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(Accelerated Life Test and Reliability Growth Management Technique Within a Car Program)

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Abstract Accelerated life testing of a car is used to get information quickly on its life distribution. Test cars are run under severe conditions and fail sooner than under usual conditions. A model is fitted to the accelerated failure times and then extrapolated to estimate the life distribution under usual conditions. This paper presents an accelerated test and the reliability growth theory, and applies it to some subsystems of cars during their prototype and pilot testing. The data presented illustrates explicitly the prediction of the reliability growth in the product development cycle. The application of these techniques is a part of the product assurance function that plays an important role in product reliability improvement.

1. Introduction

Accelerated testing of a car is conducted to obtain a timely estimate of its real life or reliability under normal operating conditions. Such testing entails exposing a sample of that automobile to environmental conditions that significantly exceed, from the standpoint of severity, the normal environmental conditions under which it is expected to operate, thus causing the product to wear out or fail within a reasonable and measurable time frame. From this measured time frame, the car's real life or reliability can be determined through extrapolative means. The environmental profile representative of the accelerated test to be applied is developed heuristically by considering excessive levels of some combination of high or low temperature, temperature cycling rate, pressure, voltage, vibration, humidity, load, etc. The results obtained under the accelerated environmental conditions are then extrapolatively projected to obtain an estimate of the characteristic life distribution under normal environmental operating conditions.[6]

The automotive new product cycle is often characterized as an evolutionary process[4]. The knowledge gained from past product performance coupled with changing environmental, consumer and business demands establishes the requirements for future product designs. These requirements eventually take the form of specific product performance, cost and durability objectives through a long period of concept planning, reviews, cost trade-off and engineering analysis. Generally, about one year prior to a new product introduction, physical prototype models are manufactured and placed on development tests. The purpose of these development tests are to evaluate the product design, uncover the weak points and provide a means to evaluate design correction. During this development testing phase, design management is continually assessing the performance of the product against program objectives. Such characteristics as gradeability, acceleration, fuel economy, cooling, handling, etc. are generally easily measured and monitored. The design manager can directly compare these measurements to stated objectives.

This paper provides a practical application of

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accelerated test and reliability growth theory within a car development program from the specification of reliability goals to prediction, verification and analysis. Implementation of this kind of testing will provide very useful information on concept selection, product/process reliability, and cost effectiveness without too much time, money and engineering effort being spent on the development of failure suspect parts.[7] Recent experience with the testing of automotive components has led to a practical method for efficiently organizing, initiating, and monitoring a reliability growth test process under a competitive automobile environment.

2. Accelerated Test Development

An automotive company undertook a major redesign program for their car development program. The redesign program entailed a complete exterior appearance change and major improvements in power train and chassis components. In this program, the initial prototype testing is commenced approximately one year prior to model introduction. The prototype phase is preceded by numerous design analyses and laboratory tests on chassis and drive train components in an attempt to achieve the product performance and reliability objectives with the minimum amount of time and resource expenditure. However, the final proof of product performance is the completed car testing.

In order to compress the development time, accelerated tests are designed to represent the most demanding driver and include road and driving conditions that are expected to be experienced during the normal life of the product. One particular accelerated test which was used in the car development program was termed "2001 test". Customer usage data indicate that the 99th percentile drive would subject their automobile to an equivalent of 10,000miles of rough road driving(i.e. Belgian blocks, hills, railroad crossings, small pot holes, spalled concrete, gravel, etc.) for an application of 100,000 miles. This test is designed to evaluate the chassis system, power train, corrosion resistance, and general product durability. A summary of the "2001 test" is shown in Table 1.

The test car was driven the test track at a constant speed of 35miles per hour and calculated the amount of time as follows:

Application Time = 1 Hour/35 Miles × 10,000 Miles = 286 Hours

A non-accelerated vibration test based on this measured data, would require 12 days of shaker time to test each axis. Considering that we presently test 250 different groups of products each year, this would require that we employ 30 shakers to complete the required workload. To decrease the test time required and thus the number of shsakers required, we investigated the possibility of increasing the vibration levels.

Using the procedure outlined and the equations presented in "Institute of Environmental Sciences Tutorial Course[9] for MIL-STD-810D - Dynamic Environments Guide to Implementation" we accelerated the overall G rms levels by a factor of 2. The following equation was used to calculate the corresponding test time:

$$(1) \quad \left[\frac{Application\ Level\ (all\ Grms)}{Test\ Level\ (all\ Grms)}\right]^{\frac{2b}{n}} = \frac{Test\ Time(T_2)}{Application Time\ (T_1)}$$

Where b= 8.8 (Stress level between the endurance limit and ultimate limit)

n= 2.4 (Stress level below 80% of the endurance limit)

Therefore $(1/2)^{7.33}$ = Test time / 286 Hours

1.78 Hours = Test time

Table 1. Accelerated "2001 test" description summary

Test purpose:

1. To determine body, sheet metal, and chassis durability over an accelerated test schedule
2. To determine ride, handling, and general operational characteristics.

Test description:

Total accumulated test miles . . . . . 10,000 miles

Consisting of

Belgian block schedule . . . . . 2,500 miles

Hill durability . . . . 2,500 miles

General durability . . . . 5,000 miles

Vehicle test weight . . . . 115% G.V.W.

Some of the test conditions during each cycle include:

Wide open throttle acceleration up to 60 mph

Engine shut down and restart
Hill climb various grades including 11.6% grade
Various forward and reverse direction maneuvers
Transmission gear shifts throughout test
Parking brake applications
Twist ditches
Gravel and paved roads
Corrosion splash trough
Turn signal and windshield operations
Horn operations and light on-off operation

Using available warranty data, this level of acceleration and time correlated well to the field. To demonstrate that a product meets the reliability requirements, the test designer chooses a sample size which will provide him confidence in the reliability. A reliability level of 99.5%(for 10 years - 100,000 miles life) at a confidence level of 50% requires that 138 samples be tested at field levels for 286 hours with zero failures. This can be calculated using:

$$R^N = \alpha \tag{2}$$

where $1-\alpha$ = confidence level, α=significance level, R=reliability level, N=number of samples test with zero failures.

3. The Reliability Growth Management

3.1 The Growth Model

A reliability growth program is one which utilizes all development testing to find reliability problems. Testing may include functional testing, environmental testing, safety testing, performance testing, as well as mobility testing. In this way reliability improvement becomes integral and visible part of the development process and follows a strategy of a constant striving to make the system better.

The most commonly accepted pattern for reliability growth was first reported by J. T. Duane[3] in 1962. In his paper Duane discussed his observations on failure data for a number of systems during development testing. He observed that the cumulative failure rate versus cumulative operating time fell close to a straight line when plotted on log-log paper. The mathematical model is defined by

$$\log \rho_c(t) = \log \lambda - \alpha \log t$$

$$\rho_c(t) = \lambda t^{-\alpha} \tag{3}$$

where

$\rho_c(t)$= cumulative failure rate at time t

λ= constant

α= growth rate

t= total test time

In this model, the failure times would be followed by the exponential distribution and the cumulative MTBF(Mean Time Between Failure) would be

$$M_c(t) = [\rho_c(t)]^{-1} = \frac{1}{\lambda} t^{\alpha}, \quad t>0. \tag{4}$$

Therefore, we can rewrite this as

$$\log M_c(t) = \log \frac{1}{\lambda} + \alpha \log t \tag{5}$$

For an interpretation of these plots, let $D(t)$ denote the number of failures by time t, $t>0$. Then, the observed cumulative failure rate $\rho_c(t)$ at time t is equal to $\rho_c(t) = D(t)/t$. Hence, from Eq.(3), $D(t) = \lambda t^{1-\alpha}$.

The instantaneous failure rate, $\rho_i(t)$, of the system is the change per unit time of $D(t)$. That is,

$$\begin{aligned}\rho_i(t) &= dD(t)/dt \\ &= \lambda(1-\alpha)t^{-\alpha}\end{aligned} \tag{6}$$

and the instantaneous MTBF would be

$$M_i(t) = \frac{1}{\lambda(1-\alpha)} t^{\alpha}, \quad t>0 \tag{7}$$

From Eq.(4)&(7), the relationship between instantaneous and cumulative MTBF is given by

Time Period(hrs)	Observed failures	Cumulativ failures	Cumulativ failure rate	Cumulative MTBF
0 - 150	19	19	0.1267	7.8945
150 - 300	8	27	0.0900	11.1111
300 - 450	7	34	0.0756	13.2345
450 - 600	4	38	0.0633	15.7903
600 - 750	6	44	0.0587	17.0445
750 - 900	7	51	0.0567	17.6460

Table 3. Production test statistics

$$M_i(t) = \frac{1}{(1-\alpha)} M_c(t) \qquad (8)$$

Crow[2] considered the same mean value properties as the Duane postulate but formulated a probabilistic model for reliability growth as an NHPP (NonHomogeneous Poisson Process). The properties of NHPP satisfy all the conditions for a Poisson process except that the mean rate varies with time. The NHPP has been used widely as a model for a system subject to improvement[5].

If we let $D(s,t) = D(t) - D(s)$ be the expected number of failures over the time interval $[s,t]$, $t \geq s \geq 0$, then we would expect $D(s,t)$ to be

$$D(s,t) = \int_s^t \rho_i(t)dt = \lambda t^{1-\alpha} - \lambda s^{1-\alpha} \qquad (9)$$

Under the NHPP assumption, the probability that exactly m units will fail in any interval [s,t] has a Poisson distribution with mean $D(s,t)$. That is, for all $t \geq s \geq 0$

$$P_r\{X=m\} = \frac{[D(s,t)]^m e^{-D(s,t)}}{m!} \qquad (10)$$

where X is the number of failures in $[s,t]$.

3.2 Test Data Analysis

The first step in the application of the Duane growth model procedure is the determination of cumulative failure rate. Table 2 is constructed using a simulated prototype test data. The next task is to fit a straight line to the plotted data. Crow[1] suggests the ML (maximum likelihood) estimates of α and λ. The foregoing analysis results in the following quantities for the line of best fit for the prototype data $\hat{\lambda}$=1.2006 and $\hat{\alpha}$=0.4488. A plot is shown in figure 1. Thus, the reliability growth model for the prototype test and development program is $M_c(t) = \frac{1}{\lambda} t^{\alpha} = 0.8329 t^{0.4488}$.

Table 3 displays a simulated data for the production test statistics. Cumulative test statistics were plotted on log-log paper using the same procedure followed for the prototype analysis. This plot is shown in Figure 1. The ML estimates was used to determine the line of best fit to the plotted data. The resulting reliability growth rate model for the production design phase is $M_c(t) = 2.3436 t^{0.3034}$. Using these statistics and Eq.(6) the current failure rate estimate at the end of a one year production design test phase (2,100hrs.) is $M_i(2,100) = 34.2654$ test hours. The current MTBF with test hours can be converted to customers usage operating period in kilometers. If we consider the situation that the test was accelerated, the current MTBF of 34.2654 hours in the test would be 5959.20 km operating period.

Thus, reliability growth model reflects continued reliability growth during the production design phase but at a slower rate. Note that the rates are compared by considering the slopes (0.4488 versus 0.3034). Also the model has determined that the final production design MTBF (34.2654) is improved over the final prototype MTBF (32.0005).

3.3 Goodness-of-Fit Test

Practically it is desirable to test the compatibility

Time Period(hrs)	Observed failures	Cumulativ failures	Cumulativ failure rate	Cumulative MTBF
0- 150	14	14	0.0933	10.7181
150- 300	10	24	0.0800	12.5000
300- 450	8	32	0.0711	14.0647
450- 600	5	37	0.0617	16.2075
600- 750	7	44	0.0587	17.0358
750- 900	2	46	0.0511	19.5695
900- 1050	5	51	0.0486	20.5761
1050- 1200	3	54	0.0450	22.2222
1200- 1500	13	67	0.0447	22.3714
1500- 1800	12	79	0.0439	22.7790
1800- 2100	9	88	0.0419	23.8663

Table 2. Prototype test statistics

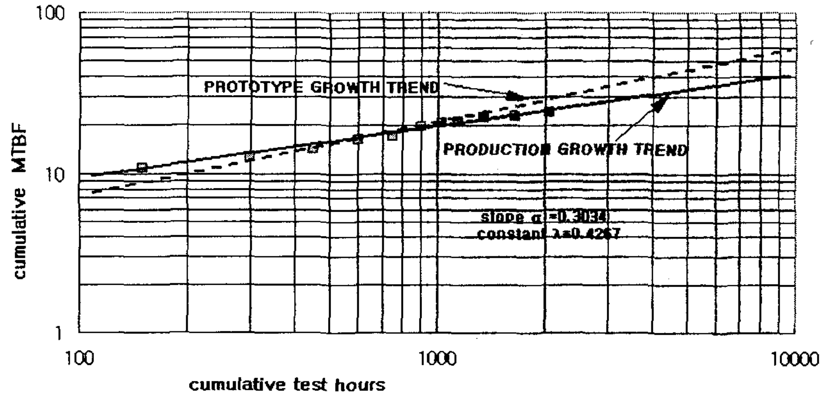

Figure 1. Production test growth trend

of a model and data by a statistical goodness-of-fit-test. One of the many goodness-of-fit tests for the exponential distribution can be used to assess the adequacy of the NHPP process. In fact any of the following tests could be applied after the appropriate modification is made [8].

- Anderson-Darling A2 Test
- Watson's U2 Test
- Kuiper's V Test
- Stephens's W* Test
- Shapiro-Wilk W Test

Crow[2] adapted a parametric Cramer-von Mises goodness-of-fit test for the multiple system NHPP model. This goodness-fit test is appropriate whenever the start times for each system is 0 and the failure data are complete over the continuous interval [0, t] with no gaps in the data. Although not as powerful as the Cramer-von Mises test, the Chi-squared test [2] can be applied under more general circumstances, regardless of the values of the starting times. It is particularly suited for the cases discussed in the vehicle development examples. This Chi-squared test uses the fact that the expected number of failures for a system over its testing time ($t_1,\ t_2$) is estimated by

$$D(t_1, t_2) = \lambda t_2^{(1-\alpha)} - \lambda t_1^{(1-\alpha)} \quad (11)$$

where $\hat{\lambda}$ and $\hat{\alpha}$ are the ML estimates.

If we illustrate this test for the situation of Table 1, the cumulative expected number of failures over the test interval t is $D(t) = \lambda t^{1-\alpha}$. For example, the expected number of failures over the test interval is estimated by

$$\hat{D}(t) = \hat{\lambda}\, 900^{\,1-\hat{\alpha}} = (1.2006)\, 900^{\,(1-0.4488)} = 51.024$$

where $\hat{\lambda}$ and $\hat{\alpha}$ are given in prototype test data analysis. To assess the statistical significance we compute the chi-square statistic

$$\chi^2 = \sum_{i=1}^{k} \frac{[N(s_i, t_i) - D(s_i, t_i)]^2}{D(s_i, t_i)} \qquad (12)$$

where k is the total number of intervals. The random variable χ^2 is approximately Chi-squared distributed with k-2 degrees of freedom. In this example, χ^2=1.9000, k=6, and the critical value at the 10 percent significance level for df=4 is 7.779.

3.4 Confidence Intervals on Growth Rate

Confidence intervals for the growth rate are now developed based on the following two different test situations, depending on how the data are recorded.

Recording failure times

First consider the test situation where failure times $t_1, t_2, \ldots, t_n$ are observed. In this case the quantity $2n(1-\alpha)/(1-\hat{\alpha})$ is Chi-square distributed with 2(n-1) degrees of freedom. Thus, an appropriate probability statement for a size 100(1-r)% is

$$P[\chi^2_{2(n-1), r/2} \le \frac{2n(1-\alpha)}{(1-\hat{\alpha})} \le \chi^2_{2(n-1), 1-r/2}] = 1 - r \qquad (13)$$

which can be algebraically changed to

$$\alpha_U = 1 - \frac{(1-\hat{\alpha})\chi^2_{2(n-1), r/2}}{2n} \qquad (14)$$

and

$$\alpha_L = 1 - \frac{(1-\hat{\alpha})\chi^2_{2(n-1), 1-r/2}}{2n} \qquad (15)$$

where $\chi^2_{\nu, \gamma}$ is the 100× γ% point of the chi-square distribution with ν degrees of freedom. It is often important to test the hypothesis $H_0: \alpha = \alpha_0$ versus $H_1: \alpha \neq \alpha_0$. Based on the result that a $2n(1-\alpha)/(1-\hat{\alpha})$ has Chi-square distribution with 2(n-1) degrees of freedom, a size 100(1-r)% test for testing any particular value of α can be constructed. The rule is to reject $H_0: \alpha = \alpha_0$ if either $\hat{\alpha} < 1 - 2n(1-\alpha_0)/\chi^2_{2(n-1), r/2}$ or $\hat{\alpha} > 1 - 2n(1-\alpha_0)/\chi^2_{2(n-1), 1-r/2}$.

Counting Failures Over a Time Interval

Let us assume that in a test situation we count the number of failures that occur over an interval of test time T. This situation could arise in practice in different ways. For example, we might have n test stands where we replace items as they fail and discontinue the test at a predetermined time. Or we might derive vehicles over a 40,000 km test schedule and elect to count failures rather than failure intervals.

In the above situation where we have observed n failures over an interval of test time T, the 100(1-r)% two-sided confidence interval is

$$\alpha_U = 1 - \frac{(1-\hat{\alpha})\chi^2_{2n, 1-r/2}}{2n} \qquad (16)$$

and

$$\alpha_L = 1 - \frac{(1-\hat{\alpha})\chi^2_{2n, r/2}}{2n}. \qquad (17)$$

For the data in prototype test data, $\hat{\alpha}$=.4488 and α_U=.5693, α_L=.3160 are 90% confidence bounds on α. A size 100(1-r)% test for $H_0: \alpha = \alpha_0$ versus $H_1: \alpha \neq \alpha_0$ is to reject if either $\hat{\alpha} < 1 - 2n(1-\alpha_0)/\chi^2_{2n, 1-r/2}$ or $\hat{\alpha} > 1 - 2n(1-\alpha_0)/\chi^2_{2n, r/2}$.

4. Conclusion

In this paper we provided an overview of practical application of accelerated test and reliability growth theory to the automobile development from the specification of reliability goals to prediction, verification and analysis. The presented analysis could be applied to successfully demonstrating the relationship between failure detection and corrective action, and the achievement of higher reliability designs. Examples and procedures specifically illustrating these methods were given for practical situations. In addition to maximum likelihood methods, goodness-of-fit tests and confidence interval procedures were discussed and illustrated by numerical examples. Specification of reliability growth and useful life and the application of the most important methods of prediction and analysis are also discussed with the aid of examples.

The development of accelerated test and selection of the growth model should be based on the type of process the car program follows. According to our survey on reliability growth models[5], the modified Duane model fits the application. We believe that these principle of test analysis are common to any automobile development program.

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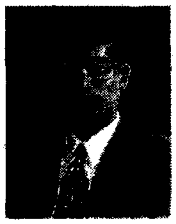

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