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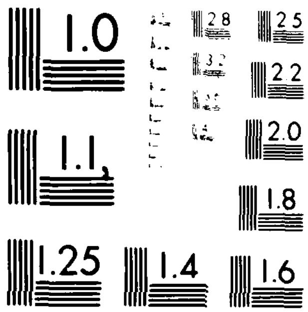

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MOTION SICKNESS INCIDENCE: DISTRIBUTION OF TIME TO FIRST EMESIS AND COMPARISON OF SOME COMPLEX MOTION CONDITIONS

by

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I. INTRODUCTION

Over the past several years, extensive experimentation has been conducted on the ONR motion generator in an effort to characterize the effects of various motion parameters on motion sickness incidence. Early research focused on single-frequency sinusoidal heave motions, but subsequent studies have also addressed the problem of more complex motion conditions. The ultimate goal is to develop a model capable of predicting motion sickness incidence in complex motion environments characteristic of ships at sea.

In this investigation, we consider 12 different data sets taken from various motion studies. Each of these experiments limited exposure time to two hours duration and each used the occurrence of frank emesis as the diagnostic motion sickness criterion. The use of frank emesis as an experimental endpoint, however, has frequently been criticized (see, for example, [8]). Accordingly, in a recent set of experiments [6], an attempt was made to identify measurable correlates of motion sickness. Part of that investigation involved characterizing the distribution of time to first emesis data. In section II we present further evidence indicating that the susceptible portion of the subject population follows a Weibull probability model.

The study mentioned above made use of dual-frequency waveforms as a first step toward understanding the effects of broadband motions. A primary question was whether there were any significant differences in severity between the conditions of that study. In section III we examine this question, using a nonparametric test which can detect very general types of differences between the motion conditions.

II. DISTRIBUTION OF TIME TO FIRST EMESIS

Ideally, any model of time to emesis should be based primarily on theoretical considerations. However, lack of knowledge about the physical mechanisms responsible for motion sickness, coupled with large differences in individual susceptibility, has forced researchers to rely on a mostly empirical approach to the modeling problem. Because of their known applicability in a wide variety of situations involving time until failure, the lognormal and Weibull models have generally been suggested. In this section we add further evidence in support of the use of the Weibull distribution as a model for the portion of the population susceptible to motion sickness.

Most of the existing experimental data on motion sickness have been obtained in experiments which limited exposure to two hours duration. Because of this truncation, Mauro and Smith [4] considered censored lognormal and censored Weibull distributions as possible models for time to emesis. They found, however, that neither of these models adequately fits the observed data. Noting that the cumulative motion sickness incidence tends to stabilize after about 90 minutes, they then postulated a statistical mixture model. This model treated the uncensored portions (i.e., emesis within 2 hours) of the populations under study as complete samples from one component of the mixture distribution. The Weibull distribution was found to fit the susceptible portions of the populations well, while the lognormal model was not consistent with the data.

Thomas, Guignard, and Willems [6,7] have advocated a mixture of three distributions to model time to first emesis, treating the uncensored portions of the samples as mixtures of two Weibull distributions, corresponding to highly susceptible and less susceptible portions of the populations. While not inconsistent with the data, this hypothesis seems to be untenable in light of the findings of Mauro and Smith. Since it has not been contradicted by the data, the more parsimonious model is preferable.

The data used in this investigation were taken from a number of sources. Seven data sets from various single-frequency studies [5] have been used, along with one single-frequency and four dual-frequency data sets from the "Correlation Study" [6]. A complete listing of the data is given in the appendix. These are the same data sets analyzed previously by Mauro and Smith. However, in that study, "quitters" were not included in the analysis of the Correlation Study data. (Quitters were included in the single frequency data.) There is substantial evidence (see, for example, [3]) indicating that those who quit before the completion of the experiment (and prior to emesis) are very similar, as a group, to those who become sick. Therefore, in this investigation the quitters have been included as part of the susceptible population.

Mauro and Smith applied goodness-of-fit tests appropriate for lognormal and Weibull samples. Since the data sets being used here have been augmented by the addition of quitters, those tests have been repeated. An additional test, directly comparing the lognormal and Weibull distributions, is also used. The power of the goodness-of-fit tests depends on the exact nature of the departures from the specified distributions. Therefore, it is difficult to compare the results from the two tests directly since they will have different power against a given alternative distribution. The additional test given here provides the link between the two distributions that is needed to choose one over the other.

(This third test is based on the assumption that the data definitely come from either a lognormal or a Weibull distribution. It must be used in conjunction with the goodness-of-fit tests.)

Table 1 gives the results of the three tests for the 12 motion conditions being considered. All tests have been conducted at the $\alpha = .05$ significance level. The first two tests have been documented in [4]. The test statistic for the third test is the n^{th} root of the ratio of maximized likelihood functions for the Weibull and lognormal distributions, where n is the sample size. The critical values are tabulated in [2]. Large values of the test statistic lead to the choice of the Weibull distribution while small values indicate that the lognormal distribution is preferable. Moderate values indicate that no choice is possible on the basis of this test. The last column lists the distribution which, based on all three tests, best fits the observed data. (Some of the results of the lognormal goodness-of-fit tests given for single-frequency data differ from those reported by Mauro and Smith [4]. That report contains some minor inaccuracies which have been corrected here. The overall conclusions have not been affected.)

The results in Table 1 show clearly that the Weibull distribution is superior to the lognormal as a model for time to emesis. The lognormal goodness-of-fit test rejects at the $\alpha = .05$ significance level in 3 of the 12 cases considered. The Weibull goodness-of-fit test does not reject for any of the data sets. Furthermore, the likelihood ratio test chooses the Weibull distribution for 5 of the 12 data sets. In the other 7 cases there is insufficient information to make a definite choice between the two distributions.

Condition Description (Single Frequency) Frequency (Hz)	Acceleration (rms)	Size of uncensored portion of sample	Reject Lognormal model	Reject Weibull model	Weibull vs Lognormal	Choice of Distribution
.167	.111	7	No	No	No Decision	Either
.167	.222	11	No	No	No Decision	Either
.250	.111	9	No	No	No Decision	Either
.250	.222	37	Yes	No	Weibull	Weibull
.333	.222	15	Yes	No	Weibull	Weibull
.333	.333	17	No	No	No Decision	Either
.500	.444	7	No	No	No Decision	Either
Correlation Study Condition						
I		17	No	No	No Decision	Either
II		18	No	No	Weibull	Weibull
III		23	No	No	No Decision	Either
IV		30	Yes	No	Weibull	Weibull
V		33	No	No	Weibull	Weibull

Table 1: Results of Goodness of Fit Tests

Further insight into how the two models fit the data can be obtained from an examination of the fitted distribution functions. In each case, two parameters must be estimated from the data. (Both the lognormal and Weibull distributions have three-parameter versions. However, the third parameter is a threshold parameter which seems inappropriate in this situation. We have found no evidence of any lag before subjects feel the effects of the various motion conditions. The threshold parameter has, therefore, been set to zero.) The lognormal probability density function is given by:

$$f(t) = \frac{1}{\sqrt{2\pi}\,\sigma\, t} \exp\left\{\frac{-(\ln t - \mu)^2}{2\,\sigma^2}\right\} \quad ; t > 0, \quad \sigma > 0.$$

The Weibull probability density function may be written as:

$$g(t) = c/b(t/b)^{c-1} \exp\left\{-(t/b)^c\right\} \quad ; t > 0, b > 0, c > 0.$$

Both of these distributions have been fit in each of the 12 cases under consideration. (For details of the estimation procedure, see [2].) The estimated parameters are given in Table 2. From these parameters, the fitted distribution functions have been calculated for each of the 12 motion conditions. Figures 1 through 12 contain plots of these functions along with the empirical distribution functions.

In most of the plots, the fitted functions both seem to follow the empirical distribution fairly well. However, in those cases where the Weibull was chosen previously (see Table 1), the plots confirm the fact that the lognormal distribution does not fit the data. The lognormal tends, in those cases, to underpredict motion sickness incidence later in time while overpredicting at earlier time points.

Condition Description (Single Frequency)		Weibull Parameters		Lognormal Parameters	
Frequency (Hz)	Acceleration (rms)	b	c	μ	σ
.167	.111	67.13	3.369	4.039	0.3467
.167	.222	30.24	1.502	3.053	0.7157
.250	.111	39.97	1.828	3.388	0.6153
.250	.222	39.57	1.534	3.296	0.8465
.333	.222	57.41	1.285	3.557	1.0692
.333	.333	35.81	1.333	3.162	0.8521
.500	.444	28.53	1.873	3.066	0.5612

Correlation Study Condition	b	c	μ	σ
I	33.90	1.560	3.184	0.6708
II	54.75	1.764	3.667	0.7479
III	42.62	1.327	3.337	0.8465
IV	38.93	1.521	3.272	0.9120
V	31.02	1.636	3.082	0.7469

Table 2: Estimated Parameters for Weibull and Lognormal Distributions

III. COMPARISON OF MOTION CONDITIONS IN THE CORRELATION STUDY

Nearly all of the existing data pertaining to motion sickness incidence have been obtained in studies using single-frequency sinusoidal motion. The Correlation Study was designed as a first step toward the study of more complex motions. Condition I of the study consisted of a single sine wave expected to produce a high rate of emesis in the subject population. The other four conditions employed harmonic combinations of two frequencies selected to examine the influence of relative amplitude, phasing, and spectral separation on motion sickness incidence. Table 3 summarizes some of the motion parameters which define the five experimental conditions of the study.

The first question to be considered is whether there are any significant differences in motion sickness incidence between the five groups in the Correlation Study. Guignard and McCauley [3] tested the hypothesis that the total proportions of subjects becoming sick in each group were equal. When the test was performed without the inclusion of quitters in the samples, it was not significant at the $\alpha = .05$ level. (It was significant at the $\alpha = .10$ level.) With the inclusion of quitters, the p-value of the test was approximately .02. (The p-value is the lowest significance level at which a test will reject the null hypothesis.)

The test given in [3] treated the observations as dichotomous. It considers only whether or not a subject became sick, disregarding the observed time until emesis. It seems reasonable that if two motion conditions induce emesis in the same total proportion of subjects, but subjects becoming sick in the first condition do so at earlier times

	Condition				
	I	II	III	IV	V
Fundamental:					
Frequency (Hz)	0.17	0.16	0.16	0.17	0.16
rms Acceleration (g)	0.14	0.14	0.14	0.12	0.08
Harmonic:					
Frequency (Hz)	---	0.32	0.33	0.50	0.33
rms Acceleration (g)	---	0.15	0.14	0.29	0.26
Phase Angle (deg)	---	0	+90	0	0
Total rms Acceleration (g)	0.14	0.20	0.19	0.31	0.27

Table 3: Delivered Motion Parameters of Correlation Study Waveforms

than those in the second condition, then the first condition should be considered more severe. The procedure discussed above cannot discriminate between such conditions since it considers only the total proportions of subjects who became sick within two hours. In this section we use a test procedure which can detect more general differences between the five conditions.

In the previous section, we showed that time to emesis can be explained by a mixture model. The susceptible portion of the population, which varies with the type of motion, is fit well by the Weibull distribution. The rest of the population follows some distribution which cannot be determined from the available data. Since the complete mixture distribution is therefore unknown, we treat the data as a set of censored samples from various unknown distributions. This lack of knowledge necessitates the use of a nonparametric test, a number of which have been proposed for similar problems.

Of the available nonparametric tests which are applicable to censored data, some are more sensitive to particular differences between distributions than are others. We have chosen to use a test developed by Breslow [1], which is particularly sensitive to differences in the hazard rates which occur early in time. (The hazard rate is defined as $f(t)/[1-F(t)]$, where $f(t)$ is the probability density function and $F(t)$ is the cumulative distribution function.) This is a generalized version of the two-sample Wilcoxon test, which may be found in any text on nonparametric statistics. It can be used with any number of samples and is applicable to censored data. The actual test procedure is fairly detailed and is not given here. A complete discussion may be found in the indicated reference.

Under the null hypothesis that k populations are equal, Breslow's test statistic has an asymptotic χ^2 distribution with k-1 degrees of freedom. When the quitters are dropped from the samples, the test statistic is:

$$\chi_1^2 = 10.269; \; p = .0361 \; .$$

This is a very conservative result since the deletion of quitters from the samples tends to equalize the five distributions. The conditions with the highest rate of emesis also have the most quitters. On the other hand, while it seems certain that most of the quitters quit because they were becoming nauseated, the actual times of emesis might have been much later if they had continued in the experiment. Therefore, inclusion of the quitters tends to overemphasize the differences between the distributions, giving a liberal significance level. The test statistic calculated with quitters included is:

$$\chi_2^2 = 16.060; \; p = .0029 \; .$$

The test statistics given above provide substantial evidence indicating that the five conditions of the Correlation Study yield different rates of emesis. Therefore, further investigation of those differences is warranted. Since a question of primary interest is which conditions are most severe, we performed all possible pairwise comparisons of the distributions. The p-values for those tests, with and without quitters, are given in Table 4. Condition V had the highest observed motion sickness incidence and from the table can be seen to be significantly more severe than the mildest motion conditions. Even without the inclusion of quitters, there is a significant difference between Conditions II and V.

(a) p-Values of Pairwise Tests Without Quitters

	I	II	III	IV
II	.4549			
III	.4460	.0972		
IV	.4851	.0599	.7791	
V	.0707	.0011	.3091	.1145

(b) p-Values of Pairwise Tests With Quitters

	I	II	III	IV
II	.4805			
III	.4666	.1152		
IV	.1820	.0122	.5609	
V	.0172	.0001	.0626	.1197

Table 4: Pairwise Tests for the Equality of Distributions in the Correlation Study

With quitters included, the comparison of Conditions I and V is also significant, as is the comparison of Conditions II and IV.

Since the sample sizes used in the Correlation Study are relatively small, it is difficult to detect subtle differences between the five motion conditions. Nonparametric tests, in particular, are not very powerful when used with small samples. However, the Correlation Study was intended to be mostly exploratory in nature. As such, it has helped to point out some of the effects of complex waveform motions and indicate possible avenues for future research.

IV. SUMMARY

In this investigation we have examined 12 sets of motion sickness incidence data. Seven of those data sets were taken from various single-frequency studies while the rest of the data comprised the five conditions of the Correlation Study, four of which were dual-frequency motion conditions. Each of the experiments limited exposure to two hours duration and each used frank emesis as the experimental endpoint.

In section II of this report we have shown that time to emesis data may be described by a statistical mixture model. The first population in the mixture is made up of the subjects who become sick within 2 hours and follows a Weibull probability distribution. We have included the quitters in that population. The second part of the mixture accounts for those who do not become sick within two hours. The distribution of that part of the mixture cannot be determined from the available data.

Both lognormal and Weibull distribution functions have been fit to the uncensored portions of the samples. These functions have been plotted along with the empirical distribution functions. The plots illustrate the differences in the way the two functions fit the data and give further evidence for the choice of the Weibull over the lognormal distribution as a model for time to emesis.

In section III we have used a nonparametric test, developed by Breslow [1], to compare the five conditions of the Correlation Study. The comparisons have been made both with and without the inclusion of quitters in the samples. In either case, the overall test that the five conditions are equal rejects at the $\alpha = .05$ level of significance.

The evidence for rejection of this hypothesis is much stronger when quitters are included. Pairwise comparisons of the conditions have also been made, showing that Condition V is significantly more severe than the mildest conditions. For the most part, however, we cannot distinguish between the conditions on the basis of the test used here. This may be a result of the fact that the test is not very powerful for the sample sizes being used.

V. APPENDIX: DATA LISTING AND FIGURES

The data given here were taken from a number of experiments performed using the ONR motion generator. Our source for the first seven data sets was [5]. The data for the Correlation Study is given in [6], with the exception that the times for the quitters were not reported there. We obtained those times from the authors. The times are given in minutes and those for quitters are marked with an asterisk. In the identification of the data sets, f denotes frequency (Hz), a denotes rms acceleration (g), and N is the total number of subjects in the experiment.

Condition: f=.167, a=.111, N=21

30	50	50*	51	66*	82	92

Condition: f=.167, a=.222, N=20

5	12	13	17	18	19	19	28	40	58	69

Condition: f=.250, a=.111, N=29

9	16	26	27	29	31	39	66	75

Condition: f=.250, a=.222, N=59

3	8	9	12	15	15*	17	18	19	20	20
20*	21	21	22	23	23*	24	28	28*	29	37
38	45	46	51	51	54	57	58	58	59	62
67	74	92	93							

Condition: f=.333, a=.222, N=28

5	6*	11	11	13	24	63	65	69	69	79
82	82	102	115							

Condition: f=.333, a=.333, N=33

4	7	9	12	14	18	19	21	23	23	25
45	46	58	70	71	92					

Condition: f=.500, a=.444, N=21

10	12	17	18	31	34	54

Correlation Study: Condition I N=33

7.02	10.02	11.33	14.00	16.02	17.83	18.50	21.22
21.50	22.98	26.25	32.70*	40.02	44.75	62.03	71.45
76.00							

Correlation Study: Condition II N=34

6.00	8.63	22.33	25.92	29.00*	29.43	32.80*	35.33
43.72	44.00	58.60	59.08	63.08	66.00	69.85	71.08
100.33	113.32						

Correlation Study: Condition III N=34

6.80	7.33	7.70	10.03	10.08	13.08	16.22	18.67
23.10	24.32	26.38	26.98	39.83	39.86	44.00	45.10*
45.40	60.75*	62.62	64.92*	75.83	107.68	120.80	

Correlation Study: Condition IV N=40

1.82*	1.82*	11.07	11.72	12.03	14.47	15.47	16.72
17.38*	19.20*	25.33	29.72	32.23	32.23	32.50*	32.50*
35.25	39.98*	40.50	42.25	43.08	44.22	45.47*	47.50
50.35*	50.83	58.45	60.02	78.45	114.47		

Correlation Study: Condition V N=40

4.07*	5.47*	5.92	7.08	8.10	8.10	10.77	11.28*
14.17	17.50	18.28*	18.47	18.53*	20.00	23.33	24.50
24.75*	25.05	27.00	27.75	28.08	31.05	38.13	39.17
39.50	39.83*	43.42	46.25	47.50	47.77*	57.92	60.23
75.13							

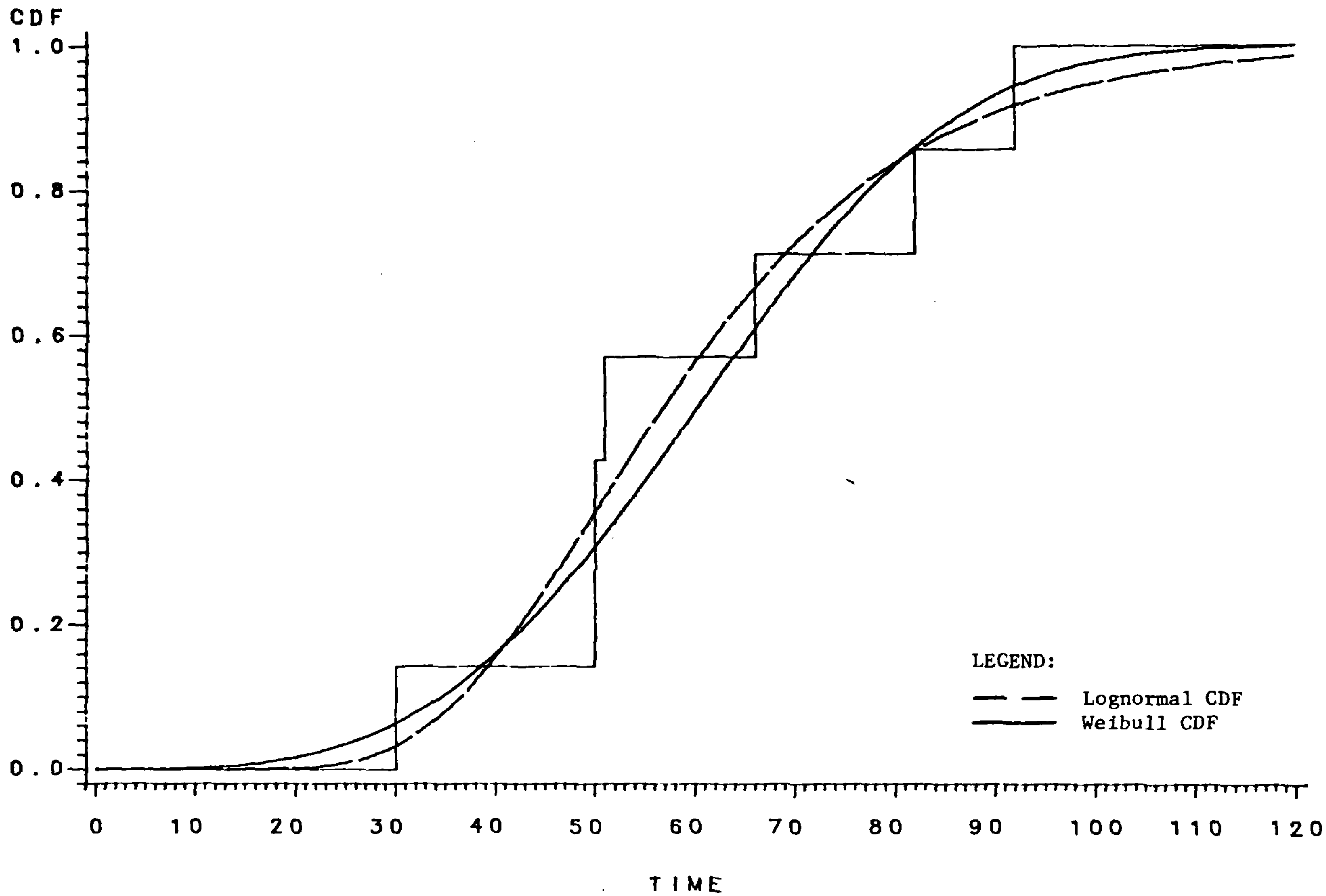

Figure 1: Comparison of fitted lognormal and Weibull cumulative distribution functions to empirical distribution function: f=.167, a=.111 .

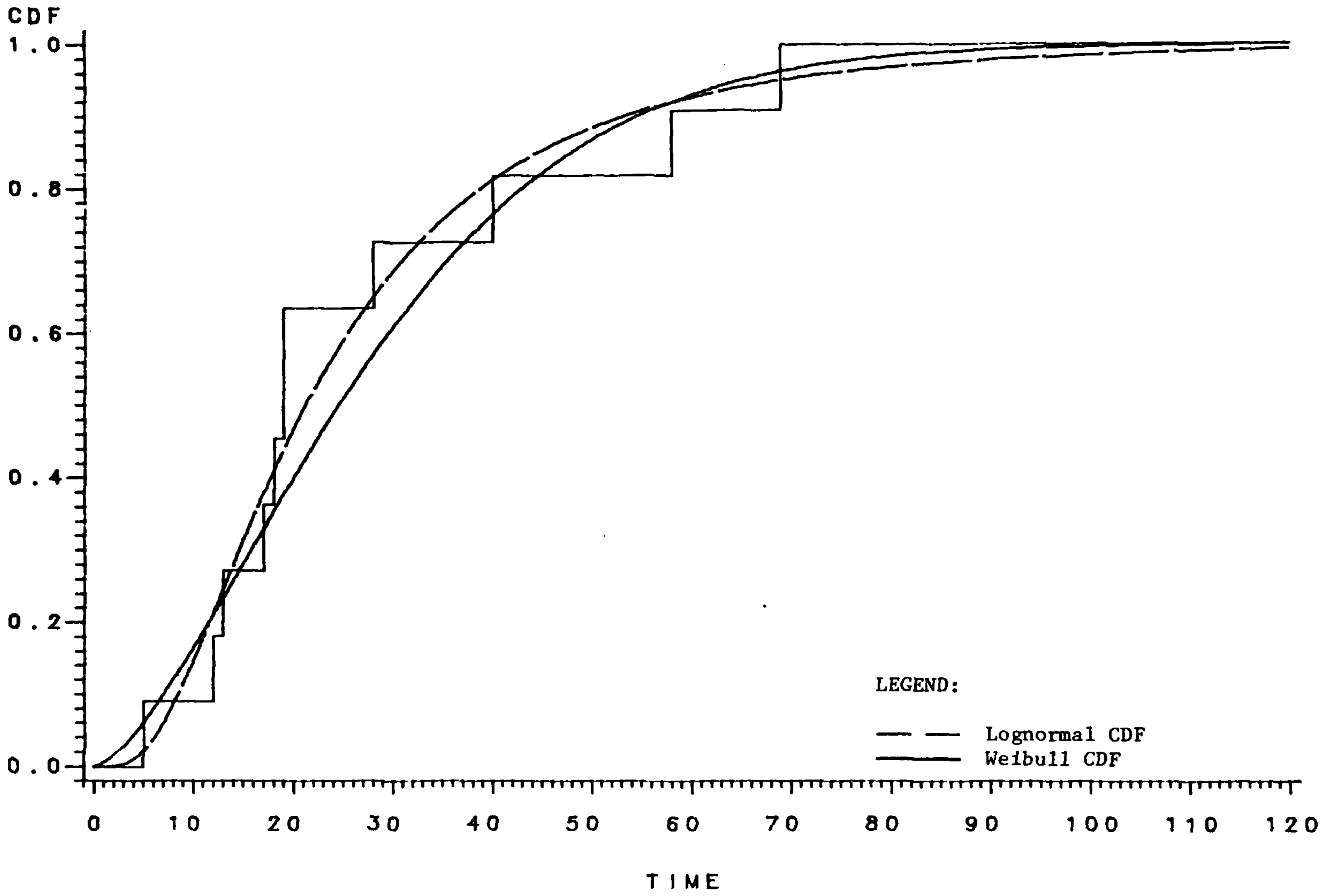

Figure 2: Comparison of fitted lognormal and Weibull cumulative distribution functions to empirical distribution function: f=.167, a=.222 .

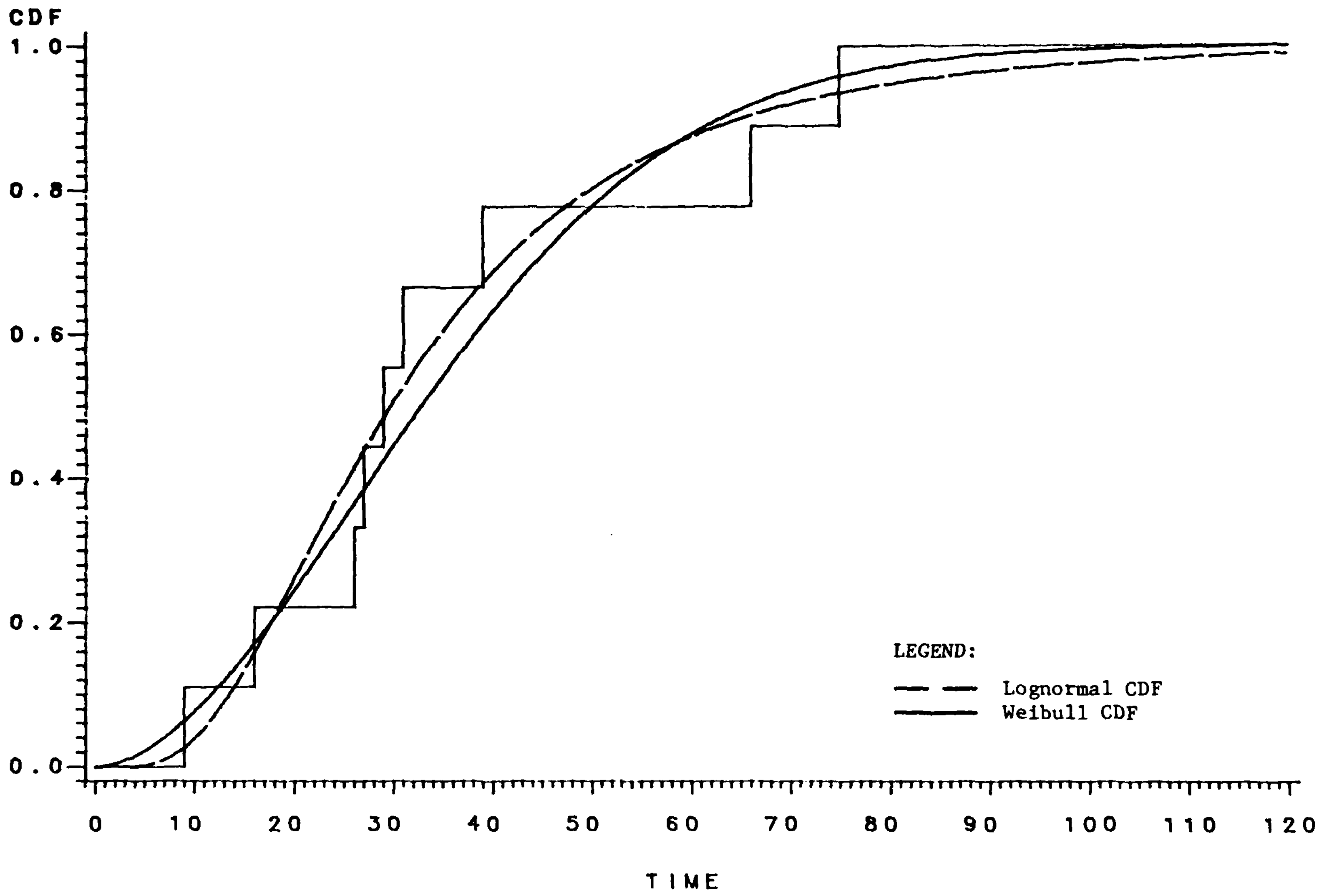

Figure 3: Comparison of fitted *lognormal* and *Weibull* cumulative distribution functions to empirical distribution function: f=.250, a=.111 .

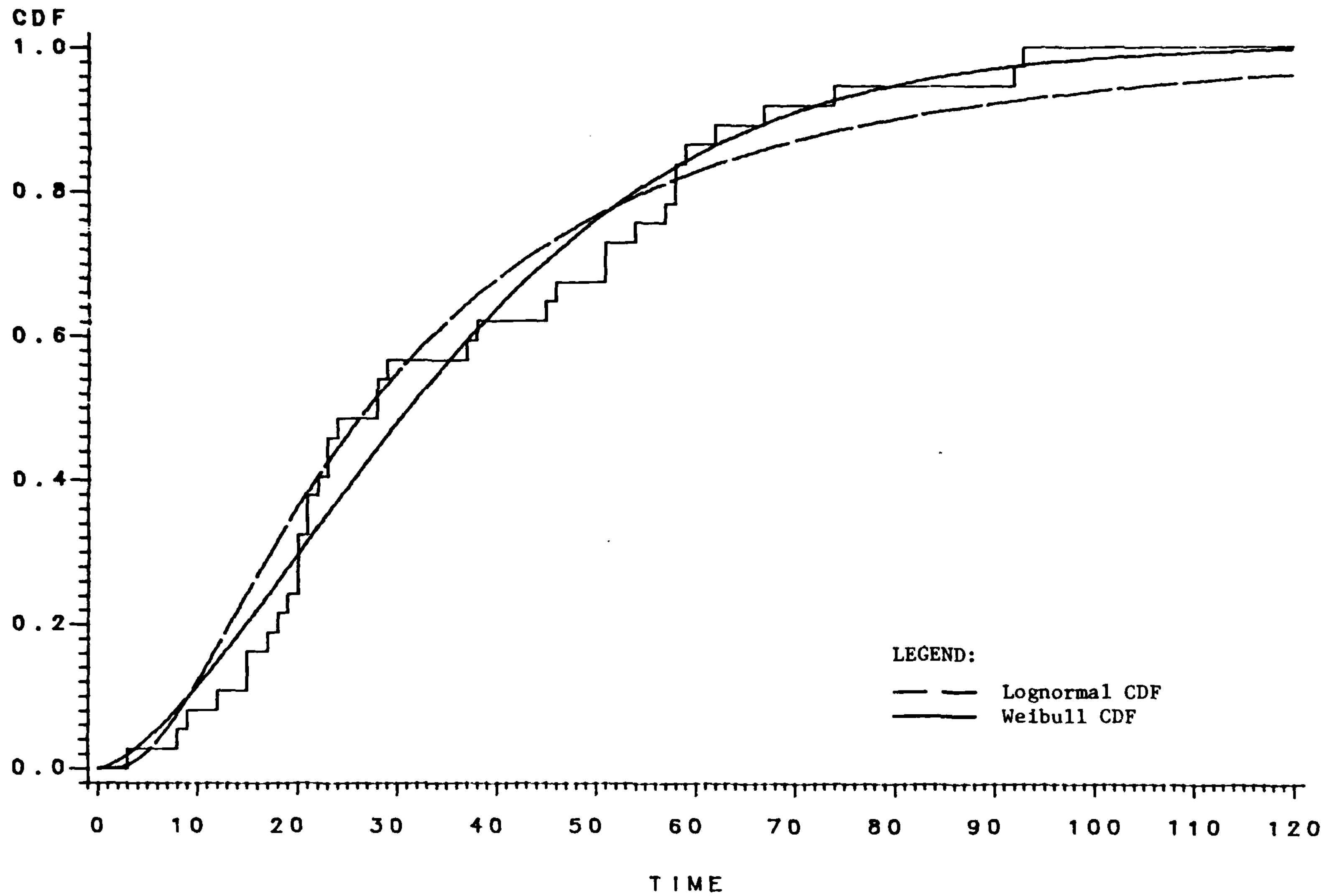

Figure 4: Comparison of fitted lognormal and Weibull cumulative distribution functions to empirical distribution function: f=.250, a=.222.

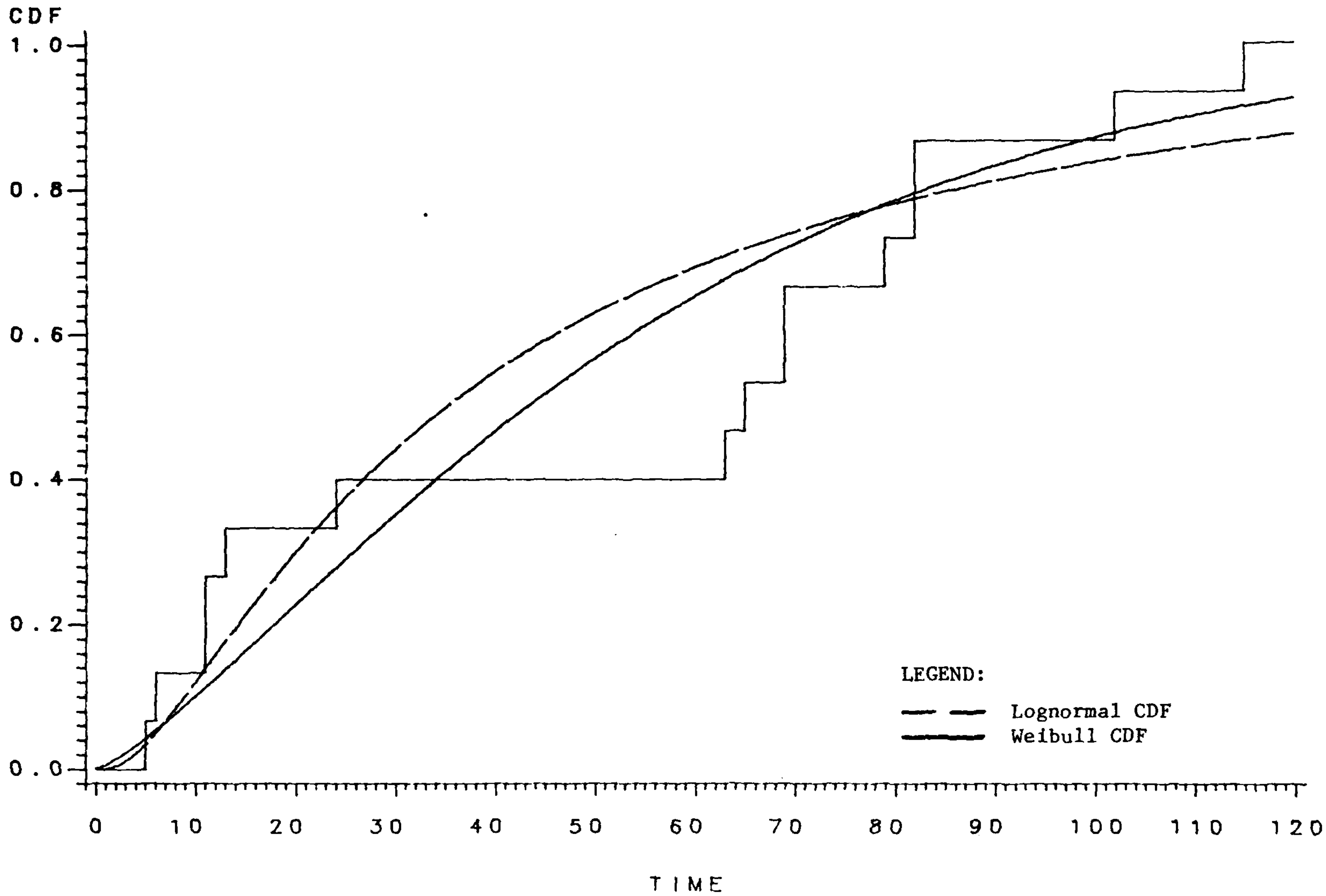

Figure 5: Comparison of fitted lognormal and Weibull cumulative distribution functions to empirical distribution function: f=.333, a=.222 .

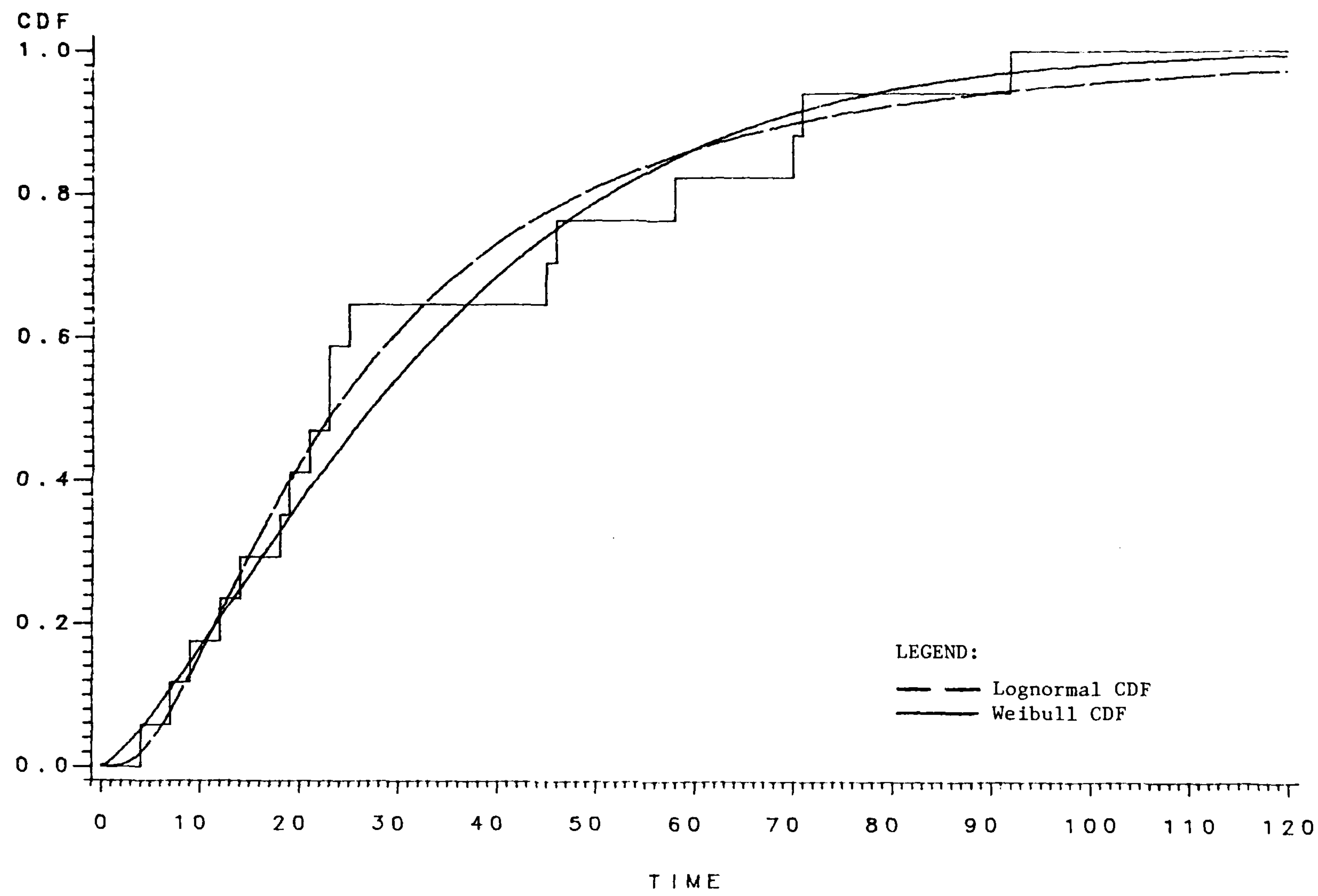

Figure 6: Comparison of fitted lognormal and Weibull cumulative distribution functions to empirical distribution function: f=.333, a=.333 .

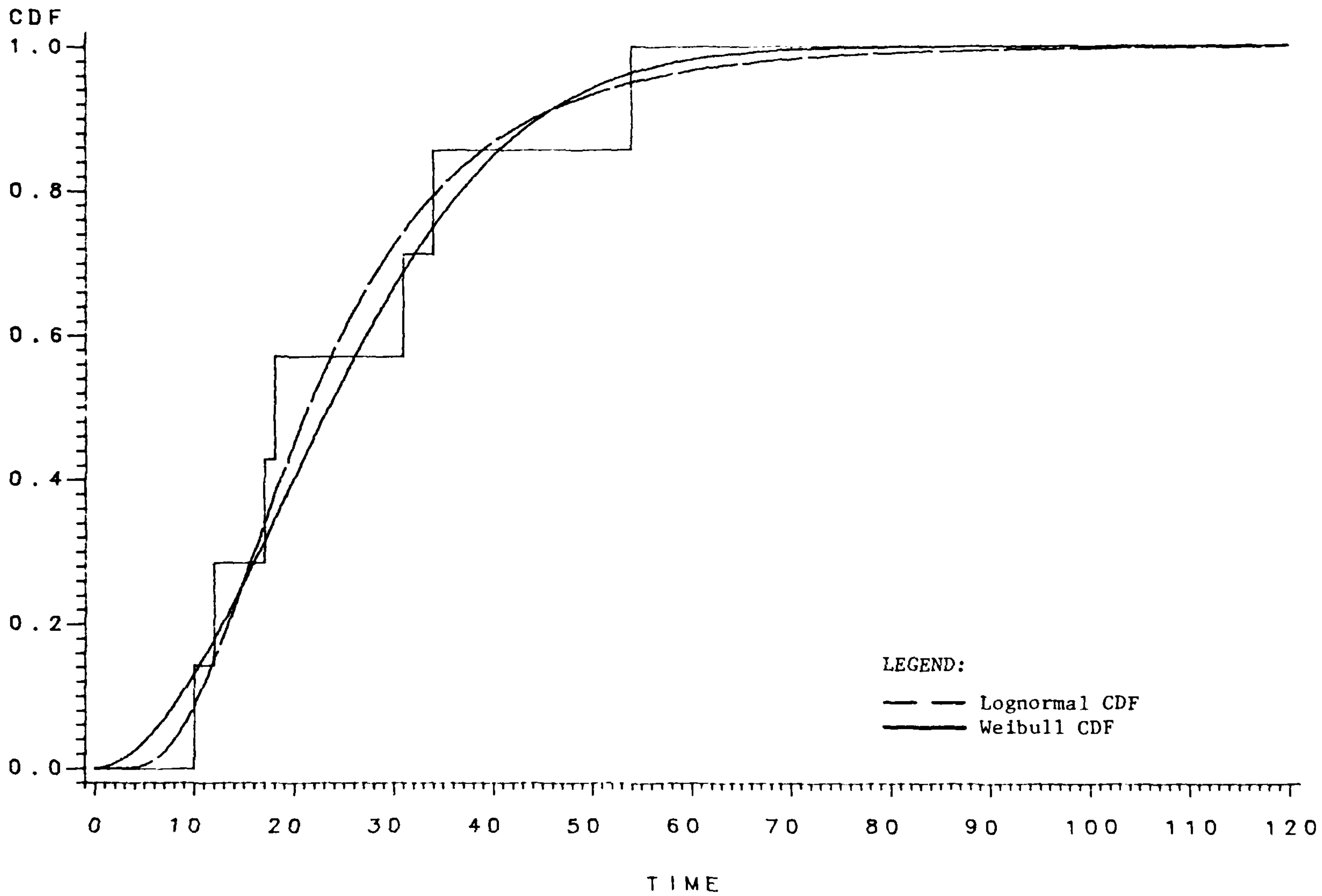

Figure 7: Comparison of fitted lognormal and Weibull cumulative distribution functions to empirical distribution function: f=.500, a=.444 .

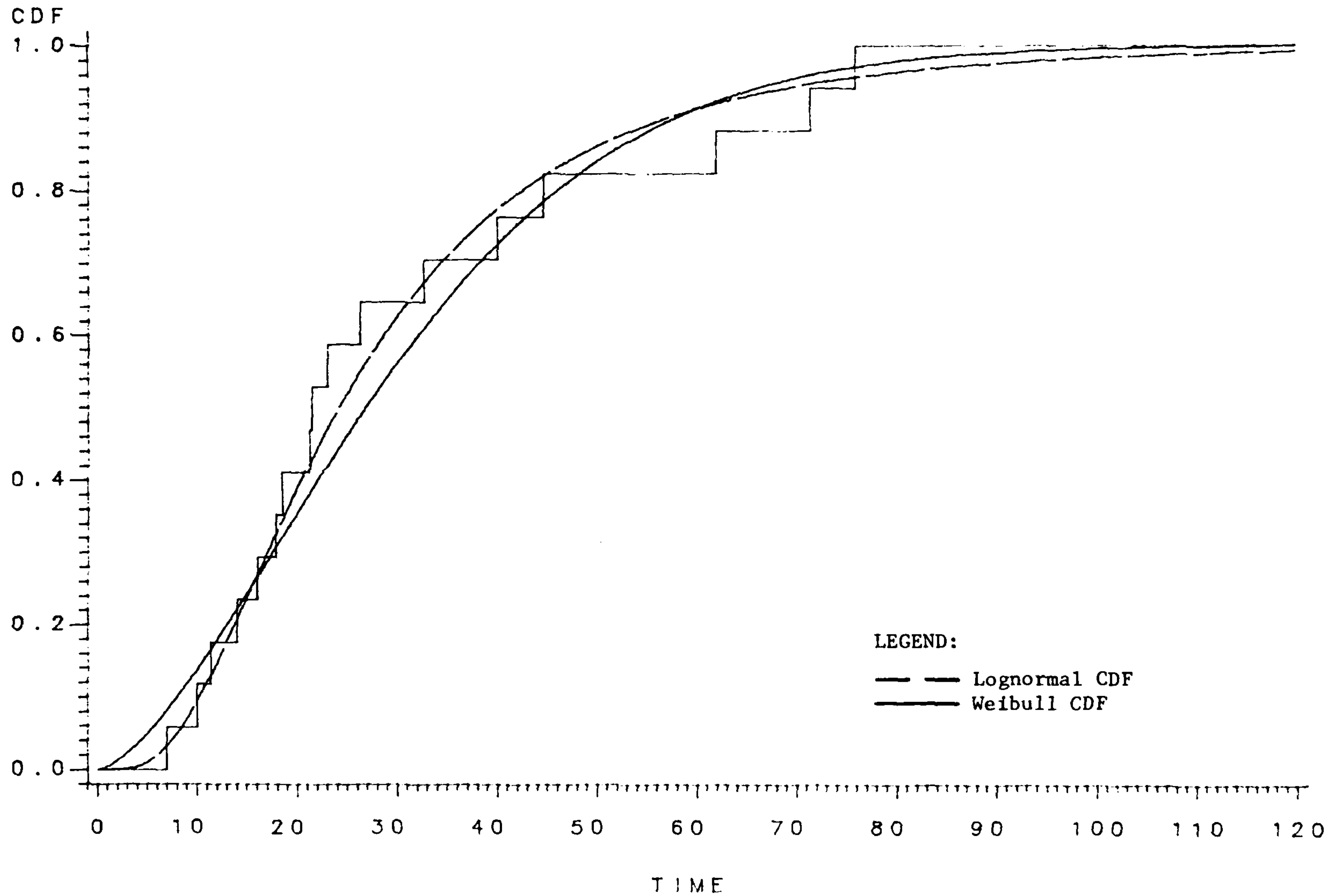

Figure 8: Comparison of fitted lognormal and Weibull cumulative distribution functions to empirical distribution function: Condition I of Correlation Study.

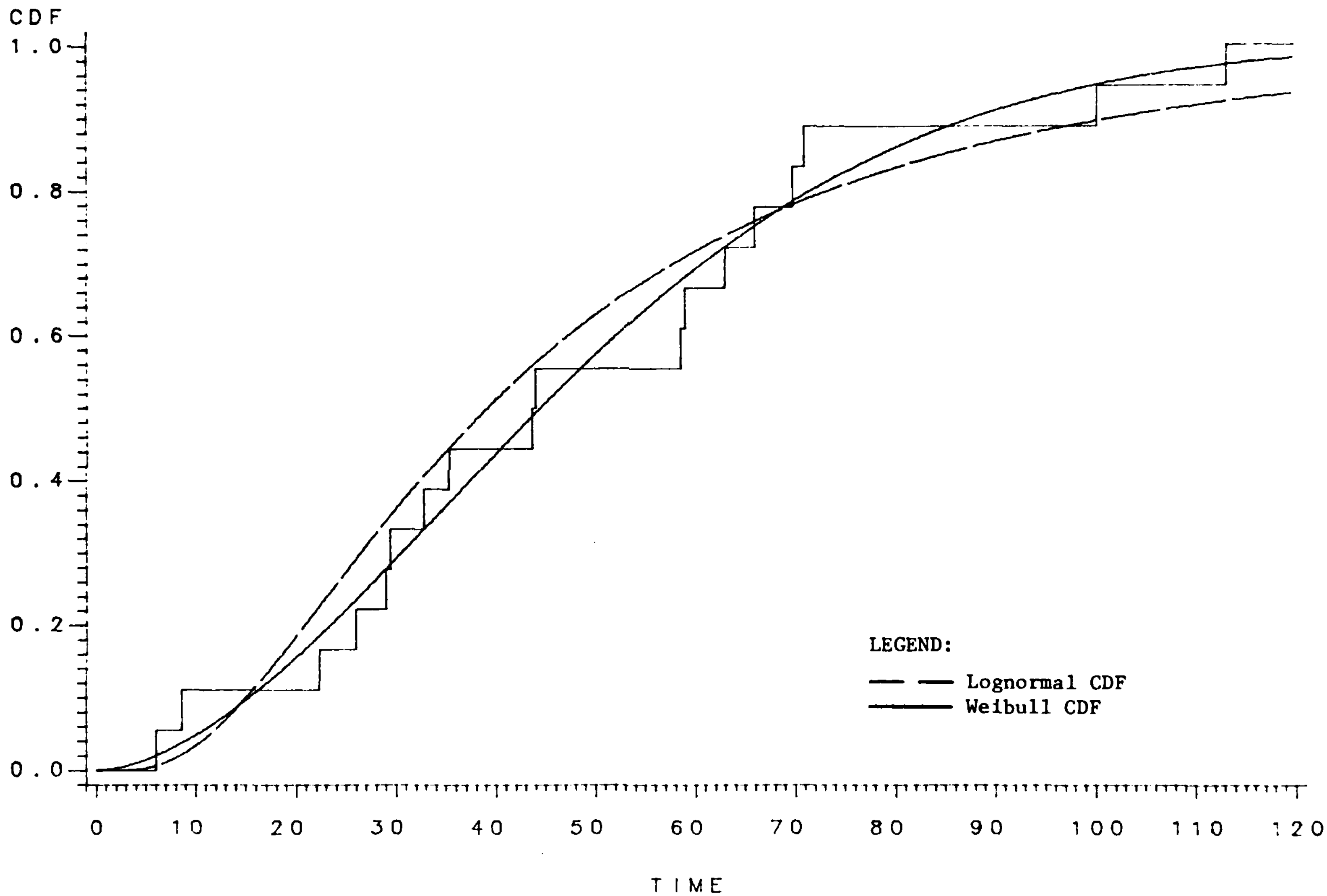

Figure 9: Comparison of fitted lognormal and Weibull cumulative distribution functions to empirical distribution function: Condition II of Correlation Study.

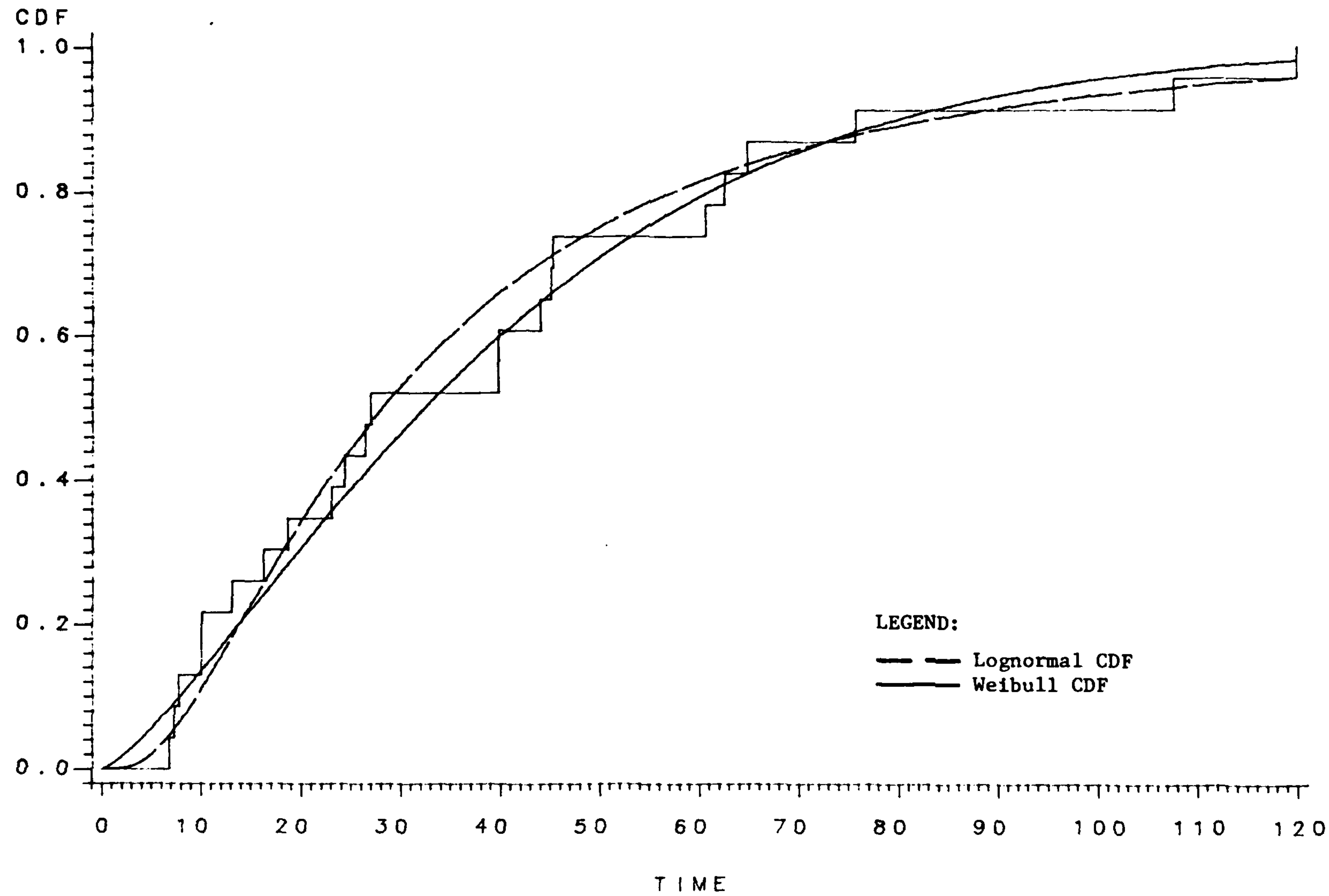

Figure 10: Comparison of fitted lognormal and Weibull cumulative distribution functions to empirical distribution function: Condition III of Correlation Study.

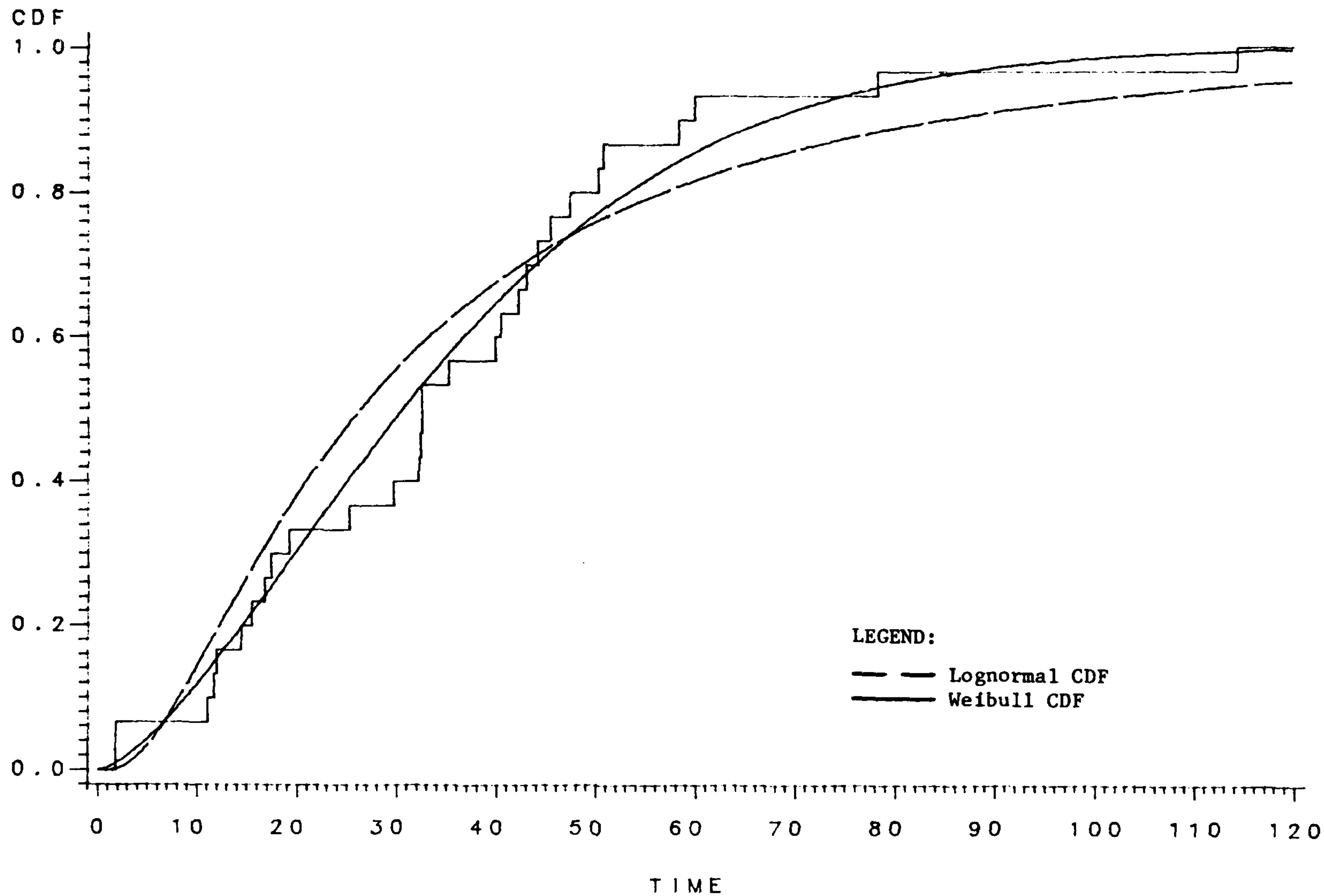

Figure 11: Comparison of fitted lognormal and Weibull cumulative distribution functions to empirical distribution function: Condition IV of Correlation Study.

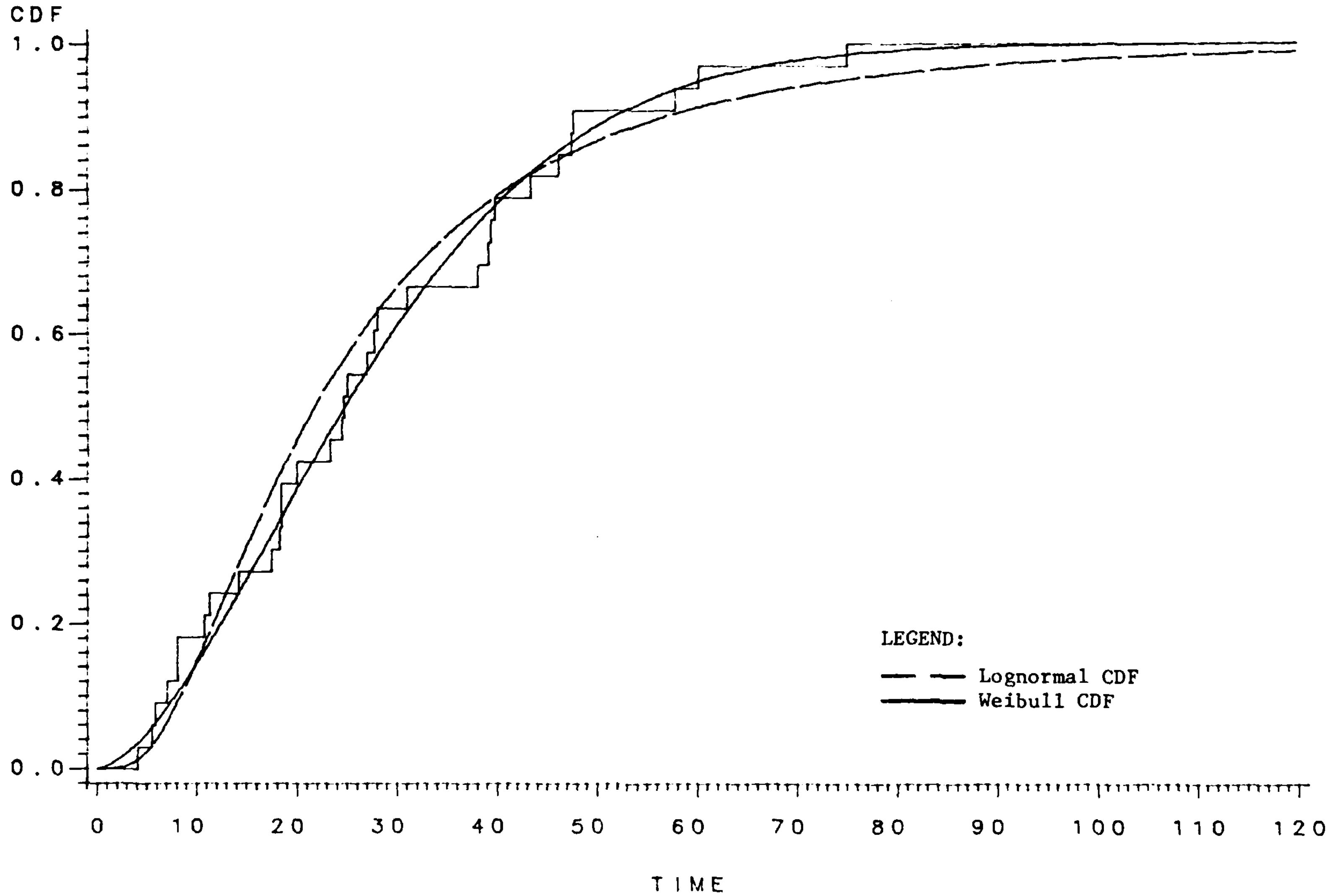

Figure 12: Comparison of fitted lognormal and Weibull cumulative distribution functions to empirical distribution function: Condition V of Correlation Study.

VI. REFERENCES

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REPORT DOCUMENTATION PAGE

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A statistical mixture model is used to fit time-to-emesis data. The Weibull probability distribution is shown to provide a good fit for those subjects who either become sick or withdraw from the experiment within two hours. The second part of the mixture accounts for those subjects who neither quit nor vomit within two hours. The lognormal probability model is shown to give a poorer fit to the data and figures showing the relative fits of the estimated Weibull and lognormal distributions are provided. A

nonparametric test is used to compare the five motion conditions of the Correlation Study. That test shows that there are significance differences in severity among the conditions.