NIST Technical Note 1418

Probabilistic Estimates of Design Load Factors for Wind-Sensitive Structures Using the "Peaks Over Threshold" Approach

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April 1996

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National Institute of Standards
and Technology
Technical Note 1418
Natl. Inst. Stand. Technol.
Tech. Note 1418
30 pages (April 1996)
CODEN: NTNOEF

U.S. Government Printing Office
Washington: 1996

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Abstract: The "peaks over threshold" method is used to estimate ratios of wind-induced loads with various long mean recurrence intervals to loads with a 50-year mean recurrence interval. The results support the conclusion that the load factor value of 1.3 specified in the ASCE Standards 7-93 and 7-95 is adequate for extratropical storm regions. However, for hurricane-prone regions, the results imply that the standard value of the load factor (even after being augmented by an importance factor specified in the standards) leads to nominal ultimate wind loads with considerably shorter mean recurrence intervals than is the case for extratropical regions. This suggests that the 1.3 load factor value specified in the ASCE Standards 7-93 and 7-95 is inadequate for wind-sensitive structures in hurricane-prone regions.

Key Words: building (codes); building technology; climatology; extreme value theory; hurricanes; load factors; structural engineering; structural reliability; threshold methods; wind (meteorology)

1 Introduction

The nominal design wind load is an extreme load with a specified probability of being exceeded during a specified time interval. For codes and standards in the United States, this interval is usually 50 years, and the specified load is based upon a 50-year nominal design wind speed. For example, for the inland Miami, Florida area, the ASCE Standard 7-93 [1] and 7-95 [2] specify a nominal 50-year load based on a nominal 50-year design wind speed of 49.17 m/s (110 mi/h). It is expected, however, that a structure or element thereof should withstand wind loads substantially in excess of the 50-year wind load without loss of integrity. The wind load beyond which loss of integrity can be expected is referred to as the ultimate wind load. The ultimate strength provided for in the design of a structure is based upon an assumed nominal ultimate wind load equal to the nominal design wind load times a wind load factor.

The wind load factor should be selected so that the probability of occurence of the ultimate wind load is acceptably small. This probabilistic concept is important from an economic or insurance point of view. To the extent that evacuation or similar measures cannot be expected to prevent loss of life, it is important also from a safety point of view. However, attempts to estimate wind load factors on a probabilistic basis have so far not been successful. This may be due at least in part to the common use in reliability calculations of the assumption that wind speeds are modeled by probability distributions with infinite upper tails, *e.g.*, Gumbel or Weibull distributions. In [3] and [12], it was assumed that the probability distribution of hurricane wind speeds is Weibull. However, the Weibull distribution is an asymptotic model for the distribution of the smallest extremes. For extreme largest values, the appropriate asymptotic model is either Gumbel, Fréchet, or reverse Weibull [4, 9]. As for the Gumbel distribution, it was found in [6] to yield what appeared to be unrealistically high ultimate wind loads.

Recent studies [9, 10] have produced evidence in support of the assumption that extreme wind speeds are modelled by the reverse Weibull distribution, which is tail-limited (*i.e.*, has a finite-length upper tail). The purpose of this report is to explore the potential offered by this finding for estimating wind load factors on a probabilistic basis. This is done separately for hurricane winds (sec. 2) and for winds in extratropical regions (sec. 3). In this work, wind directionality effects are not taken into account. It is also assumed that the dominant load is due to wind. Our results are therefore applicable to wind-sensitive structures for which wind directionality effects are not significant. (Refer to [8] for a discussion of directionality effects.)

2 Load Factors for Hurricane-Prone Regions

In this section, we are interested in the estimation of wind load factors for those portions of the United States that have hurricanes and tropical storms as their most likely source of extreme winds. This region encompasses the coastal regions of the Gulf of Mexico and the Atlantic Ocean (see Fig. 1). Data for this study were obtained via simulation of hurricane winds based upon censored probabilistic models of the climatological parameters that influence hurricane structure. Consult [3] for a more complete discussion of the model. Censoring

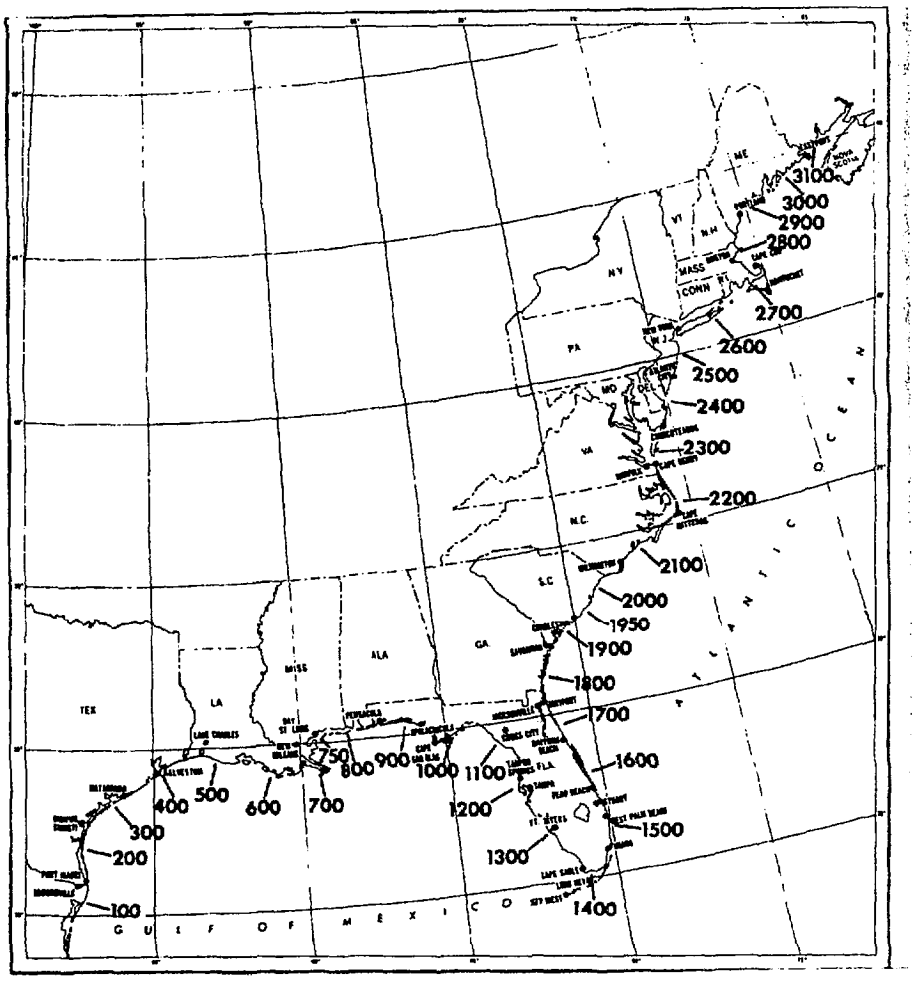


Figure 1: Locator map for the hurricane-prone region of the United States (from [11]).

was based on physical considerations and is in principle consistent with a tail-limited probabilistic model of extreme wind speeds. The data represent fastest one-minute hurricane speeds in knots at 10 m above ground over open terrain at the coastline at 55 equidistant locations. Data are available as maximum wind speeds within each of 16 half octants for each of 999 simulated hurricane events. As indicated earlier, we analyzed datasets consisting of the largest speed in each hurricane event regardless of direction. The estimated mean annual rate of occurence of hurricanes at each location is also included in the dataset. The data are available on tape and via anonymous file transfer.[1]

Analysis of the data was performed via programs that implement the de Haan version of the "peaks over threshold" method for estimating extreme value distribution parameters.[2] A discussion of this method may be found in [5]. From the estimated distribution parameters, we obtained estimates of wind speeds having specified mean recurrence intervals R. (The recurrence interval R in years is the inverse of the probability that that wind speed will be exceeded in any one year.) Under the assumption that a reverse Weibull distribution is valid,

[1]See [10] for details on obtaining the data.

[2]These programs are also available via anonymous file transfer; see the previous footnote.

the probability of no exceedance of a given threshold speed is

$$G(y) = \text{Prob}\,[Y \leq y] = 1 - \left\{[1 + (cy/a)]^{-1/c}\right\}, \tag{1}$$

where a and c are location and tail-length parameters, respectively, $a > 0$, $c < 0$, $cy > -a$, $Y = X - u$, X is the windspeed, and $u < X$ is a threshold assumed to be sufficiently high [9]. (More precisely, this is the conditional probability, given that $X > u$ for u sufficiently large.) To obtain the estimate of the wind speed, let λ represent the mean crossing rate of the threshold u per year. Therefore, we can take

$$\text{Prob}\,[Y \leq y] = 1 - 1/(\lambda R) \tag{2}$$

as an estimate of the probability of no exceedances. Equating these two probability expressions and solving for y gives

$$y = -a\left[1 - (\lambda R)^c\right]/c, \tag{3}$$

which in turn yields

$$X_R = y + u \tag{4}$$

as the estimated wind speed having a mean recurrence interval of R for the threshold u. The wind speed with an infinite mean recurrence interval, *i.e.*, the limiting upper wind speed as defined by the reverse Weibull distribution, is denoted by X_{inf}. Using eq (1) and setting $G(y) = 1$, we can solve for y and thus obtain

$$X_{inf} = u - a/c. \tag{5}$$

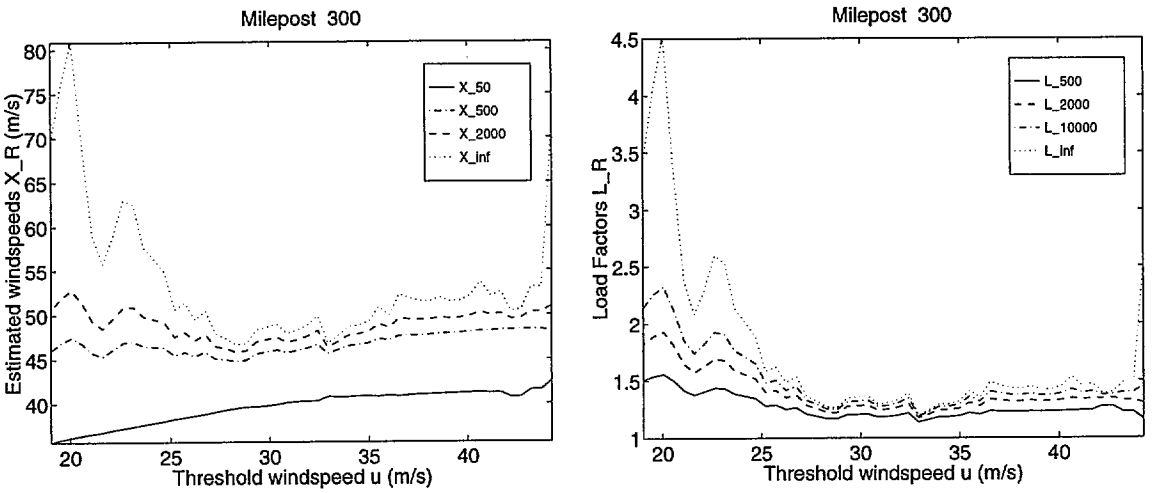
The wind load factor specified in the ASCE Standard 7-93 represents the ratio of the ultimate wind load to the wind load based upon the 50-year nominal hurricane wind speed X_{50} times a hurricane importance factor F. Since wind loads are proportional to the square of the wind speed, we form an estimate of the wind load factor L_R according to:

$$L_R = \left[X_R/(F * X_{50})\right]^2. \tag{6}$$

As specified on page 152 in the Commentary on ASCE Standard 7-95 [2], $F = 1.05$. L_{inf} is defined by eq (6) with X_{inf} replacing X_R.

We show representative plots of the estimated wind speeds X_R and estimated wind load factors L_R for various values of R in Figure 2 for simulated hurricanes at Milepost 300 (a location near Matagorda Bay, Texas).[3] Both the wind speeds X_R and wind load factors L_R display a great deal of variability for low thresholds ($u < 25$ m/s, roughly speaking). We note that inherent in the reverse Weibull model is the assumption that the thresholds u correspond to high extreme wind speeds, and violations of this assumption may lead to poor distribution parameter estimates. Also, both X_R and L_R display variability for very high thresholds ($u > 43$ m/s, approximately). This is due to the relatively small sizes (fewer than 30 data points) of the wind speed data samples exceeding these thresholds. Between these two bounding cases, the values of X_R and L_R are fairly constant, although some fluctuation clearly exists.

[3]In all figures in this report, wind speeds are fastest-minute wind speeds at 10 m above ground over open terrain in meters per second.



X_R versus u.

L_R versus u.

Figure 2: Representative plots of estimated wind speeds X_R and load factors L_R versus threshold speed u.

Graphs of estimated wind load factors versus threshold speed for various locations along the Gulf of Mexico and Atlantic Ocean coastline are provided in Appendix A. Due to the previously mentioned reasons, no results have been shown for thresholds having more than 300 exceedances or fewer than 30 exceedances. Also, estimated load factors larger than 2.5 are not shown. For comparison, we have included in these plots a dotted line at $L_R = 1.3$, representing the ASCE Standard 7-93 value of the wind load factor.

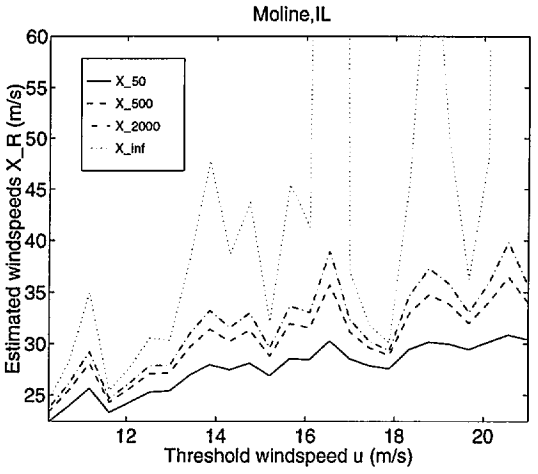
The graphs of Appendix A show noticeable variability in the load factors as a function of threshold, especially for the high recurrence intervals $R = 10,000$ years and $R = \infty$. However, certain trends are discernable. For example, the load factor L_{500}, shown as a solid line in the graphs, is close to or higher than the design standard value of 1.3 for most mileposts. This result is in keeping with the conclusions of [10], which found that the load factor standard value corresponded to winds with relatively short mean recurrence intervals. This implies that the probability of exceedance of the nominal ultimate wind load (calculated in accordance with the standard) is about 0.002 (or larger) per year or, assuming that the design lifetime of the structure is 50 years, is equal to (or larger than) about

$$1 - (1 - 0.002)^{50} = 0.095$$

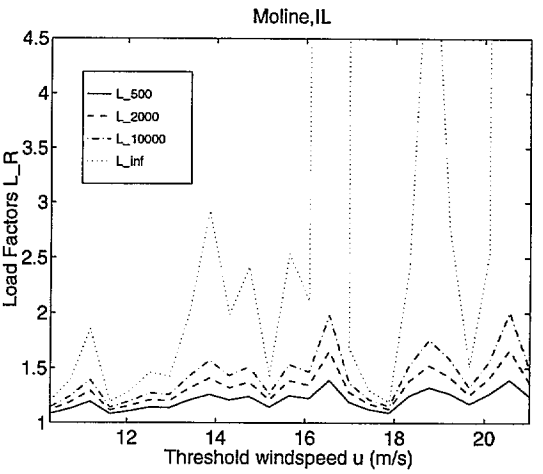
during the structure's lifetime.

3 Load Factors for Extratropical Regions

We now turn our attention to the estimation of wind load factors for areas of the United States in which tropical storms are not expected to occur. We use as our source of data



X_R versus u.



L_R versus u.

Figure 3: Representative plots of estimated wind speeds X_R and load factors L_R versus threshold speed u.

the records of the largest daily wind speeds collected at 44 U.S. weather stations that lie outside of the area described in sec. 2. Each set contains approximately 20 years worth of daily fastest mile wind data. We once again used the de Haan estimation method, and the analysis proceeded largely as described in the previous section, with one additional step.[4] In order to reduce possible correlations among the data due to a single storm producing strong winds for more than 1 day, the records were broken into intervals of 8 days, and maximum speeds in each interval were identified. If maxima of adjacent intervals (denoted by I_1 and I_2) were found to be less than 4 days apart, the following procedure was used. Let I_1 contain the smaller of the two maxima. This maximum was replaced by the highest value in I_1 separated from the maximum in I_2 by 4 days or more. This procedure insured that all data in the set were at least 4 days apart. The interval of 4 days was chosen because it represents a reasonable maximum duration of a strong wind storm. Analyses with interval lengths of 4 days and correlation periods of 2 days were performed and were found to produce no significant differences in the results. Previous studies [9] have shown that this procedure, while reducing the total number of data points used in the estimation process, tends to remove low wind speeds from consideration, resulting in a data set more representative of extreme winds.

In Figure 3, we show representative plots of the estimated wind speeds X_R and wind load factors L_R for data from Moline, IL, for which 15 years of daily wind speed data are available. Note that L_R is still defined by eq (6) for extratropical regions, but the hurricane importance factor F is now set to 1.00. As was true for the hurricanes, we note a downward trend for the estimated variates with lower thresholds. We ascribe this trend to bias associated with

[4]Again, both the data sets and analysis programs are available. See [9] for further information.

the inclusion of relatively weak winds. For this reason, and to reduce sampling errors due to small sample sizes due to very high thresholds, we have plotted in Appendix B results only for thresholds having between 30 and 450 data points. Once again, we note that there is significant variability both among the plots and within a given plot. We may, however, state unequivocally that the load factor L_{500} is considerably lower than was the case for hurricane winds for the majority of the stations. A comparison of the graphs of Appendix A and Appendix B also suggests that the tails of the load factor distributions are considerably shorter for stations in extratropical regions than in hurricane-prone stations.

4 Discussion of Results

Questions may arise as to whether our analyses of the hurricane wind speed data are affected significantly by the model used in the simulation that yielded the data. However, we note that the models upon which our data sets were based are considered reasonable for professional practice and that these data were used for the development of the ASCE Standard 7-93 wind speed map. Our analyses are therefore consistent with that wind speed map. The wind speed map of the ASCE Standard 7-95 differs from that of the ASCE Standard 7-93 in that (i) it uses peak gusts instead of fastest mile wind speeds (a difference of presentation rather than substance), and (ii) it uses a boundary layer model based on the Shapiro approximation [7] rather than an empirical boundary layer model. As was pointed out by Shapiro, this model does not describe the boundary layer structure in detail, especially near the eye wall of the hurricane where wind speeds are expected to be largest. Also, according to Shapiro, since this approximation entails a truncated spectral representation for the wind velocity, the resulting estimates can have errors of as much as 25%. For this reason it is not clear that simulations based upon Shapiro's approximation are necessarily an improvement over earlier simulations. Given the present state of the art, it is our opinion that our results have an acceptable basis as far as the quality of the data is concerned. Nevertheless, we point out that the high degree of fluctuation in the estimates is a difficulty in the study of probabilistically determined wind load factors. This suggests the need for further improvements in both the quantity and quality of the data used in the estimation process and further study of probabilistic estimation techniques.

Finally, we recall that all of our results are applicable to wind-sensitive structures for which wind directionality effects are not significant. This is true for both hurricane-prone regions and regions not subject to hurricanes. An assessment of relative values of load factors in these two regions thus has a consistent basis.

5 Conclusions

In this report, we have used the "peaks over threshold" method to estimate ratios of wind-induced loads with various long mean recurrence intervals to loads with a 50-year mean recurrence interval. According to our estimates, the load factor value of 1.3 specified in the ASCE Standards 7-93 and 7-95 is adequate for extratropical storm regions; that is, it corresponds to nominal ultimate wind loads judged to have sufficiently long mean recurrence

intervals. However, in hurricane-prone regions, the 1.3 standard value of the load factor (even after being augmented by an importance factor of $(1.05)^2$) leads to nominal ultimate wind loads with considerably shorter mean recurrence intervals than is the case for extratropical regions. To these mean recurrence intervals there correspond in most cases probabilities of exceedance of the nominal ultimate wind load on the order of ten percent during a 50 year lifetime of a structure. According to our results, an increase in the wind load factor would therefore be appropriate for structures subject to hurricane winds.

Acknowledgments: This work was completed during the author's tenure in the NIST/NRC Postdoctoral Research Associateship Program at NIST. Partial support by the NATO Scientific Affairs Division is also acknowledged with thanks. The author would like to thank Emil Simiu, who served as research advisor, for his suggestions and comments on this work. His participation in this project was partially supported by the National Science Foundation (Grant No. CMS-9411642). Also, the author would like to thank Alan Heckert of NIST for his assistance with the data sets and programs used in this study.

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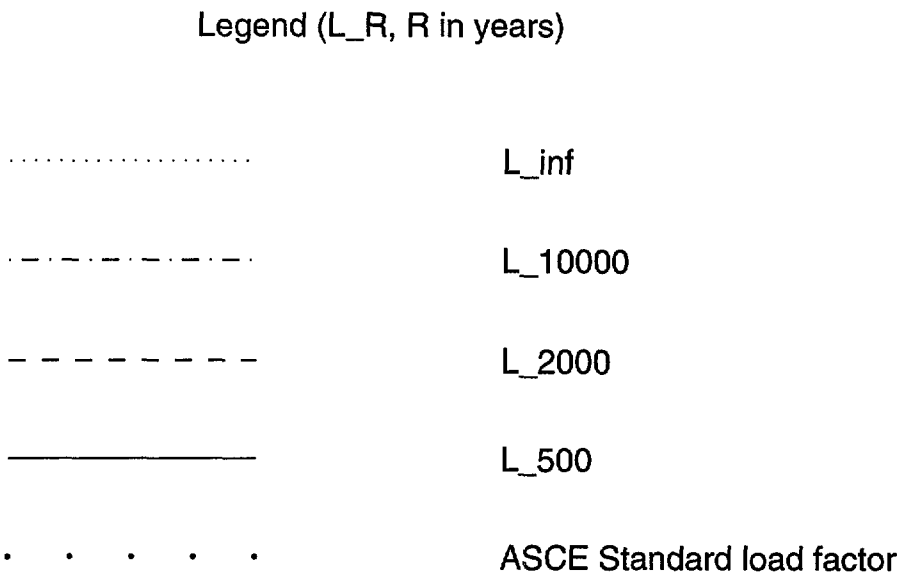
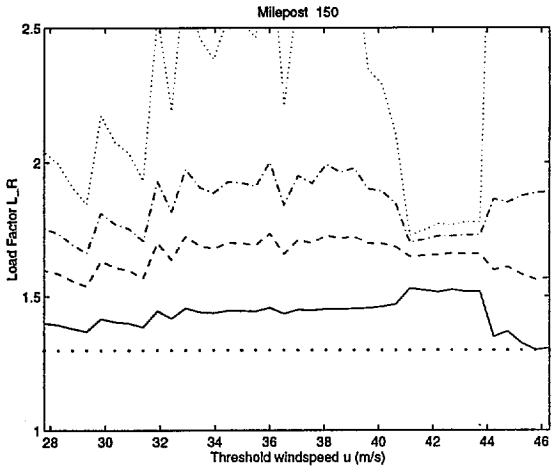
A Estimates of wind load factors versus threshold for locations in hurricane-prone regions

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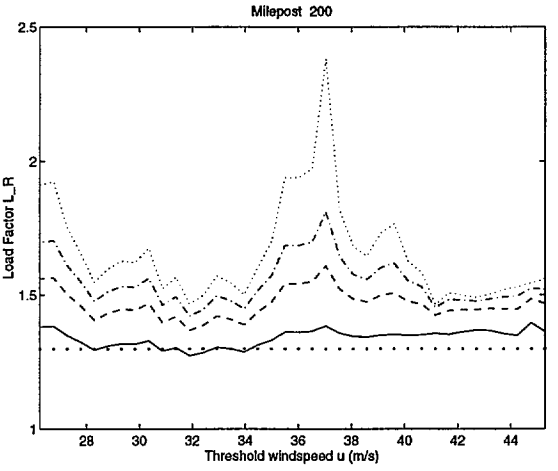
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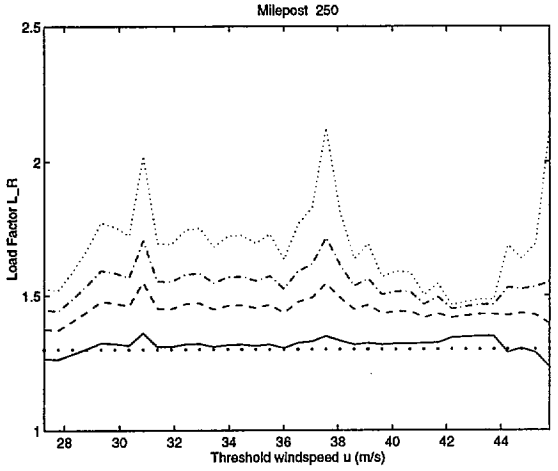
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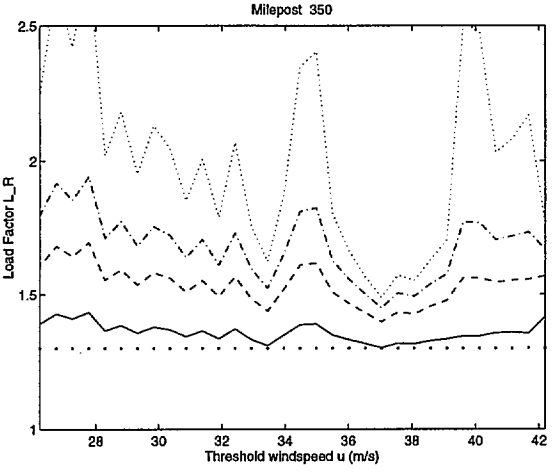
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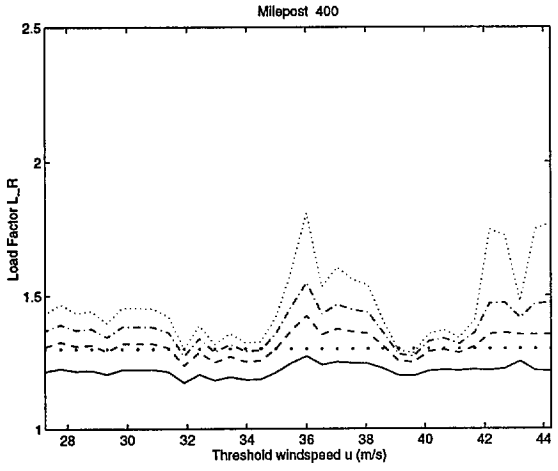
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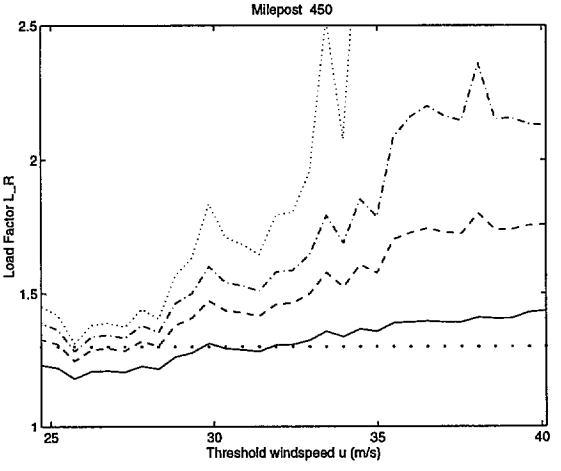
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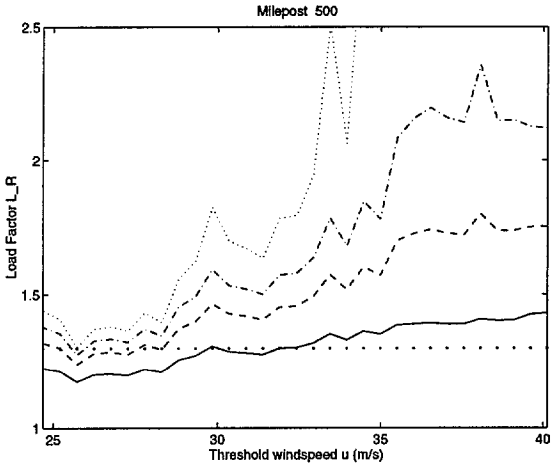
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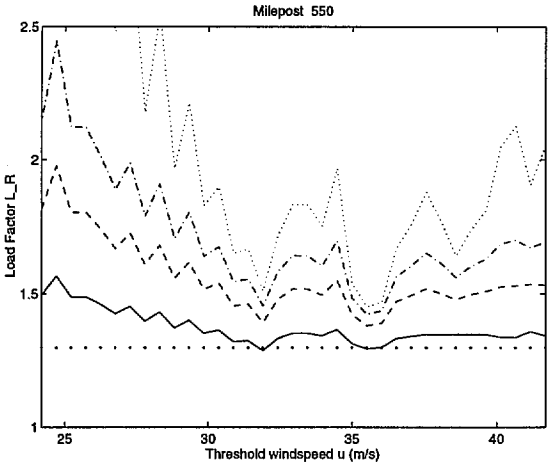
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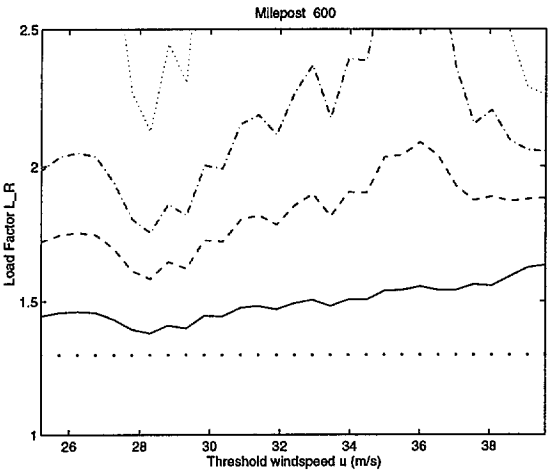
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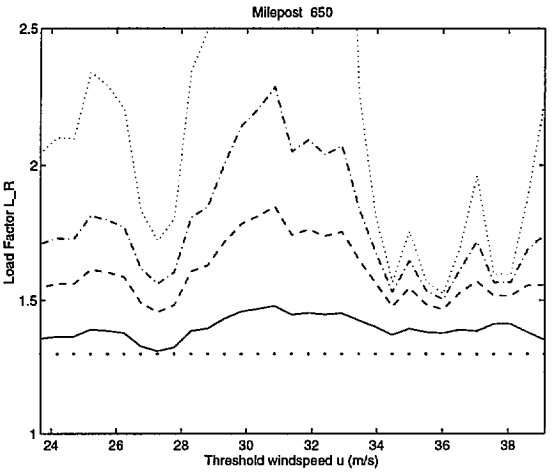
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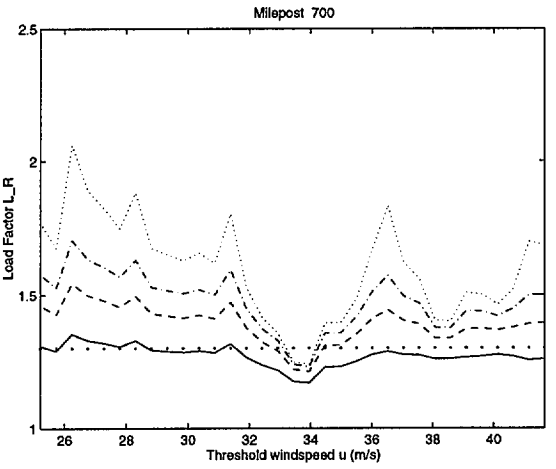
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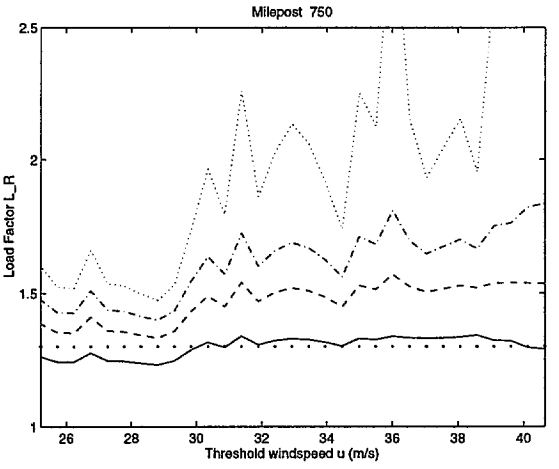
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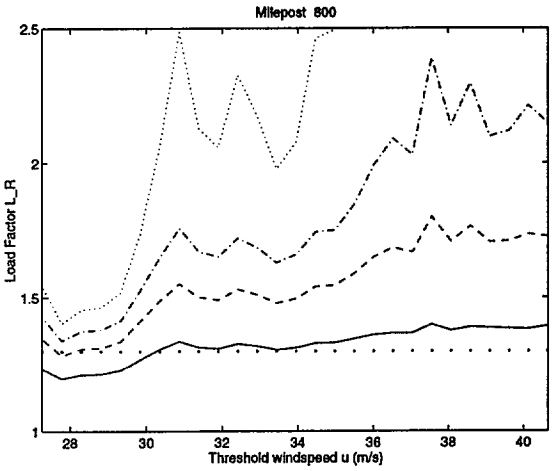
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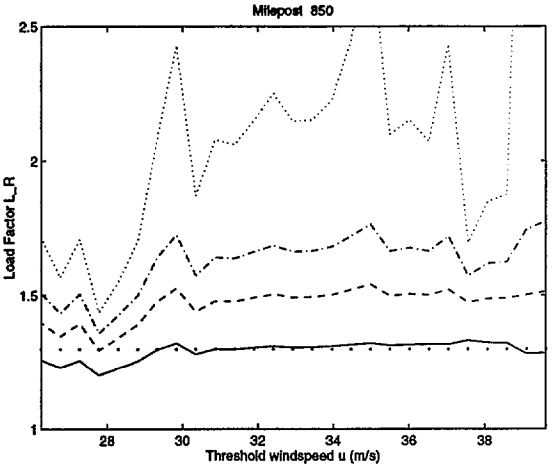
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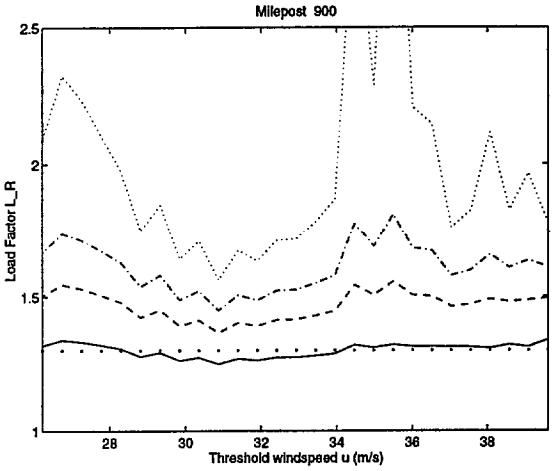
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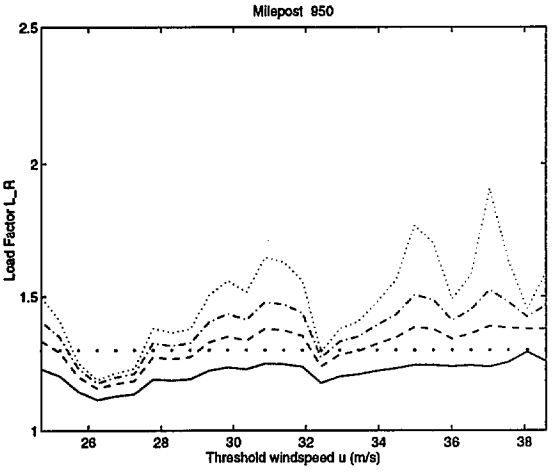
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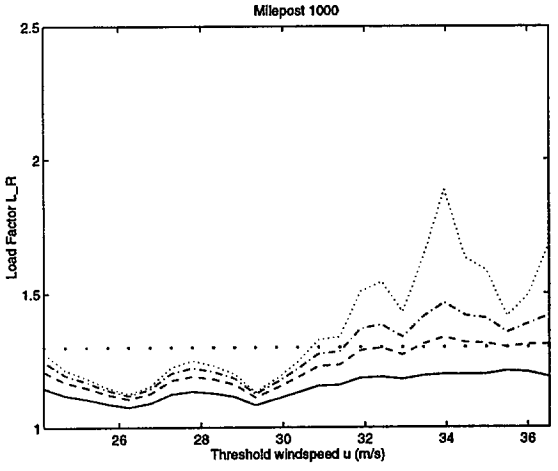
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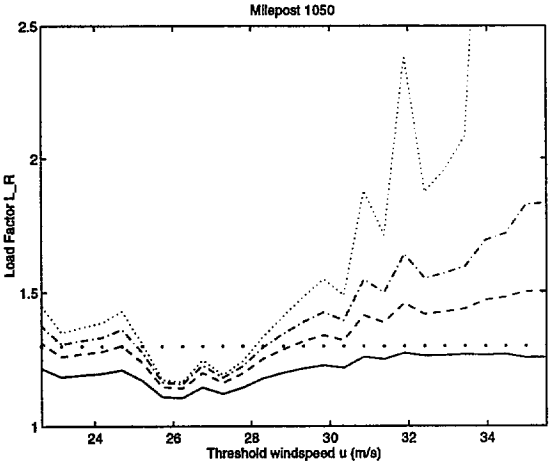
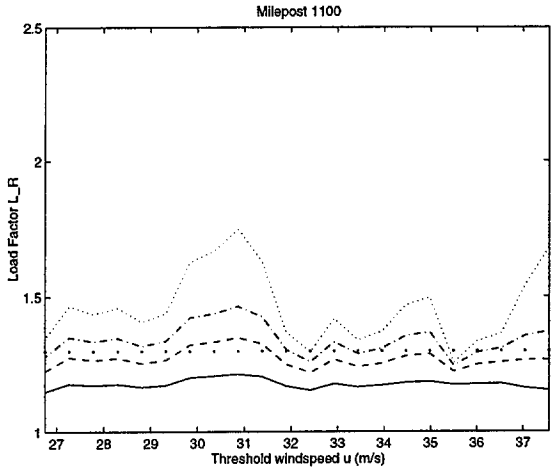
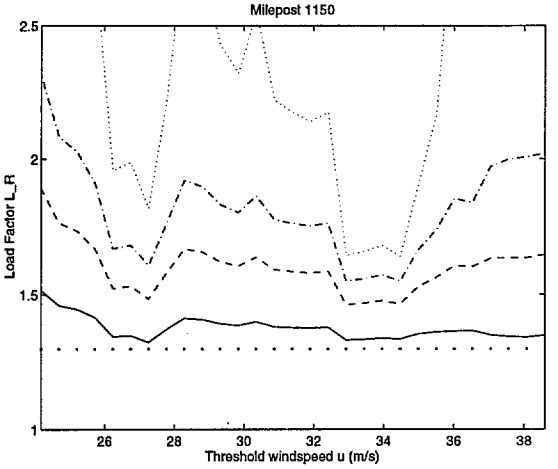
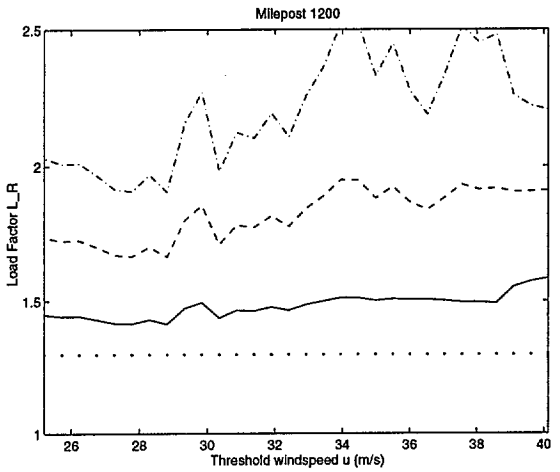
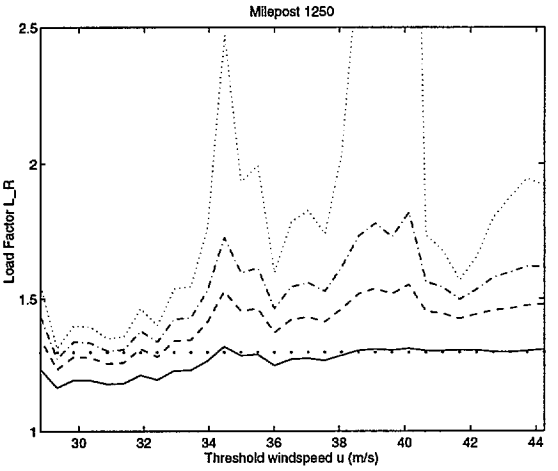
Threshold windspeed u (m/s)

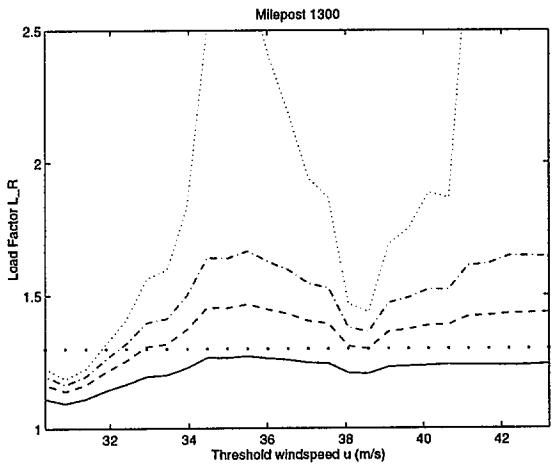

Milepost 1050
Load Factor L_R
Threshold windspeed u (m/s)

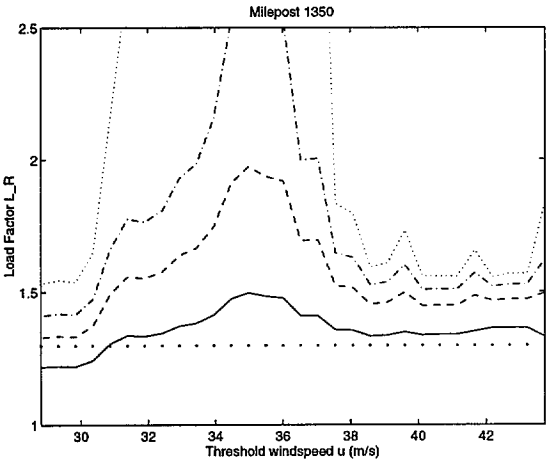

Milepost 1100
Load Factor L_R
Threshold windspeed u (m/s)

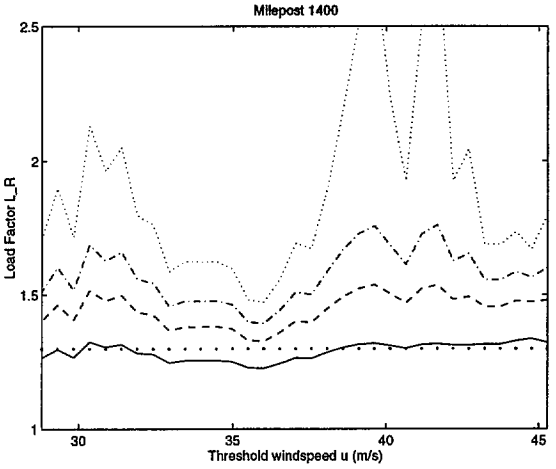

Milepost 1150
Load Factor L_R
Threshold windspeed u (m/s)

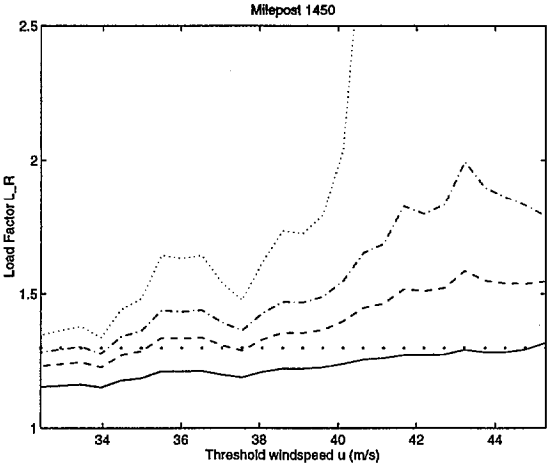

Milepost 1200
Load Factor L_R
Threshold windspeed u (m/s)

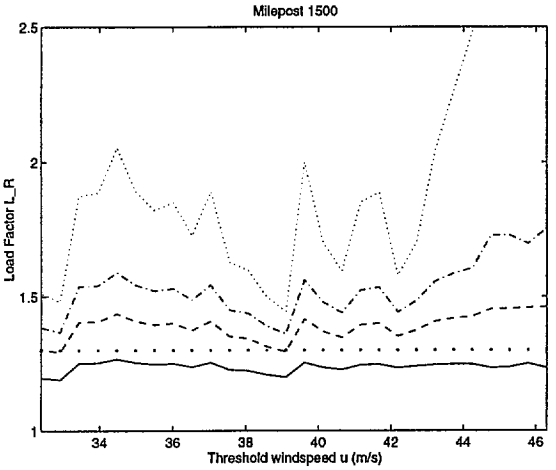

Milepost 1250
Load Factor L_R
Threshold windspeed u (m/s)

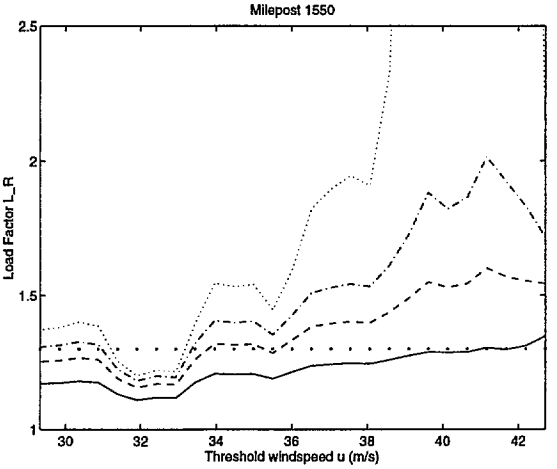

Milepost 1300
Load Factor L_R
Threshold windspeed u (m/s)

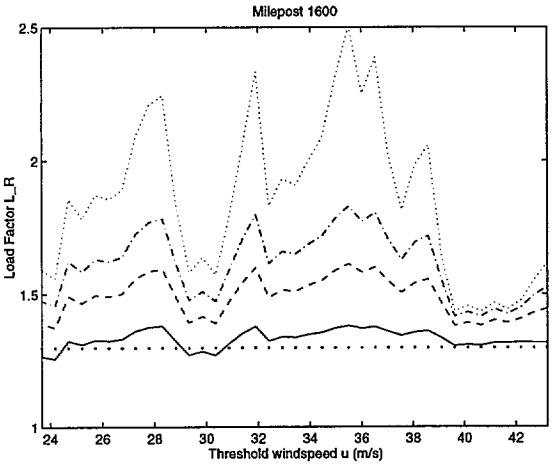

Milepost 1350
Load Factor L_R
Threshold windspeed u (m/s)

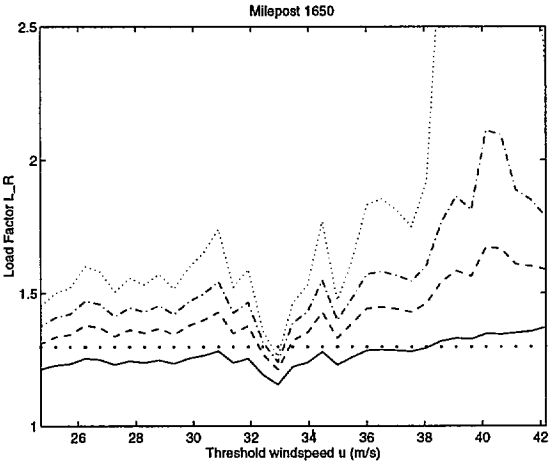

Milepost 1400
Load Factor L_R
Threshold windspeed u (m/s)

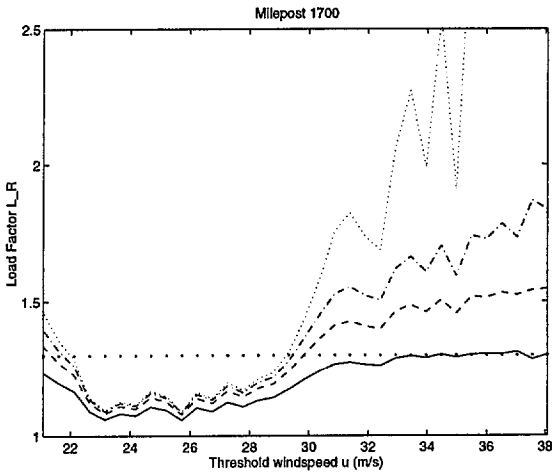

Milepost 1450
Load Factor L_R
Threshold windspeed u (m/s)

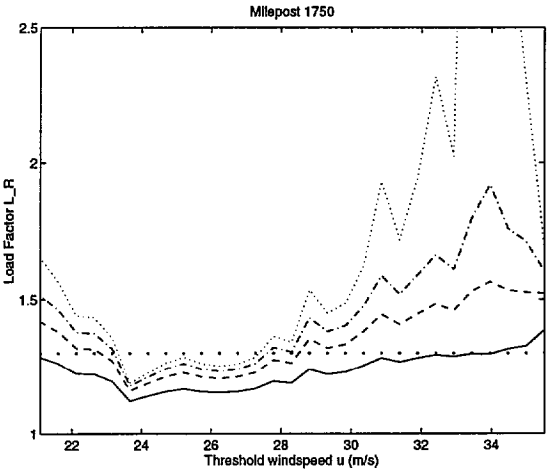

Milepost 1500
Load Factor L_R
Threshold windspeed u (m/s)

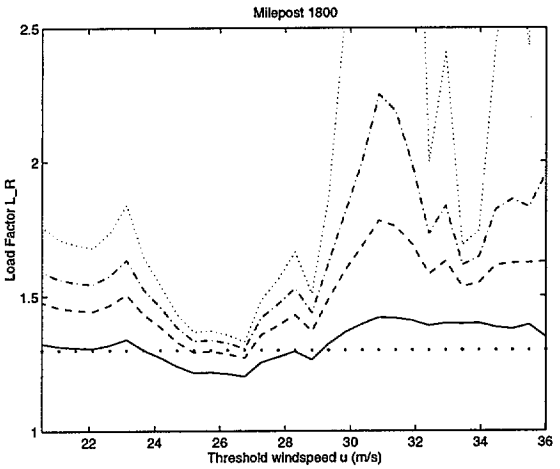

Milepost 1550
Load Factor L_R
Threshold windspeed u (m/s)

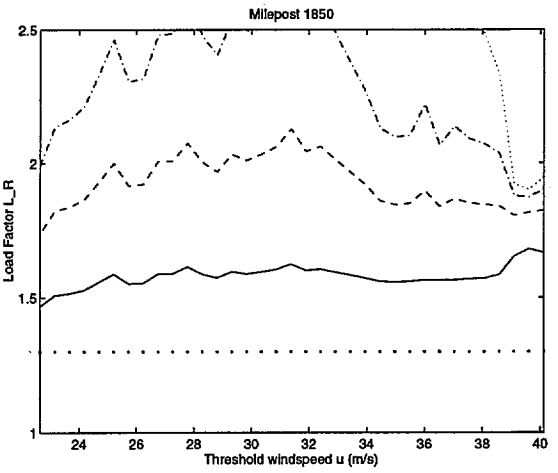

Milepost 1600
Load Factor L_R
Threshold windspeed u (m/s)

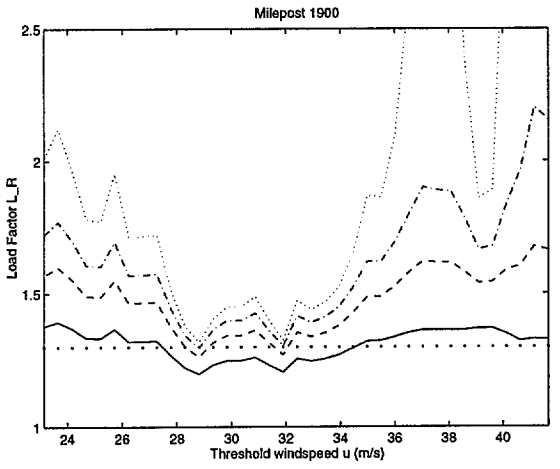

Milepost 1650
Load Factor L_R
Threshold windspeed u (m/s)

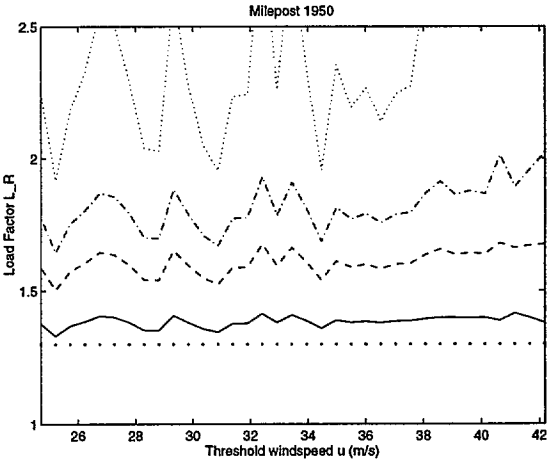

Milepost 1700
Load Factor L_R
Threshold windspeed u (m/s)

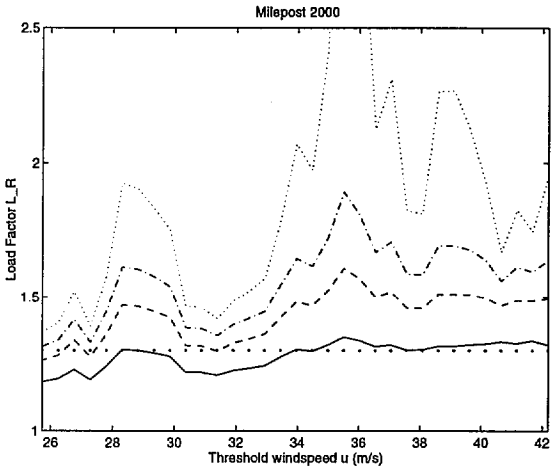

Milepost 1750
Load Factor L_R
Threshold windspeed u (m/s)

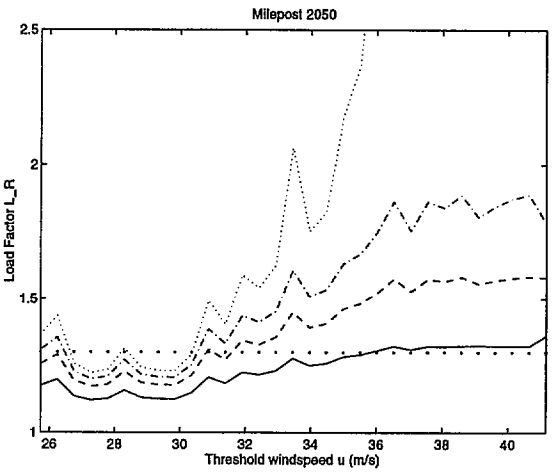

Milepost 1800
Load Factor L_R
Threshold windspeed u (m/s)

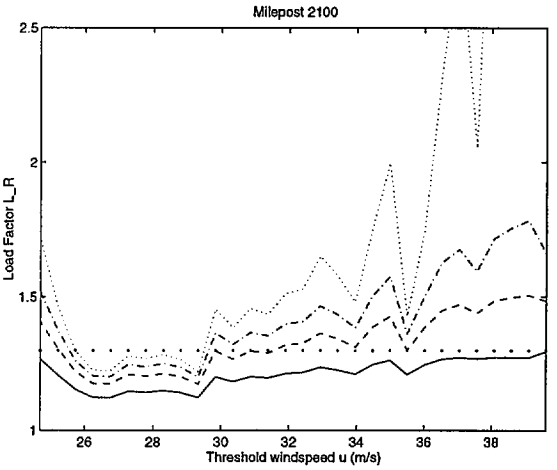

Milepost 1850
Load Factor L_R
Threshold windspeed u (m/s)

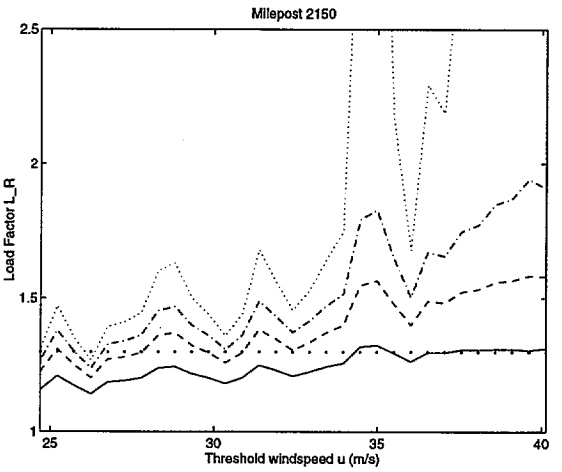

Milepost 1900
Load Factor L_R
Threshold windspeed u (m/s)

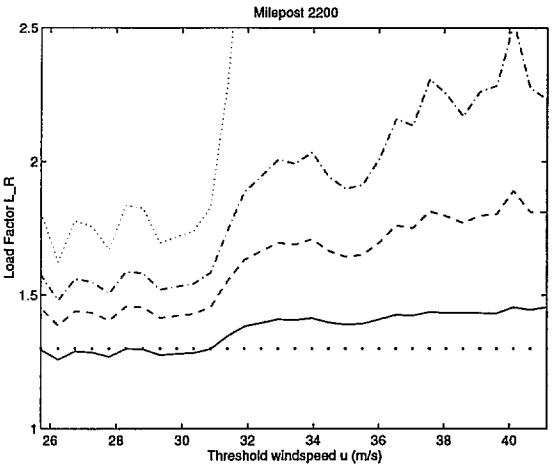

Milepost 1950
Load Factor L_R
Threshold windspeed u (m/s)

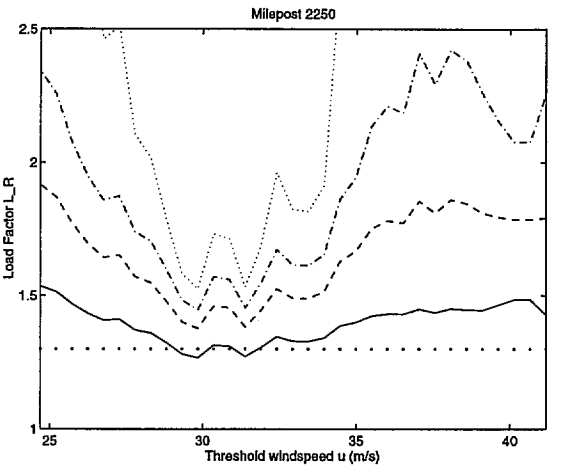

Milepost 2000
Load Factor L_R
Threshold windspeed u (m/s)

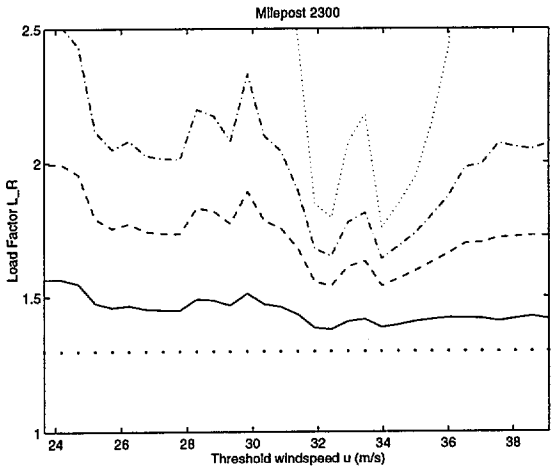

Milepost 2050
Load Factor L_R
Threshold windspeed u (m/s)

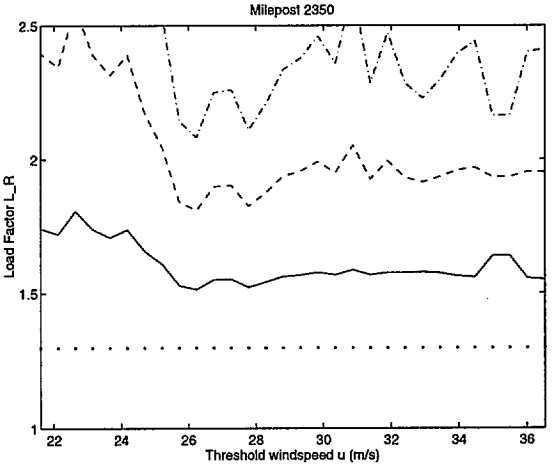

Milepost 2100
Load Factor L_R
Threshold windspeed u (m/s)

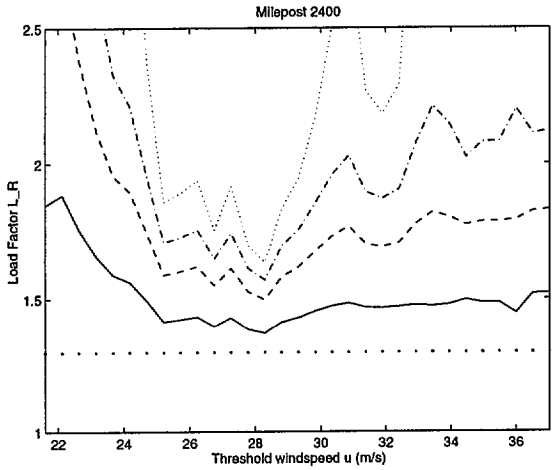

Milepost 2150
Load Factor L_R
Threshold windspeed u (m/s)

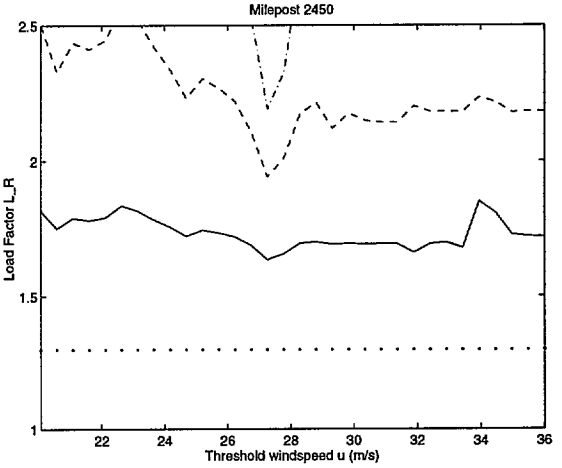

Milepost 2200
Load Factor L_R
Threshold windspeed u (m/s)

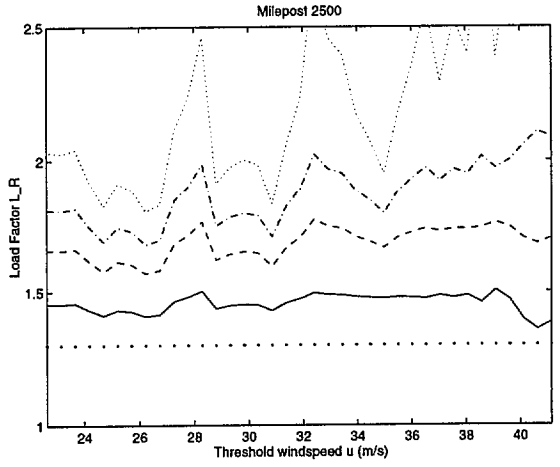

Milepost 2250
Load Factor L_R
Threshold windspeed u (m/s)

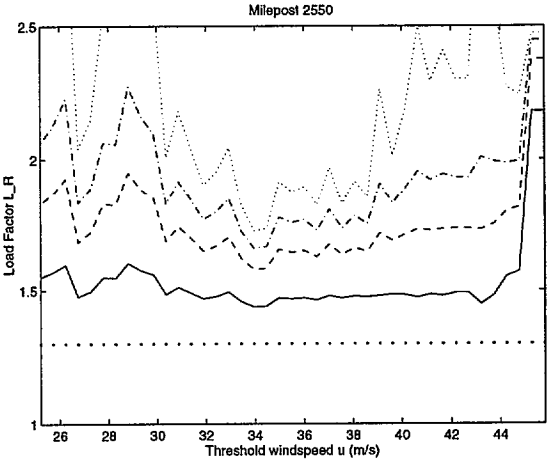

Milepost 2300
Load Factor L_R
Threshold windspeed u (m/s)

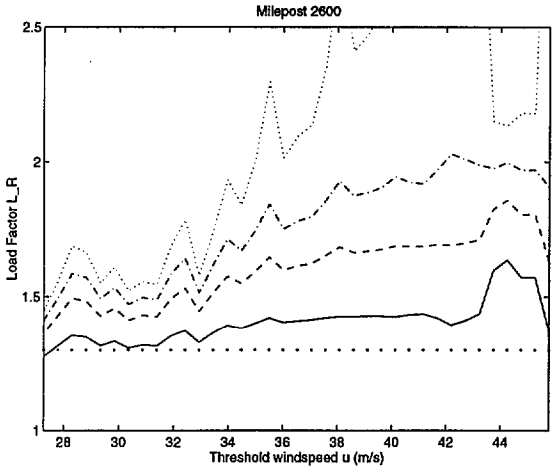

Milepost 2350
Load Factor L_R
Threshold windspeed u (m/s)

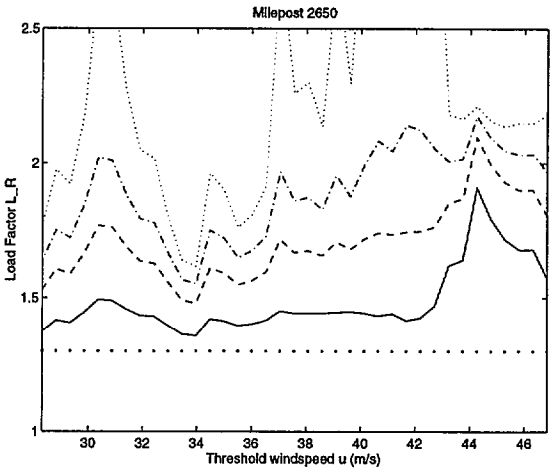

Milepost 2400
Load Factor L_R
Threshold windspeed u (m/s)

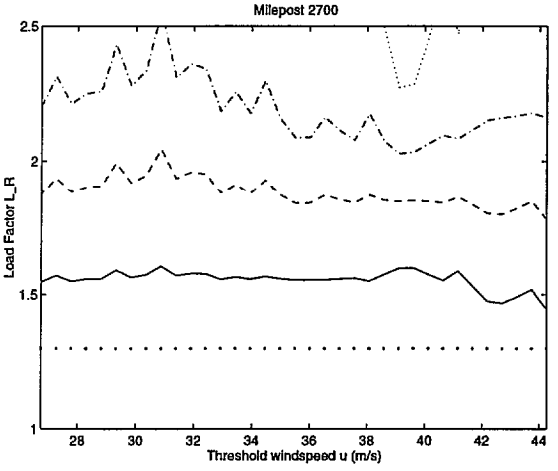

Milepost 2450
Load Factor L_R
Threshold windspeed u (m/s)

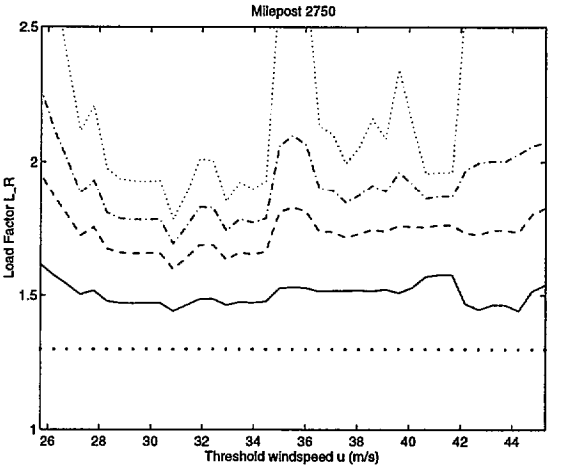

Milepost 2500
Load Factor L_R
Threshold windspeed u (m/s)

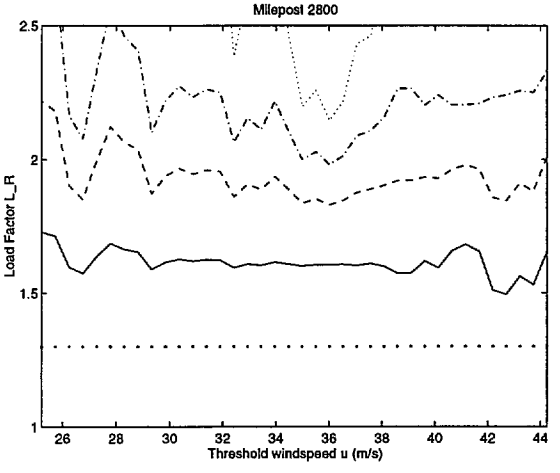

Milepost 2550
Load Factor L_R
Threshold windspeed u (m/s)

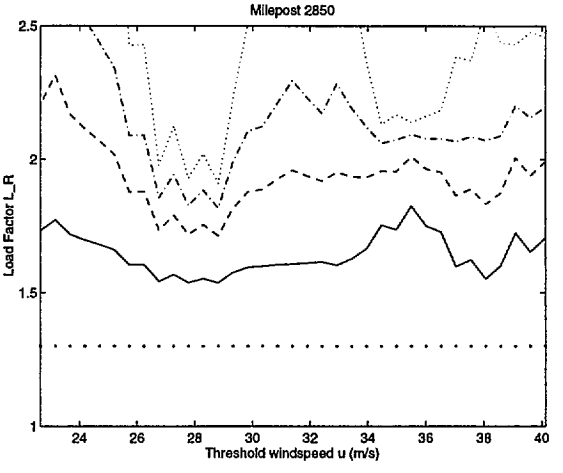

Milepost 2600
Load Factor L_R
Threshold windspeed u (m/s)


Milepost 2650
Load Factor L_R
Threshold windspeed u (m/s)


Milepost 2700
Load Factor L_R
Threshold windspeed u (m/s)


Milepost 2750
Load Factor L_R
Threshold windspeed u (m/s)

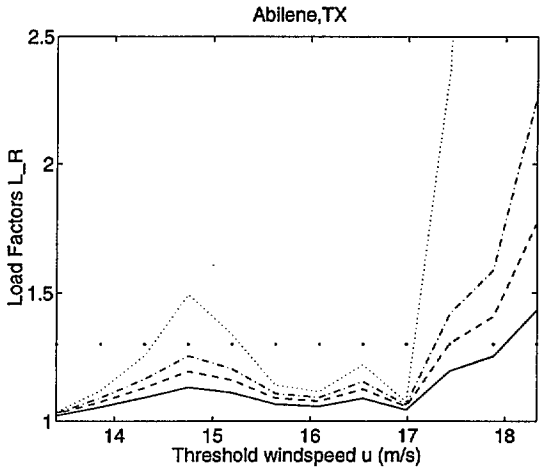

Milepost 2800
Load Factor L_R
Threshold windspeed u (m/s)

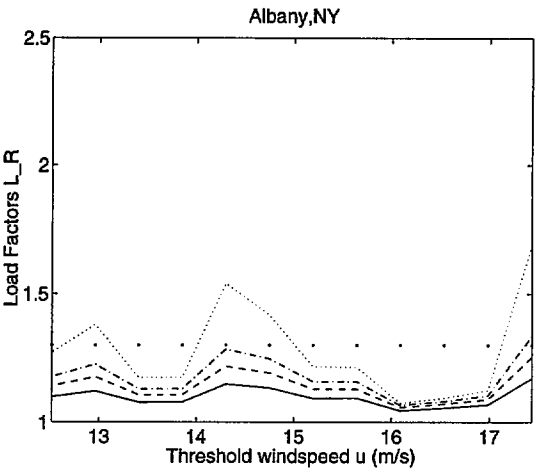

Milepost 2850
Load Factor L_R
Threshold windspeed u (m/s)

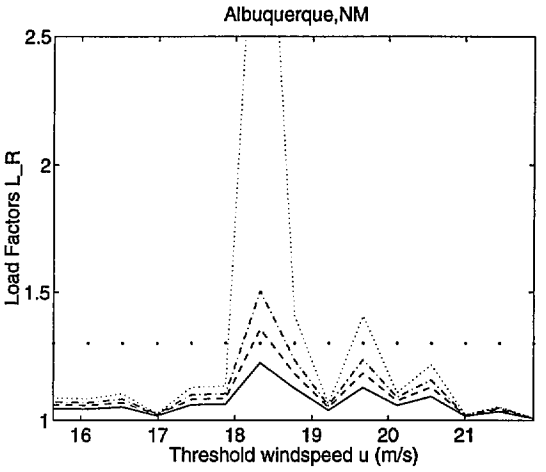
B Estimates of wind load factors versus threshold for locations in extratropical regions

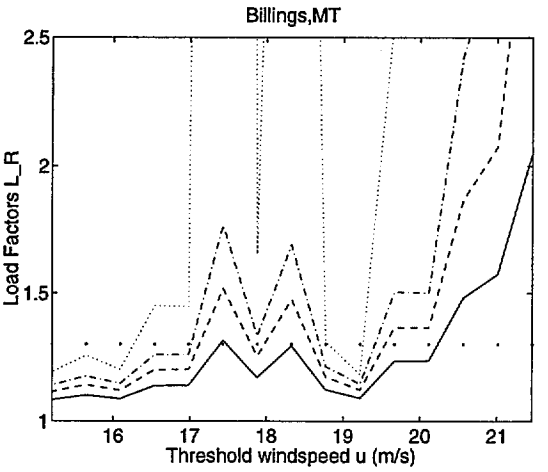
Legend (L_R, R in years)

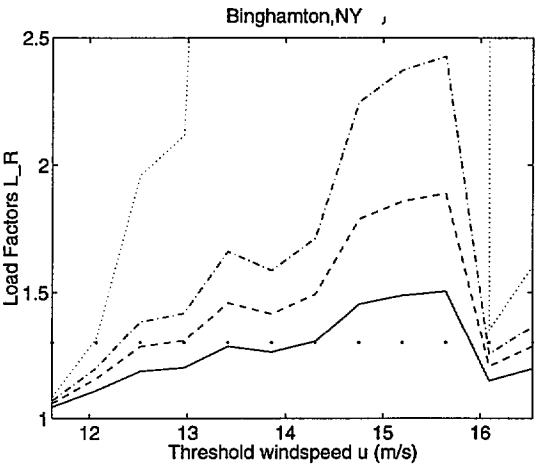
.....	L_inf
.-.-.-.-.-.-	L_10000
- - - - - - - -	L_2000
————	L_500
. . . . .	ASCE Standard load factor

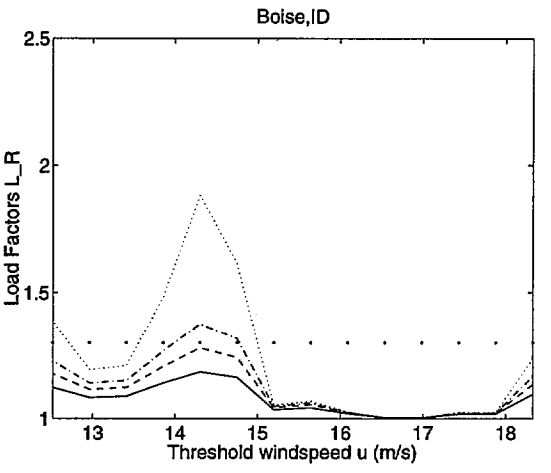

Abilene,TX
Load Factors L_R
Threshold windspeed u (m/s)

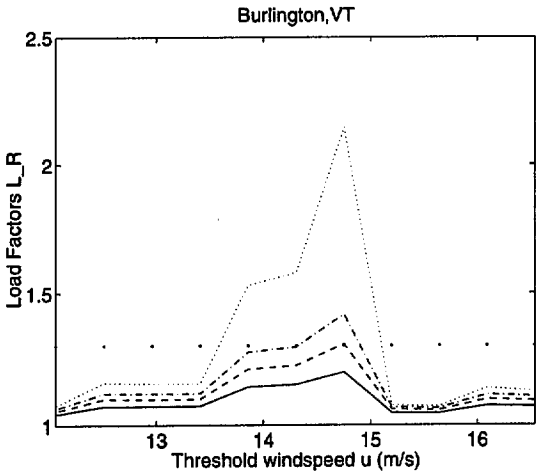

Albany,NY
Load Factors L_R
Threshold windspeed u (m/s)

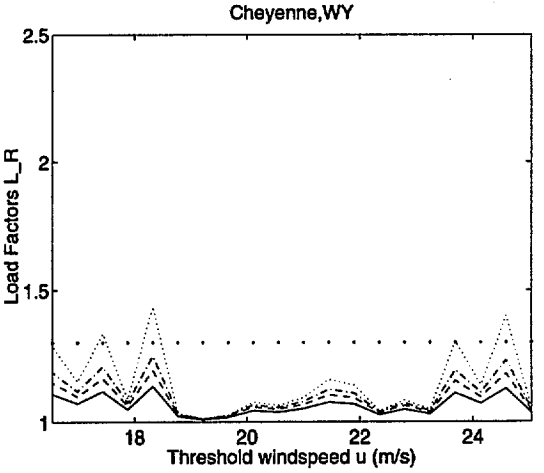

Albuquerque,NM
Load Factors L_R
Threshold windspeed u (m/s)

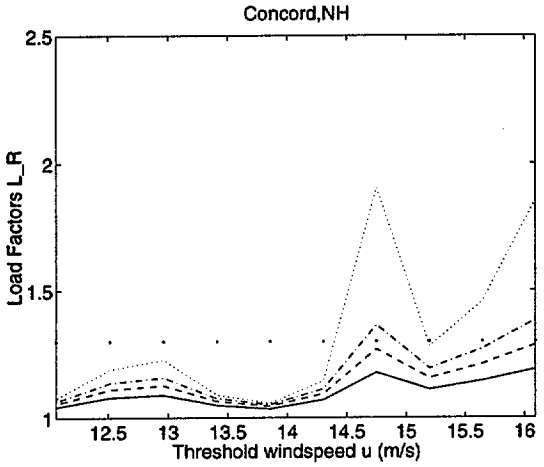

Billings,MT
Load Factors L_R
Threshold windspeed u (m/s)

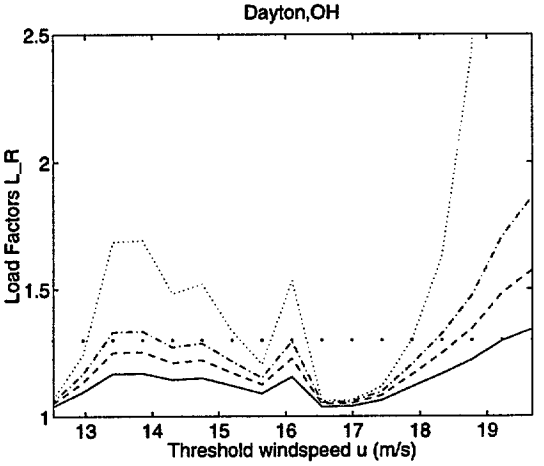

Binghamton,NY
Load Factors L_R
Threshold windspeed u (m/s)

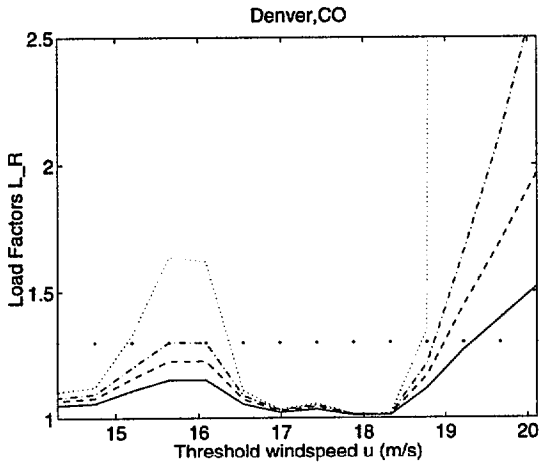

Boise,ID
Load Factors L_R
Threshold windspeed u (m/s)

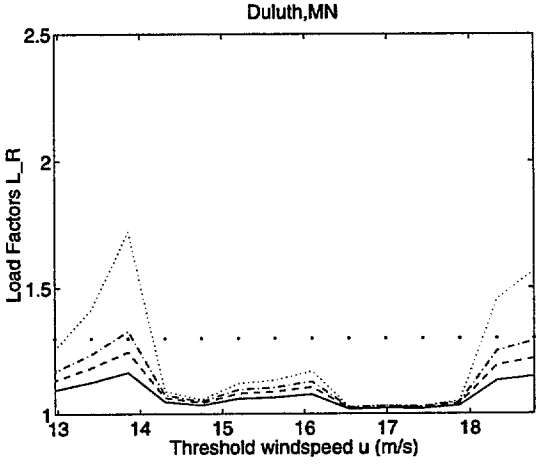

Burlington,VT
Load Factors L_R
2.5
2
1.5
1
13
14
15
16
Threshold windspeed u (m/s)

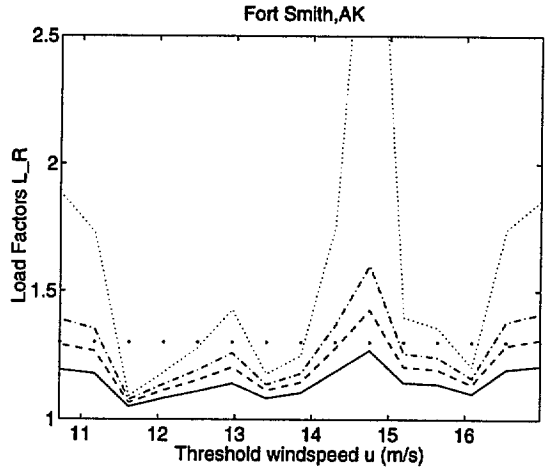

Cheyenne,WY
Load Factors L_R
2.5
2
1.5
1
18
20
22
24
Threshold windspeed u (m/s)

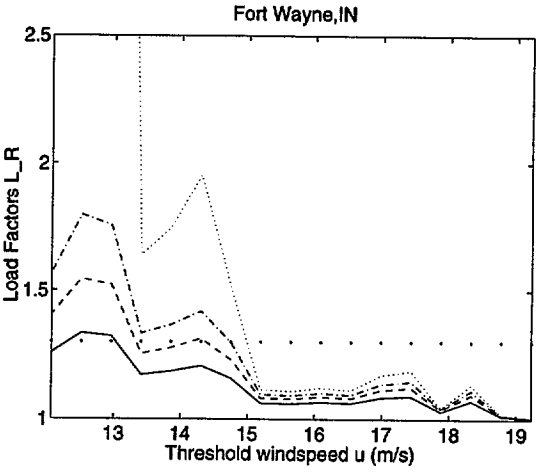

Concord,NH
Load Factors L_R
2.5
2
1.5
1
12.5
13
13.5
14
14.5
15
15.5
16
Threshold windspeed u (m/s)

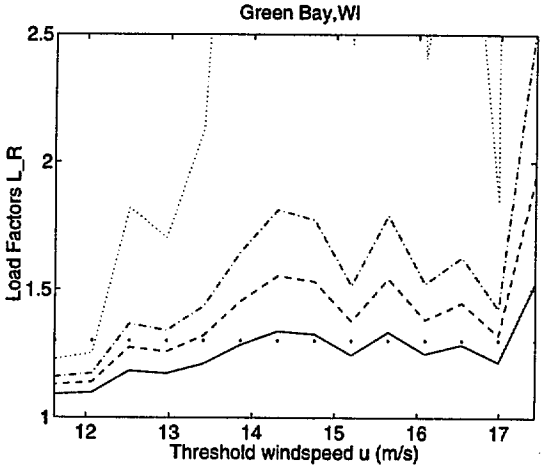

Dayton,OH
Load Factors L_R
2.5
2
1.5
1
13
14
15
16
17
18
19
Threshold windspeed u (m/s)

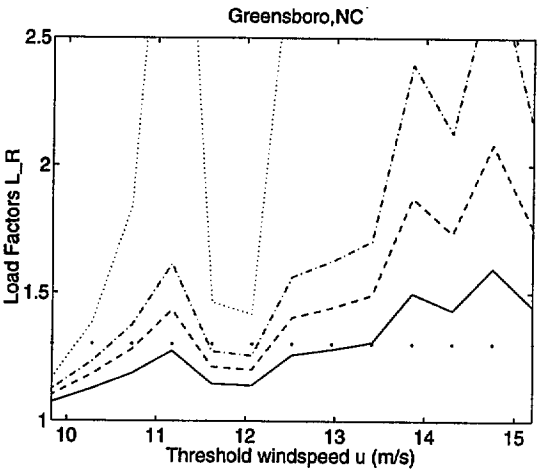

Denver,CO
Load Factors L_R
2.5
2
1.5
1
15
16
17
18
19
20
Threshold windspeed u (m/s)

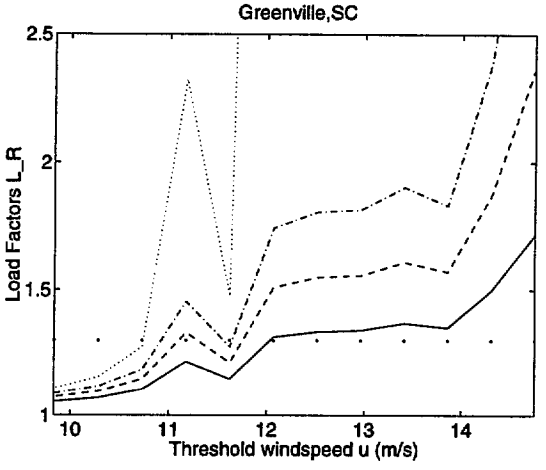

Duluth,MN
Load Factors L_R
2.5
2
1.5
1
13
14
15
16
17
18
Threshold windspeed u (m/s)

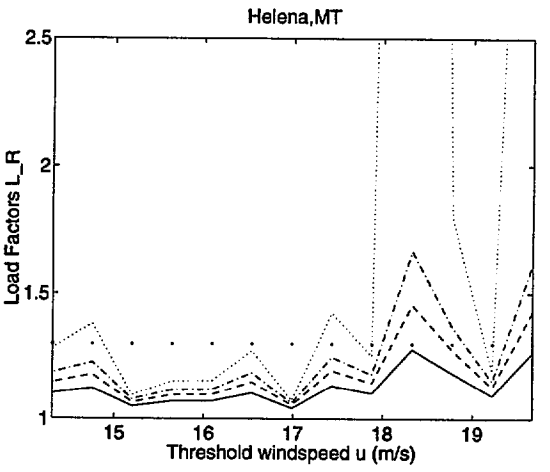

Fort Smith,AK
Load Factors L_R
Threshold windspeed u (m/s)

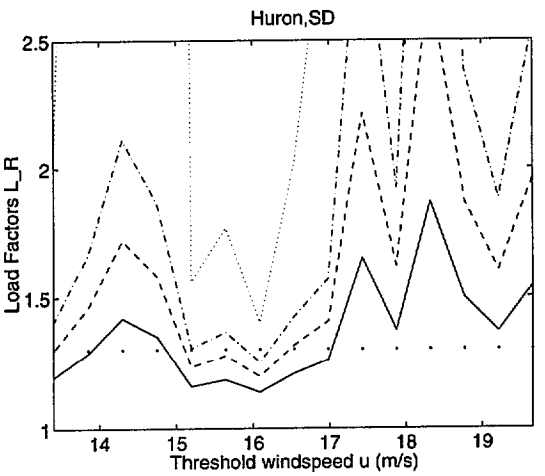

Fort Wayne,IN
Load Factors L_R
Threshold windspeed u (m/s)

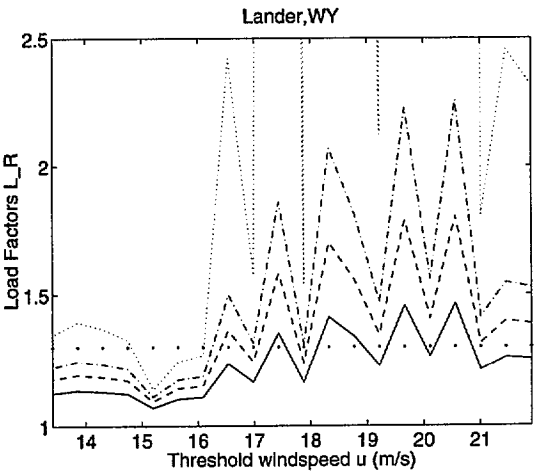

Green Bay,WI
Load Factors L_R
Threshold windspeed u (m/s)

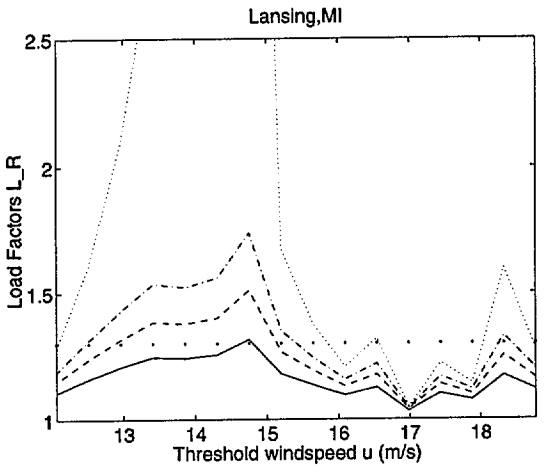

Greensboro,NC
Load Factors L_R
Threshold windspeed u (m/s)

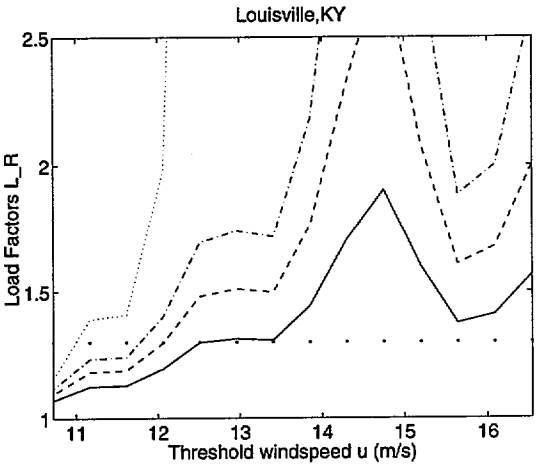

Greenville,SC
Load Factors L_R
Threshold windspeed u (m/s)

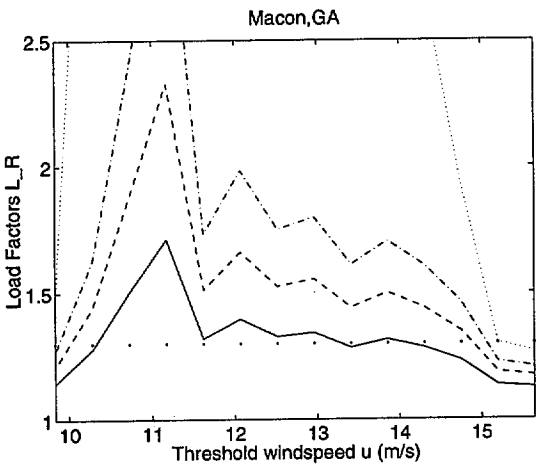

Helena,MT
Load Factors L_R
Threshold windspeed u (m/s)

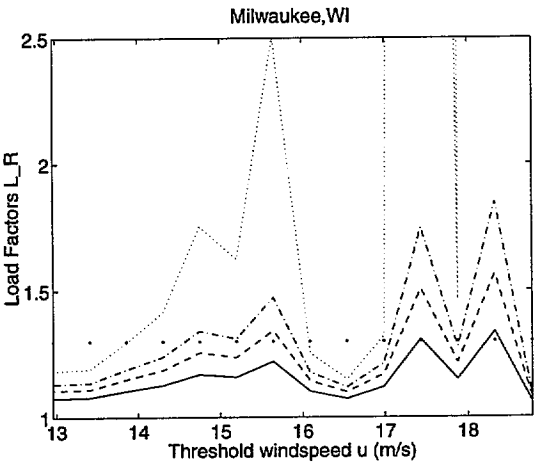

Huron,SD
Load Factors L_R
Threshold windspeed u (m/s)

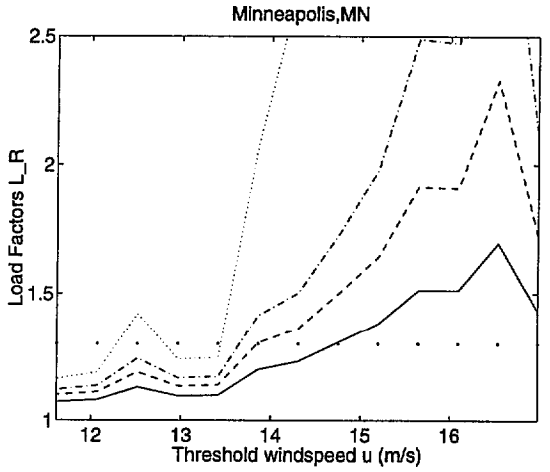

Lander,WY
Load Factors L_R
Threshold windspeed u (m/s)

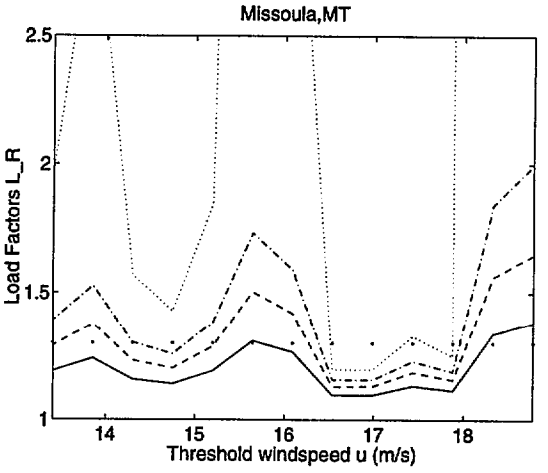

Lansing,MI
Load Factors L_R
Threshold windspeed u (m/s)

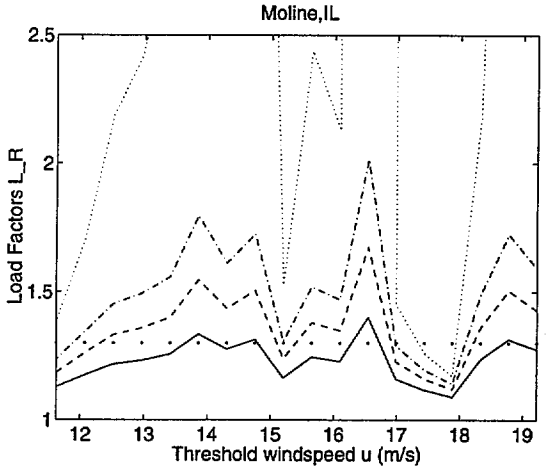

Louisville,KY
Load Factors L_R
Threshold windspeed u (m/s)

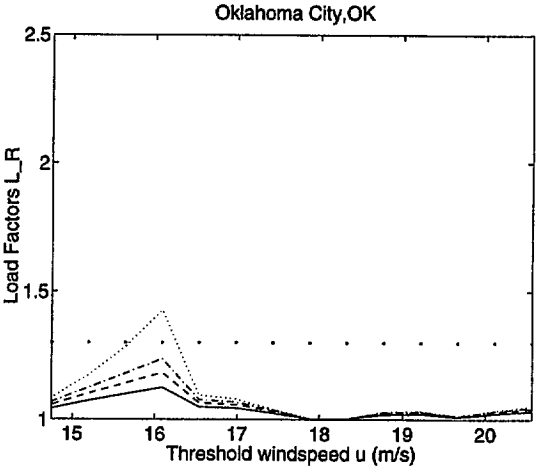

Macon,GA
Load Factors L_R
Threshold windspeed u (m/s)

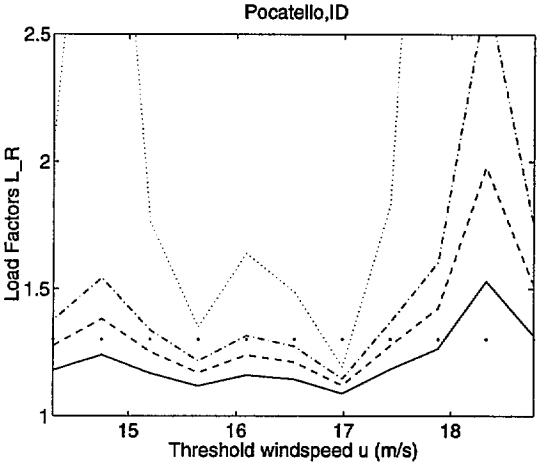

Milwaukee,WI
Load Factors L_R
Threshold windspeed u (m/s)

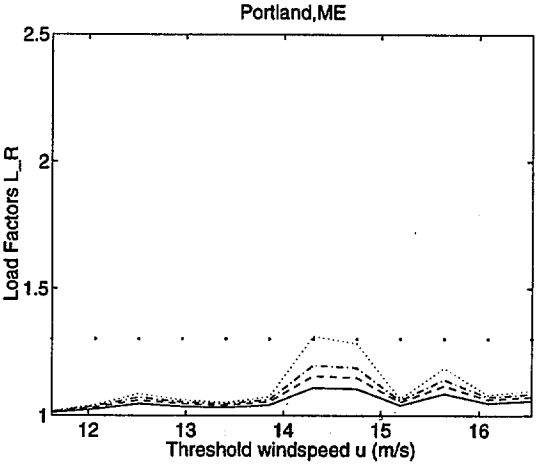

Minneapolis,MN
Load Factors L_R
Threshold windspeed u (m/s)

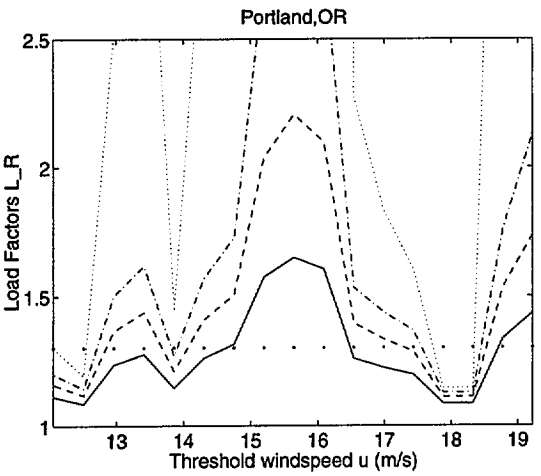

Missoula,MT
Load Factors L_R
Threshold windspeed u (m/s)

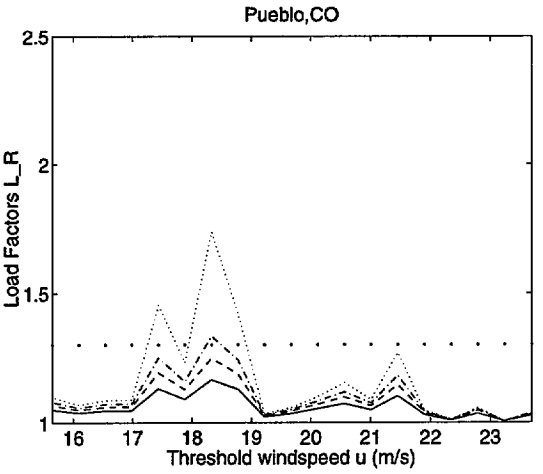

Moline,IL
Load Factors L_R
Threshold windspeed u (m/s)

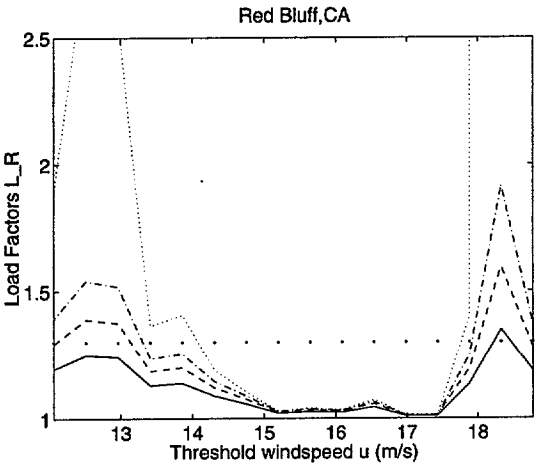

Oklahoma City,OK
Load Factors L_R
Threshold windspeed u (m/s)

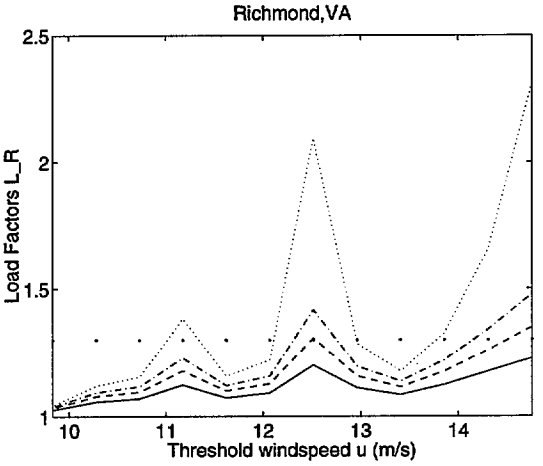

Pocatello,ID
Load Factors L_R
Threshold windspeed u (m/s)

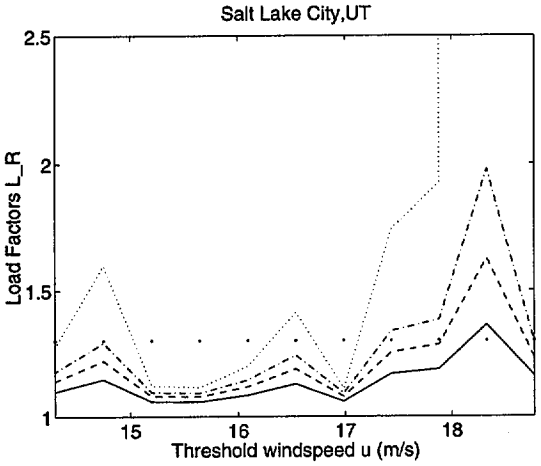

Portland,ME
Load Factors L_R
Threshold windspeed u (m/s)

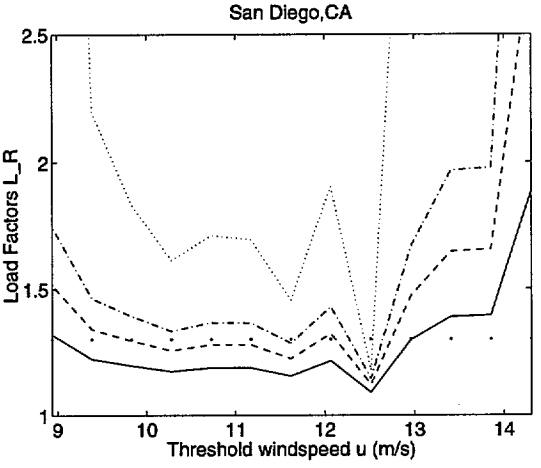

Portland,OR
Load Factors L_R
Threshold windspeed u (m/s)

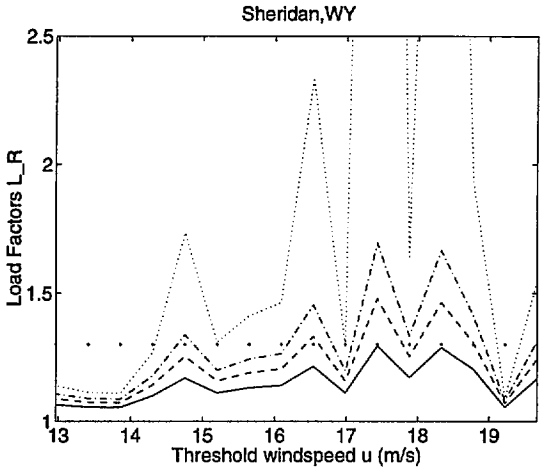

Pueblo,CO
Load Factors L_R
Threshold windspeed u (m/s)

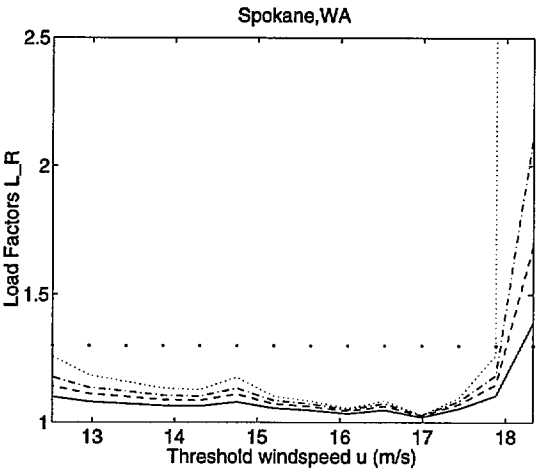

Red Bluff,CA
Load Factors L_R
Threshold windspeed u (m/s)

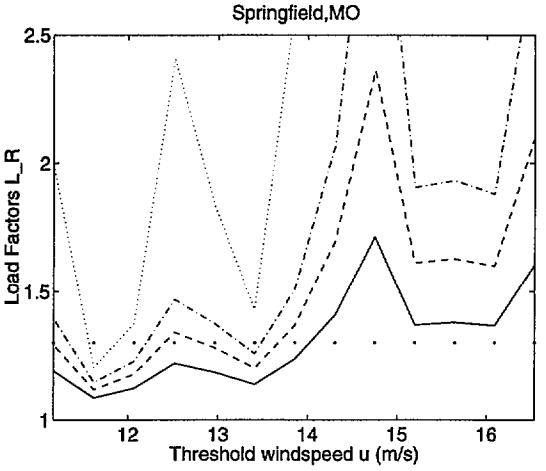

Richmond,VA
Load Factors L_R
Threshold windspeed u (m/s)

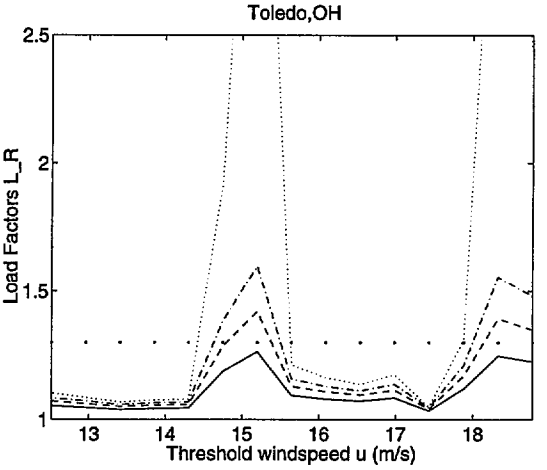

Salt Lake City,UT
Load Factors L_R
Threshold windspeed u (m/s)

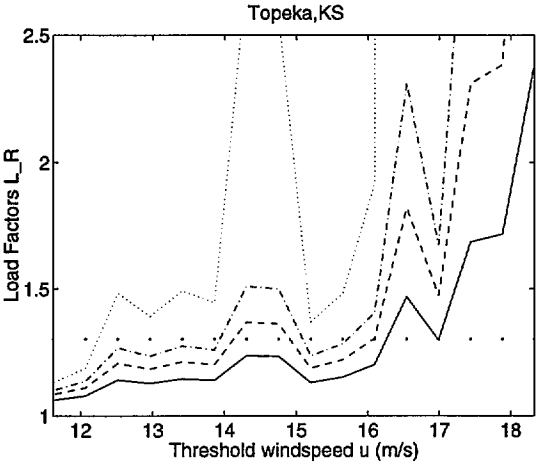

San Diego,CA
Load Factors L_R
Threshold windspeed u (m/s)

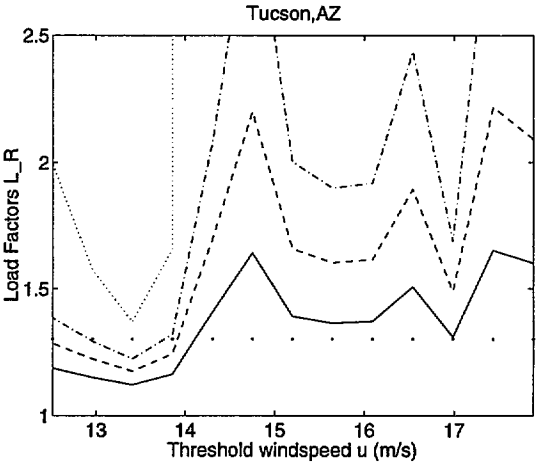

Sheridan,WY
Load Factors L_R
Threshold windspeed u (m/s)

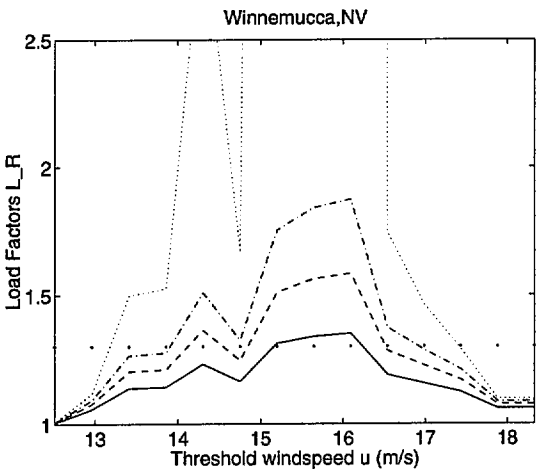

Spokane,WA
Load Factors L_R
Threshold windspeed u (m/s)

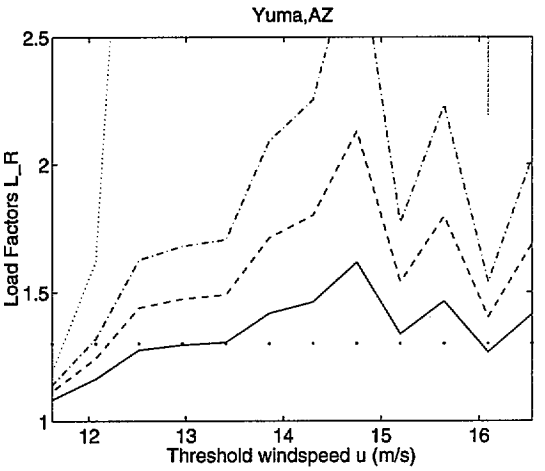

Springfield,MO
Load Factors L_R
Threshold windspeed u (m/s)


Toledo,OH
Load Factors L_R
Threshold windspeed u (m/s)


Topeka,KS
Load Factors L_R
Threshold windspeed u (m/s)


Tucson,AZ
Load Factors L_R
Threshold windspeed u (m/s)


Winnemucca,NV
Load Factors L_R
2.5
2
1.5
1
13
14
15
16
17
18
Threshold windspeed u (m/s)


Yuma,AZ
Load Factors L_R
2.5
2
1.5
1
12
13
14
15
16
Threshold windspeed u (m/s)