Software Reliability Assessment using CASRE

Internship report

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Objective

Literature survey reveals significant efforts have been made to determine the reliability of software systems. Various reliability models have been and tested to determine the chances of its failure which are based on various assumptions. The generic name given to these models is “Software Reliability Models” (SRMs). The main goal of these reliability models is to fit a theoretical distribution to time-between-failure data and failure count data to determine software reliability. As such the success of SRMs is dependent on choice of model.
Verification that the selected model is valid for the available data set usually requires iterations and analysis of the model functions. In the results obtained, prediction of reliability of software is made and comparison of the prediction values by different models is done using graphs. All the above mentioned results, predictions and comparisons were obtained by the software CASRE.

Acknowledgement

For almost one month from 1st June,2017 till 23rd June,2017. I did an internship at Subir Chowdhury School of Quality and Reliability, Indian Institute of Technology, Kharagpur.

I worked on an assessment to study the software reliability of software testing readings. This assessment was done using software named CASRE. I am very appreciated to Dr. Neeraj Kumar Goyal, my supervisor at Subir Chowdhury School of Quality and Reliability, IIT Kharagpur. He was the guiding force behind the very concept. I am grateful that I got a great opportunity to work under guidance of Dr. N.K.Goyal.

Introduction

We were given two types of data to analyse and take out reliability using software CASRE. The two types of data were TBF(Time between failure)data and FC(Failure count)data. TBF data which was given to us:

Build	Build Date	Fault Reported	Duration in Days
001	2/2/2015	3/31/2015	57
001	2/2/2015	3/10/2015	36
001	2/2/2015	3/4/2015	30
001	2/2/2015	3/10/2015	36
001	2/2/2015	3/10/2015	36
001	2/2/2015	2/23/2015	21
001	2/2/2015	2/24/2015	22
001	2/2/2015	2/24/2015	22
001	2/2/2015	2/24/2015	22
001	2/2/2015	3/26/2015	52
001	2/2/2015	3/27/2015	53
001	2/2/2015	3/13/2015	39
001	2/2/2015	3/12/2015	38
002	3/9/2015	4/7/2015	29
002	3/9/2015	4/20/2015	42
002	3/9/2015	3/19/2015	10
002	3/9/2015	3/19/2015	10
003	4/21/2015	5/8/2015	17
003	4/21/2015	5/6/2015	15
003	4/21/2015	4/29/2015	8
003	4/21/2015	4/29/2015	8
003	4/21/2015	5/13/2015	22
003	4/21/2015	5/8/2015	17
004	5/12/2015	5/18/2015	6
005	5/27/2015	6/19/2015	23
005	5/27/2015	7/10/2015	44
005	5/27/2015	6/25/2015	29
005	5/27/2015	6/11/2015	15
005	5/27/2015	6/10/2015	14
005	5/27/2015	6/8/2015	12
005	5/27/2015	6/12/2015	16
005	5/27/2015	6/11/2015	15
005	5/27/2015	6/18/2015	22
005	5/27/2015	7/8/2015	42
005	5/27/2015	6/18/2015	22
005	5/27/2015	6/23/2015	27
005	5/27/2015	6/24/2015	28
005	5/27/2015	6/24/2015	28
005	5/27/2015	6/24/2015	28
006	6/22/2015	7/2/2015	10
006	6/22/2015	7/10/2015	18
006	6/22/2015	7/2/2015	10
007	6/26/2015	7/3/2015	7
007	6/26/2015	9/14/2015	80
008	8/6/2015	9/2/2015	27
008	8/6/2015	9/8/2015	33
008	8/6/2015	9/8/2015	33
009	9/22/2015	11/19/2015	58
009	9/22/2015	11/10/2015	49
010	11/16/2015	12/4/2015	18
010	11/16/2015	12/24/2015	38
011	12/16/2015	12/29/2015	13
013	12/30/2015	1/7/2016	8

fig a. TBF data-1

Failure number	Time between failure
1	20
2	1
3	5
4	12
5	0.5
6	14
7	15
8	9
9	8
10	52
11	39
12	344
13	54
14	7
15	41

fig b. TBF data-2

fig 1: The provided TBF data-1 and data-2

FC data which were given to us:

Data-1

Days	Failures
5	4
10	32
15	44
20	57
25	66
30	70
35	74
40	75
45	79
50	81
55	83
60	85
65	86
70	86
75	86
80	86
85	86
90	86
95	86
100	86
105	86
110	86
115	86
120	86
125	86
130	86
135	86
140	86
145	86
150	86
155	86
160	86
165	86
170	86

Data-2

Duration	Failures
5	0
10	1
15	1
20	1
25	1
30	2
35	3
40	3
45	3
50	4
55	5
60	5
65	5
70	5
75	5
80	7
85	8
90	8
95	14
100	15
105	15
110	17
115	18

Data-3

Days	Failures
2	0
4	0
6	0
8	0
10	0
12	0
14	2
16	2
18	3
20	3
22	3
24	3
26	4
28	5
30	5
32	5
34	5
36	5
38	5
40	5
42	6
44	6
46	6
48	6
50	6
52	6
54	6
56	7
58	8
60	8
62	8
64	8
66	8
68	8
70	8
72	8
74	8
76	8

Data-4

Days	Failures
2	7
4	8
6	8
8	8
10	10
12	10
14	12
16	12
18	13
20	14
22	19
24	20
26	21
28	23
30	23
32	23
34	23
36	23
38	23
40	23
42	25
44	25
46	26
48	26
50	26
52	26
54	26
56	26
58	26
60	27
62	27
64	27
66	27
68	27
70	29
72	30
74	30
76	31
78	31
80	31
82	31
84	31
86	31
88	31
90	31
92	31
94	32

fig 2: The provided FC data

For CASRE fixed data format, we had to convert the above given data to CASRE's data format. Different models are available in CASRE for different data type, some models are common to both FC and TBF data. In order to do the analysis we selected models from the given models. Some models got executed, some didn't. But for each model we got model result table, from this table, analysis of reliability, next step prediction, model estimates, failure intensity, cumulative failure density was done. CASRE had option of predicting above mentioned terms for future n failures(for TBF data) and future n test intervals(for FC data).For models which got executed, CASRE provided us graphs for comparison of maximum three executed models. CASRE also provided graphs for Time between failure, failure counts(**not for TBF data**), failure intensity, test interval lengths(**not for TBF data**), cumulative failures and reliability. CASRE also provided us to analyse model evaluation data for comparison of executed models. Model evaluation contained Goodness of fit, prequential likelihood, relative accuracy, model bias, model bias trend, model noise. Last three evaluations were not done for FC data. For all executed models, it provided data table for goodness of fit and model noise and for rest graphs were plotted and data was mentioned on the graph.

Literature Review

Software reliability:

Software Reliability is the probability of failure-freesoftware operation for a specified period of time in a specified environment.

Software reliability models:

Software reliability models are statistical models which can be used to make predictions about a software system's failure rate, given the failure history of the system.

Need for Software reliability models?

Calculation of software reliability is done by using Software Reliability models and with the help of software name CASRE, we can do analysis of software failure data.

CASRE(Computer Aided Software Reliability Estimation):

It is software reliability measurement tool.

CASRE incorporates the mathematical modelling capabilities of the Statistical Modelling and Estimation of Reliability Functions for Software (SMERFS).

Based on failure data which it allows us to select, we can do the analysis of different software models.

It allows us to determine whether a set of failure data indicates that the system's reliability is increasing or decreasing.

Steps to do data analysis using CASRE:

Step 1: Select a set of failure data stored in a file.

There are two data types and each has its own format, they are:

1. Time between failures:

Format example for input data:

```
seconds
1          10          2
2          5           7
3          60          3
```

fig 3: format for TBF input data

1st line: time units for that file.

1st column: failure number

2nd column: time since last failure.

3rd column: severity of failure on scale of 1-9 .

2. Failure count:

Format example for input data:

```
minutes
1          5          20          4
2          9          30          2
3          2          40          8
```

fig 4:format for FC input data

1st line: time unit for that file.

1st column: failure interval.

2nd column: number of failures in that interval.

3rd column: length of that interval.

4th column: severity of failure on scale of 1-9.

File containing this data when opened in CASRE will look like as in fig 5 and fig 6.

Error No.	Days Since Last Failure	Severity
1	9.000000e+000	1
2	1.000000e+000	1
3	5.000000e-001	1
4	6.000000e+000	1
5	5.000000e-001	1
6	3.000000e+000	1
7	2.000000e+000	1
8	2.000000e+000	1
9	5.000000e-001	1
10	7.000000e+000	1
11	1.000000e+000	1
12	5.000000e+000	1

fig 5: Example for TBF data

Test Intvl	Number of Failures	Days in a Test Interval	Severity
1	0.000000e+000	7.000000e+000	N/A
2	3.000000e+000	7.000000e+000	1
3	3.000000e+000	7.000000e+000	1
4	3.000000e+000	7.000000e+000	1
5	2.000000e+000	7.000000e+000	1
6	2.000000e+000	7.000000e+000	1
7	1.000000e+000	7.000000e+000	1
8	2.000000e+000	7.000000e+000	1
9	0.000000e+000	7.000000e+000	N/A
10	2.000000e+000	7.000000e+000	1
11	0.000000e+000	7.000000e+000	N/A
12	0.000000e+000	7.000000e+000	N/A
13	0.000000e+000	7.000000e+000	N/A
14	3.000000e+000	7.000000e+000	1
15	1.000000e+000	7.000000e+000	1

fig 6: Example for FC data

Step2: Choose how far into the future you want to predictions to be made.

CASRE allows us to specify how far into the future predictions should be made using model results.

Depending on the data type, this represents either next ‘n’ intervals or next ‘n’ failures for which prediction is to be made.

Condition:

n should not be more than 20 or 20% of length of the failure data set, whichever is less.

Step3: Select and run models.

Depending on data type CASRE provides models to be analysed.

We can select from the models for each data type listed below:

Table 1: Models for Each Type of Failure Data

Times Between Failures(TBF) Models	**Failure Count(FC) Models**
Geometric	Generalized Poisson.
Jelinski-Moranda	Generalized Poisson – user-specified interval weighting.
Linear LV	Nonhomogeneous Poisson(NHPP).
Musa Basic	Schneidewind.
Musa-Okumoto	Schneidewind – ignore first "s" test Intervals.
NHPP(TBE)	Schneidewind – total failures in first "s" test intervals.
Quadratic LV	Shick-Wolverton.
Dynamically-Weighted Linear Combination (DLC/S/4)	Yamada S-shaped.
Equally-Weighted Linear Combination (ELC)	
Median-Weighted Linear Combination (MLC)	
Unequally-Weighted Linear Combination (ULC)	

There are three models from FC models which require additional information, they are:

Table 2: Additional information about models

Model Name	**Additional information required**
Generalized Poisson	Interval weighting factor
Schneidewind which ignores 1st s test interval	s-test interval to ignore first 's' test interval
Schneidewind for 1st s test interval	s-test interval which ignores after s- test interval.

For this a dialog box will appear to get the information.

Step4: Look at model results.

After we select and run models, Display window opens in which we get options to:

1. See Model results.
2. See plots of the results.
3. See model evaluations (based on these we choose the best model for the given data).

1. See Model results

In model results based on the data selected, a table containing columns of terms listed below are displayed:

The first three columns for FC(Failure counts) data:

Test intervals:this identifies the test intervals during which failures were actuallyobserved as well as the intervals for which predictions are made.

Failure per test interval:the number of failure observed in a test interval.

Test interval length:the length of each test interval.

The next three columns for Time between failure(TBF) data:

Failure number:gives the actual time between consecutive failure as well as the predicted times between failures.

Times since last failure: this reports the actual time elapsed since the last failure.

Rest mentioned columns are for both FC(failure count) data and TBF(Time between failure) data:

Next step prediction: this column reports the model's estimate of the number of failures that will be seen in the next interval based on the model's parameters computed using the data between the model start point and the current test interval.

Two cases:
Case 1: If the column shows the value “N/A”, the current failure number is less than or equal to the observation selected as the end of the initial parameter estimation range.
Case2: When the column shows “UNAVAILABLE”, it means that the prediction could not be made.

Model estimates:for interval i, where i is less than or equal to the number of the last interval in which failure was observed, this column shows the model’s estimate of the number of failure that will be seen in that interval. The estimation is done using all the failure data in the data range.

Estimated reliability:this column gives the estimated reliability based on the model parameter estimates at the end of the data set and the elapsed time T, computed by adding the lengths of the all test intervals in the selected data range.

Estimated cumulative number of failures:for interval i, this column gives the model's estimates and predictions of the cumulative number of failures at interval i. This value is calculated on the basis of the model parameter estimates at the end of the data set.

Failure intensity at elapsed time T:for interval i, gives the model's estimates and predictions of the failure intensity at interval i.

Actuals-Estimates: this column gives the difference between actual observed failure count and the models estimates. If the model has made estimate of "INFINITY" as the time since the last failure, this value is also set to "INFINITY".

2.To see plots of the model results,

CASRE plots graph for function names listed below:

Time between failures: It produces a plot of time since the last failure as a function of failure number.

Failure counts: It produces a plot of number of failures observed in a test interval as a function of the test interval number. It is **not for TBF data**.

Failure intensity: It produces plot for failure intensity (failures observed per unit time) as a function of total elapsed testing time.

Test interval lengths: It produces plot of the lengths of each test interval as a function of test interval number. It is **not enabled for TBF data**.

Cumulative failures: It produces plot for the total number of failures observed as a function of total time elapsed.

Reliability:reliability of the software as function of time.
We observe that reliability of software changes as more failures are observed and corrected.
Often reliability of software increase as failures are found and repaired.

3. Model evaluation:

First we need to select models from the models which was executed.

We can only select three at time.

Model evaluation criteria are:

Goodness-of-fit:
For failure count data, the Chi-square test is used to compute goodness-of-fit. For time between failures data, the Kolmogorov-Smirnov test is used.

For each model executed, the goodness-of-fit statistic is computed and displayed in a table.

Prequential likelihood:
It produces plot for the negative of the natural log of the prequential likelihood for selected model results.
The ratio of theprequential likelihood values for two models indicates how much more likely it is that one model is more applicable to the failure data than the other model.

Relative accuracy:
Displays a scatter plot of the prequential likelihood ratio for the models
selected for display.
Given two models, this ratio indicates how much more likely it is that one model will produce more accurate predictions than the other model.
The plot, then, tells you how much more likely it is that one model will produce more accurate predictions than the others.

Bias:
This capability draws a plot which indicates whether the selected models tend to predict higher or lower times between failures (or failure counts) than are actually observed.

Bias trend:
A plot is drawn which indicates any trends in the selected models' bias over time.

Bias scatter plot:
This capability draws a scatter plot of the probability of failure before the next observed error vs. error number (test interval number), indicating the direction of the selected models' bias as well as the range of failure data in which the bias is observed.

Model noise:
This draws a table displaying the model noise measurement for each model that was run. The higher the noise figure, the less accurate the predictions made by the model.

Model rankings:
This brings up a dialog box in which the user assigns weights to the following five criteria:
1. Goodness-of-fit
2. Prequential likelihood
3. Bias

4. Bias trend
5. Model noise.

Based on the weights for each criterion, each model that was executed is ranked, and a table of the model rankings is displayed.

For failure count data, the weights for the bias, bias trend, and model noise criteria are locked at a value of 0.

In “Rank summary” it displays the overall rank of each model with respect to the selected criteria.

In “Ranking details” it displays rank of each model with respect to each criterion as well as overall rank.

Step5: **Determine which model is most appropriate to the data.**

Based on model ranking summary, we choose which model is most appropriate for the data.

Step6:

Analysis of the model results, plots are then done. Analysis of data is done in next section.

Data Analysis and Result

As we were given two types of data i.e. TBF(Time between failure) data and FC(Failure counts) data.

TBF data which was given to us:

TBF data -1

Build	Build Date	Fault Reported	Duration in Days
001	2/2/2015	3/31/2015	57
001	2/2/2015	3/10/2015	36
001	2/2/2015	3/4/2015	30
001	2/2/2015	3/10/2015	36
001	2/2/2015	3/10/2015	36
001	2/2/2015	2/23/2015	21
001	2/2/2015	2/24/2015	22
001	2/2/2015	2/24/2015	22
001	2/2/2015	2/24/2015	22
001	2/2/2015	3/26/2015	52
001	2/2/2015	3/27/2015	53
001	2/2/2015	3/13/2015	39
001	2/2/2015	3/12/2015	38
002	3/9/2015	4/7/2015	29
002	3/9/2015	4/20/2015	42
002	3/9/2015	3/19/2015	10
002	3/9/2015	3/19/2015	10
003	4/21/2015	5/8/2015	17
003	4/21/2015	5/6/2015	15
003	4/21/2015	4/29/2015	8
003	4/21/2015	4/29/2015	8
003	4/21/2015	5/13/2015	22
003	4/21/2015	5/8/2015	17
004	5/12/2015	5/18/2015	6
005	5/27/2015	6/19/2015	23
005	5/27/2015	7/10/2015	44
005	5/27/2015	6/25/2015	29
005	5/27/2015	6/11/2015	15
005	5/27/2015	6/10/2015	14
005	5/27/2015	6/8/2015	12
005	5/27/2015	6/12/2015	16
005	5/27/2015	6/11/2015	15
005	5/27/2015	6/18/2015	22
005	5/27/2015	7/8/2015	42
005	5/27/2015	6/18/2015	22
005	5/27/2015	6/23/2015	27
005	5/27/2015	6/24/2015	28
005	5/27/2015	6/24/2015	28
005	5/27/2015	6/24/2015	28
006	6/22/2015	7/2/2015	10
006	6/22/2015	7/10/2015	18
006	6/22/2015	7/2/2015	10
007	6/26/2015	7/3/2015	7
007	6/26/2015	9/14/2015	80
008	8/6/2015	9/2/2015	27
008	8/6/2015	9/8/2015	33
008	8/6/2015	9/8/2015	33
009	9/22/2015	11/19/2015	58
009	9/22/2015	11/10/2015	49
010	11/16/2015	12/4/2015	18
010	11/16/2015	12/24/2015	38
011	12/16/2015	12/29/2015	13
013	12/30/2015	1/7/2016	8

fig 7: TBF data -1 (given format)

TBF Data set-2:

Failure number	Time between failure
1	20
2	1
3	5
4	12
5	0.5
6	14
7	15
8	9
9	8
10	52
11	39
12	344
13	54
14	7
15	41

fig 8: TBF Data set-2 (given format)

FC data which were given to us:

Data-1

Days	Failures
5	4
10	32
15	44
20	57
25	66
30	70
35	74
40	75
45	79
50	81
55	83
60	85
65	86
70	86
75	86
80	86
85	86
90	86
95	86
100	86
105	86
110	86
115	86
120	86
125	86
130	86
135	86
140	86
145	86
150	86
155	86
160	86
165	86
170	86

Data-2

Duration	Failures
5	0
10	1
15	1
20	1
25	1
30	2
35	3
40	3
45	3
50	4
55	5
60	5
65	5
70	5
75	5
80	7
85	8
90	8
95	14
100	15
105	15
110	17
115	18

Data-3

Days	Failures
2	0
4	0
6	0
8	0
10	0
12	0
14	2
16	2
18	3
20	3
22	3
24	3
26	4
28	5
30	5
32	5
34	5
36	5
38	5
40	5
42	6
44	6
46	6
48	6
50	6
52	6
54	6
56	7
58	8
60	8
62	8
64	8
66	8
68	8
70	8
72	8
74	8
76	8

Data-4

Days	Failures
2	7
4	8
6	8
8	8
10	10
12	10
14	12
16	12
18	13
20	14
22	19
24	20
26	21
28	23
30	23
32	23
34	23
36	23
38	23
40	23
42	25
44	25
46	26
48	26
50	26
52	26
54	26
56	26
58	26
60	27
62	27
64	27
66	27
68	27
70	29
72	30
74	30
76	31
78	31
80	31
82	31
84	31
86	31
88	31
90	31
92	31
94	32

fig 9: FC Data set 1, data set 2, data set 3 and data set 4 (given format)

The above data was converted manually to CASRE's data format as mentioned in the Literature Review.

We were given two TBF data and four FC data.

We did analysis of both of TBF data and first two of FC data.

Model result and model evaluation:

TBF Data-1:

Error No.	Days Since Last Failure	Severity			
1	2.100000e+001	1	28	1.500000e+001	1
2	1.000000e+000	1	29	1.600000e+001	1
3	3.000000e-001	1	30	2.200000e+001	1
4	3.000000e-001	1	31	2.200000e+001	1
5	8.000000e+000	1	32	2.300000e+001	1
6	6.000000e+000	1	33	2.700000e+001	1
7	3.000000e-001	1	34	2.800000e+001	1
8	3.000000e-001	1	35	2.800000e+001	1
9	2.000000e+000	1	36	2.800000e+001	1
10	1.000000e+000	1	37	2.900000e+001	1
11	6.000000e+000	1	38	7.000000e+000	1
12	5.000000e-001	1	39	1.000000e+001	1
13	7.000000e+000	1	40	1.000000e+001	1
14	1.000000e+000	1	41	1.800000e+001	1
15	4.000000e+000	1	42	4.200000e+001	1
16	7.000000e+000	1	43	4.400000e+001	1
17	1.300000e+001	1	44	2.700000e+001	1
18	7.000000e+000	1	45	3.300000e+001	1
19	5.000000e-001	1	46	3.300000e+001	1
20	9.000000e+000	1	47	8.000000e+001	1
21	2.000000e+000	1	48	4.900000e+001	1
22	5.000000e-001	1	49	1.800000e+001	1
23	6.000000e+000	1	50	5.800000e+001	1
24	2.200000e+001	1	51	1.300000e+001	1
25	1.200000e+001	1	52	1.800000e+001	1
26	1.400000e+001	1	53	8.000000e+000	1
27	1.500000e+001	1			

fig 10: TBF data set-1 to be analysed and reliability calculation using different reliability models

The data shown above is a time between failure data format. The first column of the above is the failure number, the second is the days elapsed since last failure and the third column is the severity. Severity indicates the impact of the system's failure or parts thereof on the mission, the system's users and environment, or both.

The models used for the analysis of the above data are:

1. Little wood-Verrall Model

2. Geometric Model

3. Median-Weighted Linear Combination Model

4. Dynamically-Weighted Linear Combination Model

5. Unequally-Weighted Linear Combination Model

6. Musa Okumoto Model

7. Equally Weighted Linear Combination Model

8. NHPP Model

9. Musa Basic Model

10. Jelinski-Moranda Model

In this report the best three models are analyzed and compared namely, quadratic LV, LinearLV, and Geometric Models according to model ranking. The data was executed by all the above mentioned models.

Geometric Model:

Discussion: In the next step prediction column till the 26th failure is less than or equal to the observation selected as the end of the initial parameter estimation range, hence this column has a value "N/A". The predicted value of model estimates at 63rd fault is 79.35. The failure intensity at start of testing is 0.2305, at end it comes down to 0.0214. The predicted value of failure intensity at end next 10 faults is 0.0146.The predicted reliability at end next 10 faults is 0.757.The model estimate is 3.461 at start and at end of 53rd fault is 45.92. The predicted value of reliability at the start of testing is very small, 0.0011 and at the end it grows to be 0.66. Next step prediction for the end next 10 faults (54th to 63rd faults) is "N/A" because these faults are less than or equal to the observation selected as the end of the initial parameter estimation range.

Failure no.	Days since last failure	Next step Prediction	Model Estimates	Elapsed time T from test start	Est. reliability: 8.00000e+000 Dy	Est'd cumulative failures by T	Failure intensity at elapsed time T	Actuals-Estimates
1	2.10000e+001	N/A	3.46161e+000	2.10000e+001	1.64902e-001	5.53823e+000	2.30533e-001	1.75384e+001
2	1.00000e+000	N/A	3.63806e+000	2.20000e+001	1.64902e-001	5.76746e+000	2.27921e-001	-2.63806e+000
3	3.00000e-001	N/A	3.82351e+000	2.23000e+001	1.64902e-001	5.83572e+000	2.27149e-001	-3.52351e+000
4	3.00000e-001	N/A	4.01841e+000	2.26000e+001	1.64902e-001	5.90375e+000	2.26382e-001	-3.71841e+000
5	8.00000e+000	N/A	4.22324e+000	3.06000e+001	1.95575e-001	7.63785e+000	2.07682e-001	3.77676e+000
6	6.00000e+000	N/A	4.43851e+000	3.66000e+001	2.11683e-001	8.84687e+000	1.95566e-001	1.56149e+000
7	3.00000e-001	N/A	4.66475e+000	3.69000e+001	2.11683e-001	8.90545e+000	1.94998e-001	-4.36475e+000
8	3.00000e-001	N/A	4.90253e+000	3.72000e+001	2.11683e-001	8.96387e+000	1.94432e-001	-4.60253e+000
9	2.00000e+000	N/A	5.15243e+000	3.92000e+001	2.28240e-001	9.34902e+000	1.90744e-001	-3.15243e+000
10	1.00000e+000	N/A	5.41507e+000	4.02000e+001	2.28240e-001	9.53886e+000	1.88953e-001	-4.41507e+000
11	6.00000e+000	N/A	5.69109e+000	4.62000e+001	2.45194e-001	1.06418e+001	1.78871e-001	3.08908e-001
12	5.00000e-001	N/A	5.98119e+000	4.67000e+001	2.45194e-001	1.07310e+001	1.78079e-001	-5.48119e+000
13	7.00000e+000	N/A	6.28607e+000	5.37000e+001	2.62494e-001	1.19405e+001	1.67686e-001	7.13934e-001
14	1.00000e+000	N/A	6.60649e+000	5.47000e+001	2.80087e-001	1.21075e+001	1.66300e-001	-5.60649e+000
15	4.00000e+000	N/A	6.94324e+000	5.87000e+001	2.80087e-001	1.27619e+001	1.60976e-001	-2.94324e+000
16	7.00000e+000	N/A	7.29716e+000	6.57000e+001	2.97920e-001	1.38583e+001	1.52436e-001	-2.97163e-001
17	1.30000e+001	N/A	7.66912e+000	7.87000e+001	3.34100e-001	1.57483e+001	1.38765e-001	5.33088e+000
18	7.00000e+000	N/A	8.06004e+000	8.57000e+001	3.52345e-001	1.66970e+001	1.32372e-001	-1.06004e+000
19	5.00000e-001	N/A	8.47089e+000	8.62000e+001	3.52345e-001	1.67630e+001	1.31938e-001	-7.97089e+000
20	9.00000e+000	N/A	8.90268e+000	9.52000e+001	3.70630e-001	1.79167e+001	1.24583e-001	9.73206e-002
21	2.00000e+000	N/A	9.35648e+000	9.72000e+001	3.88909e-001	1.81644e+001	1.23059e-001	-7.35648e+000
22	5.00000e-001	N/A	9.83341e+000	9.77000e+001	3.88909e-001	1.82258e+001	1.22684e-001	-9.33341e+000
23	6.00000e+000	N/A	1.03347e+001	1.03700e+002	3.88909e-001	1.89488e+001	1.18352e-001	-4.33465e+000
24	2.20000e+001	N/A	1.08614e+001	1.25700e+002	4.43280e-001	2.13973e+001	1.04788e-001	1.11386e+001
25	1.20000e+001	N/A	1.14151e+001	1.37700e+002	4.61121e-001	2.26170e+001	9.86221e-002	5.84914e-001
26	1.40000e+001	N/A	1.19970e+001	1.51700e+002	4.78763e-001	2.39524e+001	9.22871e-002	2.00305e+000
27	1.50000e+001	9.45175e+000	1.26085e+001	1.66700e+002	5.13330e-001	2.52911e+001	8.63446e-002	2.39153e+000
28	1.50000e+001	1.04185e+001	1.32512e+001	1.81700e+002	5.30204e-001	2.65463e+001	8.11211e-002	1.74883e+000
29	1.60000e+001	1.14372e+001	1.39266e+001	1.97700e+002	5.46774e-001	2.78041e+001	7.62037e-002	2.07337e+000
30	2.20000e+001	1.30482e+001	1.46365e+001	2.19700e+002	5.78928e-001	2.94143e+001	7.03409e-002	7.36349e+000
31	2.20000e+001	1.45739e+001	1.53826e+001	2.41700e+002	5.94480e-001	3.09052e+001	6.53157e-002	6.61742e+000
32	2.30000e+001	1.61319e+001	1.61667e+001	2.64700e+002	6.24475e-001	3.23540e+001	6.07765e-002	6.83331e+000
33	2.70000e+001	1.80242e+001	1.69908e+001	2.91700e+002	6.38900e-001	3.39314e+001	5.61921e-002	1.00092e+001
34	2.80000e+001	1.99437e+001	1.78568e+001	3.19700e+002	6.66574e-001	3.54463e+001	5.21155e-002	1.01432e+001
35	2.80000e+001	2.18000e+001	1.87670e+001	3.47700e+002	6.79817e-001	3.68551e+001	4.85903e-002	9.23295e+000
36	2.80000e+001	2.36003e+001	1.97237e+001	3.75700e+002	7.05109e-001	3.81715e+001	4.55119e-002	8.27633e+000
37	2.90000e+001	2.54404e+001	2.07290e+001	4.04700e+002	7.17160e-001	3.94499e+001	4.27093e-002	8.27095e+000
38	7.00000e+000	2.52242e+001	2.17857e+001	4.11700e+002	7.17160e-001	3.97467e+001	4.20838e-002	-1.47857e+001
39	1.00000e+001	2.52229e+001	2.28962e+001	4.21700e+002	7.28817e-001	4.01632e+001	4.12214e-002	-1.28962e+001
40	1.00000e+001	2.51681e+001	2.40633e+001	4.31700e+002	7.28817e-001	4.05712e+001	4.03935e-002	-1.40633e+001
41	1.80000e+001	2.58022e+001	2.52898e+001	4.49700e+002	7.40085e-001	4.12854e+001	3.89843e-002	-7.28984e+000
42	4.20000e+001	2.85534e+001	2.65789e+001	4.91700e+002	7.50969e-001	4.28596e+001	3.60498e-002	1.54211e+001
43	4.40000e+001	3.13840e+001	2.79338e+001	5.35700e+002	7.71603e-001	4.43863e+001	3.34147e-002	1.60662e+001
44	2.70000e+001	3.26973e+001	2.93576e+001	5.62700e+002	7.81368e-001	4.52689e+001	3.19802e-002	-2.35764e+000
45	3.30000e+001	3.44665e+001	3.08541e+001	5.95700e+002	7.90774e-001	4.62974e+001	3.03859e-002	2.14590e+000
46	3.30000e+001	3.61845e+001	3.24268e+001	6.28700e+002	7.99828e-001	4.72760e+001	2.89430e-002	5.73166e-001
47	8.00000e+001	4.16210e+001	3.40797e+001	7.08700e+002	8.16917e-001	4.94676e+001	2.59552e-002	4.59203e+001
48	4.90000e+001	4.45268e+001	3.58169e+001	7.57700e+002	8.24969e-001	5.07008e+001	2.44116e-002	1.31831e+001
49	1.80000e+001	4.49958e+001	3.76426e+001	7.75700e+002	8.32704e-001	5.11355e+001	2.38897e-002	-1.96426e+001
50	5.80000e+001	4.84659e+001	3.95614e+001	8.33700e+002	8.40131e-001	5.24754e+001	2.23501e-002	1.84386e+001
51	1.30000e+001	4.84846e+001	4.15779e+001	8.46700e+002	8.40131e-001	5.27639e+001	2.20318e-002	-2.85779e+001
52	1.80000e+001	4.87975e+001	4.36973e+001	8.64700e+002	8.47259e-001	5.31566e+001	2.16058e-002	-2.56973e+001
53	8.00000e+000	4.82656e+001	4.59247e+001	8.72700e+002	8.47259e-001	5.33287e+001	2.14218e-002	-3.79247e+001
54	N/A	N/A	5.07259e+001	9.16335e+002	8.54097e-001	5.42424e+001	2.04705e-002	N/A
55	N/A	N/A	5.33116e+001	9.59970e+002	8.60655e-001	5.51164e+001	1.96000e-002	N/A
56	N/A	N/A	5.60290e+001	1.00361e+003	8.60655e-001	5.59539e+001	1.88006e-002	N/A
57	N/A	N/A	5.88850e+001	1.04724e+003	8.66942e-001	5.67580e+001	1.80639e-002	N/A
58	N/A	N/A	6.18866e+001	1.09088e+003	8.72967e-001	5.75312e+001	1.73827e-002	N/A
59	N/A	N/A	6.50411e+001	1.13451e+003	8.78738e-001	5.82757e+001	1.67510e-002	N/A
60	N/A	N/A	6.83565e+001	1.17815e+003	8.78738e-001	5.89937e+001	1.61636e-002	N/A
61	N/A	N/A	7.18409e+001	1.22178e+003	8.84265e-001	5.96869e+001	1.56161e-002	N/A
62	N/A	N/A	7.55028e+001	1.26542e+003	8.89556e-001	6.03570e+001	1.51044e-002	N/A
63	N/A	N/A	7.93514e+001	1.30905e+003	8.94619e-001	6.10055e+001	1.46251e-002	N/A

fig 11: Geometric Model result for TBF data set 1

Linear LV Model:

Discussion: In the next step prediction column till the 26th failure is less than or equal to the observation selected as the end of the initial parameter estimation range, hence this column has a value "N/A". The predicted reliability at end next 10 faults is 0.554.The failure intensity at start of testing is 0.185, at end it comes down to 0.035. The predicted value of failure intensity at end next 10 faults is 0.0294. The predicted value of model estimates at 63rd fault is 30.836. The model estimate is 3.712 at start and at end of 53rd fault is 26.46. The predicted value of reliability at the start of testing is very small, 0.018 and at the end it grows

to be 0.48.

Failure no.	Days since last failure	Next step Prediction	Model Estimates	Elapsed time T from test start	Est. reliability: 8.00000e+000 Dy	Est'd cumulative failures by T	Failure intensity at elapsed time T	Actuals-Estimates
1	2.10000e+001	N/A	3.71266e+000	2.10000e+001	2.03512e-001	4.84465e+000	1.85371e-001	1.72873e+001
2	1.00000e+000	N/A	4.15013e+000	2.20000e+001	2.31021e-001	5.02865e+000	1.82645e-001	-3.15013e+000
3	3.00000e-001	N/A	4.58761e+000	2.23000e+001	2.31021e-001	5.08333e+000	1.81851e-001	-4.28761e+000
4	3.00000e-001	N/A	5.02508e+000	2.26000e+001	2.31021e-001	5.13777e+000	1.81067e-001	-4.72508e+000
5	8.00000e+000	N/A	5.46256e+000	3.06000e+001	2.57704e-001	6.51162e+000	1.63296e-001	2.53744e+000
6	6.00000e+000	N/A	5.90004e+000	3.66000e+001	2.83163e-001	7.45935e+000	1.52941e-001	9.99641e-002
7	3.00000e-001	N/A	6.33751e+000	3.69000e+001	2.83163e-001	7.50517e+000	1.52474e-001	-6.03751e+000
8	3.00000e-001	N/A	6.77499e+000	3.72000e+001	2.83163e-001	7.55084e+000	1.52011e-001	-6.47499e+000
9	2.00000e+000	N/A	7.21246e+000	3.92000e+001	2.83163e-001	7.85187e+000	1.49027e-001	-5.21246e+000
10	1.00000e+000	N/A	7.64994e+000	4.02000e+001	3.07022e-001	8.00018e+000	1.47600e-001	-6.64994e+000
11	6.00000e+000	N/A	8.08741e+000	4.62000e+001	3.07022e-001	8.86185e+000	1.39821e-001	-2.08741e+000
12	5.00000e-001	N/A	8.52489e+000	4.67000e+001	3.07022e-001	8.93162e+000	1.39226e-001	-8.02489e+000
13	7.00000e+000	N/A	8.96236e+000	5.37000e+001	3.29639e-001	9.87892e+000	1.31631e-001	-1.96236e+000
14	1.00000e+000	N/A	9.39984e+000	5.47000e+001	3.51775e-001	1.00101e+001	1.30645e-001	-8.39984e+000
15	4.00000e+000	N/A	9.83731e+000	5.87000e+001	3.51775e-001	1.05251e+001	1.26909e-001	-5.83731e+000
16	7.00000e+000	N/A	1.02748e+001	6.57000e+001	3.72048e-001	1.13926e+001	1.21078e-001	-3.27479e+000
17	1.30000e+001	N/A	1.07123e+001	7.87000e+001	3.91233e-001	1.29060e+001	1.12092e-001	2.28774e+000
18	7.00000e+000	N/A	1.11497e+001	8.57000e+001	4.09392e-001	1.36762e+001	1.08013e-001	-4.14974e+000
19	5.00000e-001	N/A	1.15872e+001	8.62000e+001	4.09392e-001	1.37301e+001	1.07738e-001	-1.10872e+001
20	9.00000e+000	N/A	1.20247e+001	9.52000e+001	4.26590e-001	1.46786e+001	1.03128e-001	-3.02469e+000
21	2.00000e+000	N/A	1.24622e+001	9.72000e+001	4.26590e-001	1.48839e+001	1.02181e-001	-1.04622e+001
22	5.00000e-001	N/A	1.28996e+001	9.77000e+001	4.26590e-001	1.49349e+001	1.01949e-001	-1.23996e+001
23	6.00000e+000	N/A	1.33371e+001	1.03700e+002	4.43589e-001	1.55385e+001	9.92762e-002	-7.33712e+000
24	2.20000e+001	N/A	1.37746e+001	1.25700e+002	4.73694e-001	1.76279e+001	9.10169e-002	8.22541e+000
25	1.20000e+001	N/A	1.42121e+001	1.37700e+002	4.88299e-001	1.86974e+001	8.72994e-002	-2.21207e+000
26	1.40000e+001	N/A	1.46495e+001	1.51700e+002	5.01526e-001	1.98924e+001	8.34891e-002	-6.49541e-001
27	1.50000e+001	9.65348e+000	1.50870e+001	1.66700e+002	5.26093e-001	2.11174e+001	7.99136e-002	-8.70161e-002
28	1.50000e+001	1.00233e+001	1.55245e+001	1.81700e+002	5.37515e-001	2.22920e+001	7.67613e-002	-5.24492e-001
29	1.60000e+001	1.03958e+001	1.59620e+001	1.97700e+002	5.48412e-001	2.34959e+001	7.37786e-002	3.80325e-002
30	2.20000e+001	1.12267e+001	1.63994e+001	2.19700e+002	5.70013e-001	2.50787e+001	7.01927e-002	5.60056e+000
31	2.20000e+001	1.18990e+001	1.68369e+001	2.41700e+002	5.79507e-001	2.65880e+001	6.70835e-002	5.16308e+000
32	2.30000e+001	1.25263e+001	1.72744e+001	2.64700e+002	5.97302e-001	2.80976e+001	6.42377e-002	5.72561e+000
33	2.70000e+001	1.33600e+001	1.77119e+001	2.91700e+002	6.05649e-001	2.97918e+001	6.13183e-002	9.28813e+000
34	2.80000e+001	1.41230e+001	1.81493e+001	3.19700e+002	6.21351e-001	3.14709e+001	5.86753e-002	9.85066e+000
35	2.80000e+001	1.47457e+001	1.85868e+001	3.47700e+002	6.36972e-001	3.30807e+001	5.63470e-002	9.41318e+000
36	2.80000e+001	1.54725e+001	1.90243e+001	3.75700e+002	6.43796e-001	3.46289e+001	5.42756e-002	8.97571e+000
37	2.90000e+001	1.63269e+001	1.94618e+001	4.04700e+002	6.56698e-001	3.61746e+001	5.23541e-002	9.53823e+000
38	7.00000e+000	1.63008e+001	1.98992e+001	4.11700e+002	6.56698e-001	3.65396e+001	5.19201e-002	-1.28992e+001
39	1.00000e+001	1.63850e+001	2.03367e+001	4.21700e+002	6.62802e-001	3.70558e+001	5.13184e-002	-1.03367e+001
40	1.00000e+001	1.64630e+001	2.07742e+001	4.31700e+002	6.62802e-001	3.75661e+001	5.07372e-002	-1.07742e+001
41	1.80000e+001	1.68305e+001	2.12117e+001	4.49700e+002	6.68691e-001	3.84703e+001	4.97389e-002	-3.21167e+000
42	4.20000e+001	1.80322e+001	2.16491e+001	4.91700e+002	6.79866e-001	4.05140e+001	4.76212e-002	2.03509e+001
43	4.40000e+001	1.92406e+001	2.20866e+001	5.35700e+002	6.91299e-001	4.25656e+001	4.56692e-002	2.19134e+001
44	2.70000e+001	1.98479e+001	2.25241e+001	5.62700e+002	6.96249e-001	4.37839e+001	4.45840e-002	4.47590e+000
45	3.30000e+001	2.06230e+001	2.29616e+001	5.95700e+002	7.05681e-001	4.52347e+001	4.33571e-002	1.00384e+001
46	3.30000e+001	2.13717e+001	2.33990e+001	6.28700e+002	7.10177e-001	4.66467e+001	4.22263e-002	9.60095e+000
47	8.00000e+001	2.34648e+001	2.38365e+001	7.08700e+002	7.23775e-001	4.99256e+001	3.98146e-002	5.61635e+001
48	4.90000e+001	2.45967e+001	2.42740e+001	7.57700e+002	7.30704e-001	5.18446e+001	3.85269e-002	2.47260e+001
49	1.80000e+001	2.48490e+001	2.47115e+001	7.75700e+002	7.35340e-001	5.25341e+001	3.80843e-002	-6.71147e+000
50	5.80000e+001	2.61600e+001	2.51489e+001	8.33700e+002	7.42514e-001	5.47038e+001	3.67556e-002	3.28511e+001
51	1.30000e+001	2.62644e+001	2.55864e+001	8.46700e+002	7.46807e-001	5.51799e+001	3.64764e-002	-1.25864e+001
52	1.80000e+001	2.64927e+001	2.60239e+001	8.64700e+002	7.46807e-001	5.58331e+001	3.61001e-002	-8.02390e+000
53	8.00000e+000	2.64614e+001	2.64614e+001	8.72700e+002	7.49300e-001	5.61212e+001	3.59365e-002	-1.84614e+001
54	N/A	N/A	2.68988e+001	9.16335e+002	7.53391e-001	5.76705e+001	3.50820e-002	N/A
55	N/A	N/A	2.73363e+001	9.59970e+002	7.59632e-001	5.91838e+001	3.42857e-002	N/A
56	N/A	N/A	2.77738e+001	1.00361e+003	7.61825e-001	6.06635e+001	3.35413e-002	N/A
57	N/A	N/A	2.82113e+001	1.04724e+003	7.69196e-001	6.21118e+001	3.28434e-002	N/A
58	N/A	N/A	2.86488e+001	1.09088e+003	7.71185e-001	6.35305e+001	3.21872e-002	N/A
59	N/A	N/A	2.90862e+001	1.13451e+003	7.74670e-001	6.49215e+001	3.15689e-002	N/A
60	N/A	N/A	2.95237e+001	1.17815e+003	7.79882e-001	6.62862e+001	3.09849e-002	N/A
61	N/A	N/A	2.99612e+001	1.22178e+003	7.81646e-001	6.76261e+001	3.04322e-002	N/A
62	N/A	N/A	3.03987e+001	1.26542e+003	7.84851e-001	6.89425e+001	2.99080e-002	N/A
63	N/A	N/A	3.08361e+001	1.30905e+003	7.89592e-001	7.02367e+001	2.94100e-002	N/A

fig 12: Linear LV Model result for TBF data set 1

Quadratic Model:

Discussion: In the next step prediction column till the 26th test fault is less than or equal to the observation selected as the end of the initial parameter estimation range, hence this column has a value "N/A". The model estimate is 3.657 at start and at end of 53rd fault is 40.311. The predicted value of reliability at the start of testing is very small, 0.0064 and at the end it grows to be 0.609.The failure intensity at start of testing is 0.0247, at end it comes down to 0.002015. The predicted value of failure intensity at end next 10 faults is 0.018. The predicted value of model estimates at 63rd fault is 55.454. The predicted reliability at end next

10 faults is 0.689. Next step prediction for the end next 10 fault(54th to 63rd faults) is “N/A” because these faults are less than or equal to the observation selected as the end of the initial parameter estimation range.

Failure no.	Days since last failure	Next step Prediction	Model Estimates	Elapsed time T from test start	Est. reliability: 8.00000e+000 Dy	Est'd cumulative failures by T	Failure intensity at elapsed time T	Actuals-Estimates
1	2.10000e+001	N/A	3.65712e+000	2.10000e+001	1.33030e-001	5.55784e+000	2.47079e-001	1.73429e+001
2	1.00000e+000	N/A	3.69628e+000	2.20000e+001	1.33030e-001	5.80382e+000	2.44872e-001	-2.69628e+000
3	3.00000e-001	N/A	3.76155e+000	2.23000e+001	1.33030e-001	5.87718e+000	2.44203e-001	-3.46155e+000
4	3.00000e-001	N/A	3.85293e+000	2.26000e+001	1.33030e-001	5.95034e+000	2.43531e-001	-3.55293e+000
5	8.00000e+000	N/A	3.97041e+000	3.06000e+001	1.53686e-001	7.82513e+000	2.25054e-001	4.02959e+000
6	6.00000e+000	N/A	4.11400e+000	3.66000e+001	1.82417e-001	9.13390e+000	2.11278e-001	1.88600e+000
7	3.00000e-001	N/A	4.28370e+000	3.69000e+001	1.82417e-001	9.19718e+000	2.10604e-001	-3.98370e+000
8	3.00000e-001	N/A	4.47950e+000	3.72000e+001	1.82417e-001	9.26026e+000	2.09932e-001	-4.17950e+000
9	2.00000e+000	N/A	4.70142e+000	3.92000e+001	1.82417e-001	9.67568e+000	2.05502e-001	-2.70142e+000
10	1.00000e+000	N/A	4.94944e+000	4.02000e+001	1.82417e-001	9.88009e+000	2.03321e-001	-3.94944e+000
11	6.00000e+000	N/A	5.22356e+000	4.62000e+001	2.16155e-001	1.10619e+001	1.90789e-001	7.76436e-001
12	5.00000e-001	N/A	5.52380e+000	4.67000e+001	2.16155e-001	1.11571e+001	1.89789e-001	-5.02380e+000
13	7.00000e+000	N/A	5.85014e+000	5.37000e+001	2.34144e-001	1.24385e+001	1.76564e-001	1.14986e+000
14	1.00000e+000	N/A	6.20259e+000	5.47000e+001	2.34144e-001	1.26142e+001	1.74790e-001	-5.20259e+000
15	4.00000e+000	N/A	6.58115e+000	5.87000e+001	2.53504e-001	1.32996e+001	1.67983e-001	-2.58115e+000
16	7.00000e+000	N/A	6.98581e+000	6.57000e+001	2.74075e-001	1.44367e+001	1.57117e-001	1.41892e-002
17	1.30000e+001	N/A	7.41658e+000	7.87000e+001	3.18166e-001	1.63643e+001	1.40062e-001	5.58342e+000
18	7.00000e+000	N/A	7.87346e+000	8.57000e+001	3.41338e-001	1.73171e+001	1.32299e-001	-8.73461e-001
19	5.00000e-001	N/A	8.35645e+000	8.62000e+001	3.41338e-001	1.73831e+001	1.31778e-001	-7.85645e+000
20	9.00000e+000	N/A	8.86554e+000	9.52000e+001	3.62148e-001	1.85290e+001	1.23066e-001	1.34459e-001
21	2.00000e+000	N/A	9.40074e+000	9.72000e+001	3.62148e-001	1.87733e+001	1.21290e-001	-7.40074e+000
22	5.00000e-001	N/A	9.96205e+000	9.77000e+001	3.62148e-001	1.88338e+001	1.20855e-001	-9.46205e+000
23	6.00000e+000	N/A	1.05495e+001	1.03700e+002	3.86193e-001	1.95438e+001	1.15874e-001	-4.54947e+000
24	2.20000e+001	N/A	1.11630e+001	1.25700e+002	4.29066e-001	2.19195e+001	1.00848e-001	1.08370e+001
25	1.20000e+001	N/A	1.18026e+001	1.37700e+002	4.66401e-001	2.30895e+001	9.43104e-002	1.97380e-001
26	1.40000e+001	N/A	1.24684e+001	1.51700e+002	4.90437e-001	2.43629e+001	8.77803e-002	1.53164e+000
27	1.50000e+001	1.26774e+001	1.31602e+001	1.66700e+002	5.08764e-001	2.56337e+001	8.18232e-002	1.83980e+000
28	1.50000e+001	1.32883e+001	1.38782e+001	1.81700e+002	5.26889e-001	2.68218e+001	7.67164e-002	1.12185e+000
29	1.60000e+001	1.39042e+001	1.46222e+001	1.97700e+002	5.62365e-001	2.80108e+001	7.20148e-002	1.37778e+000
30	2.20000e+001	1.50675e+001	1.53924e+001	2.19700e+002	5.79651e-001	2.95330e+001	6.65360e-002	6.60762e+000
31	2.20000e+001	1.60576e+001	1.61887e+001	2.41700e+002	5.96602e-001	3.09448e+001	6.19423e-002	5.81134e+000
32	2.30000e+001	1.70065e+001	1.70110e+001	2.64700e+002	6.20249e-001	3.23214e+001	5.78674e-002	5.98896e+000
33	2.70000e+001	1.81907e+001	1.78595e+001	2.91700e+002	6.40787e-001	3.38276e+001	5.38170e-002	9.14047e+000
34	2.80000e+001	1.93118e+001	1.87341e+001	3.19700e+002	6.63063e-001	3.52834e+001	5.02643e-002	9.26587e+000
35	2.80000e+001	2.02986e+001	1.96348e+001	3.47700e+002	6.73959e-001	3.66472e+001	4.72247e-002	8.36517e+000
36	2.80000e+001	2.11935e+001	2.05616e+001	3.75700e+002	6.92685e-001	3.79318e+001	4.45912e-002	7.43836e+000
37	2.90000e+001	2.25373e+001	2.15146e+001	4.04700e+002	7.13133e-001	3.91896e+001	4.22079e-002	7.48544e+000
38	7.00000e+000	2.27276e+001	2.24936e+001	4.11700e+002	7.13133e-001	3.94832e+001	4.16775e-002	-1.54936e+001
39	1.00000e+001	2.30476e+001	2.34987e+001	4.21700e+002	7.13133e-001	3.98963e+001	4.09470e-002	-1.34987e+001
40	1.00000e+001	2.33456e+001	2.45300e+001	4.31700e+002	7.23089e-001	4.03022e+001	4.02467e-002	-1.45300e+001
41	1.80000e+001	2.40248e+001	2.55873e+001	4.49700e+002	7.32863e-001	4.10159e+001	3.90560e-002	-7.58731e+000
42	4.20000e+001	2.58413e+001	2.66708e+001	4.91700e+002	7.42453e-001	4.26029e+001	3.65811e-002	1.53292e+001
43	4.40000e+001	2.76841e+001	2.77803e+001	5.35700e+002	7.61079e-001	4.41623e+001	3.43609e-002	1.62197e+001
44	2.70000e+001	2.87365e+001	2.89160e+001	5.62700e+002	7.63741e-001	4.50736e+001	3.31518e-002	-1.91600e+000
45	3.30000e+001	3.00215e+001	3.00778e+001	5.95700e+002	7.72766e-001	4.61450e+001	3.18065e-002	2.92223e+000
46	3.30000e+001	3.12808e+001	3.12657e+001	6.28700e+002	7.87643e-001	4.71742e+001	3.05868e-002	1.73434e+000
47	8.00000e+001	3.43474e+001	3.24797e+001	7.08700e+002	7.98727e-001	4.95161e+001	2.80507e-002	4.75203e+001
48	4.90000e+001	3.61640e+001	3.37198e+001	7.57700e+002	8.07019e-001	5.08577e+001	2.67326e-002	1.52802e+001
49	1.80000e+001	3.68312e+001	3.49860e+001	7.75700e+002	8.09732e-001	5.13349e+001	2.62853e-002	-1.69860e+001
50	5.80000e+001	3.88988e+001	3.62783e+001	8.33700e+002	8.17810e-001	5.28202e+001	2.49604e-002	2.17217e+001
51	1.30000e+001	3.93873e+001	3.75967e+001	8.46700e+002	8.20608e-001	5.31429e+001	2.46854e-002	-2.45967e+001
52	1.80000e+001	4.00285e+001	3.89412e+001	8.64700e+002	8.20608e-001	5.35838e+001	2.43166e-002	-2.09412e+001
53	8.00000e+000	4.03119e+001	4.03119e+001	8.72700e+002	8.20608e-001	5.37778e+001	2.41569e-002	-3.23119e+001
54	N/A	N/A	4.17086e+001	9.16335e+002	8.28466e-001	5.48136e+001	2.33295e-002	N/A
55	N/A	N/A	4.31315e+001	9.59970e+002	8.31321e-001	5.58147e+001	2.25683e-002	N/A
56	N/A	N/A	4.45804e+001	1.00361e+003	8.38956e-001	5.67840e+001	2.18653e-002	N/A
57	N/A	N/A	4.60555e+001	1.04724e+003	8.41843e-001	5.77236e+001	2.12138e-002	N/A
58	N/A	N/A	4.75567e+001	1.09088e+003	8.49255e-001	5.86360e+001	2.06079e-002	N/A
59	N/A	N/A	4.90839e+001	1.13451e+003	8.52154e-001	5.95227e+001	2.00431e-002	N/A
60	N/A	N/A	5.06373e+001	1.17815e+003	8.50902e-001	6.03856e+001	1.95148e-002	N/A
61	N/A	N/A	5.22168e+001	1.22178e+003	8.54025e-001	6.12263e+001	1.90194e-002	N/A
62	N/A	N/A	5.38224e+001	1.26542e+003	8.61178e-001	6.20460e+001	1.85539e-002	N/A
63	N/A	N/A	5.54541e+001	1.30905e+003	8.61178e-001	6.28458e+001	1.81157e-002	N/A

fig 13: Quadratic LV Model result for TBF data set 1

Model Comparison through Graphs:

From the obtained result we compare the top three model predictions:

1. Quadratic LV Model

2. Linear LV Model

3. Geometric Model

Cumulative Density function:

As it can be seen in the graph, the predicted values are near to the raw data points. Predicted value of linear LV model is lower than the other two models till 650 days. After that the linear LV predicted values are higher than the other two curves. Slope of curve by linear LV is higher than the other curves.

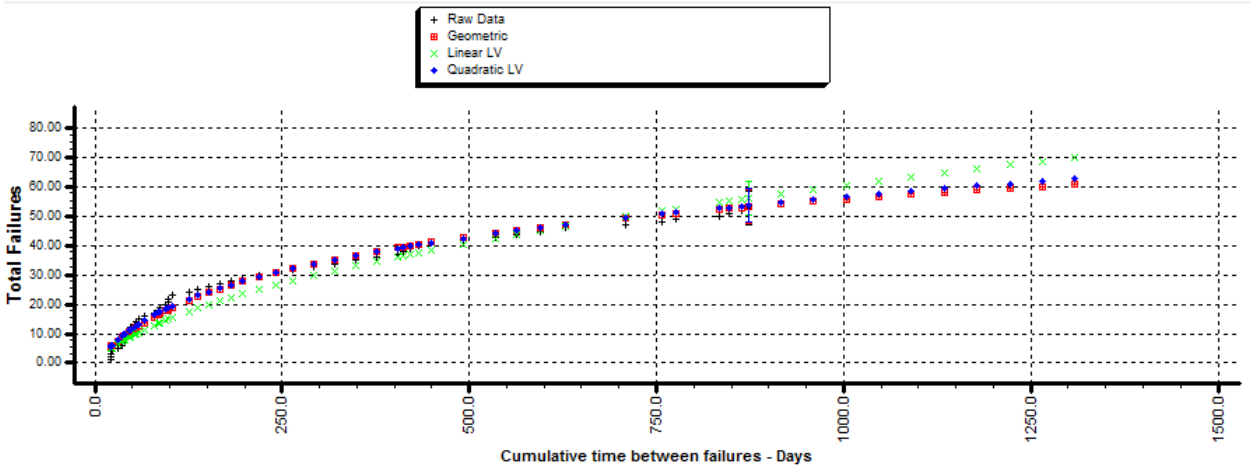

fig 14: cumulative density function vs. time(TBF data set-1)

Failure intensity:

Predicted values do not trace the raw data points at the start of the testing. After 100 days of testing, all the three models have overlapping predictions and almost trace the raw data point. Prediction shows that the failure rate is quite low after 875 days.

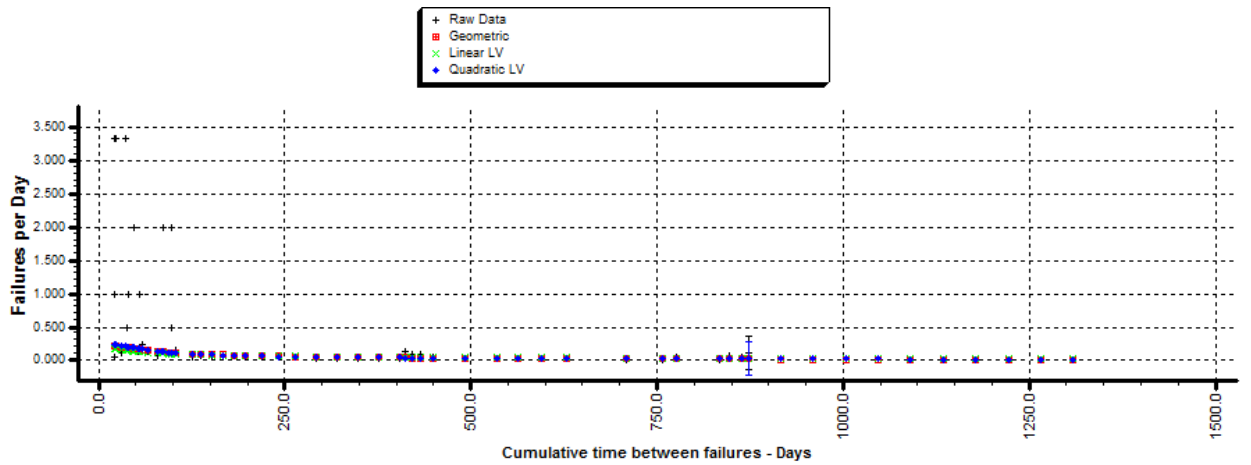

fig 15: Failure intensity function vs. time(TBF data set-1)

Time between failure:

After 26th fault, the actual value of time between consecutive faults is higher than the predicted value. Initially during testing, predicted values are higher than the actual values. Slope of geometric model curves is higher than the other two models. Linear LV model traces a straight line.

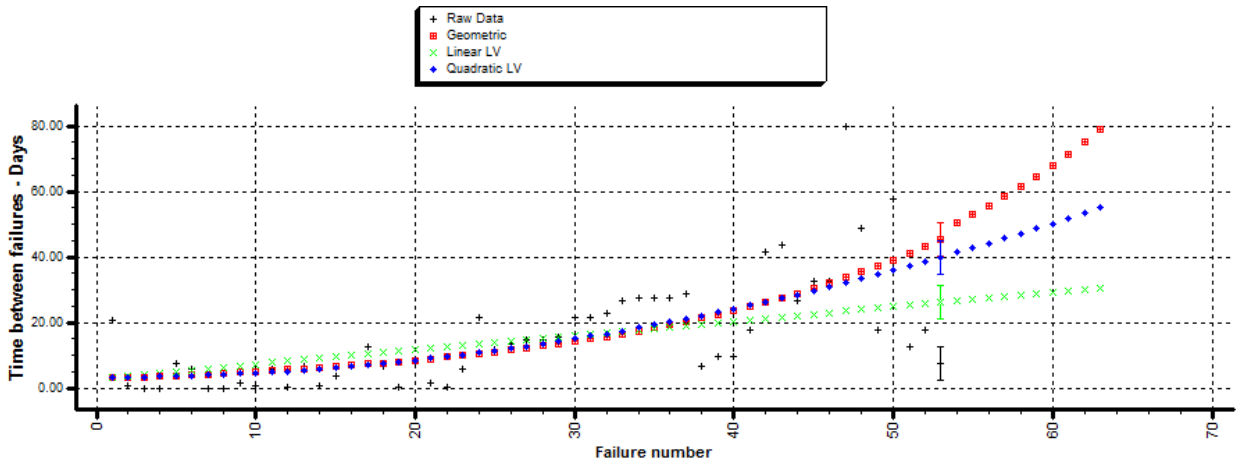

fig 16: Time between failure vs. time (TBF data set-1)

Reliability:

During initial period of testing, Linear LV model values are higher than other two. There after till 450 days, the prediction by quadratic LV and geometric is almost equal and very much higher than linear LV model. Beyond this point, between geometric and quadratic element, we see the graphs bifurcate with geometric model predicting higher values at each point.

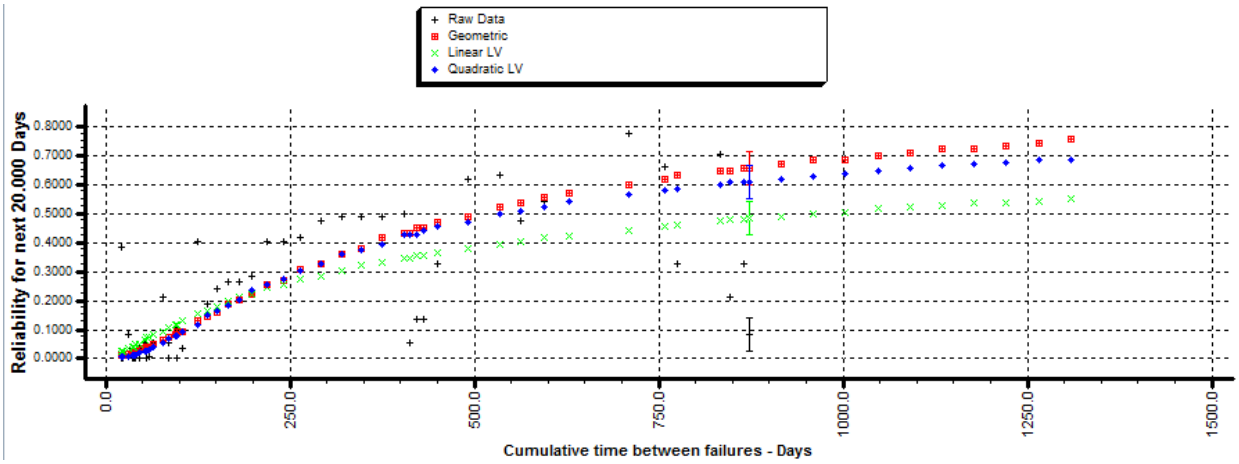

fig 17: Reliability vs. time (TBF data set-1)

Model bias:

All the three models are biased, but linear LV is most biased , followed by quadratic LV and then geometric.

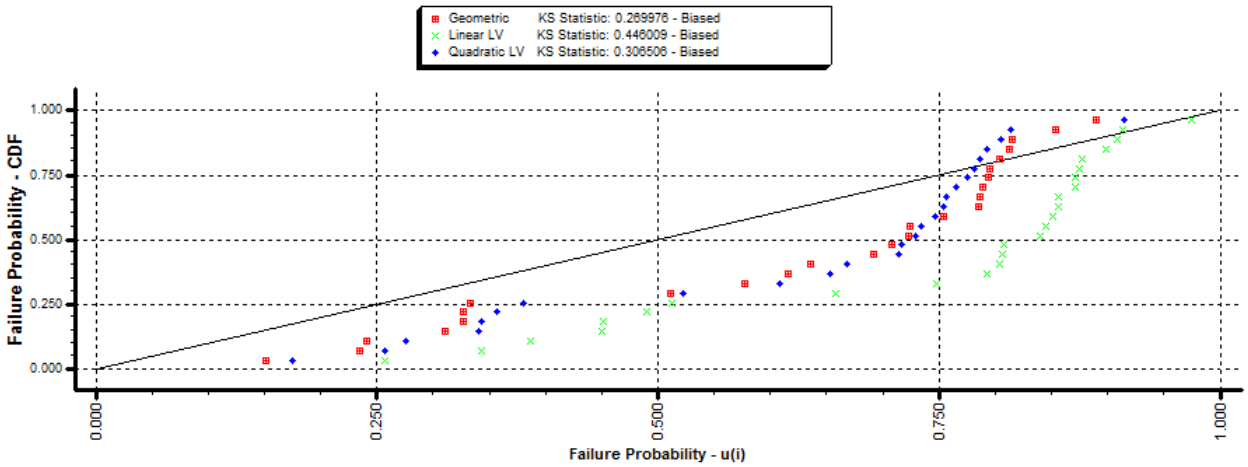

fig 18: Model bias (TBF data set-1)

TBF Data-2:

Error No.	Days Since Last Failure	Severity
1	2.000000e+001	1
2	1.000000e+000	1
3	5.000000e+000	1
4	1.200000e+001	1
5	5.000000e-001	1
6	1.400000e+001	1
7	1.500000e+001	1
8	9.000000e+000	1
9	8.000000e+000	1
10	5.200000e+001	1
11	3.900000e+001	1
12	3.440000e+002	1
13	5.400000e+001	1
14	7.000000e+000	1
15	4.100000e+001	1

fig 19: TBF data set-2 to be analysed and reliability calculation using different reliability models

The data shown above is a time between failure data format. The first column of the above is the failure number, the second is the days elapsed since last failure and the third column is the severity. Severity indicates the impact of the system's failure or parts thereof on the mission, the system's users and environment, or both.

The models used for the analysis of the above data are:

1. Little wood-Verrall Model

2. Geometric Model

3. Median-Weighted Linear Combination Model

4. Dynamically-Weighted Linear Combination Model

5. Unequally-Weighted Linear Combination Model

6. Musa Okumoto Model

7. Equally Weighted Linear Combination Model

8. NHPP Model

9. Musa Basic Model

10. Jelinski-Moranda Model

The above data could only be executed by the Quadratic Littlewood-Verrall Model

Quadratic LV Model:

Discussion:In the next step prediction column till the 7^{th} failure is less than or equal to the observation selected as the end of the initial parameter estimation range, hence this column has a value “N/A”. The reliability starts with 0.0433 and grows to be 0.625 at the end of 15^{th} fault. The predicted value of model estimates at the 25^{th} fault is 228.587. The failure intensity for the start of the testing is 0.08499 and at the end it comes down to 0.00745. The predicted value of model estimate is 8.247 in the beginning and at the end of the 15^{th} fault is 87.343.The predicted value of reliability at end next 10 fault is 0.6989. The predicted value of failure intensity at end next 10 fault is 0.005618.

Failure no.	Days since last failure	Next step Prediction	Model Estimates	Elapsed time T from test start	Est. reliability: 4.10000e+001 Dy	Est'd cumulative failures by T	Failure intensity at elapsed time T	Actuals-Estimates
1	2.00000e+001	N/A	8.24723e+000	2.00000e+001	4.33825e-002	3.31133e+000	8.49912e-002	1.17528e+001
2	1.00000e+000	N/A	9.30656e+000	2.10000e+001	4.33825e-002	3.43893e+000	8.28495e-002	-8.30656e+000
3	5.00000e+000	N/A	1.10721e+001	2.60000e+001	6.30530e-002	4.03151e+000	7.33501e-002	-6.07210e+000
4	1.20000e+001	N/A	1.35439e+001	3.80000e+001	9.04680e-002	5.21068e+000	5.72035e-002	-1.54387e+000
5	5.00000e-001	N/A	1.67218e+001	3.85000e+001	9.04680e-002	5.25397e+000	5.66848e-002	-1.62218e+001
6	1.40000e+001	N/A	2.06060e+001	5.25000e+001	1.25370e-001	6.33055e+000	4.53612e-002	-6.60604e+000
7	1.50000e+001	N/A	2.51965e+001	6.75000e+001	1.66567e-001	7.27111e+000	3.76469e-002	-1.01965e+001
8	9.00000e+000	1.08099e+001	3.04931e+001	7.65000e+001	1.66567e-001	7.76248e+000	3.42805e-002	-2.14931e+001
9	8.00000e+000	9.87853e+000	3.64959e+001	8.45000e+001	2.12272e-001	8.16410e+000	3.18170e-002	-2.84959e+001
10	5.20000e+001	2.18606e+001	4.32050e+001	1.36500e+002	3.09533e-001	1.02479e+001	2.22334e-002	8.79498e+000
11	3.90000e+001	2.76187e+001	5.06203e+001	1.75500e+002	3.57842e-001	1.14464e+001	1.84643e-002	-1.16203e+001
12	3.44000e+002	7.39696e+001	5.87418e+001	5.19500e+002	5.95552e-001	1.76795e+001	8.45565e-003	2.85258e+002
13	5.40000e+001	8.15065e+001	6.75695e+001	5.73500e+002	6.25078e-001	1.83498e+001	7.88695e-003	-1.35695e+001
14	7.00000e+000	8.25030e+001	7.71035e+001	5.80500e+002	6.25078e-001	1.84335e+001	7.81995e-003	-7.01035e+001
15	4.10000e+001	8.73436e+001	8.73436e+001	6.21500e+002	6.25078e-001	1.89094e+001	7.45416e-003	-4.63436e+001
16	N/A	N/A	9.82900e+001	6.52575e+002	6.52017e-001	1.92556e+001	7.20361e-003	N/A
17	N/A	N/A	1.09943e+002	6.83650e+002	6.52017e-001	1.95906e+001	6.97282e-003	N/A
18	N/A	N/A	1.22301e+002	7.14725e+002	6.52017e-001	1.99149e+001	6.75958e-003	N/A
19	N/A	N/A	1.35366e+002	7.45800e+002	6.76573e-001	2.02296e+001	6.56174e-003	N/A
20	N/A	N/A	1.49138e+002	7.76875e+002	6.76573e-001	2.05352e+001	6.37761e-003	N/A
21	N/A	N/A	1.63615e+002	8.07950e+002	6.76573e-001	2.08325e+001	6.20572e-003	N/A
22	N/A	N/A	1.78799e+002	8.39025e+002	6.98951e-001	2.11219e+001	6.04490e-003	N/A
23	N/A	N/A	1.94689e+002	8.70100e+002	6.98951e-001	2.14041e+001	5.89395e-003	N/A
24	N/A	N/A	2.11285e+002	9.01175e+002	6.98951e-001	2.16792e+001	5.75206e-003	N/A
25	N/A	N/A	2.28587e+002	9.32250e+002	6.98951e-001	2.19477e+001	5.61837e-003	N/A

fig 20: Quadratic LV Model result for TBF data set 2

Data study using graphs:

Cumulative density function:

From the graph given below it can be seen that in the initial testing period the the predicted value nearly matches with the raw data. The next fault occurs after 750 days. At this point the raw data and the predicted value do not coincide and after this point the graph is linearly increasing.

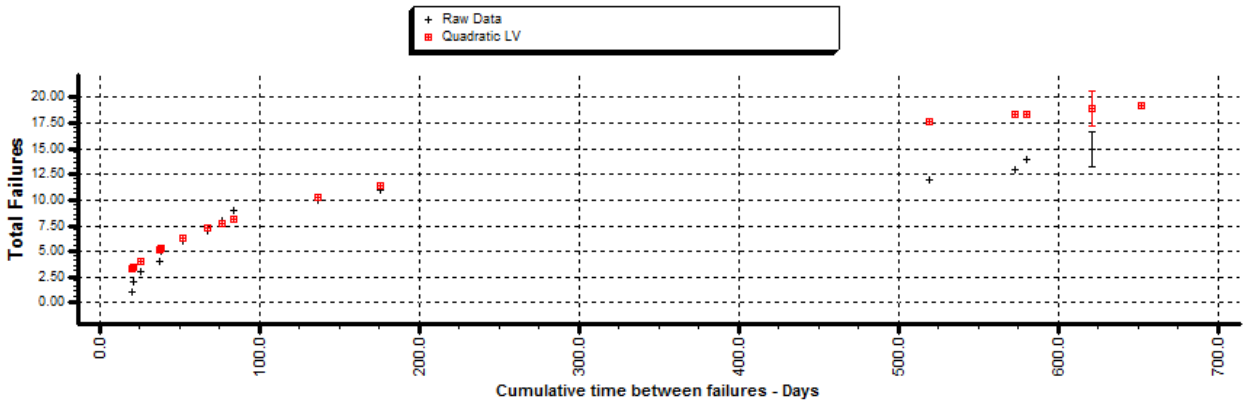

fig 21: cumulative density function vs. time(TBF data set-2)

Failure intensity function:

The graph given below shows that the predicted values do not trace raw data points in the beginning of the testing. Few raw data points have high failure intensity initially.

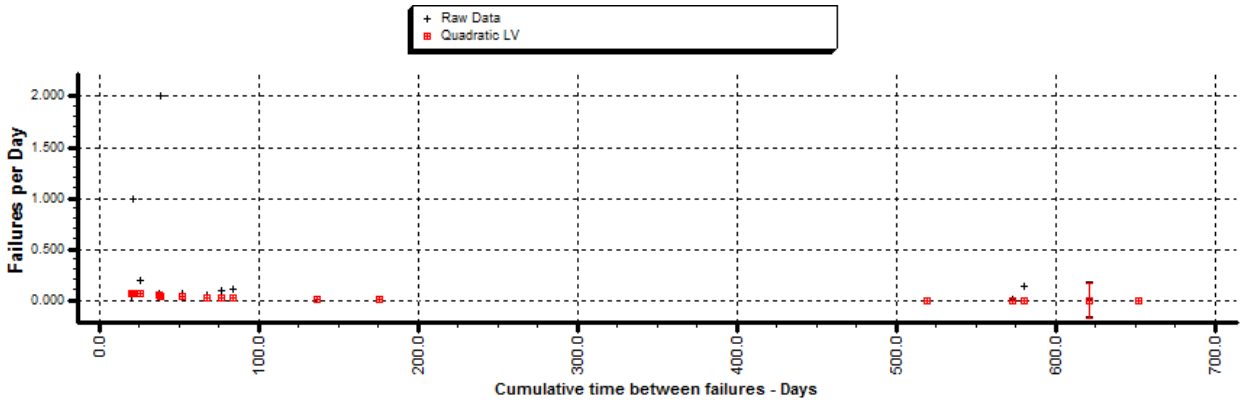

fig 22: Failure intensity function vs. time(TBF data set-2)

Reliability:

Initially the predicted reliability value is higher than the actual value. It increases as time increases and become flat or almost horizontal afterwards. This implies that as time passes the number of faults detected becomes constant.

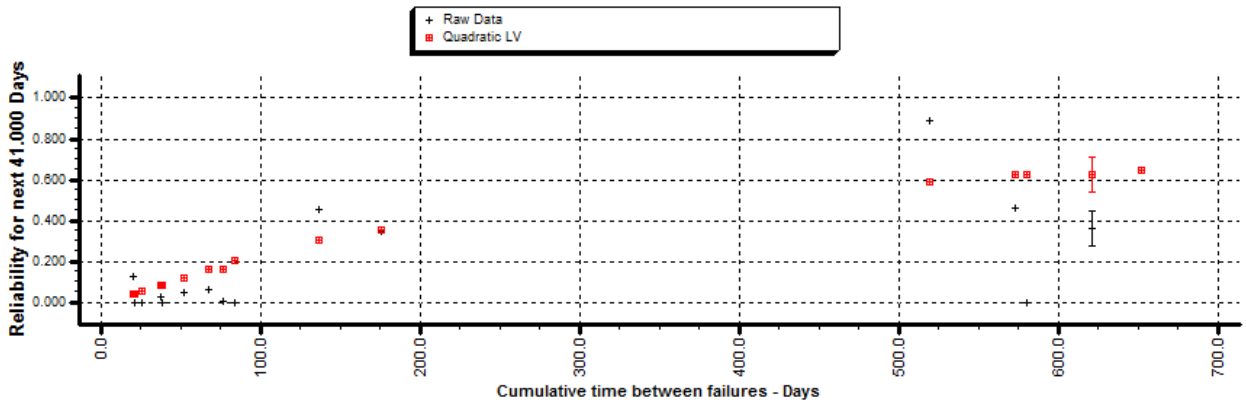

fig 23: Reliability vs. time (TBF data set-2)

Time between failure:

The predicted value traces the raw data as it can be seen from the graph. The graph is increasing exponentially.

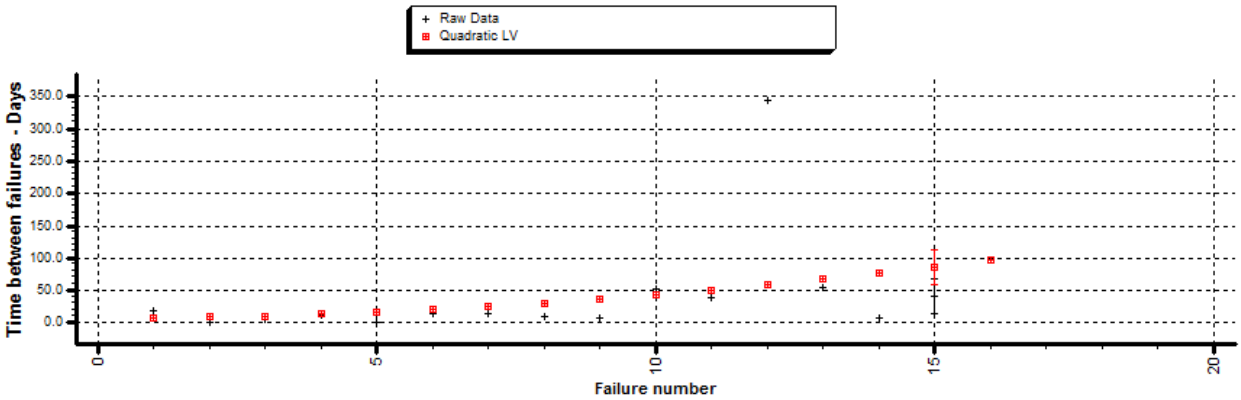

fig 24: Time between failure vs. time (TBF data set-2)

Model bias:

The model is unbiased with KS statistics equal to 0.317311.

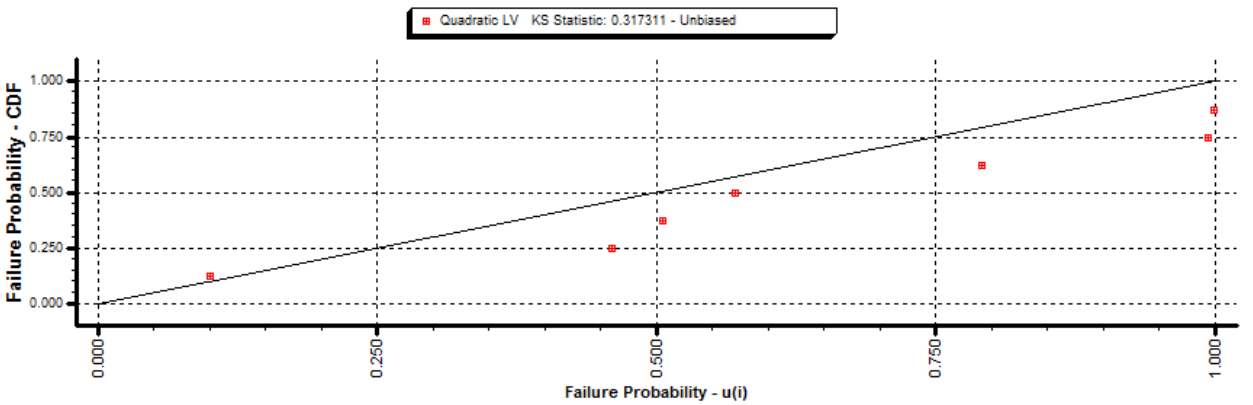

fig 25: Model bias (TBF data set-2)

FC data set-1:

Test Intvl	Number of Failures	Days in a Test Interval	Severity
1	4.000000e+000	5.000000e+000	1
2	2.800000e+001	5.000000e+000	1
3	1.200000e+001	5.000000e+000	1
4	1.300000e+001	5.000000e+000	1
5	9.000000e+000	5.000000e+000	1
6	4.000000e+000	5.000000e+000	1
7	4.000000e+000	5.000000e+000	1
8	1.000000e+000	5.000000e+000	1
9	4.000000e+000	5.000000e+000	1
10	2.000000e+000	5.000000e+000	1
11	2.000000e+000	5.000000e+000	1
12	2.000000e+000	5.000000e+000	1
13	1.000000e+000	5.000000e+000	1
14	0.000000e+000	5.000000e+000	N/A
15	0.000000e+000	5.000000e+000	N/A
16	0.000000e+000	5.000000e+000	N/A
17	0.000000e+000	5.000000e+000	N/A
18	0.000000e+000	5.000000e+000	N/A
19	0.000000e+000	5.000000e+000	N/A
20	0.000000e+000	5.000000e+000	N/A
21	0.000000e+000	5.000000e+000	N/A
22	0.000000e+000	5.000000e+000	N/A
23	0.000000e+000	5.000000e+000	N/A
24	0.000000e+000	5.000000e+000	N/A
25	0.000000e+000	5.000000e+000	N/A
26	0.000000e+000	5.000000e+000	N/A
27	0.000000e+000	5.000000e+000	N/A
28	0.000000e+000	5.000000e+000	N/A
29	0.000000e+000	5.000000e+000	N/A
30	0.000000e+000	5.000000e+000	N/A
31	0.000000e+000	5.000000e+000	N/A
32	0.000000e+000	5.000000e+000	N/A
33	0.000000e+000	5.000000e+000	N/A
34	0.000000e+000	5.000000e+000	N/A

fig 26: FC data set -1 to be analysed and reliability calculation using different reliability models

The data shown above is a failure count format data. In the above figure the first column represents the number of test intervals, the second gives the number of failure observed in each interval, the 3rd gives the size of each test interval(5 days) and the last column gives the severity. Severity is the consequences of a failure mode. Severity considers the worst potential consequence of a failure. If there are no failures detected in an interval the severity value is “N/A”.

The above data was analyzed using following reliability models:

1. Generalized Poisson

2. Nonhomogeneous Poisson(NHPP)

3. Schneidewind

4. Schick-Wolverton

5. Yamada S-Shape Model

The models that could execute the given data were NHPP, Schneidewind and Yamada S-shape.

NHPP Model:

Discussion: In the next step prediction column till the 17th test interval is less than or equal to the observation selected as the end of the initial parameter estimation range, hence this column has a value "N/A". The failure intensity at start of testing is 3.505, at end it comes down to 0.00054. The predicted value of failure intensity at end next 6 intervals is 0.000109. The predicted value of model estimates at 40th interval is 0.00062. The predicted reliability at end next 6 intervals is 0.9995.The model estimate is 20.081 at start and at end of 34th interval is 0.0031. The predicted value of reliability at the start of testing is very small(nearly equal to 0), 0.0000002 and at the end it grows to be 0.997. Next step prediction for the end next 6 intervals(35th to 40th intervals) is "N/A" because these intervals are less than or equal to the observation selected as the end of the initial parameter estimation range.

Test interval	Failures per test interval	Test Interval Length - Days	Next step Prediction	Model Estimates	Est. reliability: 5.00000e+000 Dy	Est'd cumulative number of failures	Estimated failure intensity at T	Actuals-Estimates
1	4.00000e+000	5.00000e+000	N/A	2.00813e+001	2.06535e-007	2.00813e+001	3.50595e+000	-1.60813e+001
2	2.80000e+001	5.00000e+000	N/A	1.53928e+001	7.51242e-006	3.54741e+001	2.68740e+000	1.26072e+001
3	1.20000e+001	5.00000e+000	N/A	1.17990e+001	1.18076e-004	4.72730e+001	2.05996e+000	2.01047e-001
4	1.30000e+001	5.00000e+000	N/A	9.04418e+000	9.75474e-004	5.63172e+001	1.57901e+000	3.95582e+000
5	9.00000e+000	5.00000e+000	N/A	6.93259e+000	4.92222e-003	6.32498e+001	1.21035e+000	2.06741e+000
6	4.00000e+000	5.00000e+000	N/A	5.31400e+000	1.70210e-002	6.85638e+001	9.27760e-001	-1.31400e+000
7	4.00000e+000	5.00000e+000	N/A	4.07331e+000	4.40562e-002	7.26371e+001	7.11151e-001	-7.33070e-002
8	1.00000e+000	5.00000e+000	N/A	3.12229e+000	9.13269e-002	7.57594e+001	5.45114e-001	-2.12229e+000
9	4.00000e+000	5.00000e+000	N/A	2.39331e+000	1.59688e-001	7.81527e+001	4.17843e-001	1.60669e+000
10	2.00000e+000	5.00000e+000	N/A	1.83453e+000	2.45070e-001	7.99872e+001	3.20287e-001	1.65470e-001
11	2.00000e+000	5.00000e+000	N/A	1.40621e+000	3.40311e-001	8.13935e+001	2.45508e-001	5.93788e-001
12	2.00000e+000	5.00000e+000	N/A	1.07790e+000	4.37695e-001	8.24714e+001	1.88188e-001	9.22104e-001
13	1.00000e+000	5.00000e+000	N/A	8.26233e-001	5.30822e-001	8.32976e+001	1.44250e-001	1.73767e-001
14	0.00000e+000	5.00000e+000	N/A	6.33328e-001	6.15413e-001	8.39309e+001	1.10571e-001	-6.33328e-001
15	0.00000e+000	5.00000e+000	N/A	4.85461e-001	6.89273e-001	8.44164e+001	8.47557e-002	-4.85461e-001
16	0.00000e+000	5.00000e+000	N/A	3.72118e-001	7.51836e-001	8.47885e+001	6.49673e-002	-3.72118e-001
17	0.00000e+000	5.00000e+000	N/A	2.85237e-001	8.03610e-001	8.50737e+001	4.97990e-002	-2.85237e-001
18	0.00000e+000	5.00000e+000	2.62423e-001	2.18641e-001	8.45697e-001	8.52924e+001	3.81722e-002	-2.18641e-001
19	0.00000e+000	5.00000e+000	1.95038e-001	1.67594e-001	8.79445e-001	8.54600e+001	2.92599e-002	-1.67594e-001
20	0.00000e+000	5.00000e+000	1.45656e-001	1.28465e-001	9.06222e-001	8.55884e+001	2.24284e-002	-1.28465e-001
21	0.00000e+000	5.00000e+000	1.09222e-001	9.84714e-002	9.27298e-001	8.56869e+001	1.71919e-002	-9.84714e-002
22	0.00000e+000	5.00000e+000	8.21855e-002	7.54807e-002	9.43784e-001	8.57624e+001	1.31780e-002	-7.54807e-002
23	0.00000e+000	5.00000e+000	6.20229e-002	5.78578e-002	9.56620e-001	8.58202e+001	1.01013e-002	-5.78578e-002
24	0.00000e+000	5.00000e+000	4.69231e-002	4.43494e-002	9.66576e-001	8.58646e+001	7.74288e-003	-4.43494e-002
25	0.00000e+000	5.00000e+000	3.55739e-002	3.39949e-002	9.74279e-001	8.58986e+001	5.93510e-003	-3.39949e-002
26	0.00000e+000	5.00000e+000	2.70175e-002	2.60579e-002	9.80224e-001	8.59246e+001	4.54940e-003	-2.60579e-002
27	0.00000e+000	5.00000e+000	2.05498e-002	1.99740e-002	9.84806e-001	8.59446e+001	3.48723e-003	-1.99740e-002
28	0.00000e+000	5.00000e+000	1.56500e-002	1.53106e-002	9.88333e-001	8.59599e+001	2.67304e-003	-1.53106e-002
29	0.00000e+000	5.00000e+000	1.19311e-002	1.17359e-002	9.91044e-001	8.59717e+001	2.04895e-003	-1.17359e-002
30	0.00000e+000	5.00000e+000	9.10394e-003	8.99587e-003	9.93128e-001	8.59807e+001	1.57057e-003	-8.99587e-003
31	0.00000e+000	5.00000e+000	6.95184e-003	6.89556e-003	9.94728e-001	8.59876e+001	1.20388e-003	-6.89556e-003
32	0.00000e+000	5.00000e+000	5.31176e-003	5.28561e-003	9.95957e-001	8.59928e+001	9.22804e-004	-5.28561e-003
33	0.00000e+000	5.00000e+000	4.06069e-003	4.05155e-003	9.96899e-001	8.59969e+001	7.07352e-004	-4.05155e-003
34	0.00000e+000	5.00000e+000	3.10561e-003	3.10561e-003	9.97622e-001	8.60000e+001	5.42202e-004	-3.10561e-003
35	N/A	5.00000e+000	N/A	2.38053e-003	9.98177e-001	8.60024e+001	4.15611e-004	N/A
36	N/A	5.00000e+000	N/A	1.82473e-003	9.98602e-001	8.60042e+001	3.18576e-004	N/A
37	N/A	5.00000e+000	N/A	1.39870e-003	9.98928e-001	8.60056e+001	2.44196e-004	N/A
38	N/A	5.00000e+000	N/A	1.07214e-003	9.99179e-001	8.60067e+001	1.87182e-004	N/A
39	N/A	5.00000e+000	N/A	8.21820e-004	9.99370e-001	8.60075e+001	1.43480e-004	N/A
40	N/A	5.00000e+000	N/A	6.29945e-004	9.99517e-001	8.60081e+001	1.09981e-004	N/A

fig 27: Nonhomogeneous Poisson model result for FC data set-1

Schneidewind Model:

Discussion: In the next step prediction column till the 17th test interval is less than or equal to the observation selected as the end of the initial parameter estimation range, hence this column has a value "N/A". The model estimate is 20.081 at start and at end of 34th interval is 0.0031. The predicted value of reliability at the start of testing is very small(nearly equal to 0), 0.0000002 and at the end it grows to be 0.997. The failure intensity at start of testing is 3.505, at end it comes down to 0.00054. The predicted value of failure intensity at end next 6 intervals is 0.000109. The predicted value of model estimates at 40th interval is 0.00062. The predicted reliability at end next 6 intervals is 0.9995. Next step prediction for the end next 6

intervals (35th to 40th intervals) is “N/A” because these intervals are less than or equal to the observation selected as the end of the initial parameter estimation range.

Test interval	Failures per test interval	Test Interval Length - Days	Next step Prediction	Model Estimates	Est. reliability: 5.00000e+000 Dy	Est'd cumulative number of failures	Estimated failure intensity at T	Actuals-Estimates
1	4.00000e+000	5.00000e+000	N/A	2.00813e+001	2.06535e-007	2.00813e+001	3.50595e+000	-1.60813e+001
2	2.80000e+001	5.00000e+000	N/A	1.53928e+001	7.51242e-006	3.54741e+001	2.68740e+000	1.26072e+001
3	1.20000e+001	5.00000e+000	N/A	1.17990e+001	1.18076e-004	4.72730e+001	2.05996e+000	2.01047e-001
4	1.30000e+001	5.00000e+000	N/A	9.04418e+000	9.75474e-004	5.63172e+001	1.57901e+000	3.95582e+000
5	9.00000e+000	5.00000e+000	N/A	6.93259e+000	4.92222e-003	6.32498e+001	1.21035e+000	2.06741e+000
6	4.00000e+000	5.00000e+000	N/A	5.31400e+000	1.70210e-002	6.85638e+001	9.27760e-001	-1.31400e+000
7	4.00000e+000	5.00000e+000	N/A	4.07331e+000	4.40562e-002	7.26371e+001	7.11151e-001	-7.33070e-002
8	1.00000e+000	5.00000e+000	N/A	3.12229e+000	9.13269e-002	7.57594e+001	5.45114e-001	-2.12229e+000
9	4.00000e+000	5.00000e+000	N/A	2.39331e+000	1.59688e-001	7.81527e+001	4.17843e-001	1.60669e+000
10	2.00000e+000	5.00000e+000	N/A	1.83453e+000	2.45070e-001	7.99872e+001	3.20287e-001	1.65470e-001
11	2.00000e+000	5.00000e+000	N/A	1.40621e+000	3.40311e-001	8.13935e+001	2.45508e-001	5.93788e-001
12	2.00000e+000	5.00000e+000	N/A	1.07790e+000	4.37695e-001	8.24714e+001	1.88188e-001	9.22104e-001
13	1.00000e+000	5.00000e+000	N/A	8.26233e-001	5.30822e-001	8.32976e+001	1.44250e-001	1.73767e-001
14	0.00000e+000	5.00000e+000	N/A	6.33328e-001	6.15413e-001	8.39309e+001	1.10571e-001	-6.33328e-001
15	0.00000e+000	5.00000e+000	N/A	4.85461e-001	6.89273e-001	8.44164e+001	8.47557e-002	-4.85461e-001
16	0.00000e+000	5.00000e+000	N/A	3.72118e-001	7.51836e-001	8.47885e+001	6.49673e-002	-3.72118e-001
17	0.00000e+000	5.00000e+000	N/A	2.85237e-001	8.03610e-001	8.50737e+001	4.97990e-002	-2.85237e-001
18	0.00000e+000	5.00000e+000	2.62423e-001	2.18641e-001	8.45697e-001	8.52924e+001	3.81722e-002	-2.18641e-001
19	0.00000e+000	5.00000e+000	1.95038e-001	1.67594e-001	8.79445e-001	8.54600e+001	2.92599e-002	-1.67594e-001
20	0.00000e+000	5.00000e+000	1.45656e-001	1.28465e-001	9.06222e-001	8.55884e+001	2.24284e-002	-1.28465e-001
21	0.00000e+000	5.00000e+000	1.09222e-001	9.84714e-002	9.27298e-001	8.56869e+001	1.71919e-002	-9.84714e-002
22	0.00000e+000	5.00000e+000	8.21855e-002	7.54807e-002	9.43784e-001	8.57624e+001	1.31780e-002	-7.54807e-002
23	0.00000e+000	5.00000e+000	6.20229e-002	5.78578e-002	9.56620e-001	8.58202e+001	1.01013e-002	-5.78578e-002
24	0.00000e+000	5.00000e+000	4.69231e-002	4.43494e-002	9.66576e-001	8.58646e+001	7.74287e-003	-4.43494e-002
25	0.00000e+000	5.00000e+000	3.55739e-002	3.39949e-002	9.74279e-001	8.58986e+001	5.93510e-003	-3.39949e-002
26	0.00000e+000	5.00000e+000	2.70175e-002	2.60579e-002	9.80224e-001	8.59246e+001	4.54940e-003	-2.60579e-002
27	0.00000e+000	5.00000e+000	2.05498e-002	1.99740e-002	9.84806e-001	8.59446e+001	3.48722e-003	-1.99740e-002
28	0.00000e+000	5.00000e+000	1.56500e-002	1.53106e-002	9.88333e-001	8.59599e+001	2.67304e-003	-1.53106e-002
29	0.00000e+000	5.00000e+000	1.19311e-002	1.17359e-002	9.91044e-001	8.59717e+001	2.04895e-003	-1.17359e-002
30	0.00000e+000	5.00000e+000	9.10394e-003	8.99587e-003	9.93128e-001	8.59807e+001	1.57057e-003	-8.99587e-003
31	0.00000e+000	5.00000e+000	6.95184e-003	6.89556e-003	9.94728e-001	8.59876e+001	1.20388e-003	-6.89556e-003
32	0.00000e+000	5.00000e+000	5.31176e-003	5.28561e-003	9.95957e-001	8.59928e+001	9.22804e-004	-5.28561e-003
33	0.00000e+000	5.00000e+000	4.06069e-003	4.05155e-003	9.96899e-001	8.59969e+001	7.07352e-004	-4.05155e-003
34	0.00000e+000	5.00000e+000	3.10561e-003	3.10561e-003	9.97622e-001	8.60000e+001	5.42202e-004	-3.10561e-003
35	N/A	5.00000e+000	N/A	2.38053e-003	9.98177e-001	8.60024e+001	4.15611e-004	N/A
36	N/A	5.00000e+000	N/A	1.82473e-003	9.98602e-001	8.60042e+001	3.18576e-004	N/A
37	N/A	5.00000e+000	N/A	1.39870e-003	9.98928e-001	8.60056e+001	2.44196e-004	N/A
38	N/A	5.00000e+000	N/A	1.07214e-003	9.99179e-001	8.60067e+001	1.87182e-004	N/A
39	N/A	5.00000e+000	N/A	8.21820e-004	9.99370e-001	8.60075e+001	1.43480e-004	N/A
40	N/A	5.00000e+000	N/A	6.29945e-004	9.99517e-001	8.60081e+001	1.09981e-004	N/A

fig 28: Schneidewind Model result for FC data set-1

Yamada S-shape Model:

Discussion: In the next step prediction column till the 17th test interval is less than or equal to the observation selected as the end of the initial parameter estimation range, hence this column has a value “N/A”. The model estimate is 8.547 at start and at end of 34th interval is 0.0000159. The predicted value of reliability at the start of testing is very small(nearly equal to 0), 0.0000001 and at the end it grows to be 0.999. The failure intensity at start of testing is 2.842, at end it comes down to 0.0000024. The predicted value of failure intensity at end next 6 intervals is 0.0000001. The predicted value of model estimates at 40th interval is 0.0000007. The predicted reliability at end next 6 intervals is 1. Next step prediction for the end next 6 intervals(35th to 40th intervals) is “N/A” because these intervals are less than or equal to the observation selected as the end of the initial parameter estimation range.

Test interval	Failures per test interval	Test Interval Length - Days	Next step Prediction	Model Estimates	Est. reliability: 5.00000e+000 Dy	Est'd cumulative number of failures	Estimated failure intensity at T	Actuals-Estimates
1	4.00000e+000	5.00000e+000	N/A	8.54762e+000	1.05404e-007	8.54762e+000	2.84273e+000	-4.54762e+000
2	2.80000e+001	5.00000e+000	N/A	1.60655e+001	1.17967e-007	2.46131e+001	3.34696e+000	1.19345e+001
3	1.20000e+001	5.00000e+000	N/A	1.59529e+001	1.82311e-006	4.05659e+001	2.95547e+000	-3.95286e+000
4	1.30000e+001	5.00000e+000	N/A	1.32150e+001	4.40383e-005	5.37809e+001	2.31980e+000	-2.14965e-001
5	9.00000e+000	5.00000e+000	N/A	1.00305e+001	7.24577e-004	6.38114e+001	1.70704e+000	-1.03045e+000
6	4.00000e+000	5.00000e+000	N/A	7.22992e+000	6.49813e-003	7.10413e+001	1.20590e+000	-3.22992e+000
7	4.00000e+000	5.00000e+000	N/A	5.03624e+000	3.25820e-002	7.60775e+001	8.28212e-001	-1.03624e+000
8	1.00000e+000	5.00000e+000	N/A	3.42399e+000	1.01672e-001	7.95015e+001	5.57209e-001	-2.42399e+000
9	4.00000e+000	5.00000e+000	N/A	2.28600e+000	2.22043e-001	8.17875e+001	3.69024e-001	1.71400e+000
10	2.00000e+000	5.00000e+000	N/A	1.50488e+000	3.75464e-001	8.32924e+001	2.41378e-001	4.95116e-001
11	2.00000e+000	5.00000e+000	N/A	9.79593e-001	5.31620e-001	8.42720e+001	1.56306e-001	1.02041e+000
12	2.00000e+000	5.00000e+000	N/A	6.31826e-001	6.67367e-001	8.49038e+001	1.00380e-001	1.36817e+000
13	1.00000e+000	5.00000e+000	N/A	4.04415e-001	7.73224e-001	8.53082e+001	6.40168e-002	5.95585e-001
14	0.00000e+000	5.00000e+000	N/A	2.57187e-001	8.49885e-001	8.55654e+001	4.05848e-002	-2.57187e-001
15	0.00000e+000	5.00000e+000	N/A	1.62654e-001	9.02690e-001	8.57281e+001	2.55983e-002	-1.62654e-001
16	0.00000e+000	5.00000e+000	N/A	1.02376e-001	9.37848e-001	8.58305e+001	1.60740e-002	-1.02376e-001
17	0.00000e+000	5.00000e+000	N/A	6.41669e-002	9.60723e-001	8.58946e+001	1.00540e-002	-6.41669e-002
18	0.00000e+000	5.00000e+000	4.11026e-002	4.00697e-002	9.75369e-001	8.59347e+001	6.26680e-003	-4.00697e-002
19	0.00000e+000	5.00000e+000	2.53851e-002	2.49398e-002	9.84642e-001	8.59596e+001	3.89414e-003	-2.49398e-002
20	0.00000e+000	5.00000e+000	1.56675e-002	1.54772e-002	9.90466e-001	8.59751e+001	2.41309e-003	-1.54772e-002
21	0.00000e+000	5.00000e+000	9.66008e-003	9.57956e-003	9.94102e-001	8.59847e+001	1.49158e-003	-9.57956e-003
22	0.00000e+000	5.00000e+000	5.94883e-003	5.91504e-003	9.96362e-001	8.59906e+001	9.19887e-004	-5.91504e-003
23	0.00000e+000	5.00000e+000	3.65845e-003	3.64440e-003	9.97762e-001	8.59942e+001	5.66141e-004	-3.64440e-003
24	0.00000e+000	5.00000e+000	2.24674e-003	2.24095e-003	9.98625e-001	8.59965e+001	3.47770e-004	-2.24095e-003
25	0.00000e+000	5.00000e+000	1.37783e-003	1.37546e-003	9.99158e-001	8.59979e+001	2.13258e-004	-1.37546e-003
26	0.00000e+000	5.00000e+000	8.43782e-004	8.42825e-004	9.99484e-001	8.59987e+001	1.30564e-004	-8.42825e-004
27	0.00000e+000	5.00000e+000	5.16034e-004	5.15651e-004	9.99685e-001	8.59992e+001	7.98176e-005	-5.15651e-004
28	0.00000e+000	5.00000e+000	3.15182e-004	3.15031e-004	9.99808e-001	8.59995e+001	4.87279e-005	-3.15031e-004
29	0.00000e+000	5.00000e+000	1.92268e-004	1.92209e-004	9.99883e-001	8.59997e+001	2.97099e-005	-1.92209e-004
30	0.00000e+000	5.00000e+000	1.17149e-004	1.17128e-004	9.99929e-001	8.59998e+001	1.80930e-005	-1.17128e-004
31	0.00000e+000	5.00000e+000	7.13000e-005	7.12923e-005	9.99957e-001	8.59999e+001	1.10061e-005	-7.12923e-005
32	0.00000e+000	5.00000e+000	4.33493e-005	4.33469e-005	9.99974e-001	8.60000e+001	6.68817e-006	-4.33469e-005
33	0.00000e+000	5.00000e+000	2.63296e-005	2.63290e-005	9.99984e-001	8.60000e+001	4.06028e-006	-2.63290e-005
34	0.00000e+000	5.00000e+000	1.59771e-005	1.59771e-005	9.99990e-001	8.60000e+001	2.46267e-006	-1.59771e-005
35	N/A	5.00000e+000	N/A	9.68664e-006	9.99994e-001	8.60000e+001	1.49238e-006	N/A
36	N/A	5.00000e+000	N/A	5.86790e-006	9.99996e-001	8.60000e+001	9.03645e-007	N/A
37	N/A	5.00000e+000	N/A	3.55178e-006	9.99998e-001	8.60000e+001	5.46742e-007	N/A
38	N/A	5.00000e+000	N/A	2.14824e-006	9.99999e-001	8.60000e+001	3.30559e-007	N/A
39	N/A	5.00000e+000	N/A	1.29841e-006	9.99999e-001	8.60000e+001	1.99717e-007	N/A
40	N/A	5.00000e+000	N/A	7.84231e-007	1.00000e+000	8.60000e+001	1.20585e-007	N/A

fig 29: Yamada s-shape model result for FC data set-1

Model Comparison:

The three models discussed above are compared and analyzed using graphs.

Cumulative Density Function:

In the given graph the predicted values are near to the raw data points. The predicted value of the yamada s-shaped is lower than the other two models till interval number 5, from 5 to 10 interval it is higher than the other two and after 15th interval all the models become equal and constant.

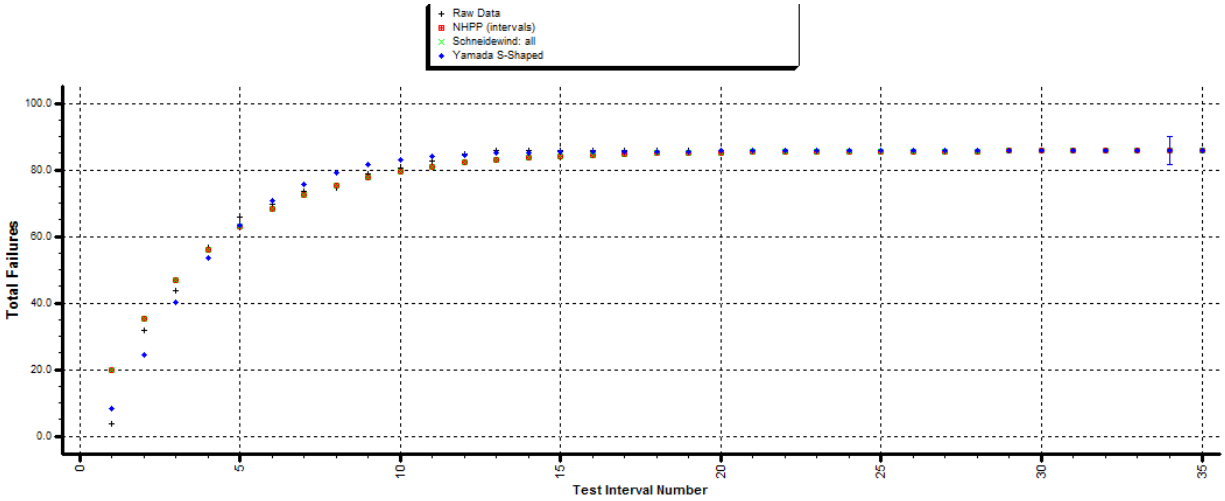

fig 30: cumulative density function vs. test interval (FC data set-1)

Failure intensity function:

From the graph we can make out that the predicted value do not match with the raw data till the 15th test interval number. The value decreases as time passes. The prediction shows that failure rate is quite low and constant after 15th test interval.

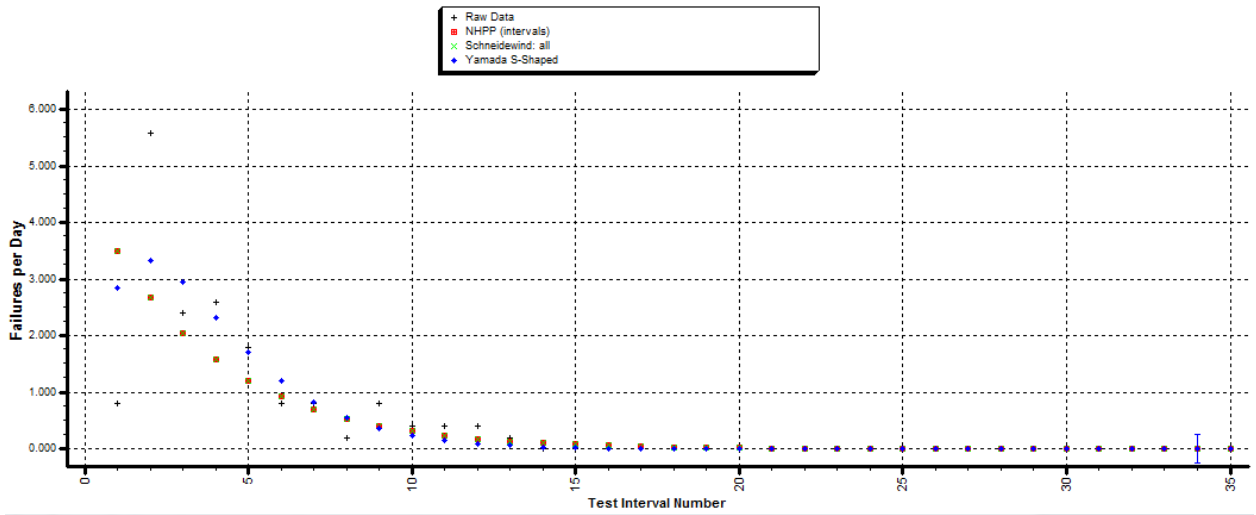

fig 31: Failure intensity function vs. test interval (FC data set-1)

Time between failure:

At first the three models trace each other and r constant till 25th test interval number. NHPP and the schneidewindmodel remain constant and the yamada s-shaped model forms a curve.

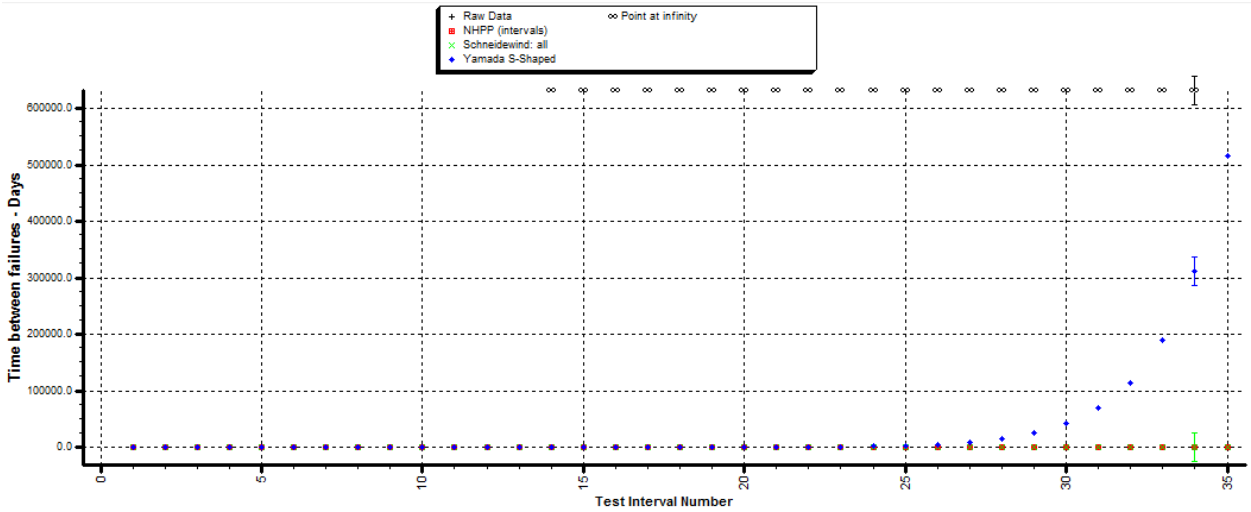

fig 32: Time between failure vs. test interval (FC data set-1)

Reliability:

The prediction values do not trace the raw points. The graph shows that the models are constant initially till the 5th test interval and from the 30th to 35th interval. Between the 10th and 25th interval the yamada model has a higher value than the other two.

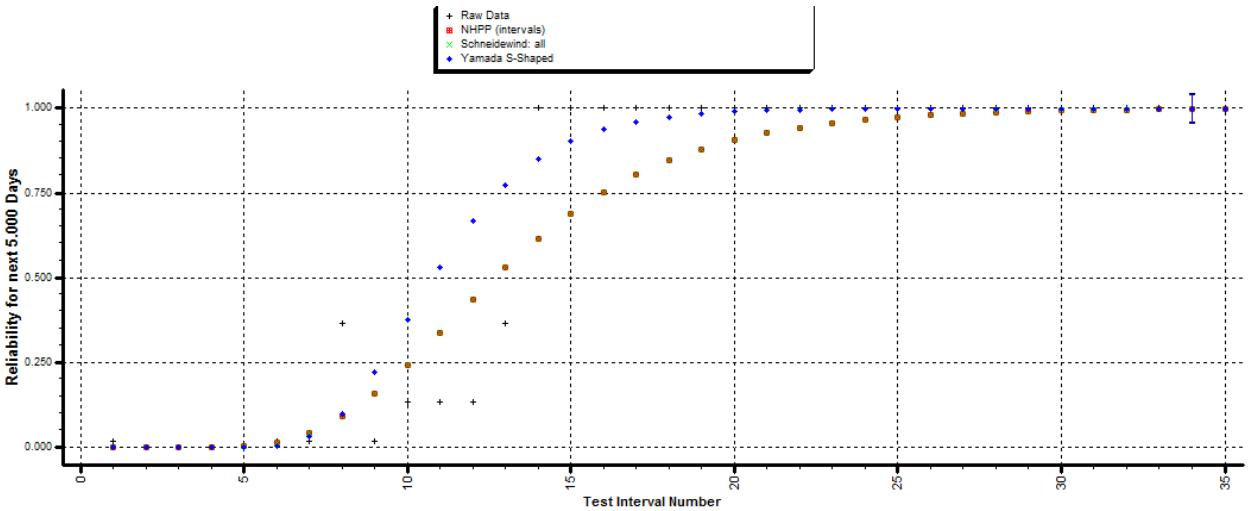

fig 33: Reliability vs. test interval (FC data set-1)

FC data set-2

Test Intvl	Number of Failures	Days in a Test Interval	Severity
1	0.000000e+000	5.000000e+000	N/A
2	1.000000e+000	5.000000e+000	1
3	0.000000e+000	5.000000e+000	N/A
4	0.000000e+000	5.000000e+000	N/A
5	0.000000e+000	5.000000e+000	N/A
6	1.000000e+000	5.000000e+000	1
7	1.000000e+000	5.000000e+000	1
8	0.000000e+000	5.000000e+000	N/A
9	0.000000e+000	5.000000e+000	N/A
10	1.000000e+000	5.000000e+000	1
11	1.000000e+000	5.000000e+000	1
12	0.000000e+000	5.000000e+000	N/A
13	0.000000e+000	5.000000e+000	N/A
14	0.000000e+000	5.000000e+000	N/A
15	0.000000e+000	5.000000e+000	N/A
16	2.000000e+000	5.000000e+000	1
17	1.000000e+000	5.000000e+000	1
18	0.000000e+000	5.000000e+000	N/A
19	6.000000e+000	5.000000e+000	1
20	1.000000e+000	5.000000e+000	1
21	0.000000e+000	5.000000e+000	N/A
22	2.000000e+000	5.000000e+000	1
23	1.000000e+000	5.000000e+000	1

fig 34: FC data set-2 to be analyzed and reliability calculation using different reliability models

The above given data is of failure count format. This data was not executed by any of the models.

The above data was analyzed using following reliability models:

1. Generalized Poisson

2. Nonhomogeneous Poisson(NHPP)

3. Schneidewind

4. Schick-Wolverton

5. Yamada S-Shape Model

FC Data set 3:

Test Intvl	Number of Failures	Days in a Test Interval	Severity
1	0.000000e+000	2.000000e+000	N/A
2	0.000000e+000	2.000000e+000	N/A
3	0.000000e+000	2.000000e+000	N/A
4	0.000000e+000	2.000000e+000	N/A
5	0.000000e+000	2.000000e+000	N/A
6	0.000000e+000	2.000000e+000	N/A
7	2.000000e+000	2.000000e+000	1
8	0.000000e+000	2.000000e+000	N/A
9	1.000000e+000	2.000000e+000	1
10	0.000000e+000	2.000000e+000	N/A
11	0.000000e+000	2.000000e+000	N/A
12	0.000000e+000	2.000000e+000	N/A
13	1.000000e+000	2.000000e+000	1
14	1.000000e+000	2.000000e+000	1
15	0.000000e+000	2.000000e+000	N/A
16	0.000000e+000	2.000000e+000	N/A
17	0.000000e+000	2.000000e+000	N/A
18	0.000000e+000	2.000000e+000	N/A
19	0.000000e+000	2.000000e+000	N/A
20	0.000000e+000	2.000000e+000	N/A
21	1.000000e+000	2.000000e+000	1
22	0.000000e+000	2.000000e+000	N/A
23	0.000000e+000	2.000000e+000	N/A
24	0.000000e+000	2.000000e+000	N/A
25	0.000000e+000	2.000000e+000	N/A
26	0.000000e+000	2.000000e+000	N/A
27	0.000000e+000	2.000000e+000	N/A
28	1.000000e+000	2.000000e+000	1
29	1.000000e+000	2.000000e+000	1
30	0.000000e+000	2.000000e+000	N/A
31	0.000000e+000	2.000000e+000	N/A
32	0.000000e+000	2.000000e+000	N/A
33	0.000000e+000	2.000000e+000	N/A
34	0.000000e+000	2.000000e+000	N/A
35	0.000000e+000	2.000000e+000	N/A
36	0.000000e+000	2.000000e+000	N/A
37	0.000000e+000	2.000000e+000	N/A
38	0.000000e+000	2.000000e+000	N/A

fig 35: FC Data set 3 also analysed in a similar manner as the above mentioned data

The above given data is of failure count format.

The above data was analyzed using following reliability models:

1. Generalized Poisson

2. Nonhomogeneous Poisson(NHPP)

3. Schneidewind

4. Schick-Wolverton

5. Yamada S-Shape Model

The model that executed the above data were:

1. Generalized Poisson

2. Schick-Wolverton

3. Yamada S-Shape Model

This data can be analysed in similar manner as the FC data set-1 and FC data set-2.

FC Data set 4:

Test Intvl	Number of Failures	Days in a Test Interval	Severity
1	7.000000e+000	2.000000e+000	1
2	1.000000e+000	2.000000e+000	1
3	0.000000e+000	2.000000e+000	N/A
4	0.000000e+000	2.000000e+000	N/A
5	2.000000e+000	2.000000e+000	1
6	0.000000e+000	2.000000e+000	N/A
7	2.000000e+000	2.000000e+000	1
8	0.000000e+000	2.000000e+000	N/A
9	1.000000e+000	2.000000e+000	1
10	1.000000e+000	2.000000e+000	1
11	5.000000e+000	2.000000e+000	1
12	1.000000e+000	2.000000e+000	1
13	1.000000e+000	2.000000e+000	1
14	2.000000e+000	2.000000e+000	1
15	0.000000e+000	2.000000e+000	N/A
16	0.000000e+000	2.000000e+000	N/A
17	0.000000e+000	2.000000e+000	N/A
18	0.000000e+000	2.000000e+000	N/A
19	0.000000e+000	2.000000e+000	N/A
20	0.000000e+000	2.000000e+000	N/A
21	2.000000e+000	2.000000e+000	1
22	0.000000e+000	2.000000e+000	N/A
23	1.000000e+000	2.000000e+000	1
24	0.000000e+000	2.000000e+000	N/A
25	0.000000e+000	2.000000e+000	N/A
26	0.000000e+000	2.000000e+000	N/A
27	0.000000e+000	2.000000e+000	N/A
28	0.000000e+000	2.000000e+000	N/A
29	0.000000e+000	2.000000e+000	N/A
30	1.000000e+000	2.000000e+000	1
31	0.000000e+000	2.000000e+000	N/A
32	0.000000e+000	2.000000e+000	N/A
33	0.000000e+000	2.000000e+000	N/A
34	0.000000e+000	2.000000e+000	N/A
35	2.000000e+000	2.000000e+000	1
36	1.000000e+000	2.000000e+000	1
37	0.000000e+000	2.000000e+000	N/A
38	1.000000e+000	2.000000e+000	1
39	0.000000e+000	2.000000e+000	N/A
40	0.000000e+000	2.000000e+000	N/A
41	0.000000e+000	2.000000e+000	N/A
42	0.000000e+000	2.000000e+000	N/A
43	0.000000e+000	2.000000e+000	N/A
44	0.000000e+000	2.000000e+000	N/A
45	0.000000e+000	2.000000e+000	N/A
46	0.000000e+000	2.000000e+000	N/A
47	1.000000e+000	2.000000e+000	1

fig 36: Data set 4 also analysed in a similar manner as the above mentioned data

The above given data is of failure count format.

The above data was analyzed using following reliability models:

1. Generalized Poisson

2. Nonhomogeneous Poisson(NHPP)

3. Schneidewind

4. Schick-Wolverton

5. Yamada S-Shape Model

All the models were able to execute the above mentioned data.

This data can be analysed in similar manner as the FC data set-1 and FC data set-2.

Conclusion

Conclusion drawn from TBF data set-1:

It will take almost 500 days of testing to increase the reliability by around 0.5.It can be expected that next 20 faults will be detected in next 500 days.As failure rate is low as witnessed from the result table, the effort to detect each next fault increases imensely. The time between failure for each next fault increases with each detection.

Conclusion drawn from TBF data set-2:

> It can be expected that next 10 faults will be detected in around next 320 days.It will take around 320 days of testing to imprive the reliability by around 0.75.Failure rate is low, the effort to detect each next fault increases. The time between failure for each next fault increases with each detection.

Conclusion drawn from FC data set-1:

The data was executed by NHPP, Schneidewind and Yamada s-shape models. The predicted values given by NHPP and Schneidewind were equal. The predicted value of reliability was very high and grew with a high rate. The failure rate was high hence the effort to detect each next fault increases.

Conclusion drawn from FC data set-2:

5 FC models were used in the analyses of this data and non of them were able to execute it. This happed because the data was unable to provide the software models with the required parameters for the prediction of values.