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.

$$CV = 100 \times \frac{\text{StandardDeviation}}{\text{Mean}} \quad (1)$$

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.

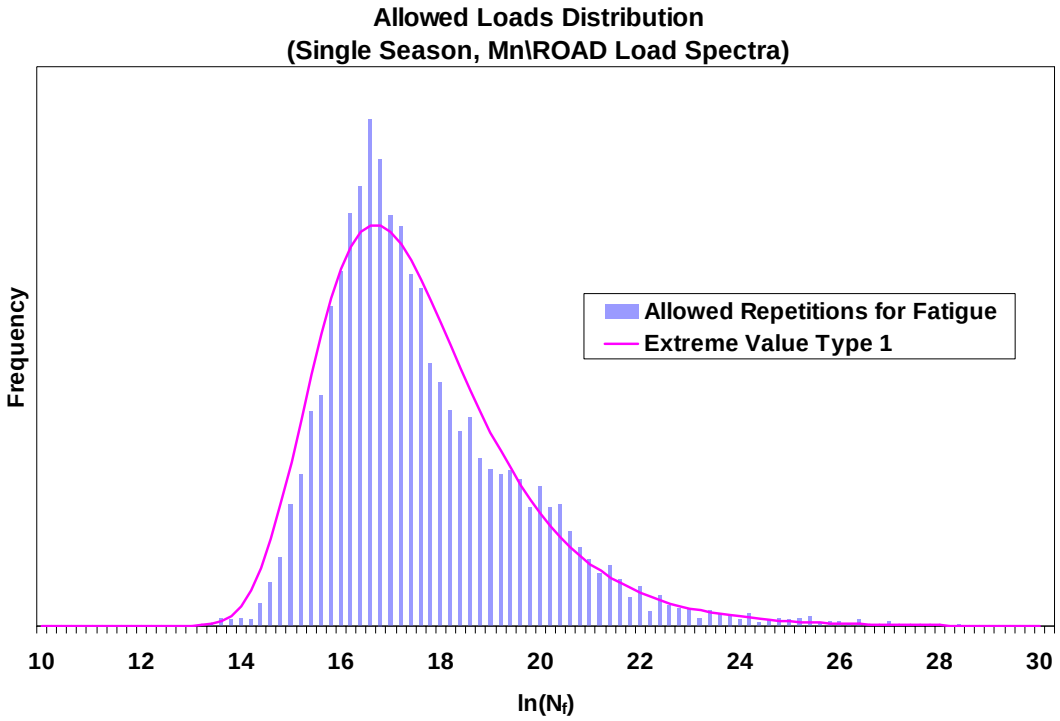


Figure 1 Single Season Load Spectra Output

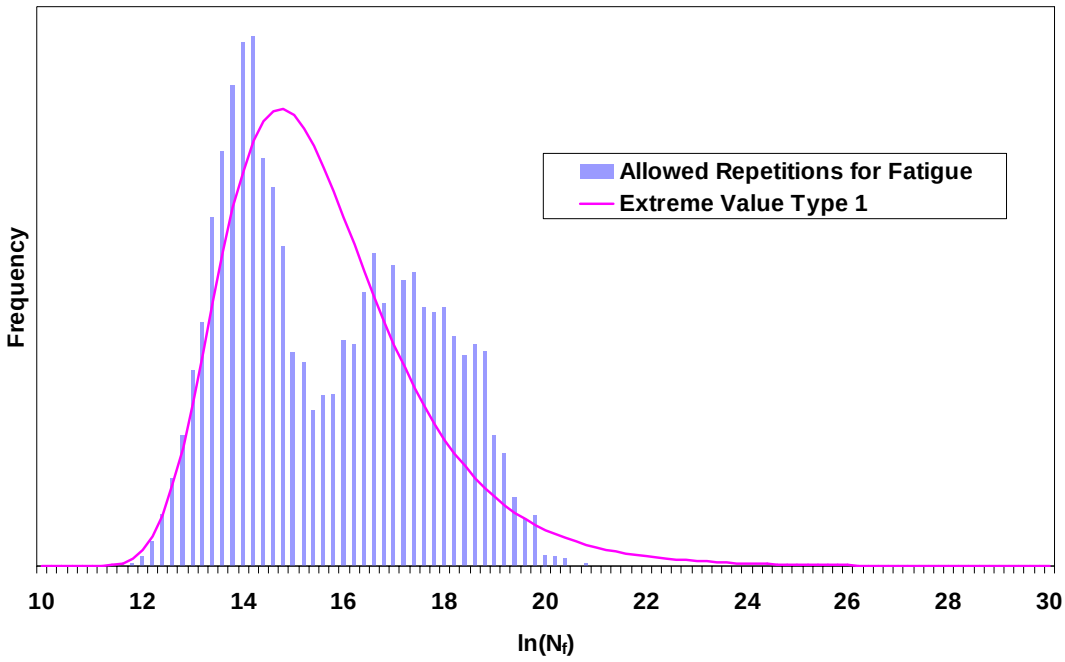


Figure 2 Four Season ESAL Output

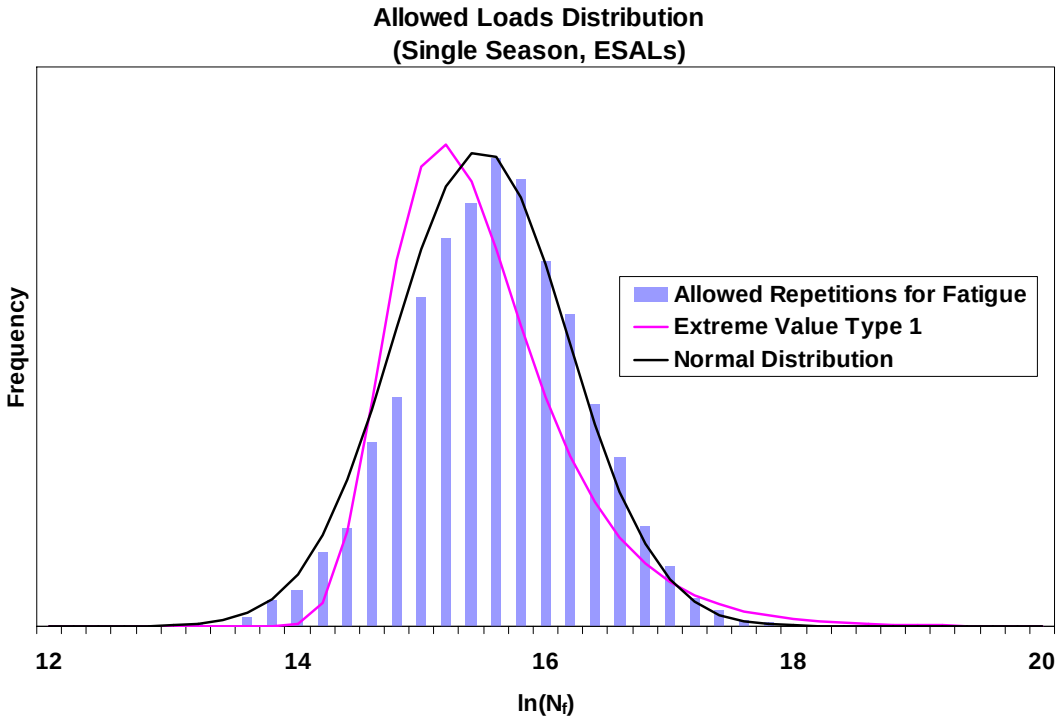


Figure 3 Single Season ESAL Output

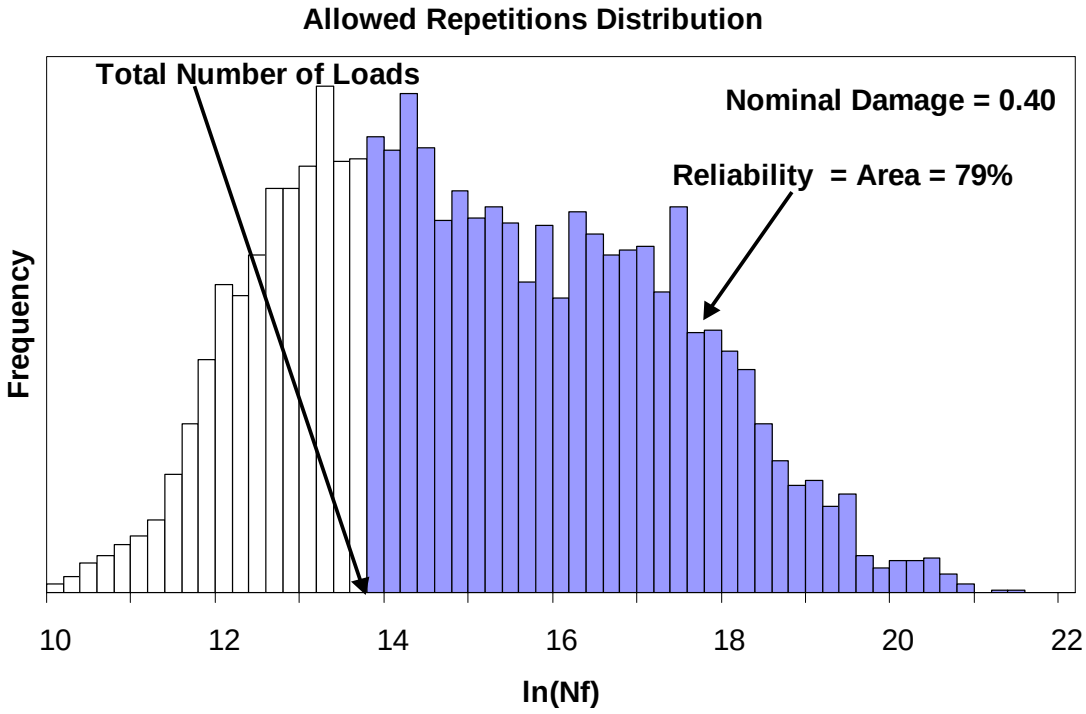


Figure 4 Example of Allowed Repetitions Reliability Calculation

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).

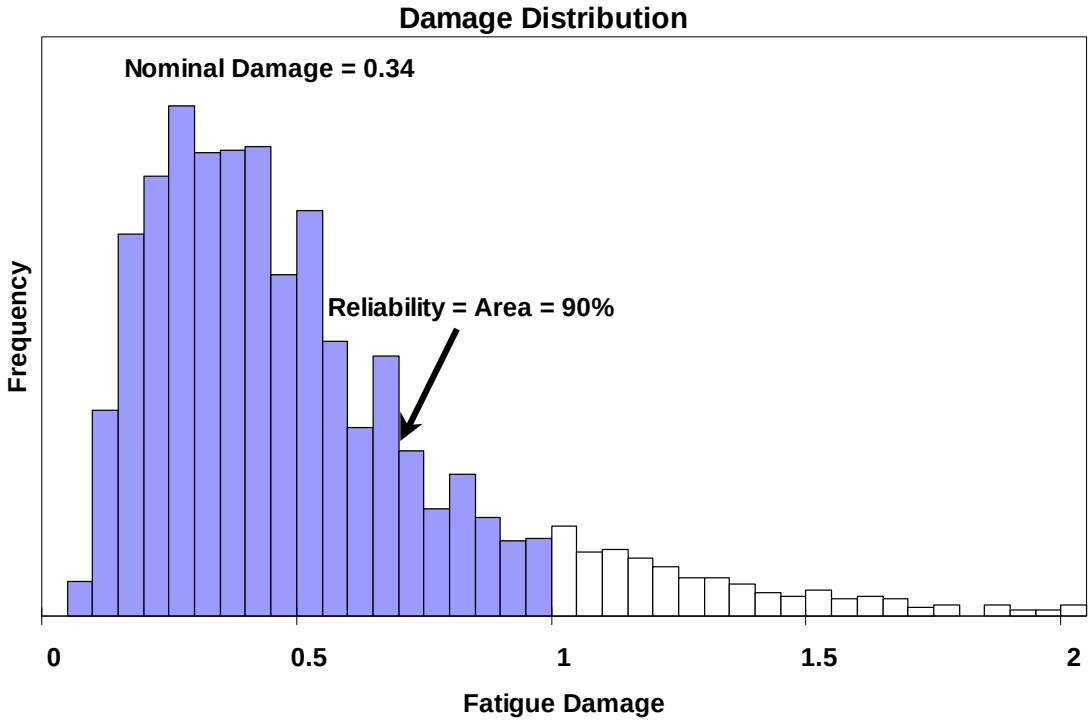


Figure 5 Example of Damage Factor Reliability Calculation

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.

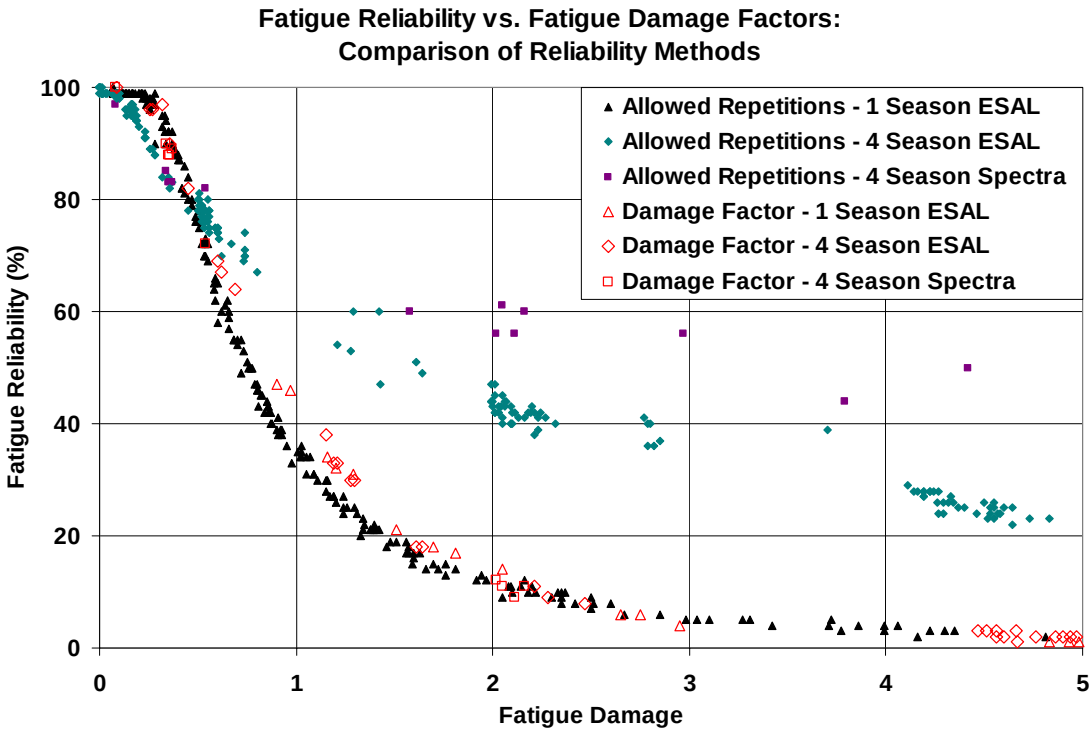


Figure 6 Anomalies in Fatigue Reliability Calculations

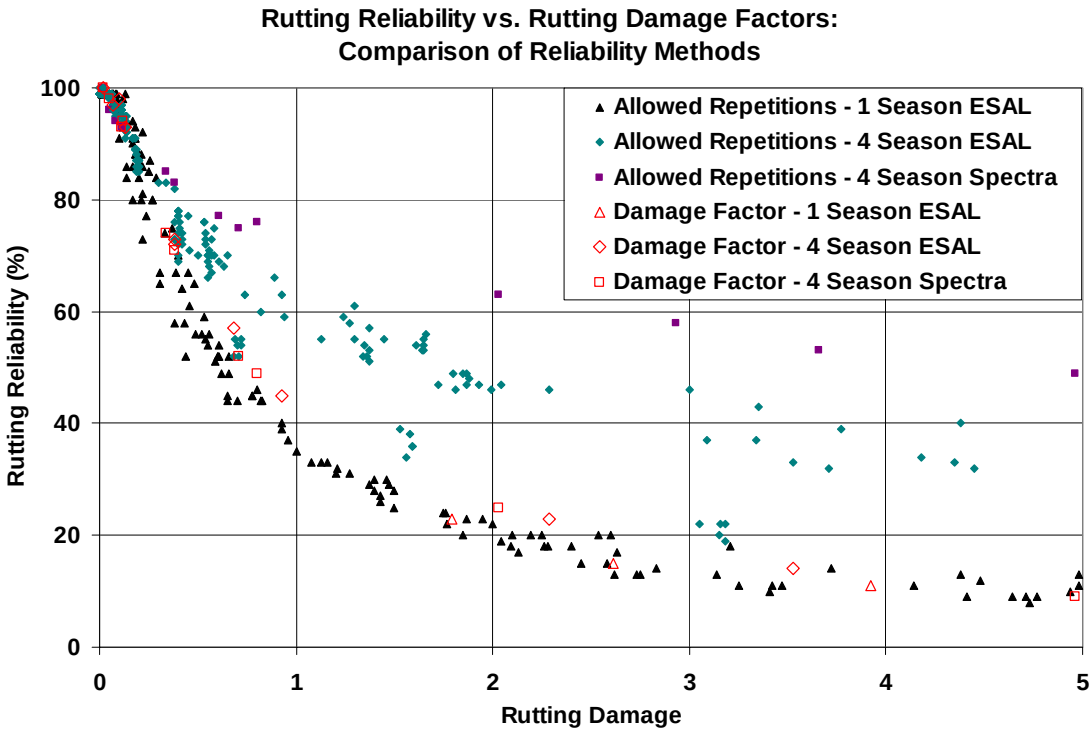


Figure 7 Anomalies in Rutting Reliability Calculations

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).

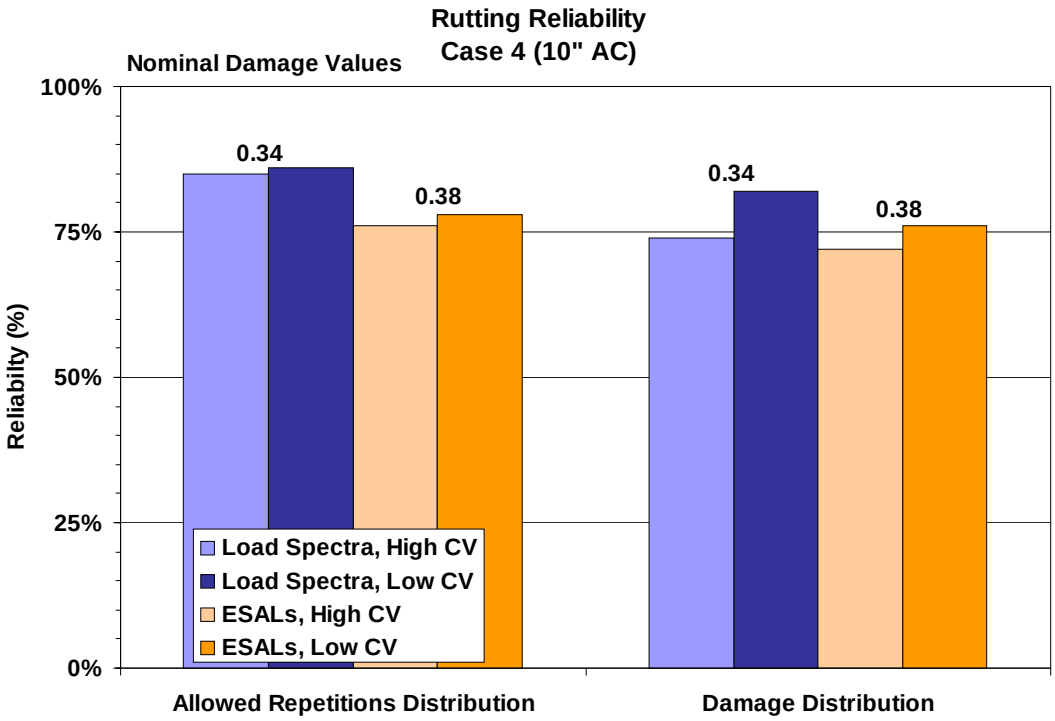


Figure 8 Comparison of Sensitivity to Changes in Modulus Variability

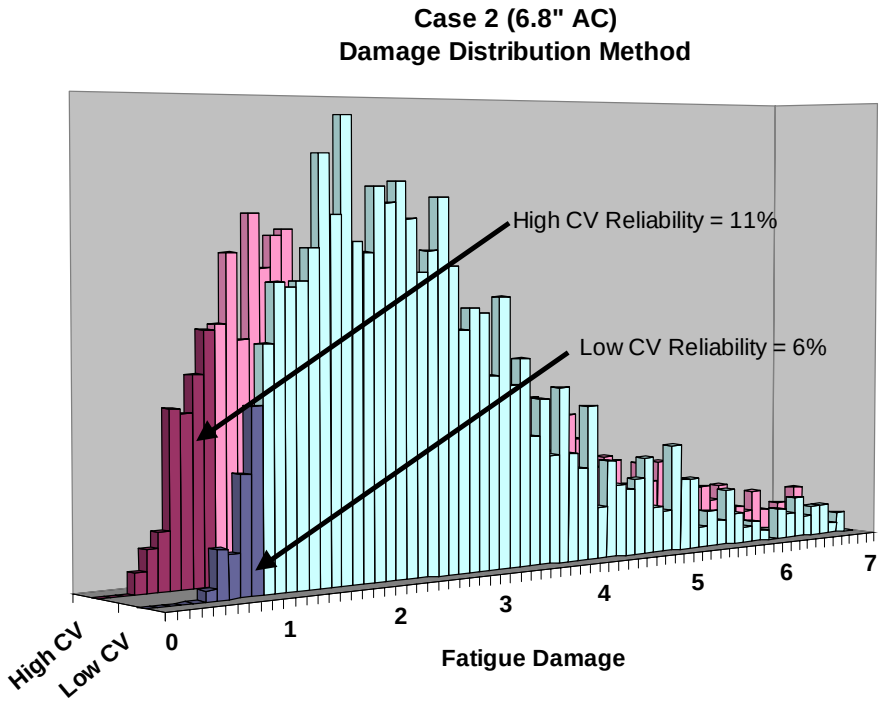


Figure 9 Comparison of Low Reliability Values for High and Low Input CV

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.

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

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.

$$Damage = \frac{n}{N} \tag{3}$$

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

$$Damage = \sum_j \sum_i \frac{n_{season_i, load_j}}{N_{season_i, load_j}} \tag{4}$$

The Allowed Repetitions method does not follow the Miner's Hypothesis model for multiple seasons and load classes. Assuming m is the number of Monte Carlo cycles and k represents any value in the set (1, 2, …, m), the damage value for each cycle k is shown in Equation 5.

$$Damage_k = \frac{\sum_j \sum_i n_{season_i, load_j}}{N_{season_k, load_k}} \quad (5)$$

Where:

$season_k$ = randomly selected season for cycle k
$load_k$ = randomly selected axle load for cycle k

This deviation from Miner's Hypothesis explains the anomalous reliability results. This method compares the allowed repetitions for $season_i$ and $load_j$ not to the expected repetitions of $load_j$ during $season_i$, but to the total expected repetitions for all seasons and loads. In effect, the simulated pavement exists in an environment where the temperature, moisture conditions are constant (equal to those of the selected season) and all loads are equal to that of the selected axle.

Comparison of Damage Distributions

The consequences of using the Allowed Repetitions method are most evident in cases with high nominal damage values (greater than 1.0). Figure 10 contains frequency distributions for both reliability methods. The height of each bar represents the percent of Monte Carlo cycles that resulted in the corresponding damage. The reliability for each distribution is equal to the area of the shaded portion.

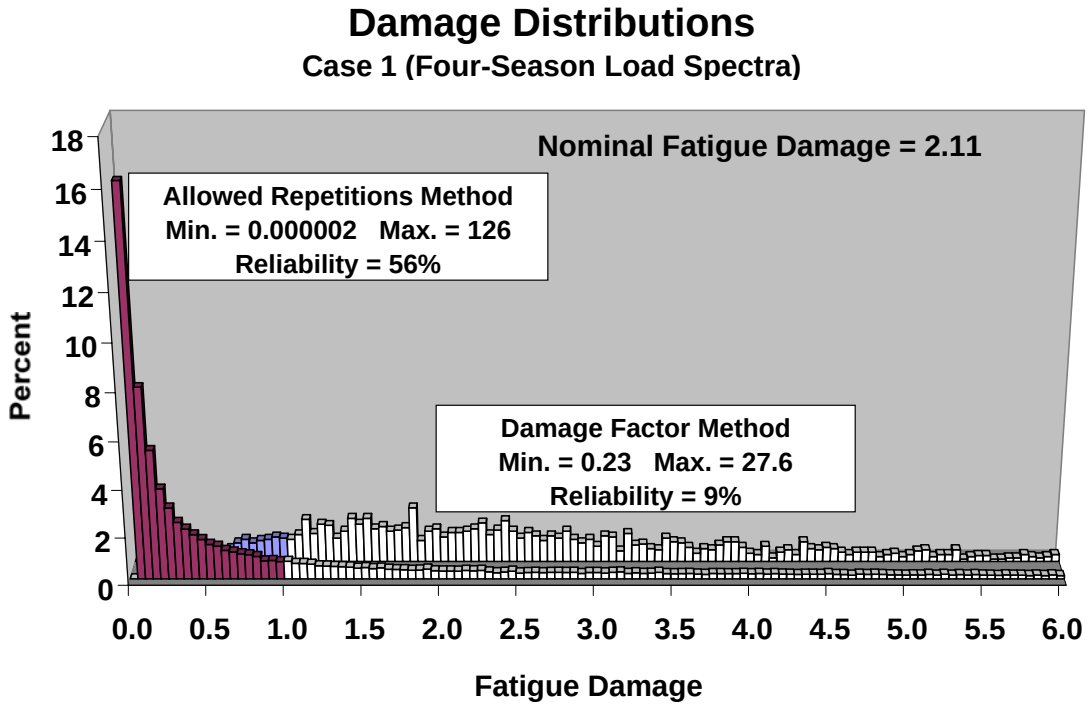


Figure 10 Comparison of Reliability Output Distributions

Figure 11 provides an indication of the source of the skewing. Three simulations were performed, ranging from the simplest to the most complex. The simplest case had one season and ESAL traffic. This distribution resembles the Damage Factor distribution from Figure 10. In this case, none of the 5,000 cycles resulted in damage of 0.1 or less. The next case had four seasons and ESAL traffic. The addition of multiple seasons caused extreme skewing, with 21% of the cycles having damage of 0.1 or less. Finally, the addition of load spectra resulted in 24% of the cycles having damage of 0.1 or less.

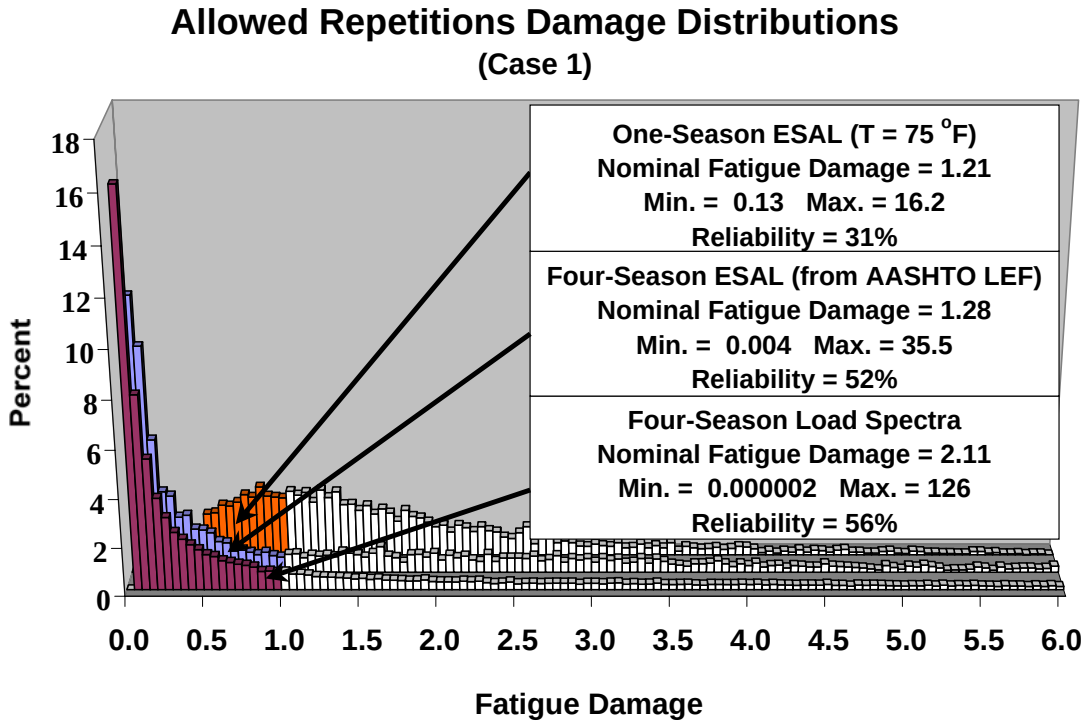


Figure 11 Progressive Skewing of Damage Distributions

The reason for the skewing and the high reliability predictions of the Allowed Repetitions method lies in its deviation from Miner's Hypothesis. In the Damage Factor method, every load and every season contribute to the overall performance of the pavement during each cycle. However the Allowed Repetitions method considers only one season and one load class per cycle. If the damage from a given season/load combination is less than 1.0, that cycle is counted as one success, no matter how insignificant the load's influence on the pavement. A season/load combination with a damage value of 0.000002 is assigned the same significance as one with a value of 0.99. Similarly, each season/load combination that results in a damage value of 1.0 or greater is counted as one failure. A season/load combination with a damage value of 126 has the same significance as one with a value of 1.0. As a result, the heavy loads and low seasonal moduli that contribute significantly to the damage in every cycle of the Damage Factor method have a relatively small influence on the final outcome of the Allowed Repetitions method.

Computing Time

One area where the Allowed Loads Distribution method has the advantage over the Damage Factor method is in computing time for the reliability calculation. While the computing times are similar for the ESAL mode, the Damage Factor requires several hours to calculate a sufficient number of Monte Carlo cycles in the Load Spectra mode. This is because unlike the Allowed Loads Distribution method, which randomly selects each input value and runs Weslea once per Monte Carlo cycle, the Damage Factor method requires that Weslea be run for every load class and every season for each Monte Carlo cycle.

For this reason, the Damage Factor method in its current form is not efficient enough to calculate reliability from load spectra data in the MnPAVE program. A possible solution to this problem is to streamline the pavement response calculations performed by Weslea. The current damage calculations require only normal strain at a few locations, while the Weslea output includes stresses, strains and deflections. Eliminating some of the unused features may save computing time. Another possible solution is to run enough simulations to develop an algebraic relationship between reliability, damage, and input CV (see Figure 12).

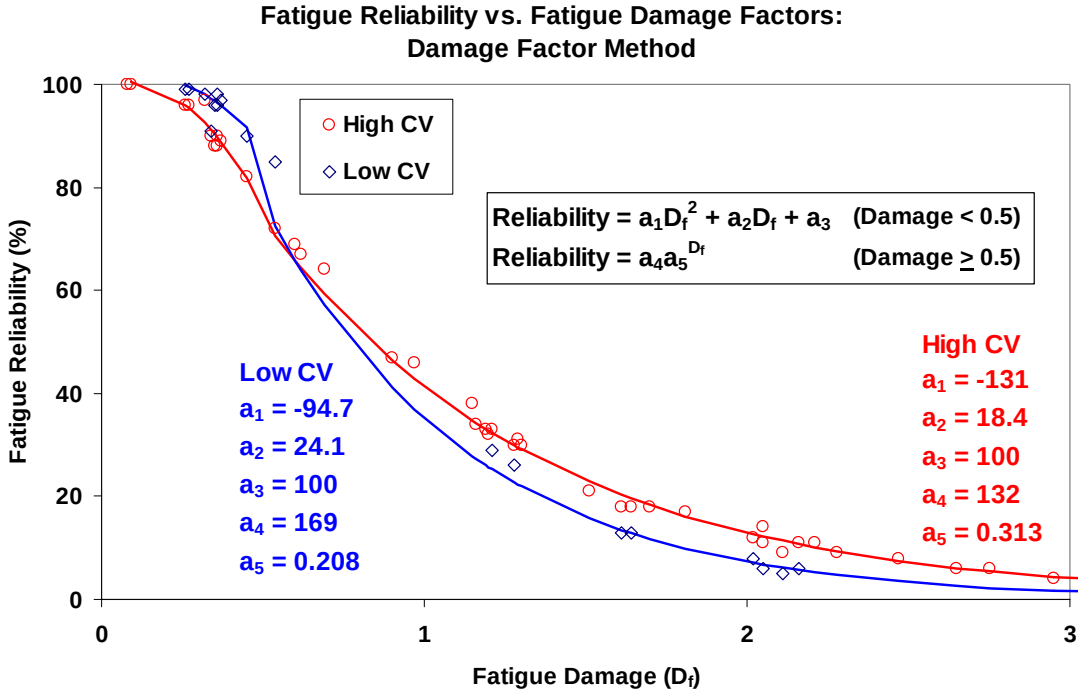


Figure 12 Relationship Between Fatigue Damage, Reliability, and CV

FATIGUE MODELS

The existing fatigue model is shown in Equation 6.

$$N_f = 2.83 \times 10^{-6} \left(\frac{1}{\varepsilon_t} \right)^{3.20596} \quad (6)$$

Where:

N_f = Number of load repetitions required to reach fatigue failure.

ε_t = Horizontal strain at the bottom of the asphalt layer.

The coefficients in this model are based on data from the Minnesota Road Research Project (Mn/ROAD). While ε_t appears to be a good predictor of fatigue failure, some researchers suggest that the modulus of the asphalt layer also plays a role. For this reason, an equation developed by F.N. Finn will also be tested to determine if will provide a better failure prediction for Minnesota pavements (see Equation 7).

$$N_f = 18.4 \left(0.00432 \varepsilon_t^{-3.291} E^{-0.854} \right) \quad (7)$$

Where:

E = Modulus of the asphalt layer (psi).

SEASONAL CONSIDERATIONS

Climatic Divisions

Air temperature data for 27 weather stations across Minnesota were obtained from the Midwest Climate Information System (MICIS). Initially, nine climatic divisions defined by the Midwestern Regional Climate Center (MRCC) were used (see Figure 13) and 30-year average daily temperature values were obtained from three weather stations in each division. These climatic divisions will be evaluated and compared to divisions used for selecting binder PG grades and for setting Spring load restrictions to determine the most appropriate divisions to use in MnPAVE.

Season Lengths

Season lengths were calculated according to a method described in a draft of the final report**,** ***Characterizing Seasonal Variations in Pavement Material Properties for Use in a Mechanistic-Empirical Design Procedure*** by Jill Ovik, Bjorn Birgisson, and David Newcomb. Table 2 shows the criteria used for defining season lengths. Table 3 shows the season lengths based on 30-year average daily air temperatures (1961 – 1990).

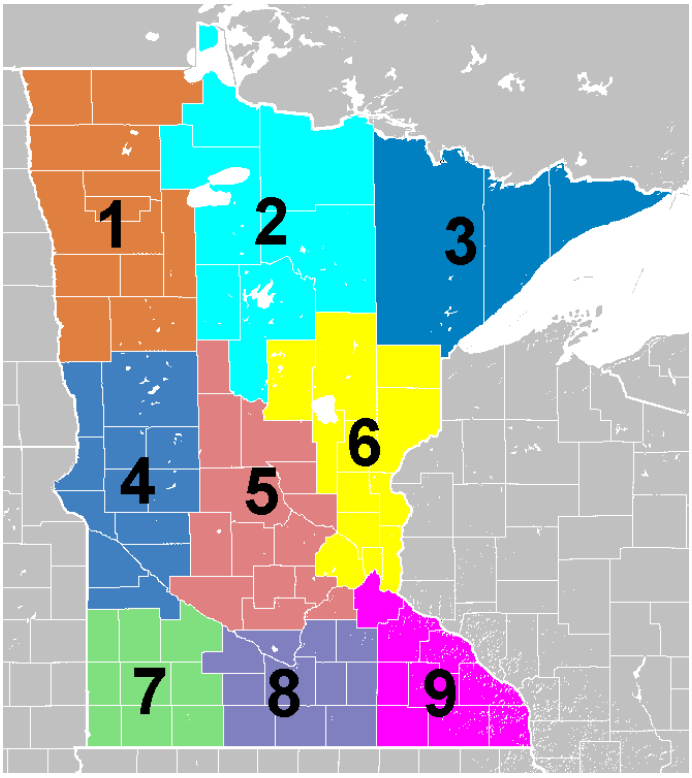


Figure 13 MRCC Climatic Divisions for Minnesota

Table 2 Seasonal Distribution of a Typical Year for Design Purposes

	Season				
	I	II	III	IV	V
Description	Winter: *Layers are Frozen*	Early Spring: *Base Thaws/ SG is Frozen*	Late Spring: *Base Recovers/ SG Thaws*	Summer: *HMA Low/ SG Recovers*	Fall: *HMA Recovers*
Estimated duration of each season					
Beginning	FI>90°C-days	TI>15°C-days	End of Season II	3-day T_{AVG} > 17°C	3-day T_{AVG} < 17°C
Ending	TI>15°C-days	Approx. 28 days later	3-day T_{AVG} > 17°C	3-day T_{AVG} < 17°C	FI>90°C-days
Pavement layer moduli relative to fall values					
E_{HMA}	High	High	Standard	Low	Standard
E_{AB}	High	Low	Low	Standard	Standard
E_{SG}	High	High	Low	Low	Standard

Table 3 Season Length (days) for Nine Climatic Divisions in Minnesota

Climatic Division	I	II	III	IV	V
	Winter	E-Spring	L-Spring	Summer	Fall
1 Northwest	114	28	46	91	86
2 North Central	112	28	60	75	90
3 Northeast	116	28	63	57	101
4 West Central	101	28	51	100	85
5 Central	96	28	47	108	86
6 East Central	102	28	51	93	91
7 Southwest	92	28	48	108	89
8 South Central	92	28	47	108	90
9 Southeast	90	28	49	108	90

Average Seasonal Pavement Temperatures

Two methods of estimating pavement temperatures were evaluated for MnPAVE. Both methods provide a means of estimating the pavement temperature at a given depth from the air temperature. A depth of 25 mm (1 in.) was chosen as the location of the representative pavement temperature for design purposes. Equation 8, known as the "Whiplash Equation", was developed by O.B. Andersland and is referenced in the Ovik report. In order to derive the pavement surface temperature from the average air temperature, Ovik used a modified form of an empirical surface temperature algorithm that was developed by the Strategic Highway Research Program (see Equation 9).

$$T(x,t) = T_{mean} + Ae^{-x\sqrt{\frac{2\pi}{P\alpha}}} \sin\left(\frac{2\pi}{P}(t) - x\sqrt{\frac{2\pi}{P\alpha}}\right) \quad (8)$$

Where:

$T(x,t)$ = Soil temperature as a function of depth and time (°C)
T_{mean} = Average temperature at surface (°C)
A = Maximum temperature amplitude (T_{max} - T_{mean})
P = Period or recurrence cycle (days)
t = Time measured from when the surface temperature passes through T_{mean} (days)
x = Depth (m)
α = thermal diffusivity (m^2/day)

$$T_{surf} = 0.859 \times T_{average} + 7.7 \quad (9)$$

Where:

T_{surf} = Average daily surface temperature (°C)
$T_{average}$ = Average daily air temperature (°C)

Equation 10 was developed by M.W. Witczak and is included in the Asphalt Institute's Thickness Design Manual (MS-1).

$$MMPT = MMAT\left(1 + \frac{1}{z+4}\right) - \frac{34}{z+4} + 6 \quad (10)$$

Where:

MMPT = mean monthly pavement temperature (°F)
MMAT = mean monthly air temperature (°F)
z = depth at which the average and standard deviation are predicted (in.)

To determine which method provided the best estimate of pavement temperatures in Minnesota, thermocouple data was collected from 19 thermocouples at a depth of 1.0 ± 0.1 in. from 10 asphalt test sections at Mn/ROAD. Figure 14 shows a comparison of the average seasonal pavement temperatures from the thermocouple measurements, the whiplash equation, and the Witczak equation. Based on these results, the Witczak model was chosen to determine the seasonal pavement temperatures for MnPAVE. The seasonal temperatures in Table 4 were calculated from 30 year average daily air temperatures.

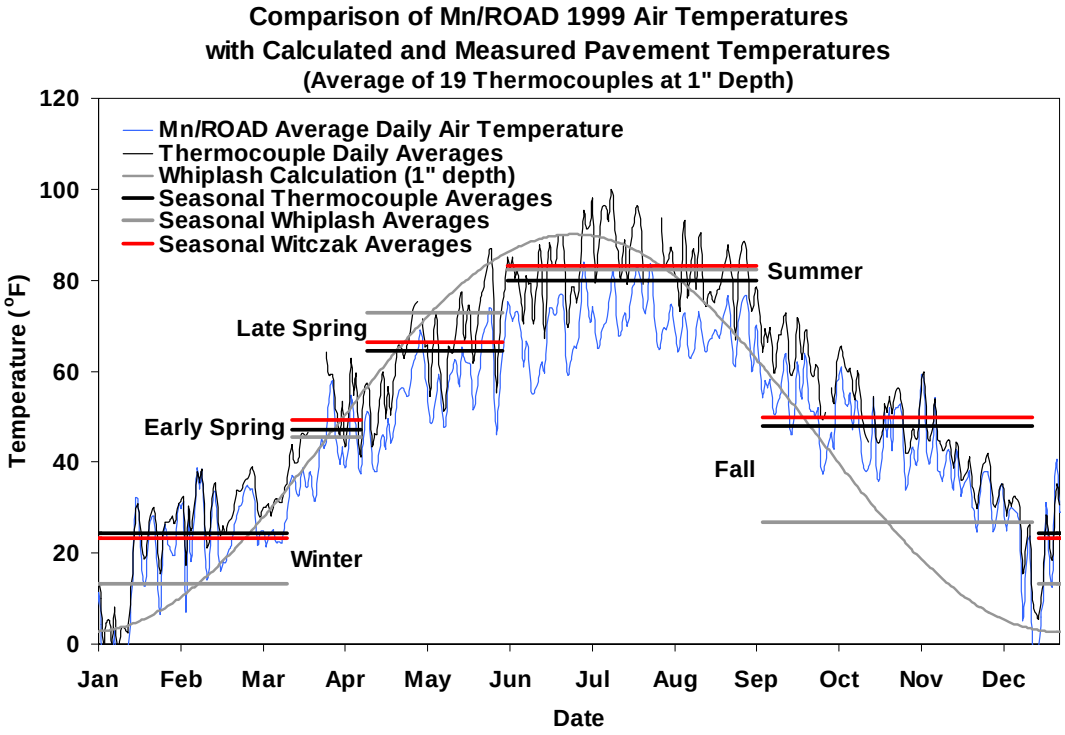


Figure 14 Comparison of Seasonal Pavement Temperature Estimates

Table 4 Season Pavement Temperature (°C / °F) for Nine Climatic Divisions in Minnesota

Climatic Division	I		II		III		IV		V	
	Winter		E-Spring		L-Spring		Summer		Fall	
1 Northwest	-11	12	6	42	17	63	26	78	10	50
2 North Central	-10	14	6	42	18	65	27	80	11	51
3 Northeast	-10	14	6	42	18	64	25	77	11	51
4 West Central	-9	16	5	41	18	65	28	82	10	50
5 Central	-8	18	6	42	18	65	28	83	10	50
6 East Central	-9	16	4	40	17	63	27	80	10	50
7 Southwest	-7	20	6	42	18	64	28	83	10	50
8 South Central	-7	20	6	42	18	65	28	83	11	51
9 Southeast	-7	20	6	42	18	65	28	83	10	50

ASPHALT MODULUS MODELS

Equation 11 is the existing equation for estimating the modulus of the asphalt layer based on temperature. It is an empirical relationship based on backcalculated moduli from AC-20 and 120/150 pen. asphalt pavements at Mn/ROAD.

$$E_{AC} = 16693.4 \times e^{\left(\frac{(T+26.2)^2}{-1459.7}\right)} \quad (11)$$

Where:

E_{AC} = Modulus of asphalt concrete (MPa)

T = pavement temperature (°C)

A model that takes into consideration various mix properties is being developed by M.W. Witczak for the 2002 Pavement Design Guide (see Equation 12). It is an empirical relationship based on data from the Long Term Pavement Performance (LTPP) database.

$$\log E = -1.249937 + 0.029232\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\rho_4 - 0.058097V_a$$
$$- 0.802208\left(\frac{V_{beff}}{V_{beff} + V_a}\right) + \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.005470\rho_{34}}{1 + e^{(-0.60333 - 0.313351\log(f) - 0.393532\log(\eta))}} \quad (12)$$

Where:

E = Dynamic modulus (10^5 psi)

η = Asphalt binder viscosity (10^6 Poise)

f = Loading frequency (Hz)

V_a = Air void content (%)

V_{beff} = Effective binder content (% by volume)

ρ_{34} = Cumul. % ret. on the 19 mm (3/4") sieve

ρ_{38} = Cumul. % ret. on the 9.5 mm (3/8") sieve

ρ_4 = Cumul. % ret. on the 4.76 mm (No. 4) sieve

ρ_{200} = % passing the 0.075 mm (No. 200) sieve

Figure 15 shows a comparison of the Mn/ROAD and Witczak models and backcalculated modulus values from Cell 33.

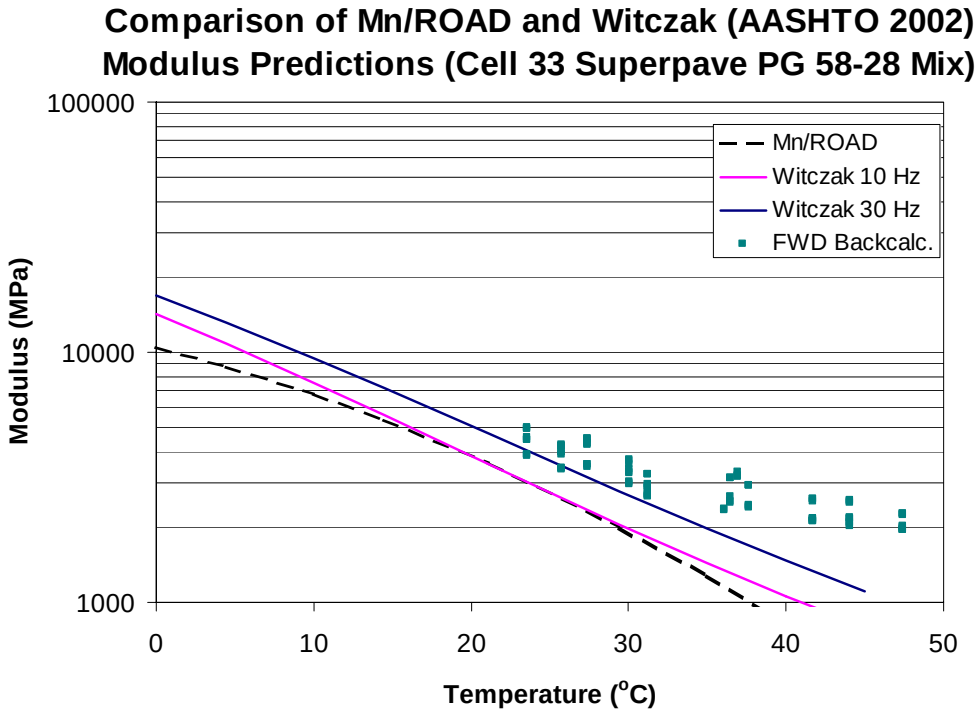


Figure 15 Comparison of Asphalt Modulus Values from Mn/ROAD and Witczak Empirical Models and Backcalculated FWD Data

CONCLUSIONS

1. While the Allowed Repetition Distribution and Damage Factor methods produce similar reliability values for a single season, single load class situation, the results can be significantly different for more complex situations.

2. The Allowed Repetitions method does not calculate reliability appropriately when multiple seasons or load spectra are used. Its method of randomly selecting one season and one axle per Monte Carlo means that each cycle consists of a climate with an unvarying temperature and moisture state, and a traffic stream with *n* repetitions of the same load (where *n* is the sum of repetitions from all axles and load classes).

3. The result of this deviation from Miner's Hypothesis is a reliability calculation in which too much significance is assigned to cases with low damage, and too little is assigned to cases with high damage. This is evident in the extreme skewing of the damage distributions and the unusually high reliability predictions of the Allowed Repetitions method.

RECOMMENDATIONS

1. It is recommended that the Allowed Repetitions method be replaced by the Damage Factor method in future upgrades of the MnPAVE software.

2. Further analysis should be conducted to determine if the reliability computing time can be reduced significantly.

3. More analysis should be conducted on the temperature data to define appropriate climatic divisions for Minnesota.

4. Once the climatic divisions have been determined, season lengths and seasonal average pavement temperatures be should be calculated using the Witczak pavement temperature model.

5. More analysis should be conducted to determine which asphalt modulus model should be implemented.

6. More analysis should be conducted to determine the appropriate fatigue transfer function.

7. The fatigue and rutting transfer functions should be further calibrated as more distress data is collected from Mn/ROAD and other research sites.

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	John Siekmeier	Shongtao Dai
	Dave Newcomb	Dave Timm	Duane Young
	Dave Bullock	Roger Olson	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:

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

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

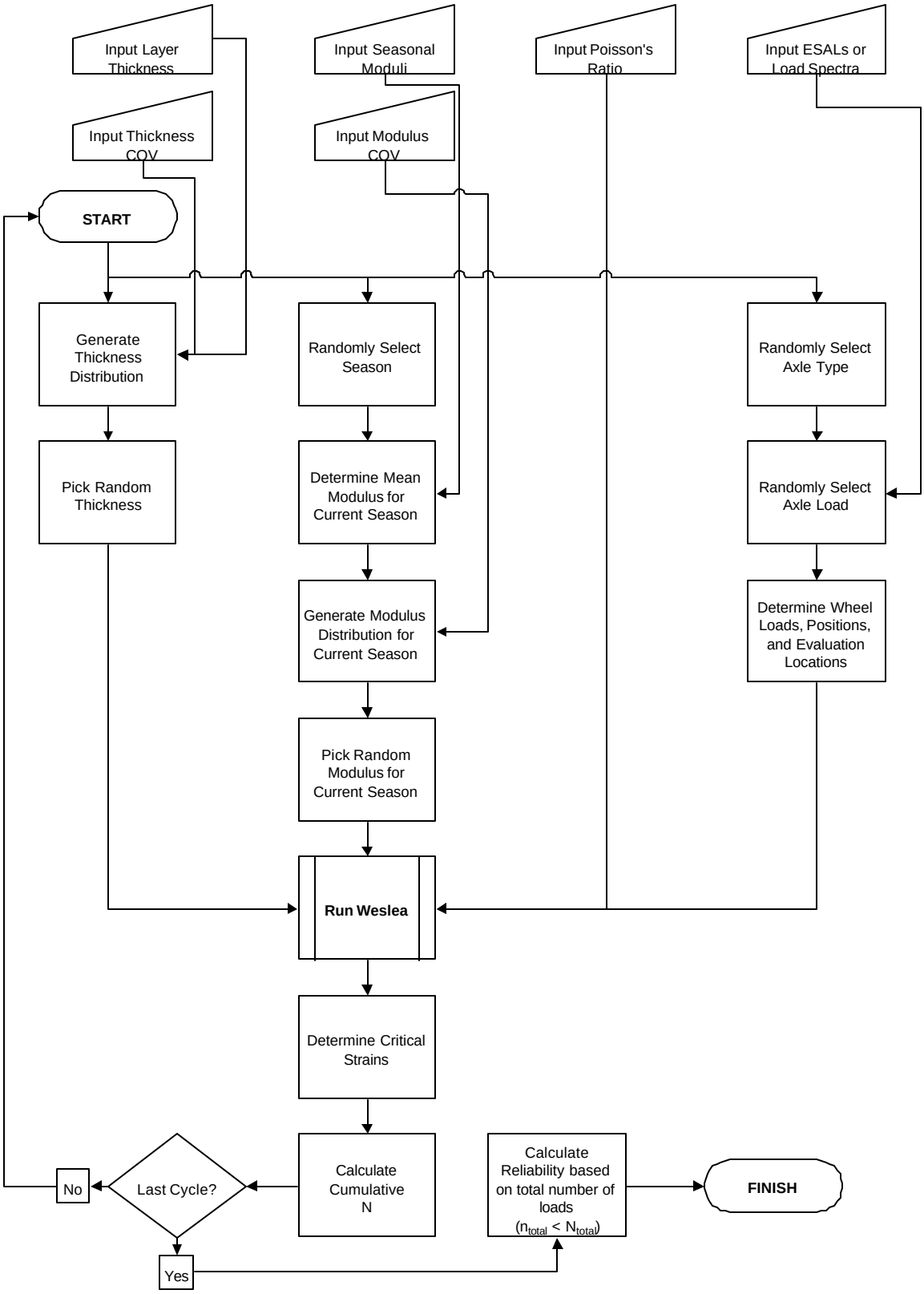


Figure C-1 Flow Chart for the Allowed Repetitions Reliability Method

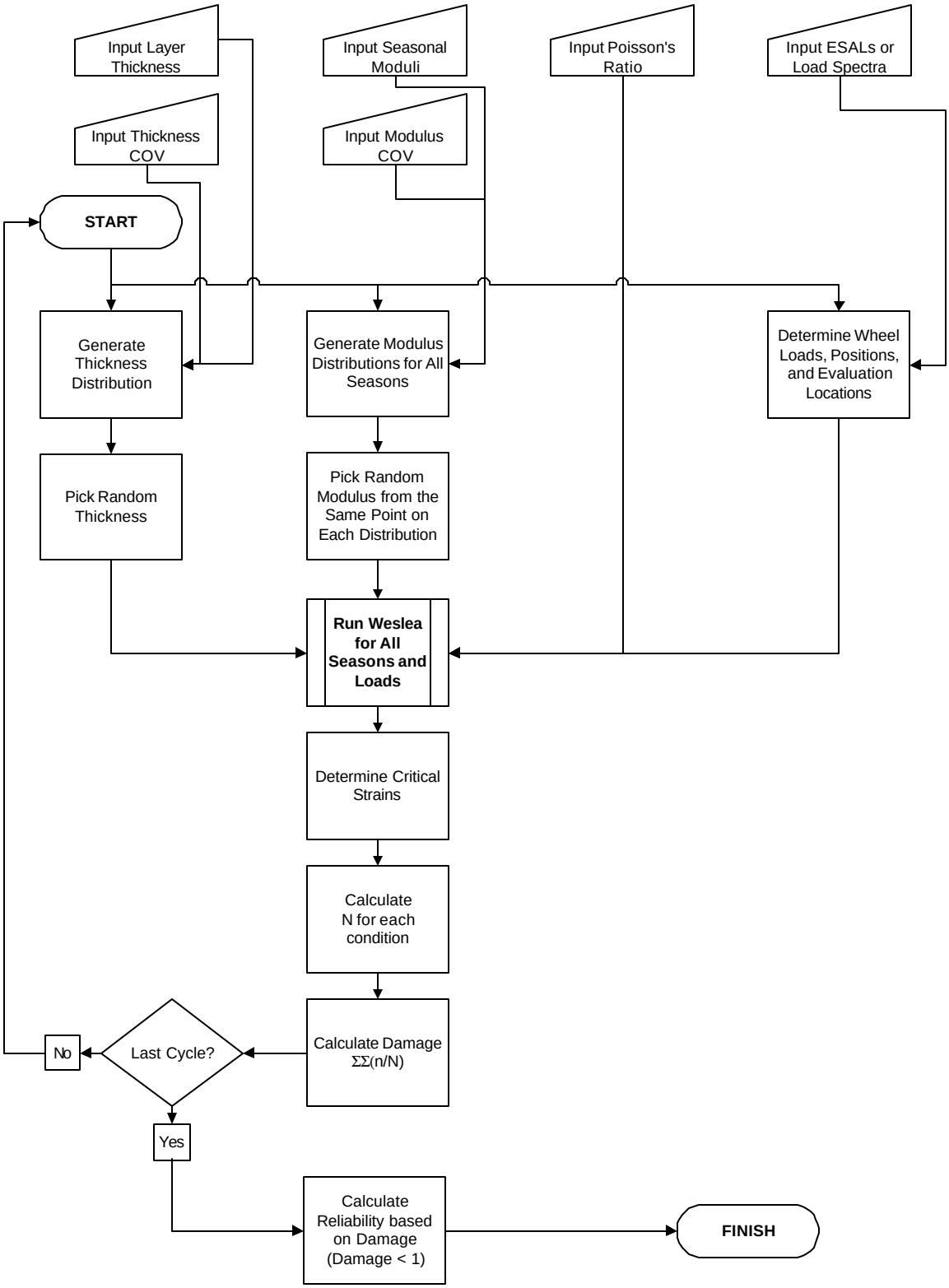
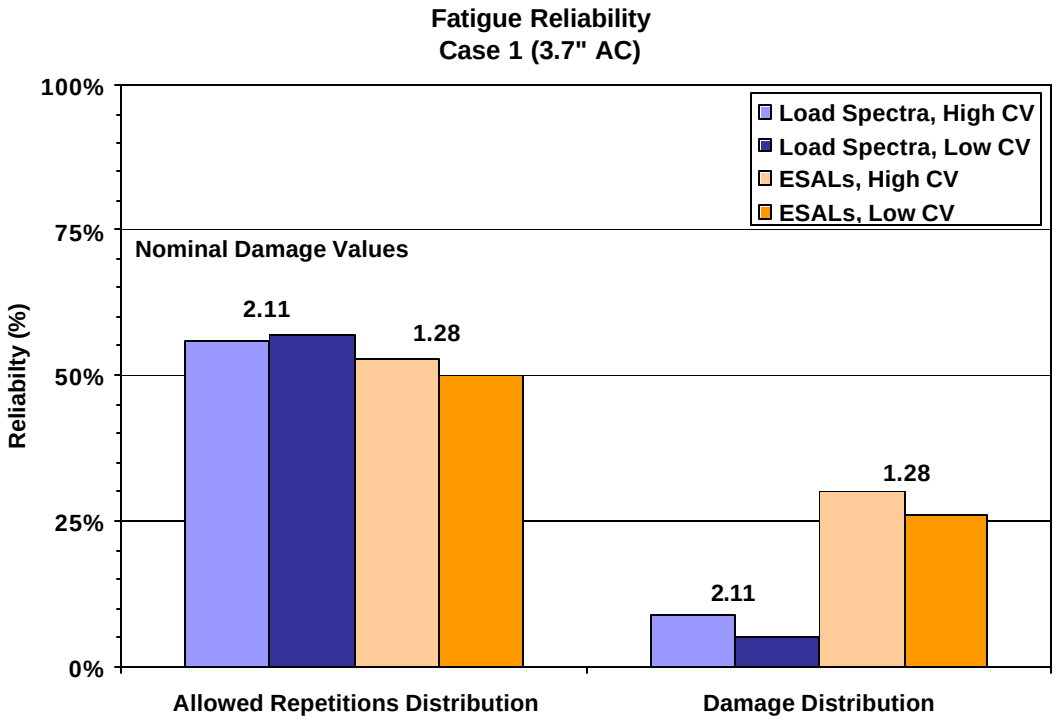
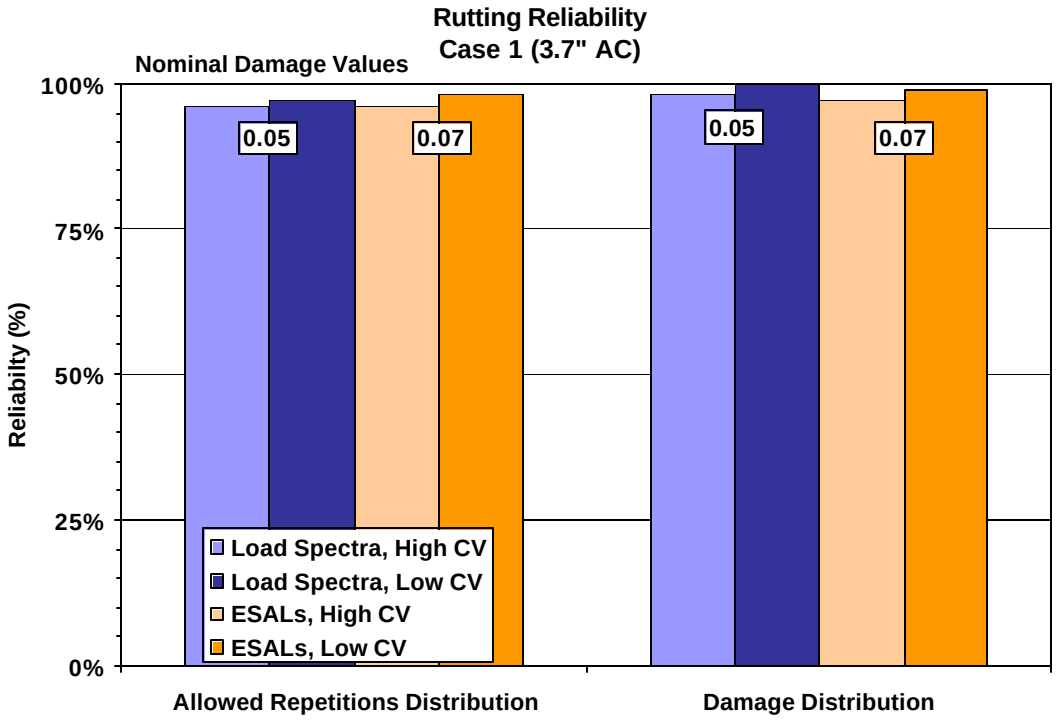


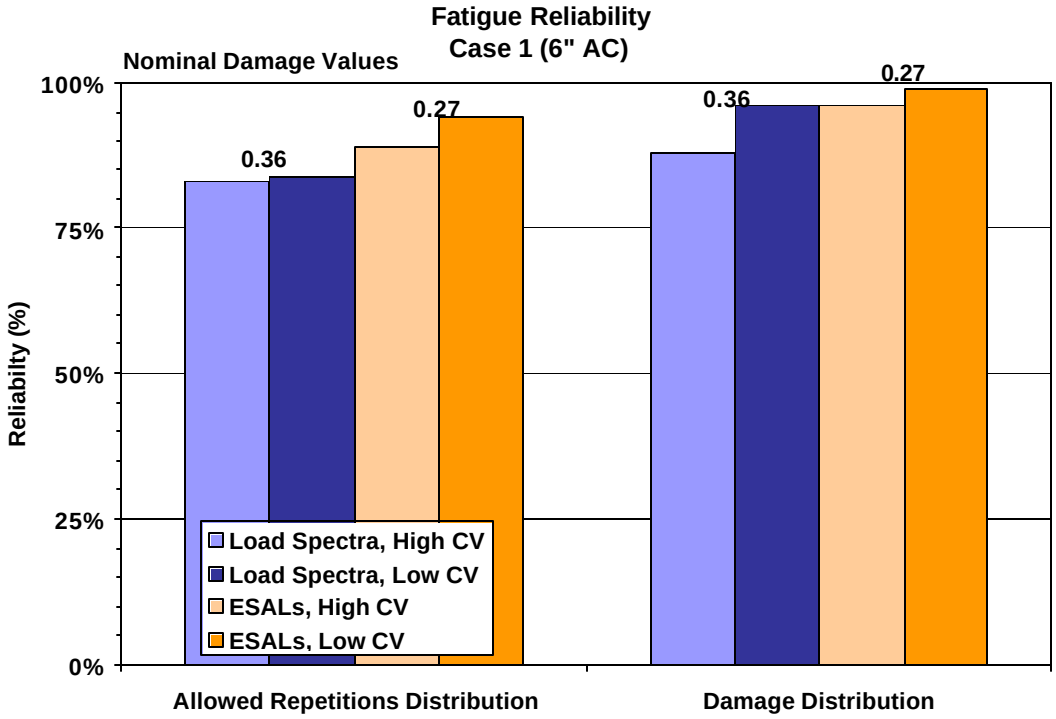
Figure C-2 Flow Chart for the Damage Factor Reliability Method

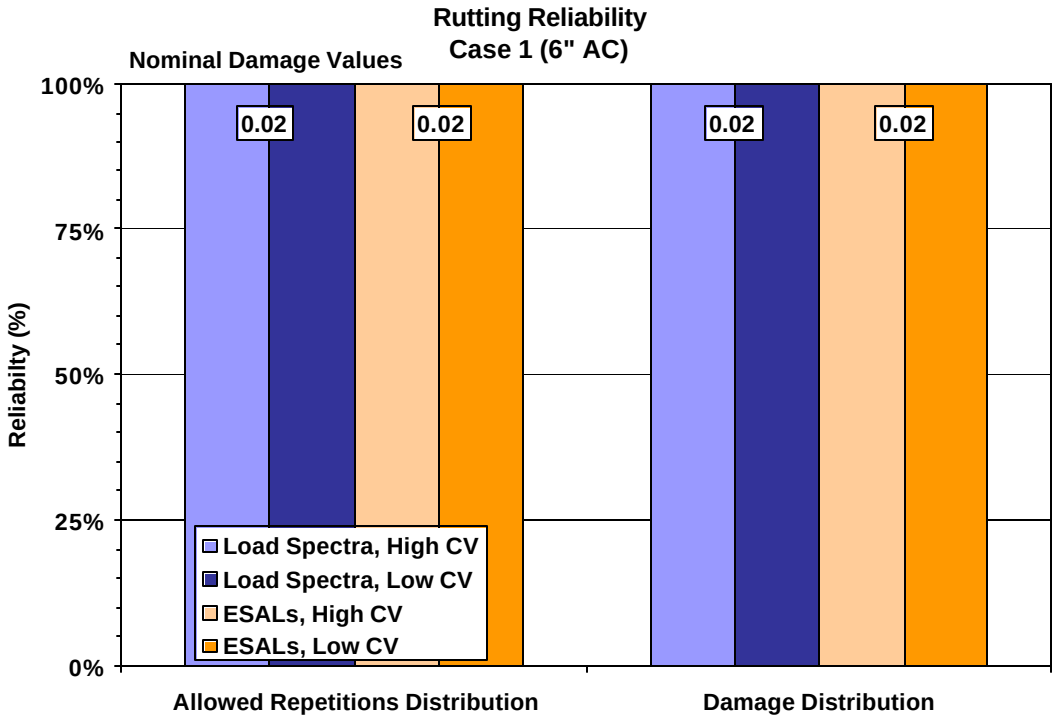
Appendix D

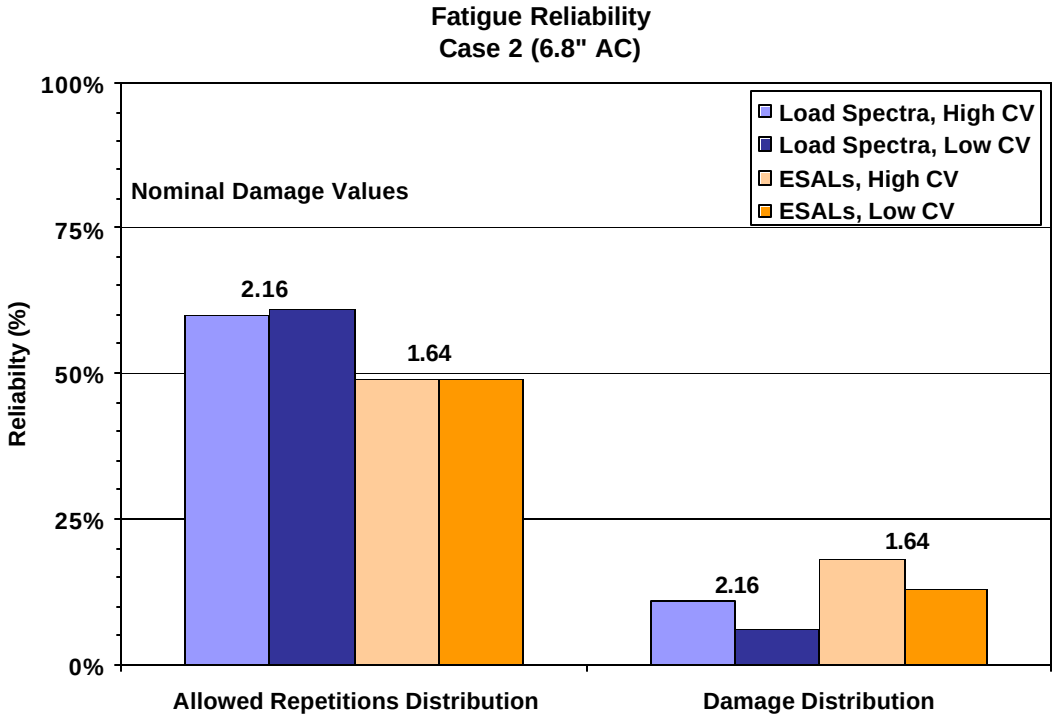
Complete Output

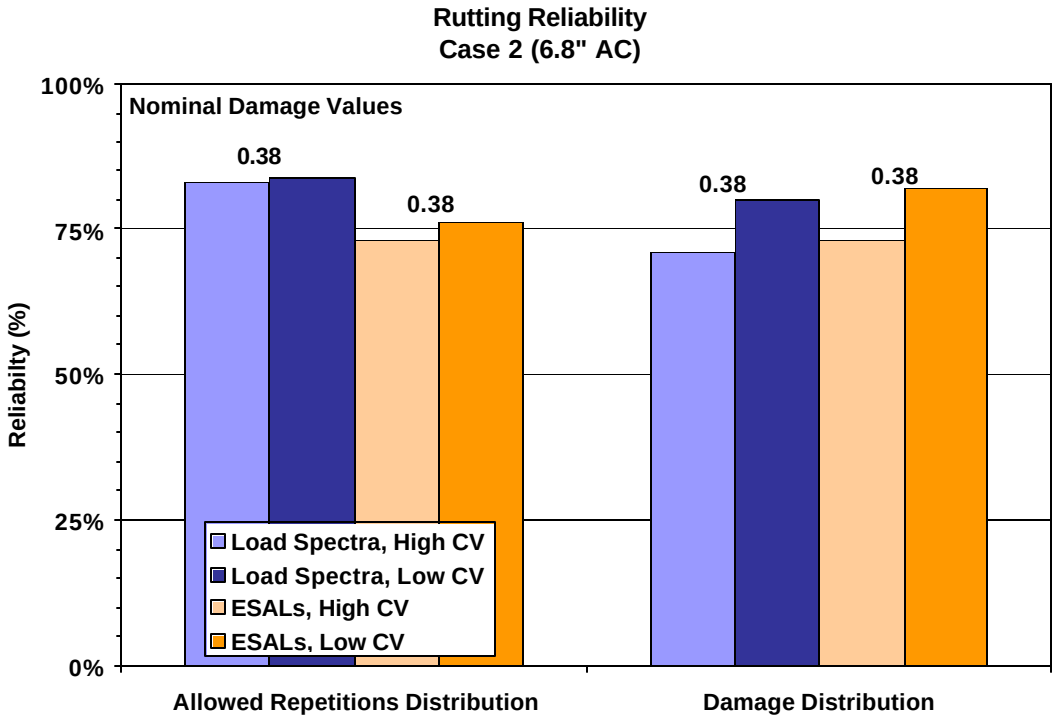

Fatigue Reliability
Case 1 (3.7" AC)
100%
75%
50%
25%
0%
Reliabilty (%)
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Nominal Damage Values
2.11
1.28
2.11
1.28
Allowed Repetitions Distribution
Damage Distribution

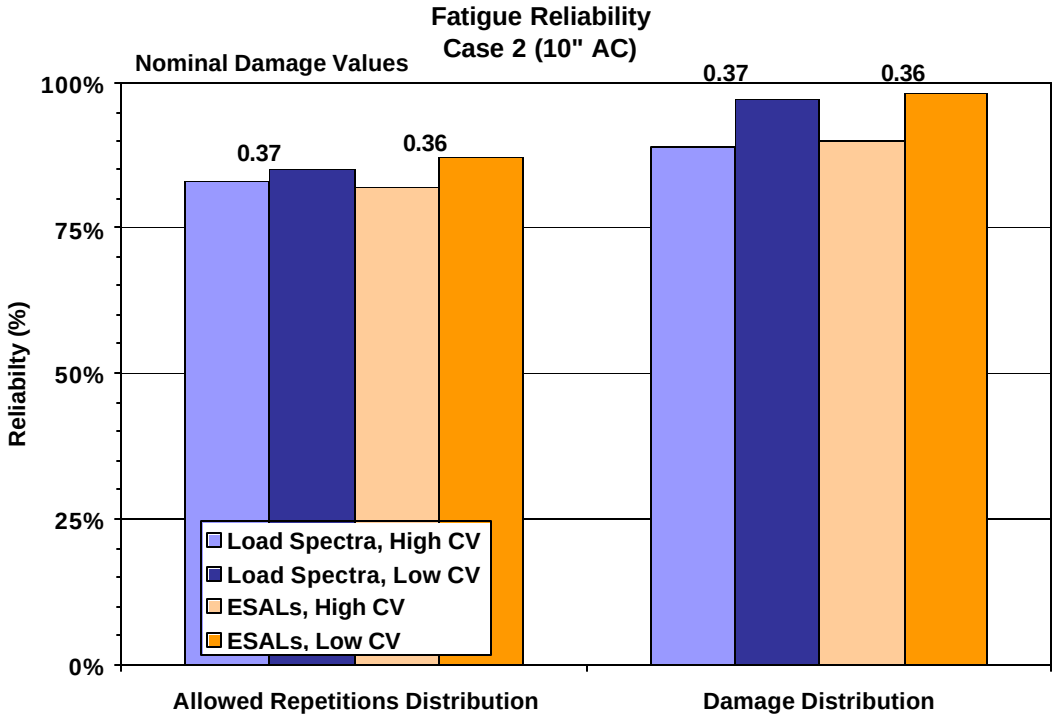

Rutting Reliability
Case 1 (3.7" AC)
Nominal Damage Values
100%
75%
50%
25%
0%
Reliabilty (%)
0.05
0.07
0.05
0.07
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution

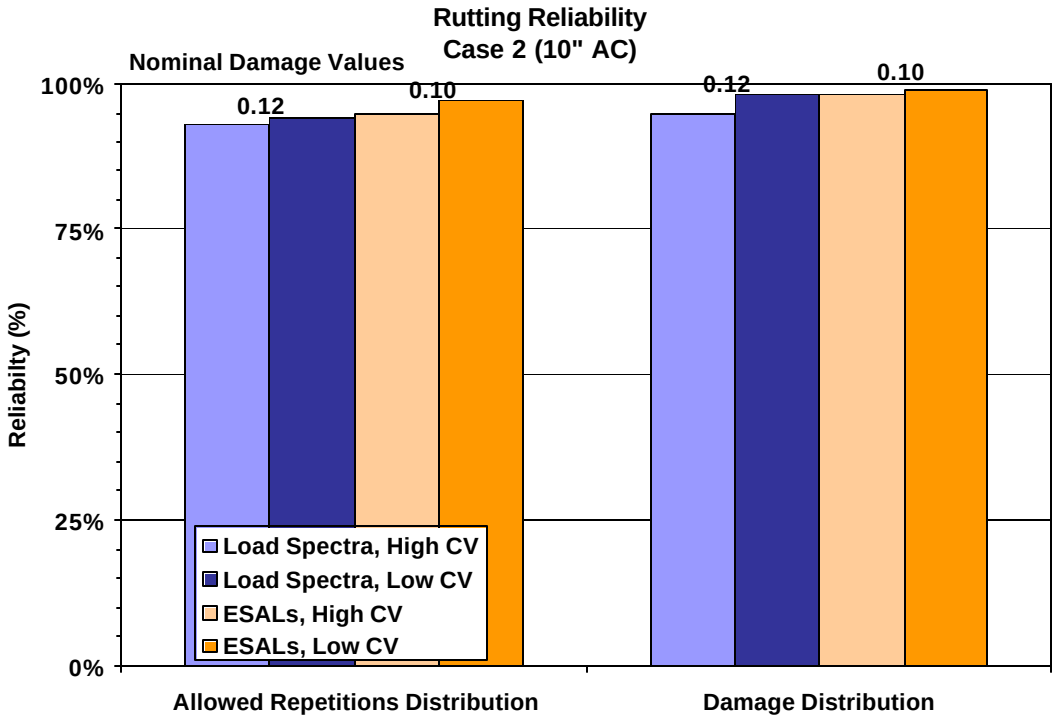

Fatigue Reliability
Case 1 (6" AC)
Nominal Damage Values
100%
75%
50%
25%
0%
Reliabilty (%)
0.36
0.27
0.36
0.27
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution

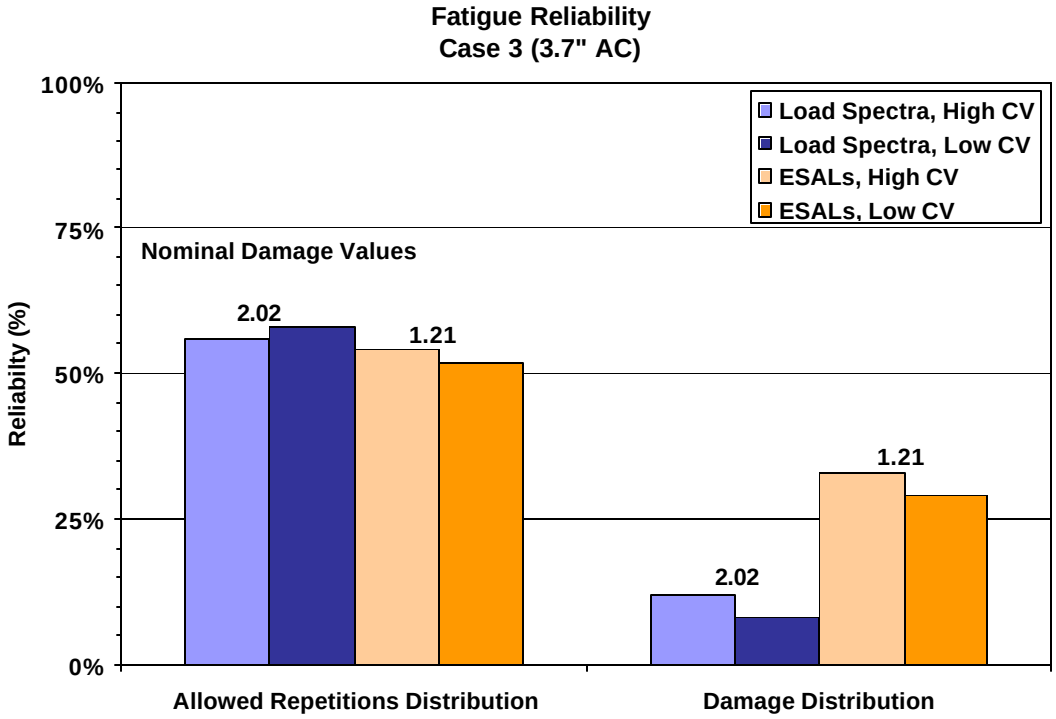

Rutting Reliability
Case 1 (6" AC)
Nominal Damage Values
100%
75%
50%
25%
0%
Reliabilty (%)
0.02
0.02
0.02
0.02
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution

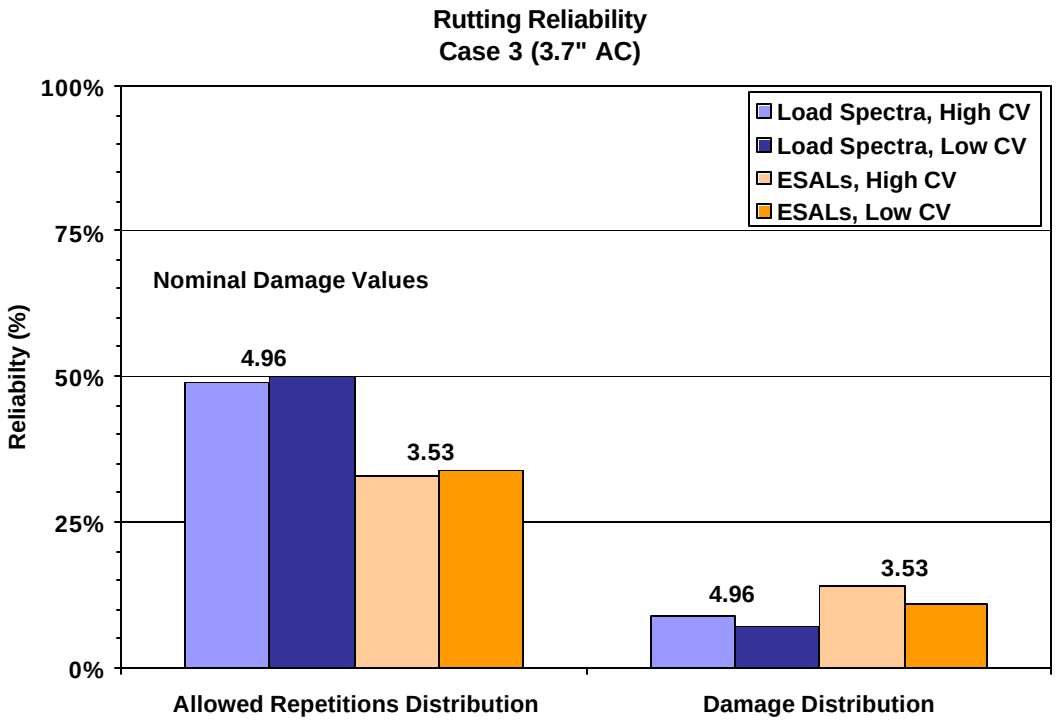

Fatigue Reliability
Case 2 (6.8" AC)
100%
75%
50%
25%
0%
Reliabilty (%)
Nominal Damage Values
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
2.16
1.64
2.16
1.64
Allowed Repetitions Distribution
Damage Distribution

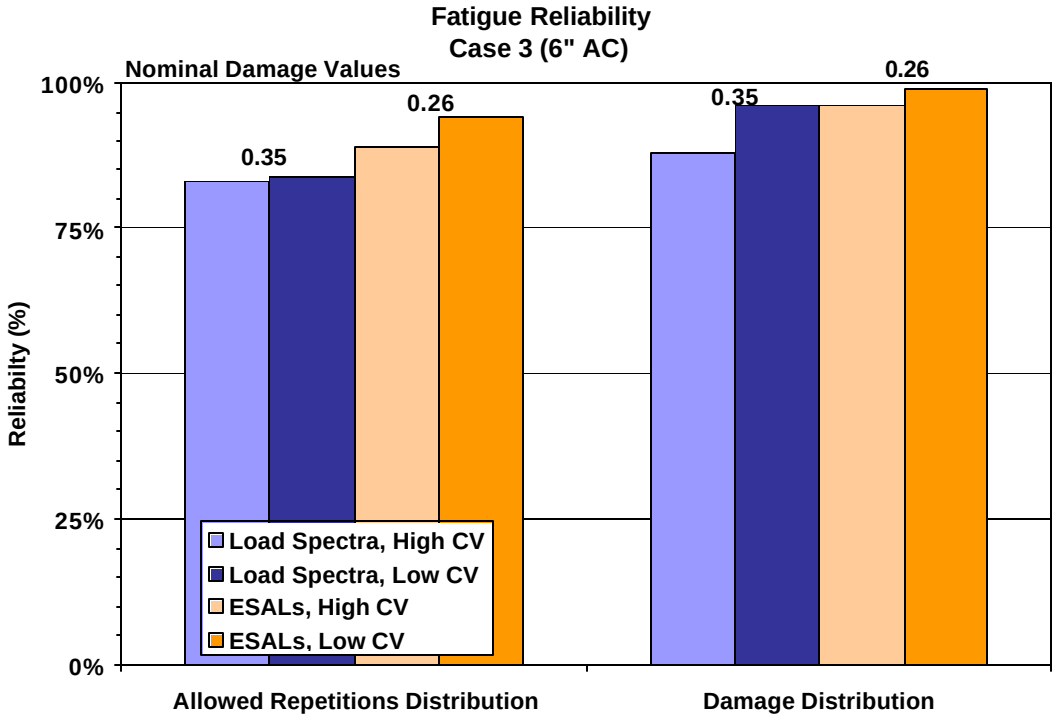

Rutting Reliability
Case 2 (6.8" AC)
100%
75%
50%
25%
0%
Reliabilty (%)
Nominal Damage Values
0.38
0.38
0.38
0.38
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution

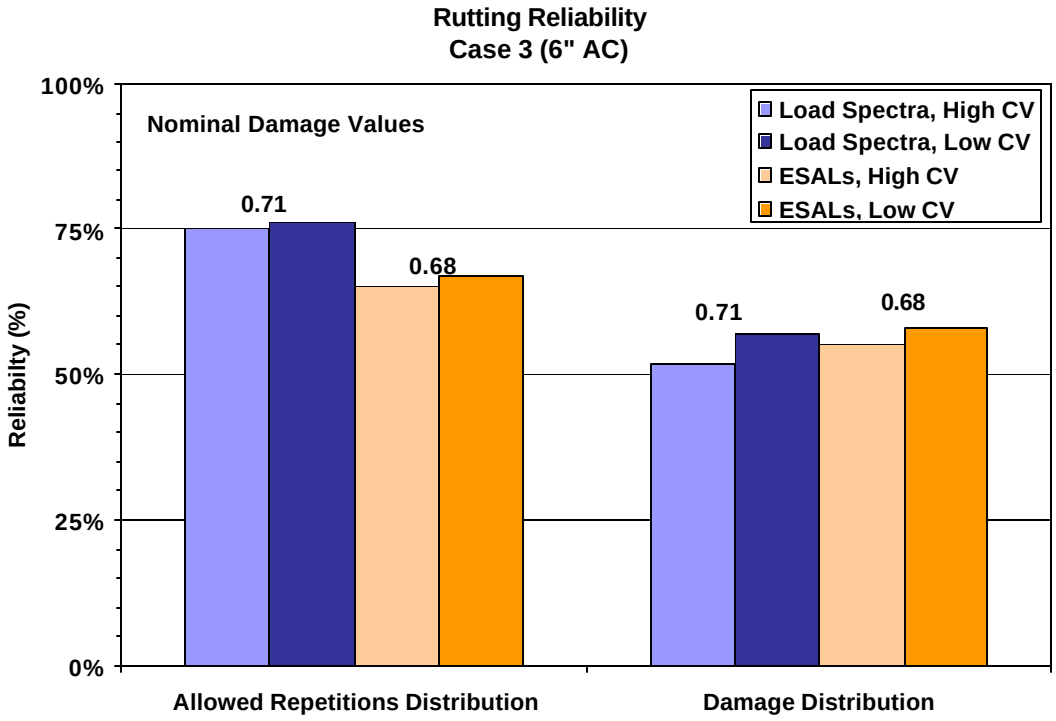

Fatigue Reliability
Case 2 (10" AC)
Nominal Damage Values
100%
75%
50%
25%
0%
Reliabilty (%)
0.37
0.36
0.37
0.36
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution

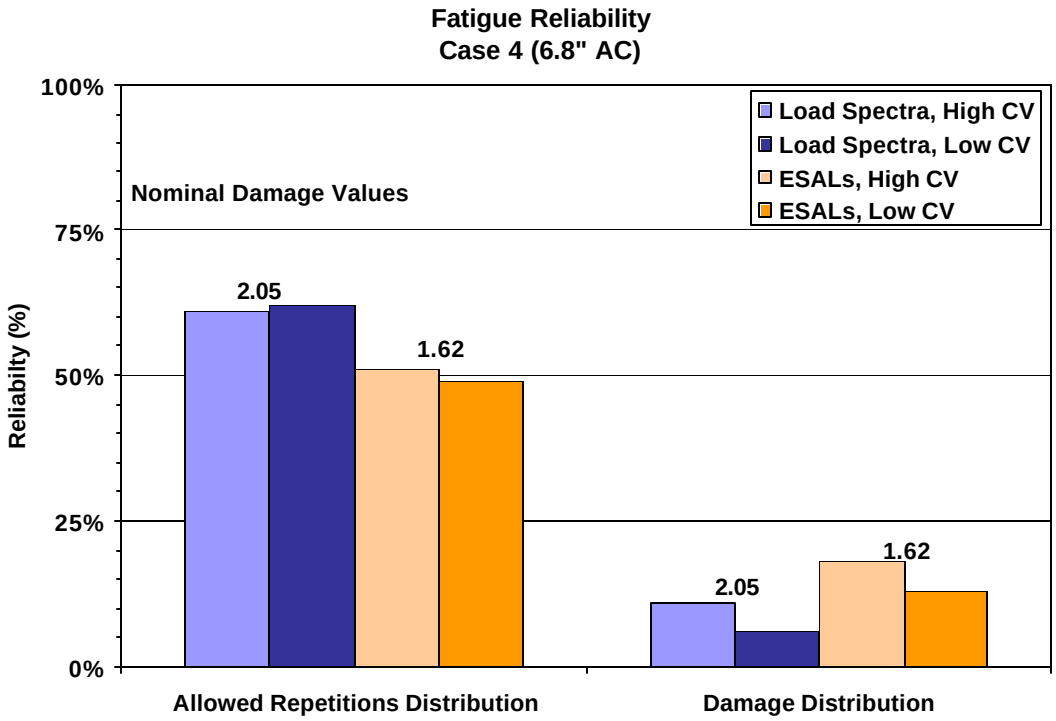

Rutting Reliability
Case 2 (10" AC)
Nominal Damage Values
100%
75%
50%
25%
0%
Reliabilty (%)
0.12
0.10
0.12
0.10
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution

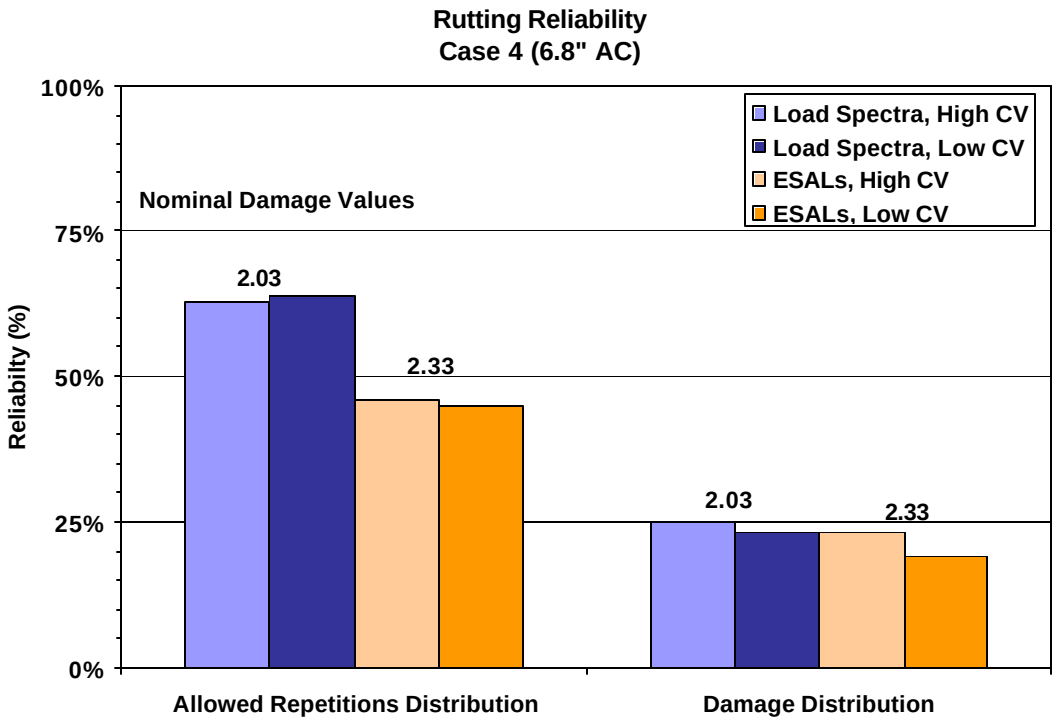

Fatigue Reliability
Case 3 (3.7" AC)
100%
75%
50%
25%
0%
Reliabilty (%)
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Nominal Damage Values
2.02
1.21
2.02
1.21
Allowed Repetitions Distribution
Damage Distribution

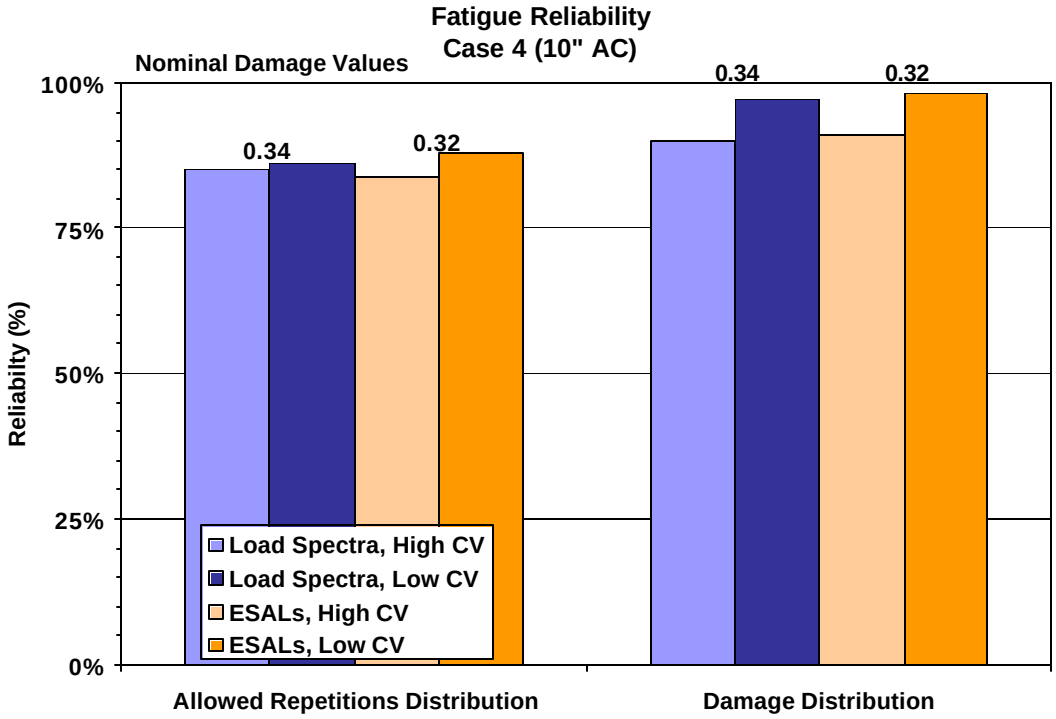

Rutting Reliability
Case 3 (3.7" AC)
100%
75%
50%
25%
0%
Reliabilty (%)
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Nominal Damage Values
4.96
3.53
4.96
3.53
Allowed Repetitions Distribution
Damage Distribution

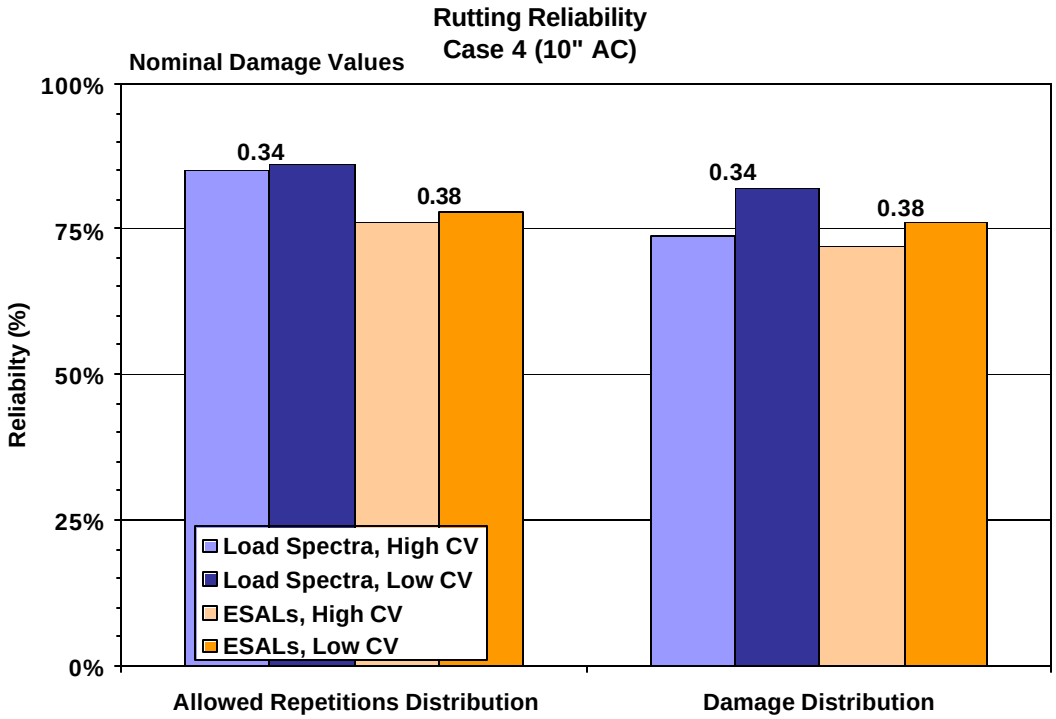

Fatigue Reliability
Case 3 (6" AC)
Nominal Damage Values
100%
75%
50%
25%
0%
Reliabilty (%)
0.35
0.26
0.35
0.26
Load Spectra, High CV
Load Spectra, Low CV
ESALs, High CV
ESALs, Low CV
Allowed Repetitions Distribution
Damage Distribution


Rutting Reliability
Case 3 (6" AC)
Nominal Damage Values
100%
75%
50%
25%
0%
Reliabilty (%)
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)
100%
75%
50%
25%
0%
Reliabilty (%)
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)
100%
75%
50%
25%
0%
Reliabilty (%)
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