

How Stress Variance in the Automotive Environment will Affect a 'True' Value of the Reliability Demonstrated by Accelerated Testing

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ABSTRACT

This paper discusses the effect of the field stress variance on the value of demonstrated reliability in the automotive testing. In many cases the acceleration factor for a reliability demonstration test is calculated based on a high percentile automotive stress level, typically corresponding to severe user or environmental conditions. In those cases the actual field ('true') reliability for the population will be higher than that demonstrated by a validation test.

This paper presents an analytical approach to estimating 'true' field reliability based on the acceleration model and stress variable distribution over the vehicle population. The method is illustrated by an example of automotive electronics reliability demonstration testing.

KEYWORDS: accelerated testing, reliability demonstration, success based testing, sample size, stress variable, test to field correlation, user severity, population reliability, Weibull distribution

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INTRODUCTION

Product validation and reliability demonstration by test are important parts of product development and are commonly included in automotive technical documentation specifying certain levels of reliability needed to be demonstrated by a product testing. Most automotive product specifications contain reliability requirements expressed as some form of reliability metrics, such as reliability $R(t)$, B_{10} - life, PPM, MTBF or others. Demonstrating this metrics is often part of a product validation testing, either design validation (DV) or process validation (PV).

The two most common ways of demonstrating reliability are: success based testing and test-to-failure (see [Appendix](#)). However, the main limitation of the reliability demonstration testing (both success-based and test-to-failure) is in the required sample size (see [Appendix](#)). Therefore the reliability numbers demonstrated by either test are relatively low compared to what is typically required by product specifications on field reliability (often 99% and higher).

This problem often causes disputes between automotive OEMs and their suppliers and also generates additional, often unnecessary amount of testing. This issue however can be addressed by taking into account variation in the field stress and/or usage conditions (e.g. driving mileage, vibration level, temperature exposure, number of on/off cycles, etc.) If a test

simulates more severe conditions than the average, which is the way it is typically done in the automotive industry, then the actual field reliability will be higher than that demonstrated by a test.

General Motors in its 2004 version of the worldwide engineering standard GMW3172 [1] provided a field to test reliability conversion table based on Customer Variability Ratio (CVR) = 99.8th-ile/50th-ile Damage. This table was helpful in comparing the reliability demonstrated during the test to the expected field reliability, however it was not specific to product failure modes and acceleration factors and was removed from the later editions of GMW 3172.

However the need for mathematical models to correlate the demonstrated reliability to the 'true' field reliability has remained, which prompted the work presented in this paper.

ACCELERATED TESTING AND FIELD STRESS VARIATION

Field stress clearly has a strong effect on the reliability of parts subject to that stress. Since different units in a vehicle population will be subjected to different stress levels, their individual reliability functions will vary, therefore the reliability estimate should be treated as population reliability.

concept of population reliability vs. individual reliability has been discussed previously by Lu and Anderson-Cook in [2] and [3].

Clearly, the higher the stress level the sooner you would expect a device to fail. Davis [4] formulates the reliability as a mathematical function affected by a wide variety of possible noise factors (e.g. part to part variation, wear-out, duty cycles, etc.). In a similar fashion, taking into account the effect of stress variables, mentioned in Introduction, the reliability of a field population can be expressed as

$$R(t) = \int_t^\infty \int_{s \in S_n} f_{S_n}(t|s) f_n(s) dn dt$$

$$= \int_{s \in S_n} R_{S_n}(t|s) f_n(s) dn dt \quad (1)$$

where S_n = stress space with variables $s_1 \dots s_n$

$\int_{s \in S_n}$ = a multiple integral over the entire stress space S_n

$R_{S_n}(t|s) = \int_t^\infty f_{S_n}(t|s) dt$ denotes the reliability at time t conditional on a given point in the stress space.

The effect of stress on reliability can be modeled using the concept of acceleration factor. The acceleration factor (AF) is defined as a ratio of the expected life in un-accelerated (field) conditions to the expected life under accelerated (test) conditions (see for example Nelson [5] or O'Connor and Kleyner [6]):

$$AF = \frac{L_{Field}}{L_{Test}} \quad (2)$$

where L_{Field} and L_{Test} are the expected product lives in field and test conditions respectively.

Acceleration factor relationship with reliability function is often modeled as [6]

$$R_{Field}(t) = R_{Test}\left(\frac{t}{AF}\right) \quad (3)$$

where:

R_{Field} = Reliability under field conditions

R_{Test} = Reliability under test conditions.

t = time in the field

Accelerated testing is usually done based on either an increased usage rate (e.g. increased number of loading cycles, extended number of driven miles, higher duty cycle, etc.) or based on an increased stress level (e.g., elevated temperature, vibration, voltage, etc.). In either case, if the total product population has variation in a usage rate or a stress level, the acceleration factor will also vary. This paper will focus on the cases where tests are accelerated by increased stress levels, although the approach to the increased usage rate analysis is very similar.

The acceleration factor AF is a function of multiple stress variables comprising the stress space S_n , therefore $AF = AF(s_1 \dots s_n)$, and thus would vary for each unit in the population depending on the stresses experienced by that unit. Therefore, by combining (1) and (3) the overall field reliability for the population can be re-expressed as

$$R_{Field}(t) = \int_{s_1}^{s_{1max}} \dots \int_{s_n}^{s_{nmax}} R_{Test}\left(\frac{t}{AF(s_1 \dots s_n)}\right) [f_1(s_1) \dots f_n(s_n)] ds_1 \dots ds_n \quad (4)$$

Where:

s_{jmax} = maximum possible stress value for the variable s_j achieved in a product population

$f(s_j)$ = probability density function (pdf) of the s_j distribution in a vehicle population

Equation (4) assumes that an accelerated test is designed properly, i.e. it would precipitate failure modes and failure mechanisms consistent with those experienced by the product in the field. Also this type of consistency often manifests itself in similar failure distributions. For example, both field and test failures would often follow Weibull distribution with similar shape parameters β , but different scale parameters η (see Appendix)

Equation (4) is multivariate, however in many practical applications one dominant stress factor is often identified and applied to calculate the test acceleration factor. For example, for a temperature cycling test the temperature excursion ΔT is often used as the key stress variable, dynamic acceleration typically dominates vibration testing, maximum ambient temperature usually defines a high temperature endurance test

and so on. In the cases where the dominant stress variable can be identified see Frenkel et. al. Chapter 27 [7], the field reliability (4) can be reduced to a simplified equation:

$$R_{Field}(t) = \int_0^{S_{max}} R_{Test} \left(\frac{t}{AF(S)} \right) f(S) dS \quad (5)$$

where S is the dominant stress variable

If both field stress levels and product failures can be modeled as random variables with probability distributions, equation (5) can be re-written in a parametric form as

$$R_{Field}(t) = \int_0^{S_{max}} R_{Test} \left(\frac{t; \theta_R}{AF(S)} \right) f(S; \psi_S) dS \quad (6)$$

where:

$\theta_R = \{\theta_1 \dots \theta_q\}$ = vector of failure (reliability) distribution parameters (dimension q)

$\psi_S = \{\psi_1 \dots \psi_p\}$ = vector of stress distribution parameters (dimension p)

The parameters of vector θ_R can be estimated based on previously collected reliability data for the product under design/test or for products similar in design and applications.

Vector ψ_S characterizes the distribution of the field stress variable and its parameters can be determined based on field environmental studies.

The following case study will illustrate the application of this method to an automotive reliability demonstration testing.

MODELS FOR STRESS ENVIRONMENTS

In order to illustrate this method let us consider three most common automotive environments, which are also used in reliability demonstration testing: high temperature exposure, temperature cycling, and vibration. The acceleration models for those environments can be found in a large number of literature sources (see for example [6], Chapter 13)

High temperature acceleration is typically described by Arrhenius model:

$$AF_T = e^{\frac{E_A}{k} \left(\frac{1}{T_{field}} - \frac{1}{T_{test}} \right)} \quad (7)$$

Where:

E_A = activation energy (typically ranging between 0.3 - 1.2 eV for electronics)

k = the Boltzmann's constant (8.62×10^{-5} eV/K)

T = the absolute temperature (Kelvin)

The most commonly used acceleration model for temperature cycling (TC) is the Coffin-Manson, where the acceleration factor can be represented in a simplified form as

$$AF_{\Delta T} = \left(\frac{\Delta T_{Test}}{\Delta T_{Field}} \right)^m \quad (8)$$

where:

ΔT_{Test} = temperature range ($T_{Max} - T_{Min}$) of the TC

ΔT_{Field} = temperature range experienced in the field

m = Coffin-Manson exponent ($m=2.65$ is often used for Lead Free solder fatigue, see for example Arnold et. al. [8])

Vibration is often modeled by the $S-N$ curve, which is similarly to Coffin-Manson is a form of the inverse power law model.

$$AF_{Vib} = \left(\frac{g_{Test}}{g_{Field}} \right)^b \quad (9)$$

Where:

g = the acceleration amplitude in the case of sinusoidal vibration and g_{RMS} in the case of the random vibration

b = the fatigue exponent, often ranging between 4.0 and 7.0 depending on the material properties and the geometry of the vibrated parts.

To generate the real life models and to be able to calculate field reliability according to (6) we will use the statistical models commonly used in the automotive reliability engineering, i.e. two-parameter Weibull for reliability (see Appendix) and the lognormal distribution for the stress variables, which will be denoted here as $f(x; \mu, \sigma)$ or $LN(\mu, \sigma)$

In the case where field failures follow the two-parameter Weibull distribution (see Appendix equation (19)), field reliability according to (3) becomes