RELIABILITY, DAMAGE, AND SEASONAL CONSIDERATIONS IN THE MNPAVE MECHANISTIC-EMPIRICAL ASPHALT PAVEMENT DESIGN COMPUTER PROGRAM

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INTRODUCTION

Mn/DOT is in the process of upgrading its Mechanistic-Empirical asphalt pavement design software (MnPAVE). In the process of evaluating the existing software, some problems with the reliability method (allowed repetitions method) were encountered. This paper presents a description of these problems and proposes the implementation of a new reliability method (damage factor method). In order to compare the reliability methods, eight pavement designs corresponding to a previous study were analyzed. In this study, two low-volume and two high-volume pavements designed using FLEXPAVE were evaluated with the existing program. Simulations were conducted to determine the damage factors and reliabilities of the FLEXPAVE designs. A memo to the M/E Design Implementation Group at Mn/DOT describes the original study (see Appendix A).

Two empirical fatigue damage models are being considered for the new software version. The transfer function used in the current version was developed at the University of Illinois and was modified using Mn/ROAD fatigue cracking data. The only input for this model is horizontal strain at the bottom of the asphalt layer. The other transfer function was developed by Dr. Fred Finn and uses both horizontal strain and asphalt modulus.

Additional default values are being developed for season lengths, mean pavement temperatures, and modulus values. Air temperature data for 27 weather stations across Minnesota were obtained from the Midwest Climate Information System (MICIS). Mn/DOT criteria were used to determine average season lengths for nine climatic division in Minnesota. The weather data will be studied further to determine if fewer climatic divisions are appropriate.

Currently, two methods of determining the modulus of the asphalt layer are being evaluated. The method currently used relies on an empirical equation derived from Mn/ROAD data. Its only input is pavement temperature. The other method is based on a model developed by Dr. Matthew Witczak for the 2002 pavement design guide. The Witczak model takes into consideration several variables related to asphalt mix design including asphalt viscosity, asphalt content, air voids, and aggregate gradation. Also needed are default modulus values for various soil and aggregate base types. Results of Mn/DOT lab and field tests as well as data from other sources will be evaluated for this purpose.

COMPARISON OF RELIABILITY METHODS

Input Values

Input values for this study were chosen to correspond as closely as possible to those of the original FLEXPAVE study. In addition to the original FLEXPAVE values, load spectra traffic input and thicker asphalt layers were included. Cases with lower variability in the modulus values were also studied. In order to compare the load spectra and ESAL methods, weigh-in-motion (WIM) measurements from Mn/ROAD were used to generate generic load spectra that roughly corresponded to the ESALs used in the original FLEXPAVE study. New ESAL values were then calculated from these load spectra using the 1993 AASHTO Pavement Design Guide. A complete listing of the input values used in this study is located in Appendix B.

Monte Carlo Reliability Method

MnPAVE uses Monte Carlo simulation to calculate the reliability (probability of success) of a given pavement design. The Monte Carlo Method works by randomly selecting input values from known distributions, and generating an output distribution from which probabilities can be determined.

Layer thicknesses are assumed to be normally distributed, and layer moduli are assumed to be lognormally distributed. Variability is expressed as a coefficient of variation (CV). The CV is calculated as shown in Equation 1.

$$CV = 100 \times \frac{\text{StandardDeviation}}{\text{Mean}} \tag{1}$$

Seasons are assumed to be of constant length, and the traffic distribution (whether described by ESALs or load spectra) is assumed to be constant (CV = 0).

Number of Monte Carlo Cycles

During the development of the original program (ROADENT), it was determined that 5,000 cycles were sufficient to produce repeatable results in a four-season, single load class (ESAL) design. For this comparison, the number of cycles was increased to 65,000 for load spectra designs using the allowed repetitions method to ensure accurate distributions were produced. The 65,000 cycle simulations required several hours of computing time on a Pentium II machine.

For the damage factor method, 2,000 cycles were used for both ESAL and load spectra designs. There was no need to increase this value for load spectra designs because all load classes are included in every cycle. Load spectra designs using this method also required several hours.

Allowed Repetitions Reliability Method

To calculate reliability, ROADENT runs a number of Monte Carlo cycles (the default is 5,000). The inputs for each cycle consist of the following:

1. Randomly selected thickness from each layer's respective distribution.

2. Randomly selected modulus from a randomly selected season (the probability of selecting a given season is determined by the season length).

3. Randomly selected axle type and load (the probability of selecting a given axle is determined by its relative frequency in the entire load distribution).

The allowed repetitions are then calculated. Once a sufficient number of cycles have been completed, a distribution of allowed repetitions can be generated. The reliability is determined by the percentage of cases where the allowed repetition value is greater than total number of axle loads (from all load categories).

This method is summarized by the flow chart in Figure C-1 (Appendix C).

Extreme Value Type 1 Distribution

To calculate the reliability of a pavement design, ROADENT assumed the output was best modeled by an Extreme Value Type 1 distribution for ln(N). However, this distribution did not fit well in many cases. When a single season was selected and typical load spectra were used, this distribution provided a fairly good fit (see Figure 1). However, multiple seasons resulted in multi-modal distributions that did not resemble the Extreme Value distribution (see Figure 2), and a the output for a single season with ESALs was better modeled by a normal distribution (see Figure 3).

A poor fit between the data and the assumed distribution resulted in errors in the calculated reliability. To quantify these errors, the reliability was calculated using the actual distribution of N values (see Figure 4). This is accomplished by dividing the number of cycles that result in a satisfactory result (n < N) by the total cycles. A comparison of results from these two methods is shown in Table 1.

For the remainder of this analysis, the Extreme Value Type 1 assumption was discarded and all reliability calculations were made using the actual distribution.

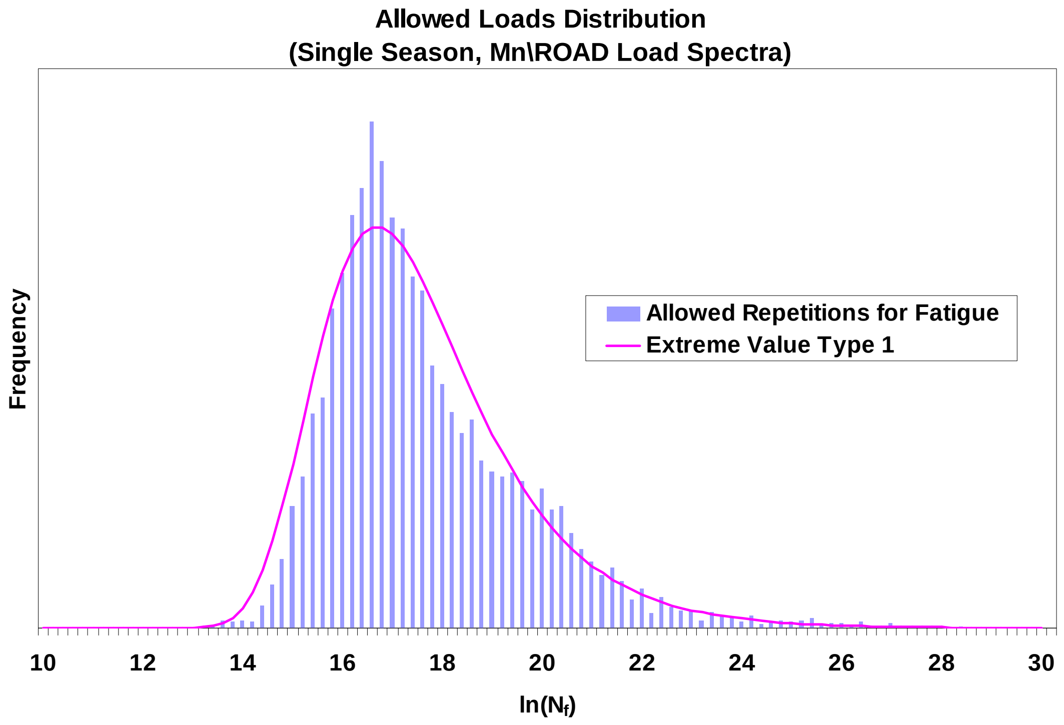


Figure 1 Single Season Load Spectra Output

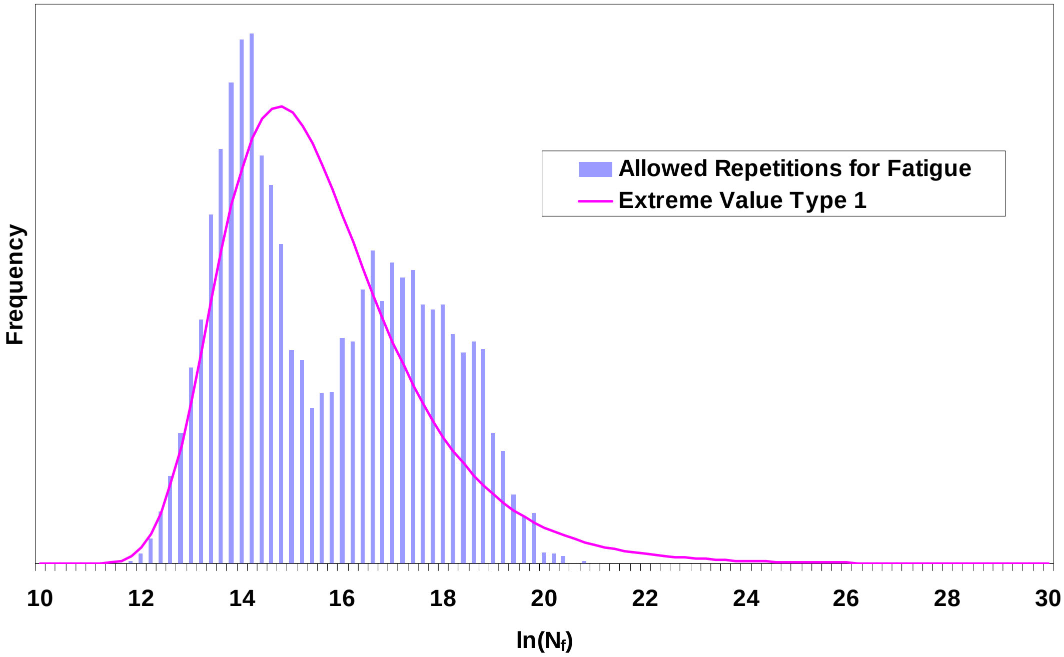


Figure 2 Four Season ESAL Output

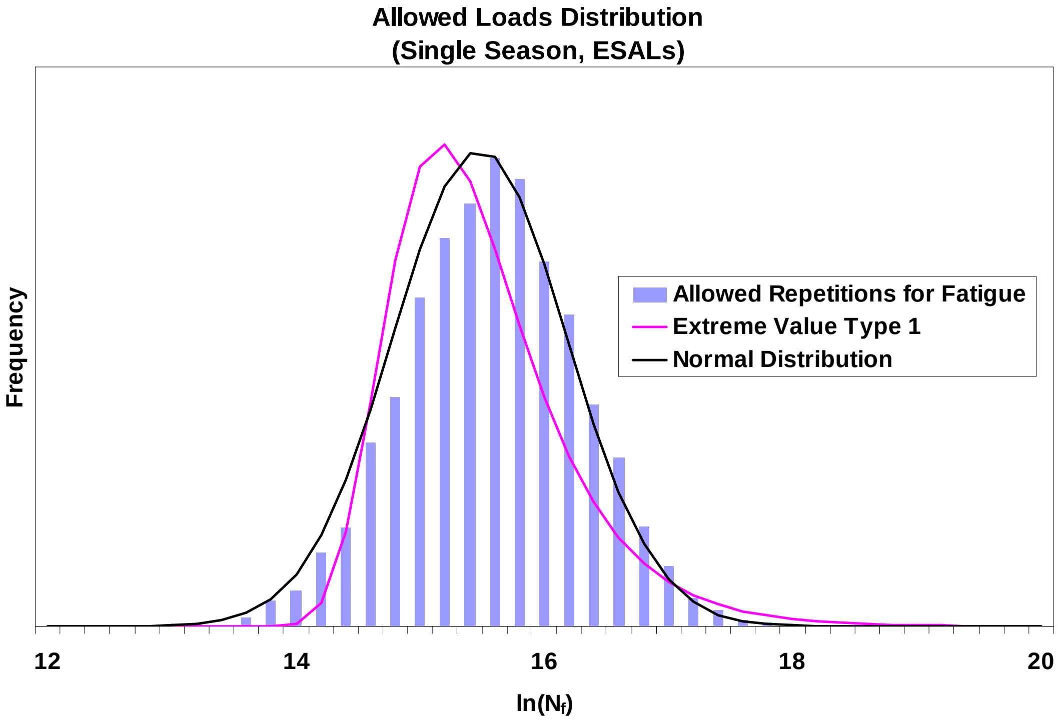


Figure 3 Single Season ESAL Output

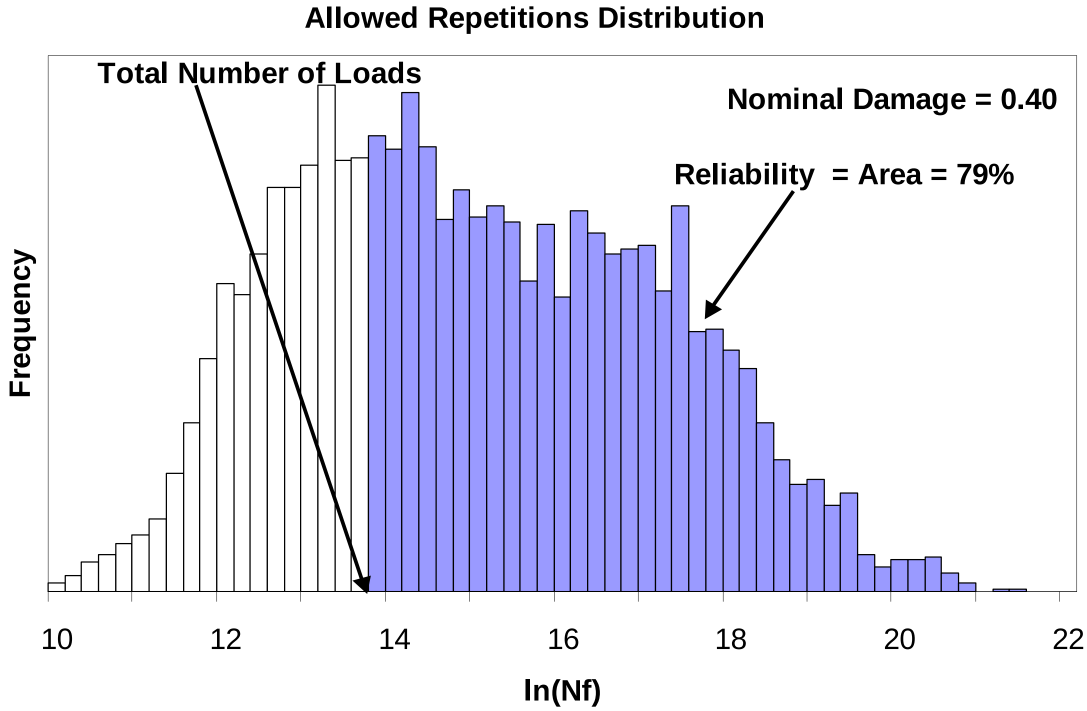


Figure 4 Example of Allowed Repetitions Reliability Calculation

Table 1 Comparison of Reliability Values From Assumed Extreme Value Type 1 Distributions and Actual Allowed Repetitions Distributions in ROADENT

Design	Fatigue Reliability		Rutting Reliability	
	Extr. Value Distribution	Actual Distribution	Extr. Value Distribution	Actual Distribution
Load Spectra, 6.8" AC	59%	61%	62%	63%
Load Spectra, 10" AC	89%	85%	87%	85%
ESAL, 6.8" AC	52%	51%	43%	46%
ESAL, 10" AC	83%	88%	76%	73%

Proposed Damage Factor Reliability Method

In the proposed damage factor reliability method, a damage factor (based on Miner's Hypothesis) is calculated for each Monte Carlo cycle. Seasonal modulus values are selected from distributions specific to each season. All seasons and axle loads are included in each Monte Carlo cycle. Once a sufficient number of Monte Carlo cycles have been completed, a distribution of damage factors is generated. The reliability corresponds to the percentage of cases where the damage is less than 1 (see Figure 5). This method is summarized by the flow chart in Figure C-2 (Appendix C).

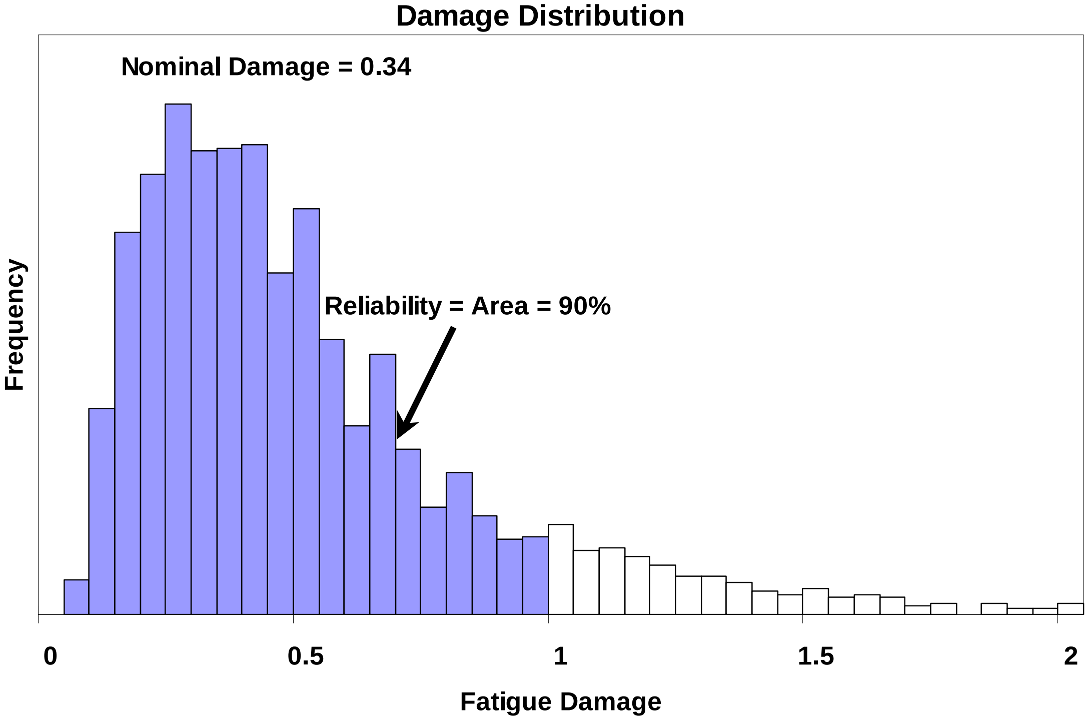


Figure 5 Example of Damage Factor Reliability Calculation

Comparison of the Allowed Repetitions and Damage Factor Methods

Similarities

One would expect a reliability method that compares actual to allowed repetitions to produce the same output as a method based on calculated damage (the ratio of actual to allowed repetitions). This is the case for a single season with a single load class (ESALs); given sufficient Monte Carlo cycles, the two methods produce nearly identical reliability values (see Figures 6 and 7). However, when multiple seasons and load spectra are used, the two methods produce very different results. The probable reason for this discrepancy is the fact that in cases with multiple seasons or loading conditions, the Allowed Repetition Distribution method deviates from Miner's Hypothesis (summing damage ratios for each loading condition and seasonal variation).

Relationship Between Damage and Reliability

An inverse relationship between damage factors and reliability is expected (a pavement with low calculated damage should have high reliability). While the Allowed Repetitions model produces apparently reasonable reliability values for damage values less than 1, the introduction of multiple seasons and loading conditions results in unusually high reliability values for damage factors greater than 1 (see Figures 6 and 7). The damage factor method produces reliability values that follow the same general trend regardless of seasonal and loading variations.

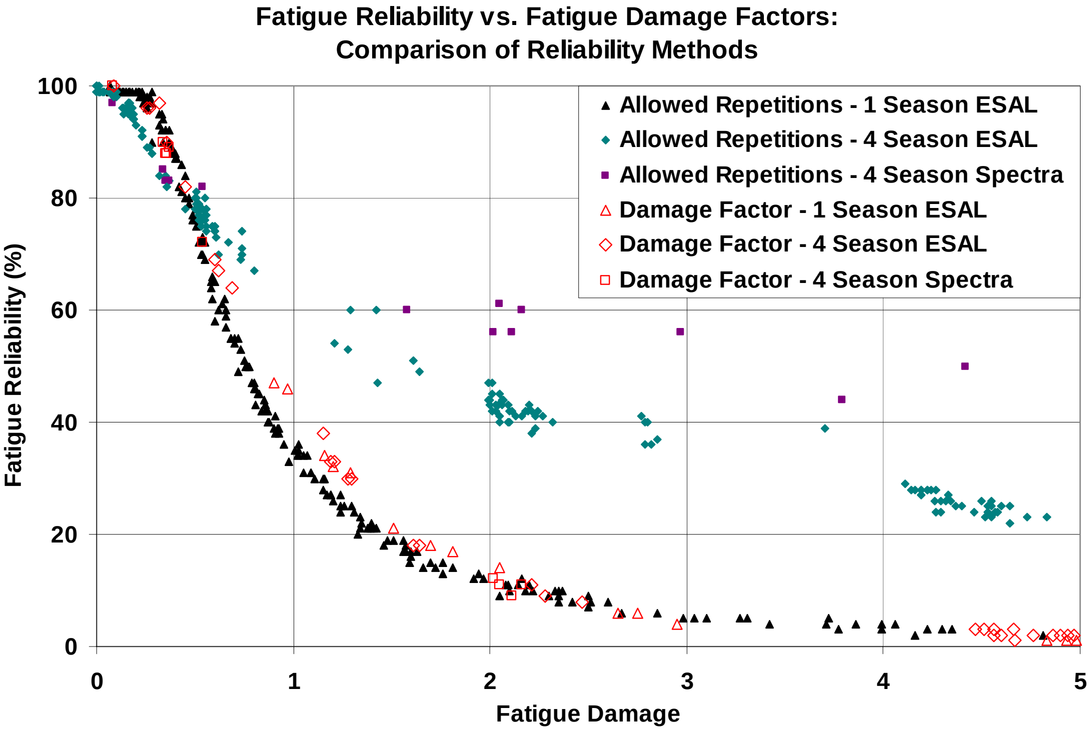


Figure 6 Anomalies in Fatigue Reliability Calculations

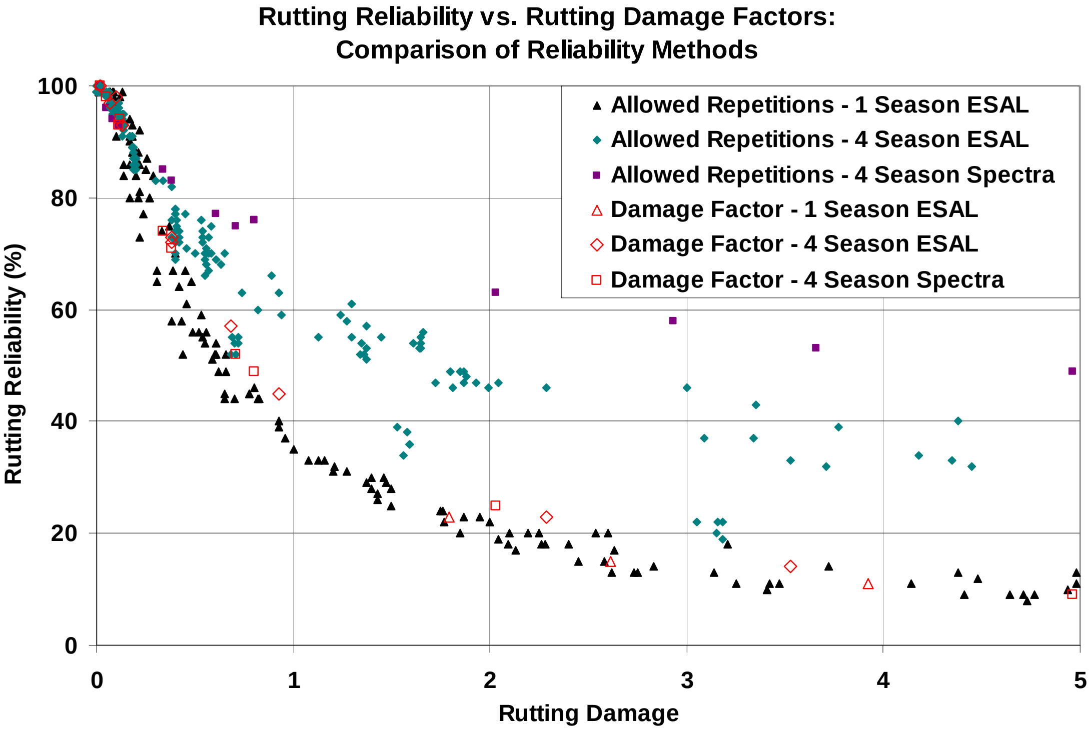


Figure 7 Anomalies in Rutting Reliability Calculations

High and Low Input Coefficients of Variation

In order to evaluate the effect of input variability on the calculated reliability, two levels of modulus variability were simulated. In the "High CV" cases, the default values from the ROADENT program were used (30%, 40%, 40%, and 50% CV for the asphalt, base, subbase, and soil layers, respectively). In the "Low CV" cases, these values were changed to 20%, 30%, 30%, and 40%, respectively.

The allowed repetitions method is relatively insensitive to changes in coefficient of variation, especially in the load spectra mode. A comparison of the two reliability methods for rutting is shown in Figure 8.

One notable effect of lowering the input CV (decreasing variability) in cases where the reliability is less than 50% is a decrease in reliability. This is because the area of concern is located in the lower tail of the output distribution. Lowering the variability decreases the size of the tails, which reduces the area used in the reliability calculation (see Figure 9).

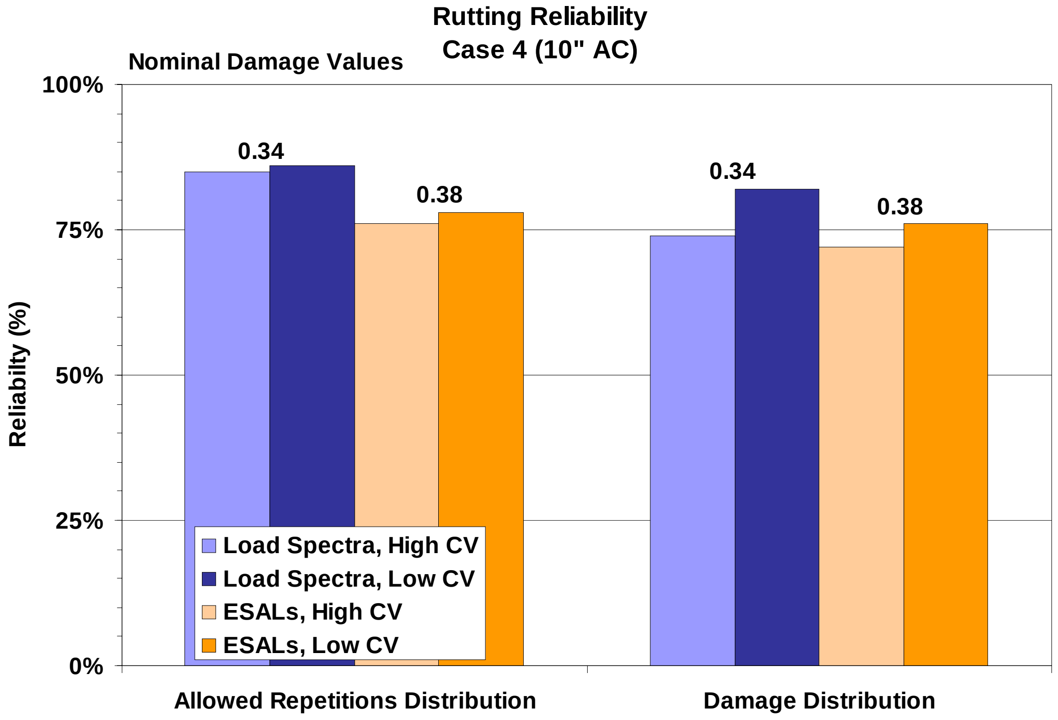


Figure 8 Comparison of Sensitivity to Changes in Modulus Variability

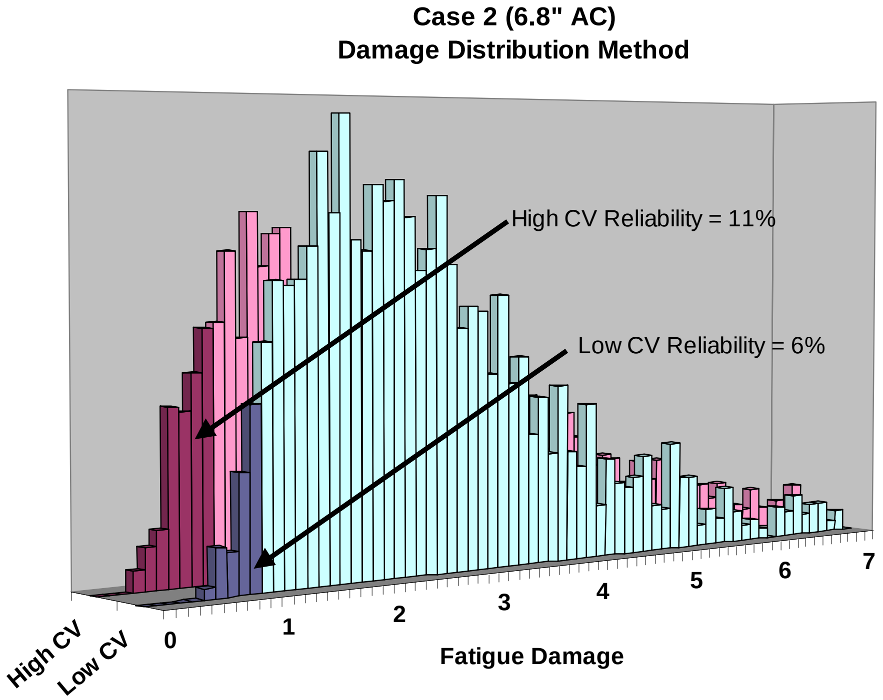


Figure 9 Comparison of Low Reliability Values for High and Low Input CV

Analysis of Reliability Methods

The anomalous reliability values predicted by the Allowed Repetitions method can be explained by examining the reliability methods in more detail. The Allowed Repetitions reliability calculation is summarized in Equation 2.

$$Reliability = 100 \times \frac{\text{number of cycles where } N > n}{\text{total number of cycles}} \qquad (2)$$

Where:

N = Allowed repetitions for a given cycle
n = Total repetitions for all axles and load classes

In the case of a single season and single load class, damage can be calculated as shown in Equation 3.

$$Damage = \frac{n}{N} \qquad (3)$$

In the case of multiple seasons and load classes, Miner's Hypothesis must be used to calculate damage as shown in Equation 4.

$$Damage = \sum_j \sum_i \frac{n_{season_i, load_j}}{N_{season_i, load_j}} \qquad (4)$$

Appendix A

FLEXPAVE Study

Minnesota Department of Transportation

MEMO

Office of Materials and Road Research
Road Research Section

DATE: November 2, 2000

TO: M/E Design Implementation Group

FROM: Dave Van Deusen Research Operations Engineer

PHONE: (651) 779-5514

SUBJECT: Meeting notes for February 1-3, 1998

PRESENT: D. Young, D. Bullock, J. Siekmeier, S. Dai, D. Van Deusen

At the last meeting of the full M/E group on January 29, 1998, the final report and beta version of ROADENT were delivered. That was the final meeting of that group. It was decided that a new M/E group should be created for purposes of implementing M/E design procedures. It was also decided that the membership of the group should remain the same.

At the January 29 meeting G. Cochran showed the results of an analysis that he had done comparing designs obtained from FLEXPAVE and ROADENT. Two different traffic and soil conditions were considered for a total of four cases:

			FLEXPAVE			ROADENT			
CASE	TRAFFIC	R	AC (in.)	BS (in.) Cl. 6	SB (in.) Cl. 3,4	FAT. DAM.	RUT. DAM.	FAT. REL.	RUT. REL.
1	500,000	12	3.7	6.0	18.0	1.65	0.22	49	88
2	5,000,000	12	6.8	6.0	22.2	2.07	0.25	46	86
3	500,000	70	3.7	6.0	-	1.65	5.65	47	23
4	5,000,000	70	6.8	6.0	2.8	2.03	3.35	50	36

The analysis started by using FLEXPAVE to obtain design thicknesses. These thicknesses (shown in table above) were then used as input to ROADENT; default values were used in all cases and the "GB" material model was used for the R=70 subgrade cases. The analysis showed that the FLEXPAVE designs failed w.r.t. fatigue in all cases and w.r.t. rutting in the two R70 cases with ROADENT. The reliability of the FLEXPAVE designs were about 50 percent in fatigue and ranged from 23 to 88 percent in rutting. Finally, it was found that, in order to attain reliability levels of over 90 percent, the asphalt thickness had to be doubled.

Based on this, the group felt a more thorough study was warranted. More importantly, any attempt to calibrate the transfer functions using field data should be postponed until these issues are resolved. A smaller group was assigned the task of coming up with a data set of pavement designs for the entire group to compare.

The idea would be for each member to use ROADENT to design the sections; notes would be compared at a subsequent meeting.

At meetings held February 1-3, 1998, a smaller group (D. Young, D. Bullock, S. Dai, J. Siekmeier, and D. Van Deusen) met to discuss this effort. To begin, the cases considered by GRC were rerun. All those involved obtained mostly the same answers. Observations and questions:

_ In order to attain reliability levels near 90 percent, the asphalt thickness had to be doubled relative to the FLEXPAVE thickness. The general consensus regarding FLEXPAVE relative to the Asphalt Institute (a M/E-based design procedure) and AASHTO 93 is that FLEXPAVE generally results in higher AC thicknesses. This leads to the statement that, at appropriate reliability levels, ROADENT results in AC thicknesses much higher than Mn/DOT and AI. The subject of reliability and its application to M/E design needs to be addressed further. In particular, what is the "reliability" of currently available M/E procedures such as AI and U of I?

_ Seasonal changes. The U of Mn final report for the project lists seasonal modulus ratios based on Mn/ROAD observations; the default moduli in ROADENT reflect these. In ROADENT, it was observed that when the value for one particular season is changed, the other values remained unchanged. An added input screen where the user can input their own seasonal modulus ratios would be useful. The program could then change all other moduli for each layer according to these ratios.

_ The pavement section for Mn/ROAD TS 28 was used as input to the program; default values were used. ROADENT was calibrated using data from this section, however, it predicted fatigue damage far less than 1.

_ For any future analyses it was decided to use the following inputs for seasonal moduli to be consistent with current procedures:

	SEASONAL MODULI (ksi)			
BASE	SPRING	SUMMER	FALL	WINTER
Cl. 3	10	15	17	40
Cl. 4	10	15	17	40
Cl. 5	15	22	25	40
Cl. 6	15	22	25	40
SUBG.				
R=12	6	10	12	40
R=70	18	18	18	40

_ For future work of this sort, it was decided that the design parameters used by GRC would suffice. The benefit of using information from soils letters was questioned. The group felt the designs done by the larger group should focus on a parametric study where the effect of the following on ROADENT thicknesses are studied:

– Duration of seasons
– Seasonal moduli
– Variability
– Reliability

_ The fact that ROADENT predicts reliability levels (in fatigue) of ~50 percent when using FLEXPAVE design thicknesses does not reflect types of distresses on Minnesota highways – fatigue is not commonly observed.

The next meeting of the full group is scheduled for February 26, 1:30 – 3:30 pm, Conference Room 1.

M/E Group:
Dave Van Deusen
Dave Newcomb
Dave Bullock
John Siekmeier
Dave Timm
Roger Olson
Shongtao Dai
Duane Young
Gene Skok

Cc:
Glenn Engstrom
Dave Rettner
Dave Janisch

Appendix B

Input Values

Seasons

Default values were used for season lengths and temperatures (see Table B-1).

Table B-1 Season Lengths and Mean Pavement Temperatures

Season	Length (weeks)	Temperature (° F)
Summer	26	85
Fall	8	50
Winter	12	32
Spring	6	50

Traffic

Both ESALs and load spectra were used to evaluate the reliability methods. The load spectra used were based on data from the weigh-in-motion (WIM) device at the Minnesota Road Research Facility (Mn/ROAD (See Table B-2). The ESALs used were calculated using the Load Equivalency Factor (LEF) method in the 1993 AASHTO Pavement Design Guide (see Table B-3). For the LEF calculations, values were interpolated to correspond to AASHTO load classes.

Table B-2 Load Spectra Used in Simulations

Axle Load (kips)	Single Axles		Tandem Axles		Steer Axles	
	High Vol.	Low Vol.	High Vol.	Low Vol.	High Vol.	Low Vol.
1	138,060	13,806	18,121	1,812	98,412	9,841
3	213,040	21,304	92,741	9,274	334,223	33,422
5	250,151	25,015	230,607	23,061	287,674	28,767
7	192,990	19,299	335,442	33,544	892,128	89,213
9	215,980	21,598	472,081	47,208	1,770,189	177,019
11	262,490	26,249	495,591	49,559	1,100,807	110,081
13	254,153	25,415	417,170	41,717	110,486	11,049
15	263,356	26,336	339,168	33,917	16,915	1,692
17	249,864	24,986	346,157	34,616	6,927	693
19	114,321	11,432	325,381	32,538	1,125	113
21	56,804	5,680	321,199	32,120	1,114	111
23	15,520	1,552	306,028	30,603		
25	8,523	852	333,887	33,389		
27	4,747	475	368,928	36,893		
29			494,333	49,433		
31			532,158	53,216		
33			464,293	46,429		
35			306,034	30,603		
37			172,668	17,267		
39			85,579	8,558		
41			53,350	5,335		
43			24,639	2,464		
45			17,250	1,725		
47			7,181	718		
49			4,701	470		
51			3,188	319		
53			745	75		
55			930	93		

Pavement Designs

The pavement designs used in the simulations were based on four designs used in a previous comparison of FLEXPAVE and ROADENT (see Tables B-3 and B-4). Cases 1 – 4 correspond to the four designs used in the original FLEXPAVE study (the calculated ESALs are lower than those assumed in the FLEXPAVE study). In Cases 1a – 4a the asphalt thickness has been increased in order to study higher reliability values.

Table B-3 Structural Values Used in Simulations

Case	Material			Thickness (in.)			AASHTO ESALs	
	Base	Subbase	Soil	Asphalt	Base	Subbase	SN^1	ESALs (millions)
1	Cl. 6	Cl. 3, 4	R = 12	3.7	6.0	18.0	3.6	0.40
1a				6.0			4.7	0.39
2	Cl. 6	Cl. 3, 4	R = 12	6.8	6.0	22.2	5.3	3.8
2a				10.0			6.8	3.8
3	Cl. 6	Cl. 3, 4	R = 70	3.7	6.0	-----	2.3	0.40
3a				6.0			3.4	0.40
4	Cl. 6	Cl. 3, 4	R = 70	6.8	6.0	2.8	4.0	4.0
4a				10.0			5.4	3.8

[1] Structural Number from the 1993 AASHTO Design Guide.

Table B-4 Seasonal Modulus Values

Season	Modulus (psi)				
	Asphalt Concrete[2]	Base (Class 6)	Subbase (Class 3, 4)	Soil (R = 12)	Soil (R = 70)
Summer	290,471	22,000	15,000	10,000	18,000
Fall	987,278	25,000	17,000	12,000	18,000
Winter	1,513,888	40,000	40,000	40,000	40,000
Spring	987,278	15,000	10,000	6,000	18,000

[2] Calculated based on mean pavement temperature:

$$E_{AC} = Q_1 \times e^{\frac{(T+Q_2)^2}{Q_3}} \tag{B-1}$$

Where:

E_{AC} = Asphalt concrete modulus (MPa)

T = Mean pavement temperature (°C)

Q_1 = 16693.4

Q_2 = 26.2

Q_3 = -1459.7

Appendix C

Flow Charts for the Allowed Repetitions and Damage Factor Reliability Methods

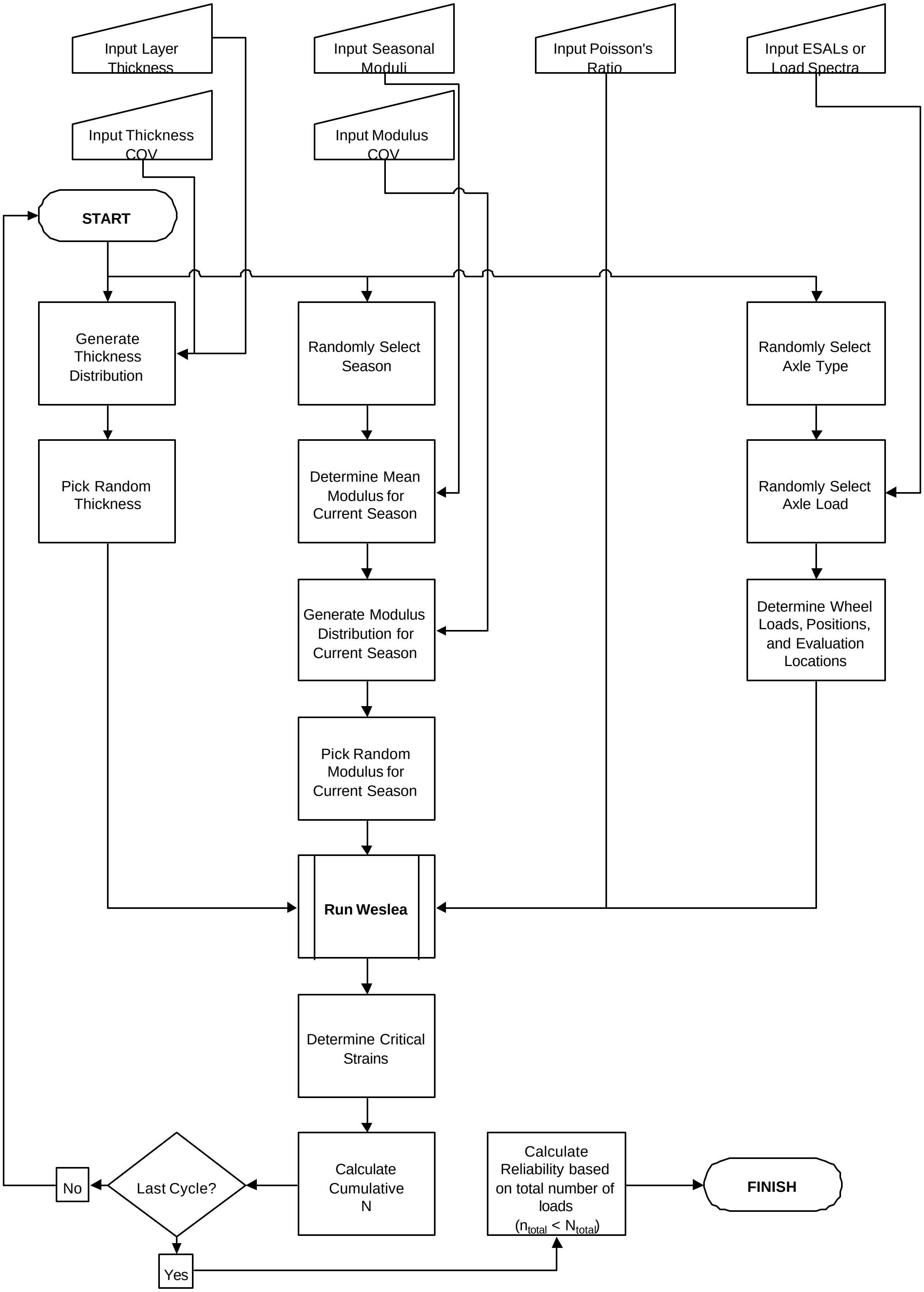


Figure C-1 Flow Chart for the Allowed Repetitions Reliability Method

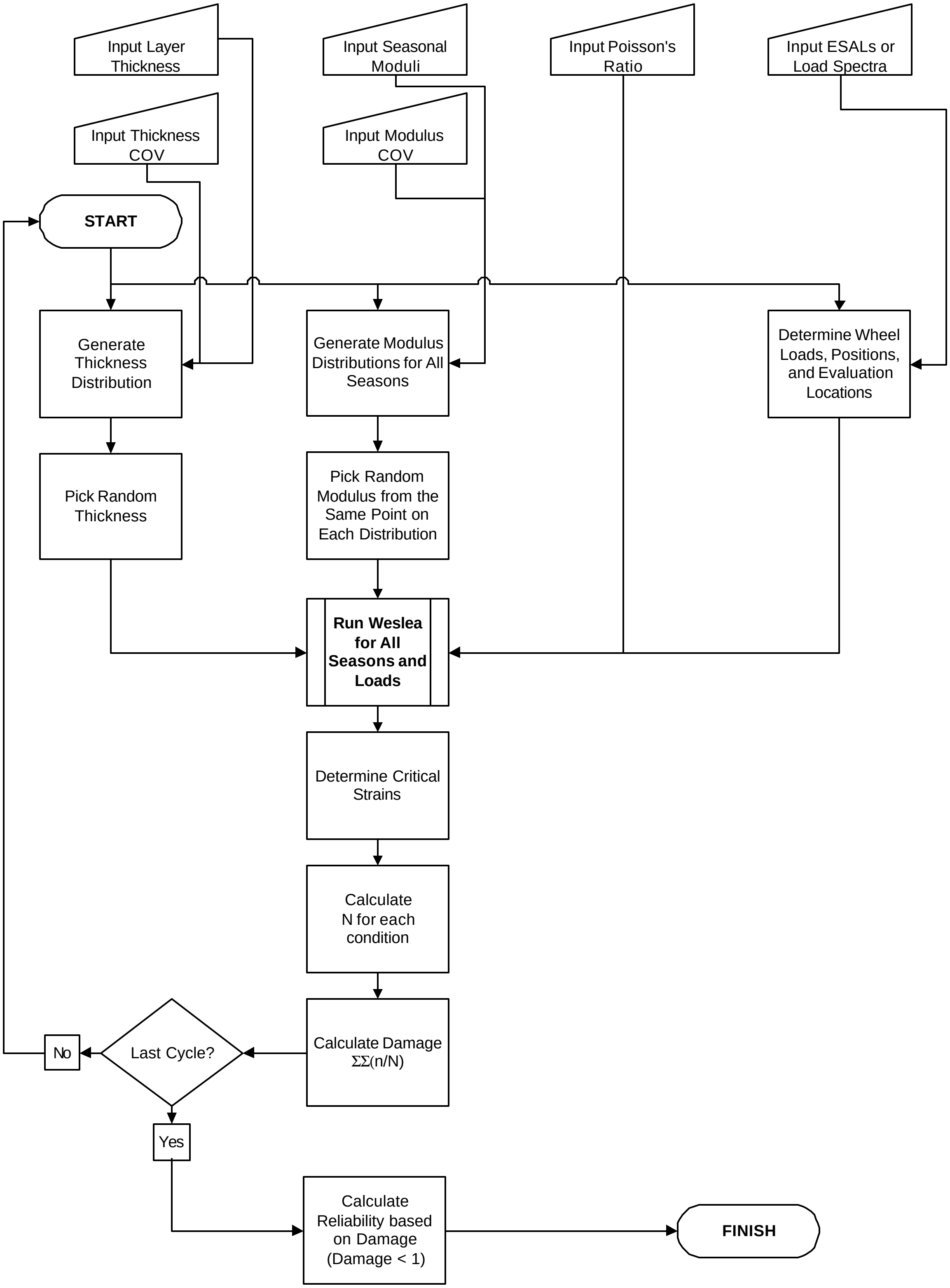
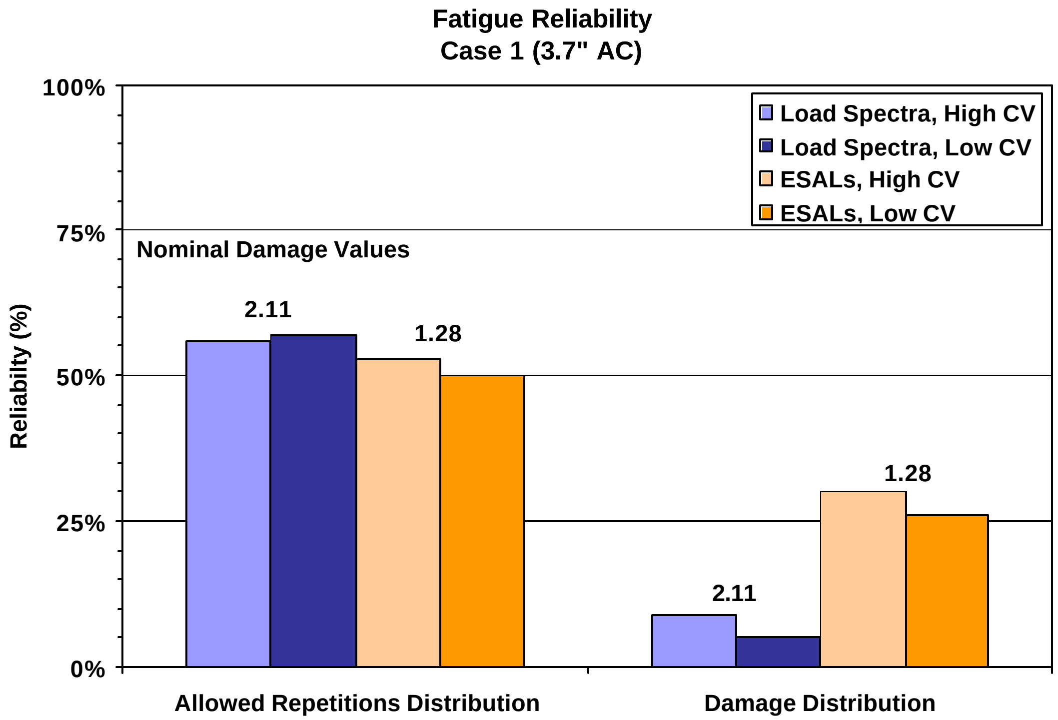
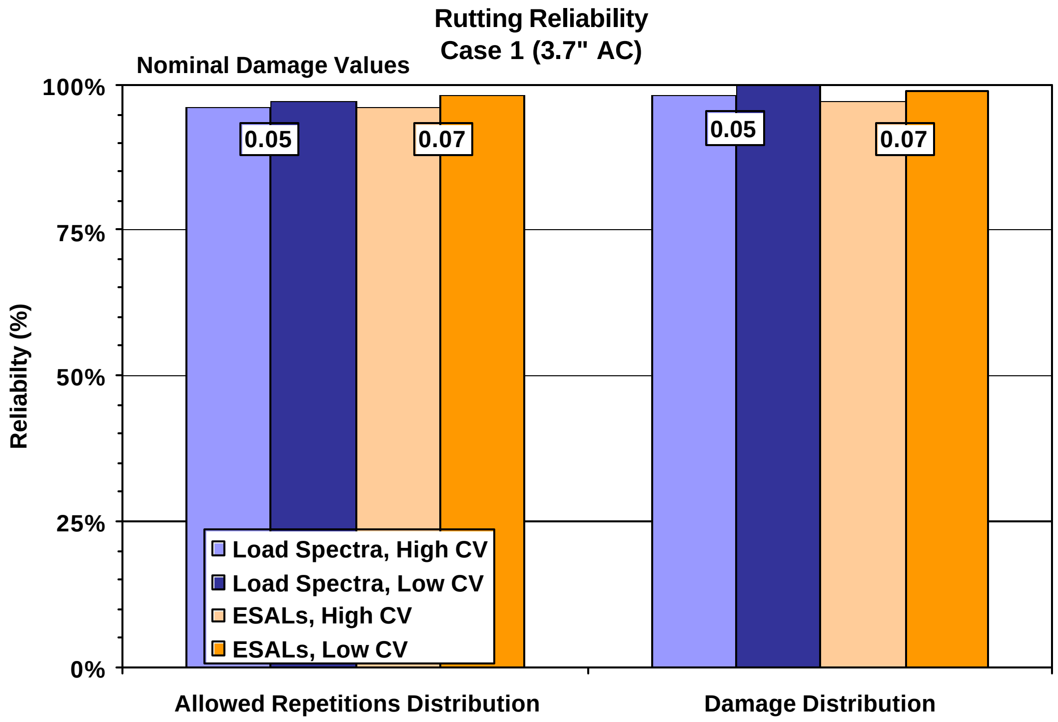


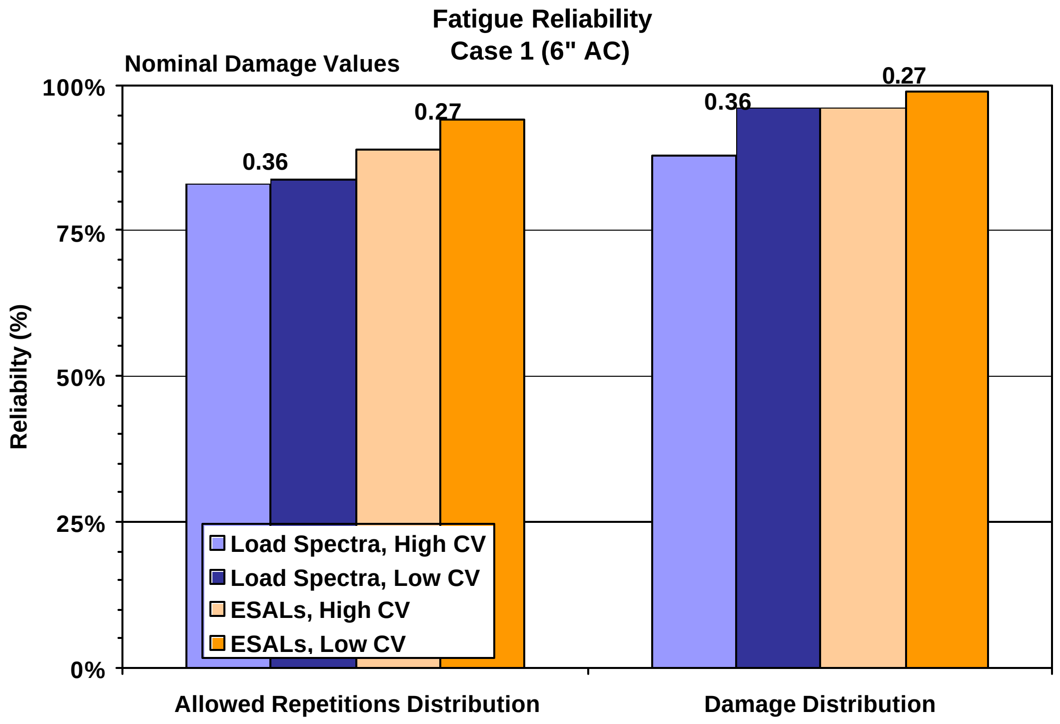
Figure C-2 Flow Chart for the Damage Factor Reliability Method

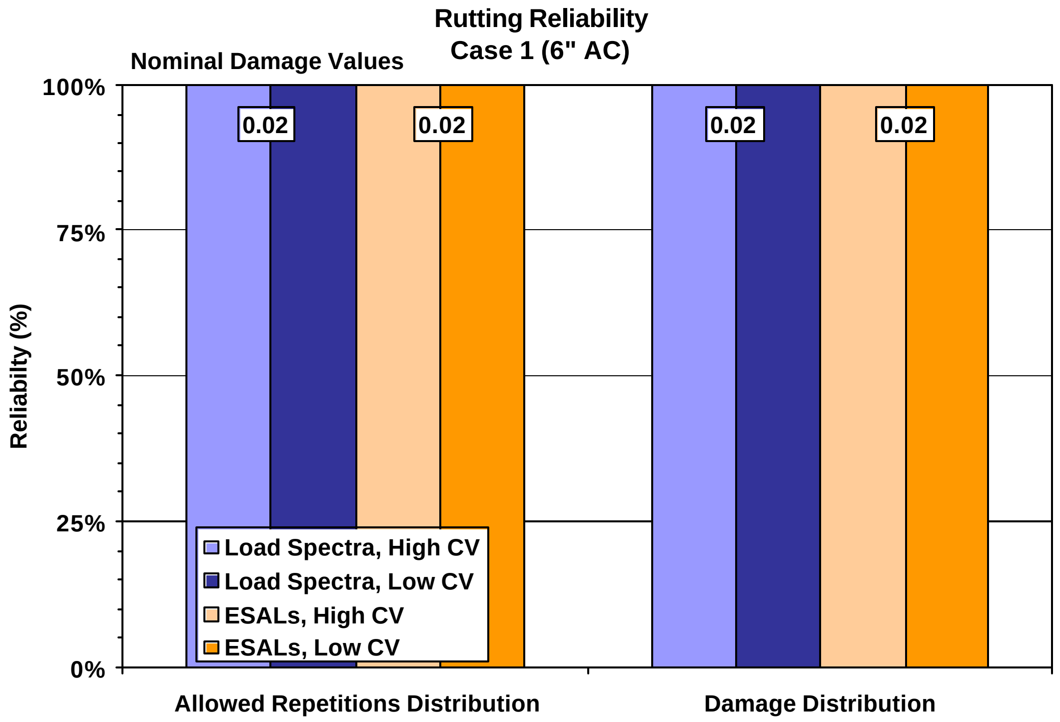
Appendix D

Complete Output


Fatigue Reliability
Case 1 (3.7" AC)
Reliabilty (%)
100%
75%
50%
25%
0%
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Nominal Damage Values
2.11
1.28
2.11
1.28
Allowed Repetitions Distribution
Damage Distribution


Rutting Reliability
Case 1 (3.7" AC)
Nominal Damage Values
Reliabilty (%)
100%
75%
50%
25%
0%
0.05
0.07
0.05
0.07
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution


Fatigue Reliability
Case 1 (6" AC)
Nominal Damage Values
Reliabilty (%)
100%
75%
50%
25%
0%
0.36
0.27
0.36
0.27
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution


Rutting Reliability
Case 1 (6" AC)
Nominal Damage Values
Reliabilty (%)
100%
75%
50%
25%
0%
0.02
0.02
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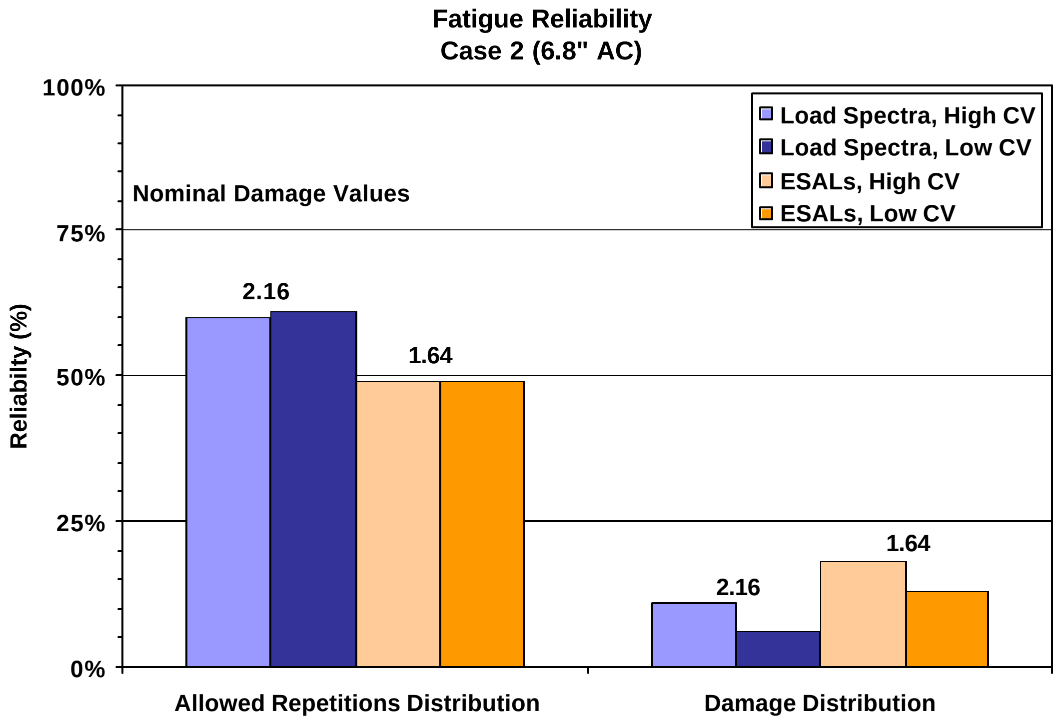
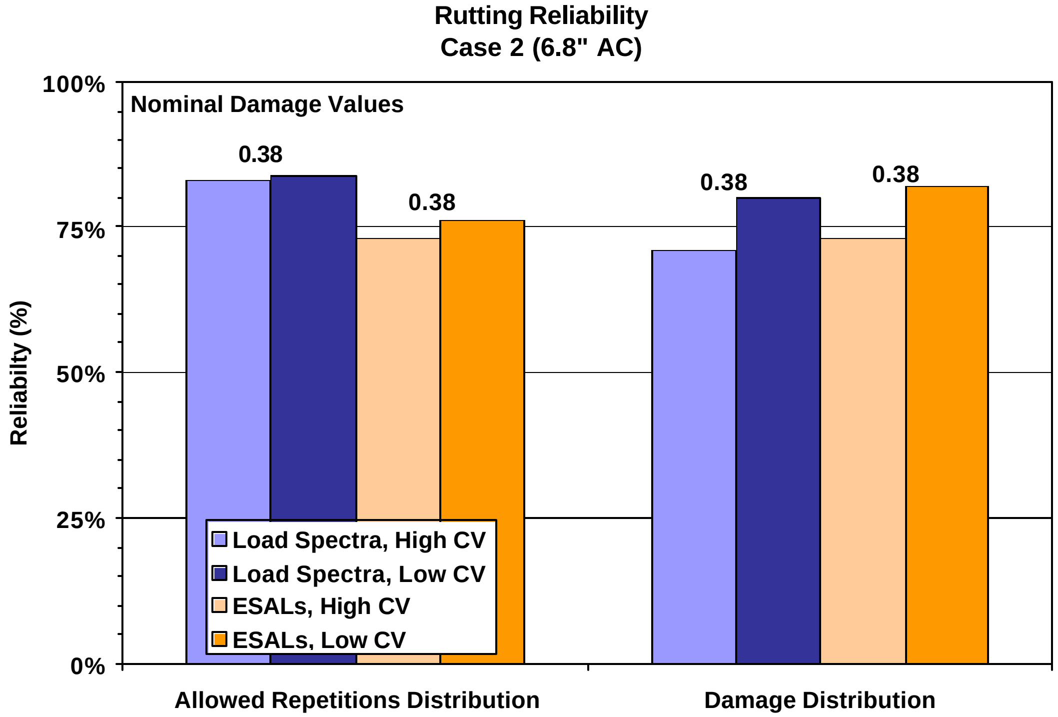
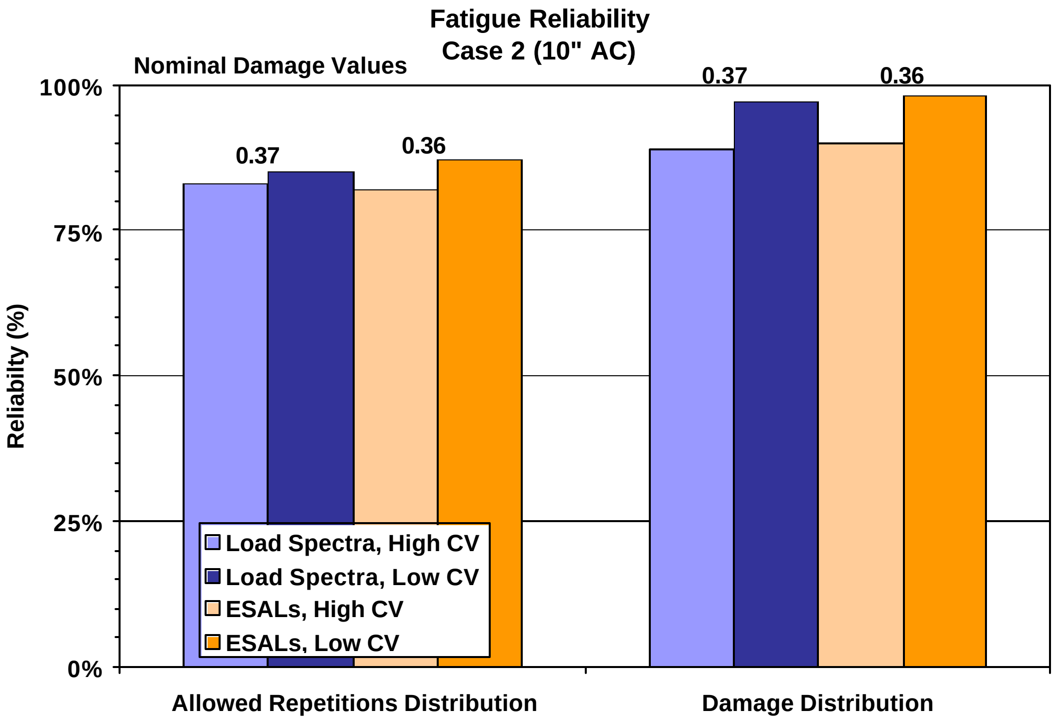
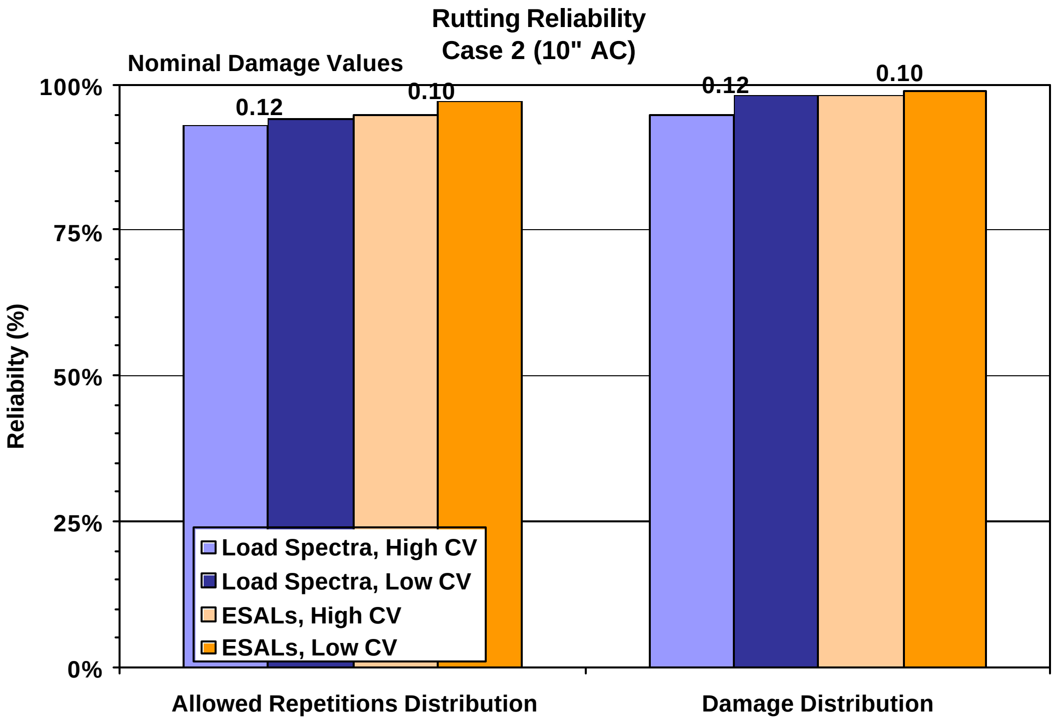
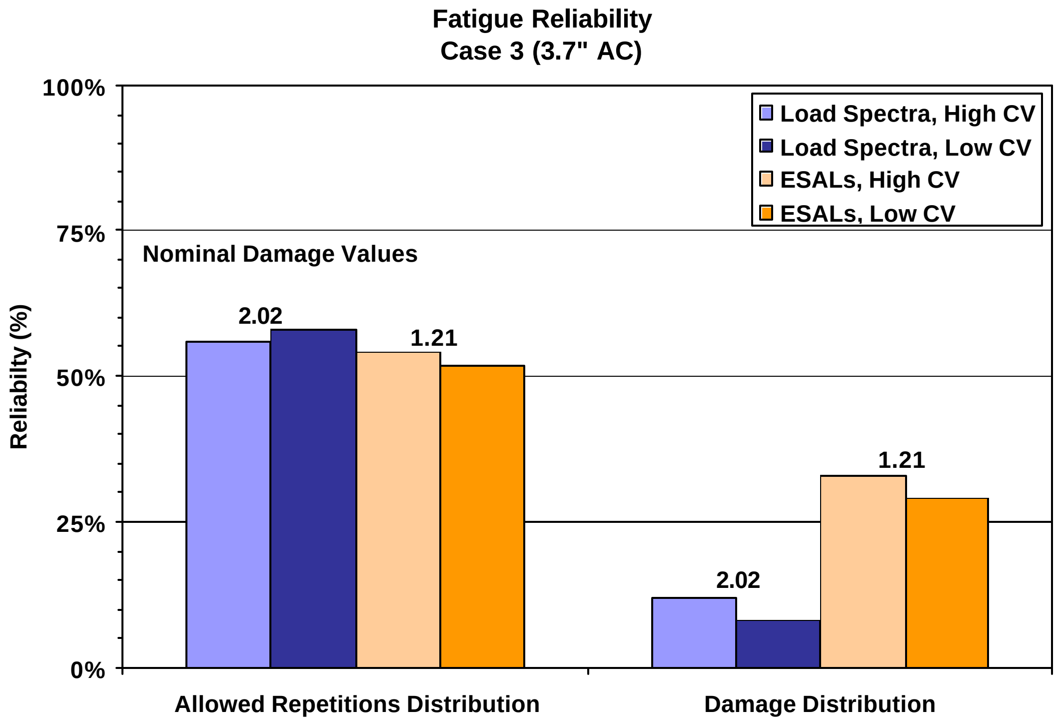
0.02
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution

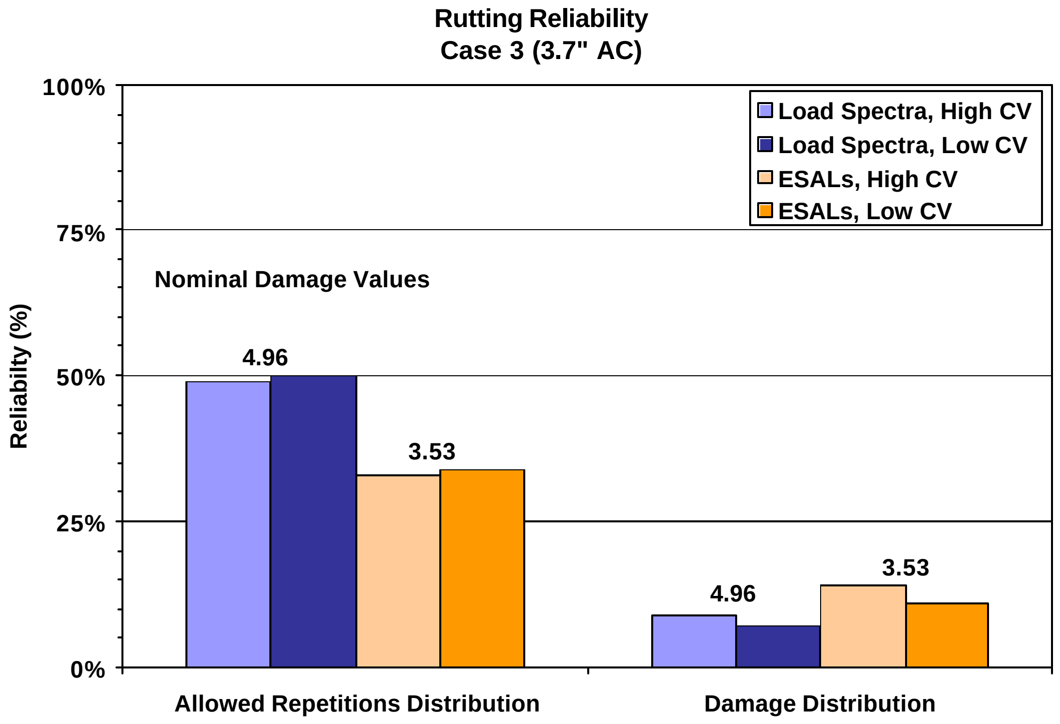

Fatigue Reliability
Case 2 (6.8" AC)
100%
75%
50%
25%
0%
Reliabilty (%)
Nominal Damage Values
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
2.16
1.64
2.16
1.64
Allowed Repetitions Distribution
Damage Distribution

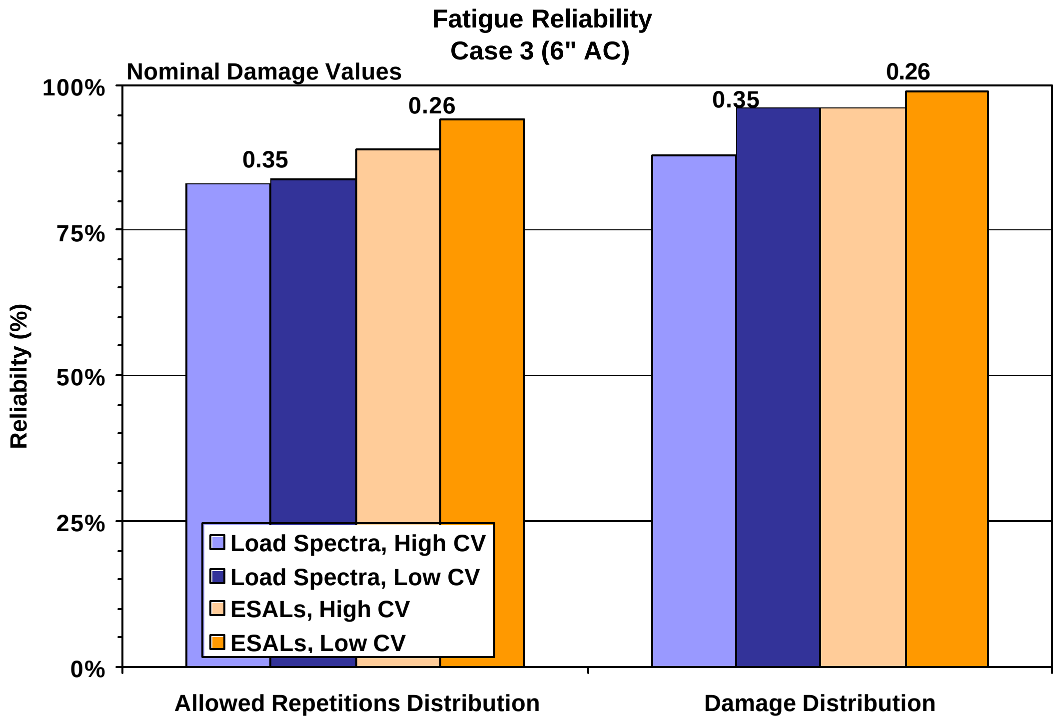

Rutting Reliability
Case 2 (6.8" AC)
100%
75%
50%
25%
0%
Reliabilty (%)
Nominal Damage Values
0.38
0.38
0.38
0.38
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution

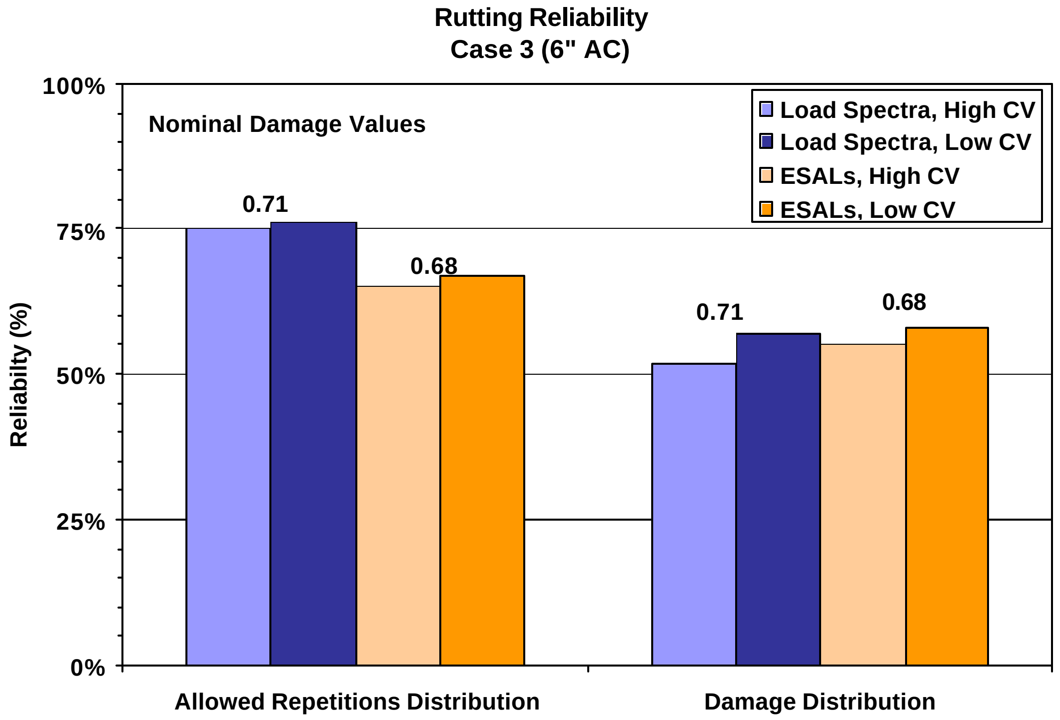

Fatigue Reliability
Case 2 (10" AC)
Nominal Damage Values
0.37
0.36
0.37
0.36
100%
75%
50%
25%
0%
Reliabilty (%)
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution

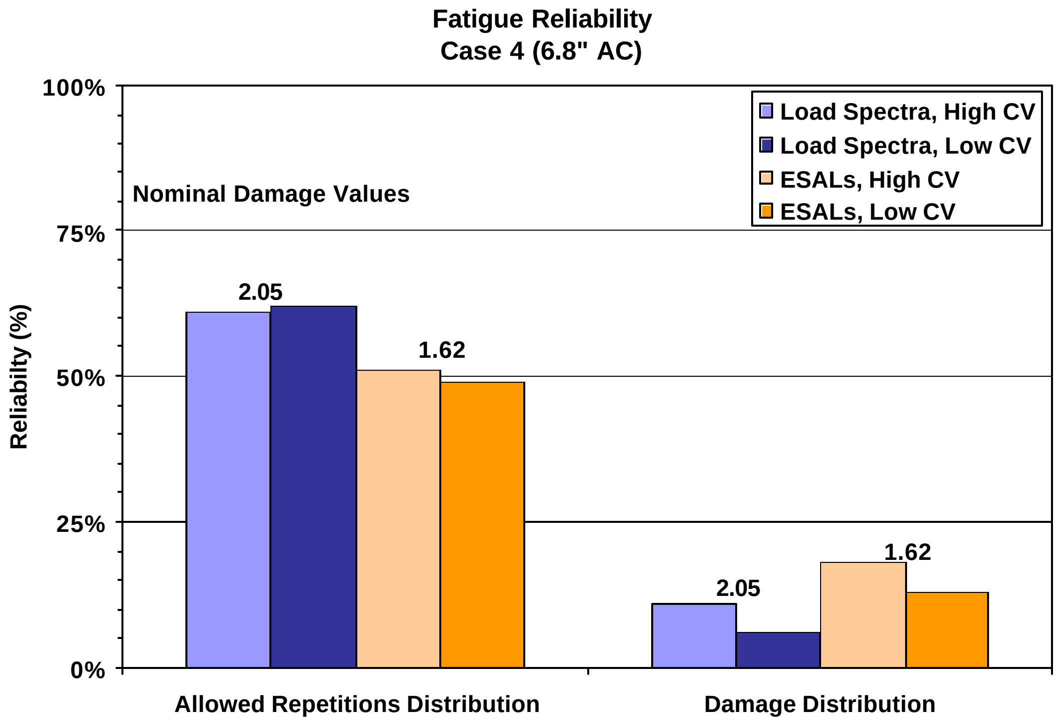

Rutting Reliability
Case 2 (10" AC)
Nominal Damage Values
0.12
0.10
0.12
0.10
100%
75%
50%
25%
0%
Reliabilty (%)
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution

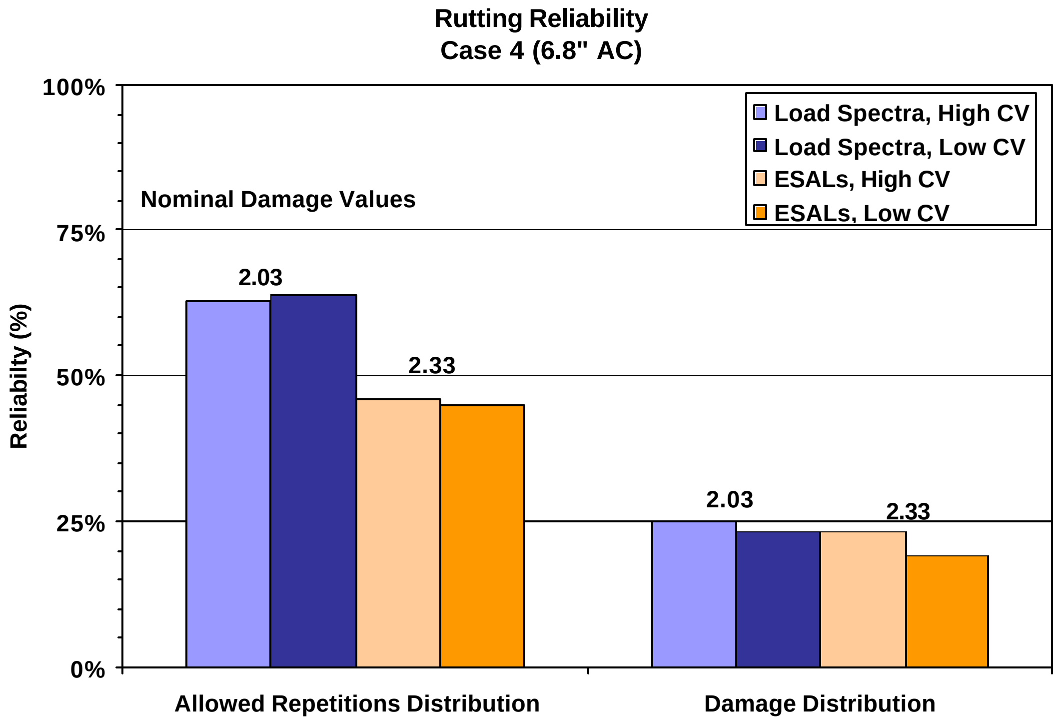

Fatigue Reliability
Case 3 (3.7" AC)
100%
75%
50%
25%
0%
Reliabilty (%)
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Nominal Damage Values
2.02
1.21
2.02
1.21
Allowed Repetitions Distribution
Damage Distribution

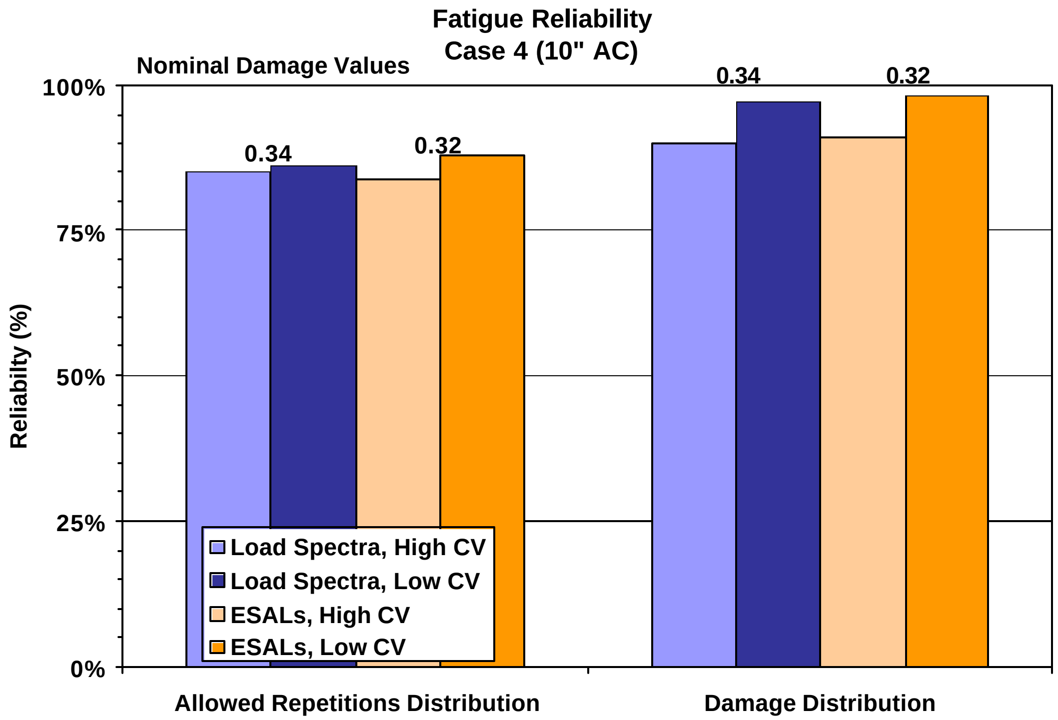

Rutting Reliability
Case 3 (3.7" AC)
100%
75%
50%
25%
0%
Reliabilty (%)
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Nominal Damage Values
4.96
3.53
4.96
3.53
Allowed Repetitions Distribution
Damage Distribution

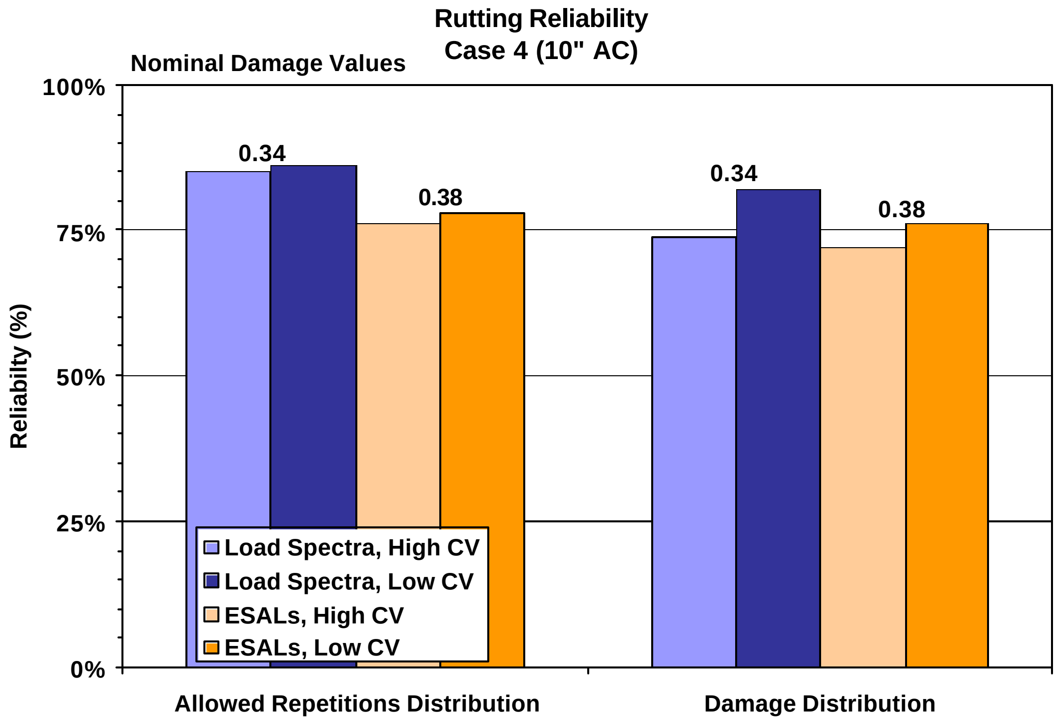

Fatigue Reliability
Case 3 (6" AC)
Nominal Damage Values
Reliabilty (%)
100%
75%
50%
25%
0%
0.35
0.26
0.35
0.26
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution


Rutting Reliability
Case 3 (6" AC)
Nominal Damage Values
Reliabilty (%)
100%
75%
50%
25%
0%
0.71
0.68
0.71
0.68
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution


Fatigue Reliability
Case 4 (6.8" AC)
Reliabilty (%)
100%
75%
50%
25%
0%
Nominal Damage Values
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
2.05
1.62
2.05
1.62
Allowed Repetitions Distribution
Damage Distribution


Rutting Reliability
Case 4 (6.8" AC)
Reliabilty (%)
100%
75%
50%
25%
0%
Nominal Damage Values
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
2.03
2.33
2.03
2.33
Allowed Repetitions Distribution
Damage Distribution


Fatigue Reliability
Case 4 (10" AC)
Nominal Damage Values
100%
75%
50%
25%
0%
Reliabilty (%)
0.34
0.32
0.34
0.32
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution


Rutting Reliability
Case 4 (10" AC)
Nominal Damage Values
100%
75%
50%
25%
0%
Reliabilty (%)
0.34
0.38
0.34
0.38
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution