RISK OF PAVEMENT WARRANTIES TO CONTRACTORS

By

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To my family

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The federal and state Departments of Transportation are currently implementing warranties in highway construction projects with objectives to improve construction quality and encourage contractor innovation. The contractors react by increasing their bids to compensate for the additional risks that the warranties impose on their businesses. Risks have long been recognized and studied in the construction industry. However, a systematic study on risk of construction warranties basically does not exist.

Many research efforts have been made to develop guidelines for implementing warranties and to evaluate their effectiveness. But all the studies are conducted from the owner's point of view. No guideline has been developed to guide contractors through the warranty process. Survey results indicate that most contractors are not familiar with warranties.

The objective of this research is to define a concept of warranty risk and develop an approach to measure the contractor's business risk exposure to pavement warranties. This research is conducted from the contractor’s perspective and begins with a review of the highway construction business. The risk of warranties to the contractor is defined as the probability that actual warranty period repair costs will exceed the estimated repair costs. Three factors for warranty risk are identified to be the uncertainty in repair work quantities, unexpected price escalation, and timing of repair. An investigation of historical pavement condition survey data is conducted to analyze the uncertainty of pavement performance after construction. Life distribution models are fitted using the performance data to model the time for each type of distress to occur. Uncertainty in future price escalation is analyzed using the historical highway construction cost index. The Box-Jenkins procedure is followed to build a time series model for assessing future price uncertainty. The Monte Carlo simulation approach is adopted to integrate all the models and produce a probability distribution for warranty risk. Value at Risk (VaR) is used as a measure of warranty risk. A real case study is conducted to demonstrate and validate the simulation approach.

CHAPTER 1
INTRODUCTION

Background

Warranty Implementation in Highway Construction

The use of warranties in highway construction has been accepted as an effective standard procedure in Europe but is still being evaluated as an innovative contracting practice in the United States (Hancher 1994). Prior to 1991, the Federal Highway Administration (FHWA) had a longstanding policy that restricted the use of warranties on Federal-aid projects to electrical and mechanical equipment with the rationale of preventing Federal-aid funds from being used for maintenance costs (FHWA 2002).

Warranty was first approved by the FHWA under Special Experimental Project No. 14 (SEP-14) as an innovative contracting practice. Eight states participated in the evaluation of pavement warranties. Seventeen states evaluated warranty specifications (FHWA 2002).

In 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) permitted states to use local procedures including warranty for Federal-aid projects located off the National Highway System (NHS) (FHWA 2002). On August 25, 1995, the FHWA published an Interim Final Rule for warranties for projects on the NHS, which prohibits warranties for items not within the control of contractors. The warranty Final Rule was published on April 19, 1996.

Warranty contracting is currently implemented by state Departments of Transportation (DOTs) with objectives to reallocate performance risk, encourage contractor innovation, increase product quality, and ultimately reduce the life cycle costs of highway projects (Anderson and Russell 2001). By 1999, at least 21 states had let about 240 highway construction projects with warranty provisions (Russell et al. 1999). It was recently estimated that more than half of the states have used warranties on highway construction projects (Bayraktar et al. 2004).

Problems in Current Research

Various studies have been conducted on the use of warranties in highway construction projects. Most of them focus on evaluating the effectiveness of warranties or developing implementation guidelines. These studies provide valuable information for the DOTs to implement warranty contracting methods on highway construction projects. But they also have significant limitations.

Warranty evaluation

Many efforts have been made to evaluate the effectiveness of pavement warranties and their impact on the involved parties, including state DOTs, contractors, and surety companies. The two major research approaches are

1. To compare the quality and costs of warranted projects with those of non-warranted projects.
2. To conduct questionnaire surveys or personal interviews with state DOTs, contractors, and surety companies.

Surveys have provided clear results with regard to the concerns and reactions of the involved parties. Some typical survey questions for the contractors include the risk premium added to their bids, innovation implemented, actual quality of the warranted projects, and ability to obtain warranty bonds, etc. The survey results can be objective and reliable, but also qualitative and intuitive. Researchers usually provided a list of fragmentary survey results without further integration or explanation.

The comparisons of warranty projects with non-warranty projects provide diversified and sometimes contrary results (Bayraktar et al. 2004). Most states reported a bid price increase as a result of warranty clauses, but some states, such as Michigan, did not perceive significant bid price increases on warranted projects. Some states, like Wisconsin, reported significant improvement in quality, but others (Colorado) did not find any measurable difference; some states (Montana and Indiana) even reported lower performance on warranted projects.

Besides the contrary results, the methodology of comparison is also questionable. A critical question is whether the warranted projects and the non-warranted projects are actually comparable. Many factors may cause the results of warranted projects to differ significantly from that of non-warranted targets. But they are usually ignored in the comparisons. Some of the factors include the following:

- The warranted projects are usually selected from those with good site conditions to reduce the contractor’s risk.
- Warranty specifications may set higher quality standards than non-warranty specifications.
- Due to the increased bonding requirements and liabilities on warranted projects, some contractors (usually small contractors) are disadvantaged and reluctant to bid on warranted projects. As a result, large contractors are more likely to win the warranty contracts.
- Some bids on warranted projects were rejected because the bid prices were too high.
- Bid prices usually vary significantly among similar projects, whether or not under warranty. The observed difference in bid price between warranted and non-warranted projects may involve project specific variation.
- All the comparisons were conducted in a “trial” period when neither the contractors nor the DOTs were experienced on warranties. Also, the motives of either party may cause biases in the results of comparison.

Due to the complexity inherent in the aforementioned research programs, it is difficult to reach a definite and reliable conclusion on warranty evaluation via analysis of currently observed outcomes. Some other evaluation approaches might be needed.

Guidelines for Implementing Warranties

The Transportation Research Board (TRB) of the National Academies, the FHWA, and state DOTs have sponsored many research projects to provide suggestions or develop guidelines and specifications for implementing warranty contracting. However, all these research projects are conducted from the perspective of the owners. No research was identified in the literature to provide guidelines to the contractors in bidding warranted projects. Current practices in highway warranties show that most contractors are inexperienced in warranty contracting. One major concern of the contractors is the risk of warranties. However, few contractors understand the risk.

Another important party involved in highway construction projects is surety companies. It is widely known that surety companies are reluctant to issue long-term warranty bonds due to the high underlying risks. Hastak et al. (2003) reported that surety companies currently do not have an appropriate procedure to underwrite warranty bonds because they do not understand the risks associated with highway warranties.

Research Objective

Given the nature of current research on highway warranties, a systematic approach is needed to analyze highway construction warranties and assess their impacts on the involved parties, including state DOTs, contractors, and surety companies.

The federal and state Departments of Transportation aim for improved quality and, ultimately, reduced life cycle costs for warranted projects. However, one major concern of the contractors and the surety companies is the risks associated with warranties. As a result, the surety companies ask a high price for issuing warranty bonds, deny bonding applications from small contractors, and are reluctant to issue long-term warranty bonds. The contractors then submit a higher bid to transfer the bonding costs to the DOTs and to compensate for the risks imposed on their businesses by warranty clauses.

The reactions of the contractors and the surety companies to warranty clauses are driven by the risks associated with warranties. It is essential for them to understand the risk before accepting it. If the risks of warranties can be understood by all the parties involved, then the DOTs will be able to address the warranty requirements appropriately to create a win-win situation. Unfortunately, the risks are perceived intuitively only. They have never been fully explored or even clearly defined.

A comprehensive analysis of the risks associated with highway construction warranties is needed. This study tries to bridge the gap in research on highway construction warranties. In particular, the study will be conducted from the contractor's perspective, and analyze the risk of warranties to the contractors. Since most of the current warranted highway projects are asphalt paving, the research is limited to asphalt pavement warranties. The objectives of this study are:

- to define a concept of warranty risk to the contractors, and
- to develop an approach to quantify the risk of pavement warranties on the contractors' business.

Research Methodology

This research was divided into six tasks.

The first task was to conduct an extensive review of literature to identify the state-of-the-art research on pavement warranties and warranty risk analysis. The categories of literature review include

- Guidelines for implementing pavement warranties
- Evaluation of pavement warranty effectiveness
- Risk analysis and modeling in the construction industry
- Warranty risk and cost analysis in other industries

The second task was to develop a concept of warranty risk to the contractors and identify major elements of the risk. A review of the construction business was conducted before the concept was developed. This review included the industry structure, the construction business process, and construction specifications including warranty specifications. Three factors of warranty risk were identified in this stage: uncertainty in quantities of repair items, timing of repair, and unexpected future unit repair cost escalation.

The third task was to investigate the uncertainty of pavement performance, which is directly related to repair works. The data used for this analysis are the asphalt pavement condition annual survey data for interstate projects in the state of Florida. Developing trends of various types of distresses are analyzed, including rutting, ride, cracking, raveling, and bleeding, etc.

Further analysis of the results obtained in Task Three indicated that the results are biased estimates of pavement performance because failed pavements were excluded in later year analysis. Probability models were developed in Task Four using the performance results obtained in Task Three. These models, also called reliability or survival models, describe the probability distribution of time when a certain type of distress occurs.

The fifth task is to model the uncertainty of future unit cost escalation. Monthly data of the highway and street construction cost index, one of the PPI series, were used for this analysis. An ARIMA time series model was fitted in this stage.

The sixth and last task was to incorporate the models developed in Task Four and Five to obtain a profile of warranty risk. This was accomplished via Monte Carlo simulation. A case study with a real warranted project was performed to illustrate the simulation approach.

Report Organization

Chapter 2 summarizes prior studies by other researchers on highway construction warranties, construction risk management, and warranty risk analysis in the manufacturing industry. Chapter 3 briefly reviews the highway construction business. Chapter 4 develops the concept of warranty risk with regard to contractors and identifies the major elements of the risk. Chapter 5 discusses the statistical aspects of asphalt pavement performance for interstate projects in the state of Florida. Chapter 6 explains in detail the modeling process and results of the pavement distresses. Chapter 7 details the modeling of uncertainty in future price escalation. The models developed in Chapters 6 and 7 are incorporated to reach a profile for warranty risk. This is accomplished via the Monte Carlo simulation and described in Chapter 8. Chapter 9 closes the report with conclusions of the study and recommendations for future research.

CHAPTER 2
LITERATURE REVIEW

This chapter documents previous studies that may provide background information for this research. These studies can be divided into five groups: guidelines for implementing pavement warranties, impacts of pavement warranties on involved parties, evaluating warranty effectiveness, construction risk analysis, and warranty risk analysis in the manufacturing industry.

Guidelines for Implementing Pavement Warranties

Anderson and Russell (2001) and Thompson et al. (2002) developed a process model to guide state DOTs in implementing warranty contracting method on highway construction projects. This process model covers all the project delivery phases including conceptual planning, program planning, bidding, contract award, construction, maintenance, and evaluation. Detailed guidelines were developed for each step, which the DOTs can follow in warranty implementation. Key elements of the guidelines include:

- Determine motivation for implementing warranties
- Review and understand industry best practice for warranty contracting
- Establish cooperation and communication between DOTs, contractors, sureties, etc.
- Prepare warranty specifications
- Select pilot projects
- Prepare bid documents
- Construction and project administration
- Evaluate effectiveness of warranties
- Review and refine the implementation process

Anderson and Russell (2001) developed model warranty specifications for asphalt pavements. The key items addressed in the warranty specifications include

- Length of warranty period
- Bonding requirements
- Maintenance responsibility
- Conflict resolution
- Contractor responsibilities
- Department responsibilities
- Performance indicators and threshold values
- Requirements for remedial actions
- Basis of payment

The Transportation Research Board (TRB 2005) is currently sponsoring another research program to develop guidelines for a project-level application of warranties. The guidelines will be able to assist state DOTs in determining whether warranties are the best option for a particular project. Warranty evaluation criteria to be considered include initial construction costs, inspection and testing costs, life-cycle costs, initial construction quality, and pavement performance.

Impacts of Warranties on Involved Parties

Hancher (1994) analyzed the impacts of warranties on DOTs, contractors, and surety companies. He concluded that the effect of warranties on bid prices is dependent on the contractor's knowledge of the conditions of the projects. If the contractor is unsure of project conditions, he or she may raise the bid price to cover perceived risk. The risk involved with warranty contracting may exclude small contractors with weak financial conditions to obtain long-term warranty bonding. This may reduce the level of competition.

Worischeck (2003) discussed local perceptions of highway warranties in Utah. He believed that warranties could increase quality and contractor awareness of their product and lower the risk of premature failure. But warranties are only as good as the contractor or the surety company. Bonding capacities may limit the number of warranty projects that the Utah DOT may have due to the lack of large contractors. The bid prices may be higher in the short term, but will fall when the contractors gain experience. Perceiving resistance from the contractors to warranty risk shift, Worischeck suggests that Utah DOT develop an asphalt pavement warranty as a long-term goal.

Stephens et al. (1998) surveyed contractors and surety companies on various issues regarding pavement warranties. Findings of the contractor survey include the following:

- The highway construction community in Montana has little experience with highway warranty contracts.
- Contractors will significantly increase their bids on warranted projects, in response to the shift of performance risk from the state to the contractors.
- Increase in initial costs may occur without substantial improvements in the quality of the projects.
- Small or medium contractors may find it difficult to survive in a warranty market, due to their financial and bonding situation.
- The most favorable type of job for warranty is total reconstruction. For other projects, too many variables are beyond the control of the contractor to reasonably evaluate the contractor's performance.

Major concerns of the surety companies include the following:

- The surety company has difficulty in estimating the financial condition of contractors several years in the future.
- Construction companies have the second highest rate of bankruptcy of all types of business. Warranty bonding will impose great risk on surety companies.
- Retainage may provide more incentive for the contractor to do a good job than bonding.

Hastak et al. (2003) surveyed all state DOTs, districts of Ohio DOT, contractors, and surety companies to identify the impact of warranties on project cost, quality, bonding, time, etc. Initial bid price increase due to warranties was estimated to be between 0-15%, but there is no significant change in maintenance cost and project life cycle cost. Quantity improvement is not as significant as bid price increase. Only slight quantity improvement is observed for warranted projects. One common objective of pavement warranties is to encourage contractor innovation. However, it is found that innovative technologies and methods are not favored by contractors because of the associated risks.

Evaluating Effectiveness of Pavement Warranties

Anderson and Russell (2001) listed the important items that should be included in the evaluation of warranties, including

- The long-term performance of the project
- Personnel needs for design, testing, and inspection
- The use of DOT and outside expertise
- Risk distribution factors
- Total amount of claims and litigations
- Total project cost including construction and project administration

The costs should be documented to evaluate the life cycle cost of the warranted project for comparison with those of traditional contracts. However evaluation of pilot projects may yield biased results if the pilot projects are intentionally chosen with a high probability of success.

Many state DOTs have participated in the evaluation of pavement warranties. The results vary significantly between states. Some of the results from selected states are summarized below.

Wisconsin DOT (WisDOT 2001) reported its five-year experience with asphalt pavement warranties. Performance and cost data for warranted pavements were compared against the statewide average for projects of the same type and similar size. Based on the data collected, the warranted pavements performed better than typical pavements, as seen in Table 2-1. The costs of warranted projects were found to be lower than those of standard projects, as seen in Table 2-2. It was also found that warranted projects required less supervision and testing than standard contract projects, and they reduced state construction delivery costs.

Table 2-1. Comparison of pavement performance, WisDOT

Pavement age	International roughness index (IRI)		Pavement distress index (PDI)	
	Warranted	State average	Warranted	State average
New	0.81	1.11	0	0
1 year	0.87	1.17	1	5
2 year	0.89	1.29	2	11
3 year	0.89	1.33	6	16
4 year	0.94	1.37	12	21
5 year	0.94	1.45	9	26

Table 2-2. Comparison of pavement costs, WisDOT

Period		1995-1999	2000
Standard contract	Bid price (state average)	$25.05/ton	$28.58/ton
	Quality management	$0.60/ton	$0.60/ton
	State maintenance	$2.07/ton	$2.07/ton
	Total	$27.72/ton	$31.25/ton
Warranty contract	Bid price	$24.34/ton	$29.45/ton

It should be noted that the warranted projects used in this comparison were specially selected for adequate subgrade support. In addition, a few bids on warranted projects were rejected by Wisconsin DOT because the bids were significantly higher than the Engineer's estimates.

Gallivan et al. (2003) evaluated the effectiveness of Indiana DOT's 5-year performance warranties. Performance of warranted asphalt pavements was compared with that of non-warranty interstate pavements 4 to 6 years old. The data showed that warranted pavements had a lower and more consistent International Roughness Index (IRI). Less rutting was observed for warranted pavements; rut depths for warranted pavement were also less variable. It was estimated that the expected life of warranted pavements is 24 years—9 years longer than non-warranted pavements. Initial bid prices for warranted projects were about 5-10% higher than non-warranted projects. But Gallivan et al. (2003) predicted there would be a 27% cost saving in maintenance over 25 years.

Ohio Department of Transportation (ODOT 2001) observed a bid price increase on warranted projects. Bid prices for asphalt pavements with 3-7 year warranties were 8.5% higher than similar non-warranty pavement. Bid prices for PCC pavements with 7-year warranties were 11% higher than non-warranted pavements. For pavement marking warranties, bid prices increased dramatically, about 90% on average.

Johnson (2004) documented the observations on Minnesota DOT’s asphalt warranty pilot projects. In all three warranted projects, the low bidder’s unit prices for asphalt concrete were comparable to the averages of non-warranted projects. But the ranges of unit prices from all bidders were relatively large due to the fact that most contractors had no prior experience with pavement warranties. Feedback from the DOT project engineers indicated that there was no measurable difference in contractor behavior and material quality between warranted and non-warranted projects.

Aschenbrener and Debios (2001) evaluated the cost-benefit of the Colorado 3-year asphalt pavement warranty projects. Each warranted project was compared with one or two control projects which used the traditional contract approach. The control projects were comparable to the warranty projects in terms of year of construction, overlay thickness, rehabilitation strategy, traffic, and original pavement condition.

The initial costs for warranty projects were compared in various ways. Subjective evaluation by members of the Cost Benefit Evaluation Committee concluded that the warranty cost was negligible. The contractor survey indicated that three contractors did not consider any warranty cost in their bids; while another three contractors added a little additional cost for potential maintenance, bonding, and unknown risk.

Warranty cost, though not explicitly defined, refers to the cost charged by the contractor to cover the potential maintenance work cost, potential lane rental fees because of warranty work, the cost of a warranty bond, and the premium for the contractor to take the warranty risk. Four objective approaches were applied to calculate warranty cost. The results are listed in Table 2-3. The estimated warranty cost, based on the average of the four approaches, was $-0.85 per ton, or -1.6% of bid price. This is an interesting result because it implies that the contractors prefer warranted projects and will lower their bid prices to take on the liabilities and risk inherent in warranty work.

Table 2-3. Warranty cost, Colorado DOT

Approach of Analysis	Average of group 1		Average of group 2	
	$/ton	%	$/ton	%
Lump sum bid of warranty			$1.68	5.1%
Based on Engineer's estimate	$1.23	3.9%		
Based on annual region avg. cost	$-8.86	-20.4%	$-1.29	-3.3%
Based on control projects	$0.81	2.6%	$-1.13	-1.2%
Based on avg. cost for all bidders	$1.15	4.5%	$0.43	2.2%

Note: Each group consists of three warranty projects.

Three-year maintenance costs were recorded for control projects. The average cost of maintenance was $7,753 per project. The maintenance cost is insignificant since the bid prices for the control projects range from, $3,472,988 to $4,634,123.

It should be noted that before the 3-year warranty experiments, two warranty projects, one with a 5-year warranty and another with a 10-year warranty, were unsuccessfully bid in Colorado because the low bids were significantly higher than the Engineer's estimates.

Wienrank (2004) reported costs of pavement warranties in Illinois. Five-year warranties were implemented in Illinois for both bituminous and concrete pavements. The warranty was included as a separate bid item on each contract. The warranty pay item costs ranged from 0.0 to 0.43% of total project cost for concrete pavement, 0.06% to 0.80% for bituminous pavements, and 1.14% to 2.38% for bituminous overlays. The data seems to indicate that the warranty cost is very low. But Wienrank (2004) claimed that the contractor might increase the cost of other pay items to hedge against the potential future cost for corrective work.

Warranty Analysis in Other Industries

Brennan (1994) developed detailed guidelines for planning, analysis, and implantation of warranties in the consumer, commercial, and government business sectors. Methodologies of warranty risk analysis and warranty costing are highlighted as follows.

Both supplier and customer assume risk in the warranty process. The supplier's major concerns of warranty risk are (a) to include sufficient cost in the sale price to cover the expected repair or replacement costs, and (b) to be competitive. The customer's major concern is the cost effectiveness of the warranty, or the value of the warranty to the customer.

A Reliability Improvement Warranty (RIW) is an incentive warranty that has been used extensively by the government since the 1970s, with the objectives of improving reliability and reducing support costs. Under a RIW, the contractor is paid a fixed price up front to perform repair services for an extended period of time. The potential risks of RIW to the government include

- High price for RIW coverage

- Reduced self-sufficiency (tied in with one contractor for future repairs)
- Administrative complexity
- Potential transition of maintenance from contractor to government.

The potential risks of RIW to the contractor include

- Possibility of large loss if the achieved reliability is lower than expected
- Fixed-price commitment with limited reliability data
- Pricing warranty too low (possibility of loss on RIW option)
- Pricing warranty too high (possibility of losing contract)

Reliability is an important consideration in warranty requirements and implementation. The expected frequency of failure is a critical parameter in warranty pricing. In addition, once the product is produced, the number of actual failures is essential in determining the achieved performance for performance guaranty determinations.

The product being warranted can be either repairable or non-repairable. A repairable item can be restored to satisfactory operation by repair actions. A non-repairable item will be removed permanently from the system when it fails. The underlying life distribution for a non-repairable product can be estimated using reliability models such as Weibull or lognormal distributions. The analysis of repairable systems is more complex than for non-repairable systems. The analysis can be performed as follows:

- If the time between failures does not exhibit a decreasing or increasing trend, then the system can be assumed to exhibit a renewal process. The product can be studied as if it were non-repairable.

- If there is a trend in failure time, a different approach is used to model the repair rates, or Rate of Occurrence of Failures (ROCOF).

- If there is a trend in failure time and a detailed system analysis is desired, the system may be analyzed using a “bottom-up” approach which goes from component failure mode to system failure rate.

There are two major components for warranty cost: warranty implementation cost and risk money. Warranty implementation cost is basically the cost needed for the contractor to perform the warranty work, including repair, transportation, administration, and field service. Risk money is a compensation for the contractor's risk exposure associated with the warranty.

Various approaches are available for formulating a warranty cost-risk model. Some typical methods include

- Sensitivity analysis. Measure the amount of change in analysis results given a small change in an input parameter.
- Bounding technique. Estimate the limits associated with each key cost driver and use these extremes to give the minimum and maximum warranty costs.
- Beta distribution approach. Estimate three different costs for each cost category: most likely cost, lowest cost, and highest cost.
- Monte Carlo simulation.

Construction Risks Analysis

The Construction Industry Institute (CII 1989) described the basic methodology of construction risk management. The risk management approach includes three consecutive stages: risk identification, risk measurement, and risk control.

Risk identification is the first step in risk management. The success of risk identification depends on the availability of historical information, formalized checklists, and the experience of project personnel. The risks can be cataloged by source, such as technical uncertainties, contractual risks, and financial risks. The CII also cataloged risks in terms of known, known-unknown, and unknown-unknown situations or conditions.

Risks from known conditions are the most common risks in a project that have to be identified. Generally they involve a continuous range of outcomes, have a relative high frequency of occurrence, and low severity. Examples of known conditions include contract provisions, project schedule, quantities of work, site conditions, material and construction quality, labor productivity, etc. A detailed checklist should be used for risk identification to minimize the potential for overlooking some risk items.

Risk from known-unknown conditions are neither explicit nor normally expected, but are foreseeable and possible. They generally tend to be discrete events, with a low frequency of occurrence and a high severity of impact when occurring. Examples of such events include extreme bad weather, extreme adverse labor activity, sudden labor shortages, or commodity shortages in the project area. Known-unknown conditions are best identified through review of historical data on similar projects.

Risks from unknown-unknown conditions are known as unforeseen risks. They cannot be identified in advance and their potential can only be acknowledged. Unforeseen risks normally have a low probability of occurrence, but have potential catastrophic effects.

Risk measurement is the process to assess the potential loss associated with risks. However, risk measurements are usually difficult due to the following problems:

- There is usually a broad range of potential loss for each individual risk
- The potential losses for some risks are hard to estimate.
- Many risks are involved in the project.

The CII listed four categories of methods that are available for measuring construction risks, including

- Traditional methods that use allowances based on past experience
- Discrete event analysis including decision trees, influence diagrams, and utility theory

- Analytic methods that use mathematics of probability to assess and combine the effects of individual risks into a an overall measure of risk
- Monte Carlo simulation

Risk control is the last stage of risk management. There are two categories of risk control: advanced planning actions and in-process risk containment actions. The advanced planning actions are designed to place risk exposure within controllable limits. Typical advance actions include risk avoidance, risk sharing, risk reduction, risk transfer to subcontractors, insurance, and risk acceptance with or without contingency. Risk containment actions are designed to reduce actual loss in the process of operation. A contingency account may be established and maintained over the life of the project.

CHAPTER 3
OVERVIEW OF HIGHWAY CONSTRUCTION BUSINESS

Industry Overview

The construction industry is one of the large industries in the United States. In 2004, the construction industry accounted for 4.6% of the gross domestic product (GPD) and created a total added value of $541.4 billion (BEA 2005). In 2002, there were 710,307 construction firms nationally, with a total employment of 7.19 million (U.S. Census Bureau 2005).

The construction industry is dominated by small firms. About 60% of the firms have less than five employees and 90% of the firms have less than 20 employees. Only 1.2% of the firms have 100 or more employees (U.S. Census Bureau 2005). The distribution of firm sizes by employment is illustrated in Figure 3-1.

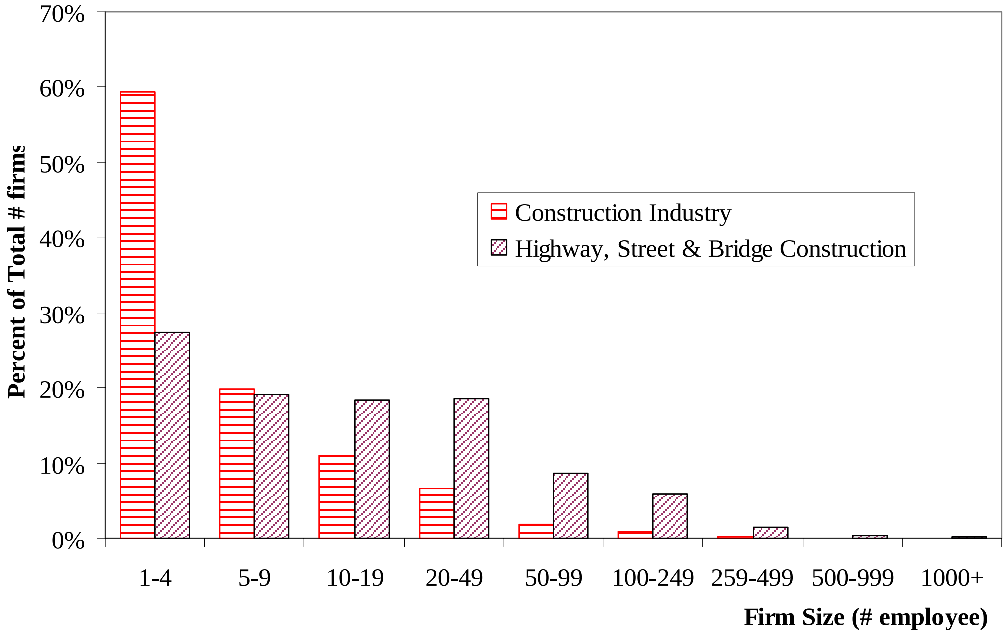

Figure 3-1. Firm size by number of employees

Highway, street, and bridge construction is a small section of the construction industry (see Table 3-1), with a total number of 11,348 firms and a total employment of 410,822 nationally in 2002 (U.S. Census Bureau 2004).

Table 3-1. Size of highway, street and bridge construction section

	Construction Industry	Highway, Street & Bridge construction	(b) as % of (a)
	(a)	(b)	(c)
Total employment	7,193,069	410822	5.71%
No. of firms	710,307	11348	1.60%
Net value of construction work	$874,853,043,000	$62,094,794,000	7.10%

Source: US Census Bureau (2004)

The highway, street, and bridge construction section is also dominated by small firms. But firm size in this section is relatively larger compared with the whole construction industry, as illustrated in Figure 3-1. Only 27.3% of total highway and bridge construction firms have less than 5 employees, compared with 59.4% of the whole construction industry. With 1.6% of the total number of firms in the construction industry, the highway, street and bridge construction section accounts for 5.7% of total employment and 7.1% of construction work value, as shown in Table 3-1.

In 2002, about 30% of highway construction firms did construction work less than $500,000 in value and 44.4% firms had construction business less than $1 million. Only 16% firms did construction work of $10 million or more in value. The distribution of business value is illustrated in Figure 3-2 (U.S. Census Bureau 2004).

Of all highway, street, and bridge construction firms, 81.8% take the form of a corporation, higher than the 67.1% ratio for the whole construction industry (see Table 3-2). C corporation and S corporation are the two major corporate forms for construction firms. Other legal forms include individual proprietorship and partners, etc. (U.S. Census Bureau 2005).

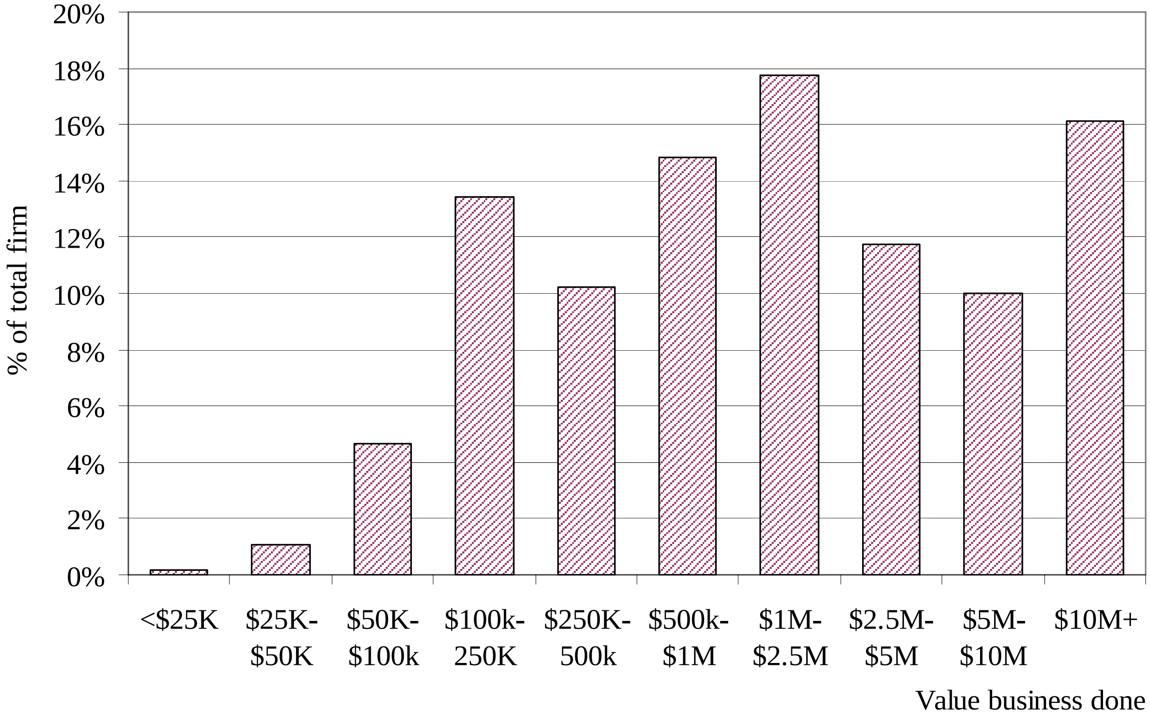

Figure 3-2. Size of highway construction firms, by value of business done

Table 3-2. Legal forms of construction firms

	Construction Industry	Highway, Street & Bridge Construction
Corporate	67.06%	81.69%
Individual proprietorship	26.03%	10.97%
Partners	5.88%	5.95%
Other or unknown	1.03%	1.39%
Total	100.00%	100.00%

Source: U.S. Census Bureau (2005)

The federal, state, and local governments collectively constitute an overwhelming majority in this section. In 2002, about 72.5% of the total value of roadway and bridge construction projects were owned by federal, state, and local governments. The other 27.5% were privately owned projects. So the roadway and bridge construction business is highly controlled by the governments.

Construction Bidding

The Competitive Low Bid System

The two most common types of contract acquisition methods are competitive bidding and negotiation. In the private construction sector, the owner has great latitude in selecting the contractors, ranging from open bidding and invited bidding to negotiation. In the public sector, however, construction contracts are generally awarded through open competitive bidding. All qualified contractors can bid on any proposed project.

For highway and street construction projects, the contractor’s bid is usually submitted on either a lump sum or unit price basis, as specified by the owner. The public owners, including federal and state DOTs, are generally required by law to award the contract to the lowest responsible bidder. However, the owner reserves the right to reject all the bids.

Cost-based Construction Pricing

The contractor’s bid estimate consists of two basic elements: (1) direct construction costs including direct labor costs, material costs, equipment costs, and field supervision costs; and (2) the markup to cover general overhead expenses and profit.

The contractor’s bid estimates are based on the quantities for those construction items specified in the plans and specifications, which are furnished by the owner. The direct construction costs can be estimated using one or a combination of the following approaches (Hendrickson 2000):

- Subcontractor quotations. When a general contractor intends to use a specialty subcontractor, he or she may solicit price quotations for those work items to be subcontracted.
- Quantity takeoffs. The project is decomposed into several items. The quantities of the items are measured from the plans. The total cost of the project is calculated as the sum of products of the quantities and the associated unit prices of the items.

- Construction procedures. If the actual construction procedures of a proposed project are considered, items such as labor, material and equipment needed to perform various tasks are estimated and used for the cost estimates.

The markup portion of the bid is the source of income to the contractor. A large markup means a higher profit. However, since only the bidder with the lowest price will win the contract, the markup is highly impacted by bid competitions. In the construction industry, most contractors specialize in a submarket of the industry and concentrate their work in particular geographic locations. So the level of demand in a submarket at a particular time can significantly influence the competition and ultimately the markups (Hendrickson 2000). The markups tend to be higher at times of low competition and lower at times of intense competition. The Construction Financial Management Association (CFMA 2003) reported that the national average gross margin for heavy and highway construction was 10.9% (or markup 12.2%) and the net margin was 3.2%.

Warranty Specifications

The traditional type of specifications for highway construction is referred to as method specifications, or prescriptive specifications. A method specification specifies exactly the material, equipment, and construction method that the contractor is required to use in construction operations. Method specifications have significant limitations because they discourage contractor innovation and the owner assumes very high responsibility on the quality and performance of the final product.

To overcome the disadvantages of method specifications and shift responsibility for quality control to the contractors, DOTs adopted Quality Assurance (QA) specifications and performance specifications (including warranty specifications).

Rather than specifying a method to construct a project, a warranty specification defines the performance of the project. The contractor is bound by the warranty to repair the product for a given time period after completion whenever certain performance criteria are not met. Accordingly, the contractor may have more freedom in selecting construction materials and methods.

There are two basic types of warranties: the materials and workmanship warranty, and the performance warranty. Currently most highway and bridge warranties are for materials and workmanship. Under a materials and workmanship warranty, the contractor is responsible for correcting defects caused by poor materials or workmanship, which are within the contractor’s control. The contractor assumes no responsibility for defects that are design-related or out of the control of the contractor. Under a performance warranty, however, the contractor is responsible for correcting all defects even though the defects are attributable to factors out of his or her control.

Some common elements of warranty specifications include

- Warranty term
- Performance criteria
- Remedial actions if performance criteria are not met
- Warranty bond
- Conflict resolution

Warranty term (or warranty period) is the period of time following the completion of construction when the contractor is held accountable for repair and maintenance. Warranty terms are usually specified in calendar time. Some states, including New Mexico, Colorado, Ohio, Minnesota, and Florida, use two dimensional terms, calendar time and traffic loads, whichever comes first (Hastak et al. 2003). The length of warranty terms varies by state as well as by project type. Typically, warranty terms range from 5 to 10 years for Portland cement concrete pavements and from 3 to 8 years for asphalt concrete pavements (FHWA 2000). New Mexico and Virginia also experienced 20-year pavement warranties for design-build projects.

Performance criteria are defined to evaluate the performance of the warranted product during the warranty term. The performance criteria include a selection of performance indicators and the associated threshold values for these indicators. Performance indicators, also called performance parameters, are the types of distresses to be measured and evaluated. Remedial actions are needed if certain threshold values are exceeded.

In the event that any of the performance criteria are not met during the warranty period, it must be determined whether or not the contractor is responsible for repairing the defects. If the contractor is held responsible for the defect, he/she shall perform the corrections at no cost to the owner. Approaches to remedial actions are usually stated in the warranty specifications. But the contractor may have the right to choose alternative approaches.

A warranty bond is issued by a surety company which guarantees that the contractor will meet his/her warranty obligations. In case of contractor default on warranties, the surety company will be held liable for the required remedial works. Warranty bonds are required by most state DOTs that are implementing warranties. Florida is the only known state that has no warranty bonding requirements. The face values of warranty bonds are usually specified as a fixed percentage (ranging 10-100%) of the bid price or a percentage (up to 100%) of worst scenario repair costs.

Disputes between the contractor and the owner arising out of warranties will be resolved through a conflict resolution team which consists of representatives of the contractor and the owner. One major dispute between the contractor and the owner is the true cause and responsibility of product failures. Since the contractor is exempt from repairing failures unrelated to his/her scope of work, the inability to identify the true cause of the failures and the inclusion of method specifications within the scope of warranty may void the contractor’s obligation on warranties.

CHAPTER 4
THE CONCEPT OF WARRANTY RISK

The federal and state DOTs are implementing pavement warranties with objectives to encourage contractor innovation and improve product quality. The contractors, on the other hand, react by increasing their bids to compensate for the additional risk imposed by warranty clauses.

Risks have long been recognized and well-studied in the construction industry. Many research efforts have been made to develop methodologies and guidelines in identifying, allocating, measuring, pricing, and controlling risks in the construction process. On the subject of highway (including pavement) warranties, however, though the risks are widely recognized, they have not yet been well-analyzed, or even clearly defined. Beginning with this chapter, the risk of warranties will be analyzed from the contractors' perspective by identifying the risk of warranties to contractors and developing an approach to measure this risk.

Definition of Warranty Risk

What is Risk?

Risk can be defined in different ways (CII 1989). It is generally defined as the probability that an adverse or unfavorable outcome may occur. Another widely accepted approach is to define risk in terms of uncertainty. Since uncertainty is the set of all potential outcomes, both favorable and unfavorable, it can be seen as a two-sided definition of risk, essentially including both risk (unfavorable outcomes) and opportunity (favorable outcomes).

Defining Warranty Risk

Under a standard contract, the contractor is generally exempt from any liability on post-construction performance of the project once it has been completed and accepted. Under a warranty contract, however, the contractor guarantees the performance of the product for a specified period of time and is responsible for the repair and replacement of any deficiencies.

Pavement warranties are essentially a transfer of pavement failure risk as well as maintenance responsibility from the owner to the contractor. The contractor feels pavement warranties are risky because he/she has to, before the pavement is actually constructed, estimate and accept a fixed price for a highly uncertain obligation of future repair work.

Performance warranties are popular for many consumer products, which are usually produced in large quantities under identical and controlled conditions. Each highway project including pavement, however, is unique with respect to factors such as site condition, design, materials, climate, and traffic, all of which all may affect the performance of the highway after opening to traffic (Stephens et al. 2002). Various models have been developed to link highway performance to these factors. But these models by far provide the best estimates of the average outcomes for all similar projects. No information is provided regarding how far the actual performance of a particular project can deviate from the estimated average. Thus it is difficult to exactly predict the actual performance of a highway after it is built.

To develop a clear and definite concept for warranty risk, the following principles are considered and followed:

- The concept should reflect the contractor’s major concerns about the warranties.

- The concept should reflect the marginal effects of warranty clauses on construction risks. In other words, the warranty risk should be or relate to the additional risk that the warranty clauses add to the contractor's business.
- The concept should be developed at the project level and should be able to be extended to a portfolio of projects or the corporate level.
- The risk to be defined should be measurable and quantifiable.
- The concept should be able to relate easily to the contractor's decision regarding warranties, including bidding and innovation.

Considering the principles above, the risk of warranties to contractors is defined as the probability that the actual warranty cost will exceed the estimated warranty cost, or alternatively, the probability that the contractor will suffer a financial loss on warranties.

It is important to distinguish between warranty risk and warranty liability. It is true that pavement warranties are risky to contractors because of the existence of warranty liability. But these concepts are not the same.

As discussed in Chapter 3, contractor bid pricing is cost-based. If the contractor is confident that he/she can predict exactly his/her future warranty liability (the actual cost to repair), he/she can simply treat the liability as a cost, add the amount to his/her bid and pass it on to the owner. In this case no contractor will feel the pressure of warranty risk. However, an accurate estimate of warranty liability (cost) is impossible, so the contractor is required to accept the liability in advance at a predetermined price. This is the essence of warranty risk. A high level of warranty liability is not necessarily an indication of high warranty risk. Warranty risk is a result of the uncertainty in warranty liability.

Factors for Warranty Risk

Warranty specifications specify the types of distresses (defects) that the contractor is responsible to repair. For example, under the FDOT (2005) asphalt pavement warranty specifications, the types of distresses that the contractor is responsible to repair include rutting, ride, cracking, raveling, delamination, bleeding, pot holes, and slippage areas.

Assume the warranty term is W years and N types of pavement distresses are responsibility of the contractor. The current unit repair costs are $\boldsymbol{C} = (c_1\ c_2\ ...\ c_N)$, where c_i is the unit repair cost for distress type i. The cost escalations are $\boldsymbol{E} = (e_1\ e_2\ ...\ e_W)$, where e_j is the cumulative cost escalation for j^{th} warranty year. The quantities for repair items are $\boldsymbol{Q} = \begin{pmatrix} q_{1,1} & q_{1,2} & \cdots & q_{1,W} \\ q_{2,1} & q_{2,2} & \cdots & q_{2,W} \\ \cdots & \cdots & \cdots & \cdots \\ q_{N,1} & q_{N,2} & \cdots & q_{N,W} \end{pmatrix}$, where $q_{i,j}$ is the quantity of type i distress repair at j^{th} warranty year. Then the total repair cost can be calculated as

$$C_R = \boldsymbol{C}\,\boldsymbol{Q}\,\boldsymbol{E'} \qquad (4\text{-}1)$$

where C_R is the total repair cost, and $\boldsymbol{E'}$ is the transpose of $\boldsymbol{E}$.

The present value of the repair costs can be calculated as

$$C_R^{/} = \sum_{i=1}^{N}\sum_{j=1}^{W}\frac{c_i q_{i,j} e_j}{(1+R)^{D+j}} \qquad (4\text{-}2)$$

where $C_R^{/}$ is the present value of repair cost, D is the construction duration, and R is the discount rate.

The current unit repair costs are known at the time of bidding. The discount rate is a constant selected by the contractor. So in formula (4-2), c_i and R can be assumed constant. But $q_{i,j}$ and e_j are unknown until they actually occur. An error in estimating either $q_{i,j}$ or e_j will result in an error in the estimate of warranty cost. If we assume the quantities of repair items are uncorrelated to future unit cost escalations. The error in estimate of repair cost can be expressed as

$$\Delta C_R^{/} = \sum_{i=1}^{N}\sum_{j=1}^{W}\frac{c_i q_{i,j}\Delta e_j}{(1+R)^{C_0+j}} + \sum_{i=1}^{N}\sum_{j=1}^{W}\frac{c_i \Delta q_{i,j} e_j}{(1+R)^{C_0+j}} \qquad (4\text{-}3)$$

where $\Delta C_R^{/}$ is the error in predicting total repair cost, $\Delta q_{i,j}$ is the error in predicting quantity for type i distress repair in j^{th} warranty year, and Δe_j is the error in predicting unit cost escalation for j^{th} warranty year repair.

Thus three factors are identified for warranty risk:

- Uncertainty in quantities of future repair items
- Uncertainty in future unit repair cost escalations
- Timing of repair

Timing of repair is included as a factor for warranty risk because it may affect the discounted total repair costs as well as the future unit price. Identification of factors for warranty risk is an important step in the analysis of pavement warranty risk. To measure the risk of pavement warranty, an assessment of the uncertain nature of its two risk elements is essential. This will be further discussed in later chapters.

Implication of the Concept to Contractors

The concept of warranty risk defines the contractor’s business risk exposure to warranties. Understanding the risk is valuable in the analysis of the contractor’s reaction to pavement warranties since it is an important factor in the contractor’s decision-making process.

One significant contribution of the concept is the partition of warranty cost, or the contractor’s bid on warranty, into two parts: expected present value of future repair cost and risk premium. Expressively

$$C_W = E(C_r^/) + RP \qquad (4\text{-}4)$$

where C_W is the cost of warranty, $E(C_r^/)$ is the expected present value of future repair cost, and RP is the warranty risk premium. If warranty bonding is required and the bonding cost is incurred, formula (4-3) will be expanded to

$$C_W = E(C_r^/) + RP + B \qquad (4\text{-}5)$$

where B is the cost of the warranty bond.

The expected present value of future repair costs can be expressed as

$$E(C_r^/) = \sum_{i=1}^{N}\sum_{j=1}^{W}\frac{c_i E(q_{i,j})E(e_j)}{(1+R)^{C_0+j}} \qquad (4\text{-}6)$$

where $E(q_{i,j})$ is the expected quantity for type i distress repair at the j^{th} warranty year, $E(e_j)$ is the expected unit cost escalation for the j^{th} warranty year repair.

As a risk averse party, the contractor will increase his/her bid price to compensate for his/her increased business risk exposure. The risk premium is a compensation for the warranty risk that the contractor bears on a warranted project. The premium is jointly determined by the level of warranty risk, the contractor’s risk attitude, competition, and other factors.

Summary

In this chapter the concept of warranty risk is defined and the three factors of the risk – uncertainty in quantities of future repair items, uncertainty in future unit price escalations, and timing of repair – are identified. In the next few chapters the two elements will be modeled and the warranty risk will be measured further.

CHAPTER 5
ANALYSIS OF ASPHALT PAVEMENT PERFORMANCE DATA

One major element of warranty risk is the uncertainty in quantities of the future remedial work items. The actual quantities of remedial works will not be known until the repairs are actually performed or the warranties expire. However, the contractors are required to estimate the quantities and accept a fixed amount of cost for potential future remedial works at the time of bidding, during which the pavement is not yet built. An accurate estimate of the quantities for future remedial works is difficult. But historical pavement performance data can be used to assess the uncertainty of future outcomes.

The pavement condition surveys conducted by state Departments of Transportation provide a good source of pavement performance and distress data. In this chapter, the researcher analyzes the performance of asphalt pavements in the state of Florida using the pavement condition survey data. In particular, the objective here is to analyze the variation as well as the mean levels of various types of pavement distresses at different pavement ages. This chapter will start with a description of the typical distresses for asphalt pavement, and then give a brief introduction of the Florida Flexible Pavement Condition Survey program. The sampling process and data analysis results will be discussed in detail.

Types of Asphalt Pavement Distress

Miller and Bellinger (2003) grouped asphalt pavement distresses into five categories:

- Cracking

- Patching and potholes
- Surface deformation
- Surface defects
- Miscellaneous distresses

Cracking

Cracking is the most common type of asphalt pavement distress. It is further divided into several subtypes.

Fatigue or alligator cracking is a series of interconnecting cracks caused by the fatigue failure of asphalt surface or stabilized base due to repeated traffic loading. Cracks develop into many sided, sharp-angled pieces.

Block cracking is caused mainly by the shrinkage of the asphalt and daily temperature cycling. The cracks divide the pavement surface into approximately rectangular pieces.

Reflection cracking occurs in asphalt overlays over jointed concrete slabs. Cracks are caused by the movement of the slab beneath due to temperature and moisture changes.

Longitudinal and transverse cracking. Cracks extend either parallel or transverse to the centerline of the pavement. Longitudinal cracks are generally related to construction defects while transverse cracks are normally related to asphalt hardening.

Patching and Potholes

Patching is the replacement of a portion of the pavement surface after original construction.

Potholes are bowl-shaped depressions in the road surface, usually less than 3 feet in diameter.

Surface Deformation

Two typical forms of surface deformation are rutting and shoving.

Rutting is the longitudinal depression in the wheel path. It can be caused by consolidation of one or more layers of the pavement.

Shoving is a longitudinal displacement of the pavement surface. It is usually located on hills or curves, or at intersections, and generally caused by braking and accelerating vehicles.

Surface Defects

Three typical types of surface defects are raveling, bleeding, and polished aggregate.

Raveling is the surface disintegration caused by the loss of fine or coarse aggregate materials.

Bleeding is usually found in the wheel path and is characterized by excess asphalt on the surface. The pavement may lose surface texture or form a shiny, glass-like, reflective, and tacky surface.

Polished aggregate is the exposition of the aggregate caused by the wearing out of the asphalt surface binder.

Miscellaneous Distresses

Lane-to-shoulder drop-off is the difference in elevation between the travel lane and the outside shoulder. It is caused by the difference in settlement between the outside travel lane and the shoulder.

Water bleeding and pumping is the seeping and ejection of water from beneath the pavement through cracks.

Roughness / Ride Quality

Pavement roughness is an expression of irregularities in the pavement surface that adversely affect the ride quality of a vehicle.

Various statistical indexes have been developed to measure the roughness or ride quality of the road. These indexes include Present Serviceability Rating (PSR), Present Serviceability Index (PSI), International Roughness Index (IRI), Ride Number (RN), etc.

PSR is a subjective rating given by panels of drivers and passengers who ride over sections of highways in passenger cars. PSI, on the other hand, estimates the pavement serviceability from objective physical measurements.

IRI, now in common use, is a measurement of the cumulative vertical movement of the wheel divided by the distance traveled. It is a mathematical processing of the longitudinal profile generated by the profiler, reported in units of m/km.

Ride Number (RN) is also a mathematical processing of the longitudinal pavement profile generated by the profiler. The Ride Number gives a pavement rating with a scale of 0 to 5.

Florida Flexible Pavement Condition Survey

The Florida Department of Transportation (FDOT) conducts an annual pavement condition survey on state maintained roadway systems to evaluate surface distress and determine ride quality of the pavement. The survey program started in 1973. Currently both asphalt pavements and concrete pavements are surveyed. In the 2006 survey year, 18,251.53 miles of asphalt pavements and 364.39 miles of concrete pavements are surveyed, representing 44.7% of total asphalt pavement miles and 36.7% of total concrete pavement miles (FDOT 2006).

Pavements under survey are divided into sections. Surface distress and ride quality items for each section evaluated under the Flexible Pavement Condition Survey Program include (FDOT 2003):

- Ride quality
- Cracking
- Rut depth
- Patching
- Raveling

Ride Quality

Both Ride Number (RN) and International Roughness Index (IRI) are calculated from the profiler data and reported as the average of the left and right wheel paths.

Before 1999, the Ride Rating is calculated using IRI as

$$Ride\ Rating = 99.7576 - 0.1569 \times IRI$$

Currently, the Ride Rating is calculated on a 0 to 100 scale as

$$Ride\ Rating = RN \times 20$$

Rutting

Rut depths are measured by the profiler at highway speed. Manual rut depths are required only if the section cannot be surveyed by the profiler. Average rut depth is reported for each section.

One point is deducted for each 1/8 inch of average rut depth. The Rut Rating, which is on a scale from 0 to 10, is obtained by subtracting from 10 the deduct points associated with the rut depth.

Cracking

Cracks are grouped into three classes:

- Class IB. Hairline cracks that are no more than 1/8 inch wide in either the longitudinal or transverse direction.

- Class II. Cracks 1/8 inch to 1/4 inch wide in either the longitudinal or transverse direction. Also include alligator cracks that are less than 1/4 inch wide.

- Class III. Cracks greater than 1/4 inch wide and cracks that are opened to the base or underlying materials. Also includes progressive class II cracks that result in severe spalling with chunks of pavement breaking out. Raveling and patching are also considered as Class III cracking.

Cracks confined to wheel path (CW) and outside of wheel path (CO) are estimated separately. Square feet of the three classes of cracks are added and recorded as the predominate type presented. Table 5-1 lists the codes for percentage. Cracking rating deduct values are also included in Table 5-1. Crack Rating is obtained by subtracting from 10 the deduct values for both CW and CO.

Table 5-1. Cracking codes and rating deduction

Percent of pavement area affected by cracking	Predominate cracking class								
	Class IB			Class II			Class III		
	Code	CW deduct	CO deduct	Code	CW deduct	CO deduct	Code	CW deduct	CO deduct
00 – 05	A	0.0	0.0	E	0.5	0.0	I	1.0	0.0
06 – 25	B	1.0	0.5	F	2.0	1.0	J	2.5	1.0
26 - 50	C	2.0	1.0	G	3.0	1.5	K	4.5	2.0
51 +	D	3.5	1.5	H	5.0	2.0	L	7.0	3.0

Source: FDOT (2003)

Patching

Patching is classified based on size of area as

- Light patching: less than 50 square feet per 100 feet of lane
- Moderate patching: 50 – 100 square feet per 100 feet of lane
- Severe patching: more than 100 square feet per 100 feet of lane

Patching is totaled with class III cracking.

Raveling

Patching is classified based on severity as

- Light raveling: The aggregate and/or binder has begun to wear away but has not progressed significantly.

- Moderate raveling: the aggregate and/or binder has worn away and the surface texture becomes rough and pitted.
- Severe raveling: the aggregate and/or binder has worn away and the surface texture is very rough and pitted.

Raveling is totaled with class III cracking.

Pavement Performance Data Collection

The Pavement Condition Survey Database

The asphalt pavement condition survey data are stored in Florida DOT's data library in the form of permanent flat file and area combined file. The permanent flat files are named as D5580954.FLEXxx.DATA, where xx is the year of survey. The area combined files are named as D5580954.FLEXxx.AREACOMB. The information stored in the two types of files is the same, although the data are coded differently.

The coding of the data is not consistent over time due to the changes in survey methods, surveyed items, and recorded items. Each file, either flat file or area combined file, consists of fixed-length records for survey results of each section in a given year. Data recorded for each survey section includes:

- Survey date.
- Roadway data, including roadway ID, roadway category, pavement type, number of lanes, speed.
- Location of the survey section, including direction, start and end mile mileposts.
- Performance and distress coding, including severity of raveling, cracking codes, patching severity, rutting depth, IRI, RN, etc.
- Performance rating scores, including crack rating, ride rating, and rut rating.
- Remarks and other information.

Data Collection Procedure

The source chosen for collecting asphalt pavement performance data is the permanent flat files that FDOT keeps for flexible pavement survey data. Performance data for interstates asphalt pavements are intented to be collected for analysis.

The following procedures are followed to collect the data:

1. Retrieve the permanent flat files from FDOT's data library. This was done by staff personnel of FDOT upon request. The files for survey data of 1991 to 2006 were obtained. Each file contains the survey data of all survey sections for a given year.
2. Convert the text format flat files into Microsoft Excel worksheets. Each worksheet contains the survey data of all survey sections for a given year.
3. Filter the survey data in the worksheet by the column of "System." A subset of the data is selected for interstates (System = 4).
4. In the data subset, identify survey sections that are recorded as "new pavement" (Type = 7) in each year from 1992 to 1999. This is a complete list of interstate survey sections that were paved between 1991 and 1998. A section ID was assigned to each of the identified sections, called tentative candidates.
5. New worksheets were created for the tentative candidates based on type of data. Each new worksheet lists only one type of performance data (such as crack rating) for each tentative candidate from 1992 to 2006, as seen in Table 5-2. Those tentative candidates that merged with a larger section or changed size significantly are eliminated from the list.

Table 5-2. Example of data format for ride rating, by calendar year

Year ID	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06
A01	76	83	83	78	79	84	78	81	82	80	82		81	80	81
A02	82	85	85	79	81	87	77	82	83	82	81		82	82	81
A03	82	85	80	82	88	87	84	89	89	89	88	87	79	78	76
A04	81	82	80	80	85	82	81	89	88	88	88	87	79	76	76
A05	80	86	80	79	90	87	84	88	87	82	88	87	81	74	77
A06	79	82	77	80	88	84	81	90	88	90	89	88	82	81	81
B01		80	79	77	82	83	80	84	87	85	82	80	67		85
B02		80	76	77	83	78	79	86	85	85	83	83	71		78
B03		88	79	78	82	83	80	84	87	85	85	85	79		80
C01			79	80	83	78	83	87	86	87	86	84	74	76	72
C02			84	85	83	79	83	90	90	90	88	85	77	78	74
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…

6. Identify the service life of the pavement for each tentative candidate. The pavement service life of a tentative candidate ended when it was later recorded as either “new pavement” or “under construction.”
7. Finalize the list of candidate sections. Those tentative candidates with a pavement life of four years or more are selected as final candidates for further analysis. The criterion of four years minimum life for candidates is set because the current warranty term in Florida is three years. A total of 232 survey sections are included in the final candidate list.

The Discarded Tentative Candidates

The primary objective in this research is to investigate the variation of pavement performance or distresses after construction. Thus it is critical to avoid biases caused in the process of sampling. A total of 30 tentative candidate sections are eliminated from the final list because their actual service lives are less than three years. It is important to examine why these sections had a short recorded pavement life. In other words, for the sake of proper scientific research, it is important that no data were intentionally eliminated from the sample due to performance.

A preliminary investigation of the eliminated tentative candidates is summarized in Table 5-3. Of the 30 survey sections with a recorded pavement life less than four years, 28 sections had no recorded pavement distress in their service lives. Light patching and light raveling were reported for two sections in the second year, but the recorded distresses are not severe enough to cause the failure of pavement in two years. Based on the above investigation, it is reasonable to assume that no early failure sections are intentionally eliminated from the sample and the sampling process will not cause observable bias in the final results.

The Sample

A total of 232 survey sections, with a total length of 1249.3 miles, are included in the sample, accounting for 46.5% of the total number of sections and 46.4% of the total length of all the survey sections for interstate asphalt pavements in 2006. A complete list of the sections in the sample is shown in Appendix A. The sample covers roadway sections from all seven districts of the FDOT, and from 38 of the 41 counties that have interstate asphalt survey sections in 2006. The pavements for these sample sections are constructed from 1991 to 1998, as seen in Table 5-4. Lengths of the sections range from 0.075 to 25.462 miles, with an average of 5.385 miles. Figure 5-1 illustrates the distribution of section lengths within the sample.

Table 5-3. Investigation of short-life sections

No. of sections	Reason for ending pavement life	Performance
10	Merged with other section under construction	Good
10	New construction, adding lane	Good
4	Recorded as new pavement in two consecutive years	Good
2	No survey data after two years	Good
4	Under construction after two years, reason for construction not identified	Two sections have recorded light raveling and light patching

Table 5-4. Construction completion year of the sample sections

Year of completion	1991	1992	1993	1994	1995	1996	1997	1998	Total
No. of sections	28	15	23	25	40	40	33	28	232

The observed pavement lives, or the time between two consequent construction efforts, for the sampled sections range from 4 to 15+ years. As seen in Table 5-5, a total of 60 sections, or 25.6% of the total sections in the sample, experienced another construction effort within seven years.

Table 5-5. Observed pavement lives for the sampled sections

Pavement life	4	5	6	7	8+	Total
No. of sections	1	16	10	23	182	232

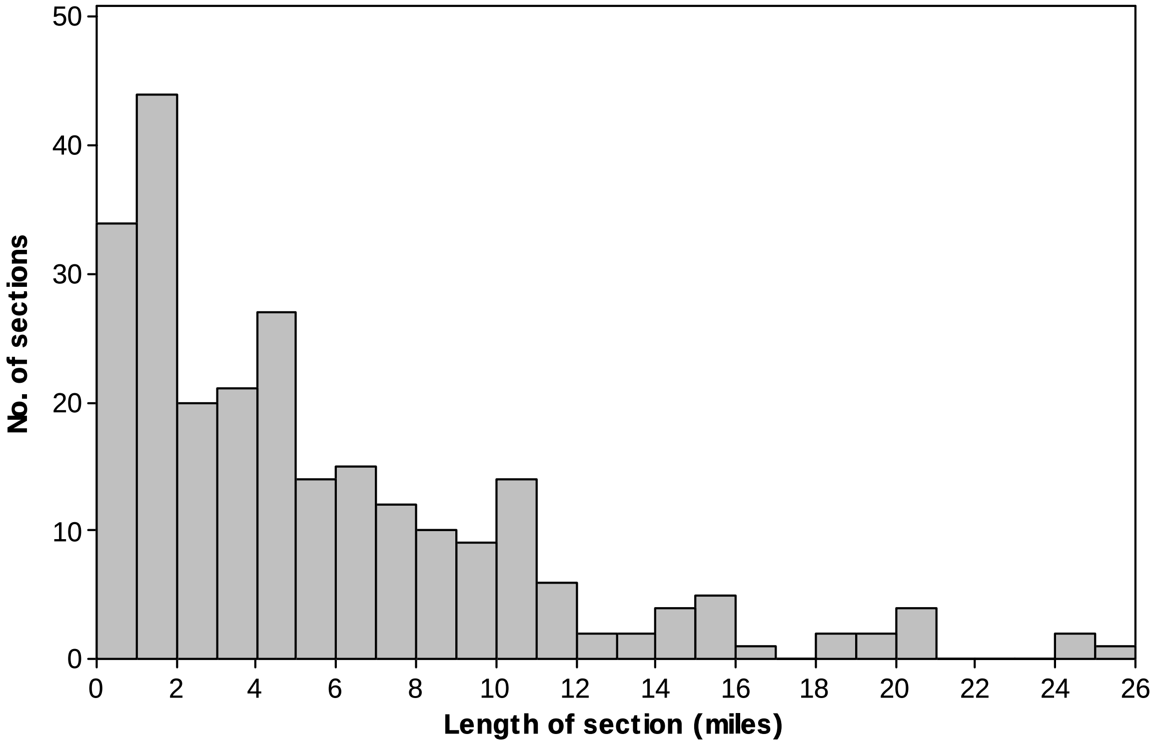

Figure 5-1. Distribution of lengths of sample sections

Performance Data Analysis

This section will summarize the statistical aspects of the asphalt pavement performance and distress data for interstates in the state of Florida. The types of distresses analyzed include rutting, ride quality, raveling, patching, cracking, bleeding, and delamination. In particular, variation as well as the mean level of each distress type at different pavement age is of interest.

Data Reorganization

The data prepared in the process of data collection were organized by section ID and calendar year, as seen in Table 5-2. Before analysis, the performance/distress data are reorganized by section ID and pavement age, as seen in Table 5-6.

Table 5-6. Example data format for ride rating, by pavement age

Age ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A01	76	83	83	78	79	84	78	81	82	80	82				
A02	82	85	85	79	81	87	77	82	83	82	81				
A03	82	85	80	82	88	87	84	89	89	89	88	87	79	78	76
A04	81	82	80	80	85	82	81	89	88	88	88	87	79	76	76
A05	80	86	80	79	90	87	84	88	87	82	88	87	81	74	77
A06	79	82	77	80	88	84	81	90	88	90	89	88	82	81	81
B01	80	79	77	82	83	80	84	87	85	82	80	67			
B02	80	76	77	83	78	79	86	85	85	83	83	71			
B03	88	79	78	82	83	80	84	87	85	85	85	79			
C01	79	80	83	78	83	87	86	87	86	84	74	76	72		
C02	84	85	83	79	83	90	90	90	88	85	77	78	74		
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…

Rutting

Rut depths have been included in the survey since 1993. So for the sections paved in 1991, with section ID’s from A01 to A30, there is no first year rut depth data. Rut depths are measured using a road profiler at the highway speeds. An average rut depth is calculated for each survey section. The average rut depth is further converted to a rut rating score.

As described in Table 5-7 and illustrated in Figure 5-2, the mean level of the sample rut depths increase gradually from 0.06 inch in the first year to 0.174 inch in the tenth year. The standard deviation and the interquartile range (IQR, the difference between the first and third quartile) of rut depths are relatively stable over time. However, the range becomes wider as pavement age increases until age 7; after then the range narrows down because some sections with large rut depths were out of service.

The rut depth data are positively skewed at all ages, with a longer higher tail. This is evidenced by all the positive skewness values in Table 5-7 and the large number of outliers at the higher end. Figure 5-3 illustrates the distribution of rut depths at various ages.

The blue dashed line in Figure 5-2 and the red dotted lines in Figure 5-3 represent the rut depth threshold value of 0.25 inch for Florida interstate pavements under current 3-year asphalt pavement warranties. If the rut depth data are evaluated using the threshold value, two sections in the first year, nine sections in the second year, and eleven sections in the third year will be identified as having a rutting problem.

Table 5-7. Basic statistics of rut depth, by pavement age

Age	N	Mean	StDev	Min	Q1	Q2	Q3	Max	IQR	Skew	Kurtosis
1	204	0.061	0.060	0.00	0.01	0.05	0.10	0.30	0.09	1.16	1.48
2	232	0.090	0.069	0.00	0.04	0.08	0.12	0.33	0.08	1.09	1.31
3	232	0.101	0.080	0.00	0.05	0.09	0.14	0.42	0.09	1.43	2.94
4	230	0.117	0.082	0.00	0.07	0.10	0.15	0.50	0.08	1.52	3.72
5	231	0.132	0.091	0.00	0.07	0.12	0.17	0.47	0.10	1.19	2.09
6	215	0.138	0.091	0.00	0.08	0.12	0.17	0.48	0.09	1.39	2.81
7	205	0.152	0.083	0.00	0.10	0.14	0.19	0.57	0.09	1.47	4.62
8	182	0.161	0.075	0.00	0.12	0.15	0.20	0.49	0.08	1.03	2.12
9	149	0.165	0.071	0.00	0.11	0.16	0.20	0.35	0.09	0.43	-0.09
10	118	0.174	0.072	0.02	0.12	0.16	0.22	0.36	0.10	0.54	-0.09

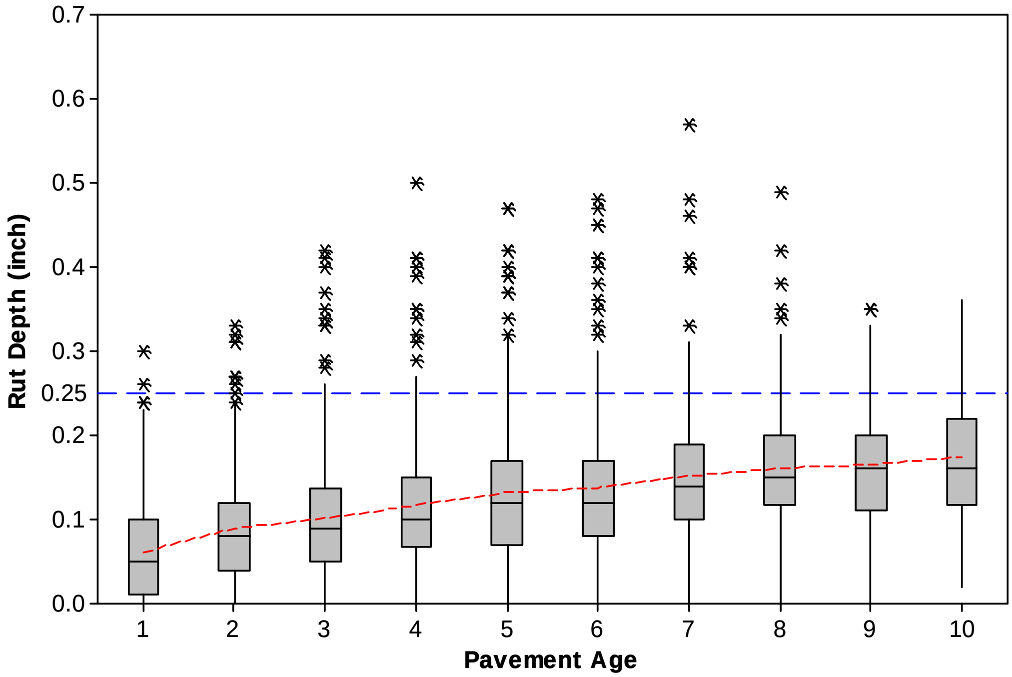

Figure 5-2. Boxplots of rut depths, by pavement age. The red dotted line is the mean connection line.

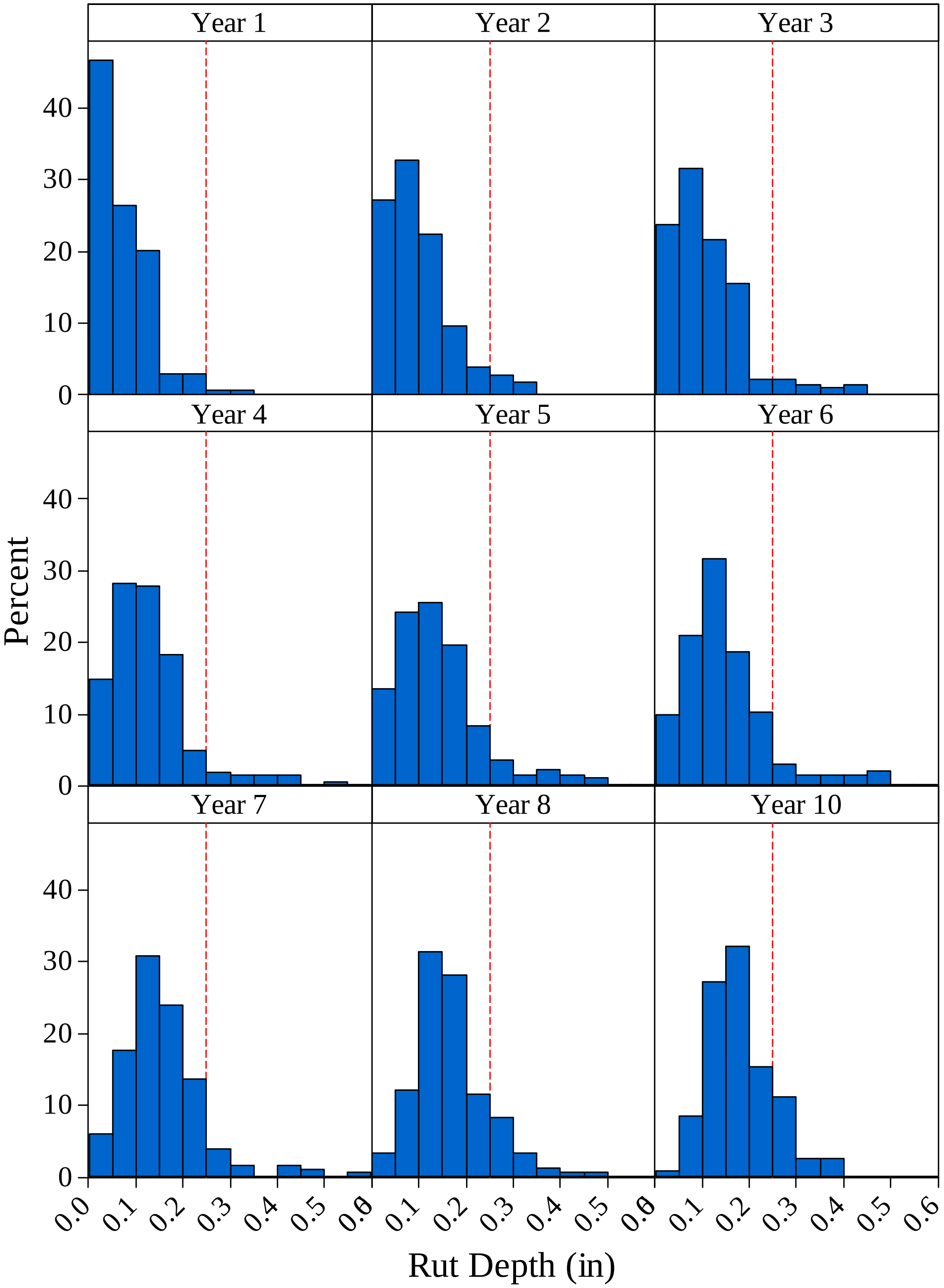

Figure 5-3. Histograms of rut depth, by pavement age

Ride Quality

Both ride number (RN) and International Roughness Index (IRI) are reported in the pavement condition survey. Before 1999, Ride Rating was calculated using IRI. Ride Numbers were not available until 1999 when the Ride Rating began to be calculated as RN multiplied by 20.

The boxplots of ride rating and RN are illustrated in Figures 5-4 and 5-5. These two figures are very similar due to the linear relationship between RN and Ride Rating. For the same reason, only RN will be discussed in this subsection.

As described in Table 5-8 and illustrated in Figure 5-5, the mean of RN decreases gradually as pavement age increases. The spreads of the data, including range, standard deviation, and IQR, however, become wider as pavement age increases. The RN data are negatively skewed at all pavement ages, with the longer tail at the lower side, as seen in Table 5-8 and Figure 5-5. Figure 5-6 illustrates the distribution of RN at various ages.

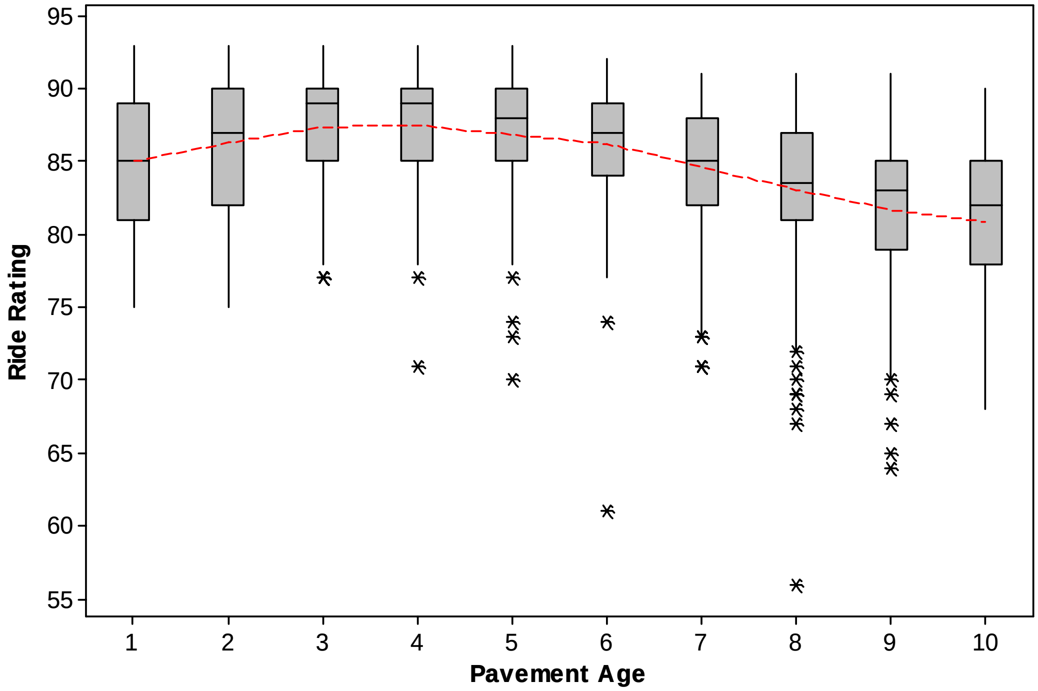

Figure 5-4. Boxplots of ride rating, by pavement age

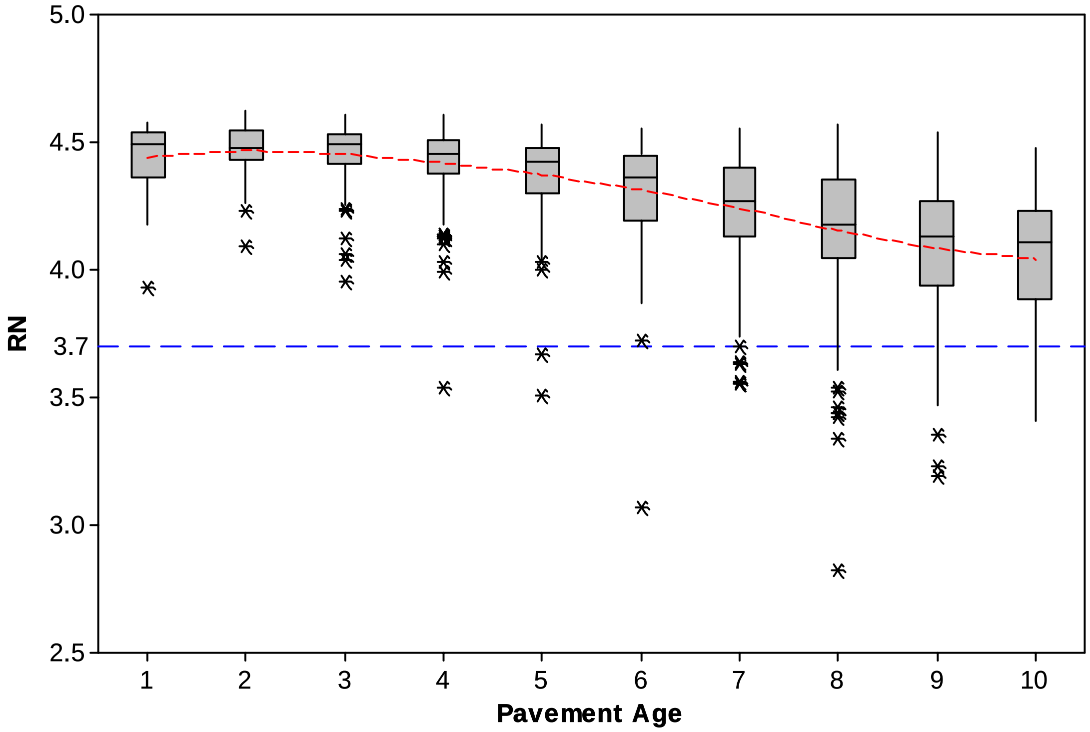

Figure 5-5. Boxplots of ride number (RN), by pavement age. The red dotted line is the mean connection line.

Table 5-8. Basic statistics of ride number (RN), by pavement age

Age	N	Mean	StDev	Min	Q1	Q2	Q3	Max	IQR	Skew	Kurtosis
1	28	4.44	0.14	3.93	4.36	4.50	4.54	4.58	0.18	-1.96	4.73
2	61	4.47	0.10	4.09	4.43	4.48	4.55	4.62	0.12	-1.24	2.16
3	101	4.45	0.12	3.95	4.42	4.49	4.53	4.61	0.12	-1.77	3.88
4	141	4.42	0.15	3.54	4.38	4.45	4.51	4.61	0.14	-2.30	8.97
5	165	4.37	0.15	3.51	4.30	4.42	4.48	4.57	0.18	-2.17	7.91
6	172	4.31	0.19	3.07	4.19	4.36	4.45	4.55	0.26	-2.15	10.46
7	177	4.24	0.20	3.55	4.13	4.27	4.40	4.55	0.27	-1.18	2.00
8	182	4.15	0.27	2.82	4.05	4.18	4.35	4.57	0.30	-1.42	3.24
9	149	4.08	0.27	3.19	3.94	4.13	4.27	4.54	0.33	-0.79	0.53
10	118	4.04	0.26	3.41	3.89	4.11	4.23	4.48	0.34	-0.55	-0.35

The blue dashed line in Figure 5-5 and the red dotted lines in Figure 5-6 represent the RN threshold value of 3.7 for Florida interstate pavements under current 3-year asphalt pavement warranties. If the RN data are evaluated using the threshold value, it is obvious that no observed RN is lower than the threshold value in the first three years.

Thus the risk of ride failure to the contractors is very low under current warranty specifications.

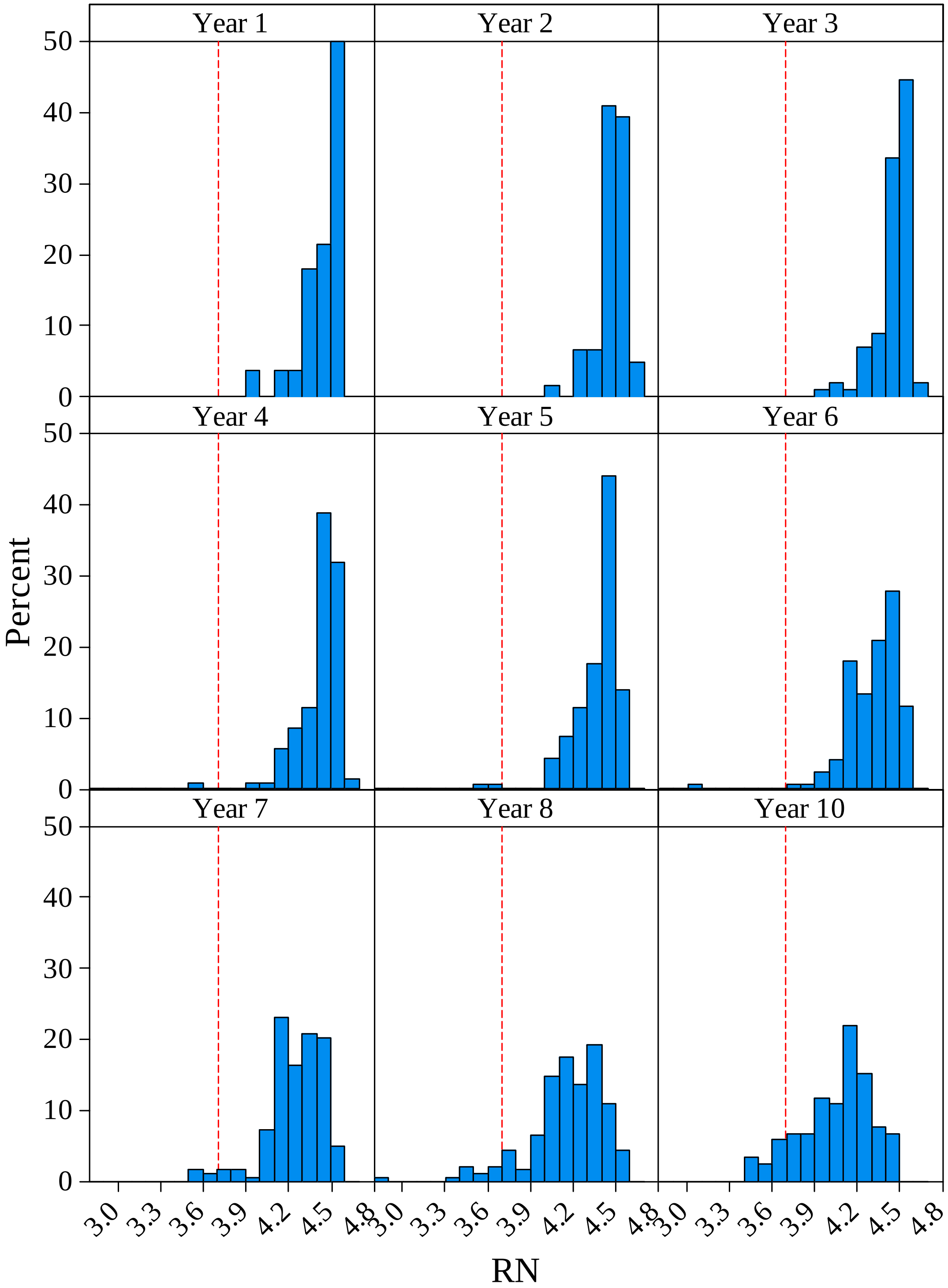

Figure 5-6. Histograms of ride number (RN), by pavement age

Raveling

Raveling is evaluated at three severity levels: light, moderate, and severe. Only the predominate level is coded in the survey. The percent of pavement area affected by raveling is recorded at four levels: 1-5%, 6-25%, 26-50%, and more than 50%. The raveling area of all severity levels for the rated section is accumulated in the total percentage of class III cracking.

The percentage in number of road sections with reported raveling is illustrated in Figure 5-7. It can be seen that a raveling problem is not common at early pavement age. Only 1.3% of survey sections have reported raveling distress at the pavement age of three. However, 40.9% of sections have reported raveling at age nine. Of all the road sections with raveling distress, in most cases the affected areas are within 5% of total pavement area.

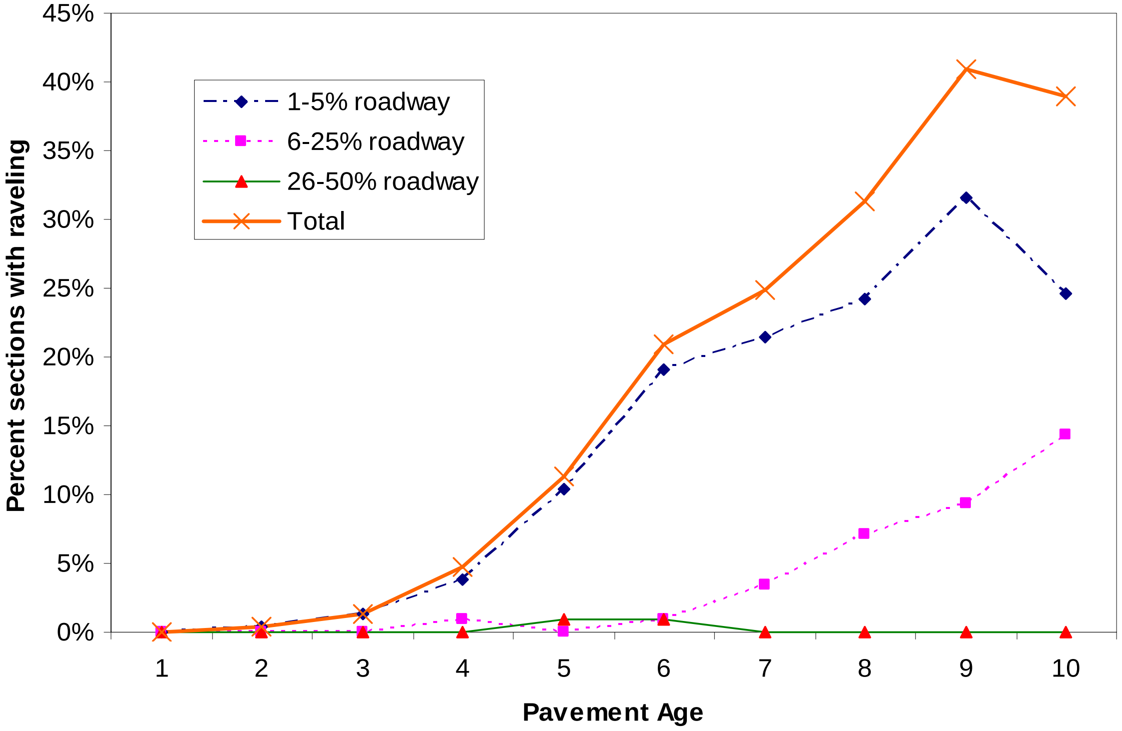

Figure 5-7. Percent sections with reported raveling, by pavement age

Patching

Patching is recorded at three severity levels: light, moderate, and severe. However, no moderate or severe patching is identified on any survey sections. The only recorded level is light patching, with less than 50 square feet patching per 100 feet of lane. The percentage in number of sections with reported patching is illustrated in Figure 5-8. About 2.6% of sections have reported patching at the pavement age of three.

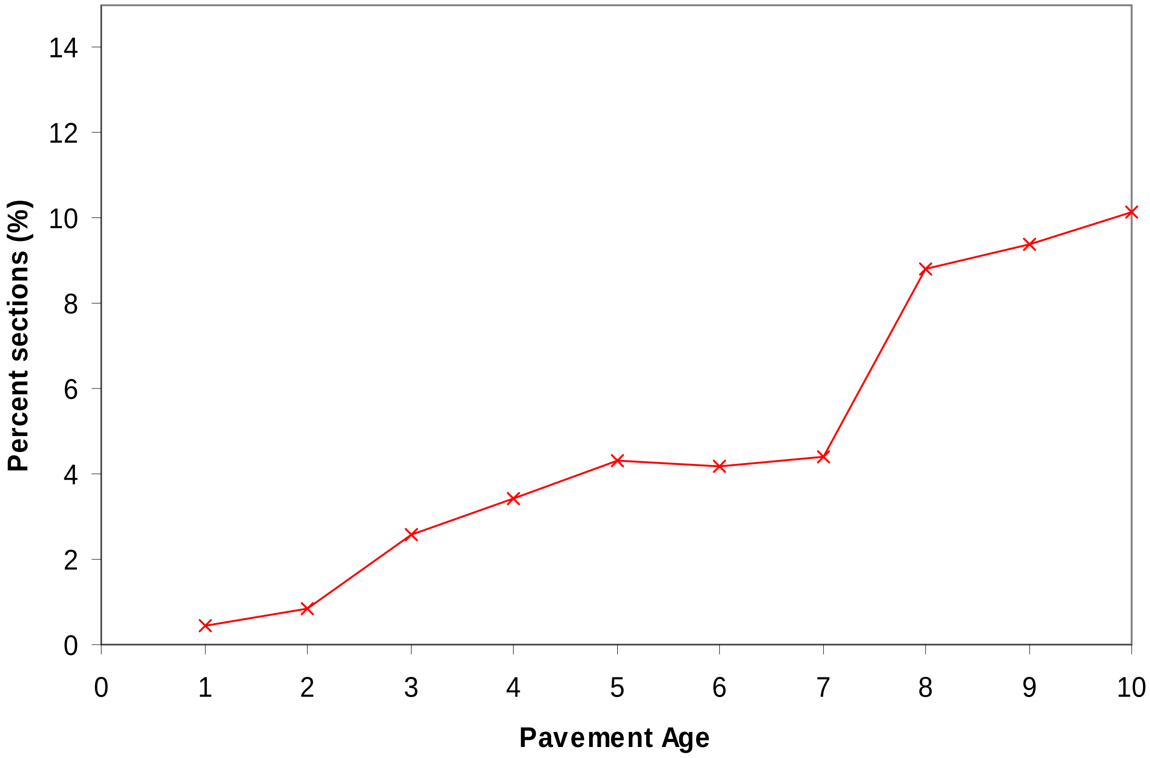

Figure 5-8. Percent sections with reported patching, by pavement age

Cracking

Cracking is a common type of distress for asphalt pavements. Cracking confined to wheel paths (CW) and cracking outside of wheel paths (CO) are estimated and coded separately. Cracks are recorded in three classes: class IB, class II, and class III. Raveling and patching are included in class III cracking.

Crack rating is a single parameter used to measure the overall cracking condition of a survey section. Crack rating is obtained by subtracting from 10.0 the deduct values for both CW and CO cracking. Distributions of crack rating at various pavement ages are described in Table 5-9 and illustrated in Figures 5-9 and 5-10.

Table 5-9. Basic statistics of crack rating, by pavement age

Age	N	Mean	StDev	Min	Q1	Q2	Q3	Max	IQR	Skew	Kurtosis
1	232	9.99	0.09	9.0	10.0	10.0	10.0	10.0	0.0	-10.7	113.47
2	232	9.97	0.20	8.0	10.0	10.0	10.0	10.0	0.0	-7.39	58.58
3	232	9.86	0.56	6.5	10.0	10.0	10.0	10.0	0.0	-4.83	24.11
4	232	9.74	0.71	4.5	10.0	10.0	10.0	10.0	0.0	-4.15	20.39
5	231	9.47	0.97	4.5	9.0	10.0	10.0	10.0	1.0	-3.06	11.4
6	215	8.95	1.35	3.5	8.5	9.5	10.0	10.0	1.5	-1.95	4.5
7	205	8.53	1.57	3.5	8.0	9.0	10.0	10.0	2.0	-1.33	1.5
8	182	8.04	1.84	1.0	7.0	8.5	9.5	10.0	2.5	-1.43	2.55
9	149	7.48	1.84	1.0	6.5	7.5	9.0	10.0	2.5	-0.74	1.04
10	118	7.11	1.91	1.0	6.5	7.0	8.3	10.0	1.8	-0.72	0.9

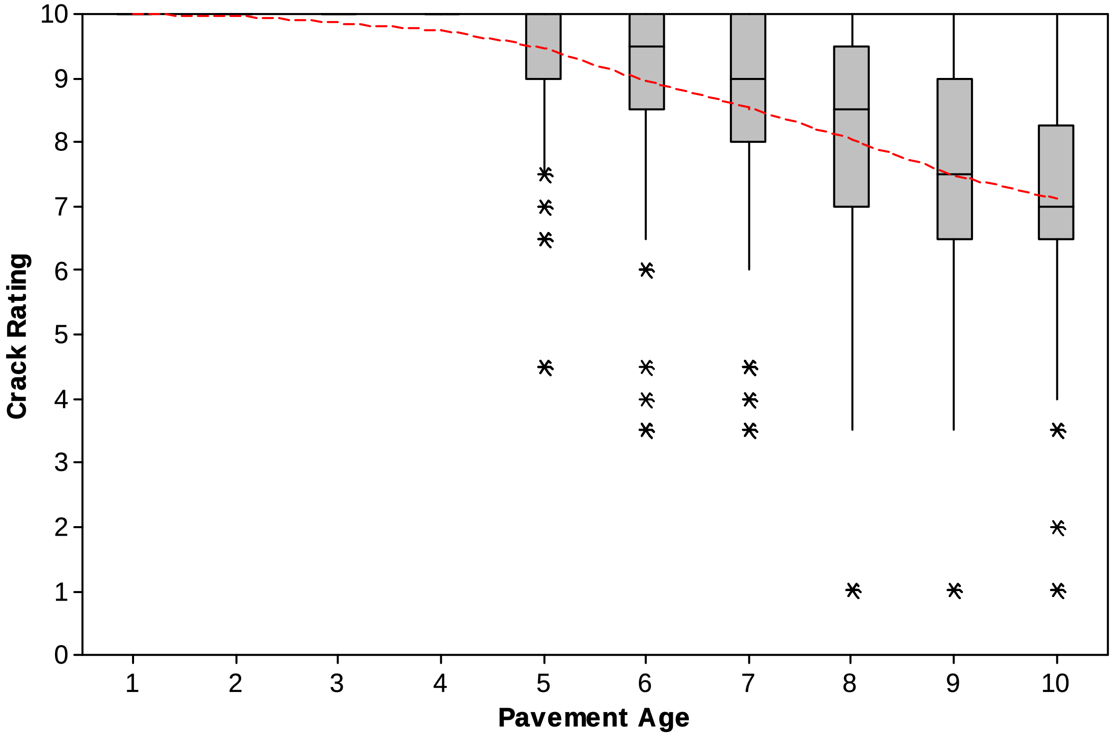

Figure 5-9. Boxplots of crack rating, by pavement age. The red dotted line is the mean connection line.

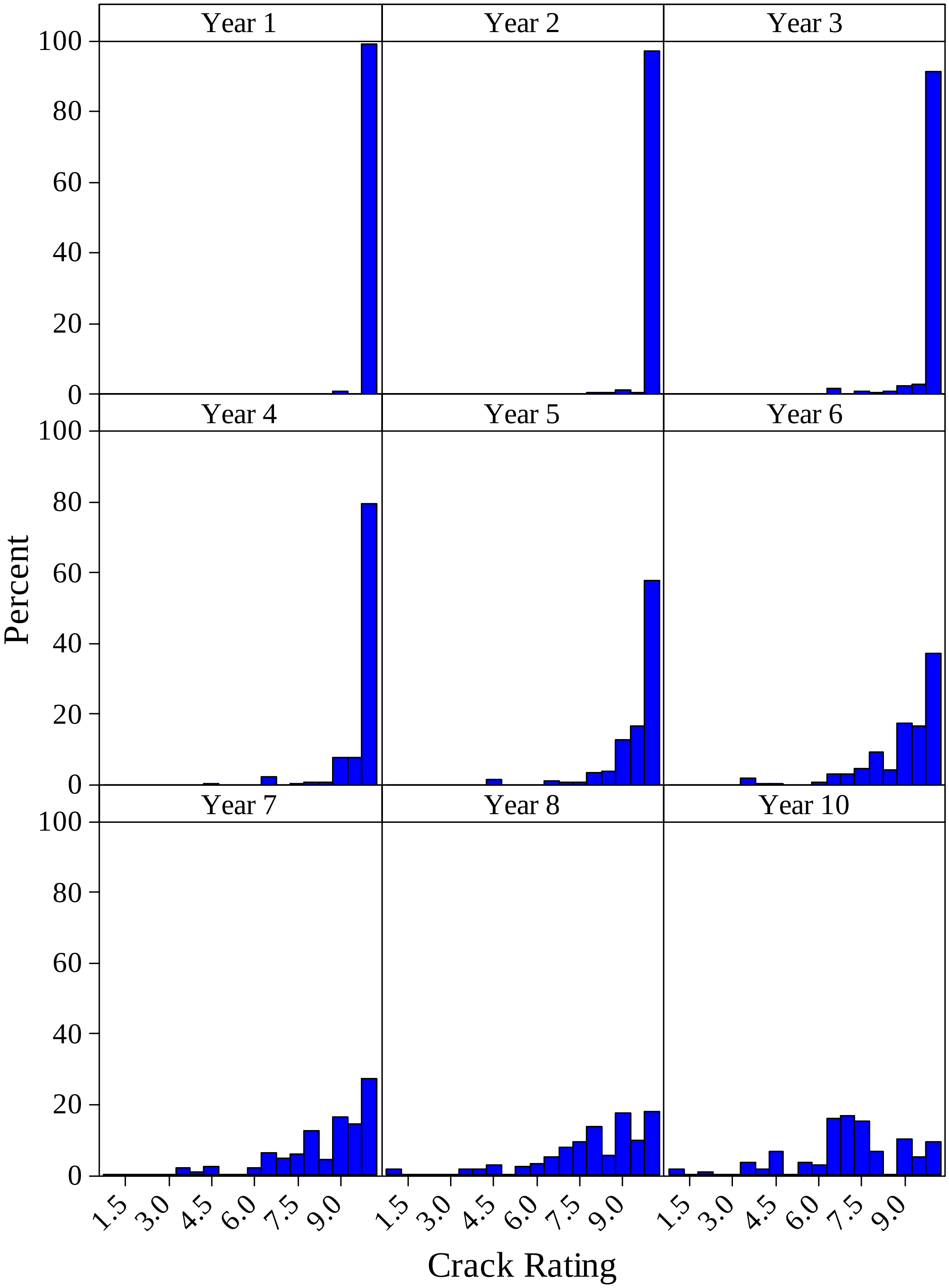

Figure 5-10. Histograms of crack rating, by pavement age

Cracking grows at an increasing speed. This is evidenced by the downward curvature of the mean connection line of Crack Rating in Figure 5-9. The spreads of crack ratings are also an increasing function of pavement age, as seen in Figure 5-10, with wider distribution for older pavements. The crack rating for first year pavement ranges from 9 to 10, with 99.1% sections having a rating of 10. The range widens from 1 to 10 at the pavement age of 8. The distribution of Crack Rating is negatively skewed at all pavement ages, with a longer tail at the lower side.

Bleeding and Delamination

Bleeding and delamination are not official survey items in the pavement condition survey. Instead, they are noted in Remarks. The percentage in number of survey sections with raveling and delamination distresses is illustrated in Figure 5-11.

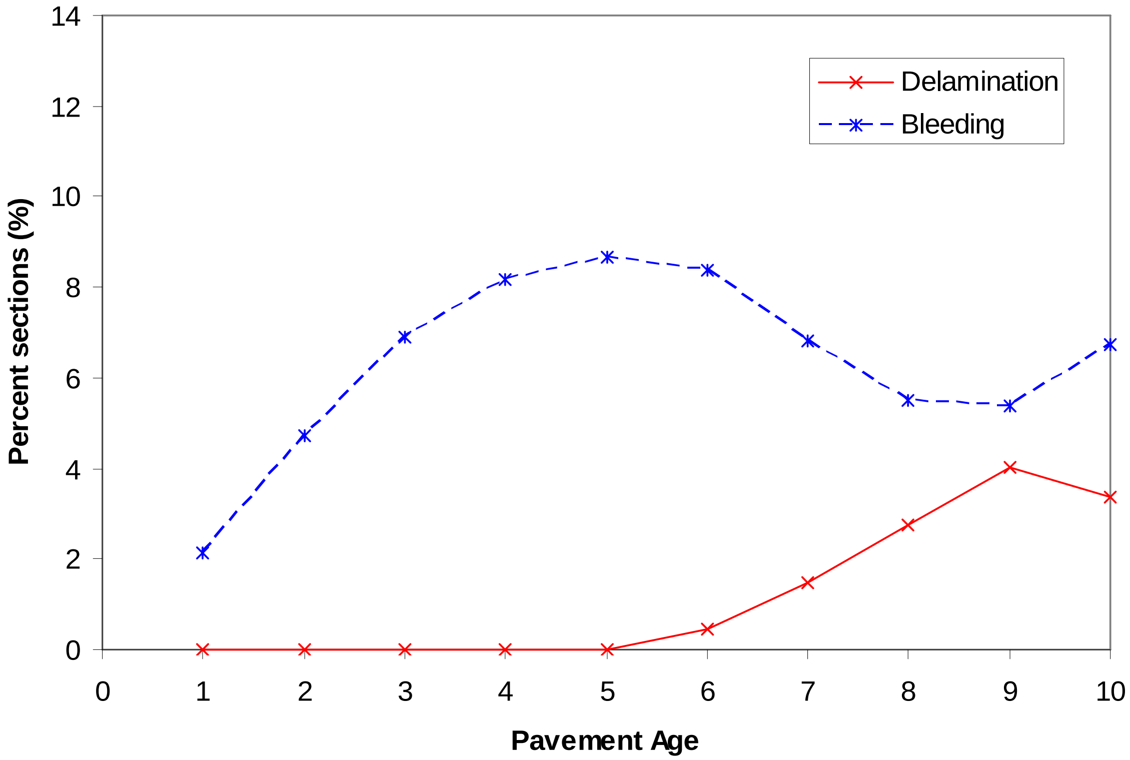

Figure 5-11. Percent sections with reported bleeding/delamination, by pavement age

The results indicate that delamination rarely occurs at early pavement ages. No survey section was identified to have delamination problem by the pavement age of five. Bleeding, however, is likely to occur at early pavement ages. About 2.2% of survey sections in first year and 6.9% of sections in the third year had a bleeding problem.

Limitations of the Survey Data

The pavement condition survey data described above provide valuable information on asphalt pavement performance and distress. However, there are some limitations on the data.

First, the results above are conditional on survival. Only those “surviving” sections are included in the analysis for a given pavement age. If a section is reconstructed due to poor performance, it is excluded from later year analysis. As a result, the overall performance of all sections appears better because early failed pavements are not counted. Thus the results discussed above are conditional rather than absolute.

Second, cracking data did not provide accurate estimates of the percent pavement area affected by cracking. Instead of an estimated definite number, the percent pavement affected by cracking is coded by ranges of 0-5%, 6-25%, 26-50%, or more than 50%. Furthermore, raveling and patching are included in cracking data.

Third, some types of distress are not included in the survey. Bleeding and delamination are evaluated under the warranty specifications. But they are not evaluated in the pavement condition surveys.

Summary

Typical pavement distresses for interstate projects in Florida are analyzed in this chapter using FDOT Pavement Condition Survey data. The variation of performance among survey sections and the developing trends of performance over time are discussed.

The types of distresses analyzed in this chapter include rutting, Ride Number (RN), cracking, raveling, patching, bleeding, and delamination.

There are some limitations on the available data. First of all, the data are on a survival basis and the results are conditional rather than absolute. Another significant limitation is that the cracking data do not provide accurate estimates of the percent pavement area affected by cracking.

In the next chapter, the distresses will be modeled and the conditional data will be transformed into “absolute” results of pavement performance.

CHAPTER 6
MODELING PAVEMENT DISRESSES

The last chapter discussed the statistical aspects of various types of asphalt pavement distresses. One major limitation of the data is that the results are conditional on survival. That is to say, for each pavement age, only those pavements in service are included in analysis. This survival effect causes the performance data to appear better because the poor-performing sections were removed from the sample when they were reconstructed.

One objective of this research is to estimate the distribution of the absolute, not conditional, performance of asphalt pavements at various ages. Fortunately, the reliability theory provides a powerful tool to handle the conditional data. In this chapter we will try to model pavement performance and distresses using reliability theory. The pavement is considered as a repairable system which will be repaired when defects are identified. The modeling process is divided into two steps: a) to model the time that a certain type of distress occurs; and b) to model the distribution and growth of a distress type after its initiation.

Two Categories of Pavement Distresses

Definition of the Two Distress Categories

Table 6-1 lists the performance parameters, or the types of distresses, and the associated threshold values for evaluating the performance of warranted asphalt pavements on interstates in Florida. Based on their characteristics, the distress types can be classified into two broad categories, namely Category I distresses and Category II distresses.

Table 6-1. Performance requirements for warranted interstate asphalt pavement

Type of distress	Threshold value (0.1 lane mile)	Remedial work
Rutting	Rut Depth>0.25 in	Remove and replace the distressed LOT(s) to the full depth of all layers, and to the full lane width
Ride	RN<3.7	Remove and replace the friction course for the full length and the full lane width of the distressed LOT(s)
Cracking	Cumulative length of cracking >30 ft for cracking > 1/8 in	Remove and replace the distressed LOT(s) to the full depth of all layers, and to the full lane width
Raveling and delamination	Individual length >= 10 ft	Remove and replace the distressed area(s) to the distressed depth and the full lane width, for the full distressed length plus 50' on each end
	Individual length < 10 ft	Patch the distressed area(s) to the full distressed depth and a minimum surface area of 150% of each distressed area
Pot holes and slippage areas	Observation by Engineer	Patch the distressed area(s) to the full distressed depth and a minimum surface area of 150% of each distressed area
Bleeding	Individual length >=10 ft and >=1 ft in width	Patch the distressed area(s) to the full distressed depth and a minimum surface area of 150% of each distressed area

Source: FDOT (2005)

Category I distresses include rutting and ride quality. A parameter value of a Category I distress is a measure of the average condition (other than the size of the defected area) of the distress type. For example, rut depth is reported as the average of all measured rut depths for a survey section. It is an indicator of the average rutting performance of the section. But no information is provided on what proportion of the pavement has rutting problems. A Category I defect is observed only when its parameter value exceeds the threshold value. Otherwise, it is considered defect-free.

Category II distresses include all the distress types in Table 6-6 other than rutting and ride. In addition to the severity of the distress, the measure of a Category II distress type also includes the size of the distress, in terms of linear foot, square foot, or percent of pavement affected. A Category II defect is observable even if its size is very small. The measure of distress size is directly related to the quantity of remedial work, if required. A threshold value for the distress type, if it exists, defines the minimum quantity condition that triggers a remedial action. It is not necessarily an indicator of defect initiation.

In Florida, the threshold values for Category I distresses (rutting and riding) are defined in warranty specifications so that the probability of pavement failure due to rutting or riding is very low, as illustrated in Figures 5-2 and 5-5. But once the threshold value is exceeded, a large portion of, or probably the entire pavement may need to be repaired under warranty provision. So the contractor will suffer a large loss if a Category I distress is identified.

The situation is different for Category II distresses. A Category II distress is observable even if its size is very small. Accordingly, under warranty contract, the contractor may be required to fix the distresses when only a small portion of the pavement is affected.

Modeling Methods for the Two Distress Categories

A pavement can be considered as a repairable system which involves various types of defects (distresses). When a certain type of distress occurs, the pavement will be repaired and continue in service until the end of its life. Modeling of the repairable system includes two steps. The first is to model the time that each type of distress occurs. The second is to model the severity or the size of the distressed area after initiation.

A measure of a Category I distress does not include any information on the size of distress affected areas. From data of Category I distress, we can tell if a pavement is defined as defective based on certain given criteria. But we don’t know what portion of the pavement is defective. The sizes of Category I distresses can only be estimated from other data sources.

Measures of Category II distress include the size of the distress affected areas, which is directly related to the quantity of repair works. After a Category II distress is identified, the values of its measure become a description of the growth process of the distress.

For a Category I distress, we can only model its distress initiation time, or the time that the observed value exceeds the threshold value. For a Category II distress, both modeling steps are achieved if the distress data are available. However, given the limitation of the survey data, the distress growth process will be modeled only for cracking. Additional data are needed to model the growth processes of other distress types.

Basics of Lifetime Distribution Models

Life distribution models are used to describe the initiation times for each type of distress. Basics of life distribution models are introduced in this section.

Lifetime Distribution Models

The probability models used to describe the distributions of product lifetime, or failure time, are known as lifetime distribution models. A life distribution model is defined over the range of time $t = [0, \infty)$. The cumulative distribution function (CDF) $F(t)$ gives the probability that a product or unit will fail by time t (NIST 2006).

The probability that a product will survive beyond time t is given by the Reliability Function $R(t)$, also known as Survival Function $S(t)$. We have

$$R(t) = S(t) = 1 - F(t) \tag{6-1}$$

The failure rate, denoted as $h(t)$, is defined as the instantaneous rate of product failure for the survivors at time t. It is sometimes called the conditional failure rate since only survivors to time t are considered. The failure rate can be calculated as

$$h(t) = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{R(t)} \tag{6-2}$$

A lifetime distribution model can be any probability distribution function defined over time range $[0, \infty)$. Some widely used distribution models include Exponential, Weibull, Smallest Extreme Value, Lognormal, and Gamma, etc.

Life Data

The data used for lifetime distribution analysis are life data or time-to-failure data of the products or units in the sample. The data are said to be complete if the exact failure time for each sample unit is known. However, in many cases, life data are incomplete, or called censored. There are three types of possible censoring: right censoring, left censoring, and interval censoring.

Right censoring is the most common type of censoring. The units that did not fail before the observation or test period ends are right censored. In this case, the exact failure time is unknown, but it is known to be on the right of, or *after*, the time point. In the case of our pavement distress analysis, a road section is said to be right censored if no failure is observed before it was taken out from the sample.

Similarly, left censoring means that the failure time is only known to be *before* a certain time. In other words, the actual failure time could be any time between zero and the censoring time.

Interval censoring is the result of periodical observations in a test. The failure time is known to be within a time interval between two consecutive observations. For our pavement distress analysis, since the pavement condition surveys were performed annually, the life data are interval censored. For example, if the failure of a road section was not observed in the 4th year survey but observed in the 5th year survey, we know that the road section failed at some time between the 4th year survey and the 5th year survey.

Life distribution models are generally used to model failure times of non-repairable systems where failed units are removed from the population instead of being repaired. Life distribution models are also able to model defect initiation times for repairable systems. In such cases, the initiation of defect is treated as failure and the “failed” unit is removed from the sample, although the unit is actually repaired and still in service.

To be consistent with the terminology used in reliability theory, we call the time an initial defect occurs: failure time. Accordingly, a pavement is said to fail when a certain defect is observed. But it should be noted that the concept of “failure,” as used here, is completely different from the concept of “pavement failure” used in practice which means the pavement is functionally insufficient and needs to be replaced.

Failure Data Collection for Category I Distresses

Definition of Failure

As discussed before, the concept of failure used here is based on warranty specifications and for purposes of modeling only. A Category I distress failure occurs when, within the warranty period, the parameter value of a distress exceeds its threshold value specified in the warranty specifications. More specifically, under current warranty specifications, a rutting failure occurs when the average rut depth of a pavement is greater than 0.25 inches within the 3-year warranty period; a ride failure occurs when the average RN of a pavement is less than 3.70 within the 3-year warranty period.

The concept of failure is defined within the warranty period. For purposes of life distribution modeling, the concept has to be extended to an infinite time limit. That is to say, a distress failure occurs whenever the threshold value is exceeded.

Data Collection Method

The data source used to generate failure data are the Rut Depth and RN data, which were analyzed in the prior chapter. Rut Depth and RN data are each stored in a spreadsheet and organized by survey section and pavement age.

The same data collection procedure is repeated for each distress type. The procedure starts from pavement age 1 and repeats for each pavement age. For rutting failure at each pavement age *t,* the following procedure is repeated:

- Find the survey sections in the sample with average Rut Depth > 0.25. These sections failed by rutting between age *t-1* and *t*. Record the number of the failed sections for time interval (*t-1, t*).
- Remove the failed sections from the sample.
- Count the survey sections that are out of service from this age due to other reasons. These sections are right censored at time *t-1*. Record the number of right-censored sections.
- Remove the right-censored sections from the sample.
- Move to the next pavement age and repeat the procedure, or stop if the sample size is zero.

The data collection procedure for ride failure is the same as that for rutting failure, except the failure criterion changes to RN < 3.7.

The collected rutting and ride failure data are listed in Table 6-2.

Table 6-2. Failure data for Category I distresses

Time interval		Rutting	Ride
Start	End		
0	1	2	0
1	2	7	0
2	3	4	0
3	4	3	1
4	5	4	1
5	6	6	0
6	7	3	4
7	8	10	7
8	9	6	9
9	10	7	11
10	11	2	4
11	12	3	6
4	*	1	1
5	*	11	16
6	*	6	10
7	*	18	23
8	*	21	27
9	*	26	22
10	*	30	25
11	*	32	32
12	*	30	33

Note: * in the column of End means right censoring.

Modeling Failure Time of Category I Distresses

Failure time modeling is performed in MiniTAB using the failure data in Table 6-2. The modeling process is divided into two steps. First, select a best fit model for each failure mode from a group of candidate models; and second, fit and test the selected models.

Model Selection

A preliminary model screening is performed to select the most appropriate model for the given data. Six distribution models are tried and the results are listed in Table 6-3.

Table 6-3. Category I distress failure model screening

Distribution Model	Ride		Rutting	
	AD statistic	Correlation	AD statistic	Correlation
Weibull	82.546	0.994	129.482	0.989
Extreme Value	82.634	0.992	129.590	0.946
Exponential	82.735	*	129.537	*
Lognormal	82.548	0.982	129.492	0.980
Logistic	82.590	0.994	129.540	0.954
Loglogistic	82.543	0.993	129.485	0.987

The Anderson-Darling (AD) statistic is a measure of the deviation of the plot points from the fitted line in a probability plot. A smaller Anderson-Darling statistic (AD) indicates that the distribution model fits the data better. The Anderson-Darling statistic suggests that loglogistic is the best candidate model for ride failure; Weibull is the best model for rutting failure.

The Pearson correlation measures the strength of the linear relationship between the two variables on a probability plot. A higher correlation value indicates the distribution model fits the data better. The Pearson correlation suggests Weibull is the best model for both ride failure and rutting failure.

Suggested by both Anderson-Darling statistic and the Pearson correlation, the Weibull is selected for modeling rutting failure. However, the Anderson-Darling statistic and the Pearson correlation have suggested different models for ride failure. We follow the suggestion from the Pearson correlation and choose the Weibull for modeling ride failure.

The Weibull is a flexible life distribution model. Its probability density function (PDF) $f(t)$ and cumulative distribution function (CDF) $F(t)$ are as follows:

$$f(t) = \frac{\gamma}{t}\left(\frac{t}{\alpha}\right)^{\gamma} \exp\left[-\left(\frac{t}{\alpha}\right)^{\gamma}\right] \qquad (6\text{-}3)$$

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^{\gamma}\right] \tag{6-4}$$

where α is the scale parameter and γ is the shape parameter.

Model Fitting

Two parameter estimation methods are used to fit life distribution models. The least squares method is achieved by regressing failure time on the rank value to form a regression line in a probability plot. The maximum likelihood method is achieved by maximizing the likelihood function. The least squares and maximum likelihood estimates of the parameters are listed in Tables 6-4 and 6-5. Although slightly different, the results from the two estimation methods are consistent.

Table 6-4. Least squares estimates for pavement failure models, Weibull

Failure Mode	Parameter	Estimate	Standard Error	95% C.I.	
				Lower	Upper
Ride	Shape (γ)	4.45257	0.60696	3.40862	5.81626
	Scale (α)	14.3533	0.78312	12.8977	15.9733
Rutting	Shape (γ)	1.48121	0.19789	1.13998	1.92457
	Scale (α)	22.9150	3.43498	17.0814	30.7408

Table 6-5. Maximum likelihood estimates for pavement failure models, Weibull

Failure Mode	Parameter	Estimate	Standard Error	95% C.I.	
				Lower	Upper
Ride	Shape (γ)	4.73200	0.598747	3.69267	6.06385
	Scale (α)	14.0424	0.668777	12.7909	15.4163
Rutting	Shape (γ)	1.55531	0.196767	1.21375	1.99299
	Scale (α)	21.7492	2.93836	16.6896	28.3428

As seen in Table 6-3, the least squares estimates yield a correlation coefficient of 0.994 for ride and 0.989 for rutting, indicating the linear regression models fit the data well for both failure modes. The probability plots for least square method (Figures 6-1 and 6-2) also indicate that the Weibull model fits the data well for both ride failure and rutting failure.

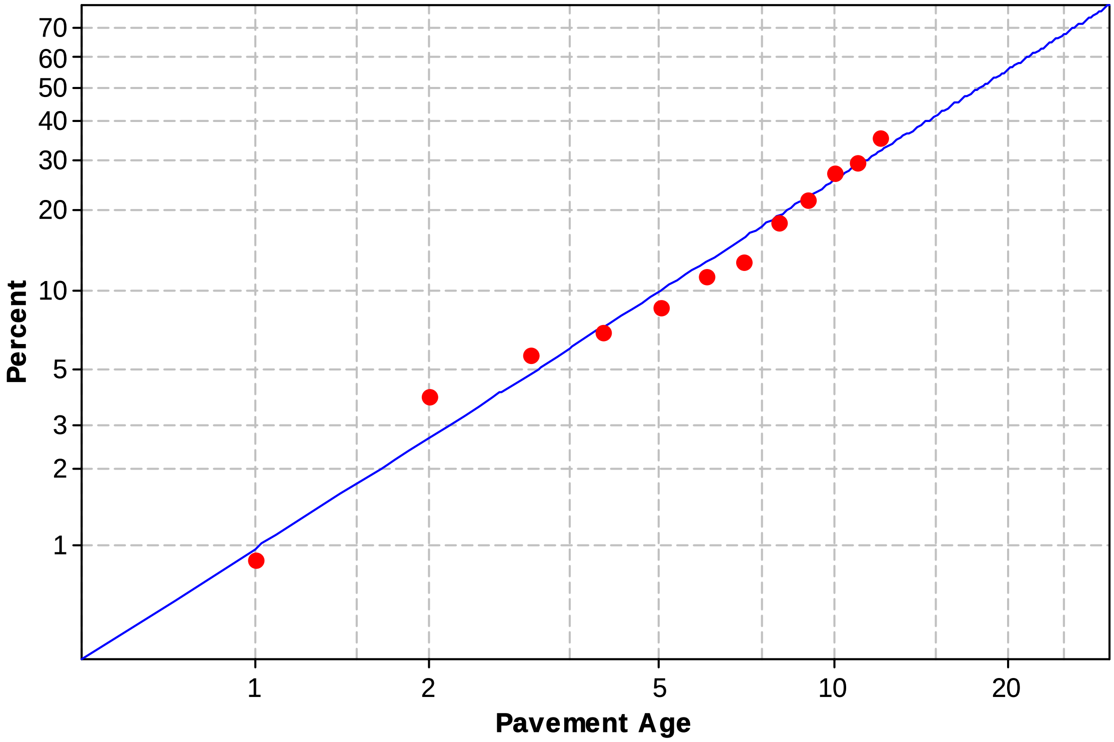

Figure 6-1. Probability plot for rutting failure, least square, Weibull

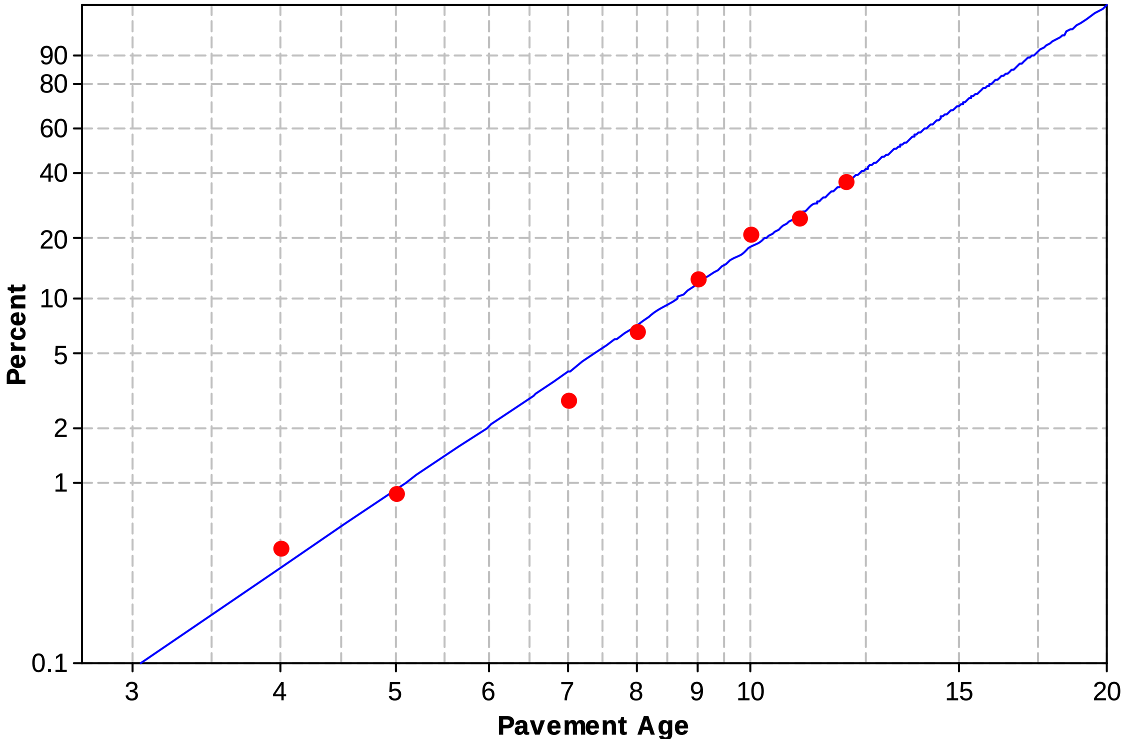

Figure 6-2. Probability plot for ride failure, least square, Weibull

Estimate of cumulative failure rates

The failure probabilities for rutting and ride are calculated using the fitted models. The least square estimates are listed in Tables 6-6 and 6-7 and illustrated in Figures 6-3 and 6-4. The cumulative failure plot for rutting is approximately linear for pavement ages less than 20, indicating the failure rate is relatively stable at different pavement ages. The cumulative failure plot for ride shows an S curve. The failure rates are very low in the first five years but the rates increase rapidly after that.

Table 6-6. Cumulative failure rates for ride, least square estimates

Pavement Age	Failure Probability	95% C.I.	
		Lower	Up
1	0.0000	0.0001	0.0000
2	0.0001	0.0011	0.0000
3	0.0009	0.0043	0.0002
4	0.0034	0.0111	0.0010
5	0.0091	0.0230	0.0036
6	0.0204	0.0420	0.0098
7	0.0401	0.0699	0.0228
8	0.0714	0.1092	0.0464
9	0.1176	0.1635	0.0840
10	0.1813	0.2383	0.1367
11	0.2635	0.3399	0.2016
12	0.3627	0.4688	0.2745

Table 6-7. Cumulative failure rates for rutting, least square estimates

Pavement Age	Failure Probability	95% C.I.	
		Lower	Up
1	0.0096	0.0236	0.0039
2	0.0266	0.0505	0.0140
3	0.0480	0.0789	0.0290
4	0.0726	0.1084	0.0483
5	0.0996	0.1392	0.0708
6	0.1284	0.1713	0.0956
7	0.1586	0.2051	0.1218
8	0.1897	0.2406	0.1486
9	0.2216	0.2779	0.1753
10	0.2538	0.3167	0.2016
11	0.2862	0.3568	0.2271
12	0.3186	0.3977	0.2519

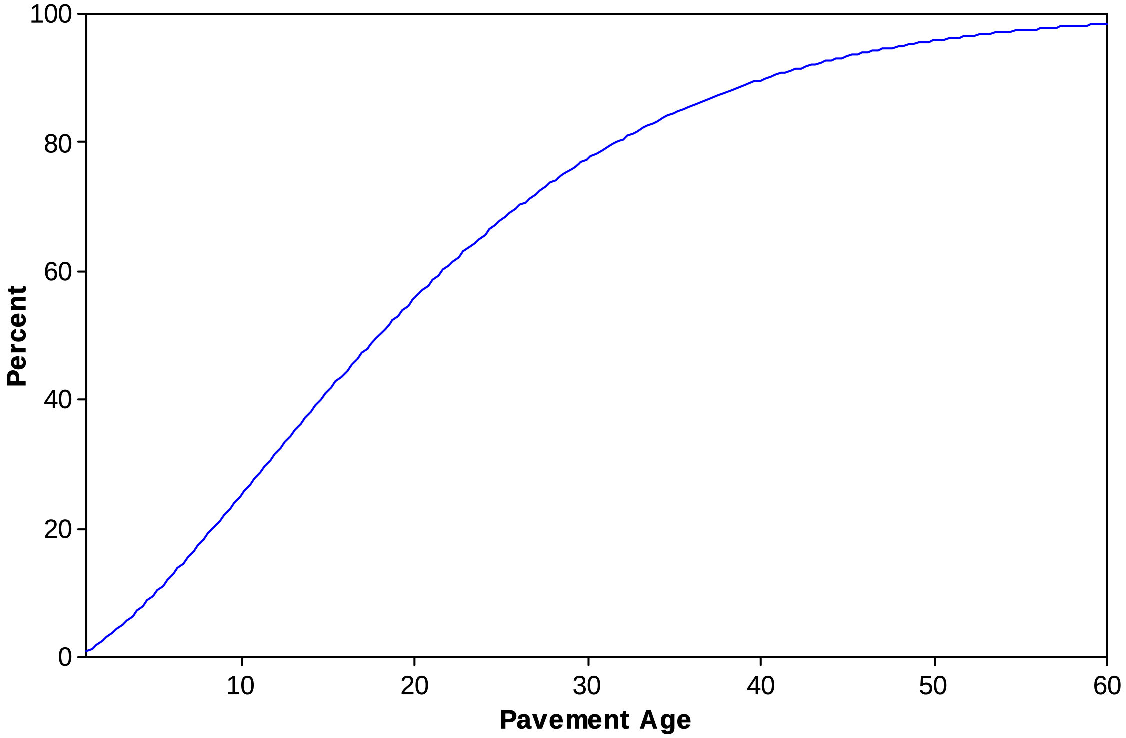

Figure 6-3. Cumulative failure plot for rutting failure, Weibull

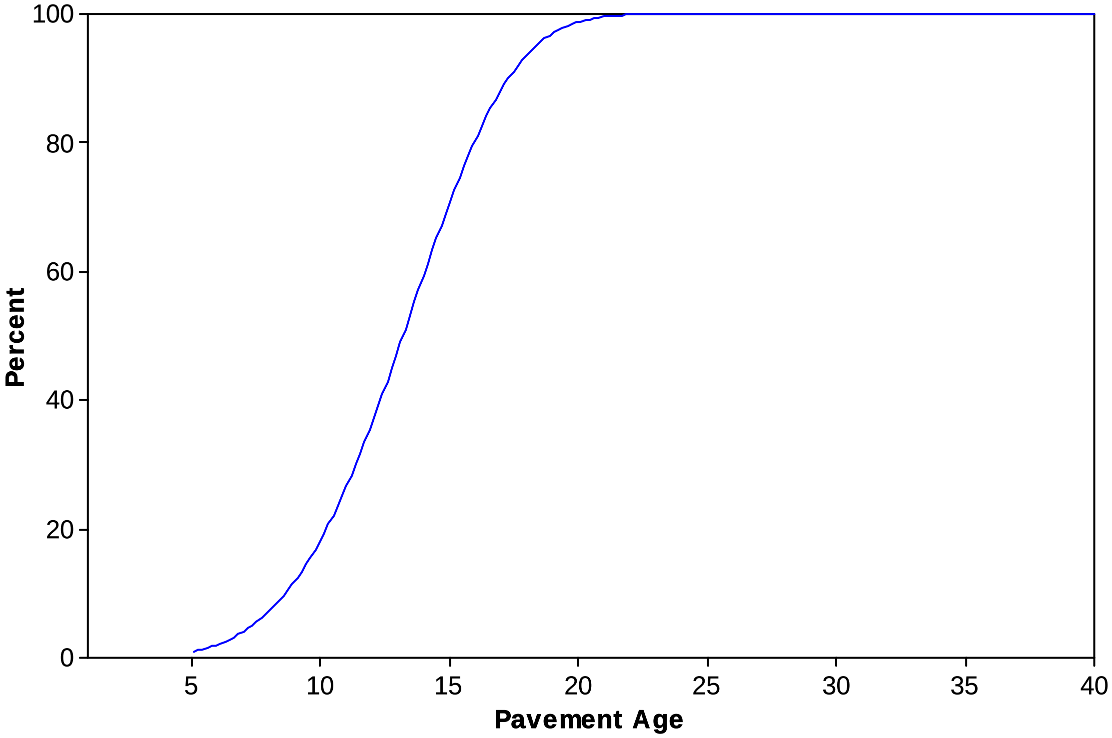

Figure 6-4. Cumulative failure plots for ride failure, Weibull

For a three-year warranty, the failure probabilities for ride and rutting are estimated to be 0.09% and 4.80%, respectively. If the warranty period extends to five years and the threshold values stay unchanged, the failure probability for ride and rutting will increase to 0.91% and 9.96%. The results indicate that the contractor's risk exposure to ride failure is very low, but risk exposure to rutting failure is relatively high.

Modeling Failure Time of Category II Distresses

Failure Data Collection

The data sources used to generate failure data are the worksheets for Category II distresses that were analyzed in the last chapter. The types of distresses to be considered include cracking, raveling, delamination, and bleeding. All these distress types are performance parameters in the FDOT warranty specifications and are included in the Flexible Pavement Condition Survey.

The failure time of each distress type for a roadway section is defined as follows:

- Cracking: the first year a non-A cracking code appeared for either within (CW) or outside (CO) of wheelpath. A non-A cracking code means either type I cracking predominates, but more than 5% of the roadway is affected by cracking, or type II/III cracking predominates.
- Raveling: the first year raveling was coded.
- Delamination: the first year delamination is recorded in the field designated "Remarks".
- Bleeding: the first year bleeding is recorded in the field designated "Remarks".

It should be noted that cracking discussed here is actually a combination of cracking, raveling, and patching. As noted before, the FDOT accumulates raveling and patching into type III cracking in its Flexible Pavement Condition Survey program. The failure time of raveling will be modeled separately, but it is considered in cracking also.

The failure data collection procedure for Category II distresses is the same as for Category I distresses. The procedure is repeated for each distress type. The failure data are summarized in Table 6-8.

Table 6-8. Failure data for Category II distresses

Time Interval		Cracking	Raveling	Bleeding	Delamination
Start	End				
0	1	1		5	
1	2	5	1	6	
2	3	14	2	5	
3	4	27	8	3	
4	5	51	15	1	
5	6	42	21	1	1
6	7	19	9		2
7	8	19	14		2
8	9	5	11		2
9	10	6	5		
10	11		3		3
11	12	2	2		1
12	13	1	1		
13	14		1		
14	15		2		
4	*		1	1	1
5	*	12	15	13	16
6	*	4	10	6	10
7	*	5	12	19	23
8	*	4	26	31	32
9	*	7	13	30	28
10	*	1	16	31	33
11	*	3	26	42	39
12	*	2	11	18	17
13	*			6	8
14	*	1	2	4	4
15	*	1	5	10	10
Sum		232	232	232	232

Note: a * in the column of End means right censoring.

Model Selection

A preliminary model screening is performed using MiniTAB software. Six distribution models are tried and the results are listed in Table 6-9.

Table 6-9. Model screening for Category II distresses

Model	Cracking		Raveling		Bleeding		Delamination	
	AD	Corr.	AD	Corr.	AD	Corr.	AD	Corr.
Weibull	0.885	0.990	27.919	0.980	131.227	0.976	129.349	0.984
Lognormal	1.244	0.989	27.475	0.995	131.227	0.981	129.347	0.994
Exponential	4.609		28.236		131.227		129.354	
Loglogistic	1.036	0.997	27.551	0.989	131.227	0.977	129.348	0.985
Extreme Value	3.303	0.892	31.517	0.898	131.228	0.889	129.351	0.964
Logistic	1.208	0.948	28.477	0.923	131.228	0.891	129.350	0.966

The Anderson-Darling (AD) statistic and the Pearson correlation both suggest the lognormal model as the best candidate for raveling, bleeding, and delamination. For cracking, the AD statistic suggests the Weibull while the Pearson correlation suggests loglogistic. We follow the suggestion of the Pearson correlation and choose the loglogistic model for cracking.

The probability density function (PDF) $f(t)$ and the cumulative distribution function (CDF) $F(t)$ of lognormal distribution are as follows:

$$f(t) = \frac{1}{\sqrt{2\pi}\sigma t} \exp\left[-\frac{(\ln t - \mu)^2}{2\sigma^2} \right] \tag{6-5}$$

$$F(t) = \int_{-\infty}^{t} \frac{1}{\sqrt{2\pi}\sigma x} \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2} \right] dx \tag{6-6}$$

where u is the location Parameter and σ is the scale parameter.

The PDF and CDF of the loglogistic distribution are as follows:

$$f(t) = \frac{\exp\left(\frac{\ln t - \mu}{\sigma} \right)}{\sigma \left[1 + \exp\left(\frac{\ln t - \mu}{\sigma} \right) \right]^2} \tag{6-7}$$

$$F(t) = \frac{1}{1 + \exp\left[-\frac{\ln t - \mu}{\sigma} \right]} \tag{6-8}$$

where u is the location Parameter and σ is the scale parameter.

Model Fitting

The least squares and maximum likelihood estimates of the parameters are summarized in Tables 6-10 and 6-11. The results from the two estimation methods are consistent for cracking, raveling, and delamination. However, there is a significant discrepancy between the estimation results for bleeding. The maximum likelihood method is generally recommended when heavy censoring and interval data are present (ReliaSoft 2006). But the least squares estimate for bleeding is more conservative than the maximum likelihood result since it provides higher cumulative failure rates.

Table 6-10. Least squares estimates of failure models for Category II distresses

Defect type	Model	Parameter	Estimate	Standard Error	95% C.I.	
					Lower	Upper
Cracking	Loglogistic	Shape(γ)	1.69323	0.03272	1.62910	1.75736
		Scale(α)	0.28953	0.01998	0.25291	0.33145
Raveling	Lognormal	Loc (μ)	2.39731	0.05869	2.28228	2.51234
		Scale(σ)	0.62925	0.04985	0.53875	0.73496
Bleeding	Lognormal	Loc (μ)	4.90663	0.45337	4.01805	5.79521
		Scale(σ)	2.46632	0.36087	1.85141	3.28546
Delamination	Lognormal	Loc (μ)	3.17491	0.18012	2.82188	3.52794
		Scale(σ)	0.54698	0.10859	0.37068	0.80715

Table 6-11. Maximum likelihood estimates of failure models for Category II distresses

Defect type	Model	Parameter	Estimate	Standard Error	95% C.I.	
					Lower	Upper
Cracking	Loglogistic	Loc (μ)	1.69968	0.03044	1.64002	1.75935
		Scale(σ)	0.26396	0.01642	0.23366	0.29819
Raveling	Lognormal	Loc (μ)	2.38193	0.05765	2.26894	2.49493
		Scale(σ)	0.63519	0.05089	0.54288	0.74319
Bleeding	Lognormal	Loc (μ)	7.57542	1.39716	4.83704	10.3138
		Scale(σ)	4.00969	0.92332	2.55332	6.29677
Delamination	Lognormal	Loc (μ)	3.34360	0.26158	2.83092	3.85628
		Scale(σ)	0.62194	0.14637	0.39213	0.98644

As seen in Table 6-10, the least squares estimation yields correlation coefficients of 0.997, 0.995, 0.981, and 0.994 for cracking, raveling, bleeding, and delamination. The high correlation coefficients indicate that the models fit the data very well. The probability plots for the maximum likelihood estimates (see Figures 6-5 to 6-8) also suggest that the models fit the data well for all four types of distresses.

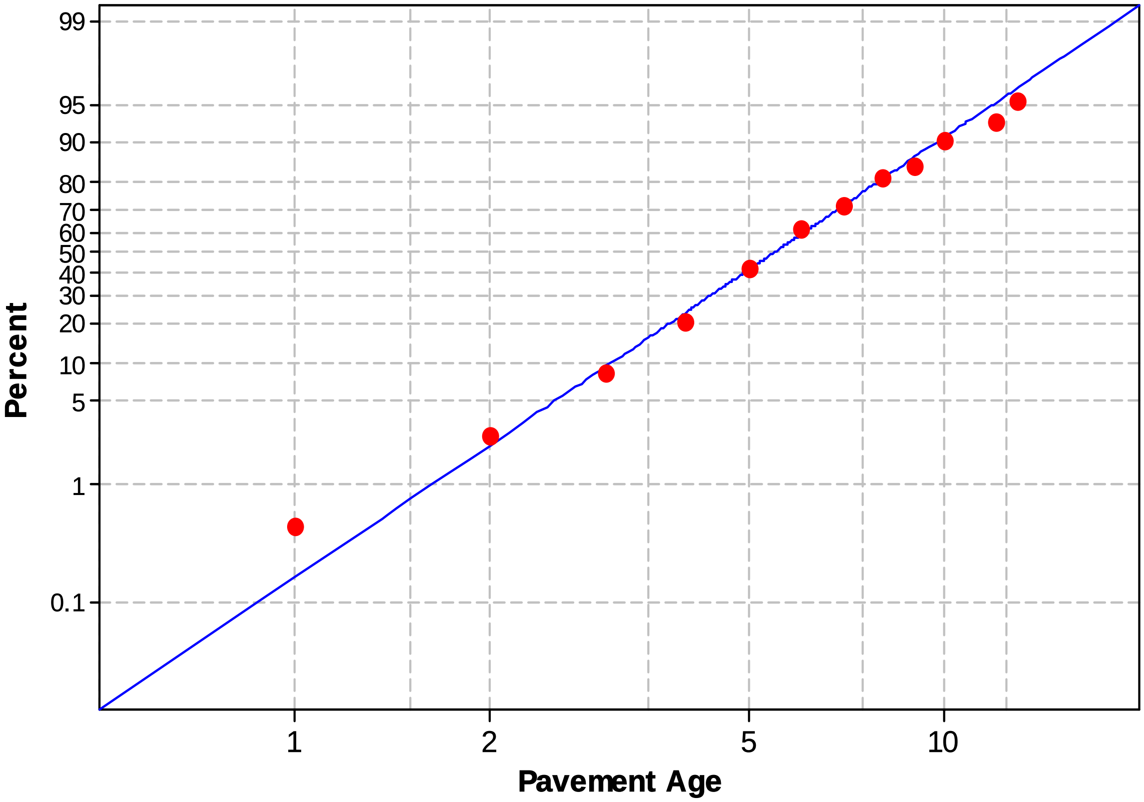

Figure 6-5. Probability plot for cracking failure model, loglogistic

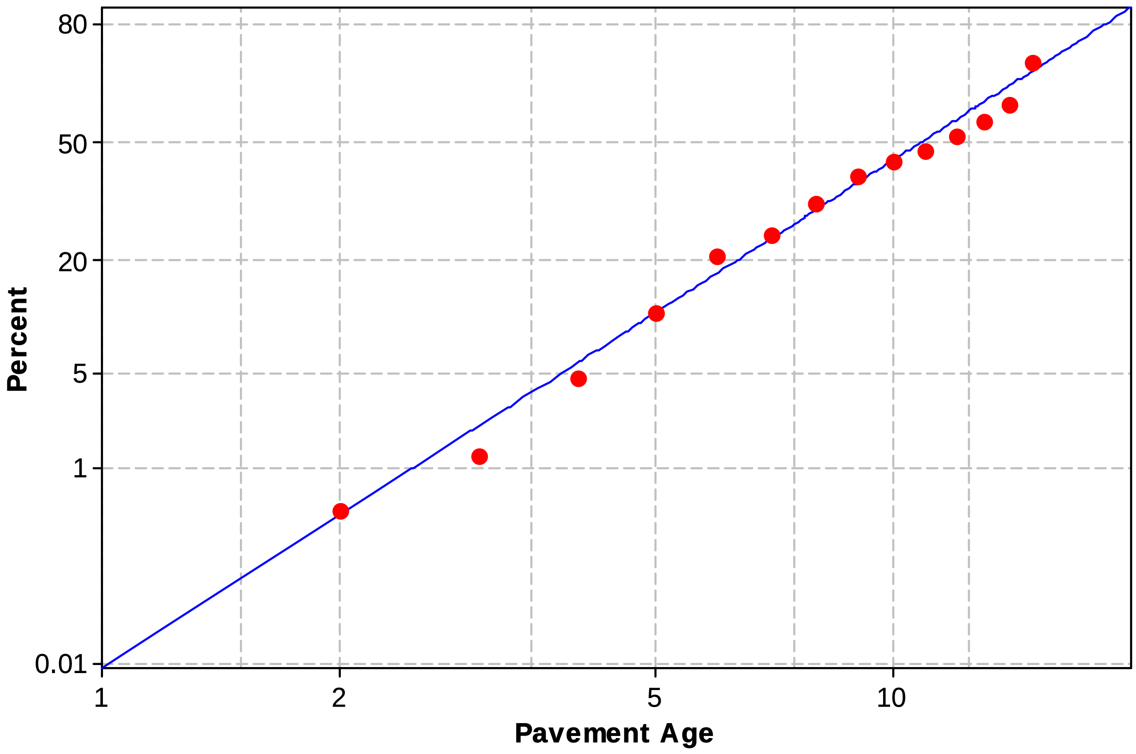

Figure 6-6. Probability plot for raveling failure model, lognormal

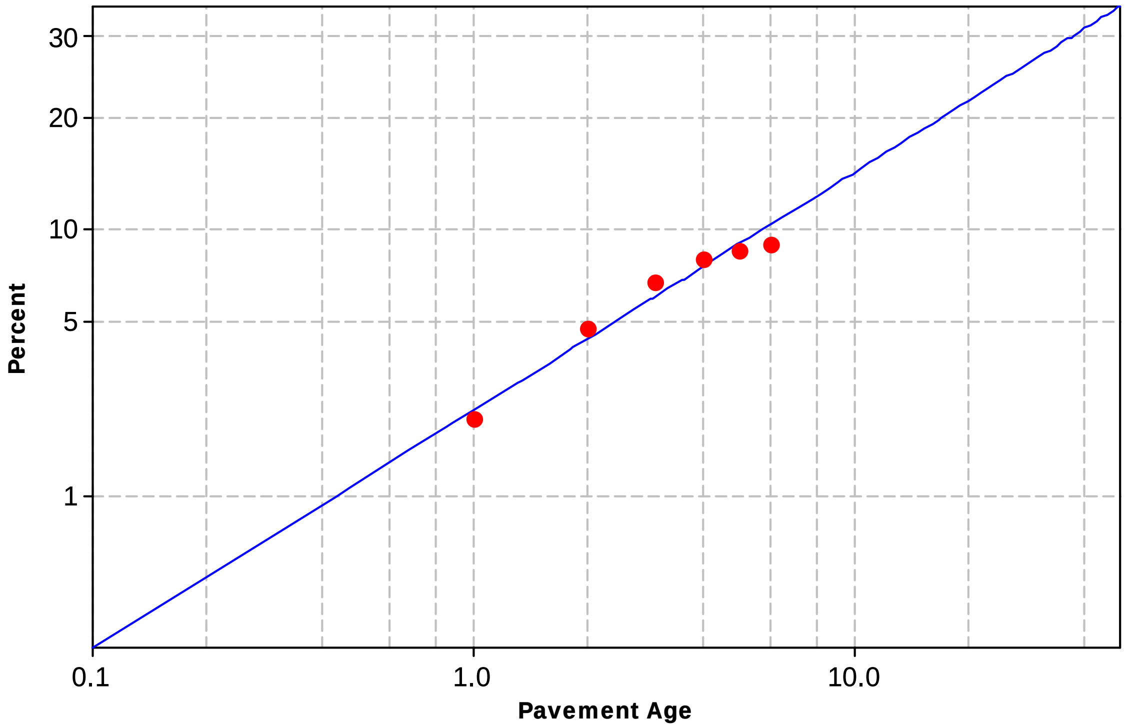

Figure 6-7. Probability plot for bleeding failure model, lognormal

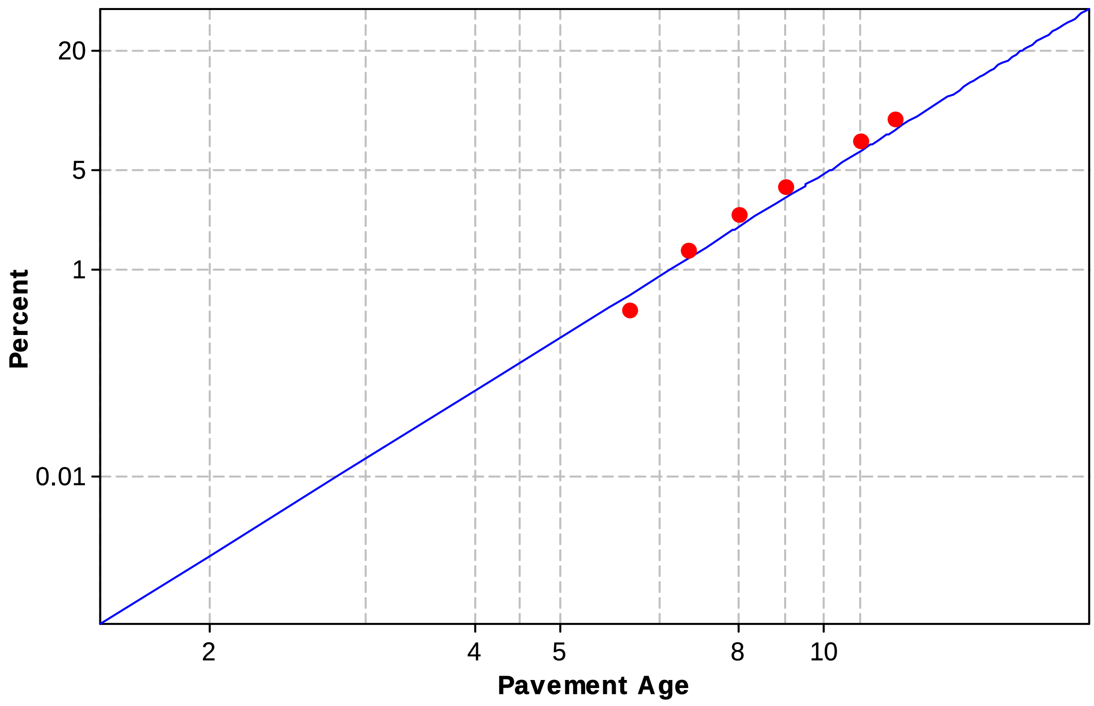

Figure 6-8. Probability plot for delamination failure model, lognormal

Estimate of Cumulative Defect Probability

The cumulative failure probabilities for each distress type are calculated using the fitted failure models. The maximum likelihood results are listed in Tables 6-12 to 6-15 and illustrated in Figures 6-9 to 6-12.

Table 6-12. Cumulative probabilities for cracking failure

Pavement Age	Failure Probability	95% C.I.	
		Lower	Up
1	0.00160	0.00071	0.00356
2	0.02160	0.01314	0.03530
3	0.09303	0.06754	0.12685
4	0.23375	0.19020	0.28378
5	0.41535	0.36137	0.47144
6	0.58633	0.52909	0.64134
7	0.71765	0.66242	0.76701
8	0.80825	0.75857	0.84974
9	0.86818	0.82543	0.90170
10	0.90755	0.87165	0.93417
11	0.93371	0.90387	0.95475
12	0.95142	0.92668	0.96811

For a three-year warranty, the probabilities for a roadway section to have each type of distress are estimated to be 9.30% for cracking (including raveling and patching), 2.17% for raveling, 5.31% for bleeding, and 0.015% for delamination. The results indicate that cracking is the most common distress type for asphalt pavements. Raveling and bleeding also have considerably high rates of occurrence at early pavement ages. But the risk of delamination is very low.

Table 6-13. Cumulative probabilities for raveling failure

Pavement Age	Failure Probability	95% C.I.	
		Lower	Up
1	0.00009	0.00001	0.00061
2	0.00392	0.00128	0.01068
3	0.02167	0.01101	0.03999
4	0.05850	0.03739	0.08802
5	0.11196	0.08141	0.14995
6	0.17641	0.13811	0.22082
7	0.24622	0.20098	0.29640
8	0.31696	0.26484	0.37298
9	0.38560	0.32658	0.44741
10	0.45029	0.38466	0.51732
11	0.51002	0.43846	0.58127
12	0.56439	0.48786	0.63858

Table 6-14. Cumulative probabilities for bleeding failure

Pavement Age	Failure Probability	95% C.I.	
		Lower	Up
1	0.02943	0.01417	0.05637
2	0.04304	0.02425	0.07216
3	0.05312	0.03200	0.08404
4	0.06135	0.03827	0.09409
5	0.06839	0.04352	0.10301
6	0.07459	0.04802	0.11114
7	0.08016	0.05196	0.11865
8	0.08524	0.05545	0.12566
9	0.08991	0.05858	0.13226
10	0.09425	0.06142	0.13850
11	0.09831	0.06402	0.14444
12	0.10212	0.06641	0.15010

Table 6-15. Cumulative probabilities for delamination failure

Pavement Age	Failure Probability	95% C.I.	
		Lower	Up
1	0.00000	0.00000	0.00013
2	0.00001	0.00000	0.00120
3	0.00015	0.00000	0.00375
4	0.00082	0.00005	0.00794
5	0.00265	0.00037	0.01383
6	0.00630	0.00150	0.02156
7	0.01231	0.00421	0.03145
8	0.02105	0.00911	0.04417
9	0.03265	0.01626	0.06075
10	0.04708	0.02509	0.08238
11	0.06418	0.03483	0.10992
12	0.08369	0.04490	0.14345

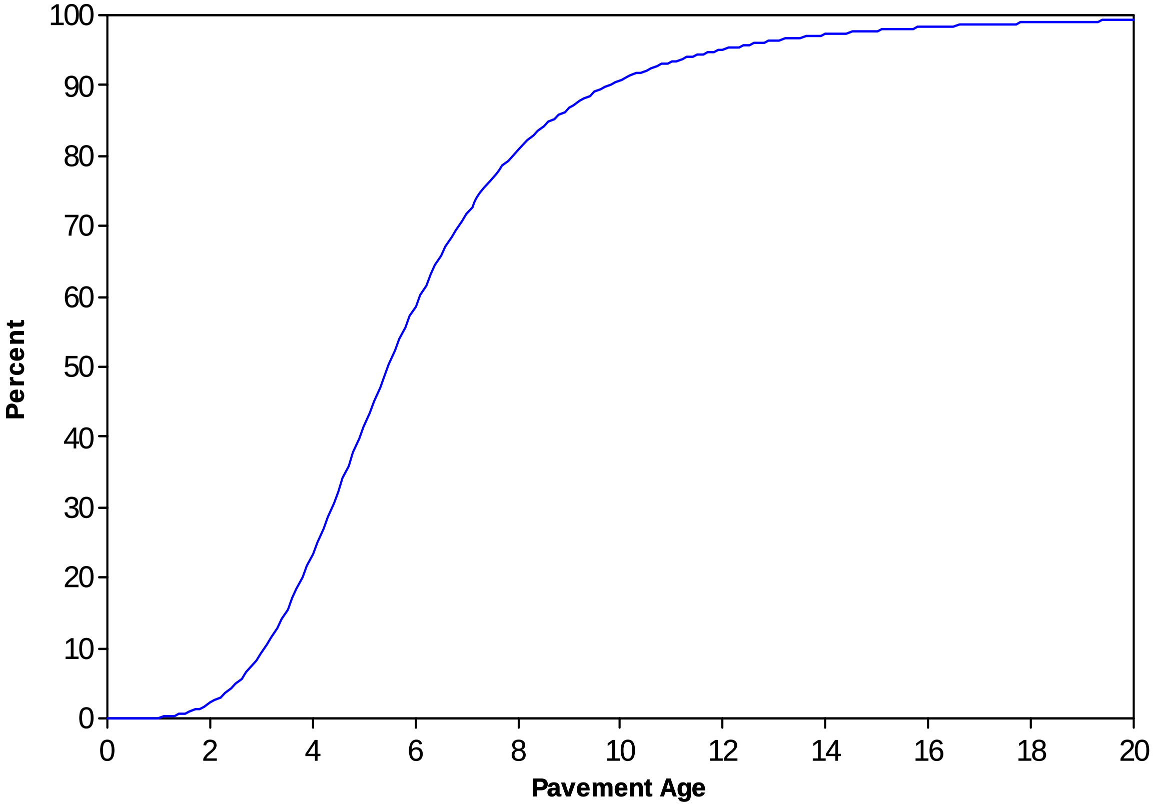

Figure 6-9. Cumulative defect probability plot for cracking

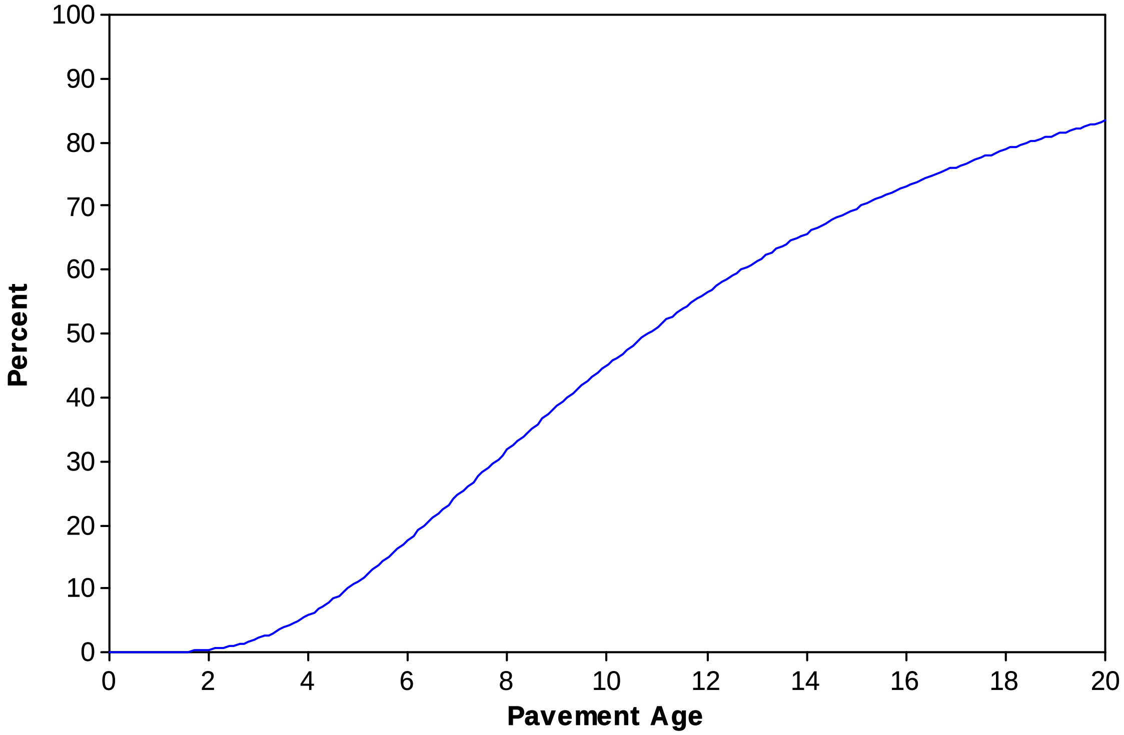

Figure 6-10. Cumulative defect probability plot for raveling

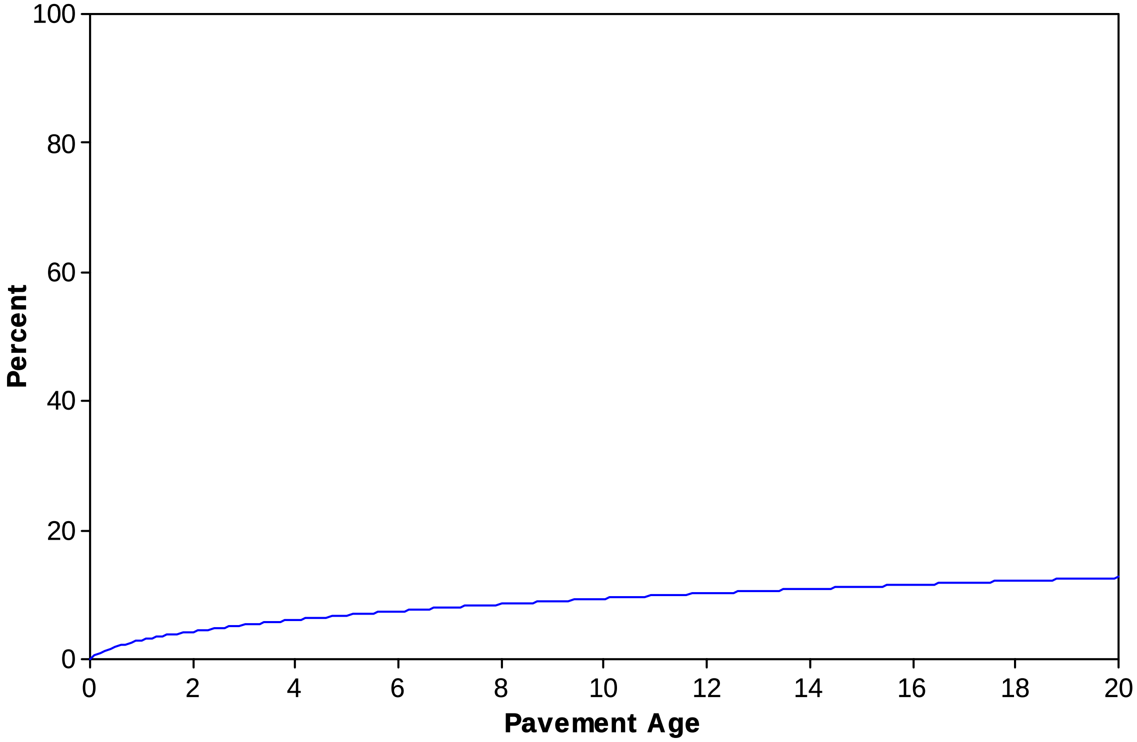

Figure 6-11. Cumulative defect probability plot for bleeding

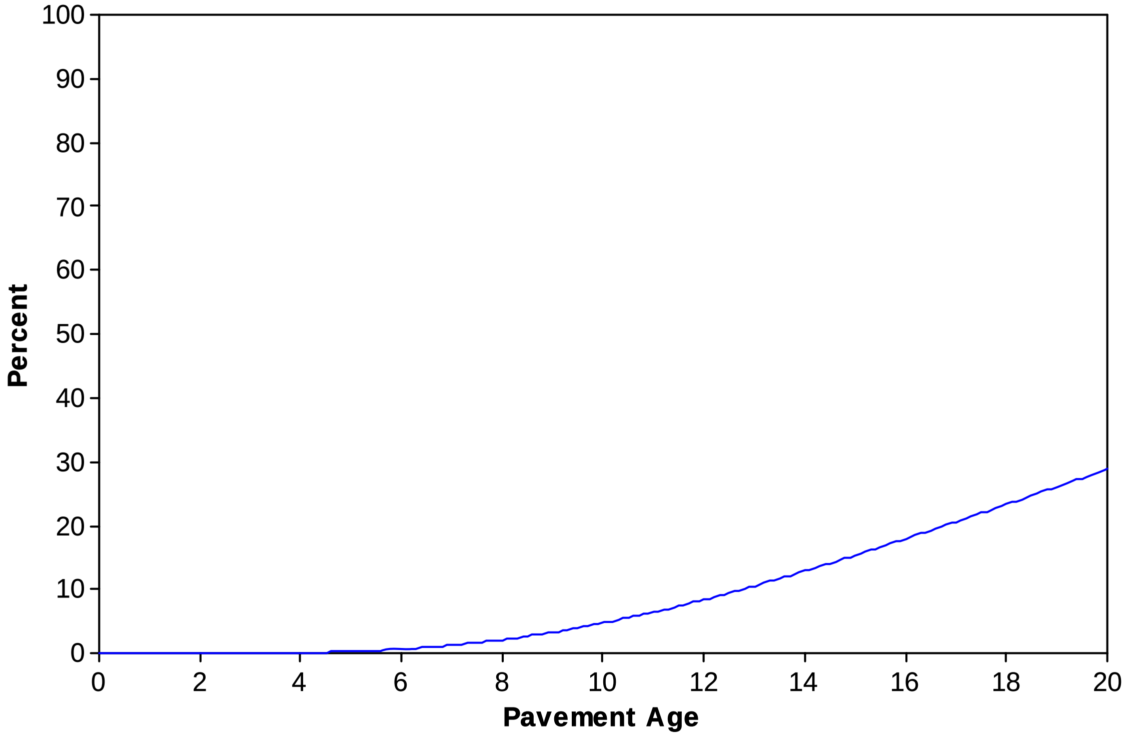

Figure 6-12. Cumulative defect probability plot for delamination

Modeling Crack Growth

In the prior sections the failure times of various distress types have been modeled. In this section the severity of distresses after initiation will be modeled.

The percent of pavement affected by distresses was estimated and coded for distresses of raveling, patching, and cracking in the FDOT Flexible Pavement Survey program. But no such information was provided for bleeding and delamination. So modeling growth of bleeding or delamination is not possible at this time without other sources of data. Since the areas affected by raveling and patching are already included in the estimates of cracking areas, we need only to model the growth of cracking. But we should keep in mind that the so-called cracking area here is actually the sum of cracking, raveling, and patching areas.

Cracking Defect Rating

The cracking data are reorganized based on crack initiation time. Beginning at the point of crack initiation, the cracking data for each year are stored in the same column in the worksheet. So the new worksheets for cracking data are organized by section ID and year after crack initiation.

The distributions of cracking rating scores for each year after cracking initialization are illustrated in Figure 6-13. Observations gathered are as follows:

- In the first year after crack initiation, most roadway sections have a rating score of 8.5 or higher. However, there are also some road sections that have a sharp drop in cracking rating (all the sections have a cracking rating score of 10 in the prior year), indicating a sudden and rapid pavement condition deterioration.
- The range of the rating scores becomes wider over time, reflecting the difference in cracking growth rates among sections. Cracking grows slowly in some sections, but very quickly in others.
- The distributions of cracking rating scores are negatively skewed, with a longer lower tail.

Estimating Cracking Affected Area

A cracking rating score is a comprehensive measure of both the severity of cracking and the size of cracking affected areas. To estimate the cracking affected areas, we have to look at the cracking codes (see Table 5-1) used to calculate the cracking rating scores.

Two cracking codes, confined to wheel path (CW) and outside of wheel path (CO), are given for each road section. However, the codes do not provide an accurate estimate of the percent pavement affected, since the represented percentage ranges are very large for each code. The estimation of cracking affected areas is achieved by fitting the cracking codes to a growth curve. An example is illustrated in Figure 6-14.

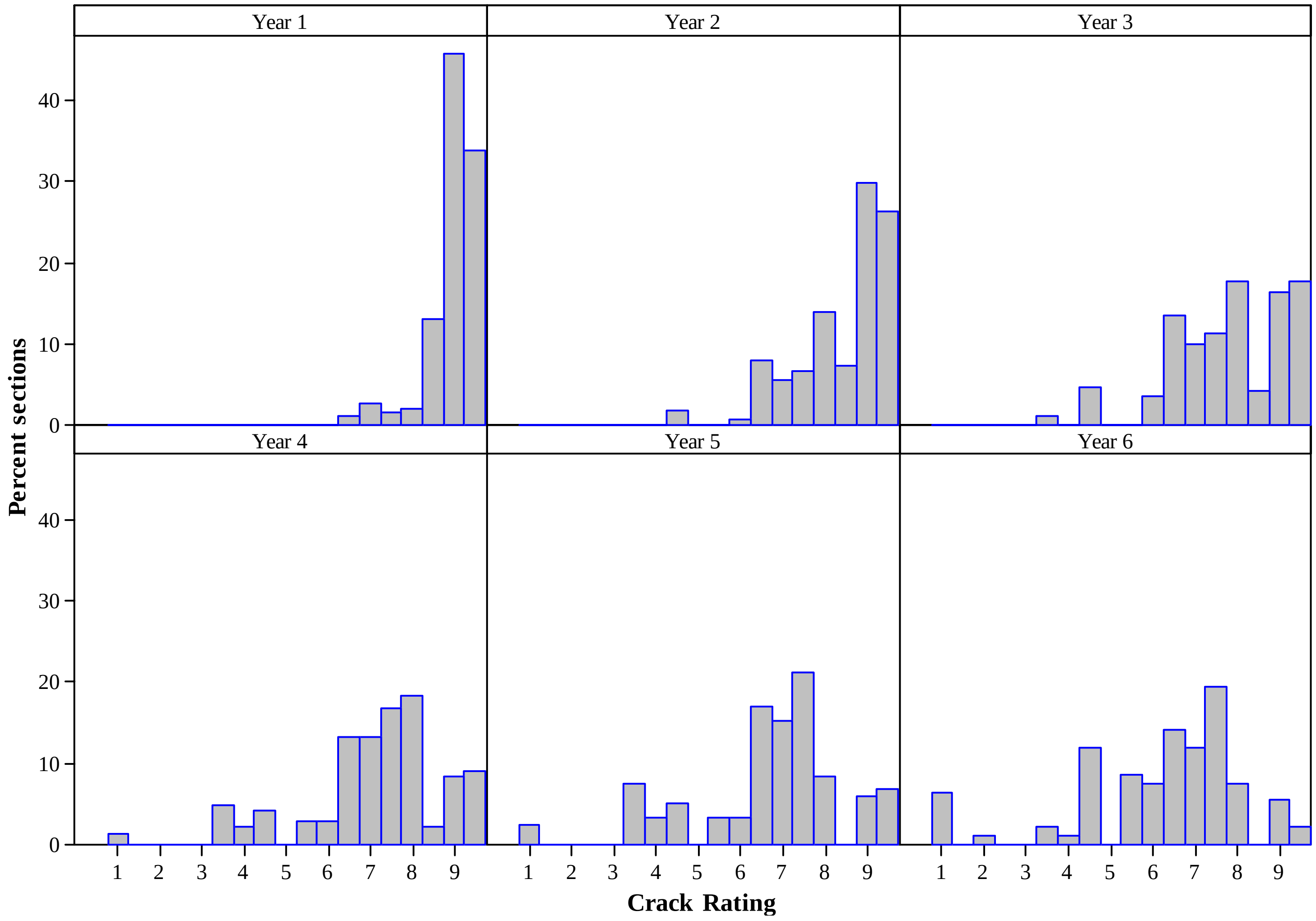

Figure 6-13. Distributions of crack rating after cracking initialization

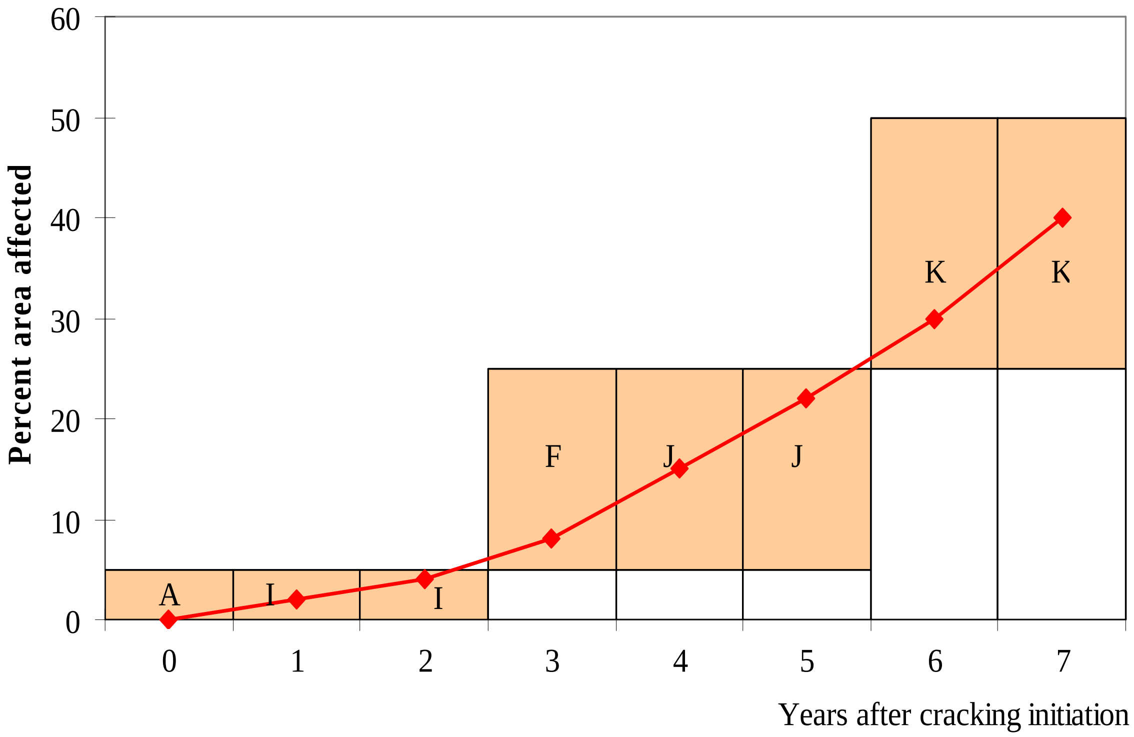

Figure 6-14. Estimating percent pavement affected by cracking

Modeling Cracking Affected Areas

A histogram illustration of percent areas affected by cracking is shown in Figure 6-15. The cracking affected areas show similar distributional characteristics with cracking rating (Figure 6-13) except with the reverse order in the x-axis.

Empirical cumulative distribution function

Without being fitted to a particular parametric distribution model, the distribution of the percent area affected by cracking can be estimated empirically. The empirical cumulative distribution function (CDF) gives the values of CDF such that $F(x)$ represents the proportion of observations in a sample less than or equal to *x*. The results are listed in Table 6-16.

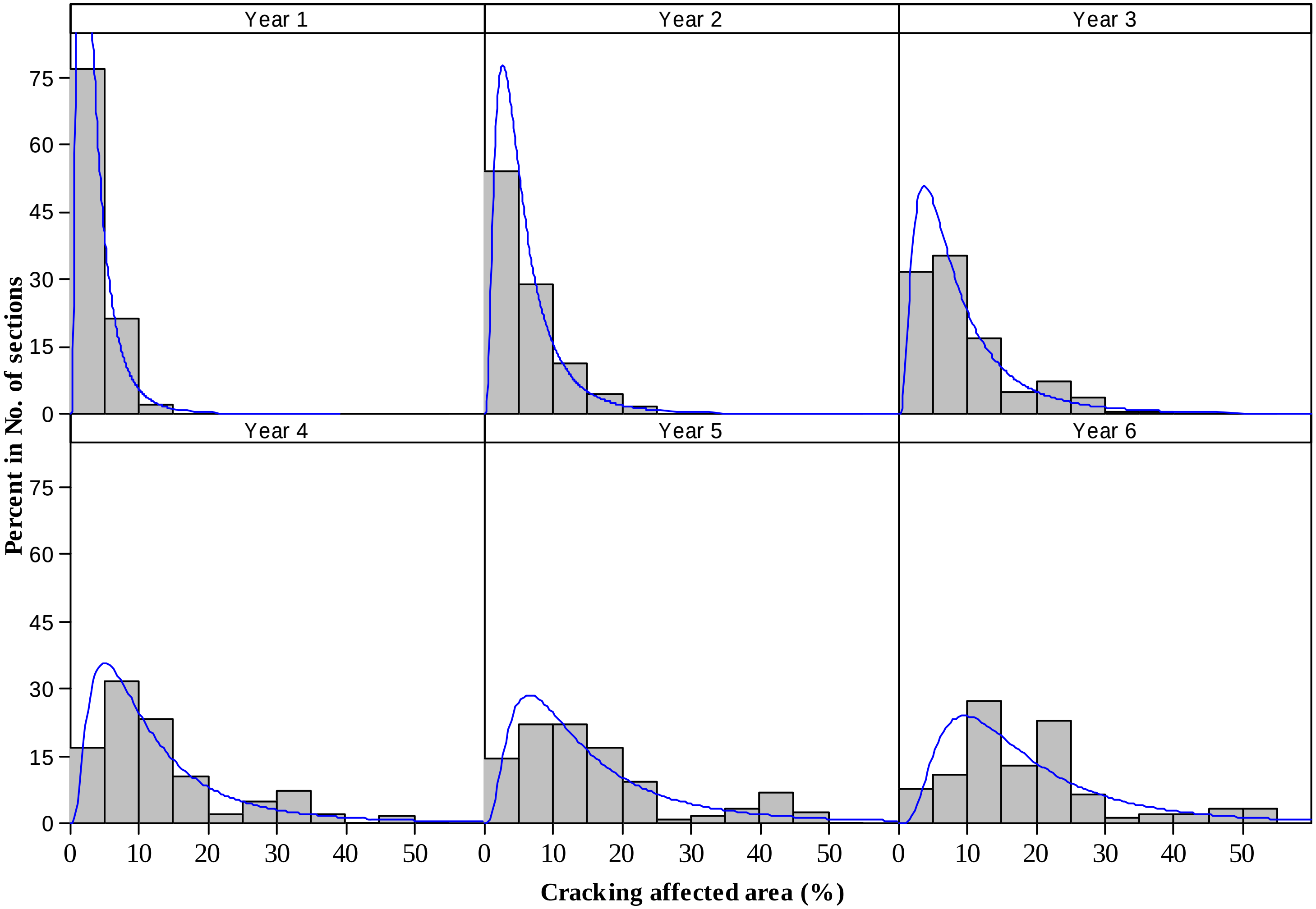

Figure 6-15. Distribution in size of cracked area after crack initiation

Table 6-16. Empirical CDF of percent pavement cracked

Percent area cracked	Year 1	Year 2	Year 3	Year 4	Year 5
0	0.00000	0.00000	0.00000	0.00000	0.00000
1	0.05128	0.00000	0.00000	0.00000	0.00000
2	0.22051	0.11236	0.05848	0.03521	0.00847
3	0.49231	0.21910	0.11696	0.08451	0.05085
4	0.66667	0.37079	0.16959	0.13380	0.11017
5	0.76923	0.53933	0.31579	0.16901	0.14407
6	0.81026	0.63483	0.38012	0.21831	0.16949
7	0.90256	0.70225	0.50877	0.28169	0.20339
8	0.94872	0.75843	0.59064	0.35211	0.23729
9	0.96410	0.78090	0.64327	0.44366	0.30508
10	0.97949	0.82584	0.66667	0.48592	0.36441
11	0.98462	0.87640	0.70760	0.56338	0.39831
12	0.99487	0.90449	0.74269	0.64085	0.46610
13	1.00000	0.92135	0.78363	0.67606	0.48305
14		0.92697	0.81287	0.71831	0.54237
15		0.93820	0.83626	0.71831	0.58475
16		0.95506	0.84795	0.74648	0.64407
17		0.96067	0.85965	0.77465	0.66949
18		0.96629	0.85965	0.80282	0.69492
19		0.97191	0.87719	0.81690	0.72034
20		0.98315	0.88304	0.82394	0.75424
21		0.98315	0.90643	0.83803	0.78814
22		0.98876	0.93567	0.83803	0.80508
23		0.99438	0.94152	0.83803	0.83051
24		1.00000	0.94152	0.83803	0.83898
25			0.95322	0.84507	0.84746
26			0.97076	0.84507	0.84746
27			0.97661	0.85211	0.84746
28			0.98246	0.86620	0.85593
29			0.98246	0.87324	0.85593
30			0.98830	0.90141	0.85593
31			0.98830	0.90845	0.85593
32			0.99415	0.91549	0.85593
33			0.99415	0.95070	0.85593
34			0.99415	0.96479	0.86441
35			0.99415	0.96479	0.87288
36			0.99415	0.96479	0.87288
37			1.00000	0.97887	0.88983
38				0.97887	0.88983
39				0.97887	0.91525

Table 6-16. Continued

Percent area cracked	Year 1	Year 2	Year 3	Year 4	Year 5
40				0.98592	0.91525
41				0.98592	0.93220
42				0.98592	0.94915
43				0.98592	0.97458
44				0.98592	0.97458
45				0.98592	0.97458
46				0.99296	0.97458
47				0.99296	0.97458
48				0.99296	1.00000
49				0.99296	
50				1.00000	

Parametric analysis

A preliminary screening indicates that lognormal is the best fitting model for the given data. The estimated parameters are listed in Table 6-17. A comparison of the fitted curves with the observed data is shown in Figure 6-15.

Table 6-17. Lognormal distribution of percent pavement affected by cracking

Years after cracking initiation	Parameter	Estimate	Standard Error	95% C.I.	
				Lower	Upper
1	Loc (μ)	0.99928	0.05112	0.89910	1.09947
	Scale (σ)	0.71382	0.03608	0.64650	0.78815
2	Loc (μ)	1.51647	0.05578	1.40714	1.62580
	Scale (σ)	0.74422	0.03985	0.67008	0.82656
3	Loc (μ)	1.91934	0.06000	1.80174	2.03693
	Scale (σ)	0.78457	0.04285	0.70493	0.87322
4	Loc (μ)	2.25146	0.06777	2.11863	2.38428
	Scale (σ)	0.80755	0.04832	0.71820	0.90802
5	Loc (μ)	2.48503	0.07261	2.34272	2.62734
	Scale (σ)	0.78873	0.05176	0.69353	0.89699

Results of chi-square goodness-of-fit tests are listed in Tables 6-18 to 6-22. The associated p-values for year 1 through year 3 are all greater than 5%, indicating the fitted lognormal models are adequate for the data of the first three years. For year 4 and year 5, however, the associated p-values are less than 1%, indicating an inadequate fit. Thus the lognormal models can be used to model the distribution of percent pavement affected by cracking for year 1 to 3 after crack initiation. For years 4 and 5, only the empirical CDF can be used.

Table 6-18. Chi square goodness-of-fit test for year 1

x	*F(x)*	Probability	Expected	Observations	χ^2	P-value
2.5	0.45372	0.45372	88.476	82	7.4566	0.0587
5.0	0.80366	0.34994	68.238	68		(DF=3)
7.5	0.92260	0.11894	23.193	35		
10.0	0.96606	0.04346	8.475	6		
12.5	0.98376	0.01770	3.451	3		
15.0	0.99166	0.00791	1.542	1		

Table 6-19. Chi square goodness-of-fit test for year 2

x	*F(x)*	Probability	Expected	Observations	χ^2	P-value
4	0.43057	0.43057	76.642	66	3.7909	0.2850
8	0.77531	0.34474	61.364	69		(DF=3)
12	0.90342	0.12811	22.803	26		
16	0.95428	0.05086	9.053	9		
20	0.97658	0.02230	3.969	5		
24	0.98721	0.01064	1.894	3		

Table 6-20. Chi square goodness-of-fit test for year 3

x	*F(x)*	Probability	Expected	Observations	χ^2	P-value
5	0.34642	0.34642	59.238	54	10.3291	0.0664
10	0.68739	0.34097	58.306	60		(DF=5)
15	0.84262	0.15522	26.543	29		
20	0.91496	0.07234	12.371	8		
25	0.95118	0.03622	6.193	12		
30	0.97054	0.01936	3.311	6		
35	0.98148	0.01094	1.871	1		
40	0.98795	0.00647	1.107	1		

Table 6-21. Chi square goodness-of-fit test for year 4

x	*F(x)*	Probability	Expected	Observations	χ^2	P-value
8	0.41566	0.41566	59.024	50	15.3548	0.0040
16	0.74064	0.32498	46.147	56		(DF=4)
24	0.87439	0.13375	18.993	13		
32	0.93367	0.05927	8.416	11		
40	0.96246	0.02880	4.089	10		
48	0.97756	0.01510	2.144	1		
56	0.98598	0.00842	1.195	1		

Table 6-22. Chi square goodness-of-fit test for year 5

x	*F(x)*	Probability	Expected	Observations	χ^2	P-value
6	0.18971	0.18971	22.385	20	27.9257	0.0000
12	0.49994	0.31023	36.607	35		(DF=5)
18	0.69635	0.19641	23.176	27		
24	0.81021	0.11386	13.436	17		
30	0.87730	0.06709	7.917	2		
36	0.91815	0.04085	4.821	2		
42	0.94388	0.02573	3.036	9		
48	0.96058	0.01671	1.971	6		

Summary

The failure time of each distress type is modeled in this chapter using life distribution models. In particular, Weibull models are fitted for ride and rutting failure; the loglogistic model is fitted for cracking failure; lognormal models are fitted for failures of raveling, bleeding, and delamination.

The growth and distribution of percent pavement affected by cracking are also modeled in this chapter. Both empirical CDF and lognormal models are used to estimate the distribution of percent pavement affected by cracking. The chi square goodness-of-fit test indicates that the lognormal model fits the data well for the first three years but is not adequate for the data of the 4th and 5th years.

CHAPTER 7
MODELING CONSTRUCTION COST ESCALATION

The two elements of warranty risk for contractors are the uncertainty in quantities of repair works and the uncertainty in future unit repair costs. The uncertainty in repair work quantities has been analyzed and modeled in previous chapters. This chapter will deal with the uncertainty in future cost escalation.

The uncertainty in future cost escalation will be assessed using the historical construction cost index. The Box-Jenkins approach is adopted to model the index series and predict the probability distribution of future unit costs.

Introduction

Existing Forecast Methods

A review of literature showed that a variety of future costs forecasting models have been developed or are in use in the construction industry. These forecasting methods can be broadly classified into three categories (Chatfield 2001):

- Judgmental forecasts based on subjective judgment, intuition, and commercial knowledge.
- Univariate time series methods where forecasts depend only on current and past values of a historical construction cost index.
- Relational methods where forecasts depend, at least partly, on the value of other macro economic variables, called predictors, indicators, or explanatory variables.

Akintoye et al. (1998) identified that unemployment level, construction output, industrial production, and the ratio of price to cost indices in manufacturing are consistently the leading indicators of construction contract prices; while gross national domestic product is a coincidental indicator. Herbsman (1986) found that the total volume of contract bids in a particular year, as well as material, labor, and equipment costs, affect construction bid price. Regression analysis, due to its simplicity in both concept and application, has been widely used to model the relationship between future construction costs and other explanatory variables (Goh and Teo 2000). Neural network technique was also used to model construction costs (Williams 1994; Wilmot and Mei 2005).

Relational models allow the impact of various alternative inputs to be evaluated. However, this approach requires information on several explanatory variables in addition to the variable to be predicted. Future value of explanatory variables may be needed to make long-term forecasts. By contrast, univariate time series models predict future cost based solely on the past values of the cost index, which is much easier to collect. Typical time series forecasting techniques include the smoothing method and the Box-Jenkins approach (Goh and Teo 2000).

Despite the existence of various forecasting models, their application in practice by contractors is limited. Herbsman (1986) found that contractors and suppliers mainly forecast future construction costs based on the intuition of experienced professionals.

The Proposed Approach

Most forecast literature is concerned with methods for calculating point forecasts, which provide single number predictions. Prediction intervals, also called confidence intervals, are sometimes calculated but not given sufficient attention. A common use of prediction intervals is to validate the fitted model.

Given the particular objectives of this study on warranty risk analysis, the interest herein is to assess the uncertainty of future construction costs. More specifically, the aim is to develop probabilistic forecasts for future unit costs. An appropriate historical construction cost index will be selected and used for this analysis.

However, a model that gives accurate point forecasts may not provide accurate probabilistic forecasts. Time series methods are concerned with the estimation of difference equations containing stochastic components, and they are concerned with uncovering the dynamic aspect of a series.

Time series models are able to uncover the dynamic aspects of a series and to model both its systematic variation and unexplained variation. The systematic variation facilitates the computation of point forecasts while the description of unexplained variation helps to model the uncertainty. The Box-Jenkins approach is adopted to model the index series and predict probabilistic distributions of future unit costs.

Rationale for Price Forecast Errors

Where Does the Forecast Error Come From?

Forecasts of future unit costs generally start from current unit costs. Let P_0 be the current unit cost and P_t be the future unit cost at time *t*. The corresponding one-period inflation I_t for time period *t* can be calculated as:

$$I_t = \frac{P_t - P_{t-1}}{P_{t-1}} \tag{7-1}$$

The equation can be rewritten as:

$$P_t = P_{t-1}(1 + I_t) \tag{7-2}$$

Expressing P_t in term of P_0, renders

$$P_t = P_0(1 + I_1)(1 + I_2)...(1 + I_t) \tag{7-3}$$

or

$$P_t = P_0 \prod_{j=1}^{t} (1 + I_j) \tag{7-4}$$

If we denote the predicted one-period inflation as $\hat{I}_t$, the predicted future cost $\hat{P}_t$ can be expressed as

$$\hat{P}_t = P_0 \prod_{j=1}^{t} (1 + \hat{I}_j) \tag{7-5}$$

An error in the forecast exists because I_t can not be accurately predicted, or $\hat{I}_t \neq I_t$. The forecast error can be expressed as

$$E_t = P_t - \hat{P}_t = P_0 \left[\prod_{j=1}^{t} (1 + I_j) - \prod_{j=1}^{t} (1 + \hat{I}_j) \right] \tag{7-6}$$

The Concept of Log-inflation

If we take the natural logarithm at both sides, equation (7-4) becomes

$$\ln P_t = \ln P_0 + \sum_{j=1}^{t} \ln(1 + I_j) \tag{7-7}$$

or

$$p_t = p_0 + \sum_{j=1}^{t} \Delta p_j \tag{7-8}$$

where

$$p_t = \ln P_t$$

$$p_0 = \ln P_0$$

$$\Delta p_j = \ln(1 + I_j)$$

The Δp_j defined above is similar to the continuously compounded return or the log-return that is widely used in finance literature. It is actually another form of expression for inflation. It is called log-inflation. To explain this definition, see the Taylor series:

$$\ln(1+x)=\sum_{n=0}^{\infty}\frac{(-1)^n}{n+1}x^{n+1} \quad \text{for } |x|<1 \tag{7-9}$$

For the case of log-inflation,

$$\Delta p_j=\ln(1+I_j)=\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{n+1}I_j^{\,n}$$

$$=I_j-\frac{I_j^{\,2}}{2}+\frac{I_j^{\,3}}{3}-\frac{I_j^{\,4}}{4}+\frac{I_j^{\,5}}{5}-\ldots \tag{7-10}$$

Since generally $|I_j|<<1$, ignoring the higher order terms renders

$$\Delta p_j \approx I_j \tag{7-11}$$

As an example, if $I_j=4\%,$ then $\Delta p_j=\ln(1+4\%)=3.922\%$. These two numbers are very close. So Δp_j can be considered as an alternative form of inflation. However, the difference between Δp_j and I_j gets larger when I_j deviates significantly from zero. For example, when $I_j=200\%,\ \Delta p_j=\ln(1+4\%)=109.86\%$; when $I_j=-100\%,\ \Delta p_j=-\infty$.

The concept of log-inflation has obvious advantages over the simple inflation. First, the multiperiod log-inflation is simply the sum of the one-period log-inflations of all the periods, as illustrated in equation (7-8). This additive form is much easier to handle in practice than the multiplicative form in equation (7-5). Second, the theoretical range for I_j is $[-1,+\infty)$, while the range for Δp_j is $(-\infty,+\infty)$. Thus Δp_j is more likely to follow a symmetric distribution and its statistical properties are more tractable.

Forecast Error under the Concept of Log-inflation

If the log-inflation is estimated as $\hat{i}_t$ for period *t*, then the predicted log-cost at the end of period t can be expressed as:

$$\hat{p}_t = p_0 + \sum_{j=1}^{t} \hat{i}_j \tag{7-12}$$

The error in predicting log-cost p_t is

$$e_t = p_t - \hat{p}_t = \sum_{j=1}^{t} (\Delta p_j - \Delta \hat{p}_j) \tag{7-13}$$

For the unit cost series, we have

$$\ln P_t - \ln \hat{P}_t = e_t \tag{7-14}$$

or

$$\frac{P_t}{\hat{P}_t} = \exp(e_t) \tag{7-15}$$

or

$$\frac{P_t - \hat{P}_t}{P_t} = 1 - \exp(-e_t) \tag{7-16}$$

Thus the error in predicting P_t can be obtained through the error in predicting p_t .

Basic Concepts of ARIMA Models

Stationarity

Stationarity is the foundation of time series analysis. A stochastic process $\{y_t\}$ is said to be stationary if its probability distribution at a fixed time is invariant for all times. However, this strict condition is hard to verify empirically. A weaker version of stationary, called weak stationary, secondary stationary, or covariance stationary, is often assumed. A series {y_t} is weakly stationary if (a) the mean of y_t is constant and (b) the covariance between y_t and y_{t-s} only depends on s, where s is an arbitrary integer.

Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF)

The autocorrelation of a time series is its correlation with itself at different points of time. The autocorrelation between y_t and y_{t-s} is called the lag-s autocorrelation. It is denoted as ρ_s and defined as:

$$\rho_s = \frac{Cov(y_t - y_{t-s})}{\sqrt{Var(y_t)Var(y_{t-s)}}} \qquad (7\text{-}17)$$

The autocorrelation (ACF) between y_t and y_{t-s}, when s>1, is the sum of (a) the direct correlation between y_t and y_{t-s}, and (b) the indirect correlation effect through y_{t-1} to y_{t-s+1}. So partial autocorrelation (PACF) is used to eliminate the indirect effects of intervening values and reflect the direct correlation between y_t and y_{t-s}.

White Noise

A white noise series {ε_t} is a sequence of independent and identically distributed random variables with finite mean and variance. The characteristics of white noise series include (a) zero mean, (b) constant variance σ_ε^2, and (c) all the ACFs are zero.

Autoregressive Models

The autoregressive model of order p for a time series {y_t} is denoted as AR(p) and expressed as:

$$y_t = \phi_0 + \sum_{i=1}^{p} \phi_i y_{t-i} + \varepsilon_t \qquad (7\text{-}18)$$

Where, $\phi_0 \ldots \phi_p$ are parameters of the model, ϕ_0 is a constant; ε_t is a white noise.

Stationarity requires $|\phi_i| < 1$ for all $i = 1 \ldots p$.

Moving Average Models

The moving average model of order q for a time series {y_t} is denoted as MA(q) and expressed as:

$$y_t = \sum_{i=1}^{q} \theta_i \varepsilon_{t-i} + \varepsilon_t \tag{7-19}$$

where, $\theta_0 \ldots \theta_p$ are parameters of the model, $\{\varepsilon_t\}$ is a white noise series.

Moving average models are always stationary.

Autoregressive Moving Average (ARMA) Models

An autoregressive moving average model ARMA(p,q) is a combination of models AR(p) and MA(q).

$$y_t = \phi_0 + \sum_{i=1}^{p} \phi_i y_{t-i} + \sum_{i=1}^{q} \theta_i \varepsilon_{t-i} + \varepsilon_t \tag{7-20}$$

Like a pure AR model, the stationarity of ARMA models requires $|\phi_i| < 1$ for $i = 1 ... p$.

Autoregressive Integrated Moving Average (ARIMA) Models

An autoregressive integrated moving average (ARIMA) model, referred to as the ARIMA(p,d,q) model, is a generalization of an ARMA model. An ARIMA(p,d,q) series can be transformed into a stationary ARMA(p,q) series after d differences. If d is zero, then the model is equivalent to an ARMA model.

Date Collection

Availability of Highway Maintenance Cost Index

To assess the uncertainty of future unit costs for remedial work on warranted highway projects, an appropriate highway maintenance cost index would be ideal for the research. However, little information can be found on such indices.

The Federal Highway Administration used to publish an annual Highway Maintenance and Operations Cost Index. This index was established in 1947 but it was discontinued in the early 1990s due to the small number of users (Kyte and Gillespie, 1998).

Virginia is the only state identified to currently have an official highway Maintenance Cost Index (MCI). The Virginia Department of Transportation uses this index to make adjustments on its allocation of street payments to localities. Kyte and Gillespie (1998) surveyed 15 states, but no state other than Virginia has a formal maintenance cost index.

Highway Construction Cost Index as a Substitute

Since an appropriate highway maintenance cost index is basically unavailable, the highway construction cost index may be tried as a substitute due to their high correlation. Another reason for using a construction cost index is the contractors, who are experienced with construction estimating, may use a construction index too, if they need to do this analysis.

The FHWA publishes a Composite Bid Price Index on National Highway System projects. This index was established in 1972 and is updated quarterly. Annual data since 1972 and quarterly data for recent years are published on the FHWA's website. Some states, such as California, Colorado, Oregon, and Washington, also develop highway construction cost indexes for their respective states.

The Bureau of Labor Statistics (BLS) of the U.S. Department of Labor publishes a Producer Price Index (PPI) for highway and street construction. The index was established in June 1986 and is reported monthly. Both monthly and annual data are available.

Comparatively, the sample size for BLS monthly data is much bigger than the FHWA and other state indices, and may provide more reliable statistical results. So the BLS monthly PPI is chosen for this study.

The BLS Highway and Street Construction PPI Data Set

The monthly data of the highway and street construction PPI series range from June 1986 to December 2005, 235 months in total. The data set is divided into two parts. The data from June 1986 to Jun 2006, called the fit set, are used to build and fit the model. The data from July 2000 to December 2005, called the test set, are kept back for comparing with the out-of-sample prediction from the fitted model. Figure 7-1 is a time plot of the index.

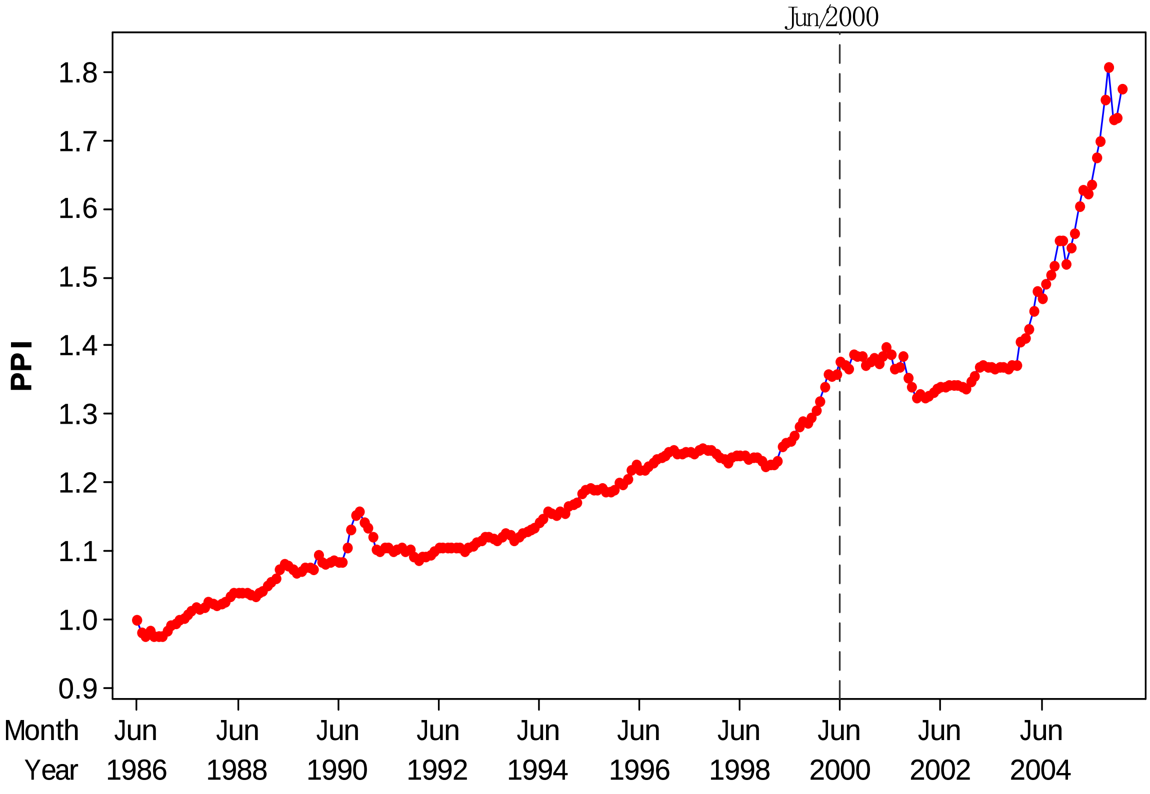

Figure 7-1. Time plot of highway and street construction PPI series

The Box-Jenkins Approach

Box and Jenkins (1976) developed a three-stage method for selecting an appropriate ARIMA model for univariate time series analyses. The three stages suggested by Box and Jenkins are:

- Model identification
- Model estimation
- Model checking

Model Identification

In time series analysis, it is common to formulate a broad set of candidate models and then select one that best fits the data. One way to identify the candidate models is to examine the time plot, the ACF, and the PACF of the raw data and of the suitably differenced series. A non-stationary series may be transformed into a stationary series by differencing or detrending. Formal procedures may be applied to test for the presence of seasonality, or of non-stationarity (unit root).

In modeling a time series, increasing the orders of the model will necessarily reduce the sum of squares of the estimated residuals and increase the R^2. However, the inclusion of extraneous coefficients may reduce the degrees of freedom and the forecast performance of the fitted model. Various model selection criteria have been developed that trade off a reduction in sum squares of residuals for a more parsimonious model. The most widely used criterion is the Akaike Information Criterion (AIC).

Model Estimation

In this stage, each of the tentatively selected models is fitted to the data. Statistical software, such as SAS, MiniTab, and SPSS, will be helpful for model estimation and diagnostic checking. In this study, the data are analyzed using MiniTab.

Model Verification

This stage is to ensure that the fitted model is consistent with the properties of the given data. Diagnostic checks on the residuals, which are the one-step-ahead forecasting errors, will be conducted. The ACF and the Ljung-Box portmanteau test are usually used to test for adequacy. If the model is adequate, the residual should form a random series. If the checks fail, the original model should be further modified.

Out-of-sample predictions provide another way to validate the model. One common approach is to divide the data into two parts, fit the model to the fit set, and compare the prediction from the model to the test set.

Model Identification

Data Transformation

The time plot of the index in Figure 7-1 shows a significant trend of increase with an upward curve. Now we take the natural logarithm of the PPI, call it log-PPI and denote it as $\{ p_t \}$. We have

$$p_t = \ln(PPI_t) \tag{7-21}$$

A time plot of the log-PPI series $\{ p_t \}$ is shown in Figure 7-2. The log-PPI time plot removes part of the upward curvature in the PPI plot, so the log-price series is more likely to follow a linear model than the PPI series.

Unit-Root Test

The upward trend in the log-PPI series suggests it is unit-root non-stationary since there is no fixed level for the series. The ACF in Figure 7-3 and PACF in Figure 7-4 also indicate that there is a single near unit significant PACF at lag-1. It is called a unit-root non-stationary because unit roots exist in the ARIMA process. Recall that stationarity requires the autoregression parameters to be less than 1 in absolute value. If this requirement is violated, the random process will be non-stationary and become an ARIMA process.

The well-known Augmented Dickey-Fuller (ADF) test is used to verify the existence of unit roots in ARIMA models. A *p*-th order autoregressive model AP(p) can be written as:

$$y_t = c + \gamma y_{t-1} + \sum_{i=1}^{p-1} \phi_i \Delta y_{t-i} + \varepsilon_t \tag{7-22}$$

where c_t is a constant or zero and $\Delta y_j = y_j - y_{j-1}$ is the first difference of y_t.

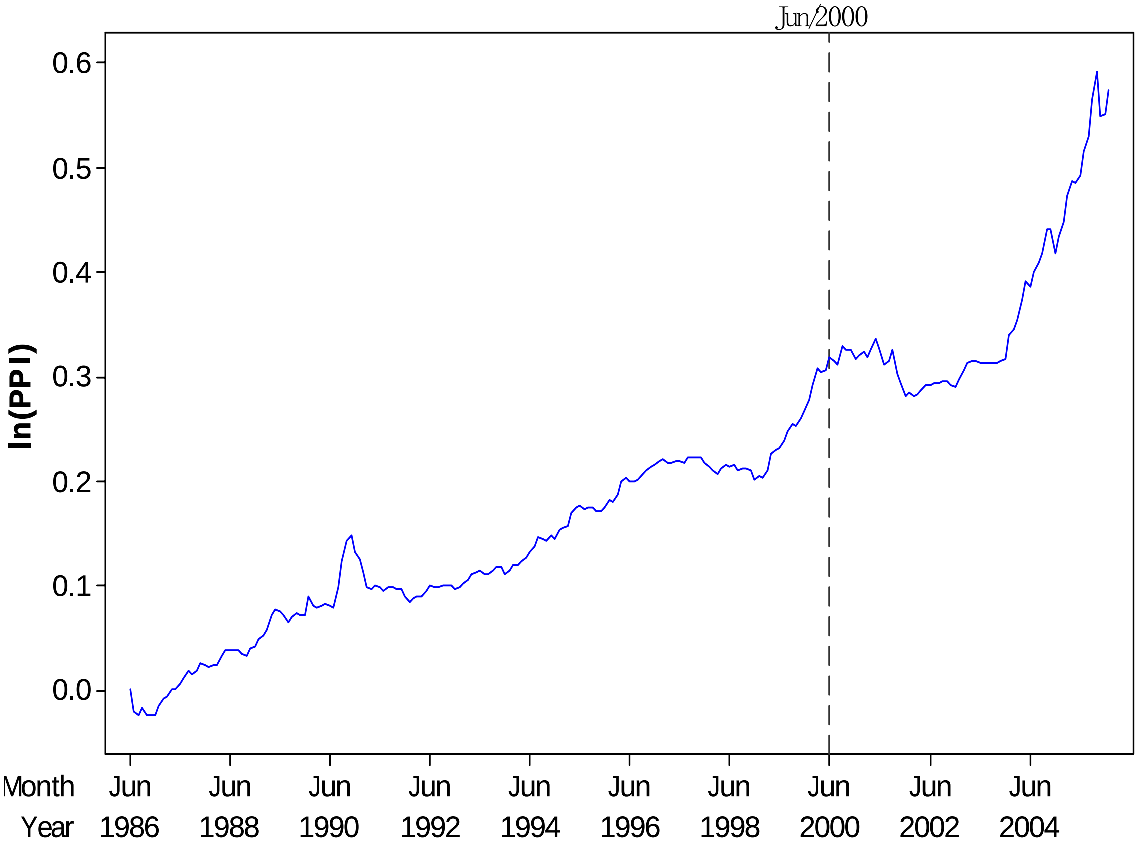

Figure 7-2. Time plot of log-PPI

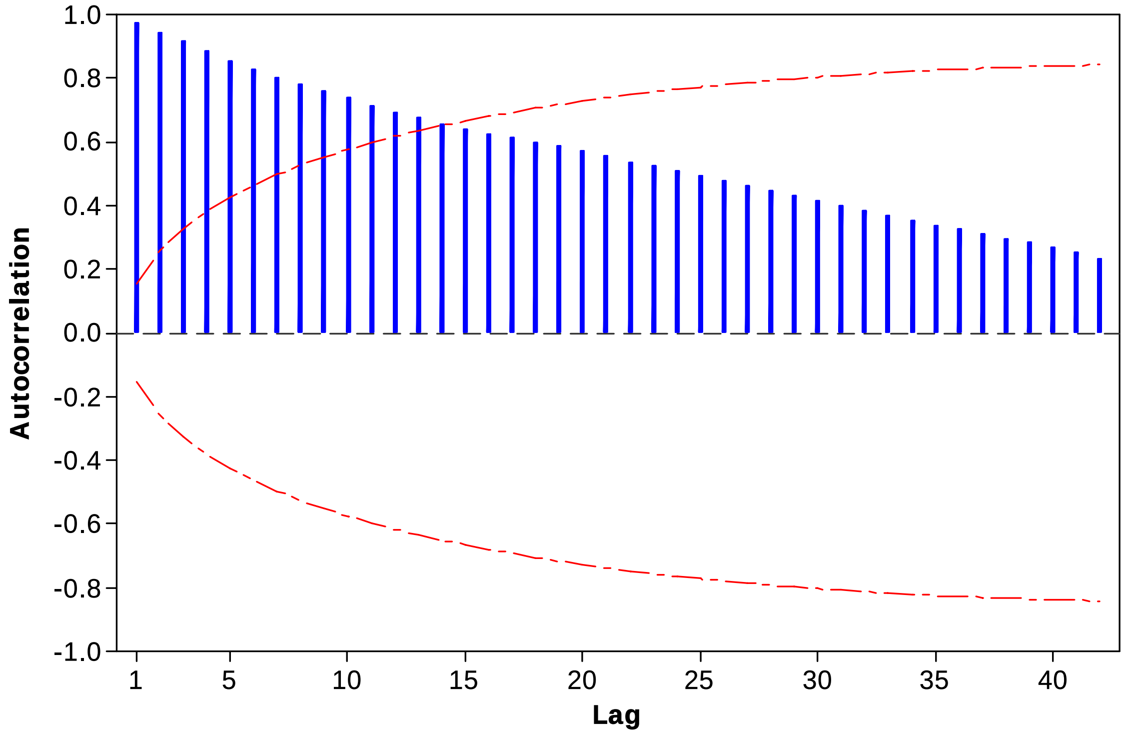

Figure 7-3. Autocorrelation function (ACF) for log-PPI

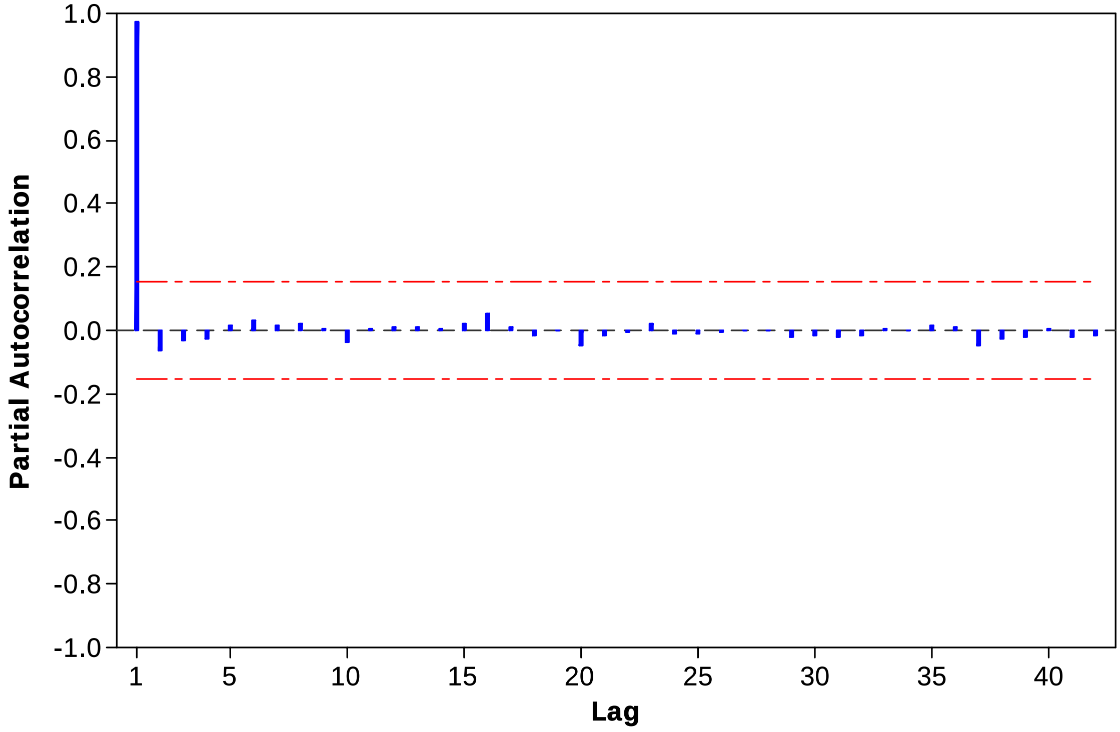

Figure 7-4. Partial autocorrelation function (PACF) for log-PPI

The hypothesis is H$_0$: $\gamma = 1$ versus H$_a$: $\gamma < 1$. The t-ratio of $\hat{\gamma} - 1$ can be calculated as:

$$ADF = \frac{\hat{\gamma} - 1}{std(\hat{\gamma})}$$

where $\hat{\gamma}$ is the least squares estimate of γ.

Equation (7-22) can be rewritten as:

$$\Delta y_t = c + \gamma_c y_{t-1} + \sum_{i=1}^{p-1} \phi_i \Delta y_{t-i} + \varepsilon_t \qquad (7\text{-}23)$$

where $\gamma_c = \gamma - 1$. Then the equivalent hypothesis is H$_0$: $\gamma_c = 0$ versus H$_a$: $\gamma_c < 0$.

The ADF unit-root test is applied to the fit set of the log-PPI series using Excel add-in developed by Annen (2005). We choose $p = 1$. Other values of *p* are also used, but they do not alternate the conclusion of the test. With $p = 1$, the resulting ADF test statistic is -0.0195 with p-value 0.9547, which indicates that the unit-root hypothesis cannot be rejected at any reasonable significance level. Thus the log-PPI series is a unit-root non-stationary series. Difference is needed to transform it into a stationary series.

Model Identification

Taking the first difference of the series {p_t}, we obtain a new series {Δp_t}, where

$$\Delta p_t = p_t - p_{t-1} \qquad (7\text{-}24)$$

is the log-inflation in time period *t*. A time plot of the {Δp_t} series is illustrated in Figure 7-5. There is no obvious trend in the mean level of the series. So it is reasonable to assume this series to be weakly stationary.

There are two general approaches for determining the order of ARMA models. One is to use the ACF and PACF, and the other is to use some information criteria.

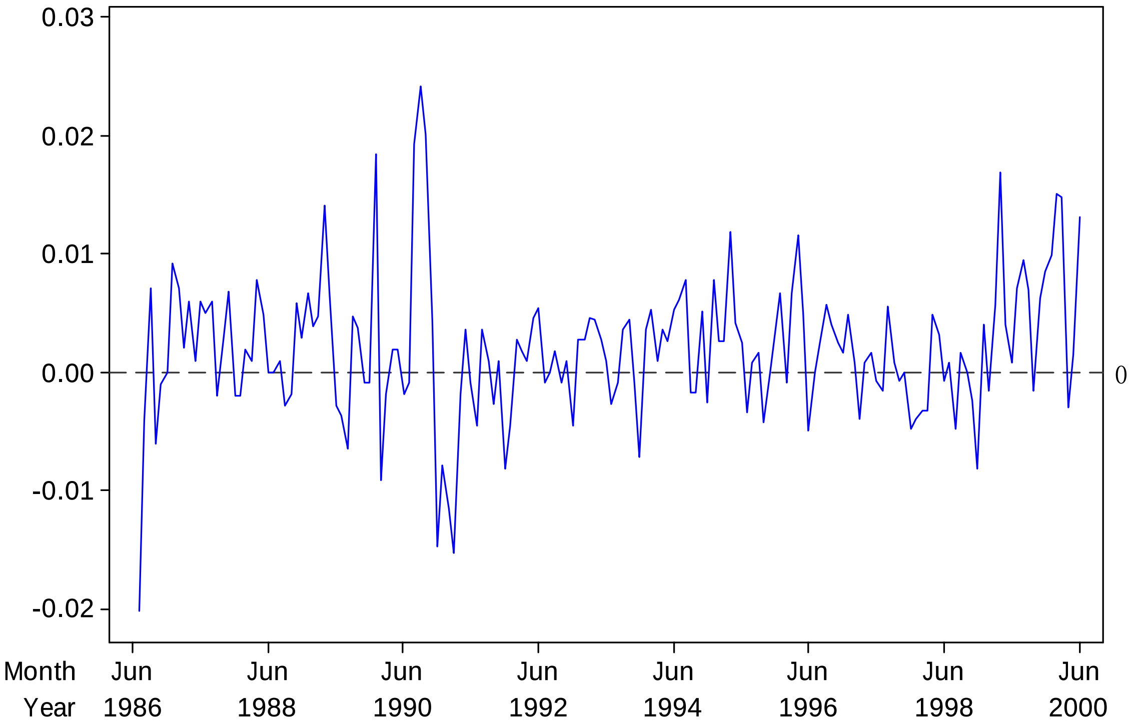

Figure 7-5. Time plot of first difference of log-PPI

The ACF and PACF of the $\{\Delta p_t\}$ series are shown in Figures 7-6 and 7-7. The two dash dotted lines of the plot denote an approximate 95% confidence interval. It can be seen that the lag-1 PACF is significant at the 95% confident level, lag-9 and lag-13 PACF's are only marginally significant. Thus the PACF suggests we consider models AR(1), AR(9), and AR(13) for the $\{\Delta p_t\}$ series.

Several information criteria are available for determining the order of an autoregressive model. The well-known Akaike Information Criterion (AIC) is defined as:

$$AIC = \frac{-2}{N}\ln(likelihood) + \frac{2}{N}(number\ of\ \ parameters) \qquad (7\text{-}25)$$

where N is the sample size (Tsay 2005). The model with the lowest AIC value is preferred by the criterion.

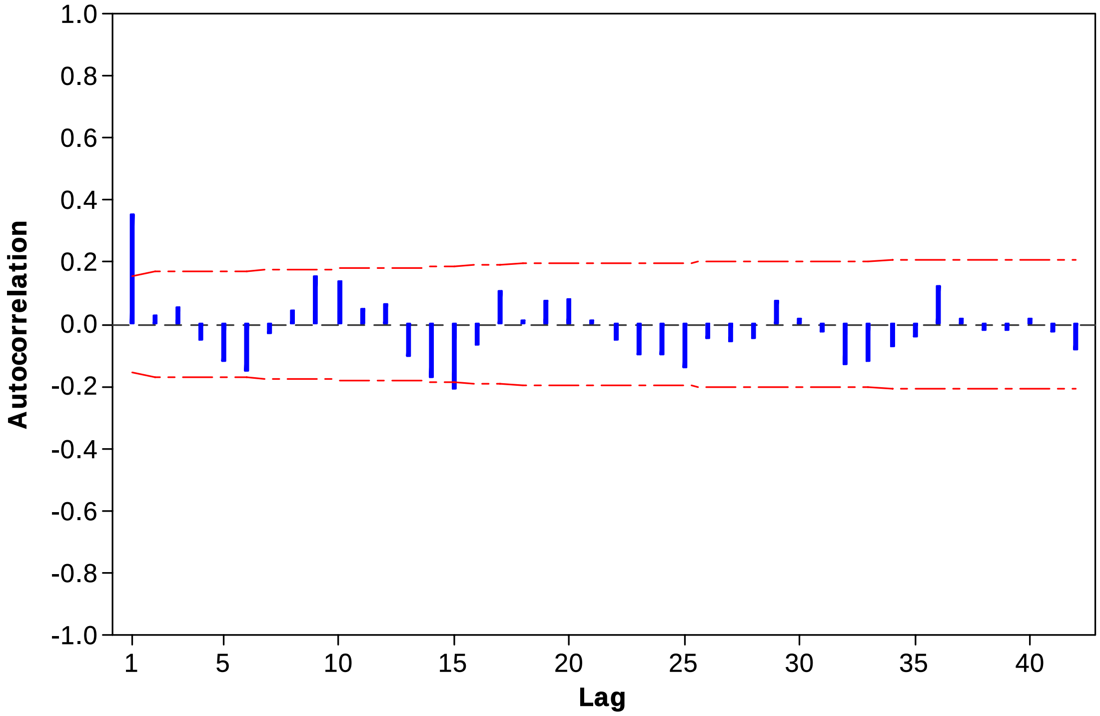

Figure 7-6. Autocorrelation function (ACF) for log-inflation

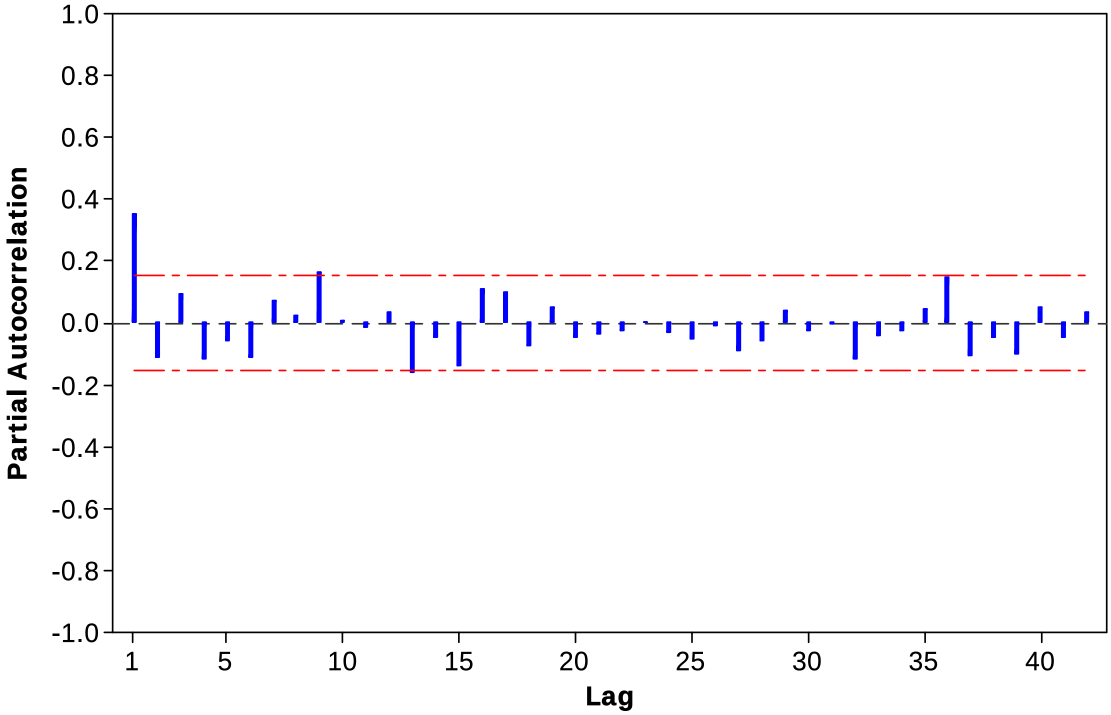

Figure 7-7. Partial autocorrelation function (PACF) for log-inflation

Table 7.1 gives the AIC for autoregressive models for { Δp_t } series with order p = 1….13. The minimum AIC value -9.4069 occurs at p = 4, suggesting that the AR(4) model is preferred by the criterion.

Table 7-1. AIC for first difference series of log-PPI

p	1	2	3	4	5	6	7
AIC	-9.4028	-9.4007	-9.3961	-9.4069	-9.3925	-9.3883	-9.3839
P	8	9	10	11	12	13	
AIC	-9.3665	-9.3764	-9.3648	-9.3451	-9.3330	-9.3506	

Considering the results from both approaches, AR(1) and AR(4) models are selected as tentative candidates for the { Δp_t } series. AR(4) is suggested by the AIC. AR(1) is suggested by the PACF with an AIC value which is very close to the minimum.

It should be noted that the autoregressive (AR) model mentioned above is for the differenced series { Δp_t }. For the log-price series { p_t }, the two corresponding candidate models are called ARIMA(1,1,0) and ARIMA(4,1,0).

Model Estimation

Parameters for the two candidate models are estimated using MiniTab. Printouts from MiniTab are included in Appendix C.

The ARIMA(1,1,0) model is fitted as:

$$\Delta p_t = 0.001129 + 0.3925\Delta p_{t-1} + \varepsilon_t \qquad \hat{\sigma}_\varepsilon = 0.005623 \qquad (7\text{-}26)$$

The ARIMA(4,1,0) model is fitted as

$$\Delta p_t = 0.001307 + 0.4517\Delta p_{t-1} - 0.1859\Delta p_{t-2} + 0.1369\Delta p_{t-3} - 0.0994\Delta p_{t-4} + \varepsilon_t$$

$$\hat{\sigma}_\varepsilon = 0.005589 \qquad (7\text{-}27)$$

The t-statistics for the parameters are shown in Table 7-2. All parameters of the ARIMA(1,1,0) model are statistically significant at the 1% confidence level. For model

ARIMA(4,1,0), only ϕ_0 , ϕ_1 , and ϕ_2 are significant at the 5% confidence level; other parameters, ϕ_3 and ϕ_3 are not significant from zero.

Table 7-2. Estimation of parameters for models AR(1) and AR(4)

Model	Parameter	Coefficient	SE Coef	T	P
ARIMA(1,1,0)	ϕ_0	0.001129	0.000434	2.60	0.010
	ϕ_1	0.3925	0.0719	5.46	0.000
ARIMA(4,1,0)	ϕ_0	0.001307	0.000431	3.03	0.003
	ϕ_1	0.4517	0.0783	5.77	0.000
	ϕ_2	-0.1859	0.0855	-2.18	0.031
	ϕ_3	0.1369	0.0863	1.59	0.115
	ϕ_4	-0.0994	0.0803	-1.24	0.218

Model Verification

In Sample Diagnostic Check

Diagnostic checks on the residuals are performed to check for possible model inadequacies. If a fitted model is adequate, the residuals should form a random series, or called a white noise. The ACF and the Ljung-Box statistics of the residuals can be used to check the closeness of the residuals series to a white noise.

The residual plot for the ARIMA(1,1,0) model is shown in Figure 7-8. It can be seen that the residuals distribute randomly around the zero level. The pattern in the distribution of the residuals does not change over time. The normal plot shows that the residuals follow approximately a normal distribution, but the tails deviate from the fitted line.

The ACF and PACF of the residuals of the ARIMA(1,1,0) model are shown in Figures 7-9 and 7-10. No ACF at any lag is significant at the 5% confidence level. The PACF, however, is marginally significant at lags 15 and 36.

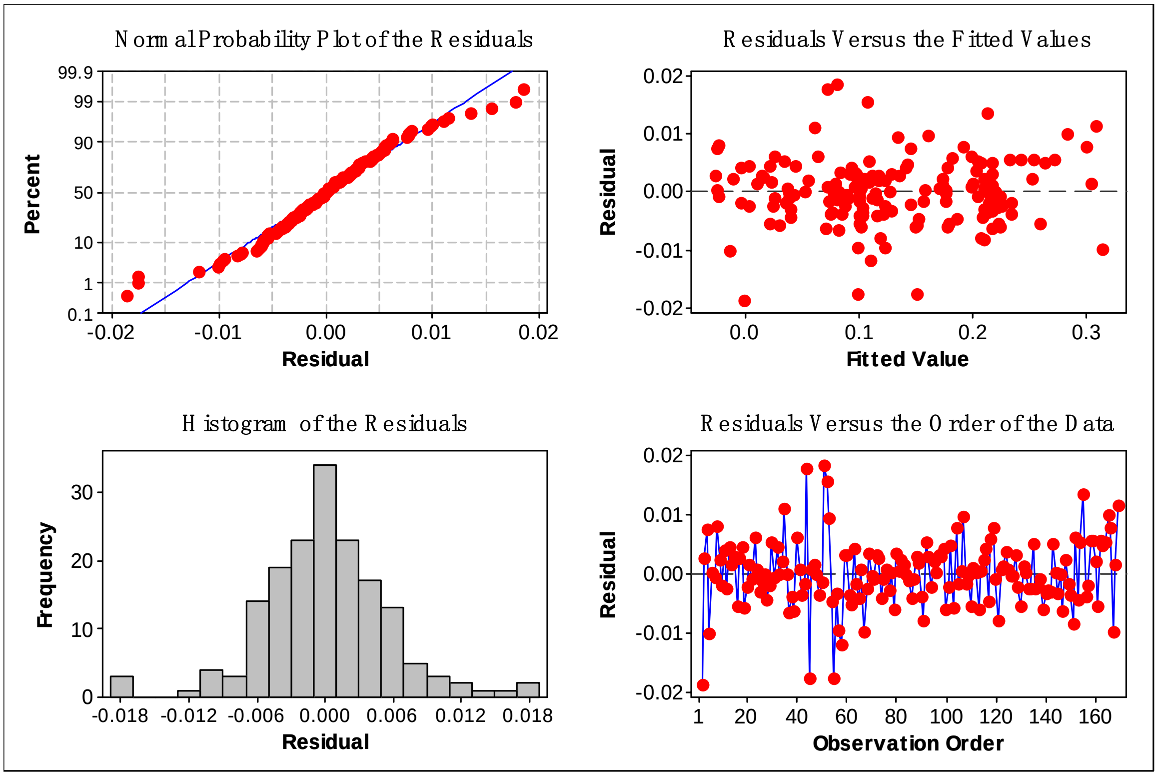

Figure 7-8. Residual plot of log-inflation, ARIMA(1,1,0)

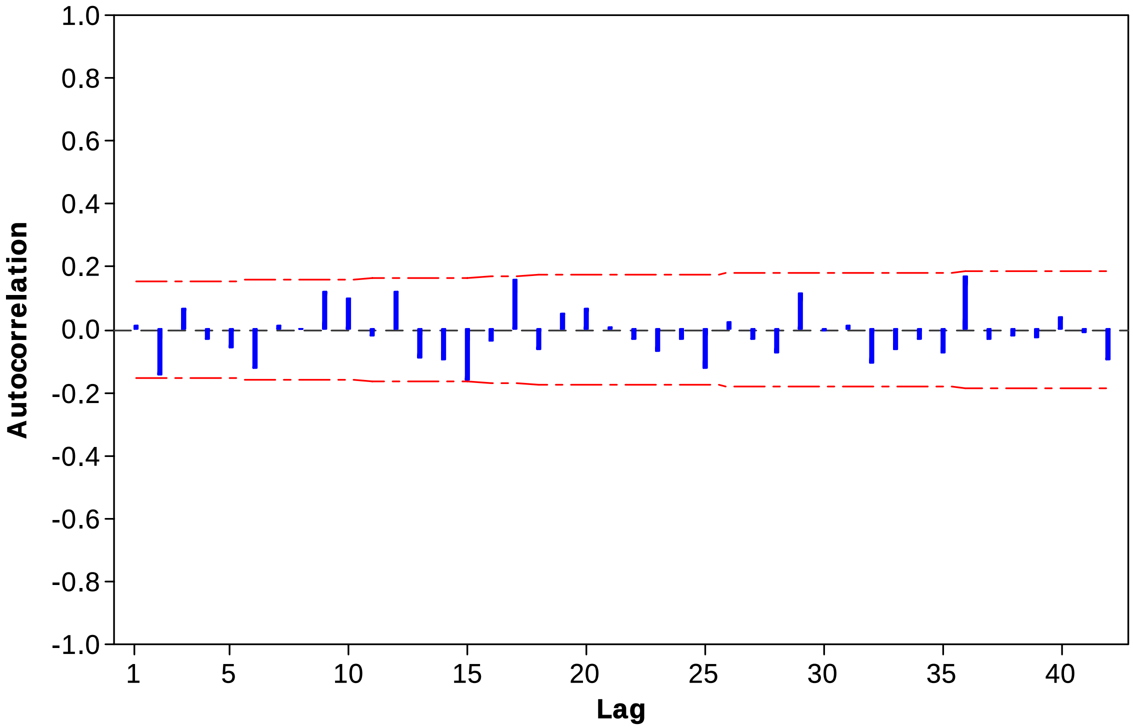

Figure 7-9. ACF of residuals of log-inflation, ARIMA(1,1,0)

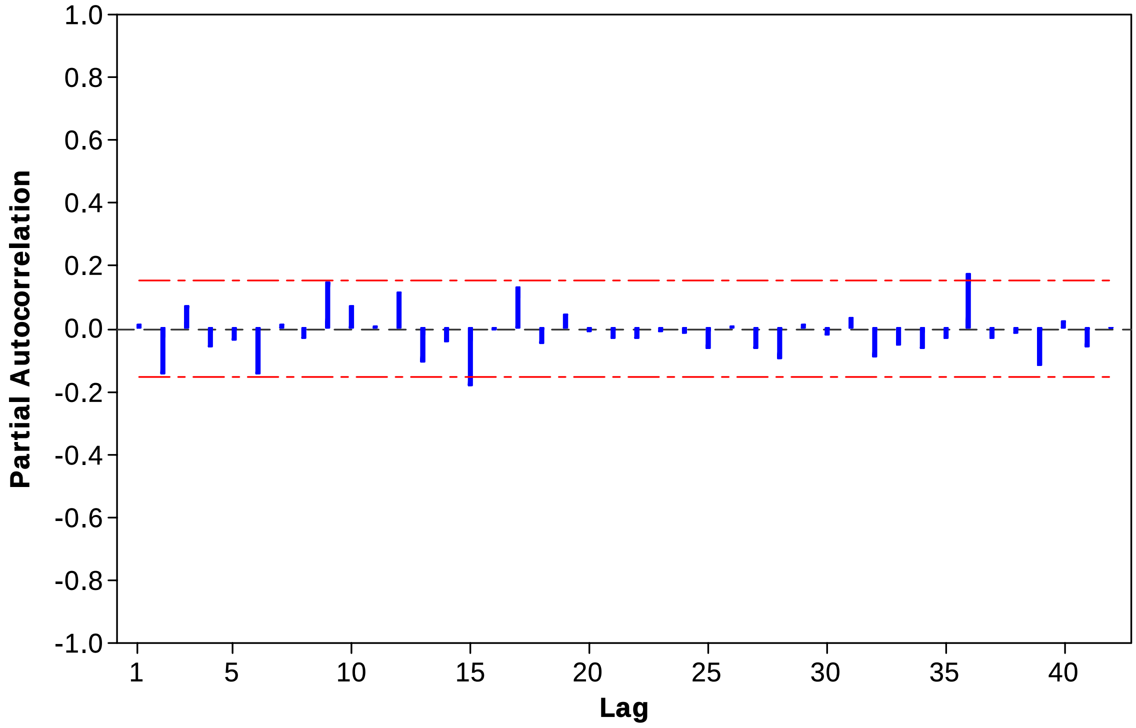

Figure 7-10. PACF of residuals of log-inflation, ARIMA(1)

The Ljung-Box Portmanteau test is used to test jointly that several autocorrelations are zero. The hypothesis is H$_0$: $\rho_1 = \rho_2 = \ldots = \rho_m = 0$ versus H$_a$: $\rho_i \neq 0$ for some $i \in \{1,\ldots,m\}$. The statistic is:

$$Q(m) = N(N+2)\sum_{l=1}^{m}\frac{\hat{\rho}_l^2}{N-l} \qquad (7\text{-}28)$$

where ρ_l is the autocorrelation of lag *l*, N is the sample size. The decision rule is to reject H$_0$ if $Q(m) > \chi_\alpha^2$. If the p-value is provided, the decision rule is to reject H$_0$ if p-value is less than α, the significance level.

The Ljung-Box statistics for selected lags are listed in Table 7-3. The statistic is significant at 5% confident level when m takes the values of 5, 12, 24, or 48. It is non-significant when m = 36. Simulation studies suggest the choice of $m \approx \ln(N)$ provides better power performance (Tsay 2005). In the case, N=168, we choose m=5, then the p-value is 0.171, indicating insignificant serial correlations in the residual series.

Table 7-3. Ljung-Box Portmanteau statistic for AR(1) model

Lag	5	12	24	36	48
Chi-Square	5.0	14.9	31.2	49.2	56.8
DF	3	10	22	34	46
P-Value	0.171	0.137	0.093	0.044	0.133

The residual plot for the ARIMA(4,1,0) model is shown in Figure 7-11. It can be seen that the residuals distributed randomly around the zero level without significant pattern. The normal plot shows that the residuals follow approximately a normal distribution, but the tails deviate from the fitted line.

The ACF and PACF of the residuals of the ARIMA(4,1,0) model are shown in Figures 7-12 and 7-13. No ACF at any lag is significant at a 5% confidence level. The PACF, however, is marginally significant at lags 17 and 36.

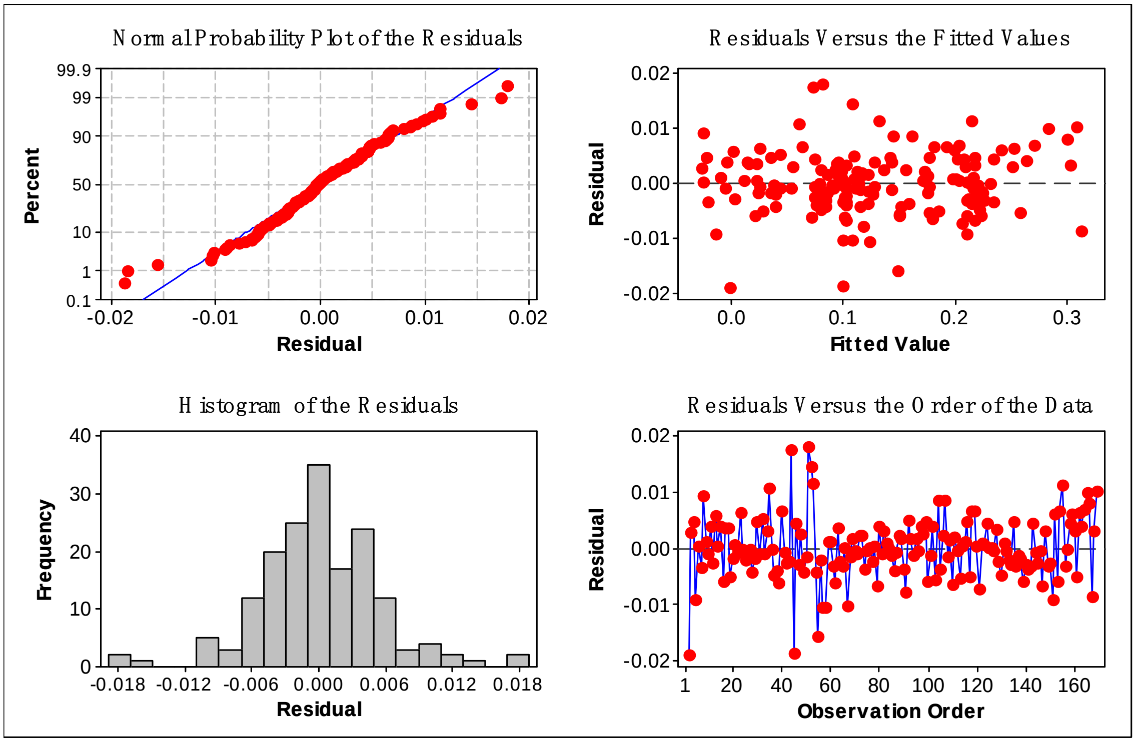

Figure 7-11. Residual plot of log-inflation, ARIMA(4,1,0)

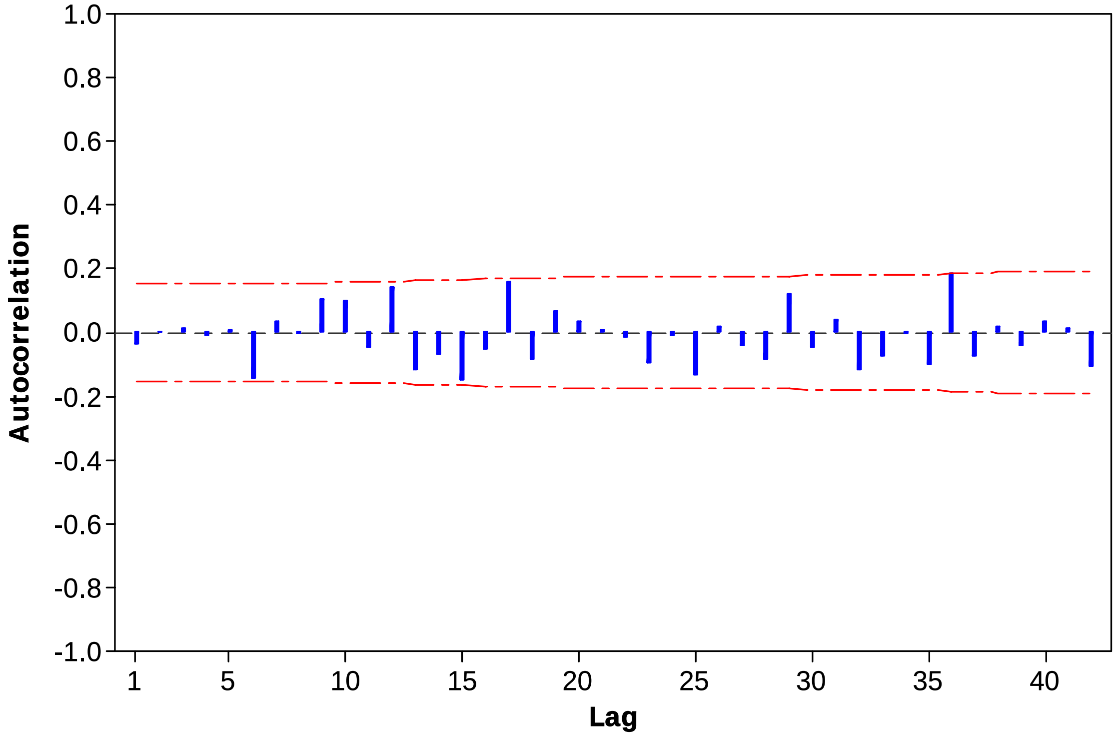

Figure 7-12. ACF of residuals of log-inflation ARIMA(4,1,0) model

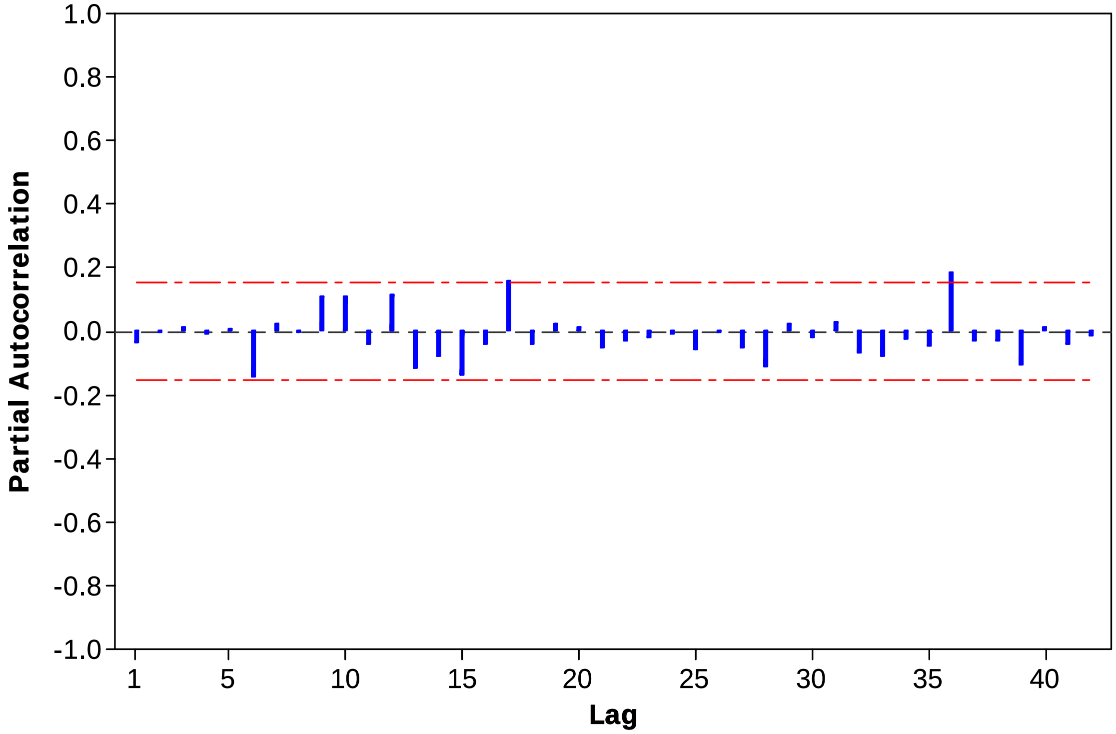

Figure 7-13. PACF of residuals of log-inflation ARIMA(4,1,0) model

The Ljung-Box statistics for selected values of m are listed in Table 7-4. The statistic is significant at the 5% confidence level when the value of m is 6, 12, or 24. It is non-significant when m is 36 or 48. If we choose m=6 for better power performance, the p-value is 0.052, indicating no significant serial correlation in the residuals.

Table 7-4. Ljung-Box Portmanteau statistic for AR(4) model

Lag	6	12	24	36	48
Chi-Square	3.79	11.8	28.7	51.2	62.5
DF	1	7	19	31	43
P-Value	0.052	0.107	0.070	0.013	0.028

In summary, the residuals from both the ARIMA(1,1,0) and the ARIMA(4,1,0) models distribute randomly around the zero level without significant pattern. The Ljung-Box tests indicate no significant correlation within the residuals. Both the ARIMA(1,1,0) and ARIMA(4,1,0) models are adequate for the fit set data.

Out-of-sample Model Verification

The out-of-sample model verification is approached by means of forecast monitoring, where the out-of-sample one-step-forecast errors are analyzed one at a time as each new observation is available. The formula used to calculate the out-of-sample one-step-forecast errors is the same as for the in-sample residuals, but the forecast is on an out-of-sample basis.

The out-of-sample one-step-forecasts are made using the test set data ranging from July 2000 to December 2005. The ACF and PACF of the out-of-sample one-step-forecast errors for model ARIMA(1,1,0) are plotted in Figures 7-14 and 7-15. It can be seen that both ACF and PACF are non-significant at any lag at the 5% confidence level. This indicates that the out-of-sample one-step-forecast errors form a random series, and the ARIMA(1,1,0) model is adequate on the test set data.

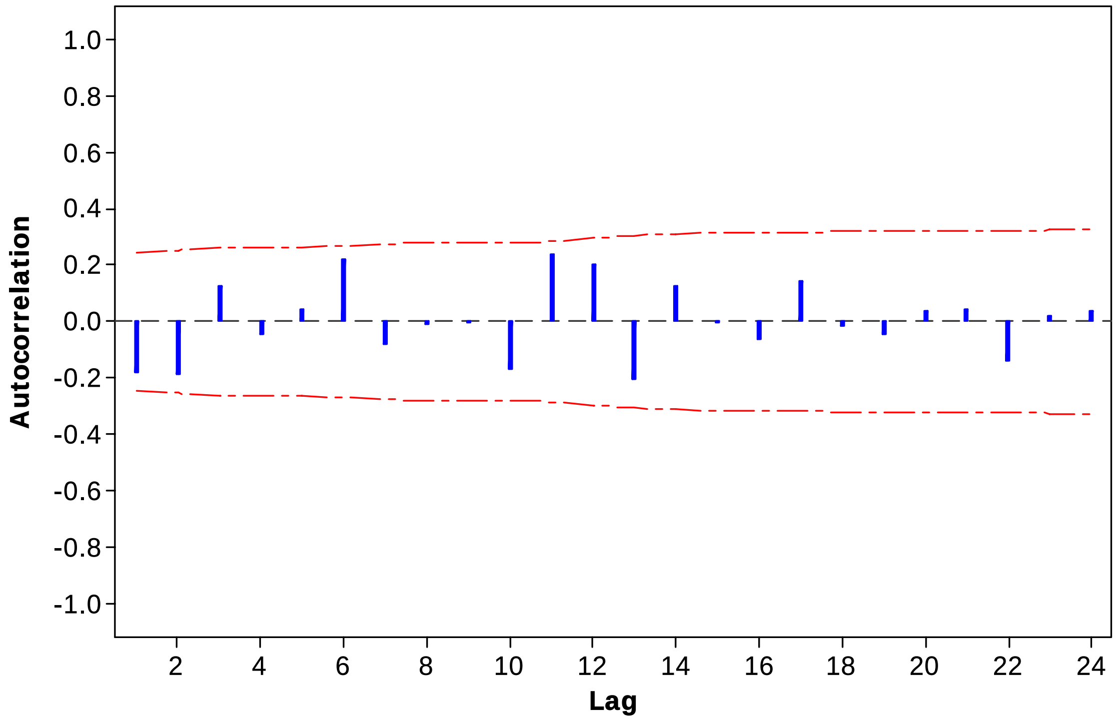

Figure 7-14. ACF of out-of-sample 1-step-forecast errors, ARIMA(1,1,0)

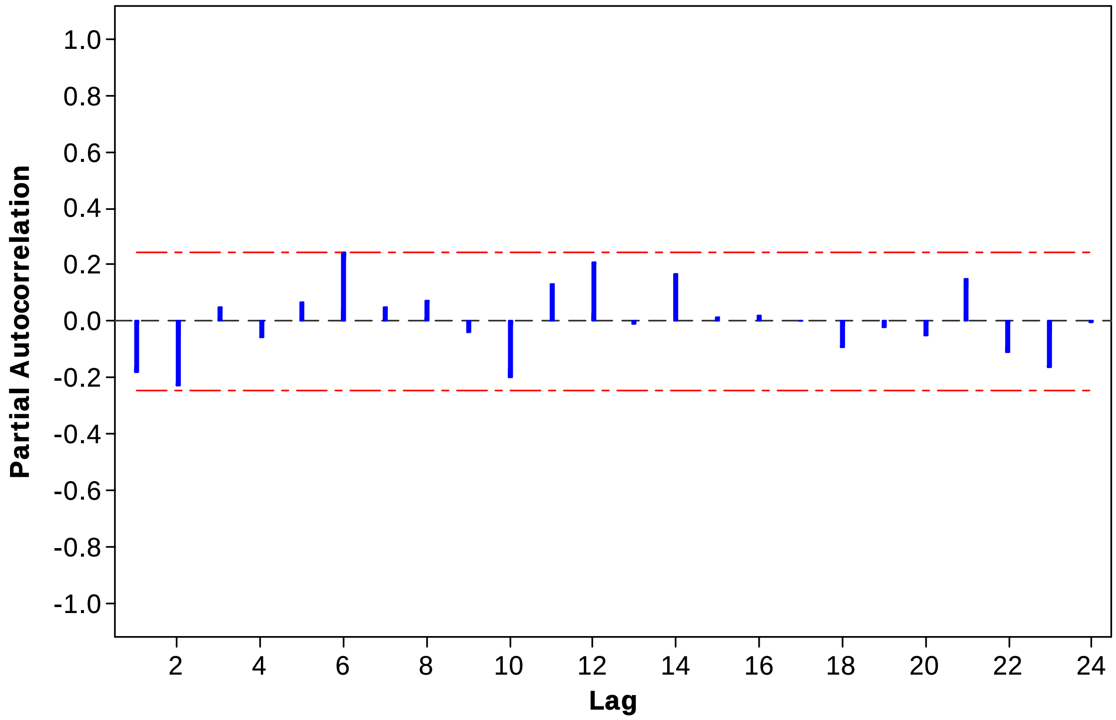

Figure 7-15. PACF of out-of-sample 1-step-forecast errors, ARIMA(1,1,0)

The ACF and PACF of the out-of-sample one-step-forecast errors for model ARIMA(4,1,0) are plotted in Figures 7-16 and 7-17. The ACF is significant at lag 6; the PACF is significant at lags 6 and 12 at the 5% confidence level. This indicates that the out-of-sample one-step-forecast errors do not form a random series, thus the ARIMA(4,1,0) model is inadequate on the test set data.

Final Selection of Model

From the above model checking it is seen that both candidate models passed the diagnostic test. The ARIMA(1,1,0) model is adequate for the test set of data, but the ARIMA(4,1,0) is inadequate. So the ARIMA(1,1,0) model is selected as the final model. The fitted model is

$$\Delta p_t = \phi_0 + \phi_1 \Delta p_{t-1} + \varepsilon_t \qquad (7\text{-}29)$$

or

$$p_t - p_{t-1} = \phi_0 + \phi_1 \Delta p_{t-1} + \varepsilon_t \qquad (7\text{-}30)$$

where, $\phi_0 = 0.001129$

$\phi_1 = 0.3925$

$\hat{\sigma}_\varepsilon = 0.005623$

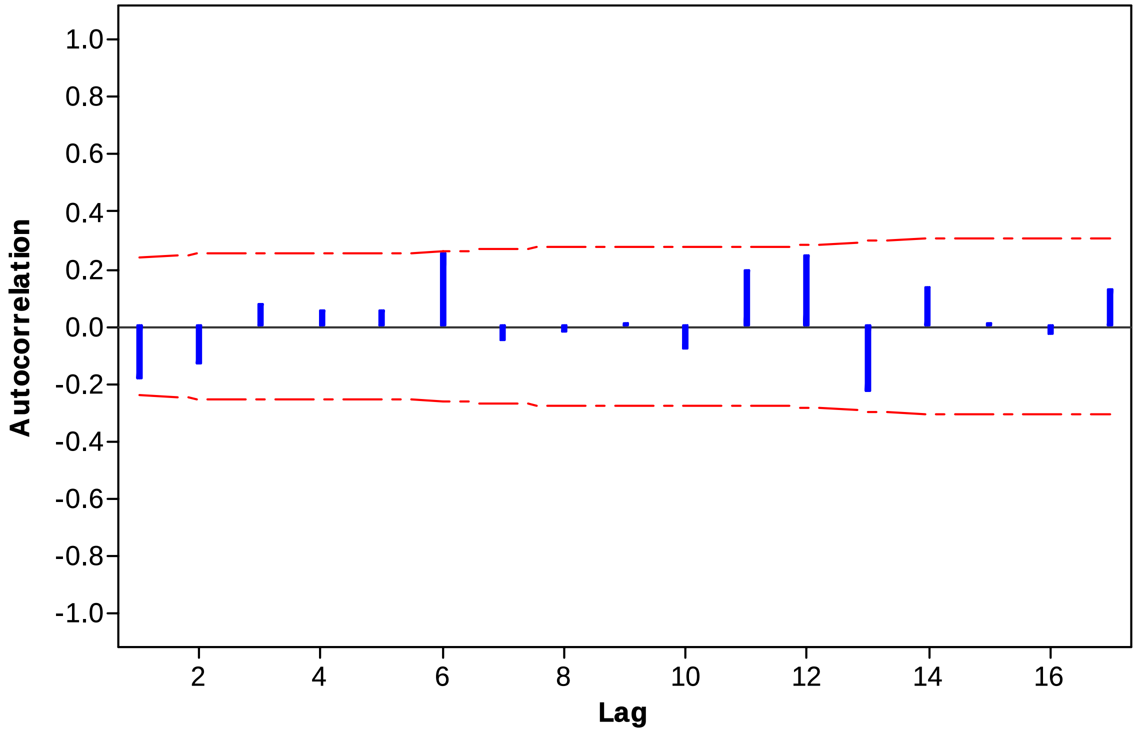

Figure 7-16. ACF of out-of-sample 1-step-forecast errors, ARIMA(4,1,0)

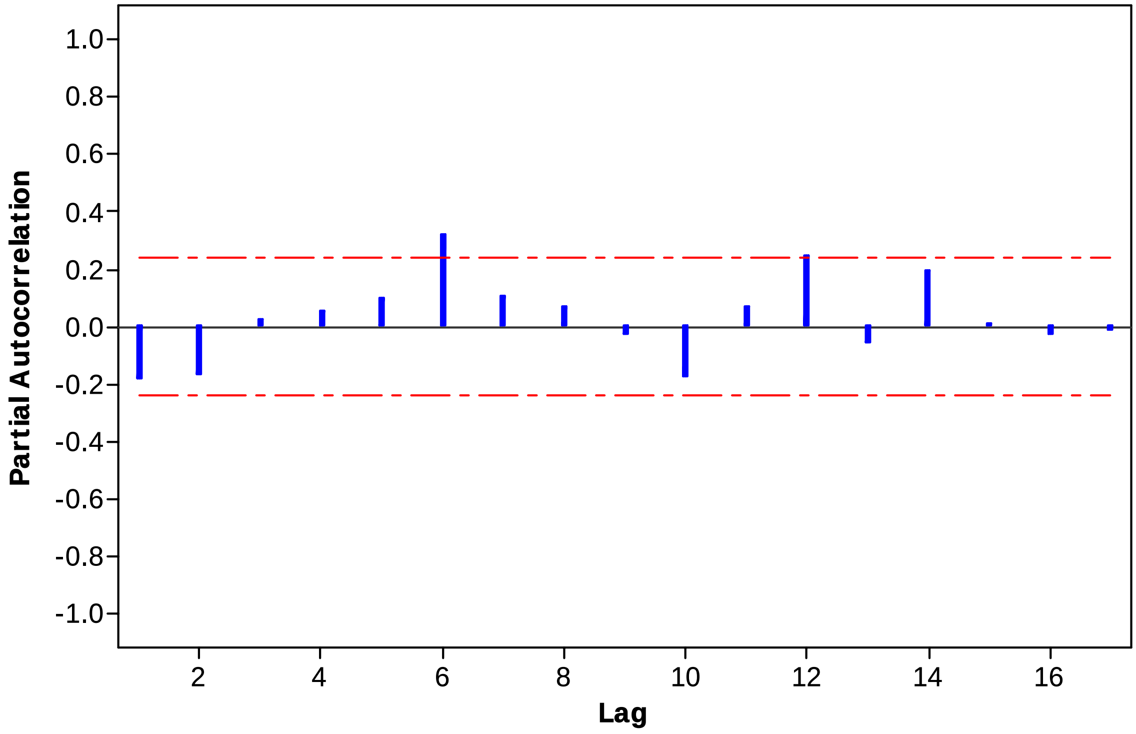

Figure 7-17. PACF of out-of-sample 1-step-forecast errors, ARIMA(4,1,0)

Forecasting

Point Forecast Using ARIMA Model

Future values of the time series are forecasted recursively from the start time point which is called the forecast origin. The total number of forecast periods is called the forecast horizon. Suppose we are at forecast origin *h* and interested in forecasting *l* periods. All of the past and current realizations of { p_t }, { Δp_t }, and { ε_t } are available at time *h*. Let $\Delta \hat{p}_h(l)$ be the forecast of Δp_{h+l}, $\hat{p}_h(l)$ be the forecast of p_{h+l}, and F_h be the collection of information available at time *h*. Then the one-step-ahead forecast is

$$\Delta \hat{p}_h(1) = E(\Delta p_{h+l} \mid F_h) = \phi_0 + \phi_1 \Delta p_h \tag{7-31}$$

$$\hat{p}_h(1) = p_h + \Delta \hat{p}_h(1) \tag{7-32}$$

The two-step-ahead forecast is

$$\Delta \hat{p}_h(2) = E(\Delta p_{h+2} \mid F_h) = \phi_0 + \phi_1 \Delta \hat{p}_h(1) \tag{7-33}$$

$$\hat{p}_h(1) = p_h + \Delta \hat{p}_h(1) + \Delta \hat{p}_h(2) \tag{7-34}$$

The *l*-step-ahead forecast can be obtained as

$$\Delta \hat{p}_h(l) = \phi_0 + \phi_1 \Delta \hat{p}_h(l-1) \tag{7-35}$$

$$\hat{p}_h(l) = p_h + \sum_{i=1}^{l} \Delta \hat{p}_h(i) \tag{7-36}$$

The fit set data from June 1986 to June 2000, 169 observations in total have been used to fit the model. Forecasts must be made for the period from July 2000 to December 2005, 66 months in total. Setting June 1986 as time period 1, the forecast origin is *h* = 169 (June 2000) and the forecast horizon is *l* = 66 (months). Figure 7-18 illustrates the out-of-sample forecasts of Δp_{h+l} using the fitted ARIMA(1,1,0) model. The two dashed lines denote the two standard-error limits of the forecasts.

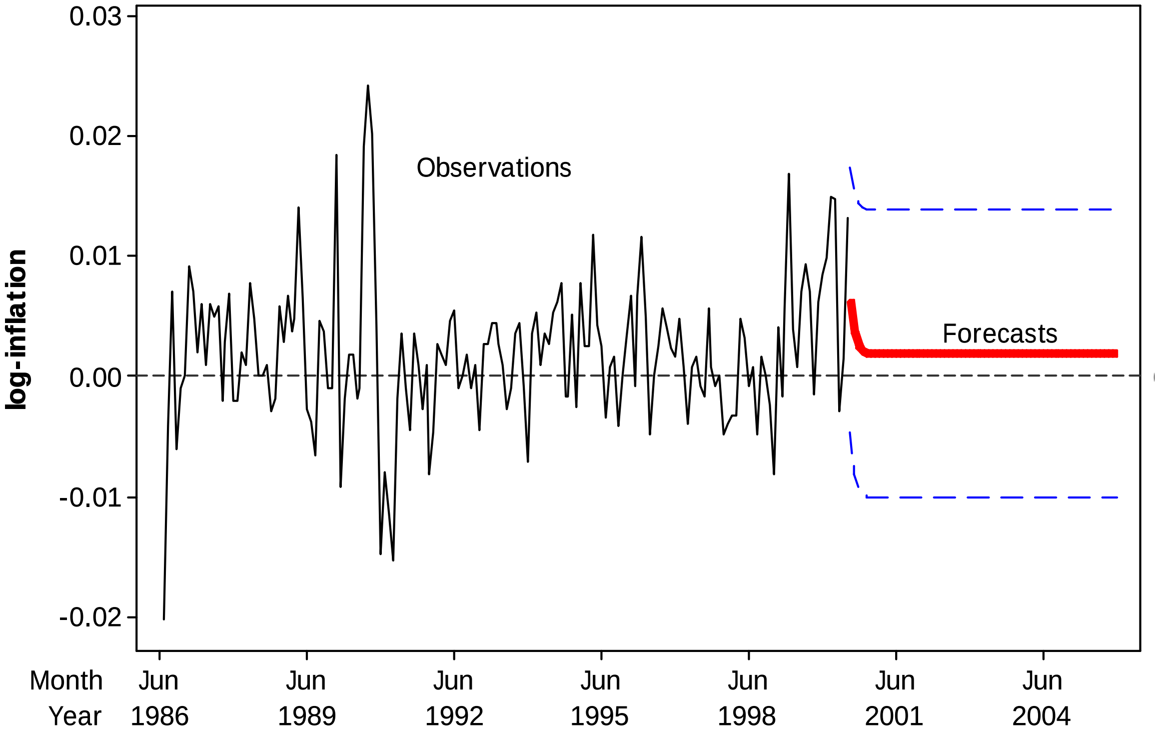

Figure 7-18. Out-of-sample forecasts of log-inflation

It is worth noting that the forecasts of Δp_{h+l} approach the steady level of 0.001858. Actually this is one of the important properties of stationary autoregressive models. In this case, the expectation of Δp_t can be calculated as

$$E(\Delta p_t) = \frac{\phi_0}{1-\phi_1} = \frac{0.001129}{1-0.3925} = 0.001858$$

The non-zero expectation in the $\{\Delta p_t\}$ series indicates that there is a stochastic trend in the $\{p_t\}$ series. The log-PPI, or p_t, is expected to increase by 0.001858 per period in the long run. This is reflected in the out-of-sample forecasts of p_t, as seen in Figure 7-19.

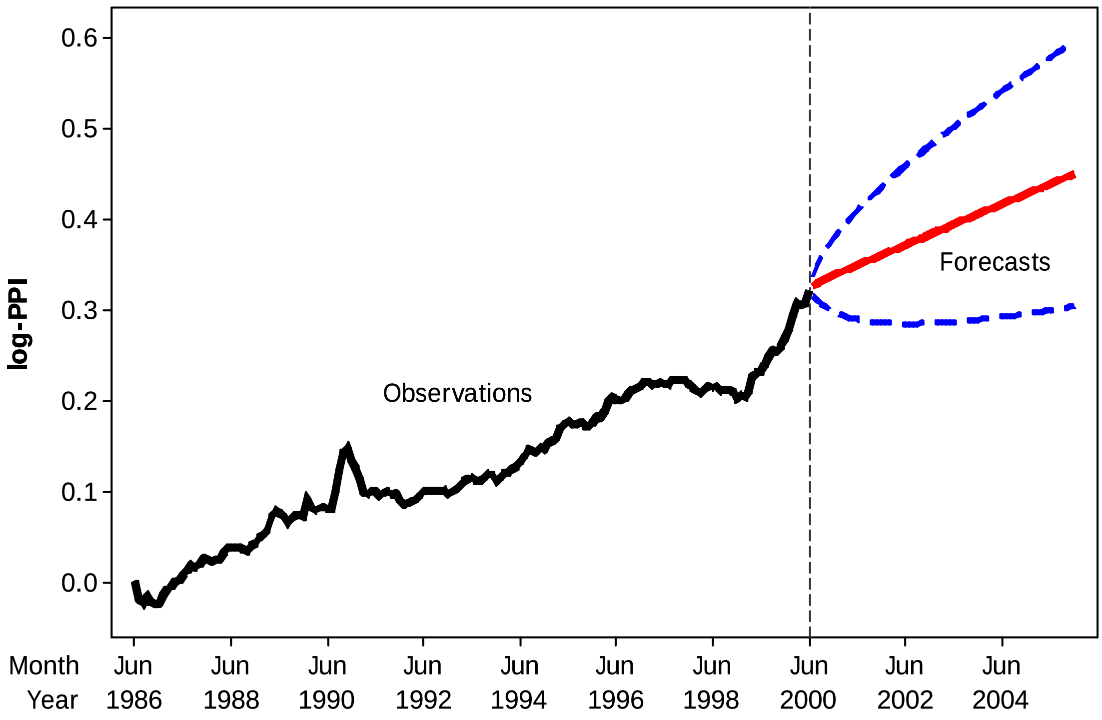

Figure 7-19. Out-of-sample forecasts of log-PPI with 95% confidence interval

Estimating Forecast Error

The ARIMA(1,1,0) model renders

$$\Delta p_{h+1} = \phi_0 + \phi_1 \Delta p_h + \varepsilon_{h+1} \tag{7-37}$$

The point forecast of Δp_{h+1} is calculated using formula (7-31) as

$$\Delta \hat{p}_h(1) = \phi_0 + \phi_1 \Delta p_h$$

Then the associated error in one-step-ahead forecast of $\{\Delta p_t\}$ is

$$e_h(1) = \Delta p_{h+1} - \Delta \hat{p}_h(1) = \varepsilon_{h+1} \tag{7-38}$$

For two-step ahead forecast of $\{\Delta p_t\}$, we have

$$\Delta p_{h+2} = \phi_0 + \phi_1 \Delta p_{h+1} + \varepsilon_{h+2} \tag{7-39}$$

The point forecast of Δp_{h+2} is calculated using formula (7-33) as

$$\Delta \hat{p}_h(2) = \phi_0 + \phi_1 \Delta \hat{p}_h(1)$$

Then the associated error in two-step ahead forecast of { Δp_t } is

$$e_h(2) = \Delta p_{h+2} - \Delta\hat{p}_h(2) = \phi_1[\Delta p_{h+1} - \Delta p_h(1)] + \varepsilon_{h+2}$$

$$= \phi_1 e_h(1) + \varepsilon_{h+2} = \varepsilon_{h+2} + \phi_1 \varepsilon_{h+1} \qquad (7\text{-}40)$$

In general, the error in the *l*-step ahead forecast of { Δp_t } is

$$e_h(l) = \varepsilon_{h+l} + \phi_1 \varepsilon_{h+l-1} + \phi_1^2 \varepsilon_{h+l-2} + \phi_1^3 \varepsilon_{h+l-3} + ... + \phi_1^{l-1} \varepsilon_{h+1} \qquad (7\text{-}41)$$

Since { ε_t } is a white noise with mean zero and variance σ_ε^2, the mean of the forecast error is

$$E[e_h(l)] = 0 \qquad (7\text{-}42)$$

and the variance is

$$Var[e_h(l)] = \sigma_\varepsilon^2[1 + \phi_1^2 + \phi_1^2 + ... + \phi_1^{2(l-1)}] \qquad (7\text{-}43)$$

Since the expected value of the forecast error is zero, the forecast $\Delta\hat{p}_h(l)$ is an unbiased estimate of Δp_{h+l}, but the forecast is necessarily inaccurate, especially when the forecast horizon *l* is long.

By definition,

$$p_{h+l} = p_h + \sum_{i=1}^{l} \Delta p_{h+i} \qquad (7\text{-}44)$$

The point forecast of p_{h+l}, as expressed in Formula (7-36), is

$$\hat{p}_h(l) = p_h + \sum_{i=1}^{l} \Delta\hat{p}_h(i)$$

The associated forecast error can be calculated as

$$e_h^*(l) = p_{h+l} - \hat{p}_h(l) = \sum_{i=1}^{l} [\Delta p_{h+i} - \Delta p_h(i)] = \sum_{i=1}^{l} e_h(i) \qquad (7\text{-}45)$$

Combining formulas (7-41) and (7-45) produces

$$e_h^*(l) = \sum_{j=0}^{l-1} \left(\frac{1-\phi_1^{j+1}}{1-\phi_1} \varepsilon_{h+l-j} \right) \qquad (7\text{-}46)$$

It is reasonable to assume that $e_h^*(l)$ follows a normal distribution with zero mean. Its variance can be calculated as

$$Var[e_h^*(l)] = \sigma_\varepsilon^2 \sum_{j=0}^{l-1} \left(\frac{1-\phi_1^{j+1}}{1-\phi_1} \right)^2 \qquad (7\text{-}47)$$

In the fitted ARIMA(1,1,0) model, $\phi_1 = 0.3925$, $\hat{\sigma}_\varepsilon = 0.005623$. The estimated standard errors of p_{h+l} forecasts for select *l*'s are listed in Table 7-5.

Table 7-5. Standard error of log-PPI forecasts

Forecast horizon	1	12	24	36	48	60
Std error forecast	0.00562	0.03055	0.04429	0.05467	0.06338	0.07103

Since the mean of $e_h^*(l)$ is zero, the forecast of p_{h+l} is unbiased. However, the variance of the forecast error is an increasing function of *l*, meaning more uncertainty in long-term forecasts than in short-term forecasts. As illustrated in Figure 7-19, the 95% confidence interval for log-PPI forecasts gets wider as the forecast horizon increases.

Forecasting PPI

Since the log-PPI series { p_t } is a transform of the PPI series { P_t }, the forecasts of PPI can be easily obtained using the forecasts of log-PPI. The *l*-step-ahead forecast of PPI can be calculated as

$$\hat{P}_h(l) = \exp[\hat{p}_h(l)] \qquad (7\text{-}48)$$

However, cautions should be taken. Since it is assumed the forecast errors of p_{h+l} follow a normal distribution, the forecast errors of P_{h+l} should follow a lognormal distribution. Thus the $\hat{P}_h(l)$ calculated above is the maximum likelihood, and biased, estimate of P_{h+l}.

Denoting the variance of p_{h+l} forecast error as $\sigma^2_{p_h(l)}$ produces an unbiased estimate of P_{h+l} given by

$$\hat{P}^*_h(l) = \exp\left[\hat{p}_h(l) + \frac{\sigma^2_{p_h(l)}}{2}\right] \tag{7-49}$$

The variance of p_{h+l} forecast error is given by

$$Var[P_{h+l} - \hat{P}^*_h(l)] = \exp\left[2\hat{p}_h(l) + \sigma^2_{p_h(l)}\right]\left[\exp(\sigma^2_{p_h(l)}) - 1\right] \tag{7-50}$$

The out-of-sample forecasts along with the observed values of PPI are illustrated in Figure 7-20. Both the biased and the unbiased point forecasts are included. It can be seen that the biased forecasts are always lower than the unbiased forecasts.

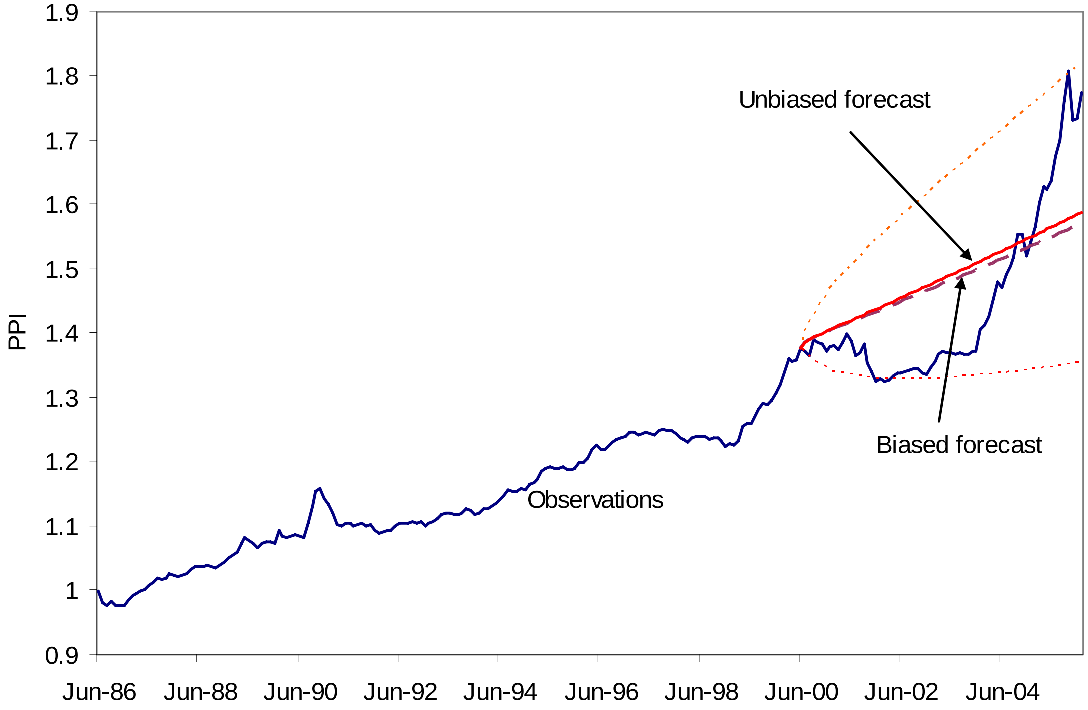

Figure 7-20. Out-of-sample forecasts of PPI

The observed values of the index within the forecast horizon deviate significantly from the point forecasts, either biased or unbiased. Of the 66 forecasts points, four observations are on or below the lower 2.5% line and one observation is above the upper 2.5% line. There were two unusual changes in the economic conditions during the forecast horizon, which were not observed during the time period of the fit set data. One is the unusual economic depression after September 2001 which caused a sudden drop in the index. Another is the oil price shocks since 2004 which caused a fast increase in the index.

Summary

This chapter presents an empirical study of the use of the Box-Jenkins approach to modeling and forecasting future cost escalation. The objective was to provide probabilistic forecasts of future unit costs. The data used for this study is the highway and street construction PPI developed by the Bureau of Labor Statistics. The ARIMA (1,1,0) model is found to fit the data well.

CHAPTER 8
ASSESSMENT OF WARRANTY RISK USING SIMULATION

In the prior two chapters we have seen the development of probability-based models for quantifying the uncertainty in pavement performance and the uncertainty in future unit costs. In this chapter we will try to incorporate all these models and produce a probability distribution of the costs of future remedial works for warranted asphalt paving projects.

Due to the complexity of the system, deriving formulae to assess the uncertainty of future repair costs is very difficult. Thus a Monte Carlo simulation approach is adopted for this analysis. Models developed in Chapters 6 and 7 will be used to generate outcomes of future remedial activities and unit prices. The simulation approach will be illustrated in a case study of a real warranted project.

Assumptions

Risk associated with pavement warranties can be estimated in many ways, including intuitive judgment and analysis of historical data. However, an accurate assessment of warranty risk is almost impossible at this time due to the lack of available information. Many parameters necessary for the assessment are currently unknown and have to be estimated empirically or even intuitively. Assumptions are also needed to simplify the modeling process since the warranty requirements and future pavement performance are usually very complicated.

The simulation approach developed in this chapter is based on the following assumptions:

- The estimation method is based on historical data. In particular, the method uses the pavement distress models developed in Chapter 6 and the price uncertainty model developed in Chapter 7.

- Two basic types of warranties are the materials and workmanship warranty and the performance warranty. Under a performance warranty, the contractor usually assumes full responsibility on remedial work, even if the defects are due to factors out of the control of the contractor. Under a materials and workmanship warranty, the contractor's responsibility is limited to factors within his control. However, no information on the causes of distress is available given the current data used in this analysis. Even in practice, the determination of distress causes is difficult and sometimes inconclusive. So, in this assessment, we assume that all the identified distresses are the potential responsibility of the contractor.

- Each project is independent of any other. There is no correlation between the actual outcomes of warranted repair work between two projects.

- The contractor has no pavement performance data on the projects built by the company. So the estimate of exposure to warranty risk is based on the Florida DOT survey data which are from projects done by many contractors.

- Various types of distresses may occur within the warranty period. Each distress type occurs independently.

- The condition of warranted pavement will be evaluated annually at the end of each year within the warranty period. Remedial work, if needed, will be performed immediately after the evaluation or at the end of the warranty period.

- Evaluation of warranted pavement is conducted LOT by LOT which is usually defined as 0.1 mile per lane. The models developed in Chapter 6, however, are based on pavement survey sections which are much larger than the size of LOT. Since no information on within-project performance variation is available, the pavement evaluation is assumed to be made at the project level.

Simulation Methodology

Unlike many formula-based approaches which calculate the "expected" results using formulae, the Monte Carlo simulation approach is achieved by generating a large number of "actual" future outcomes and analyzing the statistical aspects of these outcomes. An outline of the simulation approach is illustrated in Figure 8-1.

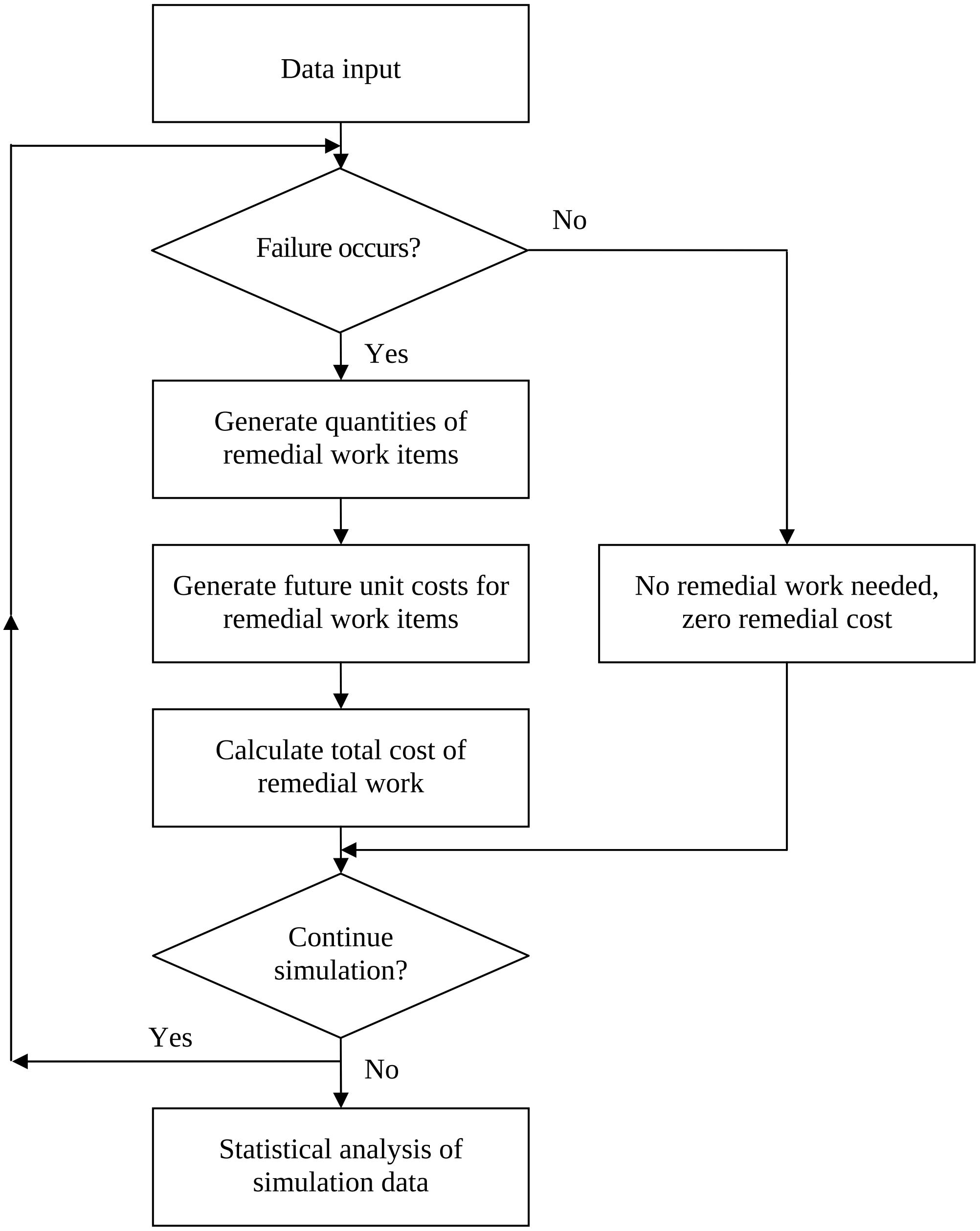

Figure 8-1. Remedial cost simulation flowchart

Determine Failure Time for Each Distress Type

In Chapter 6 probability distribution models for various types of distresses were developed. The cumulative distribution function, $F(t)$, is the probability that a pavement will fail by time t. $F(t)$ is a strictly monotonic increasing continuous function of t. If its inverse function, $F^{-1}(\upsilon)$, is well-defined for $0 \le \upsilon \le 1$, then

$$t = F^{-1}(\upsilon) \tag{8-1}$$

is the time that a pavement has a probability of υ to fail, and υ is uniformly distributed on $[0,1]$, called a $U(0,1)$ random variable. Thus the inversion of the CDF can be used to sample the failure time of a distress type.

The Weibull distribution is fitted to model rutting and ride failure time in Chapter 6. The inversion of the CDF for Weibull can be expressed as

$$t = \alpha\left[-\ln(1-\upsilon)\right]^{1/\gamma} \tag{8-2}$$

where α is the scale parameter and γ is the shape parameter.

Loglogistic models are fitted in Chapter 6 to model cracking failure time. The inversion of the loglogistic CDF can be expressed as

$$t = \exp\left[\mu - \sigma\ln\left(\frac{1}{\upsilon} - 1\right)\right] \tag{8-3}$$

where μ is the location parameter and σ is the scale parameter.

Lognormal is used to model initiation time of raveling, bleeding, and delamination. The exact formula for inverse lognormal CDF is very complicated. Fortunately, many software products provide functions to calculate the inverse value of lognormal models.

The values of the parameters for the models discussed above can be found in Chapter 6. The maximum likelihood estimates of the parameters are restated in Table 8-1.

Table 8-1. Model parameters for pavement failure/defect time simulation

Failure/defect	Model	γ	α	μ	σ
Rutting	Weibull	1.55531	21.7492		
Ride	Weibull	4.73200	14.0424		
Cracking	Loglogistic			1.69968	0.26396
Raveling	Lognormal			2.38193	0.63519
Bleeding	Lognormal			7.57542	4.00969
Delamination	Lognormal			3.34360	0.62194

The warranty term will be denoted as W. In Florida, the current warranty term for asphalt pavements is three years, or $W = 3.$ For any distress type, its failure time t can be simulated using the method discussed above. If a failure time is greater than the warranty term, or $t > W$, then this type of distress does not occur within the warranty term. However, if $t \leq W$, then the specific type of distress is formed within the warranty term and the contractor is responsible for repairing the defects.

The failure time simulated using the method discussed above can be any positive real number. However, pavement condition surveys are usually conducted annually. If it is assumed that the failure or defect can be identified only at the time of survey and the contractor will be asked to perform remedial actions immediately after the survey, then the repair time can be assumed to be the survey time. To simplify the analysis, it is further assumed that the completion of the construction and annual surveys are on the same date in each year; then the repair time will be an integer which can be calculated as

$$t' = \begin{cases} t & if\ t\, is\ an\ \mathrm{int}\, eger \\ \mathrm{int}(t) + 1 & if\ \ t\ is\ not\ an\ \mathrm{int}\, eger \end{cases} \tag{8-4}$$

where t' is the time that the failure is identified, t is the time the failure “actually” formed.

Generate Size of Distressed Areas

If a certain type of distress failure occurs within the warranty term, then it is necessary to generate the size of the distress area that has to be repaired. It is ideal to develop a probability model for the size distribution of the defect area for each failure/defect type. However, this is not easy due to the availability of field data. In Chapter 6, we have developed size distribution models for cracking affected areas (actually it is the sum of cracking, raveling, and patching). But no such model exists for other distress types, including rutting, ride, bleeding, and delamination. Subjective judgments are needed to estimate these factors.

Data input

Three types of input data are allowed for simulating the size of distressed areas, including

- single values
- probability tables
- parametric models

A single value is just a single estimate of the size of the distressed area. It is essentially assumed that the size of a distressed area is a constant. For example, the area affected by bleeding, if it exists, is estimated to be 1% of the entire pavement.

A probability table provides an empirical estimate of the probability distribution of the size of the defective area. Table 6-16 is an example of a probability table for percent pavement cracked.

A parametric model, if well-developed, can be used to simulate the size of defected areas. Lognormal models were fitted in Chapter 6 to model the distribution of percent pavement affected by cracking.

The table-look-up method

The sampling methods applied depend on the types of input data. For a single value estimate, the sampling results will always be equal to the single input value. For example, if a bleeding affected area is assumed to be 1% of the entire pavement, the sampling results will be 1% anyway.

For a probability table input, a “table-look-up” method is applied for sampling. The algorithm is explained as follows.

Assume that a random variable x takes the discrete values X_1, X_2, …, X_n, with probability $q_i = \Pr(x = X_i)$ for $i = 1 \ldots n$. The probability table is illustrated in Table 8-2. To simplify the description, add to the table a dummy outcome X_0 with zero probability, or $\Pr(x = X_0) = 0$. The cumulative distribution function (CDF) can be constructed by

$$F(X_i) = \Pr(x \le X_i) = \sum_{j=1}^{i} \Pr(x = X_i) = \sum_{j=1}^{i} q_j \qquad (8\text{-}5)$$

Table 8-2. A sample probability table

Outcome (x)	Probability $\Pr(x = X_i)$	CDF $\Pr(x \le X_i)$
X_0	0	0
X_1	q_1	q_1
X_2	q_2	$q_1 + q_2$
X_3	q_3	$q_1 + q_2 + q_3$
…	…	…
X_n	q_n	1.00

Select a $U(0,1)$ random variable, υ. The table-look-up algorithm works by choosing a value for υ and finding the probability interval that υ lands. More specifically, if

$$\sum_{j=0}^{i} q_j < \upsilon < \sum_{j=0}^{i+1} q_j$$

then we set $x = X_{i+1}$.

Sampling method for size of cracking affected area

As discussed in Chapter 6, after cracking initially forms, the size of cracked areas tends to grow over time. Cracking initiation time t can be simulated using Formula (8-3). If $t \le W$, then the cracking defect appears within the warranty period. The time t is translated into an integer number t' using Formula (8-4).

If $t' = W$, then cracking is formed in the last year of the warranty period. The size of the cracked area at the end of the warranty period follows the first-year distribution model as listed in Tables 6-16 and 6-17.

If $t' < W$, then cracking is formed at least one year before the warranty expires. The size of the cracked area will grow further over time. At the end of the warranty period, the size of the cracking affected area would have been growing for $W - t'$ years and following a $(W - t' + 1)$-year distribution model.

Table 6-16 gives empirical probability distributions of the sizes of cracking affected areas from Year 1 to Year 5 after cracking initiation. Lognormal models were found to fit the distribution data well for the first three years (see Table 6-17). Therefore, for the 1st, 2nd, or 3rd year distribution, both the inversion of the lognormal model in Table 6-17 and the table-look-up of the empirical CDF in Table 6-16 can be used to sample the size of cracking affected areas. For the 4th and 5th year distribution, however, only the table-look-up method can be used.

It should be noted that the simulation software can handle warranty terms for five years or less because the probability tables for the size of cracking affected areas were developed only for the first five years.

Generate Future Unit costs

An ARIMA(1,1,0) model was fitted for the monthly log-PPI series in Chapter 7. The fitted model (Formula 7-29) is restated as follows

$$\Delta p_m = \phi_0 + \phi_1 \Delta p_{m-1} + \varepsilon_m \qquad (8\text{-}6)$$

where m is the time period measured in months, $\phi_0 = 0.001129$, $\phi_1 = 0.3925$, $\hat{\sigma}_\varepsilon = 0.005623$.

Suppose that the forecast origin h is the bid submission date, the construction is completed T_0 months later. If remedial actions are performed at the end of the t' year, then the forecast horizon l (in months) is calculated as

$$l = T_0 + 12t' \tag{8-7}$$

The future values of the log-PPI series can be generated recursively from the forecast horizon h using formula (8-6). The simulation approach is significantly different from the forecast method described in Chapter 7. First, the forecast method yields an expected, or average, value of future outcomes, while the simulation approach produces "actual" values of future outcomes. Second, the forecast method sets all future shocks ε_m to be zero, while the simulation approach monitors the "actual" future shocks.

The simulation approach is explained as follows.

For each time period m from $h+1$ to $h+l$, a random value is generated for variable ε_m, which follows a normal distribution with a mean of zero and a standard deviation of $\hat{\sigma}_\varepsilon$. The results are listed as follows:

$$\Delta p_{h+1} = \phi_0 + \phi_1 \Delta p_h + \varepsilon_{h+1}$$

$$\Delta p_{h+2} = \phi_0 + \phi_1 \Delta p_{h+1} + \varepsilon_{h+2}$$

…

$$\Delta p_{h+l} = \phi_0 + \phi_1 \Delta p_{h+l-1} + \varepsilon_{h+l}$$

The "actual" log-PPI at period $h+l$ is

$$p_{h+l} = p_h + \sum_{m=h}^{h+l} \Delta p_m \tag{8-8}$$

and the "actual" future unit cost at period $h+l$ will be

$$P_{h+l} = P_h \exp\left(\sum_{m=h}^{h+l} \Delta p_m\right) \qquad (8\text{-}9)$$

where P_{h+l} is the future unit cost and P_h is the current unit cost.

Calculate Cost of Remedial Work

When the “actual” sizes of future defect areas and the “actual” future unit costs are simulated, the calculation of repair cost is simple and straightforward. But caution should be taken because the required repair area is usually larger than the defect area. As an example, for bleeding defect, the FDOT (2005) warranty specifications require the contractor to “[r]emove and replace the distressed area(s) to the full distressed depth, and to a minimum surface area of 150% of each distressed area.”

The future cost of repair can be calculated using the following formula

$$C_r = \lambda x A P_{h+l} \qquad (8\text{-}10)$$

where, C_r is the future cost of repair

λ is a constant greater than 1

x is the percentage of pavement defected

A is the total area of warranted pavement

P_{h+l} is the future unit cost of repair

The present value of the future repair cost is

$$C_r^{/} = PV(C_r) = \frac{C_r}{(1+R)^{l/12}} \qquad (8\text{-}11)$$

Where, $C_r^{/}$ is the present value of C_r

R is the discount rate

l is forecast horizon in months.

The method described above can be used to simulate repair cost for any type of distress. If two or more types of distresses occur within the warranty period, the cost of each type of repair is calculated individually. The total cost of remedial work is the sum of all types of repairs.

A Case Study: Florida Turnpike

The realization of the simulation approach is illustrated in this section on a real warranted asphalt pavement resurfacing project. This project is located on the Florida Turnpike. It is not an interstate project, but since the designated construction criteria for the Turnpike are identical to the interstate criteria, it is appropriate to analyze its pavement performance using interstate performance data.

It should be noted that the purpose of this simulation is to demonstrate the methodology developed in this research. The simulation results of this analysis are undoubtedly inaccurate and probably biased because they involve the researcher's subjective judgments which may deviate significantly from the reality. The simulated results cannot, therefore, be applied to any project, directly or indirectly, as an assessment of warranty risk.

Overview of the Construction Project

The project is located on Florida's Turnpike from milepost 275.677 to milepost 281.834, with a total roadway length of 6.157 miles. The improvements under this contract consisted of milling, resurfacing, base work, drainage improvements, upgrading guardrail, highway signing, pavement marking, etc.

The resurfaced pavement was subject to a three year warranty. It consisted of 2 existing southbound lanes for 6.157 miles including shoulders. The southbound lanes were milled 2" average depth (the milling ranged from 1" to 4", depending on typical section and location), an asphalt rubber membrane interlayer was placed and 3”-6.25” of traffic level “C” with polymer modified asphalt was placed depending on the station location and proposed cross-slope. Six different typical sections were given with different milling depths and pavement layer thickness for each. A 0.75” FC-5 friction course with rubber was placed atop the structural course.

The project was let on October 12, 2004. Construction began on December 13, 2004 and was completed on September 20, 2005. The programmed budget was $14,599,025 and the winning bid was $12,666,667. A breakdown of the winning bid is listed in Table 8-3. If the costs of mobilization, maintenance of traffic, site clearing, and contingency are proportioned to the other categories, the adjusted total cost for the warranted pavements (including shoulders) is $4,246,168.25, accounting for 33.52% of the total bid.

Table 8-3. Summary of the winning bid

No.	Category	Amount
1	Mobilization and maintenance of traffic	1,741,132.30
2	Clearing Construction site	78,035.85
3	Earthwork	1,545,529.88
4	Base	88,301.40
5	Asphalt surface courses (warranted)	3,586,056.20
6	Structures	362,054.23
7	Incidental construction	5,042,678.76
8	Traffic control	72,878.04
9	initial contingency amount	150,000.00
	Sum	12,666,666.66

Data Input

All the project specific data needed for the simulation are designed as inputs to the simulation program. These data include construction schedule, project size, unit costs of repair, etc. A detailed list of the input data is included in Table 8-4. The discount rate is the contractor’s debt rate.

Table 8-4. Project specific input data for simulation

Category	Variable	Value	Remarks
Schedule	Bid letting	October 2004	
	Construction completion	September 2005	
	Warranty duration	3 years	
Project size	Pavement area	85,424 SY	
	Shoulder & median area	51,178 SY	
Current unit cost for repair	Ride	\$5.13/SY	
	Rutting	\$36.22/SY	
	Cracking (incl. raveling)	\$31.08/SY	Pavement&shoulder
	Bleeding	\$31.08/SY	Pavement&shoulder
	Delamination	\$5.13/SY	Pavement&shoulder
Financial	Discount rate	5%	Debt rate

Additional Assumptions

Models for various types of pavement distresses have been developed in Chapter 6. But there are still many parameters unknown. Before accurate estimates of these parameters are available, subjective estimates of these unknown parameters are needed to run the simulation.

When a distressed area is to be repaired, the repaired area is usually larger than the distressed area. The assumed factors of repaired area to distressed area are listed in Table 8-5.

Table 8-5. Assumed factors of repaired area to distressed area

Type of distress	Repaired area / distressed area
Rutting, ride	110%
Cracking, raveling, delamination, bleeding, pot holes, etc.	150%

Distributions of the size of the affected area for cracking (including raveling and patching) are well monitored in Chapter 6. For other distress types, however, no such data are currently available. For the purpose of simulation, additional assumptions are made on the sizes of distressed areas, as listed in Table 8-6.

Table 8-6. Assumed distribution of size of distressed area

Type of distress	% pavement distressed	Probability
Rutting	10% 25% 40%	50% 35% 15%
Ride	20% 35% 50%	50% 35% 15%
Cracking (incl. raveling & potholes)	(see models)	
Bleeding	1%	
Delamination	2%	

The warranted pavements under this contract include both travel lanes and shoulders. For shoulders, no requirements on rutting and ride distresses are specified in the warranty specifications. But the contractor still has to repair distresses of other types including cracking, raveling, delamination, bleeding, pot holes, etc. The distress models were developed using travel lane pavement performance data. No data were collected on shoulder distresses. In this simulation, we assume the shoulder and the travel lane pavements have similar performance so the pavement models can be applied to the shoulders too.

The Simulation Results

The simulation is performed in Microsoft Excel worksheets using an Excel simulation add-in called Simtools, which was developed by Professor Roger Myerson at the Northwestern University. The output of the simulation is the present value (PV) of repair costs for each simulated outcome. A total of 50,000 simulation outcomes are collected for the given project. The simulated PVs of pavement repair costs range from \$0 to \$2,167,184, with an average of \$59,129 and a standard deviation of \$185,797. The distribution of the discounted repair costs is illustrated in Figures 8-2 and 8-3.

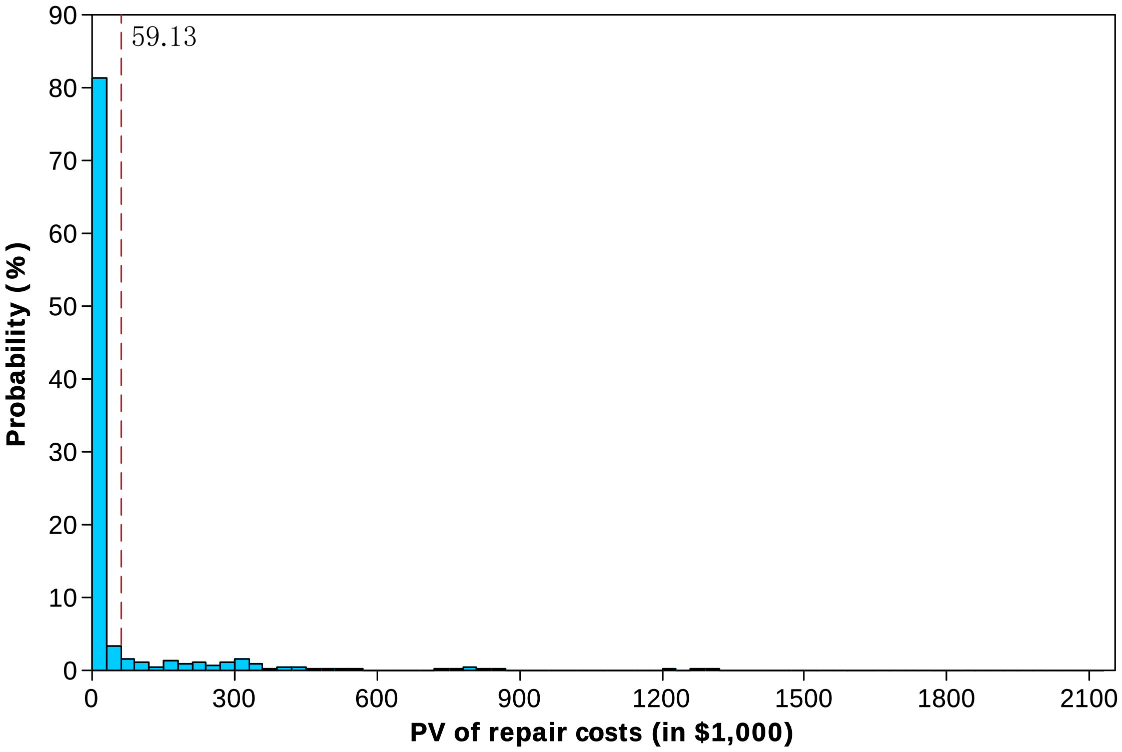

Figure 8-2. Histogram of repair costs for the warranted pavement

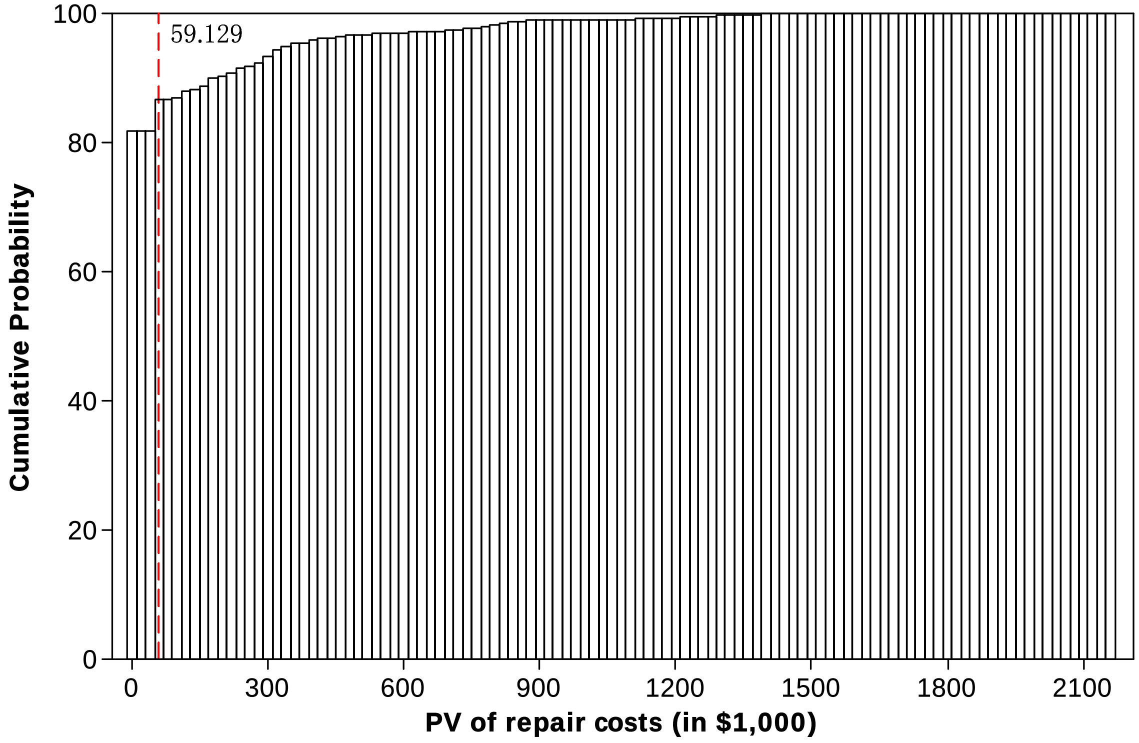

Figure 8-3. Cumulative distribution function for PV of repair costs

The simulated range of repair costs is reasonable if it is compared with two extreme scenarios. In the best case, the pavement is perfect without any repair within the warranty period. In the worst case, the pavement may fail completely and the contractor has to replace the entire pavement at his own expense (current cost is $4,246,168).

Some findings from the simulated results are summarized as follows:

- The expected PV of future repair costs is about 1.39% of the (adjusted) bid price for milling and resurfacing work, and 0.47% of the total bid.
- The range of the outcomes is very large. The lower bound of repair costs is zero; while the theoretical upper bound is approximately the total milling and resurfacing construction costs.
- The distribution of the discounted repair costs is highly skewed to the right.
- In most cases, the discounted repair costs are very low. About 81.8% simulated outcomes yield a discounted repair cost of less than 1% of the bid price for the warranted work. However, there are also some unlikely scenarios that the repair cost is very high.

Value at Risk (VaR) Measure of Warranty Risk

Let us assume the contractor estimated the future repair cost of the warranted pavement as its expected value, or the average of all of its possible future outcomes. The contractor will suffer a loss on the warranty if the actual discounted repair cost is higher than the expected value. On the other hand, the contractor will have a gain on the warranty if the actual repair cost is lower. The gain or loss on warranty can be calculated by subtracting the actual discounted repair cost from the expected cost. A positive number indicates a gain while a negative number means a loss.

For the simulated results of the Florida Turnpike project, if we subtract each of the simulated repair costs from $59,129, the average repair cost, we can get the distribution of the contractor’s gain/loss on the warranty, as illustrated in Figure 8-4. The figure indicates that it is very likely (84.68% probability) that the contractor will have a gain on the warranty. But the maximum gain is only $59,129, when no repair work is needed. On the other hand, the probability of loss is relative low (15.32%), however the loss tends to be large.

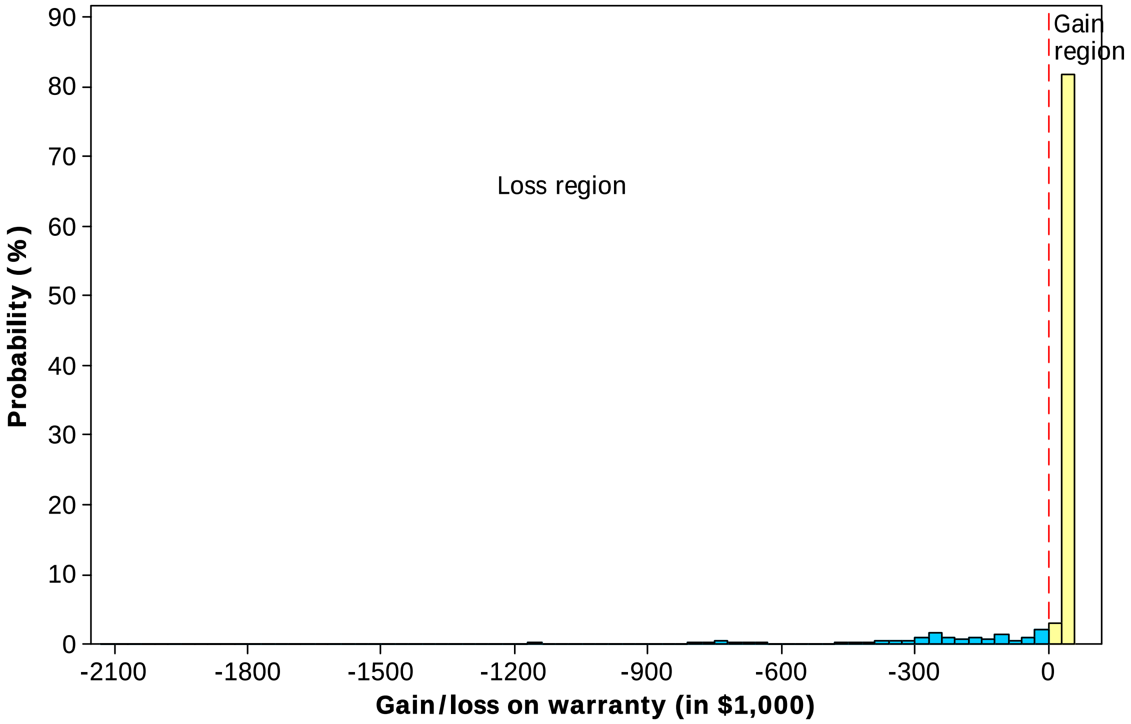

Figure 8-4. Probability distribution of warranty gain/loss

Standard deviation is a traditional and popular single measure of uncertainty or risk. For the simulated warranty project discussed above, the simulated standard deviation of discounted warranty period repair cost is $185,797. However, the use of standard deviation to measure risk has significant limits. A general assumption underlying this application is that the outcomes conform to a normal distribution. But obviously the distribution of the simulated results, as illustrated in Figure 8-4, is neither normal nor symmetric.

Value at Risk (VaR) is another popular, and probably the best, single risk-measurement technique available. VaR is widely used by banks, securities firms, commodity merchants, energy merchants, and other trading organizations to measure their portfolios' exposure to market risk.

Value at Risk is defined as the value that is expected to be lost under severe adverse conditions. It is based on the probability distribution for the value of an asset or a portfolio. In the context of our simulated pavement warranty project, if a severe loss on warranty is defined as a loss that has a $\alpha\%$ probability to occur, then we call it a $(1-\alpha)\%$ VaR. It is equivalent to say that there is a $\alpha\%$ chance the actual loss will be greater than the $(1-\alpha)\%$ VaR.

If the present value of warranty period repair cost is estimated to be $59,129, the 99% VaR and 95% VaR are calculated as $930,251 and $293,862, respectively (see Figure 8-5). That is to say, there is a 1% probability the loss on warranty is greater than $930,251, and there is a 5% probability the loss on warranty is greater than $293,862.

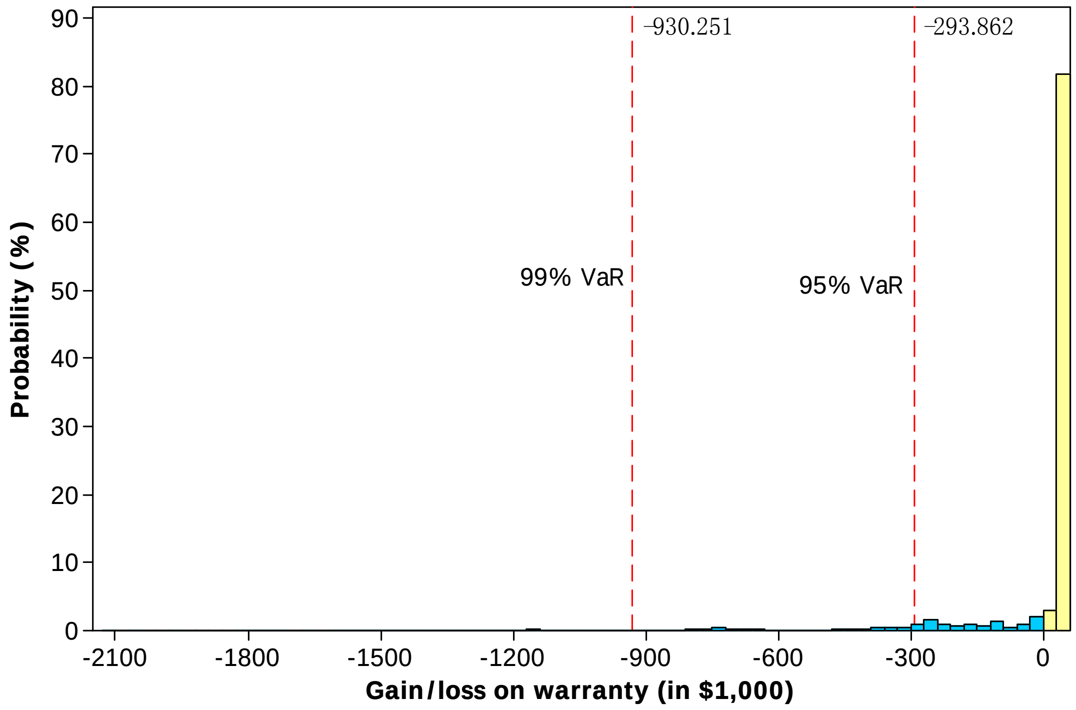

Figure 8-5. VaR measure of warranty risk

Risk Attribution

The simulation approach for estimating the distribution of warranty risk and its VaR is described in the previous sections. However, this alone is not sufficient for risk measurement. It is usually necessary to decompose the overall risk and analyze the contribution of each risk component to overall risk exposure. The simulation approach used for measuring overall warranty risk can be further extended to analyze the risk contribution of each risk component.

Stand-alone Risk for Each Risk Factor

Three factors of warranty risk are identified in Chapter 4, including uncertain quantities of repair work, uncertain price escalation for repair work, and timing of repair. The stand-alone risk for any risk factor is estimated by setting the variations on all other risk factors equal to zero. In other words, the stand-alone risk for a risk factor is calculated by replacing the variables of other risk factors with their expected values.

The expected values for variables of all risk factors are summarized Table 8-7. The simulated resulting stand-alone risks for each risk factor are summarized in Table 8-8.

Table 8-7. Expected values for risk factors

Risk factor	Variable	Year 1	Year 2	Year 3	Total
Quantities (percent pavement defective)	Rutting	0.1924	0.3402	0.4278	0.9605
	Ride	0.0003	0.0042	0.0237	0.0282
	Bleeding	0.0294	0.0136	0.0101	0.0531
	Delamination	0.0000	0.0000	0.0003	0.0003
	Cracking	0.0067	0.0883	0.3556	0.4506
	Raveling	included in cracking			
Timing (year of repair)	Rutting				2.2451
	Ride				2.8298
	Bleeding				1.6357
	Delamination				2.9333
	Cracking				2.7742
	Raveling	included in cracking			
Escalation	P_t/P_0	1.0588	1.0826	1.1071	

Table 8-8. Stand-alone risk for each risk factor

Risk factor	Escalation	Quantity	Timing	All factors
No. of replications	25000	50000	50000	50000
Mean	$60,343	$60,552	$60,242	$59,129
Standard deviation	$3,288	$185,185	$701	$185,797
Skewness	0.158	4.323	0.497	4.483
Minimum	$47,574	$0	$59,360	$0
Maximum	$75,327	$2,166,570	$62,589	$2,167,184
99% VaR	$8,098	$876,343	$1,617	$930,251
95% VaR	$5,573	$290,784	$916	$293,862
90% VaR	$4,294	$173,672	$912	$129,054

The simulated results in Table 8-8 show that the quantity of repair work constitutes the single largest factor of warranty risk. In fact, it constitutes almost the entire warranty risk. Comparatively, under the current three-year pavement warranty, the risk contributions from price escalation and timing of repair are minor and ignorable.

Stand-alone Risk for Each Distress Type

The stand-alone risk for a distress type is the warranty risk if we ignore all other distress types. It is estimated by setting the quantities of repair work for all other distresses equal to zero.

The simulated results of distress-type-specific, stand-alone risks are summarized in Table 8-9. Some observations are as follows:

- The expected repair cost of the project ($59,129) is the sum of the expected repair costs of each individual distress type. Rutting and cracking (including raveling) contribute approxiamately 94.5% to the total repair cost. Bleeding contributes to 5.3% of the total repair cost. The contributions of ride and delamination are trivial and ignorable.
- Compared with the average level, the standard deviation of repair costs for each individual distress type is very high, meaning the repair cost is highly uncertain for each individual distress type.
- Rutting and cracking (including raveling), which contribute significantly to the total expected cost, have also the highest risk contribution to the total risk (represented by both standard deviation and VaR). On the other hand, ride and delamination have the lowest risk contribution to the total risk.

Table 8-9. Stand-alone risk for each distress type

	Ride	Rutting	Bleeding	Delamin.	Cracking	Total
No. replications	50,000	50,000	50,000	50,000	50,000	50,000
Mean	$87	$30,129	$3,142	$4	$25,768	$59,129
Std. deviation	$3,501	$155,524	$13,215	$262	$100,440	$185,797
Skewness	44.792	6.029	3.987	74.596	5.905	4.483
Minimum	$0	$0	$0	$0	$0	$0
Maximum	$236,648	$1,486,144	$73,373	$20,245	$2,167,184	$2,167,184
99% VaR	$0	$816,041	$58,763	$0	$452,180	$930,251
95% VaR	$0	$0	$50,104	$0	$188,982	$293,862
90% VaR	$0	$0	$0	$0	$0	$129,054

In summary, rutting and cracking (including raveling) account for most of the total warranty risk as well as the total expected repair cost, thus constituting the major sources of warranty risk. The contractor's risk exposure due to ride and delamination failure is trivial and ignorable.

The Effect of Multiple Projects

Up to now the analysis on warranty risk has been limited to one warranted project only. Since many states are trying to move pavement warranties from innovative contracting to standard practice, more and more contractors will be engaged in the construction of two or more warranted projects. This section will focus on the risk of warranty for multiple projects.

Suppose a contractor won n bids on warranted pavement projects. The present value of warranty period repair costs for each project is w_i, $i = 1,...,n.$ Each w_i is a random variable following a distribution similar to that illustrated in Figure 8-2. The average repair cost can be calculated as

$$\overline{C}_r = \frac{1}{n}\sum_{i=1}^{n} C_{r(i)} \qquad \text{(8-12)}$$

where $\overline{C}_r$ is the average repair cost, $C_{r(i)}$ is the repair cost for project *i*.

The expected value of w can be easily calculated as

$$E(\overline{C}_r) = \frac{1}{n}\sum_{i=1}^{n} E(C_{r(i)}) \qquad (8\text{-}13)$$

However, the distribution of $\overline{C}_r$ is complicated due to the complexity in the distribution for $C_{r(i)}$ and the potential correlation between projects.

The simulation approach developed in the prior sections can be extended to analyze warranty risk for multiple projects. "Actual" repair costs can be simulated for each project using the simulation program, and the average repair cost can be calculated using Formula (8-12). With a large number of replications, a sample for $\overline{C}_r$ can be obtained and its distribution can be easily analyzed.

As an example, let us analyze the impact of multiple warranted projects on the winning contractor of the Turnpike warranty project. Suppose the contractor wins several bids on warranted paving projects. For simplicity, assume all the warranted projects are identical in all aspects including size, design, physical condition, schedule, and bid (although this will never happen). We further assume no correlation between the outcomes of the projects. Statistics of the simulated results are summarized in Table 8-10. The distributions for total repair costs of two, four, and ten projects are illustrated in Figures 8-6 to 8-8.

Table 8-10. Comparison of average repair costs for multiple projects

No. of projects	1	2	4	10
No. of replications	20,000	20,000	20,000	20,000
Mean	$60,182	$59,354	$59,410	$59,772
Standard deviation	$185,664	$131,755	$92,658	$58,934
Skewness	4.379	3.204	2.177	1.432
99% VaR	$934,710	$592,578	$333,666	$195,425
95% VaR	$292,226	$316,297	$210,004	$114,773

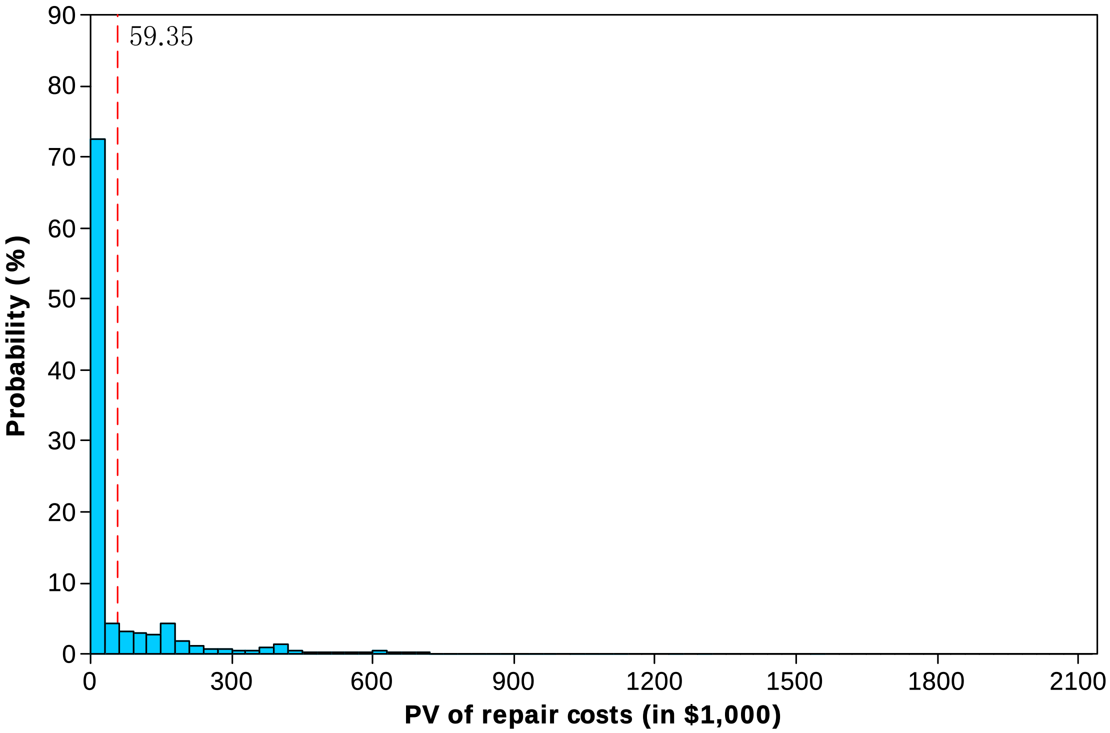

Figure 8-6. Histogram of average repair costs for two warranted projects

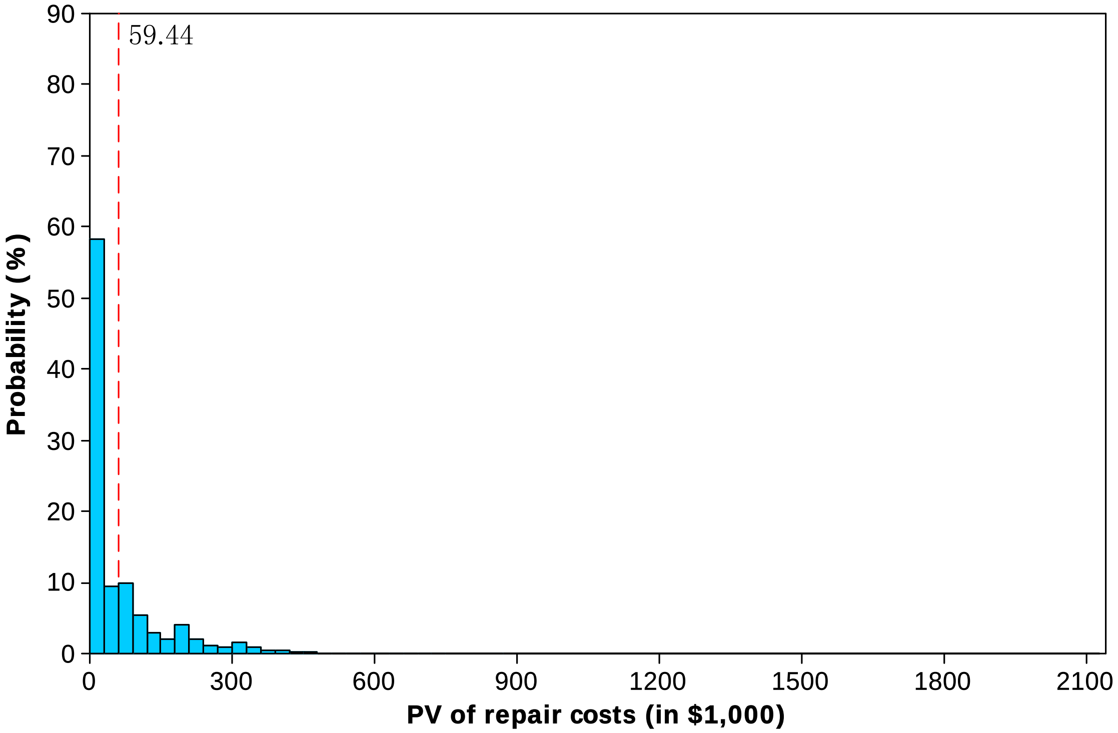

Figure 8-7. Histogram of average repair costs for four warranted projects

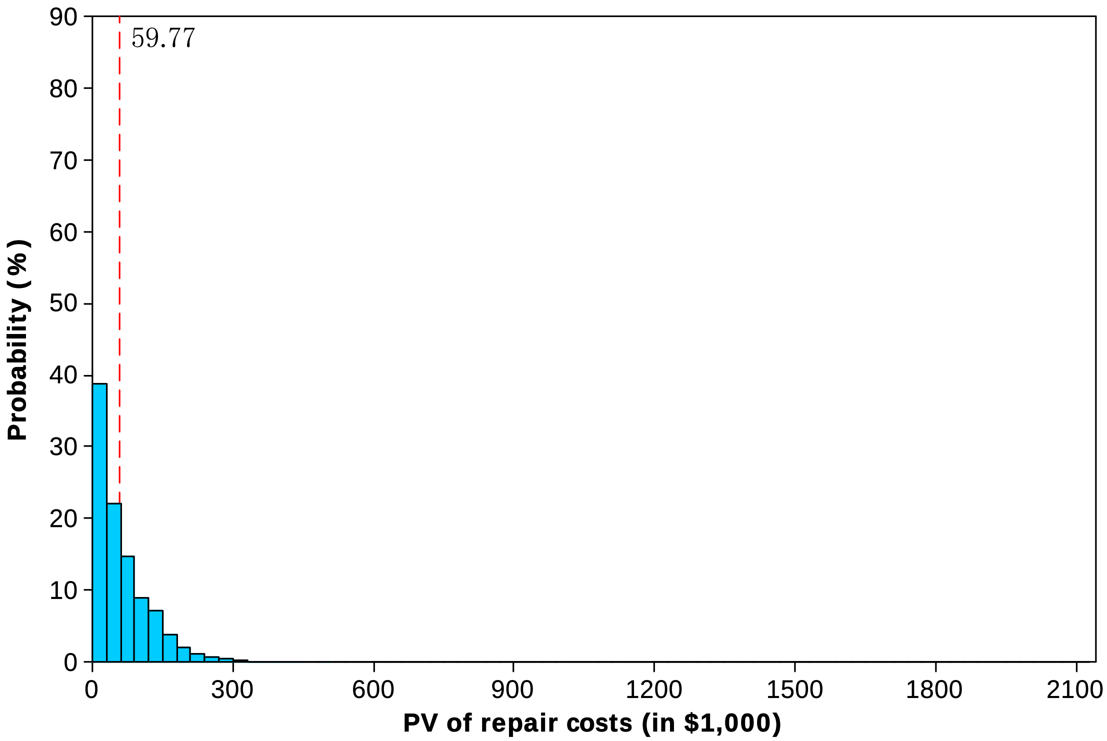

Figure 8-8. Histogram of average repair costs for ten warranted projects

As seen in Table 8-10, in this simplified example, the expected value of average repair costs is the same as that for a single project. However, the standard deviation and VaR decreases as the number of projects increases. The standard deviation and VaR for n projects are approximately $1/\sqrt{n}$ of the corresponding values for a single project.

The above observations can be explained by the Central Limit Theorem. The theorem states that the average of n observations from any population with mean μ and standard deviation σ will approach normal distribution as n increases. The mean of the sum is μ and the standard deviation of the sum is given by $\sigma / \sqrt{n}$.

This effect of multiple projects is called diversification. As more projects are put in a portfolio, the total risk of the portfolio is lower than the sum of risks for each individual project in the portfolio. Thus diversification reduces the total risk in a portfolio.

Some implications of the diversification effect are summarized as follows:

- A large contractor engaged in many warranted projects can gather more benefits from diversification and thus have significant advantages over small contractors in doing warranty business. A small contractor, on the other hand, has higher risk exposure on warranties.

- The benefit of diversification is limited when a small number of warranted projects are in the portfolio. Currently, pavement warranties are regarded as an innovative contracting practice by most states. Only a few warranted projects are let each year in a state. As a result, even the large contractors can't enjoy the benefit of significant diversification.

- The construction industry is dominated by small contractors. The total number of construction projects finished by each contractor is limited. Comparatively, each state DOT holds a much larger portfolio of projects than the contractors. So essentially, the pavement warranties transfer project failure risk from the well diversified parties to the less diversified parties.

- As noted above, each contractor holds a very limited number of construction projects. This is significantly different from the manufacturing industry where a manufacturer can produce thousands or millions of units of products each year. The benefits of diversification can be realized in the manufacturing industry when warranties are implemented. But the diversification effect will be always limited in the construction industry.

Summary

This chapter details the simulation approach to quantifying warranty risk using the models developed in prior chapters. The simulation methodology is illustrated on an actual pavement warranty project on Florida Turnpike. The simulation is further extended to analyze the impact of multiple projects on warranty risk. Value at risk (VaR) is used to measure the warranty risk.

CHAPTER 9
CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The federal and state Departments of Transportation (DOTs) are implementing warranties in highway construction projects, with an objective to encourage contractor innovation, and to improve construction quality and highway performance. Various research projects have been conducted to develop guidelines for implementing warranties and evaluating the effectiveness of warranties. All these studies are from the owner's perspective and provide guidelines to the DOTs. Prior research indicated that few contractors are familiar with warranties.

One major concern of the contractors regarding pavement warranties is risk. Unfortunately the risk of pavement warranties is not well-understood. Risks have long been recognized and well-studied in the construction industry. But a comprehensive study on the risk of pavement warranties basically does not exist.

This research is conducted from the contractor's perspective, with objectives to define clearly the risk of pavement warranties for the contractors, and to develop an approach to model and measure this risk. The risk of warranties, from the contractor's viewpoint, is defined as the probability that the actual warranted repair cost exceeds the estimated repair cost, or the probability that the contractor will suffer a financial loss on warranties. Two major elements of warranty risk are identified: the uncertainty in quantities of repair items and the uncertainty in future escalations of unit repair costs.

A study on the uncertainty in pavement performance after construction was conducted using Florida DOT's annual asphalt pavement condition survey data on interstates. The data show that as the pavement ages increase, the average performance of the sample deteriorates and the dispersion of the performance usually increases, implying higher risk for long-term warranties. However, the statistical results of the performance data was found to be distorted and conditional because failed pavements were excluded from later year statistics. To reflect the "true" performance of the pavements, life distribution models were fitted to model the occurring time for each type of pavement defect. Statistical distribution models were also fitted to model the growth and dispersion sizes of cracking areas.

The uncertainty in unit repair cost escalation was assessed using historical cost data. The data used were the monthly PPI series for highway and street construction. Time series models are able to model both the systematic variation and the unexplained variation in the series. The systematic variation facilitates the computation of point forecasts while the description of unexplained variation helps to model the uncertainty. The Box-Jenkins approach was followed to fit the time series models. An ARIMA(1,1,0) model was found to fit the data well and was able to compute the probabilistic distribution of future escalations.

The Monte Carlo simulation was adopted to quantify the risk of warranties using the pavement performance models and time series model developed in this study. The basic steps to generate a simulated outcome are as follows:

- Generate initiation time for each distress type using the life distribution models
- If a type of defect occurs within the warranty period, generate the severity of the defect (Percent pavement affected)

- If repair is needed, generate the escalation of unit repair cost using the fitted time series model
- Compute total repair costs. If no repair needed, the cost is zero.

Value at Risk (VaR) was adopted as a measure of warranty risk. A real project case study is performed to demonstrate the approach developed in this study. The simulated results indicate that under the current three-year asphalt pavement warranties in Florida, in most cases the warranty period repair costs are trivial compared to the project costs; however, there are considerable chances that the contractor may suffer huge loss on warranties.

The concept of warranty risk is directly related to the risk premium that the contractor adds to his/her bid on the warranted project. The approach developed in this study may act as a guide to the contractors in assessing their business risk exposure to pavement warranties. It may also help the DOTs in addressing warranty requirements and evaluating warranty effectiveness.

Limitations

Total validation of the results of this research may have been somewhat compromised by the following limitations.

First, the pavement performance data were not prepared for the particular purpose of this research. The main purposes of the Florida DOT's pavement condition survey include rating pavement conditions, estimating rehabilitation funding needs, and prioritizing rehabilitation projects. The survey provides valuable information for this study, but some data such as the percent pavement affected by cracking are not satisfactorily accurate. Some necessary data like the sizes of bleeding and delamination areas are not available.

Second, under warranty specifications, the pavements should be evaluated for each LOT which is defined as 0.1 lane-mile of travel way. However, the source data used for pavement performance analysis were organized by survey sections which ranged from less than 1 mile to more than 25 miles. No information was provided on the variation of pavement performance between LOTs within a construction project or a survey section.

Third, the data sources used to assess pavement performance are from non-warranted projects. Due to the limited numbers of pavement warranty projects and the availability of performance data on warranted pavements, data from non-warranted pavements may act as a substitute for current research. However, the performance of warranted pavements may deviate from that of non-warranted.

Fourth, the pavement distress models are developed using pavement performance data from projects done by many contractors. However, a contractor's performance may deviate significantly from the average level of all contractors. The variation of pavement performance from projects done by one contractor may also be lower than that from a pool of projects within the state.

Fifth, it is assumed in the case study that the contractor is fully responsible for repair of all defects occurring within the warranty period. Since the contractor's warranty liability is limited to the scope under his/her control, this may overestimate the risk as well as the expected repair cost.

Sixth, a key assumption in the analysis is that the performance of each individual project is independent. This assumption simplified the analysis. But it should be noted that correlation of performance may exist when multiple projects are done by a single contractor.

Seventh, the fitted time-to-defect models are project-type specific and tied to the threshold values for the distresses to be warranted. The data were from Florida interstate asphalt pavement projects. The results may not fit other categories of highway or interstate sections in other states. The models for rutting and ride failures are tied to the current threshold values of these distresses as specified in the warranty specifications. The models must be refitted if the threshold values change. However, the methodology developed in this study is able to model project defects for other types of pavements or non-pavement projects.

In addition, the distress models are built using data from interstate projects in the state of Florida. The approach developed in this research can be used to model pavement performance of non-interstate projects or interstate projects in other states. But the fitted models are appropriate for interstate projects in Florida only.

Finally, the modeling of pavement distresses is not complete. Due to the limitation of available information, some parameters necessary for warranty risk assessment are still unknown. Subjective estimates of these parameters were used in the simulation.

Recommendations for Future Research

This study proposed a comprehensive approach to modeling and measuring the risk of warranties for contractors. Due to limitations in available data, the set of pavement distress models is not complete. Further studies are needed to model some unknown parameters, including but not limited to

- Variation of pavement performance within a construction project.
- Growth and dispersion of percent pavement affected by each distress type other than cracking.

The pavement distress models were developed using performance data from Florida interstate asphalt pavement resurfacing projects. However, the methodology developed in this study is able to handle the performance modeling of other pavement or non-pavement projects. An expansion of this approach to other warranted highway construction projects is recommended.

Hopefully this work presents just a beginning of an on-going effort to analyze the impact of warranties from the contractor's perspective. As it stands now, the contractors' reactions to warranties, including decision on bidding and innovation, are highly affected by their risk exposure to warranties. The success and effectiveness of warranties, from the owner's perspective, depend at least partially on the contractors' reactions to it. Thus this study may build a foundation for a series of future studies on pavement warranties. Following are some potential research topics that may relate to the concept of warranty risk developed in this study:

- Relationship between the contractor's warranty risk exposure and the risk premium he/she charges,
- Incentives for contractor innovation,
- Warranty bonding issues, including the surety companies' risk exposure to warranty bonding and underwriting process, and the DOTs' policy on warranty bonding,
- Optimizing length of warranty period considering the contractor's risk exposure,
- Determination of threshold values for performance parameters.

APPENDIX A
LIST OF ROAD SECTIONS IN THE SAMPLE

Table A-1. Road sections in the sample

ID	Completion year	Roadway ID	US Rd.	Roadway	BMP	EMP	Length (miles)
A01	1991	10190000	275	2	1.200	4.112	2.912
A02	1991	10190000	275	3	1.200	4.112	2.912
A03	1991	13175000	275	2	1.307	3.566	2.259
A04	1991	13175000	275	3	1.406	3.553	2.147
A05	1991	13175000	275	2	3.884	5.327	1.443
A06	1991	13175000	275	3	3.898	5.327	1.429
A07	1991	70220000	95	2	14.335	21.453	7.118
A08	1991	70220000	95	3	14.378	14.682	0.304
A09	1991	75280000	4	3	0.000	7.698	7.698
A10	1991	75280000	4	2	1.828	2.236	0.408
A11	1991	75280000	4	2	2.236	7.647	5.411
A12	1991	75280000	4	2	7.647	8.954	1.307
A13	1991	75280000	4	3	7.698	8.747	1.049
A14	1991	75280000	4	3	8.747	14.825	6.078
A15	1991	75280000	4	2	8.954	10.752	1.798
A16	1991	75280000	4	2	10.752	14.715	3.963
A17	1991	78080000	95	2	15.300	19.950	4.650
A18	1991	78080000	95	3	15.300	19.950	4.650
A19	1991	78080000	95	2	31.500	34.855	3.355
A20	1991	78080000	95	3	31.700	34.855	3.155
A21	1991	86095000	595	3	9.971	11.171	1.200
A24	1991	87004000	195	2	3.916	4.910	0.994
A25	1991	87004000	195	3	3.916	4.910	0.994
A26	1991	87075000	75	3	0.000	1.018	1.018
A27	1991	87075000	75	2	1.018	5.442	4.424
A28	1991	87075000	75	3	1.018	5.442	4.424
A29	1991	93220000	95	2	0.000	4.509	4.509
A30	1991	93220000	95	3	0.000	4.509	4.509
B01	1992	15170000	275	2	4.247	5.495	1.248
B02	1992	15170000	275	3	4.247	5.495	1.248
B03	1992	15170000	275	2	5.495	7.310	1.815
B04	1992	15170000	275	3	5.495	7.310	1.815
B05	1992	17075000	75	3	34.445	37.160	2.715
B08	1992	77160000	4	2	7.400	8.161	0.761

Table A-1. Continued

ID	Completion year	Roadway ID	US Rd.	Roadway	BMP	EMP	Length (miles)
B09	1992	77160000	4	3	7.400	8.900	1.500
B10	1992	77160000	4	2	8.161	8.900	0.739
B11	1992	78080000	95	2	0.000	15.300	15.300
B12	1992	78080000	95	3	0.000	15.300	15.300
B13	1992	78080000	95	2	19.950	26.180	6.230
B14	1992	78080000	95	3	19.950	26.180	6.230
B15	1992	79110000	4	2	14.668	25.274	10.606
B16	1992	79110000	4	3	14.668	25.274	10.606
B20	1992	87075000	75	2	0.000	0.333	0.333
C01	1993	3175000	75	2	0.000	24.274	24.274
C02	1993	3175000	75	2	24.274	30.089	5.815
C03	1993	15190000	75	2	14.631	16.649	2.018
C06	1993	32100000	75	2	0.000	8.874	8.874
C07	1993	32100000	75	3	0.000	8.874	8.874
C08	1993	50001000	10	2	20.437	31.538	11.101
C09	1993	50001000	10	3	20.437	31.538	11.101
C10	1993	53002000	10	2	13.609	19.504	5.895
C11	1993	53002000	10	3	13.609	19.504	5.895
C12	1993	55320000	10	2	15.630	19.755	4.125
C13	1993	55320000	10	3	15.630	19.755	4.125
C14	1993	60002000	10	2	18.100	24.061	5.961
C15	1993	60002000	10	3	18.100	24.061	5.961
C16A	1993	70225000	95	2	13.797	16.468	2.671
C16B	1993	70225000	95	2	16.468	22.509	6.041
C17A	1993	70225000	95	3	13.797	16.468	2.671
C17B	1993	70225000	95	3	16.468	22.509	6.041
C18	1993	72290000	95	2	4.314	10.468	6.154
C19	1993	72290000	95	3	4.314	10.468	6.154
C20	1993	74160000	95	2	0.000	11.989	11.989
C21	1993	74160000	95	3	0.000	11.989	11.989
C22	1993	93220000	95	2	15.565	17.000	1.435
C23	1993	93220000	95	3	15.565	17.000	1.435
D01	1994	10190000	275	2	0.000	1.200	1.200
D02	1994	10190000	275	3	0.000	1.200	1.200
D04	1994	13075000	275	2	3.750	8.288	4.538
D05	1994	13075000	275	3	3.750	8.288	4.538
D06	1994	13075000	275	2	12.896	15.723	2.827
D07	1994	13075000	275	3	12.896	15.723	2.827
D08	1994	15190000	275	3	14.631	16.649	2.018
D09	1994	16320000	4	2	31.947	32.022	0.075
D10	1994	16320000	4	3	31.947	32.022	0.075

Table A-1. Continued

ID	Completion year	Roadway ID	US Rd.	Roadway	BMP	EMP	Length (miles)
D15	1994	50001000	10	3	1.160	11.896	10.736
D16	1994	50001000	10	2	1.278	11.896	10.618
D17	1994	53002000	10	2	10.351	13.609	3.258
D18	1994	53002000	10	3	10.351	13.609	3.258
D19	1994	58002000	10	2	2.586	5.491	2.905
D20	1994	58002000	10	3	2.586	5.491	2.905
D21A	1994	70220000	95	2	0.000	14.335	14.335
D22	1994	73001000	95	2	0.000	18.729	18.729
D23	1994	73001000	95	3	0.000	18.729	18.729
D26	1994	87004000	95	2	2.664	3.916	1.252
D27	1994	87004000	95	3	2.664	3.916	1.252
D30	1994	92130000	4	2	6.821	7.885	1.064
D31	1994	92130000	4	3	7.058	7.885	0.827
D32	1994	93220000	95	2	4.275	8.400	4.125
D33	1994	93220000	95	3	4.275	8.400	4.125
D34	1994	93220000	95	2	8.400	9.252	0.852
E01	1995	8150000	75	2	0.000	3.846	3.846
E02	1995	8150000	75	3	0.000	3.846	3.846
E05	1995	13175000	275	3	0.000	1.406	1.406
E06	1995	13175000	275	2	0.470	1.406	0.936
E07	1995	14140000	75	2	0.000	8.173	8.173
E08	1995	14140000	75	3	0.000	8.173	8.173
E09	1995	17075000	75	2	29.039	34.340	5.301
E10	1995	17075000	75	3	29.510	34.340	4.830
E13	1995	36210000	75	2	0.000	4.094	4.094
E14	1995	36210000	75	3	0.000	4.094	4.094
E15	1995	36210000	75	2	5.968	13.140	7.172
E16	1995	36210000	75	3	5.968	13.140	7.172
E17	1995	36210000	75	2	18.664	22.500	3.836
E18	1995	36210000	75	3	18.664	22.500	3.836
E19	1995	52002000	10	2	16.627	21.224	4.597
E20	1995	52002000	10	3	16.627	21.224	4.597
E21	1995	53002000	10	2	0.000	8.680	8.680
E22	1995	53002000	10	3	0.000	8.680	8.680
E23	1995	53002000	10	2	8.680	10.351	1.671
E24	1995	53002000	10	3	8.680	10.351	1.671
E25	1995	55320000	10	2	4.573	8.576	4.003
E26	1995	55320000	10	3	4.573	8.576	4.003
E27	1995	55320000	10	2	8.576	15.630	7.054
E28	1995	55320000	10	3	8.576	15.630	7.054
E29	1995	61001000	10	2	12.908	17.380	4.472

Table A-1. Continued

ID	Completion year	Roadway ID	US rd. No.	Roadway	BMP	EMP	Length (miles)
E30	1995	61001000	10	3	12.908	17.380	4.472
E31	1995	61001000	10	2	17.380	23.969	6.589
E32	1995	61001000	10	3	17.380	23.969	6.589
E33	1995	70220000	95	2	21.453	25.360	3.907
E34	1995	70220000	95	2	25.360	31.252	5.892
E35	1995	70225000	95	2	5.332	13.797	8.465
E36	1995	70225000	95	3	5.332	13.797	8.465
E37	1995	72270000	10	2	16.388	17.050	0.662
E38	1995	72270000	10	3	16.388	17.162	0.774
E39	1995	75280000	4	2	2.130	3.347	1.217
E40	1995	75280000	4	3	2.130	3.347	1.217
E41	1995	86070000	95	2	8.750	10.956	2.206
E42	1995	86070000	95	3	8.750	10.956	2.206
E43	1995	87270000	95	2	13.441	13.846	0.405
E44	1995	87270000	95	3	13.441	13.846	0.405
F01	1996	10190000	275	2	4.112	6.110	1.998
F02	1996	10190000	275	3	4.112	6.110	1.998
F03	1996	14140000	75	2	8.173	20.386	12.213
F04	1996	14140000	75	3	8.173	20.386	12.213
F05	1996	15190000	275	2	13.451	14.631	1.180
F06	1996	15190000	275	3	13.451	14.631	1.180
F07	1996	18130000	75	2	21.730	28.996	7.266
F08	1996	18130000	75	3	21.740	28.996	7.256
F09A	1996	27090000	10	2	0.000	9.439	9.439
F09B	1996	27090000	10	2	9.439	25.462	16.023
F10	1996	27090000	10	3	0.000	25.462	25.462
F11	1996	29180000	75	2	19.369	26.718	7.349
F12	1996	29180000	75	3	19.369	26.718	7.349
F13	1996	36210000	75	2	4.094	5.968	1.874
F14	1996	36210000	75	3	4.094	5.968	1.874
F15	1996	36210000	75	2	13.140	18.664	5.524
F17	1996	57002000	10	2	8.201	17.041	8.840
F18	1996	57002000	10	3	8.201	17.041	8.840
F21	1996	70225000	95	2	22.509	26.506	3.997
F22	1996	70225000	95	3	22.509	26.506	3.997
F23	1996	70225000	95	2	26.902	31.190	4.288
F24	1996	70225000	95	3	26.902	31.190	4.288
F25	1996	72001000	295	2	19.960	21.340	1.380
F26	1996	72001000	295	3	19.960	21.490	1.530
F29	1996	74170000	10	2	0.000	0.710	0.710
F30	1996	74170000	10	3	0.000	0.710	0.710

Table A-1. Continued

ID	Completion year	Roadway ID	US Rd.	Roadway	BMP	EMP	Length (miles)
F31A	1996	79002000	95	2	0.000	6.771	6.771
F31B	1996	79002000	95	2	6.771	27.402	20.631
F32A	1996	79002000	95	3	0.000	6.771	6.771
F32B	1996	79002000	95	3	6.771	27.402	20.631
F35	1996	79002000	95	2	35.397	35.982	0.585
F36	1996	79002000	95	3	35.397	35.982	0.585
F37	1996	89095000	95	2	8.500	11.600	3.100
F38	1996	89095000	95	3	8.450	11.500	3.050
F39	1996	89095000	95	2	11.600	24.967	13.367
F40	1996	89095000	95	3	11.500	24.967	13.467
F43	1996	93220000	95	2	34.750	36.232	1.482
F44	1996	93220000	95	3	34.750	36.232	1.482
F45	1996	94001000	95	2	0.000	15.379	15.379
F46	1996	94001000	95	3	0.000	15.379	15.379
G01	1997	13075000	75	2	8.288	10.307	2.019
G02	1997	13075000	75	3	8.288	10.307	2.019
G03	1997	13075000	75	2	11.049	12.896	1.847
G04	1997	13075000	75	3	11.049	12.896	1.847
G07	1997	15190900	275	2	0.000	1.139	1.139
G08	1997	15190900	275	3	0.000	1.139	1.139
G09	1997	16320000	4	2	12.636	31.947	19.311
G10	1997	16320000	4	3	12.636	31.947	19.311
G11	1997	26260000	75	2	34.740	35.190	0.450
G12	1997	26260000	75	3	34.740	35.190	0.450
G13	1997	29170000	10	2	10.105	20.690	10.585
G14	1997	29170000	10	3	10.105	20.690	10.585
G19	1997	29180000	75	2	9.369	19.450	10.081
G20	1997	29180000	75	3	9.369	19.450	10.081
G21	1997	36210000	75	2	22.500	23.506	1.006
G22	1997	36210000	75	3	22.500	38.282	15.782
G23	1997	36210000	75	2	23.506	38.282	14.776
G24	1997	37120000	10	2	15.099	25.523	10.424
G25	1997	37120000	10	3	15.099	25.523	10.424
G26	1997	70220000	95	2	31.252	41.503	10.251
G27	1997	70220000	95	3	31.252	41.503	10.251
G28	1997	70225000	95	2	3.195	4.505	1.310
G29	1997	70225000	95	3	3.195	4.505	1.310
G30	1997	72001000	295	2	4.970	5.698	0.728
G31	1997	72001000	295	3	4.970	5.698	0.728
G32	1997	72001000	295	2	8.786	9.628	0.842
G33	1997	72001000	295	3	8.786	9.678	0.892

Table A-1. Continued

ID	Completion year	Roadway ID	US Rd.	Roadway	BMP	EMP	Length (miles)
G34	1997	75280000	4	2	18.775	19.197	0.422
G35	1997	75280000	4	3	18.955	19.460	0.505
G36	1997	79002000	95	2	27.402	31.528	4.126
G37	1997	79002000	95	3	27.402	31.528	4.126
G38	1997	79002000	95	2	35.982	45.804	9.822
G39	1997	79002000	95	3	35.982	45.804	9.822
H01	1998	18130000	75	2	15.329	21.730	6.401
H02	1998	18130000	75	3	15.329	21.740	6.411
H03	1998	32100000	75	2	19.175	28.746	9.571
H04	1998	32100000	75	3	19.175	28.746	9.571
H05	1998	35090000	10	2	0.000	11.333	11.333
H06	1998	35090000	10	3	0.000	11.333	11.333
H07	1998	37120000	10	2	5.861	15.099	9.238
H08	1998	37120000	10	3	5.861	15.099	9.238
H09	1998	37130000	75	2	0.000	3.277	3.277
H10	1998	37130000	75	3	0.000	3.277	3.277
H12	1998	70225000	95	3	0.000	3.342	3.342
H13	1998	70225000	95	2	4.505	5.332	0.827
H14	1998	70225000	95	3	4.665	5.332	0.667
H15	1998	72270000	10	2	0.000	2.427	2.427
H16	1998	72270000	10	3	0.000	2.623	2.623
H17	1998	72270000	10	2	3.220	5.102	1.882
H18	1998	72270000	10	3	3.547	13.233	9.686
H19	1998	72270000	10	2	6.083	15.864	9.781
H20	1998	79110000	4	2	0.503	14.668	14.165
H21	1998	79110000	4	3	0.503	14.668	14.165
H22	1998	92130000	4	3	3.226	3.836	0.610
H23	1998	92130000	4	2	3.226	3.887	0.661
H24	1998	92130000	4	3	4.557	5.300	0.743
H25	1998	92130000	4	2	4.618	5.175	0.557
H26	1998	92130000	4	2	5.175	6.250	1.075
H27	1998	92130000	4	3	5.300	6.301	1.001
H28	1998	29180000	75	2	26.718	30.447	3.729
H29	1998	29180000	75	3	26.718	30.447	3.729

APPENDIX B
COMPUTER PRINTOUTS FOR PAVEMENT FAILURE MODELING

Distribution Analysis, Rutting, Least Squares

```
Variable Start: Start  End: End
Frequency: Rutting

Censoring Information    Count
Right censored value       175
Interval censored value     57

Estimation Method: Least Squares (failure time(X) on rank(Y))

Distribution:   Weibull


Parameter Estimates

                     Standard   95.0% Normal CI
Parameter  Estimate     Error    Lower    Upper
Shape       1.48121  0.197887  1.13998  1.92457
Scale       22.9150   3.43498  17.0814  30.7408

Log-Likelihood = -254.266

Goodness-of-Fit
Anderson-Darling (adjusted) = 129.482
Correlation Coefficient = 0.989


Characteristics of Distribution

                                   Standard   95.0% Normal CI
                          Estimate     Error    Lower    Upper
Mean(MTTF)                 20.7188   3.39406  15.0288  28.5631
Standard Deviation         14.2320   3.91784  8.29741  24.4111
Median                     17.8919   2.23785  14.0020  22.8624
First Quartile(Q1)         9.88138  0.893639  8.27633  11.7977
Third Quartile(Q3)         28.5686   4.98077  20.2996  40.2060
Interquartile Range(IQR)   18.6873   4.51621  11.6368  30.0095


Table of Percentiles

                     Standard    95.0% Normal CI
Percent  Percentile     Error       Lower     Upper
    0.1    0.216217  0.110538  0.0793828  0.588918
      1     1.02646  0.316757   0.560617   1.87938
```

```
       2     1.64459  0.409575    1.00942   2.67945
       3     2.16990  0.466399    1.42391   3.30672
       4     2.64423  0.505798    1.81752   3.84698
       5     3.08495  0.534900    2.19613   4.33350
       6     3.50141  0.557358    2.56299   4.78341
       7     3.89933  0.575358    2.92007   5.20700
       8     4.28259  0.590349    3.26866   5.61104
       9     4.65393  0.603367    3.60964   6.00033
      10     5.01539  0.615191    3.94362   6.37843
      20     8.32400  0.761298    6.95798   9.95822
      30     11.4248   1.07428    9.50185   13.7368
      40     14.5602   1.57003    11.7864   17.9867
      50     17.8919   2.23785    14.0020   22.8624
      60     21.6017   3.10371    16.3000   28.6277
      70     25.9744   4.24913    18.8494   35.7926
      80     31.5973   5.87702    21.9447   45.4958
      90     40.2402   8.64462    26.4120   61.3084
      91     41.4743   9.06192    27.0268   63.6446
      92     42.8332   9.52721    27.6982   66.2384
      93     44.3492   10.0532    28.4403   69.1573
      94     46.0689   10.6582    29.2738   72.4998
      95     48.0638   11.3710    30.2302   76.4181
      96     50.4526   12.2390    31.3614   81.1655
      97     53.4542   13.3512    32.7626   87.2139
      98     57.5525   14.9060    34.6422   95.6144
      99     64.2530   17.5307    37.6402   109.682


Table of Survival Probabilities

                     95.0% Normal CI
Time  Probability     Lower     Upper
   1     0.990378  0.976369  0.996098
   2     0.973367  0.949466  0.986046
   3     0.951976  0.921111  0.970955
   4     0.927407  0.891575  0.951716
   5     0.900431  0.860823  0.929229
   6     0.871622  0.828679  0.904422
   7     0.841439  0.794925  0.878213
   8     0.810260  0.759407  0.851422
   9     0.778409  0.722122  0.824689
  10     0.746162  0.683256  0.798433
  11     0.713759  0.643159  0.772878
  12     0.681408  0.602274  0.748112
  13     0.649288  0.561080  0.724149
  14     0.617556  0.520042  0.700964
  15     0.586345  0.479589  0.678523
```

Distribution Analysis, Rutting, Maximum Likelihood

```
Variable Start: Start  End: End
Frequency: Rutting

Censoring Information    Count
Right censored value       175
Interval censored value     57
```

```
Estimation Method: Maximum Likelihood

Distribution:   Weibull


Parameter Estimates

                     Standard   95.0% Normal CI
Parameter  Estimate     Error    Lower    Upper
Shape       1.55531  0.196767  1.21375  1.99299
Scale       21.7492   2.93836  16.6896  28.3428

Log-Likelihood = -254.186

Goodness-of-Fit
Anderson-Darling (adjusted) = 129.482


Characteristics of Distribution

                                      Standard   95.0% Normal CI
                          Estimate       Error    Lower    Upper
Mean(MTTF)                 19.5541     2.84683  14.6999  26.0113
Standard Deviation         12.8418     3.19993  7.87994  20.9281
Median                     17.1831     1.95071  13.7553  21.4652
First Quartile(Q1)         9.76220    0.832127  8.26022  11.5373
Third Quartile(Q3)         26.8319     4.20254  19.7393  36.4729
Interquartile Range(IQR)   17.0697     3.78295  11.0557  26.3553


Table of Percentiles

                     Standard    95.0% Normal CI
Percent  Percentile     Error     Lower     Upper
    0.1    0.256276  0.119129  0.103046  0.637361
      1     1.12961  0.319066  0.649385   1.96497
      2     1.76967  0.405161   1.12983   2.77187
      3     2.30430  0.457025   1.56212   3.39909
      4     2.78168  0.492690   1.96581   3.93615
      5     3.22156  0.518936   2.34938   4.41754
      6     3.63447  0.539178   2.71746   4.86091
      7     4.02681  0.555432   3.07292   5.27680
      8     4.40288  0.569013   3.41768   5.67210
      9     4.76573  0.580847   3.75306   6.05165
     10     5.11760  0.591619   4.08003   6.41903
     20     8.29108  0.720267   6.99302   9.83008
     30     11.2092  0.983289   9.43855   13.3120
     40     14.1213   1.39630   11.6335   17.1412
     50     17.1831   1.95071   13.7553   21.4652
     60     20.5605   2.66585   15.9466   26.5093
     70     24.5063   3.60564   18.3670   32.6976
     80     29.5343   4.93058   21.2924   40.9666
     90     37.1821   7.16034   25.4926   54.2318
     91     38.2672   7.49448   26.0689   56.1735
     92     39.4605   7.86648   26.6977   58.3244
     93     40.7894   8.28628   27.3923   60.7390
```

```
     94     42.2944   8.76838   28.1717   63.4968
     95     44.0368   9.33515   29.0652   66.7203
     96     46.1187   10.0239   30.1210   70.6131
     97     48.7282   10.9040   31.4271   75.5536
     98     52.2798   12.1304   33.1766   82.3827
     99     58.0609   14.1912   35.9612   93.7418


Table of Survival Probabilities

                     95.0% Normal CI
Time  Probability     Lower     Upper
   1     0.991720  0.979637  0.996645
   2     0.975859  0.954073  0.987378
   3     0.955126  0.926068  0.972929
   4     0.930698  0.896209  0.954019
   5     0.903374  0.864643  0.931460
   6     0.873772  0.831315  0.906146
   7     0.842405  0.796093  0.879001
   8     0.809710  0.758874  0.850887
   9     0.776069  0.719692  0.822515
  10     0.741815  0.678761  0.794384
  11     0.707246  0.636468  0.766792
  12     0.672623  0.593308  0.739888
  13     0.638173  0.549817  0.713732
  14     0.604100  0.506529  0.688334
  15     0.570577  0.463937  0.663686
```

Distribution Analysis, Ride, Least Squares

```
* NOTE * 17 cases were used
* NOTE * 4 cases contained missing values or was a case with zero
frequency.

Variable Start: Start  End: End
Frequency: Ride

Censoring Information    Count
Right censored value       189
Interval censored value     43

Estimation Method: Least Squares (failure time(X) on rank(Y))

Distribution:   Weibull


Parameter Estimates

                     Standard   95.0% Normal CI
Parameter  Estimate     Error    Lower    Upper
Shape       4.45257  0.606958  3.40862  5.81626
Scale       14.3533  0.783123  12.8977  15.9733

Log-Likelihood = -168.651

Goodness-of-Fit
```

```
Anderson-Darling (adjusted) = 82.546
Correlation Coefficient = 0.994


Characteristics of Distribution

                                     Standard   95.0% Normal CI
                           Estimate     Error    Lower    Upper
Mean(MTTF)                  13.0904  0.637544  11.8987  14.4016
Standard Deviation          3.33244  0.539415  2.42650  4.57661
Median                      13.2192  0.613776  12.0693  14.4786
First Quartile(Q1)          10.8500  0.377864  10.1341  11.6165
Third Quartile(Q3)          15.4459  0.967153  13.6620  17.4627
Interquartile Range(IQR)    4.59585  0.778636  3.29726  6.40586


Table of Percentiles

                      Standard   95.0% Normal CI
Percent  Percentile      Error    Lower    Upper
    0.1     3.04252   0.525658  2.16856  4.26871
      1     5.10816   0.533950  4.16188  6.26959
      2     5.97539   0.505836  5.06185  7.05380
      3     6.55258   0.480702  5.67502  7.56584
      4     6.99801   0.459007  6.15380  7.95804
      5     7.36625   0.440246  6.55201  8.28169
      6     7.68318   0.423978  6.89556  8.56076
      7     7.96329   0.409873  7.19914  8.80854
      8     8.21556   0.397686  7.47194  9.03318
      9     8.44599   0.387230  7.72013  9.24009
     10     8.65879   0.378358  7.94809  9.43304
     20     10.2483   0.356536  9.57280  10.9715
     30     11.3867   0.412050  10.6071  12.2236
     40     12.3434   0.503556  11.3949  13.3709
     50     13.2192   0.613776  12.0693  14.4786
     60     14.0743   0.739152  12.6976  15.6002
     70     14.9644   0.883876  13.3285  16.8010
     80     15.9724    1.06172  14.0213  18.1950
     90     17.3102    1.31645  14.9131  20.0926
     91     17.4851    1.35111  15.0277  20.3442
     92     17.6736    1.38884  15.1508  20.6165
     93     17.8793    1.43038  15.2845  20.9145
     94     18.1070    1.47682  15.4320  21.2457
     95     18.3641    1.52984  15.5977  21.6212
     96     18.6629    1.59216  15.7892  22.0595
     97     19.0251    1.66876  16.0201  22.5938
     98     19.4985    1.77049  16.3196  23.2965
     99     20.2261    1.93034  16.7754  24.3864


Table of Survival Probabilities

                    95.0% Normal CI
Time  Probability     Lower    Upper
   1      0.99999  0.999882  1.00000
   2      0.99985  0.998860  0.99998
   3      0.99906  0.995695  0.99980
```

```
   4      0.99662  0.988935  0.99897
   5      0.99090  0.976966  0.99642
   6      0.97963  0.958026  0.99018
   7      0.95995  0.930132  0.97720
   8      0.92860  0.890827  0.95365
   9      0.88237  0.836524  0.91600
  10      0.81868  0.761667  0.86328
  11      0.73652  0.660079  0.79840
  12      0.63730  0.531214  0.72553
  13      0.52549  0.385806  0.64748
  14      0.40863  0.244479  0.56632
  15      0.29618  0.129760  0.48431
```

Distribution Analysis, Ride, Maximum Likelihood

```
* NOTE * 17 cases were used
* NOTE * 4 cases contained missing values or was a case with zero
frequency.

Variable Start: Start  End: End
Frequency: Ride

Censoring Information    Count
Right censored value       189
Interval censored value     43

Estimation Method: Maximum Likelihood

Distribution:   Weibull


Parameter Estimates

                    Standard   95.0% Normal CI
Parameter  Estimate    Error    Lower    Upper
Shape       4.73200  0.598747  3.69267  6.06385
Scale       14.0424  0.668777  12.7909  15.4163

Log-Likelihood = -168.530

Goodness-of-Fit
Anderson-Darling (adjusted) = 82.552


Characteristics of Distribution

                                  Standard   95.0% Normal CI
                          Estimate    Error    Lower    Upper
Mean(MTTF)                 12.8522  0.546335  11.8248  13.9688
Standard Deviation         3.09554  0.453713  2.32261  4.12570
Median                     12.9958  0.532210  11.9935  14.0819
First Quartile(Q1)         10.7918  0.348400  10.1301  11.4967
Third Quartile(Q3)         15.0459  0.818153  13.5249  16.7380
Interquartile Range(IQR)   4.25411  0.654601  3.14652  5.75158
```

```
Table of Percentiles

                     Standard   95.0% Normal CI
Percent  Percentile     Error     Lower    Upper
    0.1     3.26216  0.499348  2.41663  4.40353
      1     5.31187  0.497567  4.42094  6.38234
      2     6.15641  0.470424  5.30012  7.15105
      3     6.71443  0.447312  5.89254  7.65096
      4     7.14307  0.427778  6.35198  8.03269
      5     7.49621  0.411092  6.73227  8.34683
      6     7.79930  0.396737  7.05922  8.61698
      7     8.06657  0.384348  7.34736  8.85617
      8     8.30680  0.373664  7.60579  9.07242
      9     8.52585  0.364490  7.84057  9.27102
     10     8.72783  0.356675  8.05602  9.45566
     20     10.2277  0.333731  9.59410  10.9032
     30     11.2934  0.373760  10.5841  12.0502
     40     12.1840  0.444585  11.3431  13.0873
     50     12.9958  0.532210  11.9935  14.0819
     60     13.7853  0.633191  12.5985  15.0839
     70     14.6042  0.750498  13.2049  16.1518
     80     15.5280  0.895030  13.8693  17.3852
     90     16.7489   1.10203  14.7225  19.0543
     91     16.9080   1.13017  14.8319  19.2748
     92     17.0795   1.16079  14.9495  19.5131
     93     17.2665   1.19449  15.0771  19.7738
     94     17.4733   1.23215  15.2178  20.0632
     95     17.7068   1.27513  15.3759  20.3909
     96     17.9776   1.32561  15.5585  20.7729
     97     18.3058   1.38761  15.7785  21.2379
     98     18.7340   1.46987  16.0637  21.8482
     99     19.3911   1.59891  16.4974  22.7924


Table of Survival Probabilities

                    95.0% Normal CI
Time  Probability     Lower    Upper
   1      1.00000  0.999939  1.00000
   2      0.99990  0.999281  0.99999
   3      0.99933  0.996940  0.99985
   4      0.99738  0.991433  0.99920
   5      0.99248  0.980943  0.99704
   6      0.98227  0.963343  0.99147
   7      0.96358  0.936168  0.97935
   8      0.93260  0.896426  0.95644
   9      0.88529  0.840057  0.91835
  10      0.81825  0.761172  0.86291
  11      0.72986  0.653313  0.79220
  12      0.62168  0.516101  0.71065
  13      0.49947  0.362337  0.62206
  14      0.37314  0.216692  0.52969
  15      0.25503  0.104765  0.43711
```

Distribution Analysis, Cracking, Least Squares

```
* NOTE * 22 cases were used
* NOTE * 5 cases contained missing values or was a case with zero
frequency.

Variable Start: Start  End: End
Frequency: Cracking

Censoring Information    Count
Right censored value        40
Interval censored value    192

Estimation Method: Least Squares (failure time(X) on rank(Y))

Distribution:   Loglogistic


Parameter Estimates

                      Standard    95.0% Normal CI
Parameter  Estimate      Error     Lower     Upper
Location    1.69323  0.0327192   1.62910   1.75736
Scale      0.289530  0.0199759  0.252910  0.331453

Log-Likelihood = -469.416

Goodness-of-Fit
Anderson-Darling (adjusted) = 1.036
Correlation Coefficient = 0.997


Characteristics of Distribution

                                      Standard   95.0% Normal CI
                          Estimate      Error    Lower    Upper
Mean(MTTF)                 6.26601  0.244588  5.80450  6.76420
Standard Deviation         4.02699  0.519504  3.12731  5.18550
Median                     5.43703  0.177895  5.09930  5.79712
First Quartile(Q1)         3.95567  0.153287  3.66636  4.26781
Third Quartile(Q3)         7.47313  0.299174  6.90917  8.08311
Interquartile Range(IQR)   3.51745  0.279612  3.00998  4.11048


Table of Percentiles

                      Standard     95.0% Normal CI
Percent  Percentile      Error      Lower      Upper
0.00001   0.0511270  0.0164877  0.0271738  0.0961944
 0.0001   0.0995820  0.0275608  0.0578893   0.171302
  0.001    0.193960  0.0448347   0.123297   0.305120
   0.01    0.377793  0.0701686   0.262517   0.543688
    0.1    0.736032   0.103538   0.558673   0.969697
      1     1.43736   0.138502    1.18999    1.73614
      2     1.76197   0.146737    1.49662    2.07437
      3     1.98734   0.150467    1.71327    2.30525
      4     2.16645   0.152496    1.88726    2.48694
```

```
      5     2.31805   0.153670    2.03561    2.63969
      6     2.45121   0.154351    2.16661    2.77319
      7     2.57103   0.154723    2.28498    2.89289
      8     2.68076   0.154894    2.39373    3.00220
      9     2.78254   0.154930    2.49487    3.10339
     10     2.87792   0.154874    2.58984    3.19806
     20     3.63954   0.153280    3.35118    3.95271
     30     4.25423   0.154451    3.96203    4.56798
     40     4.83479   0.161623    4.52817    5.16217
     50     5.43703   0.177895    5.09930    5.79712
     60     6.11428   0.207776    5.72031    6.53538
     70     6.94867   0.259621    6.45801    7.47661
     80     8.12224   0.354147    7.45696    8.84688
     90     10.2717   0.571722    9.21013    11.4557
     91     10.6238   0.611484    9.49047    11.8925
     92     11.0272   0.658232    9.80970    12.3958
     93     11.4978   0.714289    10.1797    12.9866
     94     12.0599   0.783253    10.6184    13.6970
     95     12.7526   0.871053    11.1547    14.5794
     96     13.6450   0.988384    11.8391    15.7265
     97     14.8748    1.15718    12.7712    17.3249
     98     16.7774    1.43281    14.1916    19.8343
     99     20.5664    2.02633    16.9548    24.9473
```

```
Table of Survival Probabilities

                     95.0% Normal CI
Time  Probability     Lower     Upper
   1     0.997123  0.993533  0.998723
   2     0.969355  0.949994  0.981367
   3     0.886325  0.846142  0.917042
   4     0.742714  0.690093  0.789131
   5     0.571853  0.516457  0.625504
   6     0.415736  0.361675  0.471904
   7     0.294689  0.244655  0.350211
   8     0.208512  0.164593  0.260496
   9     0.149221  0.112090  0.195937
  10     0.108648  0.077891  0.149580
  11     0.080630  0.055361  0.116017
  12     0.060977  0.040233  0.091397
  13     0.046940  0.029855  0.073066
  14     0.036729  0.022580  0.059207
  15     0.029169  0.017374  0.048574
```

Distribution Analysis, Cracking, Maximum Likelihood

```
* NOTE * 22 cases were used
* NOTE * 5 cases contained missing values or was a case with zero
frequency.

Variable Start: Start  End: End
Frequency: Cracking

Censoring Information    Count
Right censored value        40
```

```
Interval censored value    192

Estimation Method: Maximum Likelihood

Distribution:   Loglogistic


Parameter Estimates

                      Standard    95.0% Normal CI
Parameter  Estimate      Error     Lower     Upper
Location    1.69968  0.0304412   1.64002   1.75935
Scale      0.263958  0.0164217  0.233657  0.298189

Log-Likelihood = -468.309

Goodness-of-Fit
Anderson-Darling (adjusted) = 0.984


Characteristics of Distribution

                                    Standard   95.0% Normal CI
                          Estimate     Error    Lower    Upper
Mean(MTTF)                 6.15363  0.213330  5.74940  6.58628
Standard Deviation         3.46245  0.370797  2.80690  4.27110
Median                     5.47222  0.166581  5.15528  5.80865
First Quartile(Q1)         4.09471  0.141266  3.82699  4.38116
Third Quartile(Q3)         7.31314  0.265102  6.81157  7.85163
Interquartile Range(IQR)   3.21842  0.232874  2.79289  3.70880


Table of Percentiles

                      Standard    95.0% Normal CI
Percent  Percentile      Error      Lower     Upper
0.00001   0.0777063  0.0205705  0.0462514  0.130553
 0.0001    0.142697  0.0324207  0.0914158  0.222745
  0.001    0.262044  0.0497345   0.180642  0.380126
   0.01    0.481218  0.0734287   0.356827  0.648972
    0.1    0.883901   0.102325   0.704472   1.10903
      1     1.62704   0.129775    1.39157   1.90236
      2     1.95895   0.135604    1.71041   2.24360
      3     2.18614   0.138078    1.93160   2.47424
      4     2.36508   0.139344    2.10715   2.65458
      5     2.51551   0.140028    2.25550   2.80549
      6     2.64691   0.140392    2.38557   2.93689
      7     2.76463   0.140568    2.50240   3.05433
      8     2.87199   0.140628    2.60918   3.16128
      9     2.97125   0.140618    2.70804   3.26004
     10     3.06396   0.140567    2.80048   3.35223
     20     3.79529   0.140312    3.53001   4.08050
     30     4.37555   0.143296    4.10352   4.66562
     40     4.91680   0.151398    4.62884   5.22267
     50     5.47222   0.166581    5.15528   5.80865
     60     6.09038   0.192002    5.72545   6.47856
     70     6.84375   0.233895    6.40034   7.31788
```

```
     80     7.89009   0.307923    7.30908   8.51729
     90     9.77336   0.474027    8.88707   10.7480
     91     10.0783   0.503978    9.13741   11.1161
     92     10.4266   0.539062    9.42184   11.5385
     93     10.8315   0.580963    9.75068   12.0322
     94     11.3133   0.632273    10.1395   12.6229
     95     11.9042   0.697249    10.6132   13.3523
     96     12.6614   0.783526    11.2152   14.2941
     97     13.6977   0.906654    12.0311   15.5951
     98     15.2864     1.10555   13.2661   17.6143
     99     18.4047     1.52657   15.6432   21.6536
   99.9     33.8784     4.03428   26.8264   42.7844


Table of Survival Probabilities

                     95.0% Normal CI
Time  Probability      Lower     Upper
   1     0.998405  0.996440  0.999286
   2     0.978400  0.964697  0.986857
   3     0.906967  0.873154  0.932463
   4     0.766253  0.716225  0.809803
   5     0.584651  0.528562  0.638629
   6     0.413667  0.358663  0.470913
   7     0.282353  0.232986  0.337576
   8     0.191746  0.150264  0.241428
   9     0.131825  0.098301  0.174567
  10     0.092450  0.065833  0.128351
  11     0.066288  0.045247  0.096129
  12     0.048578  0.031895  0.073324
  13     0.036332  0.023018  0.056900
  14     0.027685  0.016969  0.044859
  15     0.021454  0.012751  0.035879
```

Distribution Analysis, Raveling, Least Squares

```
* NOTE * 25 cases were used
* NOTE * 2 cases contained missing values or was a case with zero
frequency.

Variable Start: Start  End: End
Frequency: Raveling

Censoring Information    Count
Right censored value       137
Interval censored value     95

Estimation Method: Least Squares (failure time(X) on rank(Y))

Distribution:   Lognormal


Parameter Estimates

                      Standard    95.0% Normal CI
Parameter  Estimate      Error     Lower     Upper
```

```
Location    2.39731  0.0586878   2.28228   2.51234
Scale      0.629249  0.0498535  0.538746  0.734955

Log-Likelihood = -341.521

Goodness-of-Fit
Anderson-Darling (adjusted) = 27.475
Correlation Coefficient = 0.995


Characteristics of Distribution

                                      Standard   95.0% Normal CI
                           Estimate      Error    Lower    Upper
Mean(MTTF)                  13.4004    1.07949  11.4432  15.6924
Standard Deviation          9.34003    1.56338  6.72775  12.9666
Median                      10.9936   0.645189  9.79904  12.3337
First Quartile(Q1)          7.19142   0.349784  6.53752  7.91072
Third Quartile(Q3)          16.8059    1.38424  14.3006  19.7503
Interquartile Range(IQR)    9.61452    1.21623  7.50327  12.3198


Table of Percentiles

                          Standard    95.0% Normal CI
Percent  Percentile          Error       Lower     Upper
0.00001    0.417126  0.0965734  0.264970  0.656656
 0.0001    0.552238   0.115881  0.366025  0.833184
  0.001    0.750986   0.139858  0.521328   1.08182
   0.01     1.05879   0.169533  0.773594   1.44912
    0.1     1.57269   0.205396   1.21751   2.03147
      1     2.54329   0.244939   2.10581   3.07166
      2     3.01920   0.256197   2.55659   3.56550
      3     3.36633   0.262395   2.88940   3.92198
      4     3.65353   0.266672   3.16652   4.21543
      5     3.90512   0.270021   3.41018   4.47189
      6     4.13286   0.272888   3.63118   4.70386
      7     4.34346   0.275513   3.83568   4.91845
      8     4.54111   0.278042   4.02758   5.12010
      9     4.72866   0.280573   4.20952   5.31182
     10     4.90814   0.283173   4.38336   5.49575
     20     6.47353   0.320300   5.87523   7.13275
     30     7.90371   0.388018   7.17865   8.70200
     40     9.37355   0.493692   8.45420   10.3929
     50     10.9936   0.645189   9.79904   12.3337
     60     12.8936   0.858520   11.3161   14.6910
     70     15.2914    1.16910   13.1634   17.7633
     80     18.6697    1.66582   15.6743   22.2375
     90     24.6241    2.66620   19.9157   30.4456
     91     25.5587    2.83500   20.5647   31.7655
     92     26.6143    3.02902   21.2931   33.2653
     93     27.8254    3.25581   22.1230   34.9977
     94     29.2433    3.52677   23.0871   37.0409
     95     30.9487    3.86004   24.2370   39.5192
     96     33.0800    4.28711   25.6596   42.6461
     97     35.9022    4.86951   27.5214   46.8351
     98     40.0300    5.75291   30.2034   53.0538
```

```
     99     47.5205    7.44033   34.9630   64.5884


Table of Survival Probabilities

                    95.0% Normal CI
Time  Probability     Lower    Upper
   1     0.999930  0.999512  0.99999
   2     0.996618  0.990759  0.99890
   3     0.980486  0.963934  0.99008
   4     0.945940  0.918568  0.96546
   5     0.894730  0.858768  0.92355
   6     0.832060  0.789215  0.86885
   7     0.763425  0.714171  0.80761
   8     0.693275  0.637508  0.74489
   9     0.624748  0.562578  0.68383
  10     0.559829  0.491910  0.62603
  11     0.499629  0.427081  0.57219
  12     0.444643  0.368840  0.52253
  13     0.394961  0.317322  0.47702
  14     0.350421  0.272272  0.43549
  15     0.310714  0.233208  0.39769
```

Distribution Analysis, Raveling, Maximum Likelihood

```
* NOTE * 25 cases were used
* NOTE * 2 cases contained missing values or was a case with zero
frequency.

Variable Start: Start  End: End
Frequency: Raveling

Censoring Information    Count
Right censored value       137
Interval censored value     95

Estimation Method: Maximum Likelihood

Distribution:   Lognormal


Parameter Estimates

                      Standard    95.0% Normal CI
Parameter  Estimate      Error     Lower     Upper
Location    2.38193  0.0576517   2.26894   2.49493
Scale      0.635188  0.0508904  0.542882  0.743189

Log-Likelihood = -341.438

Goodness-of-Fit
Anderson-Darling (adjusted) = 27.500


Characteristics of Distribution
```

```
                                    Standard   95.0% Normal CI
                          Estimate     Error    Lower    Upper
Mean(MTTF)                 13.2456   1.05448  11.3320  15.4823
Standard Deviation         9.33793   1.56375  6.72522  12.9657
Median                     10.8258  0.624127  9.66914  12.1209
First Quartile(Q1)         7.05338  0.346332  6.40622  7.76591
Third Quartile(Q3)         16.6159   1.34916  14.1713  19.4823
Interquartile Range(IQR)   9.56256   1.19886  7.47925  12.2261


Table of Percentiles

                            Standard    95.0% Normal CI
Percent  Percentile        Error       Lower      Upper
0.00001    0.398271  0.0952665  0.249213  0.636483
 0.0001    0.528674   0.114742  0.345498  0.808966
  0.001    0.721031   0.139085  0.494037   1.05232
   0.01     1.01985   0.169476  0.736357   1.41250
    0.1     1.52053   0.206677   1.16492   1.98469
      1     2.47012   0.248585   2.02794   3.00871
      2     2.93709   0.260733   2.46805   3.49526
      3     3.27814   0.267412   2.79378   3.84648
      4     3.56057   0.271959   3.06552   4.13556
      5     3.80815   0.275439   3.30482   4.38814
      6     4.03240   0.278331   3.52217   4.61654
      7     4.23986   0.280895   3.72356   4.82775
      8     4.43466   0.283291   3.91277   5.02615
      9     4.61958   0.285624   4.09235   5.21472
     10     4.79661   0.287968   4.26414   5.39556
     20     6.34297   0.320246   5.74535   7.00274
     30     7.75891   0.380917   7.04712   8.54259
     40     9.21665   0.479315   8.32350   10.2056
     50     10.8258   0.624127   9.66914   12.1209
     60     12.7160   0.831447   11.1864   14.4546
     70     15.1050    1.13656   13.0339   17.5053
     80     18.4769    1.62841   15.5457   21.9608
     90     24.4336    2.62592   19.7928   30.1625
     91     25.3700    2.79481   20.4432   31.4840
     92     26.4279    2.98909   21.1733   32.9865
     93     27.6421    3.21640   22.0052   34.7228
     94     29.0642    3.48820   22.9721   36.7720
     95     30.7757    3.82286   24.1254   39.2592
     96     32.9157    4.25219   25.5529   42.3999
     97     35.7515    4.83843   27.4218   46.6113
     98     39.9030    5.72912   30.1157   52.8710
     99     47.4465    7.43435   34.9004   64.5027


Table of Survival Probabilities

                      95.0% Normal CI
Time  Probability      Lower     Upper
   1     0.999912  0.999387  0.99999
   2     0.996078  0.989324  0.99872
   3     0.978328  0.960011  0.98899
   4     0.941498  0.911985  0.96261
   5     0.888040  0.850055  0.91859
```

```
   6     0.823590  0.779178  0.86189
   7     0.753785  0.703599  0.79902
   8     0.683043  0.627020  0.73516
   9     0.614396  0.552593  0.67342
  10     0.549708  0.482678  0.61534
  11     0.489977  0.418733  0.56154
  12     0.435608  0.361418  0.51214
  13     0.386625  0.310813  0.46704
  14     0.342813  0.266625  0.42601
  15     0.303830  0.228352  0.38876
```

Distribution Analysis, Bleeding, Least Squares

```
* NOTE * 18 cases were used
* NOTE * 9 cases contained missing values or was a case with zero
frequency.

Variable Start: Start  End: End
Frequency: Bleeding

Censoring Information    Count
Right censored value       211
Interval censored value     21

Estimation Method: Least Squares (failure time(X) on rank(Y))

Distribution:   Lognormal


Parameter Estimates

                     Standard   95.0% Normal CI
Parameter  Estimate     Error    Lower    Upper
Location    4.90663  0.453368  4.01805  5.79521
Scale       2.46632  0.360870  1.85141  3.28546

Log-Likelihood = -115.459

Goodness-of-Fit
Anderson-Darling (adjusted) = 131.227
Correlation Coefficient = 0.981


Characteristics of Distribution

                                    Standard   95.0% Normal CI
                          Estimate     Error    Lower     Upper
Mean(MTTF)                 2829.91   3650.86  225.755   35473.7
Standard Deviation         59173.2    128506  838.653   4175111
Median                     135.183   61.2877  55.5923   328.723
First Quartile(Q1)         25.6136   7.35539  14.5892   44.9684
Third Quartile(Q3)         713.468   477.070  192.401   2645.70
Interquartile Range(IQR)   687.855   471.490  179.490   2636.04


Table of Percentiles
```

```
                      Standard     95.0% Normal CI
Percent  Percentile      Error       Lower      Upper
0.00001   0.0003646  0.0005555  0.0000184  0.0072199
 0.0001   0.0010952  0.0014949  0.0000754  0.0158981
  0.001   0.0036539  0.0043563  0.0003531  0.0378090
   0.01   0.0140426  0.0140527  0.0019753  0.0998301
    0.1   0.0662134  0.0518763  0.0142578   0.307495
      1    0.435662   0.231139   0.154009    1.23240
      2    0.853361   0.381324   0.355446    2.04876
      3     1.30733   0.519337   0.600133    2.84791
      4     1.80196   0.653311   0.885398    3.66736
      5     2.33940   0.787289    1.20961    4.52442
      6     2.92139   0.924152    1.57152    5.43074
      7     3.54968    1.06638    1.97004    6.39591
      8     4.22607    1.21630    2.40411    7.42883
      9     4.95253    1.37624    2.87270    8.53817
     10     5.73113    1.54854    3.37480    9.73269
     20     16.9611    4.49665    10.0876    28.5181
     30     37.0879    11.7049    19.9799    68.8447
     40     72.3702    27.5975    34.2740    152.811
     50     135.183    61.2877    55.5923    328.723
     60     252.514    134.185    89.1165    715.503
     70     492.734    304.980    146.473    1657.56
     80     1077.43    780.888    260.297    4459.77
     90     3188.63    2790.45    573.716    17721.9
     91     3689.93    3304.62    637.821    21347.0
     92     4324.22    3968.98    715.538    26132.6
     93     5148.21    4851.61    811.884    32645.1
     94     6255.40    6066.82    934.789    41859.7
     95     7811.61    7821.37    1097.68    55591.2
     96     10141.4    10529.1    1325.45    77595.3
     97     13978.4    15149.7    1670.83     116946
     98     21414.7    24510.0    2272.35     201813
     99     41946.5    52040.0    3686.98     477221


Table of Survival Probabilities

                    95.0% Normal CI
Time  Probability     Lower     Upper
   1     0.976674  0.950458  0.990086
   2     0.956220  0.923464  0.976597
   3     0.938707  0.902240  0.963561
   4     0.923262  0.884080  0.951452
   5     0.909370  0.867893  0.940299
   6     0.896699  0.853121  0.930029
   7     0.885020  0.839436  0.920550
   8     0.874168  0.826627  0.911767
   9     0.864020  0.814549  0.903600
  10     0.854480  0.803100  0.895974
  11     0.845470  0.792201  0.888827
  12     0.836930  0.781790  0.882106
  13     0.828807  0.771821  0.875764
  14     0.821061  0.762251  0.869762
  15     0.813654  0.753049  0.864065
```

Distribution Analysis, Bleeding, Maximum Likelihood

```
* NOTE * 18 cases were used
* NOTE * 9 cases contained missing values or was a case with zero
frequency.

Variable Start: Start  End: End
Frequency: Bleeding

Censoring Information    Count
Right censored value       211
Interval censored value     21

Estimation Method: Maximum Likelihood

Distribution:   Lognormal


Parameter Estimates

                     Standard   95.0% Normal CI
Parameter  Estimate     Error    Lower    Upper
Location    7.57542   1.39716  4.83704  10.3138
Scale       4.00969  0.923315  2.55332  6.29677

Log-Likelihood = -111.139

Goodness-of-Fit
Anderson-Darling (adjusted) = 131.229


Characteristics of Distribution

                                                      95.0% Normal CI
                           Estimate Standard Error   Lower       Upper
Mean(MTTF)                  6042017       30476307 307.375 1.18767E+11
Standard Deviation      1.87240E+10    1.63603E+11 683.804 5.12703E+17
Median                      1949.69        2724.02 126.096     30146.0
First Quartile(Q1)          130.442        108.671 25.4846     667.659
Third Quartile(Q3)          29141.6        58179.1 582.304     1458400
Interquartile Range(IQR)    29011.2        58076.9 573.534     1467475


Table of Percentiles

                      Standard      95.0% Normal CI
Percent  Percentile      Error      Lower        Upper
0.00001   0.0000017  0.0000060  0.0000000    0.0016693
 0.0001   0.0000103  0.0000319  0.0000000    0.0044865
  0.001   0.0000730  0.0001938  0.0000004    0.0132898
   0.01   0.0006512  0.0014070  0.0000094    0.0449630
    0.1   0.0081035  0.0129468  0.0003538     0.185621
      1    0.173337   0.163451  0.0273044      1.10040
      2    0.517119   0.378756   0.123067      2.17290
      3     1.03460   0.636392   0.309879      3.45425
      4     1.74317   0.943634   0.603336      5.03643
      5     2.66463    1.31872    1.01013      7.02903
```

```
      6     3.82385    1.78954    1.52807      9.56881
      7     5.24856    2.39191    2.14845      12.8220
      8     6.96931    3.16752    2.85972      16.9847
      9     9.01966    4.16226    3.65082      22.2838
     10     11.4363    5.42546    4.51305      28.9802
     20     66.7384    47.2975    16.6390      267.684
     30     238.111    226.756    36.8275      1539.53
     40     705.975    831.906    70.1054      7109.31
     50     1949.69    2724.02    126.096      30146.0
     60     5384.44    8723.74    224.928       128895
     70     15964.3    29721.4    415.365       613577
     80     56957.9     122288    847.291      3828912
     90      332387     846075    2264.38     48790782
     91      421444    1095442    2583.72     68743809
     92      545431    1449620    2981.65     99775161
     93      724252    1971496    3489.99    150298933
     94      994098    2777553    4160.40    237532703
     95     1426571    4103023    5082.95    400378584
     96     2180664    6482407    6430.47    739494170
     97     3674147   11358448    8584.36   1572552180
     98     7350872   23886645    12599.7   4288612882
     99    21930041   76731079    23055.2  2.08598E+10


Table of Survival Probabilities

                     95.0% Normal CI
Time  Probability     Lower     Upper
   1     0.970573  0.943632  0.985830
   2     0.956956  0.927842  0.975747
   3     0.946876  0.915957  0.968001
   4     0.938650  0.905907  0.961729
   5     0.931610  0.896987  0.956479
   6     0.925408  0.888865  0.951976
   7     0.919837  0.881355  0.948042
   8     0.914762  0.874341  0.944554
   9     0.910088  0.867741  0.941422
  10     0.905749  0.861497  0.938582
  11     0.901692  0.855563  0.935984
  12     0.897878  0.849905  0.933591
  13     0.894275  0.844493  0.931372
  14     0.890859  0.839302  0.929303
  15     0.887607  0.834314  0.927366
```

Distribution Analysis, Delamination, Least Squares

```
* NOTE * 18 cases were used
* NOTE * 9 cases contained missing values or was a case with zero
frequency.

Variable Start: Start  End: End
Frequency: Delamination

Censoring Information    Count
Right censored value       221
Interval censored value     11
```

```
Estimation Method: Least Squares (failure time(X) on rank(Y))

Distribution:   Lognormal


Parameter Estimates

                     Standard    95.0% Normal CI
Parameter  Estimate     Error     Lower     Upper
Location    3.17491  0.180121   2.82188   3.52794
Scale      0.546982  0.108586  0.370676  0.807145

Log-Likelihood = -61.465

Goodness-of-Fit
Anderson-Darling (adjusted) = 129.347
Correlation Coefficient = 0.994


Characteristics of Distribution

                                   Standard   95.0% Normal CI
                          Estimate    Error    Lower    Upper
Mean(MTTF)                 27.7852  6.53640  17.5214  44.0612
Standard Deviation         16.4089  7.52480  6.67938  40.3110
Median                     23.9246  4.30933  16.8084  34.0537
First Quartile(Q1)         16.5432  1.95196  13.1276  20.8475
Third Quartile(Q3)         34.5996  8.59389  21.2642  56.2981
Interquartile Range(IQR)   18.0564  6.83120  8.60202  37.9020


Table of Percentiles

                     Standard   95.0% Normal CI
Percent  Percentile     Error     Lower    Upper
0.00001     1.39231  0.569083  0.624915  3.10206
 0.0001     1.77690  0.641963  0.875261  3.60734
  0.001     2.32121  0.718745   1.26516  4.25875
   0.01     3.12887  0.790450   1.90699  5.13366
    0.1     4.41323  0.832762   3.04886  6.38815
      1     6.70221  0.789371   5.32066  8.44249
      2     7.77990  0.756162   6.43046  9.41252
      3     8.55185  0.742974   7.21288  10.1394
      4     9.18263  0.745120   7.83244  10.7656
      5     9.72989  0.759625   8.34936  11.3387
      6     10.2213  0.784231   8.79423  11.8800
      7     10.6726  0.817094   9.18545  12.4004
      8     11.0935  0.856693   9.53530  12.9063
      9     11.4907  0.901784   9.85247  13.4014
     10     11.8689  0.951370   10.1433  13.8880
     20     15.0979   1.58284   12.2936  18.5419
     30     17.9586   2.34945   13.8968  23.2077
     40     20.8287   3.24210   15.3521  28.2590
     50     23.9246   4.30933   16.8084  34.0537
     60     27.4807   5.64340   18.3750  41.0988
     70     31.8726   7.42409   20.1905  50.3139
```

```
     80     37.9117   10.0734   22.5218  63.8179
     90     48.2258   15.0347   26.1765  88.8478
     91     49.8131   15.8402   26.7096  92.9007
     92     51.5967   16.7573   27.3006  97.5149
     93     53.6317   17.8188   27.9650  102.855
     94     55.9994   19.0731   28.7256  109.169
     95     58.8277   20.5976   29.6175  116.847
     96     62.3337   22.5247   30.6998  126.564
     97     66.9314   25.1110   32.0834  139.630
     98     73.5726   28.9567   34.0173  159.123
     99     85.4028   36.0959   37.2999  195.540


Table of Survival Probabilities

                    95.0% Normal CI
Time  Probability     Lower    Upper
   1      1.00000  0.999980  1.00000
   2      1.00000  0.999557  1.00000
   3      0.99993  0.997896  1.00000
   4      0.99946  0.994286  0.99997
   5      0.99790  0.988273  0.99973
   6      0.99428  0.979528  0.99871
   7      0.98768  0.967688  0.99593
   8      0.97740  0.952178  0.99034
   9      0.96306  0.932096  0.98139
  10      0.94462  0.906292  0.96935
  11      0.92228  0.873809  0.95510
  12      0.89643  0.834431  0.93956
  13      0.86760  0.788849  0.92333
  14      0.83637  0.738409  0.90672
  15      0.80331  0.684743  0.88991
```

Distribution Analysis, Delamination, Maximum Likelihood

```
* NOTE * 18 cases were used
* NOTE * 9 cases contained missing values or was a case with zero
frequency.

Variable Start: Start  End: End
Frequency: Delamination

Censoring Information    Count
Right censored value       221
Interval censored value     11

Estimation Method: Maximum Likelihood

Distribution:   Lognormal


Parameter Estimates

                     Standard    95.0% Normal CI
Parameter  Estimate     Error     Lower     Upper
Location    3.34360  0.261576   2.83092   3.85628
```

```
Scale      0.621942  0.146369  0.392127  0.986444

Log-Likelihood = -61.150

Goodness-of-Fit
Anderson-Darling (adjusted) = 129.346


Characteristics of Distribution

                                    Standard   95.0% Normal CI
                          Estimate     Error    Lower    Upper
Mean(MTTF)                 34.3640   11.9735  17.3587  68.0283
Standard Deviation         23.6158   14.8036  6.91236  80.6825
Median                     28.3210   7.40809  16.9611  47.2893
First Quartile(Q1)         18.6177   3.20828  13.2813  26.0980
Third Quartile(Q3)         43.0816   15.3313  21.4476  86.5379
Interquartile Range(IQR)   24.4640   12.2971  9.13403  65.5227


Table of Percentiles

                     Standard   95.0% Normal CI
Percent  Percentile     Error     Lower    Upper
0.00001     1.11619  0.584183  0.400167  3.11339
 0.0001     1.47293  0.676400  0.598812  3.62303
  0.001     1.99589  0.777132  0.930482  4.28120
   0.01     2.80273  0.875000   1.51998  5.16800
    0.1     4.14399  0.935179   2.66273  6.44927
      1     6.66421  0.873509   5.15439  8.61628
      2     7.89549  0.835240   6.41702  9.71461
      3     8.79216  0.836021   7.29721  10.5934
      4     9.53319  0.866916   7.97688  11.3931
      5     10.1818  0.920671   8.52817  12.1561
      6     10.7685  0.991359   8.99069  12.8979
      7     11.3107   1.07442   9.38928  13.6253
      8     11.8193   1.16652   9.74048  14.3417
      9     12.3016   1.26531   10.0557  15.0493
     10     12.7630   1.36917   10.3429  15.7495
     20     16.7796   2.55101   12.4558  22.6043
     30     20.4393   3.91170   14.0463  29.7420
     40     24.1924   5.49492   15.5003  37.7586
     50     28.3210   7.40809   16.9611  47.2893
     60     33.1543   9.83536   18.5364  59.2996
     70     39.2421   13.1329   20.3651  75.6168
     80     47.8008   18.1442   22.7163  100.585
     90     62.8439   27.8014   26.4059  149.563
     91     65.2010   29.3975   26.9444  157.776
     92     67.8620   31.2234   27.5415  167.211
     93     70.9134   33.3475   28.2128  178.242
     94     74.4838   35.8719   28.9813  191.428
     95     78.7759   38.9597   29.8827  207.667
     96     84.1355   42.8924   30.9767  228.520
     97     91.2267   48.2183   32.3754  257.057
     98     101.587   56.2299   34.3309  300.601
     99     120.356   71.3612   37.6511  384.733
```

```
Table of Survival Probabilities

                      95.0% Normal CI
Time  Probability     Lower     Upper
   1      1.00000  0.999867  1.00000
   2      0.99999  0.998801  1.00000
   3      0.99985  0.996252  1.00000
   4      0.99918  0.992063  0.99995
   5      0.99735  0.986171  0.99963
   6      0.99370  0.978443  0.99850
   7      0.98769  0.968547  0.99579
   8      0.97895  0.955829  0.99089
   9      0.96735  0.939254  0.98374
  10      0.95292  0.917622  0.97491
  11      0.93582  0.890084  0.96517
  12      0.91631  0.856547  0.95510
  13      0.89471  0.817625  0.94493
  14      0.87135  0.774363  0.93478
  15      0.84658  0.727984  0.92465
```

APPENDIX C
COMPUTER PRINTOUTS FOR TIME SERIES ANALYSIS

Table C-1. Augmented Dickey-Fuller (ADF) unit root test on ln(P)

Null Hypothesis: logP has a unit root Exogenous: Constant Lag Length: 1 (Fixed)				
			t-Statistic	Prob.*
Augmented Dickey-Fuller test statistic			-0.019506	0.954686
Test critical values:	1% level		-3.469737	
	5% level		-2.878723	
	10% level		-2.576009	
*MacKinnon (1996) one-sided p-values.				
Augmented Dickey-Fuller Test Equation Dependent Variable: D(logP) Method: Least Squares Date: 7/18/2006 Time: 1:32:40 AM Included observations: 167 after adjusting endpoints				
Variable	Coefficient	Std. Error	t-Statistic	Prob
logP(-1)	-0.000104	0.005334	-0.019506	0.984461
D(logP(-1))	0.361362	0.070871	5.098894	0.000001
C	0.001384	0.000804	1.720891	0.087156
R-squared	0.138810		Mean dependent var	0.002032
Adjusted R-squared	-0.435317		S.D. dependent var	0.005848
S.E. of regression	0.005460		Akaike info criterion	-7.576855
Sum squared resid	0.004889		Schwarz criterion	-7.539514
Log likelihood	634.667432		F-statistic	13.217043
Durbin-Watson stat	1.867131		Prob(F-statistic)	0.000371

Note: This table was created using Excel add-in developed by Kurt Annen.

MiniTab Printout for ln(P) ARIMA(1,1,0) Model Estimation

```
Estimates at each iteration

Iteration      SSE   Parameters
        0  1.36858  0.100  0.092
        1  0.01379  0.126  0.009
        2  0.00616  0.276  0.003
        3  0.00534  0.358  0.002
        4  0.00531  0.385  0.001
        5  0.00531  0.391  0.001
        6  0.00531  0.392  0.001
        7  0.00531  0.393  0.001

Relative change in each estimate less than 0.0010


Final Estimates of Parameters

Type           Coef    SE Coef     T      P
AR   1       0.3925     0.0719  5.46  0.000
Constant  0.0011291  0.0004339  2.60  0.010


Differencing: 1 regular difference
Number of observations:  Original series 169, after differencing 168
Residuals:    SS =  0.00524920 (backforecasts excluded)
              MS =  0.00003162  DF = 166


Modified Box-Pierce (Ljung-Box) Chi-Square statistic

Lag            12     24     36     48
Chi-Square   14.9   31.2   49.2   56.8
DF             10     22     34     46
P-Value     0.137  0.093  0.044  0.133


Correlation matrix of the estimated parameters

       1
2  0.013


Forecasts from period 169

                   95 Percent Limits
Period  Forecast     Lower     Upper  Actual
   170  0.325478  0.314454  0.336502
   171  0.329079  0.310180  0.347978
   172  0.331622  0.306169  0.357075
   173  0.333749  0.302737  0.364760
   174  0.335713  0.299867  0.371559
   175  0.337613  0.297466  0.377760
   176  0.339488  0.295440  0.383535
   177  0.341353  0.293718  0.388988
   178  0.343214  0.292241  0.394187
```

179	0.345074	0.290967	0.399180
180	0.346933	0.289864	0.404001
181	0.348791	0.288908	0.408675
182	0.350650	0.288077	0.413223
183	0.352509	0.287358	0.417660
184	0.354367	0.286736	0.421999
185	0.356226	0.286203	0.426249
186	0.358085	0.285748	0.430421
187	0.359943	0.285365	0.434521
188	0.361802	0.285048	0.438556
189	0.363661	0.284791	0.442531
190	0.365519	0.284589	0.446450
191	0.367378	0.284438	0.450318
192	0.369237	0.284334	0.454139
193	0.371095	0.284275	0.457915
194	0.372954	0.284258	0.461650
195	0.374813	0.284279	0.465346
196	0.376671	0.284337	0.469005
197	0.378530	0.284429	0.472630
198	0.380388	0.284554	0.476223
199	0.382247	0.284710	0.479784
200	0.384106	0.284895	0.483317
201	0.385964	0.285107	0.486821
202	0.387823	0.285347	0.490299
203	0.389682	0.285611	0.493752
204	0.391540	0.285899	0.497181
205	0.393399	0.286211	0.500587
206	0.395258	0.286544	0.503971
207	0.397116	0.286899	0.507334
208	0.398975	0.287273	0.510676
209	0.400834	0.287668	0.514000
210	0.402692	0.288081	0.517304
211	0.404551	0.288511	0.520590
212	0.406409	0.288960	0.523859
213	0.408268	0.289425	0.527112
214	0.410127	0.289906	0.530348
215	0.411985	0.290403	0.533568
216	0.413844	0.290915	0.536774
217	0.415703	0.291441	0.539964
218	0.417561	0.291982	0.543141
219	0.419420	0.292536	0.546304
220	0.421279	0.293104	0.549454
221	0.423137	0.293684	0.552591
222	0.424996	0.294277	0.555715
223	0.426855	0.294882	0.558827
224	0.428713	0.295499	0.561928
225	0.430572	0.296127	0.565017
226	0.432431	0.296767	0.568094
227	0.434289	0.297417	0.571161
228	0.436148	0.298078	0.574218
229	0.438006	0.298749	0.577264
230	0.439865	0.299430	0.580300
231	0.441724	0.300122	0.583326
232	0.443582	0.300822	0.586343
233	0.445441	0.301532	0.589350
234	0.447300	0.302251	0.592348
235	0.449158	0.302979	0.595338

MiniTab Printout for ln(P) ARIMA(4,1,0) Model Estimation

```
Estimates at each iteration

Iteration       SSE               Parameters
        0  0.623534  0.100   0.100  0.100   0.100  0.061
        1  0.007737  0.214   0.003  0.138   0.049  0.005
        2  0.005288  0.364  -0.132  0.149  -0.042  0.002
        3  0.005144  0.438  -0.184  0.139  -0.105  0.001
        4  0.005142  0.449  -0.186  0.138  -0.101  0.001
        5  0.005142  0.451  -0.186  0.137  -0.100  0.001
        6  0.005142  0.452  -0.186  0.137  -0.099  0.001
        7  0.005142  0.452  -0.186  0.137  -0.099  0.001

Relative change in each estimate less than 0.0010


Final Estimates of Parameters

Type           Coef    SE Coef      T      P
AR   1       0.4517     0.0783   5.77  0.000
AR   2      -0.1859     0.0855  -2.18  0.031
AR   3       0.1369     0.0863   1.59  0.115
AR   4      -0.0994     0.0803  -1.24  0.218
Constant  0.0013065  0.0004314   3.03  0.003


Differencing: 1 regular difference
Number of observations:  Original series 169, after differencing 168
Residuals:    SS =  0.00509149 (backforecasts excluded)
              MS =  0.00003124  DF = 163


Modified Box-Pierce (Ljung-Box) Chi-Square statistic

Lag            12     24     36     48
Chi-Square   11.8   28.7   51.2   62.5
DF              7     19     31     43
P-Value     0.107  0.070  0.013  0.028


Correlation matrix of the estimated parameters

        1       2       3      4
2  -0.402
3   0.133  -0.417
4  -0.061   0.139  -0.420
5   0.009   0.010  -0.004  0.022
```

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BIOGRAPHICAL SKETCH

Kelu Guo was born in Shandong, China. He earned a Bachelor of Engineering in transportation from Tongji University in July 1993. He worked as a civil engineer in China for seven years before he went to Florida. He received a Master of Engineering in civil engineering from the University of Florida in August 2003. He continued his study at the University of Florida and graduated in December 2006 with the degree of Doctor of Philosophy in civil engineering. He is looking forward to further contribution to the construction industry in China in the future.