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Guaranteed reliability sampling (GRS) plans for intermittent sampling inspection based on Lomax failure model

S Devaarul and Ramya D

Abstract
In this article an algorithm is proposed to guarantee reliability on the products during testing and hence a decision is made on batches based on the results of type-I censoring. The operating reliability rate for intermittent testing is derived and the necessary proofs are given. The efficiency measure values are compared with existing reliability sampling plans. It is found when the reliability increases then the probability of rejection decreases which is satisfactory for producers. Consumers are also happy with the new algorithm since a guaranteed reliability is obtained through these reliability sampling plans. Tables are constructed to facilitate easy implementation of reliability plans. Illustrations are presented so as to select the relevant reliability sampling plans.

Keywords: Type I censoring, intermittent testing, guaranteed reliability sampling, lomax distribution, operating reliability rate

1. Introduction

Reliability sampling plans are widely utilised in life testing experiments to determine the acceptability of a lot or a particular batch in a testing process. In reliability sampling plans, a set of test units are chosen randomly and they are subjected to certain test procedures. Then based on the results the set of units or batches are either accepted or rejected. But there is no guarantee for the reliability of the units in the lot during intermittent testing. Customer does not have the knowledge about the reliability of the products. Hence to offset the disadvantages in reliability sampling plans, guaranteed reliability sampling plans are being developed. In this article, a special type of reliability sampling plans called, Guaranteed Reliability Sampling (GRS) plans are developed based on Lomax life distribution. Reliability models are generally defined by life time random variables and their corresponding distributions. The intermittent testing reliability sampling plans are being designed with the assumption that the life of the units follows a Lomax distribution. Lomax distribution is a Pareto distribution of second kind and is used in life testing experiments in the recent years because of wide applications in reliability engineering.

In the lifetime context the main advantages of the Lomax model is that it belongs to the family of decreasing failure rate, for details please refer Chahkandi and Ganjali [1]. It arises as a limiting distribution of residual lifetimes during wear and tear period, see, Balkema and de Hann [2]. It was originally introduced for modelling business failure data and now it has wide variety of applications in quality and life testing arena. Hence Lomax failure distribution is augmented in determination of minimum assured reliability before disposing the lots or batches.

Devaarul [3] developed new type of Reliability Sampling Plans based on exponential model. Devaarul and Jemmy Joyce [4] have developed reliability sampling plans based on minimum angle technique. Suresh and Devaarul [5] developed maximum acquired reliability sampling plans. Lomax [6] introduced this distribution in the analysis of business failure data. Kim and Yum [7] suggested that a reduction in testing effect and administrative convenience may be obtained by using intermittent inspection whereby items are inspected only at certain points of time. Park and Yum [8] developed Reliability Acceptance Sampling Plans assuming that degradation tests are conducted at the use with two accelerated stress conditions. Kantam and Rosaiah [9] suggested acceptance sampling plans based on life tests when the failure density model of the products is half the logistic distribution. Kantam, Rosaiah, and Rao [10] studied the acceptance sampling based on life tests when the failure density model of the products is a log-logistic distribution. Mughal *et al.* [11] developed economic reliability group acceptance sampling plans for life times following a Marshal-Olkin extended distribution. Lio, Sai and Wu [12] developed acceptance sampling plans from truncated life tests based on the Burr type XII percentiles. Al- Awadhi and Ghitany [13] has derived a discrete distribution called Poisson Lomax, based on mixing a Poisson parameter with Lomax distribution. Childs, Balakrishnan, and Moshref [14] derived some recurrence relations for the single and the product moments of order statistics from n independent and non-identically distributed Lomax and right-truncated Lomax random variables. Hassan and Al. Ghamdi [15] determined optimal times of changing stress level for simple stress level under a cumulative exposure model using Lomax distribution for a wide range of values of the model parameters. Cramer and Schmiedt [16] developed progressively type-II censored competing risks data from Lomax distributions. Soundarrajan [17] has developed MAPD single sampling inspection by attributes plan. Fertig and Mann [18] discussed life test sampling plans for two parameter Weibull populations. Bassiouny, Abdo and Shahen [19] proposed a new generalization of Lomax distribution called Exponential Lomax distribution. Many authors have proposed various types of reliability sampling plans to suit industries. But the literature is scarce in the development of sampling plans which guarantees reliability. Hence GRS Plans are being developed and is suitable for increasing or decreasing failure rate hazard model.

A random variable t is said to follow the Lomax distribution, if the probability density function (pdf) of Lomax distribution is defined as follows:

$$f(t,\alpha,\lambda)=\frac{\alpha}{\lambda}\left(1+\frac{t}{\lambda}\right)^{-(\alpha+1)},t>0,(\alpha,\lambda)>0 \quad (1)$$

The cumulative distribution function (cdf) of Lomax distribution is given by,

$$F(t,\alpha,\lambda)=1-\left(1+\frac{t}{\lambda}\right)^{-\alpha},t>0,(\alpha,\lambda)>0 \quad (2)$$

where λ is the scale parameter and α is the shape parameter.

1.1 Formulation of the plan

Let r_m be the reliability of each component in the lot. Let n denote the number of units tested in time period t and x, $0 \le x \le n$, denote the number of successful units at time period t. Thus r_m is the chance that any item tested during period t will result in a success, or it is reliable towards success such that r_m= 1-F(x, λ, α) = 1-p. In sampling plan literature, the probability of acceptance of the batch or process if r_m is reliability is given as

$$P_a(p)=\sum_{x=0}^{c}\binom{n}{x}p^x(1-p)^{n-x} \quad (3)$$

Where $$p=1-\left(1+\frac{t}{\lambda}\right)^{-\alpha} \quad (4)$$

When x is the minimum number of survival units required in the sample before acceptance of the batch then the probability of rejection is given by

$$P(r)=1-\sum_{x=0}^{c}\binom{n}{x}p^x(1-p)^{n-x} \quad (5)$$

And also $$r_m=1-p=\left(1+\frac{t}{\lambda}\right)^{-\alpha},t>0,(\alpha,\lambda)>0 \quad (6)$$

If α is the producer risk then $P_a(r_m)\ge 1-\alpha$ (7)

If β is the consumer risk then $P_a(r_m)\le \beta$ (8)

If α, β and r_m are known, one can determine the smallest value of n, and the largest value of x_t such that the batch is accepted if the number of survival $S = x_t \ge x_t^*$. But in testing, the reliability r_m may or may not depend on time t and is unknown. Hence to overcome this disadvantage, r_m is determined using simple calculus.

1.2 Algorithm for sentencing a batch or process

Step 1: Draw a random sample of size n and put them into life test for specified time t (type I censoring)
Step 2: Count the number of specimens successful in the test. Let it be S.
Step 3: If $S \geq x^*$ accept the batch or lot.
Step 4: If $S < x^*$ reject the batch or lot.
Step 5: Rejected lots are sent to rework or scrap section.

1.3 Designing GRS Plans

The Probability of rejection of batches if r_m is reliability with type II probabilities is defined as

$$P(r) = 1 - \sum_{x=0}^{c} \frac{e^{-np}(np)^x}{x!} \tag{9}$$

When 'c'is the acceptance number and n is the sample size then the tangent to the probability of rejection curve at the deflection point touches the x-axis at

$$r_t = \left(1 - \frac{c}{n}\right) + \frac{c!}{nc^c e^{-c}}\left(1 - \sum_{x=0}^{c} \frac{e^{-c} c^x}{x!}\right)$$

1.3.1 Equation of tangent

Equation of tangent passing through $\left(1 - \frac{c}{n}, 1 - \sum_{x=0}^{c} \frac{e^{-np}(np)^x}{x!}\right)$ with slope $\frac{n(np)^c e^{-np}}{c!}$ is given by the equation

$$f(r_t) - \left(1 - \sum_{x=0}^{c} \frac{e^{-np}(np)^x}{c!}\right) = -\frac{n(np)^c e^{-np}}{c!}\left(r_t - \left(1 - \frac{c}{n}\right)\right) \tag{10}$$

The root of the above equation is obtained by equating $f(r_t) = 0$

$$r_t - \left(1 - \frac{c}{n}\right) = -\frac{c!}{n(np)^c e^{-np}}\left(1 - \sum_{x=0}^{c} \frac{e^{-np}(np)^x}{x!}\right)$$

$$r_t = \left(1 - \frac{c}{n}\right) - \frac{c!}{n(np)^c e^{-np}}\left(1 - \sum_{x=0}^{c} \frac{e^{-np}(np)^x}{x!}\right) \tag{11}$$

At the deflection point, $n(1-r_m) = np = c$ (12)

therefore the point at which the tangent touches the x-axis is given by

$$r_t = \left(1 - \frac{c}{n}\right) - \frac{c!}{nc^c e^{-c}}\left(1 - \sum_{x=0}^{c} \frac{e^{-c}(c)^x}{x!}\right) \tag{13}$$

Similarly,
If 'c' is the acceptance number and n is the sample size then the normal to the probability of rejection curve at the deflection point touches the x-axis at $r_n = \left(1 - \frac{c}{n}\right) - \frac{ne^{-c}c^c}{c!}\left(1 - \sum_{x=0}^{c} \frac{e^{-c}c^x}{x!}\right)$

1.3.2 Equation of normal

Equation of the normal passing through $\left(\left(1 - \frac{c}{n}\right), 1 - \sum_{x=0}^{c} \frac{e^{-np}(np)^x}{x!}\right)$ with slope $-\frac{c!}{n(np)^c e^{-np}}$ is given by the equation

$$f(r_n)-\left(1-\sum_{x=0}^{c}\frac{e^{-np}(np)^x}{x!}\right)=-\frac{c!}{n(np)^c e^{-np}}\left(r_n-\left(1-\frac{c}{n}\right)\right) \tag{14}$$

The root of the above equation is obtained by equating $f(r_n)=0$

$$r_n-\left(1-\frac{c}{n}\right)=\frac{n(np)^c e^{-np}}{c!}\left(1-\sum_{x=0}^{c}\frac{e^{-np}(np)^x}{x!}\right)$$

$$r_n=\left(1-\frac{c}{n}\right)+\frac{n(np)^c e^{-np}}{c!}\left(1-\sum_{x=0}^{c}\frac{e^{-np}(np)^x}{x!}\right) \tag{15}$$

At the deflection point, $n(1-r_m)=np = C$ (16)

therefore, the point at which the normal touches the x-axis is given by

$$r_n=\left(1-\frac{c}{n}\right)+\frac{ne^{-c}c^c}{c!}\left(1-\sum_{x=0}^{c}\frac{e^{-c}c^x}{x!}\right) \tag{17}$$

Differentiating Equation (9) with respect to p twice and equating to zero, we get

$$\frac{d(P(r))}{dp}=\frac{n(np)^c e^{-np}}{c!} \tag{18}$$

$$\frac{d^2(P(r))}{dp^2}=\frac{n(np)^c e^{-np}}{c!}\frac{(c-np)}{p}=0 \tag{19}$$

The Guaranteed reliability in the lot is obtained from Equation (19), Since

$$p=\frac{c}{n} \tag{20}$$

Hence $$r_m=1-p=1-\frac{c}{n}=\frac{n-c}{n}=\frac{s}{n} \tag{21}$$

Therefore the minimum sample size required is

$$n=\frac{c}{(1-r_m)} \tag{22}$$

1.3.3 Operating reliability rate at tangent point

Let the operating reliability rate of the tangent be $z_t=\frac{r_t}{r_m}$ (23)

Using equation (13) and equation (21), we get

$$z_t=\frac{\left(1-\frac{c}{n}\right)-\frac{c!}{nc^c e^{-c}}\left(1-\sum_{x=0}^{c}\frac{e^{-c}(c)^x}{x!}\right)}{1-\frac{c}{n}} \tag{24}$$

Hence $$z_t = \frac{r_m - \frac{(1-r_m)(c-1)!}{c^c e^{-c}}\left(1-\sum_{x=0}^{c}\frac{e^{-c}(c)^x}{x!}\right)}{r_m} \quad (25)$$

1.3.4 Operating reliability rate at normal point

Let the operating reliability rate of the normal be $Z^* = \frac{r_m}{r_n}$ (26)

using equation (17) and equation (21), we get

$$Z^* = \frac{1-\frac{c}{n}}{\left(1-\frac{c}{n}\right)+\frac{ne^{-c}c^c}{c!}\left(1-\sum_{x=0}^{c}\frac{e^{-c}c^x}{x!}\right)} \quad (27)$$

Hence $$Z^* = \frac{r_m}{r_m + \frac{c^c e^{-c}}{(1-r_m)(c-1)!}\left(1-\sum_{x=0}^{c}\frac{e^{-c}c^x}{x!}\right)} \quad (28)$$

2.1 Selection of Termination Time

The parameters of the heavy tailed distribution are λ and α in case of Lomax distribution. Hence the cumulative failure rate values are simulated using MATLAB program for the known Scale and Shape parameters of the Lomax distribution. Twenty random values were generated and hence the corresponding F(t) values are obtained using equation (2). Thereafter r_m is obtained from equation (6). For the specified shape parameter the different tables are constructed in order to make easy selection of reliability sampling plans.

The following are the steps involved in simulating values using MATLAB program:

Step 1: The random number for Lomax distribution works in the randraw.m option.

Step 2: In the MATLAB command window type the following script:
Y = randraw ('pareto2',[0,5,2.4], 20);
The 'pareto2' option is used for Lomax distribution because Lomax is a pareto second type distribution.

Step 3: When executing the call in step 2, it produces 20 random numbers which has the scale parameter as 0.5 and shape parameter as 2.4.

Step 4: In order to get more random numbers the sample size could be increased.

Step 5: These random numbers so generated are taken as t/λ values and used for construction of tables.

2.2 Construction of tables

(i) Table 1 & 2: The operating reliability rates of tangent (Z_t) are obtained by using Equation (24) for the known survival units and are presented in Table 1. The operating reliability rates for the normal (Z^*) are obtained by using Equation (27)and are presented in Table 2.

(ii) Table 3& 4: The required sample size n for making a decision with different r_m and t/λ values are obtained for GRS plans by using Equation (22). The values are given in Table 3 along with the number of maximum allowable failures C and α=2. Substituting the r_m values in Equation (2) the corresponding values of t/λ is calculated and given in the Table 4.

(iii) Table 5: For the known t/λ values of r_m are calculated using Equation (6) and there by the probability of rejection is calculated using Equation (9). From Table 5 one can find that whenever t/λ increases r_m decreases. Hence the research is intended in finding the minimum reliability required for acceptance of a lot.

Table 1: Operating Reliability Rates (Z_t) for α=2, Known Acceptance Number (C) & the Termination Time t/λ at Tangent

t/λ	F(t)	r_m	C	Z_t
0.0038	0.0076	0.9924	1	0.9945
0.0414	0.0779	0.9221	2	0.9495
0.0623	0.1139	0.8861	3	0.9326
0.0713	0.1287	0.8713	4	0.9299
0.1275	0.2134	0.7866	5	0.8813
0.1496	0.2433	0.7567	6	0.8686
0.1531	0.2479	0.7521	7	0.8732
0.1583	0.2547	0.7453	8	0.8753
0.1586	0.2550	0.7450	9	0.8809
0.1648	0.2629	0.7371	10	0.8811

Table 2: Operating Reliability Rates (Z*) known Acceptance Number (C) & the Termination Time t/λ at Normal

t/λ	F(t)	r_m	C	Z^*
0.0038	0.0076	0.9924	1	0.0716
0.0414	0.0779	0.9221	2	0.2910
0.0623	0.1139	0.8861	3	0.2985
0.0713	0.1287	0.8713	4	0.2788
0.1275	0.2134	0.7866	5	0.3325
0.1496	0.2433	0.7567	6	0.3267
0.1531	0.2479	0.7521	7	0.3082
0.1583	0.2547	0.7453	8	0.2944
0.1586	0.2550	0.7450	9	0.2797
0.1648	0.2629	0.7371	10	0.2709

Table 3: Minimum Sample Sizes Necessary to Assume the Average Life to Exceed a Given Value, t/λ and the Corresponding Allowable Failures C, with α=2.

t/λ	F(t)	r_m	C=1	C=2	C=3	C=4	C=5	C=6	C=7	C=8	C=9	C=10
0.0038	0.0076	0.9924	132	265	397	529	662	794	926	1059	1191	1323
0.0414	0.0779	0.9221	13	26	38	51	64	77	90	103	115	128
0.0623	0.1139	0.8861	9	18	26	35	44	53	61	70	79	88
0.0713	0.1287	0.8713	8	16	23	31	39	47	54	62	70	78
0.1275	0.2134	0.7866	5	9	14	19	23	28	33	37	42	47

Table 4: Life Test Termination Time (t/λ) for Lomax Distribution with α=2.

C \ n	20	30	40	50	60	70	80	90	100
1	0.0260	0.0171	0.0127	0.0102	0.0084	0.0072	0.0063	0.0056	0.0050
2	0.0541	0.0351	0.0260	0.0206	0.0171	0.0146	0.0127	0.0113	0.0102
3	0.0847	0.0541	0.0398	0.0314	0.0260	0.0221	0.0193	0.0171	0.0153
4	0.1180	0.0742	0.0541	0.0426	0.0351	0.0299	0.0260	0.0230	0.0206
5	0.1547	0.0954	0.0690	0.0541	0.0445	0.0377	0.0328	0.0290	0.0260
6	0.1952	0.1180	0.0847	0.0660	0.0541	0.0458	0.0398	0.0351	0.0314
7	0.2403	0.1421	0.1010	0.0783	0.0640	0.0541	0.0468	0.0413	0.0370
8	0.2910	0.1677	0.1180	0.0911	0.0742	0.0626	0.0541	0.0476	0.0426
9	0.3484	0.1952	0.1359	0.1043	0.0847	0.0712	0.0615	0.0541	0.0483
10	0.4142	0.2247	0.1547	0.1180	0.0954	0.0801	0.0690	0.0607	0.0541

Table 5: Probability of Rejection Values of The Reliability Sampling Plan Under Lomax Distribution for the Known Termination Time (t/λ) (α=2, n=10) with Guaranteed Reliability.

t/λ	F(t)	Reliability (r)	Probability of Rejection P(r)
0.0038	0.0076	0.9924	0.0006
0.0414	0.0779	0.9221	0.0445
0.0623	0.1139	0.8861	0.1075
0.0713	0.1287	0.8713	0.1399
0.1275	0.2134	0.7866	0.3595
0.1496	0.2433	0.7567	0.4390
0.1531	0.2479	0.7521	0.4508
0.1583	0.2547	0.7453	0.4681
0.1586	0.2550	0.7450	0.4690
0.1648	0.2629	0.7371	0.4889
0.1660	0.2645	0.7355	0.4927
0.1758	0.2767	0.7233	0.5226
0.1758	0.2767	0.7233	0.5226
0.2185	0.3265	0.6735	0.6335
0.3136	0.4205	0.5795	0.7904
0.4473	0.5226	0.4774	0.8931
0.6533	0.6342	0.3658	0.9516
0.7064	0.6566	0.3434	0.9590
1.6295	0.8554	0.1446	0.9911
2.7647	0.9294	0.0706	0.9951

2.3 Reliability Curve for Lomax distribution

In support to Table 5 a graph is presented in Fig. 1 by taking the reliability of the lot or batch in x-axis and the probability of rejection in y-axis. In the Fig. 1the point at which the tangent touches the x-axis is taken as r_t and the point at which the normal touches the x-axis is taken as r_n. At the intersection of the tangent line, normal line and the reliability curve, a line is drawn towards the x-axis and the point is denoted by r_m. This point r_m is the Minimum Assured Reliability. From the Fig.1 it can be observed that whenever the reliability of the lot increases, the Probability of rejection decreases.

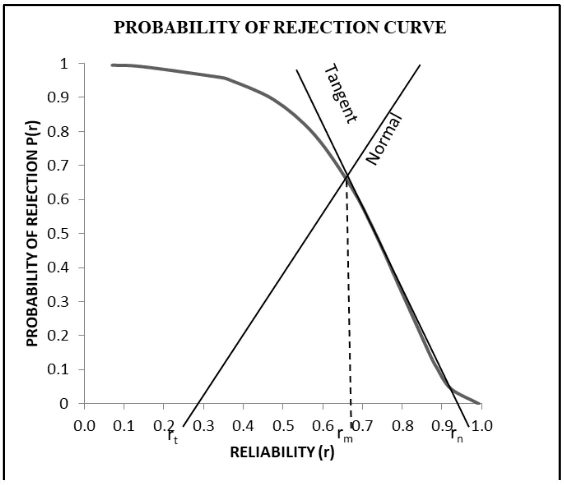

Fig 1: Probability of Rejection Curve

2.4 Illustration 1

In an electric bulb manufacturing company if the consumer expects an operating reliability rate Z^*as 0.3325 and if $t/\lambda = 0.1275$, determine the GRS – Lomax reliability sampling plan.

Solution:

From Table 1, the maximum allowable failures corresponding to the given operating reliability rate $Z^* = 0.3325$ is C = 5.

From Table 3 the minimum sample size for the given t/λ and the corresponding survival unit C = 5 is n=23. Hence S = n-C = 17.

Hence the algorithm for sentencing the lot is as follows:

Step 1: Draw a random sample of size 23 and put them into life test for a specified time 13 hours (t/λ=0.1275) under type I censoring.

Step 2: Count the number of specimens successful in the test. Let it be S.

Step 3: If S ≥ 5, the lot is accepted.

Step 4: If S < 5, the lot is rejected.

From Table 5, it is found that the Guaranteed Reliability is 0.7866 and the corresponding probability of rejection of the reliability sampling plan under Lomax distribution is 0.3595.

2.5 Comparative study

(i) Table 6: In the Table 6 the sample size values of two different plans namely GRS-Lomax plans and the ordinary log logistic plans are compared. It is evident from Table 6 that GRS plans require minimum sample sizes when compared to the Log- logistic plans. So these plans could be chosen to reduce the inspection cost and to get minimum assured reliability.

Table 6: Comparison of sample sizes for the two plans – MARS Lomax plans and Log logistic plans

t/σ	C	MARS Lomax (n)	Log- logistic (n)
0.628	1	2	16
0.942	2	3	14
1.257	3	4	13
1.571	4	5	13
2.356	5	5	13
3.141	6	6	14
3.927	7	7	15
4.712	8	8	16

2.6 Conclusion

In this article Guaranteed Reliability Sampling (GRS) plans using Lomax distribution have been developed for intermittent inspection. The drawback faced during the implementation of reliability sampling plans is eliminated by giving guaranteed reliability value to the customer. In industries once termination time is fixed, the reliability value fluctuates due to sporadic production and changes in number of failures. These drawbacks are eliminated in GRS Plans. The main advantage in GRS plan is that reliability is assured before accepting the lot or batches. Since the termination time is fixed based on past experience the cost of testing is also reduced. Another advantage is the reduction in the sample size which support lesser in cost of inspection. Hence one can make use of GRS-Lomax reliability sampling plans in any quality control section.

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