INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI®

Bell & Howell Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

University of Alberta

Infrastructure Construction and Rehabilitation: Risk-Based Life Cycle Cost Analysis

by

Ossama M. Salem ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of ***Doctor of Philosophy***

in

Construction Engineering and Management

Department of Civil and Environmental Engineering

Edmonton, Alberta

Spring 1999

National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisitions et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

Our file Notre référence

0-612-39588-X

University of Alberta

Library Release Form

Name of Author:	Ossama M. Salem
Title of Thesis:	Infrastructure Construction and Rehabilitation: Risk-Based Life Cycle Cost Analysis
Degree:	Doctor of Philosophy
Year this Degree Granted:	1999

Ossama M. Salem
105 RH Michener Park
Edmonton, Alberta
Canada, T6H 4M4

Dated: Feb. 12, 1999

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Infrastructure Construction and Rehabilitation: Risk-Based Life Cycle Cost Analysis" submitted by Ossama M. Salem in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Construction Engineering and Management.

Dr. S. AbouRizk

Dr. S. Ariaratnam

Dr. D. Sego

Dr. M. Zuo

Dr. G. Smith

Approved on February 12, 1999

ABSTRACT

The objective of this research is to provide a prediction model of life cycle costs for civil infrastructure construction and rehabilitation alternatives, taking into consideration the uncertainty involved in determining the service life of civil infrastructure units. The ability to determine the uncertainty values that accompany the predicted life-cycle costs allows decision-makers to select construction and rehabilitation alternatives with a knowledge of the inherent risks. This research utilizes a risk-based approach to predict probabilities of occurrence of total life cycle costs associated with the construction/rehabilitation of civil infrastructure unit. The uncertainty component of the model is introduced through the statistical probability distributions that represent the times-to-failure (i.e., service life) of infrastructure units.

In the developed risk-based life cycle cost model, the service life of each construction/rehabilitation alternative is input to the model using random variables sampled from the fitted statistical distributions that represent the service life of the infrastructure units. Computer simulation is used to generate the probability distribution of the model outcome (i.e., life cycle costs of construction alternatives). The resulting life cycle cost distribution is then statistically analyzed to provide a measure of risk. As a result, decision-makers can determine the probabilities associated with various values of total life cycle costs. This enables them to make informed decisions regarding the construction/rehabilitation alternative that can be applied and the level of risk they wish to accept.

This dissertation provides a detailed explanation of the process involved in developing the risk-based life cycle model for civil engineering infrastructure. These process include: 1) defining factors affecting infrastructure performance; 2) performing statistical stratification of infrastructure inventory and failure data; 3) developing reliability and statistical models; and 4) applying simulation and risk analysis techniques. The model concept and its applicability are demonstrated using highway pavement data in the province of Alberta, Canada.

ACKNOWLEDGMENTS

First of all, many thanks to God for helping me complete this work. Then, my love and deep appreciation to my Mom and Dad for their prayers, support and encouragement, which made the completion of this dissertation possible.

I would like to express my appreciation and thanks to my supervisor, mentor and friend Dr. Simon AbouRizk, for his support, trust, and guidance. I am proud and fortunate that I've worked under him for the past few years. I learned from him that it is possible to be one of the best and hardworking scholars and yet be a great human and family man. Also, I learned from him that it is possible to motivate and manage people with a smile and a humble attitude.

I would like to thank Dr. Sam Ariaratnam for serving, as Co-supervisor, on my dissertation committee, and for his time, ideas and contribution to this research.

Special thanks to Mr. Jay Ramotar, the Assistant Deputy Minister, and Ms. Jane Stock, IMS Project Manager of Alberta Transportation and Utilities (AT&U), for their encouragement and trust over the past three years. Their support, enthusiasm and practical experience gave this dissertation a greater value and brought it up to another level. I would like also to thank all the wonderful people of (AT&U) for the friendly atmosphere and the best times I've ever had during my professional career.

I would like also to thank Dr. Garry Smith of Iowa State University for serving as an external examiner on my final defense. Also, many thanks to Dr. David Sego and Dr. MingJian Zuo for serving on my dissertation committee. I would like also to thank Professor Peter Dozzi and Dr. Ehab El-Mallah for serving on my candidacy examining committee, and for their contribution to this research.

Finally, my thanks and love to my wife Mai, my son Omar, and my Sisters Gihan and Heba for their love, understanding, and support throughout the past years.

TABLE OF CONTENTS

CHAPTER 1

1.1 PROBLEM STATEMENT AND OBJECTIVES 1

1.2 RESEARCH METHODOLOGY AND THESIS ORGANIZATION......... 1

CHAPTER 2

2.1 INTRODUCTION.. 5

2.2 LIFE CYCLE COST ANALYSIS CURRENT ISSUES & PRACTICES... 7

2.2.1 Related Life Cycle Cost Models 10

2.3 LIFE CYCLE COST MODEL COMPONENTS 14

CHAPTER 3

3.1 INTRODUCTION.. 18

3.2 INFRASTRUCTURE PERFORMANCE MEASURES 20

3.3 FACTORS AFFECTING INFRASTRUCTURE SERVICE LIFE 24

3.4 ANALYSIS OF PAVEMENT DATA FOR THE PRIMARY HIGHWAY NETWORK IN ALBERTA 26

3.4.1 Factorial Analysis and Interaction 41

3.5 STRATIFICATION OF PAVEMENT CLASSES............................ 44

3.5.1 Multiple Comparison Tests 44

3.5.2 Duncan's Multiple Range Test.. 48

3.5.3 Tukey's Multiple Comparison Test 49

3.5.4 Final Pavement Groups 57

CHAPTER 4

4.1 INTRODUCTION 63
4.2 IDENTIFYING CANDIDATE DISTRIBUTIONS 64
4.3 ESTIMATING PARAMETERS OF CANDIDATE DISTRIBUTIONS ... 66
4.4 PERFORMING GOODNESS-OF-FIT TESTS 67
4.5 APPLICATION OF INPUT DATA MODELING ON PAVEMENT GROUPS 68

CHAPTER 5

5.1 INTRODUCTION TO SIMULATION AND RISK ANALYSIS 82
5.2 LIFE CYCLE COST MODEL 86
5.2.1 Components of the Life Cycle Cost Model *89*
5.3 ANALYSIS OF CONSTRUCTION AND REHABILITATION ALTERNATIVES 95
5.4 ECONOMIC EVALUATION EXAMPLE USING THE RISK-BASED LIFE CYCLE COST ANALYSIS 96

CHAPTER 6

6.1 SUMMARY OF RESEARCH 107
6.2 CONCLUSIONS AND CONTRIBUTIONS 111
6.3 RECOMMENDATIONS 112
BIBLIOGRAPHY 115
APPENDIX A - Multiple Comparison Test Results Using Duncan's and Tukey's Procedures 121

APPENDIX B - Distribution Fittings and Parameters of Various Pavement Data Groups..182

LIST OF TABLES

TABLE 2.1 - EXPECTED FLEXIBLE PAVEMENT REHABILITATION TREATMENT SERVICE LIVES AND RELATIVE COST (TAC, 1997) 17

TABLE 3.1 – BREAKDOWN STATISTICS BY PAVEMENT TYPE AND SOIL TYPE FOR THE ENTIRE PRIMARY HIGHWAY NETWORK IN ALBERTA 35

TABLE 3.2 – BREAKDOWN STATISTICS BY PAVEMENT TYPE AND SOIL TYPE FOR CENTRAL CLIMATIC REGION IN ALBERTA 36

TABLE 3.3 – BREAKDOWN STATISTICS BY PAVEMENT TYPE AND SOIL TYPE FOR NORTHERN CLIMATIC REGION IN ALBERTA 37

TABLE 3.4 – BREAKDOWN STATISTICS BY PAVEMENT TYPE AND SOIL TYPE FOR SOUTHERN CLIMATIC REGION IN ALBERTA 38

TABLE 3.5 - FACTORIAL ANALYSIS 43

TABLE 3.6 – RESULTS OF THE MULTIPLE COMPARISON TESTS BETWEEN SOIL TYPES 52

TABLE 3.7 – RESULTS OF THE MULTIPLE COMPARISON TESTS BETWEEN PAVEMENT TYPES 52

TABLE 3.8 – RESULTS OF THE MULTIPLE COMPARISON TESTS BETWEEN ESAL LEVELS 53

TABLE 3.9 – RESULTS OF THE MULTIPLE COMPARISON TESTS BETWEEN CLIMATIC REGIONS 53

TABLE 3.10 - DIFFERENT "CLASS" DEFINITIONS FOR THE GB PAVEMENT TYPE 55

TABLE 3.11 - DIFFERENT "CLASS" DEFINITIONS FOR THE SC PAVEMENT TYPE 56

TABLE 3.12 - DIFFERENT "CLASS" DEFINITIONS FOR THE FD PAVEMENT TYPE 56

TABLE 3.13 – EXAMPLE FOR A MULTIPLE COMPARISON TESTS PERFORMED BETWEEN CLASSES FOR GB PAVEMENT TYPE AND BO SOIL TYPE AT 90% & 95% CONFIDENCE LEVEL 59

TABLE 3.14 – MULTIPLE COMPARISON TEST FOR THE GB PAVEMENT TYPE AND THE BO SOIL TYPE AT 95% & 90% CONFIDENCE LEVELS 60

TABLE 3.15 - FINAL PAVEMENT "GROUPS" AFTER STRATIFICATION 61

TABLE 4.1 - RELATIVE SCORES AND RANKINGS OF CANDIDATE DISTRIBUTIONS FOR PAVEMENT DATA GROUP # 3 (NEW CONSTRUCTION) 71

TABLE 4.2 - SAMPLE SUMMARY FOR PAVEMENT DATA GROUP # 3 (NEW CONSTRUCTION)........... 71

TABLE 4.3 – CANDIDATE DISTRIBUTION MOMENTS AND CHARACTERISTICS FOR PAVEMENT GROUP DATA # 3 (NEW CONSTRUCTION).. 76

TABLE 4.4 - RELATIVE SCORES AND RANKINGS OF CANDIDATE DISTRIBUTIONS FOR PAVEMENT DATA GROUP # 3 (OVERLAY) 77

TABLE 4.5 - SAMPLE SUMMARY FOR PAVEMENT DATA GROUP # 3 (OVERLAY) 77

TABLE 4.6 – CANDIDATE DISTRIBUTION MOMENTS AND CHARACTERISTICS FOR PAVEMENT GROUP DATA # 3 (OVERLAY)... 81

TABLE 5.1 - SUMMARY OF SIMULATION INPUT DATA 99

LIST OF FIGURES

FIGURE 3-1 – DEVELOPMENT STEPS FOR THE RISK-BASED LIFE CYCLE COST MODEL................. 19

FIGURE 3.2 - CLASSIFICATION OF SOIL TYPES IN ALBERTA ALONG THE PRIMARY HIGHWAY NETWORK 33

FIGURE 3.3 - CLASSIFICATION OF PAVEMENT TYPES IN ALBERTA ALONG THE PRIMARY HIGHWAY NETWORK.. 33

FIGURE 3.4 - AVERAGE SERVICE LIFE IN YEARS FOR THE THREE CLIMATIC REGIONS 39

FIGURE 3.5 - AVERAGE SERVICE LIFE IN YEARS FOR THE SIX SOIL TYPES.................................... 39

FIGURE 3.6 - AVERAGE SERVICE LIFE IN YEARS FOR THE THREE PAVEMENT TYPES.................... 40

FIGURE 4.1 – DISTRIBUTION FUNCTION AND PROBABILITY PLOT COMPARISONS BETWEEN PAVEMENT DATA GROUP # 3 AND A FITTED WEIBUL DISTRIBUTION (NEW CONSTRUCTION) 72

FIGURE 4.2 – DISTRIBUTION FUNCTION AND PROBABILITY PLOT COMPARISONS BETWEEN PAVEMENT DATA GROUP # 3 AND A FITTED LOG-LOGISTIC DISTRIBUTION (NEW CONSTRUCTION)... 73

FIGURE 4.3 – DISTRIBUTION FUNCTION AND PROBABILITY PLOT COMPARISONS BETWEEN PAVEMENT DATA GROUP # 3 AND A FITTED LOG-LAPLACE DISTRIBUTION (NEW CONSTRUCTION)... 74

FIGURE 4.4 – DISTRIBUTION FUNCTION AND PROBABILITY PLOT COMPARISONS BETWEEN PAVEMENT DATA GROUP # 3 AND A FITTED GAMMA DISTRIBUTION (NEW CONSTRUCTION) 75

FIGURE 4.5 – DISTRIBUTION FUNCTION AND PROBABILITY PLOT COMPARISONS BETWEEN PAVEMENT DATA GROUP # 3 AND A FITTED WEIBUL DISTRIBUTION (OVERLAY) 78

FIGURE 4.6 – DISTRIBUTION FUNCTION AND PROBABILITY PLOT COMPARISONS BETWEEN PAVEMENT DATA GROUP # 3 AND A FITTED GAMMA DISTRIBUTION (OVERLAY).................. 79

FIGURE 4.7 – DISTRIBUTION FUNCTION AND PROBABILITY PLOT COMPARISONS BETWEEN PAVEMENT DATA GROUP # 3 AND A FITTED LOG-LOGISTIC DISTRIBUTION (OVERLAY)....... 80

FIGURE 5.1 – SIMULATION OUTPUT - COMPARISONS OF CDF DISTRIBUTIONS OF LIFE CYCLE COSTS FOR ALTERNATIVE "A" AT R = 4, 5, 6, 7, & 8 % 101

FIGURE 5.2 – SIMULATION OUTPUT - CDF DISTRIBUTION OF LIFE CYCLE COSTS FOR ALTERNATIVE "A" AT R = 4% 103

FIGURE 5.3 – SIMULATION OUTPUT - CDF DISTRIBUTION OF LIFE CYCLE COSTS FOR ALTERNATIVE "B" AT R = 4% 103

FIGURE 5.4 – SIMULATION OUTPUT - CDF DISTRIBUTION OF LIFE CYCLE COSTS FOR ALTERNATIVE "C" AT R = 4% 104

FIGURE 5.5 – SIMULATION OUTPUT - COMPARISONS OF CDF DISTRIBUTIONS OF LIFE CYCLE COSTS FOR ALTERNATIVE "A, B, & C" AT R = 4% 104

FIGURE 5.6 – SIMULATION OUTPUT - CDF DISTRIBUTION OF LIFE CYCLE COSTS FOR ALTERNATIVE "A" AT R = 8% 105

FIGURE 5.7 – SIMULATION OUTPUT - CDF DISTRIBUTION OF LIFE CYCLE COSTS FOR ALTERNATIVE "B" AT R = 8% 105

FIGURE 5.8 – SIMULATION OUTPUT - CDF DISTRIBUTION OF LIFE CYCLE COSTS FOR ALTERNATIVE "C" AT R = 8% 106

FIGURE 5.9 – SIMULATION OUTPUT - COMPARISONS OF CDF DISTRIBUTIONS OF LIFE CYCLE COSTS FOR ALTERNATIVE "A, B, & C" AT R = 8% 106

CHAPTER 1. INTRODUCTION

1.1 PROBLEM STATEMENT AND OBJECTIVES

Most approaches to modeling life cycle costs for civil infrastructure construction and rehabilitation alternatives assume deterministic behavior for their service lives (Haas 1994, TAC 1997, and Hudson 1997). The analysis of life cycle costs should be related to the process of failures of infrastructure and should account for the uncertainty involved. In addition, the analysis should provide decision-makers with a way to evaluate the various alternatives with respect to different budgets and the avoidance of risks and uncertainties.

The objective of this research is to provide a prediction model of life cycle costs for civil infrastructure construction and rehabilitation alternatives, taking into consideration the uncertainty involved in determining the service life of an infrastructure unit.

1.2 RESEARCH METHODOLOGY AND THESIS ORGANIZATION

This research utilizes a risk analysis-based approach to predict probabilities of occurrence of different life cycle costs of constructing/rehabilitating an infrastructure unit. Uncertainty in the life cycle model is introduced through the reliability functions (probabilities of failures) of different construction/rehabilitation alternatives. This results in probability distribution functions (PDF) representing failure times (i.e., service lives). In the developed risk-based life cycle model, the service life of each construction/rehabilitation alternative is input to the model using random variables sampled from fitted statistical distributions that represent the reliability of infrastructure units. Computer simulation is used to generate the probability distribution of the model outcome (i.e., life cycle costs of construction alternatives). The resulting life cycle cost distribution can then be statistically analyzed to provide a measure of risk. Decision-makers can determine the probabilities associated with various values of total life cycle costs, as long as the probability distributions for the input variables used in the model are determined. This enables decision-makers to make informed decisions regarding the construction alternatives that can be applied and the level of risk they may accept. Historical highway pavement inventory and performance data provided by Alberta Transportation and Utilities (AT&U) are used to demonstrate the model concept.

This dissertation provides a detailed explanation of the different steps and areas involved in developing the risk-based life cycle model for civil infrastructure. These areas include: 1) factors affecting infrastructure performance; 2) statistical stratification of infrastructure inventory and failure data; 3) reliability and statistical input data modeling; and 4) simulation and risk analysis.

Chapter two reviews the findings of previous and ongoing research efforts in the area of life cycle cost analysis of civil infrastructure and manufacturing.

Chapter three introduces and describes the development of probabilistic models representing the service lives of infrastructure units. It discuses various criteria (measures) for evaluating performance, and the factors affecting the service life of various type of civil infrastructure such as sewer and water pipelines, pavements, bridges and railway tracks. It further details pavement-related performance factors and criteria. This chapter also introduces a statistical approach of stratifying infrastructure units according to their historical performance. The combinations of the different factors affecting performance and their levels can result in an unmanageable number of classes. Also, the effects of various levels of these factors must be analyzed before proceeding with modeling the times-to-failure (service lives) for each group of classes. The classes are grouped such that classes within each group should show insignificant differences between their service life means when analyzing their variances using statistical multiple comparison tests. This results in a set of groups, each representing a number of infrastructure classes (each class is one combination of the levels of factors affecting service lives).

Chapter four illustrates the fitting of infrastructure failure data for each group to statistical models (distributions). This involves estimation of parameters and assessment of the quality of fit of each group. The model parameters are then identified for use as input data for the simulation needed to generate the risk-based life cycle costs.

Chapter five details the development of the risk-based life cycle cost model, including the application of Monte Carlo simulation and utilization of the model outcomes in the form of the Cumulative Density Functions (CDFs) for risk analysis. It also presents a case study to demonstrate the use of the model and its potential value to the decision-making process regarding the selection of construction and rehabilitation alternatives.

Chapter six provides a summary and conclusions of the research. It also outlines future research directions that can be studied in the area of infrastructure management and life cycle cost analysis.

CHAPTER 2. LITERATURE REVIEW

2.1 INTRODUCTION

When evaluating infrastructure construction and rehabilitation alternatives, it is imperative that life cycle costs be considered. Life cycle cost analysis (LCCA) is the evaluation of agency, user, and other relevant costs over the life of investment alternatives. It serves as a tool to improve decision-making and generate trade-offs between capital, maintenance, and operational investments. Although its basic principles were articulated more than 100 years ago, systematic implementation of LCCA in North America began only 25 to 30 years ago. The basic tenet of LCCA is to reduce total costs over the life of the project. When selecting alternative strategies for construction or rehabilitation, the alternative showing the lowest total life cycle cost is usually selected. However, other considerations such as owner preference, technical standards, budget availability, pollution effects, and maintainability should affect the final decision.

Dell'Isola and Kirk (1983) define life cycle cost analysis as "an economic assessment of competing design alternatives, considering all significant costs of ownership over the economic life of each alternative, expressed in equivalent dollars". They further acknowledge that LCCA can be used to evaluate the consequences of decisions made by the owners for budgeting purposes. This reference also mentions that LCCA can be applied during any phase of a project's life, however it is preferable to use it early in the project life for more significant savings and lower costs of making changes to plans and specifications. They summarize the procedure for evaluating life cycle costs as:

1. Identifying all costs (i.e., initial costs, maintenance and operational costs, rehabilitation costs) for each alternative.
2. Determining total costs per year of the analysis period.
3. Discounting all costs to a common timeline (i.e., present value).
4. Selecting the lowest cost alternative.
5. Evaluating the lowest cost alternative with other non-economic factors (i.e., political considerations and technical feasibility).

Dhillon (1989) provides a comprehensive review of the life cycle cost concepts and techniques, but from mechanical systems perspective. However, many of the concepts and techniques can be applied to civil engineering infrastructures with some modifications.

2.2 LIFE CYCLE COST ANALYSIS CURRENT ISSUES AND PRACTICES

LCCA can be used to evaluate and compare a variety of new construction, rehabilitation and maintenance alternatives. A 1993 survey on life cycle cost was conducted by the American Association of State Highway and Transportation (AASHTO). The incentive behind the survey was the emphasis placed by the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) on "the use of life cycle cost in the design and engineering of bridges, tunnels, and pavements". In addition, Executive Order 12893, "Principles of Federal Infrastructure Investment", "requires that benefits and costs of infrastructure investment be measured and appropriately discounted over the full life cycle of each project". All the US states were contacted; 38 states responded. The survey results revealed that 28 States use LCCA, and 20 have used it for at least 10 years (FHWA 1994). The survey further indicated that LCCA is most widely used for pavements, and is used less frequently for bridges. However, all responding States mentioned that they would use LCCA at the program development level to meet the requirement of the ISTEA. The survey responses revealed that most of the departments of transportation (DOTs) use LCCA to evaluate pavement type selection for new and reconstructed pavement. Regarding the analysis period, a large variance in responses was found (e.g., for pavements it ranged from 18 to 60 years and for bridges it ranged from 20 to 100 years). Some of the States' implementation concerns center on the difficulty of predicting service life, salvage value, user costs, discount rates and procedures for addressing environmental trade-offs. Fewer than half of the states using LCCA include user costs in their LCCA. One of the biggest concern, is the difficulty in estimating the value of delays on users (FHWA 1994).

Arditi and Messiha (1996) conducted a survey in 1995 of the largest cities in the United States to investigate current practices of life cycle cost analysis. 195 cities were contacted (each has a population of 100,000 or more); 121 cities responded, which is equivalent to a 62% response rate. 40% of the returned responses said they used LCCA. The rest of the cities (60%) indicated that they do not use LCCA mainly because of the lack of formal guidelines and reliable past data, and the difficulty of estimating future costs. In cities where LCCA is used, 67% indicated the use of LCCA for municipal facilities (e.g., city-owned buildings and sanitation operating facilities), 55% use it for transportation projects (e.g., bridges, major roads, traffic signals, and transit), 47% are using LCCA for sewer systems, and 29% for water systems.

The survey further indicated that 84% of those using LCCA use it mainly for new construction; 73% and 71% use the analysis for reconstruction and rehabilitation work respectively, and 41% use it for maintenance work. Additionally, almost all cities (98%) reported the use of LCCA during the design stage, versus 14% during the bidding phase and 8% during the construction phase.

In a report published by the US Federal Highway Administration on LCCA, several implementation issues were identified. The key issues were how to determine the service life, analysis period and discount rate for use in the LCCA. Other key issues were identified as the need to improve methods of estimating the user delay costs and understanding the relationship between routine maintenance and enhanced performance of the infrastructure unit (FHWA 1994).

A symposium held by the FHWA and the American Association of State Highway and Transportation (AASHTO) recommended that the credibility of LCCA be increased by improving the technical aspects of estimating life cycle costing components such as service life, discount rate, and user cost. Furthermore, one of the speakers at this symposium stressed the need to overcome the difficulty "in predicting how long structures and pavements will last", because "in many cases, it is not known when rehabilitation will be needed and what it will cost" (Quote from Mr. Dean Testa of Kansas Department of Transportation), (FHWA 1994).

2.2.1 Related Life Cycle Cost Models

A number of life cycle cost models used by the construction and manufacturing industry, were examined during the literature review and are presented below.

2.2.1.1 Life Cycle Cost Model for Major Appliances

Turiel et al. (1981) express life cycle cost of major appliances as:

$$L_{CCA} = ACA + \sum_{j=1}^{LY} CEN_j \left[\frac{FC(1+R_f)^j}{(1+i)^j} \right] \ldots\ldots\ldots\ldots\ldots (2.1)$$

Where:

L_{CCA} is the life cycle cost of a major appliance

LY is the service life of the appliance

i is the discount rate

ACA is the acquisition cost of the appliance

CEN_j is the jth year's energy consumption expressed in million BTUs

R_f is the yearly fuel escalation rate (%) expressed in constant dollars

FC is the cost of fuel in year one expressed in constant dollars per million BTUs

This model assumes fixed service life times for various appliances. For example, freezers, electric dryers, gas dryers, air conditioners, ovens and refrigerators service life times are 20, 14, 11, 10, 14 and 15 years respectively.

2.2.1.2Life Cycle Cost Model for Health Care Facilities

This life cycle cost model is composed of two major components: 1) capital cost and 2) operating cost, and is expressed by the following formula (Eddins-Earls 1981):

$$L_{CCHCF} = CC + OC \text{.........} (2.2)$$

$$CC = \sum_{i-1}^{8} CC_i \text{...........} (2.3)$$

$$OC = \sum_{i=1}^{19} OC_i \text{..........} (2.4)$$

Where:

L_{CCHCF}	is the life cycle cost of a health care facility
CC	is the capital cost
OC	is the operating cost
CC_i	is the component *i* of capital cost (e.g., financing cost, land acquisition cost, construction or purchase cost, equipment, etc..)
OC_i	is the component *i* of operating cost (e.g., equipment maintenance, structural maintenance, utilities and fuel cost, etc..)

2.2.1.3 Life Cycle Cost Model for Cars

Bhuyan (1982) presents a model concerned with estimating the life cycle cost of a car. This model is given by the following equation:

$$L_{CCC} = AC_C + \sum_{i=1}^{NL} (SMC_i + OC_i + URC_i) + DC \ldots\ldots\ldots\ldots\ldots (2.5)$$

Where:

L_{CCC}	is the life cycle cost of a car
AC_c	is the acquisition cost of the car
NL	is the lifetime of the car

SMC_i is the scheduled maintenance cost (e.g., tune-up, lubrication, etc..) of the car for year i; ($i = 1, 2, 3, \ldots\ldots, NL$)

OC_i is the operating cost (e.g., tires, oil, gas, etc..) of the car for year i; ($i = 1, 2, 3, \ldots\ldots, NL$)

SMC_i is the unscheduled repair cost (i.e., dependent on failure rate of the car) of the car for year i; ($i = 1, 2, 3, \ldots\ldots, NL$)

DC is the disposal cost of the car

2.2.1.4 Life Cycle Cost Model for Electric Motors

In this application, life cycle costing is applied to electric motor selection using the following formula (Ganapathy 1983):

$$L_{mcc} = MAC + MOC_{TPW} \ldots\ldots\ldots (2.6)$$

Where:

$$MOC_{TPW} = \sum_{j=1}^{n} MOC_j \left(\frac{1}{1+i}\right)^j \ldots\ldots\ldots (2.7)$$

L_{mcc} is the motor life cycle cost

MAC is the acquisition cost of the motor

MOC_{TPW} is the present worth of the motor total operating cost

i is the discount rate

MOC_j is the motor operating cost in year j such that $j = 1,2,3...,n$

n is the motor service life

2.3 LIFE CYCLE COST MODEL COMPONENTS

Novick (1990) recognizes the lack of a rational method for estimating life cycle costs of engineering structures as a major obstacle to life cycle costing analysis. He also cites the importance of collection and analysis of existing data on total costs for all life cycle phases of existing infrastructure including bridges, roads, etc. and the use of realistic methods for calculating probable useful life of these infrastructure. Life cycle considerations for any typical infrastructure project include the following phases (Novick, 1990):

1. Capital programming
2. Concept study/alternative analysis
3. Design and contract documentation preparation
4. Construction, including management and inspection
5. Operations, inspection, and maintenance
6. Repair and rehabilitation
7. Reconstruction, replacement, or disinvestment

LCCA models are based on the concept of discounted cash-flow analysis. The sum of the costs expected to occur over a pre-specified period of time (i.e. construction, maintenance, rehabilitation, etc.) are estimated and converted to an equivalent uniform annual cost (EUAC) for the purpose of comparison. Costs are discounted to reflect the opportunity cost of funds, or equivalently, the time value of money. Budget availability and political influence have a major role in decision-making, especially in most public agencies (Novick, 1990). Most public agencies are facing budget shortage and are under political pressure to produce short-term results. As a result, many of the investment decisions are made solely based on initial costs and without considerations of life cycle costs (Novick, 1990).

A fully developed life cycle cost model will include a component that evaluates differing construction and rehabilitation strategies by calculating project present worth. Although several different economic models may be used (i.e. equivalent uniform annual cost method, rate-of-return method, benefit-cost ratio method, etc.), the "basic" functional parameters used in transportation infrastructure LCCA should include the parameters shown in equation 2.8:

$$\text{Present Worth} = f\,(\text{ICC, RC, AMC, UC, SV}) \qquad \text{..........(2.8)}$$

where;

ICC = initial construction cost

RC = rehabilitation cost

AMC = annual maintenance cost (based on treatment alternative)

UC = user cost (including travel time, accidents, discomfort, etc.)

SV = salvage value

Expected service life is an important parameter for assessing alternative treatment strategies because it drives any performance prediction model. Factors including weather conditions, traffic mix (ESAL), structure type, and subgrade soil type play key roles in determining the expected service life for pavement. The Transportation Association of Canada (TAC) lists some approximate values for pavement rehabilitation alternatives. Table 2.1 contains a listing of expected pavement rehabilitation treatment service lives and relative cost of flexible pavement structures (TAC, 1997). The TAC's "Pavement Design and Management Guide" notes that actual service lives can vary widely depending on local conditions, traffic, climate, etc. It also mentions that the expected service lives listed in Table 2.1 are very approximate and should be considered as a guide only (TAC, 1997). The nature of expected service life of civil engineering infrastructure is not deterministic, as has been assumed by most civil engineering and construction applications. As mentioned in chapter one of this thesis, the main objective of this research study is to provide a methodology to model the stochastic nature of the service lives of civil infrastructures, and incorporate these probabilistic models into the LCCA to produce a risk-based estimate of total life cycle costs.

Table 2-1 - Expected Flexible Pavement Rehabilitation Treatment Service Lives and Relative Cost (TAC, 1997)

Rehabilitation Alternative (X)	**Expected Service Life (Years)**	**Relative Cost**
Reconstruction	up to 12 - 15	High
Resurfacing (Thin Overlay)	up to 8 – 10	Low
Resurfacing (Thick Overlay)	up to 12 – 15	High
Milling and Resurfacing	up to 10 – 12	Medium
Hot In-Place Recycling	up to 10 – 12	Medium
Cold In-Place Recycling	up to 10 - 12	Medium
Full Depth Reclamation	up to 12 - 15	Low

CHAPTER 3. ANALYSIS AND STRATIFICATION OF INFRASTRUCTURE PERFORMANCE DATA

3.1 INTRODUCTION

As mentioned in previous chapters, the main objective of this research is to provide a prediction of life-cycle costs for civil infrastructure construction and rehabilitation alternatives, taking into consideration the uncertainty involved in determining the service life of an infrastructure unit. To achieve this objective, the reliability of the infrastructure unit is statistically modeled. Considering the reliability, when analyzing life-cycle costs, provides a more realistic representation of the unit's useful life. Additionally, the ability to determine the uncertainty values, which accompany the predicted life-cycle costs, allows decision-makers to select construction and rehabilitation alternatives with a good knowledge of the inherent risks.

This chapter and the following ones provide a detailed explanation of the different steps and areas involved in developing the risk-based life cycle model for civil engineering infrastructure. These areas as depicted in Figure 3.1 include: 1) factors affecting infrastructure performance; 2) stratification of infrastructure inventory and failure data; 3) reliability analysis and input data modeling; and 4) simulation and risk analysis. The model concept and development are demonstrated using flexible pavement infrastructure. Figure 3.1 highlights the overall decision support model for evaluating construction/rehabilitation alternatives of civil infrastructures. It shows other factors affecting decisions regarding construction/rehabilitation alternatives such as the available budgets, polices, materials availability, and past experiences. It also lists the various steps leading to the prediction of infrastructure service lives (see the shaded boxes). The model's components within the shaded boxes represent the scope of this study.

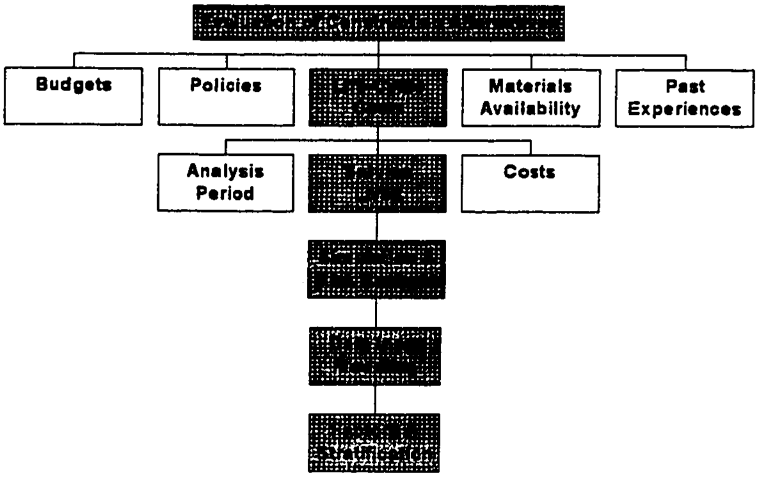


Figure 3-1 – Development Steps for The Risk-Based Life Cycle Cost Model

3.2 INFRASTRUCTURE PERFORMANCE MEASURES

Identifying the factors affecting the life cycle performance of an infrastructure unit is the first step toward predicting its service life. Prior to that, however, performance measures (indices) and their criteria must be defined.

Hudson et al. (1997) groups infrastructure performance indicators into four categories: 1) service and user perception; 2) safety and sufficiency; 3) physical conditions; and 4) structural integrity/load capacity. Harty and Peterson (1984) organizes infrastructure performance measures into categories, including quality of service and system effectiveness; productivity and efficiency; and resource utilization and cost-effectiveness. The former authors further suggest that infrastructure performance can be evaluated from a functional and/or structural perspective. The functional performance can be evaluated in terms of quality, efficiency/adequacy, and safety of the function(s) carried by the infrastructure unit.

Examples of performance indices used to measure infrastructure functional quality include:

- Riding Comfort Index (RCI), Present Serviceability Index (PSI), and/or International Roughness Index (IRI). These are used by most of the public agencies to measure the pavement roughness and the riding quality (Hass, 1994);
- Sufficiency Rating (SR). This provides an overall composite rating for different bridge components (i.e., deck, superstructure, substructure, and foundation), also Condition Index (CI) measures distress of bridge decks (Hudson, 1987);
- Track Quality Index (TQI). This evaluates railroad tracks based on track geometry and alignment, bad-tie counts, and deflection under load (Fazio, 1980);
- Performance index for water, waste-water, and gas pipelines. This is based on leakage and/or breaks either per year or per 1000 km (Hudson, 1997).

The functional efficiency/adequacy measures the performance of an infrastructure unit based on its ability to adequately fulfill its designed function. For example, a highway can be used throughout its design life without having any physical failure requiring rehabilitation. However, in order to meet functionality standards, the highway is designed to maintain a specific level of service (LOS) (i.e., level of service "A"). Level of service is defined as those operational conditions within a traffic stream as perceived by users of the traffic facility (ITE, 1992). Six levels of service, "A" through "F" are usually defined. For an uninterrupted flow along freeways and highways, level of service "A" represents a free flow with individual vehicles remaining unaffected by the presence of other vehicles. Level of service "E" represents operating conditions at capacity, while "F" defines breakdown flow conditions (ITE, 1992). If the highway doesn't maintain the desired level of service through out its life, this indicates that it was inadequately designed to meet its intended usage.

Functional safety is defined as the extent to which injuries, loss of lives, and severe damage to structures, equipment, and environment can be avoided (ITE, 1992). One example of a safety indicator used for evaluating infrastructure performance is the skid resistance index (SRI) for pavements which provides early indication of poor drainage and hydroplaning problems incurred by the traffic.

Structural performance can be assessed using indices such as the structural adequacy index (SAI), which is used for pavements and is based on carrying out deflection tests (i.e., Benkelman Beam tests and Falling Weight Deflectometer tests). For railroad tracks, track modulus index (TMI) is used as a structural performance indicator based on deflection and fatigue testing (Hudson, 1997). In the case of bridge structures, the structural performance is evaluated using the structural rating index (SRI) and the "remaining life" concept.

For this study, highway pavement data in the province of Alberta, Canada, are used to demonstrate and implement the risk-based life cycle cost analysis approach of civil infrastructure construction and rehabilitation alternatives. The performance indicator that is selected to provide a measure for pavement failure is the riding comfort index (RCI). The RCI, which is an index used to measure pavement roughness, is rated on a scale of 0 to 10, with 10 representing a smooth pavement providing an excellent ride. Roughness is defined as "a distortion of the pavement surface that contributes to an undesirable or uncomfortable ride" (Hudson, 1987). In Alberta, the RCI of new pavements is in the range of 8.5 to 9.0. The RCI criterion (trigger value) for rehabilitation actions for the primary highway network in Alberta has been set at 5.5 (AT&U, 1997). The reasons behind the RCI selection as a failure indicator for this study are as follows:

- Historical data and expert knowledge in Alberta revealed that the vast majority of rehabilitation needs in the past were triggered by the reduction of pavement's RCI values below the accepted level of "5.5". It is stated in the pavement design manual of Alberta Transportation and Utilities (AT&U) that "a significant portion of pavements are rehabilitated due to an unacceptable ride rather than due to structural problems. For this reason roughness monitoring constitutes an important rehabilitation design input" (AT&U, 1997).

- RCI data has been collected since the early 1950s, and it is the most complete and consistent data of all the performance indices contained in AT&U database.

3.3 FACTORS AFFECTING INFRASTRUCTURE SERVICE LIFE

Identifying and analyzing the factors that affect life cycle performance of a civil infrastructure unit is essential for predicting service life. These variables can either be identified from historical performance data or from accelerated failure tests. Hudson et al (1997) lists factors affecting infrastructure deterioration in five categories. These categories are: 1) load/usage, 2) environment, 3) material, 4) construction quality, and 5) interaction effects. Furthermore, the Building Research Board (BRB) defines the service life as, "the period in years over which a building, component, or subsystem provides adequate performance; a technical parameter that depends on design, construction quality, operations and maintenance practices, use, and environmental factors" (BRB, 1991). This definition can be applied to most civil engineering infrastructure (Hudson, 1997). In a study aimed at evaluating the conditions of the sewer system in Edmonton, several factors were identified as impacting the expected service life of sewer pipes. These include hydraulic loading, waste-water quality, soil conditions, pipe materials, location, and construction quality (City, 1996). In another study, several factors affecting bridge deterioration in two areas of Ontario were defined. These factors include bridge type, climatic conditions, salt/sand usage, and traffic (Ariaratnam, 1994). Turay and Hass (1991) presented several factors affecting pavement deterioration that were considered in constructing the transition probability matrices for a Markov process to predict deterioration. The factors presented in the study include environmental condition, subgrade type, traffic volume, pavement type, and pavement thickness.

This thesis utilized the pavement performance factors used by Turay and Hass (1991), as well as the factors considered in formulating the design formula in the widely used "AASHTO Guide for Design of Pavement Structures" (AASHTO, 1986). These factors are:

- Traffic – Equivalent Single Axle Load (ESAL)
- Environment – Climatic Region
- Subgrade Condition – Soil Type
- Pavement – Type and Thickness

3.4 ANALYSIS OF PAVEMENT DATA FOR THE PRIMARY HIGHWAY NETWORK IN ALBERTA

This section details the first step involved in the development of probabilistic models to represent the service life of civil infrastructure units. The pavement data for the primary highway network in the province of Alberta is used to explain the model development concept, and the application of formal input data modeling techniques to develop these models. Statistics regarding the primary highway network in Alberta and the factors affecting its pavement performance are also discussed.

In Alberta, there are more than 14,250 kilometers of paved highways on the primary highway network. Performance evaluation and rehabilitation decisions for the pavement in this network are mainly based on roughness data, which have been collected by the transportation department since early 1950s. Roughness data is an indication of the longitudinal irregularities of the pavement surface which influence vehicle ride, and it is a good indicator of how well the road is serving the travelling public. Car road meters were used for data collection until 1984 and the Cox road meter has been used since then. Currently, roughness data is collected by mounting the Cox Road Meter on a trailer and towing it with a van. This van is equipped with an operator control panel that enables the control and monitoring of the testing operation. The data collected are recorded on a cassette tape. The roughness data from the cassette tape is subsequently downloaded onto a mainframe computer to be analyzed and converted into the Riding Comfort Index (RCI) (Haas, 1994). The RCI data is then averaged over 400 meters and presented in graphical and tabular format. The RCI is measured on a scale of 0 to10, with 10 being a perfectly smooth road. The minimum acceptable level of RCI that triggers a need for a treatment (rehabilitation or reconstruction) is 5.5.

To perform this research study, pavement data for the primary highway network was obtained from the Alberta Transportation and Utilities (AT&U) database. This database is stored in the department's mainframe in a flat text file format and includes information dating back to the 1950s. The database is organized by inventory section along each highway and contains extensive historical information regarding construction history, pavement performance, traffic volumes, environmental conditions, material types, and rehabilitation and overlay information. A typical record in the database contains the following information:

- Highway control section number
- Location and length of each control section
- Pavement inventory by designated section, width, and lane direction
- Climatic region of each pavement inventory section
    - Northern region
    - Central region
    - Southern region
- Pavement layer types and thickness
    - GB – Granular Base
    - SC – Soil-Cement base
    - FD – Full Depth pavement
- Subgrade soil types according to the Unified Soil Classification System as modified by P.F.R.A.
    - CL – Inorganic clays of low plasticity, gravelly clays, sandy clays, silty clays, lean clays
    - CI – Inorganic clays of medium plasticity, gravelly clays, sandy clays, silty clays
    - CH – Organic clays of high plasticity, fat clays
    - BO – Rock layer
- Traffic data
    - AADT – Annual Average Daily Traffic

  - ESAL/Day - Equivalent (18-kip) Single Axle Loads per day
- Year of construction
- RCI readings for each section
- Years of rehabilitation activities
- Years of failure due to RCI

Both Microsoft Excel and Microsoft Access applications are used to read the flat text files and transfer the data to a spreadsheet and relational database formats, respectively. The database contained unnecessary records (from the point of view of this study), and it initially had more than 20,000 records. The first step involved in the preliminary analysis of the data was filtering and querying the database. A subset of the database was generated; it limited the records to those control sections that have an RCI of 5.5 or less. Furthermore, new fields were created to indicate the service lives of both newly constructed pavements and rehabilitated ones according to the length of time until their RCI dropped to the trigger value of 5.5.

Data analysis is performed using the SPSS statistical analysis package. This software is selected because of its flexibility and ease of importing the data from Microsoft Excel. The effect of the following factors on pavement service life (i.e., time to failures of pavement sections) is analyzed:

1. Pavement type
2. Soil Type
3. Climatic region
4. ESAL (Equivalent Single Axle Load)
5. Equivalent Granular Base Thickness.

The first three parameters are represented by discrete integers: from 1 to 6 to represent the six soil types, from 1 to 3 for the three pavement types and from 1 to 3 to represent the three climatic regions. Initially, the ESAL values were divided into three groups according to the current design practices at AT&U:

• ESAL ≤ 500	Low
• ESAL between 500 and 1000	Medium
• ESAL ≥ 1000	High

The equivalent granular-base (GB) pavement thickness was calculated using the following formulas (Haas, 1997):

° 1 centimeter of asphalt concrete pavement = 2.25 centimeters of GB

° 1 centimeter of Soil Cement (SC) = 1.75 centimeters of GB

Since pavement thickness is directly related to traffic volume, the AASHTO procedure for designing pavement structures provides similar pavement thickness for the same level of traffic (i.e., low, medium, high) (AASHTO, 1986; AT&U, 1997). This was verified through the correlation analysis performed between traffic volume and pavement thickness. The combinations of the various levels of the previous mentioned factors resulted in 162 pavement classes.

Since the inventory sections within the database are not of equal length, each record in the database was then weighted according to the inventory section's length. A highway inventory section length can vary from 30 meters to 11 kilometers. A constant length of 400 meters is used (RCI readings are taken every 400 meters) as a basic unit. For example, an inventory section of four-kilometer length will take a weight of ten, and a section of 800-meter length will take a weight of two.

Figures 3.2 and 3.3 illustrate the percentages of each subgrade soil and pavement type, respectively, within the primary highway network in Alberta. More than 90% of the total length of the network was built on six soil types. These types are BO, CH, CI, CI-CH, CL, and CL-CI. In a similar fashion, three pavement types constitute about 98% of the network pavement structures. These types are GB, SC, and FD.

Furthermore, the analysis shown in table 3.1 illustrates the breakdown statistics of the total length of paved roads within each combination of pavement and soil type. Three climatic regions are used to reflect the climatic effects on the network. They are defined as Central, Northern, and Southern regions. Similar breakdown statistical analysis to the one shown in table 3.1 is performed on each climatic region, and the results are shown in tables 3.2, 3.3 and 3.4.

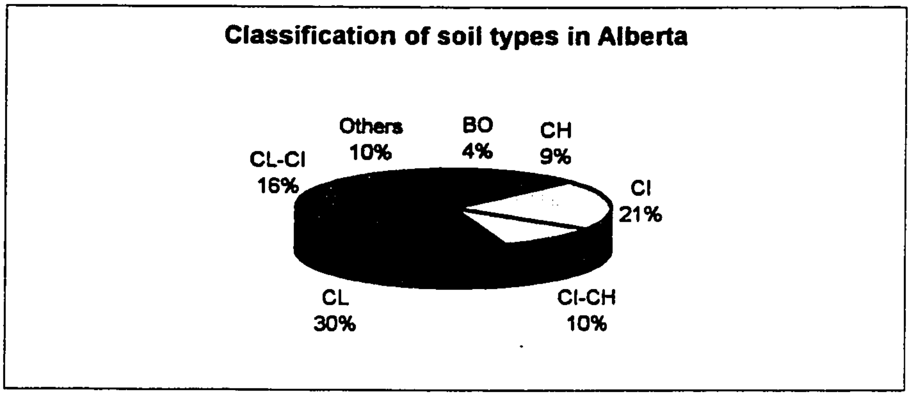


Figure 3.2 - Classification of Soil Types in Alberta along the Primary Highway network

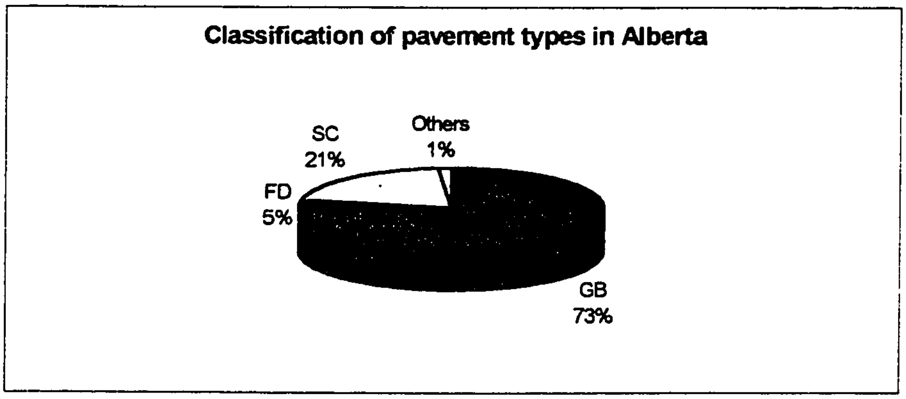


Figure 3.3 - Classification of Pavement Types in Alberta along the Primary Highway Network

In addition, the preliminary investigation included a calculation of the average service life of newly constructed pavements when only one parameter is changed (i.e. two parameters remained constant while changing the third parameter). The three parameters are soil type, pavement type, and climatic region. This experiment was conducted nine times to test the effect of each parameter on service life. Figures 3.4 to 3.6 illustrate the results. The results show that the overall service life in the Northern climactic region is the lowest of the three regions. They also indicate that the GB pavement type has the longest service life.

Table 3.1 – Breakdown Statistics by Pavement Type and Soil Type for the Entire Primary Highway Network in Alberta

SOIL	GB	SC	CS	SA	Full d.	Total	Percent
BO	421.04	53.11	28.8	0	1.65	504.6	3.54%
CH	861.61	390.65	31.21	0	62.36	1345.83	9.44%
CI	2235.56	532.9	0	0	248.29	3016.75	21.17%
CI-CH	1044.18	364.93	0	16.34	62.86	1488.31	10.44%
CL	3234.95	803.89	69.91	0	194.83	4303.58	30.20%
CL-CI	1520.04	555.3	16.89	0	125.5	2217.73	15.56%
Others	1080.76	252.33	0.58	20.61	19.48	1373.76	10%
Total	10398	2953.1	147.39	36.95	714.97	14251	
Percent	73%	21%	1%	0%	5%		

Note: Lengths are in Km.

Table 3.2 – Breakdown Statistics by Pavement Type and Soil Type for Central Climatic Region in Alberta

SOIL	GB	SC	CS	SA	Full d.	Total	Percent
BO	185.95	28.04			1.65	215.64	4.35%
CH	225.02	97.57	2.42		25.42	350.43	7.06%
CI	692.66	110.19			123.3	926.15	18.66%
CI-CH	210.6	70.93			39.26	320.79	6.46%
CL	1299.5	286.25	36.17		35.65	1657.57	33.40%
CL-CI	706.78	244.03	16.89		45.67	1013.37	20.42%
GC	49.57					49.57	1.00%
GF						0	0.00%
GP	21.12					21.12	0.43%
GW						0	0.00%
ML	5.02					5.02	0.10%
SC	97.74	57.03	0.58			155.35	3.13%
SC-CL	37.47	12.37			0.8	50.64	1.02%
SF	35.7	31.1				66.8	1.35%
SF-CL	7.62					7.62	0.15%
SP	12.42					12.42	0.25%
SU	49.1	20.79		4.46		74.35	1.50%
SW						0	0.00%
XX	35.85					35.85	0.72%
Total	3672.12	958.3	56.06	4.46	271.75	**4963**	
Percent	73.99%	19.31%	1.13%	0.09%	5.48%		

Table 3.3 – Breakdown Statistics by Pavement Type and Soil Type for Northern Climatic Region in Alberta

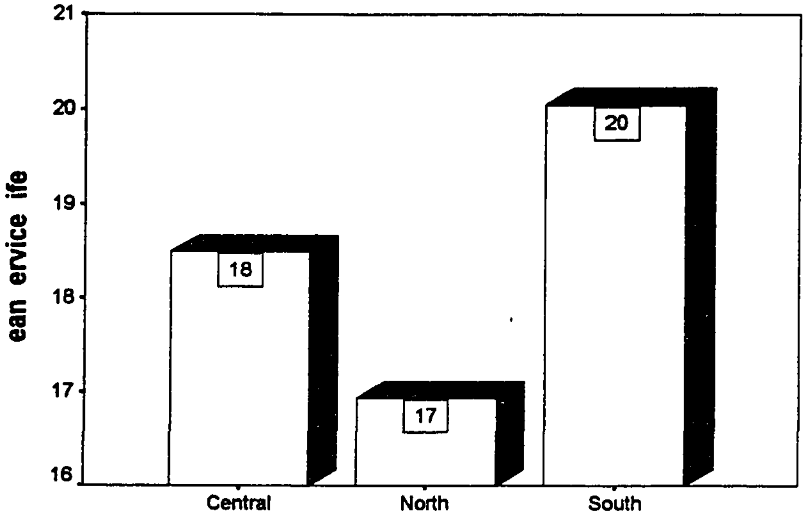
SOIL	GB	SC	CS	SA	Full d.	Total	Percent
BO	48.07	25.07	28.8			101.94	2.49%
CH	498.93	283.55	28.79		14.42	825.69	20.21%
CI	531.28	307.63			47.8	886.71	21.70%
CI-CH	499.28	213.3		16.34	23.6	752.52	18.42%
CL	296.35	383.8	15.44		0.48	696.07	17.04%
CL-CI	364.52	133.55			24.83	522.9	12.80%
GC	4.39					4.39	0.11%
GF						0	0.00%
GP						0	0.00%
GW	1.57					1.57	0.04%
SC	3.41	32.77				36.18	0.89%
SC-CL	4.88					4.88	0.12%
SF	2.33	0.36			0.42	3.11	0.08%
SF-CL	0.76	14.9				15.66	0.38%
SP	17.42					17.42	0.43%
SU	26.51	5.19			7.29	38.99	0.95%
SW						0	0.00%
XX	170.1				7.71	177.81	4.35%
Total	2469.8	1400.1	73.03	16.34	126.55	4086	
Percent	60.45%	34.27%	1.79%	0.40%	3.10%		

Note: Lengths are in

Table 3.4 – Breakdown Statistics by Pavement Type and Soil Type for Southern Climatic Region in Alberta

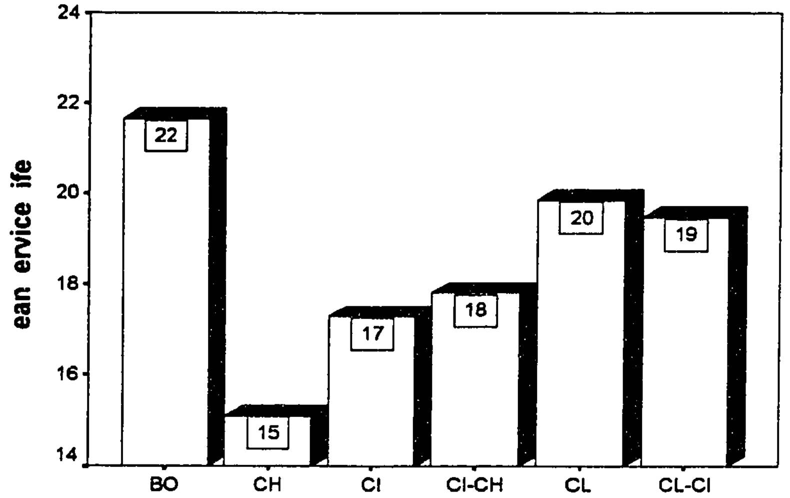
SOIL	GB	SC	CS	SA	Full d.	Total	Percent
BO	187.0					187.02	3.59%
CH	137.6	9.5			22.5	169.71	3.26%
CI	1011.6	115.0			77.1	1203.9	23.14%
CI-CH	334.	80.				415	7.98%
CL	1639.	133.8	18.		158.	1949.9	37.48%
CL-CI	448.7	177.7			55	681.46	13.10%
GC	35.6					35.61	0.68%
GF	106.6					106.69	2.05%
GP	7.1					7.12	0.14%
GW	3					3	0.06%
SC	31.0	42.4			3.2	76.74	1.48%
SC-CL	27.	10				37.3	0.72%
SF	131.4					131.44	2.53%
SF-CL	80.4	19.5				99.96	1.92%
SP	34.0			16.1		50.23	0.97%
SU		0.4				0.47	0.01%
SW	9.8	5.3				15.24	0.29%
XX	31.7					31.78	0.61%
Others	498.3	77.8	0	16.1	3.2	595.58	11.45%
Total	4256.8	594.69	18.3	16.15	316.67	5203	
Percent	81.82%	11.43%	0.35%	0.31%	6.09%		

Note: Lengths are in Km.



Weather Region

Figure 3.4 - Average Service Life in years for the Three Climatic Regions



Soil Type

Figure 3.5 - Average Service Life in years for the Six Soil Types

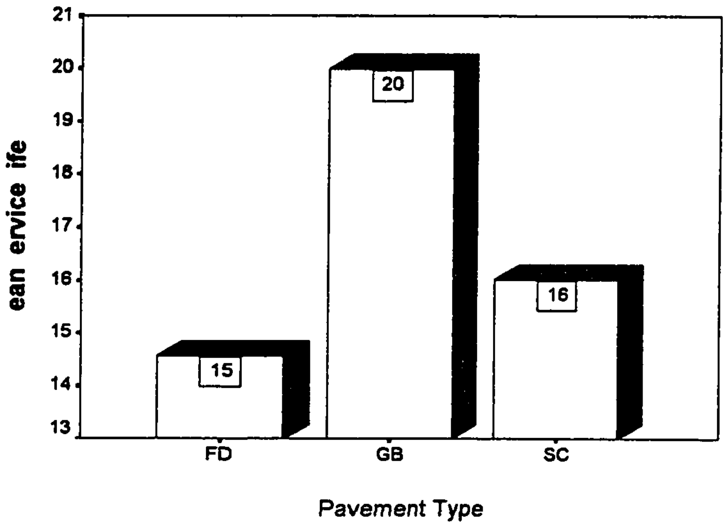


Figure 3.6 - Average Service Life in years for the Three Pavement Types

3.4.1 Factorial Analysis and Interaction

More detailed statistical analysis was performed using the statistical computer software "SPSS". This analysis includes Multi-way Factorial Analysis of Variance, which is a simultaneous analysis of the effect of three or more factors on population means. The main advantages of such experimental design include: 1) the fact that one experiment can suffice for the analysis, and it is not necessary to perform a one-way Analysis of Variance (ANOVA) for each factor, and 2) the factorial analysis of variance procedures can test for interaction among factors (Montgomery, 1991). For this study, a "crossed" experiment is used, which means that all possible combinations of factors' levels are considered. For example, if there are "a" levels of factor "A" and "b" levels of factor "B", then each replicate will contain all "ab" treatment combinations.

The effect of a factor is defined as the change in response produced by the change in the level of the factor (Montgomery, 1991). This is frequently called a "main effect" because it refers to the primary factors of interest in the experiment. In some experiments, we may find that the difference in response between the levels of one factor is not the same at all levels of the other factors. When this occurs, there is an "interaction" between the factors.

The main effects (factors) considered for this analysis are as follows:

- Pavement type – Three types (GB, SC, and FD)
- Soil type – Six Types (BO, CH, CI, CL, CI-CH, and CL-CI)
- Climatic region – Three Regions (Central, Northern, and Southern)
- ESAL - Three levels (Low, Medium, and High)

The "interaction" is defined as the effect of the interference of two or more parameters on the results (Montgomery, 1991). For example, the interaction between pavement type and climatic region may have an effect on service life. The factorial analyses were performed to test the significance of each of the previous main factors on the pavement service life. In addition, the interactions between these main effects, each having several levels, were performed. The output result presented in table 3.5 reveals that all the main factors have a significant effect on the service life. Most of these effects are significant to a higher than 99% confidence level. The interaction significance between the main factors was calculated. All main factor combinations showed a significance interaction as well.

Table 3.5 - Factorial Analysis

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Noncent. Parameter	Observed Power[a]
Corrected Model	166008.7[b]	45	3689.081	121.772	.000	5479.761	1.000
Intercept	4189.429	1	4189.429	1788.733	.000	1788.733	1.000
SOIL	4229.267	3	1409.756	46.534	.000	139.603	1.000
WEA	175.012	2	87.506	2.888	.056	5.777	.567
PAV	2788.807	2	1394.404	46.028	.000	92.055	1.000
ESALCL	17.378	1	17.378	.574	.449	.574	.118
SOIL * WEA	3279.757	6	546.626	18.044	.000	108.261	1.000
SOIL * PAV	2092.180	5	418.436	13.812	.000	69.061	1.000
SOIL * ESALCL	3679.821	3	1226.607	40.489	.000	121.467	1.000
WEA * PA	246.133	4	61.533	2.031	.088	8.125	.612
WEA * ESALCL	1064.445	2	532.223	17.568	.000	35.136	1.000
PAV * ESALCL	122.549	2	61.274	2.023	.133	4.045	.419
SOIL * WEA * PA	842.066	7	120.295	3.971	.000	27.796	.986
SOIL * WEA * ESALCL	1976.079	2	988.039	32.614	.000	65.228	1.000
SOIL * PAV * ESALCL	1017.533	4	254.383	8.397	.000	33.588	.999
WEA * PA * ESALCL	672.880	2	336.440	11.106	.000	22.211	.992
SOIL * WEA * PA * ESALCL	.000	0	.	.	.	.000	.
Error	251265.7	8294	30.295				
Total	2282272	8340					
Corrected Total	417274.3	8339					

3.5 STRATIFICATION OF PAVEMENT CLASSES

For the purpose of this study, a pavement class is defined as each combination of factors' levels that affect pavement service life. For example, the combination of climatic region "Central", pavement type "GB", soil type "CL", and Traffic Level "medium" is considered a one-pavement class. And the combination of climatic region "South", pavement type "GB", soil type "CL", and Traffic Level "medium" is considered another pavement class.

The objective of this section is to group the various pavement classes in such away to ensure that each group represents pavement classes that have no significant differences between their service-life means. A Multiple Comparison Analysis of mean differences (i.e., Duncan's multiple-range test and Tukey's test) is performed on the pavement classes resulting from all possible combinations of different levels of the considered factors. As a result, all pavement classes within each group will have a similar behavior in terms of their service lives.

3.5.1 Multiple Comparison Tests

Before applying any of the statistical multiple comparison tests (post hoc tests), the mean of pavement service life for each pavement class must be calculated. In many cases, the statistical "F" test, in an analysis of variance (ANOVA) table, can be used to show whether a significant difference among a group of means exists or not. In most practical cases, this is not enough. In this research, it is desirable not only to know whether a difference exists among the means (service life means of all pavement classes), but also which mean differs from another. In other words, the interest of this study is to compare all pairs of service life means for all pavement classes. In this case, the null hypotheses that should be tested are:

$$H_o: \quad \mu_i = \mu_j, \qquad \text{for all } i \neq j \ldots\ldots\ldots\ldots(3.1)$$

Where μ_i, μ_j are the means of service life for pavement class "i" and "j" respectively.

The two-sample "t" test can be used to test for significant differences between all possible pairs of service life means. However, this test has many limitations when testing a large number of means. This procedure will require a large number of "t" tests even if the number of means is relatively small. Testing for significant difference between pairs of "N" means will require performing the test for

$$\binom{N}{2} = \frac{N(N-1)}{2} \text{ times} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.2)$$

For example, if the resulting pavement classes are equal to 72, this will require 2556 "t" tests to check for significant differences between the pairs of means. Additionally, the probability (confidence level) associated with the "t" test assumes that only one test is performed. When several means are tested pairwise, the probability of finding one significant pair by chance increases rapidly with the number of pairs (Miller, 1990). For example, if a 0.05 significance level is used to test whether means "a" and "b" are equal, and means "c" and "d" are equal, the overall confidence level in this case would be less than the assumed 0.95 (95%) and would be equal to $0.95 \times 0.95 = 0.9025$.
For 10 pairs of means tested at the 0.05 significance level, the confidence level will go down to less than 0.6 (60%). As a result, these tests are not independent and they will show, in many cases, significant differences between pairs of means even when such difference does not exist.

There are several multiple comparison tests that overcome the disadvantages of the two-sample "t" test solution. Some of these more widely used tests are:

- Duncan's Multiple Range Test
- Tukey's test
- The Least Significant Difference (LSD) Method

- Bonferroni Method
- The Newman-Keuls Test

Professional statisticians often disagree over the utility of the various multiple comparison methods. Among the more popular of these methods is Duncan's multiple range test (Duncan, 1955). Several statistical references indicate that Duncan's multiple range test is quite powerful and very effective at detecting differences between means when they exist; it should be satisfactory for many general applications (Carmer, 1973; Miller, 1990; and Montgomery, 1991). On the other hand, Tukey's multiple comparison test is considered to be more conservative and less powerful in detecting differences between means than most of the other procedures (Montgomery, 1991). However, if the number of comparisons is large, the Tukey's test becomes more sensitive in detecting differences, and is highly recommended (SPSS, 1998).

As a result of the previous discussion, This research utilizes Duncan's method, and also uses Tukey's test for validation to stratify the pavement classes. To check the sensitivity of the results to different significance levels (alpha), Three different values for alpha are used: 0.1, 0.05, and 0.01. The sensitivity analysis showed that the stratification results from the multiple comparison tests are consistent for different alpha values. As a sort of validation, expert knowledge and engineering judgement are finally integrated to provide the final stratification list.

3.5.2 Duncan's Multiple Range Test

As explained by Montgomery (1991), to apply Duncan's multiple range test, all the treatment means are arranged in ascending order, and the standard error of each mean is determined as

$$S_{y_i} = \sqrt{\frac{MS_E}{n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

Where,

MS_E = Mean Square of Error

n = Sample Size

From Duncan's table of significant ranges, The "r_α (p, f)" value for $p = 2,3, \ldots, a,$ can be determined. Where "α" is the significance level and "f" is the number of degrees of freedom for error. The next step is to convert the means differences into a set of "a-1" least significant ranges by calculating

$$R_p = r_\alpha (p,f)\, S_{y_i} \qquad for\ p=2,3,\ldots\ldots, a \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

The observed differences between means are tested, starting with the largest and compared with the least significant range R_a. Next, the difference between the largest and the second smallest variable is computed and compared with the least significant range $R_{a-1.}$ These comparisons are continued until all means have been compared with the largest mean. Then, the difference between the second largest mean and the smallest is computed and compared to the least significant range $R_{a-1.}$ This process is continued until the differences of all possible *a(a-1)/2* pairs of means have been considered. If an observed difference is greater than the corresponding least significant range, it is concluded that the pair of means in question is significantly different (Montgomery, 1991).

3.5.3 Tukey's Multiple Comparison Test

Tukey's procedure is largely based on the studentized range statistic. It requires the use of the upper "$\propto$" percentage point of the studentized range for groups of means of size "a" and "f" error degrees of freedom "$q_{\propto}(a,f)$". This "$q_{\propto}(a,f)$" is necessary for determining the critical value for all comparisons between pairs of means. Hence, Tukey's test assumes that a pair of means is significantly different if the absolute value of their differences exceeds

$$T_\alpha = q_\alpha(a,f)S_{yi} \quad \text{..............................(3.5)}$$

Where,

$q_\alpha(a,f)$ can be determined from the table of percentage points of the studentized range statistics (Montgomery, 1991), and

S_{yi} is the standard error and can be determined as

$$S_{yi} = \sqrt{\frac{MS_E}{n}} \quad \text{....................................(3.6)}$$

Where,

MS_E = Mean Square of Error

n = Sample Size

The next step is to examine all the levels within each performance factor (i.e., pavement type, soil type, climatic region, etc.). For each main effect (i.e., factor), the Duncan's and Tukey's multiple comparison tests are performed to investigate whether significant differences exist within the various levels of the main effect itself. For example, in the case of the "soil type" main effect (or factor), which is comprised of six levels (types), the multiple comparison test indicates that the differences between two pairs of service life means are not significant (i.e., CI & CI-CH, and CL & CL-CI). Each of those soil type pairs would then be treated as one type (level). This would result in reducing the number of soil levels to four instead of six. Table 3.6 illustrates the results of the multiple comparison test between the mean differences of service life for the six soil type levels.

The same procedure is repeated for the "pavement type" main effect. This time, the test resulted in three distinct pavement types, as shown in table 3.7.

As for the ESAL levels, the results in table 3.8 recommend combining the Low and the Medium categories into one category. This result is also supported by the AASHTO design procedure, which provides similar pavement thickness for low and medium traffic levels, and increased pavement thickness for high traffic levels (AT&U 1997).

For the climatic regions, the multiple comparison test shows significant difference among the means of the three climatic regions. Table 3.9 is an illustration for the result.

Table 3.6 – Results of the Multiple Comparison Tests between Soil Types

Soil Type	N	Subset for alpha = .05			
		1	2	3	4
CH	2325	15.1062			
CI	3660		17.2930		
CI-CH	1255		17.8058		
CL-CI	2892			19.4768	
CL	6720			19.8637	
BO	753				21.6571
Sig.		1.000	.193	.508	1.000

Table 3.7 – Results of the Multiple Comparison Tests between Pavement Types

Tukey HSD

Pavement Type	N	Subset for alpha = .05		
		1	2	3
FD	1475	14.5794		
SC	4306		16.0280	
GB	11825			19.9899
Sig.		1.000	1.000	1.000

Table 3.8 – Results of the Multiple Comparison Tests between ESAL Levels

ESAL Classification	N	Subset for alpha = .05	
		1	2
High	4889	16.5171	
Low	1723		19.1068
Medium	10994		19.3947
Sig.		1.000	.187

Table 3.9 – Results of the Multiple Comparison Tests between Climatic Regions

Weather Region	N	Subset for alpha = .05		
		1	2	3
North	5466	16.9382		
Central	5728		18.5559	
South	6277			20.0688
Sig.		1.000	1.000	1.000

As a result of applying the multiple comparison procedures to the individual factors, the number of pavement classes (combinations of all factor levels) is reduced from 162 to 72 (4 soil types × 3 pavement types × 3 climatic regions × 2 ESAL levels). Table 3.10, 3.11 and 3.12 show the resulting 72 pavement classes for pavement types GB, SC and FD respectively. Note that some of the classes are not shown in any of the tables, which means that they do not have enough pavement records at the time of the analysis (3 records or less).

Table 3.10 - Different "Class" definitions for the GB Pavement Type

Class	Region	Soil	ESAL
1	Central	BO	Medium
2	Central	CH	Medium
3	Central	CH	High
4	Central	CI, CI-CH	Medium
5	Central	CI, CI-CH	High
6	Central	CL, CL-CI	Medium
7	Central	CL, CL-CI	High
8	North	BO	Medium
9	North	BO	High
10	North	CH	Medium
11	North	CH	High
12	North	CI, CI-CH	Medium
13	North	CI, CI-CH	High
14	North	CL, CL-CI	Medium
15	South	BO	Medium
16	South	BO	High
17	South	CH	Medium
18	South	CH	High
19	South	CI, CI-CH	Medium
20	South	CI, CI-CH	High
21	South	CL, CL-CI	Medium
22	South	CL, CL-CI	High

Table 3.11 - Different "Class" definitions for the SC Pavement Type

Class	Region	Soil	ESAL
1	Central	BO	Medium
2	Central	CH	Medium
3	Central	CH	High
4	Central	CI, CI-CH	Medium
5	Central	CI, CI-CH	High
6	Central	CL, CL-CI	Medium
7	Central	CL, CL-CI	High
8	North	CH	Medium
9	North	CI, CI-CH	Medium
10	North	CL, CL-CI	Medium
11	South	CI, CI-CH	Medium
12	South	CL, CL-CI	Medium

Table 3.12 - Different "Class" definitions for the FD Pavement Type

Class	Region	Soil	ESAL
1	Central	CH	Medium
2	Central	CI, CI-CH	Medium
3	Central	CI, CI-CH	High
4	Central	CL, CL-CI	Medium
5	Central	CL, CL-CI	High
6	North	CH	Medium
7	North	CH	High
8	North	CI, CI-CH	Medium
9	North	CI, CI-CH	High
10	North	CL, CL-CI	Medium
11	South	CH	Medium
12	South	CI, CI-CH	Medium
13	South	CL, CL-CI	Medium
14	South	CL, CL-CI	High

3.5.4 Final Pavement Groups

The multiple comparison tests are then applied in such away that the variability arising from pavement types can be controlled. Pavement types are used as 3 blocks, and each of the 24 combinations (classes) of the other factor levels (3 climatic regions, 4 soil types and 2 traffic levels) is assigned as a treatment for each pavement type. The objective of this design is to determine whether the difference in service lives' means between various pairs of treatments within each pavement type is significant or not. Consequently, the multiple comparison test is performed on the pavement classes in order to stratify them into groups within each pavement type. An example of one of the multiple comparison test result is shown in Table 3.13. It illustrates the service life mean differences between each pair of pavement classes and the level of significance of such differences. If there were no significant difference in means at a certain confidence level (i.e., 95%), this would be an indication that the two classes should be combined in one group. For example, class 1 and class 15 can be combined in one group, while class 1 and class 8 may not in a different group. Additionally, Table 3.14 illustrates the outcomes of the multiple comparison tests by both Duncan and Tukey for pavement class GB for confidence levels 90%, and 95%. The rest of the test results for GB, FD and SC pavement types at various confidence levels (90%, 95%, and 99%) can be reviewed in Appendix "A". Finally, Table 3.15 presents the final result of the stratification and defines the classes within each group. This grouping considered the outcomes of the various multiple comparison tests, and the expert and engineering knowledge in Alberta.

Table 3.13 – Example for a Multiple Comparison Tests performed between Classes for GB Pavement Type and BO Soil type at 90% & 95% Confidence level

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROU	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	1	8	10.2997*	.810	.000	8.2186	12.3809
		15	-.8554	.562	.425	-2.3000	.5892
		16	-2.1114*	.560	.001	-3.5513	-.6714
	8	1	-10.2997*	.810	.000	-12.3809	-8.2186
		15	-11.1552*	.880	.000	-13.4154	-8.8949
		16	-12.4111*	.879	.000	-14.6684	-10.1538
	15	1	.8554	.562	.425	-.5892	2.3000
		8	11.1552*	.880	.000	8.8949	13.4154
		16	-1.2560	.657	.223	-2.9444	.4325
	16	1	2.1114*	.560	.001	.6714	3.5513
		8	12.4111*	.879	.000	10.1538	14.6684
		15	1.2560	.657	.223	-.4325	2.9444

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	90% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	1	8	10.2997*	.810	.000	8.4435	12.1560
		15	-.8554	.562	.425	-2.1438	.4330
		16	-2.1114*	.560	.001	-3.3956	-.8271
	8	1	-10.2997*	.810	.000	-12.1560	-8.4435
		15	-11.1552*	.880	.000	-13.1711	-9.1392
		16	-12.4111*	.879	.000	-14.4244	-10.3978
	15	1	.8554	.562	.425	-.4330	2.1438
		8	11.1552*	.880	.000	9.1392	13.1711
		16	-1.2560	.657	.223	-2.7619	.2500
	16	1	2.1114*	.560	.001	.8271	3.3956
		8	12.4111*	.879	.000	10.3978	14.4244
		15	1.2560	.657	.223	-.2500	2.7619

Table 3.14 – Multiple Comparison test for the GB Pavement Type and the BO Soil Type at 95% & 90% Confidence Levels

Service Life

			Subset for alpha = .05		
	GROUP	N	1	2	3
Tukey HSD[a]	8	53	12.7255		
	1	299		23.0253	
	15	137		23.8807	23.8807
	16	138			25.1366
	Sig.		1.000	.652	.322
Duncan[a,b]	8	53	12.7255		
	1	299		23.0253	
	15	137		23.8807	23.8807
	16	138			25.1366
	Sig.		1.000	.246	.089

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 109.292

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Service Life

			Subset for alpha = 0.1		
	GROUP	N	1	2	3
Tukey HSD[a]	8	53	12.7255		
	1	299		23.0253	
	15	137		23.8807	23.8807
	16	138			25.1366
	Sig.		1.000	.652	.322
Duncan[a,b]	8	53	12.7255		
	1	299		23.0253	
	15	137		23.8807	
	16	138			25.1366
	Sig.		1.000	.246	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 109.292

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Table 3.15 - Final Pavement "Groups" after Stratification

Group	Pavement	Soil Types	Regions	ESAL	Mean	N
1	FD	CH	South	Medium	11.68	236
		CI, CI-CH	South	Medium		
		CI, CI-CH	Central	High		
2	FD	CL, CL-CI	North	High	21.00	15
		CH	North	High		
3	FD	CH	North	Medium	15.11	1155
		CH	Central	Medium		
		CI, CI-CH	Central	Medium		
		CL, CL-CI	Central	Medium		
		CL, CL-CI	Central	High		
		CI, CI-CH	North	High		
		CL, CL-CI	North	High		
		CL, CL-CI	South	Medium		
		CL, CL-CI	South	High		
4	GB	CH	Central	High	11.84	204
		BO	North	Medium		
5	GB	CH	South	Medium	14.36	565
		CI, CI-CH	South	High		
6	GB	CH	North	Medium	17.78	3721
		CH	Central	Medium		
		CH	North	High		
		CI, CI-CH	North	Medium		
		CI, CI-CH	North	High		
		CL, CL-CI	South	High		
		CI, CI-CH	Central	High		

Table 3.15 (Continued) - Final Pavement Groups after Stratification

Group	Pavement	Soil Types	Regions	ESAL	Mean	N
7	GB	CH	South	High	13.21	420
8	GB	CI, CI-CH	South	Medium	22.41	3498
		CL, CL-CI	North	Medium		
		CL, CL-CI	South	Medium		
9	GB	CI, CI-CH	Central	Medium	25.27	1629
		CL, CL-CI	Central	Medium		
10	GB	CL, CL-CI	Central	High	16.03	1518
11	GB	BO	Central	Medium	23.74	575
		BO	South	Medium		
		BO	South	High		
12	SC	CI, CI-CH	North	Medium	13.21	1709
		CI, CI-CH	Central	Medium		
		CI, CI-CH	Central	High		
		BO	Central	Medium		
		CH	North	Medium		
		CL, CL-CI	Central	High		
		CH	Central	Medium		
13	SC	CH	Central	High	8.61	115
14	SC	CL, CL-CI	Central	Medium	17.02	1600
		CL, CL-CI	North	Medium		
15	SC	CI, CI-CH	South	Medium	21.12	818
		CL, CL-CI	South	Medium		

CHAPTER 4. MODELING INPUT DATA FOR SIMULATION OF INFRASTRUCTURE TIMES TO FAILURE

4.1 INTRODUCTION

The service lives of infrastructure units of one type (i.e., pavements, bridges, etc..) are subject to variations due to the uncertainty involved in many of the determining factors such as traffic volumes and material properties. When an infrastructure unit has a service life of a random duration, its present value of future rehabilitation/reconstruction cost is consequently subject to uncertainty. The objective of this chapter is to develop a systematic approach to modeling the random process of infrastructure times-to-failure for each of the previous defined pavement groups (see chapter three). This is achieved through fitting the collected failure data to statistical distributions and estimating the distribution parameters. These parameters are then used as input data for simulating times-to-failure, which will be used to predict life cycle costs, as will be detailed in chapter five.

Banks and Carson (1984) states that "even if the model structure is valid, if the input data are incorrectly collected, inappropriately analyzed, or not representative of the environment, the simulation output data will be misleading and possibly damaging." Proper input in the form of statistical models for work-task durations (i.e., service life durations) is essential to ensure meaningful simulation outputs (AbouRizk, 1990). The steps normally followed in modeling input data are: 1) identifying candidate distributions, 2) estimating parameters of each of the candidate distributions, 3) performing goodness-of-fit tests.

4.2 IDENTIFYING CANDIDATE DISTRIBUTIONS

An understanding of the failure process and properties of the considered statistical distribution is helpful in identifying candidate distributions. Plotting a histogram of failure time data gives the shape of the probability density function (PDF) of the underlying statistical distribution. Additionally, computing sample statistics (i.e., mean, median, variance, coefficient of skewness and kurtosis) and relating them to the properties of theoretical distributions can further facilitate the selection of candidate distribution(s). The coefficient of skewness and kurtosis of failure times are a good indicator of the shape properties of the underlying distribution (AbouRizk, 1992). For example, if the mean and median of the times-to-failure are approximately equal, then the data may possibly come from either a Normal distribution or Weibull distribution with a kurtosis value around 3 and coefficient of skewness of approximately zero. However, if the mean is significantly larger than the median, then a skewed-to-the-right Weibull distribution or Lognormal can provide a good fit. In the case of data coming from an exponential distribution, the mean and standard deviation of the times to failure sample would be expected to be approximately equal.

Furthermore, AbouRizk and Halpin (1992) presents a table of coefficient of skewness and kurtosis of commonly used distributions. The values of the coefficient of skewness and kurtosis of the times-to-failure can be calculated and compared to those of a known distribution. The coefficient of skewness of a data sample is calculated as follows:

$$\sqrt{\beta_1} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{X_i - \mu}{\sigma}\right)^3 \text{............}(4.1)$$

And the kurtosis of the same sample can be calculated as follows:

$$\beta_2 = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{X_i - \mu}{\sigma}\right)^4 \text{............}(4.2)$$

Where μ = the mean of the sample

σ = the standard deviation of the sample

4.3 ESTIMATING PARAMETERS OF THE CANDIDATE DISTRIBUTIONS

Once candidate distributions are identified, the parameters of the distributions have to be determined using techniques such as moment matching, percentile matching, maximum likelihood, least square, or any other methods. AbouRizk and Halpin (1990) encourages the use of all of fitting methods available within the software used and the selection of the parameters that produce the best fit to the collected data. Law and Kelton (1991), and Kapur and Lamberson (1977) discuss the topic of distribution fitting in great detail. They provide a comprehensive review of the methods used for estimating parameters of various distributions such as the Normal, Lognormal, Exponential, and Weibull distributions. Also, AbouRizk et al. (1994) provide a detailed discussion on fitting beta distributions using various methods such as the moment matching, maximum likelihood, ordinary least squares, and diagonally weighted least squares.

4.4 PERFORMING GOODNESS-OF-FIT TESTS

The next step in identifying the statistical distribution is to check for the goodness-of-fit using statistical tests that compare the quality of fit between the theoretical distribution and the empirical one. These tests usually compare a null hypothesis (H_0) that suggests that the failure times data is coming from the assumed distribution, with an alternative hypothesis (H_1) that suggests that the data is not coming from the assumed distribution. Test statistics are computed based on the sample data and are compared with critical values calculated from formulas or obtained from tables unique for each test. The critical values are dependent on the desired level of significance (i.e., confidence level) and the sample size. The smaller the critical values compared to the test statistics, the higher the confidence that the sample data is not coming from the specified distribution. The chi-square and the Kolmogorov-Smirnov tests are two widely used methods to test the goodness of fit, and they are discussed in details in many statistics and simulation literatures such as Law and Kelton (1991), Montgomery, (1991), Zar (1984), and Fishman (1973). Visual assessment of the goodness of fit using plots such as the probability plots and cumulative density functions is another approach for evaluating the quality of fit. It proves in many cases to be as powerful as any other test, and could be used along with other statistical tests (AbouRizk, 1990).

4.5 APPLICATION OF INPUT DATA MODELING ON PAVEMENT GROUPS

The conclusion of the previous chapter was a table (see Table 3.15) that presents the final stratification of the identified pavement classes. This resulted in 15 pavement groups, each representing a set of pavement classes in Alberta that have no significant difference between the means of their service lives. In this section, the input data modeling approach, presented earlier in this chapter, will be applied to the data within each group to identify the parameters and the statistical distributions that represent the service lives (times to failure) of pavements within each group.

Since, identifying the statistical distribution that represents a sample data is a tedious and time consuming process when carried out manually, the process can be more effective with the use of computer software. One of the packages that is widely used is UNIFIT (Law, 1994), a commercial package that fits a wide variety of distributions to a given data set and performs goodness of fit tests. Another computer package is FITTRI (Venkatraman, 1988) which is in the public domain and fits Johnson Translation Systems to sample data. Also, there is BetaFit (AbouRizk, 1989) which fits beta distributions to a set of sample observations.

For this study, UNIFIT is selected because it supports a wide variety of statistical distributions and it is being used widely by many organizations and research institutions for the last fifteen years. The algorithm that UNIFIT uses to select the best distribution is based on the analysis of more than 35,000 data sets from known distributions, from 15 to 5,000 in size (Law, 1994). After entering the data to the software, UNIFIT will first display a list of the best distributions (models) based on the overall ranking algorithm. Each distribution is assigned a relative evaluation score from 0 to 100, with 100 indicating the best relative overall fit. If the score of the second- or third-best distribution is close to the score of the best distribution, then these distributions should be considered and further evaluated to select the best fit. For this research, the pavement times to failure data within the stratified pavement groups, for newly constructed pavements and rehabilitated ones (i.e., overlaid), are entered to and read by UNIFIT. The top three distributions (in some cases the top four) suggested by UNIFIT are tested to find the best fit to the times to failure data among them. The goodness-of-fit tests are performed using statistical tests such as the chi-square or by visually assessing the quality of the fit using probability plots and cumulative density functions. Figures 4.1 through 4.7 illustrate the distribution selection and fitting of pavement data group number 3, for both the "new construction" and "overlay" data. In this example, the top 4 candidate distributions suggested by the software (Weibull, Log-logistic, Log-Laplace, and Gamma) were further evaluated by visually assessing the goodness of fit between the theoretical and the actual distributions, using the cumulative density functions and probability plots. Furthermore, the data summary and the parameters of each candidate distribution are presented in Tables 4.1 through 4.6. The rest of the distribution rankings, fittings and parameters, for the other pavement groups, are illustrated in Appendix B. This information is used as the input data for the simulation of pavement service lives. In the next chapter, this input data is fed to the risk-based life cycle cost model to produce a probabilistic estimate of present worth costs for different construction/rehabilitation alternatives.

Table 4.1 - Relative Scores and Rankings of Candidate Distributions for Pavement Data Group # 3 (New Construction)

Models	Score (0-100)	Ranking
1-Weibull	100.0	1
2-Log-logistic	86.4	2
3-Log-Laplace	77.3	3
4-Gamma	75.0	4
5-Lognormal	65.9	5
6-Random Walk	56.8	6
7-Inverse Gaussian	47.7	7
8-Pearson Type 6	36.4	8
9-Pearson Type 5	27.3	9
A-Inverted Weibull	18.2	10
B-Exponential	9.1	11
C-Pareto (E)	0	12

Table 4.2 - Sample Summary for Pavement Data Group # 3 (New Construction)

Sample Characteristic	Value
Observation Type	Real Valued
Number of Observations	1168
Minimum Observation	2.00000
Maximum Observation	28.0000
Mean	15.1250
Median	16.0000
Variance	16.9527
Coefficient of Variation	.27222
Skewness	-.72061
Kurtosis	3.66457

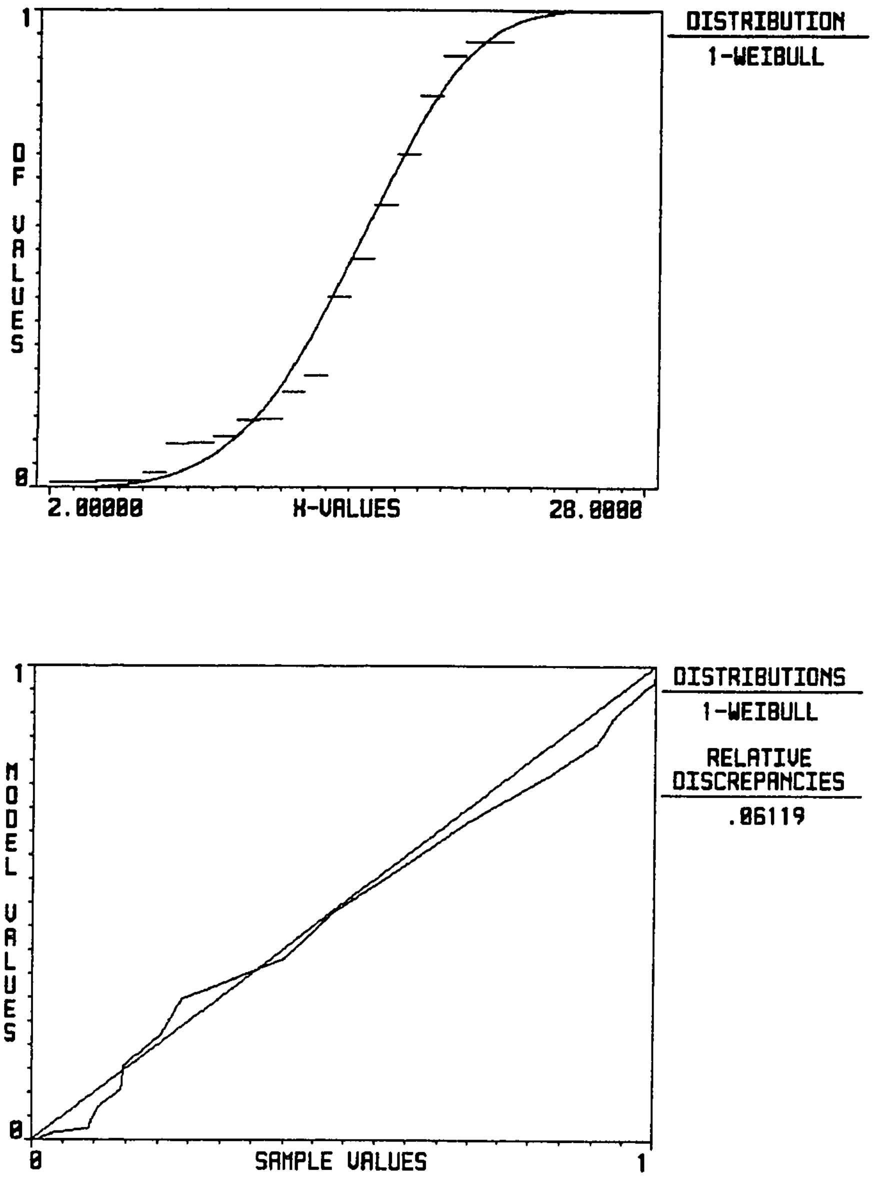


Figure 4.1 – Distribution Function and Probability Plot Comparisons between Pavement Data Group # 3 and a Fitted Weibul Distribution (New Construction)

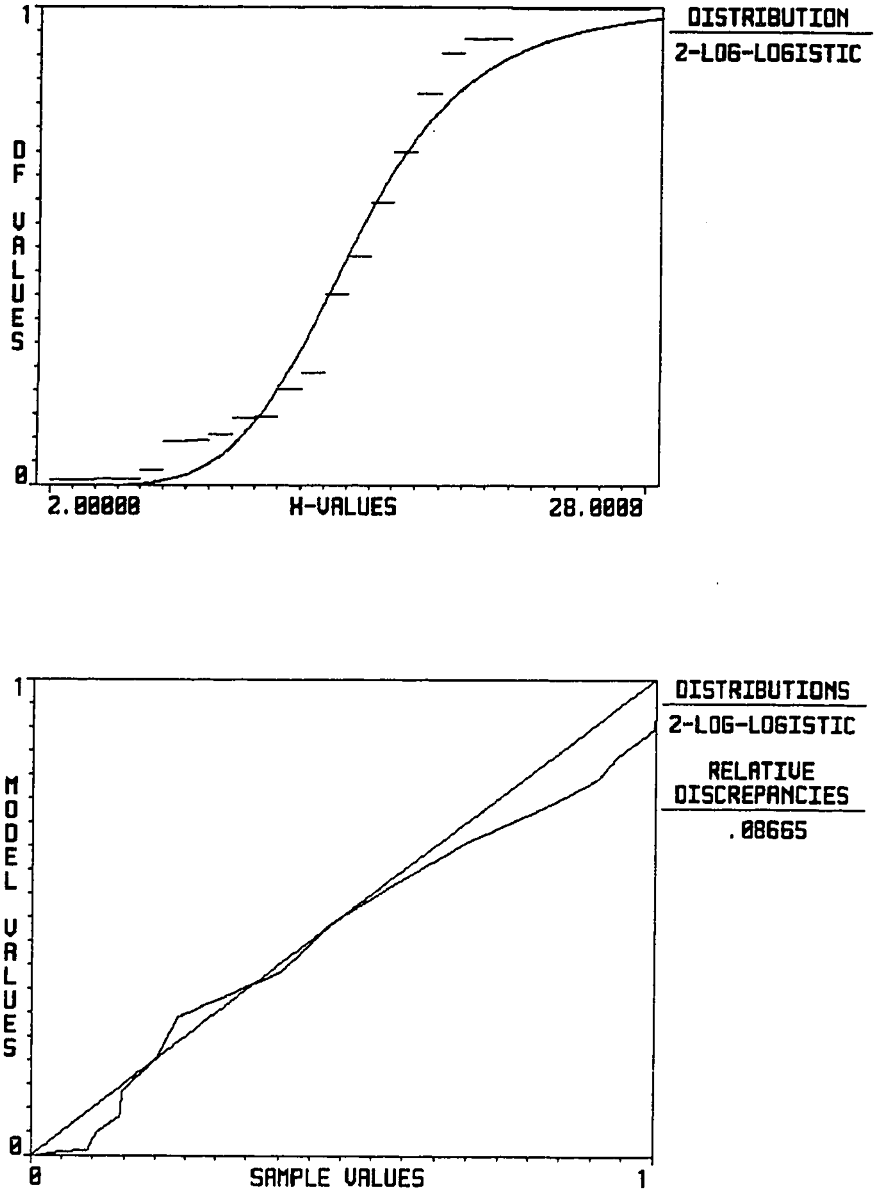


Figure 4.2 – Distribution Function and Probability Plot Comparisons between Pavement Data Group # 3 and a Fitted Log-logistic Distribution (New Construction)

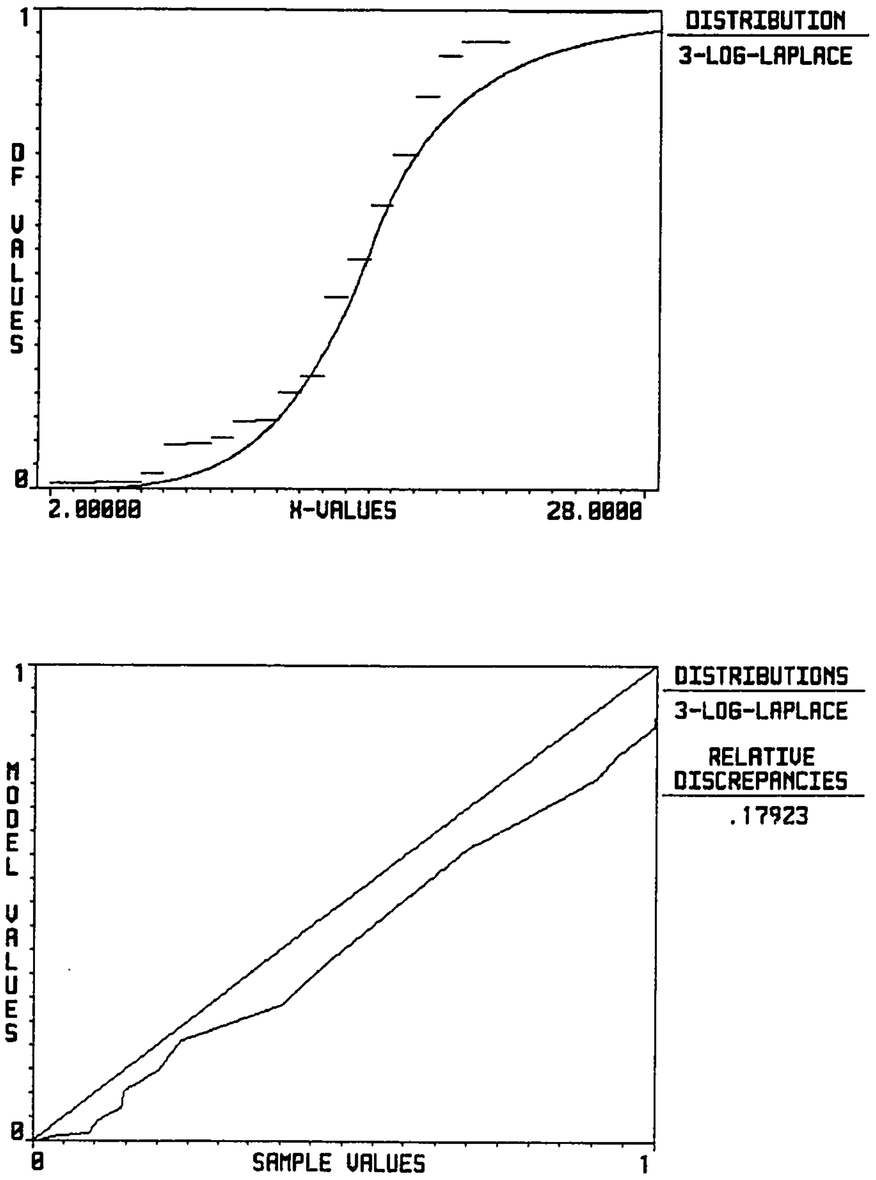


Figure 4.3 – Distribution Function and Probability Plot Comparisons between Pavement Data Group # 3 and a Fitted Log-Laplace Distribution (New Construction)

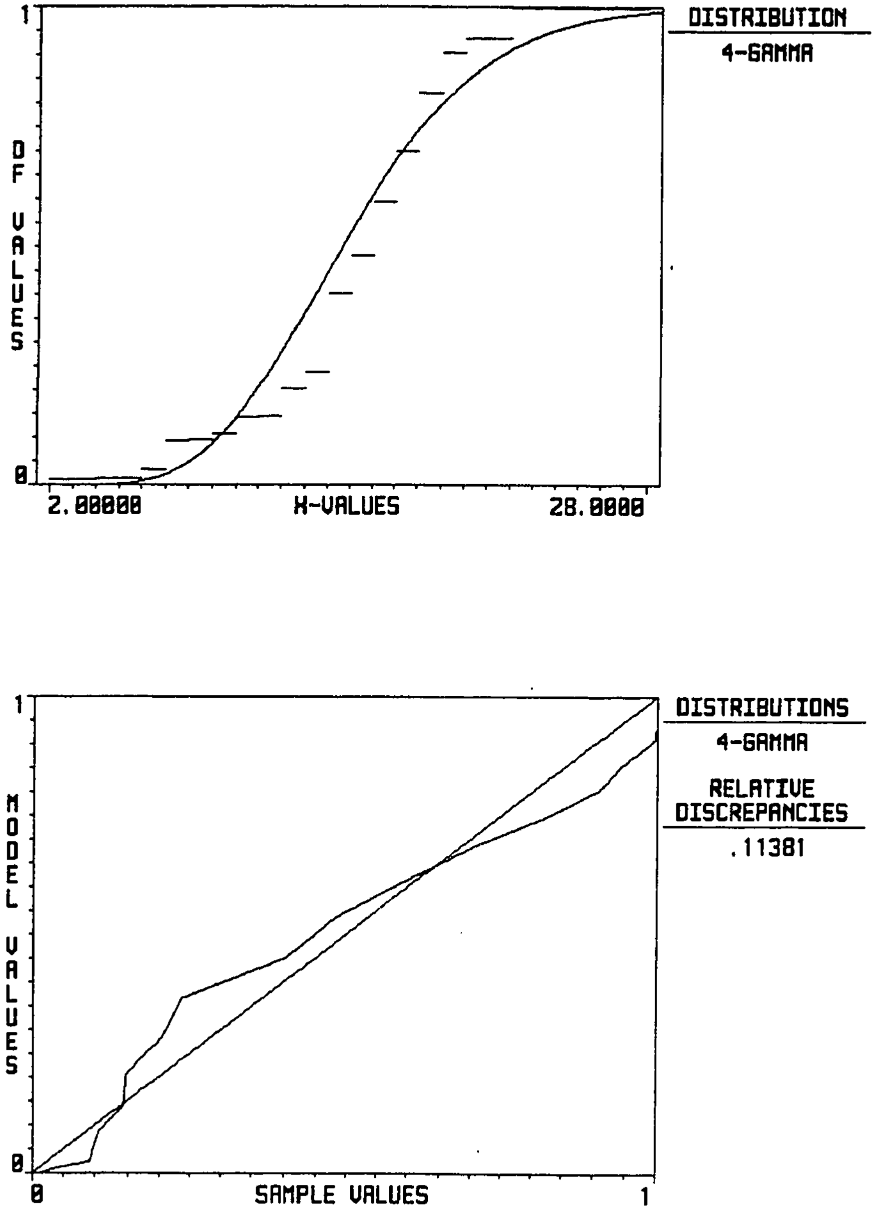


Figure 4.4 – Distribution Function and Probability Plot Comparisons between Pavement Data Group # 3 and a Fitted Gamma Distribution (New Construction)

Table 4.3 – Candidate Distribution Moments and Characteristics For Pavement Group Data # 3 (New Construction)

Model 1: Weibull Distribution	
Scale Parameter	16.5809
Shape Parameter	4.33060
Mean	15.0977
Variance	15.5360
Skewness	-.14947
Kurtosis	2.78586

Model 2: Log-logistic Distribution	
Scale Parameter	15.1746
Shape Parameter	5.79617
Mean	15.9438
Variance	9.61089
Skewness	1.92105
Kurtosis	16.3458

Model 3: Log-Laplace Distribution	
Scale Parameter	16.0000
Shape Parameter	4.25284
Mean	16.9364
Variance	41.8511
Skewness	4.31566
Kurtosis	191.026

Model 4: Gamma Distribution	
Scale Parameter	1.58940
Shape Parameter	9.51616
Mean	15.1250
Variance	24.0397
Skewness	.64833
Kurtosis	3.63051

Table 4.4 - Relative Scores and Rankings of Candidate Distributions for Pavement Data Group # 3 (Overlay)

Models	Score (0-100)	Ranking
1-Weibull	100.0	1
2-Gamma	86.4	2
3-Log-logistic	79.5	3
4-Lognormal	65.9	4.5
5-Log-Laplace	65.9	4.5
6-Random Walk	56.8	6
7-Inverse Gaussian	45.5	7
8-Pearson Type 6	40.9	8
9-Pearson Type 5	29.5	9
A-Inverted Weibull	20.5	10
B-Exponential	9.1	11
C-Pareto (E)	0	12

Table 4.5 - Sample Summary for Pavement Data Group # 3 (Overlay)

Sample Characteristic	Value
Number of Observations	619
Minimum Observation	2.00000
Maximum Observation	15.0000
Mean	8.49758
Median	9.00000
Variance	10.0336
Coefficient of Variation	.37276
Skewness	-.27115
Kurtosis	2.46224

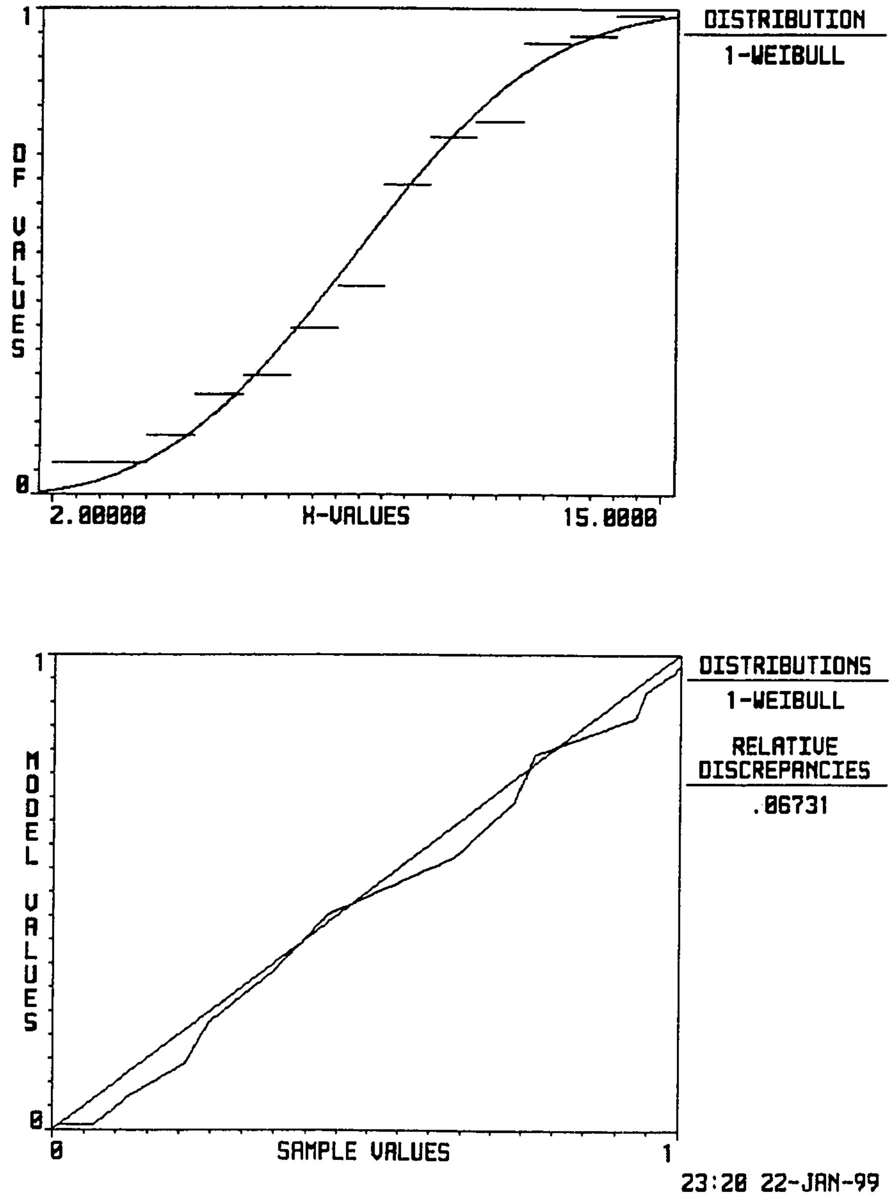


Figure 4.5 – Distribution Function and Probability Plot Comparisons between Pavement Data Group # 3 and a Fitted Weibul Distribution (Overlay)

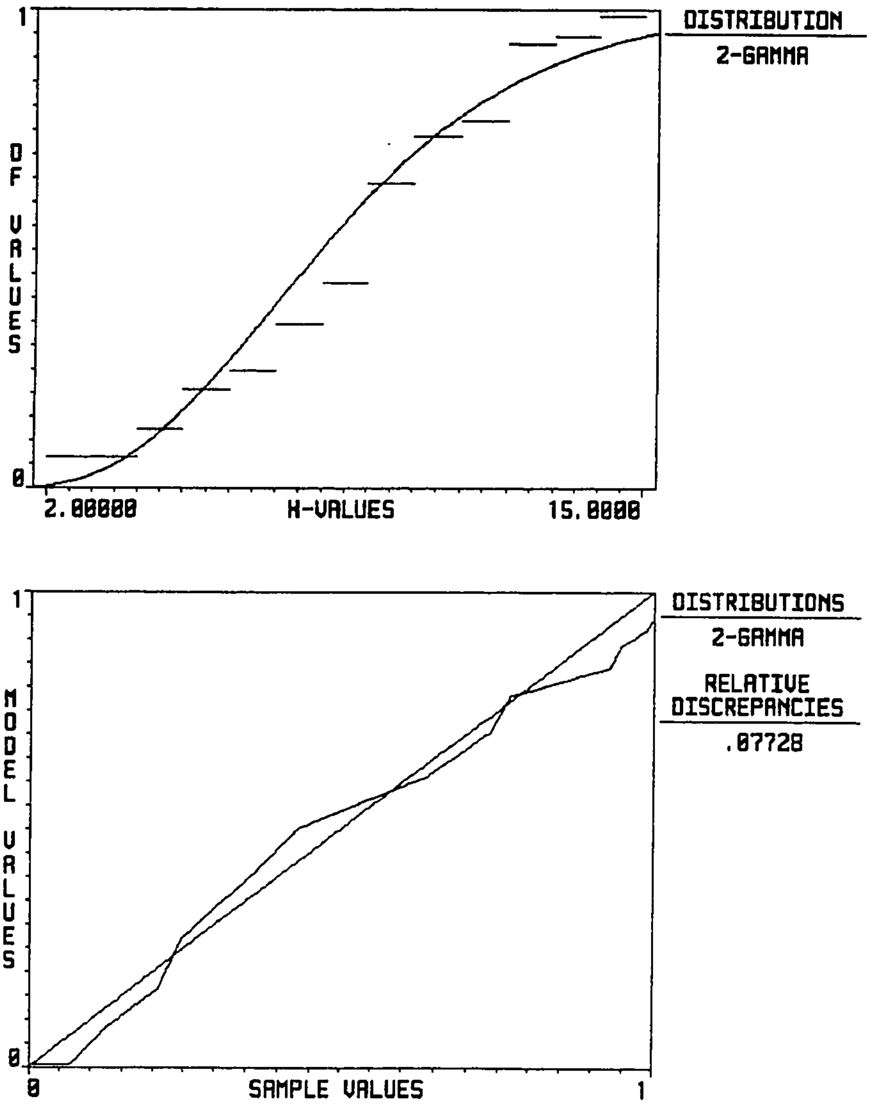


Figure 4.6 – Distribution Function and Probability Plot Comparisons between Pavement Data Group # 3 and a Fitted Gamma Distribution (Overlay)

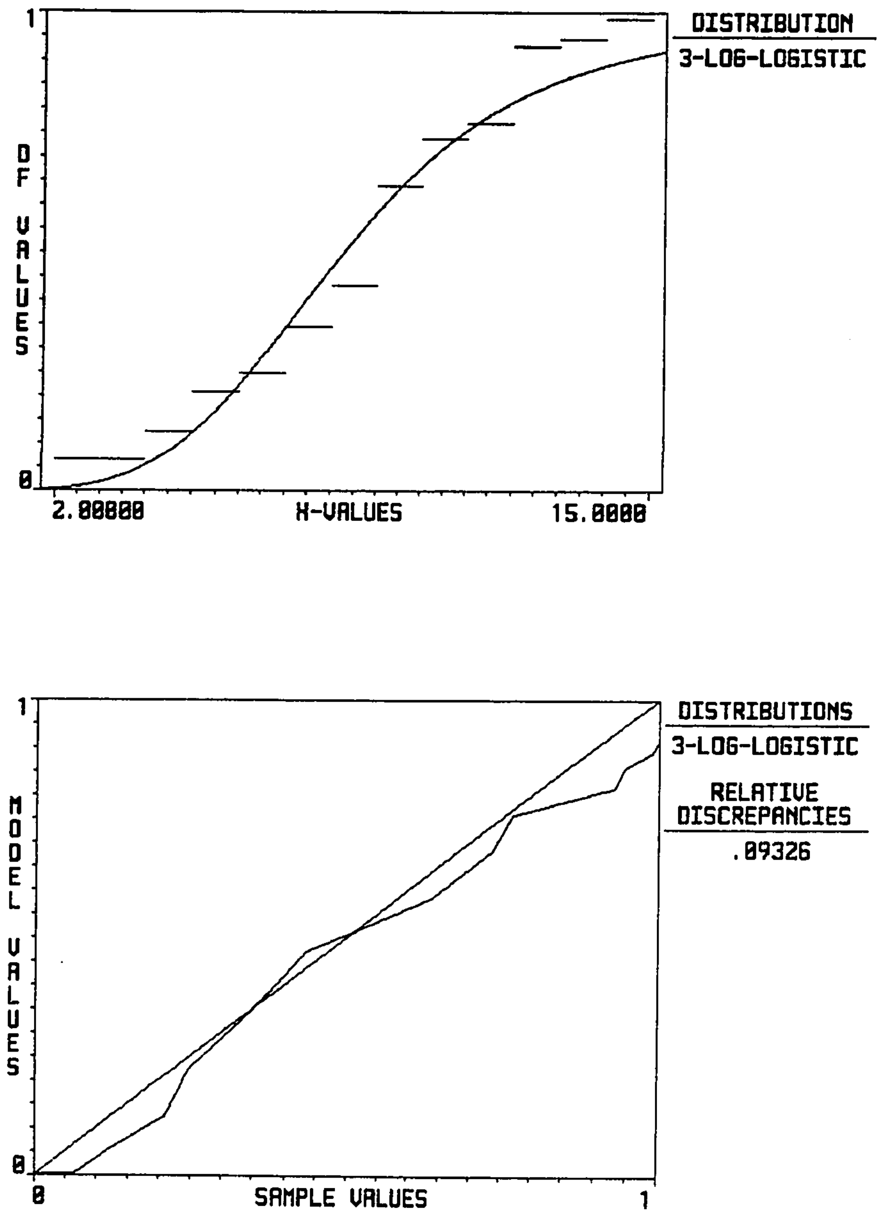


Figure 4.7 – Distribution Function and Probability Plot Comparisons between Pavement Data Group # 3 and a Fitted Log-logistic Distribution (Overlay)

Table 4.6 – Candidate Distribution Moments and Characteristics For Pavement Group Data # 3 (Overlay)

Model 1: Weibull Distribution	
Scale Parameter	9.50889
Shape Parameter	2.99475
Mean	8.49059
Variance	9.55258
Skewness	.16982
Kurtosis	2.73008
Model 2: Gamma Distribution	
Scale Parameter	1.58314
Shape Parameter	5.36754
Mean	8.49758
Variance	13.4529
Skewness	.86326
Kurtosis	4.11783
Model 3: Log-logistic Distribution	
Scale Parameter	8.26710
Shape Parameter	3.92540
Mean	9.22036
Variance	12.5909
Skewness	4.56220
Kurtosis	Does Not Exist

CHAPTER 5. APPLICATION OF PROBABILISTIC SERVICE LIFE MODELS TO LIFE CYCLE COST ANALYSIS

5.1 INTRODUCTION TO SIMULATION AND RISK ANALYSIS

Infrastructure life cycle performance of similar units is subject to a wide range of fluctuations. This is due to the uncertainty existing in most of the acting variables such as traffic projections, material properties, and climatic conditions. As a result of such uncertainties, service life is subject to random variations and should be predicted using risk analysis techniques. Risk analysis is used to predict the probabilities of occurrence of future events as a result of taking or not taking an action (Ang, 1975). These probabilities provide decision-makers with information regarding the relationship between consequences (i.e., costs, delays, and safety hazardous) they might face and decisions they would make. The first step in risk analysis and modeling is recognizing the presence of a risky situation. The second step is quantifying the risk identified for the uncertain situation. Quantifying risk means determining all possible values a variable could have, and determining the relative likelihood of each value.

There are two basic approaches to risk analysis; both aim to derive a probability distribution that describes the possible outcomes of an uncertain situation. The goal of both approaches is to help the decision-maker in choosing a course of action by giving him/her a better understanding of the possible outcomes that could occur for an uncertain situation. The first approach uses analytical techniques to model the uncertainties. This method requires that the distributions for all uncertain variables in a model be described mathematically. The equations for these distributions are then combined mathematically to derive another equation, which describes the distribution of possible outcomes. It is not a simple task to describe distributions as equations, and it is even more difficult to combine distributions analytically given even moderate complexity in the selected model.

The second approach to risk analysis is simulation, which relies on the ability of computers to use a large number of possible combinations of input variable values repeatedly. Simulation is often defined as "the development of a mathematical-logical model of a system and the experimental manipulation of the model on a computer" (Pritsker, 1985; Biles, 1987). Monte Carlo Simulation utilizes probability distributions in presenting the quantified risk for the input variables as well as the uncertainty that accompanies the model output. Generally, Monte Carlo simulation uses two distinct operations. The first operation is "sampling", which is a process by which values are randomly drawn from input probability distributions. The second operation is "running iterations", which recalculates the output of a given model for each sampled value. For all iterations, one sample is drawn from each input probability distribution. With enough iterations, the sampled values for a probability distribution will become distributed in a manner which approximates the known input probability distribution. By the end of the last iteration, the single-valued output results, calculated using the individual sampled values, are consolidated to produce one output distribution.

This research utilizes a risk-based approach to predict probabilities of occurrence of different life cycle costs of constructing/rehabilitating civil infrastructure units. Uncertainty in the life cycle cost model is introduced through the reliability functions (probabilities of failures) of various construction/rehabilitation alternatives. This results in probability distribution functions (PDF) representing times to failure. As mentioned previously, it is difficult and in many cases impossible, to analytically determine the output distribution function representing the random values of the total life cycle cost of an alternative. As a result, simulation is used to generate the probability distribution of the model outcome (i.e., life cycle costs of construction alternatives). The output probability distribution enables decision-makers to make informed decisions regarding the construction alternative that can be applied and the level of risk they wish to accept. As long as the probability distributions for the input variables used in the model are determined, one can determine the probabilities associated with various levels of total life cycle costs.

Once the life cycle cost model is constructed, values of the input variables are provided, and the output in terms of life cycle costs is derived. Traditionally, life cycle cost models are fixed in nature since one set of variables is allowed as input and the corresponding deterministic output is produced. In the proposed Monte Carlo simulation analysis, the life cycle cost model takes input in the form of random variables sampled from the fitted statistical distributions discussed in Chapter four. A risk analysis computer software called "@ RISK" is then used to perform experiments with many variations of the input and generate sets of life cycle costs in the form of probabilistic distributions. The life cycle cost distribution can then be statistically analyzed to provide a measure of risk. The following steps summarizes this procedure:

1. Defining the life cycle cost model including the input and output variables that need analysis.
2. Identifying uncertainty in variables and specifying their possible values with probability distributions.

3. Analyzing the model with simulation to determine the range and probabilities of all possible outcomes of the model output (i.e., life cycle costs)
4. Making a decision based on the results provided, and on engineering judgement.

5.2 LIFE CYCLE COST MODEL

There are a number of models that can be used to analyze life cycle costs of infrastructure construction and rehabilitation alternatives. These methods can be described as follows (Hudson, 1997):

1) Present Worth Method
2) Equivalent Uniform Annual Cost Method
3) Rate-of-Return Method
4) Cost Effectiveness Method

The literature presents many discussions on each of these economic analysis methods, along with the basic considerations in selecting the most appropriate method (Hudson, 1997; TAC, 1997; Haas, 1994). For this study, the Present Worth method is used because of its wide applicability and usage. Wohl and Martin (1967), after considering the advantages and disadvantages of all the other economic analysis methods, concludes that the Present Worth method gives the most reliable answers. Furthermore, AASHTO Guide (1986), Haas et al. (1994), Hudson et al. (1997), and TAC (1997) recommend the use of the present worth method to evaluate construction and rehabilitation alternatives for infrastructure projects and particularly pavement and highway projects. The advantages of using this method in the civil infrastructure area, include the following (Hudson, 1997):

1) Alternatives with different service lives can be easily compared
2) Future costs are presented in present-day terms
3) The application of this method is straightforward and simple

The Present Worth method involves discounting of all future costs to the present using a specific discount rate. The following is the developed formulation that illustrates the risk-based life cycle cost model using the present worth method, and application of Mote Carlo simulation for N iterations to produce a random variable of life cycle cost:

Eq. 5.1

$$LCC_{a,n} = Ci_a + \sum_{t=0}^{n} pwf_{r,t}(Cf)_{a,t} + \sum_{t=0}^{n} pwf_{r,t}(Cmo)_{a,t} + \sum_{t=0}^{n} pwf_{r,t}(Cu)_{a,t} - pwf_{r,n}(Sv)_{a,n}$$

$$LCC_1 = Ci + Cf_1 + Cmo_1 + Cu_1 - Sv_1$$

$$LCC_2 = Ci + Cf_2 + Cmo_2 + Cu_2 - Sv_2$$

$$. \quad = \quad . \; + \; . \; + \; . \quad + \; . \; - \; .$$

$$. \quad = \quad . \; + \; . \; + \; . \quad + \; . \; - \; .$$

$$. \quad = \quad . \; + \; . \; + \; . \quad + \; . \; - \; .$$

$$LCC_N = Ci + Cf_N + Cmo_N + Cu_N - Sv_N$$

Where

$LCC_{a,n}$ = present worth of life cycle cost for alternative *a,* for analysis period of *n* years

Ci_a = initial capital cost for construction for alternative *a*

$Pwf_{r,t}$ = present worth factor of a future amount at time *t* years at a discount rate = *r*

= $1/(1 + r)^t$

$Cf_{a,t}$ = cost of failure (rehabilitation) for alternative *a* at year *t*

$Cmo_{a,t}$ = cost of maintenance and operation for alternative *a* at year *t*

$Cu_{a,t}$ = user costs due to failure for alternative *a* at year *t*

$Pwf_{r,n}$ = present worth factor of a future amount at the end of the analysis period *n* at a discount rate = *r*

= $1/(1 + r)^n$

$Sv_{a,n}$ = Salvage value for alternative *a* at the end of the analysis period *n*

N = Number of simulation iterations

And,

$$\sum_{t=0}^{n} pwf_{r,t}\,(Cf)_{a,t} = pwf_{r,t_{1}-l}\left(Cf_{t_1} + Cf_{t_2} + Cf_{t_3} + \ldots\ldots\ldots\ldots Cf_{t_l}\right) \quad \ldots\ldots\ldots(5.2)$$

for

$t_l \leq n < t_{l+1}$

Where,

$Pwf_{r,n}$ = present worth factor of a future amount at the end of the analysis period *n* at a discount rate $r = 1/(1 + r)^n$

$Cf_{a,t}$ = cost of failure (rehabilitation) for alternative *a* at year *t*

t_l = the sum of times-to-failure for "*l*" rehabilitations (last rehabilitation during the analysis period)

t_{l+1} = the sum of times-to-failure for "*l* + *1*" rehabilitations

5.2.1 Components of the Life Cycle Cost Model

The components of the life cycle cost model are composed of the following variables:

Initial Capital Costs

This item constitutes the cost of the investments to design and construct/rehabilitate a highway. Items include surfacing, base course, grading, right-of-way, signing, signals and engineering.

Failure Costs

This includes costs associated with improving or overlaying a pavement when its performance decreases to a minimum level of acceptability. Items include overlays, recycling, seal coats and reconstruction.

Maintenance Costs

These are the costs that are essential to maintain a pavement at a specified condition level or at a specified rate of deterioration. Items include crack filling, crack repair, grinding, and patching.

User Costs

Those costs are generally more difficult to quantify compared to the other input costs.

Delay times due to repairs and rehabs can be used as an indicator for user costs.

Salvage Value

Salvage value of a construction/rehabilitation alternative is the value of an infrastructure at the end of its analysis period. Consideration of this negative cost allows for a more realistic evaluation of alternatives that have different costs and different remaining lives at the end of its analysis period. Although the life cycle cost analysis of alternatives is performed over a specific analysis period, the service life of the last treatment (i.e., rehabilitation) can extend beyond the analysis period. This extension can be of a different length for each alternative, and should be considered in the analysis. Determination of the salvage value of the number of years that an alternative lasts beyond the specified analysis period is calculated by multiplying the cost of the last rehabilitation by the ratio between the remaining life beyond the analysis period and the service life of the last rehabilitation. This can be illustrated by the following formula:

$$pwf_{i,n}(Sv)_{a,n} = pwf_{i,n}\left(Cf_l \times \frac{t_{l+1} - n}{t_{l+1} - t_l}\right) \quad \text{.........(5.3)}$$

Where,

$Pwf_{i,n}(Sv)_{a,n}$ = present worth of the salvage value for alternative "*a*" that occurs at the end of the analysis period n at a discount rate i, where $i = 1/(1 + i)^n$

$Pwf_{i,n}$ = present worth factor of a future amount at the end of the analysis period n at a discount rate = I

Cf_l = cost of failure (rehabilitation) for the last rehabilitation during the analysis period

For example, if a rehabilitation (i.e., an overlay) is made at year 20 of the analysis, the salvage value at the end of a 30 year analysis period (assuming a service life of 15 years for the overlay) will be equal to the ratio between the remaining life, five years (15 – 10) and the service life, multiplied by the original cost of the overlay (i.e., (5/15) * (Overlay cost)).

Service Life

The service life is the estimate of the time period for which the pavement will provide adequate structural and/or ride quality performance before rehabilitation is necessary.

Service lives are subject to a wide level of variability and consequently should be modeled using probabilistic phenomena. Reliability analysis of infrastructure performance data results in statistical models for each infrastructure group that represent failure times (service lives) and are used for modeling input data for simulation of life cycle costs.

Analysis Period

The analysis period is the time period over which the economic analysis is conducted. Generally, the analysis period should be within the range of reliable forecasts (Hudson 1997). Most pavement-related life cycle cost analysis use a range of 20 to 30 years for the analysis period (TAC 1997). An alternative approach is to use an analysis period depending on the discount factor, and is determined as that time in the future where the future costs become negligible when discounted to the present worth (Haas 1994). Additionally, Service life estimates can be used as a guideline for selecting the analysis period (Hudson 1997). Generally, the analysis period chosen is a policy decision set by the agency concerned.

Discount Rate

It is the rate of interest used to adjust future values to present values. It is different from the nominal interest rate which is associated with the costs of borrowing money, and accounts for inflation. In analyzing life cycle costs, inflation can be neutralized by either;

1) using the nominal rate of interest (including its inflation rate) for discounting, while all costs are determined using its inflated values, or
2) using a discount rate equal to the difference between the interest rate and inflation, while using current values for future costs (AASHTO 1986).

For the purpose of evaluating different construction/rehabilitation alternatives, inflation should only be accounted for in setting the discount rate, and not in determining future costs associated with maintenance, operation and rehabilitation items (Hudson, 1997). The rational behind this practice is the fact that accounting for inflation adds to the uncertainty involved in the evaluation, benefits as well as costs would likely increase at the same relative rate, and the uninflated cost of alternatives is more meaningful to decision makers than the inflated costs (Hudson, 1997).

The discount rate used by decision-makers is usually a policy decision, and it depends on the factors being analyzed, level of accepted risks, and anticipated inflation rates. However, most infrastructure public agencies use a single rate that is equal to the difference between interest rate and inflation (Haas, 1994). For the pavement infrastructure, discount rates between 4 and 8 percent are currently common in Canada (TAC, 1997). Since future inflation and interest rates are not easy to predict, it is therefore important to evaluate life cycle costs using a range of discount rates (i.e. 4 to 8 percent) (Flanagan, 1984). This is because the fact that as discount rate increases, life cycle cost model becomes less sensitive to future maintenance and rehabilitation costs.

5.3 ANALYSIS OF CONSTRUCTION AND REHABILITATION ALTERNATIVES

The life cycle cost analysis of construction/rehabilitation alternatives is usually preceded by a technical evaluation of all feasible alternatives. This technical evaluation can be based on (TAC, 1997): 1) Engineering judgement and experience; 2) A decision tree which formally models the engineering judgement and practices; and 3) A computerized decision support system that utilizes artificial intelligence techniques such as "Expert Systems" and "Artificial Neural Networks". The selection of a feasible construction/rehabilitation alternative is dependent on many factors such as material availability and previous experiences. For example, the selection of a construction alternative for flexible pavements involves a study of subgrade soil and paving materials, their behavior under load and the selection of the pavement structure to carry that load under all climatic conditions (Yoder, 1975). In Alberta, granular base pavements are used as the standard pavement type based on long experience (AT&U, 1997). However, this use is dependent on the availability of good quality gravel and whether it is economical to haul it to the construction site. On the other side, cement stabilized base pavements (i.e., soil cement) usually costs more, but they can be an economical alternative if there is a lack of gravel supply or the costs associated with hauling it is too high. The following example explains with numbers the application of the risk-based life cycle model to evaluate pavement construction alternatives.

5.4 ECONOMIC EVALUATION EXAMPLE USING THE RISK-BASED LIFE CYCLE COST ANALYSIS

Highway 16:20, from km 0.8 to km 22.33, is located in central Alberta east of Edmonton in the direction of Elk Island National Park. Highway 16:20 is a two-lane roadway with 3.75-m wide lanes and 2.0 m wide paved shoulders. The traffic volume report indicates that the traffic volume in terms of ESALs/day/direction is equal to 872, which is considered to be high level traffic according to the design practices in Alberta. The subgrade soil at this location is known to be inorganic clays of low plasticity (CL). Based upon review of all available information and field observations, reconstruction of this section was required to address pavement roughness as well as structural needs. Three construction alternatives were identified as:

1. Soil cement pavement which costs initially $238,000/km for construction

2. Full depth pavement which costs initially $250,000/km for construction
3. Granular Base Pavement which costs initially $260,000/km for construction.

Each of these alternatives will require a non-structural overlay for their first rehabilitation need, and it will cost $57,000/km. Maintenance costs and user costs are not included because they are assumed to be relatively equal for all alternatives. The current practices at AT&U uses 4% for discount rate over a 30 year analysis period.

Utilizing the stratification and input data modeling techniques described in the previous two chapters, the service life of each alternative (reconstruction and overlay) is found to follow the following groups and distributions:

1. Alternative "A" - SC

• Pavement group:		12
• Service life statistical distribution (reconstruction):		Weibull
• Distribution Parameters:	Shape parameter:	3.6277
	Scale parameter:	14.6604
• Service life statistical distribution (overlay):		Weibull

- Distribution Parameters: Shape parameter: 2.6347
  Scale parameter: 10.2350

2. Alternative "B" – FD

- Pavement group: 03
- Service life statistical distribution (reconstruction): Weibull
- Distribution Parameters: Shape parameter: 4.3306
  Scale parameter: 16.5809
- Service life statistical distribution (overlay): Weibull
- Distribution Parameters: Shape parameter: 2.9948
  Scale parameter: 9.5089

3. Alternative "C" – GB

- Pavement group: 10
- Service life statistical distribution (reconstruction):
  Lognormal
- Distribution Parameters: Mean: 16.0407
  Standard Deviation: 5.9396
- Service life statistical distribution (overlay): Weibull
- Distribution Parameters: Shape parameter: 3.3149
  Scale parameter: 15.2214

The summery of the input information to the risk-based life cycle model is shown in Table 5.1.

Table 5.1 - Summary of Simulation input Data

Alternatives	A (SC)	B (FD)	C (GB)
Initial Cost $ / km	238,000	250,000	260,000
Rehab Cost $ / km	57,000	57,000	57,000
Group	12	03	10
Distribution (Constrct'n)	Weibull	Weibull	Lognormal
Distribution Parameters	Shape: 3.628 Scale: 14.66	Shape: 4.331 Scale: 16.58	Mean: 16.04 Std: 5.94
Distribution (Rehab)	Weibull	Weibull	Weibull
Distribution Parameters	Shape: 2.635 Scale: 10.24	Shape: 2.995 Scale: 9.509	Shape: 3.315 Scale: 12.22

The risk-based life cycle cost model presented earlier, can be rewritten as:

$$LCC_{a,n} = Ci_a + \sum_{t=0}^{n} pwf_{r,t}(Cf)_{a,t} - pwf_{r,n}(Sv)_{a,n} \quad ......(5.4)$$

The input data are then fed to the risk-based life cycle cost model which is developed in a spreadsheet format. The total life cycle cost is modeled as a random variable that is the sum of several cost items that are random variables themselves. The resulting CDF can be used to predict the probability of executing a construction/rehabilitation alternative, over a specified analysis period, at or below a certain life cycle cost. In addition, the computation of the CDF of the total life cycle cost of an alternative can help decision-makers specify margins of contingency for the levels of budget required. The Monte Carlo simulation is then conducted on a spreadsheet using the risk analysis computer package "@Risk". The number of iterations chosen was 2,000 so that the simulation results can converge to their analytical values. To test the sensitivity of the model to the discount rate "r" input, several values were used to run the simulation at, (i.e., r = 4%, 5%, 6%, 7% & 8%) according to the recommendation by Hass et al (1994) for this type of infrastructure. Figure 5.1 shows a comparison among the various discount rates (i.e., r = 4%, 5%, 6%, 7% & 8%) for alternative "A".

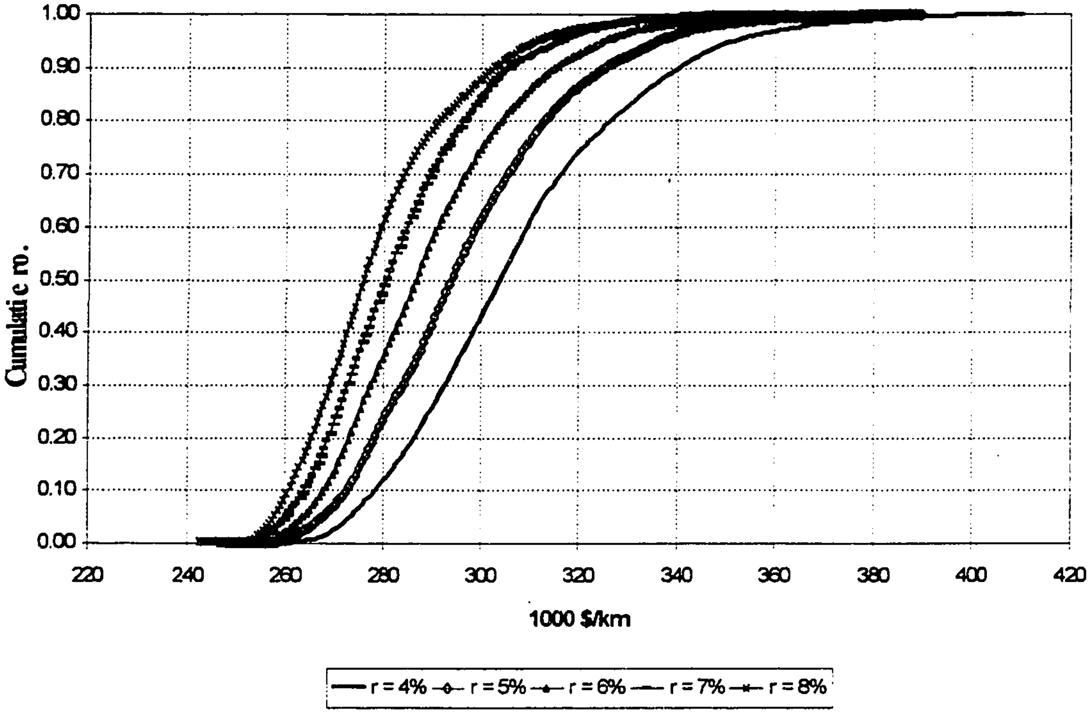


Figure 5. 1 – Simulation Output - Comparisons of CDF Distributions of Life Cycle Costs for Alternative "A" at r = 4, 5, 6, 7, & 8 %

Figures 5.2 to 5.4 and Figures 5.6 to 5.8 depict the output of the simulation in the form of the CDFs for alternative "A", "B" and "C" for a discount rate of 4% and 8% respectively. Figures 5.5 and 5.9 illustrate the three alternatives over imposed in one graph for discount rate values of 4% and 8% respectively. According to the level of risk the decision-maker is willing to take, one can select the appropriate alternative. Using 4% as the discount rate, if the budget available to carry on the work on highway 16 (for the 21.53-km section) is $6,243,700 or $290,000 per km, then:

- For alternative "A", there is a 77.5% chance that the total life cycle cost will be within budget.
- For alternative "B", there is an 82.5% chance that the total life cycle cost will be within budget.
- For alternative "C", there is a 70.0% chance that the total life cycle cost will be within budget.

According to the previous probabilities, alternative "B" is the one that the decision-maker should select since it provides the best chance of meeting the budget. In case of the decision-maker is not comfortable with this confidence level (82.5%), and prefers a 90% confidence level, then the budget required will be $6,394,410.

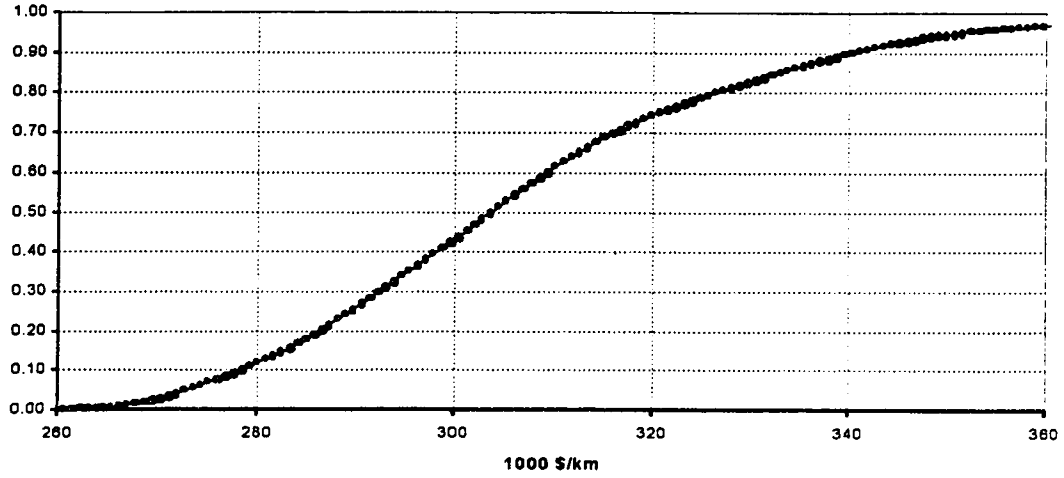


Figure 5.2 – Simulation Output - CDF Distribution of Life Cycle Costs for Alternative "A" at r = 4%

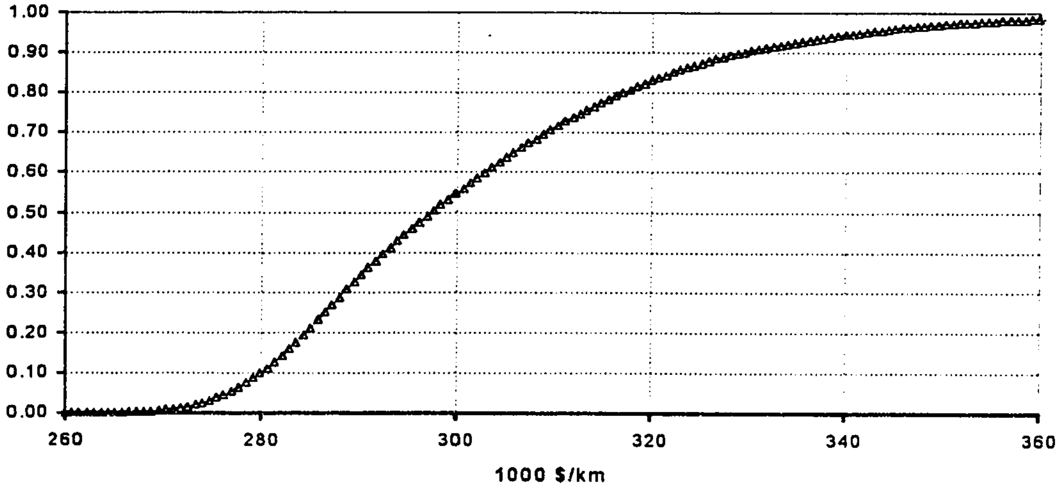


Figure 5.3 – Simulation Output - CDF Distribution of Life Cycle Costs for Alternative "B" at r = 4%

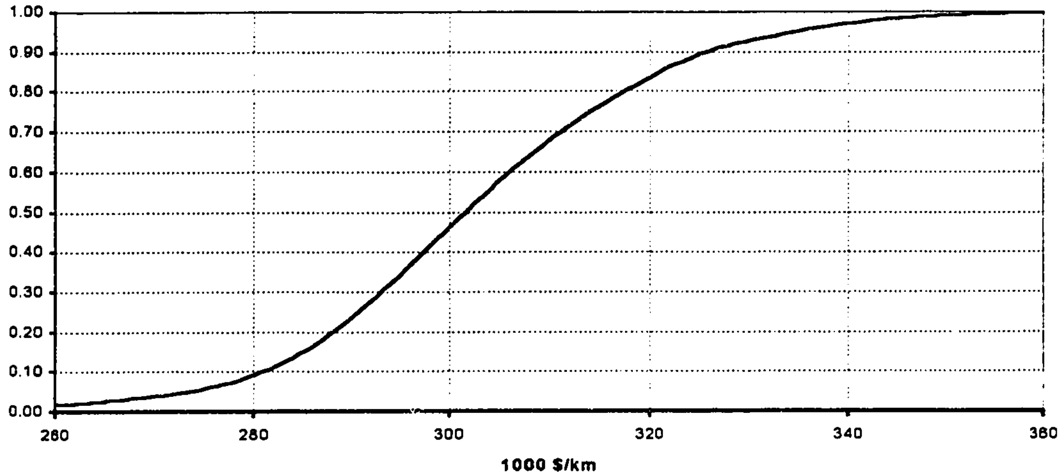


Figure 5.4 – Simulation Output - CDF Distribution of Life Cycle Costs for Alternative "C" at r = 4%

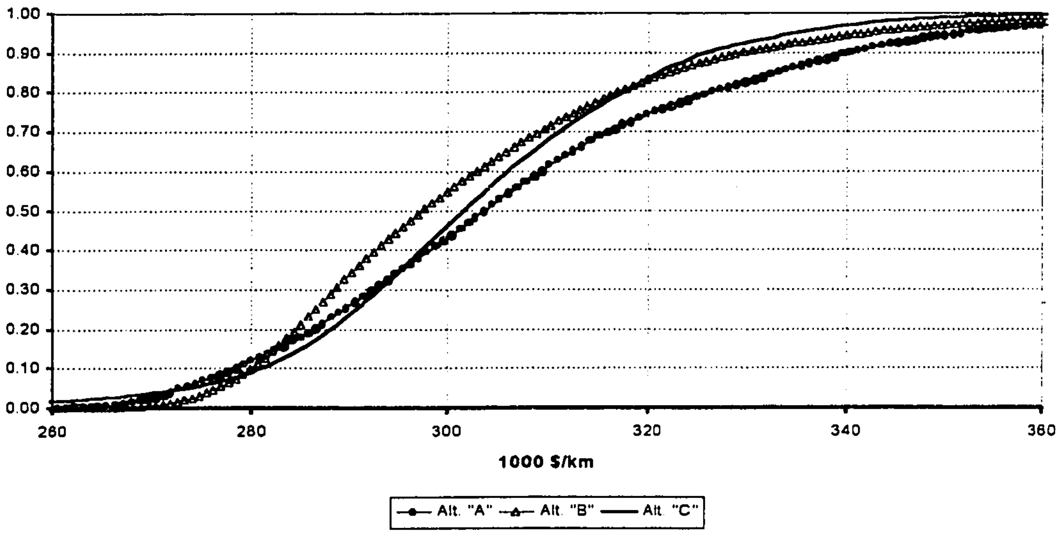


Figure 5.5 – Simulation Output - Comparisons of CDF Distributions of Life Cycle Costs for Alternative "A, B, & C" at r = 4%

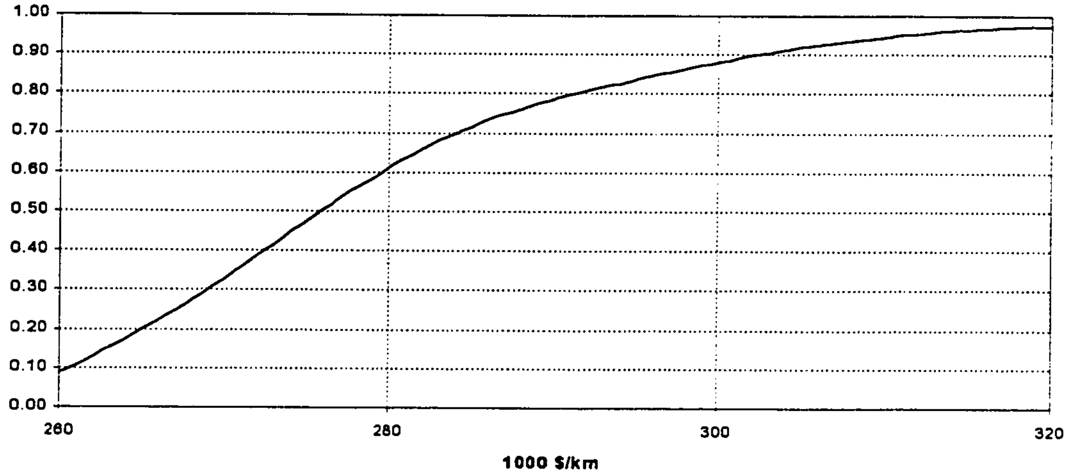


Figure 5.6 – Simulation Output - CDF Distribution of Life Cycle Costs for Alternative "A" at r = 8%

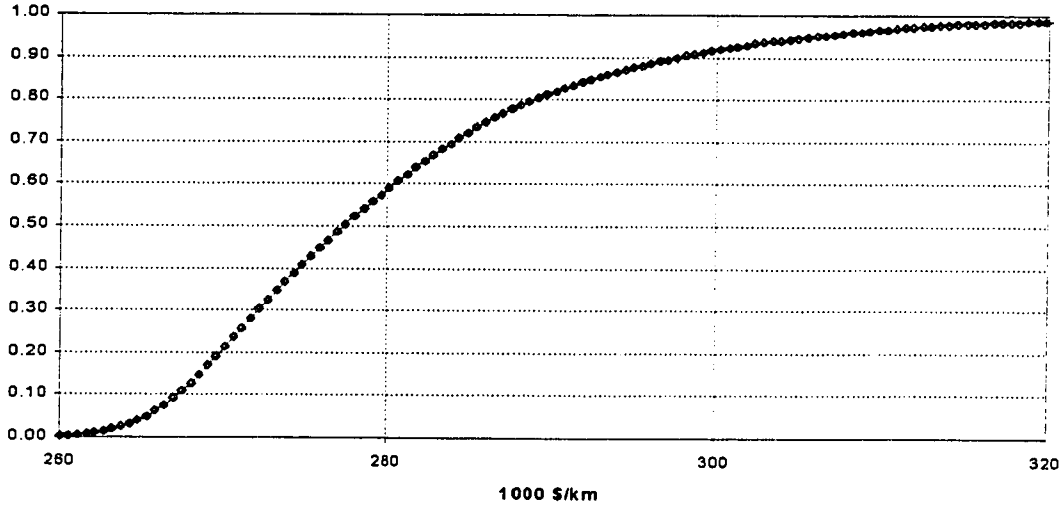


Figure 5.7 – Simulation Output - CDF Distribution of Life Cycle Costs for Alternative "B" at r = 8%

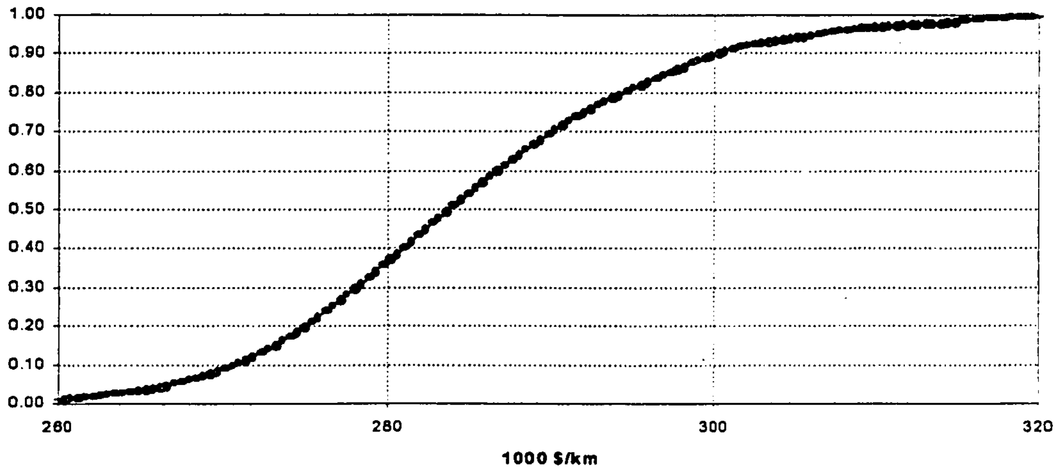


Figure 5.8 – Simulation Output - CDF Distribution of Life Cycle Costs for Alternative "C" at r = 8%

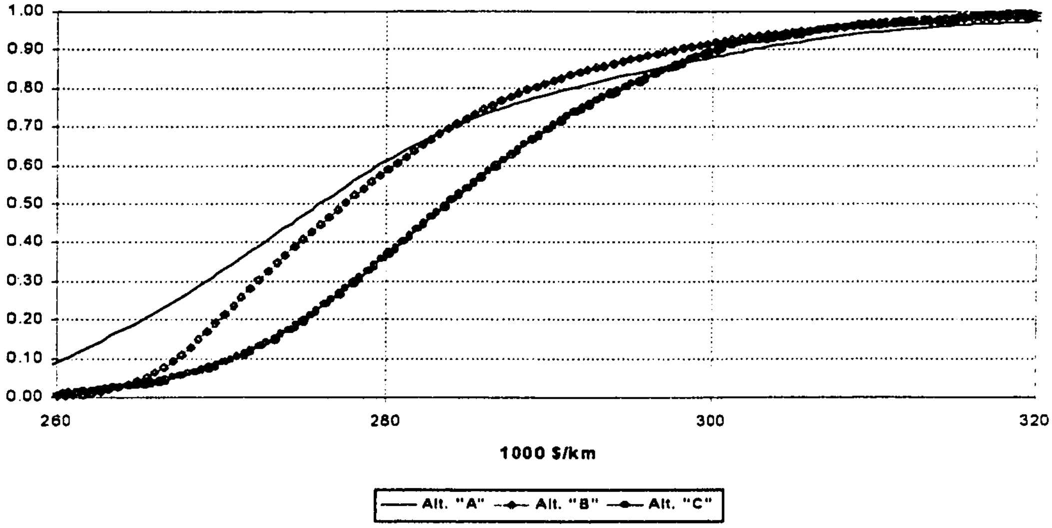


Figure 5.9 – Simulation Output - Comparisons of CDF Distributions of Life Cycle Costs for Alternative "A, B, & C" at r = 8%

CHAPTER 6. CONCLUSIONS

6.1 SUMMARY OF RESEARCH

This thesis provides a new technique for estimating life cycle costs of civil infrastructure construction and rehabilitation alternatives derived from reliability and simulation application. This technique allows decision-makers to fully utilize historical performance data for the concerned infrastructure, and provides them with an extra dimension of knowledge to evaluate infrastructure alternatives. This extra dimension of knowledge is in the form of certainty levels that accompany the estimated total life cycle costs.

Identifying the factors that affect the life cycle performance of an infrastructure is essential for predicting the service life and consequently, life cycle costs. The analysis of the historical data concludes that several factors are contributing to the deterioration of pavements, leading to their potential failure. These factors include; pavement type, pavement thickness, soil type, traffic mix, and climatic region assuming that the quality of design and construction, as well as the maintenance level factors are acceptable and performed according to well established standards. The index selected to measure performance is the RCI and the trigger value for rehabilitation need is set at RCI of 5.5 on scale of 0 to 10.

Service lives are subject to a wide level of variability and consequently should be modeled using a probabilistic approach. In order to consider this stochastic nature of infrastructure failure times, *infrastructure data is stratified according to the identified significant* factors. The stratification of the pavement historical data (more than 34,000 pavement records) is performed in a way that each pavement group should represent pavement classes that have no significance difference among their service life means. A Multiple Comparison analysis test of mean differences is performed on the pavement classes resulted from all possible combinations of different levels of the considered factors. This step resulted in reducing the number of pavement classes (combinations) from 162 to 15 groups.

Infrastructure failures and rehabilitation needs are modeled by following a formal input data modeling procedure. This procedure includes fitting statistical distributions to pavement failure data within each pavement group, testing the goodness of fit, and determining the distribution parameters. Weibull distribution is found to be successful in representing failure times of most of pavement construction and rehabilitation alternatives.

Infrastructure life-cycle costs are dependent on probabilities of when failures occur. This research utilizes a risk analysis-based approach to predict probabilities of occurrence of different life cycle costs of constructing/rehabilitating an infrastructure unit. Uncertainty in the life cycle model is introduced through the probabilities of failures of construction/rehabilitation alternatives. This results in probability distribution functions (PDF) representing times to failure for each group of infrastructure units.

It is not an easy task to analytically determine the output distribution function representing the random values of the total life cycle cost of an alternative. On the other hand, simulation allows flexibility in testing different scenarios and ease in implementing models with complex mathematical functions. In this thesis, simulation is used to generate the probability distribution of the model outcome (i.e., life cycle costs of infrastructure alternatives).

Once the life cycle cost model is constructed, values of the input variables are provided, and the output in terms of life cycle costs is derived. Traditionally, life cycle costs have been modeled as a deterministic function since one set of variables is allowed as input and the corresponding output is produced. In the Monte Carlo simulation analysis presented, the life cycle cost model takes input in the form of random variables sampled from fitted statistical distributions. A risk analysis computer software called "@ RISK" then used to perform experiments with many variations of the input and generate sets of life cycle costs in the form of probabilistic distributions. The life cycle cost distribution is then statistically analyzed to provide a measure of risk.

The resulted probability distributions enable decision-makers to make informed decisions regarding the construction alternative that can be applied, and the level of risk they may accept. The resulting CDF of total life cycle costs can provide valuable information regarding the probability of executing a construction/rehabilitation alternative at or below a certain life cycle cost (i.e., budget). In addition, the analysis of the generated CDF can help decision-makers specify margins of contingency for the levels of budget required.

6.2 CONCLUSIONS AND CONTRIBUTIONS

The following bullets provide a summery of the thesis conclusions and a highlight of the research contributions:

- Life-cycle costs are dependent on probabilities of when failures occur.
- Civil infrastructure service lives (times to failure) are subject to a wide level of variability and consequently should be modeled using a probabilistic approach.
- This research investigated the factors that are contributing to the deterioration of pavements in Alberta, leading to their potential failure.
- A Multiple comparison statistical analysis of mean service life differences is performed on the pavement classes resulted from all possible combinations of different levels of the considered factors. This step is resulted in reducing the number of pavement classes (combinations) from 162 to 15 groups.
- Formal input data modeling approach was utilized to fit statistical distributions to time-to-failure data groups.
- Weibull distribution is found to be successfully representing time-to-failure data of most of pavement construction and rehabilitation alternatives in Alberta.
- Simulation allows flexibility in testing different scenarios and ease in implementing models with complex mathematical functions.

- This research provides a new technique for estimating life cycle costs of infrastructure construction and rehabilitation alternatives derived from reliability and simulation application.
- This technique allows decision-makers to fully utilize historical performance data and provides them with an extra dimension of knowledge to evaluate infrastructure construction and rehabilitation alternatives.
- This extra dimension of knowledge is in the form of certainty levels that accompany the estimated CDF of total life cycle costs.
- The resulting CDF of total life cycle costs can provide valuable information regarding the probability of executing a construction/ rehabilitation alternative at or below a certain life cycle cost (i.e., budget). In addition, it can help decision-makers specify margins of contingency for the levels of budget required

6.3 RECOMMENDATIONS

The development of a risk-based life cycle cost model based on the reliability of infrastructure alternatives produces a more realistic determination of costs that are more closely related to the deterioration of various infrastructure units. In this model, the randomness of the process is introduced through probability distributions representing failure times (i.e., service lives) of the infrastructure alternatives. An extension of the work carried out in this research could be modeling the inflation and costs components of the model using historical trends and economic indicators to account for the uncertainty involved in the prediction of these input parameters.

Additionally, the variability inherited from traffic predictions, materials properties, and construction quality could be studied and accounted for. This might improve the prediction accuracy of the risk-based life cycle cost model.

Civil Infrastructure databases should have reliable data regarding delay times due to various maintenance and rehabilitation activities. This can help decision-makers account for user costs when evaluating life cycle costs of different alternatives.

The developed risk-based life cycle cost model should be evaluated and updated on a yearly basis when new data is collected and added to the database.

The developed approach for modeling and predicting total life cycle costs of pavement construction and rehabilitation alternatives could be applied to other civil infrastructure types such as bridges, utility pipes, railway tracks, tunnels, buildings, etc.

Data needs (i.e., collection, frequency, sampling, organization, storage, validation, integrity, security, and accessibility) for life cycle costing should be well studied and defined.

The results of this research could be implemented in an infrastructure management system capable of generating prioritize need lists based on budget availability, life cycle costs, and level of uncertainty involved for each alternative strategy.

This research can be used as a base for public owners to evaluate infrastructure design/built proposals.

BIBLIOGRAPHY

AbouRizk, S., (1989). BetaFit User's Guide. Division of Construction Engineering and Management, Purdue University, West Lafayette, I.N.

AbouRizk, S. and Halpin, D. (1990). Probabilistic Simulation Studies for Repetitive Construction Processes. ASCE Journal of Construction Engineering and Management. Vol. 116, No. 4, Dec. 1990.

AbouRizk, S. and Halpin, D. (1992). Statistical Properties of Construction Duration Data. ASCE Journal of Construction Engineering and Management. Vol. 118, No. 3, Sep. 1992.

AbouRizk, S., Halpin, D. and Wilson, J. (1994). Fitting Beta Distributions Based on Sample Data. ASCE Journal of Construction Engineering and Management. Vol. 120, No. 2, June. 1994.

(AT&U) Alberta Transportation and Utilities, (1997). Pavement Design Manual, First Edition, Alberta Transportation and Utilities Report, Edmonton, Alberta.

(AASHTO) American Association of State Highway and Transportation Officials, (1986). AASHTO Guide For Design Of Pavement Structures. Washington, D.C.

Andrews, J. D. and Moss, T. R., (1993). Reliability and Risk Assessment, First Edition. Longman Scientific & Technical, England.

Ang, A., and Tang, W., (1975). Probability Concepts in Engineering Planning and Design. John Wiley & Sons, Inc., New York, N.Y.

Arditi, A. D. and Messiha, H. M., (1996). Life-Cycle Costing In Municipal Construction Projects. Journal of Infrastructure Systems, Vol. 2, No. 1, March, 1996.

Ariaratnam, S. T., (1994). The Investigation of Methods to Assist Decision Makers Regarding Bridge Maintenance, Rehabilitation, and Restoration Activities. Ph.D. Thesis, Department of Civil Engineering, University of Illinois at Urbana-Champaign, Illinois

Banks, J., and Carson, J. S., (1984). Discrete-event System Simulation. Prentice-Hall Inc., Englewood Cliffs, N.J.

Biles, W. E., (1987). Introduction to Simulation. Proceeding of the 1987 Winter Simulation Conference, American Statistical Association.

Brealey, R. A. and Myers, S. C., (1998). Principles of Corporate Finance, Third Edition, McGraw-Hill, New York, N.Y.

Bhuyan, S.K., (1982). Cost of Quality as a Customer Perception, Proceedings of the American Society for Quality Control Annual Congress, 1982, pp. 459-464

(BRB) Building Research Board, (1991). Pay Now or Pay Latter. National Research Council, Washington, D.C.

Carmer, C., and Swanson, M., (1973), "Evaluation of Ten Pairwise Multiple Comparison Procedures by Monte Carlo Methods", Journal of the American Statistical Association, Vol. 68, No. 314, 1973.

City of Edmonton, "Standard Sewer Condition Rating System Report," Internal Report, Edmonton, AB, 1996.

Dell'Isola, A., and Kirk, S., (1983). Life Cycle Cost Data. McGraw-Hill Co. Inc., New York, N.Y.

Dhillon, B. S., (1989). Life Cycle Costing. Gordon and Breach Science Publishers S.A., New York, NY.

Duncan, D., (1955), "Multiple Range and Multiple F tests", Biometrics, Vol. 11, 1955.

Ebeling, C. E., (1997). An Introduction to Reliability and Maintainability Engineering. McGraw-Hill, New York, N.Y.

Turiel, I., Estrada, H., and Levine, M. (1981), Life Cycle Cost Analysis of Major Appliances, Energy, Vol. 6, 1981, pp. 945-970

Eddins-Earls, M. (1981). Factors, Formulas, and Structures for Life Cycle Costing. Eddins-Earls, 89 Lee Drive, Concord, Mass.01742, 1981

El-Assaly, A., Salem, O. and Hammad, A. (1998). Analysis and Stratification of Pavement Data for the Primary Highway Network in Alberta. University of Alberta.

Fazio, A. E., and Prybella, (1980). Development of an Analytical Approach to Track Maintenance Planning. TRR 744, Transportation Research Board, National Research Council, Washington, D.C.

FHWA (1994), *Searching for Solutions - Life Cycle Cost Analysis*, U.S. Department of Transportation – Federal Highway Administration, Washington, D.C.

Fishman, G. S., (1973). Concepts and Methods in Discrete-Event Digital Simulation. John Wiley & Sons, New York, NY.

Flanagan, R., (1984). Life Cycle Costing - the Issues Involved. Third International Symposium On Building Economics. England

Ganapathy, V., (1983). Life Cycle Costing Applied to Motor Selection, Process Engineering, pp. 51-52

Haas, R., Hudson, W. R. and Zaniewski, A., (1994). Modern Pavement Management. Krieger Publishing Company, Malabar, Florida.

Haas, R., Cockfield, R. W. and Kuzyk, P., (1990). Performance-Based Specifications for Pavements. Canadian Journal of Civil Engineering, Vol. 18 , No 6, Dec1991.

Hudson, S., Carmichael III, R., Moser, L., Hudson, W., and Wilkes, W., (1987), "Bridge Management Systems", NCHRP Report 300, TRB, Washington, D.C., 1987.

Hudson, W. R., Haas, R. and Uddin, W., (1997). Infrastructure Management. McGraw-Hill, New York, N.Y.

(ITE) Institute of Transportation Engineers, (1992), "Traffic Engineering Handbook" Prentice Hall Inc., Englewood Cliffs, New Jersey, 1992.

Kapur, K. C., and Lamberson, L. R., (1977). Reliability in Engineering Design. John Wiley & Sons, New York, NY.

Kirk, S. and Dell'Isola, A., (1995). Life Cycle Costing for design professionals. McGraw-Hill Co. Inc., New York, N.Y.

Law, A. M., and Vincent, S. G., (1985). Unifit User's Guide. Simulation Modeling and Analysis Co., Tucson, Arizona.

Law, A. M., and Vincent, S. G., (1994). ExpertFit User's Guide. Simulation Modeling and Analysis Co., Tucson, Ariz.

Law, A. M., and Kelton, W. D., (1991). Simulation Modeling and Analysis. McGraw-Hill, New York, NY.

Lifson, M. W. and Shaifer, E. F.,(1982). Decision and Risk Analysis for Construction Management. John Wiley & Sons, New York, NY.

Miller, I., Freund, J. E. and Johnson, R. A., (1990). Probability and Statistics for Engineers, Fourth Edition. Prentice Hall / Englewood Cliffs, New Jersy.

Modarres, M., (1993). What Every Engineer Should Know About Reliability and Risk Analysis. Marcel Dekker, New York, NY.

Mohseni, A., Darter, M. I. and Hall, J. P., (1992). Alternative Methods for Pavement Network Rehabilitation Management. Research Report, University of Illinois at Urbana-Champaign, Illinois.

Montgomery, D., "Design and Analysis of Experiments" (1991), John Wiley & Sons Inc., New York, N.Y., 1991

Novick, D., (1990). Life Cycle Considerations in Urban Infrastructure Engineering. ASCE Journal of Management in Engineering, Vol. 6, No 2, April 1990.

Nicherson , R.L., Veshosky, D., (1992). Highway Bridges- Life Cycle Cost vs. Life Cycle Performance, A Decision Criteria For Bridge Selection.

(the Annual International Bridge Conference , Pittsburgh, Pennsylvania, June 1992

Project Management Institute, (1996). A Guide to the Project Management Body of Knowledge. Upper Darby, PA.

Pritsker, A. B., (1995). Introduction to Simulation and SLAM II, Fourth Edition. Systems Publishing Corporation, West Lafayette, Indiana.

SPSS Base 8.0, (1998), "Applications Guide", SPSS Inc. Chicago, IL, 1998

(TAC) Transportation Association of Canada, (1997), Pavement Design and Management Guide, Ottawa, Ontario.

Turay, S., and Haas, R., (1991), "A Road Network Investment System (RONIS) for Developing Countries", TRB, Research Record 1291, Vol 1

Venkatraman, S., and Wilson, J. R., (1988). Modeling Univariate Populations with Johnson's Translation Systems – Description of the FITTRI software. Purdue University, West Lafayette, I.N.

Wohl, M., and Martin, B., (1967), "Evaluation of Mutually Exclusive Design Projects", Special Report No. 92, Highway Research Board, Washington, D. C.

Yoder, E., and Witczak, W., (1975), "Principles of Pavement Design", John Wiley & Sons, New York, N.Y.

Zar, J. H.,(1984). Biostatistical Analysis, Second Edition. Prentice Hall, Englewood Cliffs, New Jersey.

Appendix A:

Multiple Comparison Test Results Using Duncan's and Tukey's Procedures

Multiple Comparison test for the GB Pavement Type and the BO Soil Type at 95% Confidence Level

Service Life

			Subset for alpha = .05		
	GROUP	N	1	2	3
Tukey HSD[a]	8	53	12.7255		
	1	299		23.0253	
	15	137		23.8807	23.8807
	16	138			25.1366
	Sig.		1.000	.652	.322
Duncan[a,b]	8	53	12.7255		
	1	299		23.0253	
	15	137		23.8807	23.8807
	16	138			25.1366
	Sig.		1.000	.246	.089

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 109.292

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	1	8	10.2997*	.810	.000	8.2186	12.3809
		15	-.8554	.562	.425	-2.3000	.5892
		16	-2.1114*	.560	.001	-3.5513	-.6714
	8	1	-10.2997*	.810	.000	-12.3809	-8.2186
		15	-11.1552*	.880	.000	-13.4154	-8.8949
		16	-12.4111*	.879	.000	-14.6684	-10.1538
	15	1	.8554	.562	.425	-.5892	2.3000
		8	11.1552*	.880	.000	8.8949	13.4154
		16	-1.2560	.657	.223	-2.9444	.4325
	16	1	2.1114*	.560	.001	.6714	3.5513
		8	12.4111*	.879	.000	10.1538	14.6684
		15	1.2560	.657	.223	-.4325	2.9444

Multiple Comparison test for the GB Pavement Type and the CH Soil Type at 95% Confidence Level

Service Life

	GROUP	N	Subset for alpha = .05			
			1	2	3	4
Tukey HSD[a]	3	150	11.5301			
	17	235		14.5959		
	10	694			17.8888	
	2	50			18.0327	
	11	206			18.3278	
	18	42			20.2129	
	Sig.		1.000	1.000	.083	
Duncan[a,b]	3	150	11.5301			
	17	235		14.5959		
	10	694			17.8888	
	2	50			18.0327	
	11	206			18.3278	
	18	42				20.2129
	Sig.		1.000	1.000	.639	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 99.042

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	2	3	6.5026*	.999	.000	3.6552	9.3499
		10	.1439	.896	1.000	-2.4083	2.6962
		11	-.2951	.965	1.000	-3.0441	2.4540
		17	3.4368*	.953	.004	.7217	6.1520
		18	-2.1801	1.280	.529	-5.8267	1.4665
	3	2	-6.5026*	.999	.000	-9.3499	-3.6552
		10	-6.3586*	.552	.000	-7.9324	-4.7849
		11	-6.7976*	.658	.000	-8.6738	-4.9214
		17	-3.0657*	.641	.000	-4.8919	-1.2395
		18	-8.6827*	1.068	.000	-11.7258	-5.6396
	10	2	-.1439	.896	1.000	-2.6962	2.4083
		3	6.3586*	.552	.000	4.7849	7.9324
		11	-.4390	.487	.946	-1.8269	.9489
		17	3.2929*	.463	.000	1.9734	4.6124
		18	-2.3241	.972	.159	-5.0930	.4448
	11	2	.2951	.965	1.000	-2.4540	3.0441
		3	6.7976*	.658	.000	4.9214	8.6738
		10	.4390	.487	.946	-.9489	1.8269
		17	3.7319*	.586	.000	2.0632	5.4006
		18	-1.8851	1.038	.453	-4.8364	1.0662
	17	2	-3.4368*	.953	.004	-6.1520	-.7217
		3	3.0657*	.641	.000	1.2395	4.8919
		10	-3.2929*	.463	.000	-4.6124	-1.9734
		11	-3.7319*	.586	.000	-5.4006	-2.0632
		18	-5.6170*	1.025	.000	-8.5367	-2.6972
	18	2	2.1801	1.280	.529	-1.4665	5.8267
		3	8.6827*	1.068	.000	5.6396	11.7258
		10	2.3241	.972	.159	-.4448	5.0930
		11	1.8851	1.038	.453	-1.0662	4.8364
		17	5.6170*	1.025	.000	2.6972	8.5367

Multiple Comparison test for the GB Pavement Type and the **CI/CI-CH Soil Type at 95% Confidence Level**

Service Life

	GROUP	N	Subset for alpha = .05				
			1	2	3	4	5
Tukey HSD[a]	20	328	14.1902				
	12	1076		17.1005			
	5	334		17.1914			
	13	245			19.4151		
	19	864				21.6403	
	4	350					24.3969
	Sig.		1.000	1.000	1.000	1.000	1.000
Duncan[a,b]	20	328	14.1902				
	12	1076		17.1005			
	5	334		17.1914			
	13	245			19.4151		
	19	864				21.6403	
	4	350					24.3969
	Sig.		1.000	.850	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 398.935

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	4	5	7.2056*	.518	.000	5.7289	8.6822
		12	7.2964*	.417	.000	6.1089	8.4840
		13	4.9819*	.564	.000	3.3752	6.5885
		19	2.7567*	.429	.000	1.5338	3.9796
		20	10.2067*	.520	.000	8.7243	11.6892
	5	4	-7.2056*	.518	.000	-8.6822	-5.7289
		12	9.088E-02	.424	1.000	-1.1188	1.3006
		13	-2.2237*	.570	.001	-3.8468	-.6006
		19	-4.4489*	.437	.000	-5.6933	-3.2045
		20	3.0012*	.526	.000	1.5009	4.5014
	12	4	-7.2964*	.417	.000	-8.4840	-6.1089
		5	-9.0879E-02	.424	1.000	-1.3006	1.1188
		13	-2.3146*	.479	.000	-3.6799	-.9492
		19	-4.5398*	.310	.000	-5.4219	-3.6576
		20	2.9103*	.427	.000	1.6936	4.1270
	13	4	-4.9819*	.564	.000	-6.5885	-3.3752
		5	2.2237*	.570	.001	.6006	3.8468
		12	2.3146*	.479	.000	.9492	3.6799
		19	-2.2252*	.490	.000	-3.6214	-.8290
		20	5.2249*	.571	.000	3.5965	6.8532
	19	4	-2.7567*	.429	.000	-3.9796	-1.5338
		5	4.4489*	.437	.000	3.2045	5.6933
		12	4.5398*	.310	.000	3.6576	5.4219
		13	2.2252*	.490	.000	.8290	3.6214
		20	7.4501*	.439	.000	6.1988	8.7013
	20	4	-10.2067*	.520	.000	-11.6892	-8.7243
		5	-3.0012*	.526	.000	-4.5014	-1.5009
		12	-2.9103*	.427	.000	-4.1270	-1.6936
		13	-5.2249*	.571	.000	-6.8532	-3.5965
		19	-7.4501*	.439	.000	-8.7013	-6.1988

Multiple Comparison test for the GB Pavement Type and the **CL/CL-CI Soil Type at 95% Confidence Level**

Service Life

	GROUP	N	Subset for alpha = .05				
			1	2	3	4	5
Tukey HSD[a]	7	1518	16.0326				
	22	1113		18.0745			
	14	703			21.7100		
	21	1930				23.0094	
	6	1278					25.5050
	Sig.		1.000	1.000	1.000	1.000	1.000
Duncan[a,b]	7	1518	16.0326				
	22	1113		18.0745			
	14	703			21.7100		
	21	1930				23.0094	
	6	1278					25.5050
	Sig.		1.000	1.000	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 1168.624

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	6	7	9.4725*	.221	.000	8.8689	10.0760
		14	3.7950*	.274	.000	3.0486	4.5415
		21	2.4957*	.210	.000	1.9223	3.0690
		22	7.4305*	.239	.000	6.7787	8.0823
	7	6	-9.4725*	.221	.000	-10.0760	-8.8689
		14	-5.6774*	.266	.000	-6.4027	-4.9522
		21	-6.9768*	.200	.000	-7.5223	-6.4313
		22	-2.0420*	.230	.000	-2.6694	-1.4146
	14	6	-3.7950*	.274	.000	-4.5415	-3.0486
		7	5.6774*	.266	.000	4.9522	6.4027
		21	-1.2993*	.257	.000	-1.9997	-.5990
		22	3.6355*	.281	.000	2.8696	4.4013
	21	6	-2.4957*	.210	.000	-3.0690	-1.9223
		7	6.9768*	.200	.000	6.4313	7.5223
		14	1.2993*	.257	.000	.5990	1.9997
		22	4.9348*	.219	.000	4.3364	5.5332
	22	6	-7.4305*	.239	.000	-8.0823	-6.7787
		7	2.0420*	.230	.000	1.4146	2.6694
		14	-3.6355*	.281	.000	-4.4013	-2.8696
		21	-4.9348*	.219	.000	-5.5332	-4.3364

Multiple Comparison test for the SC Pavement Type and the **CH Soil Type at 95% Confidence Level**

Service Life

	GROUP	N	Subset for alpha = .05	
			1	2
Tukey HSD[a]	3	115	8.6061	
	8	560		13.1442
	2	4		14.0000
	Sig.		1.000	.834
Duncan[a,b]	3	115	8.6061	
	8	560		13.1442
	2	4		14.0000
	Sig.		1.000	.566

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 12.687

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	2	3	5.3939*	1.821	.009	1.1249	9.6629
		8	.8558	1.794	.882	-3.3499	5.0616
	3	2	-5.3939*	1.821	.009	-9.6629	-1.1249
		8	-4.5381*	.385	.000	-5.4398	-3.6364
	8	2	-.8558	1.794	.882	-5.0616	3.3499
		3	4.5381*	.385	.000	3.6364	5.4398

Multiple Comparison test for the SC Pavement Type and the CI/CI-CH Soil Type at 95% Confidence Level

Service Life

	GROUP	N	Subset for alpha = .05 1	 2
Tukey HSD[a]	9	676	12.9934	
	4	156	13.6179	
	5	20	13.6792	
	11	230		20.4803
	Sig.		.842	1.000
Duncan[a,b]	9	676	12.9934	
	4	156	13.6179	
	5	20	13.6792	
	11	230		20.4803
	Sig.		.441	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 65.807

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Tukey HSD	4	5	-6.1290E-02	1.117	1.000	-2.9320	2.8095
		9	.6246	.422	.450	-.4602	1.7093
		11	-6.8624*	.493	.000	-8.1290	-5.5957
	5	4	6.129E-02	1.117	1.000	-2.8095	2.9320
		9	.6858	1.067	.918	-2.0542	3.4259
		11	-6.8011*	1.097	.000	-9.6181	-3.9841
	9	4	-.6246	.422	.450	-1.7093	.4602
		5	-.6858	1.067	.918	-3.4259	2.0542
		11	-7.4869*	.363	.000	-8.4202	-6.5536
	11	4	6.8624*	.493	.000	5.5957	8.1290
		5	6.8011*	1.097	.000	3.9841	9.6181
		9	7.4869*	.363	.000	6.5536	8.4202

Multiple Comparison test for the SC Pavement Type and the **CL/CL-CI Soil Type at 95% Confidence Level**

Service Life

	GROUP	N	Subset for alpha = .05		
			1	2	3
Tukey HSD[a]	7	231	13.8462		
	6	640		16.6563	
	10	960		17.2667	
	12	587			21.3738
	Sig.		1.000	.288	1.000
Duncan[a,b]	7	231	13.8462		
	6	640		16.6563	
	10	960		17.2667	
	12	587			21.3738
	Sig.		1.000	.077	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 463.270

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	6	7	2.8100*	.403	.000	1.7743	3.8457
		10	-.6105	.268	.103	-1.2991	7.810E-02
		12	-4.7176*	.300	.000	-5.4887	-3.9465
	7	6	-2.8100*	.403	.000	-3.8457	-1.7743
		10	-3.4205*	.385	.000	-4.4094	-2.4316
		12	-7.5276*	.408	.000	-8.5756	-6.4796
	10	6	.6105	.268	.103	-7.8100E-02	1.2991
		7	3.4205*	.385	.000	2.4316	4.4094
		12	-4.1071*	.275	.000	-4.8141	-3.4001
	12	6	4.7176*	.300	.000	3.9465	5.4887
		7	7.5276*	.408	.000	6.4796	8.5756
		10	4.1071*	.275	.000	3.4001	4.8141

Multiple Comparison test for the FD Pavement Type and the **CH Soil Type at 95% Confidence Level**

Service Life

	GROUP	N	Subset for alpha = .05 1	2	3
Tukey HSD[a]	11	37	11.5043		
	6	90	14.0000	14.0000	
	1	28		14.9282	
	7	5			21.0000
	Sig.		.174	.873	1.000
Duncan[a,b]	11	37	11.5043		
	6	90		14.0000	
	1	28		14.9282	
	7	5			21.0000
	Sig.		1.000	.449	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 15.256

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
Tukey HSD	1	6	.9282	.727	.577	-.9386	2.7950
		7	-6.0718*	1.604	.001	-10.1921	-1.9515
		11	3.4239*	.839	.000	1.2672	5.5805
	6	1	-.9282	.727	.577	-2.7950	.9386
		7	-7.0000*	1.516	.000	-10.8945	-3.1055
		11	2.4957*	.656	.001	.8101	4.1813
	7	1	6.0718*	1.604	.001	1.9515	10.1921
		6	7.0000*	1.516	.000	3.1055	10.8945
		11	9.4957*	1.573	.000	5.4543	13.5371
	11	1	-3.4239*	.839	.000	-5.5805	-1.2672
		6	-2.4957*	.656	.001	-4.1813	-.8101
		7	-9.4957*	1.573	.000	-13.5371	-5.4543

Multiple Comparison test for the FD Pavement Type and the **CI/CI-CH Soil Type at 95% Confidence Level**

Service Life

			Subset for alpha = .05			
	GROUP	N	1	2	3	4
Tukey HSD[a]	3	7	10.0000			
	12	190	11.7759	11.7759		
	2	308	14.6016	14.6016		
	8	85		15.6887		
	9	10			21.0000	
	Sig.		.056	.150	1.000	
Duncan[a,b]	3	7	10.0000			
	12	190	11.7759	11.7759		
	2	308		14.6016	14.6016	
	8	85			15.6887	
	9	10				21.0000
	Sig.		.300	.099	.526	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 20.052

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	2	3	4.6016	1.986	.139	-.8147	10.0178
		8	-1.0871	.662	.470	-2.8921	.7179
		9	-6.3984*	1.731	.002	-11.1191	-1.6777
		12	2.8257*	.499	.000	1.4634	4.1880
	3	2	-4.6016	1.986	.139	-10.0178	.8147
		8	-5.6887*	2.047	.043	-11.2722	-.1052
		9	-11.0000*	2.597	.000	-18.0854	-3.9146
		12	-1.7759	2.000	.902	-7.2324	3.6806
	8	2	1.0871	.662	.470	-.7179	2.8921
		3	5.6887*	2.047	.043	.1052	11.2722
		9	-5.3113*	1.801	.026	-10.2230	-.3997
		12	3.9128*	.705	.000	1.9905	5.8351
	9	2	6.3984*	1.731	.002	1.6777	11.1191
		3	11.0000*	2.597	.000	3.9146	18.0854
		8	5.3113*	1.801	.026	.3997	10.2230
		12	9.2241*	1.748	.000	4.4573	13.9909
	12	2	-2.8257*	.499	.000	-4.1880	-1.4634
		3	1.7759	2.000	.902	-3.6806	7.2324
		8	-3.9128*	.705	.000	-5.8351	-1.9905
		9	-9.2241*	1.748	.000	-13.9909	-4.4573

Multiple Comparison test for the FD Pavement Type and the **CL/CL-CI Soil Type at 95% & 90% Confidence Levels**

Service Life

	GROUP	N	Subset for alpha = .05 1	 2	 3
Tukey HSD[a]	4	114	13.9669		
	5	50	14.0342		
	14	284		15.5892	
	10	55		16.1174	
	13	137		16.5826	
	Sig.		1.000	.197	
Duncan[a,b]	4	114	13.9669		
	5	50	14.0342		
	14	284		15.5892	
	10	55		16.1174	16.1174
	13	137			16.5826
	Sig.		.884	.252	.313

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 86.968

b.

The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	4	5	-6.7275E-02	.514	1.000	-1.4694	1.3349
		10	-2.1505*	.499	.000	-3.5108	-.7902
		13	-2.6157*	.385	.000	-3.6659	-1.5654
		14	-1.6223*	.337	.000	-2.5415	-.7031
	5	4	6.727E-02	.514	1.000	-1.3349	1.4694
		10	-2.0832*	.592	.004	-3.6988	-.4676
		13	-2.5484*	.500	.000	-3.9132	-1.1836
		14	-1.5550*	.464	.007	-2.8218	-.2883
	10	4	2.1505*	.499	.000	.7902	3.5108
		5	2.0832*	.592	.004	.4676	3.6988
		13	-.4652	.485	.873	-1.7870	.8566
		14	.5282	.447	.763	-.6921	1.7485
	13	4	2.6157*	.385	.000	1.5654	3.6659
		5	2.5484*	.500	.000	1.1836	3.9132
		10	.4652	.485	.873	-.8566	1.7870
		14	.9933*	.316	.014	.1322	1.8545
	14	4	1.6223*	.337	.000	.7031	2.5415
		5	1.5550*	.464	.007	.2883	2.8218
		10	-.5282	.447	.763	-1.7485	.6921
		13	-.9933*	.316	.014	-1.8545	-.1322

Multiple Comparison test for the FD Pavement Type and the **Central Zone at 95% Confidence Level**

Service Life

			Subset for alpha = .05	
	GROUP	N	1	2
Tukey HSD[a]	3	7	10.0000	
	4	114		13.9669
	5	50		14.0342
	2	308		14.6016
	1	28		14.9282
	Sig.		1.000	.955
Duncan[a,b]	3	7	10.0000	
	4	114		13.9669
	5	50		14.0342
	2	308		14.6016
	1	28		14.9282
	Sig.		1.000	.528

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 25.308

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

						95% Confidence Interval	
	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
Tukey HSD	1	2	.3266	.949	.997	-2.2611	2.9144
		3	4.9282	1.974	.091	-.4575	10.3139
		4	.9613	1.015	.878	-1.8071	3.7297
		5	.8940	1.136	.934	-2.2038	3.9919
	2	1	-.3266	.949	.997	-2.9144	2.2611
		3	4.6016	1.775	.072	-.2402	9.4434
		4	.6347	.531	.755	-.8149	2.0842
		5	.5674	.736	.939	-1.4411	2.5758
	3	1	-4.9282	1.974	.091	-10.3139	.4575
		2	-4.6016	1.775	.072	-9.4434	.2402
		4	-3.9669	1.811	.183	-8.9076	.9738
		5	-4.0342	1.882	.201	-9.1667	1.0984
	4	1	-.9613	1.015	.878	-3.7297	1.8071
		2	-.6347	.531	.755	-2.0842	.8149
		3	3.9669	1.811	.183	-.9738	8.9076
		5	-6.7275E-02	.820	1.000	-2.3037	2.1691
	5	1	-.8940	1.136	.934	-3.9919	2.2038
		2	-.5674	.736	.939	-2.5758	1.4411
		3	4.0342	1.882	.201	-1.0984	9.1667
		4	6.727E-02	.820	1.000	-2.1691	2.3037

***Multiple Comparison test for the FD Pavement Type and the* Northern Zone at 95% Confidence Levels**

Service Life

	GROUP	N	Subset for alpha = .05	
			1	2
Tukey HSD[a]	6	90	14.0000	
	8	85	15.6887	
	10	55	16.1174	
	9	10		21.0000
	7	5		21.0000
	Sig.		.638	1.000
Duncan[a,b]	6	90	14.0000	
	8	85	15.6887	
	10	55	16.1174	
	9	10		21.0000
	7	5		21.0000
	Sig.		.193	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 15.200

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	6	7	-7.0000*	1.890	.002	-12.1542	-1.8458
		8	-1.6887	.636	.061	-3.4230	4.562E-02
		9	-7.0000*	1.396	.000	-10.8093	-3.1907
		10	-2.1174*	.721	.027	-4.0840	-.1508
	7	6	7.0000*	1.890	.002	1.8458	12.1542
		8	5.3113*	1.892	.040	.1500	10.4726
		9	3.553E-15	2.264	1.000	-6.1759	6.1759
		10	4.8826	1.922	.082	-.3614	10.1266
	8	6	1.6887	.636	.061	-4.5617E-02	3.4230
		7	-5.3113*	1.892	.040	-10.4726	-.1500
		9	-5.3113*	1.400	.001	-9.1303	-1.4923
		10	-.4287	.728	.977	-2.4140	1.5566
	9	6	7.0000*	1.396	.000	3.1907	10.8093
		7	-3.5527E-15	2.264	1.000	-6.1759	6.1759
		8	5.3113*	1.400	.001	1.4923	9.1303
		10	4.8826*	1.441	.006	.9527	8.8125
	10	6	2.1174*	.721	.027	.1508	4.0840
		7	-4.8826	1.922	.082	-10.1266	.3614
		8	.4287	.728	.977	-1.5566	2.4140
		9	-4.8826*	1.441	.006	-8.8125	-.9527

***Multiple Comparison test for the FD Pavement Type and the* Southern Zone at 95% Confidence Level**

Service Life

			Subset for alpha = .05	
	GROUP	N	1	2
Tukey HSD[a]	11	37	11.5043	
	12	190	11.7759	
	14	284		15.5892
	13	137		16.5826
	Sig.		.960	.266
Duncan[a,b]	11	37	11.5043	
	12	190	11.7759	
	14	284		15.5892
	13	137		16.5826
	Sig.		.620	.070

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 94.064

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

						95% Confidence Interval	
	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
Tukey HSD	11	12	-.2716	.669	.977	-1.9896	1.4465
		13	-5.0783*	.690	.000	-6.8504	-3.3061
		14	-4.0849*	.650	.000	-5.7557	-2.4141
	12	11	.2716	.669	.977	-1.4465	1.9896
		13	-4.8067*	.420	.000	-5.8849	-3.7285
		14	-3.8133*	.351	.000	-4.7153	-2.9113
	13	11	5.0783*	.690	.000	3.3061	6.8504
		12	4.8067*	.420	.000	3.7285	5.8849
		14	.9933	.390	.053	-7.8451E-03	1.9945
	14	11	4.0849*	.650	.000	2.4141	5.7557
		12	3.8133*	.351	.000	2.9113	4.7153
		13	-.9933	.390	.053	-1.9945	7.845E-03

Multiple Comparison test for the GB Pavement Type and the **Central Zone at 95% Confidence Level**

Service Life

			Subset for alpha = .05				
	GROUP	N	1	2	3	4	5
Tukey HSD[a]	3	150	11.5301				
	7	1518		16.0326			
	5	334		17.1914	17.1914		
	2	50			18.0327		
	1	299				23.0253	
	4	350				24.3969	24.3969
	6	1278					25.5050
	Sig.		1.000	.463	.803	.254	.520
Duncan[a,b]	3	150	11.5301				
	7	1518		16.0326			
	5	334		17.1914	17.1914		
	2	50			18.0327		
	1	299				23.0253	
	4	350					24.3969
	6	1278					25.5050
	Sig.		1.000	.054	.162	1.000	.066

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 188.741

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	1	2	4.9926*	.890	.000	2.3697	7.6155
		3	11.4951*	.584	.000	9.7733	13.2170
		4	-1.3717*	.460	.045	-2.7275	-1.5838E-02
		5	5.8339*	.465	.000	4.4625	7.2052
		6	-2.4798*	.375	.000	-3.5859	-1.3737
		7	6.9927*	.370	.000	5.9033	8.0821
	2	1	-4.9926*	.890	.000	-7.6155	-2.3697
		3	6.5026*	.951	.000	3.6986	9.3065
		4	-6.3642*	.880	.000	-8.9595	-3.7689
		5	.8413	.883	.964	-1.7621	3.4448
		6	-7.4723*	.839	.000	-9.9463	-4.9983
		7	2.0001	.837	.202	-.4665	4.4667
	3	1	-11.4951*	.584	.000	-13.2170	-9.7733
		2	-6.5026*	.951	.000	-9.3065	-3.6986
		4	-12.8668*	.570	.000	-14.5463	-11.1873
		5	-5.6612*	.574	.000	-7.3533	-3.9692
		6	-13.9749*	.504	.000	-15.4601	-12.4897
		7	-4.5024*	.500	.000	-5.9753	-3.0296
	4	1	1.3717*	.460	.045	1.584E-02	2.7275
		2	6.3642*	.880	.000	3.7689	8.9595
		3	12.8668*	.570	.000	11.1873	14.5463
		5	7.2056*	.447	.000	5.8878	8.5234
		6	-1.1081*	.352	.028	-2.1471	-6.9117E-02
		7	8.3644*	.346	.000	7.3432	9.3856
	5	1	-5.8339*	.465	.000	-7.2052	-4.4625
		2	-.8413	.883	.964	-3.4448	1.7621
		3	5.6612*	.574	.000	3.9692	7.3533
		4	-7.2056*	.447	.000	-8.5234	-5.8878
		6	-8.3136*	.359	.000	-9.3728	-7.2545
		7	1.1588*	.353	.018	.1171	2.2005
	6	1	2.4798*	.375	.000	1.3737	3.5859
		2	7.4723*	.839	.000	4.9983	9.9463
		3	13.9749*	.504	.000	12.4897	15.4601
		4	1.1081*	.352	.028	6.912E-02	2.1471
		5	8.3136*	.359	.000	7.2545	9.3728
		7	9.4725*	.222	.000	8.8182	10.1267
	7	1	-6.9927*	.370	.000	-8.0821	-5.9033
		2	-2.0001	.837	.202	-4.4667	.4665
		3	4.5024*	.500	.000	3.0296	5.9753
		4	-8.3644*	.346	.000	-9.3856	-7.3432
		5	-1.1588*	.353	.018	-2.2005	-.1171
		6	-9.4725*	.222	.000	-10.1267	-8.8182

Multiple Comparison test for the GB Pavement Type and the **Northern Zone at 95% Confidence Level**

Service Life

	GROUP	N	Subset for alpha = .05 1	2	3	4
Tukey HSD[a]	8	53	12.7255			
	12	1076		17.1005		
	10	694		17.8888	17.8888	
	11	206		18.3278	18.3278	
	13	245			19.4151	
	14	703				21.7100
	Sig.		1.000	.370	.147	1.000
Duncan[a,b]	8	53	12.7255			
	12	1076		17.1005		
	10	694		17.8888		
	11	206		18.3278	18.3278	
	13	245			19.4151	
	14	703				21.7100
	Sig.		1.000	.064	.084	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 190.828

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	8	10	-5.1632*	.872	.000	-7.6490	-2.6775
		11	-5.6022*	.943	.000	-8.2896	-2.9148
		12	-4.3750*	.861	.000	-6.8290	-1.9210
		13	-6.6895*	.927	.000	-9.3322	-4.0469
		14	-8.9845*	.872	.000	-11.4691	-6.4999
	10	8	5.1632*	.872	.000	2.6775	7.6490
		11	-.4390	.487	.946	-1.8266	.9487
		12	.7883	.299	.089	-6.3655E-02	1.6402
		13	-1.5263*	.456	.011	-2.8252	-.2274
		14	-3.8212*	.329	.000	-4.7575	-2.8850
	11	8	5.6022*	.943	.000	2.9148	8.2896
		10	.4390	.487	.946	-.9487	1.8266
		12	1.2272	.467	.090	-.1027	2.5572
		13	-1.0873	.580	.417	-2.7397	.5650
		14	-3.3823*	.486	.000	-4.7678	-1.9967
	12	8	4.3750*	.861	.000	1.9210	6.8290
		10	-.7883	.299	.089	-1.6402	6.366E-02
		11	-1.2272	.467	.090	-2.5572	.1027
		13	-2.3146*	.434	.000	-3.5517	-1.0774
		14	-4.6095*	.298	.000	-5.4580	-3.7610
	13	8	6.6895*	.927	.000	4.0469	9.3322
		10	1.5263*	.456	.011	.2274	2.8252
		11	1.0873	.580	.417	-.5650	2.7397
		12	2.3146*	.434	.000	1.0774	3.5517
		14	-2.2949*	.455	.000	-3.5916	-.9983
	14	8	8.9845*	.872	.000	6.4999	11.4691
		10	3.8212*	.329	.000	2.8850	4.7575
		11	3.3823*	.486	.000	1.9967	4.7678
		12	4.6095*	.298	.000	3.7610	5.4580
		13	2.2949*	.455	.000	.9983	3.5916

Multiple Comparison test for the GB Pavement Type and the **Southern Zone at 95% Confidence Level**

Service Life

			Subset for alpha = .05					
	GROUP	N	1	2	3	4	5	6
Tukey HSD[a]	20	328	14.1902					
	17	235	14.5959					
	22	1113		18.0745				
	18	42			20.2129			
	19	864			21.6403	21.6403		
	21	1930				23.0094	23.0094	
	15	137					23.8807	23.8807
	16	138						25.1366
	Sig.		.999	1.000	.441	.498	.914	.611
Duncan[a,b]	20	328	14.1902					
	17	235	14.5959					
	22	1113		18.0745				
	18	42			20.2129			
	19	864				21.6403		
	21	1930					23.0094	
	15	137					23.8807	23.8807
	16	138						25.1366
	Sig.		.558	1.000	1.000	1.000	.208	.070

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 166.778

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	15	16	-1.2560	.762	.721	-3.5665	1.0546
		17	9.2848*	.679	.000	7.2254	11.3442
		18	3.6678*	1.112	.022	.2990	7.0367
		19	2.2404*	.582	.003	.4777	4.0031
		20	9.6905*	.643	.000	7.7414	11.6396
		21	.8713	.559	.775	-.8235	2.5661
		22	5.8061*	.573	.000	4.0706	7.5416
	16	15	1.2560	.762	.721	-1.0546	3.5665
		17	10.5408*	.677	.000	8.4875	12.5940
		18	4.9238*	1.110	.000	1.5587	8.2889
		19	3.4964*	.579	.000	1.7408	5.2519
		20	10.9464*	.641	.000	9.0038	12.8890
		21	2.1273*	.557	.003	.4399	3.8146
		22	7.0621*	.570	.000	5.3339	8.7903
	17	15	-9.2848*	.679	.000	-11.3442	-7.2254
		16	-10.5408*	.677	.000	-12.5940	-8.4875
		18	-5.6170*	1.055	.000	-8.8148	-2.4191
		19	-7.0444*	.465	.000	-8.4531	-5.6357
		20	.4057	.540	.995	-1.2302	2.0416
		21	-8.4135*	.436	.000	-9.7362	-7.0908
		22	-3.4787*	.453	.000	-4.8531	-2.1042
	18	15	-3.6678*	1.112	.022	-7.0367	-.2990
		16	-4.9238*	1.110	.000	-8.2889	-1.5587
		17	5.6170*	1.055	.000	2.4191	8.8148
		19	-1.4274	.995	.841	-4.4428	1.5880
		20	6.0226*	1.032	.000	2.8947	9.1506
		21	-2.7965	.982	.084	-5.7727	.1796
		22	2.1383	.990	.376	-.8612	5.1378
	19	15	-2.2404*	.582	.003	-4.0031	-.4777
		16	-3.4964*	.579	.000	-5.2519	-1.7408
		17	7.0444*	.465	.000	5.6357	8.4531
		18	1.4274	.995	.841	-1.5880	4.4428
		20	7.4501*	.410	.000	6.2081	8.6920
		21	-1.3691*	.259	.000	-2.1537	-.5844
		22	3.5657*	.287	.000	2.6966	4.4348
	20	15	-9.6905*	.643	.000	-11.6396	-7.7414
		16	-10.9464*	.641	.000	-12.8890	-9.0038
		17	-.4057	.540	.995	-2.0416	1.2302
		18	-6.0226*	1.032	.000	-9.1506	-2.8947
		19	-7.4501*	.410	.000	-8.6920	-6.2081
		21	-8.8192*	.377	.000	-9.9626	-7.6757
		22	-3.8843*	.397	.000	-5.0873	-2.6814
	21	15	-.8713	559	.775	-2.5661	.8235
		16	-2.1273*	.557	.003	-3.8146	-.4399
		17	8.4135*	.436	.000	7.0908	9.7362
		18	2.7965	.982	.084	-.1796	5.7727
		19	1.3691*	.259	.000	.5844	2.1537
		20	8.8192*	.377	.000	7.6757	9.9626
		22	4.9348*	.238	.000	4.2134	5.6562
	22	15	-5.8061*	.573	.000	-7.5416	-4.0706
		16	-7.0621*	.570	.000	-8.7903	-5.3339
		17	3.4787*	.453	.000	2.1042	4.8531
		18	-2.1383	.990	.376	-5.1378	.8612
		19	-3.5657*	.287	.000	-4.4348	-2.6966
		20	3.8843*	.397	.000	2.6814	5.0873
		21	-4.9348*	.238	.000	-5.6562	-4.2134

Multiple Comparison test for the SC Pavement Type and the **Central Zone at 95% Confidence Level**

Service Life

			Subset for alpha = .05		
	GROUP	N	1	2	3
Tukey HSD[a]	3	115	8.6061		
	1	58	12.3843	12.3843	
	4	156		13.6179	13.6179
	5	20		13.6792	13.6792
	7	231		13.8462	13.8462
	2	4		14.0000	14.0000
	6	640			16.6563
	Sig.		.075	.895	.266
Duncan[a,b]	3	115	8.6061		
	1	58		12.3843	
	4	156		13.6179	
	5	20		13.6792	
	7	231		13.8462	
	2	4		14.0000	
	6	640			16.6563
	Sig.		1.000	.294	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 22.392

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	1	2	-1.6157	2.222	.991	-8.1670	4.9355
		3	3.7782*	.723	.000	1.6453	5.9112
		4	-1.2336	.690	.557	-3.2685	.8012
		5	-1.2949	1.155	.922	-4.7005	2.1106
		6	-4.2720*	.615	.000	-6.0862	-2.4577
		7	-1.4620	.659	.286	-3.4062	.4823
	2	1	1.6157	2.222	.991	-4.9355	8.1670
		3	5.3939	2.183	.170	-1.0432	11.8311
		4	.3821	2.173	1.000	-6.0232	6.7874
		5	.3208	2.362	1.000	-6.6423	7.2839
		6	-2.6563	2.150	.880	-8.9949	3.6824
		7	.1538	2.163	1.000	-6.2233	6.5309
	3	1	-3.7782*	.723	.000	-5.9112	-1.6453
		2	-5.3939	2.183	.170	-11.8311	1.0432
		4	-5.0119*	.553	.000	-6.6424	-3.3813
		5	-5.0731*	1.079	.000	-8.2536	-1.8926
		6	-8.0502*	.456	.000	-9.3954	-6.7050
		7	-5.2402*	.514	.000	-6.7561	-3.7243
	4	1	1.2336	.690	.557	-.8012	3.2685
		2	-.3821	2.173	1.000	-6.7874	6.0232
		3	5.0119*	.553	.000	3.3813	6.6424
		5	-6.1290E-02	1.057	1.000	-3.1768	3.0543
		6	-3.0383*	.401	.000	-4.2218	-1.8549
		7	-.2283	.466	.999	-1.6027	1.1461
	5	1	1.2949	1.155	.922	-2.1106	4.7005
		2	-.3208	2.362	1.000	-7.2839	6.6423
		3	5.0731*	1.079	.000	1.8926	8.2536
		4	6.129E-02	1.057	1.000	-3.0543	3.1768
		6	-2.9770*	1.009	.050	-5.9532	-8.5897E-04
		7	-.1670	1.037	1.000	-3.2242	2.8901
	6	1	4.2720*	.615	.000	2.4577	6.0862
		2	2.6563	2.150	.880	-3.6824	8.9949
		3	8.0502*	.456	.000	6.7050	9.3954
		4	3.0383*	.401	.000	1.8549	4.2218
		5	2.9770*	1.009	.050	8.590E-04	5.9532
		7	2.8100*	.346	.000	1.7902	3.8298
	7	1	1.4620	.659	.286	-.4823	3.4062
		2	-.1538	2.163	1.000	-6.5309	6.2233
		3	5.2402*	.514	.000	3.7243	6.7561
		4	.2283	.466	.999	-1.1461	1.6027
		5	.1670	1.037	1.000	-2.8901	3.2242
		6	-2.8100*	.346	.000	-3.8298	-1.7902

Multiple Comparison test for the SC Pavement Type and the **Northern Zone at 95% Confidence Level**

Service Life

	GROUP	N	Subset for alpha = .05 1	 2
Tukey HSD[a]	9	676	12.9934	
	8	560	13.1442	
	10	960		17.2667
	Sig.		.832	1.000
Duncan[a,b]	9	676	12.9934	
	8	560	13.1442	
	10	960		17.2667
	Sig.		.564	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 697.085

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	 Upper Bound
Tukey HSD	8	9	.1508	.279	.851	-.5021	.8036
		10	-4.1226*	.259	.000	-4.7301	-3.5151
	9	8	-.1508	.279	.851	-.8036	.5021
		10	-4.2734*	.245	.000	-4.8472	-3.6995
	10	8	4.1226*	.259	.000	3.5151	4.7301
		9	4.2734*	.245	.000	3.6995	4.8472

Multiple Comparison test for the FD Pavement Type and the **CH Soil Type at 99% Confidence Level**

Service Life

	GROUP	N	Subset for alpha = .01		
			1	2	3
Tukey HSD[a]	11	37	11.5043		
	6	90	14.0000		
	1	28	14.9282		
	7	5		21.0000	
	Sig.		.027	1.000	
Duncan[a,b]	11	37	11.5043		
	6	90	14.0000	14.0000	
	1	28		14.9282	
	7	5			21.0000
	Sig.		.042	.449	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 15.256

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	99% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	1	6	.9282	.727	.577	-1.3341	3.1905
		7	-6.0718*	1.604	.001	-11.0650	-1.0787
		11	3.4239*	.839	.000	.8104	6.0374
	6	1	-.9282	.727	.577	-3.1905	1.3341
		7	-7.0000*	1.516	.000	-11.7195	-2.2805
		11	2.4957*	.656	.001	.4530	4.5383
	7	1	6.0718*	1.604	.001	1.0787	11.0650
		6	7.0000*	1.516	.000	2.2805	11.7195
		11	9.4957*	1.573	.000	4.5982	14.3932
	11	1	-3.4239*	.839	.000	-6.0374	-.8104
		6	-2.4957*	.656	.001	-4.5383	-.4530
		7	-9.4957*	1.573	.000	-14.3932	-4.5982

Multiple Comparison test for the FD Pavement Type and the **CH Soil Type at 90% Confidence Level**

Service Life

	GROUP	N	Subset for alpha = .1 1	2	3
Tukey HSD[a]	11	37	11.5043		
	6	90	14.0000	14.0000	
	1	28		14.9282	
	7	5			21.0000
	Sig.		.174	.873	1.000
Duncan[a,b]	11	37	11.5043		
	6	90		14.0000	
	1	28		14.9282	
	7	5			21.0000
	Sig.		1.000	.449	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 15.256

b.

The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	90% Confidence Interval Lower Bound	Upper Bound
Tukey HSD	1	6	.9282	.727	.577	-.7368	2.5932
		7	-6.0718*	1.604	.001	-9.7467	-2.3969
		11	3.4239*	.839	.000	1.5003	5.3474
	6	1	-.9282	.727	.577	-2.5932	.7368
		7	-7.0000*	1.516	.000	-10.4735	-3.5265
		11	2.4957*	.656	.001	.9923	3.9991
	7	1	6.0718*	1.604	.001	2.3969	9.7467
		6	7.0000*	1.516	.000	3.5265	10.4735
		11	9.4957*	1.573	.000	5.8911	13.1003
	11	1	-3.4239*	.839	.000	-5.3474	-1.5003
		6	-2.4957*	.656	.001	-3.9991	-.9923
		7	-9.4957*	1.573	.000	-13.1003	-5.8911

Multiple Comparison test for the FD Pavement Type and the **CI/CI-CH Soil Type at 99% Confidence Level**

Service Life

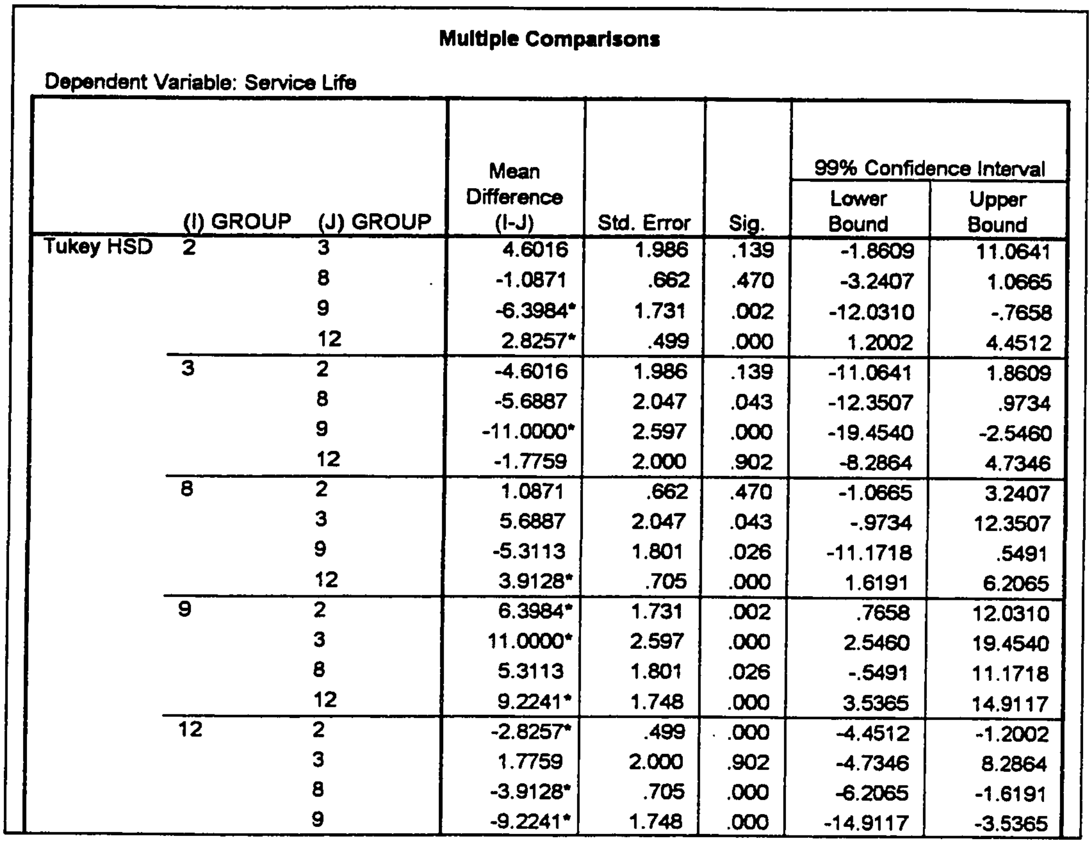
			Subset for alpha = .01		
	GROUP	N	1	2	3
Tukey HSD[a]	3	7	10.0000		
	12	190	11.7759	11.7759	
	2	308	14.6016	14.6016	
	8	85		15.6887	15.6887
	9	10			21.0000
	Sig.		.056	.150	.017
Duncan[a,b]	3	7	10.0000		
	12	190	11.7759	11.7759	
	2	308		14.6016	
	8	85		15.6887	
	9	10			21.0000
	Sig.		.300	.029	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 20.052

b.

The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.



Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	99% Confidence Interval Lower Bound	Upper Bound
Tukey HSD	2	3	4.6016	1.986	.139	-1.8609	11.0641
		8	-1.0871	.662	.470	-3.2407	1.0665
		9	-6.3984*	1.731	.002	-12.0310	-.7658
		12	2.8257*	.499	.000	1.2002	4.4512
	3	2	-4.6016	1.986	.139	-11.0641	1.8609
		8	-5.6887	2.047	.043	-12.3507	.9734
		9	-11.0000*	2.597	.000	-19.4540	-2.5460
		12	-1.7759	2.000	.902	-8.2864	4.7346
	8	2	1.0871	.662	.470	-1.0665	3.2407
		3	5.6887	2.047	.043	-.9734	12.3507
		9	-5.3113	1.801	.026	-11.1718	.5491
		12	3.9128*	.705	.000	1.6191	6.2065
	9	2	6.3984*	1.731	.002	.7658	12.0310
		3	11.0000*	2.597	.000	2.5460	19.4540
		8	5.3113	1.801	.026	-.5491	11.1718
		12	9.2241*	1.748	.000	3.5365	14.9117
	12	2	-2.8257*	.499	.000	-4.4512	-1.2002
		3	1.7759	2.000	.902	-4.7346	8.2864
		8	-3.9128*	.705	.000	-6.2065	-1.6191
		9	-9.2241*	1.748	.000	-14.9117	-3.5365

Multiple Comparison test for the FD Pavement Type and the CI/CI-CH Soil Type at 90% Confidence Level

Service Life

			Subset for alpha = .1		
	GROUP	N	1	2	3
Tukey HSD[a]	3	7	10.0000		
	12	190	11.7759	11.7759	
	2	308		14.6016	
	8	85		15.6887	
	9	10			21.0000
	Sig.		.838	.150	1.000
Duncan[a,b]	3	7	10.0000		
	12	190	11.7759		
	2	308		14.6016	
	8	85		15.6887	
	9	10			21.0000
	Sig.		.300	.526	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 20.052

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	90% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	2	3	4.6016	1.986	.139	-.2820	9.4852
		8	-1.0871	.662	.470	-2.7146	.5403
		9	-6.3984*	1.731	.002	-10.6549	-2.1420
		12	2.8257*	.499	.000	1.5973	4.0540
	3	2	-4.6016	1.986	.139	-9.4852	.2820
		8	-5.6887*	2.047	.043	-10.7231	-.6543
		9	-11.0000*	2.597	.000	-17.3885	-4.6115
		12	-1.7759	2.000	.902	-6.6958	3.1440
	8	2	1.0871	.662	.470	-.5403	2.7146
		3	5.6887*	2.047	.043	.6543	10.7231
		9	-5.3113*	1.801	.026	-9.7399	-.8827
		12	3.9128*	.705	.000	2.1795	5.6461
	9	2	6.3984*	1.731	.002	2.1420	10.6549
		3	11.0000*	2.597	.000	4.6115	17.3885
		8	5.3113*	1.801	.026	.8827	9.7399
		12	9.2241*	1.748	.000	4.9261	13.5221
	12	2	-2.8257*	.499	.000	-4.0540	-1.5973
		3	1.7759	2.000	.902	-3.1440	6.6958
		8	-3.9128*	.705	.000	-5.6461	-2.1795
		9	-9.2241*	1.748	.000	-13.5221	-4.9261

Multiple Comparison test for the FD Pavement Type and the **CL/CL-CI Soil Type at 90% Confidence Level**

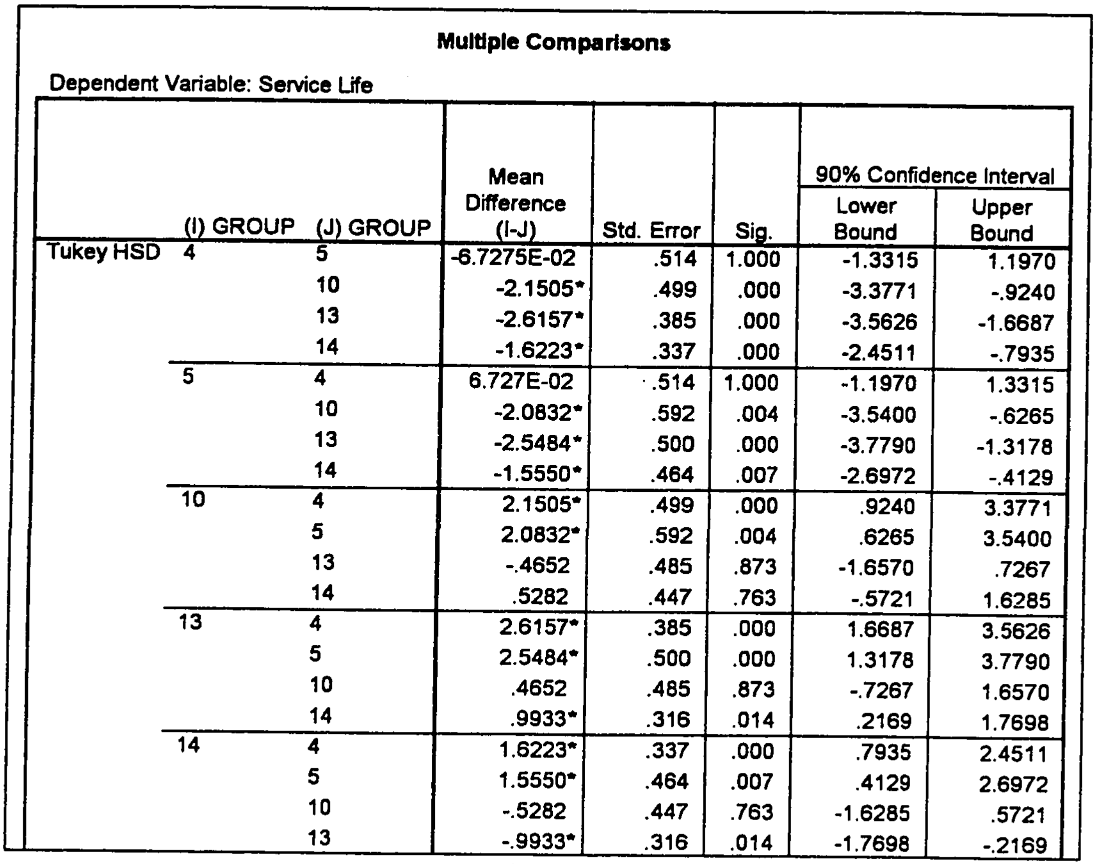
Service Life

	GROUP	N	Subset for alpha = .1 1	2	3
Tukey HSD[a]	4	114	13.9669		
	5	50	14.0342		
	14	284		15.5892	
	10	55		16.1174	
	13	137		16.5826	
	Sig.		1.000	.197	
Duncan[a,b]	4	114	13.9669		
	5	50	14.0342		
	14	284		15.5892	
	10	55		16.1174	16.1174
	13	137			16.5826
	Sig.		.884	.252	.313

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 86.968

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.



Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	90% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	4	5	-6.7275E-02	.514	1.000	-1.3315	1.1970
		10	-2.1505*	.499	.000	-3.3771	-.9240
		13	-2.6157*	.385	.000	-3.5626	-1.6687
		14	-1.6223*	.337	.000	-2.4511	-.7935
	5	4	6.727E-02	.514	1.000	-1.1970	1.3315
		10	-2.0832*	.592	.004	-3.5400	-.6265
		13	-2.5484*	.500	.000	-3.7790	-1.3178
		14	-1.5550*	.464	.007	-2.6972	-.4129
	10	4	2.1505*	.499	.000	.9240	3.3771
		5	2.0832*	.592	.004	.6265	3.5400
		13	-.4652	.485	.873	-1.6570	.7267
		14	.5282	.447	.763	-.5721	1.6285
	13	4	2.6157*	.385	.000	1.6687	3.5626
		5	2.5484*	.500	.000	1.3178	3.7790
		10	.4652	.485	.873	-.7267	1.6570
		14	.9933*	.316	.014	.2169	1.7698
	14	4	1.6223*	.337	.000	.7935	2.4511
		5	1.5550*	.464	.007	.4129	2.6972
		10	-.5282	.447	.763	-1.6285	.5721
		13	-.9933*	.316	.014	-1.7698	-.2169

Multiple Comparison test for the FD Pavement Type and the **CL/CL-CI Soil Type at 99% Confidence Level**

Service Life

			Subset for alpha = .01	
	GROUP	N	1	2
Tukey HSD[a]	4	114	13.9669	
	5	50	14.0342	
	14	284		15.5892
	10	55		16.1174
	13	137		16.5826
	Sig.		1.000	.197
Duncan[a,b]	4	114	13.9669	
	5	50	14.0342	
	14	284		15.5892
	10	55		16.1174
	13	137		16.5826
	Sig.		.884	.040

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 86.968

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	99% Confidence Interval Lower Bound	99% Confidence Interval Upper Bound
Tukey HSD	4	5	-6.7275E-02	.514	1.000	-1.7403	1.6057
		10	-2.1505*	.499	.000	-3.7736	-.5274
		13	-2.6157*	.385	.000	-3.8688	-1.3626
		14	-1.6223*	.337	.000	-2.7190	-.5256
	5	4	6.727E-02	.514	1.000	-1.6057	1.7403
		10	-2.0832*	.592	.004	-4.0109	-.1555
		13	-2.5484*	.500	.000	-4.1768	-.9199
		14	-1.5550*	.464	.007	-3.0665	-4.3621E-02
	10	4	2.1505*	.499	.000	.5274	3.7736
		5	2.0832*	.592	.004	.1555	4.0109
		13	-.4652	.485	.873	-2.0423	1.1120
		14	.5282	.447	.763	-.9278	1.9842
	13	4	2.6157*	.385	.000	1.3626	3.8688
		5	2.5484*	.500	.000	.9199	4.1768
		10	.4652	.485	.873	-1.1120	2.0423
		14	.9933	.316	.014	-3.4141E-02	2.0208
	14	4	1.6223*	.337	.000	.5256	2.7190
		5	1.5550*	.464	.007	4.362E-02	3.0665
		10	-.5282	.447	.763	-1.9842	.9278
		13	-.9933	.316	.014	-2.0208	3.414E-02

Multiple Comparison test for the GB Pavement Type and the BO Soil Type at 99% Confidence Level

Service Life

	GROUP	N	Subset for alpha = .01		
			1	2	3
Tukey HSD[a]	8	53	12.7255		
	1	299		23.0253	
	15	137		23.8807	
	16	138		25.1366	
	Sig.		1.000	.022	
Duncan[a,b]	8	53	12.7255		
	1	299		23.0253	
	15	137		23.8807	23.8807
	16	138			25.1366
	Sig.		1.000	.246	.089

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 109.292

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	99% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	1	8	10.2997*	.810	.000	7.7777	12.8218
		15	-.8554	.562	.425	-2.6060	.8952
		16	-2.1114*	.560	.001	-3.8563	-.3664
	8	1	-10.2997*	.810	.000	-12.8218	-7.7777
		15	-11.1552*	.880	.000	-13.8942	-8.4161
		16	-12.4111*	.879	.000	-15.1465	-9.6757
	15	1	.8554	.562	.425	-.8952	2.6060
		8	11.1552*	.880	.000	8.4161	13.8942
		16	-1.2560	.657	.223	-3.3021	.7901
	16	1	2.1114*	.560	.001	.3664	3.8563
		8	12.4111*	.879	.000	9.6757	15.1465
		15	1.2560	.657	.223	-.7901	3.3021

Multiple Comparison test for the GB Pavement Type and the BO Soil Type at 90% Confidence Level

Service Life

	GROUP	N	Subset for alpha = 0.1		
			1	2	3
Tukey HSD[a,]	8	53	12.7255		
	1	299		23.0253	
	15	137		23.8807	23.8807
	16	138			25.1366
	Sig.		1.000	.652	.322
Duncan[a,b]	8	53	12.7255		
	1	299		23.0253	
	15	137		23.8807	
	16	138			25.1366
	Sig.		1.000	.246	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 109.292

b.

The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	90% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	1	8	10.2997*	.810	.000	8.4435	12.1560
		15	-.8554	.562	.425	-2.1438	.4330
		16	-2.1114*	.560	.001	-3.3956	-.8271
	8	1	-10.2997*	.810	.000	-12.1560	-8.4435
		15	-11.1552*	.880	.000	-13.1711	-9.1392
		16	-12.4111*	.879	.000	-14.4244	-10.3978
	15	1	.8554	.562	.425	-.4330	2.1438
		8	11.1552*	.880	.000	9.1392	13.1711
		16	-1.2560	.657	.223	-2.7619	.2500
	16	1	2.1114*	.560	.001	.8271	3.3956
		8	12.4111*	.879	.000	10.3978	14.4244
		15	1.2560	.657	.223	-.2500	2.7619

Multiple Comparison test for the GB Pavement Type and the **CH Soil Type at 90% Confidence Level**

Service Life

			Subset for alpha = 0.1			
	GROUP	N	1	2	3	4
Tukey HSD[a]	3	150	11.5301			
	17	235		14.5959		
	10	694			17.8888	
	2	50			18.0327	18.0327
	11	206			18.3278	18.3278
	18	42				20.2129
	Sig.		1.000	1.000	.996	.125
Duncan[a,b]	3	150	11.5301			
	17	235		14.5959		
	10	694			17.8888	
	2	50			18.0327	
	11	206			18.3278	
	18	42				20.2129
	Sig.		1.000	1.000	.639	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 99.042

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	90% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	2	3	6.5026*	.999	.000	3.9161	9.0890
		10	.1439	.896	1.000	-2.1744	2.4622
		11	-.2951	.965	1.000	-2.7921	2.2020
		17	3.4368*	.953	.004	.9705	5.9031
		18	-2.1801	1.280	.529	-5.4925	1.1322
	3	2	-6.5026*	.999	.000	-9.0890	-3.9161
		10	-6.3586*	.552	.000	-7.7881	-4.9291
		11	-6.7976*	.658	.000	-8.5018	-5.0934
		17	-3.0657*	.641	.000	-4.7246	-1.4069
		18	-8.6827*	1.068	.000	-11.4469	-5.9185
	10	2	-.1439	.896	1.000	-2.4622	2.1744
		3	6.3586*	.552	.000	4.9291	7.7881
		11	-.4390	.487	.946	-1.6997	.8217
		17	3.2929*	.463	.000	2.0943	4.4915
		18	-2.3241	.972	.159	-4.8392	.1910
	11	2	.2951	.965	1.000	-2.2020	2.7921
		3	6.7976*	.658	.000	5.0934	8.5018
		10	.4390	.487	.946	-.8217	1.6997
		17	3.7319*	.586	.000	2.2161	5.2476
		18	-1.8851	1.036	.453	-4.5659	.7957
	17	2	-3.4368*	.953	.004	-5.9031	-.9705
		3	3.0657*	.641	.000	1.4069	4.7246
		10	-3.2929*	.463	.000	-4.4915	-2.0943
		11	-3.7319*	.586	.000	-5.2476	-2.2161
		18	-5.6170*	1.025	.000	-8.2691	-2.9648
	18	2	2.1801	1.280	.529	-1.1322	5.4925
		3	8.6827*	1.068	.000	5.9185	11.4469
		10	2.3241	.972	.159	-.1910	4.8392
		11	1.8851	1.036	.453	-.7957	4.5659
		17	5.6170*	1.025	.000	2.9648	8.2691

Multiple Comparison test for the GB Pavement Type and the **CH Soil Type at 99% Confidence Level**

Service Life

			Subset for alpha = 0.01		
	GROUP	N	1	2	3
Tukey HSD[a]	3	150	11.5301		
	17	235		14.5959	
	10	694			17.8888
	2	50			18.0327
	11	206			18.3278
	18	42			20.2129
	Sig.		1.000	1.000	.083
Duncan[a,b]	3	150	11.5301		
	17	235		14.5959	
	10	694			17.8888
	2	50			18.0327
	11	206			18.3278
	18	42			20.2129
	Sig.		1.000	1.000	.013

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 99.042

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	99% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	2	3	6.5026*	.999	.000	3.1415	9.8636
		10	.1439	.896	1.000	-2.8687	3.1565
		11	-.2951	.965	1.000	-3.5400	2.9499
		17	3.4368*	.953	.004	.2319	6.6418
		18	-2.1801	1.280	.529	-6.4845	2.1243
	3	2	-6.5026*	.999	.000	-9.8636	-3.1415
		10	-6.3586*	.552	.000	-8.2162	-4.5010
		11	-6.7976*	.658	.000	-9.0122	-4.5830
		17	-3.0657*	.641	.000	-5.2214	-.9101
		18	-8.6827*	1.068	.000	-12.2748	-5.0907
	10	2	-.1439	.896	1.000	-3.1565	2.8687
		3	6.3586*	.552	.000	4.5010	8.2162
		11	-.4390	.487	.946	-2.0772	1.1992
		17	3.2929*	.463	.000	1.7353	4.8504
		18	-2.3241	.972	.159	-5.5924	.9443
	11	2	.2951	.965	1.000	-2.9499	3.5400
		3	6.7976*	.658	.000	4.5830	9.0122
		10	.4390	.487	.946	-1.1992	2.0772
		17	3.7319*	.586	.000	1.7622	5.7016
		18	-1.8851	1.036	.453	-5.3688	1.5986
	17	2	-3.4368*	.953	.004	-6.6418	-.2319
		3	3.0657*	.641	.000	.9101	5.2214
		10	-3.2929*	.463	.000	-4.8504	-1.7353
		11	-3.7319*	.586	.000	-5.7016	-1.7622
		18	-5.6170*	1.025	.000	-9.0634	-2.1705
	18	2	2.1801	1.280	.529	-2.1243	6.4845
		3	8.6827*	1.068	.000	5.0907	12.2748
		10	2.3241	.972	.159	-.9443	5.5924
		11	1.8851	1.036	.453	-1.5986	5.3688
		17	5.6170*	1.025	.000	2.1705	9.0634

Multiple Comparison test for the GB Pavement Type and the CI/CI-CH Soil Type at 99% Confidence Level

Service Life

			Subset for alpha = 0.01				
	GROUP	N	1	2	3	4	5
Tukey HSD[a]	20	328	14.1902				
	12	1076		17.1005			
	5	334		17.1914			
	13	245			19.4151		
	19	864				21.6403	
	4	350					24.3969
	Sig.		1.000	1.000	1.000	1.000	1.000
Duncan[a,b]	20	328	14.1902				
	12	1076		17.1005			
	5	334		17.1914			
	13	245			19.4151		
	19	864				21.6403	
	4	350					24.3969
	Sig.		1.000	.850	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 398.935

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	99% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	4	5	7.2056*	.518	.000	5.4625	8.9486
		12	7.2964*	.417	.000	5.8947	8.6982
		13	4.9819*	.564	.000	3.0854	6.8783
		19	2.7567*	.429	.000	1.3132	4.2002
		20	10.2067*	.520	.000	8.4569	11.9566
	5	4	-7.2056*	.518	.000	-8.9486	-5.4625
		12	9.088E-02	.424	1.000	-1.3370	1.5188
		13	-2.2237*	.570	.001	-4.1396	-.3078
		19	-4.4489*	.437	.000	-5.9178	-2.9800
		20	3.0012*	.526	.000	1.2303	4.7721
	12	4	-7.2964*	.417	.000	-8.6982	-5.8947
		5	-9.0879E-02	.424	1.000	-1.5188	1.3370
		13	-2.3146*	.479	.000	-3.9262	-.7029
		19	-4.5398*	.310	.000	-5.5811	-3.4984
		20	2.9103*	.427	.000	1.4741	4.3465
	13	4	-4.9819*	.564	.000	-6.8783	-3.0854
		5	2.2237*	.570	.001	.3078	4.1396
		12	2.3146*	.479	.000	.7029	3.9262
		19	-2.2252*	.490	.000	-3.8732	-.5772
		20	5.2249*	.571	.000	3.3028	7.1469
	19	4	-2.7567*	.429	.000	-4.2002	-1.3132
		5	4.4489*	.437	.000	2.9800	5.9178
		12	4.5398*	.310	.000	3.4984	5.5811
		13	2.2252*	.490	.000	.5772	3.8732
		20	7.4501*	.439	.000	5.9731	8.9270
	20	4	-10.2067*	.520	.000	-11.9566	-8.4569
		5	-3.0012*	.526	.000	-4.7721	-1.2303
		12	-2.9103*	.427	.000	-4.3465	-1.4741
		13	-5.2249*	.571	.000	-7.1469	-3.3028
		19	-7.4501*	.439	.000	-8.9270	-5.9731

Multiple Comparison test for the GB Pavement Type and the **CI/CL-CI Soil Type at 90% Confidence Level**

Service Life

			Subset for alpha = 0.1				
	GROUP	N	1	2	3	4	5
Tukey HSD[a]	20	328	14.1902				
	12	1076		17.1005			
	5	334		17.1914			
	13	245			19.4151		
	19	864				21.6403	
	4	350					24.3969
	Sig.		1.000	1.000	1.000	1.000	1.000
Duncan[a,b]	20	328	14.1902				
	12	1076		17.1005			
	5	334		17.1914			
	13	245			19.4151		
	19	864				21.6403	
	4	350					24.3969
	Sig.		1.000	.850	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 398.935

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	90% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	4	5	7.2056*	.518	.000	5.8642	8.5469
		12	7.2964*	.417	.000	6.2177	8.3751
		13	4.9819*	.564	.000	3.5225	6.4413
		19	2.7567*	.429	.000	1.6459	3.8675
		20	10.2067*	.520	.000	8.8602	11.5533
	5	4	-7.2056*	.518	.000	-8.5469	-5.8642
		12	9.088E-02	.424	1.000	-1.0079	1.1897
		13	-2.2237*	.570	.001	-3.6980	-.7493
		19	-4.4489*	.437	.000	-5.5792	-3.3185
		20	3.0012*	.526	.000	1.6384	4.3639
	12	4	-7.2964*	.417	.000	-8.3751	-6.2177
		5	-9.0879E-02	.424	1.000	-1.1897	1.0079
		13	-2.3146*	.479	.000	-3.5548	-1.0744
		19	-4.5398*	.310	.000	-5.3411	-3.7384
		20	2.9103*	.427	.000	1.8051	4.0155
	13	4	-4.9819*	.564	.000	-6.4413	-3.5225
		5	2.2237*	.570	.001	.7493	3.6980
		12	2.3146*	.479	.000	1.0744	3.5548
		19	-2.2252*	.490	.000	-3.4934	-.9570
		20	5.2249*	.571	.000	3.7458	6.7040
	19	4	-2.7567*	.429	.000	-3.8675	-1.6459
		5	4.4489*	.437	.000	3.3185	5.5792
		12	4.5398*	.310	.000	3.7384	5.3411
		13	2.2252*	.490	.000	.9570	3.4934
		20	7.4501*	.439	.000	6.3135	8.5866
	20	4	-10.2067*	.520	.000	-11.5533	-8.8602
		5	-3.0012*	.526	.000	-4.3639	-1.6384
		12	-2.9103*	.427	.000	-4.0155	-1.8051
		13	-5.2249*	.571	.000	-6.7040	-3.7458
		19	-7.4501*	.439	.000	-8.5866	-6.3135

Multiple Comparison test for the GB Pavement Type and the **CL/CL-CI Soil Type at 90% Confidence Level**

Service Life

			Subset for alpha = 0.1				
	GROUP	N	1	2	3	4	5
Tukey HSD[a]	7	1518	16.0326				
	22	1113		18.0745			
	14	703			21.7100		
	21	1930				23.0094	
	6	1278					25.5050
	Sig.		1.000	1.000	1.000	1.000	1.000
Duncan[a,b]	7	1518	16.0326				
	22	1113		18.0745			
	14	703			21.7100		
	21	1930				23.0094	
	6	1278					25.5050
	Sig.		1.000	1.000	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 1168.624

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	90% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	6	7	9.4725*	.221	.000	8.9283	10.0167
		14	3.7950*	.274	.000	3.1220	4.4681
		21	2.4957*	.210	.000	1.9787	3.0126
		22	7.4305*	.239	.000	6.8428	8.0182
	7	6	-9.4725*	.221	.000	-10.0167	-8.9283
		14	-5.6774*	.266	.000	-6.3314	-5.0235
		21	-6.9768*	.200	.000	-7.4686	-6.4850
		22	-2.0420*	.230	.000	-2.6077	-1.4763
	14	6	-3.7950*	.274	.000	-4.4681	-3.1220
		7	5.6774*	.266	.000	5.0235	6.3314
		21	-1.2993*	.257	.000	-1.9308	-.6679
		22	3.6355*	.281	.000	2.9449	4.3260
	21	6	-2.4957*	.210	.000	-3.0126	-1.9787
		7	6.9768*	.200	.000	6.4850	7.4686
		14	1.2993*	.257	.000	.6679	1.9308
		22	4.9348*	.219	.000	4.3953	5.4744
	22	6	-7.4305*	.239	.000	-8.0182	-6.8428
		7	2.0420*	.230	.000	1.4763	2.6077
		14	-3.6355*	.281	.000	-4.3260	-2.9449
		21	-4.9348*	.219	.000	-5.4744	-4.3953

Multiple Comparison test for the GB Pavement Type and the **CL/CL-CI Soil Type at 99% Confidence Level**

Service Life

			Subset for alpha = 0.01				
	GROUP	N	1	2	3	4	5
Tukey HSD[a]	7	1518	16.0326				
	22	1113		18.0745			
	14	703			21.7100		
	21	1930				23.0094	
	6	1278					25.5050
	Sig.		1.000	1.000	1.000	1.000	1.000
Duncan[a,b]	7	1518	16.0326				
	22	1113		18.0745			
	14	703			21.7100		
	21	1930				23.0094	
	6	1278					25.5050
	Sig.		1.000	1.000	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 1168.624

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed..

Multiple Comparisons

Dependent Variable: Service Life

			Mean Difference (I-J)	Std. Error	Sig.	99% Confidence Interval	
	(I) GROUP	(J) GROUP				Lower Bound	Upper Bound
Tukey HSD	6	7	9.4725*	.221	.000	8.7523	10.1926
		14	3.7950*	.274	.000	2.9044	4.6857
		21	2.4957*	.210	.000	1.8116	3.1798
		22	7.4305*	.239	.000	6.6528	8.2082
	7	6	-9.4725*	.221	.000	-10.1926	-8.7523
		14	-5.6774*	.266	.000	-6.5428	-4.8121
		21	-6.9768*	.200	.000	-7.6276	-6.3259
		22	-2.0420*	.230	.000	-2.7906	-1.2934
	14	6	-3.7950*	.274	.000	-4.6857	-2.9044
		7	5.6774*	.266	.000	4.8121	6.5428
		21	-1.2993*	.257	.000	-2.1349	-.4638
		22	3.6355*	.281	.000	2.7217	4.5493
	21	6	-2.4957*	.210	.000	-3.1798	-1.8116
		7	6.9768*	.200	.000	6.3259	7.6276
		14	1.2993*	.257	.000	.4638	2.1349
		22	4.9348*	.219	.000	4.2209	5.6488
	22	6	-7.4305*	.239	.000	-8.2082	-6.6528
		7	2.0420*	.230	.000	1.2934	2.7906
		14	-3.6355*	.281	.000	-4.5493	-2.7217
		21	-4.9348*	.219	.000	-5.6488	-4.2209

Multiple Comparison test for the SC Pavement Type and the **CH Soil Type at 99% Confidence Level**

Service Life

	GROUP	N	Subset for alpha = 0.01	
			1	2
Tukey HSD[a]	3	115	8.6061	
	8	560		13.1442
	2	4		14.0000
	Sig.		1.000	.834
Duncan[a,b]	3	115	8.6061	
	8	560		13.1442
	2	4		14.0000
	Sig.		1.000	.566

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 12.687

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	99% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	2	3	5.3939*	1.821	.009	8.704E-02	10.7008
		8	.8558	1.794	.882	-4.3724	6.0841
	3	2	-5.3939*	1.821	.009	-10.7008	-8.7040E-02
		8	-4.5381*	.385	.000	-5.6590	-3.4172
	8	2	-.8558	1.794	.882	-6.0841	4.3724
		3	4.5381*	.385	.000	3.4172	5.6590

Multiple Comparison test for the SC Pavement Type and the **CH Soil Type at 90% Confidence Level**

Service Life

	GROUP	N	Subset for alpha = 0.1 1	 2
Tukey HSD[a]	3	115	8.6061	
	8	560		13.1442
	2	4		14.0000
	Sig.		1.000	.834
Duncan[a,b]	3	115	8.6061	
	8	560		13.1442
	2	4		14.0000
	Sig.		1.000	.566

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 12.687

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	90% Confidence Interval Lower Bound	 Upper Bound
Tukey HSD	2	3	5.3939*	1.821	.009	1.6557	9.1321
		8	.8558	1.794	.882	-2.8270	4.5387
	3	2	-5.3939*	1.821	.009	-9.1321	-1.6557
		8	-4.5381*	.385	.000	-5.3276	-3.7485
	8	2	-.8558	1.794	.882	-4.5387	2.8270
		3	4.5381*	.385	.000	3.7485	5.3276

Multiple Comparison test for the SC Pavement Type and the **CI/CI-CH Soil Type at 90% Confidence Level**

Service Life

			Subset for alpha = 0.1	
	GROUP	N	1	2
Tukey HSD[a]	9	676	12.9934	
	4	156	13.6179	
	5	20	13.6792	
	11	230		20.4803
	Sig.		.842	1.000
Duncan[a,b]	9	676	12.9934	
	4	156	13.6179	
	5	20	13.6792	
	11	230		20.4803
	Sig.		.441	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 65.807

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

			Mean Difference (I-J)	Std. Error	Sig.	90% Confidence Interval	
	(I) GROUP	(J) GROUP				Lower Bound	Upper Bound
Tukey HSD	4	5	-6.1290E-02	1.117	1.000	-2.6217	2.4992
		9	.6246	.422	.450	-.3430	1.5921
		11	-6.8624*	.493	.000	-7.9921	-5.7326
	5	4	6.129E-02	1.117	1.000	-2.4992	2.6217
		9	.6858	1.067	.918	-1.7580	3.1297
		11	-6.8011*	1.097	.000	-9.3136	-4.2886
	9	4	-.6246	.422	.450	-1.5921	.3430
		5	-.6858	1.067	.918	-3.1297	1.7580
		11	-7.4869*	.363	.000	-8.3194	-6.6545
	11	4	6.8624*	.493	.000	5.7326	7.9921
		5	6.8011*	1.097	.000	4.2886	9.3136
		9	7.4869*	.363	.000	6.6545	8.3194

Multiple Comparison test for the SC Pavement Type and the **CI/CI-CH Soil Type at 99% Confidence Level**

Service Life

	GROUP	N	Subset for alpha = 0.01	
			1	2
Tukey HSD[a]	9	676	12.9934	
	4	156	13.6179	
	5	20	13.6792	
	11	230		20.4803
	Sig.		.842	1.000
Duncan[a,b]	9	676	12.9934	
	4	156	13.6179	
	5	20	13.6792	
	11	230		20.4803
	Sig.		.441	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 65.807

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	99% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	4	5	-6.1290E-02	1.117	1.000	-3.5402	3.4176
		9	.6246	.422	.450	-.6900	1.9391
		11	-6.8624*	.493	.000	-8.3973	-5.3274
	5	4	6.129E-02	1.117	1.000	-3.4176	3.5402
		9	.6858	1.067	.918	-2.6347	4.0063
		11	-6.8011*	1.097	.000	-10.2148	-3.3873
	9	4	-.6246	.422	.450	-1.9391	.6900
		5	-.6858	1.067	.918	-4.0063	2.6347
		11	-7.4869*	.363	.000	-8.6180	-6.3559
	11	4	6.8624*	.493	.000	5.3274	8.3973
		5	6.8011*	1.097	.000	3.3873	10.2148
		9	7.4869*	.363	.000	6.3559	8.6180

Multiple Comparison test for the SC Pavement Type and the **CL/CL-CI Soil Type at 99% Confidence Level**

Service Life

	GROUP	N	Subset for alpha = 0.01		
			1	2	3
Tukey HSD[a]	7	231	13.8462		
	6	640		16.6563	
	10	960		17.2667	
	12	587			21.3738
	Sig.		1.000	.288	1.000
Duncan[a,b]	7	231	13.8462		
	6	640		16.6563	
	10	960		17.2667	
	12	587			21.3738
	Sig.		1.000	.077	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 463.270

b.

The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	99% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	6	7	2.8100*	.403	.000	1.5549	4.0651
		10	-.6105	.268	.103	-1.4450	.2240
		12	-4.7176*	.300	.000	-5.6520	-3.7832
	7	6	-2.8100*	.403	.000	-4.0651	-1.5549
		10	-3.4205*	.385	.000	-4.6189	-2.2221
		12	-7.5276*	.408	.000	-8.7977	-6.2575
	10	6	.6105	.268	.103	-.2240	1.4450
		7	3.4205*	.385	.000	2.2221	4.6189
		12	-4.1071*	.275	.000	-4.9639	-3.2503
	12	6	4.7176*	.300	.000	3.7832	5.6520
		7	7.5276*	.408	.000	6.2575	8.7977
		10	4.1071*	.275	.000	3.2503	4.9639

Multiple Comparison test for the SC Pavement Type and the CL/CL-CI Soil Type at 90% Confidence Level

Service Life

	GROUP	N	Subset for alpha = 0.1			
			1	2	3	4
Tukey HSD[a]	7	231	13.8462			
	6	640		16.6563		
	10	960		17.2667		
	12	587			21.3738	
	Sig.		1.000	.288	1.000	
Duncan[a,b]	7	231	13.8462			
	6	640		16.6563		
	10	960			17.2667	
	12	587				21.3738
	Sig.		1.000	1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.

[a] Uses Harmonic Mean Sample Size = 463.270

[b] The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Multiple Comparisons

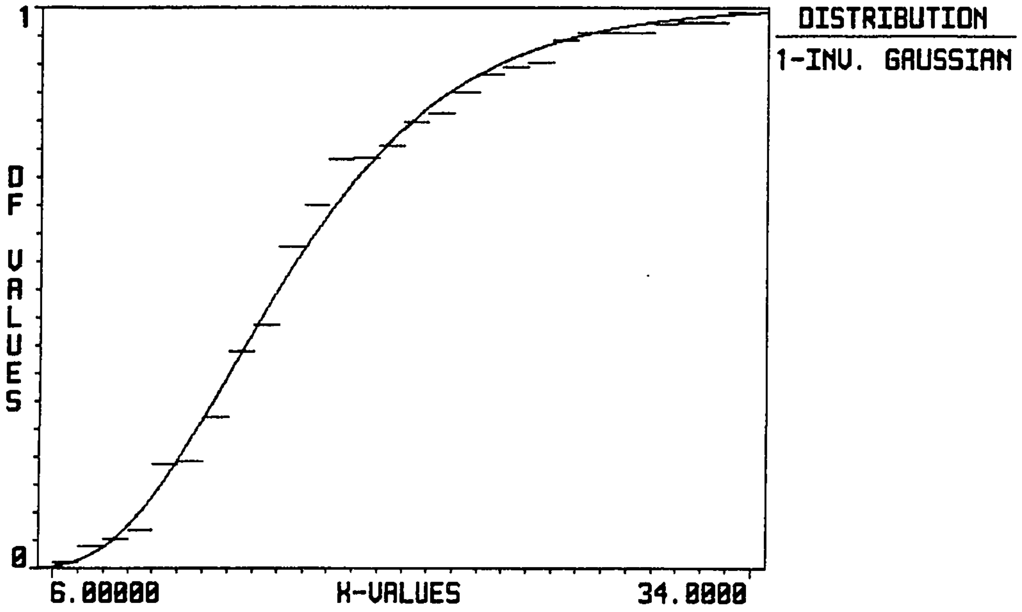
Dependent Variable: Service Life

	(I) GROUP	(J) GROUP	Mean Difference (I-J)	Std. Error	Sig.	90% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	6	7	2.8100*	.403	.000	1.8862	3.7338
		10	-.6105	.268	.103	-1.2246	3.669E-03
		12	-4.7176*	.300	.000	-5.4053	-4.0299
	7	6	-2.8100*	.403	.000	-3.7338	-1.8862
		10	-3.4205*	.385	.000	-4.3025	-2.5385
		12	-7.5276*	.408	.000	-8.4624	-6.5928
	10	6	.6105	.268	.103	-3.6690E-03	1.2246
		7	3.4205*	.385	.000	2.5385	4.3025
		12	-4.1071*	.275	.000	-4.7377	-3.4765
	12	6	4.7176*	.300	.000	4.0299	5.4053
		7	7.5276*	.408	.000	6.5928	8.4624
		10	4.1071*	.275	.000	3.4765	4.7377

Appendix B:

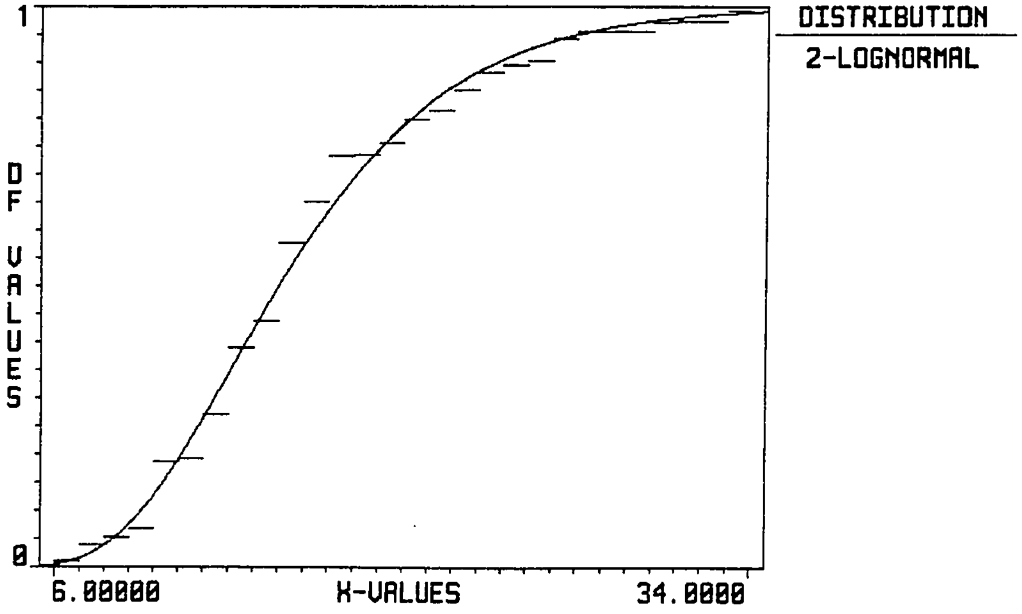
Distribution Fittings and Parameters of Various Pavement Data Groups

DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM C10.DAT

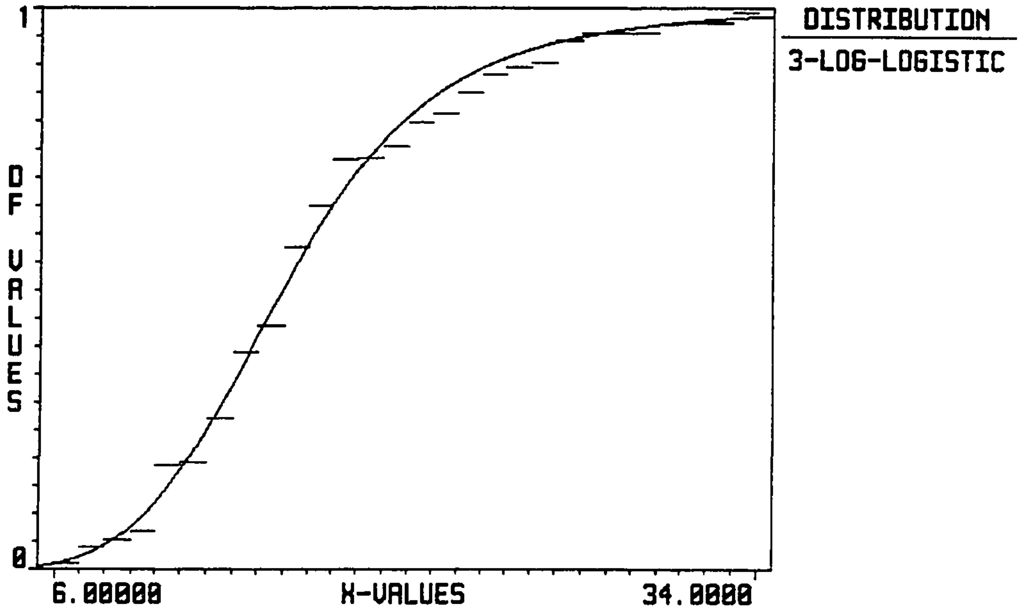


23:29 22-JAN-99

DISTRIBUTION FUNCTION PLOT OF MODEL 2
AND SAMPLE: DATA FROM C10.DAT

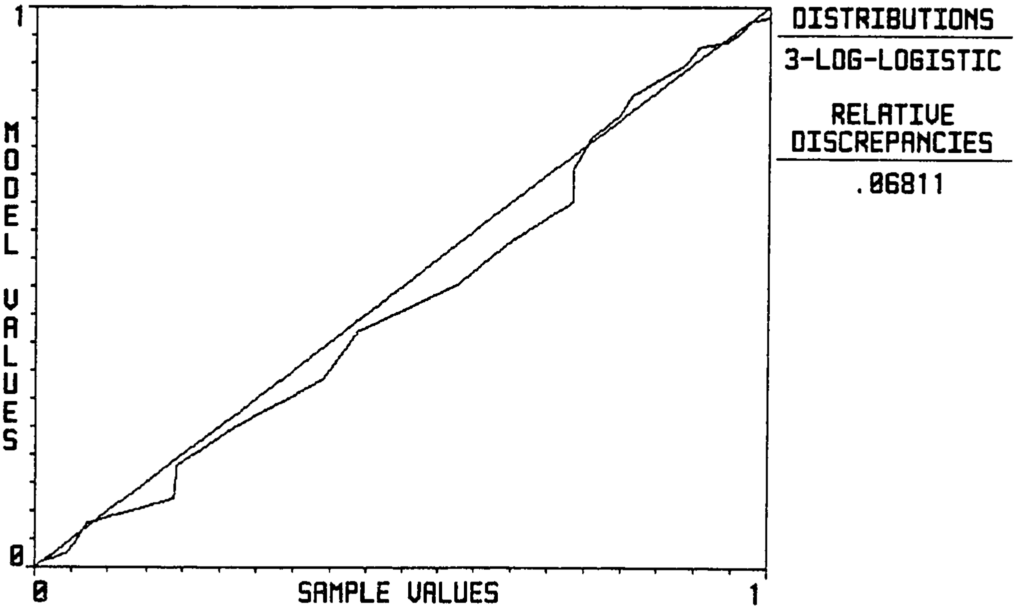


17:23 3-JUL-98



DISTRIBUTION FUNCTION PLOT OF MODEL 3
AND SAMPLE: DATA FROM C10.DAT

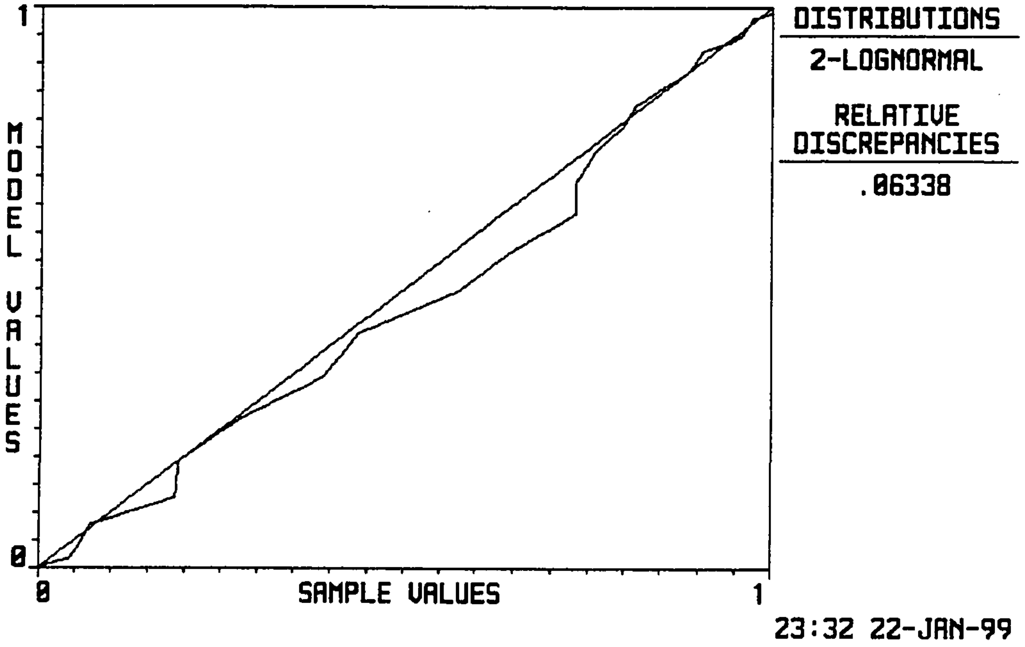
23:30 22-JAN-99



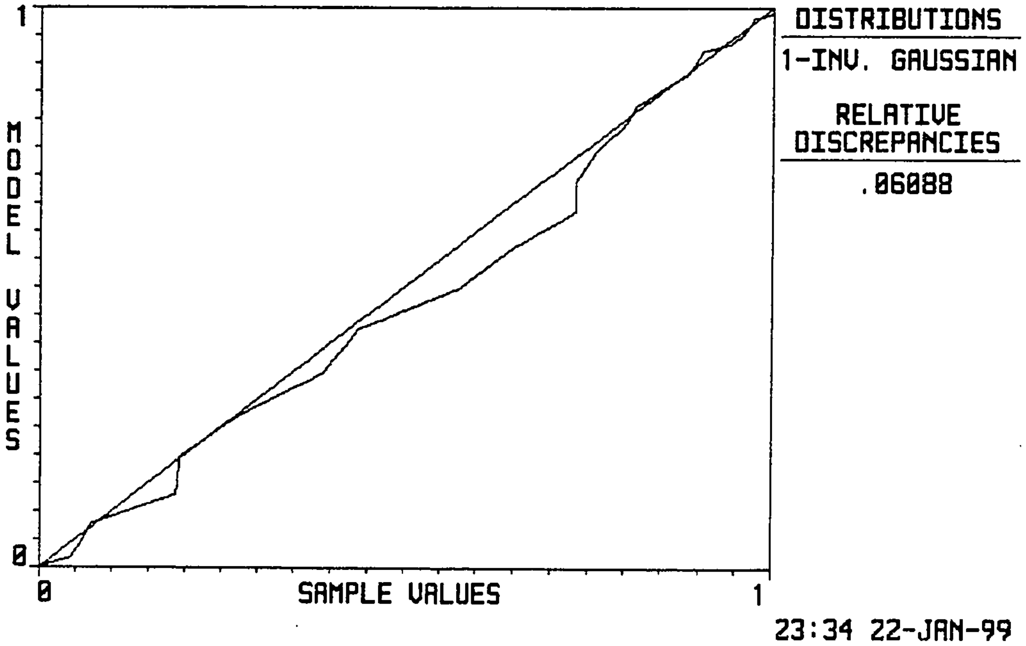
P-P PLOT OF MODEL 3
AND SAMPLE: DATA FROM C10.DAT

23:31 22-JAN-99

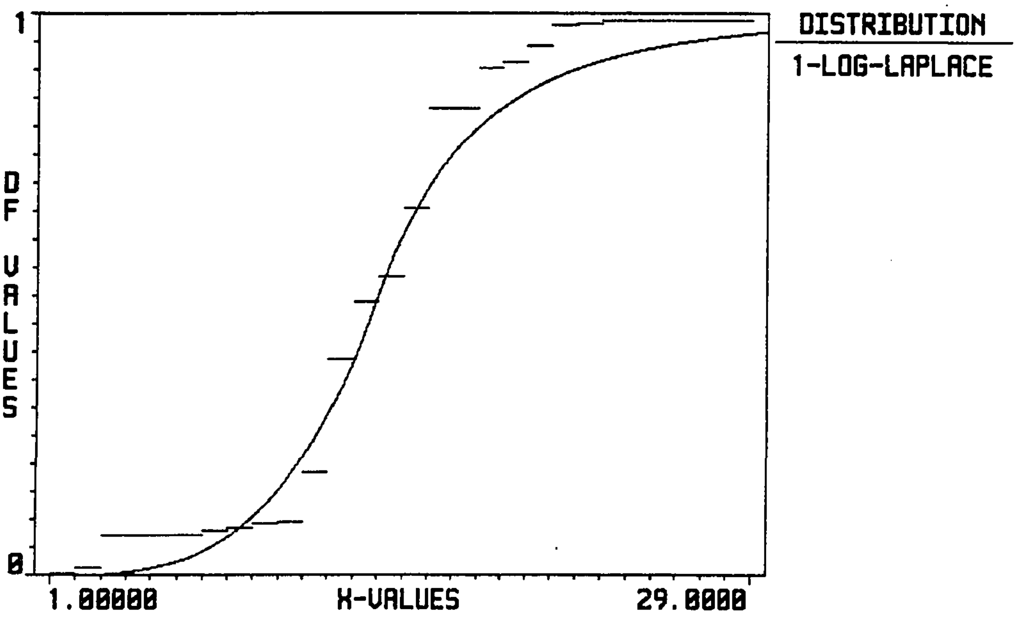
P-P PLOT OF MODEL 2
AND SAMPLE: DATA FROM C10.DAT



P-P PLOT OF MODEL 1
AND SAMPLE: DATA FROM C10.DAT

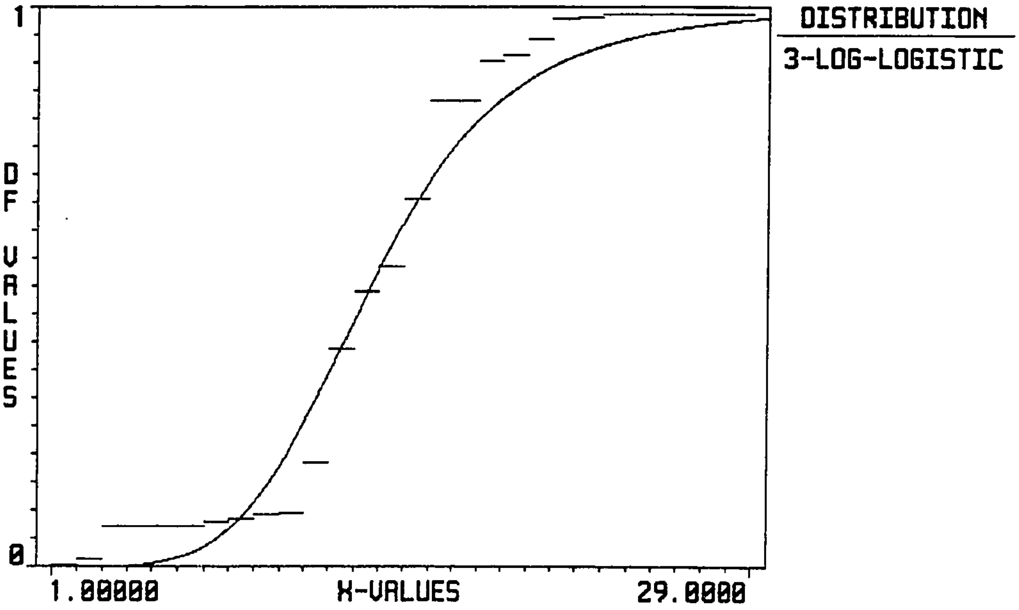


DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM C2_10.DAT



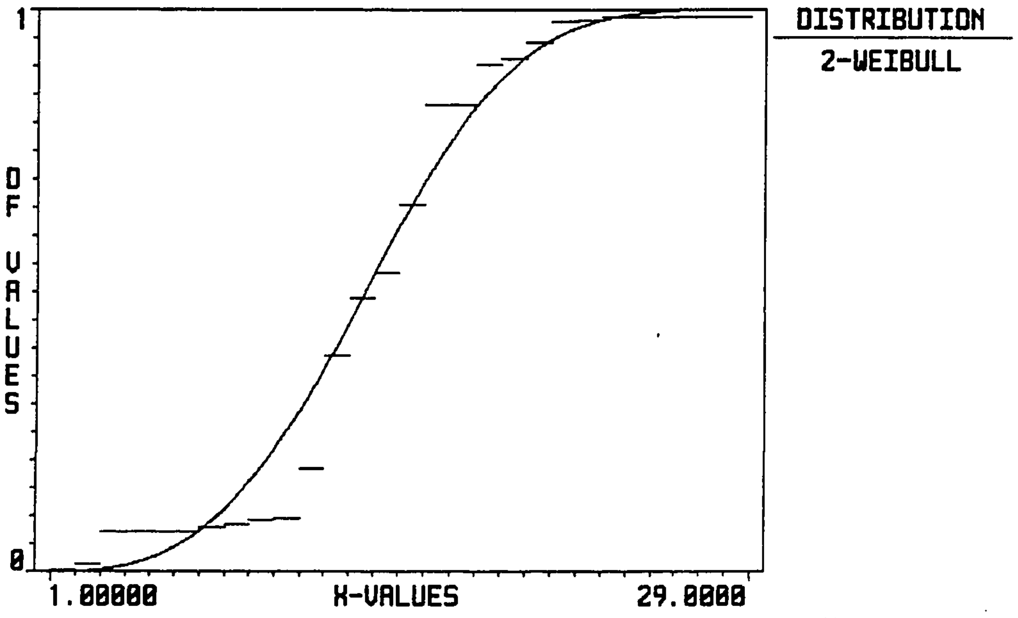
23:43 22-JAN-99

DISTRIBUTION FUNCTION PLOT OF MODEL 3
AND SAMPLE: DATA FROM C2_10.DAT



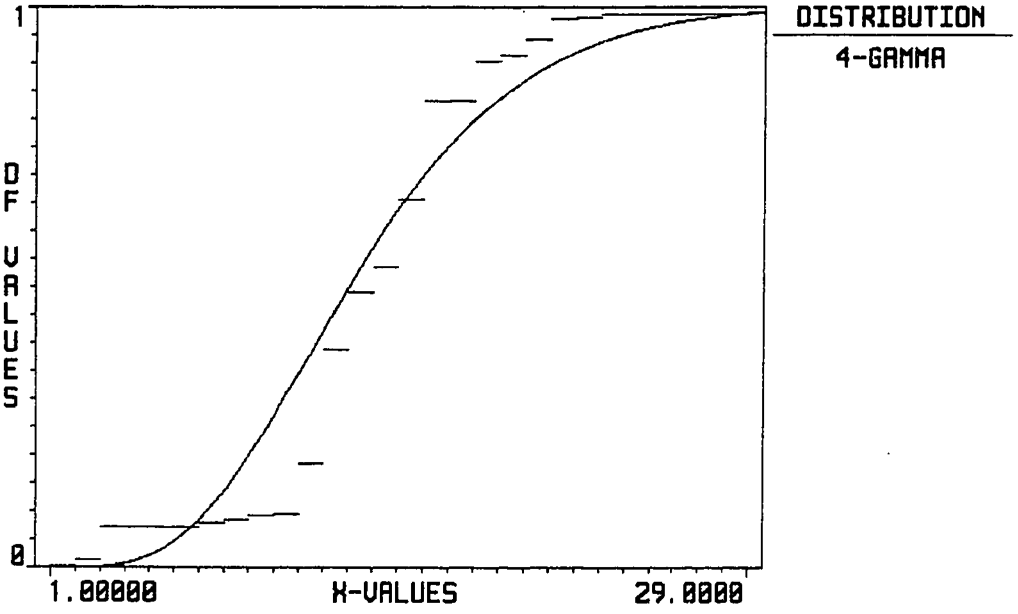
23:44 22-JAN-99

DISTRIBUTION FUNCTION PLOT OF MODEL 2
AND SAMPLE: DATA FROM C2_10.DAT

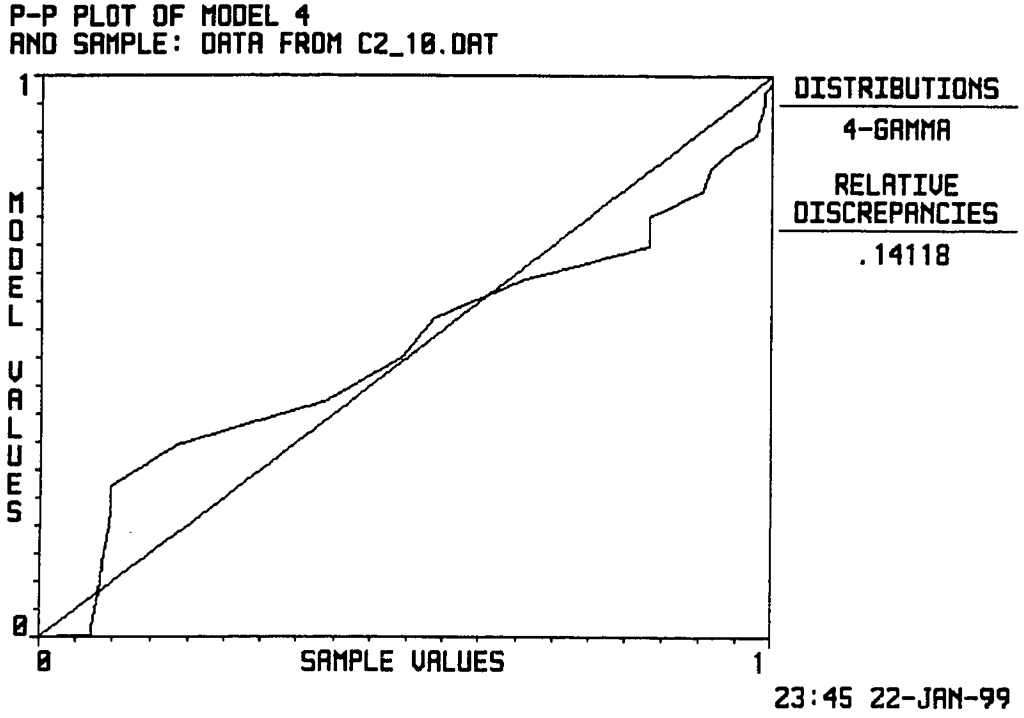


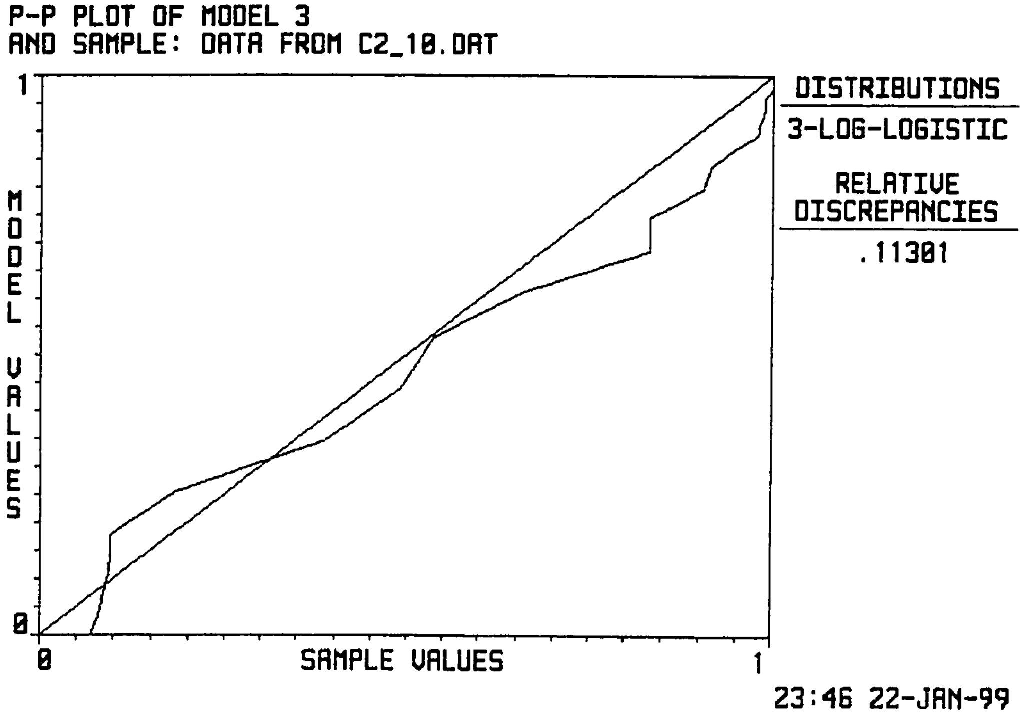
21:17 1-JUL-98

DISTRIBUTION FUNCTION PLOT OF MODEL 4
AND SAMPLE: DATA FROM C2_10.DAT

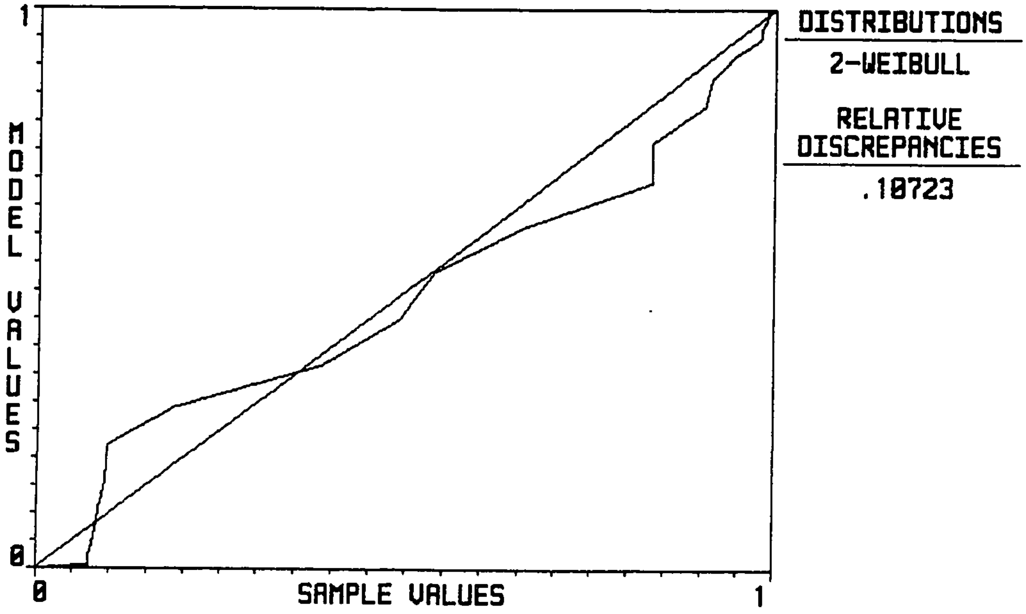


23:44 22-JAN-99


P-P PLOT OF MODEL 4
AND SAMPLE: DATA FROM C2_10.DAT
1
0
MODEL VALUES
0
SAMPLE VALUES
1
DISTRIBUTIONS
4-GAMMA
RELATIVE
DISCREPANCIES
.14118
23:45 22-JAN-99

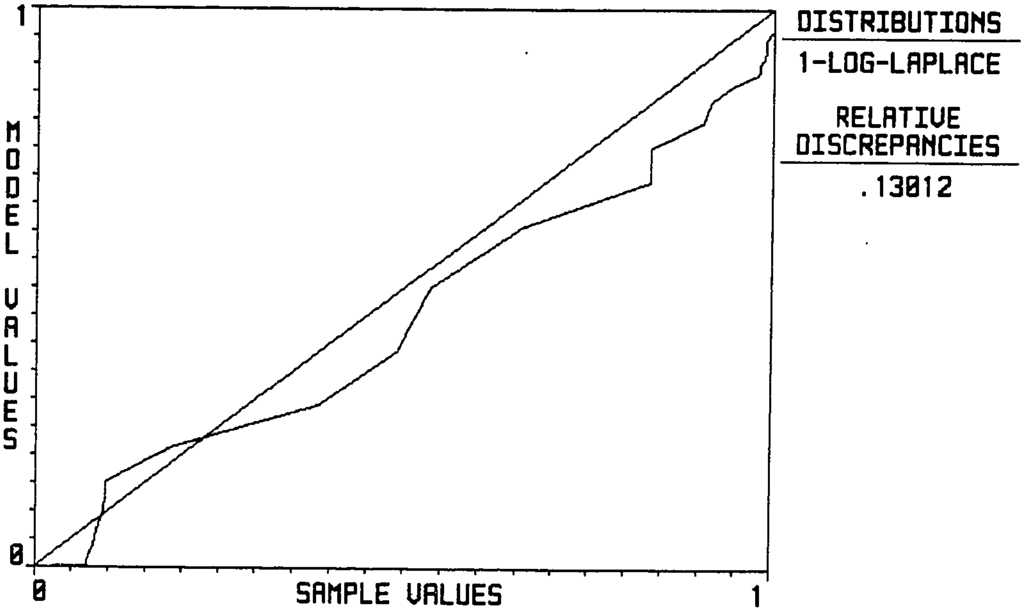

P-P PLOT OF MODEL 3
AND SAMPLE: DATA FROM C2_10.DAT
1
0
MODEL VALUES
0
SAMPLE VALUES
1
DISTRIBUTIONS
3-LOG-LOGISTIC
RELATIVE
DISCREPANCIES
.11301
23:46 22-JAN-99

P-P PLOT OF MODEL 2
AND SAMPLE: DATA FROM C2_10.DAT



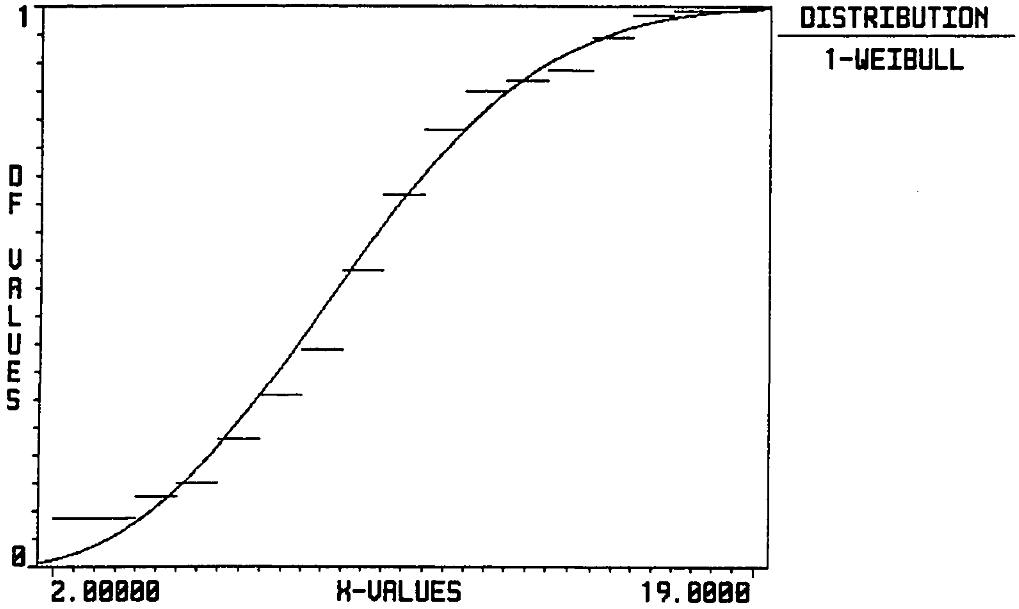
23:47 22-JAN-99

P-P PLOT OF MODEL 1
AND SAMPLE: DATA FROM C2_10.DAT



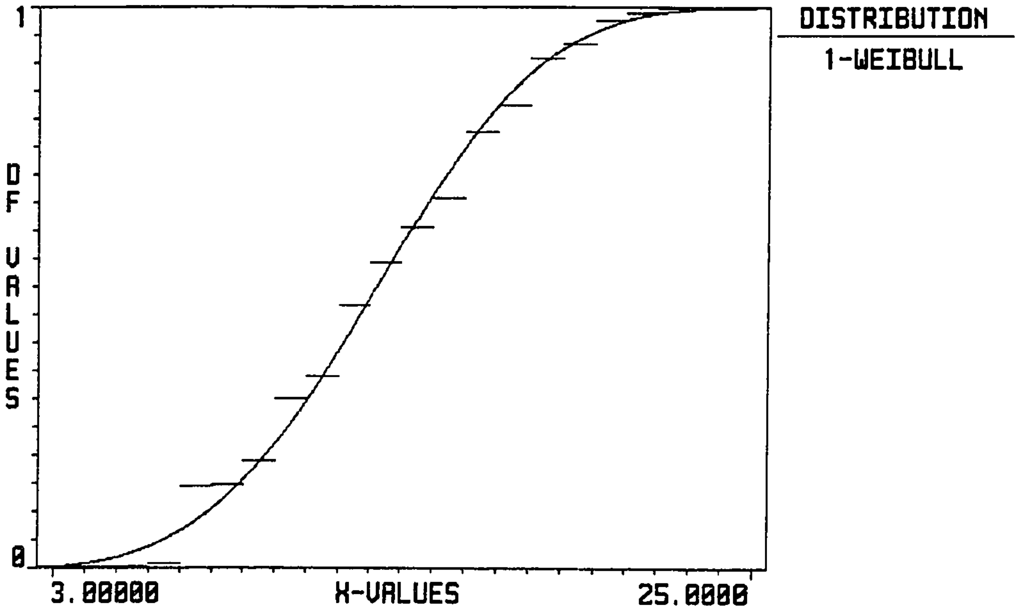
23:48 22-JAN-99

DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM CA12.DAT

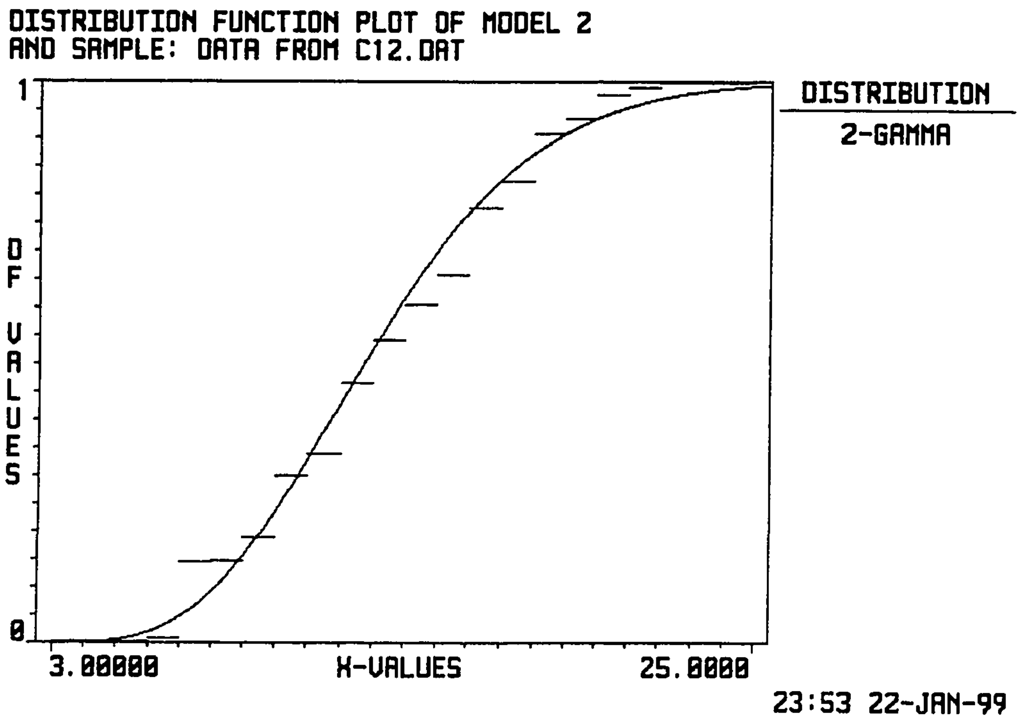


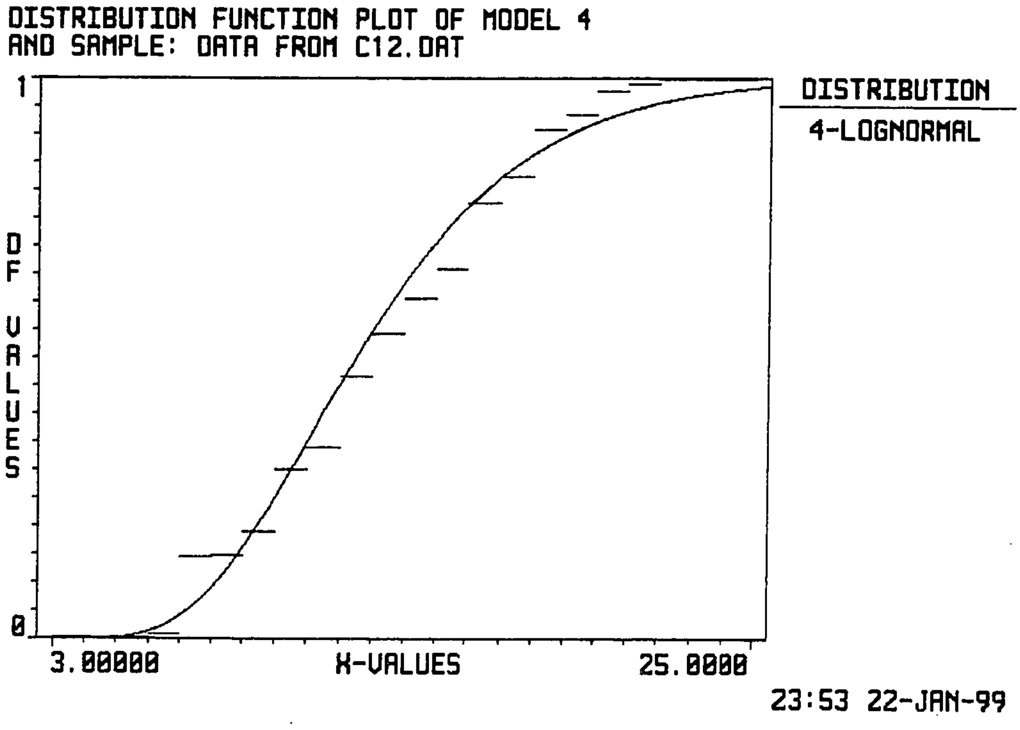
20:13 30-JUN-98

DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM C12.DAT

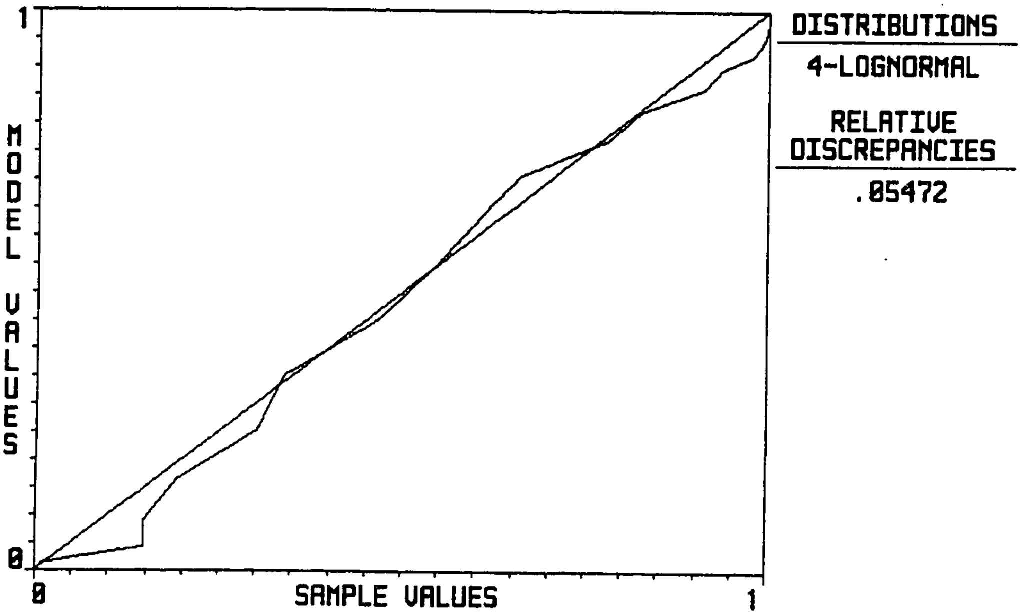


16:51 3-JUL-98


DISTRIBUTION FUNCTION PLOT OF MODEL 2
AND SAMPLE: DATA FROM C12.DAT
1
0
DF VALUES
3.00000
X-VALUES
25.0000
DISTRIBUTION
2-GAMMA
23:53 22-JAN-99

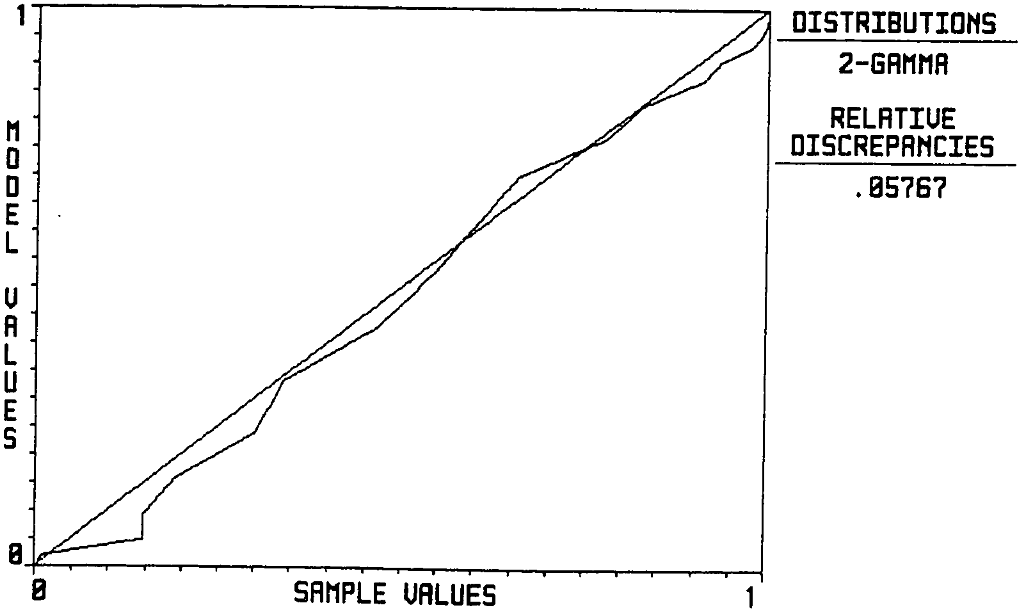

DISTRIBUTION FUNCTION PLOT OF MODEL 4
AND SAMPLE: DATA FROM C12.DAT
1
0
DF VALUES
3.00000
X-VALUES
25.0000
DISTRIBUTION
4-LOGNORMAL
23:53 22-JAN-99

P-P PLOT OF MODEL 4
AND SAMPLE: DATA FROM C12.DAT

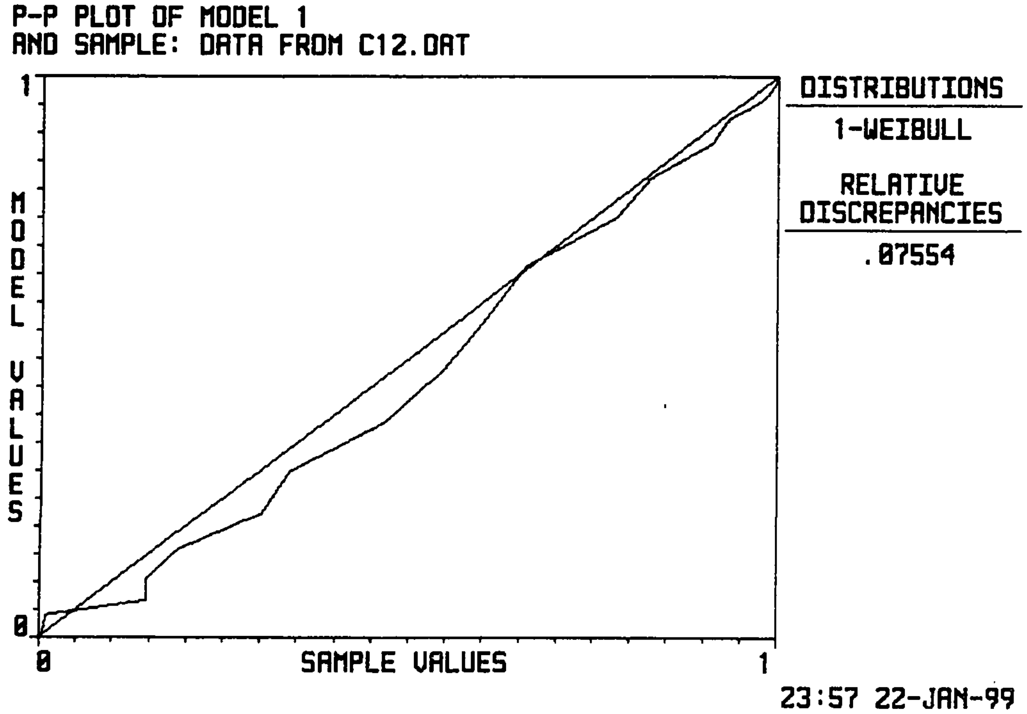


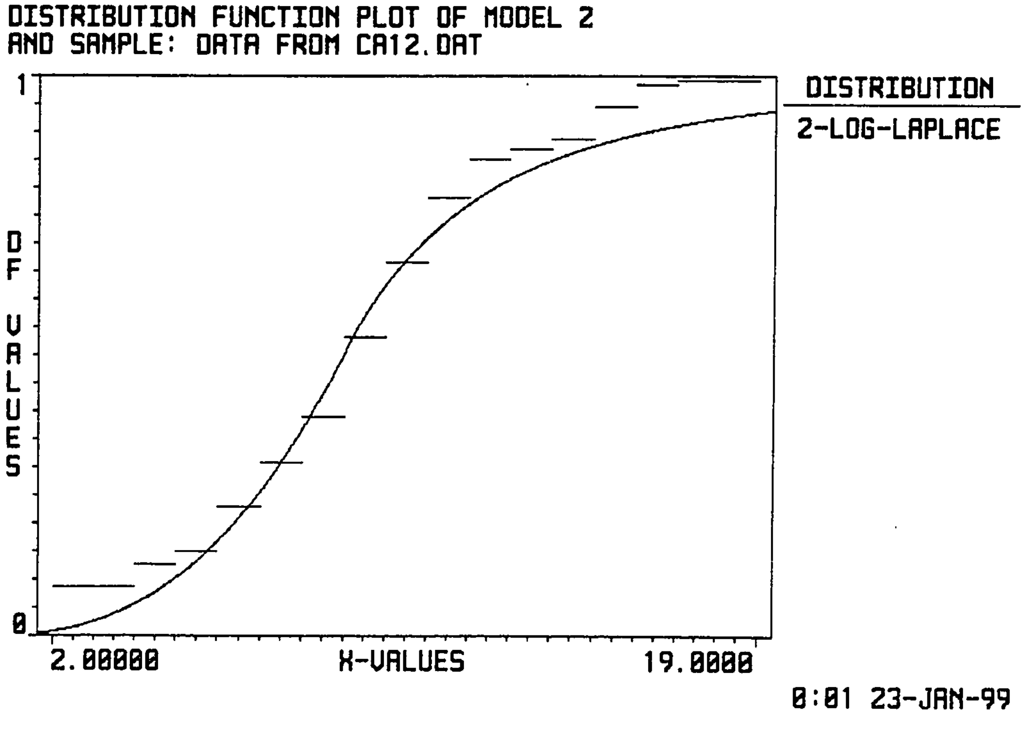
23:55 22-JAN-99

P-P PLOT OF MODEL 2
AND SAMPLE: DATA FROM C12.DAT

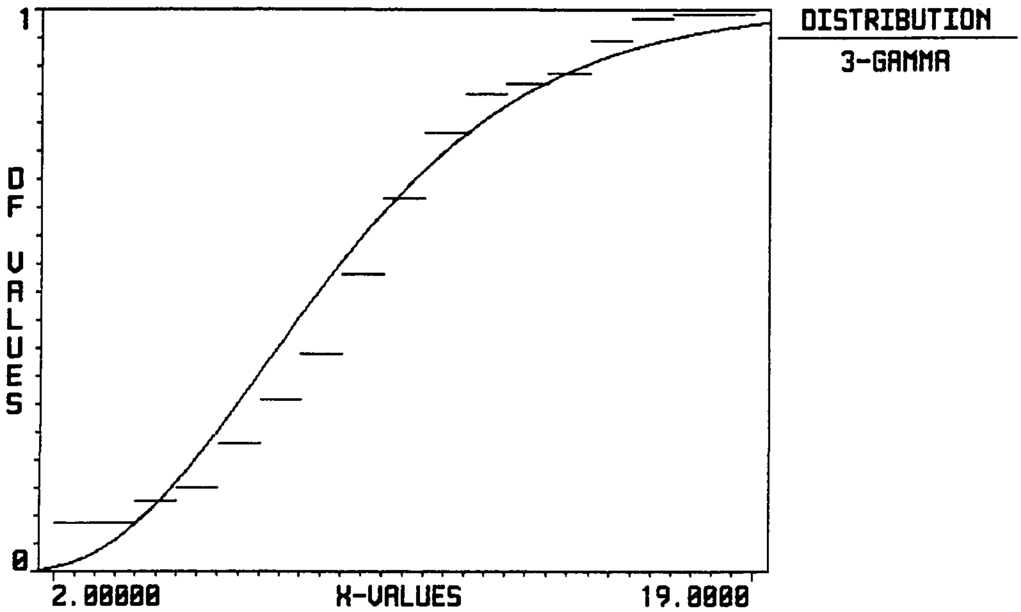


23:56 22-JAN-99


P-P PLOT OF MODEL 1
AND SAMPLE: DATA FROM C12.DAT
1
0
MODEL VALUES
0
SAMPLE VALUES
1
DISTRIBUTIONS
1-WEIBULL
RELATIVE DISCREPANCIES
.07554
23:57 22-JAN-99

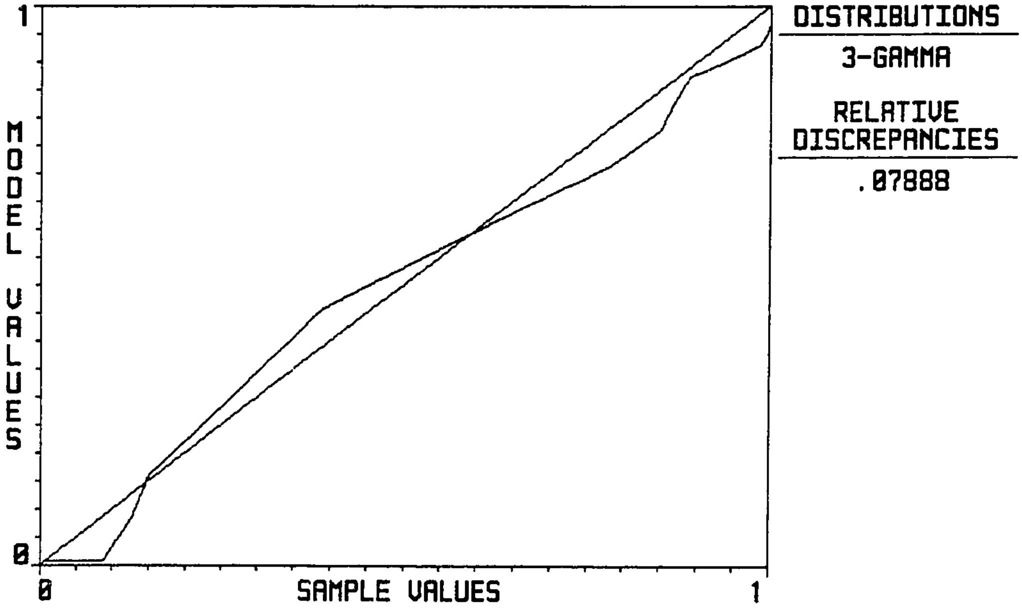

DISTRIBUTION FUNCTION PLOT OF MODEL 2
AND SAMPLE: DATA FROM CA12.DAT
1
0
DF VALUES
2.00000
X-VALUES
19.0000
DISTRIBUTION
2-LOG-LAPLACE
0:01 23-JAN-99

DISTRIBUTION FUNCTION PLOT OF MODEL 3
AND SAMPLE: DATA FROM CA12.DAT

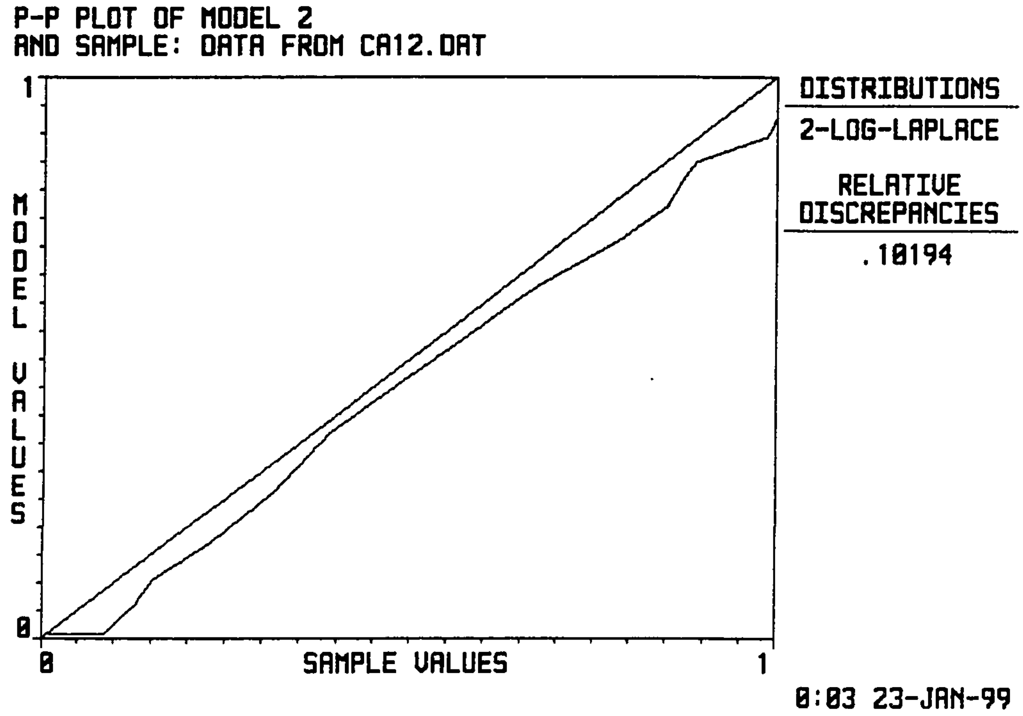


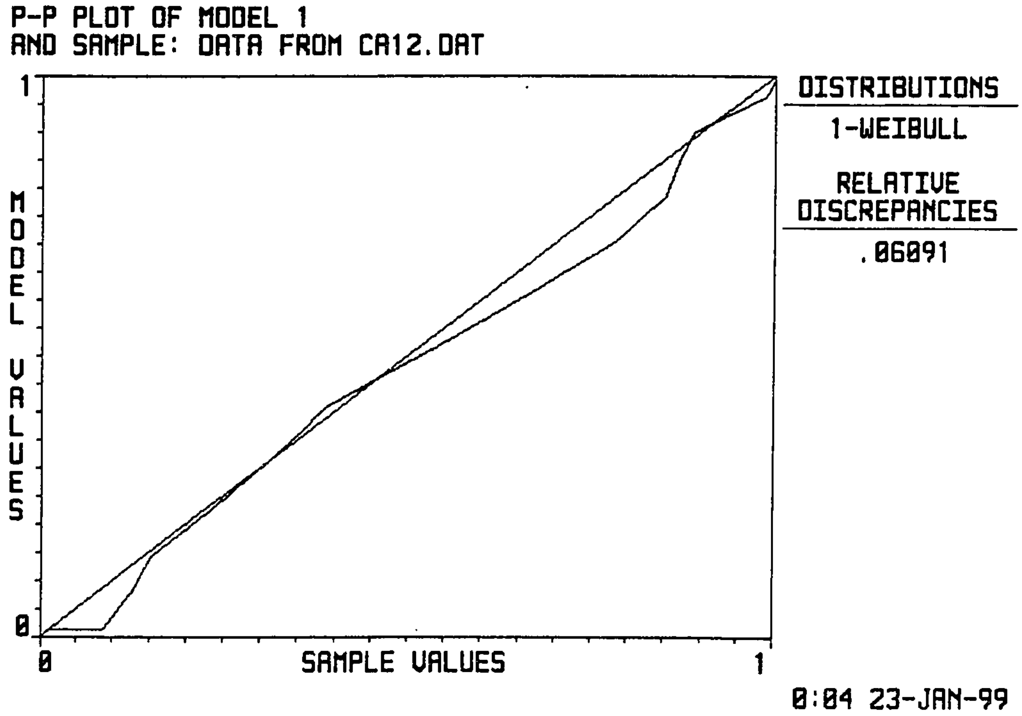
0:01 23-JAN-99

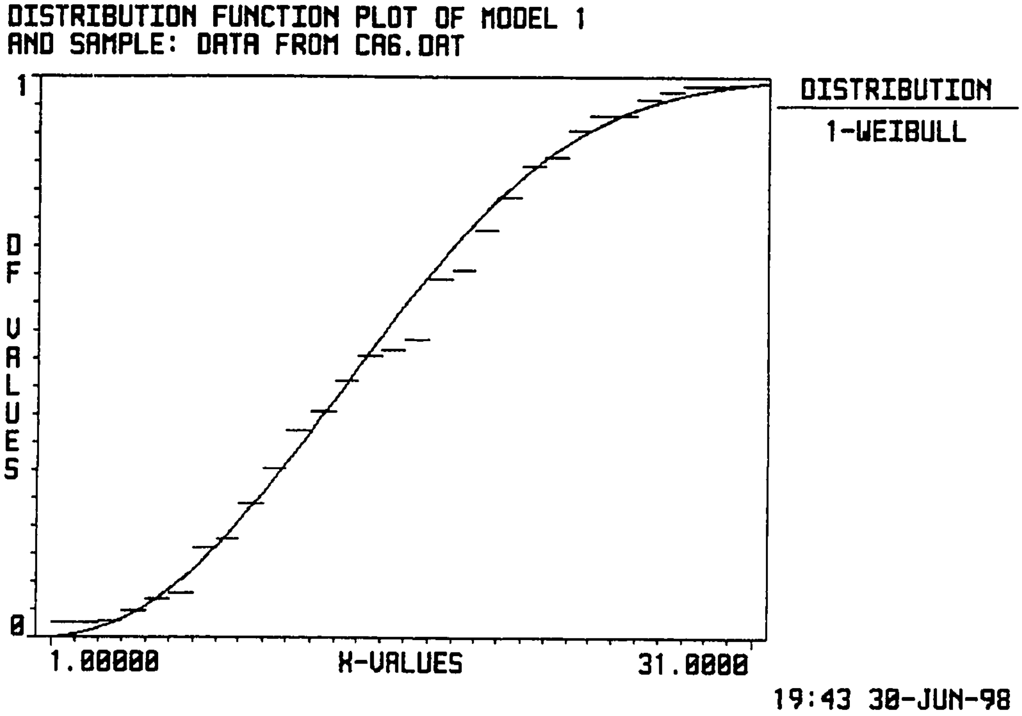
P-P PLOT OF MODEL 3
AND SAMPLE: DATA FROM CA12.DAT



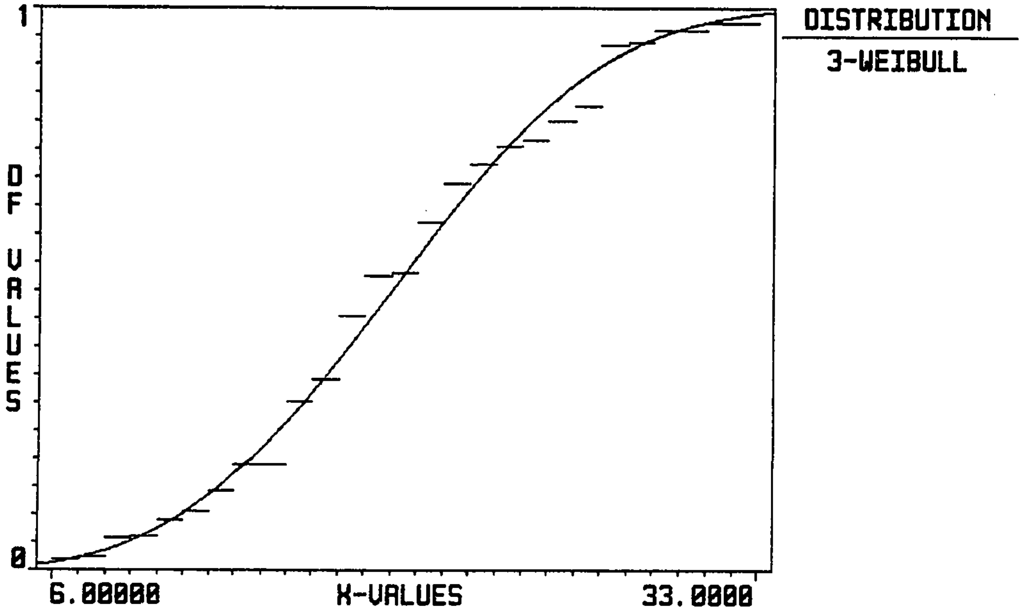
0:02 23-JAN-99


P-P PLOT OF MODEL 2
AND SAMPLE: DATA FROM CA12.DAT
1
0
MODEL VALUES
0
SAMPLE VALUES
1
DISTRIBUTIONS
2-LOG-LAPLACE
RELATIVE DISCREPANCIES
.10194
0:03 23-JAN-99


P-P PLOT OF MODEL 1
AND SAMPLE: DATA FROM CA12.DAT
1
0
MODEL VALUES
0
SAMPLE VALUES
1
DISTRIBUTIONS
1-WEIBULL
RELATIVE DISCREPANCIES
.06091
0:04 23-JAN-99

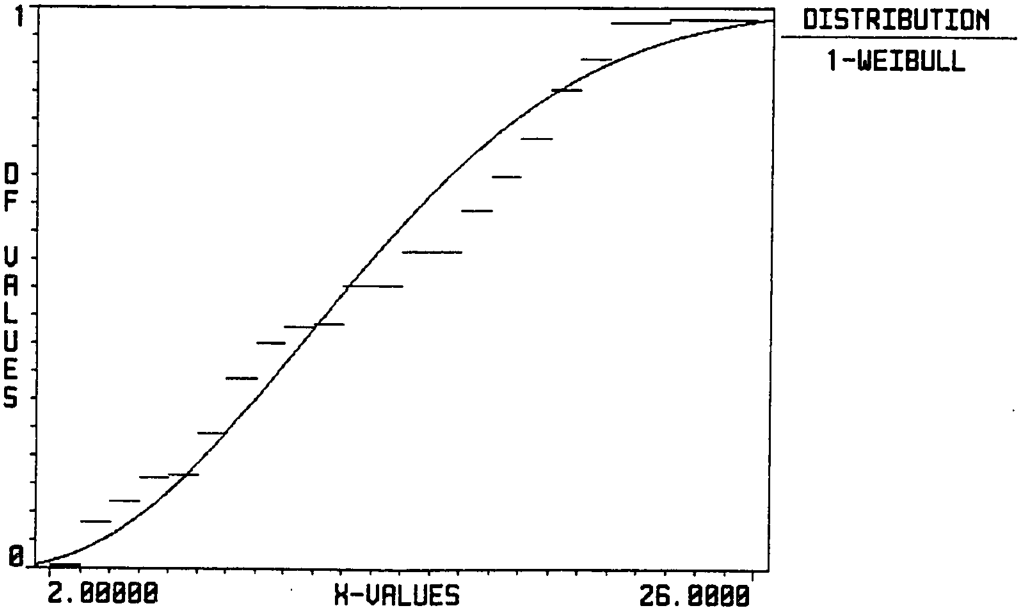

DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM CA6.DAT
1
0
DF VALUES
1.00000
X-VALUES
31.0000
DISTRIBUTION
1-WEIBULL
19:43 30-JUN-98

DISTRIBUTION FUNCTION PLOT OF MODEL 3
AND SAMPLE: DATA FROM CA8.DAT

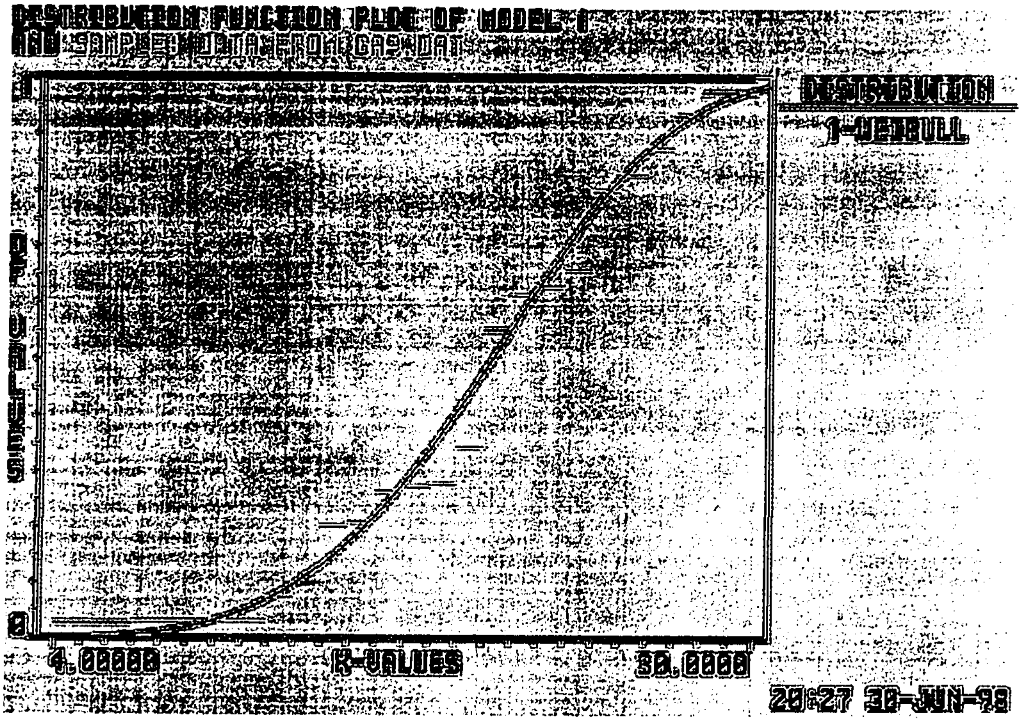


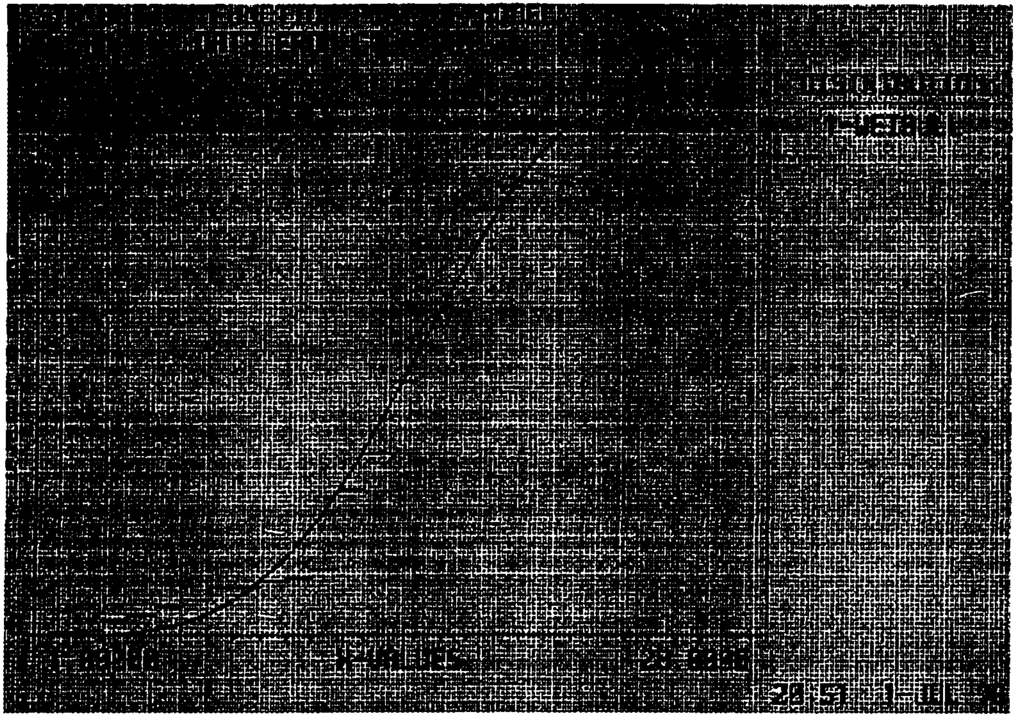
19:50 30-JUN-98

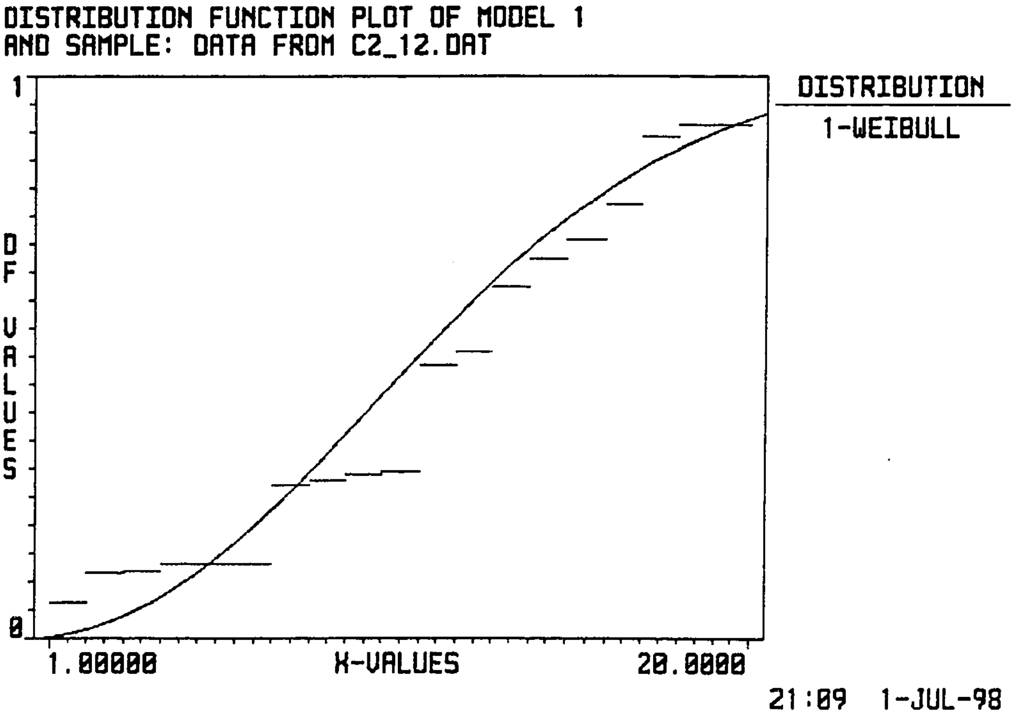
DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM CA14.DAT

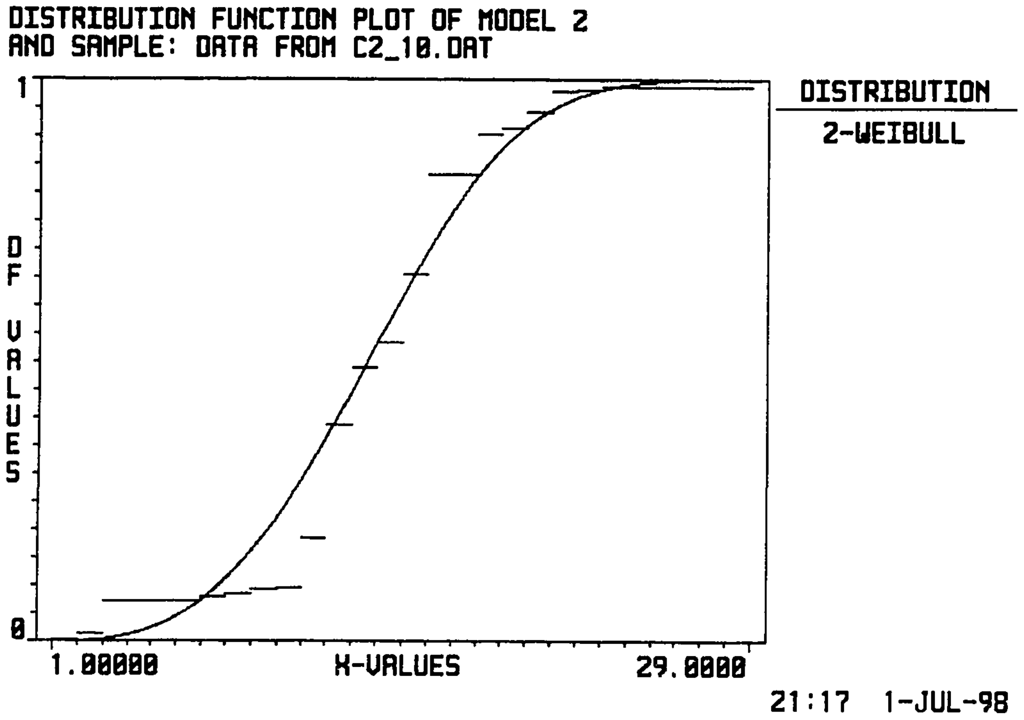


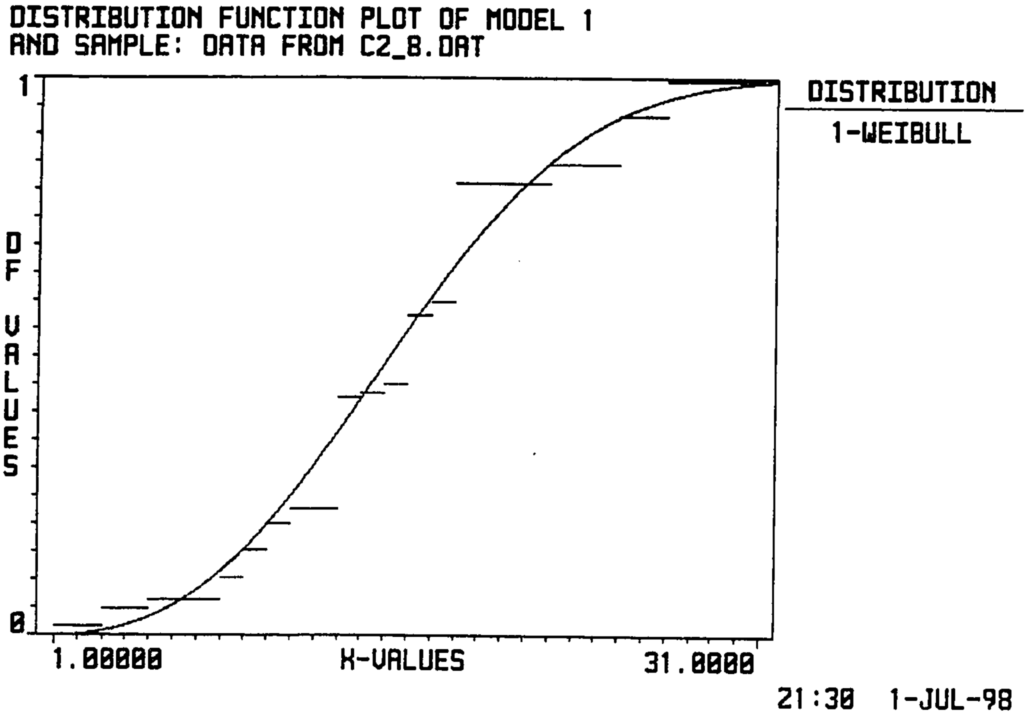
20:20 30-JUN-98


DISTRIBUTION FUNCTION PLOT OF MODEL-1
AND SAMPLE DATA FROM GAP.DAT
DISTRIBUTION
1-WEIBULL
1
0
SAMPLE
4.00000
K-VALUES
30.0000
20:27 30-JUN-98

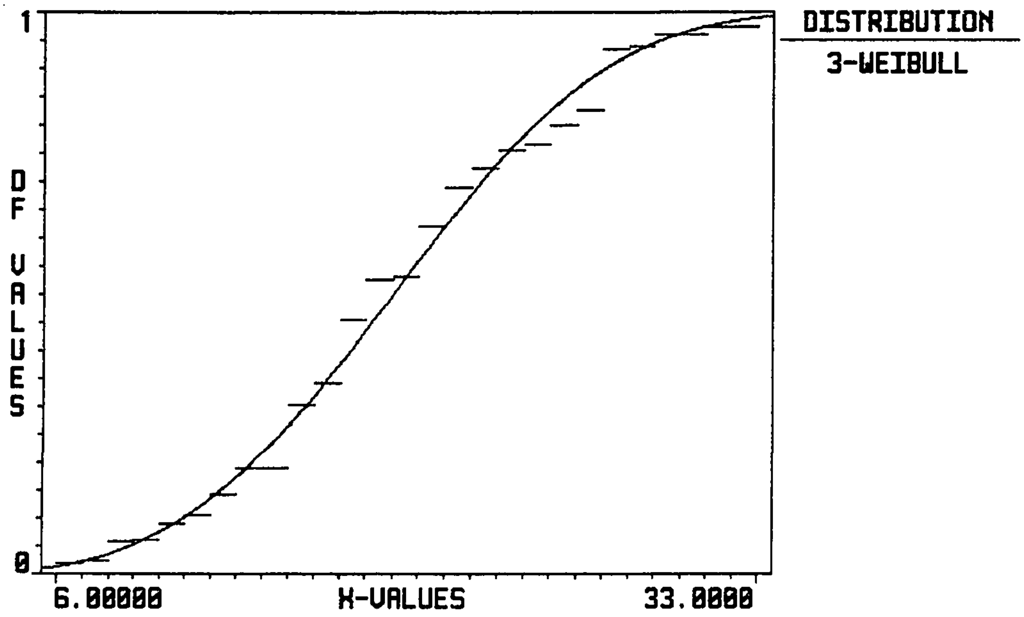



DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM C2_12.DAT


DISTRIBUTION FUNCTION PLOT OF MODEL 2
AND SAMPLE: DATA FROM C2_10.DAT
1
0
DF VALUES
1.00000
X-VALUES
29.0000
DISTRIBUTION
2-WEIBULL
21:17 1-JUL-98

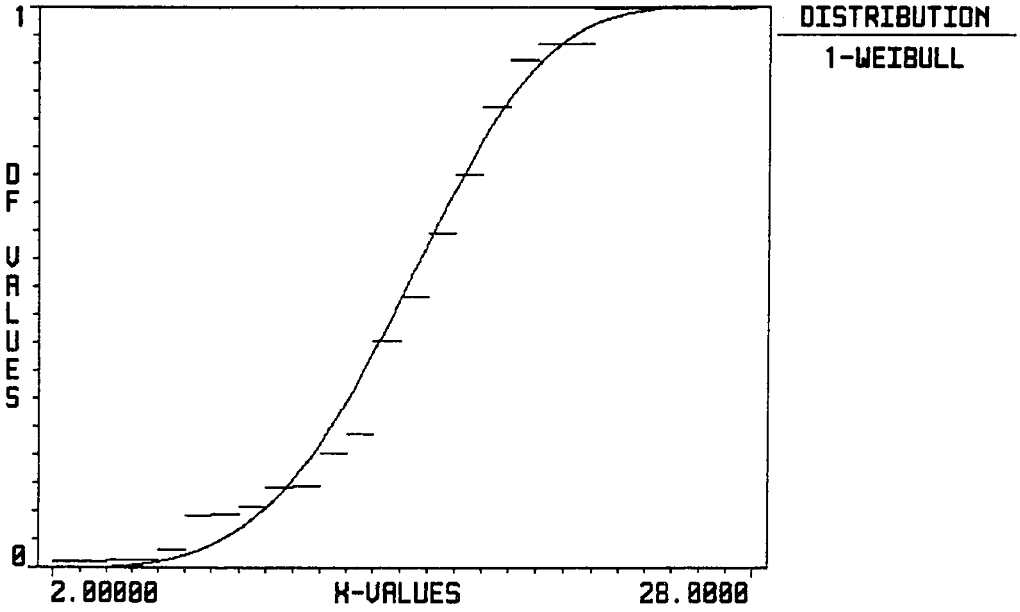
DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM C2_8.DAT
1
0
DF VALUES
1.00000
X-VALUES
31.0000
DISTRIBUTION
1-WEIBULL
21:30 1-JUL-98

DISTRIBUTION FUNCTION PLOT OF MODEL 3
AND SAMPLE: DATA FROM CA8.DAT

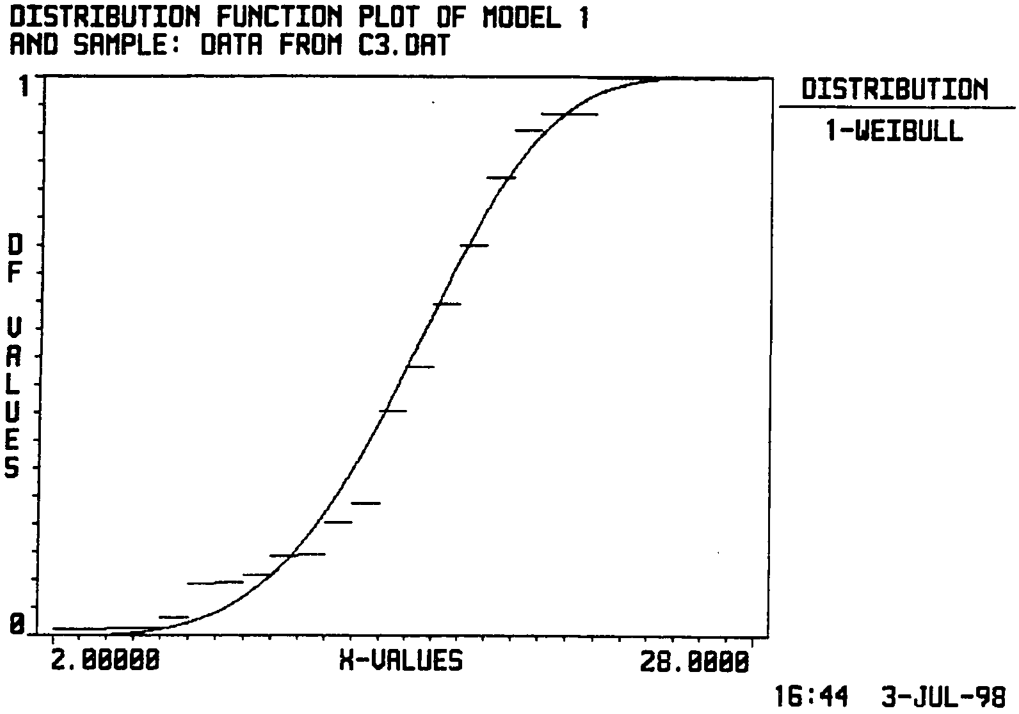


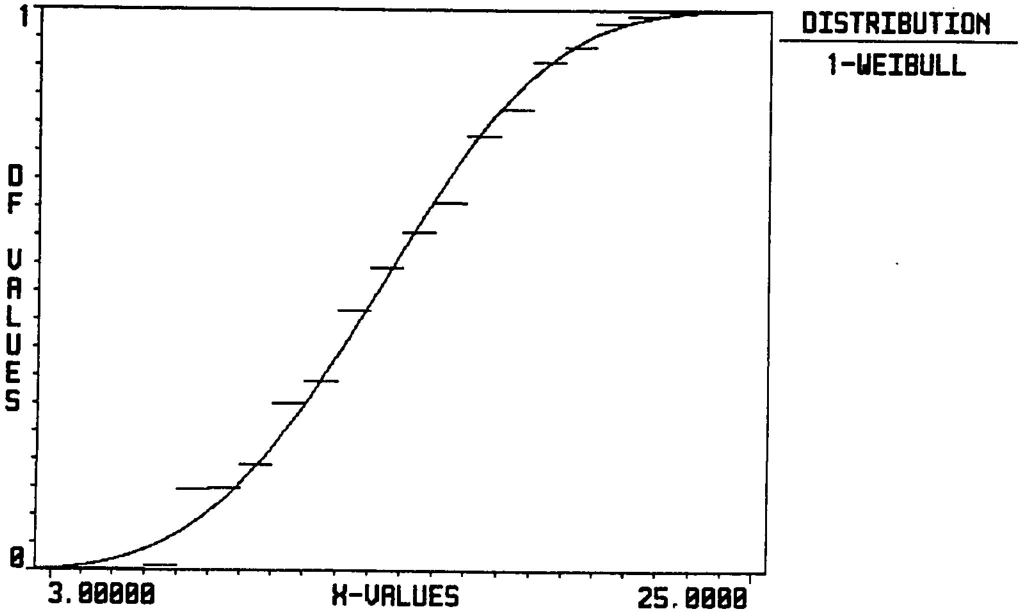
21:40 1-JUL-98

DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM C3.DAT

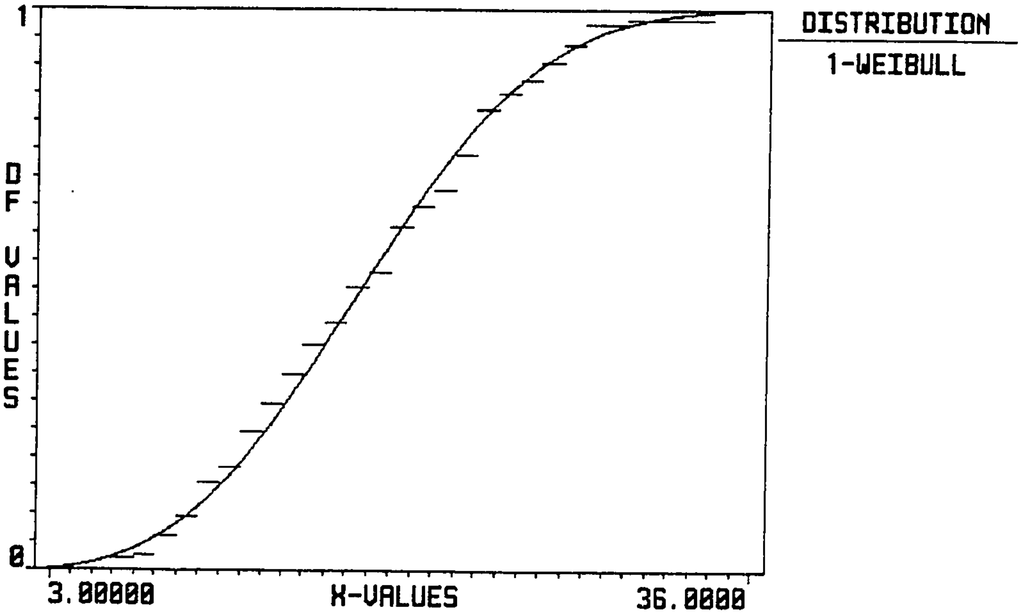


16:44 3-JUL-98


DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM C3.DAT
1
0
DF VALUES
2.00000
X-VALUES
28.0000
DISTRIBUTION
1-WEIBULL
16:44 3-JUL-98

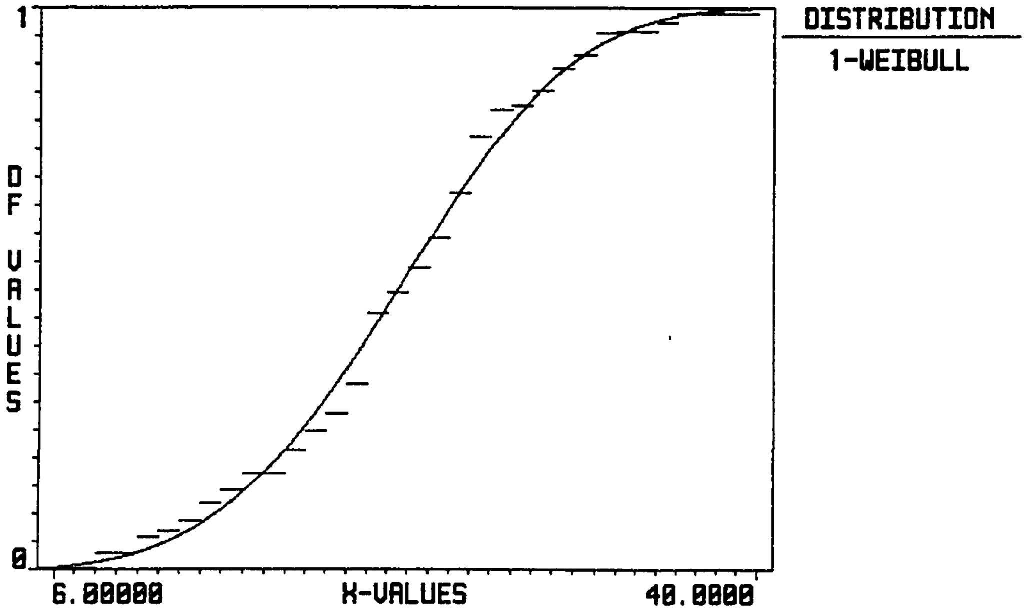

DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM C12.DAT

16:51 3-JUL-98


DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM C6.DAT

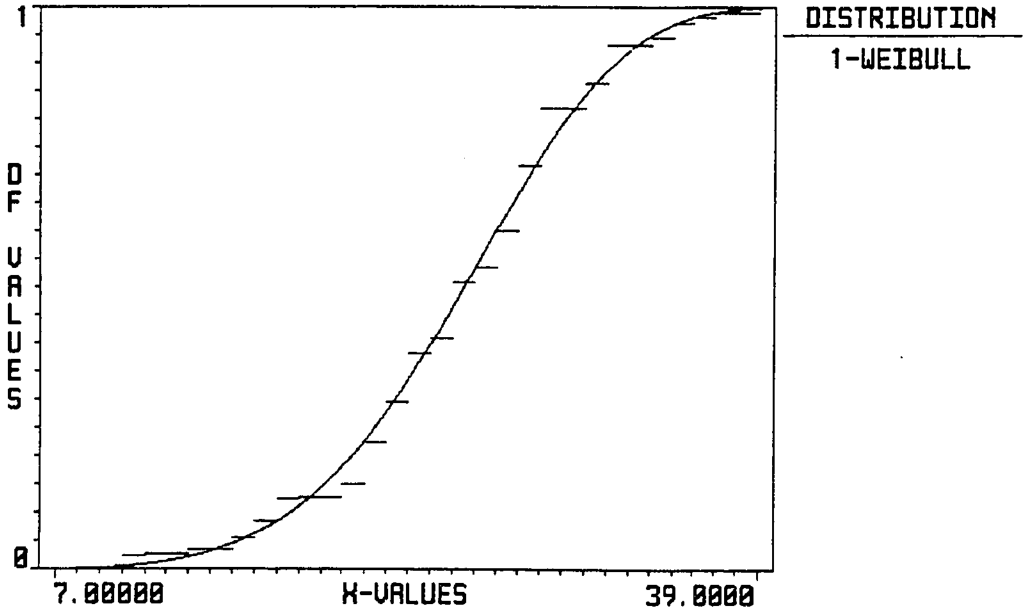
16:58 3-JUL-98

DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM C8.DAT

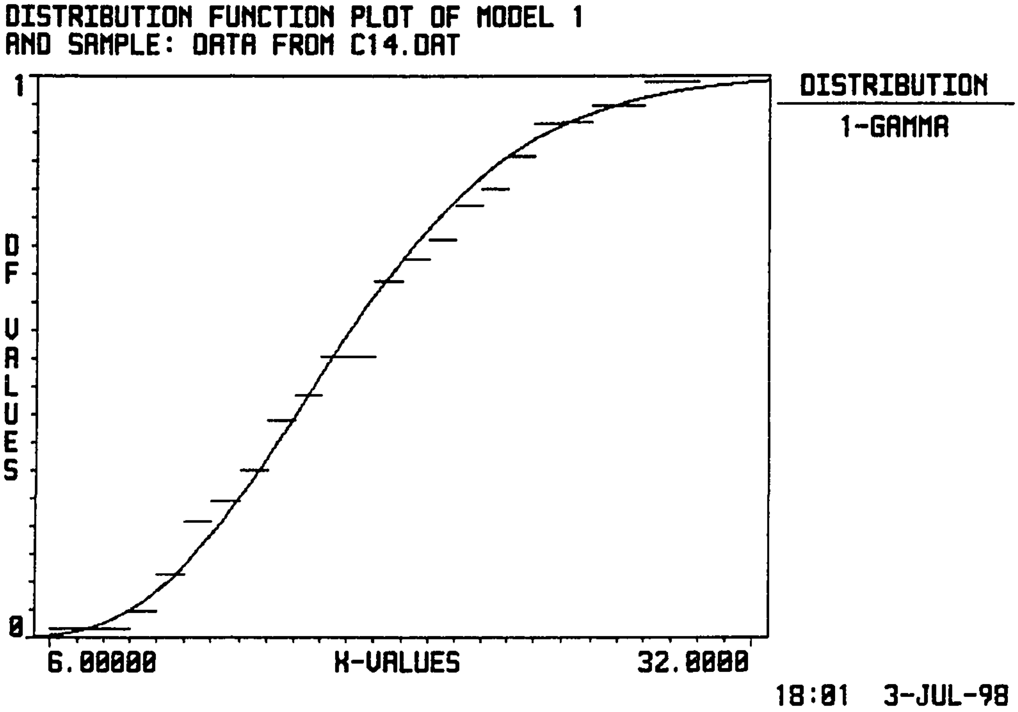


17:14 3-JUL-98

DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM C9.DAT



17:52 3-JUL-98


DISTRIBUTION FUNCTION PLOT OF MODEL 1
AND SAMPLE: DATA FROM C14.DAT
1
0
DF VALUES
6.00000
X-VALUES
32.0000
DISTRIBUTION
1-GAMMA
18:01 3-JUL-98