Mission Profile Clustering Using a Universal Quantile Criterion

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***Abstract*—The current trend in the automotive industry towards increasingly detailed and more granular mission profiles (MPs) is also giving rise to an enormous number of various MPs, distinguishing each individual application and use case imaginable. To keep an overview in the face of this flood of data, to filter out and select the qualification relevant MPs, and to create a suitable and simply designed reliability requirement, a MP clustering approach using a quantile criterion is presented. This generic approach is universally applicable and therefore not limited to the automotive industry.**

Based on equivalent test times (ETTs) and acceleration factors (AFs), after determining the quantile criterion, a representative MP can be selected either from an existing best fit MP or an artificially generated MP, obtained by numerical methods. Furthermore, the coverage of these MP requirements by technology reliability capabilities can be evaluated with ease. This approach is a generic concept and can therefore be applied to all well-known and commonly used damage accumulation and failure acceleration models. In the presented automotive case studies, the temperature accelerated Arrhenius model, multidimensional MPs with temperature and voltage acceleration, the temperature cycling Coffin-Manson model as well as a non-linear damage accumulation model are investigated.

***Keywords* — mission profile; reliability methodology; automotive electronics; reliability capability**

I. Introduction

IN the last years the automotive industry has seen one of the biggest changes in automotive history. In the future, the car will be a full electrical self-driving vehicle with high performance entertainment and therefore always connected with the digital world. For the electronic control units (ECUs) and semiconductor devices which will deliver these new functions, the requirements will become more and more complex.

Different types of stressors like temperature, electrical current and voltage, and mechanical or chemical stress are responsible for the aging of electronic components. The goal of the qualification of an ECU is to test and to guarantee that the devices can fulfill the requirements for the dedicated use case. For every relevant stressor a mission profile (MP) should exist which describes the application and environmental conditions in detail.

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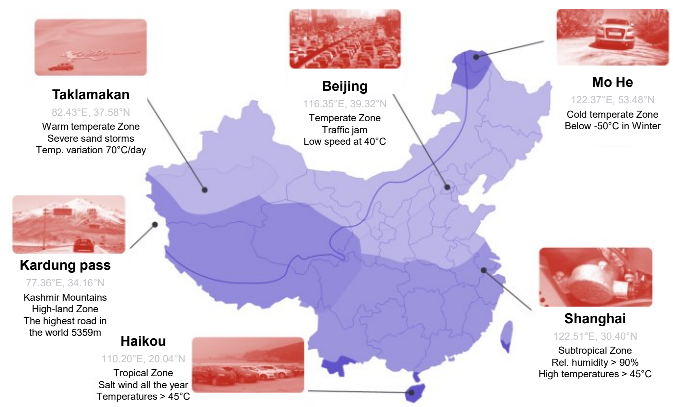

Fig. 1. Different environmental conditions in China.

To create a MP for an electronic component, first, the automotive original equipment manufacturer (OEM) has to define a set of application MPs. A MP example is the thermal budget for automotive electronic devices. In the past, the power-on times of such components have been commonly specified with 8 000 h [1]. In the future, the average active times of ECUs will become longer. For example, 54 000 h for charging applications and up to 136 000 h for always-on control units. In addition, the future temperature MP is more complex, since it does not represent a single uniform temperature distribution but a set of temperature–time data, in which different temperatures are weighted with different ratios. This leads to a significant amount of MP raw data just for the thermal budget.

An OEM first defines the target geographies where his future vehicles will be used. At different geographical locations, different climatic conditions exist. Even in a single but geographically diverse country, very different environmental conditions with respect to temperature, humidity, elevation, chemical loads etc. are found (Fig. 1). Even at the same geographical location, these conditions change during the day and throughout the year. Furthermore, there are various kinds of vehicle drivers, use cases and traffic laws in different countries. All these circumstances lead to a large number of individual MPs on the OEM's side. Every vehicle has to work reliably and robustly for the intended set of use cases and reliability and robustness targets.

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In the next steps within the supply chain, the OEM's upstream suppliers, denoted as Tier 1 ... n, break down the MPs from the OEM or their respective downstream Tier $n-1$ to specific MPs for every single sub-component of the electronic system. This assessment and design step is necessary since every sub-component will receive a different amount of local stress, which is different from the initial MP of the OEM or Tier $n-1$. This breakdown leads to a further, rather explosive, increase in the number of sub-component specific MPs on Tier n level due to the potentially large sizes of the respective design spaces.

As is obvious from our statements above, the automotive OEM cannot build different vehicles for each individual use case and MP. The same holds for the Tier n, since they cannot build system components just for one use case or one OEM or one Tier $n-1$. The examples in the previous passages show that the number of MPs that are used and communicated within the supply chain need to be limited to a needful set. An approach to this problem is to create or select a small set of representative MPs which cover the relevant application MPs. The selected MPs must be extensive enough to cover a wide range of stresses and consequently a lot of different applications, but on the other hand they should not lead to over- or under-engineering of the electronic components with respect to reliability and robustness.

The goal of this paper is to demonstrate how MPs can be clustered using a universal quantile criterion and how a small set of representative MPs used in the supply chain can be either chosen or mathematically derived.

II. Deriving Effective Stresses from Mission Profiles

In order to reduce and cluster MP requirements to useful abstraction levels like effective stress or equivalent test time (ETT) at a specified stress level, a few conditions have to be met. As already deduced in [2], for linear cumulative damage models like the cumulative exposure model [3] or the tampered random variable model [4], an effective acceleration factor (AF) can be derived for a specific mission profile. This method is independent of the acceleration model or equation which is used and can also be implemented by exclusively using empirically derived AFs.

In this work, the acceleration models used are the Arrhenius law for temperature acceleration $\mathrm{AF_T}$, the power law voltage acceleration $\mathrm{AF_U}$ and the Coffin-Manson model for temperature cycling $\mathrm{AF_{TC}}$ [5],

$$\mathrm{AF_T} = \exp\left(\frac{E_\mathrm{a}}{k_\mathrm{B}}\left(\frac{1}{T_\mathrm{ref}} - \frac{1}{T_\mathrm{MP}}\right)\right) \tag{1a}$$

$$\mathrm{AF_U} = \left(\frac{U_\mathrm{ref}}{U_\mathrm{MP}}\right)^{-m} \tag{1b}$$

$$\mathrm{AF_{TC}} = \left(\frac{\Delta T_\mathrm{MP}}{\Delta T_\mathrm{ref}}\right)^{c} \tag{1c}$$

with the activation energy E_a, the Boltzmann constant k_B, the reference temperature T_ref and the respective temperatures T_MP that are present in the mission profile. The other stressors, voltage U and temperature cycle ΔT, are denoted with identical indices. The voltage acceleration model also contains the acceleration exponent m, and the Coffin-Manson model exhibits the respective acceleration exponent c.

The effective acceleration factor $\mathrm{AF_{eff}}$ of a mission profile is then deduced as the weighted harmonic mean of those individual AFs for the different stress level states i of the mission profile with the temporal weights p_i, which sum up to $\sum p_i = 1$ [2], [6], [7]. The terms t_i are the respective stress level durations.

$$\mathrm{AF_{eff}} = \frac{1}{\sum_{i=1}^{n} \frac{p_i}{\mathrm{AF}_i}}, \quad \text{with } p_i = \frac{t_i}{t_\mathrm{MP}} \tag{2}$$

Subsequently, equivalent test times can then be calculated as $\mathrm{ETT} = \mathrm{AF_{eff}} \cdot t_\mathrm{MP}$, with t_MP being the cumulated mission profile lifetime of all individual stress levels $t_\mathrm{MP} = \sum t_i$. For failure mechanisms that are accelerated by more than one stressor, it is of crucial importance for the reliability assessment to consider stressor interdependencies, for example in cases when the damage mechanism depends on acting voltage and temperature, or when combining different operating states within a single mission profile.

In general, the effective AF in dependency of multiple stressors X, Y and Z can be derived with the respective stress levels i, j, k, and their temporal weights $p_{i,j,k}$, as:

$$\mathrm{AF_{eff}} = \frac{1}{\sum_i \sum_j \sum_k \frac{p_{i,j,k}}{\mathrm{AF}_{\mathrm{X}_i} \cdot \mathrm{AF}_{\mathrm{Y}_j} \cdot \mathrm{AF}_{\mathrm{Z}_k}}} \tag{3}$$

Note that simply multiplying the $\mathrm{AF_{eff}}$ of different stressors calculated according to (2) does not yield the same results as (3) and will neglect any stressor interdependencies that are critical for a realistic and genuine reliability assessment of the mission profile. [8]

When evaluating AFs or ETTs of a mission profile, the reference stress level is an important parameter for the calculation, as it will affect the resulting reliability figures. Nevertheless, when deriving a quantile criterion of a number of mission profiles, we are only interested in the relative differences, i.e. the ratios, of the regarded AFs and ETTs. These relations are not affected by the choice of the reference stress level as the respective T_ref, U_ref, and ΔT_ref will cancel out.

Deriving effective stress levels for mission profiles as described in this section is always dependent on the acceleration parameters of the respective failure model, in this case the activation energy E_a and the acceleration exponents m and c in (1a–1c). Due to the fact that the respective reliability figures AF and ETT are always related to just one set of acceleration parameters, they are only applicable for a narrowed down selection of failure mechanisms that exhibits exactly this set of parameters.

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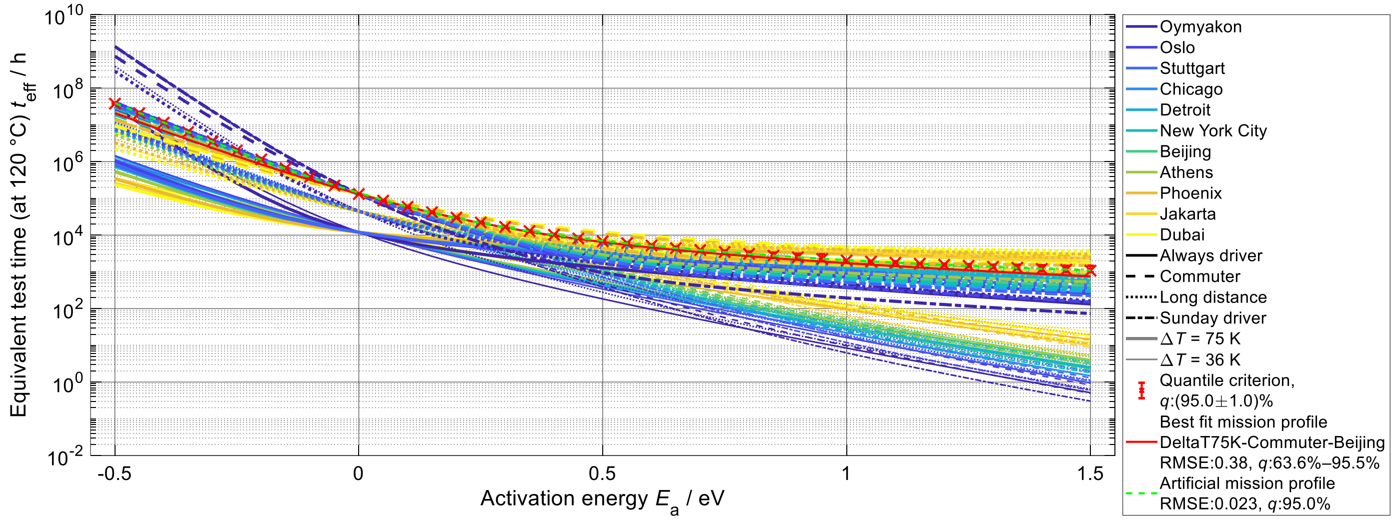

Fig. 2. Equivalent test times of 88 different automotive mission profiles are evaluated for different acceleration parameters E_a of the Arrhenius model. The MPs are obtained by combining each of the 11 environments with 4 use cases and 2 mounting locations as in (6). The weighted 95 % quantile is derived in order to represent the desired reliability requirement criterion of a realistic portrayal of different markets and driver profiles of the fleet. This quantile criterion can be approached by either picking the best fitting MP or generate an artificial MP that describes the ETTs as a function of E_a accurately.

Thus, a method is presented which preserves the universal applicability of AFs and ETTs concerning the acceleration parameters. This is done by comparing the reliability figures of various mission profiles over the entire range of parameters, that are technically relevant, in order to derive a quantile criterion that represents this given sets of mission profiles for a certain acceleration model.

III. Deriving a Mission Profile Quantile Criterion

Evaluating multiple MPs to deduce reliability requirements for the supply chain is a difficult task and the results often lack expressiveness as well as transparency. To solve this task at hand, it is useful to plot the AFs or the respective ETTs of each mission profile as a function of the respective acceleration parameters such as in Fig. 2.

Starting from this plot, the deduction of the required reliability quantiles for all mission profiles is done piecewise for every set of acceleration parameters by the following procedure:

The individual AFs and ETTs are calculated according to section II and are ranked subsequently. This is done in an analogous way to how plotting positions of cumulative distribution functions are determined and is derived exemplarily by utilizing the midpoint position

$$q(k) = (k - 0.5)/n \quad (4)$$

with quantile q for rank k and total number of mission profiles n. The rank k is defined as an integer from 1 to n, corresponding to the respective ranking from smallest to largest value of each individual ETT. Other functions may also be used instead of (4).

Additionally, the MPs can also be weighted to improve the relevance of specific areas of application, e.g. more people

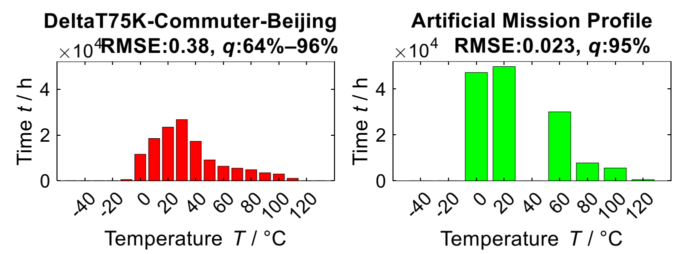

Fig. 3. a) Best fitting mission profile and b) numerically fitted artificial MP to represent the quantile criterion of Fig. 2 in order to facilitate the communication of this MP reliability requirement along the supply chain.

live in Mediterranean regions than in Arctic regions. For this, the positive weights w, which are normalized to $\sum w_k = n$, are summed up to substitute the previously used rank k in (4).

$$q(k, w) = \left(\sum_{i=1}^{k} w_i - \frac{w_k}{2}\right)/n \quad (5)$$

When deriving continuous values for the quantile q, they are deduced by linear interpolation between the ETT values of the two nearest given ranks or if required by the respective interpolation method of the utilized acceleration model.

With this, the mission profile ETT requirements can be abstracted to yield a universal quantile criterion in form of ETTs given as function over the entire parameter range of each acceleration model. In Fig. 2, a quantile criterion of 95 % is depicted as red crosses with error bars of length ±1 % (percentage point) for the purpose of clarity. This reliability quantile criterion can then be passed on along the supply chain to facilitate the communication of reliability requirements that otherwise would include the entire set of MP raw data.

Here, the subsequent question is: “Can this quantile ETT criterion be expressed as – or transformed into – an effective or corresponding mission profile for further reliability analysis?” Two different approaches were developed to answer this question.

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For one, an existing mission profile as in Fig. 3a can be selected from the available mission profile collection that fits the quantile criterion best. This can be achieved by simply calculating and comparing goodness of fit (GOF) figures of the existing mission profiles, such as root-mean-squared-error (RMSE). As will be further discussed in the next sections, depending on the available mission profile data, it is more or less likely to find a profile that matches satisfyingly well.

For another, an artificial mission profile like in Fig. 3b can be fitted with numerical methods to the quantile criterion, usually resulting in a much better fitting mission profile in regards to GOF and, if desired, also in a simplified profile with fewer sampling points, which may further contribute to the facilitation of the subsequent mission profile handling and evaluation along the supply chain.

IV. Application and Case Studies of Mission Profile Clustering

In order to demonstrate the utilization of the mission profile quantile criterion, the formerly described procedure in Section III is implemented for different MP examples.

A. Origin of the mission profile example data

The MP data used comes from a numerical method that enables an efficient and transparent computation of realistic temperature profiles for multiple users [9]. The fundamental principle for this approach is the decoupling of environment, use case and acting thermal load (local heating at mounting location). This facilitates time-efficient computation of different user types, virtually driving in different parts of the world. For this paper, in total 88 fictive cases, representing the following combinations, were analyzed:

- 11 environments representing different climatic conditions, like Dubai as a rather hot geographical location and Oymyakon as a rather cold location,
- 4 archetypal users, like the commuter (driving twice a day) or the *Sunday driver* (driving only on Sundays),
- 2 typical mounting locations representing moderate (good cooling) and high (reduced cooling) self-heating. These are arbitrarily assigned to the interior space (with moderate temperature during driving) and engine compartment (as rather hot mounting location) of the vehicle but can also be ascribed differently.

$$\overbrace{\begin{pmatrix}\text{Athens}\\ \text{Beijing}\\ \text{Chicago}\\ \text{Detroit}\\ \text{Jakarta}\\ \text{Dubai}\\ \text{New York}\\ \text{Oymyakon}\\ \text{Oslo}\\ \text{Phoenix}\\ \text{Stuttgart}\end{pmatrix}}^{\textbf{Environments}} \times \overbrace{\begin{pmatrix}\text{Commuter}\\ \text{Sunday driver}\\ \text{Always driver}\\ \text{Long distance}\end{pmatrix}}^{\textbf{Use cases}} \times \overbrace{\begin{pmatrix}\text{Interior space}\\ \text{Engine compartment}\end{pmatrix}}^{\textbf{Mounting locations}} \quad (6)$$

Fig. 4. Mission profiles for constant temperature and thermal cycling (on the right) are derived by binning from transient temperature profiles (on the left), in this case, for a commuter in Stuttgart.

This selection of scenarios serves the purpose of using as different and extreme corner-cases as possible to demonstrate that the clustering algorithm is able to handle wide-spread MPs, although we are aware that this exact combination shown in (6) does not necessarily represent a realistic scenario of application.

For each user, the transient temperature load for one calendar year was simulated. For this calculation the following considerations are taken into account:

- heating during driving,
- cooling while parking,
- ambient temperature, and
- heating due to solar radiation.

From this computed transient time series, mission profiles for constant temperatures, as well as for thermal cycles, were derived by counting the occurrences in each bin, such as in Fig. 4.

B. Weighted mission profiles

Figure 2 displays the first case study, in which the full set of 88 mission profiles is evaluated for temperature accelerated failure mechanisms, which can be modeled with the Arrhenius law in (1a), and transformed with (2) into ETTs as a function of the activation energy E_a. In the example, the entire MP is used with active and passive operation states over the full lifetime with up to 131 400 h. The goal is to reduce this set of MPs to a quantile criterion of 95 %.

It is apparent that the equivalent test times vary by several orders of magnitudes for the individual MPs but also over the considered parameter range of E_a = (-0.5–1.5) eV. In general, MPs from environments with higher temperatures, which are colored in lighter colors, reach higher ETTs for positive activation energies than colder environments with darker colors. Additionally, the MPs split into two branches with increasing E_a correlating with their installation locations. Thereby, the MPs of the engine compartment with $\Delta T = 75$ K achieve higher ETTs than those of the interior space with $\Delta T = 36$ K.

On the other hand, for negative E_a, colder environments are the harsher MPs. Here, especially the use cases with reduced passive lifetime shares, like *always driver* and *long-distance* fall behind with their ETTs in comparison because of the reduced impact of the environment on their MP.

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For $E_a = 0$ eV, when no temperature acceleration occurs, the mission profiles split up into three distinct values. This is due to the fact that only the use cases of commuter and *Sunday driver* exhibit the full length of 15 years, whereas *always drivers* reach their reliability target of 8 000 h active time within 1.4 years, followed by the *long-distance* use case with just over 5.1 years.

To evaluate the quantile criterion, (5) is used to calculate the weighted quantile of 95 % at every E_a step of 0.05 eV. In this example, (5) was used for the reason that by weighting the individual MP characteristics, different markets and driver profiles of the fleet can be represented more accurately. The resulting ETT dependency on the activation energy constitutes the abstracted validation or test requirement from the total set of mission profiles in this example. From a mathematical point of view, no further transformation of this curve is necessary in order to use it to define necessary test durations. However, communicating and subsequently processing the information in the form of a MP is seen as more adequate as it allows detailed reliability studies. How to derive this MP information will now be considered in more detail.

The first approach is the possibility to select one or few individual MPs from the existing set of 88 MPs that best fit the derived quantile criterion. For that, a GOF figure of merit is chosen for the purpose of comparability. Different approaches like the RMSE of the logarithmic ETTs or the most consistent ranking near the quantile criterion can be chosen. In our example, we used the RMSE which led to the mission profile in Fig. 3a of an engine compartment installation location of a commuter vehicle driving in Beijing.

Even though this is the best fitting MP, it constantly falls short of the targeted quantile criterion reaching only a 63.6 % percentile in one or more points of evaluation. Better representations of the target quantile criterion can be achieved by dividing the acceleration parameter range into smaller segments and searching for additional locally best fitting MPs. For example, Fig. 2 could be split into a positive and a negative activation energy evaluation with one best fitting MP for each case.

The alternative approach to achieve better representations is to numerically fit a mission profile to the derived quantile criterion. For instance, the artificial mission profile in Fig. 3b leads, even visually, to a tighter fit in Fig. 2. Additionally, the RMSE is an order of magnitude smaller, confirming the first visual impression. This can be achieved despite the fact that fewer sampling points have been used and the quantile criterion can be expressed by solely six temperature-time pairs. An additional advantage of the artificial mission profile is that it is by far easier to communicate along the supply chain and practically equivalent to the initial quantile criterion.

C. *Multidimensional mission profiles*

The described approach to reduce a multitude of MPs to a single quantile criterion can also be extended to more complex acceleration models, for example, a failure mechanism which is accelerated by temperature (1a) as well as voltage (1b). Note that for interdependent stressors and for MPs combining different operation states like active, passive, stand-by or other modes, (3) has to be applied in order to calculate correct effective acceleration factors and ETTs.

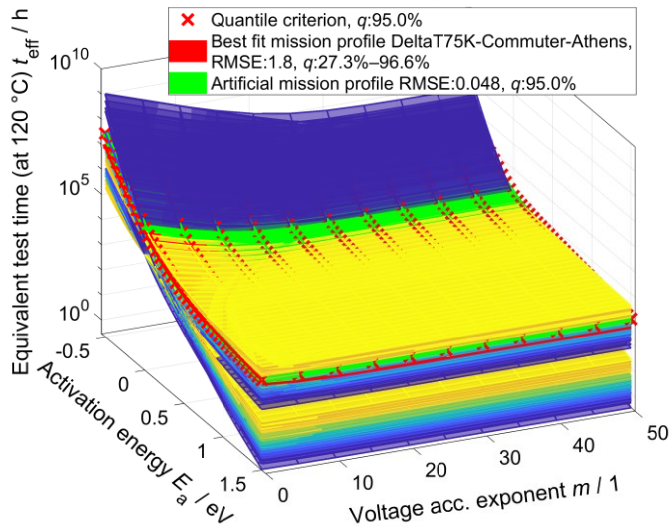

Fig. 5. Equivalent test times derived from multidimensional mission profiles of the interdependent stressors temperature and voltage. Color coding and raw data correspond to those in Fig. 2.

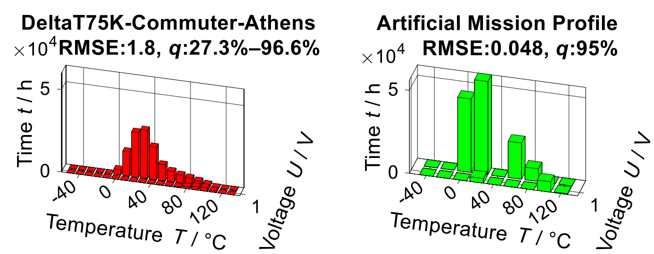

Fig. 6. a) Best fitting mission profile and b) numerically fitted artificial MP of the quantile criterion in Fig. 5.

Here, the already introduced set of MPs from Section IV A and identical weighting factors as in Section IV B was used. To distinguish the operating modes, different voltages are applied during active and passive operation hours. Figure 5 illustrates the two-dimensional acceleration parameter space for this case. The cross-section of this surface plot at $m = 0$, i.e. the left-hand border of the plotted planes, equals the curves in Fig. 2, where no voltage acceleration is applied. Following these planes on the voltage acceleration axis from $m = 0$ to 50, this initial temperature acceleration behavior changes according to (1b) and (3) with an increased influence of the voltage acceleration on the ETTs.

The determination of the 95 % quantile criterion is performed according to (5) for every pair of the parameters E_a and m. In addition as introduced before, a best fitting mission profile in regards to a chosen GOF figure in Fig. 6a and also an artificially generated and fitted MP in Fig. 6b can be derived for these given multidimensional MPs. This illustrates that the procedure and characteristics of the one-dimensional case can also be extended to multiple interdependent stressors.

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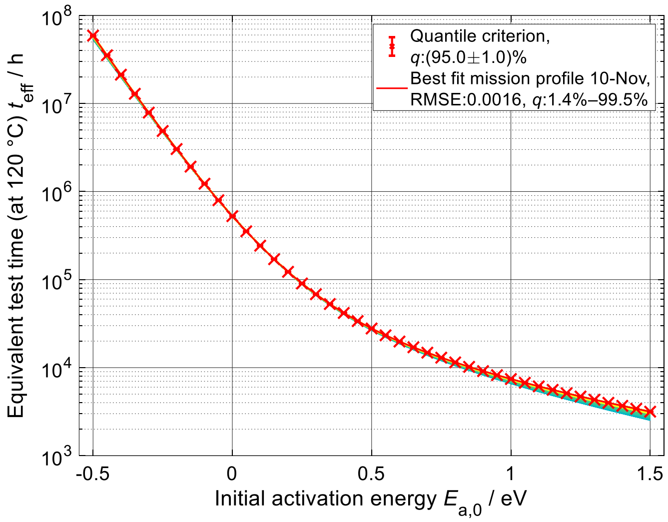

Fig. 7. Equivalent test times are derived for a failure mechanism that exhibits non-linear damage accumulation. Exemplarily, the mission profile of an engine compartment of a commuter driving in Stuttgart is evaluated with different purchase dates to select the best fitting date for the 95 % quantile criterion.

D. *Non-linear damage accumulation models*

The next case study for applicability of the presented quantile criterion approach is a failure mechanism which exhibits a non-linear damage accumulation model. This implies that the stress history is of importance and that the previously used equations for AF_{eff} (2) and (3) are no longer valid. Instead, a failure model based on [10] is utilized. According to [10], it is suggested that for thermal interface materials, which exhibit degradation, the thermal conductance of those materials is impaired as well, and subsequently the effect of self-heating successively leads to higher temperatures for future power-on states. This effect can either be modeled by adjusting the MP temperature or – what has been shown to be equivalent – the respective temperature acceleration parameter.

This failure acceleration model has been implemented for the data in Fig. 7. For this purpose, an engine compartment MP of a commuter in Stuttgart is used exemplarily, starting on 365 different days of the year, each one at midnight, representing different purchase dates of the respective cars. The duration of all MPs is identical. The quantile criterion can be derived by (4) in the same way as previously conducted. Also, a best fitting MP can be selected from the plotted set. In this case, the MP of November 10th exhibits the smallest RMSE.

An artificial MP has not been derived for this example due to a more complex fitting algorithm and a lack of necessary boundary conditions for this time-series MP. Apart from that, the determination of a quantile criterion for a more efficient und clearer communication of MPs along the supply chain is also applicable for known failure mechanism that exhibit non-linear damage accumulation as long as the failure acceleration can be modeled.

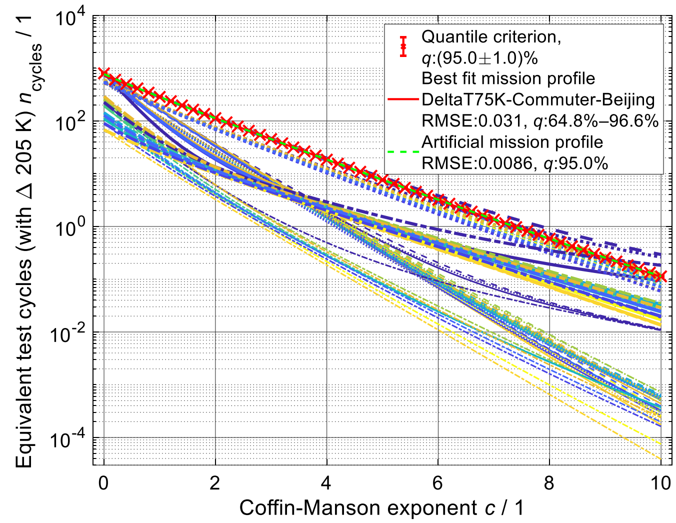

Fig. 8. Equivalent test times of the same 88 different automotive mission profiles from Fig. 2 are evaluated here for different acceleration parameters c of the Coffin-Manson model for temperature cycling. Color coding and raw data correspond to those in Fig. 2.

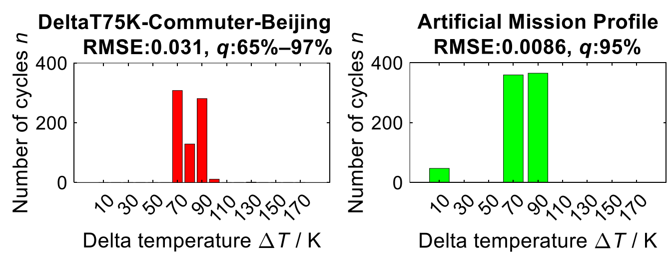

Fig. 9. a) Best fitting mission profile and b) numerically fitted artificial MP of the quantile criterion in Fig. 8.

E. *Temperature cycling mission profiles*

Additionally, this procedure cannot only be applied for constant stress levels like Arrhenius accelerated temperature and voltage profiles but also for temperature gradients and cycling MPs. Therefore, the Coffin-Manson model in (1c) is utilized in connection with (2) for the calculation of AF_{eff} with the same set of MPs as described in Section IV A and with the weighting of Section IV B. Of course, the critical lifetime goal for temperature cycling is not stress time t but number of stress cycles n. Apart from that, the methodology for evaluating equivalent test cycles (ETCs) is analogous to that in (2).

Similar to Section IV B, very distinct mission profile characteristics become apparent in Fig. 8. Installation locations with a high ΔT of 75 K consequently achieve higher ETCs than locations witch smaller temperature differences. Also, use cases with extensive large temperature swings and long lifetimes, like commuters, followed by *long-distance*, exhibit high overall ETCs, while *always drivers* do not have enough time to cool down in-between on-states and therefore do not experience large temperature swings during their short lifetimes. Similarly, *Sunday drivers* simply lack enough operating days and have a small overall number of temperature cycles. For the mission profile environments, no distinct trend is identifiable, however, the ranking is consistent across the different types of MPs. For every combination of installation location and use case, the moderate environment mission profiles – especially those of

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Athens – exhibit high ETCs. The exception to this is Oymyakon, which alone accounts for the highest ETCs for large Coffin-Manson exponents c.

The principles and characteristics for the derived quantile criterion, best fit MP, and artificial MP apply to temperature cycling MPs in the same way as previously demonstrated. After the determination of the 95 % quantile criterion according to (5), the mission profile of the engine compartment of a commuter in Beijing in Fig. 9a is determined as the best fitting MP of the given MP set, whereas the artificially generated, simplified MP in Fig. 9b achieves a RMSE which is an order of magnitude smaller and only consists of 3 data pairs of temperature swings and respective number of cycles.

V. Comparison and Alignment of Reliability Capabilities and Mission Profiles

Another field of application in which the visualization of quantile criteria becomes relevant and quite helpful is when performing lifetime tests and evaluating the reliability capabilities of electronic systems and their technologies. For that, the test duration of lifetime tests or extrapolated lifetimes from parameter drift analyses can be overlaid to the given MP requirements and compared for coverage.

As illustrated in Fig. 10, the mission profile ETTs of Fig. 2 and the 95 % quantile criterion of Section IV B are plotted in the background for comparison with three 2 000 h lifetime tests at different temperatures. The lifetime test at 120 °C, which is the same as the reference temperature T_{ref} in Fig. 10, results in a horizontal line over the entire range of the acceleration parameter, since $\mathrm{AF}_{\mathrm{eff}} = 1$ for any E_{a} in (1a), in which T_{MP} is substituted by the test temperature T_{test}. This results in the conclusion, that this test can only cover the derived quantile criterion for any failure mechanism that has an activation energy $E_{\mathrm{a}} > 1.0$ eV. Testing at higher temperatures can cover a higher range of parameters, e.g. $E_{\mathrm{a}} > 0.4$ eV for 175 °C, because the calculated line in Fig. 10 exhibits a positive slope. For temperatures lower than the reference temperature, the slope of the plotted line is negative and has the potential to cover the required ETTs of failure mechanism with negative acceleration parameters, in this case $E_{\mathrm{a}} < -0.35$ eV.

The reason for the observed coverage gap between -0.35 eV $< E_{\mathrm{a}} <$ 0.40 eV of the 2 000 h lifetime tests is their point of intersection at $E_{\mathrm{a}} = 0.0$ eV, which is significantly shorter than the investigated mission profiles as there is essentially no acceleration. This gap can only be closed by testing for longer times, shifting the lines to higher ETTs, and/or at higher or lower temperatures, respectively, in order to change the slope. A different choice of T_{ref} solely changes the appearance but not the characteristics nor the validity of Fig. 10. Note that the depicted lifetime tests for stresses different from the reference stress are only plotted as straight lines due to the fact that the logarithmic ETT axis corresponds to the exponential acceleration in the Arrhenius model (1a) and can vary for other types of acceleration models or axis definitions.

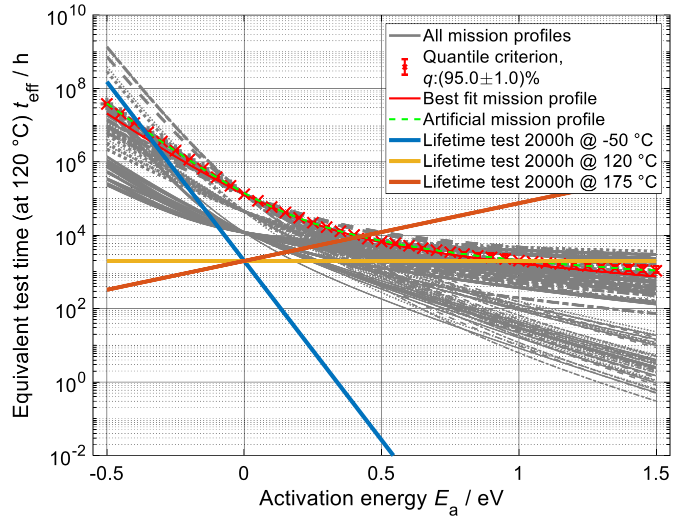

Fig. 10. All mission profiles from Fig. 2 are displayed in gray color and overlaid with the ETT representations of performed lifetime tests at different test temperatures. Since these lifetime tests have different behaviors, they cover different sections of the 95 % quantile criterion MP requirement on the activation energy axis.

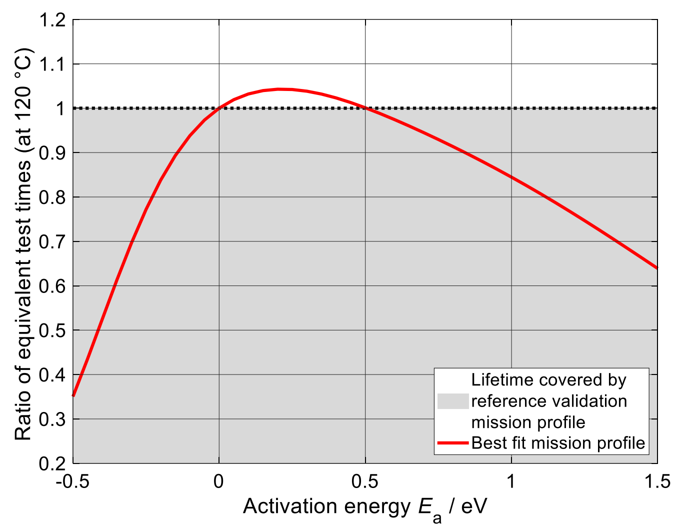

Fig. 11. The best fit mission profile from Fig. 10 is compared with the validation mission profile from Table I to deduce the degree of coverage.

TABLE I
Assumed Validation Mission Profile

Junction temperature T_{j} / °C	Time t / h
-40	1 000
-10	11 500
0	16 500
25	54 000
40	17 900
50	12 000
75	10 000
90	5 000
100	2 000
110	1 250
125	250

Another possibility to describe the reliability capabilities of a device, instead of providing the lifetime test specification, is giving a validation mission profile that is guaranteed to be within the capabilities of the device. The approach of using validation mission profiles instead of lifetime test specifications

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as reliability requirement has been described already [11]. It allows failure mechanism specific reliability engineering during development and failure mechanism specific reliability assessment during qualification. This enlarges the design options, helps reducing cost without sacrificing reliability, and enhance time to market at the same time.

To quantify the coverage of the required best fitting mission profile, it is set in relation to the validation mission profile. Assuming the validation mission profile provided is given in Table I, the graphical result of the assessment is shown in Fig. 11.

The comparative assessment of both mission profiles discloses that the validation mission profile is more severe for failure mechanisms with an activation energy of $E_\mathrm{a} > 0.5$ eV and $E_\mathrm{a} < 0.0$ eV. Any further reliability assessment or data exchange can thus be limited to failure mechanisms with an activation energy that is not already covered by the guaranteed validation mission profile. Whether the remaining region is even relevant depends on the technology and design.

To conclude, the presented method proves its advantages also under the aspect of reliability capabilities as an instrument for clear presentation and simple communication of mission profile requirements and reliability results.

VI. Utilizing a Mission Profile Data Format

Effective clustering of mission profiles and the transfer of MP information within the supply chain benefit from a dedicated electronic data format for MPs that allows to define loads and capabilities in a formal way and, thereby, enables computer-aided processing of these data. For this purpose, we propose the so-called "Mission Profile and Capability Exchange Format (MPFo)" [12], a domain-specific data format based on XML, to be standardized starting from 2022.

At its core, an MPFo document defines entities as well as corresponding loads, capability profiles as well as use cases and application scenarios. An MPFo entity is a structural model of a physical component, either a real one or a virtual one, if we want to describe the capabilities of a technology. Entities have ports that can represent, e.g., static and flow connections, a component's mounting location, and they act as property-holders of environmental factors such as ambient temperature and humidity.

Load and capability profiles are defined as a sequence of physical quantities applied to an entity's port. These physical quantities can describe static loads, time-dependent and multi-dimensional loads as quantities that are of acoustic, fluid, mechanical, thermal, electrical, radiation or chemical nature [13]. In the simplest case of a static load, the physical quantity comprises a number (real number in double-precision floating-point format, integer, or complex number), a (derived) SI unit [14], and an optional absolute or relative tolerance. Besides scalar quantities, MPFo also supports vector and tensor quantities.

For the definition of loads and capabilities, MPFo supports a catalog of elementary mathematical functions. Alternatively,

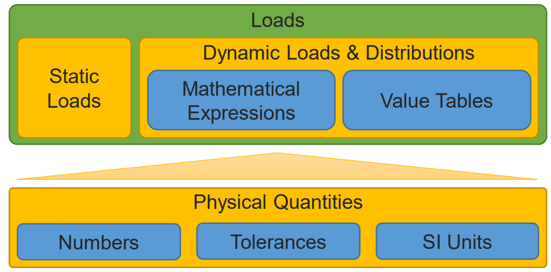

Fig. 12. Load definition using mathematical primitives in the electronic MPFo data format.

functions can also be represented by their value table, e.g., if finding the closed form is too complicated or unfeasible. Finally, continuous and discrete random quantities can be specified by their probability density function/probability mass function or by a histogram. Fig. 12 gives an overview of how loads can be described with the elements of the MPFo.

VII. Discussion and Limitations

Our investigations on randomly generated mission profiles prior to this paper, as well as on realistic MPs examined in section IV, revealed several significant results:

For the entire scope of the acceleration parameter of an evaluated failure acceleration model, there are only few worst-case MPs ranking at the highest quantile. For more moderate quantile criteria, there is a different matching MP for almost every different set of acceleration parameters. In order to reduce the number of MPs that have to be communicated within the supply chain to pass on the necessary reliability requirements to the next tier, it is possible to determine a single best fitting MP to a quantile criterion from a given set of MPs. However, this is particularly accurate when the number of available MPs is sufficiently large or when tradeoffs in the range of acceleration parameters or the quality of the conformance are accepted.

These issues can be resolved by generating an artificial MP with numerical means. The derived MP corresponds to the quantile criterion far more accurately over the entire range of the acceleration parameters. This methodology extends from the simple case of a one-parametric acceleration model, in this case the Arrhenius model, to the application of multi-dimensional mission profiles with interdependent stressors or multiple operation states, non-linear damage accumulation models, as well as failure acceleration models of cycling stresses. This underpins the versatility and the wide-ranging potential of clustering mission profiles and utilizing quantile criteria for the description of MP reliability requirements or reliability capabilities.

For the implementation of such an MP clustering, it has to be taken into consideration that a failure acceleration model has to be explicitly stated. For that reason, a determined ETT quantile criterion or derived MP is only valid for this specific model, which however can be applicable for multiple different failure mechanisms. With this, the most common acceleration models can be covered with only a few different quantile criteria that can be represented by best fitting or artificial MPs.

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Despite the fact that the quantile criteria are evaluated and subsequently fitted over a broad range of activation energies, voltage acceleration exponents, and thermal cycling parameters, not all of which match important failure mechanisms, the representative MPs are neither over-designed nor lead to too conservative MP requirements. Contrary to this concern, a reduction of sampling points of the quantile criterion results in a limitation of the general validity of the quantile criterion for the considered acceleration models. Nevertheless, if the target technology and its dominant failure mechanisms are well known, it is also possible to tailor the region of interest to the relevant acceleration model parameters. Furthermore, as exemplarily shown above, an artificial MP in particular can accurately reproduce the quantile criterion better than 1 percentage point over nearly the entire range of evaluated acceleration parameters.

Prior studies on sets of 10^1 to 10^6 randomly generated MPs revealed that the more MPs are available to derive a quantile criterion, the more well-formed is the dependency of the quantile criterion ETT function on the acceleration parameters. Thus, a smoother ETT function can be more accurately reflected by an existing MP or more closely fitted by an artificial MP, than a quantile criterion that exhibits discontinuities of its function or first derivative. Consequently, we can conclude, the more raw MPs are used to derive a MP quantile criterion, the better they can be reduced and the more closely they are represented by the resulting MPs of this mission profile clustering process.

VIII. Conclusion

In this work, we have presented a data-driven method that enables an automatized selection and/or generation of representative MPs from a given set of related MPs. This mission profile clustering approach is a transparent process that enables and facilitates easy communication of MP requirements along the supply chain and can also be examined and traced retrospectively. The electronic data format MPFo is proposed to transfer MP load and capability information within the supply chain, thus facilitating the engineering discussion.

This approach is a generic concept and therefore can be applied to all well-known and commonly used damage accumulation and failure acceleration models, like the temperature accelerated Arrhenius model, multidimensional MPs with temperature and voltage acceleration, and the temperature cycling Coffin-Manson model. Furthermore, the MP clustering approach was applied to a non-linear damage accumulation model and a quantile criterion was successfully derived.

By deriving effective stresses and equivalent testing times in dependence of acceleration model parameters, mission profile requirements can also be evaluated for their degree of coverage by the reliability capabilities of examined technologies as well as compared with publicly available standard reference MPs, further facilitating the communication of MP requirements.

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