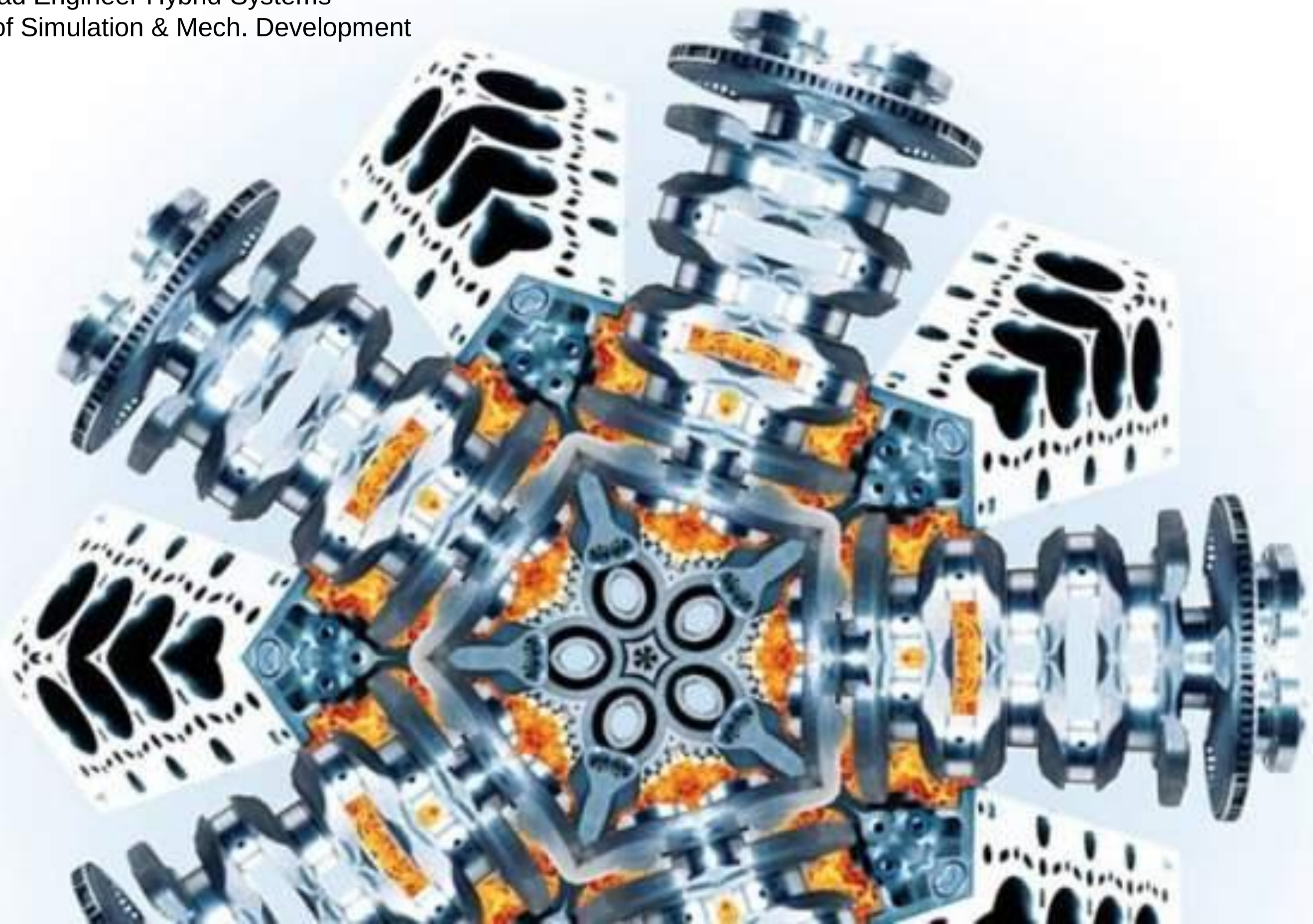
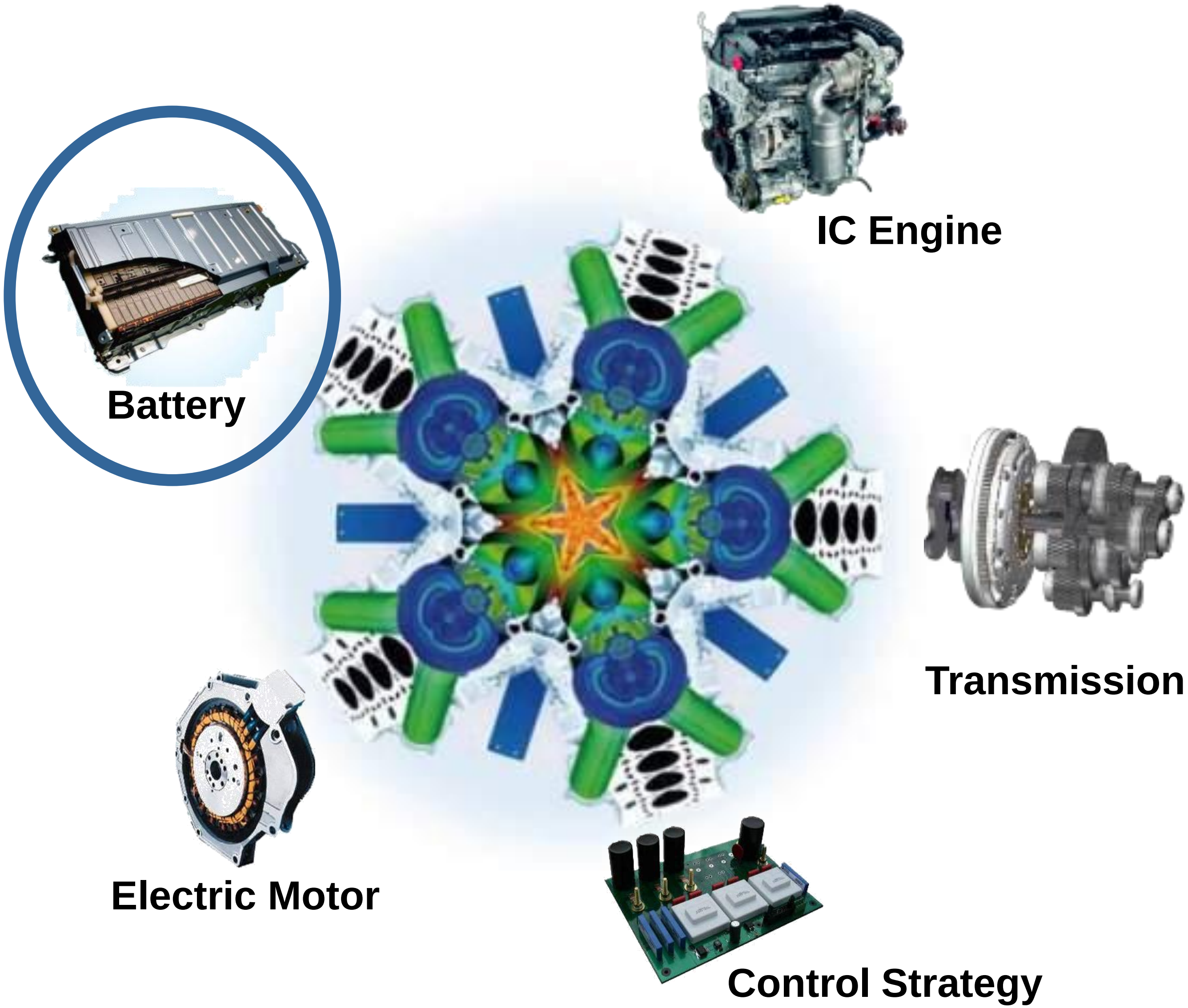
Reliability & Safety of Lithium Battery Packs

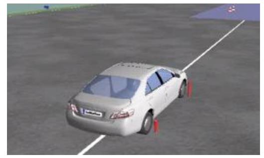
P. Gollob, Project Manager Battery Systems
Dr. U. Wiedemann, Product Manager Battery Systems
B. Kaltenegger, Analysis Engineer
Dr. K. Denkmayr, Manager Reliability Engineering
Dr. V. Hennige, Program Manager Battery Systems
Dr. H. Hick, Manager Mech. Development & Validation
T. Li, Development Engineer Hybrid
R. Schneider, Lead Engineer Hybrid Systems
F. Zieher, Head of Simulation & Mech. Development

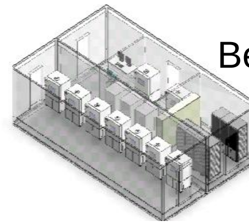


FIVE ELEMENTS OF THE POWERTRAIN

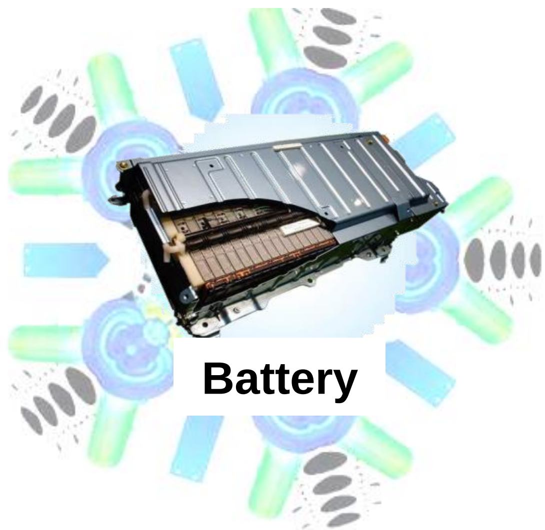


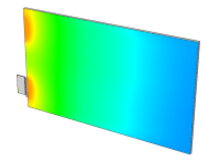
OVERVIEW ABOUT AVL´S BATTERY ACTIVITIES


Test equipment development


Testing & Benchmarking

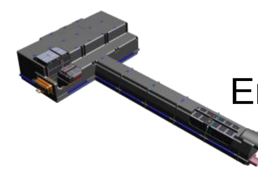
Cell/Pack Production Process Assurance




Thermal simulation

System validation

Validation target:	
300.000 km cycle life	✔
12 years calendar life	✔
EMC targets fulfilled	✔
System interaction ok	✔


Design Engineering


BMS series development (SW & HW)


Prototype built-up

AVL Battery Pack Development Market Overview

Battery Cell Manufacturers

Battery Module Integrators

Powertrain Integration "Opportunity"

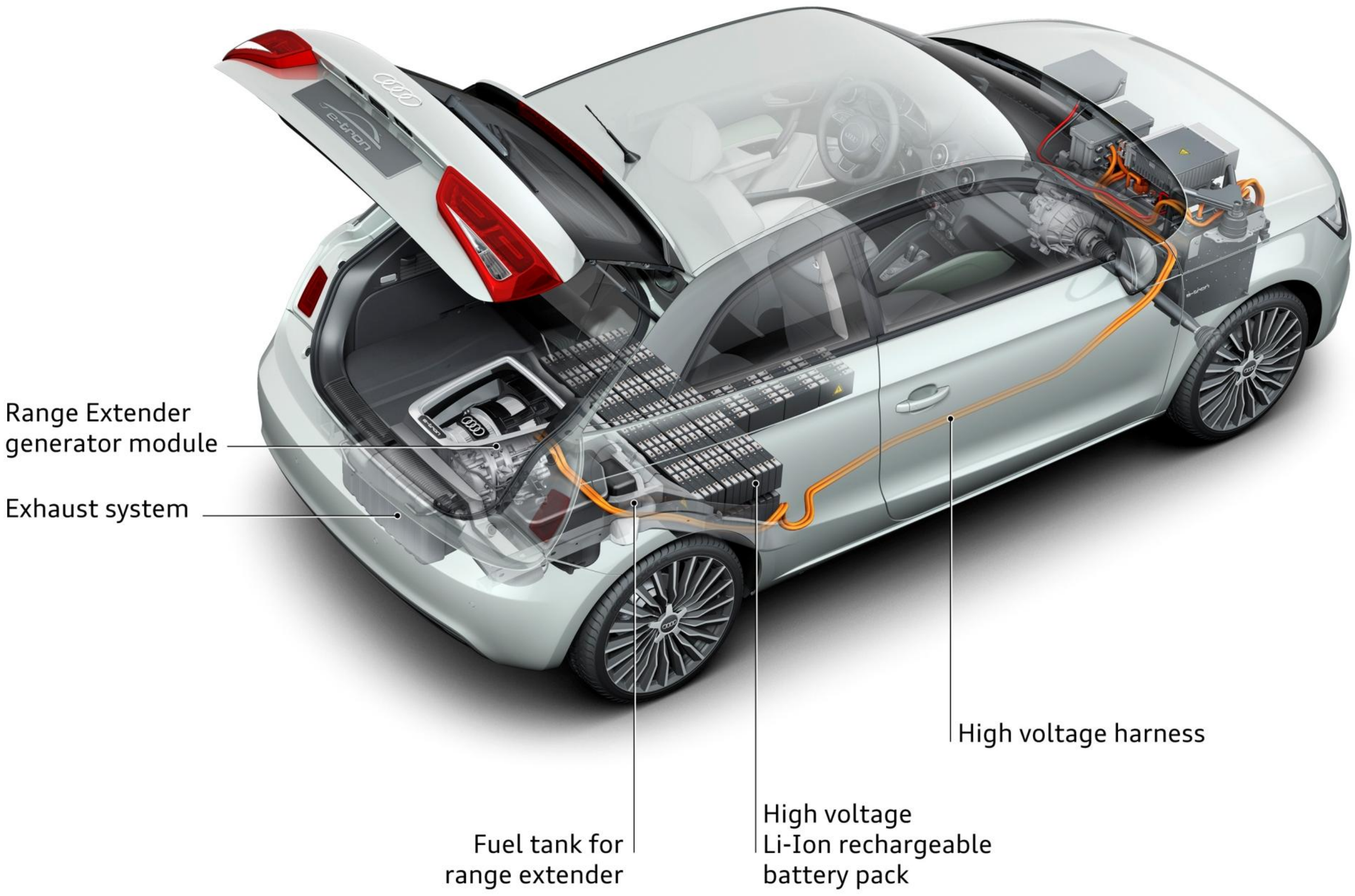
- Battery cell & module developers have limited automotive experience
- OEMs have market demand for hybrid powertrains and a need for "Proven" component suppliers
- OEMs can not invest the time, resources and capital to develop component suppliers & therefore need trusted engineering service providers to take on this development role

Hybrid/Electric Vehicle Manufacturers

AVL has established this trusted partnership with the automotive OEMs

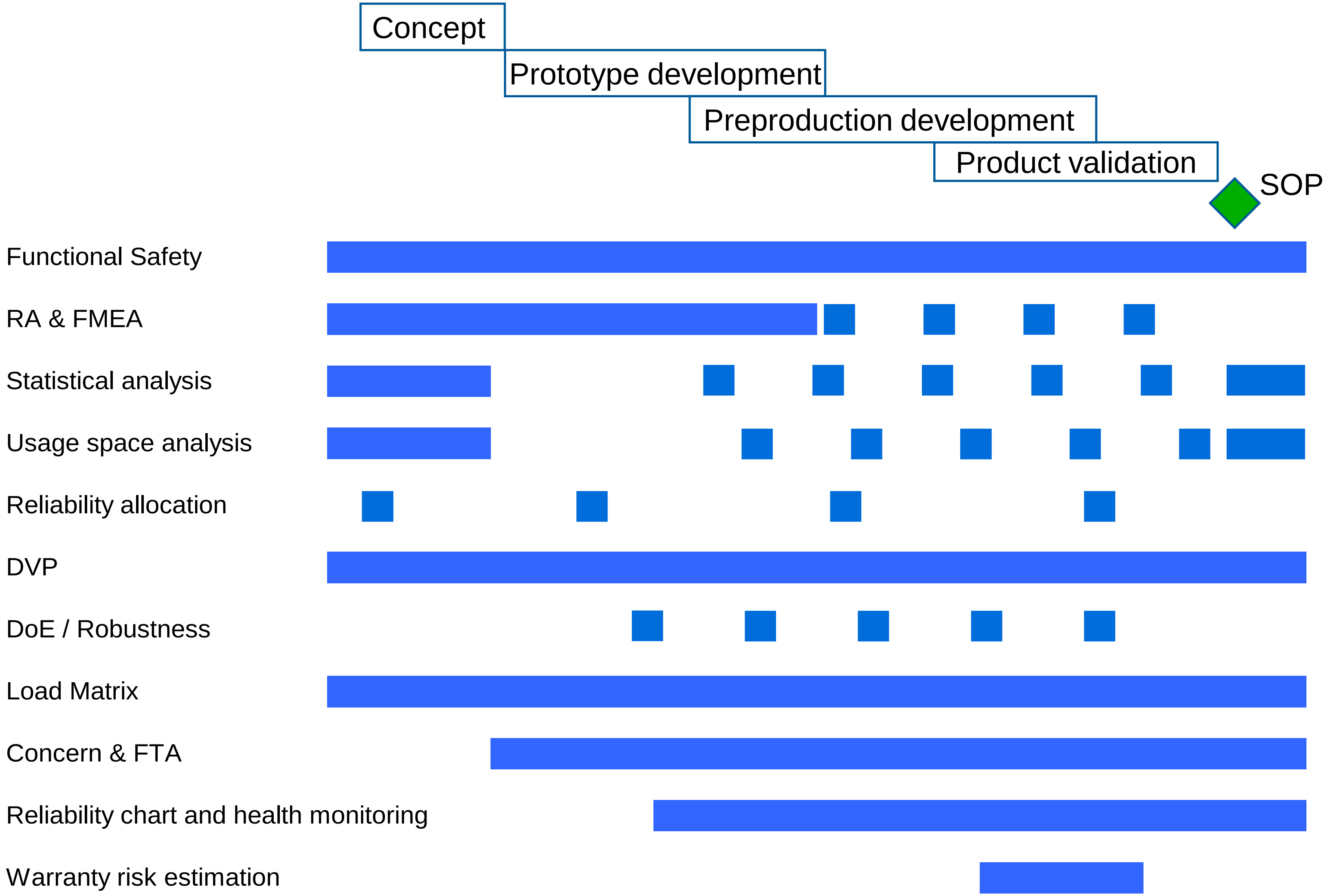
AVL is now focused on the development of strategic alliances with component suppliers who have unique product offerings suitable for automotive market introduction

AUDI A1 E-TRON
with AVL RANGE EXTENDER



Source: AUDI

BATTERY RELIABILITY PROCESS



TYPICAL SITUATION

High innovation pressure by legislation and competition

Reliability problems diminish profit and market reputation

For new systems / applications no test programs are available

Test program is not capable to demonstrate reliability targets

Acceleration factors of tests are estimated globally

Certain modes of operation and applications are not tested at all

Optimization of the test time and resources is required

➔ Load Matrix

LOAD MATRIX PROCESS

System Analysis	**Component oriented analysis w.r.t. damaging operating conditions, risk based prioritisation of failure modes**
Applications and Targets	**Identification of usage space, definition of reference duty cycles and reliability targets**
Test Program and Load Analysis	**Determination of acceleration factors, damage modeling, adaptation of test program**
Evaluation and Optimization	**Reliability and durability analysis of test program, timing & costs, warranty risk reduction**

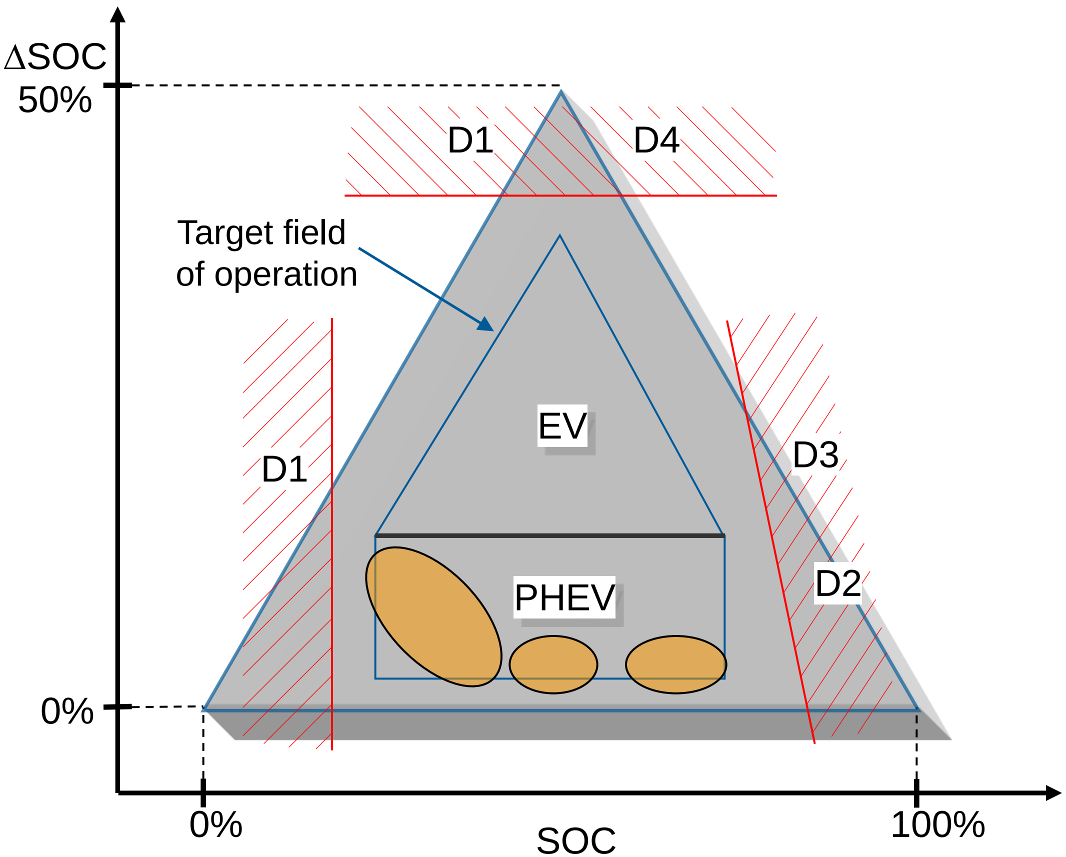
LOAD MATRIX SYSTEM ANALYSIS
SELECTION OF RELEVANT COMPONENTS

Vehicle	**Hybrid or Electric Vehicle**				
System	**Battery System**				
Subsystem	**Battery module**	**Cooling system (air or liquid)**	**Electronic components**	**Battery housing**	**Connectors + wires**
Components	Cell	Fan	Battery control board	Housing	High voltage wires
	Cell sensors	Heat exchanger	System sensors	Overpressure valve	HV-connector to vehicle
	Cell connector	Pipe/ channels/ manifolds	Insulation monitoring	Pressure balance device	Module connectors (busbar)
	Module housing	Sensors	Fuse(s)	Electrical insulation	Service disconnect
	Module sensors	Gaskets	Interlock system	Thermal insulation	Main contactor and precharge relay
	Gaskets			Gaskets	Signal wires
					Signal- connectors to vehicle

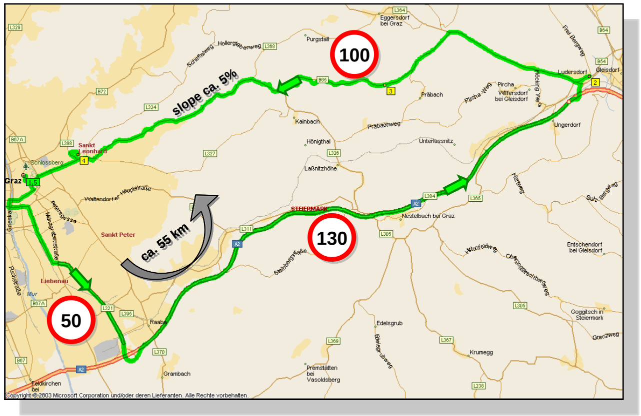
SELECTED KEY FAILURE MODES OF LITHIUM ION CELLS

	FAILURE MODE	CAUSE OF FAILURE	INFLUENCE FACTORS	
D1	Increase of internal resistance Reduced capacity	Degradation of SEI at negative electrode	SOC	High @ low SOC and discharging Medium @ other conditions
			DSOC	High
			Temperature	High
			Power	Medium
			Vibration / shock	Medium
D2	Increased self discharge Hard short circuit and subsequent cell venting	Lithium plating at negative electrode	SOC	High @ high SOC and charging at low T Low @ other conditions
			DSOC	Low
			Temperature	High
			Power	Medium
			Vibration / shock	Low
D3	Increased resistance Cell swelling and subsequent ell venting	Decomposition of electrolyte	SOC	High @ high SOC and charging Medium @ other conditions
			DSOC	Medium
			Temperature	High
			Power	Low
			Vibration / shock	Low
D4	Increased resistance and reduced power Reduced capacity	Crack of conducting paths	SOC	Low
			DSOC	Medium
			Temperature	Low
			Power	Low
			Vibration / shock	High

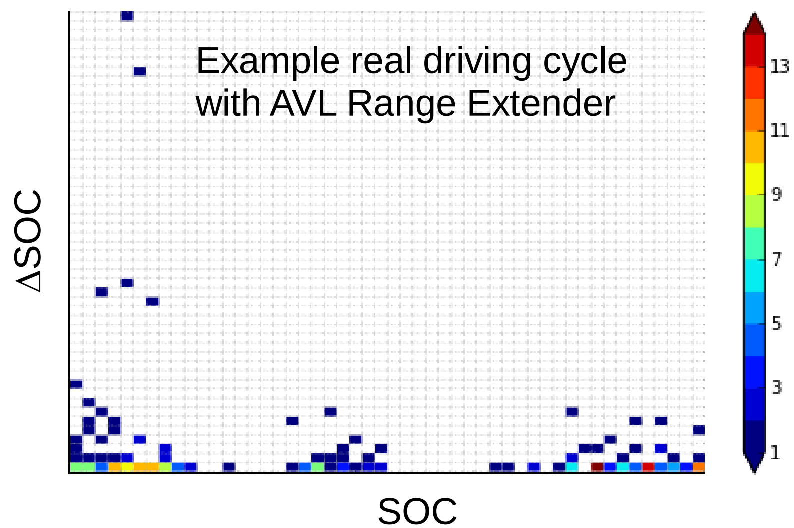
DEFINITION OF THE OPERATING DIMENSIONS



…Battery load during real driving cycle (AVL Range Extender)



Graz – test drive route



LOAD MATRIX PROCESS

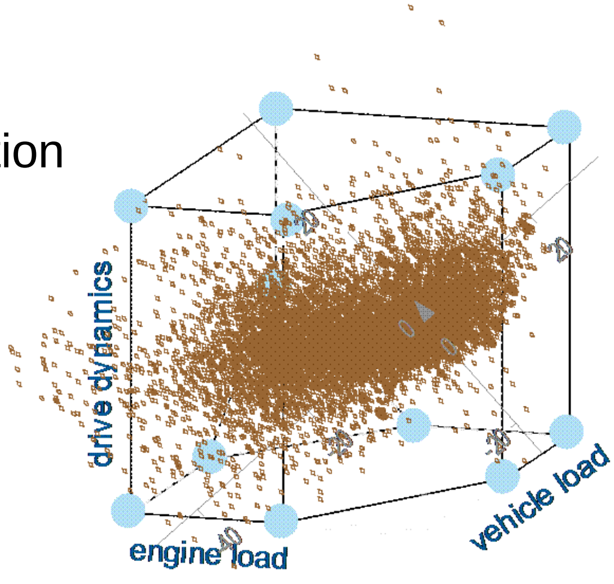
System Analysis	Component oriented analysis w.r.t. damaging operating conditions, risk based prioritisation of failure modes
Applications and Targets	Identification of usage space, definition of reference duty cycles and reliability targets
Test Program and Load Analysis	Determination of acceleration factors, damage modeling, adaptation of test program
Evaluation and Optimization	Reliability and durability analysis of test program, timing & costs, warranty risk reduction

USAGE SPACE ANALYSIS
IDENTIFICATION OF CRITICAL DRIVING CONDITIONS

Statistical analysis of relevant damaging parameters and variation of in-field use conditions

Southern California	≠	Northern Europe
City Driving	≠	Mixed Driving Cycle
Sporty Driver	≠	Economic Driver
Frequent Use	≠	Occasional Use

Identification of **Key Customers** for system validation



usage space with 3 factors

RELIABILITY TARGET ALLOCATION (RTA)

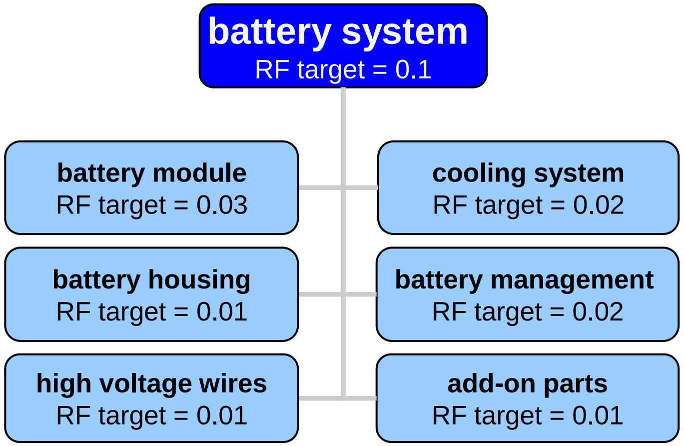
Our mission is a reliability target of 0 ppm.

This can not be demonstrated statistically.

➔Adequate targets for validation have to be determined

The target determines the validation effort

1. **Optimize adequate system target regarding**
   - legal requirements and warranty strategy
   - planned volume production incl. scale-up
   - available time to test
   - concentration of failure modes (Pareto principle)
2. **Derive component- and subsystem specific targets**
   consider development, production and economic risks
3. **Adapt component targets iteratively throughout development process**
   - take the feasibility of demonstration at certain time point into account
   - targets are stated separately for major failure modes
4. **Evaluate resulting improvement using Load Matrix update**

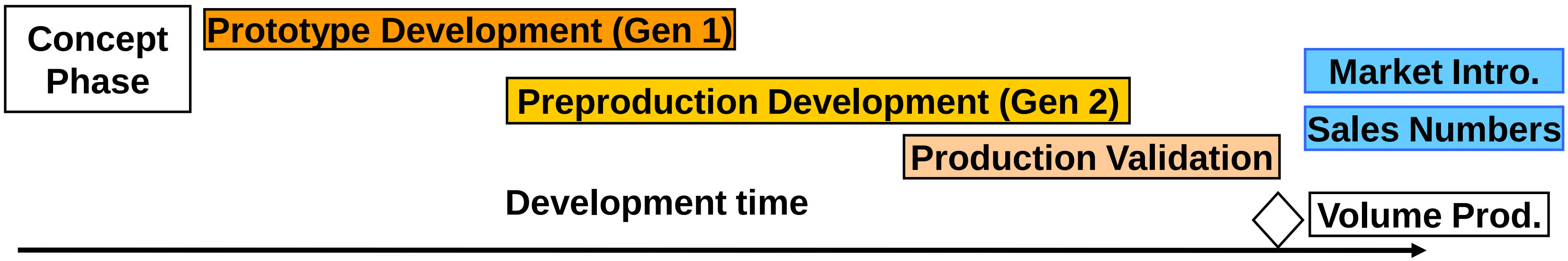


RF…Repair Frequency

LOAD MATRIX PROCESS

System Analysis	Component oriented analysis w.r.t. damaging operating conditions, risk based prioritisation of failure modes
Applications and Targets	Identification of usage space, definition of reference duty cycles and reliability targets
Test Program and Load Analysis	Determination of acceleration factors, damage modeling, adaptation of test program
Evaluation and Optimization	Reliability and durability analysis of test program, timing & costs, warranty risk reduction

DEFINITION OF THE VALIDATION PLAN (DURABILITY TEST PROGRAM)



A key element to reach the defined targets is the Validation Plan Design

A) General Validation Plan Design Issues

- Overall number of testing hours for reliability demonstration for the different applications
- Balancing between component, system and vehicle testing
- Balancing between Generation 1, Generation 2 and Production Validation phase
- ….

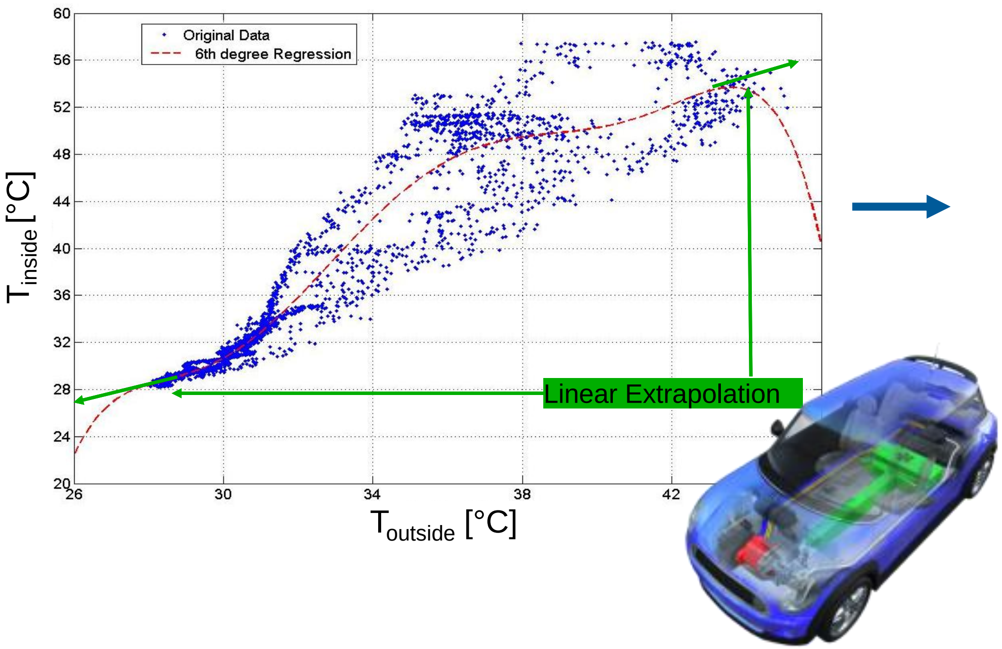
B) Detailed Analysis

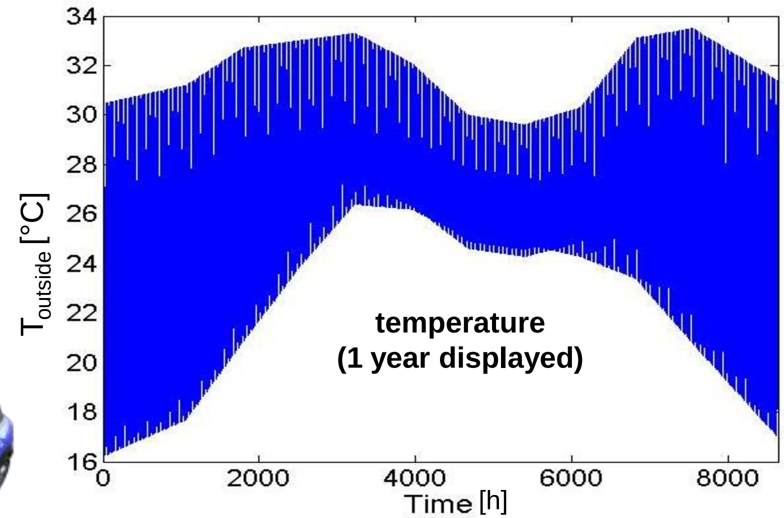
- Test cycle analysis
- Length (number of hours or kilometers) of tests
- Failure modes not validated due to not optimized test cycles
- Failure modes only validated in the vehicles
- ..

C) Validation Timing Analysis

- Validation status at the end of the specific phases (Gen.1, Gen.2 and PV phase)
- Validation beyond SOP

BATTERY TEMPERATURE WITHIN THE VEHICLE

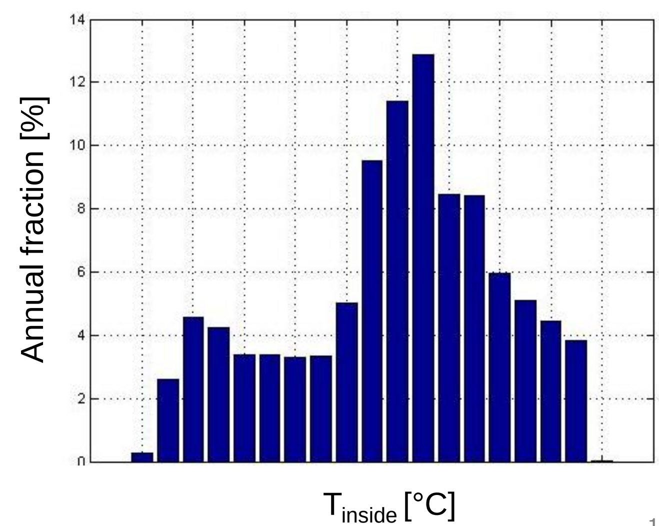




Measured and calculated relation between outside and battery temperature.

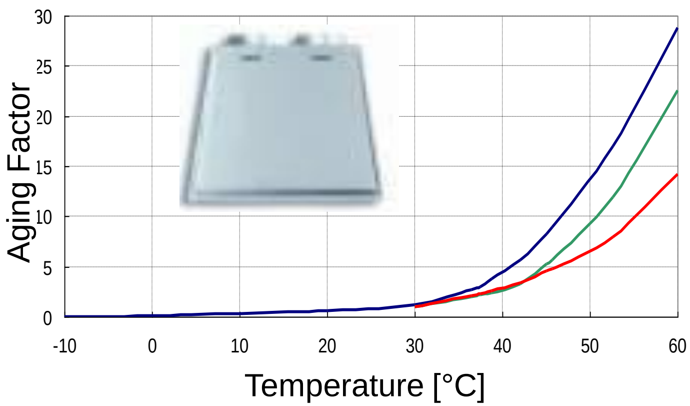
With outside temperature profile over the whole year the battery temperature profile is calculated.

Statistical analysis gives the frequency of occurrence and the dwell time in the different temperature bands.



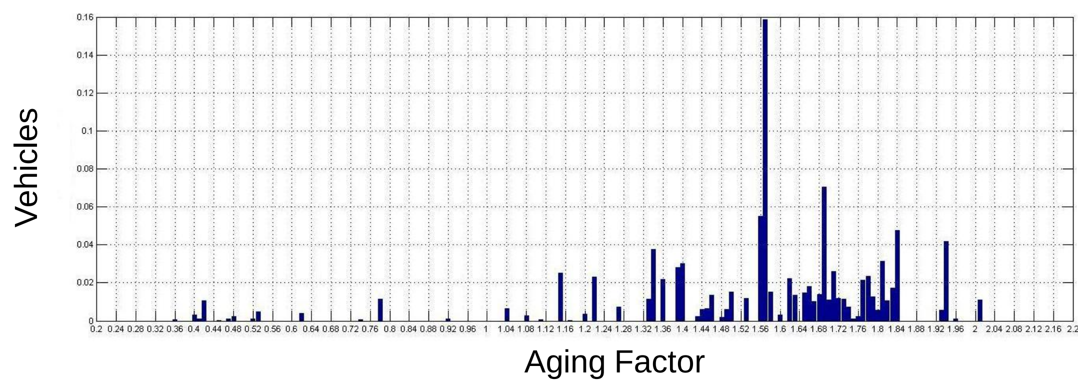
CALENDARIC AGING FACTOR & DISTRIBUTION OF VEHICLES IN INDIA

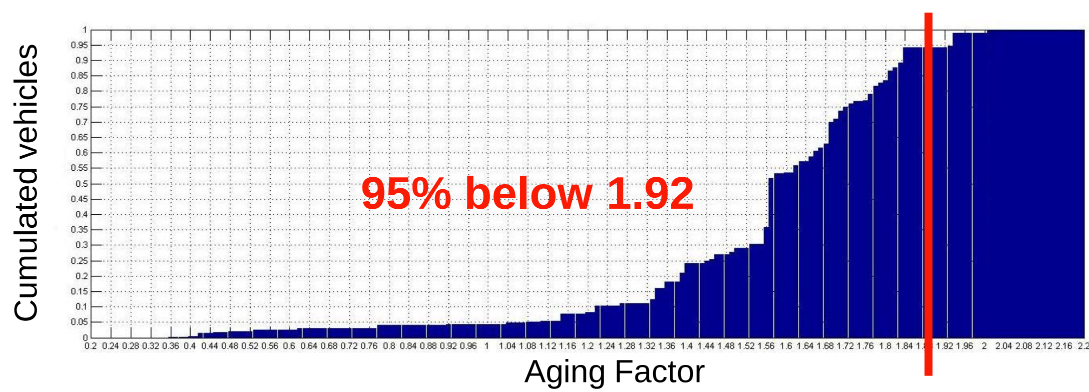
Calendaric aging



Number of vehicles and aging factor per region:

Region	No. of Vehicles	Aging Factor
Bangalore Urban	228570	1,1495
Mumbai City	354229	1,6933
New Delhi	1222706	1,5723
...	...	...
District 107	...	...





Aging-distribution:

Out of supplier data or lifetime test program a relation between calendaric aging and temperature is established.

Aging Factor = 1 corresponds to a lifetime of the battery determined at 25 °C

AVL DOE TEST MATRIX FOR CELLS

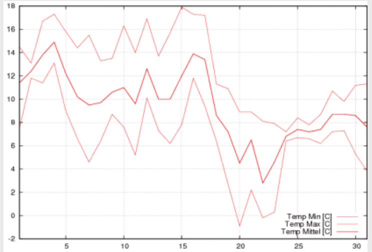
Temperature / Aging Condition	-15 °C	30 °C	70 °C
Storage tests (no cycling)	5 cells (SOC 10 %) 2 cells (SOC 50 %) 5 cells (SOC 90 %)	2 cells (SOC 10 %) 2 cells (SOC 50 %) 2 cells (SOC 90 %)	5 cells (SOC 10 %) 2 cells (SOC 50 %) 5 cells (SOC 90 %)
Constant current cycling	5 cells (SOC 20 %, DSOC 10 %) 5 cells SOC 50 %, DSOC 80 %) 5 cells (SOC 80 %, DSOC 10 %)	3 cells (SOC 20 %, DSOC 10 %) 3 cells (SOC 50 %, DSOC 80 %) 3 cells (SOC 80 %, DSOC 10 %)	5 cells (SOC 20 %, DSOC 10 %) 5 cells (SOC 50 %, DSOC 80 %) 5 cells (SOC 80 %, DSOC 10 %)

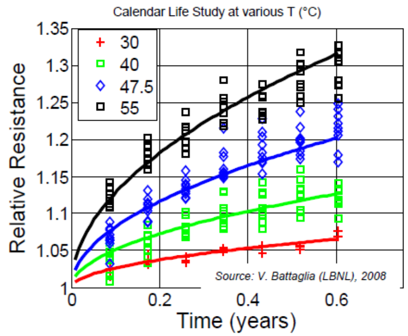
Boundary test matrix is shown – intermediate matrix points are required.
Number of cells at each matrix point depends on size of planned annual vehicle sales.

ENDURANCE LIFE PREDICTION / ACCELERATION FACTORS
ONGOING R&D PROGRAM

Data + Model

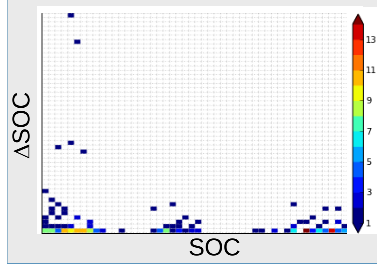
Temperature spectrum

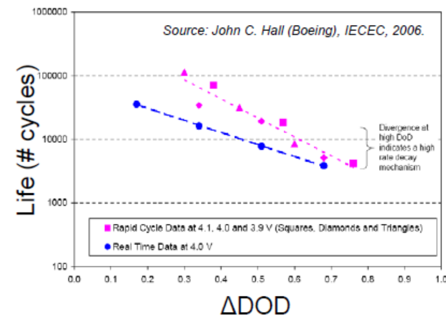




Data + Model

SOC load spectrum



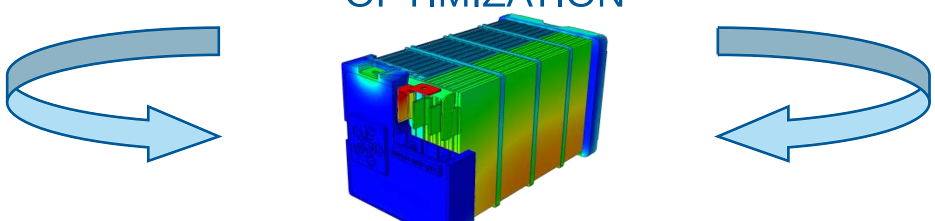


Calculated calendar life
(for simulated / measured temperature profile)

Calculated cycle life
(for simulated / measured SOC- profile)

Combined life endurance of battery
(estimated value, forecast)

OPTIMIZATION

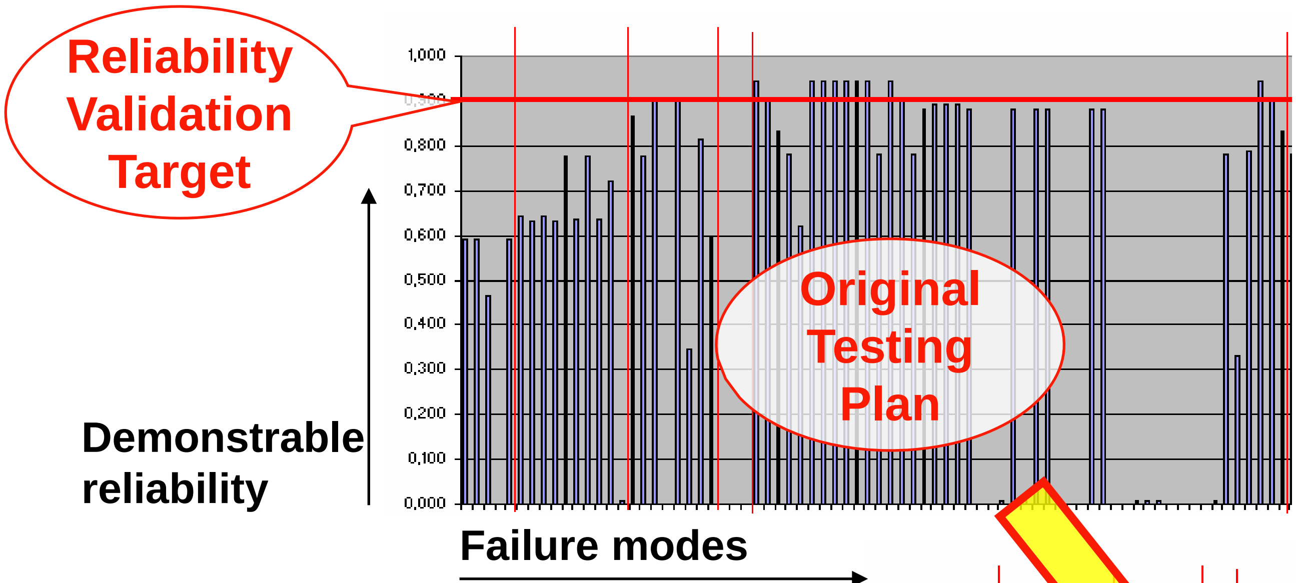


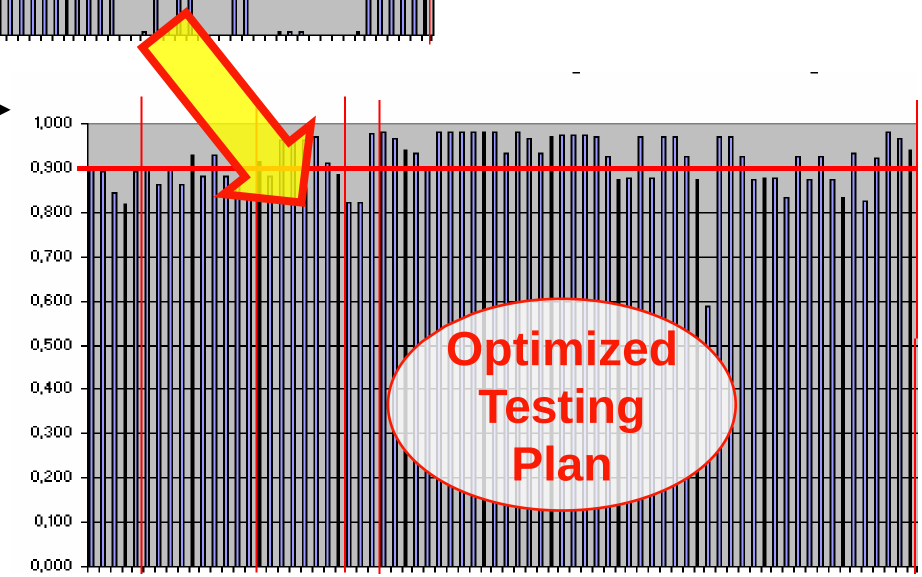
Combined life endurance of battery
(actual value from vehicle usage and validation program)

LOAD MATRIX PROCESS

System Analysis	**Component oriented analysis w.r.t. damaging operating conditions, risk based prioritisation of failure modes**
Applications and Targets	**Identification of usage space, definition of reference duty cycles and reliability targets**
Test Program and Load Analysis	**Determination of acceleration factors, damage modeling, adaptation of test program**
Evaluation and Optimization	**Reliability and durability analysis of test program, timing & costs, warranty risk reduction**

LOAD MATRIX: OPTIMIZED TESTING AND VALIDATION





Load Matrix

- → Systematic methodology to optimize the testing plan before start of development
- → The reliability shown in the testing plan is demonstrated when the test runs are completed without failure

LOAD MATRIX RESULTS

Demonstrable reliability, durability coverage

Characterisation of tests

Optimised test procedures for maximum acceleration

Complete, balanced test program for

- optimised duration, number of samples to test under given budgetary situation
- optimised balance between rig, dyno, vehicle and supplier tests
- optimised test sequence

Assessment check list for intermediate and final parts assessment

Test acceleration factors

Track analysis / customer usage profile analysis

Overview of critical and validation-relevant components and failure modes

Overall mileage accumulated for critical components / failure modes

Durability / reliability / warranty risk at SOP or other important milestones

AVL LOAD MATRIX SUMMARY

Analysis and optimization of product validation regarding

- Timing vs. product release
- Reliability demonstration and lifetime coverage
- Validation costs and warranty risks

Integration of internal and external contributions on a common platform

- Validation contributions of all departments and suppliers
- Economic, market, legal and sales requirements

Simple implementation into existing development process and tools

Generic methodology (Applicable to powertrain, hybrid, fuel cell, …)

Technical risk management and tracking

Demonstration of improved reliability reduces risk of failure and hence warranty costs.