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OPERATING CHARACTERISTIC CURVES AND OTHER FEATURES OF TRUNCATED LIFE TESTS WITH REPLACEMENT

by
BENJAMIN EPSTEIN

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DEPARTMENT OF MATHEMATICS
WAYNE UNIVERSITY
DETROIT, MICHIGAN
1. Summary

In [1] we considered the properties of truncated life tests under the assumption that the underlying life distribution is exponential. The purpose of this report is to furnish some tables and graphs for the replacement case when items which fail are replaced at once by new items.

The underlying probability density function of life is assumed throughout to be

\[ f(x; \theta) = \frac{x}{\theta} e^{-x/\theta}, \quad x > 0, \theta > 0. \]

The test is started with \( n \) items drawn at random from (1). Any item which fails is replaced at once by a new item drawn from (1). The experiment is truncated at time \( T = \min(X_{T_0:n}, T_0) \), where \( X_{T_0:n} \) is the time (measured from the beginning of the experiment) when the \( r_0 \) th failure occurs and \( T_0 \) is a truncation time beyond which the experiment is not permitted to run.
2. Recapitulation of Necessary Formulae

We recall certain results proved in [1] concerning the truncated replacement situation. Briefly, it was shown that $\Pr(r=k|\theta)$, the probability of reaching a decision which requires exactly $k$ failures is given by

\begin{equation}
\Pr(r=k|\theta) = p(k; \lambda_\theta), \quad k = 0, 1, 2, \ldots, r_o-1
\end{equation}

and

\begin{equation}
\Pr(r=r_o|\theta) = 1 - \sum_{k=0}^{r_o-1} p(k; \lambda_\theta),
\end{equation}

where $p(k; \lambda_\theta) = \lambda_\theta^k e^{-\lambda_\theta}/k!$ and $\lambda_\theta = nT_o/\theta$.

While $E_\theta(r)$, the expected number of observations required to reach a decision can be written down at once from the definition of expectation, it is useful for computational reasons to use the formula

\begin{equation}
E_\theta(r) = \theta \left[ \sum_{k=0}^{r_o-2} p(k; \lambda_\theta) \right] + r_o \left[ 1 - \sum_{k=0}^{r_o-1} p(k; \lambda_\theta) \right].
\end{equation}

In this form one can use Molina's tables on the Poisson distribution [2].

Further $E_\theta(T)$, the expected waiting time to reach a decision, is related to $E_\theta(r)$, by the formula

\begin{equation}
E_\theta(T) = \theta E_\theta(r).
\end{equation}

A useful quantity to tabulate is the ratio $E_\theta(T)/T_o$ (this must obviously be $\leq 1$). From the definition of $\lambda_\theta$ and (5) it follows at once that

\begin{equation}
E_\theta(T)/T_o = E_\theta(r)/\lambda_\theta.
\end{equation}
Suppose we use the following rule of action:

(i) If \( \min(X_{r_0:n} T_0) = X_{r_0:n} \) (i.e., \( r_0 \) failures occur before time \( T_0 \)),

reject the hypothesis that \( \theta = \theta_0 \).

(ii) If \( \min(X_{r_0:n} T_0) = T_0 \) (i.e., the \( r_0 \)th failure occurs after time \( T_0 \)),

accept the hypothesis that \( \theta = \theta_0 \). Then \( L(\theta) \), the probability of accepting \( \theta = \theta_0 \) when \( \theta \) is the true value, is simply

\[
L(\theta) = \sum_{k=0}^{r_0-1} p(k; \lambda_0).
\]

It is convenient to express various features of the test procedures in terms of the dimensionless parameter \( \lambda = nT_0/\theta \). In Table 1 we give \( L(\lambda) \), \( E(\lambda) \), and \( E(\lambda)/T_0 \) for \( r_0 = 1(1)20(5)100 \). Graphs of each of these functions are given for \( r_0 = 1(1)10(5)25 \) in Figures 1, 2, and 3. The tables and figures are useful in all cases where \( r_0 \), \( T_0 \), and \( n \) are preassigned.

The extension of the tables beyond the values tabulated can be easily performed, since for sufficiently small \( \lambda \), \( E(\lambda) \sim \lambda \) and \( E(\lambda)/T_0 \sim 1 \).

For sufficiently large \( \lambda \), \( E(\lambda) \sim r_0 \), and \( E(\lambda)/T_0 \sim (r_0/\lambda) \).

It often happens in practice that it is important to preassign the truncation time \( T_0 \). This involves finding a truncated replacement test (i.e., a suitable \( r_0 \) and \( n \)) whose operating characteristic curve is such that \( L(\theta_0) = 1-\alpha \) and \( L(\theta_1) \leq \beta(\theta_0 > \theta_1) \). Now it can easily be shown that the

\[
L(\theta) \text{ is the ordinate of the operating characteristic curve of the test procedure.}
\]
best(2) acceptance region (of size $\alpha$) for $H_0$ based on the first $r$ out of $n$ failures, is for preassigned $r$ and $n$, given by (3)

$$X_{r,n} > 0 = \theta_o \chi^2_{1-\alpha}(2r)/2n.$$

In order that the test based on this acceptance region have an operating characteristic curve for which $L(\theta_o) = 1-\alpha$ and $L(\theta_1) \leq \beta$, we need to choose $r$ suitably. The appropriate values for $r$ (which we call $r_o$) are given in Table 2. A decision rule based on (8) is clearly truncated with truncation time $C$. In order to truncate experimentation at $\min[X_{r_o}n,T_o]$ it is necessary to choose $n$ suitably. For all practical purposes one can choose $n$ as

$$n = \left[ o \chi^2_{1-\alpha}(2r_o)/2T_o \right]$$

where $[x]$ means the greatest integer $\leq x$. If this value of $n$ is used, it is easy to verify that using $X_{r_o,n}$ as the acceptance region for $H_0$ will result in having $L(\theta_o) \geq 1-\alpha$, but $L(\theta_1)$ might in some cases be slightly $> \beta$. (4)

It is interesting to note that the appropriate $n$ (for fixed $\alpha$ and $\beta$) is

(2) In the sense of Neyman and Pearson.

(3) We denote a chi-square variable with $n$ degrees of freedom as $\chi^2_n$ and define $\eta$ such that $Pr(\chi^2_n > \eta) = \gamma$ as $\eta = \chi^2_n(\gamma)$. $n$

(4) This could be avoided easily by giving the experimenter the freedom to use instead of $T_o$, the slightly larger truncation time $T'_o = \theta_o \chi^2_{1-\alpha}(2r_o)/n$, where $n$ is given by (9). The test based on using $X_{r_o,n} > T'_o$ as acceptance region for $H_0$ will have $L(\theta_o) = 1-\alpha$ and $L(\theta_1) \leq \beta$. If one uses $n+1$ items throughout the test, then one could use instead of $T_o$, the slightly smaller truncation time $T'_o = \theta_o \chi^2_{1-\alpha}(2r_o)/(n+1)$. The test based on using $X_{r_o,n+1} > T'_o$ as acceptance region for $H_0$ will have $L(\theta_o) = 1-\alpha$ and $L(\theta_1) \leq \beta$. 


inversely proportional to the time of truncation, $T_o$. Thus, e.g., to reduce
the truncation time by a factor of two requires doubling $n$.

3. Numerical Examples

Problem 1. A sample of 20 tubes is drawn at random from a lot
whose life is assumed to follow the exponential density (1). Tubes that fail
are replaced at once by new tubes drawn from the lot. The following rule of
action is followed: If 2 failures occur before 500 hours have elapsed, the
test is stopped as soon as the second failure has occurred and the lot is
rejected. If, however, 500 hours have elapsed before 2 failures have occurred,
the test is stopped at 500 hours and the lot is accepted.

Question 1: What is the probability of accepting a lot whose mean
life $\theta = 2000$ hours? What is the expected number of hours required to make
the decision if $\theta = 2000$? How many items will be failed on the average if
$\theta = 2000$? Using Table 1 and noting that $n = 20$, $r_o = 2$, and $T_o = 500$, it is
clear that $\lambda = nT_o/\theta = 5$. Hence the probability of accepting a lot with
$\theta = 2000$ is $0.04$. The expected waiting time to reach a decision is 185 hours
and the expected number of failures is 1.95.

Question 2: Same as question 1 for $\theta = 10,000$ hours. In this
case $\lambda = 1$. The probability of accepting the lot is 0.736, the expected
waiting time is 48 hours, and the expected number of items failed before
reaching a decision is 0.896.

Question 3: How large should $\theta$ be in order that there be a
probability that a lot with mean life $\theta$ is accepted 95% of the time? It is
easy to compute that this requires $\lambda = .355$. Hence from the relation
$\lambda = nT_o/\theta$, it follows that $\theta = 10,000/.355 = 28,170$. Hence a lot with a
mean life of 28,170 is accepted 95% of the time by this plan.
Question 4: Same as 3, except that we want the lot rejected 95% of the time. This requires $\lambda = 4.75$ and $\theta = 2105$ hours. Hence a lot having a mean life of 2105 hours will be rejected by this plan 95% of the time.

Problem 2. Find a truncated replacement plan for which $T_0 = 200$, and which will accept a lot with a mean life of 3000 hours, 90% of the time, and reject a lot with a mean life of 1000 hours, 90% of the time. In this case $\theta_0 = 3000$, $\theta_1 = 1000$, $\alpha = 0.1$. Since $\theta_0/\theta_1 = 3$, it follows from Table 2 that $r_0 = 6$. Consequently $n = \left[ \frac{\theta_0 \chi^2_{.05}(12)/100}{400} \right] = \left[ \frac{(3000)(6.301)}{400} \right] = 4.7$. Thus the following truncated replacement plan should be used: Start with $n = 4.7$ items. As soon as any item fails, replace it by a new one. Accept the lot if $\min \left[ x_{6,4.7}, 200 \right] = 200$ and reject the lot if $\min \left[ x_{6,4.7}, 200 \right] = x_{6,4.7}$. If the lot is rejected experimentation is stopped at $x_{6,4.7}$, the time of occurrence of the sixth failure. It is readily verified that this plan meets the conditions specified.
REFERENCES


Figure 1: Operating Characteristic Curve of Truncated Replacement Life Test
Figure 2: Expected number of failures required to reach a decision in truncated replacement life tests.
FIGURE 3: EXPECTED WAITING TIME TO REACH A DECISION IN TRUNCATED REPLACEMENT LIFE TESTS
Table 1

Characteristics of Truncated Replacement Procedures in the Exponential Case.

\( r_0 = 1 \)

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<th>( \lambda = \frac{r_0}{\theta} )</th>
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* The description of the test procedure is given in Sections 1 and 2 of this report. The definitions of \( r_0, T_0, \lambda \), and formulae for \( L(\lambda) \), \( E_{\lambda}(T) \), and \( E_{\lambda}(T)/T_0 \) are given in Section 2. A more detailed development of the underlying mathematics is given in [1].
\[ r_o = 2 \]

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\( \lambda = n \pi / \theta \)

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\begin{table}
\centering
\begin{tabular}{|c|c|c|c|}
\hline
$\lambda = \frac{n^2 \theta}{\theta}$ & $L(\lambda)$ & $E_\lambda(r)$ & $E_{\lambda(T)}/T_o$ \\
\hline
70 & 1.000 & 69.999 & 1.000 \\
75 & .997 & 74.992 & 1.000 \\
80 & .983 & 79.988 & .999 \\
85 & .939 & 84.771 & .997 \\
90 & .842 & 89.250 & .992 \\
92 & .765 & 90.878 & .988 \\
94 & .729 & 92.383 & .983 \\
96 & .645 & 93.748 & .977 \\
98 & .567 & 94.961 & .969 \\
100 & .487 & 96.015 & .960 \\
105 & .296 & 98.335 & .934 \\
110 & .158 & 99.169 & .902 \\
125 & .031 & 99.983 & .800 \\
150 & .000 & 100.000 & .667 \\
\hline
\end{tabular}
\caption{Table with data points for $r_o = 100$.}
\end{table}
Table 2
Values of \( r_o \) needed to meet the condition that the test based on using
\( X_{r_0,n} > c \) as acceptance region in the replacement case will have the
property that \( L(\theta_0) = 1-\alpha \) and \( L(\theta_1) \geq \beta \)

\[ \alpha = .01 \quad \alpha = .05 \]

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<th>( \beta = .05 )</th>
<th>( \beta = .10 )</th>
<th>( \theta_0/\theta_1 )</th>
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\[ \alpha = .10 \]

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