Lifetime Analysis of Electronics and Power Electronic Components in Electric Vehicles

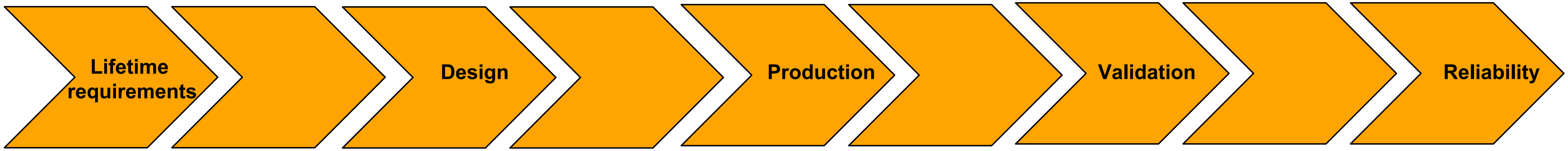
EVS32, Lyon, France 20.05.2019

Dr. Martin Brüll, Dr. Ayman Ayad, Dr. Andreas Greif, Sebastian Rogge, Matthias Töns

Motivation

Reliability is key

Lifetime requirements are an essential part of the automotive development process!



Lifetime requirements → Design → Production → Validation → Reliability

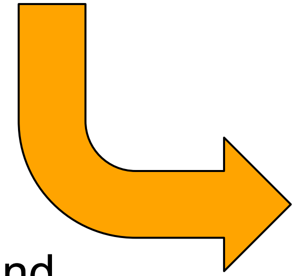
Typical Vehicle Lifetime Requirements

Classical view: Driving mode

Range [km]	Driving time [h]	Average speed [km/h]	Lifetime [y]	Yearly Mileage [km]
300 000	**8 000**	**37.5**	**15**	**20 000**
240 000	7 000	34.3	15	16 000
...	…	…	…	…

Car manufacturer dependent requirements

Realistic driving profile (including hilly driving cycles and acceleration runs) to be applied (→ load collective)

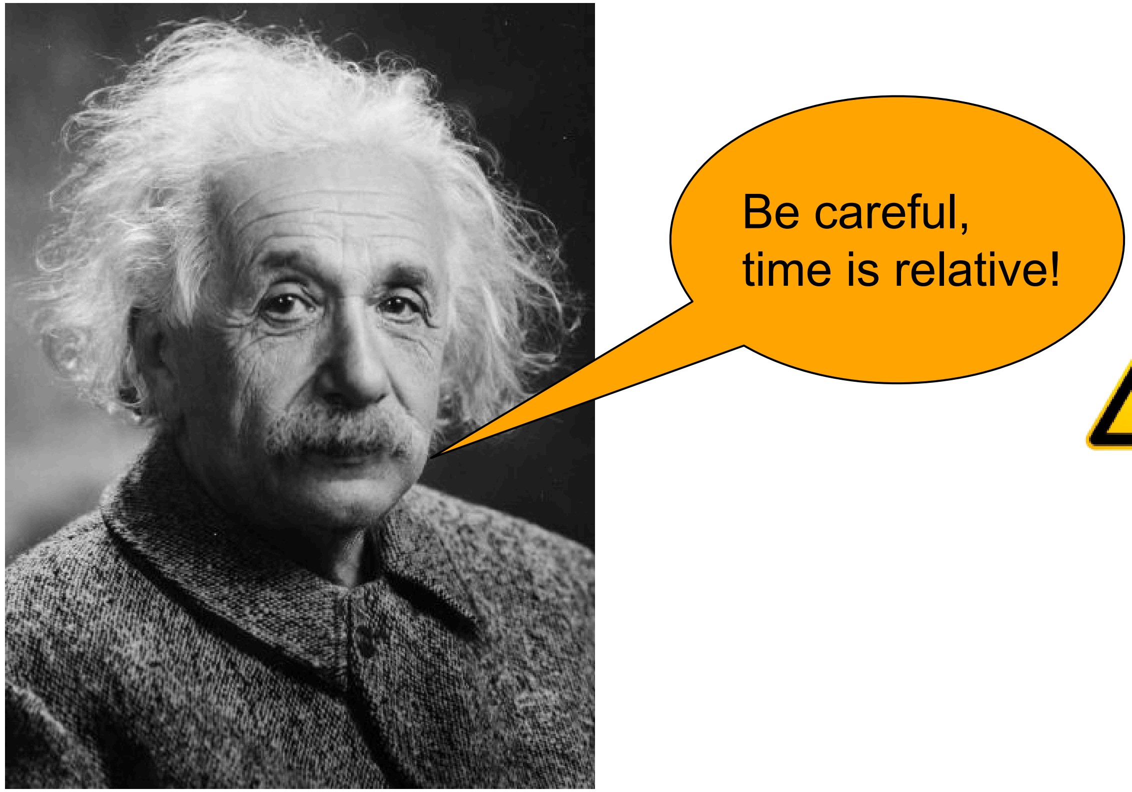


Mission Profile	Duration [s]	Average speed [km/h]	Number of repetitions	Overall distribution [%]
WLTC	1800	46.5	2020	15
Artemis Urban	993	17.65	1815	8
US Highway	775	76.51	200	0.7
OEM city 1	1740	61	419	4
OEM hilly road	1236	36	872	12
OEM cycle…	…	…	…	…
Acceleration (0...80km/h)	48	38.49	2000	0.4
Acceleration (80...120km/h)	27	99.07	1000	0.12
Total				**100%**

Target: No electronic failure

Vehicle Lifetime Requirements

Classical view: Charging mode



Source: https://upload.wikimedia.org/wikipedia/commons/d/d3/Albert_Einstein_Head.jpg

Conservative Model:

- Charge 7.3 hours per day
- Charge every day in 15 years
- 300.000 km range

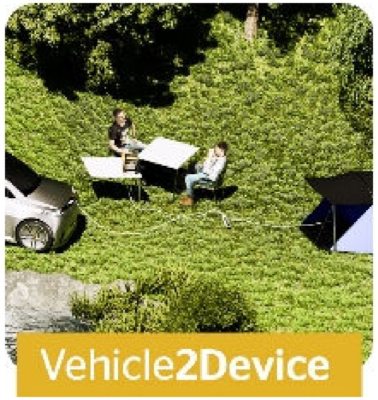
→ Charging time : **40.000 hours**
→ More than 5 times longer than driving!
→ So charging hurts the electronics 5 times more?

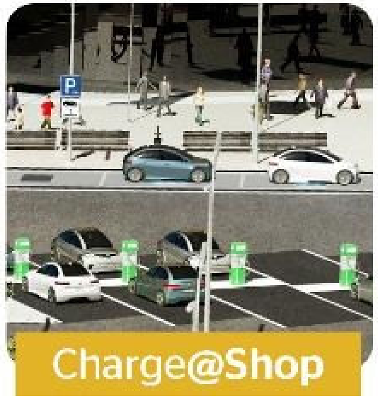
Rule of Thumb:
11kW ~ 1km/min = 60km/h charging speed !

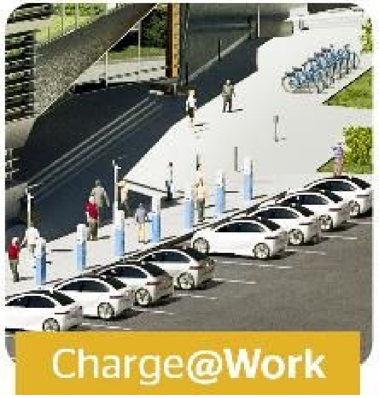
→ **7.5 km/h** (1.38 kW = 6A*230V) **charging speed**

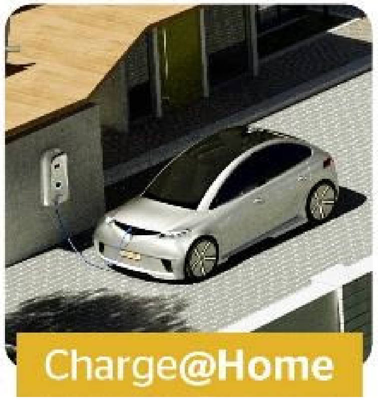
Charging is NOT like Refilling Gasoline

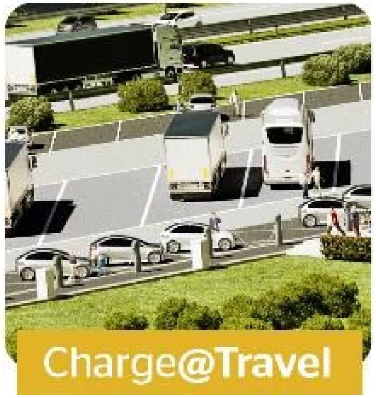
≠



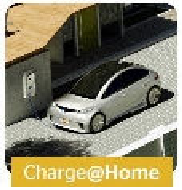


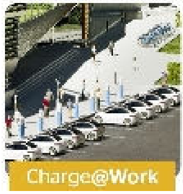


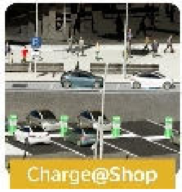


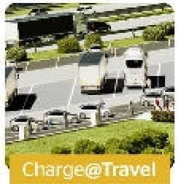


Vehicle Lifetime Requirements
Realistic view: Charging mode









Scenario 1 (example)

	Charging Power [kW]	Occurrence [%]	Charging speed [km/h]	Charging time [h]
Home	3.7	50	20	7 500
Work	11	25	60	1 250
Public	22	20	120	500
DC		5		

	Charging Power [kW]	Occurrence [%]	Charging speed [km/h]	Charging time [h]
Home	3.7	50	20	7 500
Work	11	25	60	1 250
Public	22	20	120	500
DC	≥50	5	≥240	≤62.5

	Charging Power [kW]	Occurrence [%]	Charging speed [km/h]	Charging time [h]
Home	3.7	50	20	7 500
Work	11	25	60	1 250
Public	22	20	120	500
DC	≥50	5	≥240	≤62.5

	Charging Power [kW]	Occurrence [%]	Charging speed [km/h]	Charging time [h]
Home	3.7	50	20	7 500
Work	11	25	60	1 250
Public	22	20	120	500
DC	≥50		≥240	≤62.5

Ø 32.2 km/h

Scenario 2 (example)

	Charging Power [kW]	Occurrence [%]	Charging speed [km/h]	Charging time [h]
Anywhere	6.6	100	35.7	8 400

My personal scenario

10% 2.3kW	2413h
80% 11kW	4000h
10% 22kW	250h
→	**6663h**

45 km/h charging speed

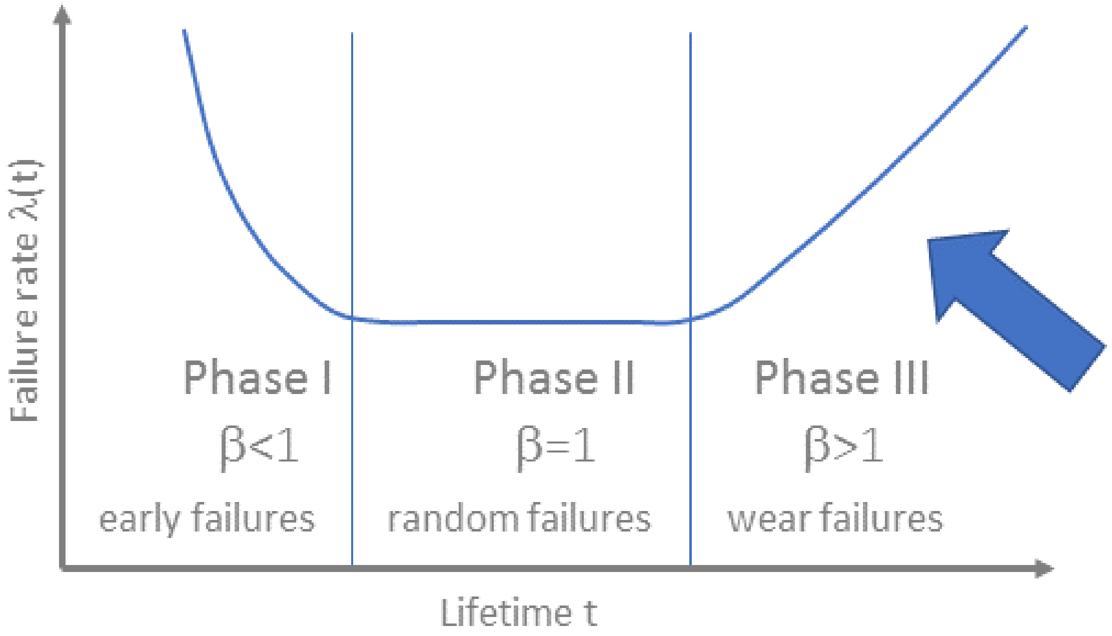
Charging speed = Driving speed

Charging time = Driving time

Driving time [h]	Average speed [km/h]
8 000	37.5

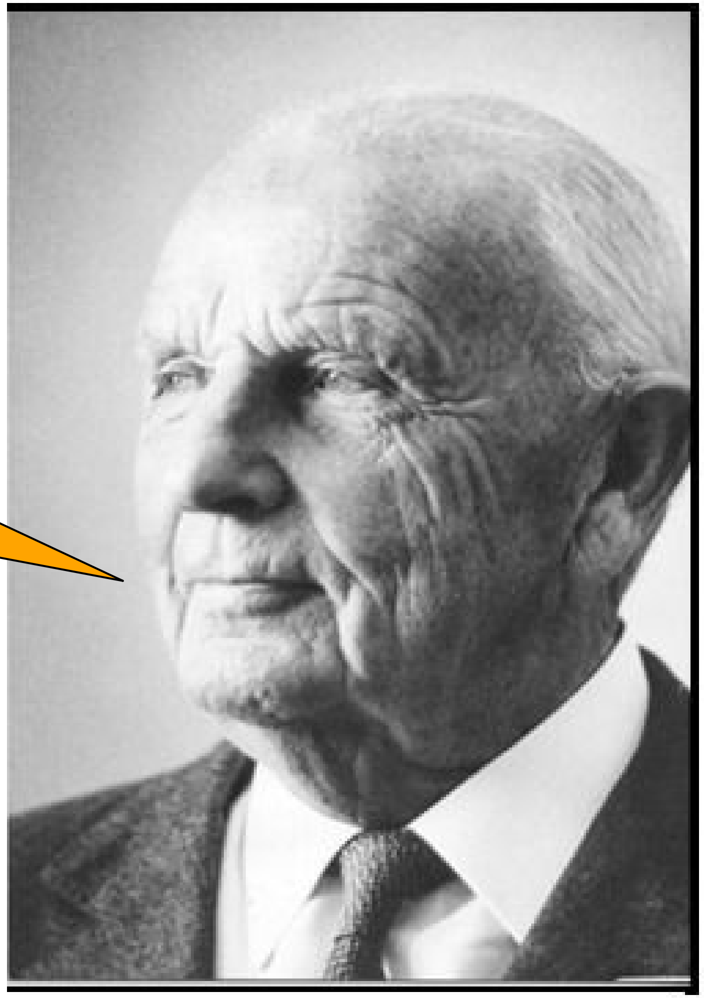
Lifetime Calculation for E/PE

Weibull Bathtub curve



$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1}$$

with $\eta > 0, -\infty < \gamma < \infty$ and $t \geq \max(0; \gamma)$



Wallodi Weibull 1887-1979

Photo by Sam C. Saunders

Source: https://www.geni.com/people/Waloddi-Weibull/6000000067858021078

Static Qualification of Tier2 Supplier Part

In relation to 1000 h positive test time

Failure rate

$$\lambda = \lambda_{ref} \times \overset{\text{voltage}}{\pi_U} \times \overset{\text{current}}{\pi_I} \times \overset{\text{temperature}}{\pi_T} \times \overset{\text{environment}}{\pi_E} \times \overset{\text{switching rate}}{\pi_S} \times \overset{\text{electrical stress}}{\pi_{ES}}$$

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1}$$

Failure rate under reference conditions

Useful lifetime

$$t_t = t_{op} \times \Pi_x$$

Operating time

Test time (Budget: 1000h)

$$\pi_T = e^{\left[\frac{E_{\alpha 1}}{k_0}\left(\frac{1}{T_{ref}} - \frac{1}{T_{op}}\right)\right]}$$

Svante Arrhenius

$E_{\alpha 1}$: activation energy
k_0 : Boltzmann constant
T_{op} : operation temperature
T_{ref} : reference temperature

IEC 61709

INTERNATIO L
STANDARD

NORME
INTERNATIO E

Part Categories	U	I	T
Capacitors (C)	yes	-	yes
Resistors (R)	-	-	yes
Inductors (L)	-	-	yes
Integ. Semi-Cond. (IC)	yes	-	yes
Discrete Semi-Cond. (T)	yes	-	yes
Diodes (D)	-	-	yes
Optocoupler (OC)	-	-	yes

$$\pi_U = e^{\left[C_3\left(\left(\frac{U_{op}}{U_{rat}}\right)^{C_2} - \left(\frac{U_{ref}}{U_{rat}}\right)^{C_2}\right)\right]}$$

U_{op}: operating voltage
U_{ref}: reference voltage
U_{rat}: rated voltage
C_2 and C_3: empirical constants

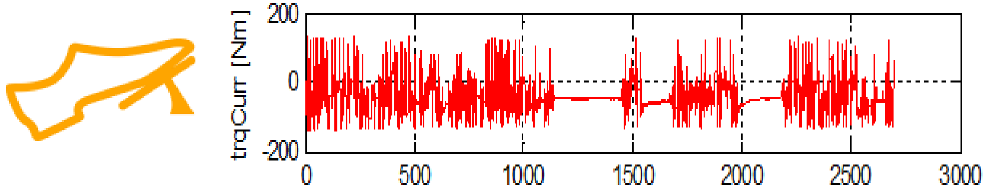
Example: Capacitor

$$t_t = t_{OP} \times \pi_T \times \pi_U = 48\,000\ h \times 0.094 \times 0.176 = 794\ h$$ ✓

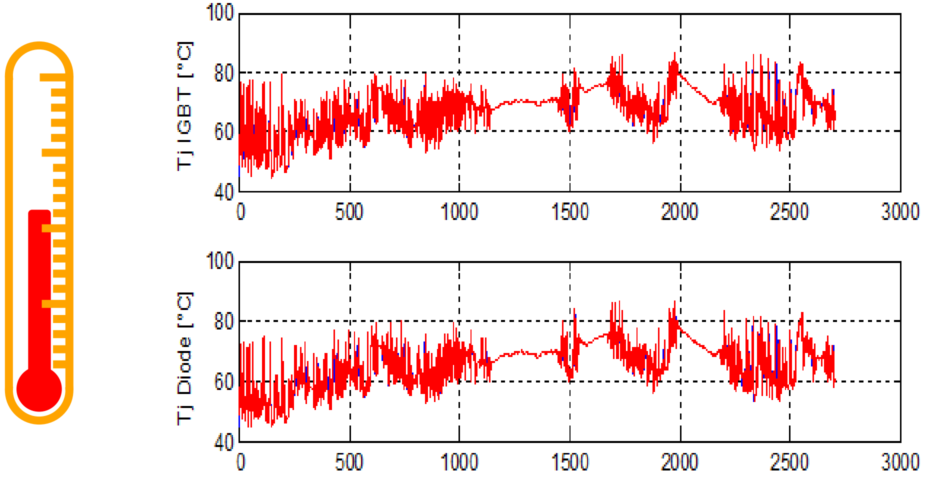
Source: https://de.wikipedia.org/wiki/Svante_Arrhenius#/media/File:Svante_Arrhenius_01.jpg

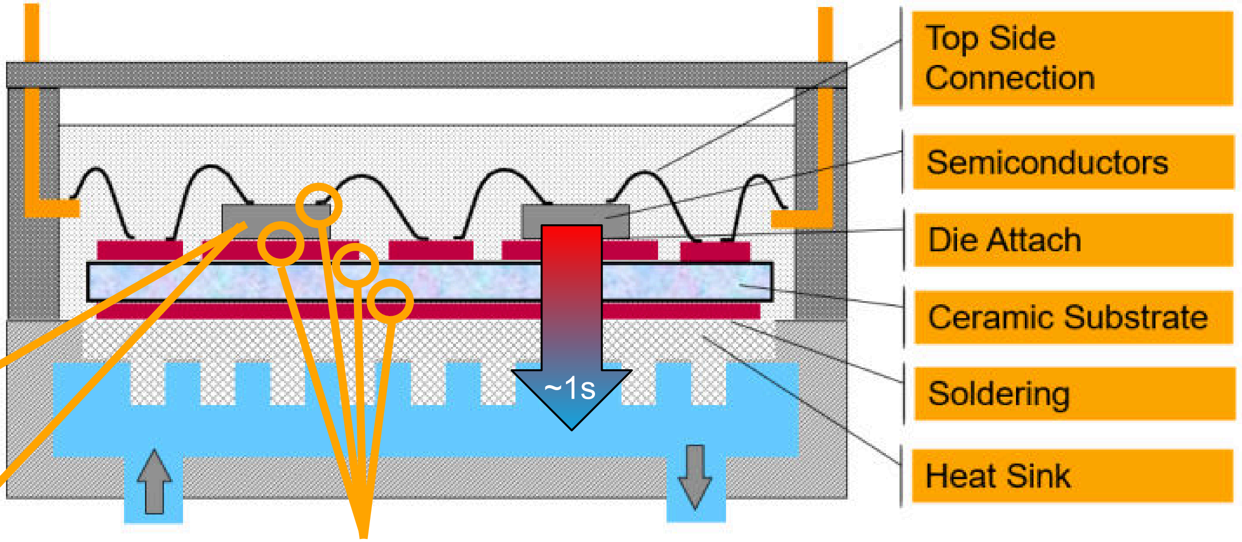
Dynamic Qualification via System Simulation

Thermal stress



Torque requests results in temperature at IGBT and Diode



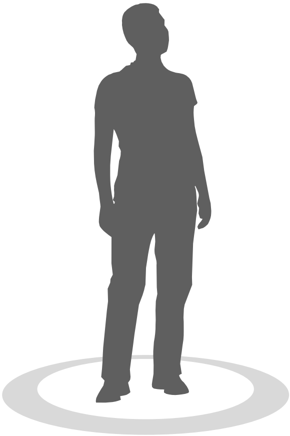


Thermal Stress → Aging

While **charging** the power semiconductors see a constant load
→ stay on a constant temperature
→ **Aging** of interconnections is **very small**

Palmgren-Miner Rule

A Lifetime Budget



A. Milton Miner

Considering k different stress levels S_i

Partial damage at this stress level after n_i cycles

$$W_i = n_i * S_i$$

Failure at this stress level would appear after N_i cycles

$$W_{i,Failure} = N_i * S_i$$

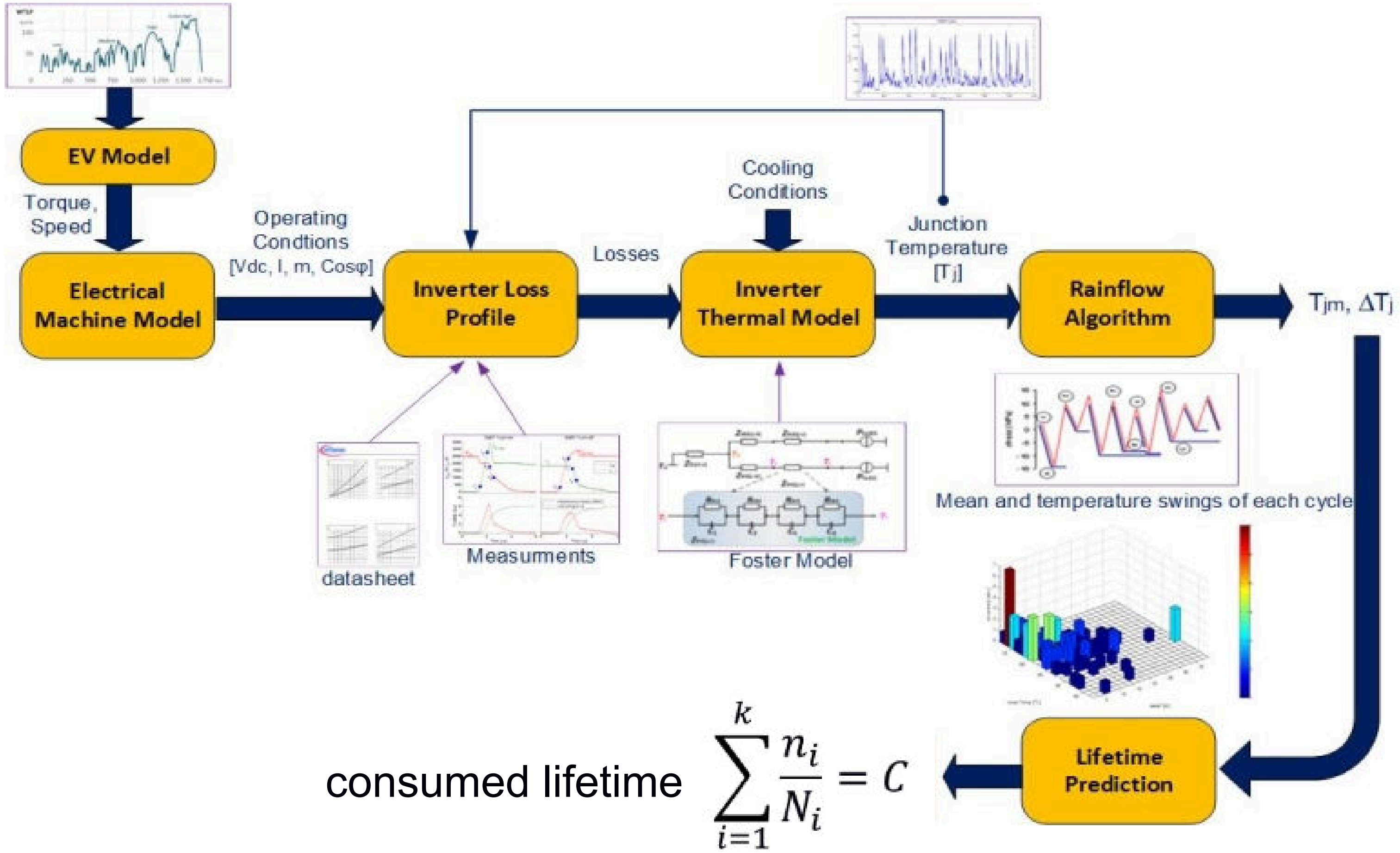
Arvid Palmgren

$$\sum_{i=1}^{k} \frac{W_i}{W_{i,Failure}} = \sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

C is then the proportion of consumed lifetime, which reaches 0 when new and 1 at the end of life

Source: https://sok.riksarkivet.se/Sbl/Mobil/Artikel/7995

Lifetime Analysis Algorithm



EV Model

Torque, Speed

Electrical Machine Model

Operating Condtions [Vdc, I, m, Cosφ]

Inverter Loss Profile

datasheet

Measurments

Losses

Cooling Conditions

Inverter Thermal Model

Foster Model

Junction Temperature [Tj]

Rainflow Algorithm

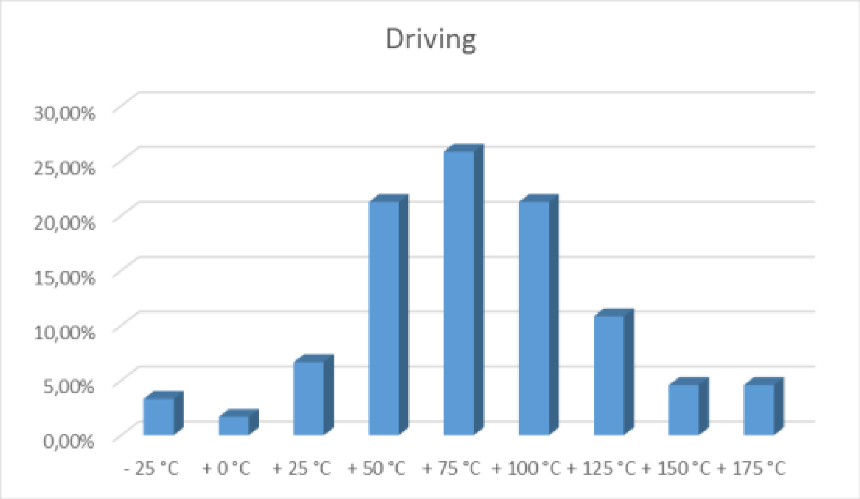
Tjm, ΔTj

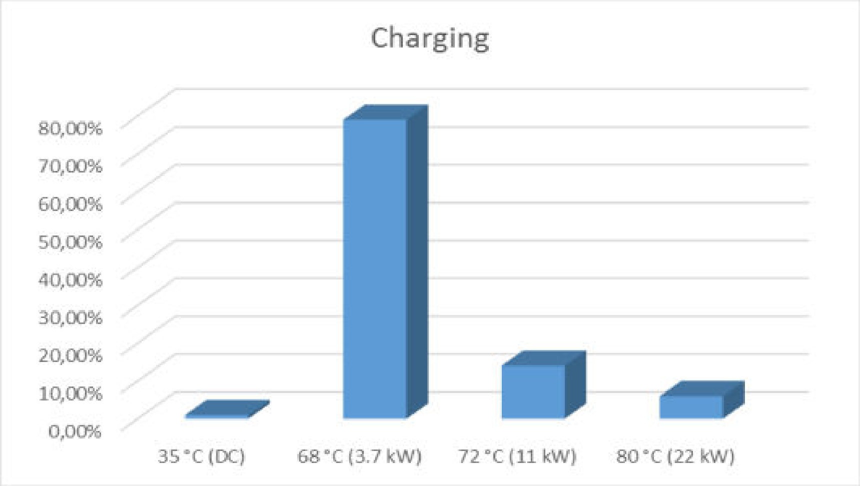
Mean and temperature swings of each cycle

Lifetime Prediction

consumed lifetime $\sum_{i=1}^{k} \frac{n_i}{N_i} = C$

Temperature Profile





Driving

$$\text{weighted } \pi_T = 0.0355$$

$$t_{t,driving} = t_{OP} \times \pi_T = 8\,000h \times 0.0355 = 284h$$ ✓

Test time (Budget: 1000h)

Charging

$$\text{weighted } \pi_T = 0.0021$$

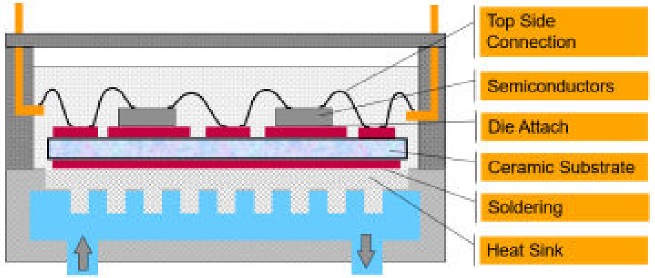
$$t_{t,charging} = t_{OP} \times \pi_T = 10\,000h \times 0.0021 = 21h$$ ✓

Test time (Budget: 1000h)

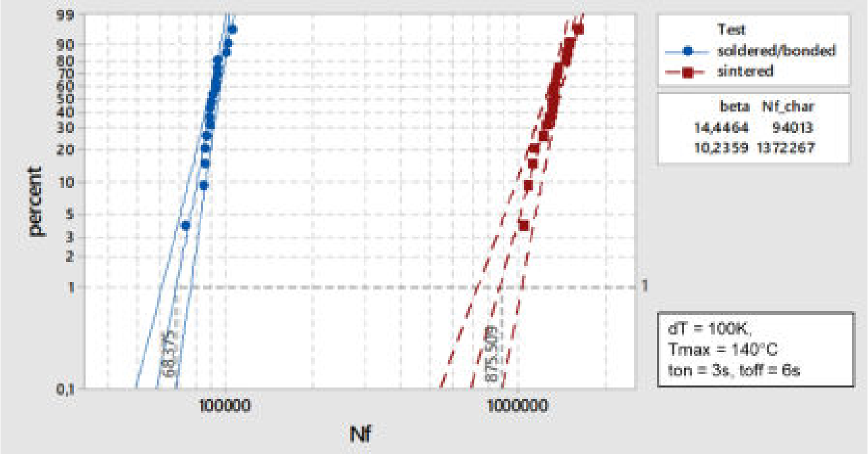
→ Charging consumes just 2% of Driving Lifetime Budget

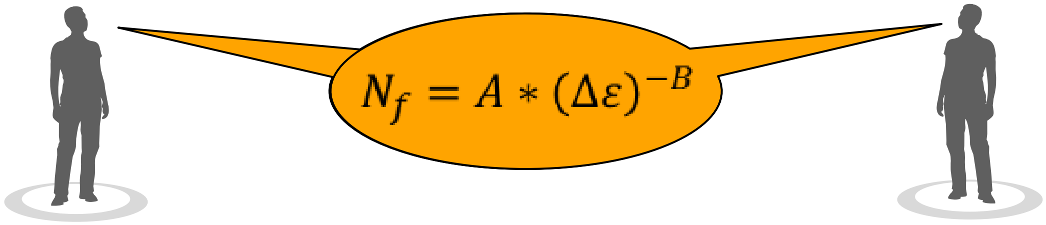
Integration, Assembly and Connection Technology

Experimental determination of coefficients



Exemplary comparison of soldered/bonded vs. sintered technology



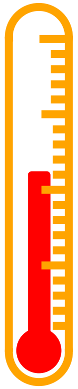


$$N_f = A * (\Delta\varepsilon)^{-B}$$

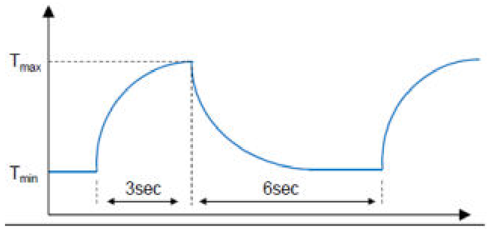
L.F. Coffin

S.S. Manson

N_f : Failure time (fatigue life)
$\Delta\varepsilon$: fatigue coefficient $\Delta\varepsilon$
(strain amplitude ~ infinitesimal deformation per cycle)
A : Coffin-Manson coefficient A
(material constant: To be determined experimentally)
B : damage coefficient
(material dependent: To be determined experimentally)



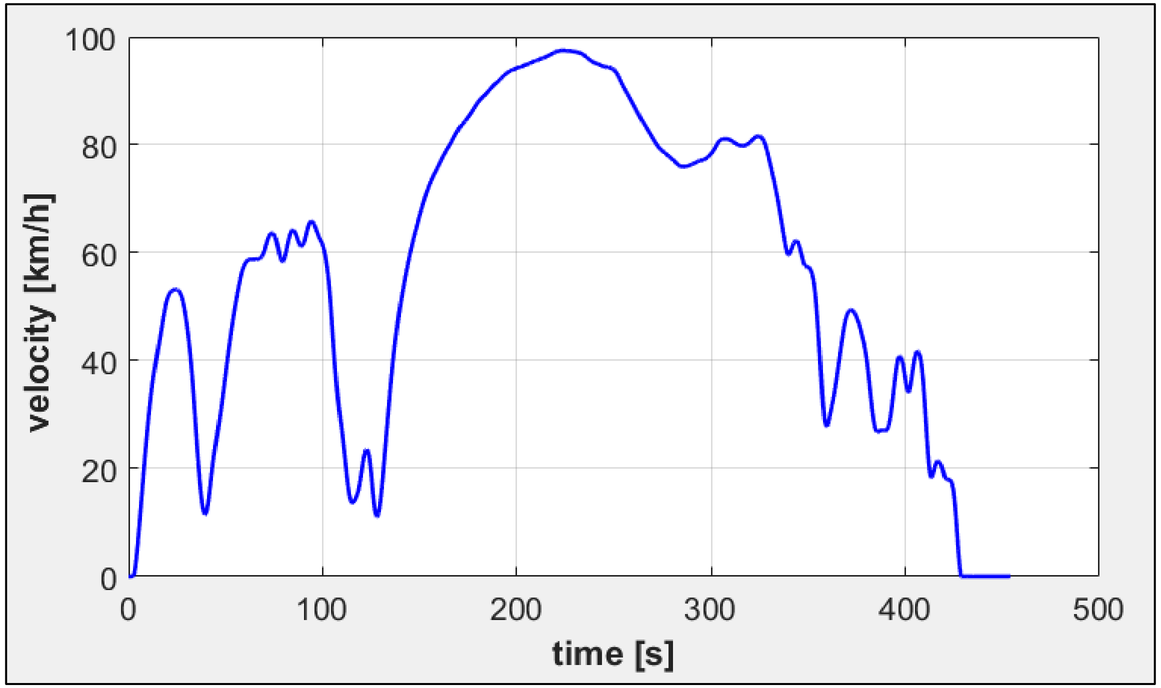
e.g. 100K
temperature shock



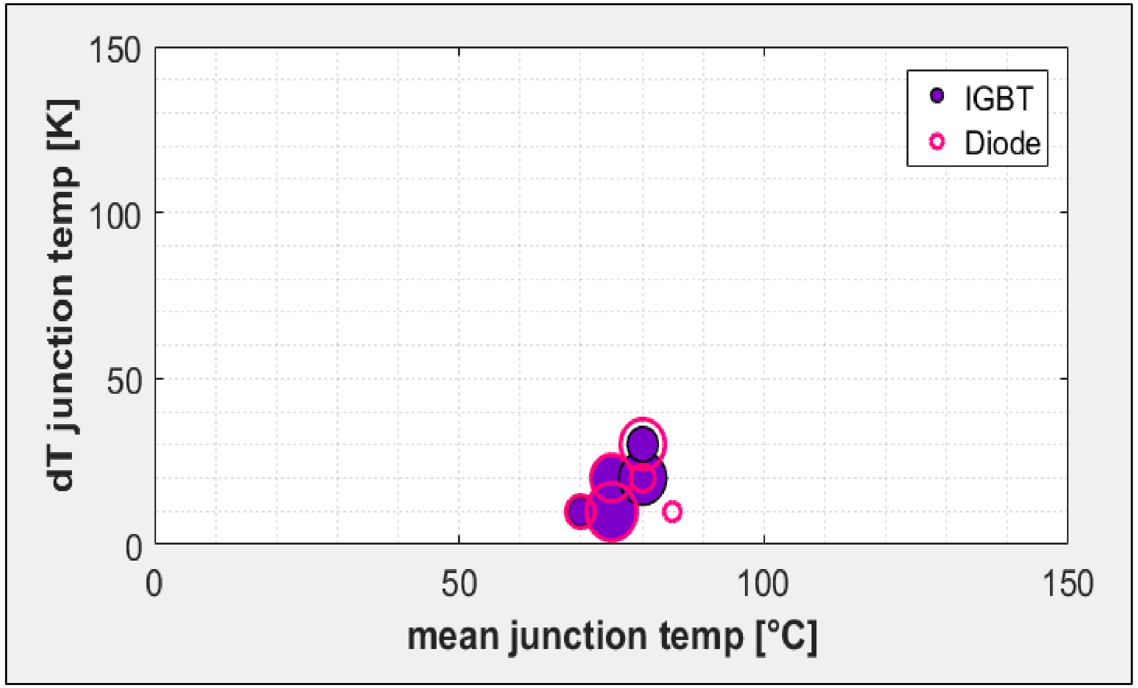
System Simulation Results

Urban mission profile

Mission profile



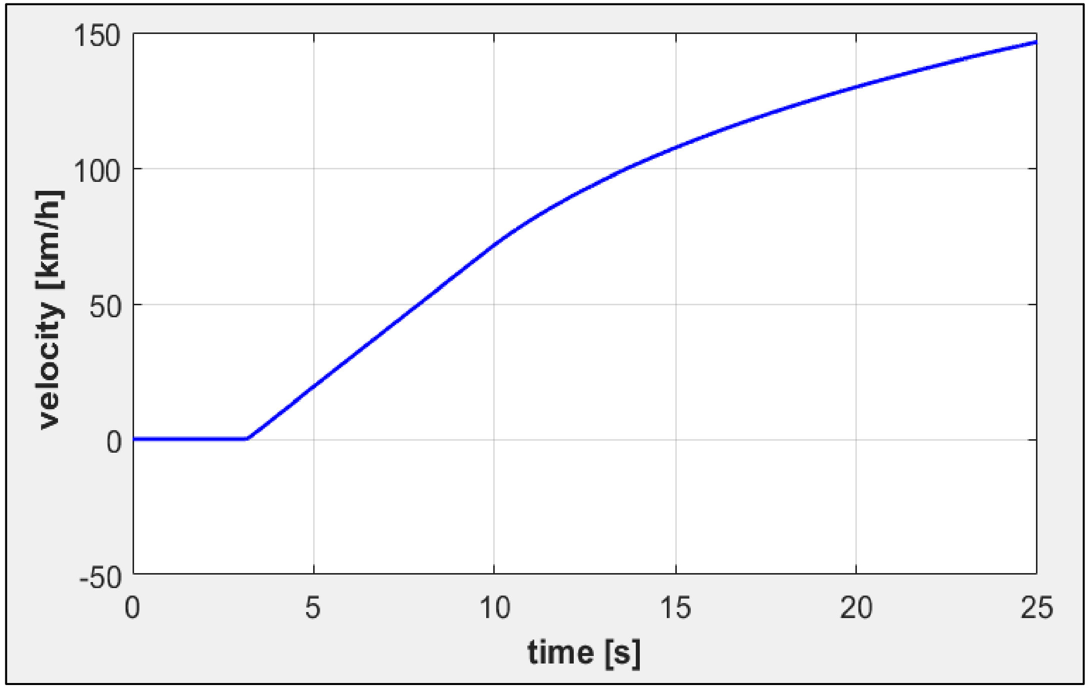
Inverter temperature



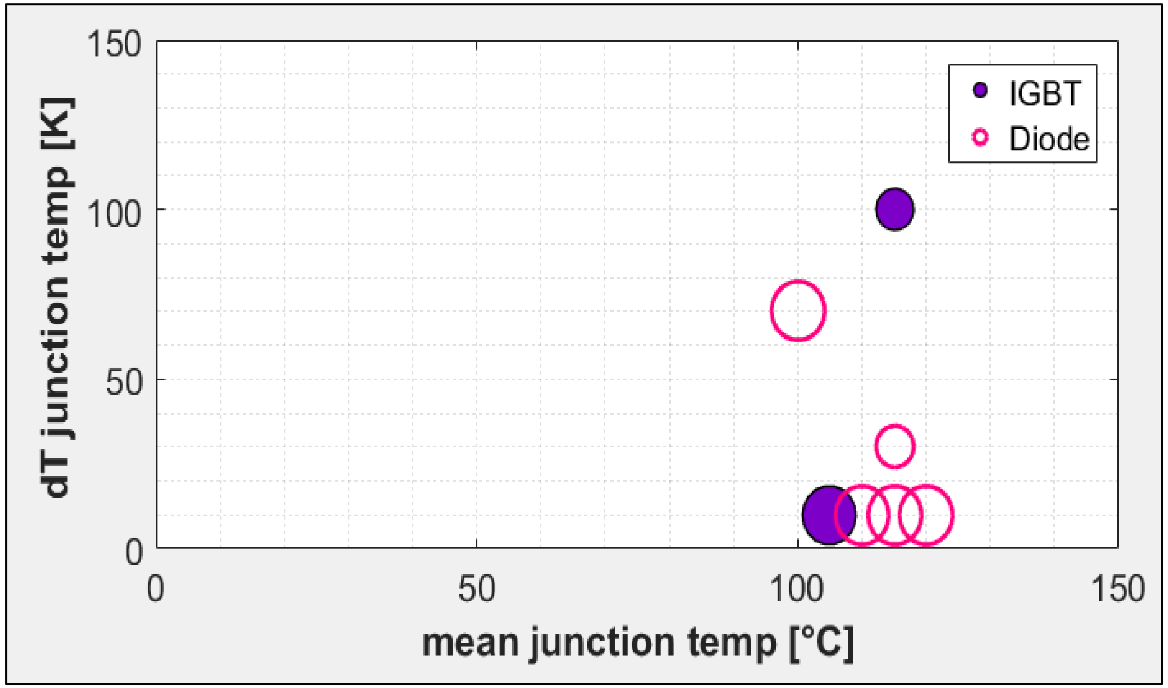
System Simulation Results

Full accelerator pedal mission profile

Mission profile

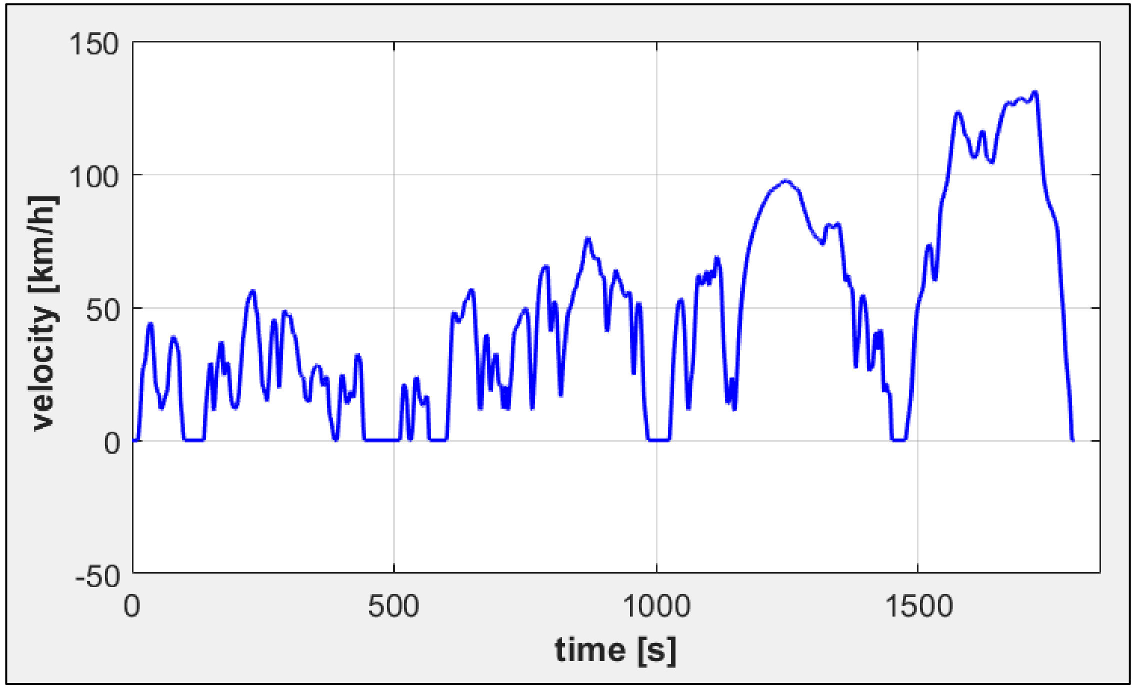


Inverter temperature

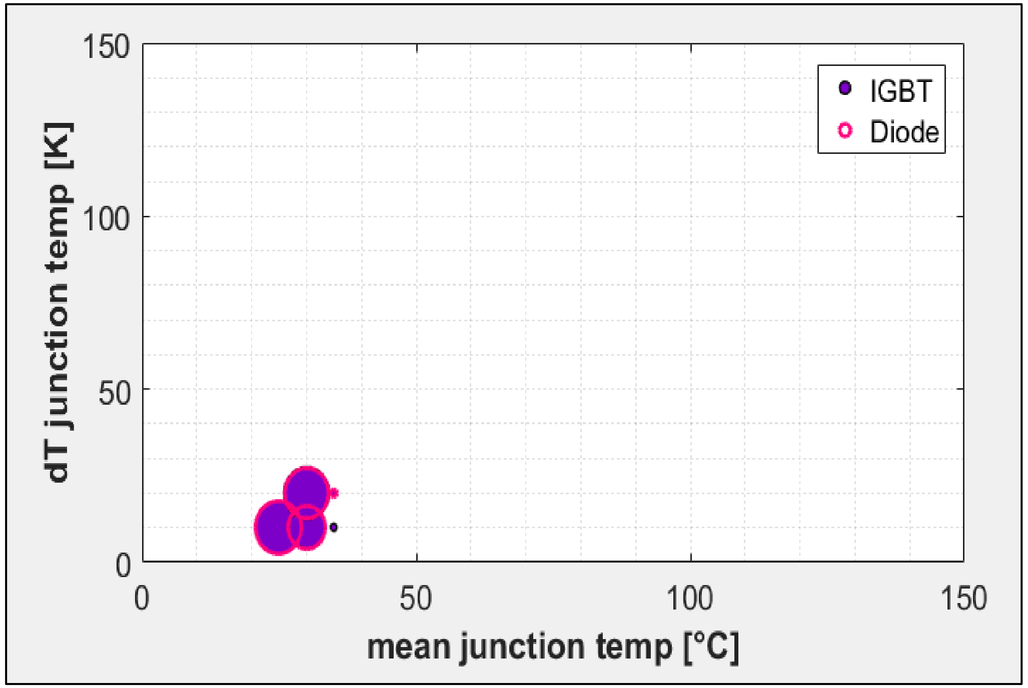


System Simulation Results
WLTC mission profile

Mission profile



Inverter temperature



Conclusion

Automotive Quality

- Tier2 supplier parts: Only positive tests (1000 h) available (room for improvement!)
- Key parameter to be derived via experiments
- System simulation
  - is key for proper lifetime prediction
  - supports proper technology choice, e.g. connection technology and manufacturing process

Automotive use cases

- 8.000 h driving vs. 40.000 h charging not realistic mainstream → Define reasonable missions!
- Charging profiles do affect the lifetime less (~2% of drivetrain's lifetime budget)
- Drivetrain integrated charging is not affected by lifetime issues.

Outlook

- Enabling of additional functions for the power electronics
- E.g. vehicle-to-load applications

Thank you very much for your attention