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Modified Approach for the Rainflow Counting Analysis of Temperature Load Signals in Power Electronics Modules

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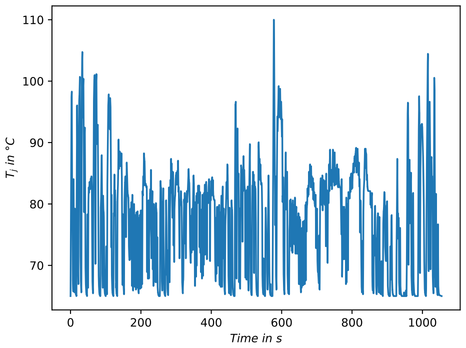
Introduction

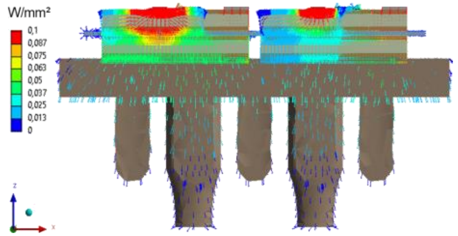
Rainflow Counting Basics

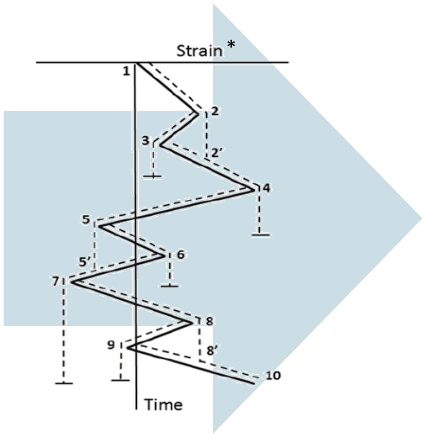
What is *Rainflow Counting*?

- Algorithm to identify damage relevant „thermal cycles“ and their corresponding characteristic properties (e.g. $\Delta T_j, T_{j,m}, t_{on}$)



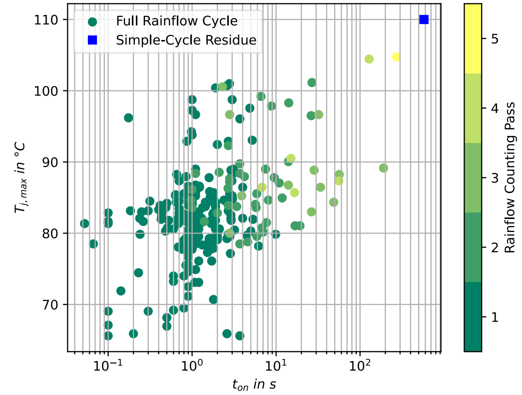
Chip Temperature-Time Profile

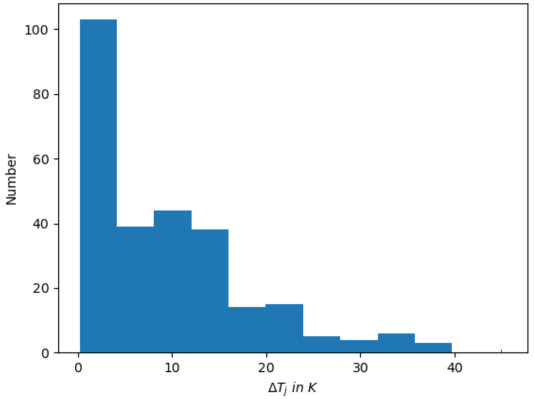




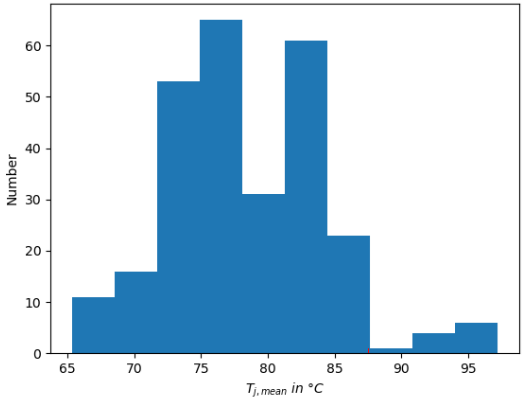
Rainflow Counting Analysis (RCA)

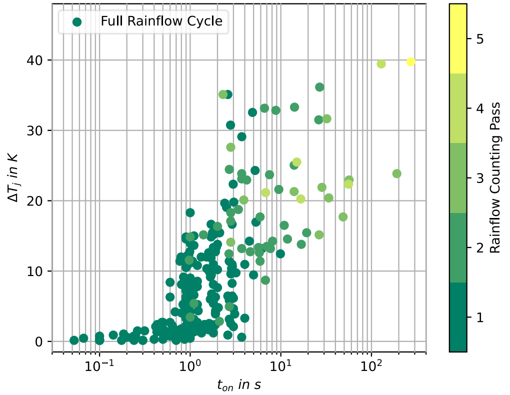
*Shinde, Vaibhav & Jha, Jyoti & Tewari, Asim & Miashra, Sushil. (2018). Modified Rainflow Counting Algorithm for Fatigue Life Calculation. 10.1007/978-981-10-6002-1_30





Rainflow Counting Results



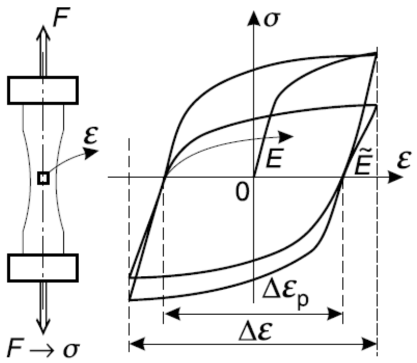


Introduction

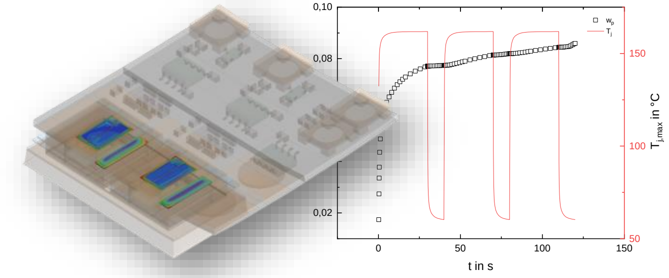
Rainflow Counting Basics

What is a damage relevant *(thermal) cycle*?

- Original: A cycle in stress- or strain-time signals that produces a closed mechanical stress-strain hysteresis loop in a uniaxial fatigue test → Uniaxial fatigue damage equation
- In power electronics: Application to chip temperature-time signals: $\varepsilon_{th} = \alpha \Delta T$ → CTE-Mismatch → Cyclic stress and strain → Power cycling damage equation
- Typical failure mechanisms: Bond wire lift-off, Solder/sinter fatigue

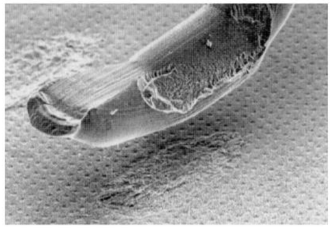


Lemaitre J., Desmorat R. Engineering Damage Mechanics. Springer-Verlag Berlin Heidelberg 2005. ISBN 3-540-21503-4.

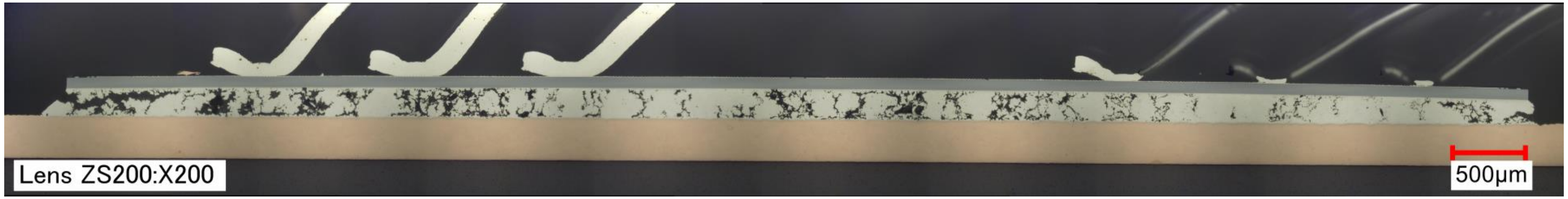


Thermal Stresses in Power Packages

Bond wire lift-off*



Solder fatigue



*S. Yang, D. Xiang, A. Bryant, P. Mawby, L. Ran and P. Tavner, "Condition Monitoring for Device Reliability in Power Electronic Converters: A Review," in *IEEE Transactions on Power Electronics*, vol. 25, no. 11, pp. 2734-2752, Nov. 2010, doi: 10.1109/TPEL.2010.2049377.

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Introduction

Rainflow Counting Basics

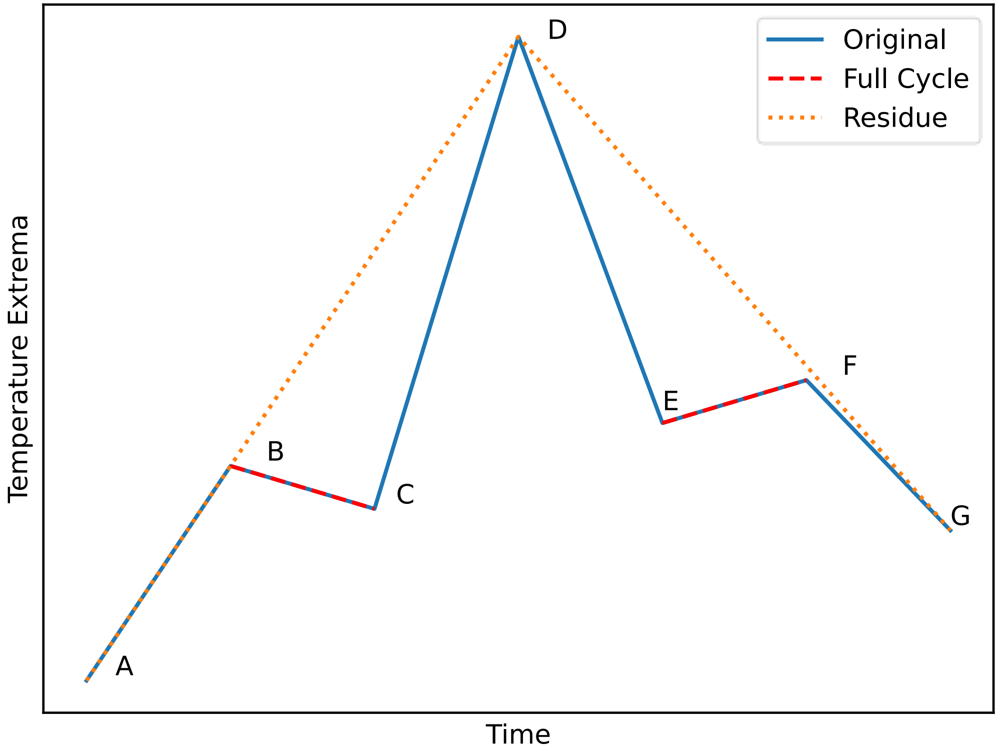
How does Rainflow Counting work?

- Filter temperature-time signal for local extreme values
- Apply 4-Point-Criterion to extreme value signal

$$|x_{n-1} - x_n| \geq |x_n - x_{n+1}| \leq |x_{n+1} - x_{n+2}| \quad n = 2, 3, 4, \dots, N-2$$

- Count and remove cycle, if criterion is met
- If not, go one point ahead
- Repeat until no cycles can be found anymore

- Take residue into account: Half or Simple Cycles or both



Introduction

Damage and Lifetime Calculation

Basic calculation procedure

- Calculation of damage per drive with Palmgren-Miner Rule

Counted cycles at load i from temperature profile

$$D = \sum_{i=1}^{p} \frac{n_i}{N_{f_i}} = \sum_{i=1}^{p} n_i \left(N_{f,i}^{63\%} \sqrt[\beta]{-ln(1-F)} \right)^{-1}$$

Rearranged Weibull CDF

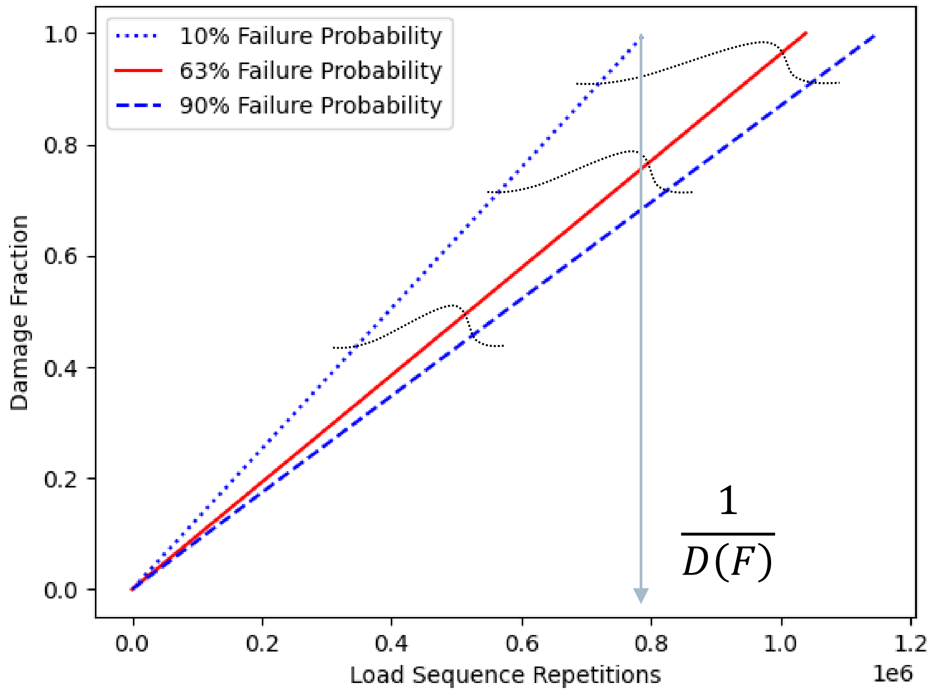
Bearable cycles at load i (Lifetime model)

- Calculation of number of drives by 1/D and corresponding lifetime

$$t_f = \frac{t_{pd}}{D}$$

Temperature profile duration

Damage for a single drive (upper equation)

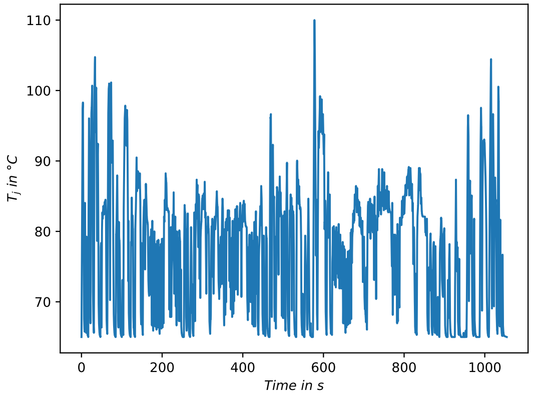


Linear extrapolation to failure

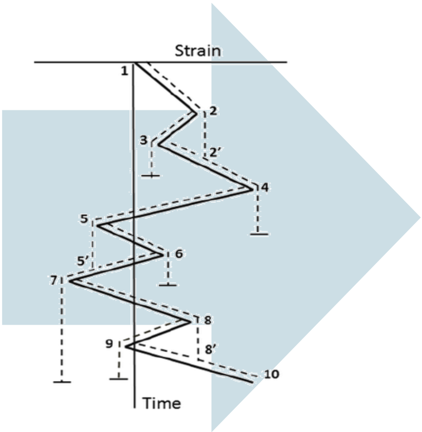
Introduction
Motivation

Observation in many lifetime calculations

- Very strong impact of residue on predicted lifetime
- Sometimes larger differences between residue processing methods



Motorway IGBT-Chip Temperature Profile



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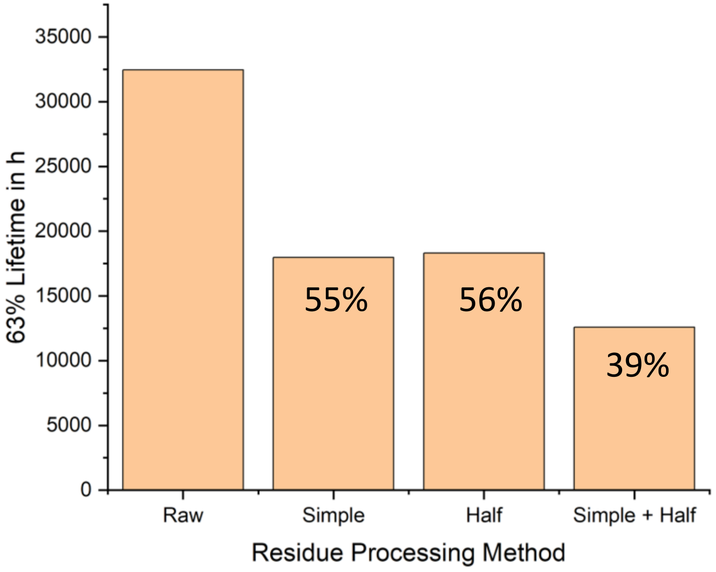
$$D = \sum_{i=1}^{p} \frac{n_i}{N_{f_i}}$$

Damage / Lifetime Calculation

CIPS08**

**R. Bayerer, T. Herrmann, T. Licht, J. Lutz and M. Feller, "Model for Power Cycling lifetime of IGBT Modules - various factors influencing lifetime," *5th International Conference on Integrated Power Electronics Systems*, Nuremberg, Germany, 2008, pp. 1-6.



Is that realistic?

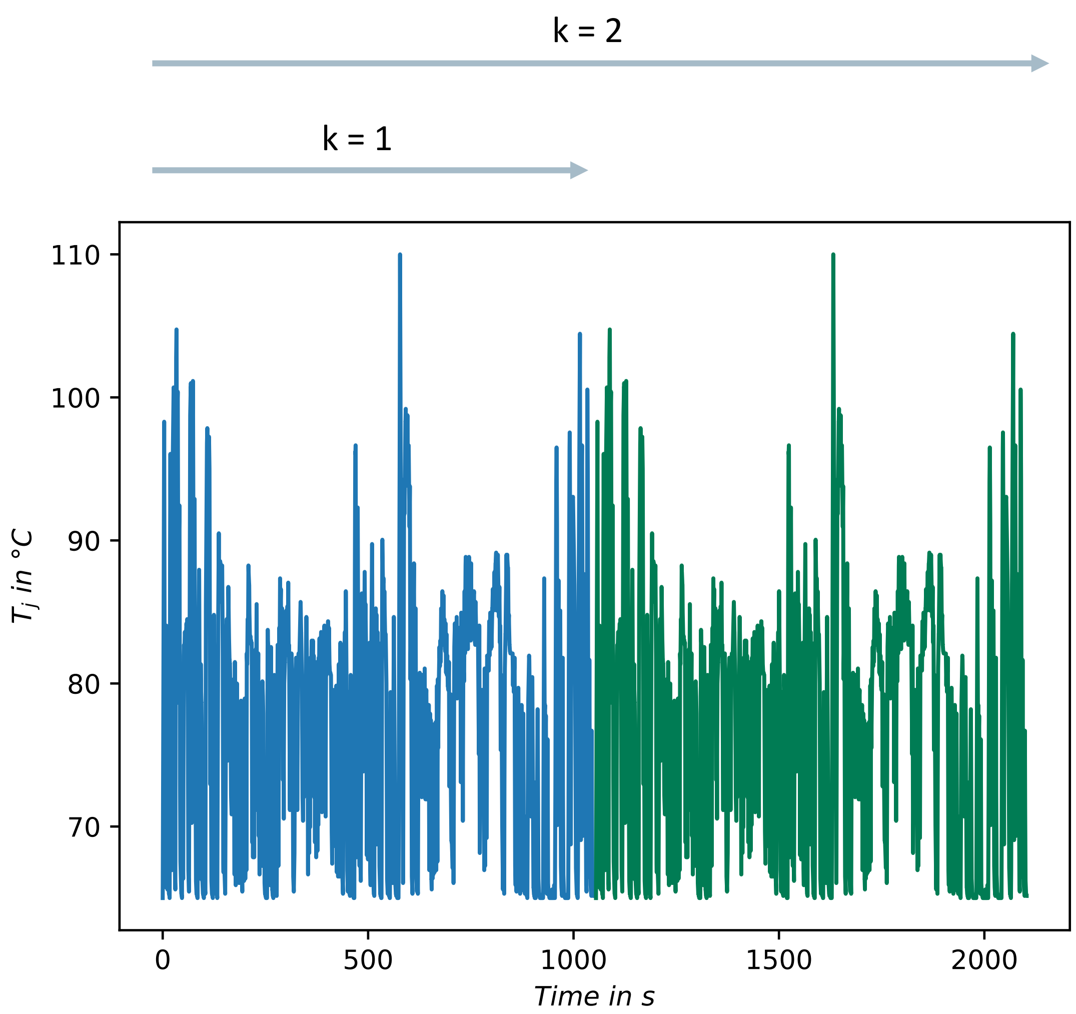
Experiments

Variable

Thought Experiment

- Imagine two consecutive mission profile drives and consider both as a new single mission profile
- Number of total drives to failure must halve and lifetime in hours must remain constant – if counting method (and residue processing) is correct

- Study of the profile length k influence on lifetime
- Artificial extension of profile with themselves k-times



Experiments

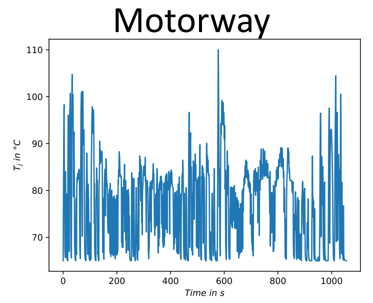
Parameters

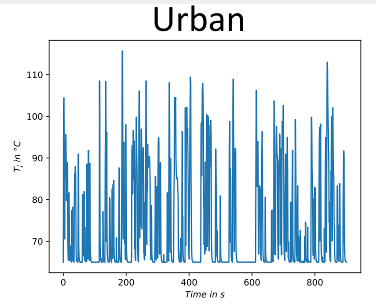
Effect of further parameters

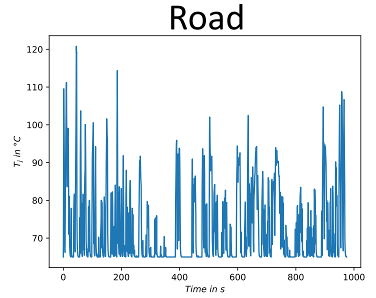
- Physics of failure model (Power Cycling Model)
- Mission Profile (IGBT T_j vs. t)

Model	Equation	Stressors
LESIT[1]	$N_f = a\Delta T_j^{-n} e^{\frac{E_A}{k_B T_{j,m}}}$	$\Delta T_j, T_{j,m}$
CIPS08[2]	$N_f = K\Delta T_j^{\beta_1} e^{\frac{\beta_2}{T_j+273}} t_{on}^{\beta_3} I^{\beta_4} V^{\beta_5} D^{\beta_6}$	$\Delta T_j, T_j, t_{on}$
SKiM93[3]	$N_f = A_0 A_1^{e^{\frac{-(\Delta T_j - T_0)}{\lambda}}} \Delta T_j^{\alpha - e^{\frac{-(\Delta T_j - T_0)}{\lambda}}} e^{\frac{E_A}{k_B T_{j,m}}} \frac{C + t_{on}^{\gamma}}{C + 2^{\gamma}} k_t$	$\Delta T_j, T_{j,m}, t_{on}$

[1]M. Held, P. Jacob, G. Nicoletti, P. Scacco and M. . -H. Poech, "Fast power cycling test of IGBT modules in traction application," *Proceedings of Second International Conference on Power Electronics and Drive Systems*, Singapore, 1997, pp. 425-430 vol.1, doi: 10.1109/PEDS.1997.618742.
[2]R. Bayerer, T. Herrmann, T. Licht, J. Lutz and M. Feller, "Model for Power Cycling lifetime of IGBT Modules - various factors influencing lifetime," *5th International Conference on Integrated Power Electronics Systems*, Nuremberg, Germany, 2008, pp. 1-6.
[3]https://www.semikron-danfoss.com/dl/service-support/downloads/download/semikron-application-note-power-cycle-model-for-igbt-product-lines-en-2021-08-24-rev-01/







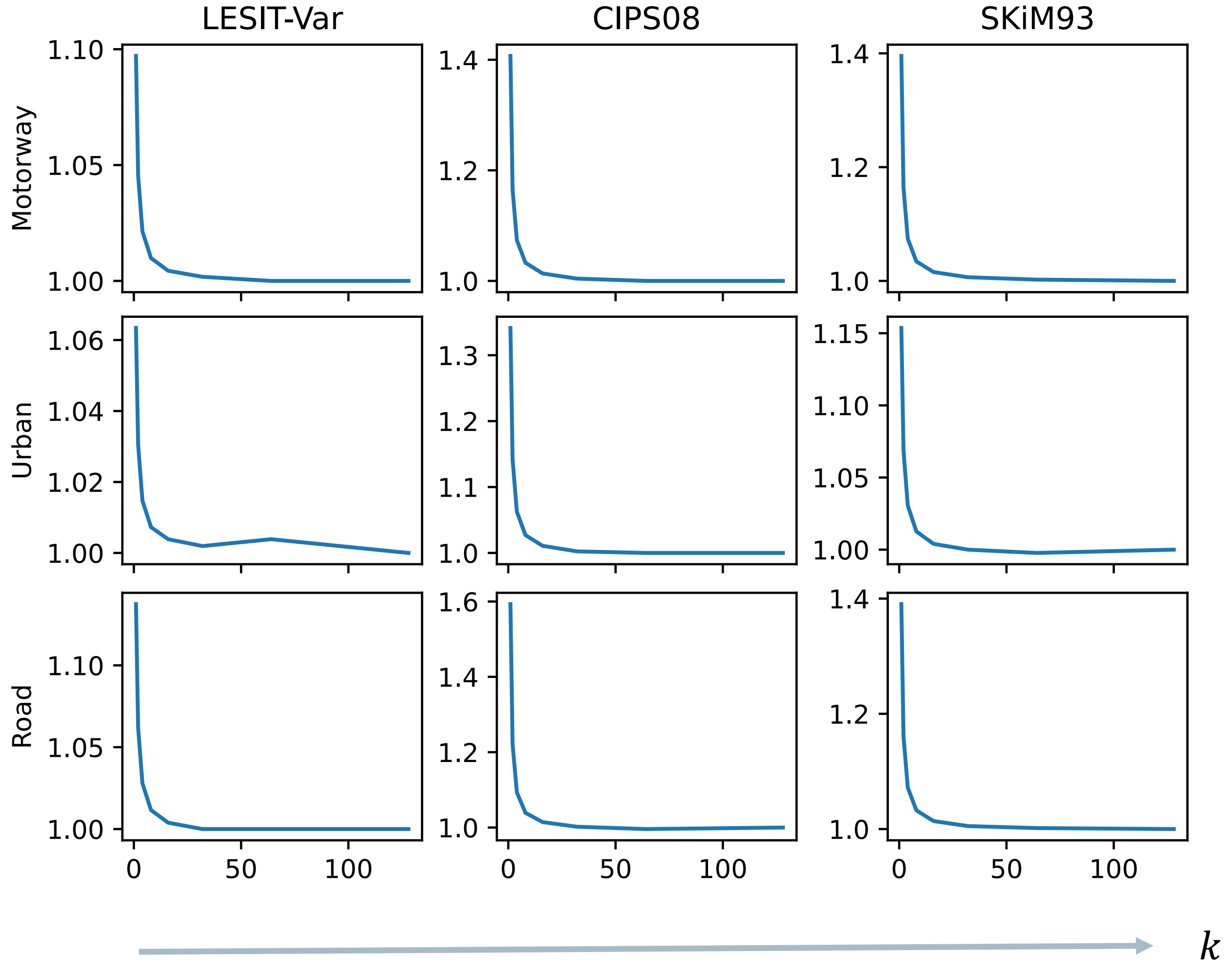
Results

Without Residue Processing (raw)

Observations

- Normalized lifetime results
- Decrease and convergence with increasing profile length
- Change in lifetime from length 64 to 128 is less than 1 % for all combinations
- Difference between initial and converged prediction depends on model and profile

$$t_f^r = \frac{t_f^r(k)}{t_f^r(k = 128)}$$

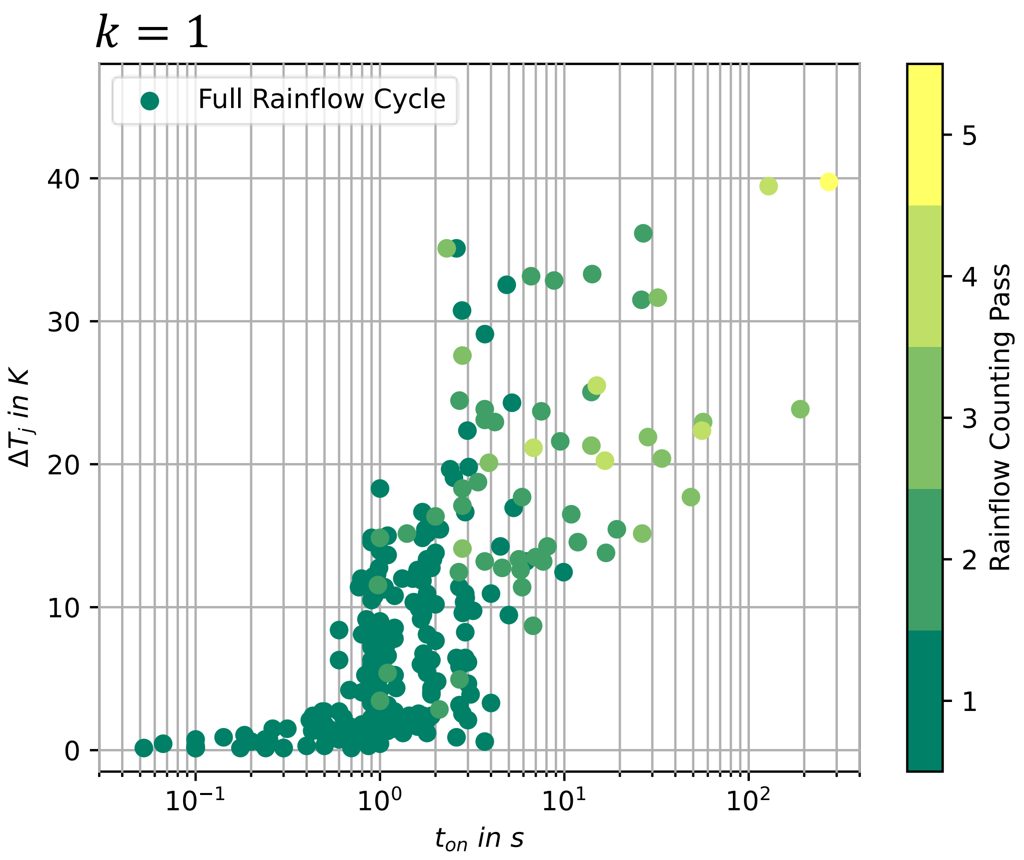


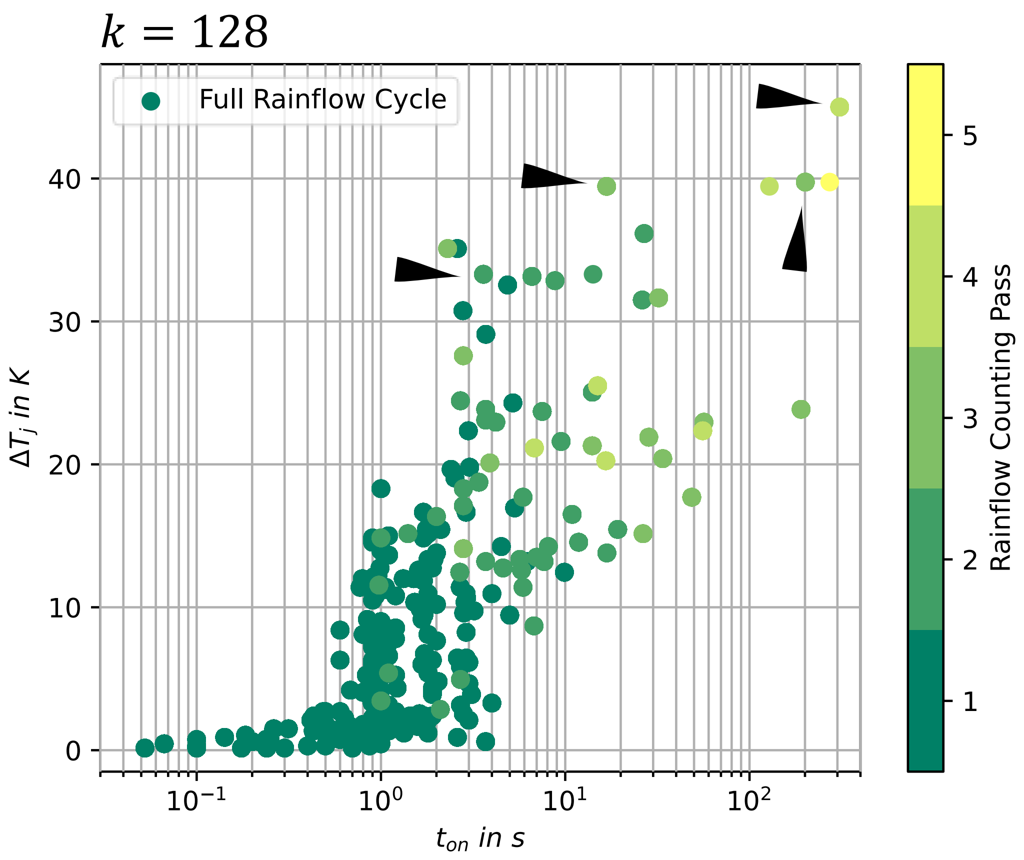
Results

Without Residue Processing (raw)

Rainflow Counting Result Analysis

- Additional cycles are identified in the longer profiles
- Highest ΔT_j and t_{on} values → decrease of lifetime with
- Identification of additional cycles decreases with increasing profile length → lifetime saturates





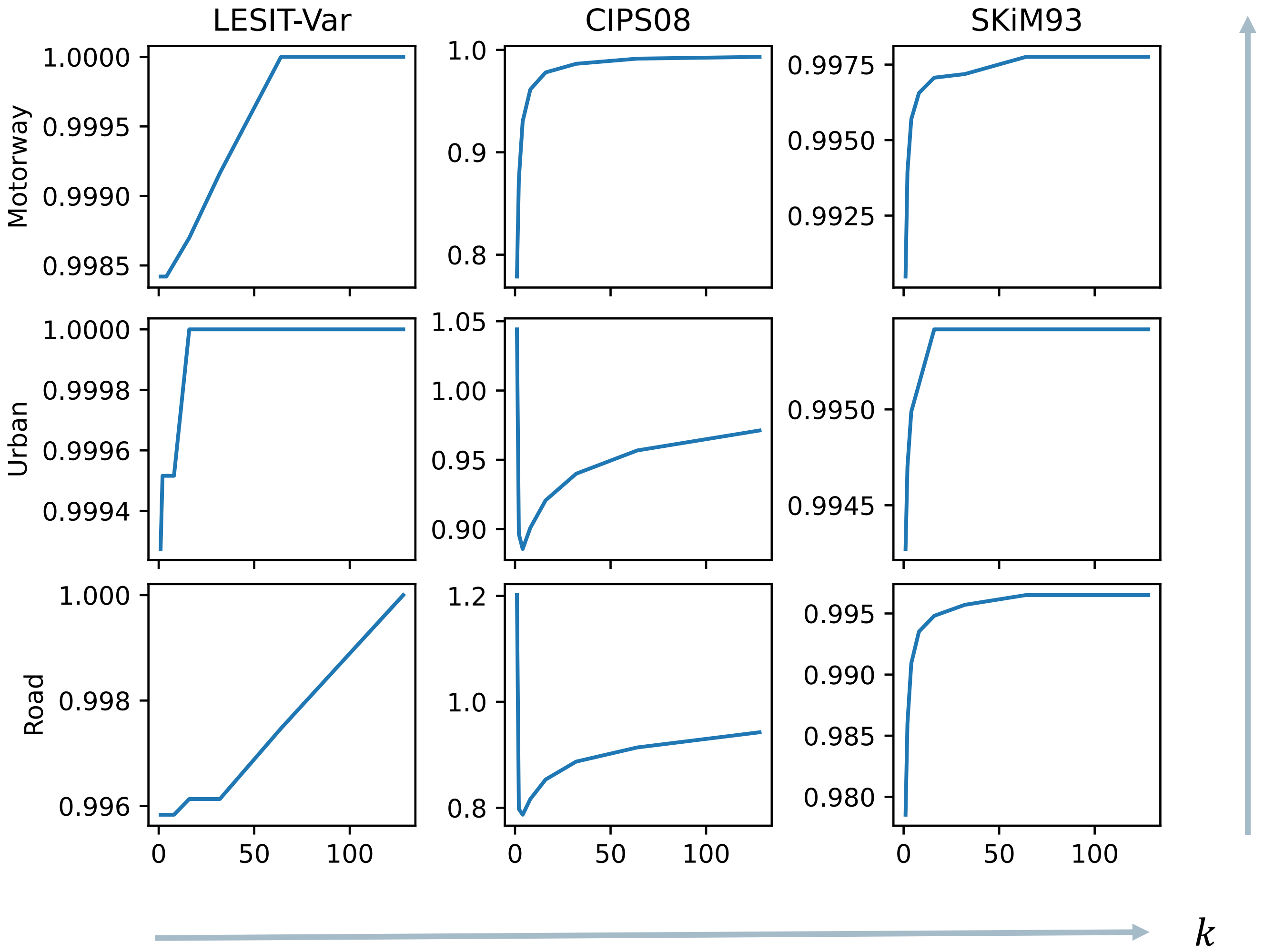
Results

Half Cycle Residue Processing (half)

$$t_f^h = \frac{t_f^h(k)}{t_f^r(k = 128)}$$

Observations

- Normalized lifetime based on converged result without residue processing
- Converging trends towards the lifetime without residue processing
- Converged results are very close and sometimes equal to the converged results without residue processing
- Convergence trend is mainly in upwards direction. Thus, results at k1 = 1 underestimate the lifetime in most cases.



 13.03.2024

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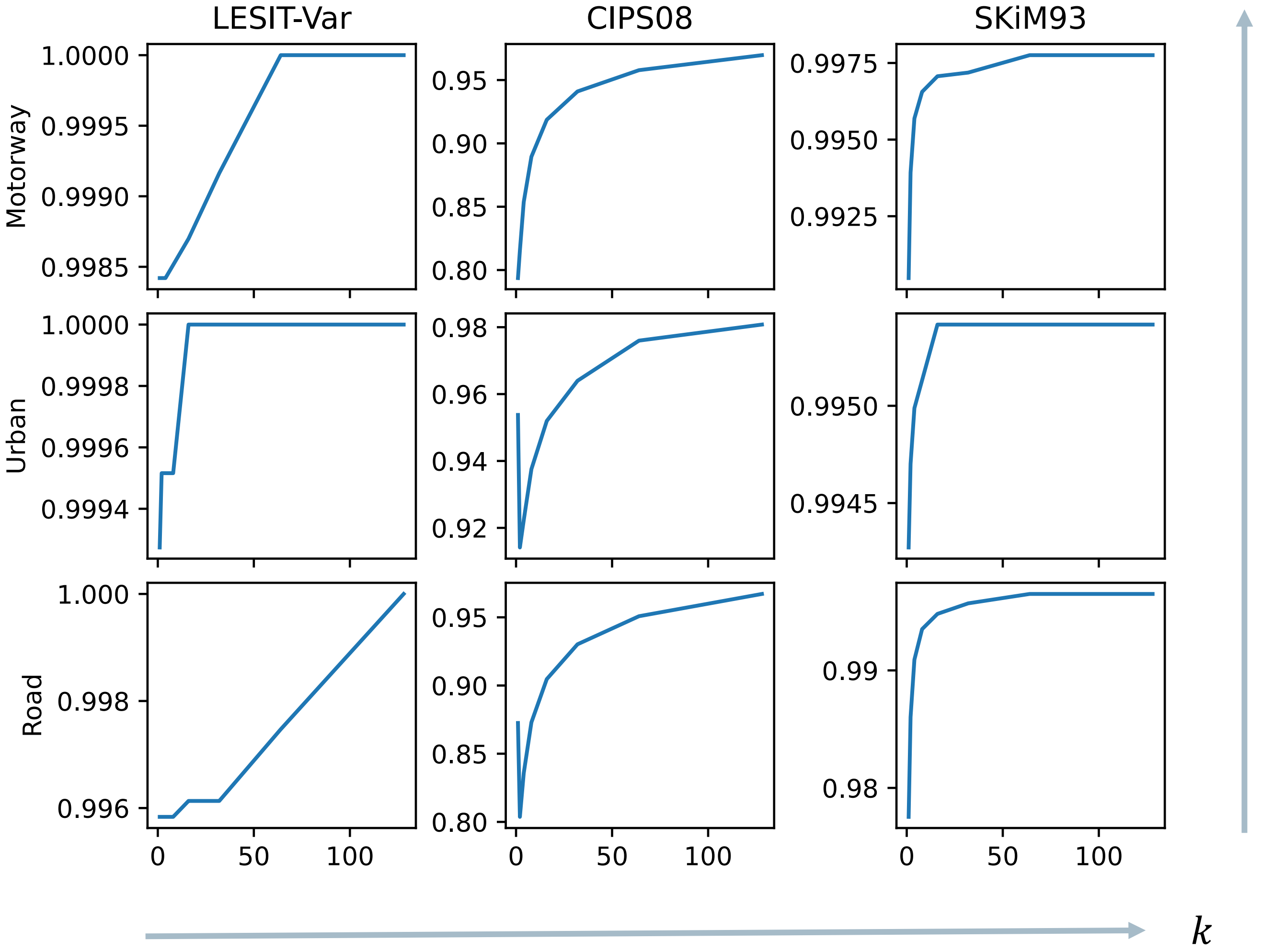
Results

Simple Cycle Residue Processing (simple)

$$t_f^s = \frac{t_f^s(k)}{t_f^r(k = 128)}$$

Observations

- Normalized lifetime based on converged result without residue processing
- Converging trends towards the lifetime without residue processing
- Converged results are very close and sometimes equal to the converged results without residue processing
- Convergence trend is mainly in upwards direction. Thus, results at k1 = 1 underestimate the lifetime in most cases.



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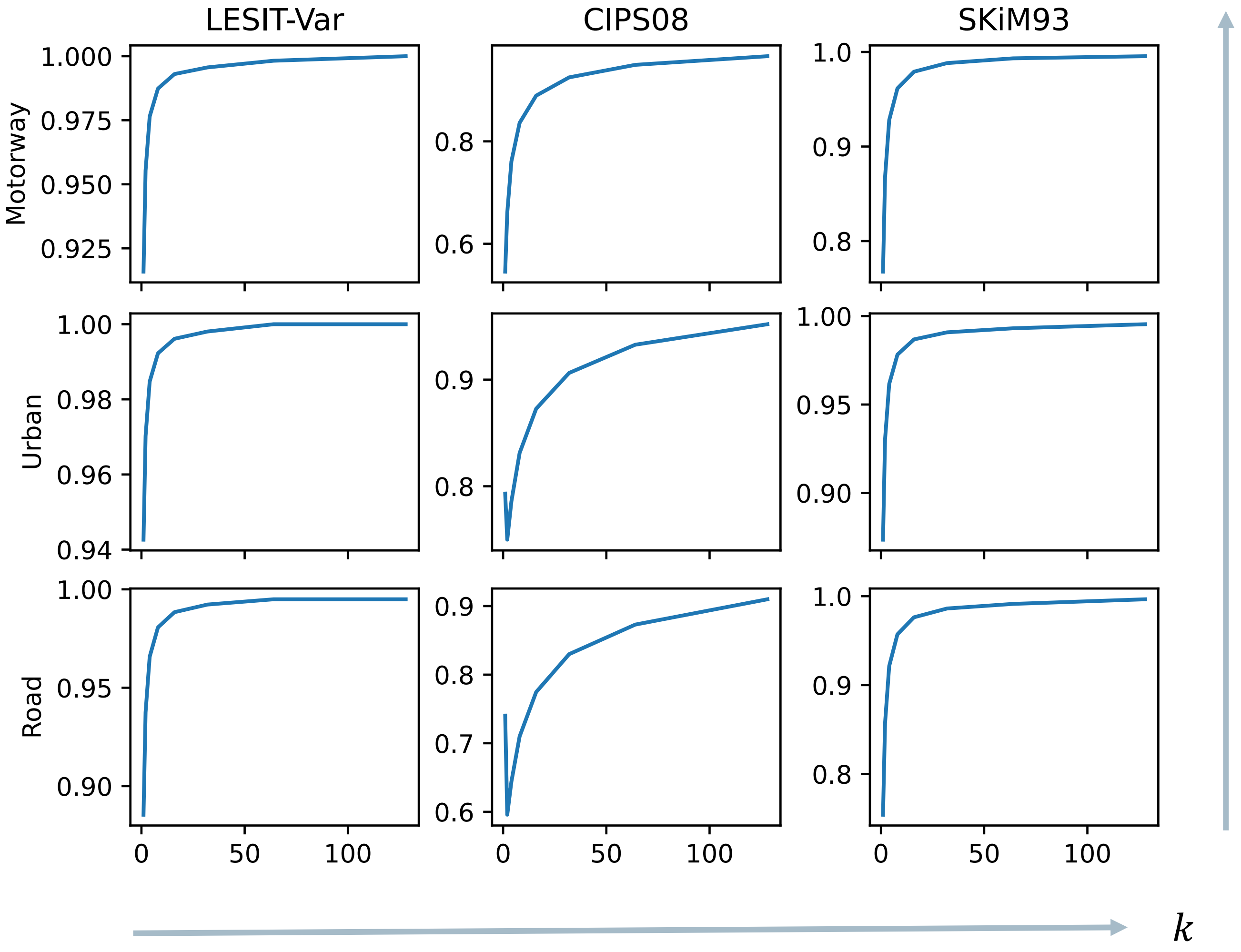
Results

Both Residue Processing Methods (simple + half)

$$t_f^{sh} = \frac{t_f^{sh}(k)}{t_f^{r}(k = 128)}$$

Observations

- Combined residue processing variant produces the most conservative lifetime estimation at k1 = 1
- CIPS08 model, deviations of more than - 60 % can be observed.
- Also, the SKiM93 model shows over - 20 % and even the
- LESIT-Var model yields up to - 10 % difference to the converged results

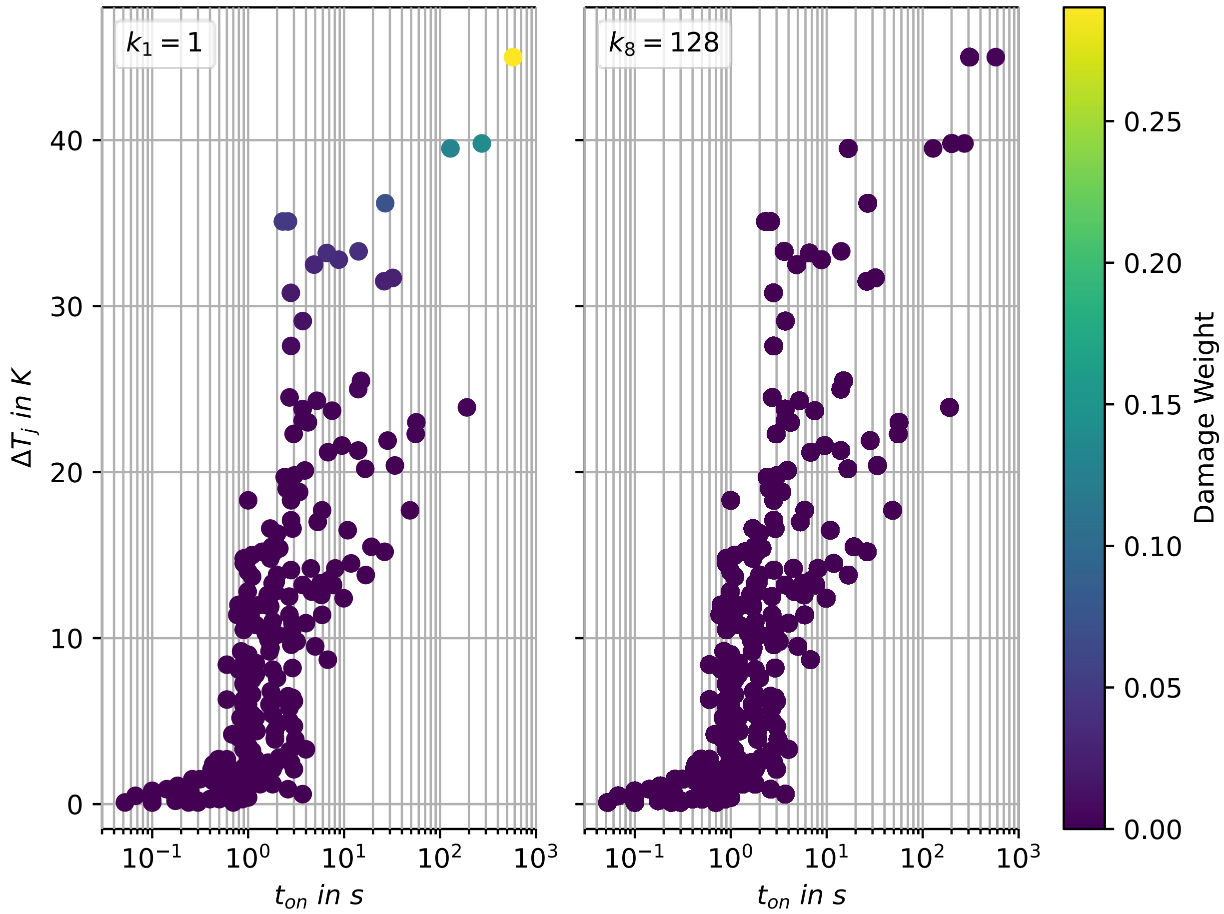


Results

Simple Cycle Residue Processing (simple)

Rainflow Counting Result Analysis

- Damage weight of the thermal cycles identified by RCA and simple-cycle counting from the Motorway profile for the SKiM93 model
- The highest impact of around 30 % is obtained for the simple-cycle residue in the profile with k1 = 1
- All other single cycles produce significantly less damage in the range of < 5 %.
- In case of the longer profile with k8 = 128, the effect of the simple-cycle residue is reduced to a level of < 1 %

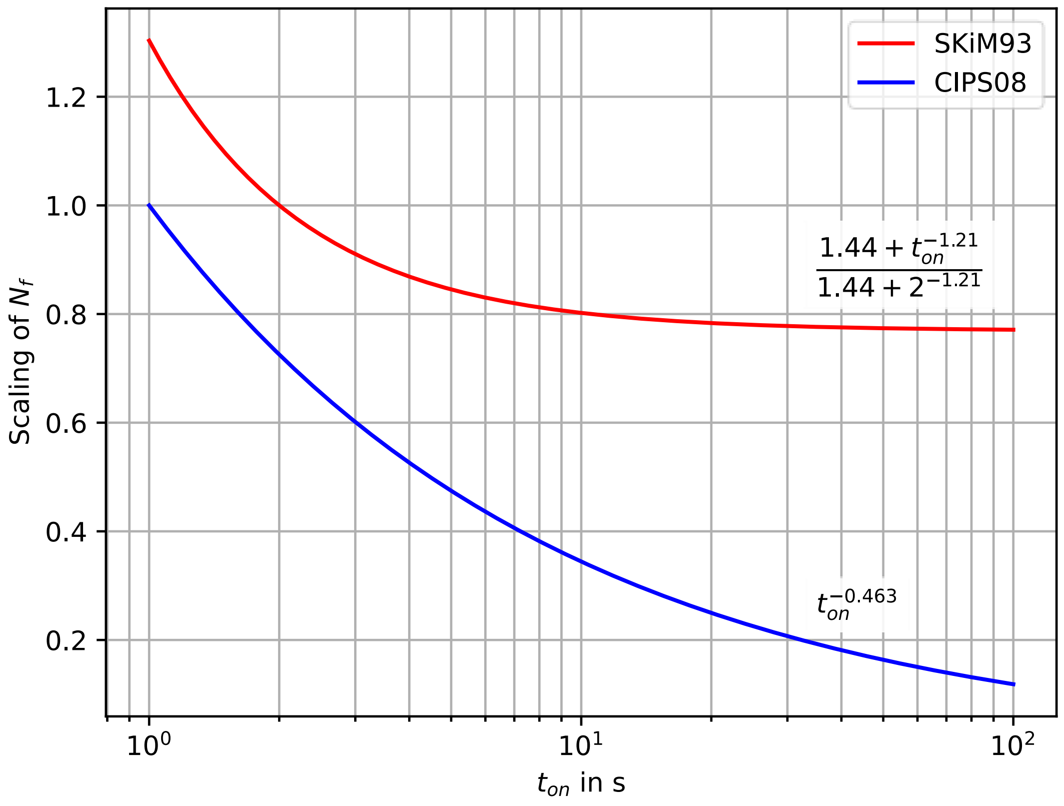


Results

Power Cycling Lifetime Model

Time-dependence

- CIPS08 model reduces the predicted lifetime significantly more for larger heating times than the SKiM93 model.
- Stronger deviations between the initial and the converged result can be explained for the CIPS08 model.
- The remaining behavior differences come from the mean temperature and the temperature amplitude terms in the models.



Summary & Conclusions

Modified Rainflow Counting Analysis

- Lifetimes predicted with different residue processing methods may vary, depending on the sensitivity of the lifetime model and the temperature profile.
- There is no general accurate residue processing method – field experience can show!
- The weaker the heating time dependence in the longer duration range, the less lifetime variance will be generated.
- Lifetime predictions converge to a unique result, regardless of which method has been selected, if the temperature profile length is artificially increased by multiple concatenation with themselves to balance out the total residue weighting.
- A convergence study of the predicted lifetime over the profile length can minimize these uncertainties.

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Results

Simple Cycle Residue Processing (simple)

- Residue among the highest thermal loads
- At a profile length of k1 = 1, their impact on the lifetime prediction is significant

Rainflow Counting Result Analysis

$k = 1$