CONDUCTING DATA ANALYSIS FOR ELECTROHYDRAULIC VALVES

Cristian Soimaru, Liviu Jelenschi, Gabriel Sandu, Sebastian Zaharia

Transilvania University of Brasov, Department of Mechanical Engineering, Politehnicii Street, No. 1, Brasov

Corresponding author: Cristian Soimaru, cristian.soimaru@unitbv.ro

Abstract: Electohydraulic valves represent a very important component of VarioCam Plus Variable Valve Viming system of Porche's internal combustion engine. Due to fact that functions in the oil system it get's blocked by contaminants present in the oil system. The purpose of this work is to determine the lifetime of the electrohydraulic valve in different test conditions which simulate real conditions. Using DOE Taguchi method a test plan was designed in order to combine efficiently the parameters and their levels also, that are considered to have the biggest influence over the lifetime of valve. After one trial test, within the Taguchi test plan, the data obtained needed to be analyzed. Hence, the methodology for analyzing data will be presented so that the medium life span of the valve, in predetermined conditions, could be determined.

Key words: DOE, Taguchi, Weibull, internal combustion engine, valve, test.

1. INTRODUCTION

In order to make cars friendlier with environment, to obtain less fuel consumption and better performance, internal combustion engine specialists have designed practical solutions to meet requirements above. Thus, one of the solutions is represented by variable valve timing mechanism VarioCam Plus produced by Porsche AG. Within it the electrohydraulic valve is found, which has a fundamental role obtaining different lifts of the internal combustion valve.

Due to the fact that it functions in the internal combustion engine oil system, after a number of cycles it gets blocked. The root cause that produces valve's blocking it is represented by contaminant present in the oil. There are several causes for having contaminant in the oil: air filter malfunction, which allows dust to be inducted in the engine; wear of components in relative motion, being cause for having magnetic contaminant in the oil; gums resulted from oil degradation etc.

So, what this paper assumes to do is determining life span of the valve in different laboratory conditions which simulate reality.

2. GENERAL INFORMATION

After a brainstorming technique, were identified the factors that influence most the life of valve. Among them, four were identified as being the most important: A – contaminant quantity, B – dimension of contaminant, C – Mounting postion of the valves, D – type of contaminant.

With this parameters using Taguchi DOE method, a test plan was designed. It is presented in table 1.

Table 1. Taguchi Orthogonal array

Factors / Nr. of experiment	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	2	1	1	2
4	2	2	2	1
5	3	1	2	1
6	3	2	1	2
7	4	1	2	2
8	4	2	1	1

Factor A involves 4 levels, e.g. four values of contaminant quantity represented by the numbers 1 up to 4. First level 60 grams, second 90 grams, third 120 grams and the forth 150 grams.

Factor B involves only two levels: 45 μm and 150 μm. Factor C, involves two levels: horizontal and vertical mounting positions. Factor D, involves two leves: magnetic contaminant and non-magnetic contaminant. Within the test plan presented in table 1 only the first experiment was run. This consists in testing simultaneously four valves from a total number of 28 valves per experiment.

3. METHODOLOGY

The methodology of data analysis consists in the next steps: 1 – Running experiment on the test bed; 2 – Collecting experimental data; 3 – Verifying statistical homogeneity of experimental data; 3.1 – Verifying the randomness of data; 3.2 – Ouliar detection; 4 – Choosing theoretical distribution; 5 – Estimating distribution's parameters; 6 – Validating theoretical distribution, using Goodness-of-fit test; 7 –

Accepting/rejecting theoretical distribution; 8– Estimating reliability parameters of the accepted distribution (Martinescu and Popescu, 1995).

Table 2. Function time of the valves

Test number	Hours	Minutes	Nr of cycles
1	1:49	109	22890
2	1:45	105	22050
3	1:53	113	23730
4	1:55	115	24150
5	1:33	93	19530
6	1:37	97	20370
7	1:26	86	18060
8	1:30	90	18900
9	1:27	87	18270
10	1:32	92	19320
11	1:40	100	21000
12	1:39	99	20790
13	1:18	78	16380
14	1:15	75	15750
15	1:25	85	17850
16	1:31	91	19110
17	2:15	135	28350
18	1:45	105	22050
19	1:47	107	22470
20	1:40	100	21000
21	1:41	101	21210
22	1:46	106	22260
23	1:40	100	21000
24	1:52	112	23520
25	1:09	69	14490
26	1:29	89	18690
27	1:36	96	20160
28	1:22	82	17220

The first two steps of the methodology are sinthesized in table 2. In order to analyze easier the results, the data was converted from hours into cycles of functioning.

After the experimental data was collected it is necessary to verify statistical homogeneity. First its randomness must be evaluated. Using bibliographic reference (Martinescu and Popescu, 1995) the method named “Criteria length of iteration K” was used.

The philosophy of this method consists in:

Defining null hypothesis H_0: the data does not have a random characteristic of distribution.

Defining alternate hypothesis H_1: the data has a random characteristic of distribution.

The number of values that compose an iteration represent the length of the iteration and it is marked as K. Decision regarding statistical hypothesis H_0 is taken considering the next facts:

a. if $K_{max} \leq K_{n,\alpha}$ then H_0 is accepted;

b. if $K_{max} > K_{n,\alpha}$ then H_1 is accepted;

K_{max} represents the maximum length of existing iterations; $K_{n,\alpha}$ may be determined with the following formula:

$$K_{n,\alpha} = \frac{\lg \frac{-0{,}43429 \cdot n}{\lg(1-\alpha)}}{\lg 2} - 1 \qquad (1)$$

where „n” is number of samples and „α” represents the confidence level. Consecutive values of analyzed characteristic, which have the same property e.g. they are either bigger or smaller than the median of the data, represents iteration. They are grouped, considering, the median of the data in: bigger values (a), smaller values (b) and equal with median (c) (Martinescu and Popescu, 1995). Having this background, the data analyzed is presented in table 3. It can be observed that there exist 5 iterations. M = median is equal to 16800 cycles, *It* represents the abbreviation for iteration, n = 28 and α = 0.05, thus $K_{n,\alpha}$= 8.09 and K_{max} is equal to 12.

Considering condition “b” presented above H_1 is accepted, so data has a random characteristic of distribution**.** That means the fact only natural causes have influenced the analyzed process, so data is homogeneous (Martinescu and Popescu, 1995).

Table 3. Determining randomness of data

Nr. crt	Nr. of cycles, xi	xi>M=a, xi<M=b, xi=M=m	It number	It length	Obs
1	22890	a	1	12	k1=12 =kmax
2	22050	a			
3	23730	a			
4	24150	a			
5	19530	a			
6	20370	a			
7	18060	a			
8	18900	a			
9	18270	a			
10	19320	a			
11	21000	a			
12	20790	a			
13	16380	b	2	2	k2=2
14	15750	b			
15	17850	a	3	10	k3=10
16	19110	a			
17	28350	a			
18	22050	a			
19	22470	a			
20	21000	a			
21	21210	a			

22	22260	a			
23	21000	a			
24	23520	a			
25	14490	b	4	1	k4=1
26	18690	a	5	3	k5=3
27	20160	a			
28	17220	a			

Another step in data analysis and which is enclosed in chapter 2 is outliars detection**.**

In order to detect outliars Grubbs method was used. The main reason for choosing it is represented by the fact that:

1. it is easy to understand it.
2. allows specification of confidence level (http://www.graphpad.com, 10/01/2012).
3. it is a test which may be used for all theoretical distributions used in reliability (Martinescu and Popescu, 1995).

In order to observe if there are outliars or not, formula (2) will be used

$$Z = \frac{\left|\bar{x} - x_i\right|}{SD} \tag{2}$$

Where: Z represents the comparison ratio, $\bar{x}$- arithmetical mean of the values, x_i current value of number of cycles and SD standard deviation of data. Using source (http://www.graphpad.com, 10/01/2012) a critical value Z_{crt} was determined at 2.88, the significance level "α"was chosen to be equal with 0.05 and the final result looks like in table 4:

Table 4. Outliar detection

Nr. crt	Nr. of cycles	Z
1	22890	0.87
2	22050	0.58
3	23730	1.15
4	24150	1.30
5	19530	0.29
6	20370	0.00
7	18060	0.80
8	18900	0.51
9	18270	0.73
10	19320	0.36
11	21000	0.21
12	20790	0.14
13	16380	1.38
14	15750	1.59
15	17850	0.87
16	19110	0.44
17	28350	2.75
18	22050	0.58
19	22470	0.72
20	21000	0.21
21	21210	0.29
22	22260	0.65
23	21000	0.21
24	23520	1.08
25	14490	2.03
26	18690	0.58
27	20160	0.07
28	17220	1.09

Looking in this table it can be seen that all values of Z are smaller than $Z_{crt,}$ so the conclusion is that there are no outliars in the experimental data.

After it has been proven that there are no outliars, the next step is to choose the theoretical distribution. So, a Weibull distribution is chosen to represent this data. Its probability density function is presented in formula (3).

$$f(T) = \frac{\beta}{\eta} \cdot \left(\frac{T-\gamma}{\eta}\right)^{\beta-1} \cdot e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}} \tag{3}$$

where: $f(T) \geq 0, T \geq \gamma, \beta > 0, \eta > 0, -\infty < \gamma < \infty$

β represents shape parameter, η represents scale parameter, γ represents position parameter and T represents cycles of functioning (Kececioglu, 2002).

The reasons for adopting Weibull distribution are:

1.Due to fact that electrohydraulic valves are part of mechanical domain it is recommended that Weibull distribution should be used (Martinescu and Popescu, 1995).

2.Weibull distribution is used in corrosion and wear studies, especially in durability calculus for bearings, tools, gear transmissions, study of mechanical and electrical products endurance, material fatigue (Zaharia, 2010).

3.Weibull distribution with γ >0 and β > 1 occur naturally for wear-out situations (Kececioglu, 2002).

4.The life distribution of cycles to failure of solids subjected to fatigue stresses is well represented by Weibull distribution (Kececioglu, 2002).

5.The Weibull distribution probability density function describes well the life characteristics of parts and components (Kececioglu, 2002).

Further, once it has been adopted the Weibull distribution it is necessary to estimate the parameters, which means determining the estimate value for: β, η and γ. There are two main ways to estimate parameters: a. graphical; b. analytical. Within Weibull ++7 software was used graphical method named Probability Plotting for a Weibull distribution with two parameters, γ was considered to be zero. Probability Plotting assumes a graphical representation of empirical estimation function $F_n(t_i)$ depending on t_i – functioning time for every sample within the batch with volume 28 components, which is also represented in figure 1.

If all the points fit to the line it means that there is a Weibull distribution with two parameters and estimated values of β and η are right, so it is not necessary to find the estimated value for the third one, γ, because this is equal to zero. The third parameter of Weibull distribution is used when the data do not fall on a straight line (http://www.reliasoft.com, 15/01/2012). Looking on figure 1, it can be observed that the spherical points do not fit the blue line, so γ is needed.

Thus, using the same software and method – Probability Plotting a three parameter Weibull distribution it was used. In the same figure it can be observed that the rectangular black points fit better to the line, which means that exist more exact estimated values of parameters β, η and γ.

In conclusion Probability Plotting method was used only to know if it is necessary to use a two or three parameter Weibull distribution. Further, analytical method named Maximum Likelihood Estimation (MLE) was used to determine the estimated values of the parameters and it is considered the most robust of the parameter estimation techniques (http://www.reliasoft.com, 15/01/2012).

Basically the MLE method relies on solving the log-likelihood function of each of the three parameters β, η and γ.

The log-likelihood function has the next mathematical expression:

$$\ln(L)=\Lambda=\sum_{i=1}^{F_e} N_i \cdot \ln\left[\frac{\beta}{\eta}\cdot\left(\frac{T_i-\gamma}{\eta}\right)^{\beta-1}\cdot e^{-\left(\frac{T_i-\gamma}{\eta}\right)^{\beta}}\right]-$$

$$\sum_{i=1}^{S} N_i' \cdot\left(\frac{T_i'-\gamma}{\eta}\right)^{\beta}+\sum_{i=1}^{F_i} N_i'' \cdot \ln\left[e^{-\left(\frac{T_{Li}''-\gamma}{\eta}\right)^{\beta}}-e^{-\left(\frac{T_{Ri}''-\gamma}{\eta}\right)^{\beta}}\right] \quad (4)$$

Where: F_e – number of groups of times to failure data group; N_i – the number of times to failure in the i^{th} time to failure data group; β – the shape parameter of Weibull distribution; T_i is the time of the i^{th} group of time to failure data; S is the number of groups of suspension data points; N_i' is the number of suspensions in the i_{th} group of suspension data points; T_i' is the time of the ith suspension data group; F_i is the number of interval failure data groups; N_i" is the number of intervals in the i^{th} group of data intervals; T_{Li}" is the beginning of the i^{th} interval; T_{Ri}"is the ending of the i^{th} interval; γ is the location parameter.

Solution of the equation 5 gives the estimate values of parameters, but not before solving each of the next three equations:

$$\frac{\partial\Lambda}{\partial\beta}=0;\frac{\partial\Lambda}{\partial\eta}=0;\frac{\partial\Lambda}{\partial\gamma}=0 \quad (5)$$

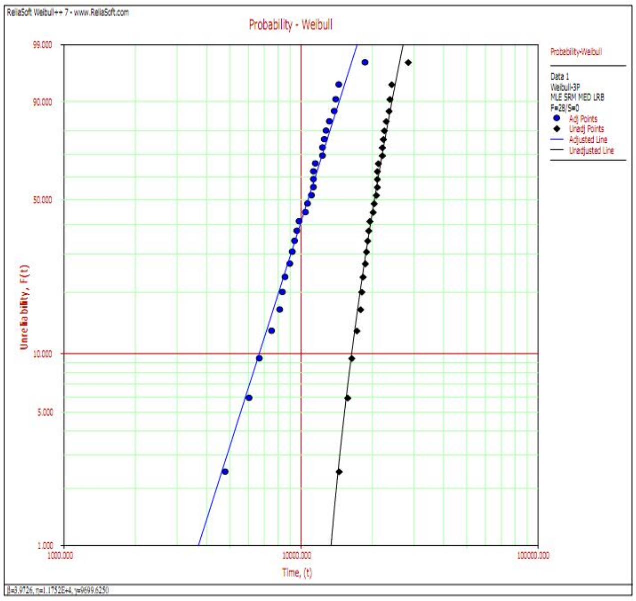

Fig. 1. Probability Plotting for 3 parameter Weibull distribution

Using the same software with equations 4 and 5, the estimated values of β, η and γ with 90% confidence are: β = 3.9726, η = 11752, γ = 9699.625

After the weibull distribution was chosen, the natural question that must be put is: does this distribution fits to the experimental data? The answer of this question is given by *Goodness-of-fit tests* that indicate wheather or not it is resonable to assume that a random sample comes from a specific distribution (http://www.itl.nist.gov, 19/01/2012).

Now, a test of fit consists in testing a null hypothesis, H_0, which in this case may be defined as:

H_0: the data comes from weibull CDF (Cumulative Distribution Function) with general form given be equation 6

$$F(x,a,b,c)=1-e^{-\left(\frac{x-a}{b}\right)^{c}} \quad (6)$$

It must be specified that experimental data represents complete data.

One of the tests which may answer the question wheather the data set can be described by Weibull distribution is the most well-known EDF statistic function Kolmogorov–Smirnov (K-S test) (Rinne, 2009). Kolmogorov – Smirnov function has the main role to measure the minimum distance between the EDF and Weibull CDF defined above.

The EDF function is given by:

$$F_n(x)=\begin{cases}0, x < X_{1:n}\\ \frac{i}{n}, X_{i:n}\le x\le X_{i+1:n}, i=1..n-1\\ 1, x > X_{n:n}\end{cases} \quad (7)$$

The K-S function represents the maximum distance between CDF and EDF [7] and it is calculated as

$$D = \max\left\{D_n^+, D_n^-\right\} \qquad (8)$$

where : D_n^+ represents the largest vertical difference when EDF is bigger than CDF; D_n^- represents the largest vertical difference when EDF is smaller than CDF (Rinne, 2009).
Values of D in excess of the critical value lead to rejection of null hypothesis (Murthy, 2004).
With this theoretical background and with the help of Easy Fit 5.5 trial version software, a K-S test was applied to the experimental data obtained on the test bench, figure 2.

EasyFit - Evaluation Version

Goodness of Fit - Summary

#	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
		Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Weibull (3P)	0.076778	1	0.2561219	1	1.478481	1

Goodness of Fit - Details [hide]

Weibull (3P) [#1]

Kolmogorov-Smirnov

Sample Size	28
Statistic	0.076778
P-Value	0.9920776
Rank	1

α	0.2	0.1	0.05	0.02	0.01
Critical Value	0.1968	0.22497	0.24993	0.27942	0.29971
Reject?	No	No	No	No	No

Fig. 2. K-S test using Easy Fit 5.5

For any confidence levels assigned to the null hypothesis it is clear that the data is well represented by Weibull distribution, looking on figure 2.

4. RESULTS

For the results box, the last point in the methodology will be presented. Thus, the main reliability characteristics of Weibull distribution are: reliability function, unreliability function, failure rate function. Their formulas are:

-Reliability function:

$$R(T) = e^{-\left(\frac{T-\gamma}{\eta}\right)^{\beta}} \qquad (9)$$

-Unreliability function:

$$F(T) = 1 - R(T) \qquad (10)$$

-Failure rate function:

$$\lambda(T) = \frac{\beta}{\eta} \cdot \left(\frac{T-\gamma}{\eta}\right)^{\beta-1} \qquad (11)$$

Using Weibull ++7 the functions have been represented graphically, figures 3, 4, 5 and the value of each reliability characteristic for each sample within experimental data are presented in table 5:

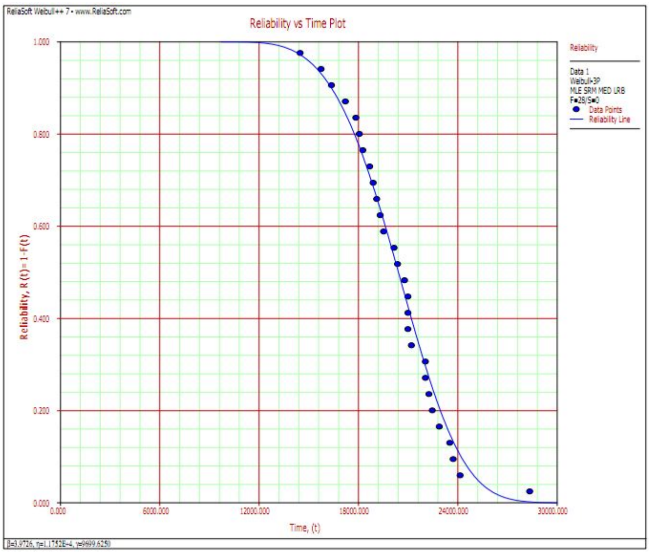

Fig. 3. Reliability function

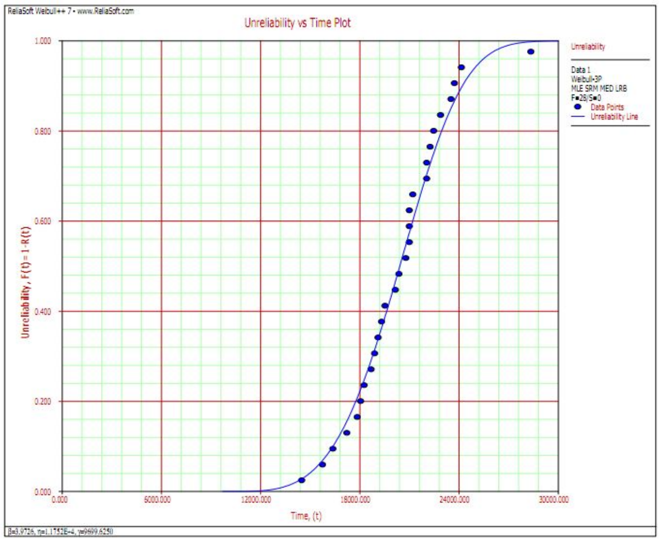

Fig. 4. Unreliability function

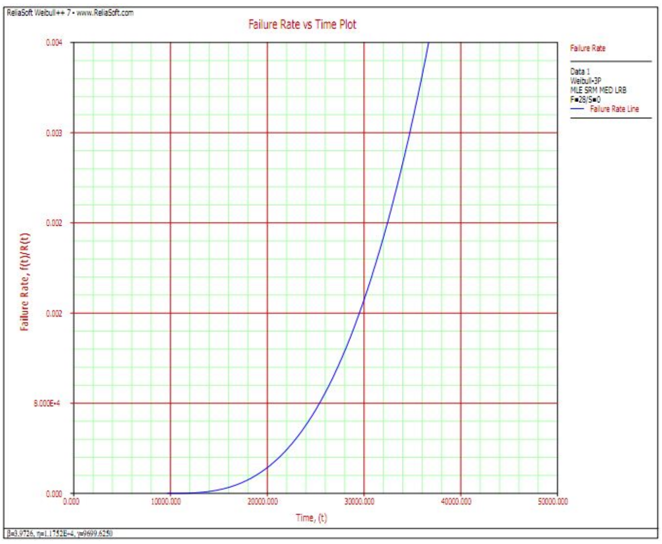

Fig. 5. Failure rate function

Table 5. Values of Weibull distribution reliability characteristics

Nr. of cycles	Reliability	Unreliability	Failure rate function
14490	0.9721	0.0279	0.0000235
15750	0.9310	0.0690	0.0000470
16380	0.8994	0.1006	0.0000631
17220	0.8439	0.1561	0.0000897
17850	0.7916	0.2084	0.0001139
18060	0.7722	0.2278	0.0001228
18270	0.7518	0.2482	0.0001322
18690	0.7082	0.2918	0.0001525
18900	0.6851	0.3149	0.0001633
19110	0.6612	0.3388	0.0001746
19320	0.6366	0.3634	0.0001865
19530	0.6114	0.3886	0.0001988
20160	0.5328	0.4672	0.0002391
20370	0.5059	0.4941	0.0002537
20790	0.4519	0.5481	0.0002845
21000	0.4249	0.5751	0.0003009
21000	0.4249	0.5751	0.0003009
21000	0.4249	0.5751	0.0003009
21210	0.3982	0.6018	0.0003178
22050	0.2958	0.7042	0.0003918
22050	0.2958	0.7042	0.0003918
22260	0.2719	0.7281	0.0004119
22470	0.2488	0.7512	0.0004328
22890	0.2056	0.7944	0.0004765
23520	0.1489	0.8511	0.0005473
23730	0.1324	0.8676	0.0005724
24150	0.1030	0.8970	0.0006249
28350	0.0019	0.9981	0.0013341

The Weibull distribution characteristics are also calculated:

1.The Mean of probability distribution function:

$$\overline{T} = \gamma + \eta \cdot \Gamma \cdot \left(\frac{1}{\beta} + 1 \right) = 20351.64 \qquad (12)$$

The value of 20351.64 cycles represents the valve's lifetime of well functioning in conditions of first trial within Taguchi test plan.

2.The Median:

$$T_{median} = \gamma + \eta \cdot (\ln 2)^{\frac{1}{\beta}} = 20415.9 \qquad (13)$$

T_{median} represents the median cycles value of the experimental data

3.The Mode:

$$T_{mode} = \gamma + \eta \cdot \left(1 - \frac{1}{\beta} \right)^{\frac{1}{\beta}} = 20624.34 \qquad (14)$$

This value represents the maximum cycles value of probability density function, represented in figure 6, and may be explained as the maximum malfunctions per unit of time.

1.The Standard Deviation:

$$\Gamma_T = \eta \cdot \sqrt{\Gamma \cdot \left(\frac{2}{\beta} + 1 \right) - \left(\Gamma \cdot \left(\frac{1}{\beta} + 1 \right) \right)^2} \qquad (15)$$

$$= 3228.97$$

In figure number 6 is presented the probability density function.

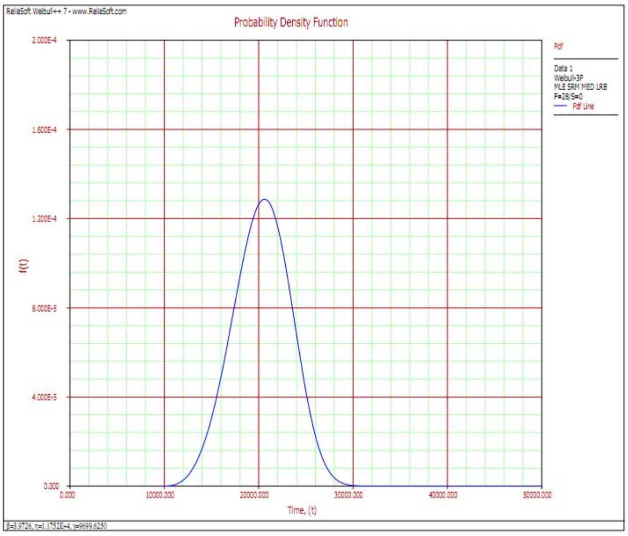

Fig. 6. Probability density function

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