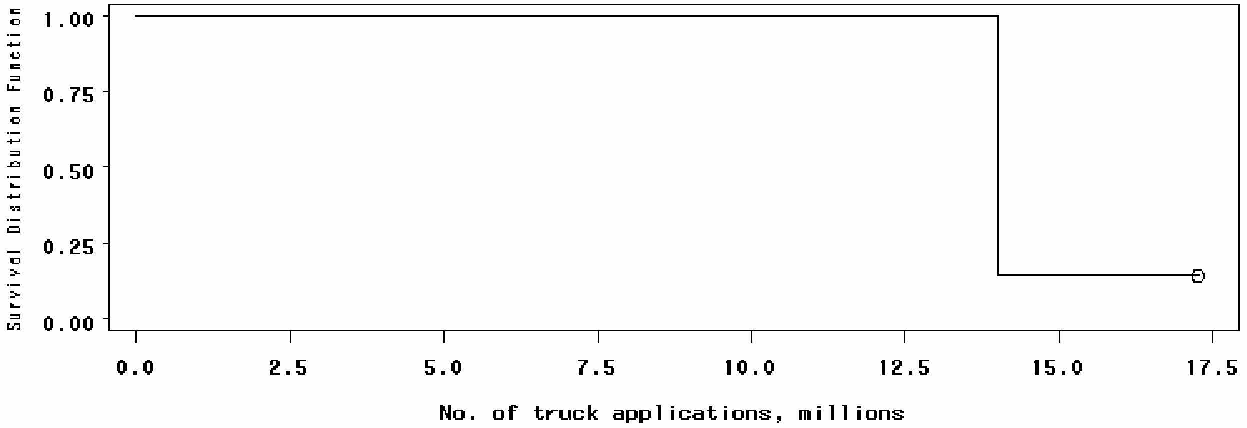


Figure A-19. Age- and truck traffic-based survival plots for R1B rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.

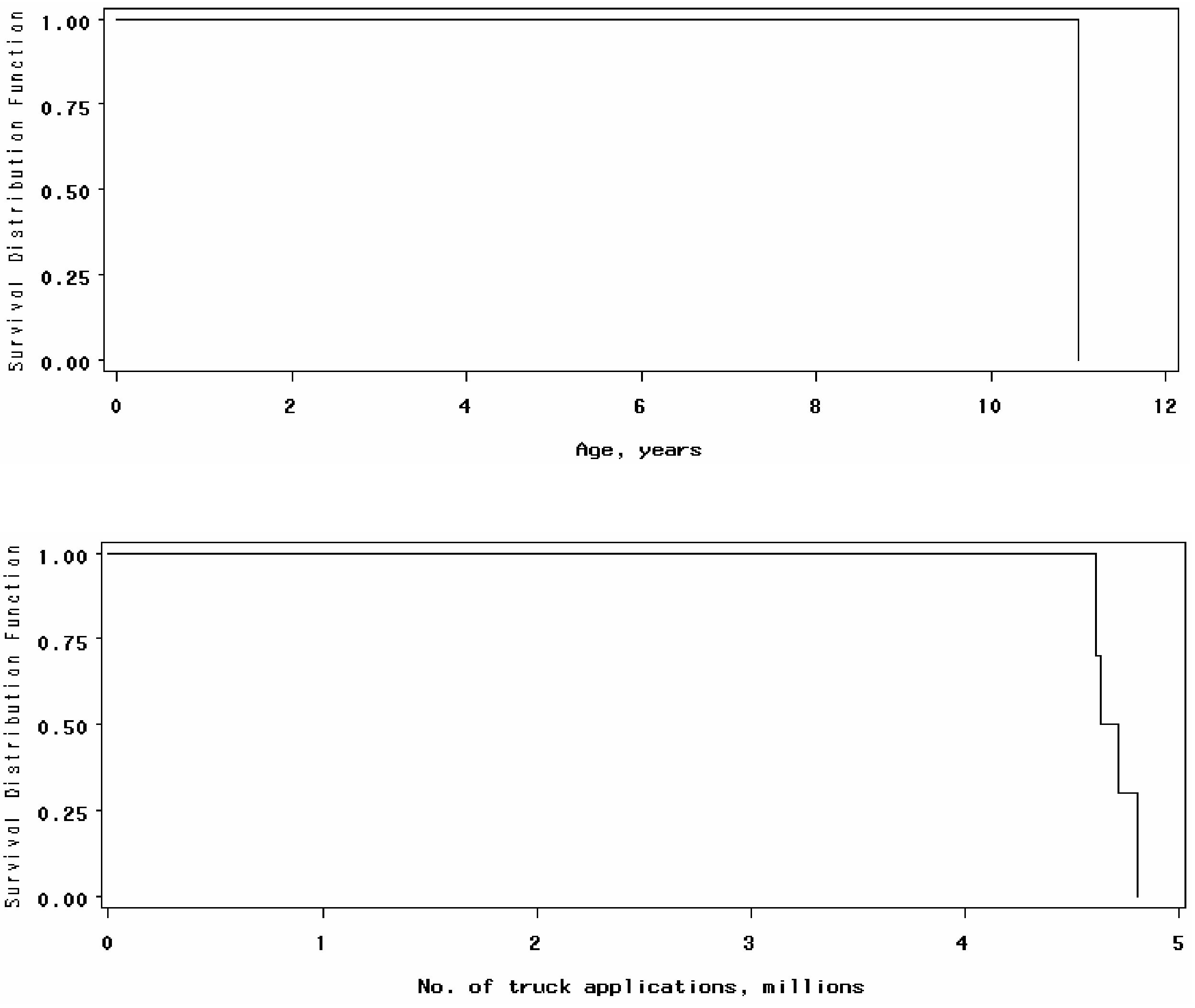
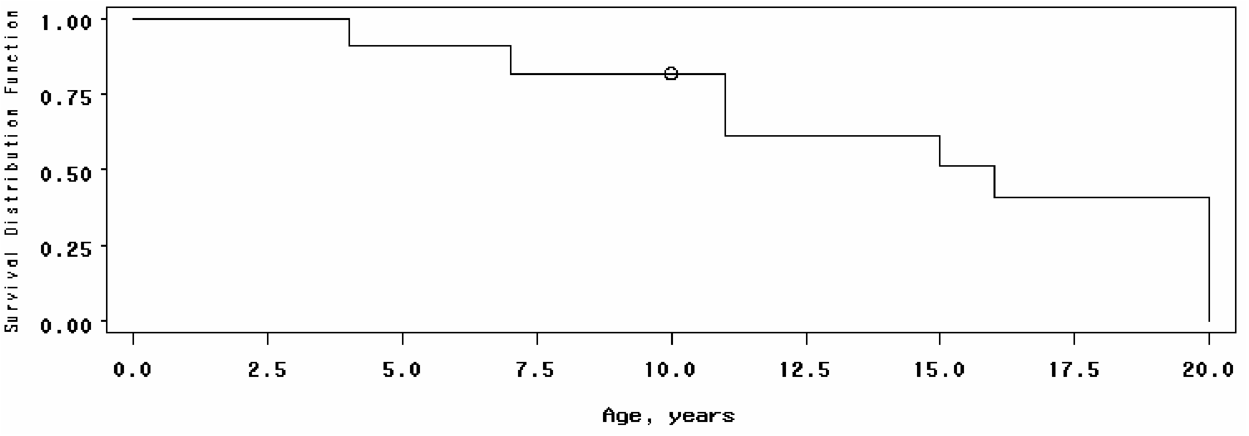


Figure A-20. Age- and truck traffic-based survival plots for R1B rehabilitation treatments applied to asphalt Interstate pavements located in cool-wet climate.



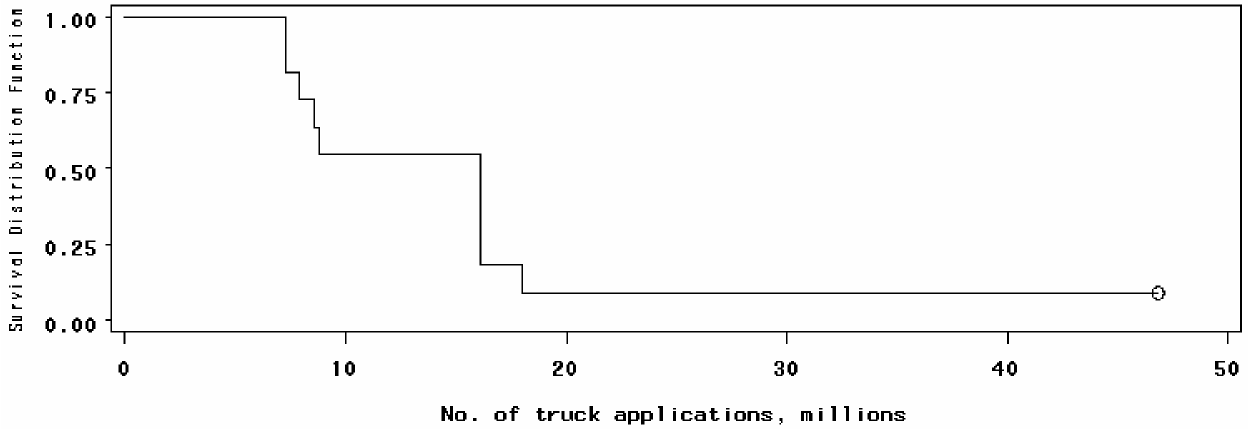


Figure A-21. Age- and truck traffic-based survival plots for R2A rehabilitation treatments applied to asphalt Interstate pavements located in hot-dry climate.

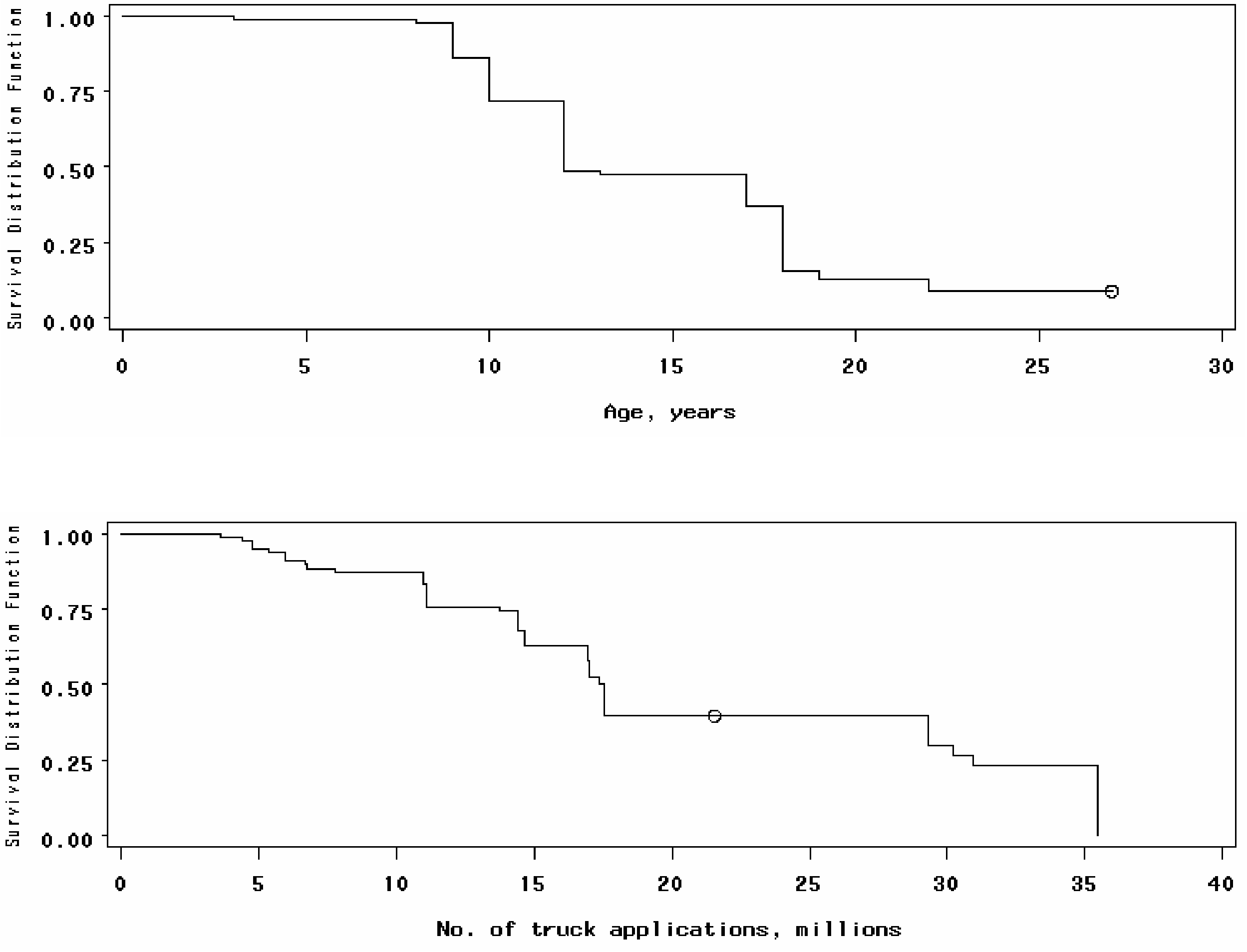
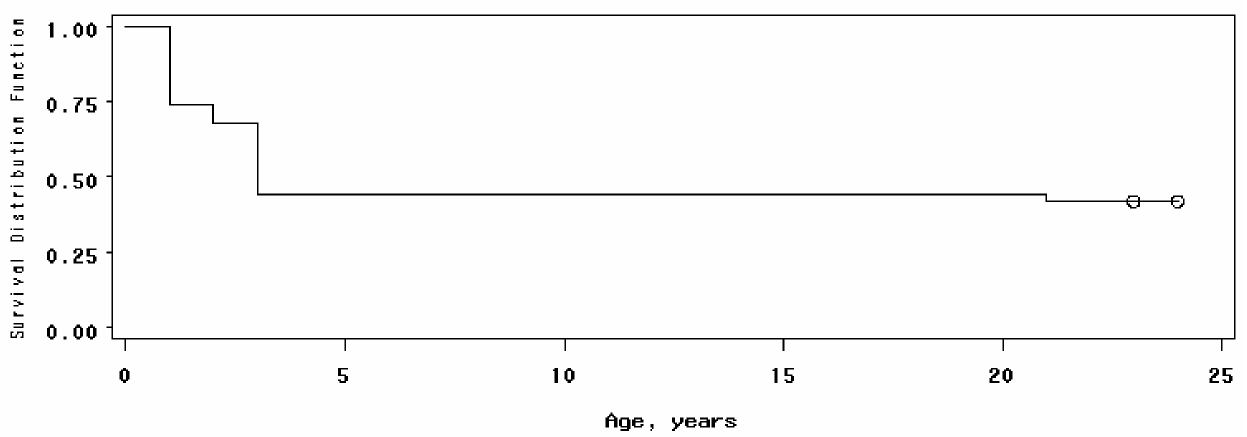


Figure A-22. Age- and truck traffic-based survival plots for R2A rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.



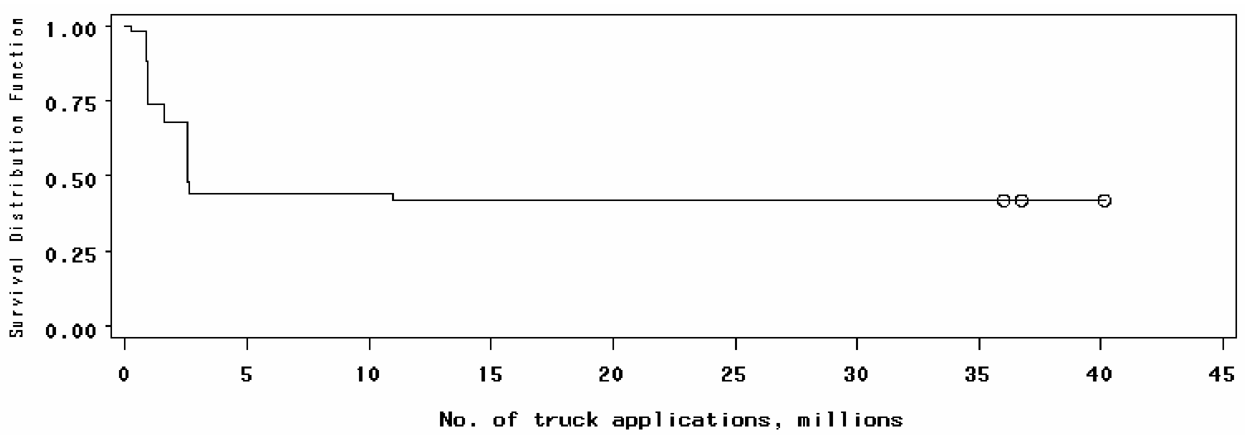
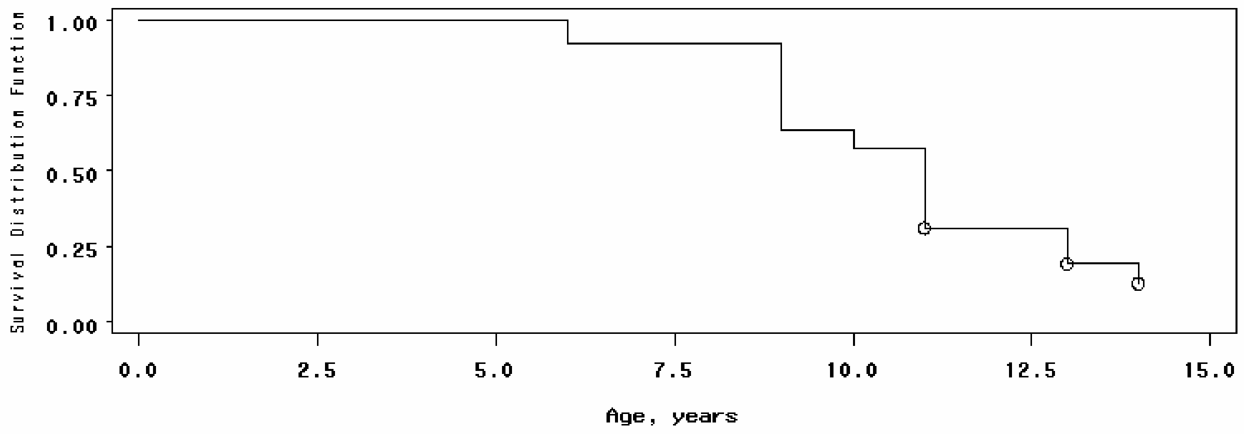


Figure A-23. Age- and truck traffic-based survival plots for R2A rehabilitation treatments applied to asphalt Interstate pavements located in cool-wet climate.



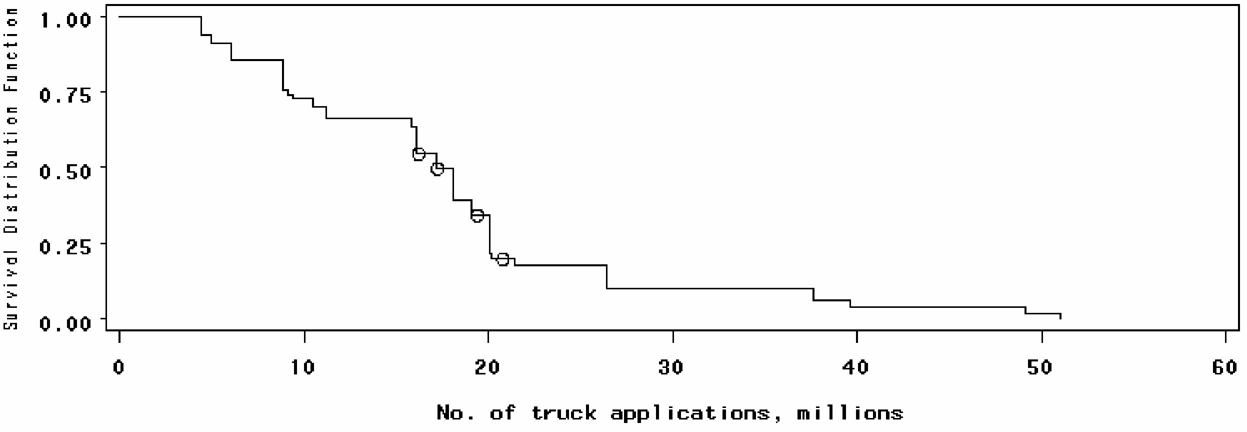


Figure A-24. Age- and truck traffic-based survival plots for R3A rehabilitation treatments applied to asphalt Interstate pavements located in hot-dry climate.

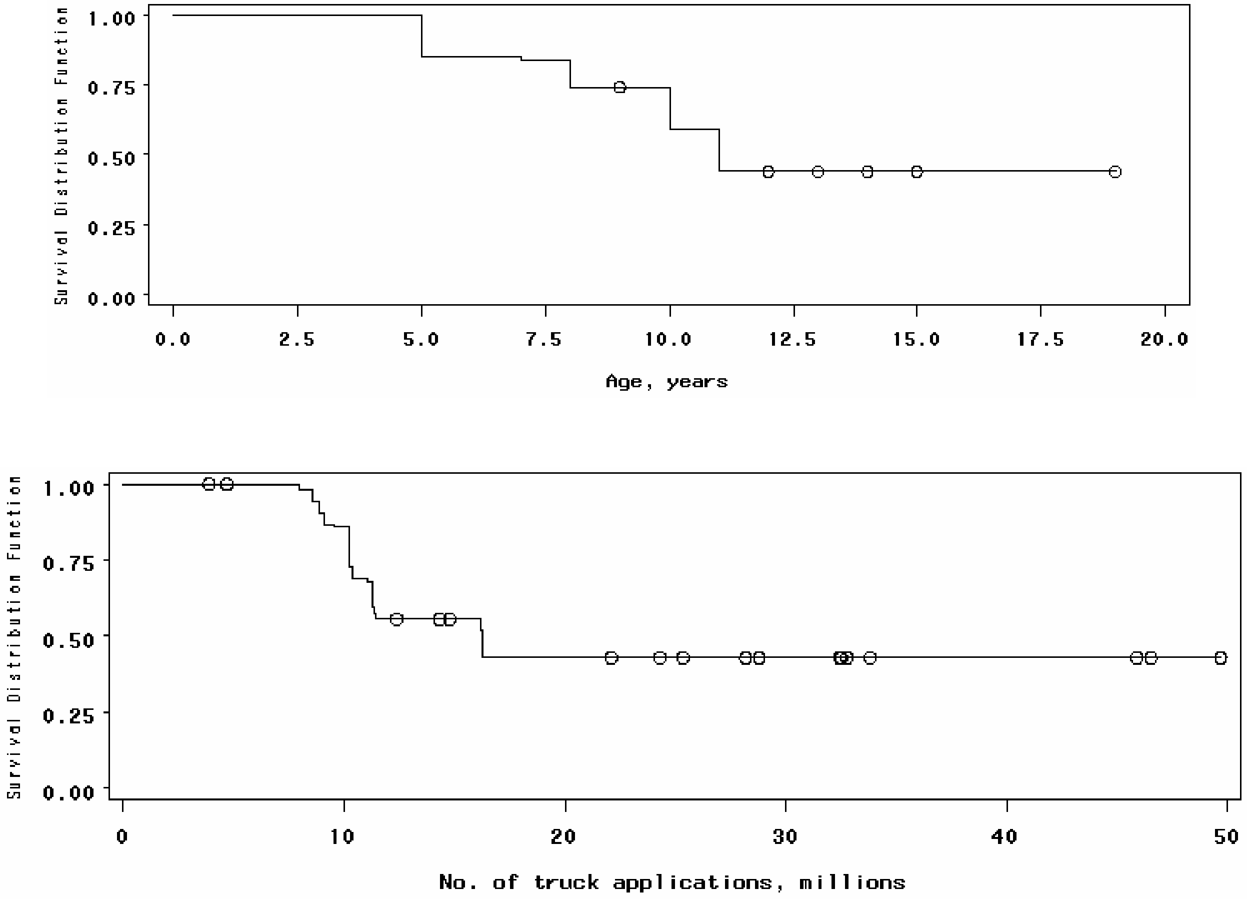
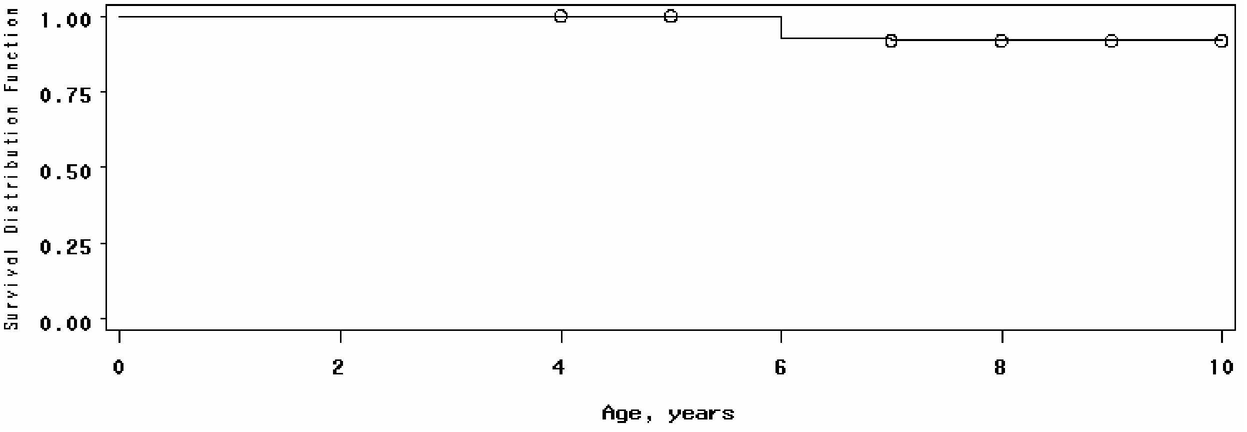


Figure A-25. Age- and truck traffic-based survival plots for R3A rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.



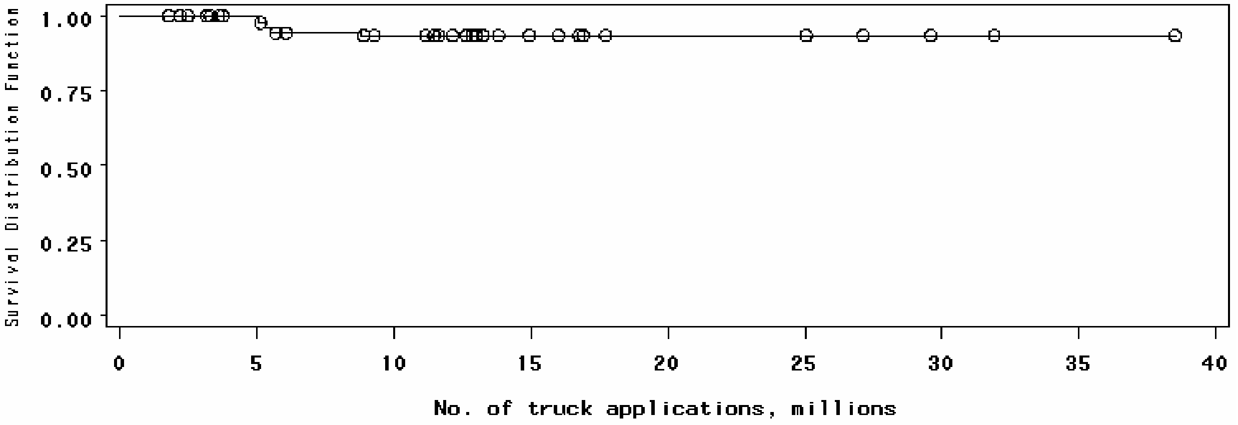
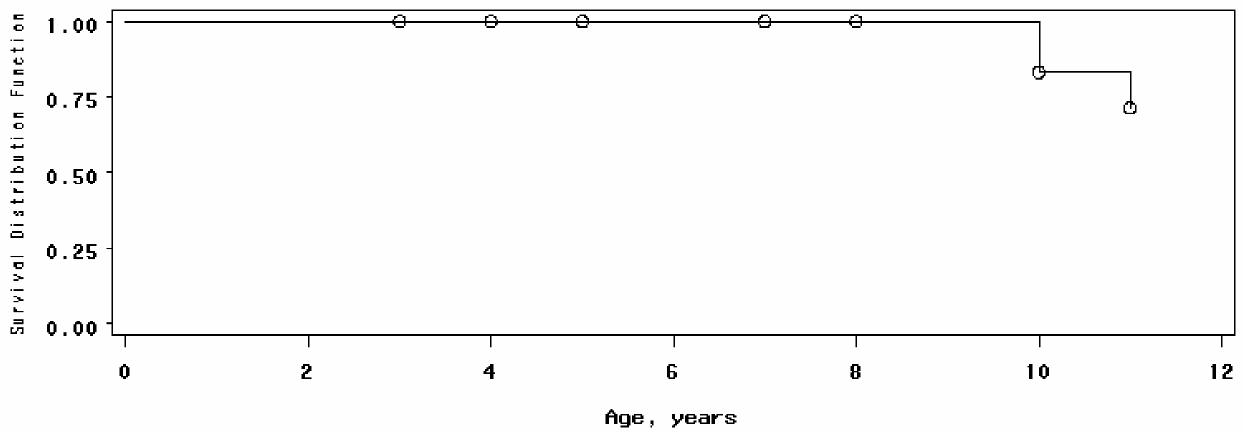


Figure A-26. Age- and truck traffic-based survival plots for R3B rehabilitation treatments applied to asphalt Interstate pavements located in hot-dry climate.



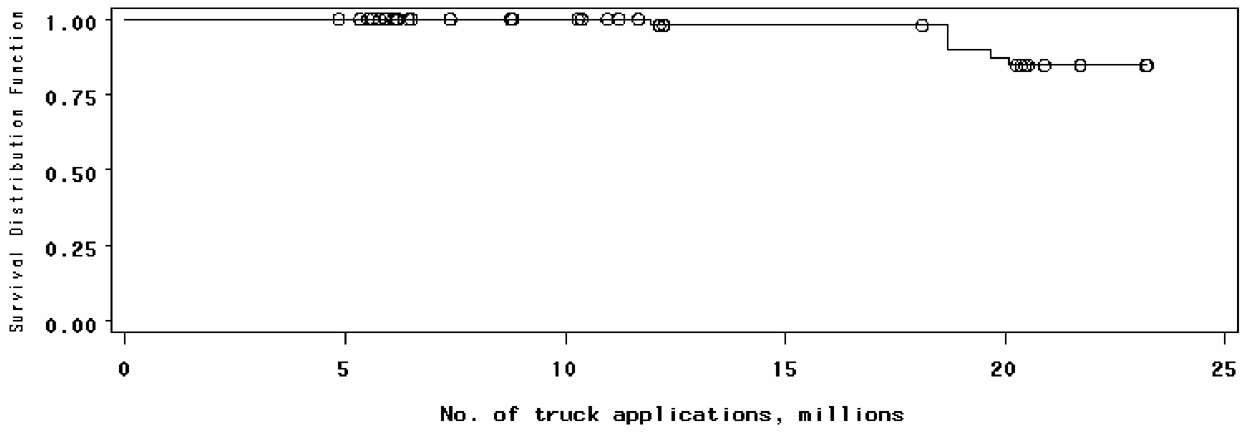


Figure A-27. Age- and truck traffic-based survival plots for R3B rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.

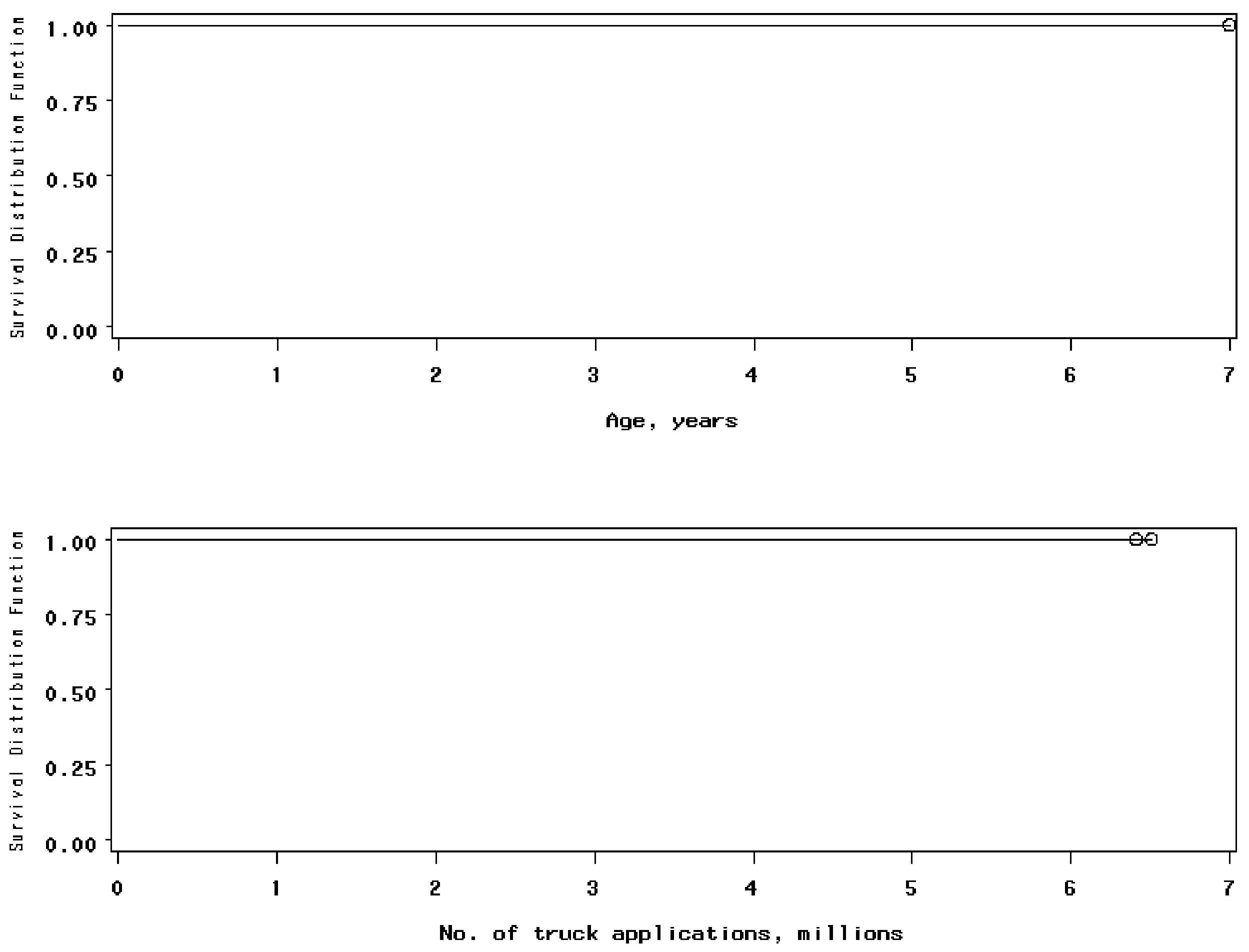


Figure A-28. Age- and truck traffic-based survival plots for R3B rehabilitation treatments applied to asphalt Interstate pavements located in cool-wet climate.

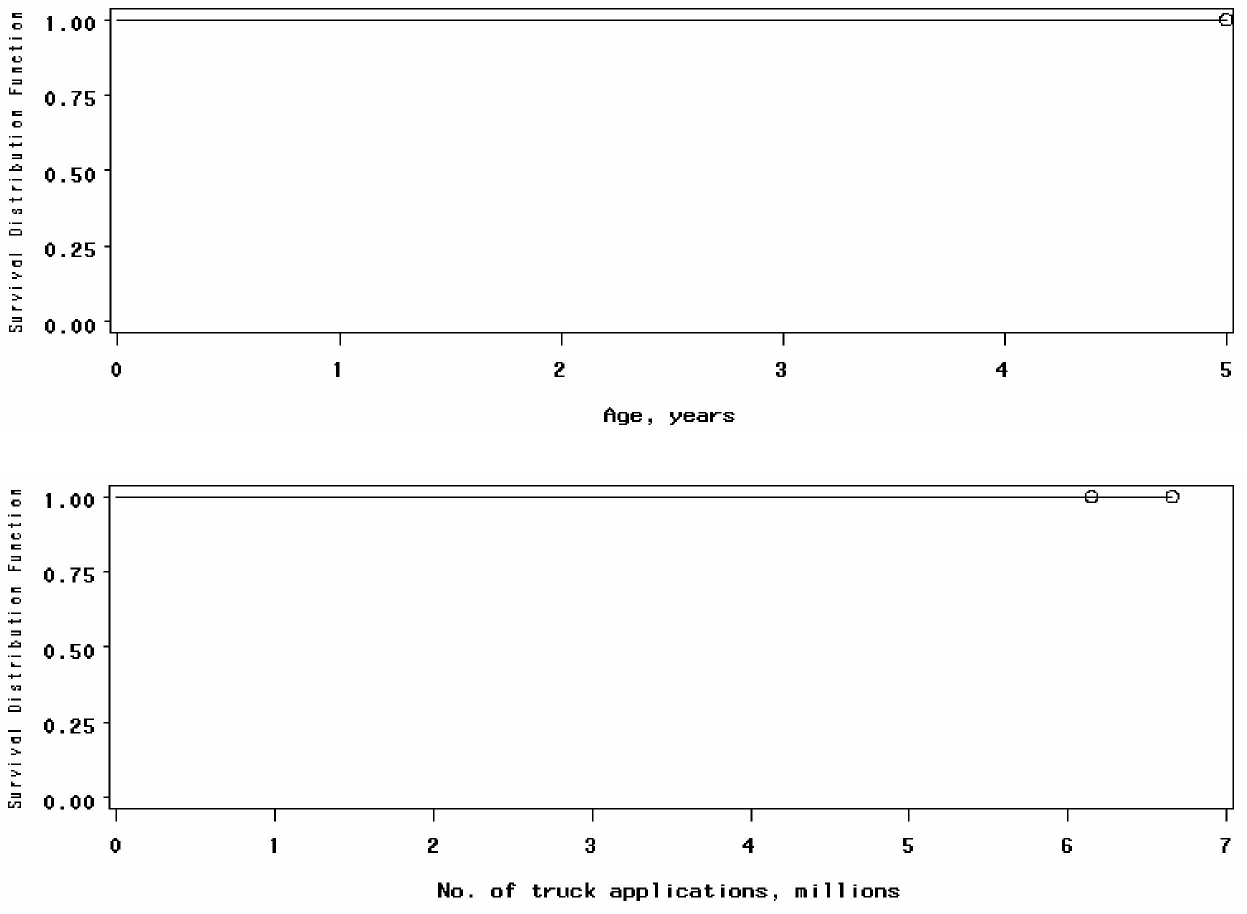


Figure A-29. Age- and truck traffic-based survival plots for R3C rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.

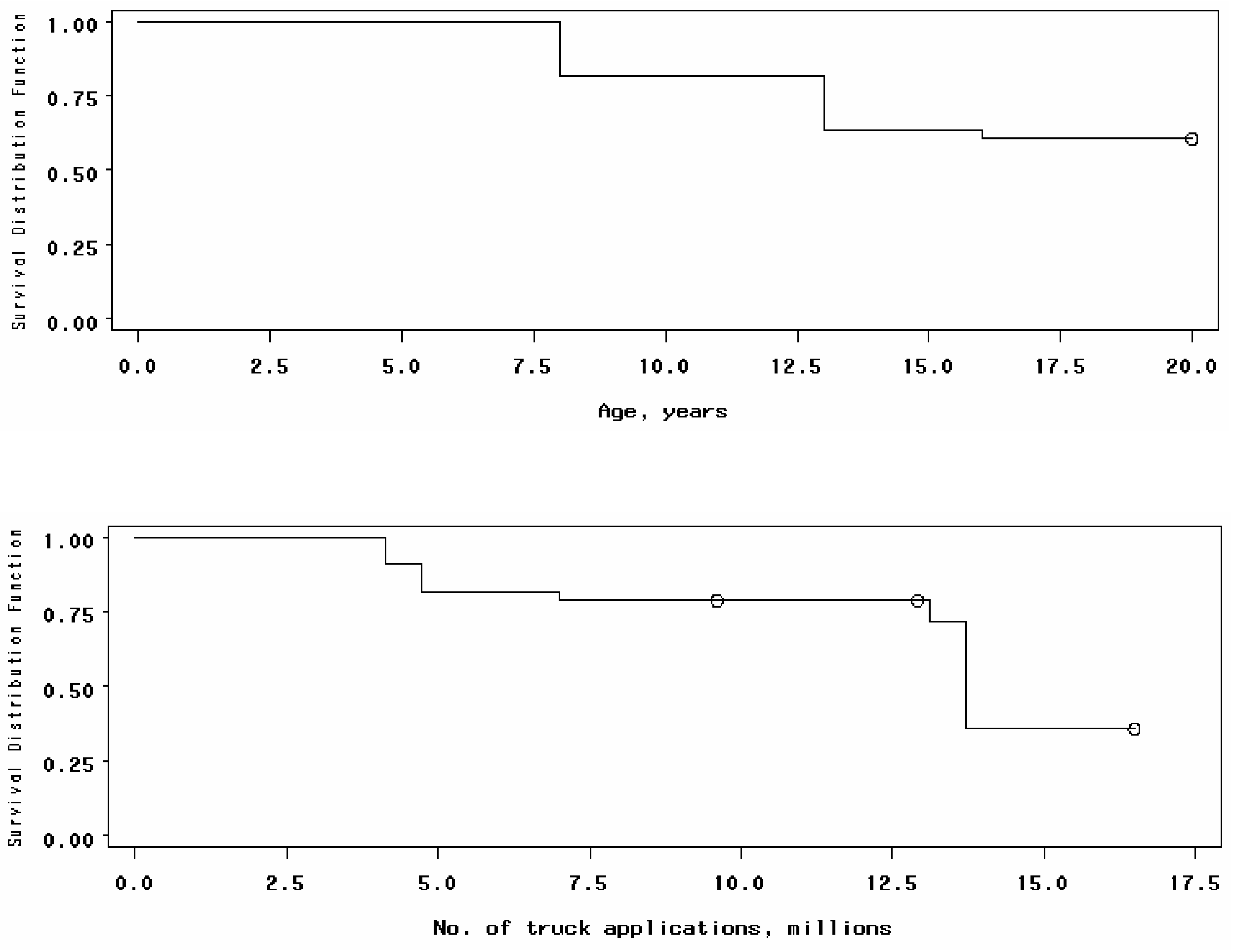


Figure A-30. Age- and truck traffic-based survival plots for R3D rehabilitation treatments applied to asphalt Interstate pavements located in hot-dry climate.

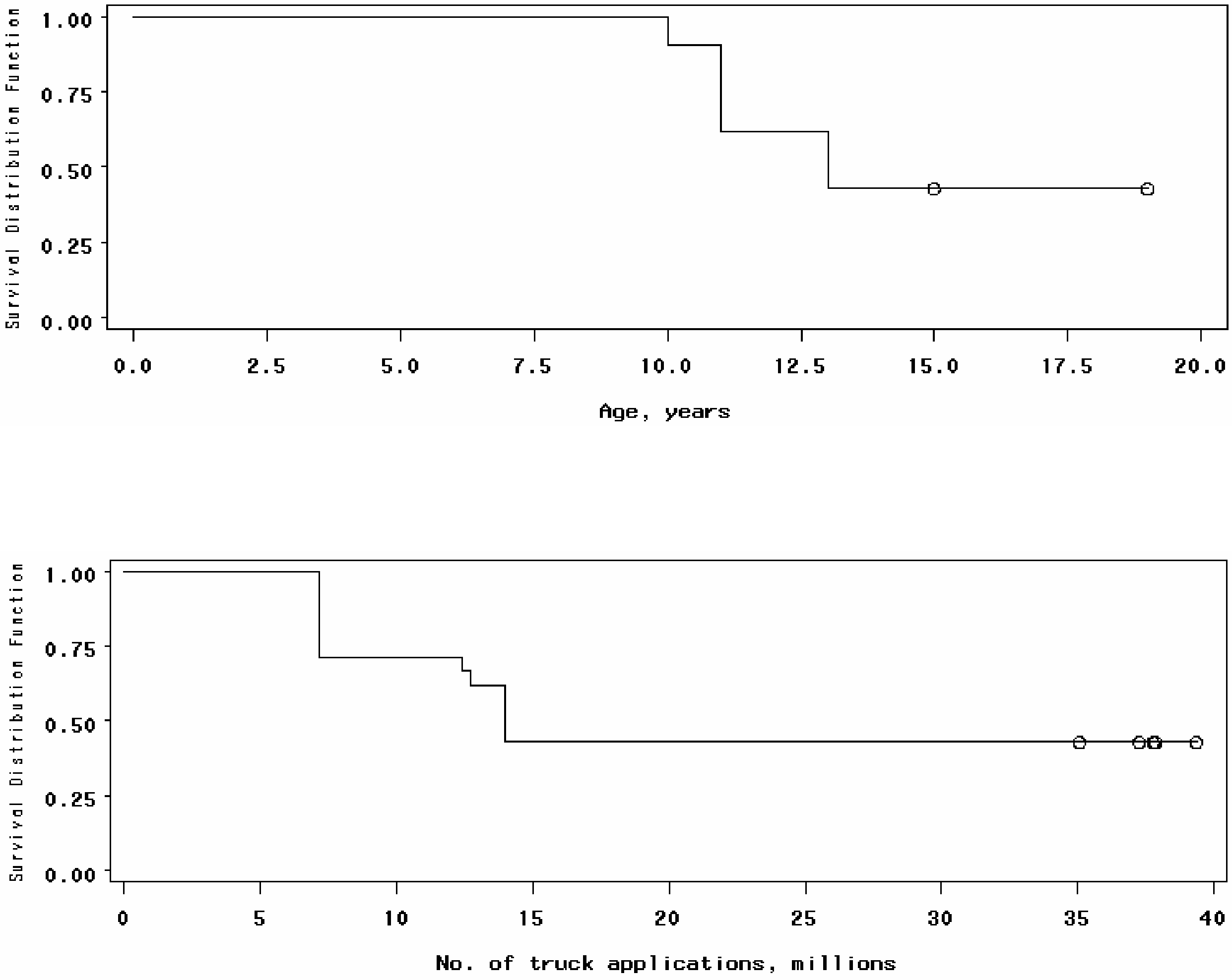
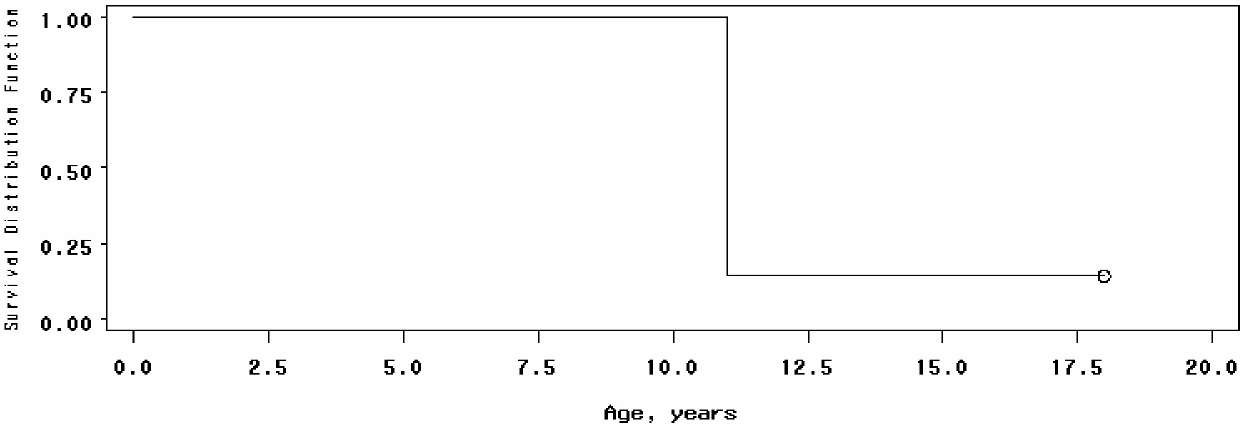


Figure A-31. Age- and truck traffic-based survival plots for R3D rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.



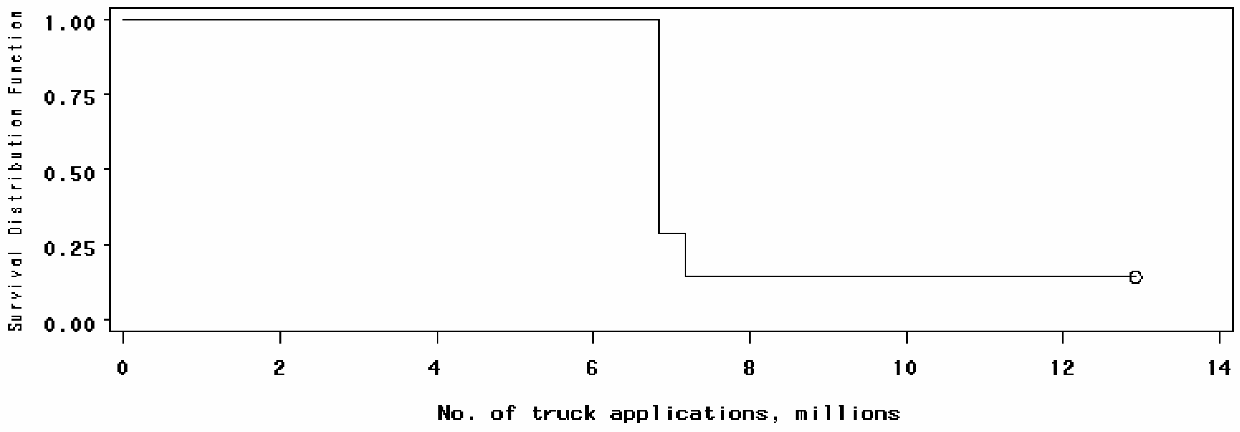


Figure A-32. Age- and truck traffic-based survival plots for R3D rehabilitation treatments applied to asphalt Interstate pavements located in cool-wet climate.

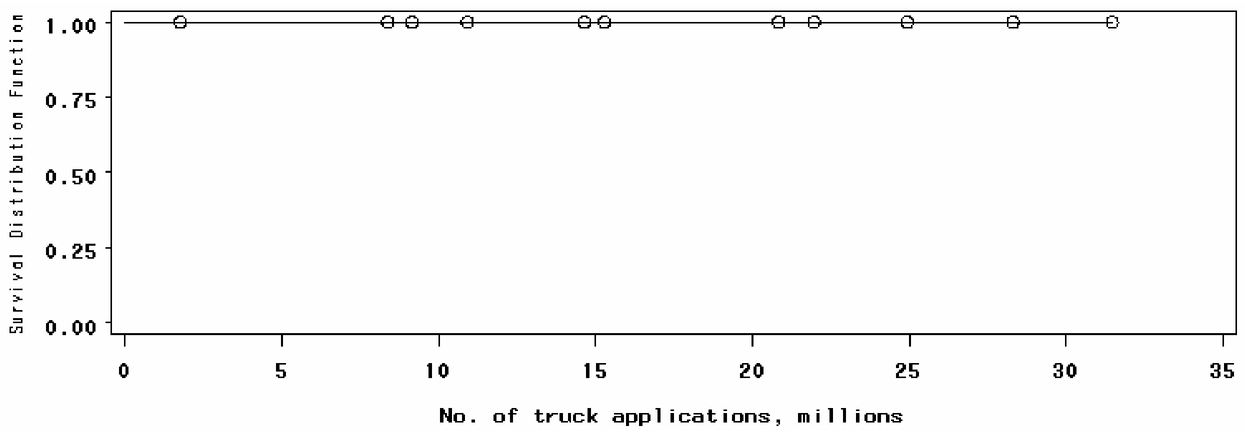


Figure A-33. Age- and truck traffic-based survival plots for R4A rehabilitation treatments applied to asphalt Interstate pavements located in hot-dry climate.

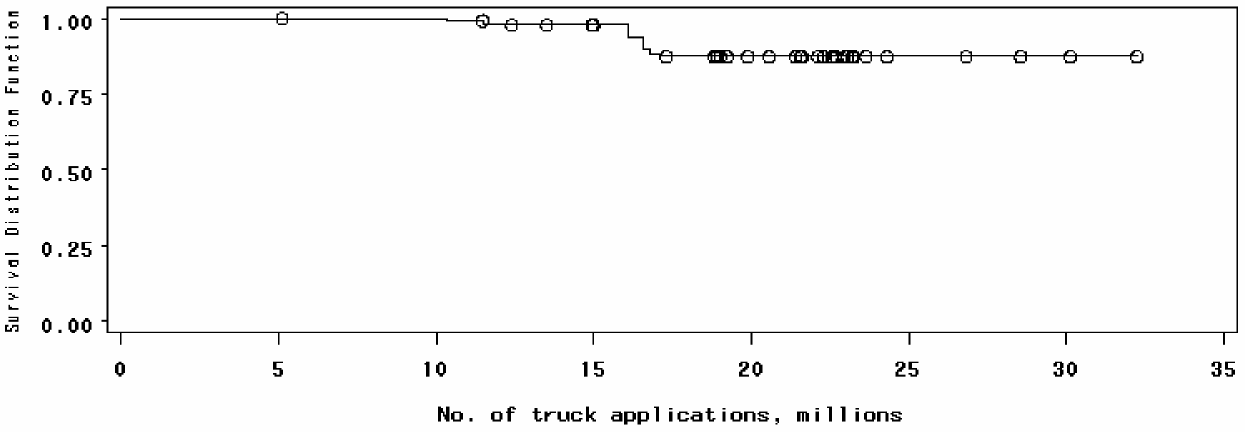
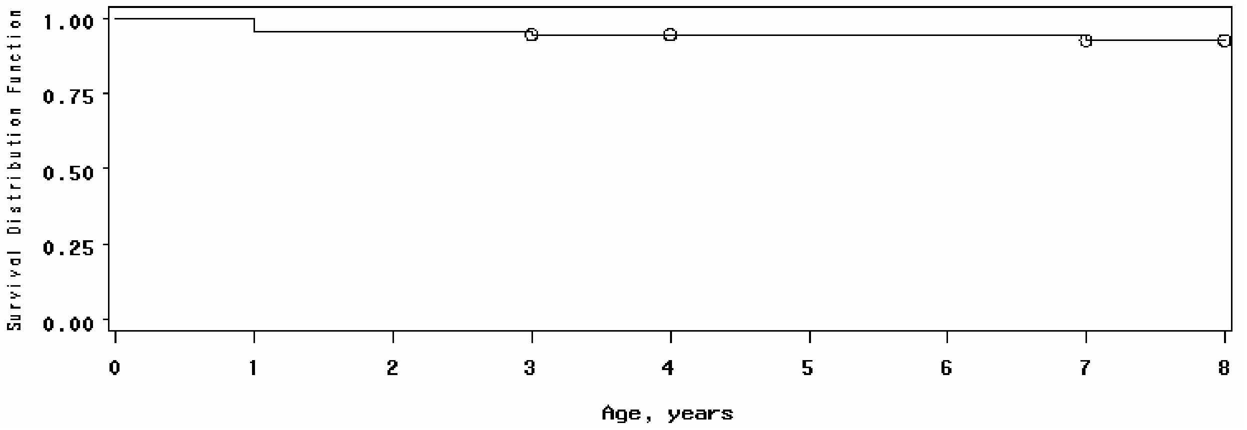


Figure A-34. Age- and truck traffic-based survival plots for R4A rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.



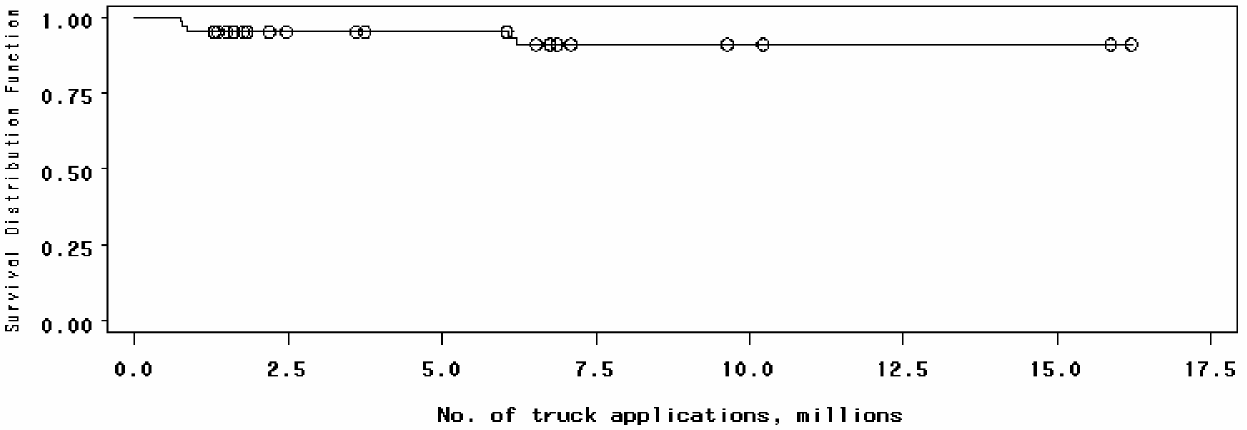
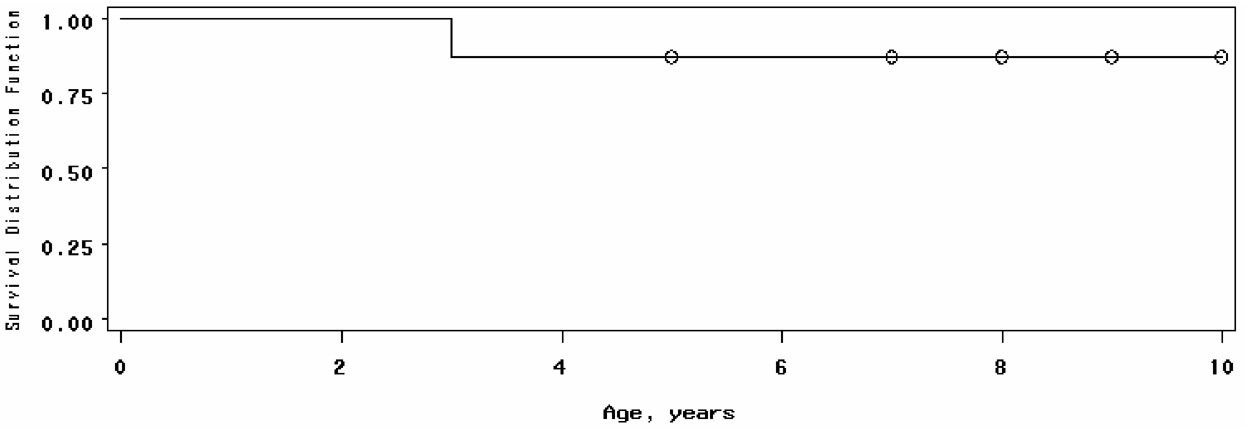


Figure A-35. Age- and truck traffic-based survival plots for R4B rehabilitation treatments applied to asphalt Interstate pavements located in hot-dry climate.



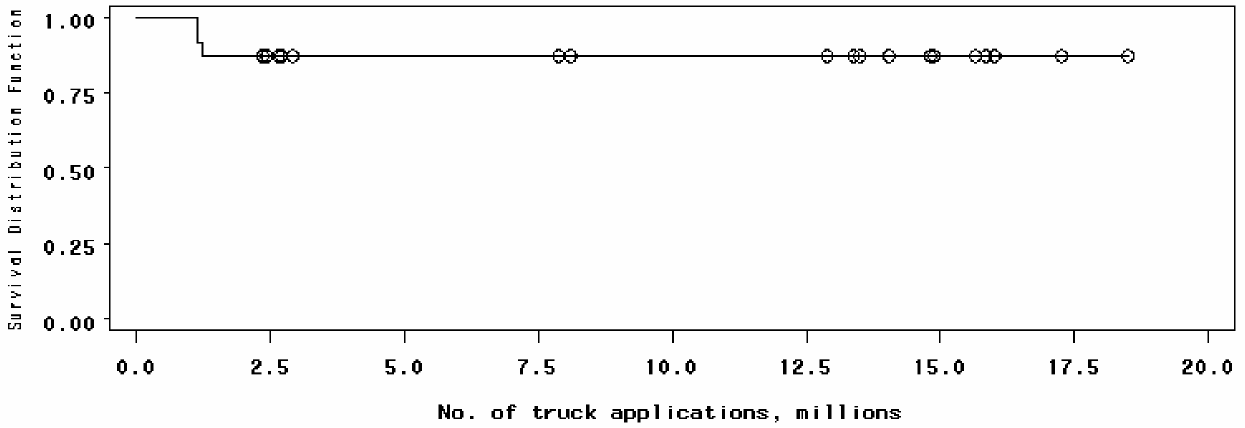


Figure A-36. Age- and truck traffic-based survival plots for R4B rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.

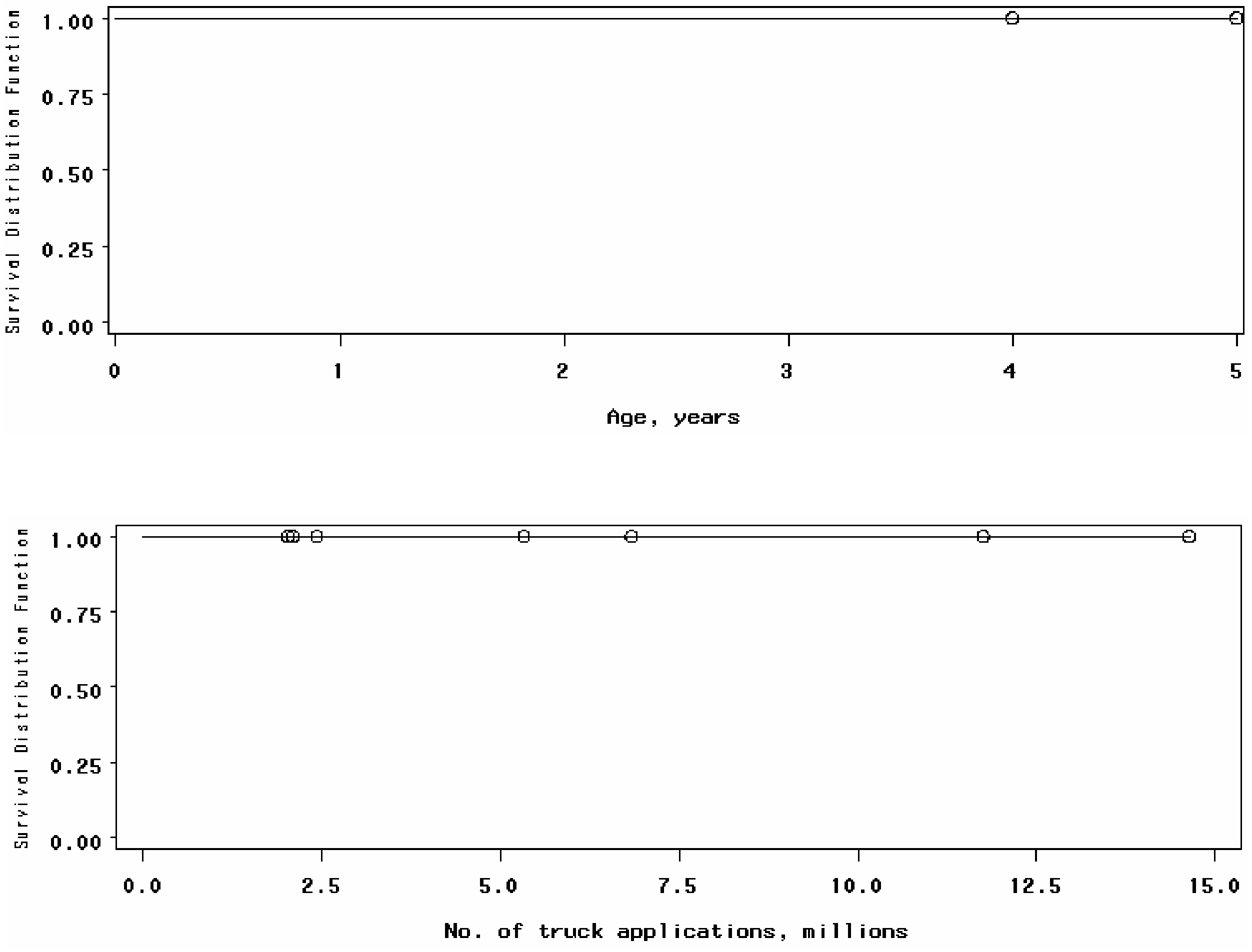
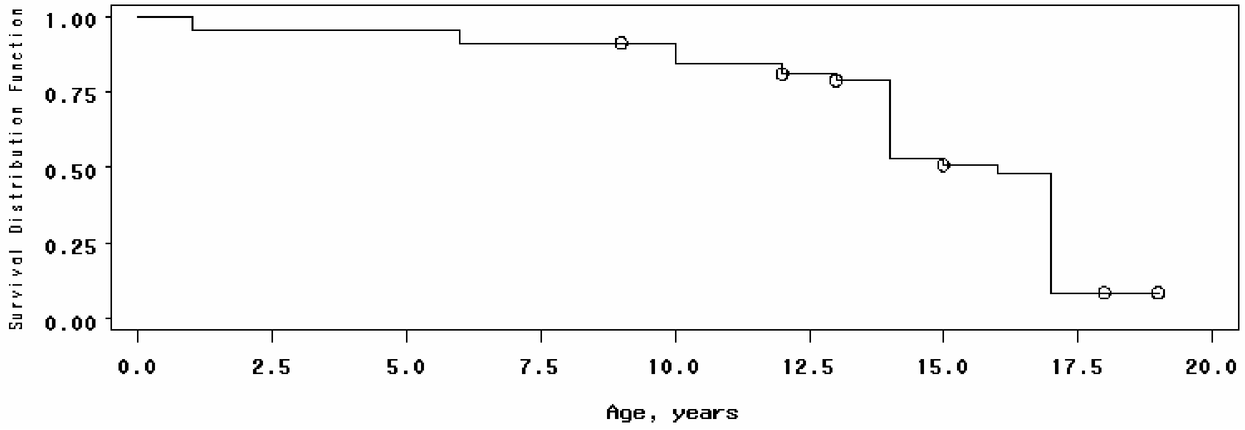


Figure A-37. Age- and truck traffic-based survival plots for R4C rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.



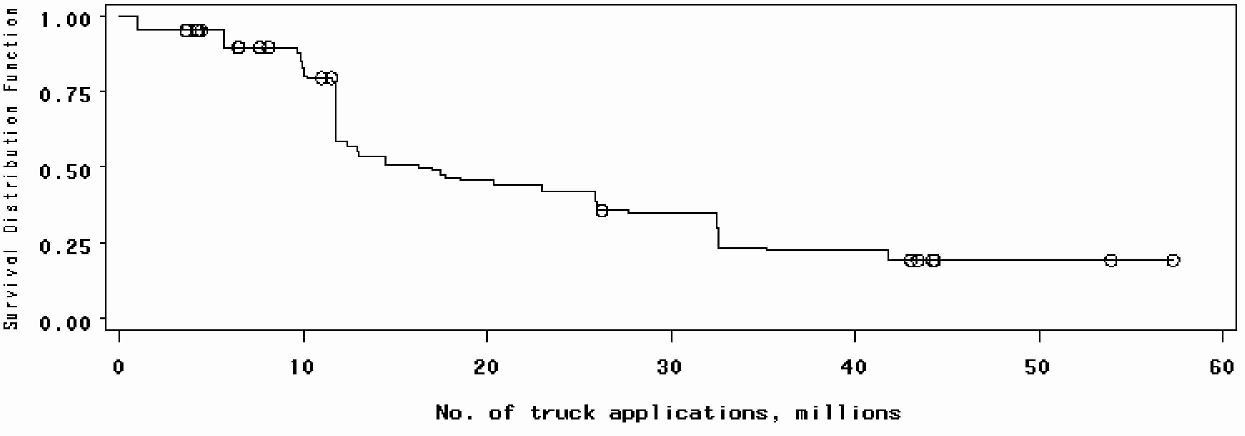
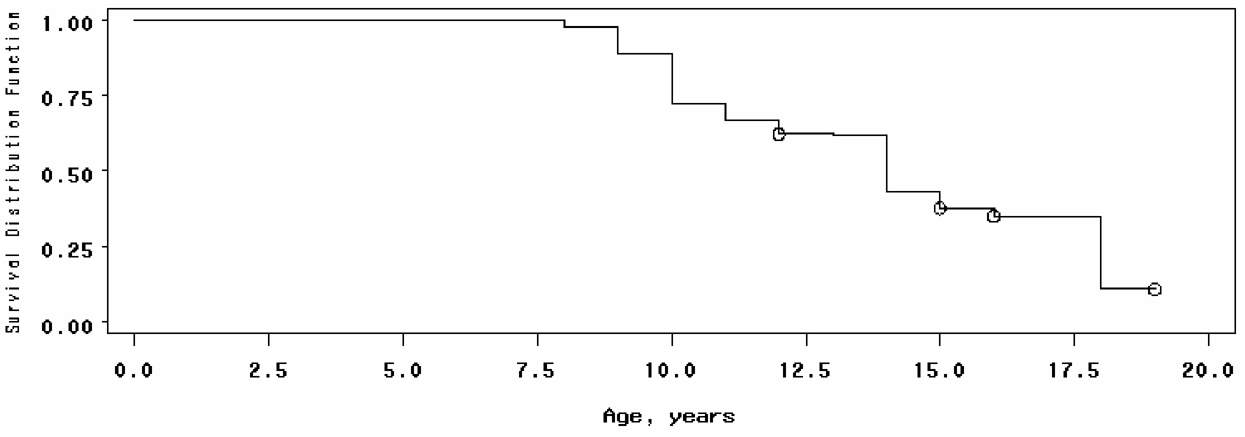


Figure A-38. Age- and truck traffic-based survival plots for R4D rehabilitation treatments applied to asphalt Interstate pavements located in hot-dry climate.



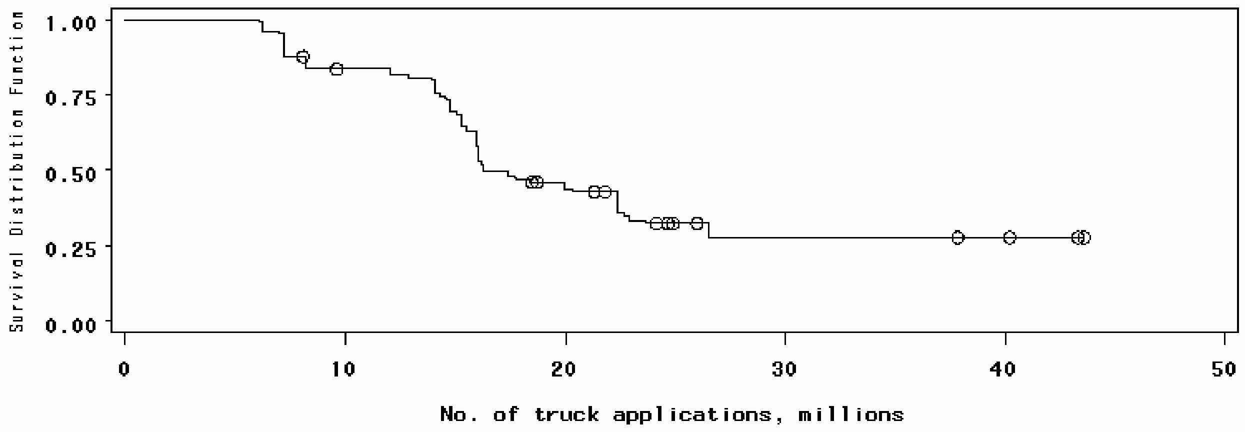
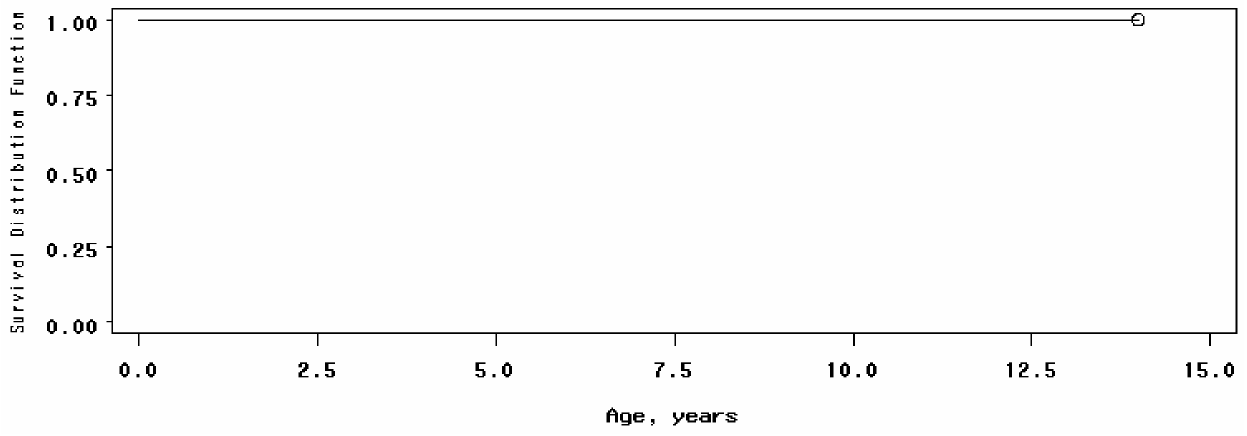


Figure A-39. Age- and truck traffic-based survival plots for R4D rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.



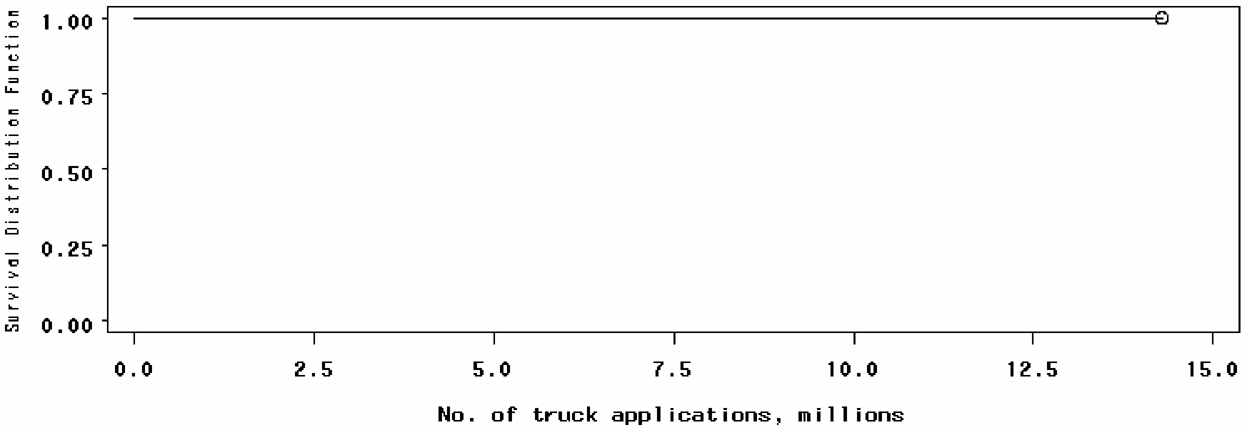
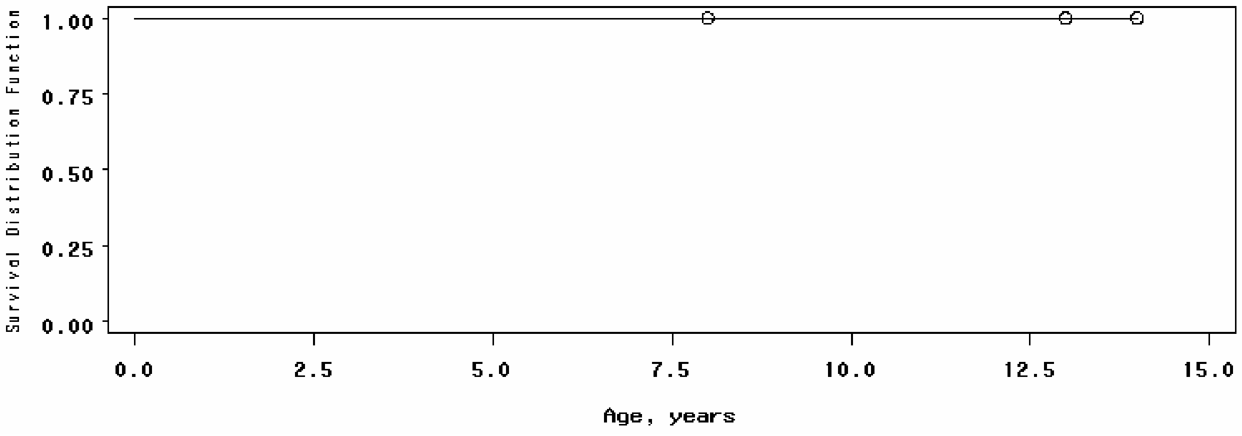


Figure A-40. Age- and truck traffic-based survival plots for R5A rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.



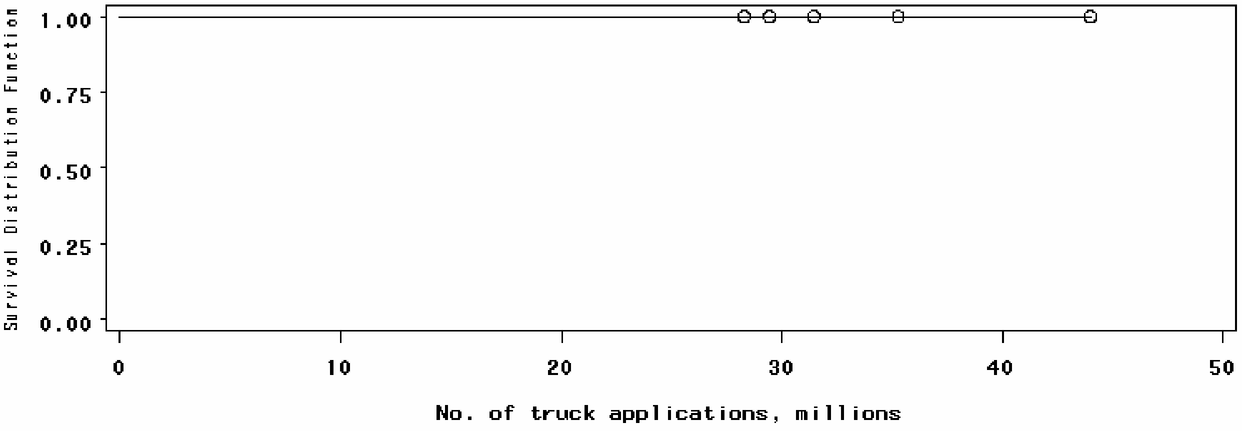


Figure A-41. Age- and truck traffic-based survival plots for R6A rehabilitation treatments applied to asphalt Interstate pavements located in hot-dry climate.

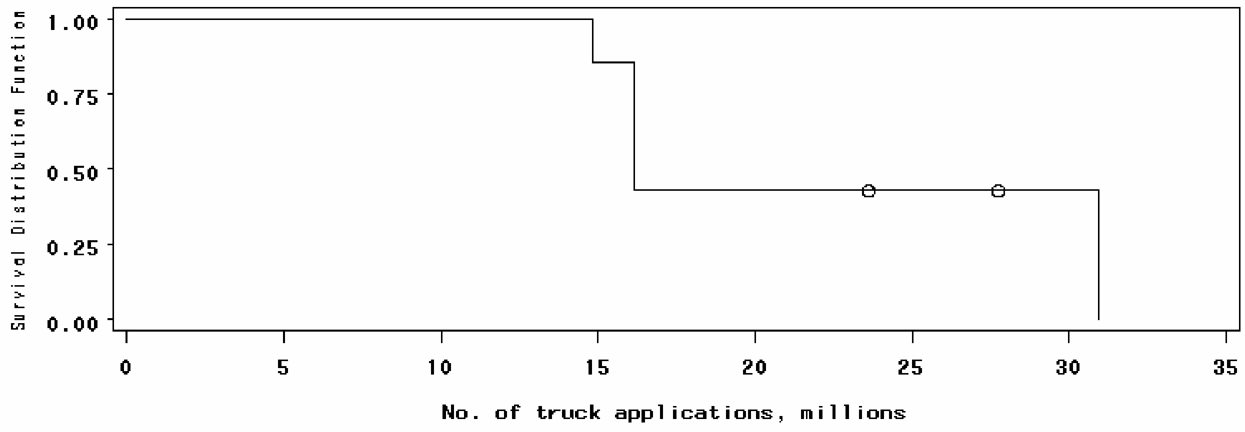
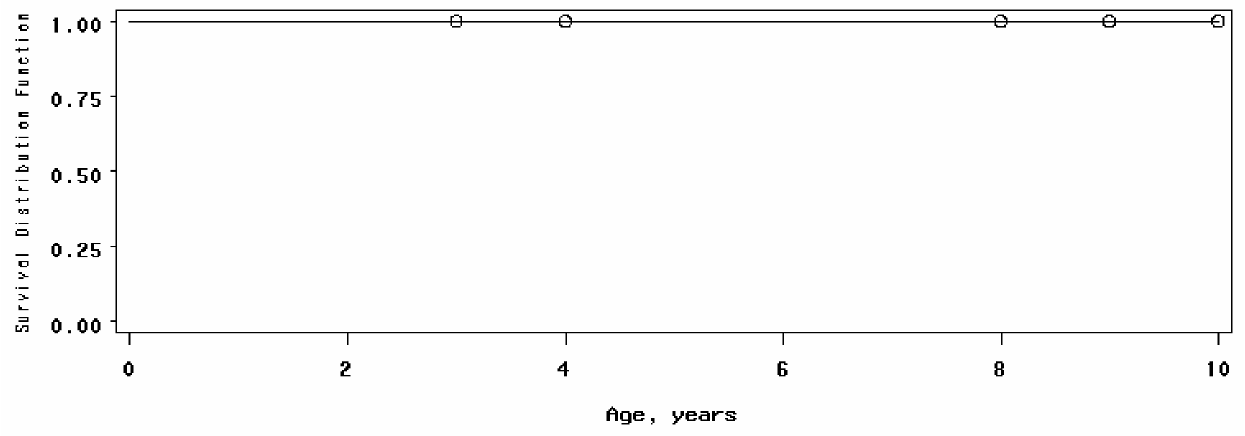


Figure A-42. Age- and truck traffic-based survival plots for R6A rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.



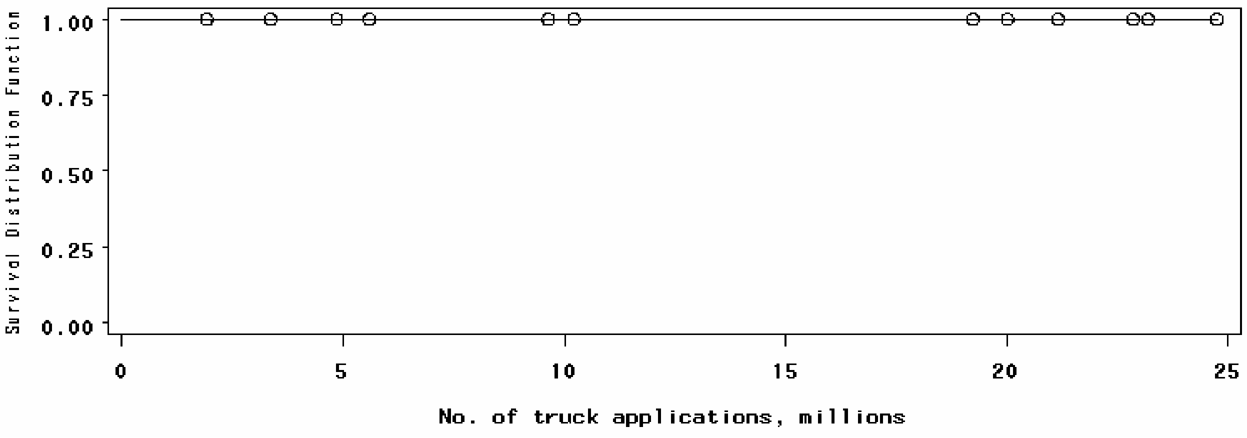
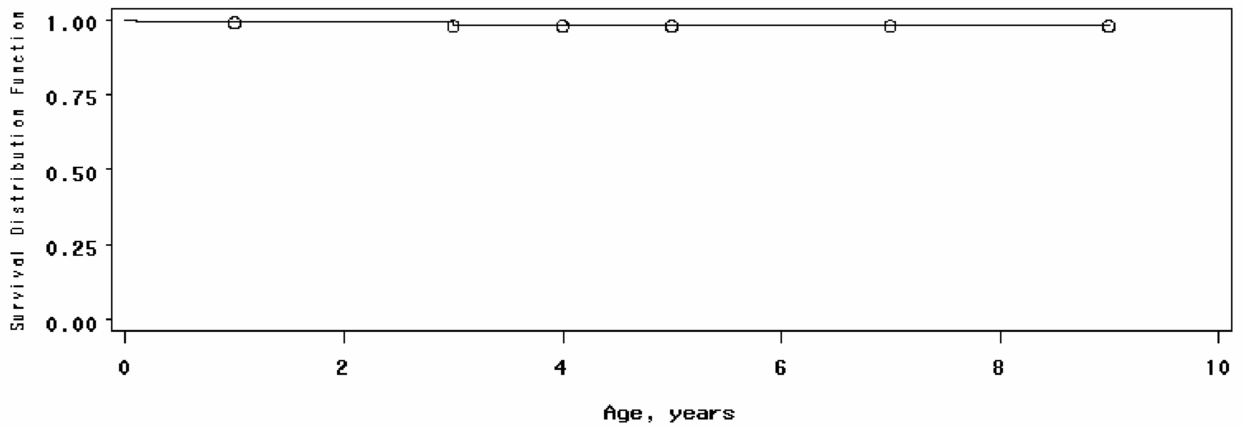


Figure A-43. Age- and truck traffic-based survival plots for R6B rehabilitation treatments applied to asphalt Interstate pavements located in hot-dry climate.



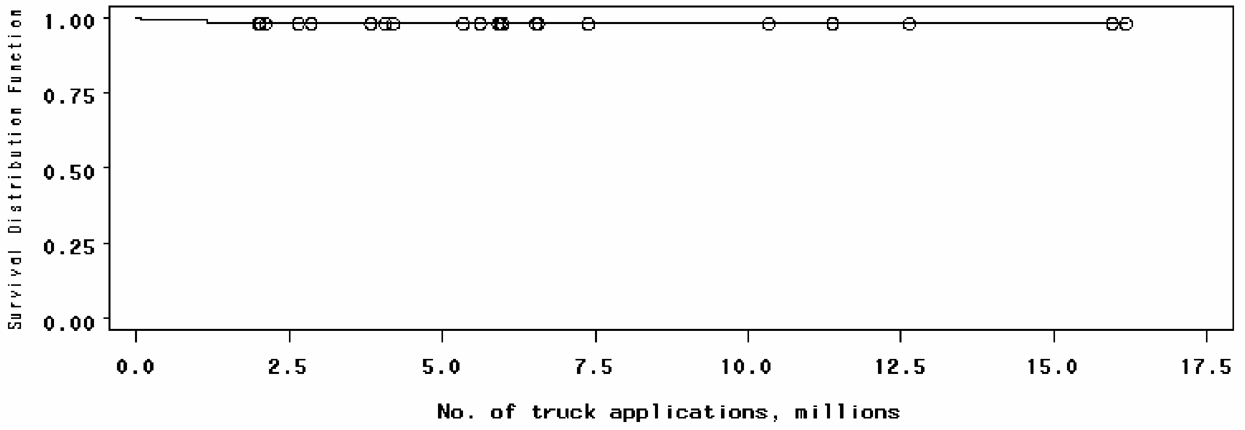
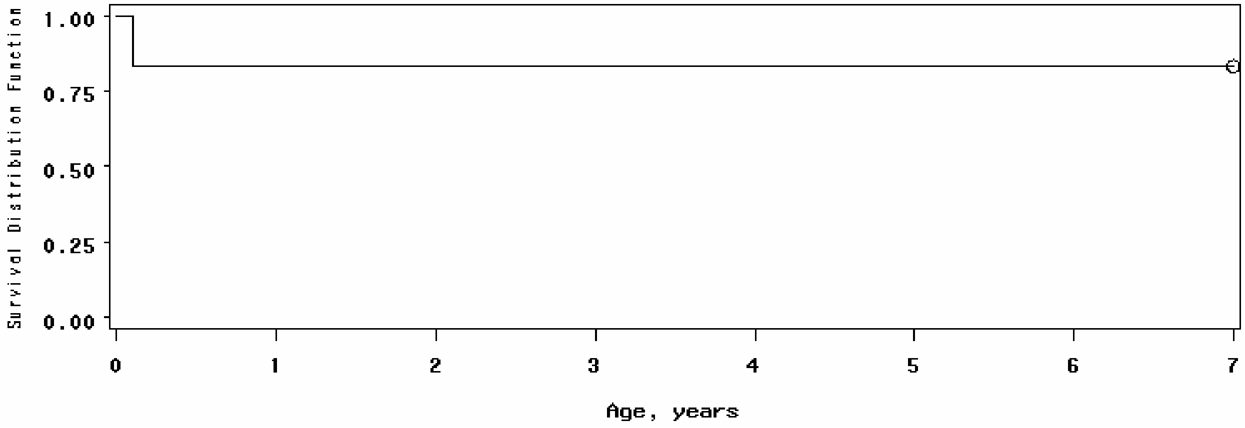


Figure A-44. Age- and truck traffic-based survival plots for R6B rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.



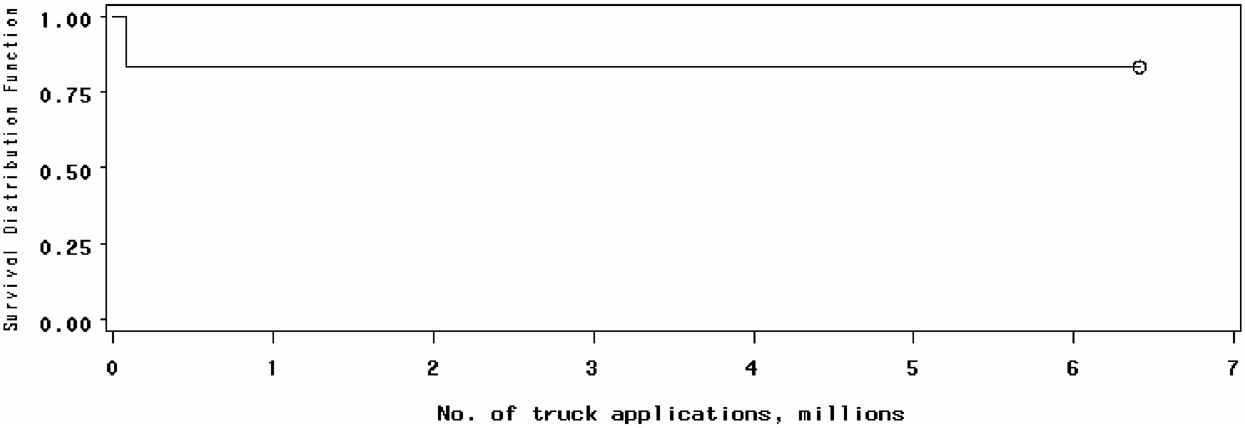
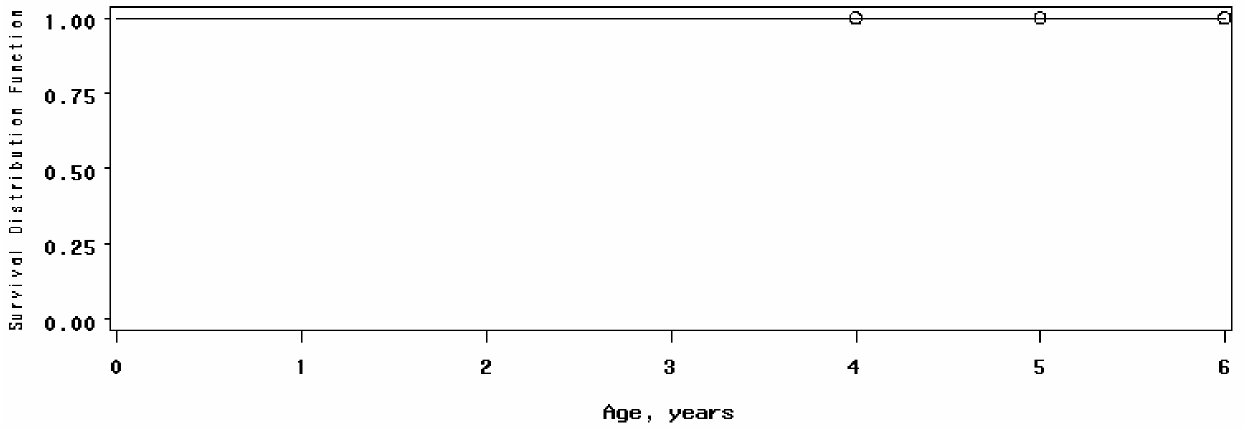


Figure A-45. Age- and truck traffic-based survival plots for R6B rehabilitation treatments applied to asphalt Interstate pavements located in cool-wet climate.



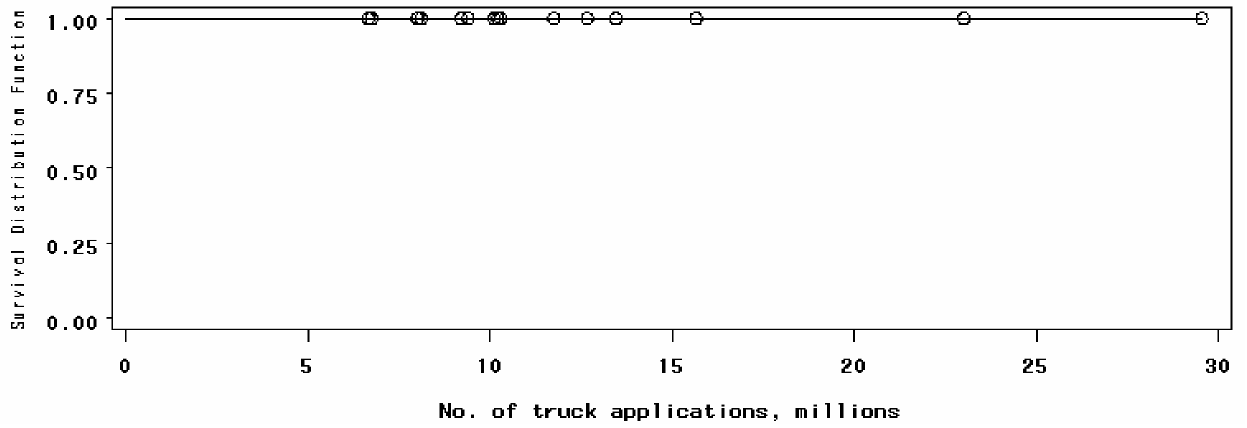
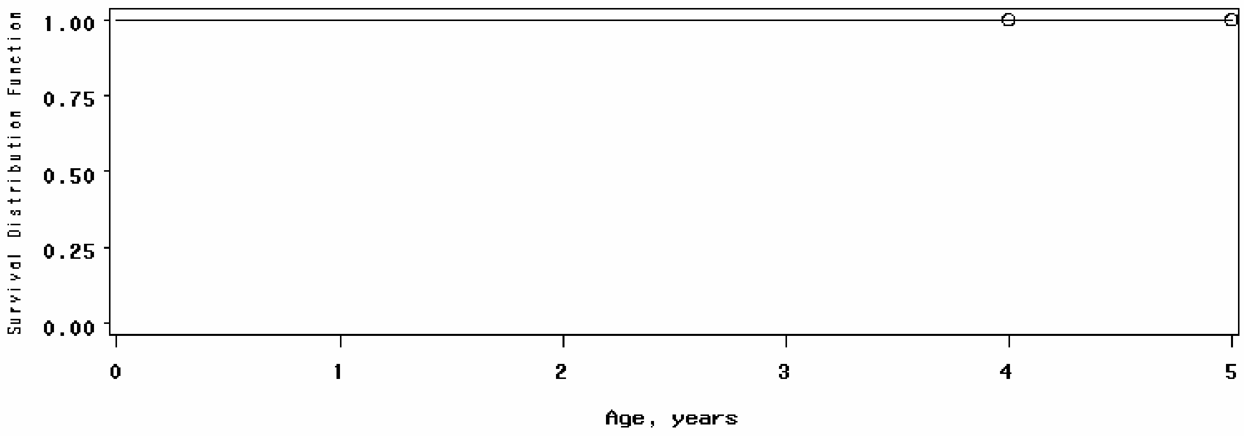


Figure A-46. Age- and truck traffic-based survival plots for R6C rehabilitation treatments applied to asphalt Interstate pavements located in hot-dry climate.



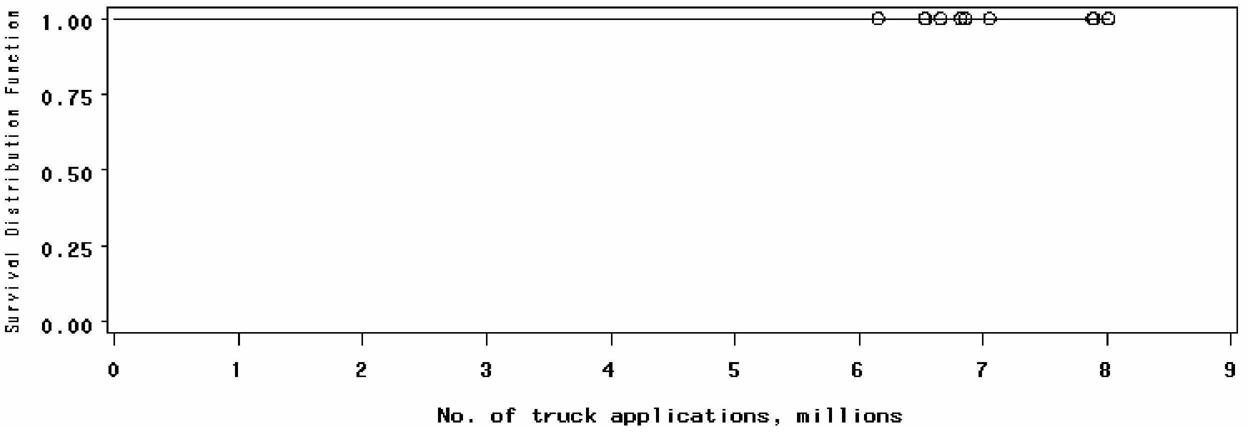
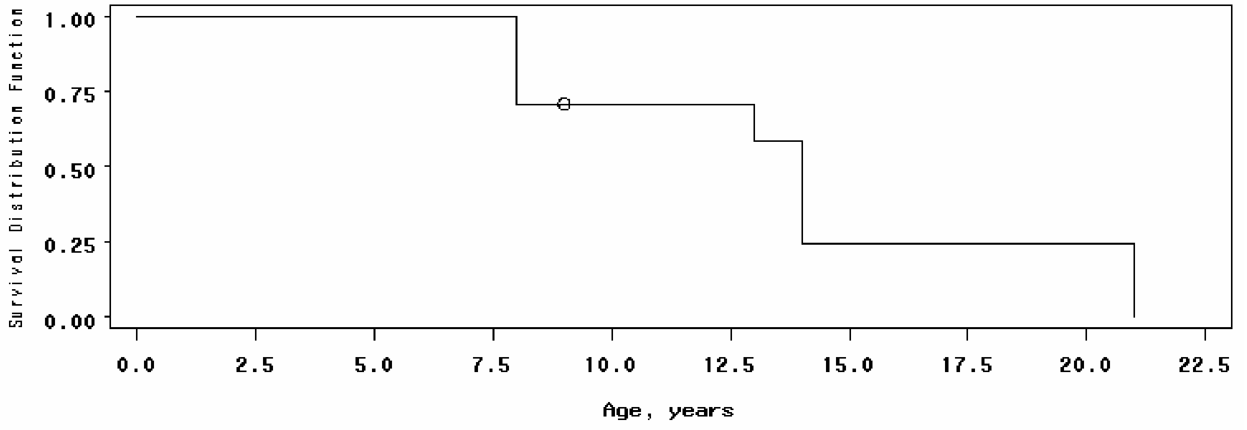


Figure A-47. Age- and truck traffic-based survival plots for R6C rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.



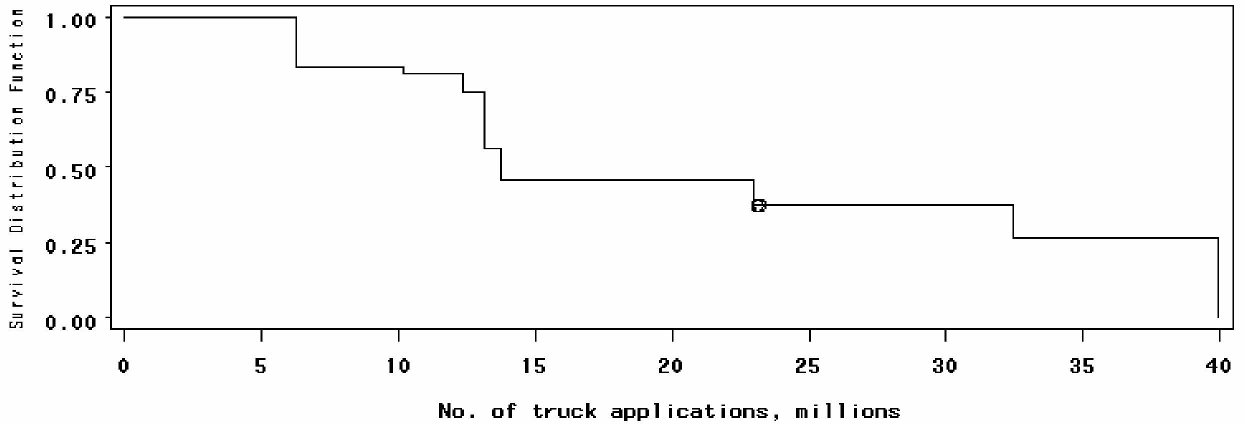
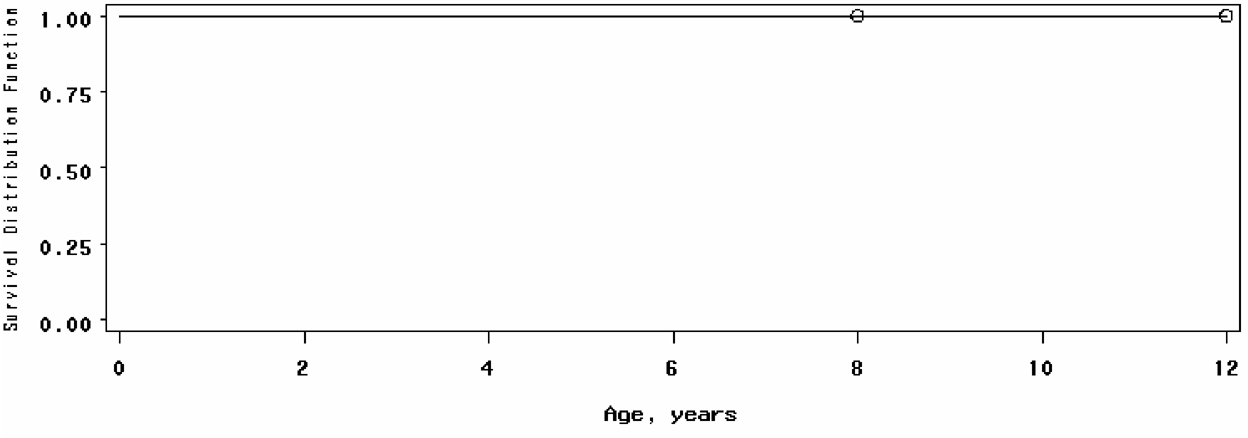


Figure A-48. Age- and truck traffic-based survival plots for R6D rehabilitation treatments applied to asphalt Interstate pavements located in hot-dry climate.



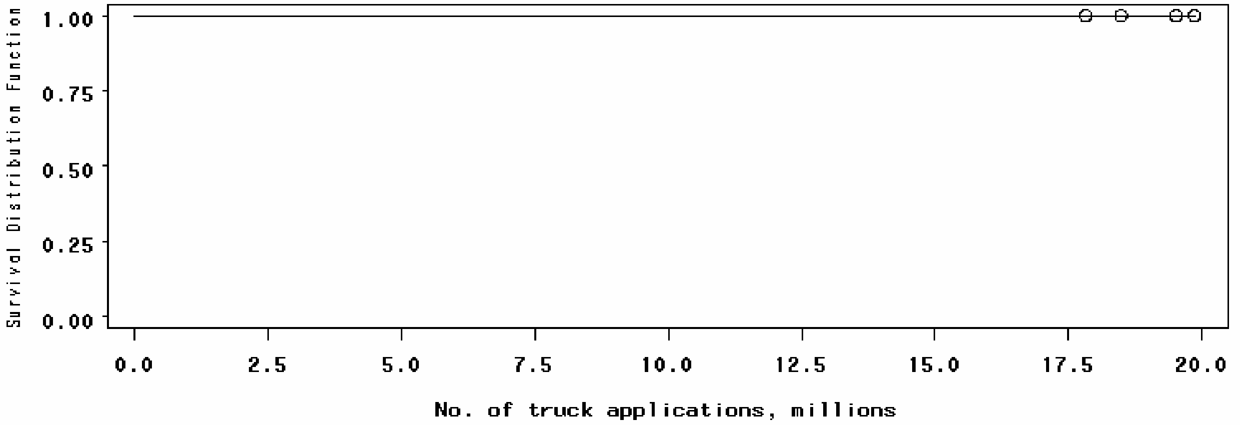
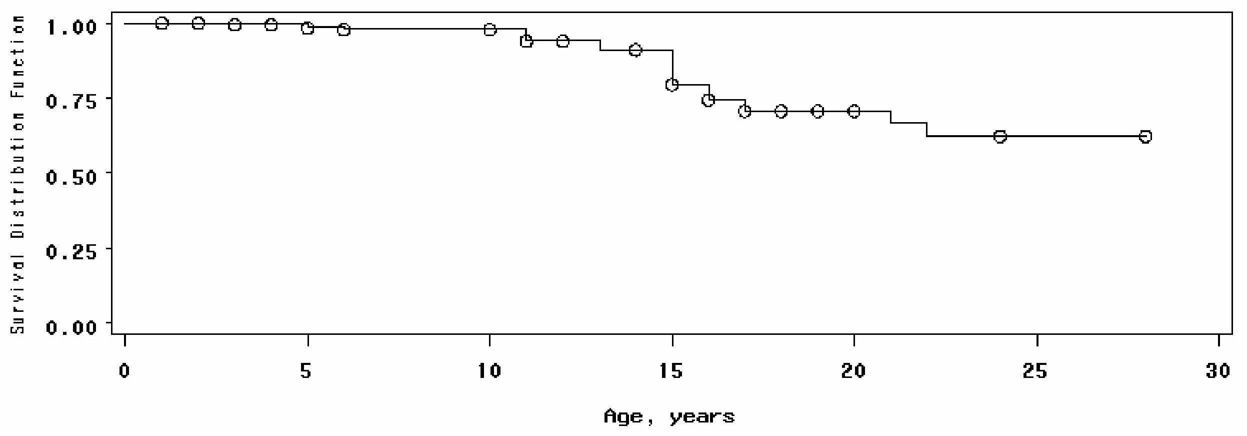


Figure A-49. Age- and truck traffic-based survival plots for R6D rehabilitation treatments applied to asphalt Interstate pavements located in moderate climate.



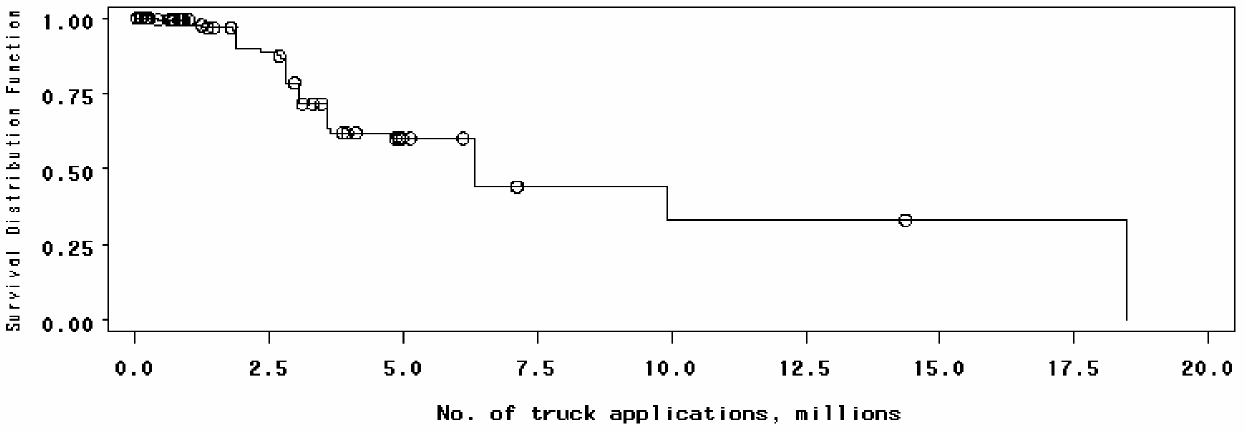


Figure A-50. Age- and truck traffic-based survival plots for R1A rehabilitation treatments applied to asphalt Non-Interstate pavements located in hot-dry climate.

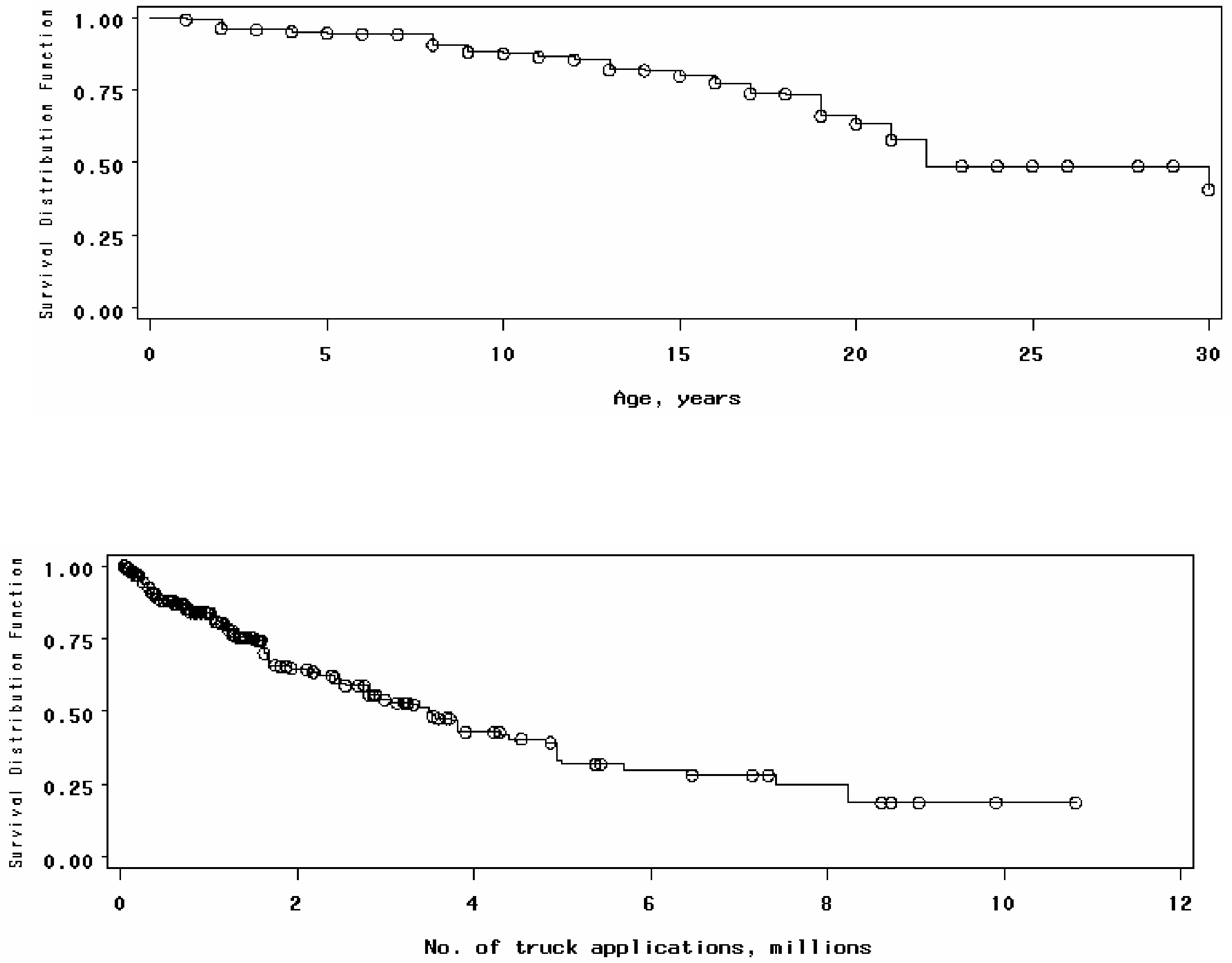
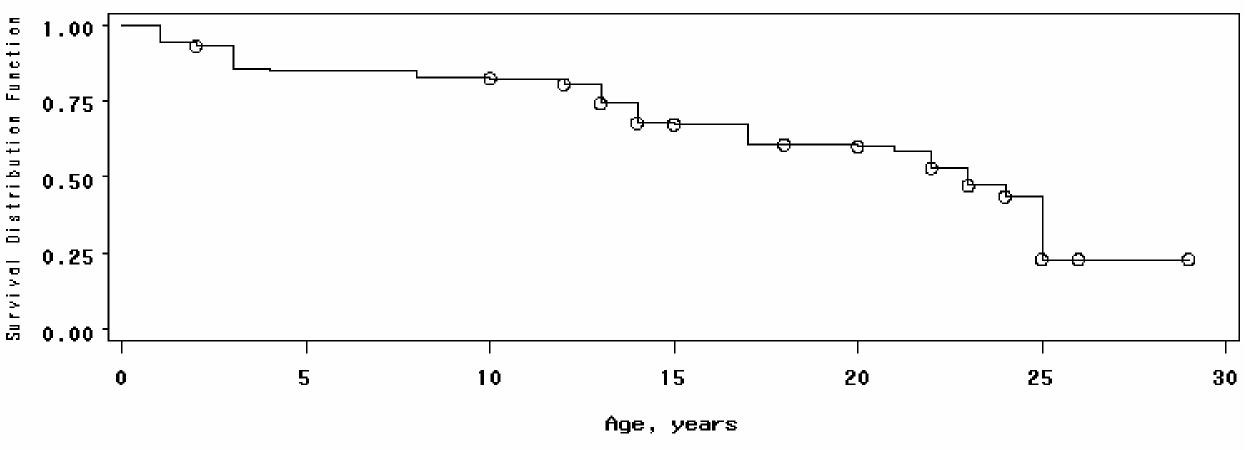


Figure A-51. Age- and truck traffic-based survival plots for R1A rehabilitation treatments applied to asphalt Non-Interstate pavements located in moderate climate.



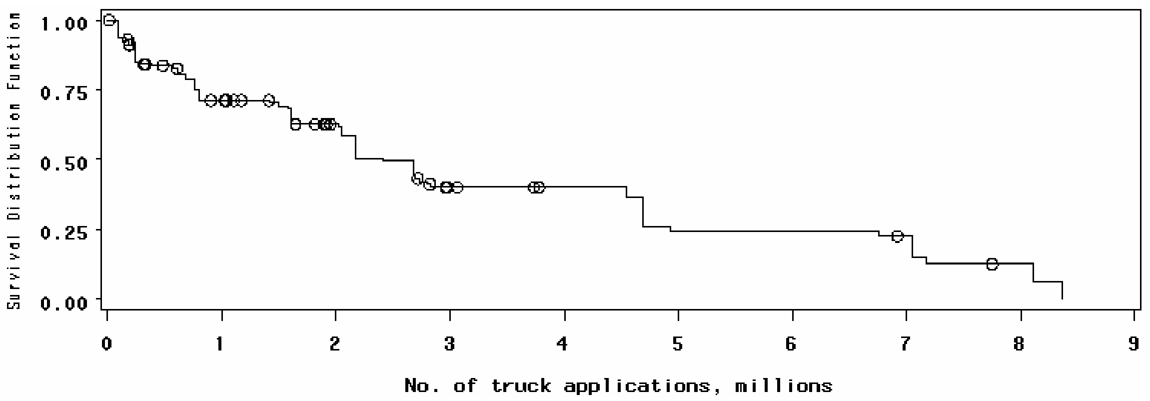


Figure A-52. Age- and truck traffic-based survival plots for R1A rehabilitation treatments applied to asphalt Non-Interstate pavements located in cool-wet climate.

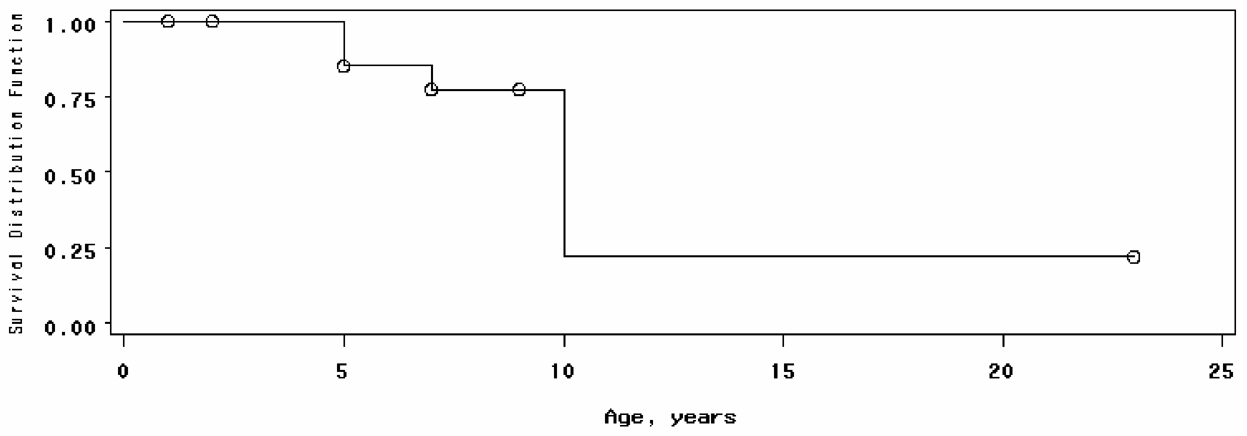
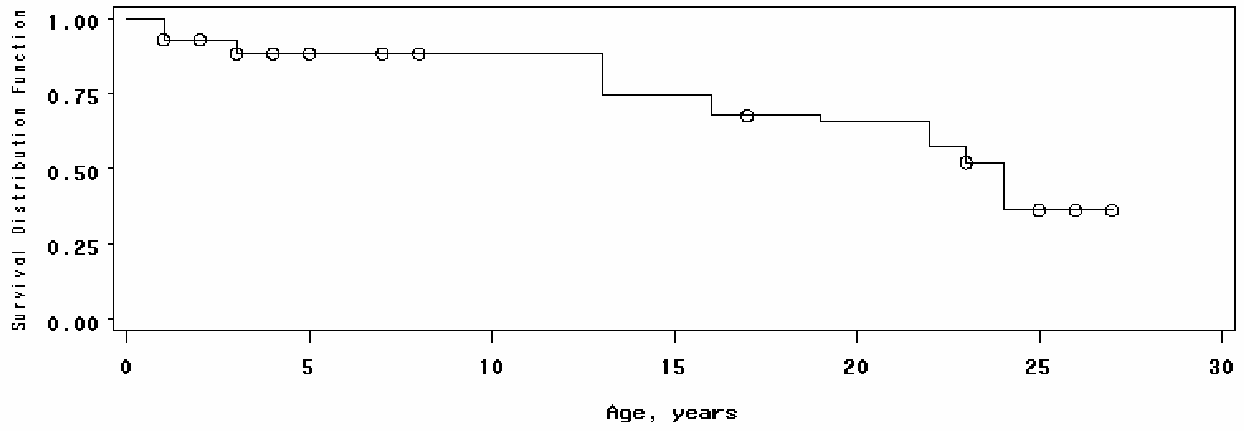


Figure A-53. Age- and truck traffic-based survival plots for R1B rehabilitation treatments applied to asphalt Non-Interstate pavements located in hot-dry climate.



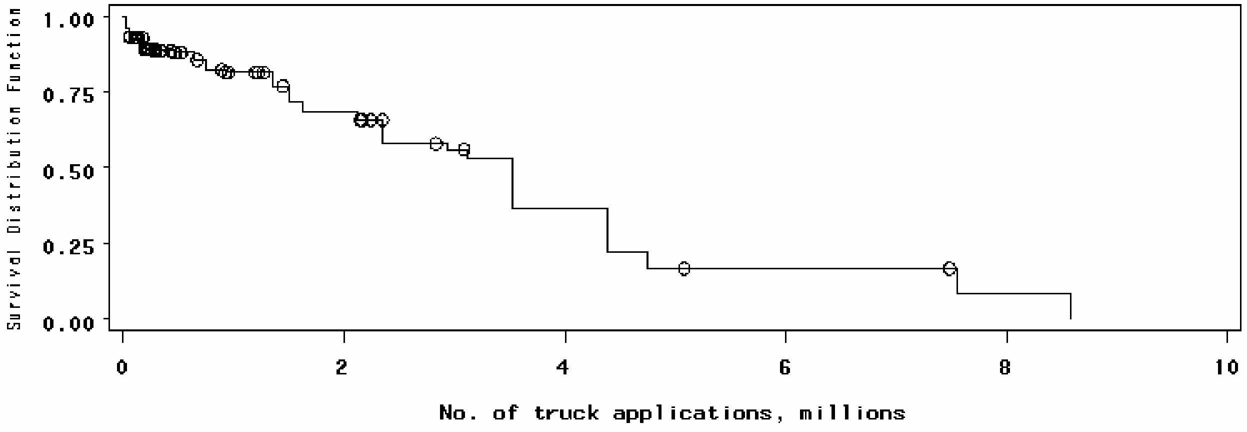
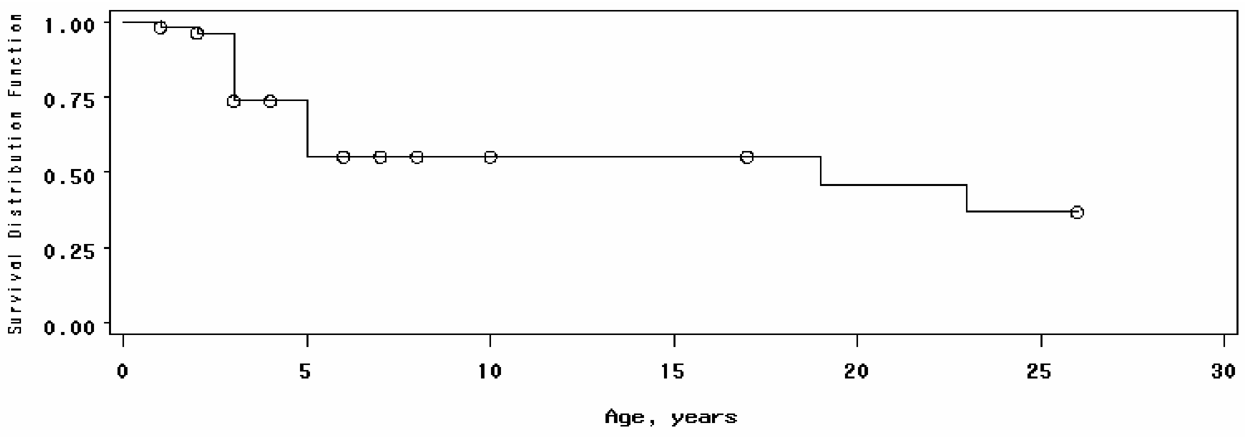


Figure A-54. Age- and truck traffic-based survival plots for R1B rehabilitation treatments applied to asphalt Non-Interstate pavements located in moderate climate.



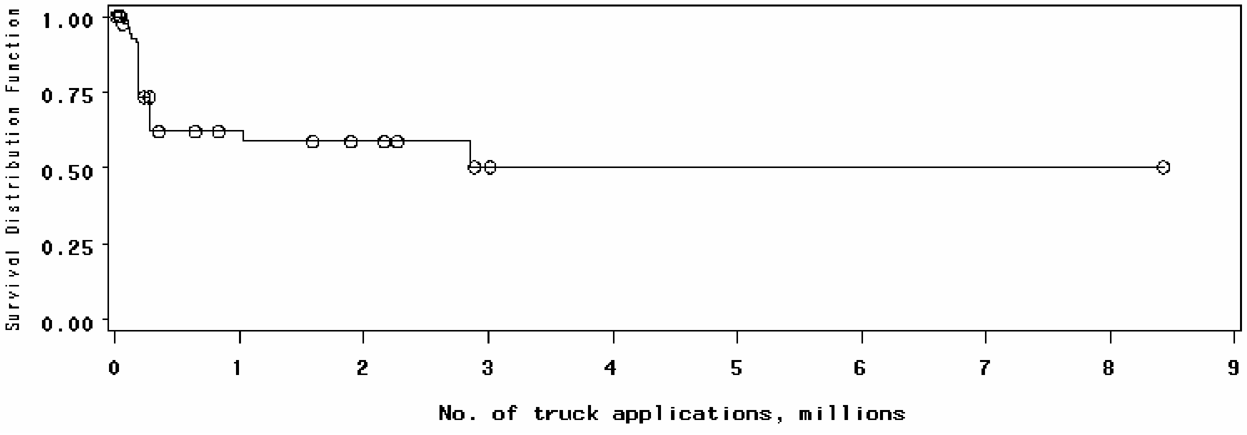


Figure A-55. Age- and truck traffic-based survival plots for R1B rehabilitation treatments applied to asphalt Non-Interstate pavements located in cool-wet climate.

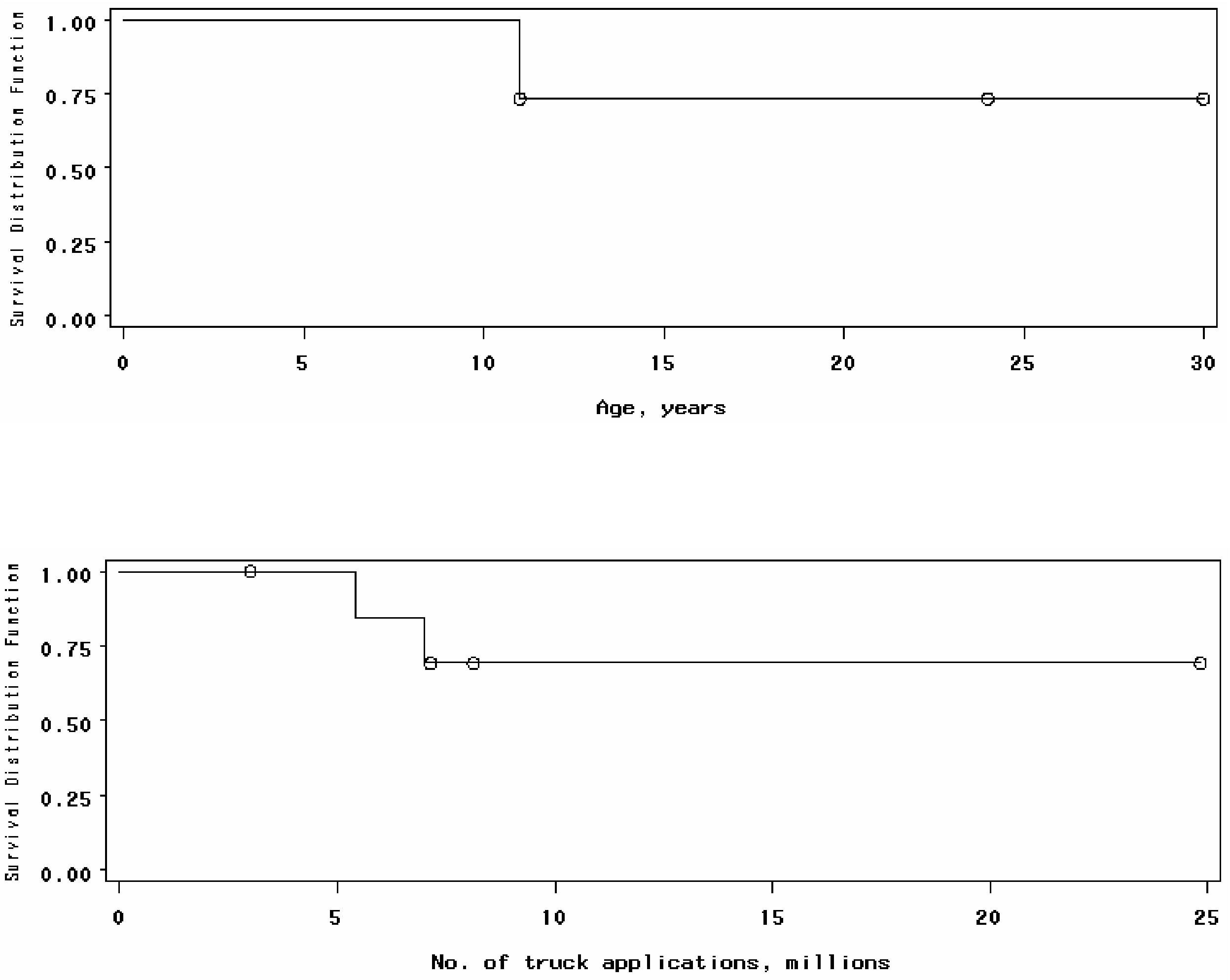
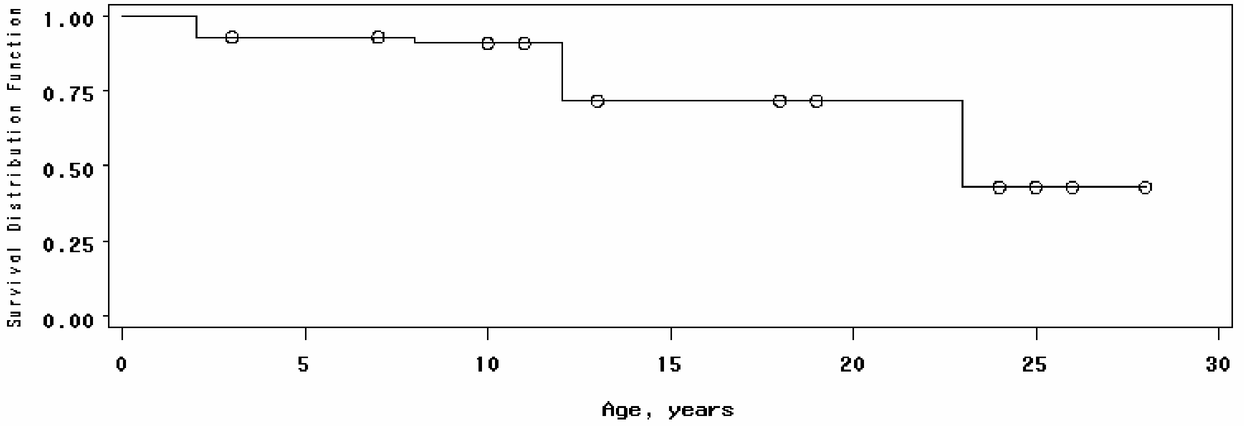


Figure A-56. Age- and truck traffic-based survival plots for R2A rehabilitation treatments applied to asphalt Non-Interstate pavements located in hot-dry climate.



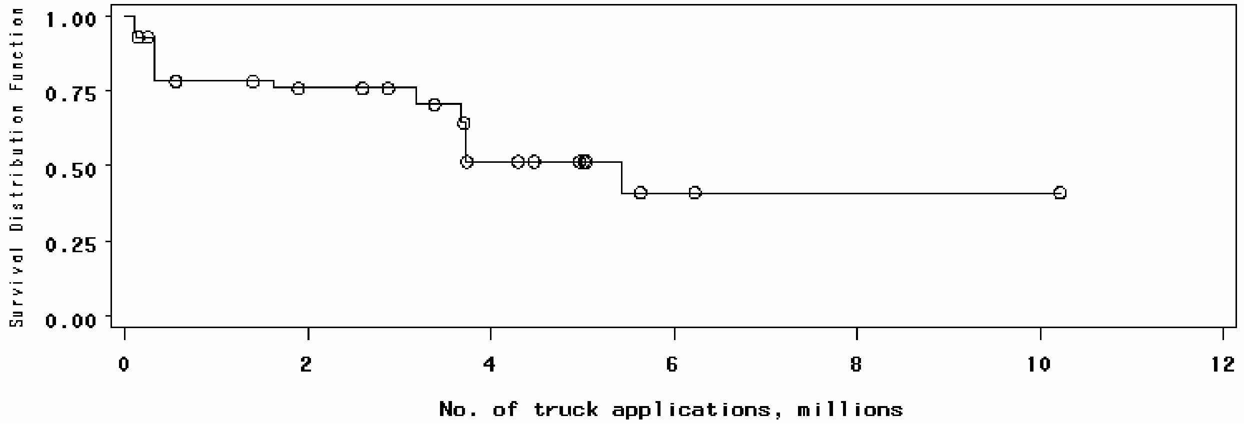
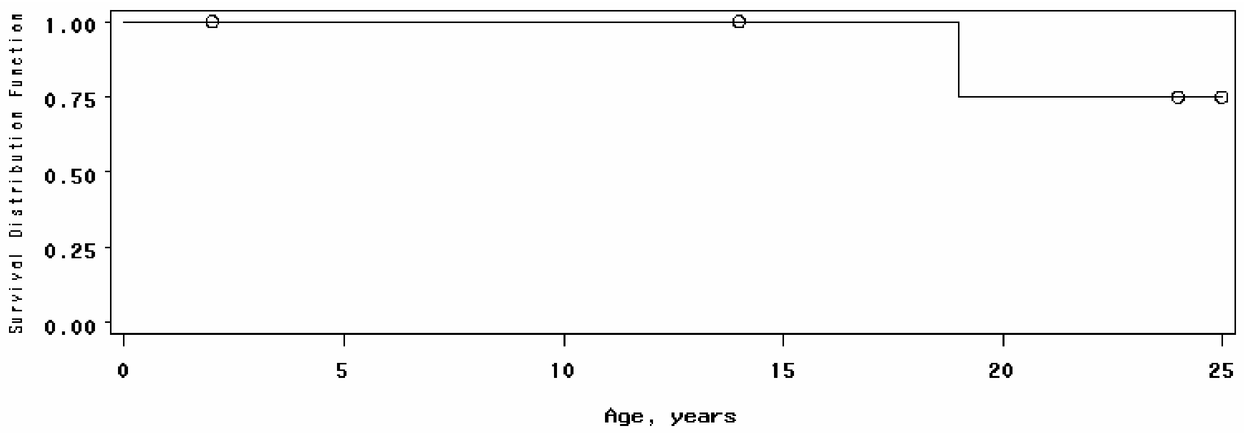


Figure A-57. Age- and truck traffic-based survival plots for R2A rehabilitation treatments applied to asphalt Non-Interstate pavements located in moderate climate.



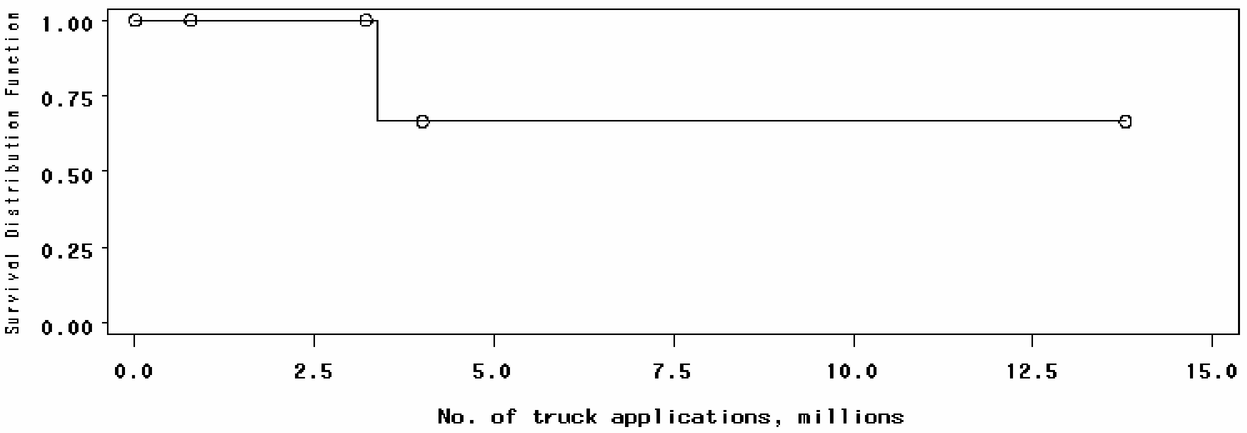
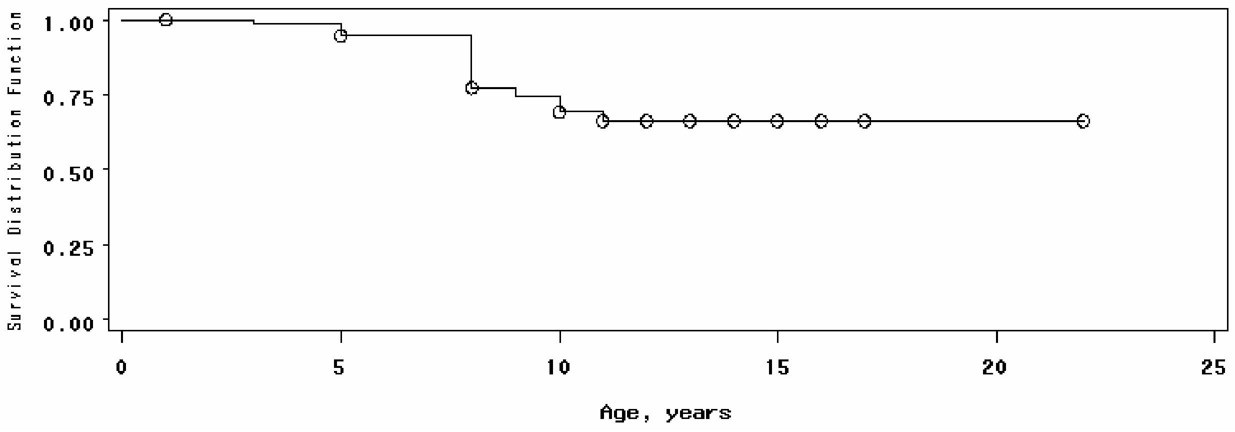


Figure A-58. Age- and truck traffic-based survival plots for R2A rehabilitation treatments applied to asphalt Non-Interstate pavements located in cool-wet climate.



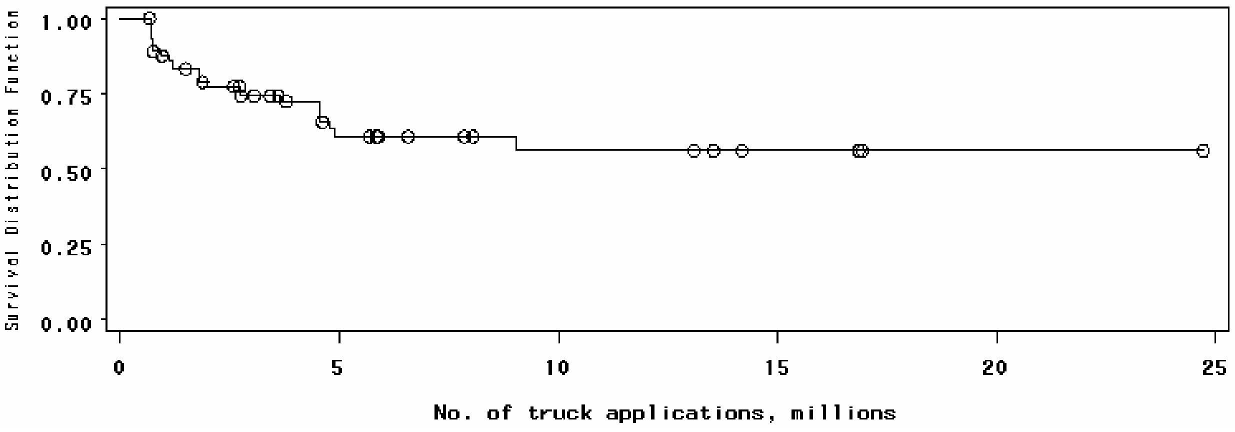


Figure A-59. Age- and truck traffic-based survival plots for R3A rehabilitation treatments applied to asphalt Non-Interstate pavements located in hot-dry climate.

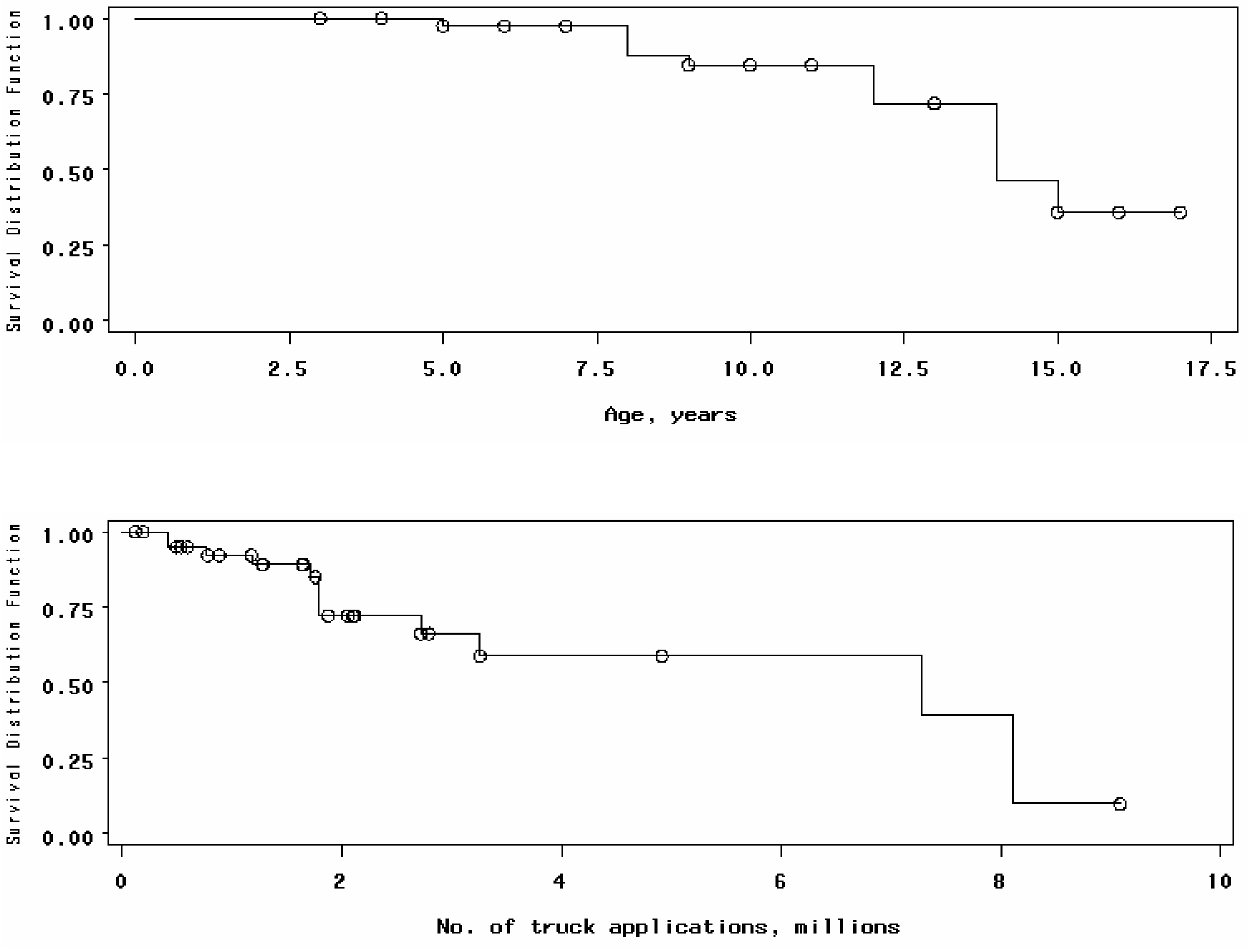


Figure A-60. Age- and truck traffic-based survival plots for R3A rehabilitation treatments applied to asphalt Non-Interstate pavements located in moderate climate.

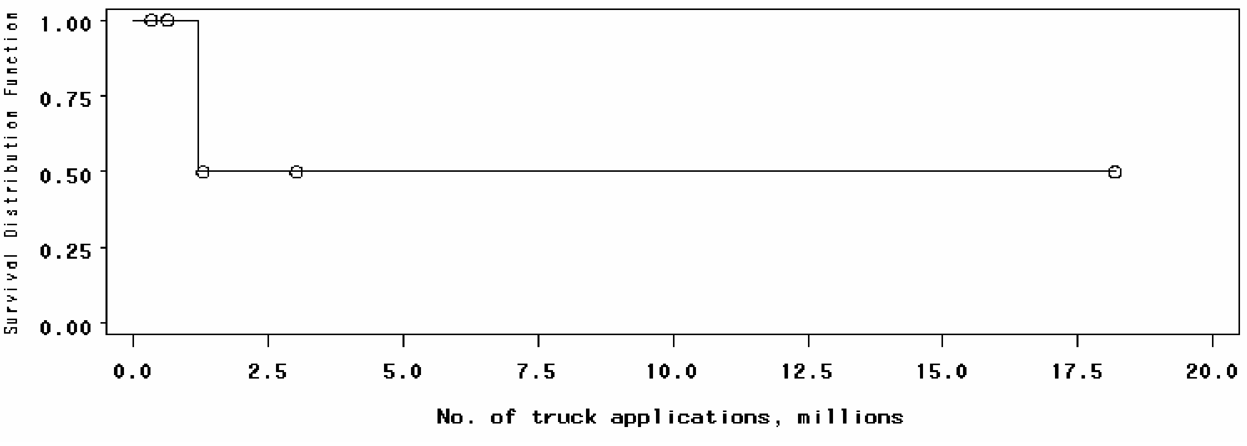


Figure A-61. Age- and truck traffic-based survival plots for R3A rehabilitation treatments applied to asphalt Non-Interstate pavements located in cool-wet climate.

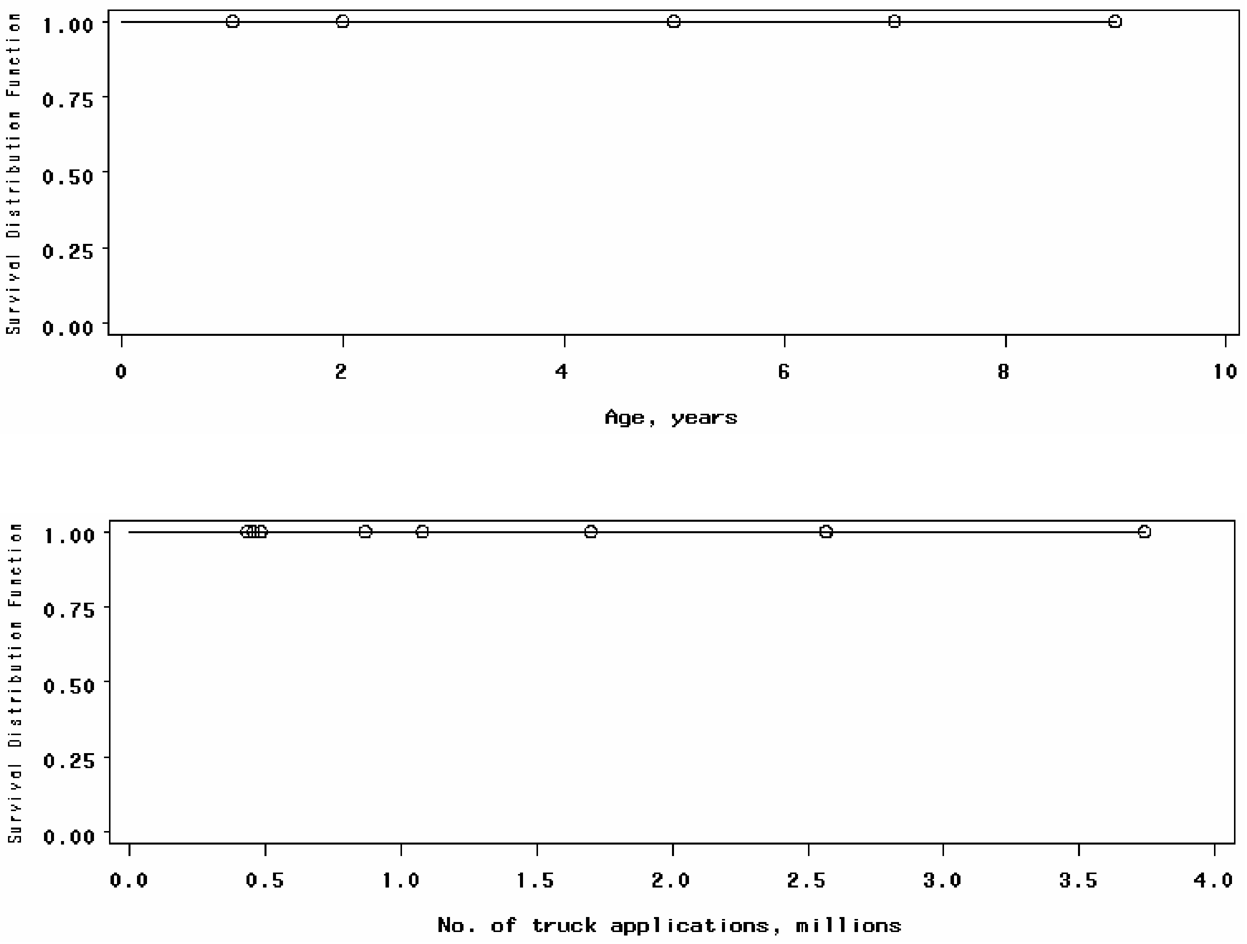
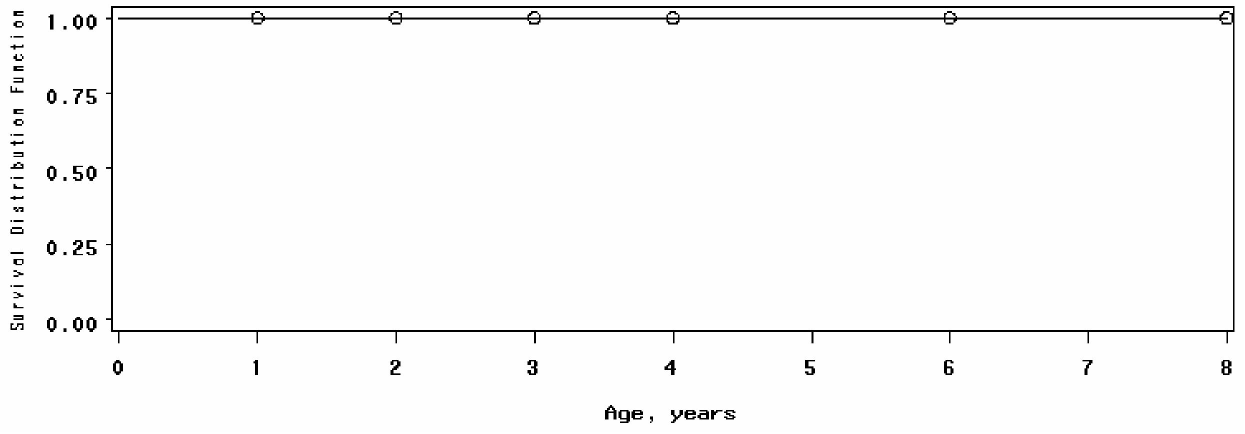


Figure A-62. Age- and truck traffic-based survival plots for R3B rehabilitation treatments applied to asphalt Non-Interstate pavements located in hot-dry climate.



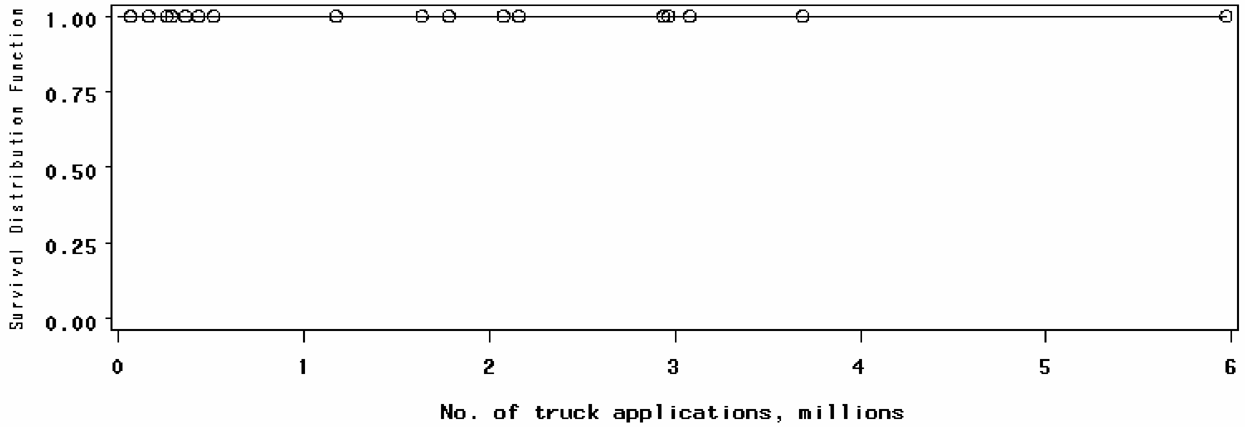
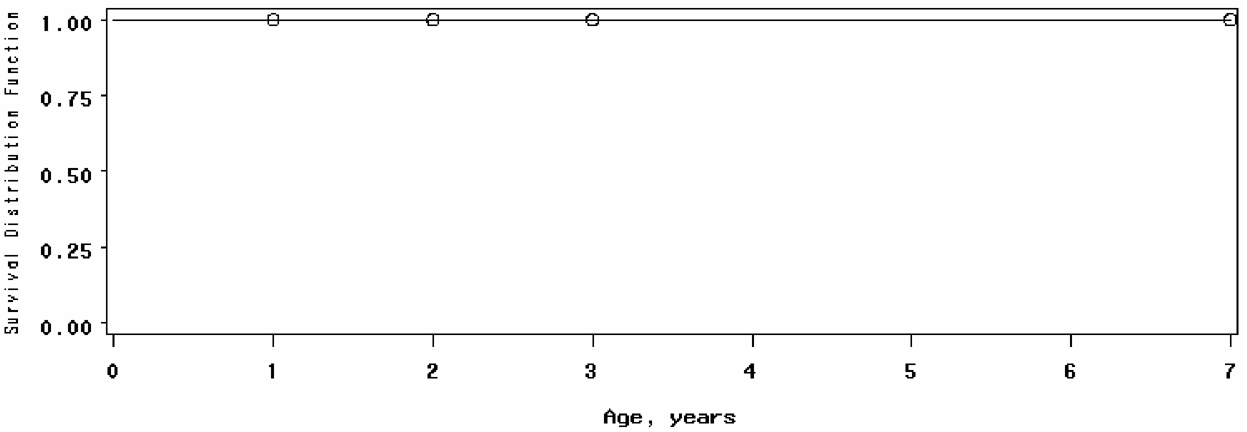


Figure A-63. Age- and truck traffic-based survival plots for R3B rehabilitation treatments applied to asphalt Non-Interstate pavements located in moderate climate.



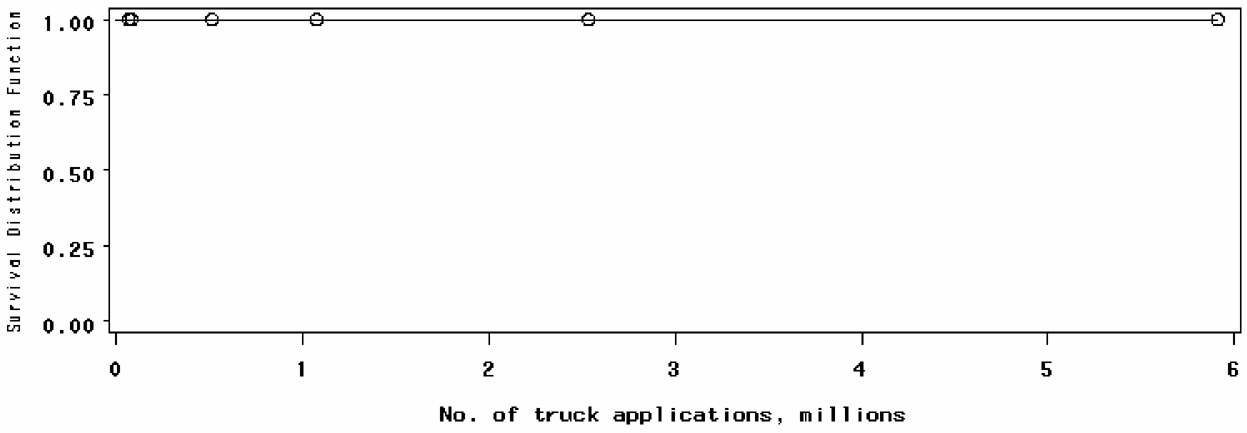
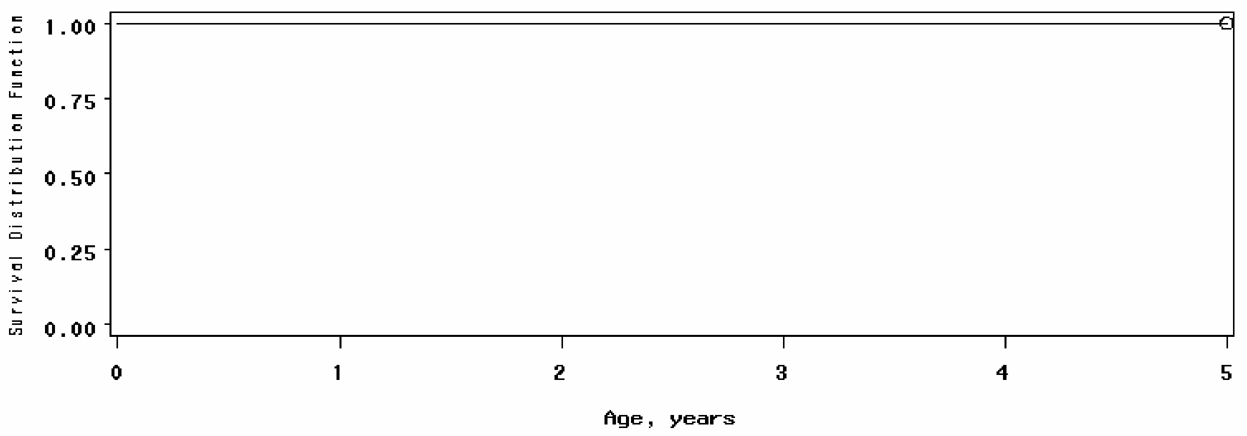


Figure A-64. Age- and truck traffic-based survival plots for R3B rehabilitation treatments applied to asphalt Non-Interstate pavements located in cool-wet climate.



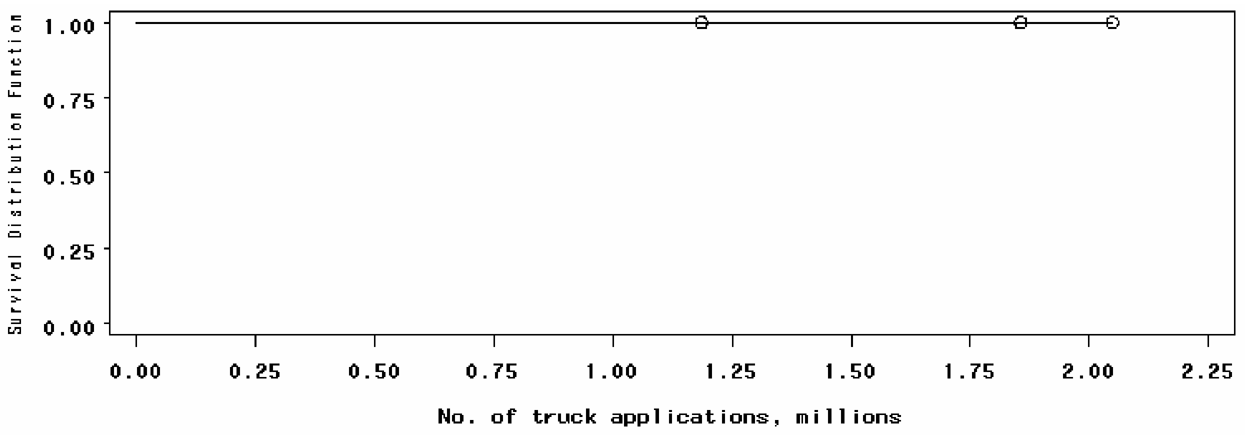


Figure A-65. Age- and truck traffic-based survival plots for R3C rehabilitation treatments applied to asphalt Non-Interstate pavements located in hot-dry climate.

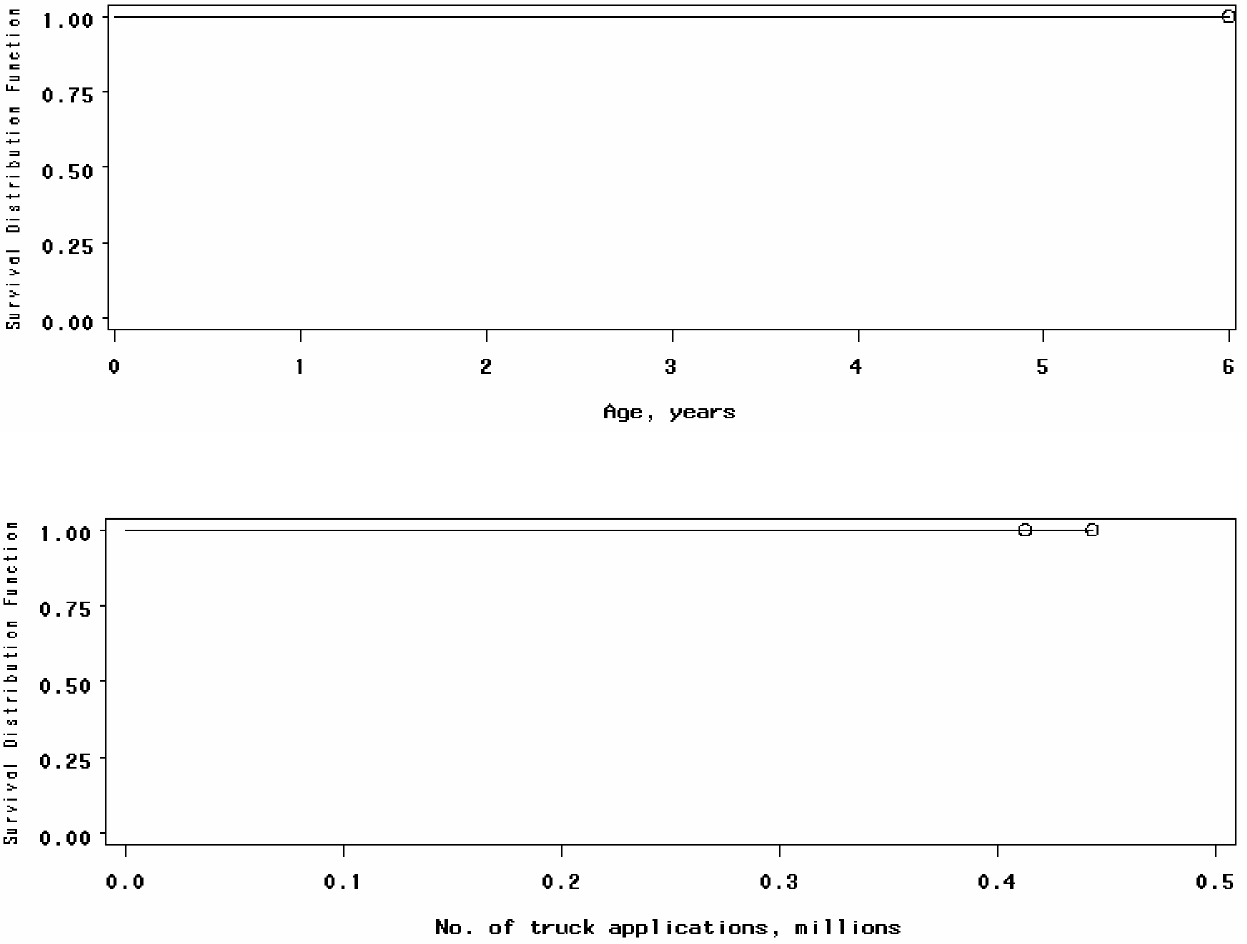


Figure A-66. Age- and truck traffic-based survival plots for R3C rehabilitation treatments applied to asphalt Non-Interstate pavements located in moderate climate.

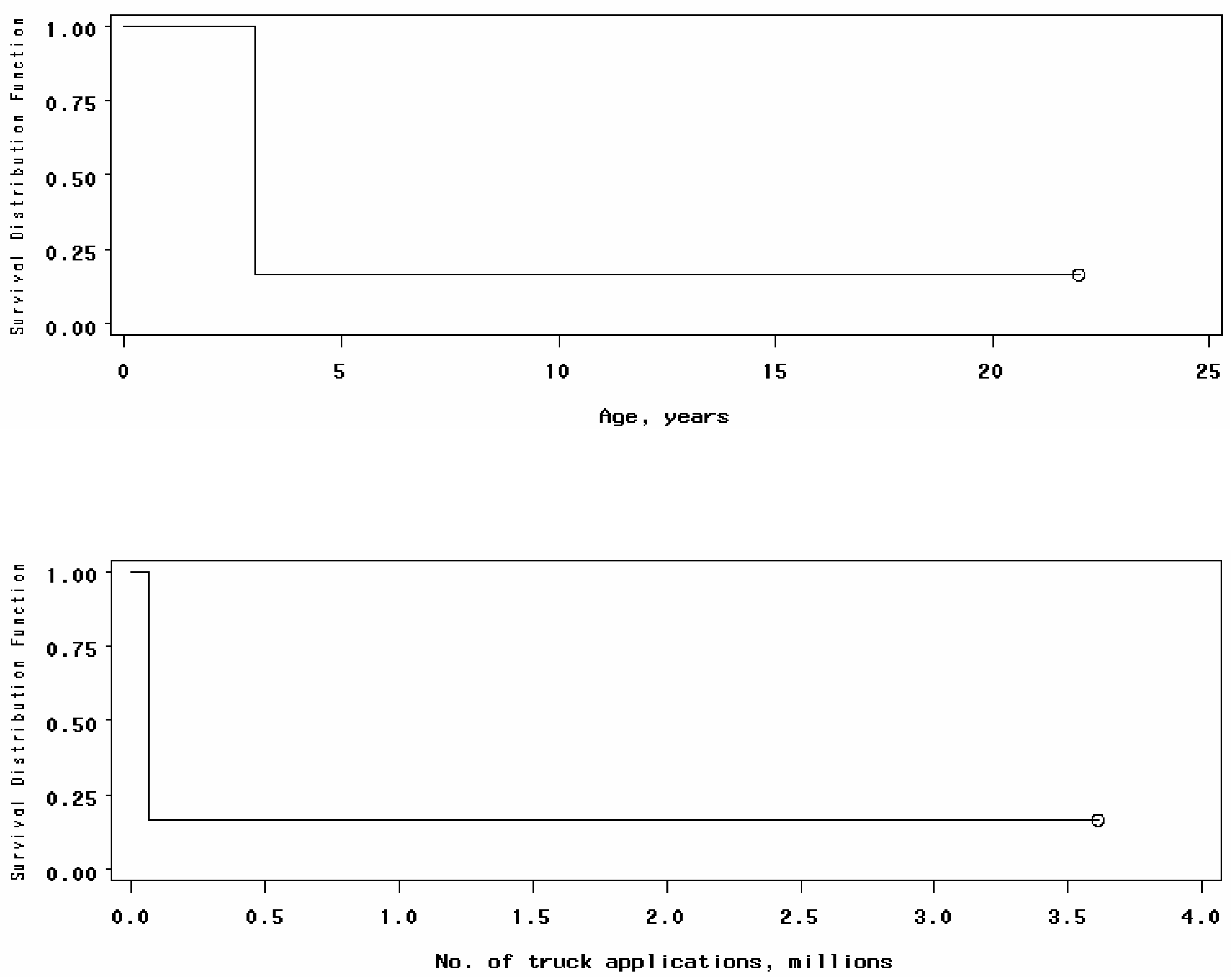
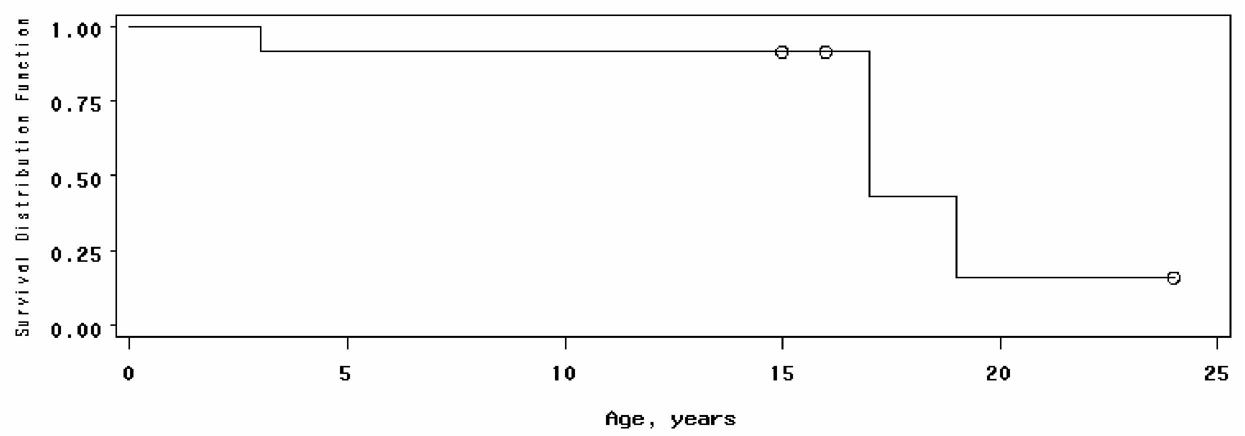


Figure A-67. Age- and truck traffic-based survival plots for R3D rehabilitation treatments applied to asphalt Non-Interstate pavements located in hot-dry climate.



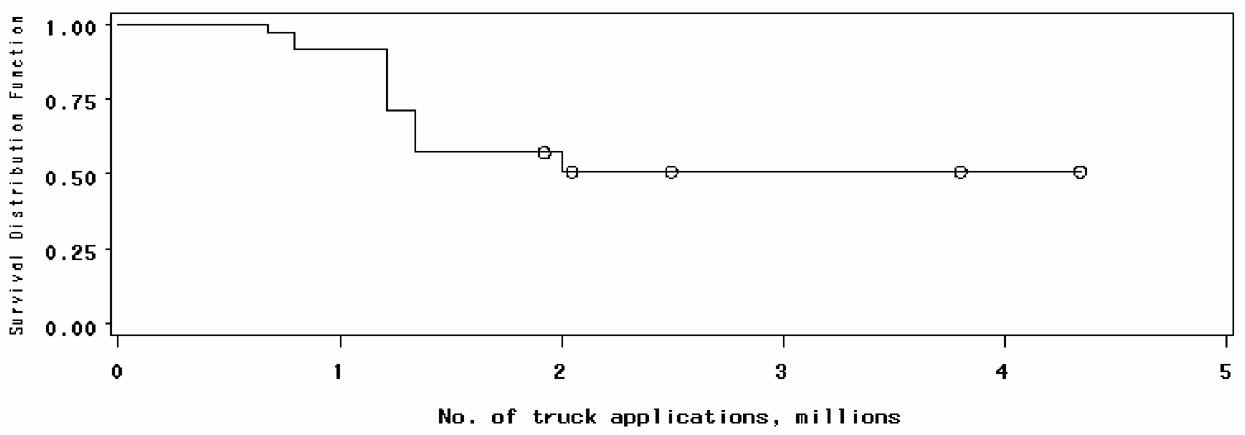
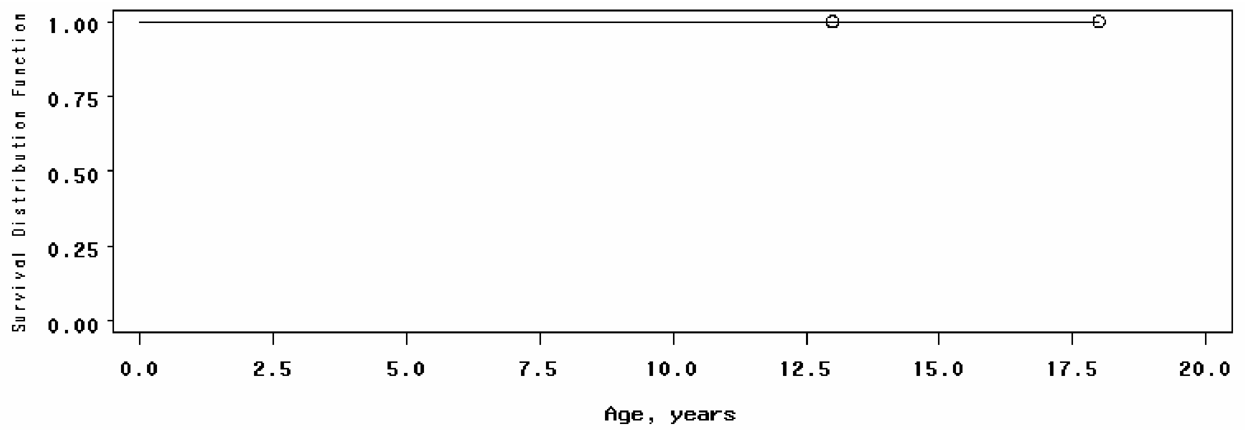


Figure A-68. Age- and truck traffic-based survival plots for R3D rehabilitation treatments applied to asphalt Non-Interstate pavements located in moderate climate.



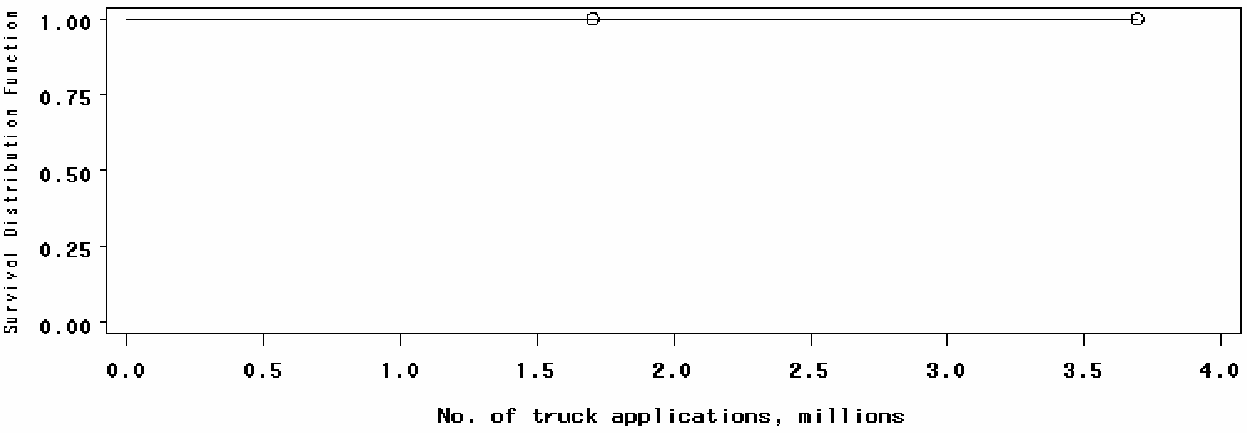
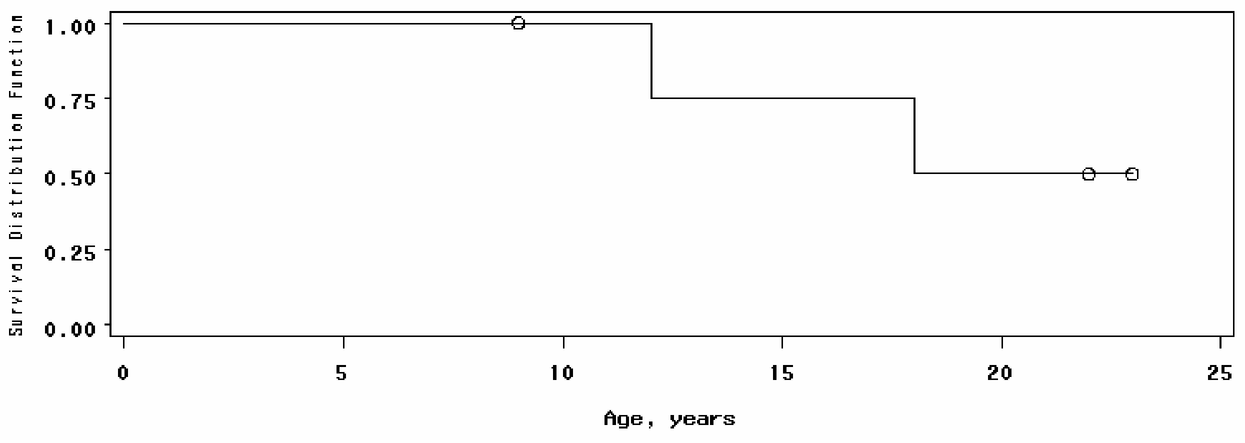


Figure A-69. Age- and truck traffic-based survival plots for R3D rehabilitation treatments applied to asphalt Non-Interstate pavements located in cool-wet climate.



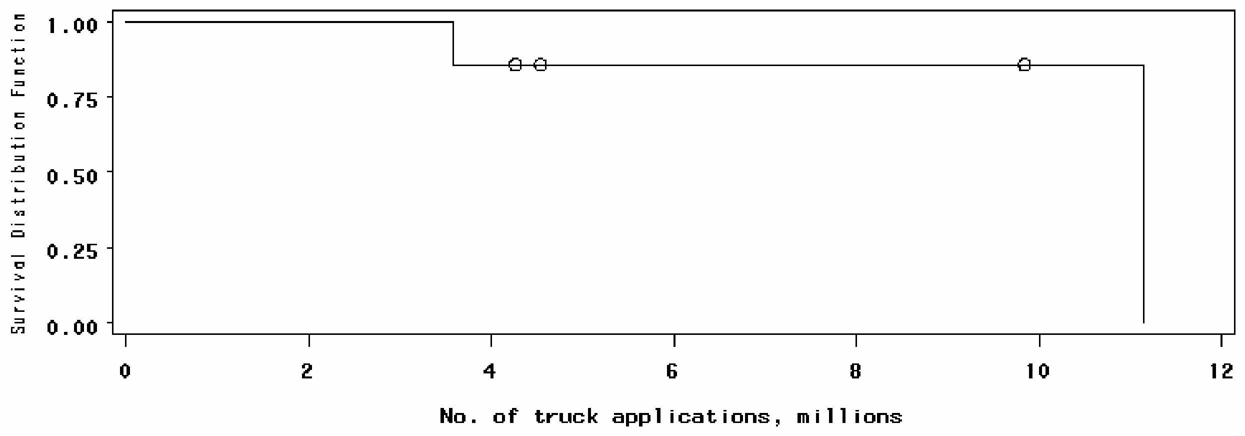


Figure A-70. Age- and truck traffic-based survival plots for R4A rehabilitation treatments applied to asphalt Non-Interstate pavements located in hot-dry climate.

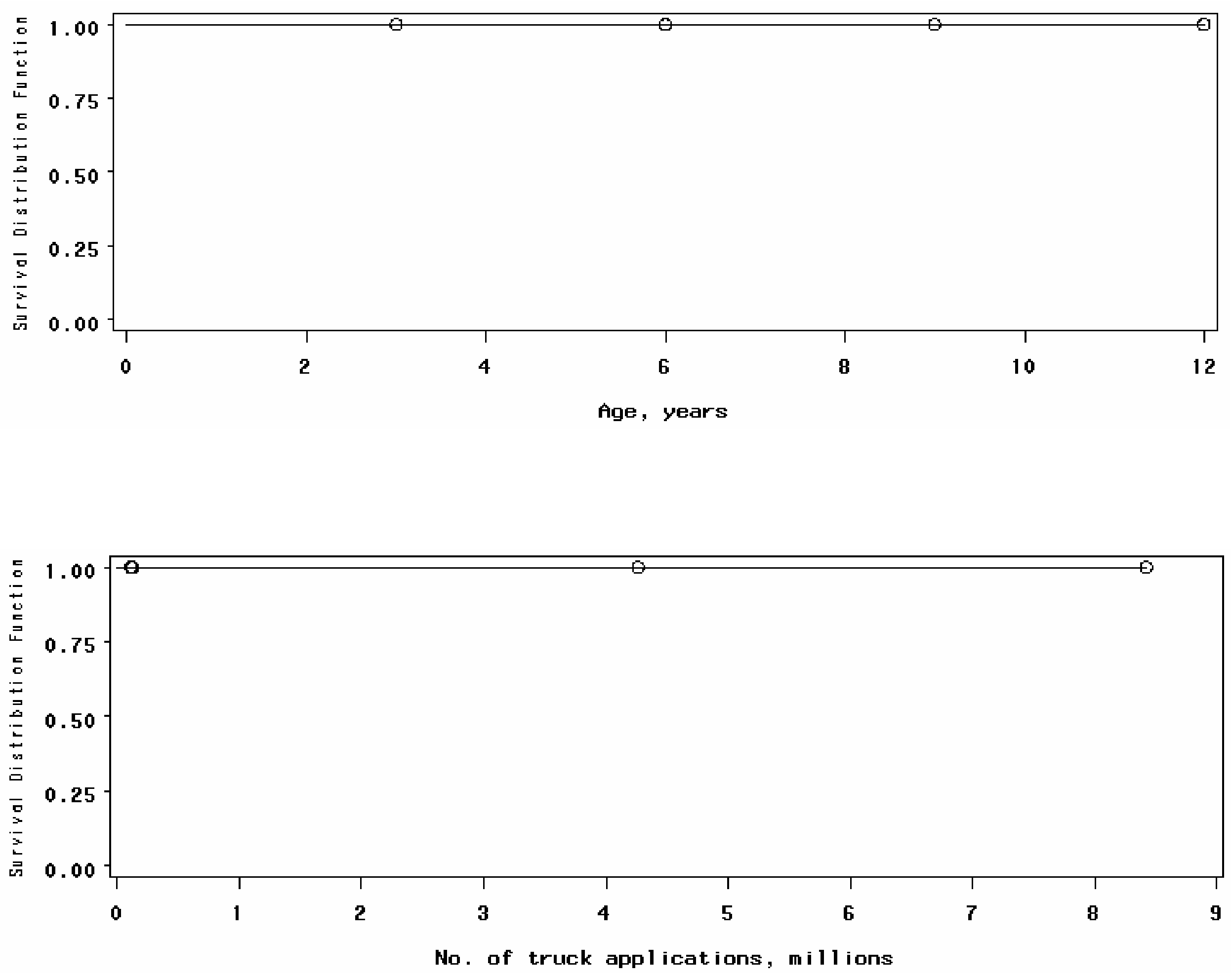
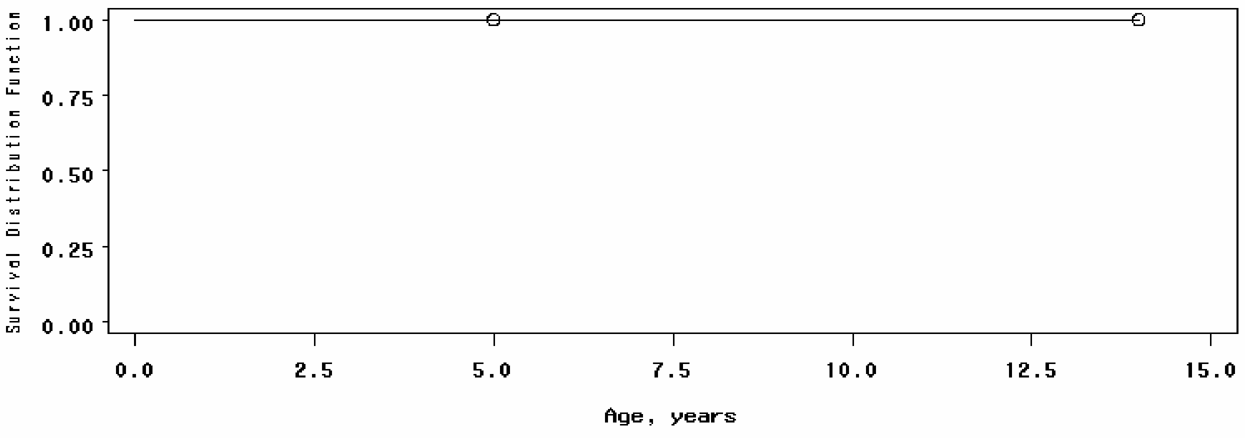


Figure A-71. Age- and truck traffic-based survival plots for R4A rehabilitation treatments applied to asphalt Non-Interstate pavements located in moderate climate.



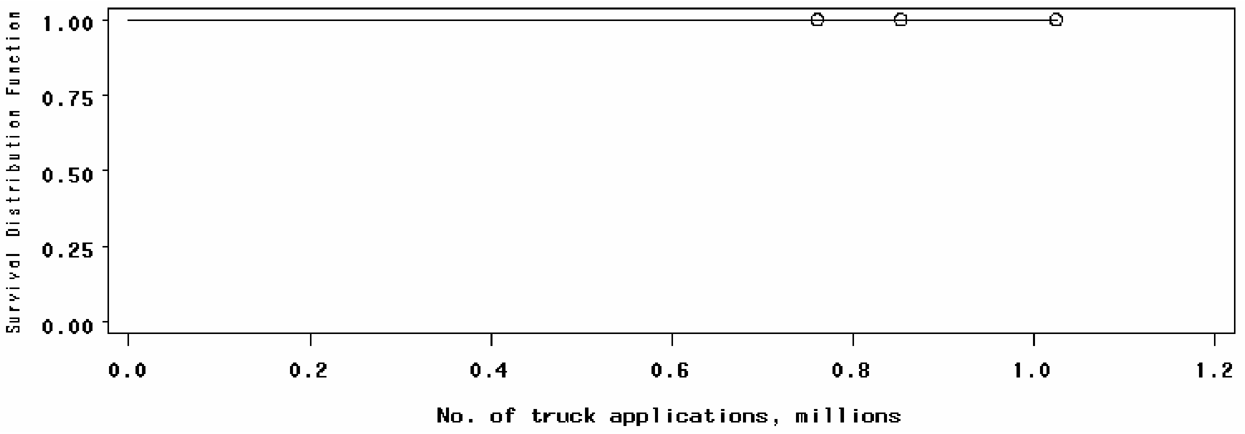
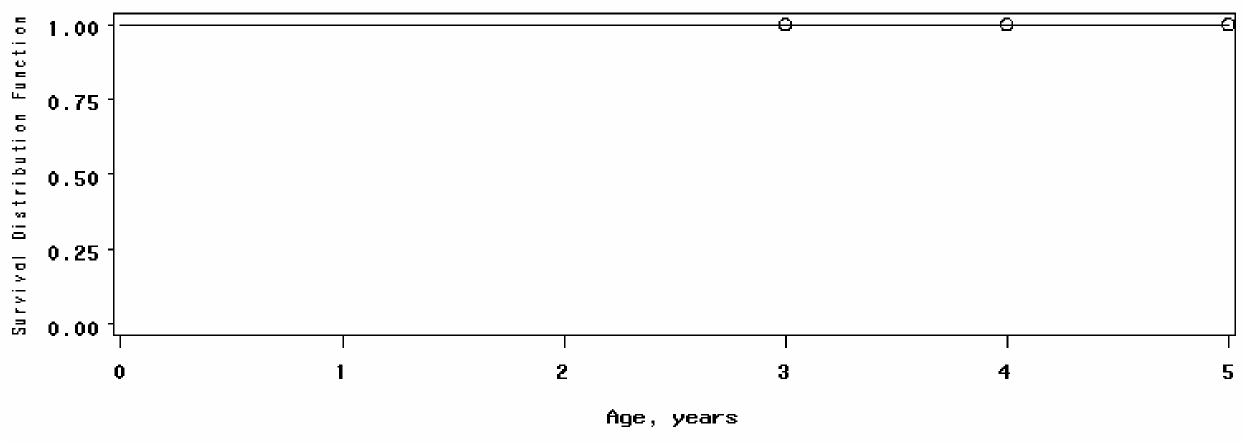


Figure A-72. Age- and truck traffic-based survival plots for R4A rehabilitation treatments applied to asphalt Non-Interstate pavements located in cool-wet climate.



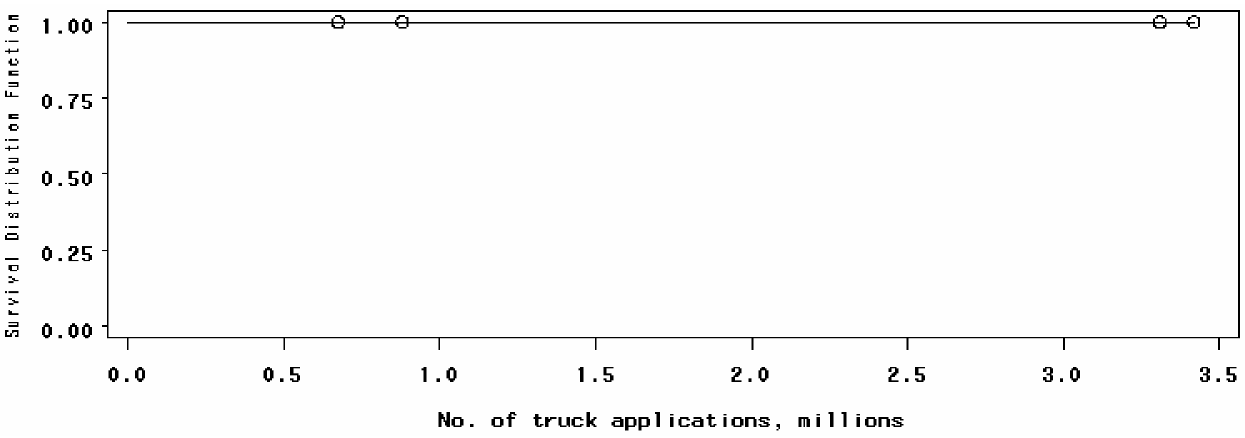
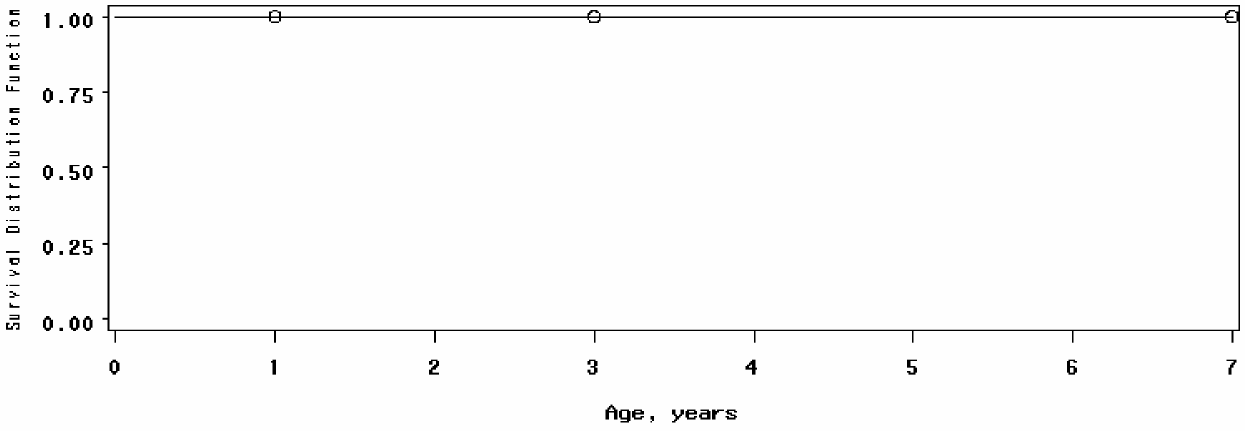


Figure A-73. Age- and truck traffic-based survival plots for R4B rehabilitation treatments applied to asphalt Non-Interstate pavements located in hot-dry climate.



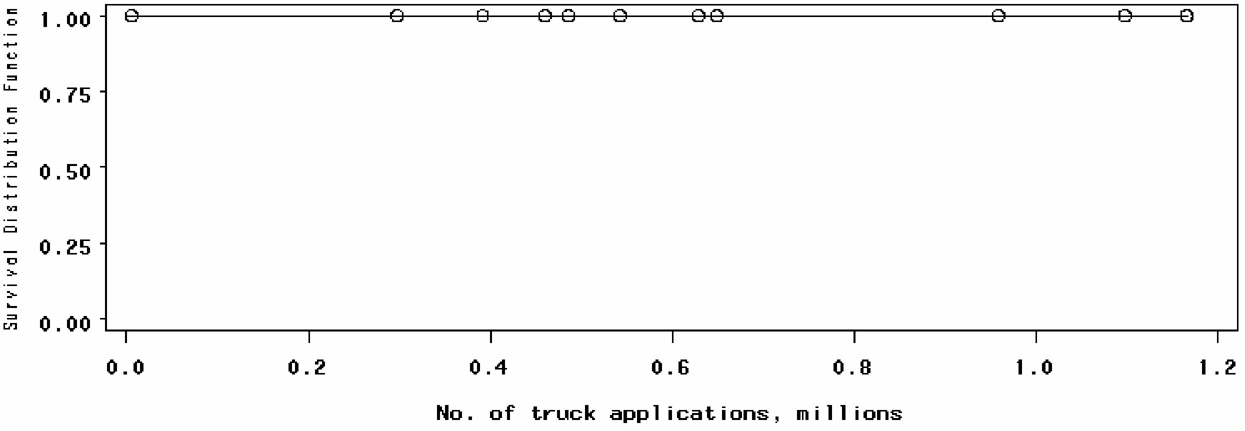
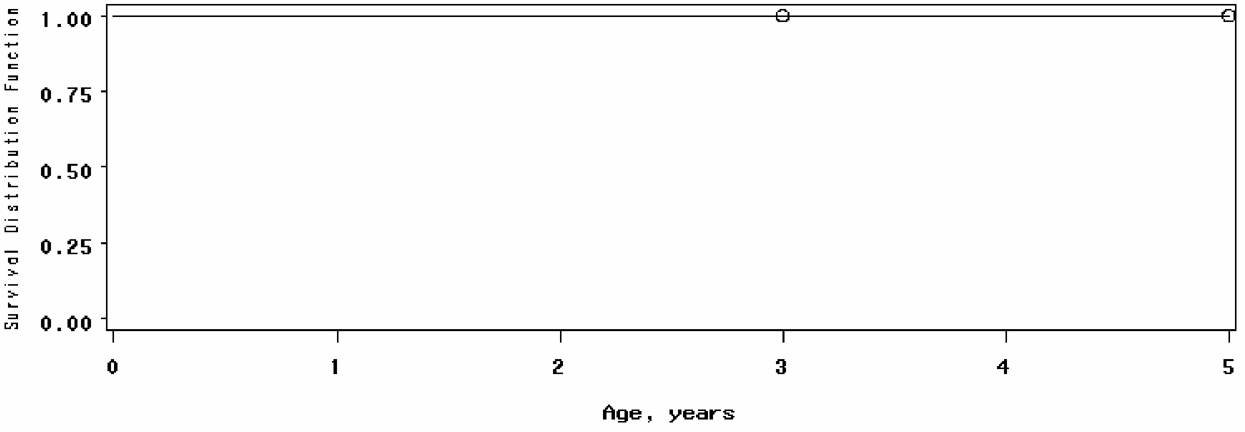


Figure A-74. Age- and truck traffic-based survival plots for R4B rehabilitation treatments applied to asphalt Non-Interstate pavements located in moderate climate.



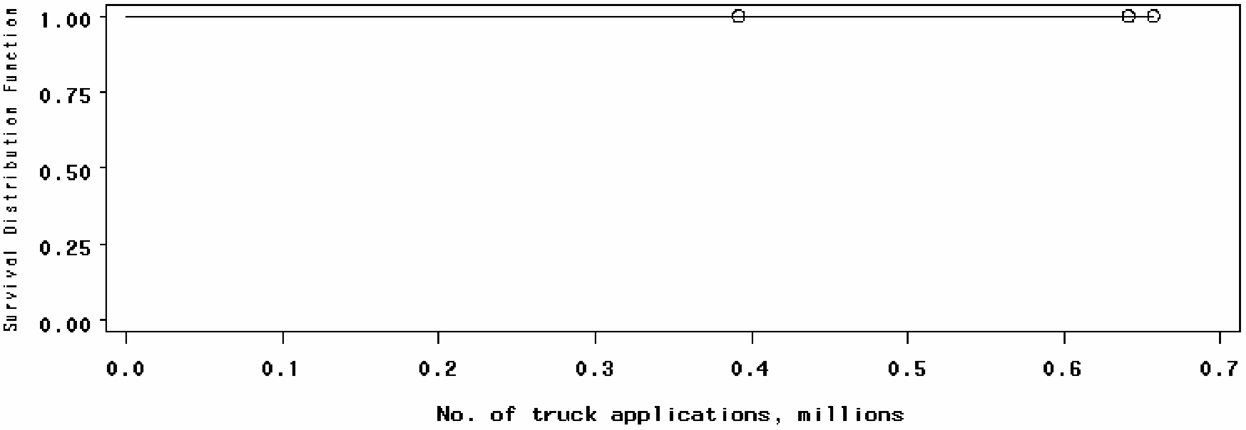
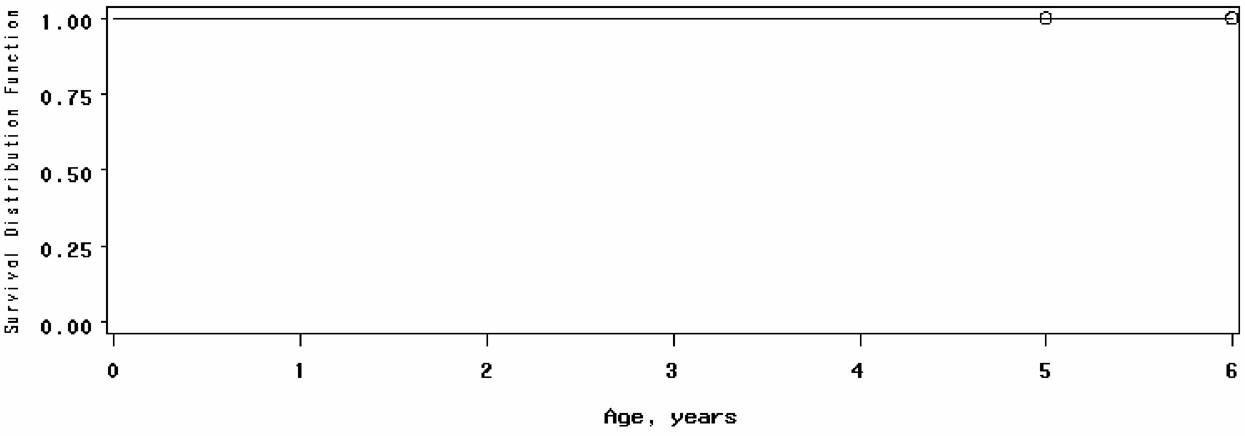


Figure A-75. Age- and truck traffic-based survival plots for R4B rehabilitation treatments applied to asphalt Non-Interstate pavements located in cool-wet climate.



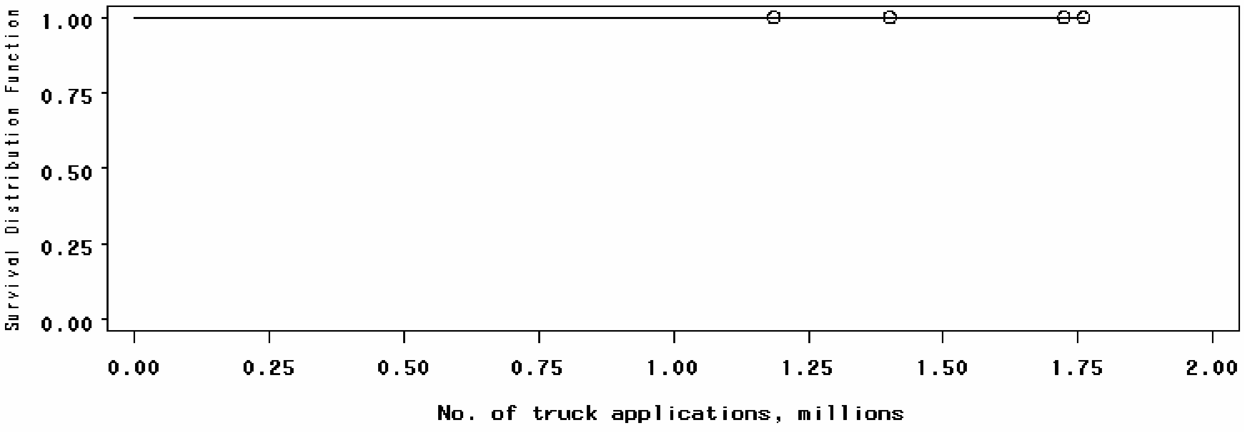


Figure A-76. Age- and truck traffic-based survival plots for R4C rehabilitation treatments applied to asphalt Non-Interstate pavements located in hot-dry climate.

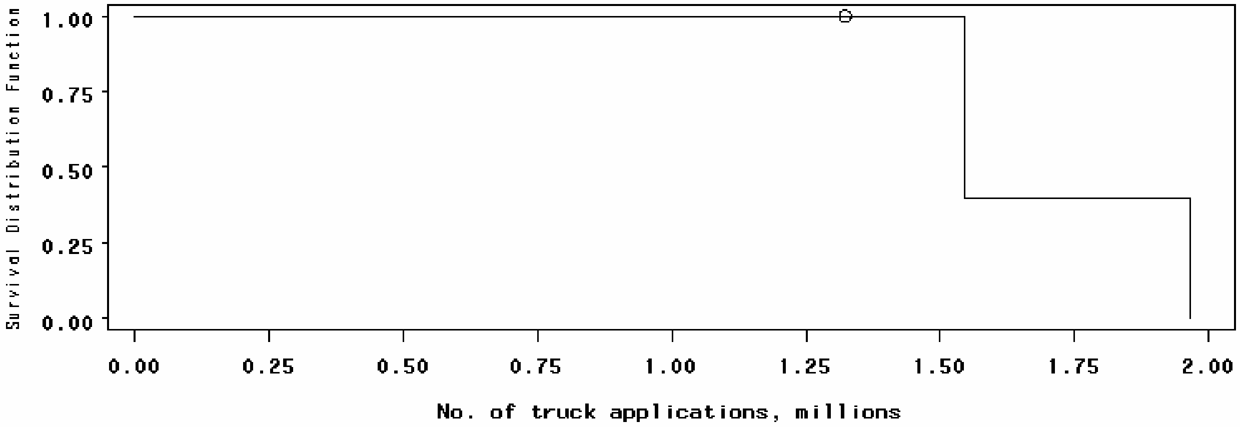
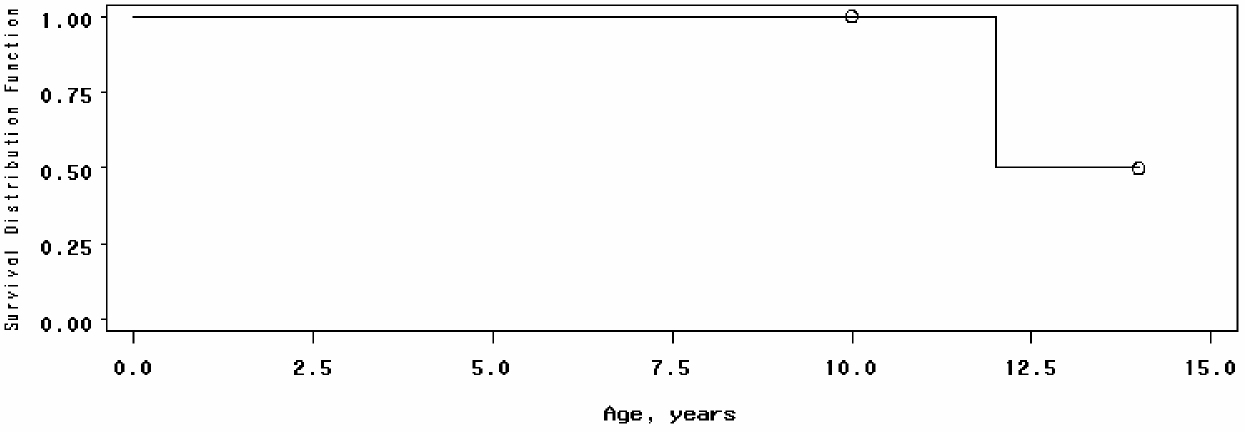


Figure A-77. Age- and truck traffic-based survival plots for R4D rehabilitation treatments applied to asphalt Non-Interstate pavements located in hot-dry climate.



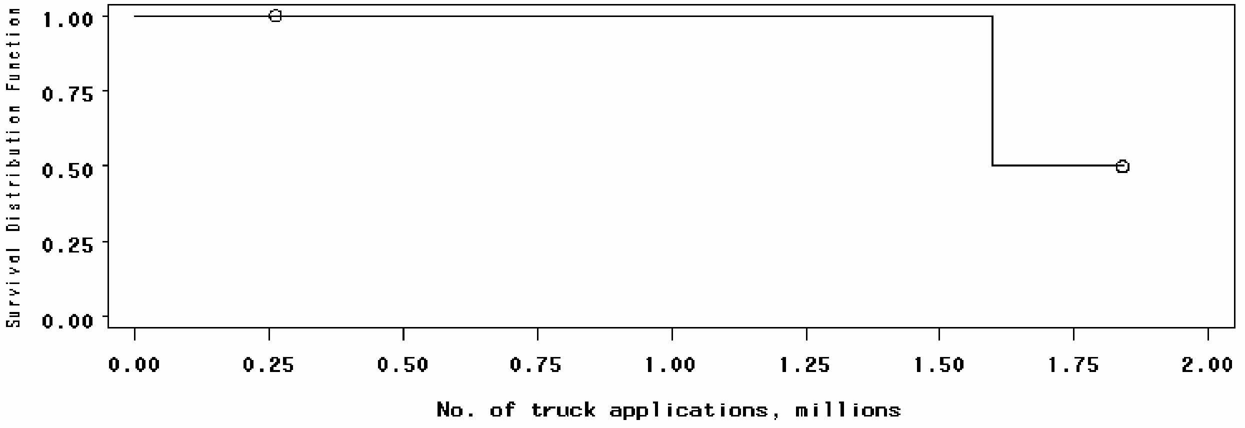
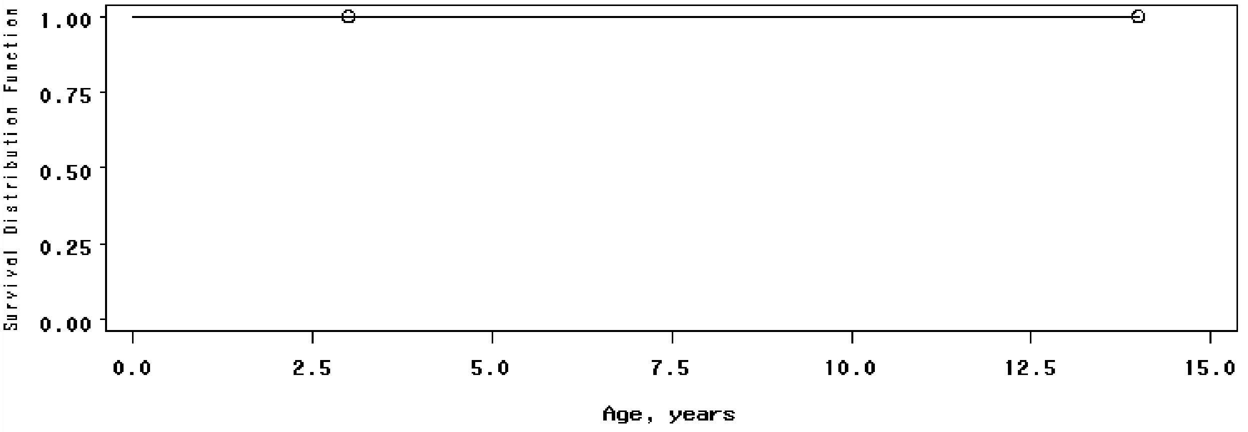


Figure A-78. Age- and truck traffic-based survival plots for R4D rehabilitation treatments applied to asphalt Non-Interstate pavements located in moderate climate.



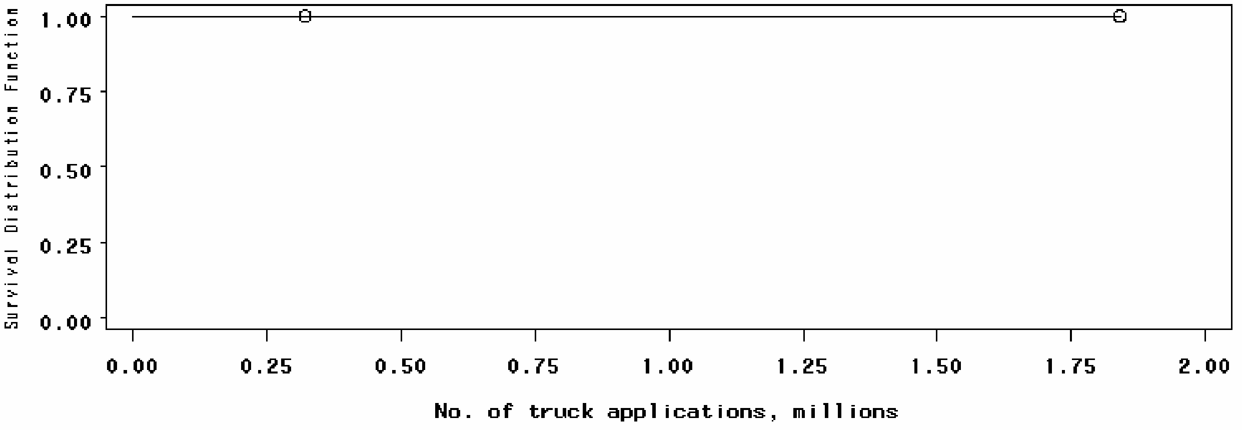


Figure A-79. Age- and truck traffic-based survival plots for R4D rehabilitation treatments applied to asphalt Non-Interstate pavements located in cool-wet climate.

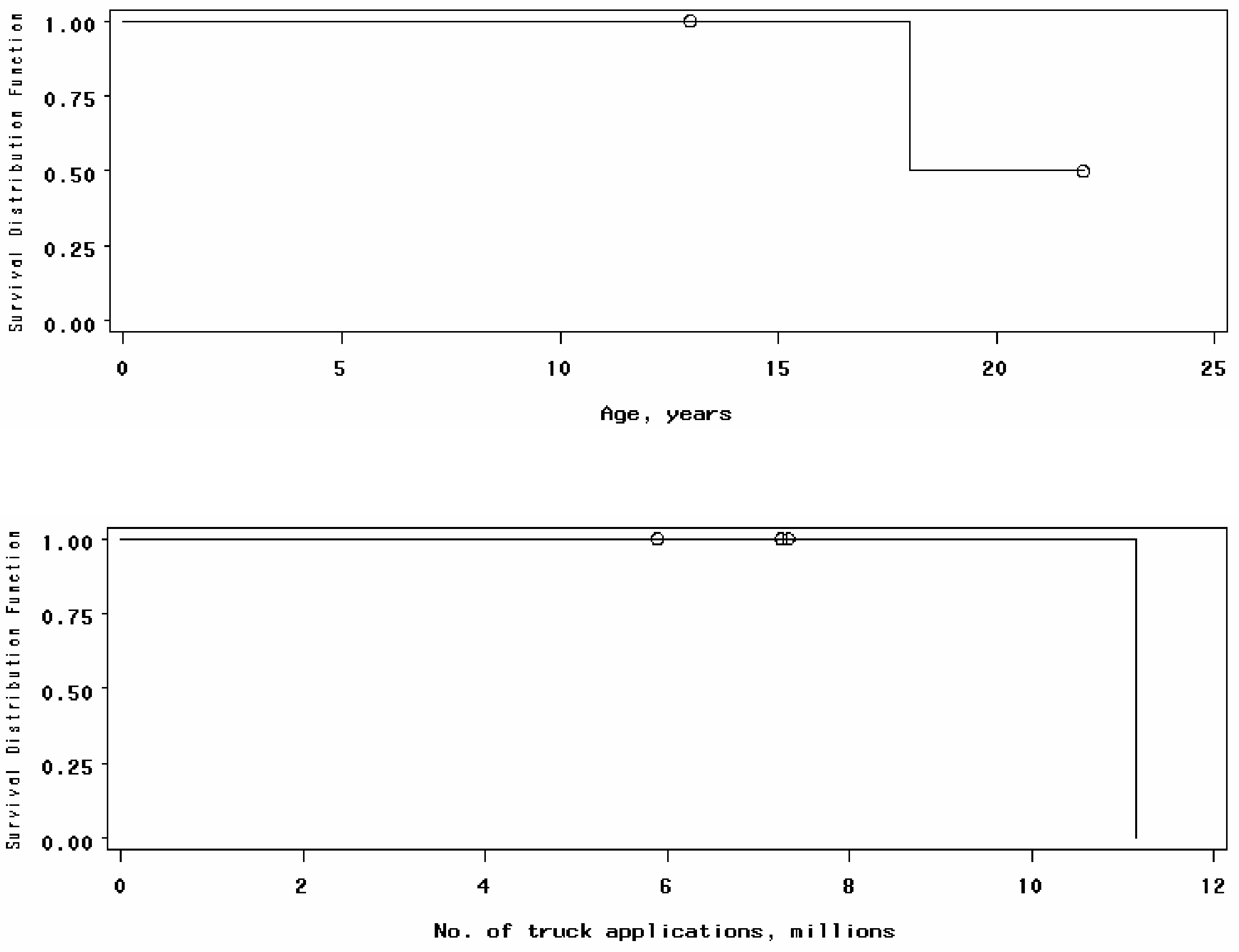


Figure A-80. Age- and truck traffic-based survival plots for R6A rehabilitation treatments applied to asphalt Non-Interstate pavements located in hot-dry climate.

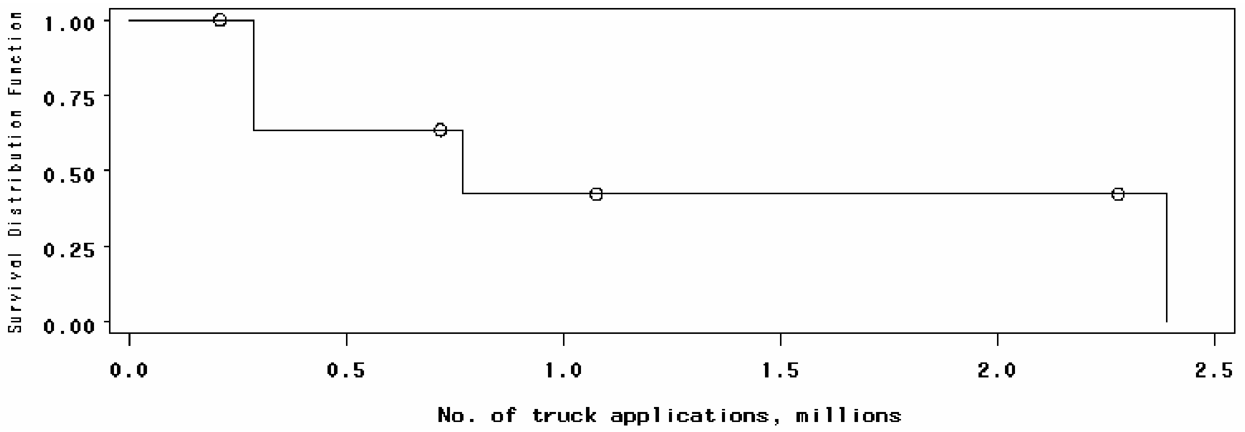
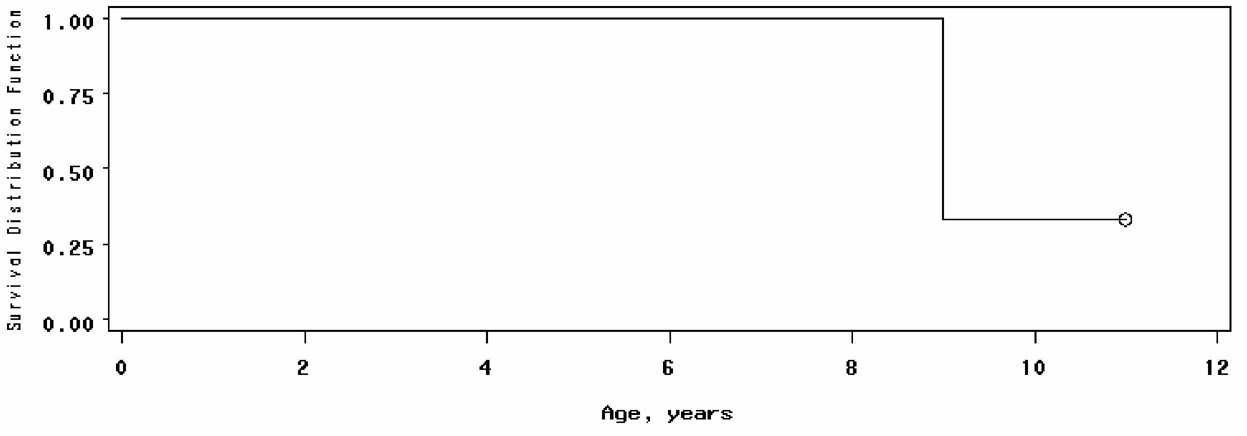


Figure A-81. Age- and truck traffic-based survival plots for R6A rehabilitation treatments applied to asphalt Non-Interstate pavements located in moderate climate.



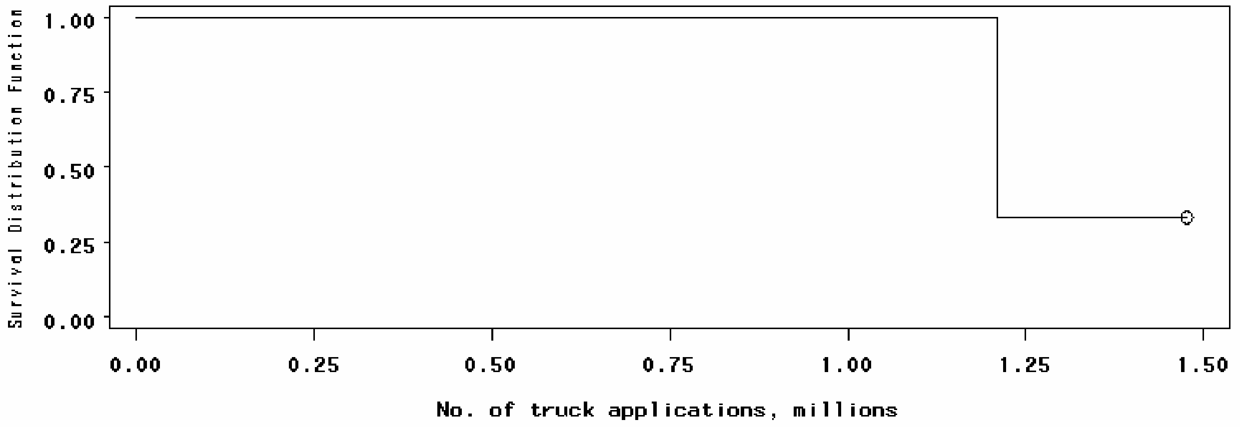


Figure A-82. Age- and truck traffic-based survival plots for R6A rehabilitation treatments applied to asphalt Non-Interstate pavements located in cool-wet climate.

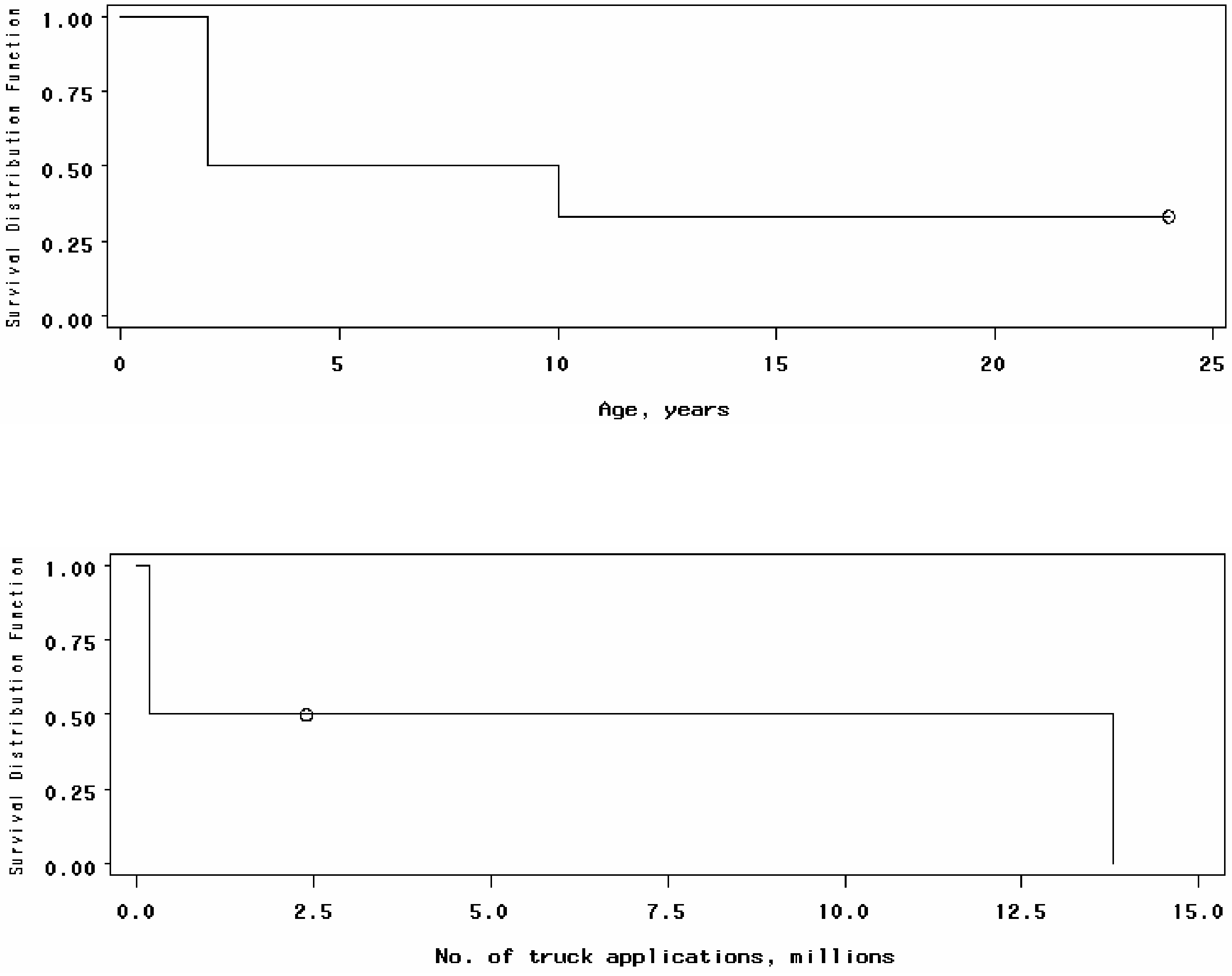
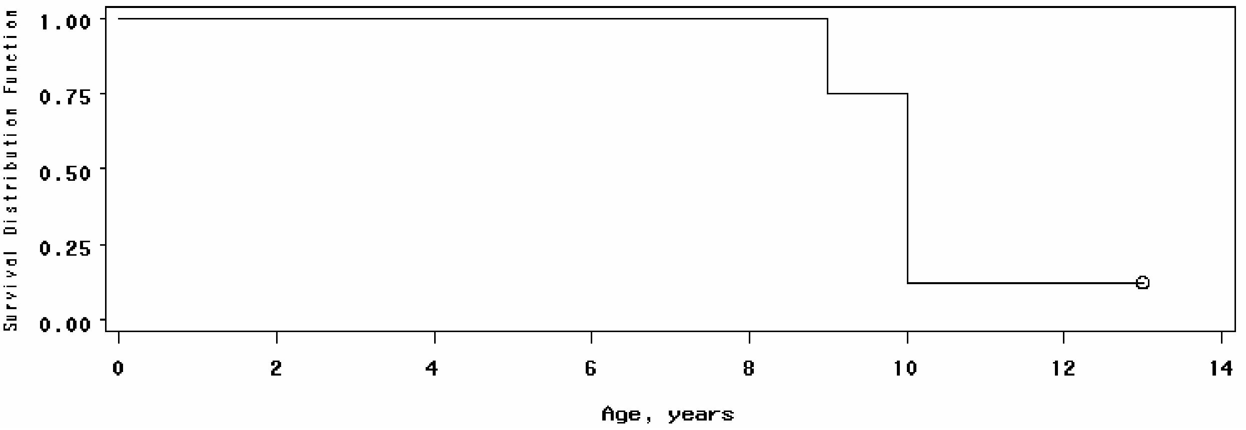


Figure A-83. Age- and truck traffic-based survival plots for R1A rehabilitation treatments applied to JPC pavements located in moderate climate.



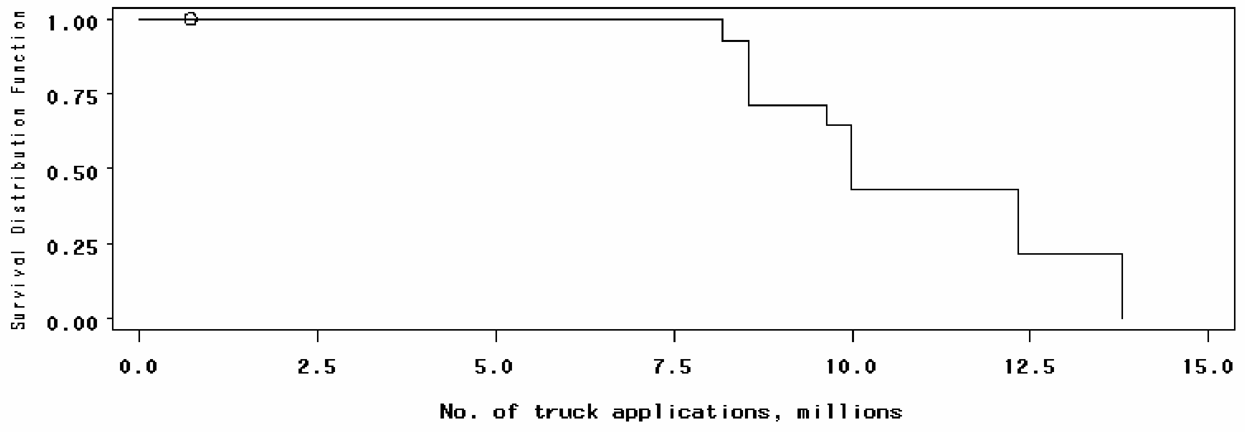
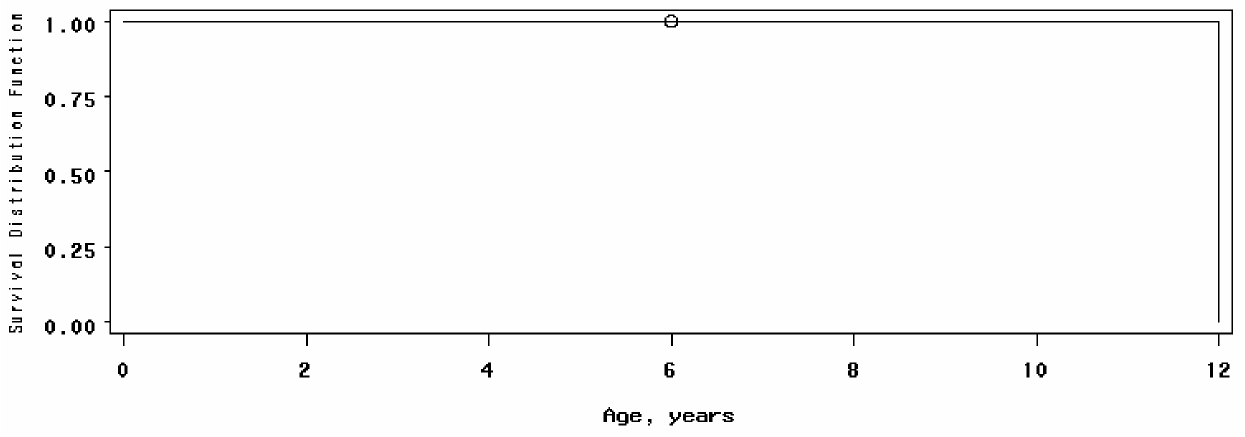


Figure A-84. Age- and truck traffic-based survival plots for R1A rehabilitation treatments applied to JPC pavements located in cool-wet climate.



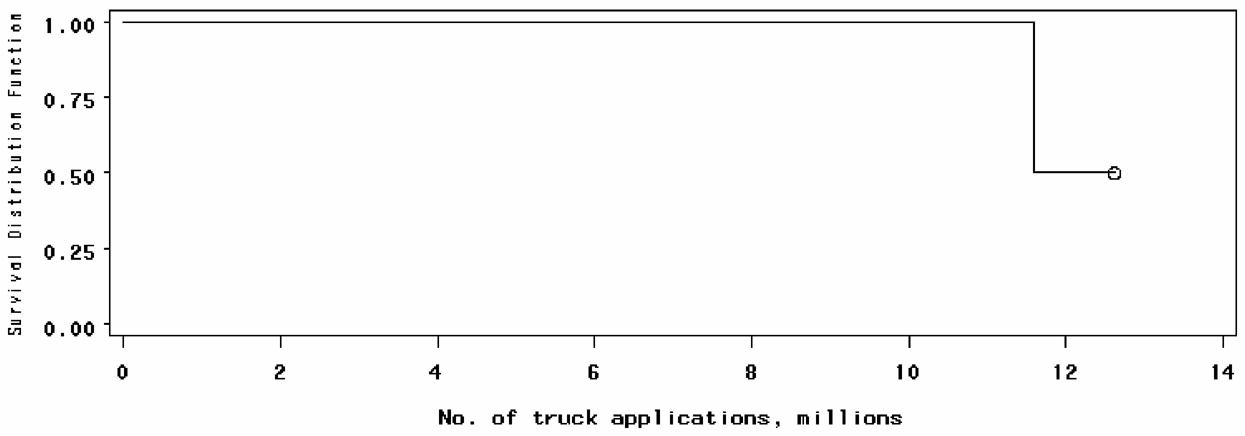
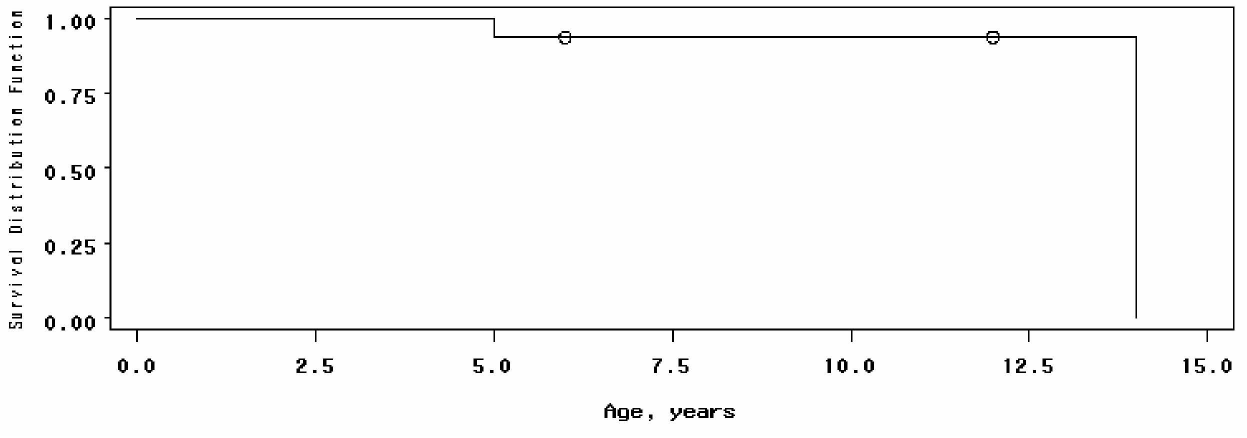


Figure A-85. Age- and truck traffic-based survival plots for R1B rehabilitation treatments applied to JPC pavements located in moderate climate.



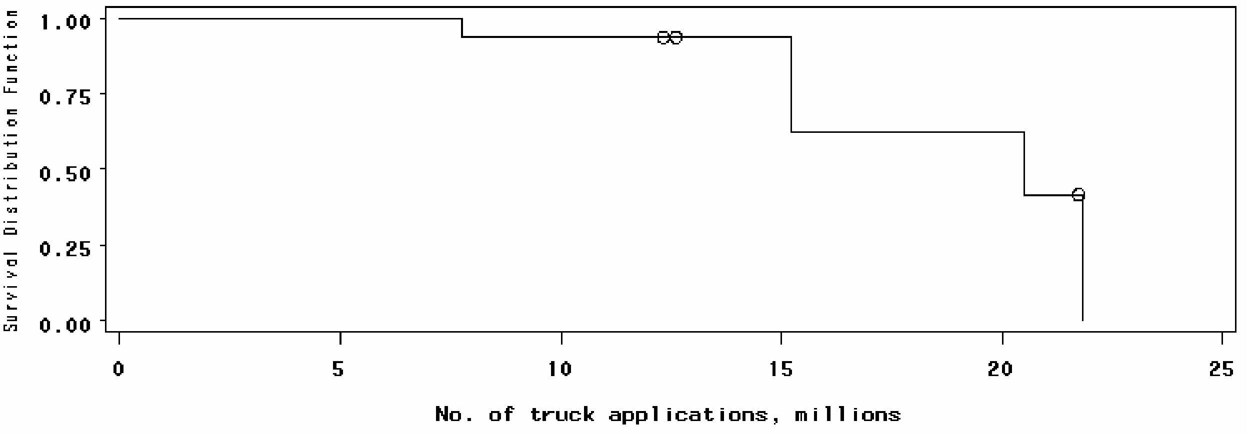
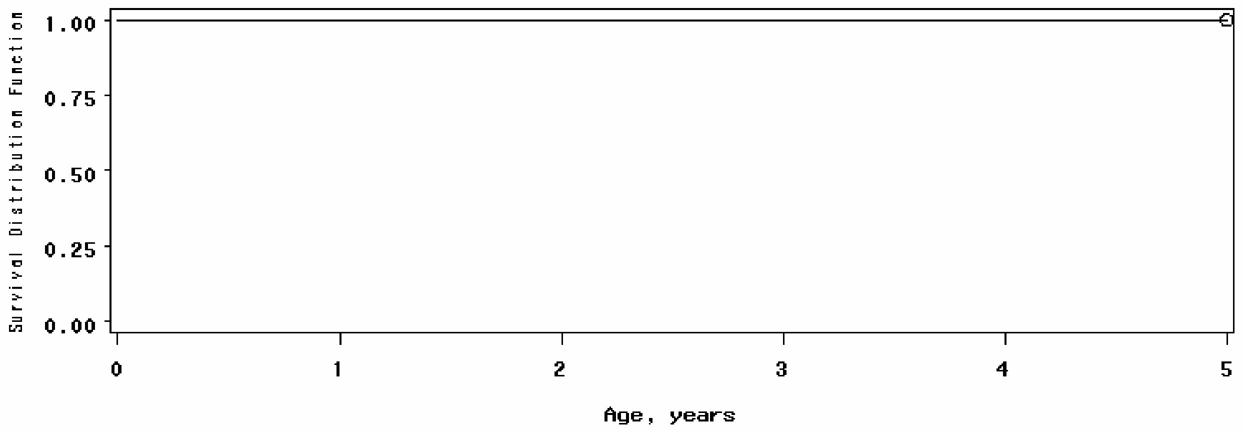


Figure A-86. Age- and truck traffic-based survival plots for R1B rehabilitation treatments applied to JPC pavements located in cool-wet climate.



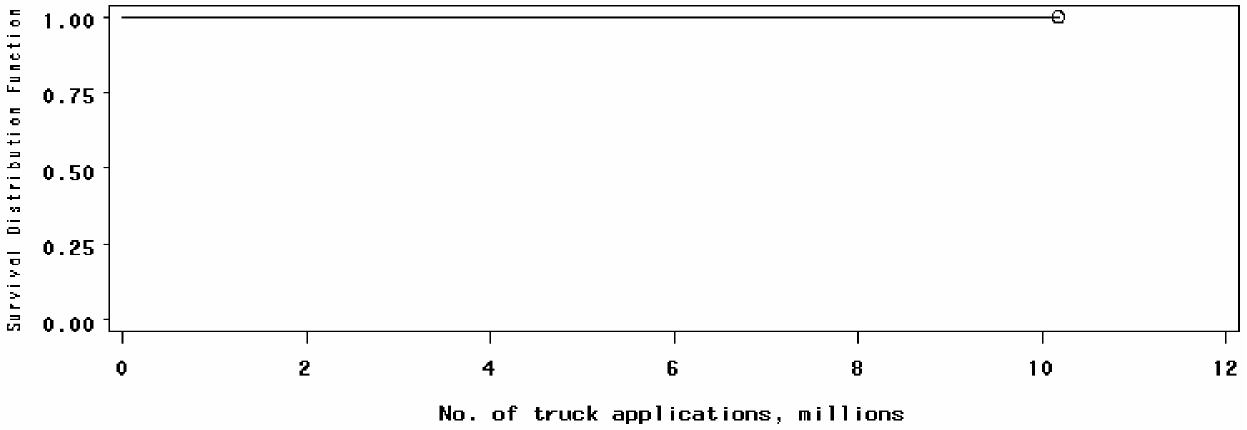
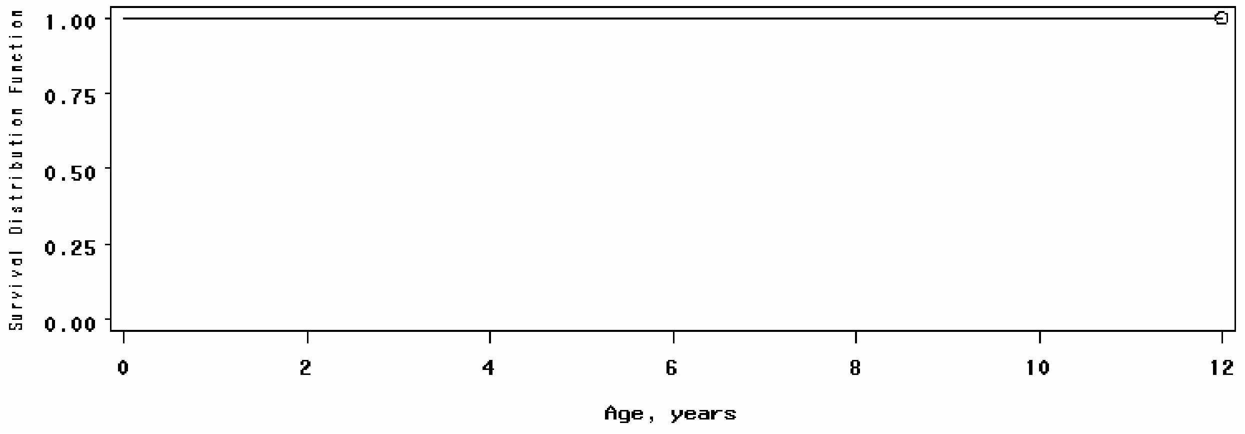


Figure A-87. Age- and truck traffic-based survival plots for R2B rehabilitation treatments applied to JPC pavements located in moderate climate.



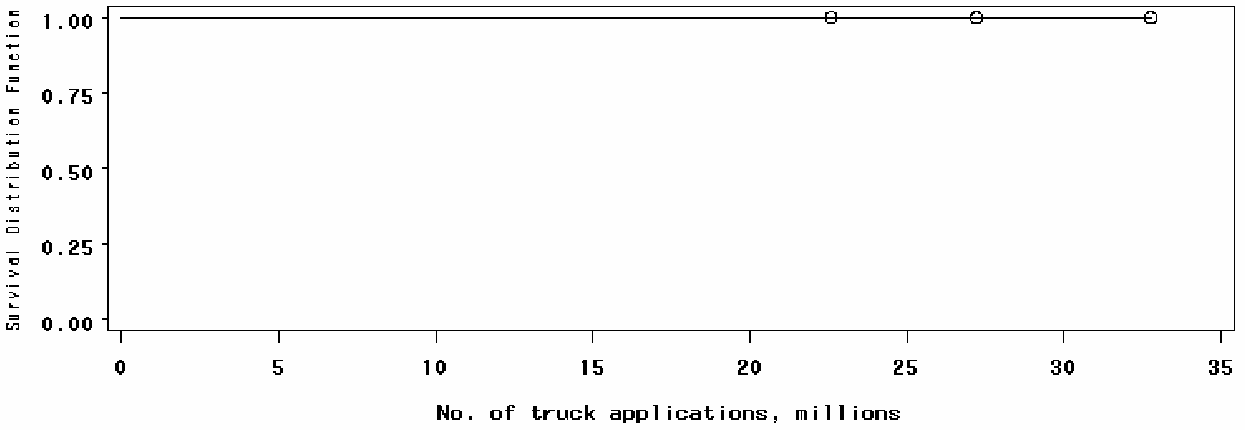
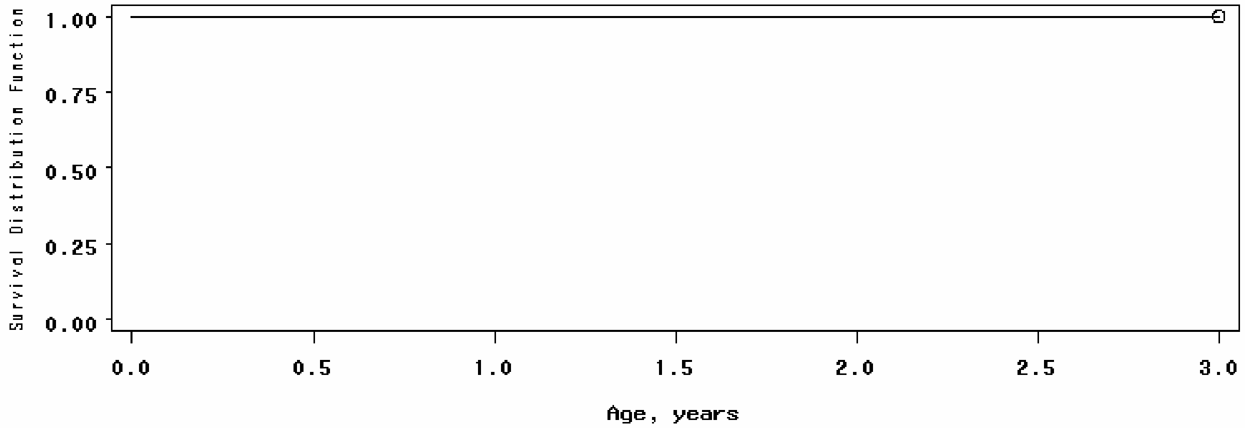


Figure A-88. Age- and truck traffic-based survival plots for R2B rehabilitation treatments applied to JPC pavements located in cool-wet climate.



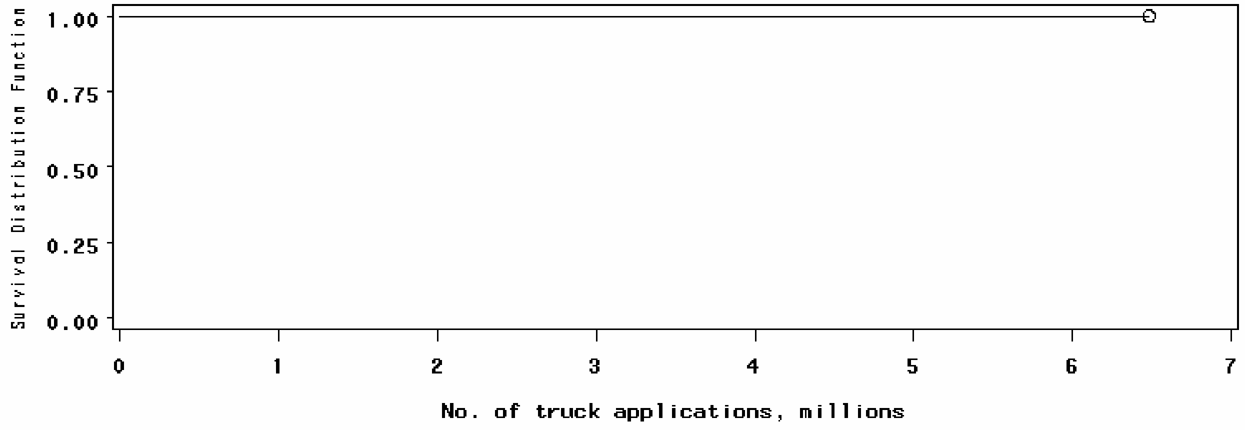
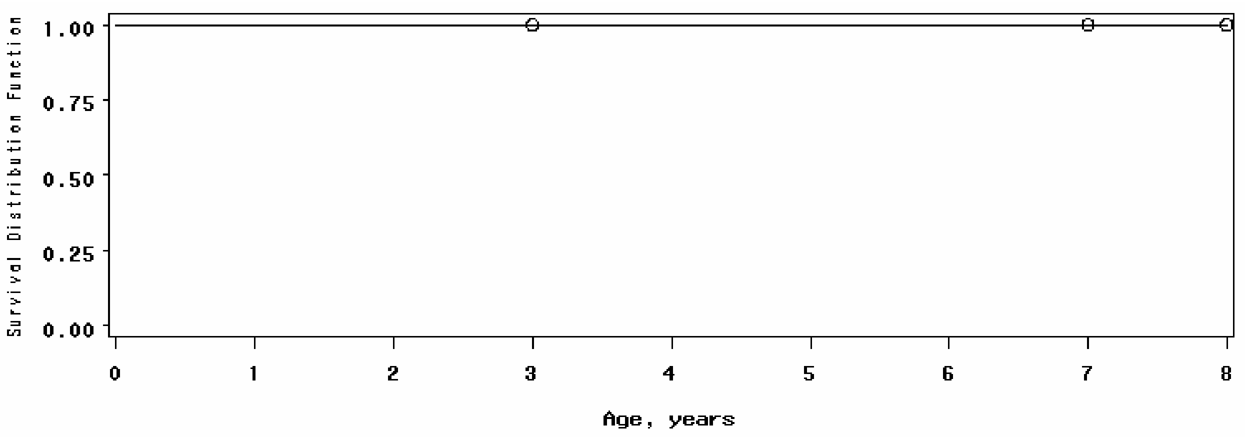


Figure A-89. Age- and truck traffic-based survival plots for R3B rehabilitation treatments applied to JPC pavements located in moderate climate.



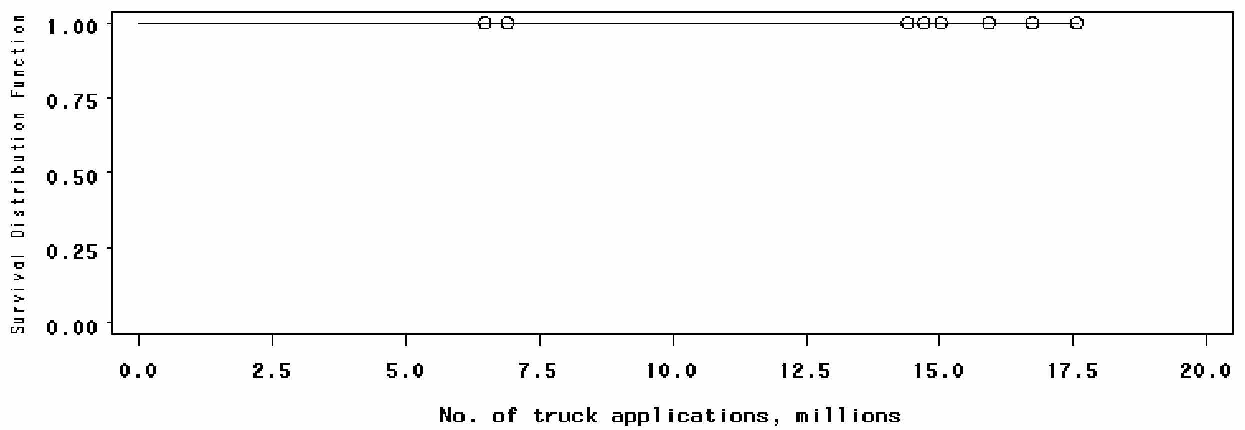
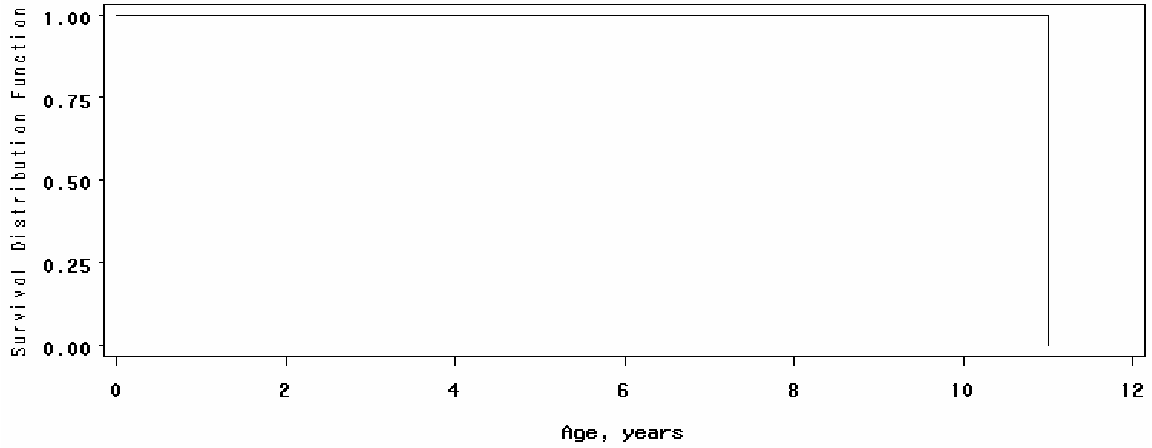


Figure A-90. Age- and truck traffic-based survival plots for R3B rehabilitation treatments applied to JPC pavements located in cool-wet climate.



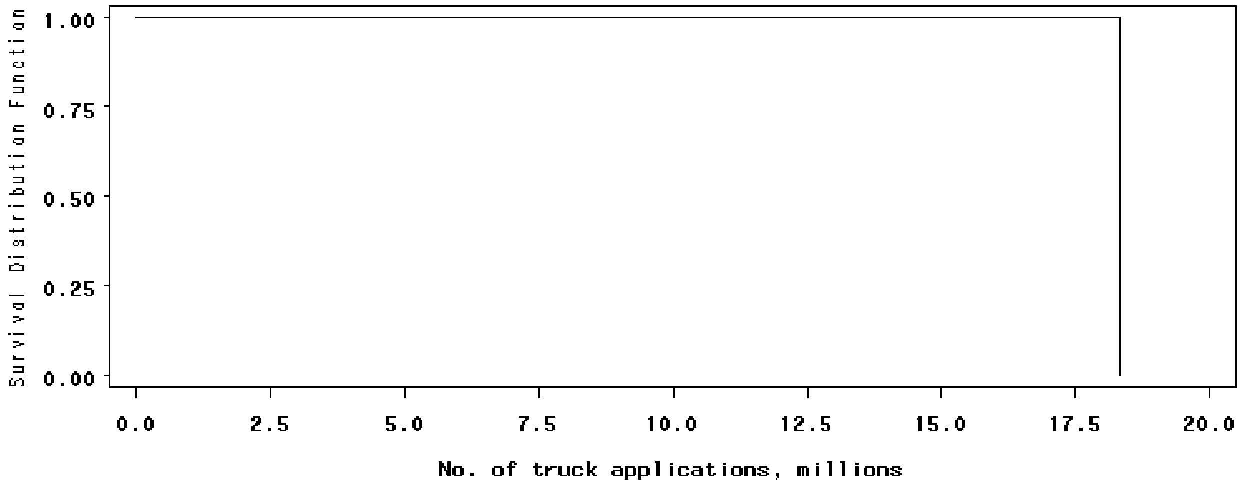
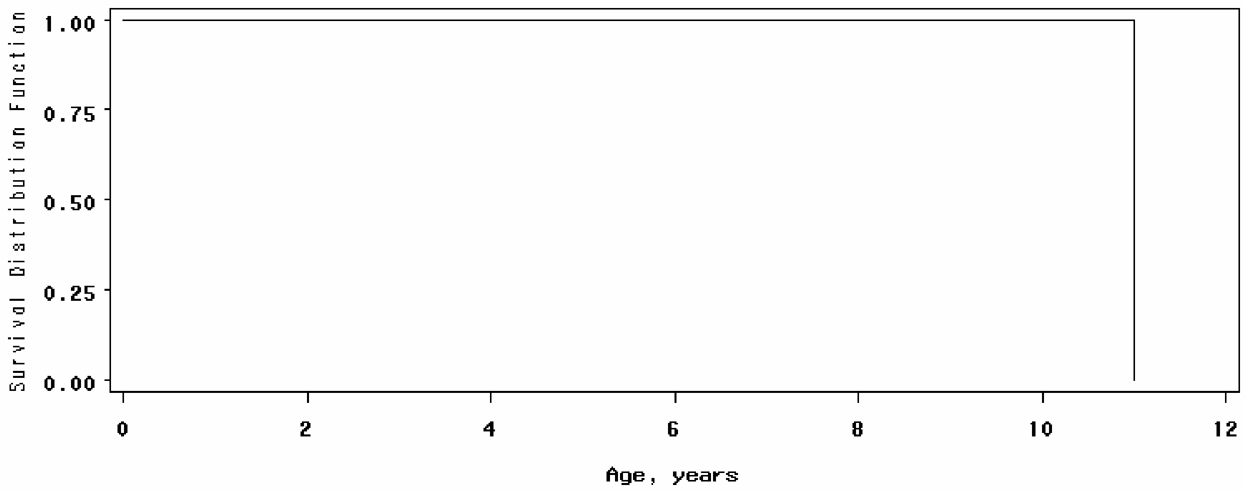


Figure A-91. Age- and truck traffic-based survival plots for R5A rehabilitation treatments applied to JPC pavements located in moderate climate.



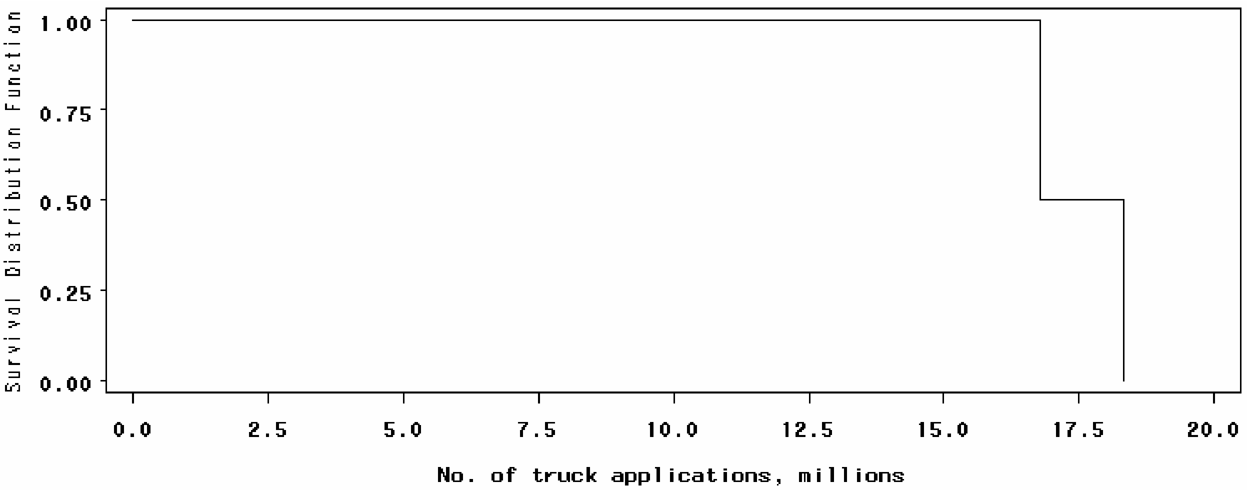
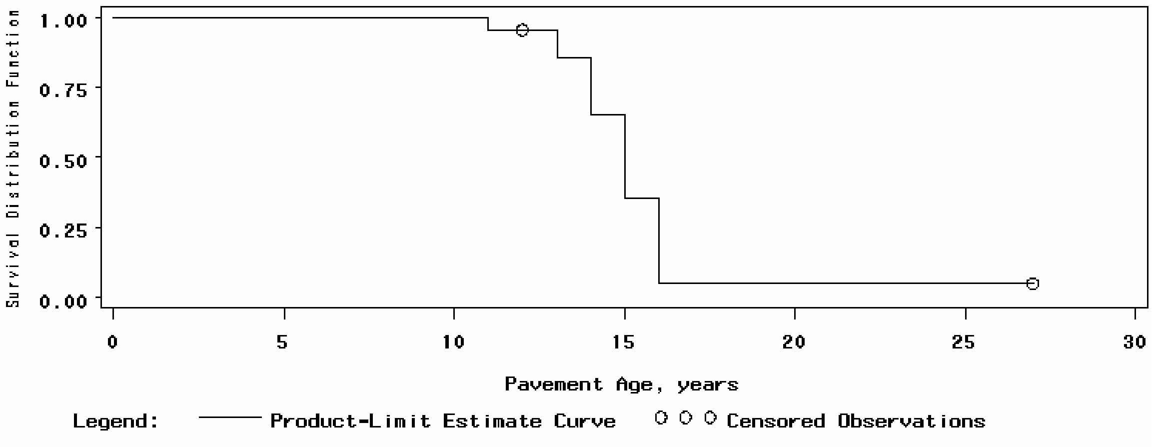


Figure A-92. Age- and truck traffic-based survival plots for R5A rehabilitation treatments applied to JPC pavements located in cool-wet climate.



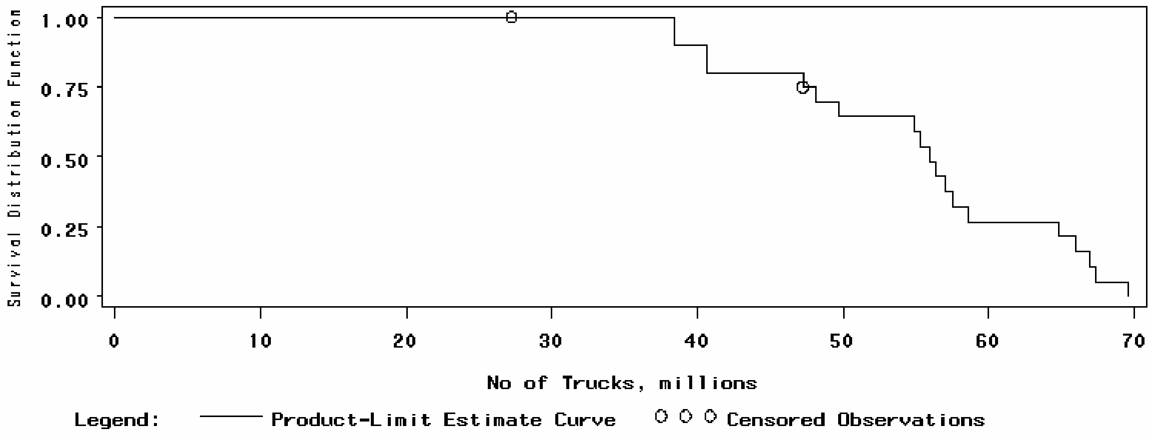
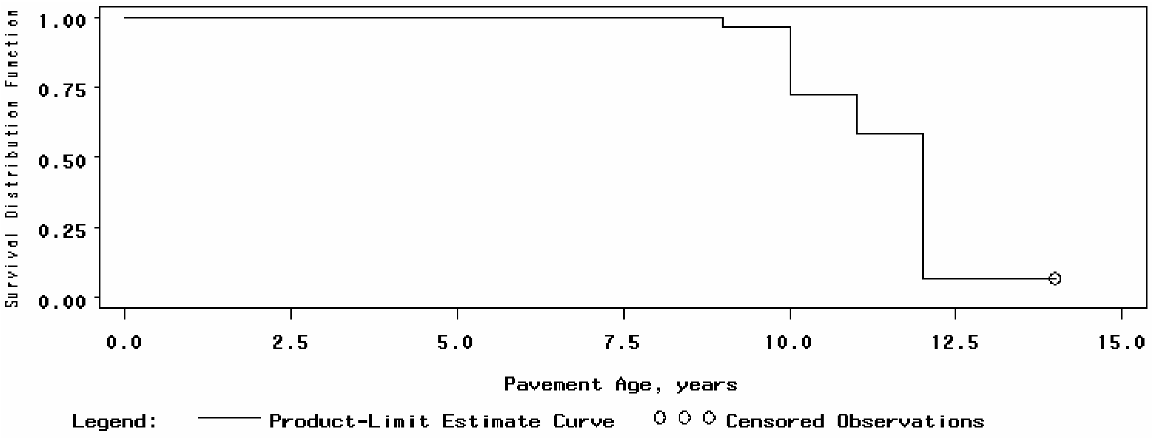


Figure A-93. Age- and truck traffic-based survival plots for R7 rehabilitation treatments applied to JPC pavements located in hot-dry climate.



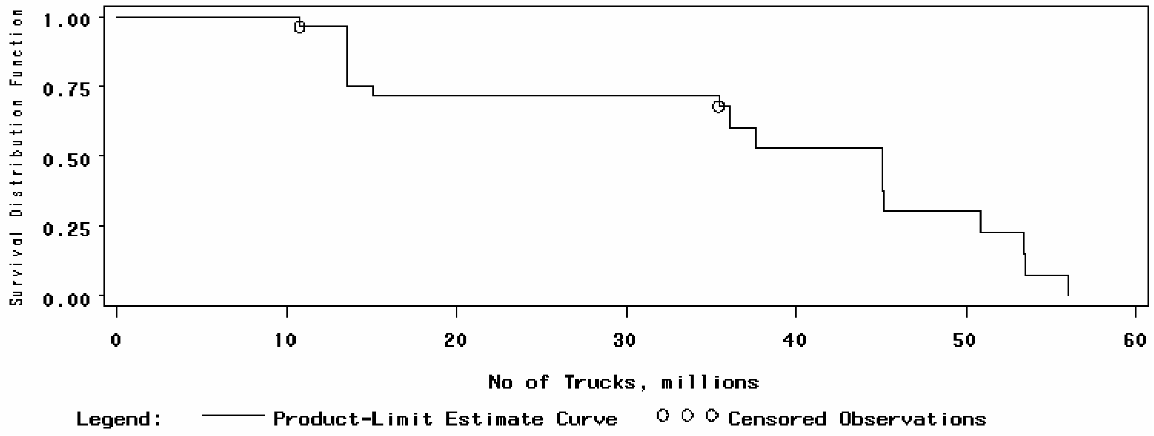
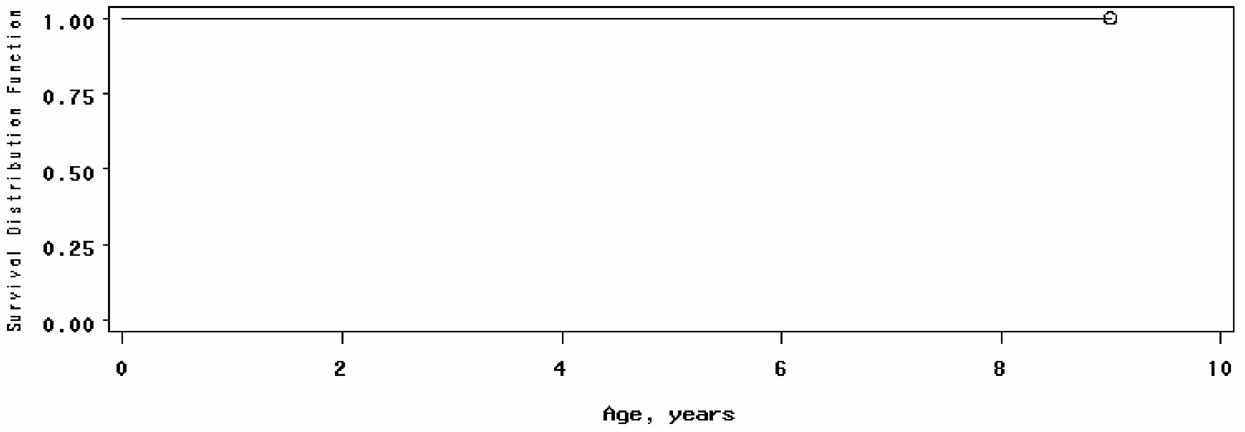


Figure A-94. Age- and truck traffic-based survival plots for R7 rehabilitation treatments applied to JPC pavements located in moderate climate.



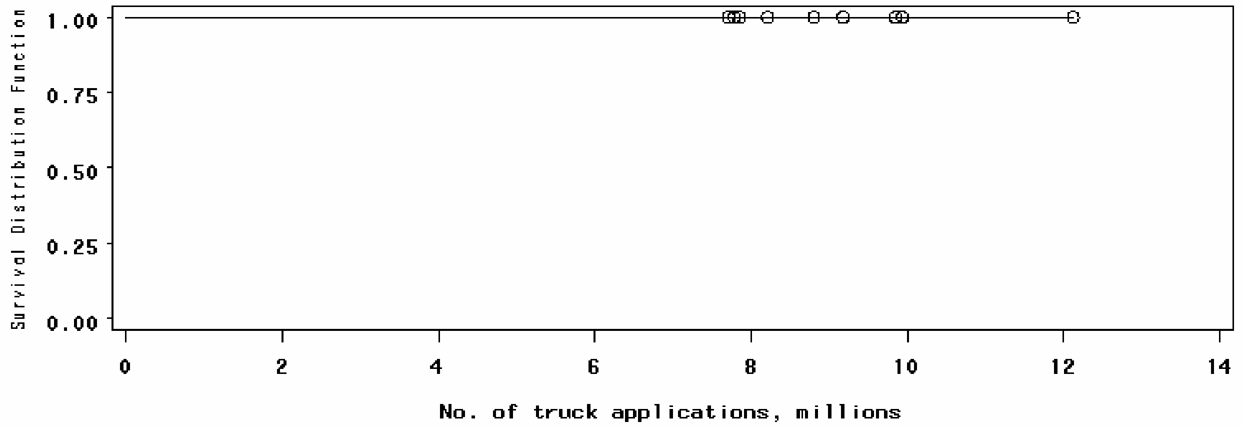
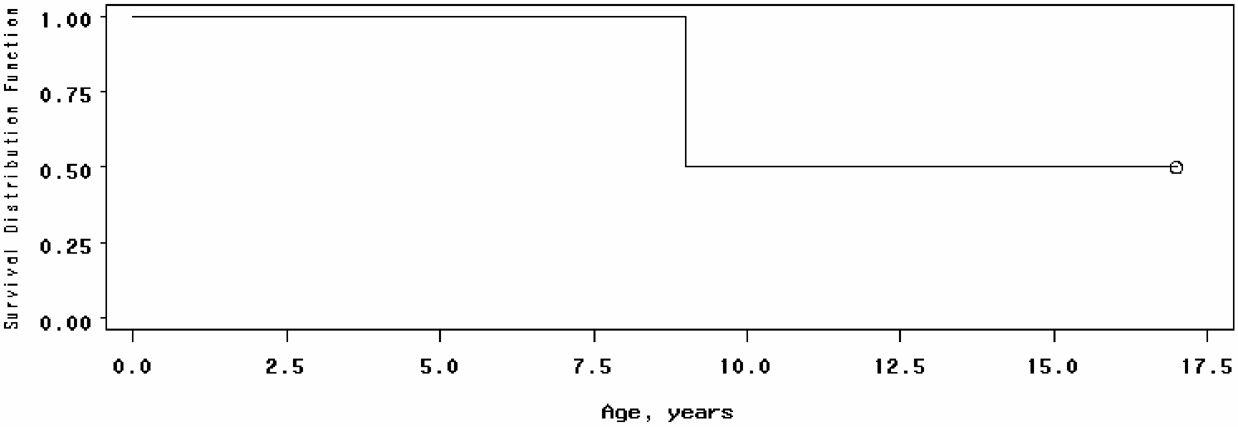


Figure A-95. Age- and truck traffic-based survival plots for R10B rehabilitation treatments applied to JPC pavements located in cool-wet climate.



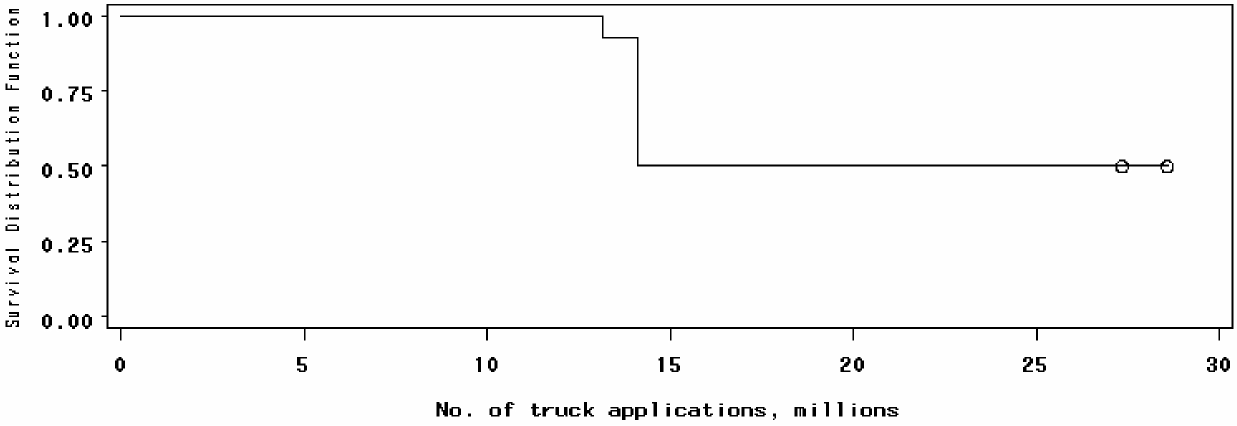
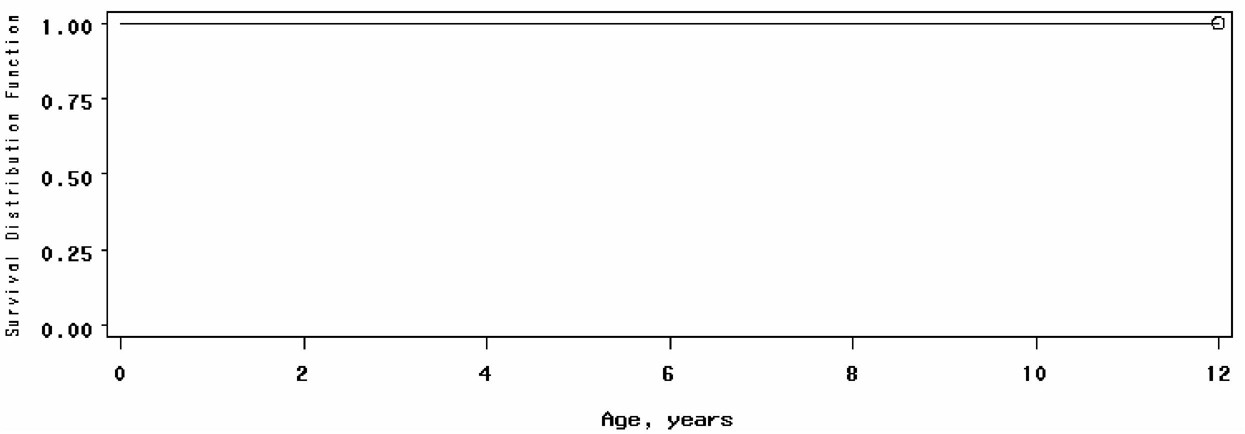


Figure A-96. Age- and truck traffic-based survival plots for R12A rehabilitation treatments applied to JPC pavements located in cool-wet climate.



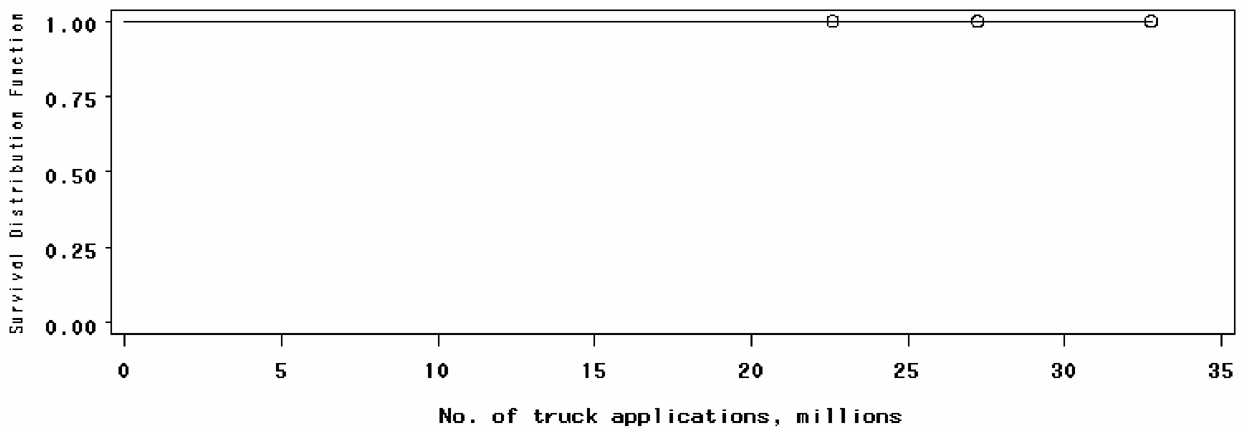


Figure A-97. Age- and truck traffic-based survival plots for R13B rehabilitation treatments applied to JPC pavements located in cool-wet climate.

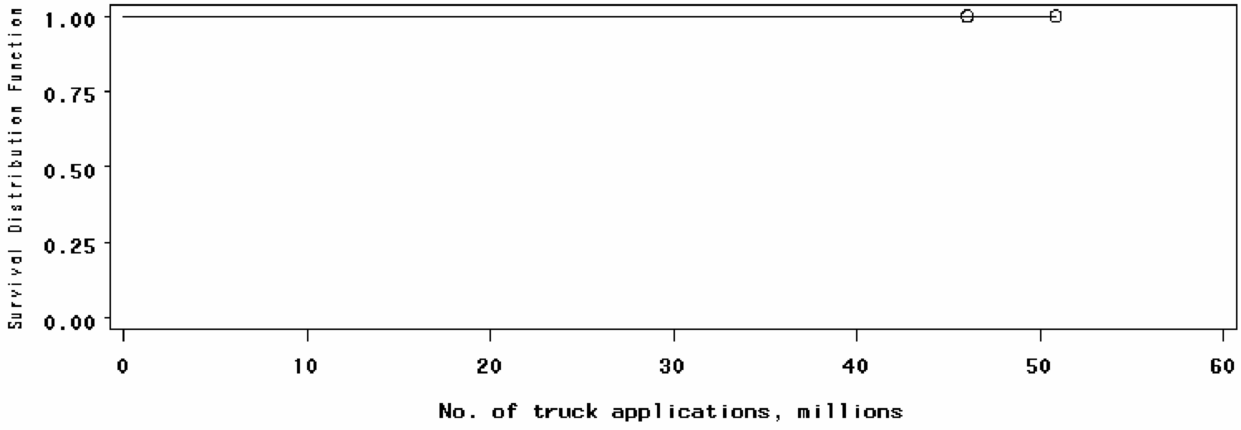


Figure A-98. Age- and truck traffic-based survival plots for R7 rehabilitation treatments applied to JPCD and CRC pavements located in hot-dry climate.