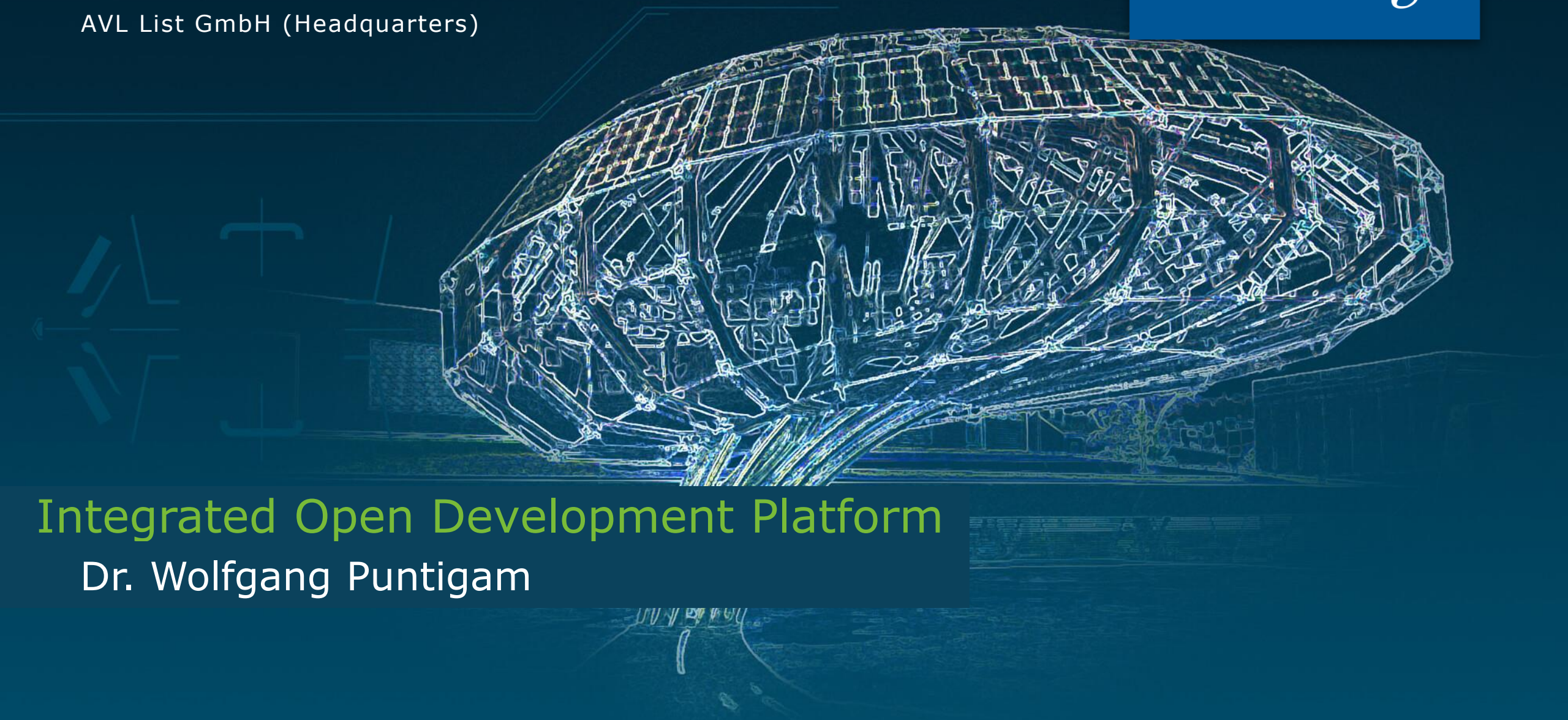
AVL List GmbH (Headquarters)



Integrated Open Development Platform

Dr. Wolfgang Puntigam

What is the purpose of AVL´s Integrated and open development platform approach?

SIMULATION	LAB	ROAD

We virtualize product and process

“By 2025, 80% of the prototypes will be virtualized”

Over the whole vehicle development process out of a **functional view**

…

Why we are doing it …

SIMULATION	LAB	ROAD

… to empower our customers to react faster on change

Consistent Models

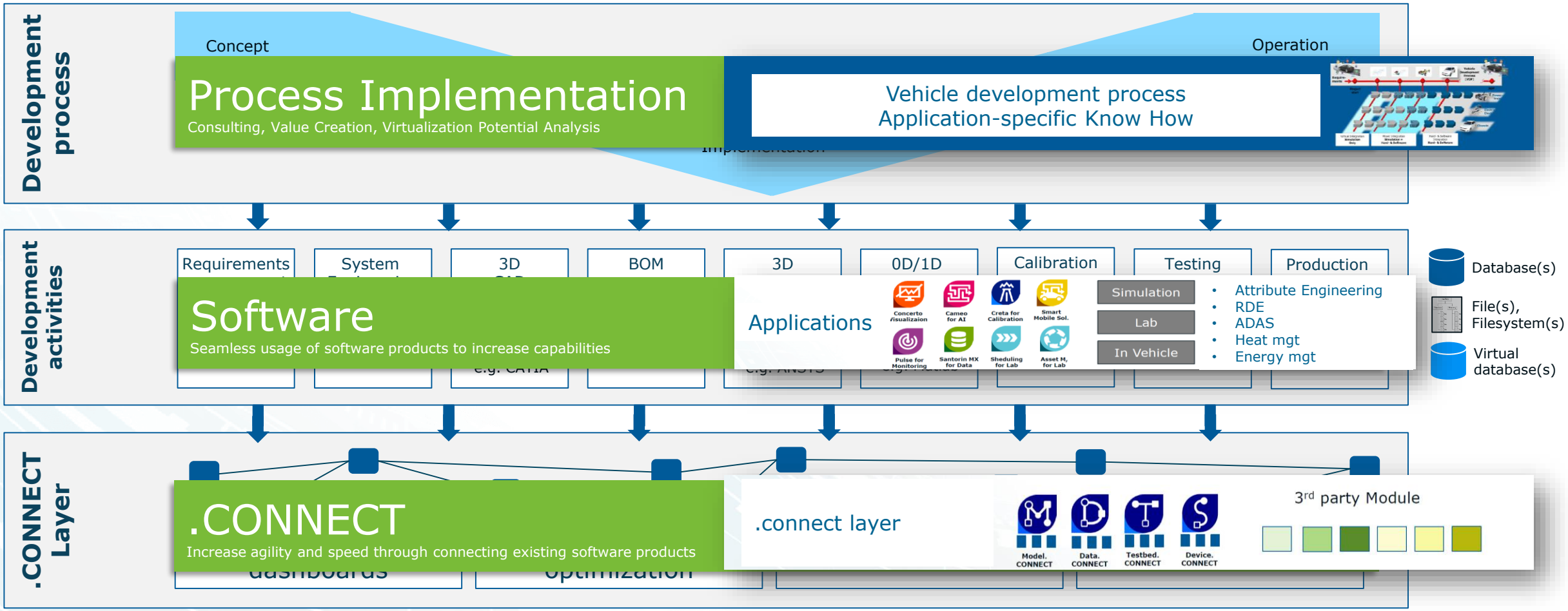
Same Test Procedures

Seamless Data Management

Efficient and Effective Methods

Connect existing tools

IODP Software Ecosystem



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… connecting things and enhancing capabilities

Efficient Electric Vehicle Development

Reusing Testbeds, Tools, Methods & Know-How

Rainer Schantl
Veronika Obersteiner

Efficient Electric Vehicle Development

AVL

The Future Powertrain
Technology Trend

Advanced Vehicle Development
The Big Picture – Front Loading

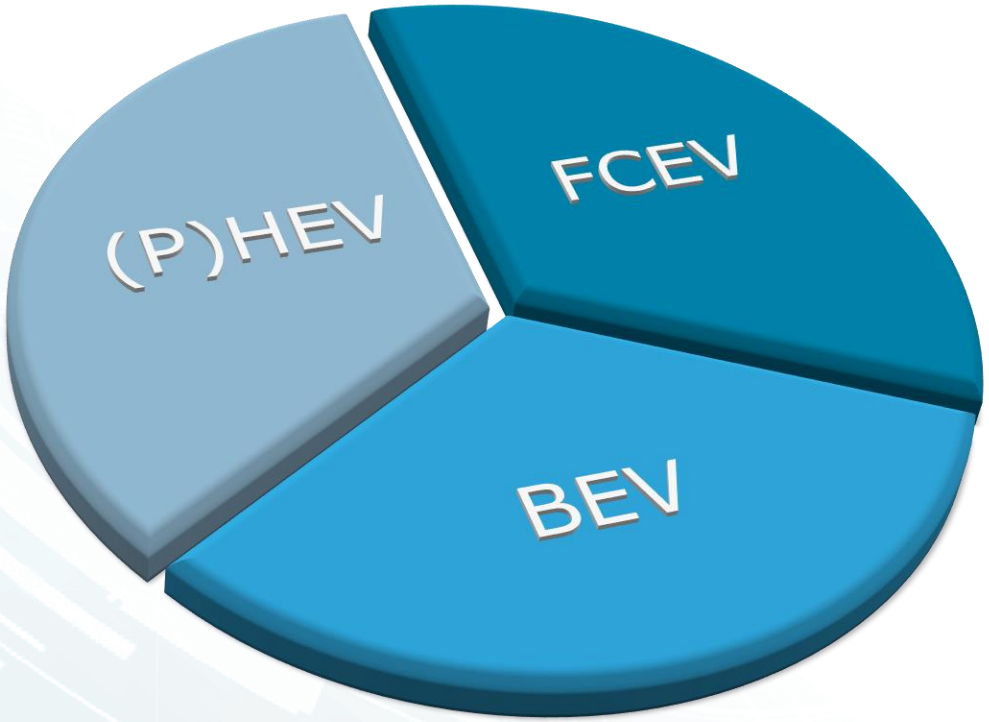
(P)HEV and BEV Development
On Different Testing Environments

E-Motor and Inverter
Advanced E-Drive Calibration

Battery
Digital Twining and Battery Monitoring

The Future Powertrain

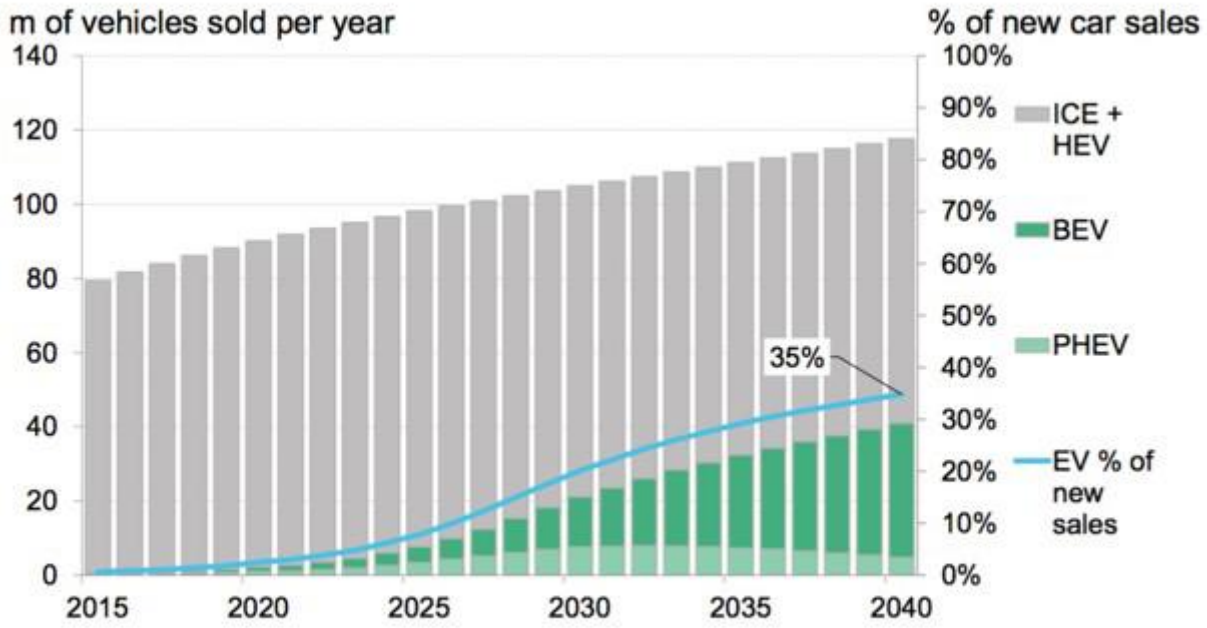
Future Powertrain Technology Trend



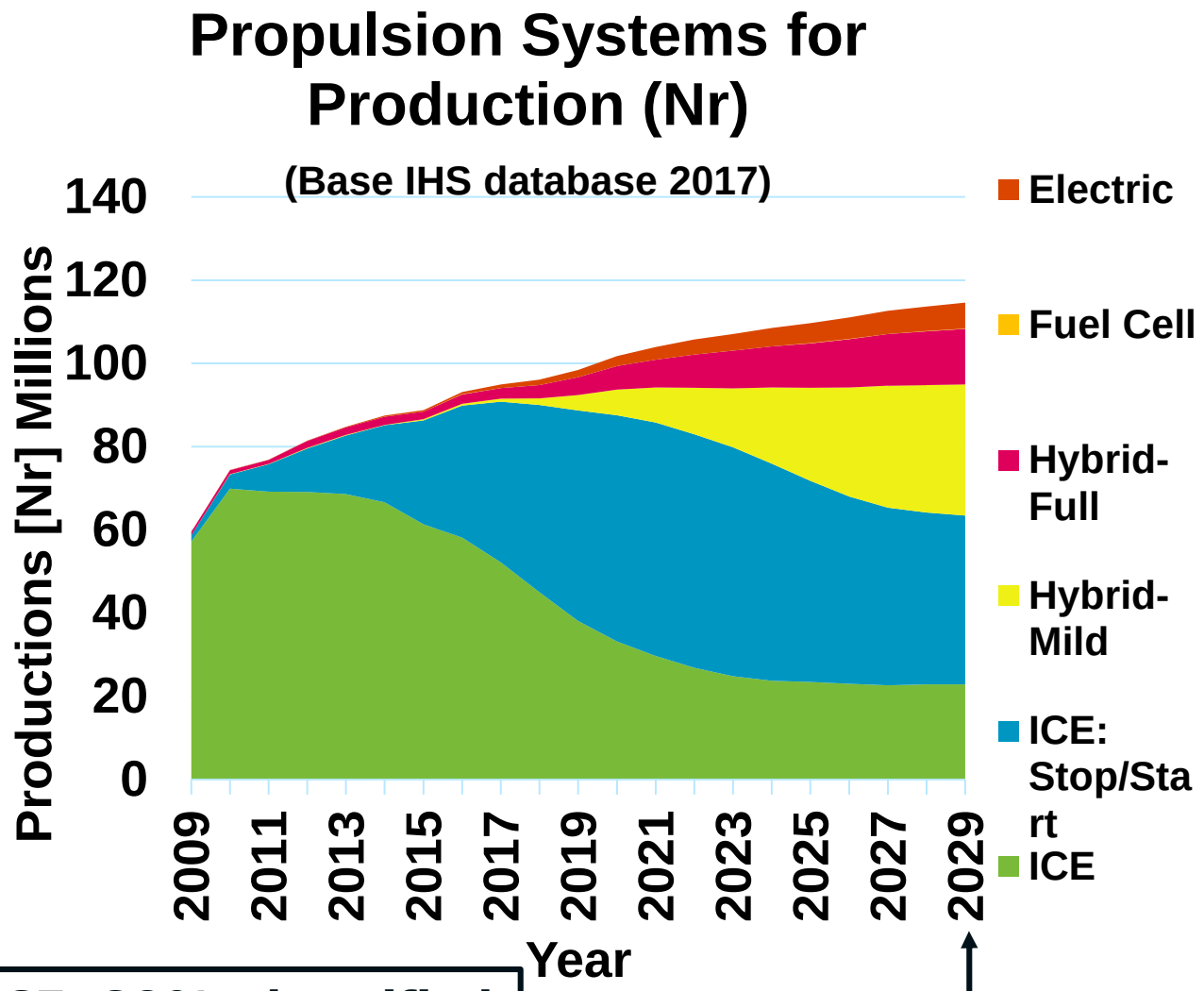
- There will be a **split of different propulsion systems** in use
- **ICE Engine** (in form of HEV) will remain but within an electrified powertrain
- **Fuel Cell Electrical Vehicles FCEV** will be used for long distance traveling
- **Battery Electrical Vehicle BEV** will become important in the urban area

Why is it so important ?

Electric Vehicles Sales Trend:
Global LDV and EV yearly sales,
2015 – 2040 (million of vehicles sold per year, %)



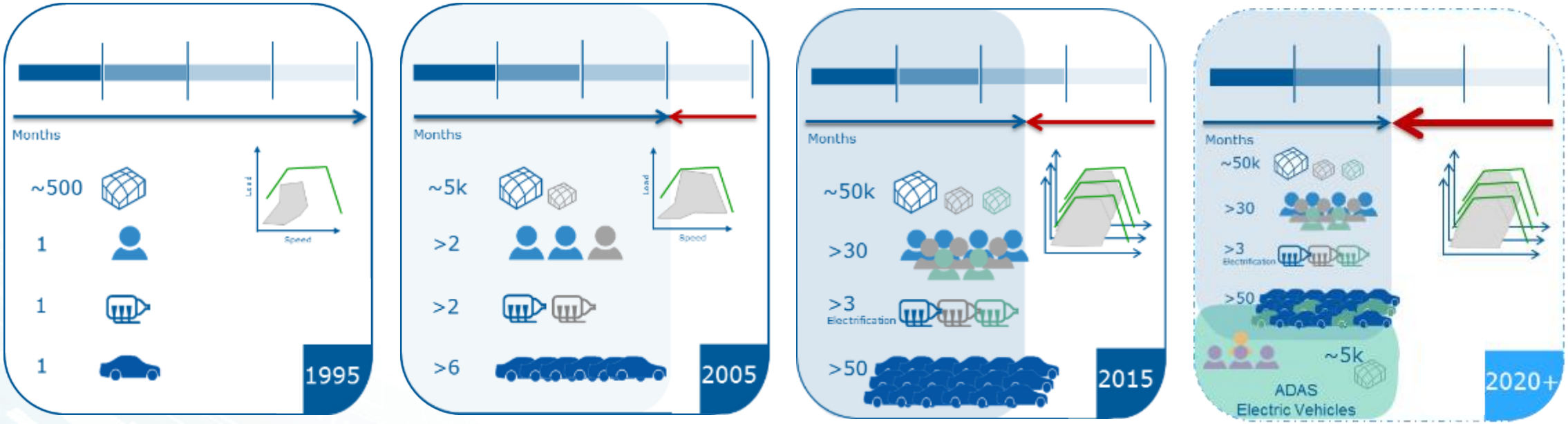
Source: Bloomberg New Energy Finance Note:
ICE+HEV = internal combustion engine and hybrid vehicles,
BEV = battery electric vehicles,
PHEV = plug in hybrid electric vehicles



2030: 80% ICE; 80% electrified

The Vehicle Development Process

Evolution of powertrain calibration



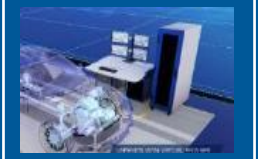
ECU Parameters TCU Electr./Non-powertrain

New approaches are required achieve cost, time & quality targets

Screening– The big picture

Testing environment → INDICATIV

Development and testing activities ↓

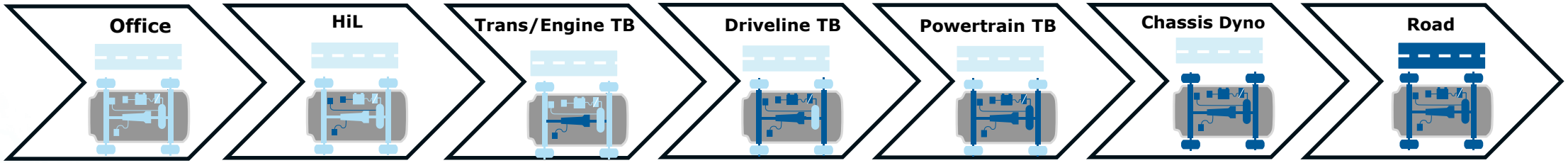
	Simulation	Virtual Test Bed	Component Test Bed	Engine Test Bed	Powertrain Test Bed	Chassis Dyno	Road Testing
							
Performance							
Emissions							
Fuel consumption							
OBD							
Drivability							
Handling							
ADAS							
Sound / NVH							
Functional safety							
Durability / Robustn.							
Climate comfort							

Shifting efforts from right to left: faster, cheaper, higher quality

Today Future

Evaluation of working environments

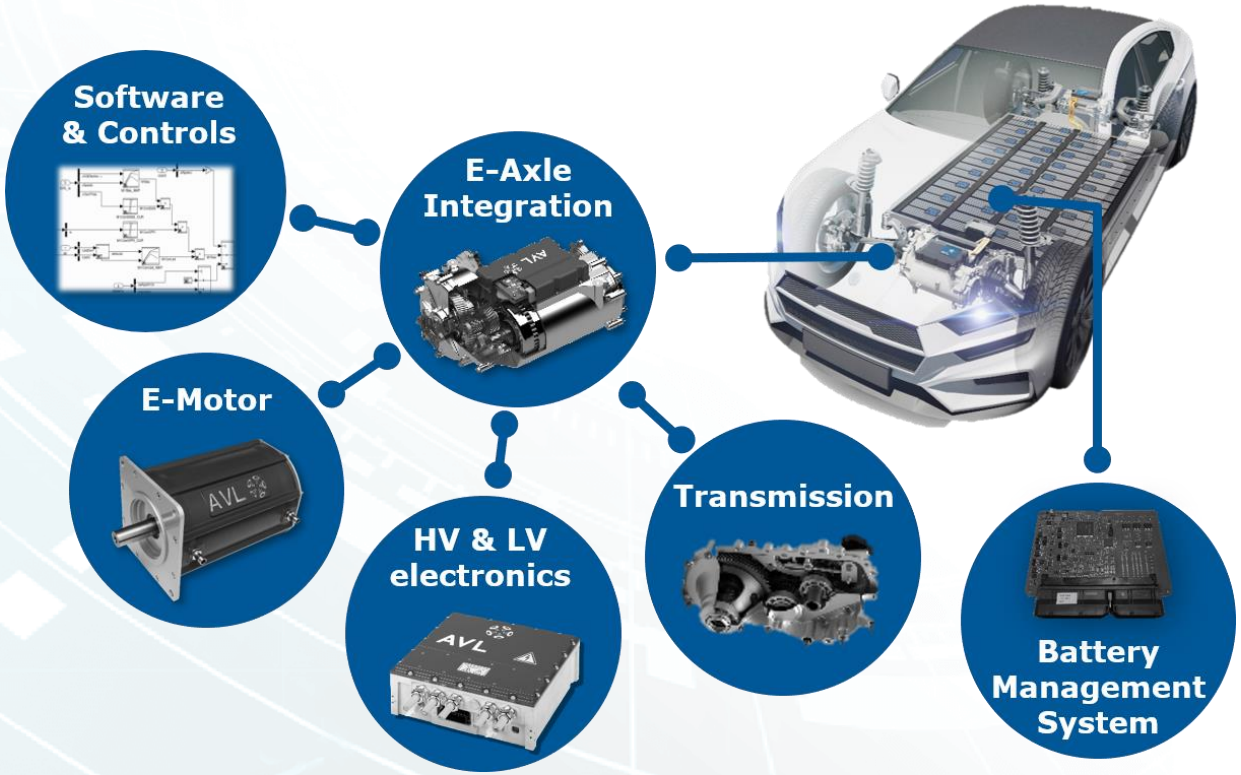
Working environments used during optimization & validation of powertrains:

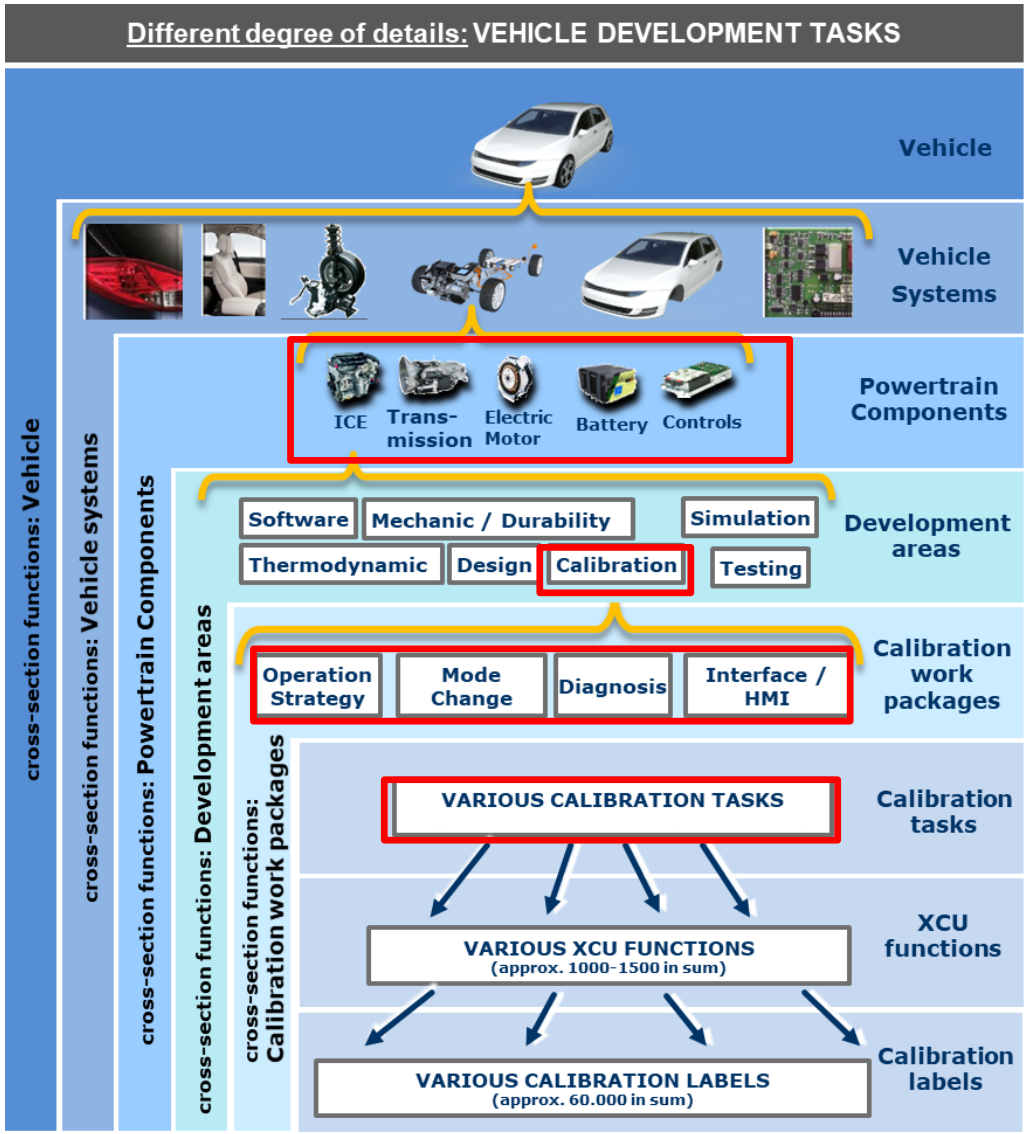


(P)HEV and BEV Development

E-Vehicle Development – Calibration Tasks

- Several calibration tasks on different levels along the vehicle development process

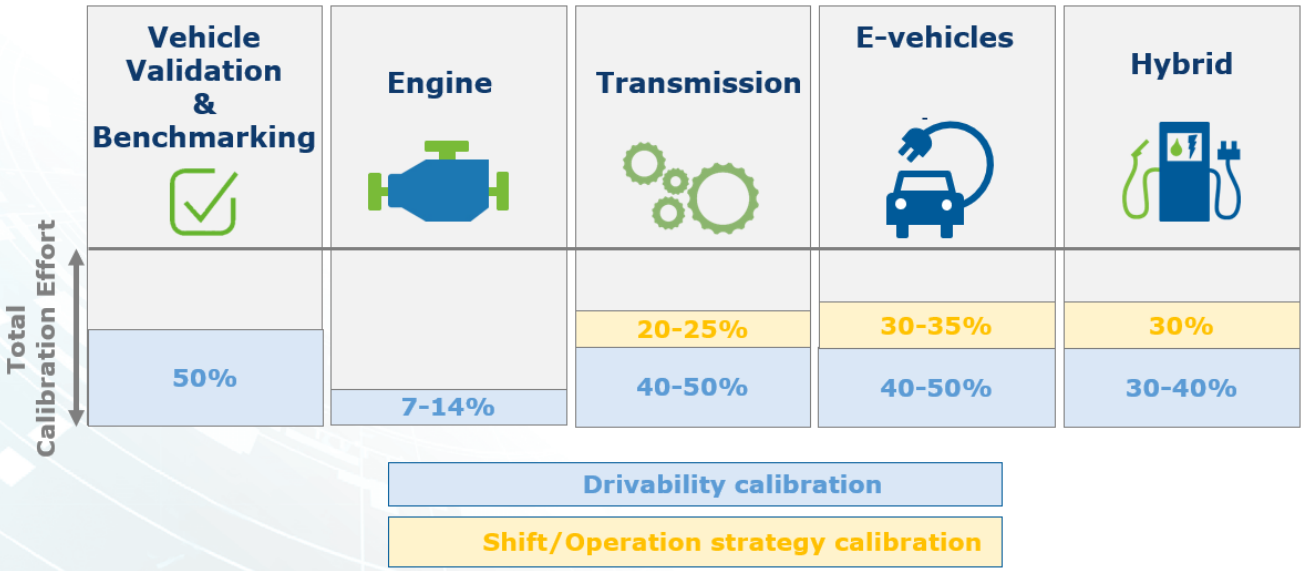




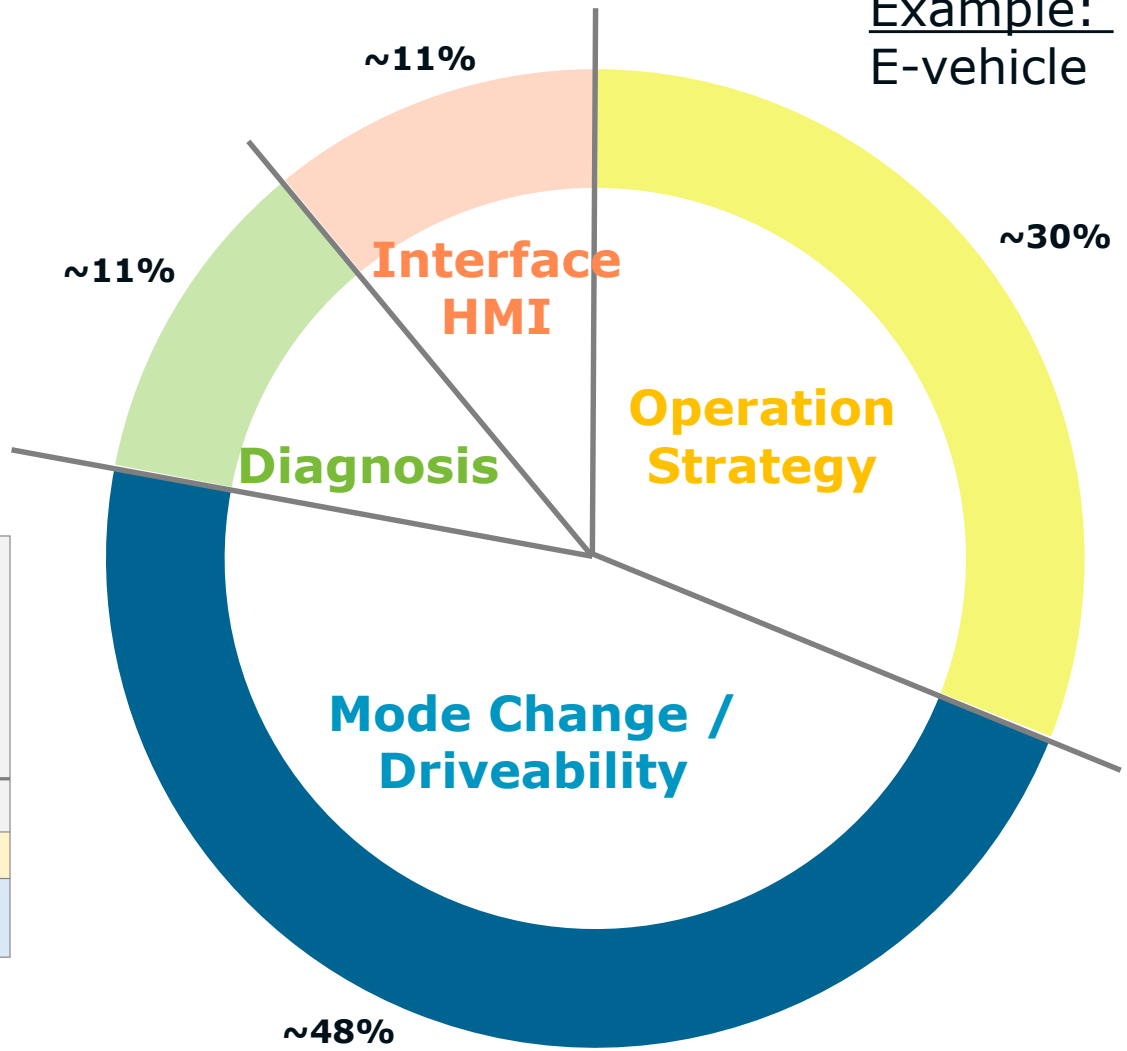
Calibration Effort: HEV & EV

Steeply rising complexity and interdependencies of functions (number of calibration parameters, drive modes, components in the powertrain)

Multi-dimensional optimization of calibration parameters



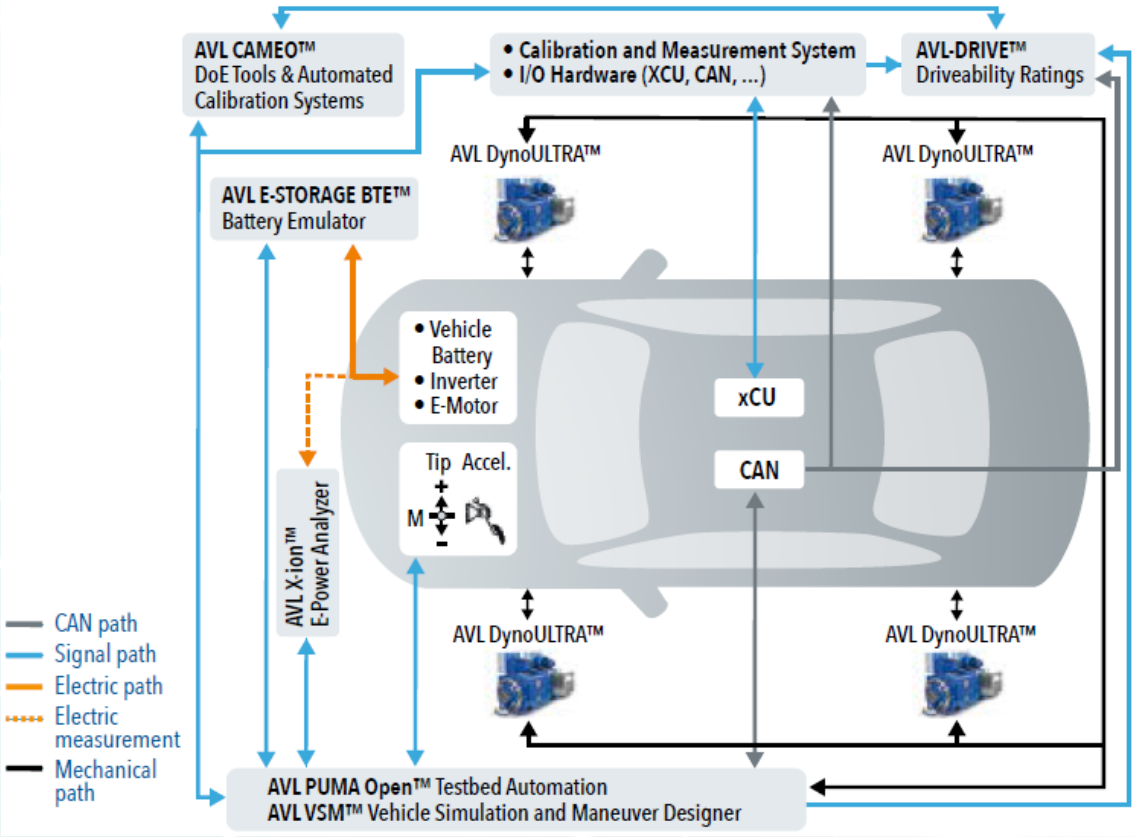
Example:
E-vehicle



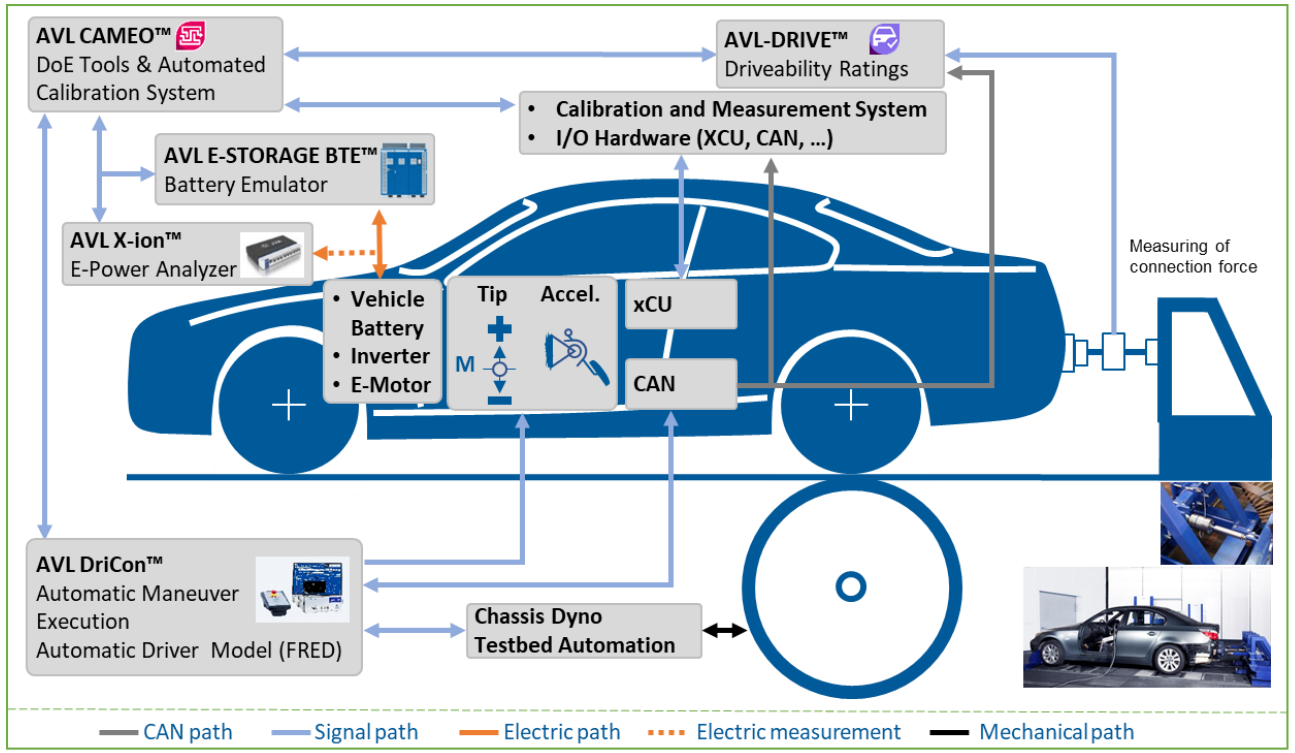
The AVL Solution

AVL's CONNECTED Toolchain "Advanced Calibration for Driveability" (ACD) enables to calibrate driveability tasks in earlier process stages due to a powerful methodology and tool chain, combined with flexibility in choosing working environments and application know-how, drawn from years of experience

@ powertrain testbed



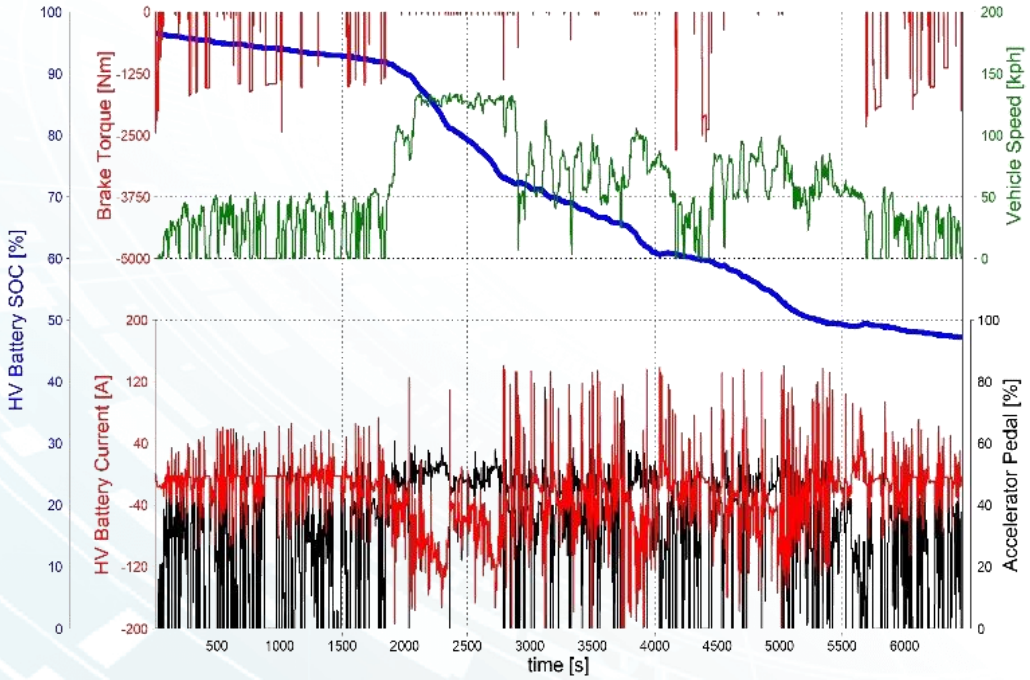
@ chassis dyno



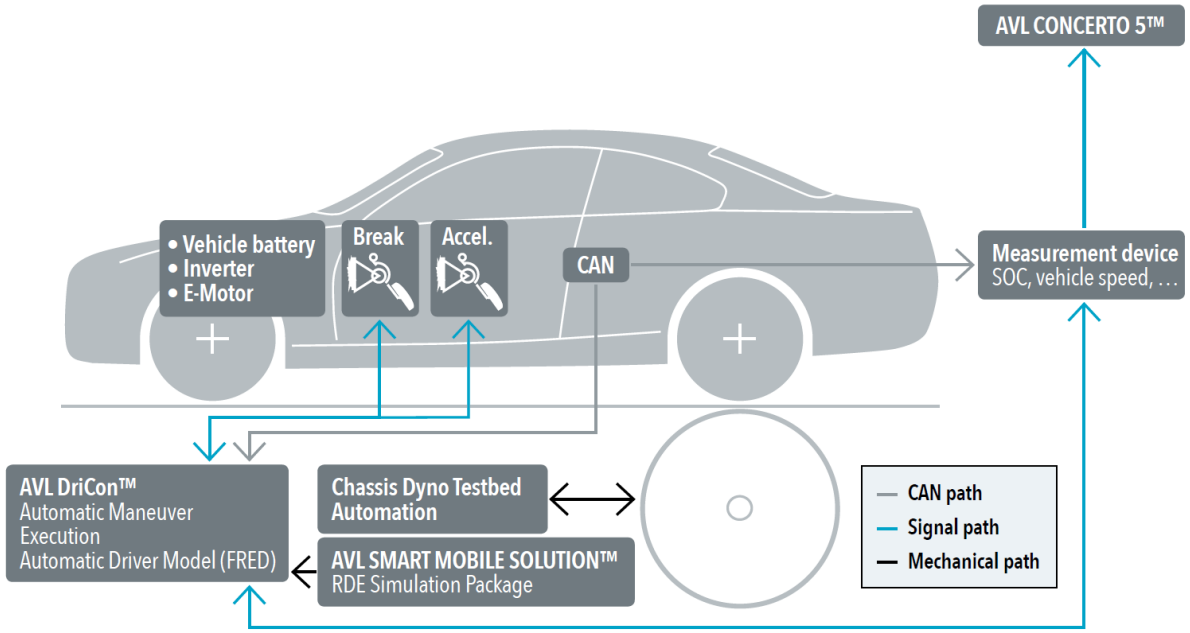
RDX in the lab

Electric range – validation and optimization

EXAMPLE 1: BATTERY STATE OF CHARGE (SOC) DURING THE AVL RDE TEST CYCLE.



TOOLCHAIN FOR ELECTRIC RANGE VERIFICATION



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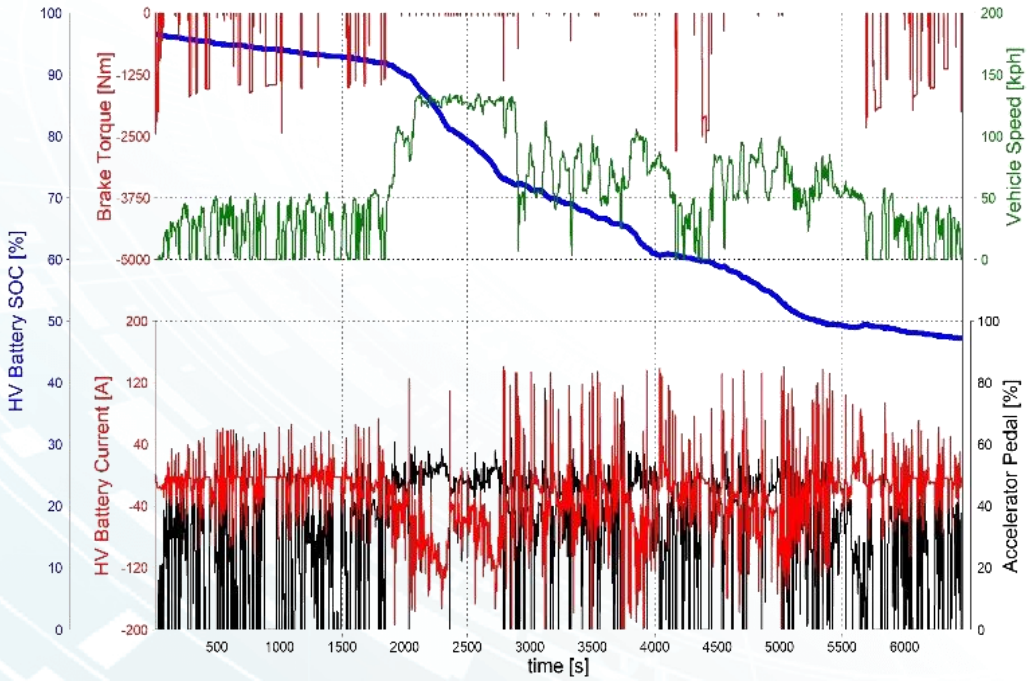
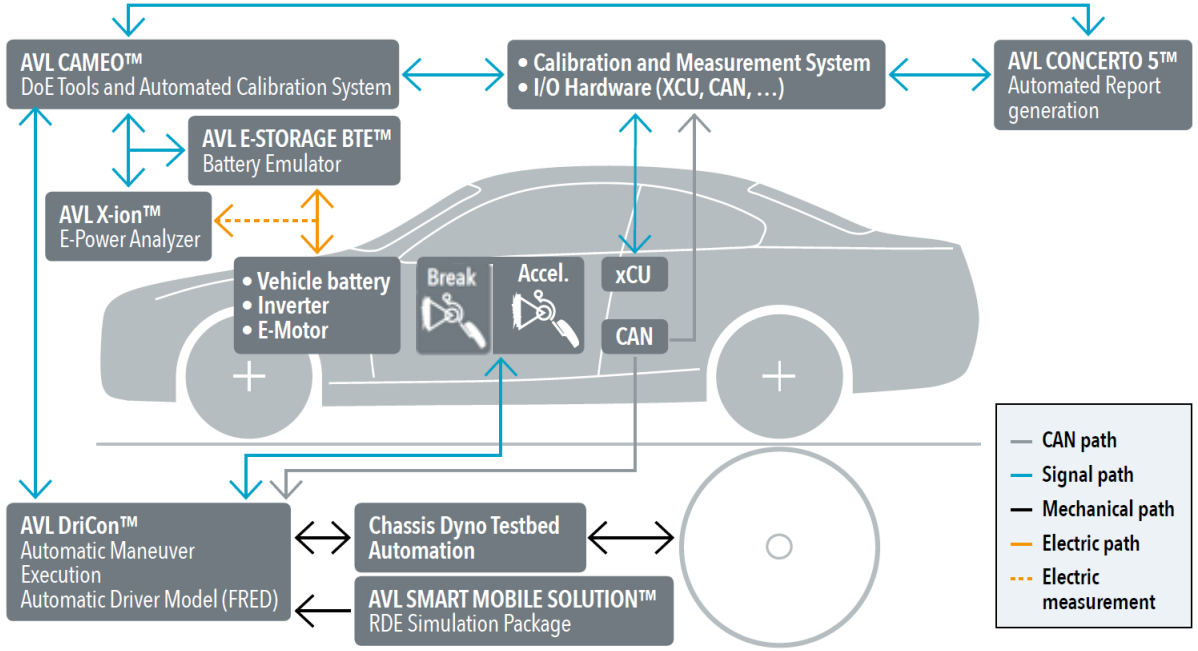
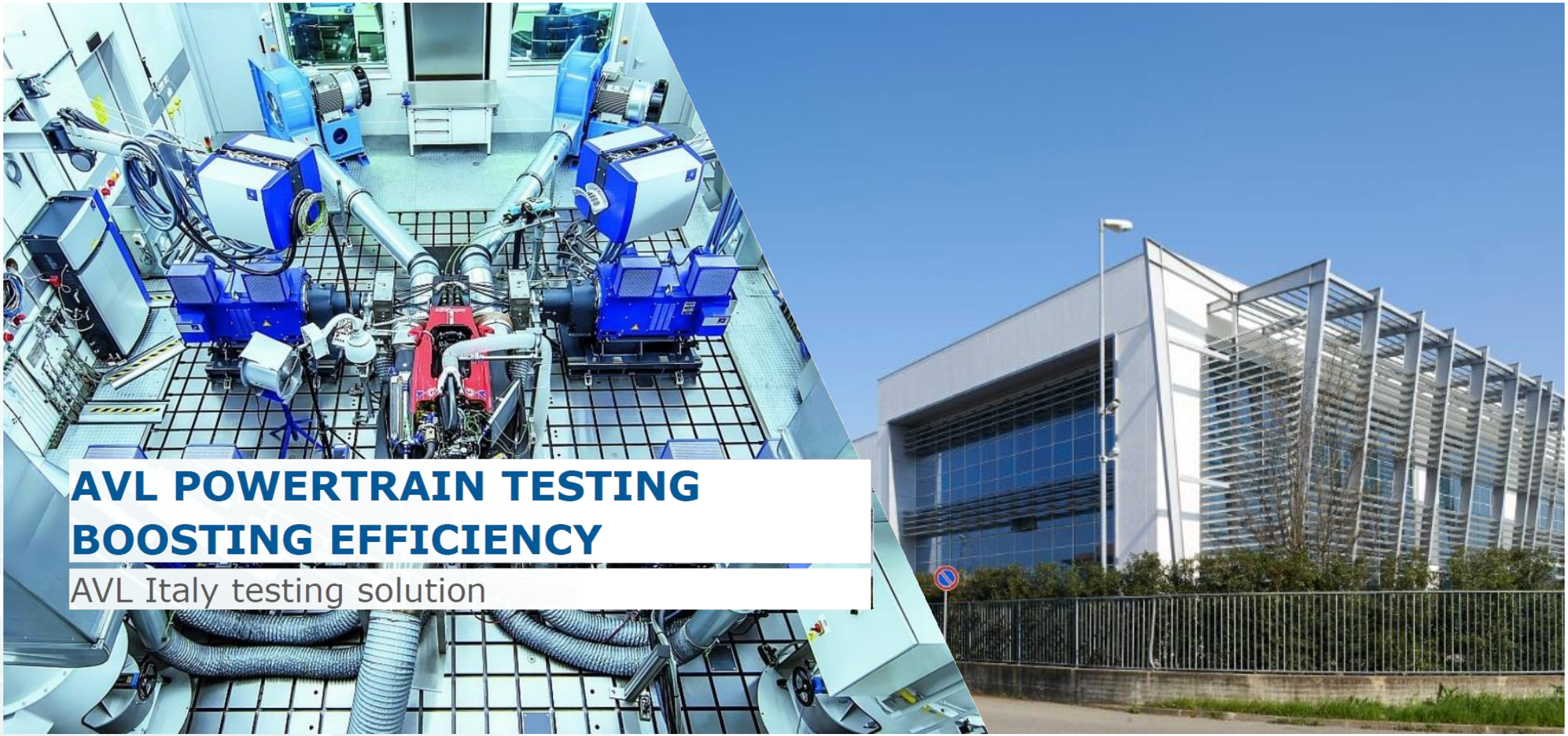


TOOLCHAIN FOR ELECTRIC RANGE OPTIMIZATION AND VERIFICATION

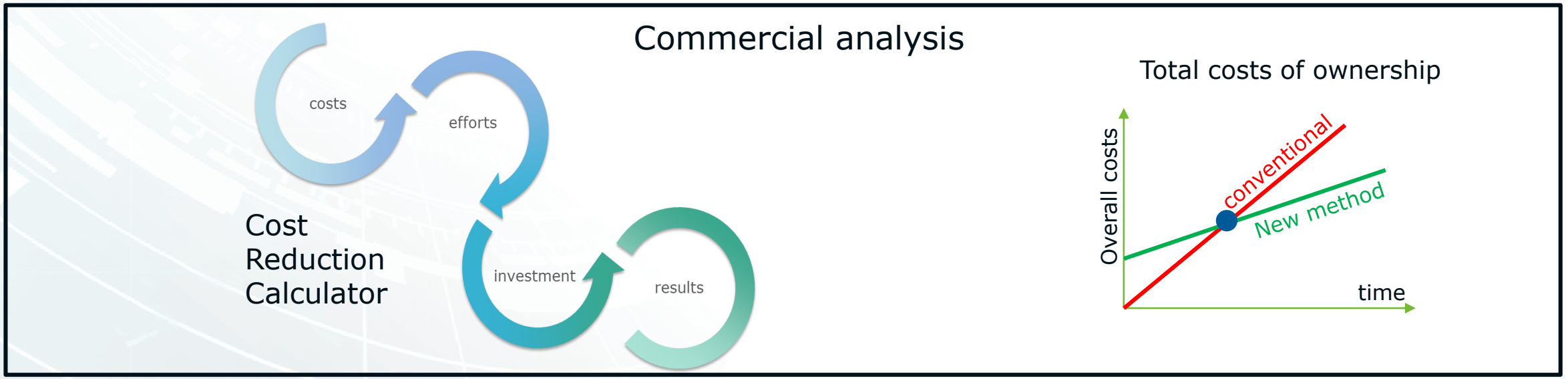


Tech Center Italy



Customer Benefits

- 3 times faster maneuver execution (customer feedback)
- Minimized testing duration & prototype utilization via 24 / 7 testing capabilities
- 3 times reduced number of measurement points by use special DoE adapted to dynamic optimization
- Highest reproducibility & repeatability
- Increase security – shift of safety critical maneuvers from test track to test facilities
- Integration into customer process and evaluation of customer benefits (time-costs-quality) considering the specific boundary conditions of every customer

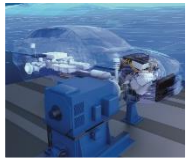


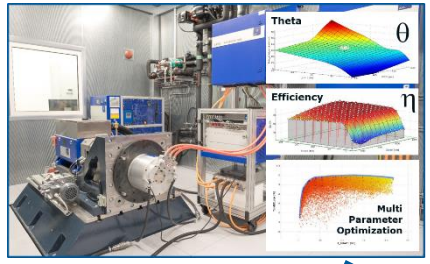
E-Motor and Inverter

OVERVIEW of AVL´s E-DRIVE ACTIVITIES:

FROM Concept to Start of Production

- Test equipment for e-Drive
- Turnkey lab solutions



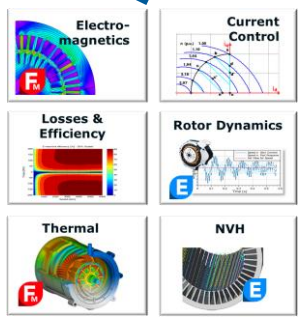


- Testing & Benchmarking
- E-Drive characterization
- Control SW calibration

- System validation
- Planning, optimization & monitoring

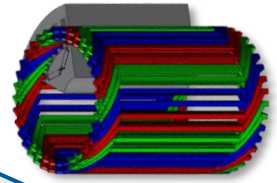
Validation target:	
300.000 km cycle life	✔
12 years calendar life	✔
EMC targets fulfilled	✔
Performance OK	✔

Systems & Production Engineering

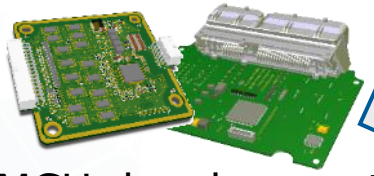


- Component development
- System Integration
- EMAG Simulation
- Thermal Simulation
- Mechanical Simulation
- Electric Simulation
- EMC Simulation
- NVH Simulation

- Prototype build
- Front-loading of virtual calibration models



- Electrical & Mechanical Design Engineering
- Design for Production



- BMS & MCU development (SW & HW)

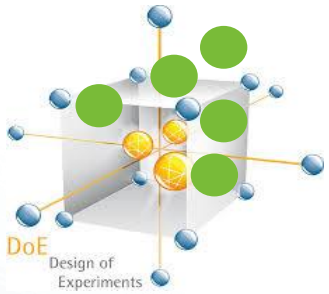
E-Drive Focus Topic
Advanced E-Drive Calibration

Calibration task definition

Test design

Test constraints

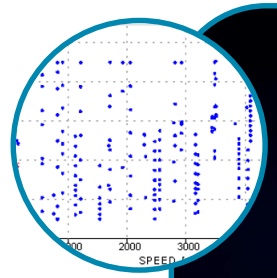
MTPA
Maximum Torque per Ampere

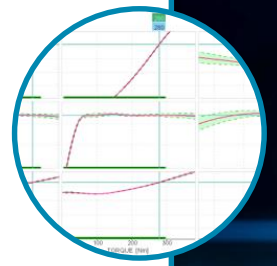


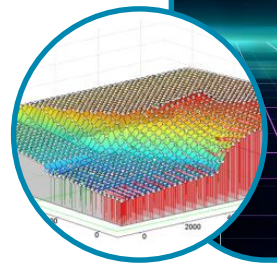
Temp. Limits

Fully automated
Test Execution

Unit under Test





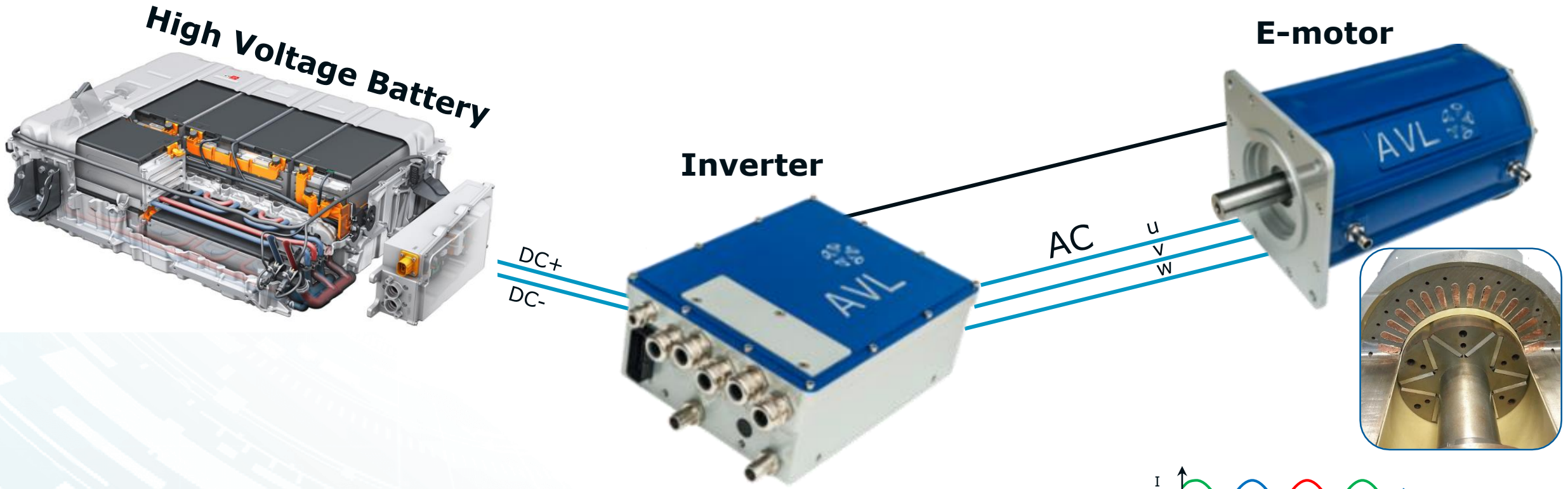


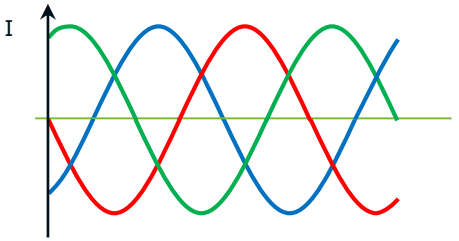
Test Results

Modeling

Optimization

E-Drive: E-Motor and Inverter





- Inverter converts DC power from battery to AC power for E-motor
- **Frequency** change in AC leads to **speed** change
- **Amplitude** change of AC leads to **torque** change

E-Drive Testbed Applications

Functional Tests

Insulation resistance, Short circuit, Locked rotor, etc.

Performance Tests

Stationary operation point, Continuous load, Peak load, etc.

System Tests

Torque response test, Drive cycle tests, etc.

Thermal Tests

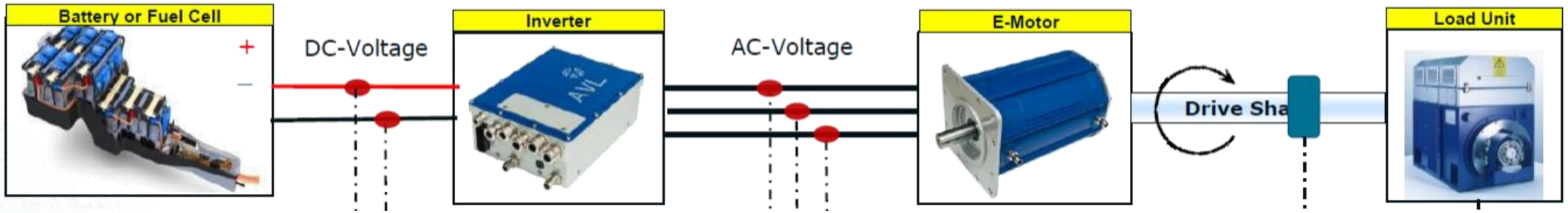
High temperature endurance, temperature cycle test, etc.

- Efficiency Measurement
- EMC Emission Measurement
- NVH Testing
- Environment and Durability Testing
- Safety and Functions

E-Drive Calibration

- Base Calibrations
- Controller Optimization
- Derating
- Diagnostic Calibration

E-drive Calibration - Example

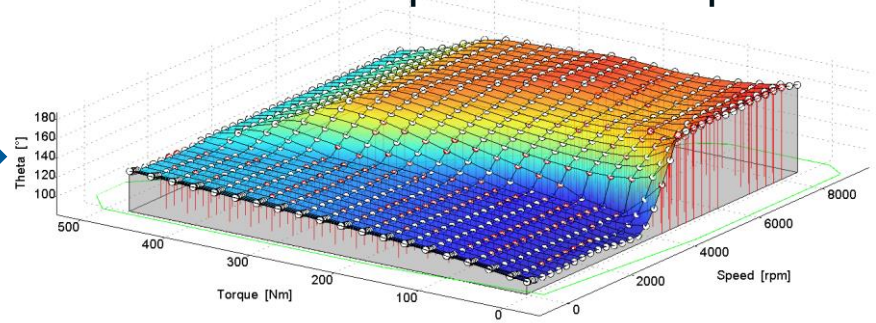


- The **current** provided by the battery should be transformed into an optimum **torque** and **speed** to obtain **maximum efficiency** and **maximum range**.
- Different **load conditions** + different **boundary conditions** given by temperature limits, back EMF, NVH, etc. + lots of **interdependencies**!
- Calibration = efficiently finding the datapoints where the motor should run → optimized map

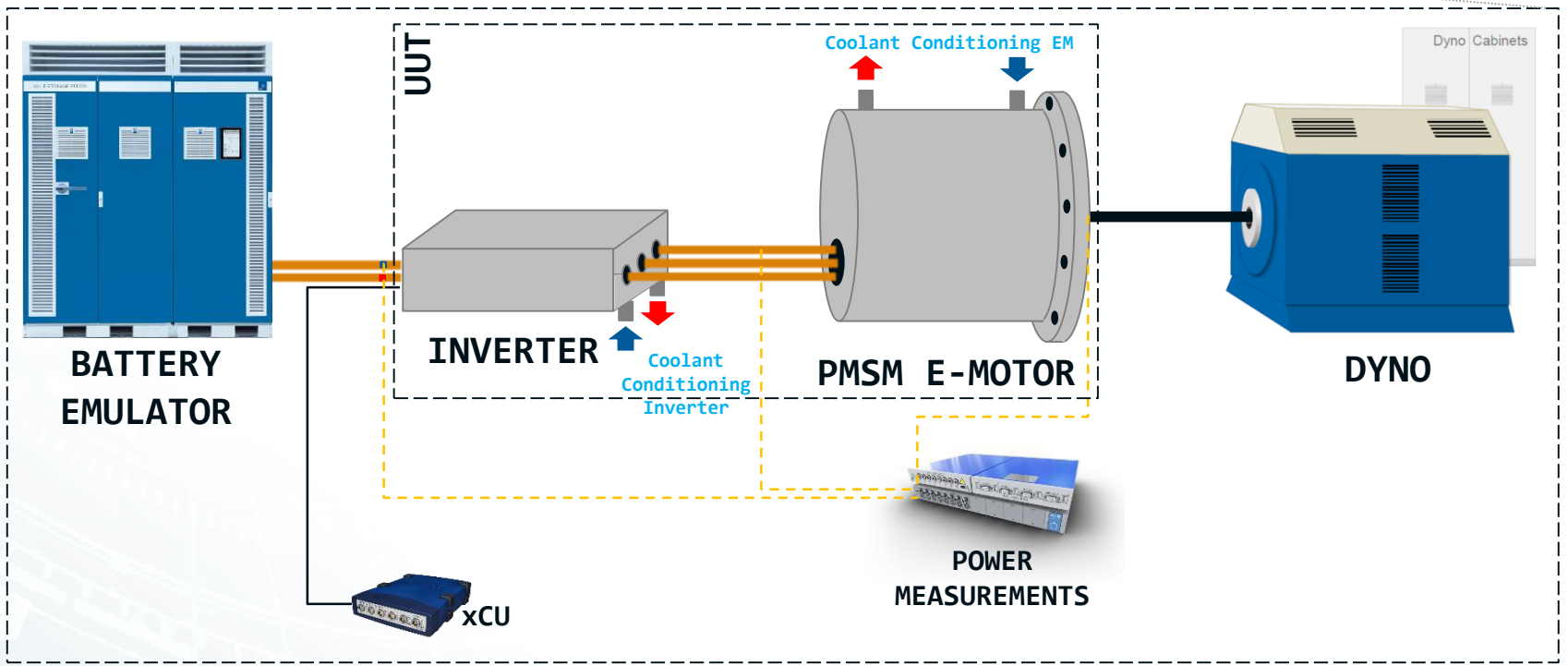
High amount of input parameters

Multi-dimensional calibration

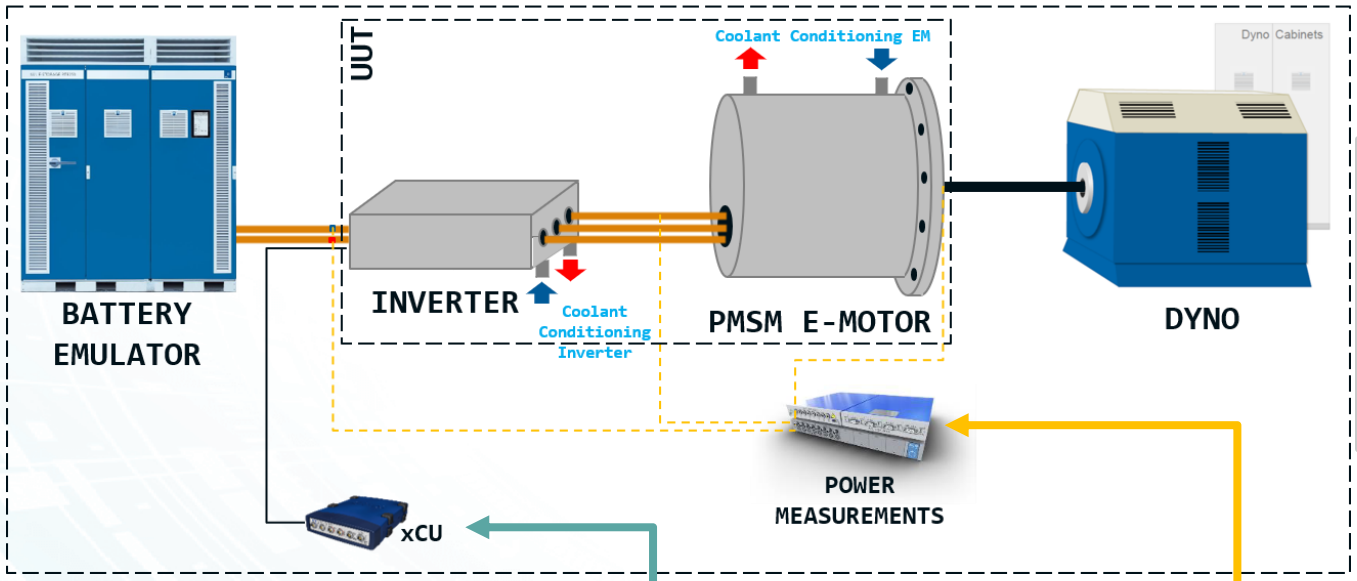
Respecting physical limits



E-Drive Testbed



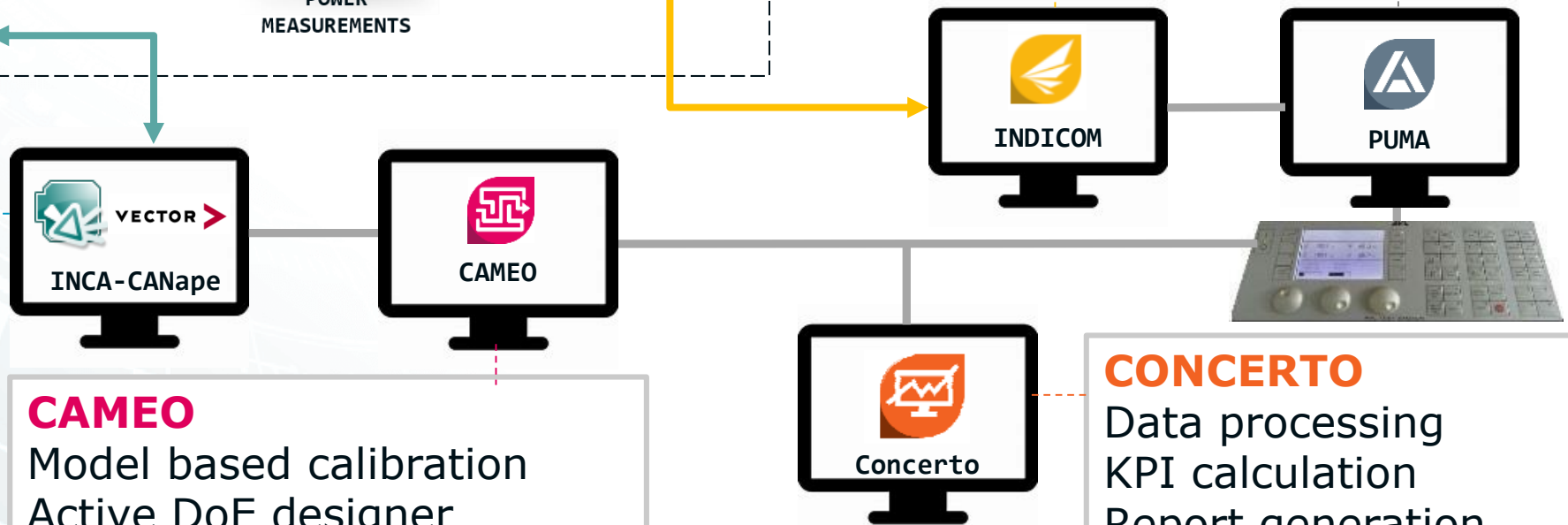
Advanced E-Drive Testbed



INDICOM
High frequency power measurement
Data Acquisition

PUMA
Testbed automation system
- Automation
- Control
- Data Storage

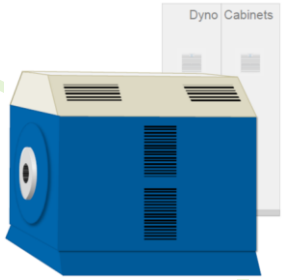
INCA
Communication to control unit



CAMEO
Model based calibration
Active DoE designer

CONCERTO
Data processing
KPI calculation
Report generation

Connected Toolchain



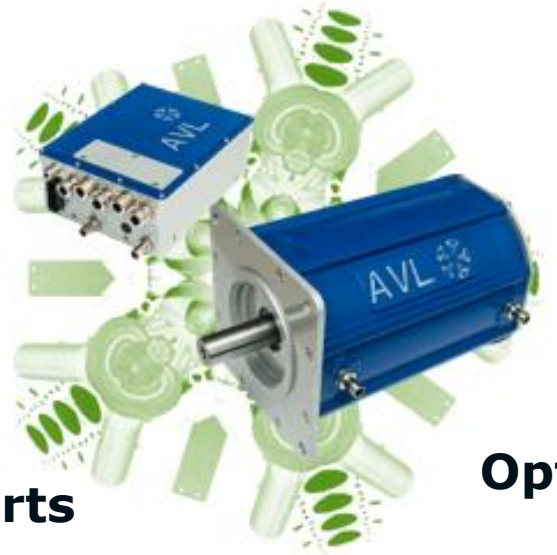
PUMA

Advanced Automation

24/7

INDICOM

Development Time Reduction



Max Torque, Efficiency, Range

Automatic Reports

Optimized E-drive Efficiency

Simulation Environment

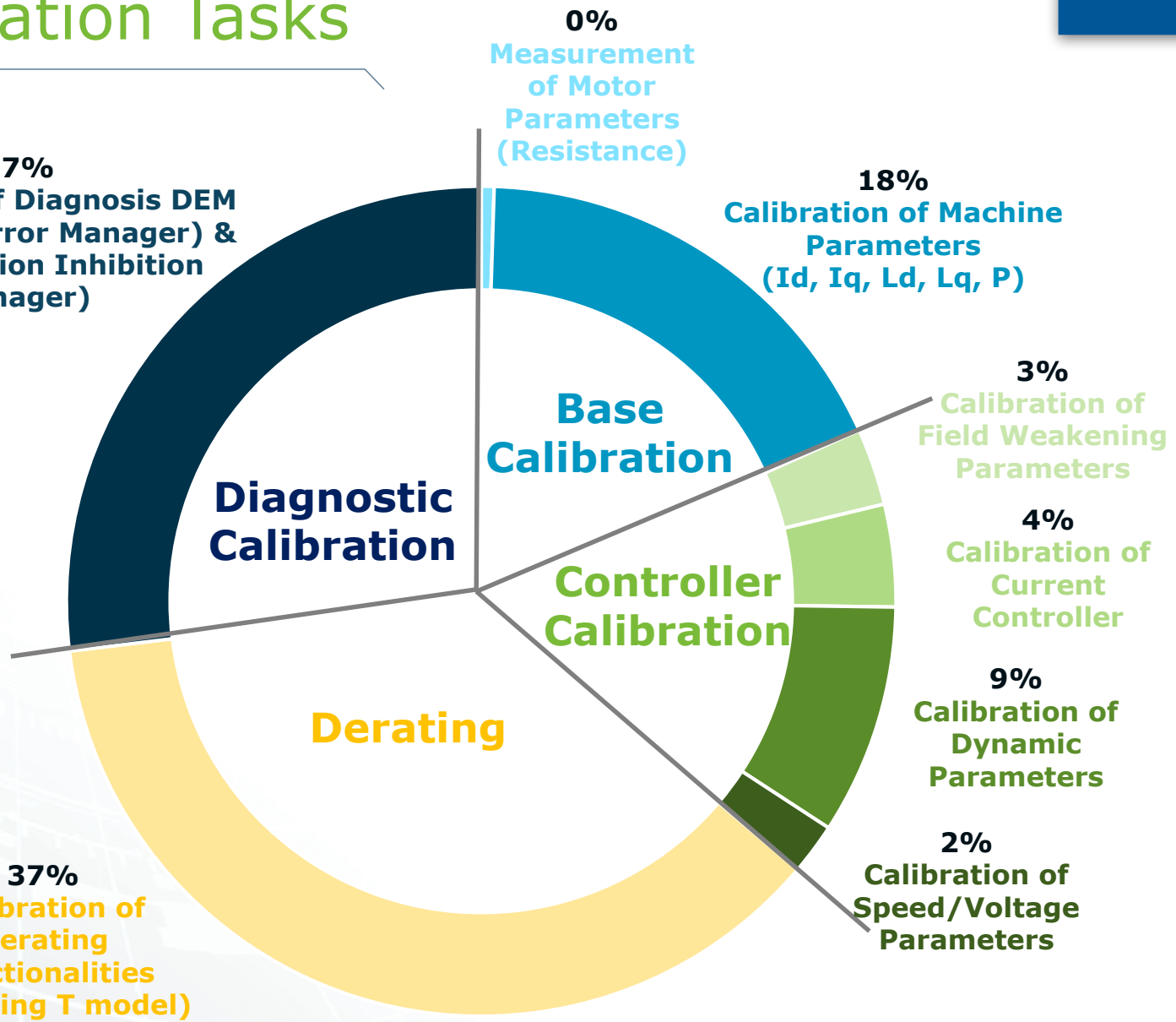
CAMEO

VECTOR

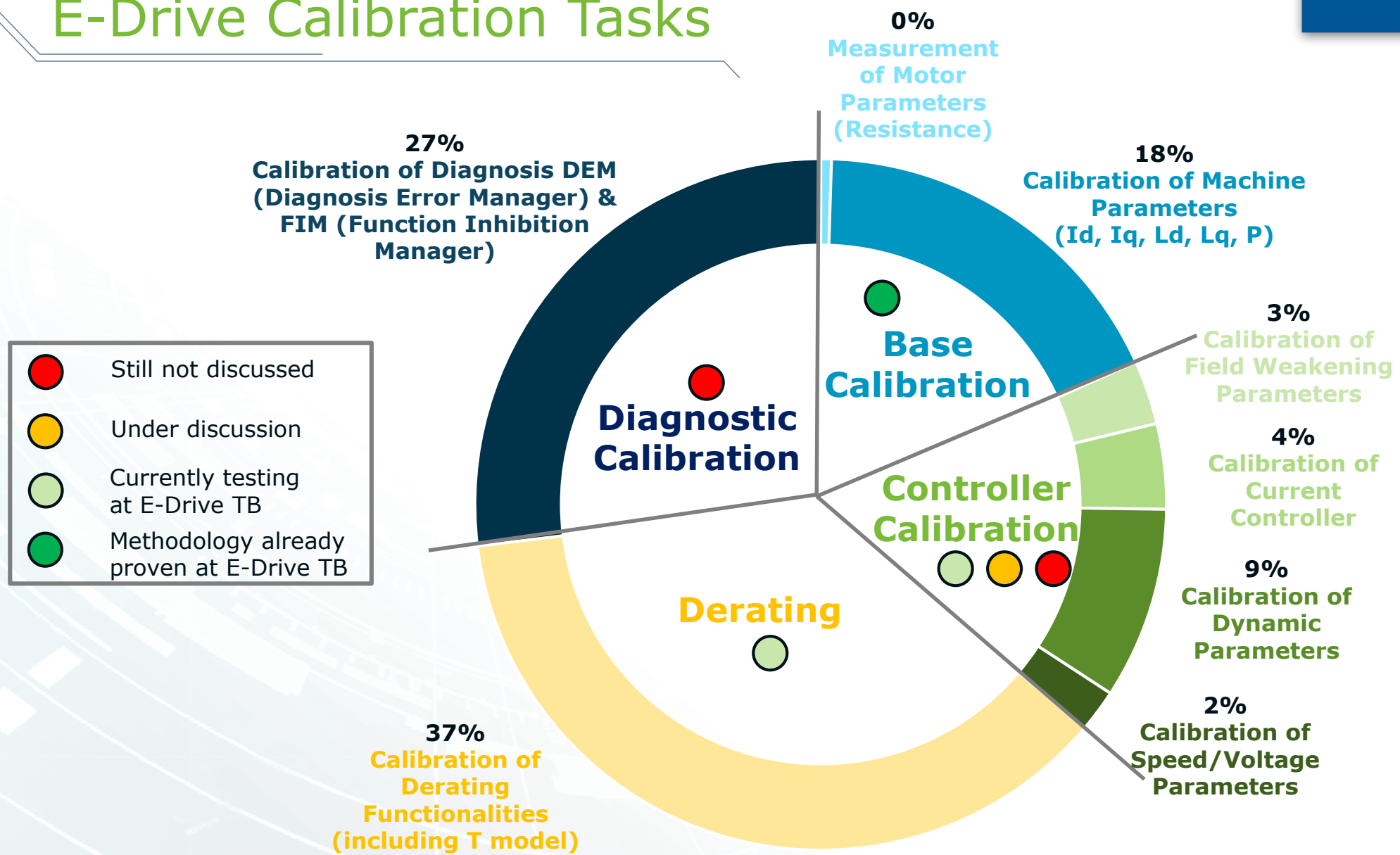
INCA-CANape

Concerto

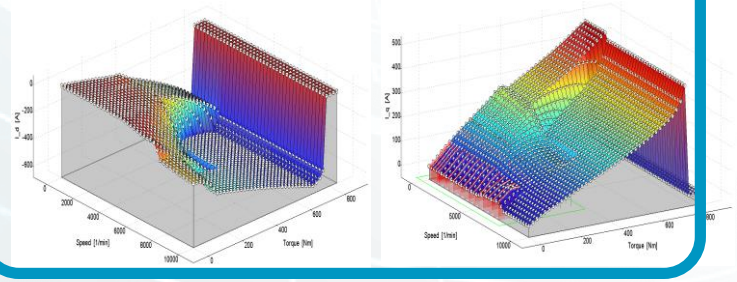
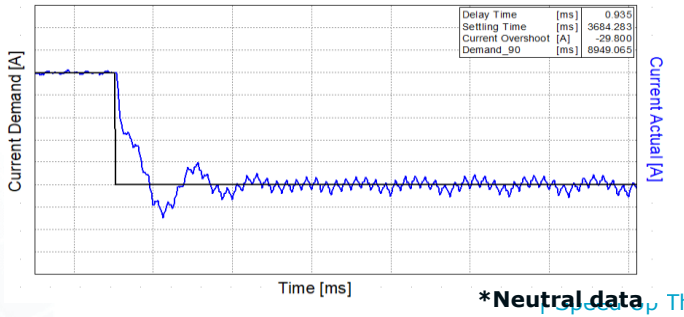
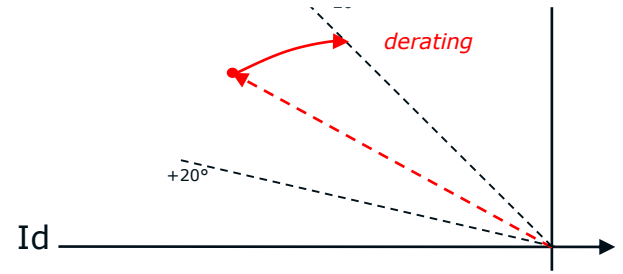
E-Drive Calibration Tasks



E-Drive Calibration Tasks

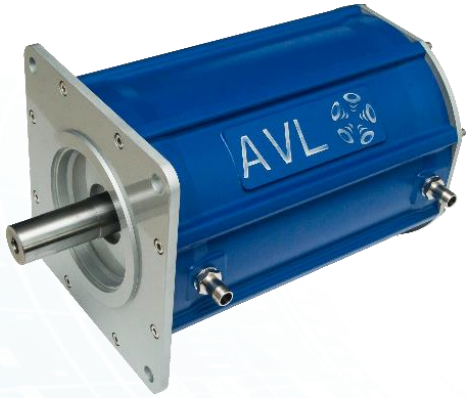


Use Cases

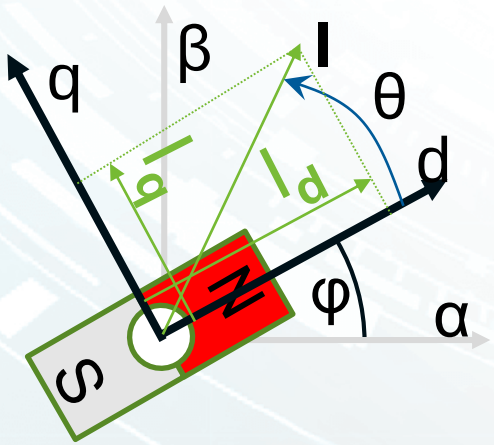
	I. Base Calibration	II. Transient Calibration of Current Controller	III. Derating Function Optimization
Task			
Design Variables	Angle Theta, I_Amp	P & I Values	Derating parameters P&I for Id and Iq (built in AVL PI controller)
Limits	Back EMF, T_rotor, T_stator	Back EMF, T_rotor, T_stator	T_IGBT
Results	Optimized Id and Iq Maps 	Optimized P & I Values 	P & I values for Smooth derating 

*Neutral data

Calibration of Machine Parameters

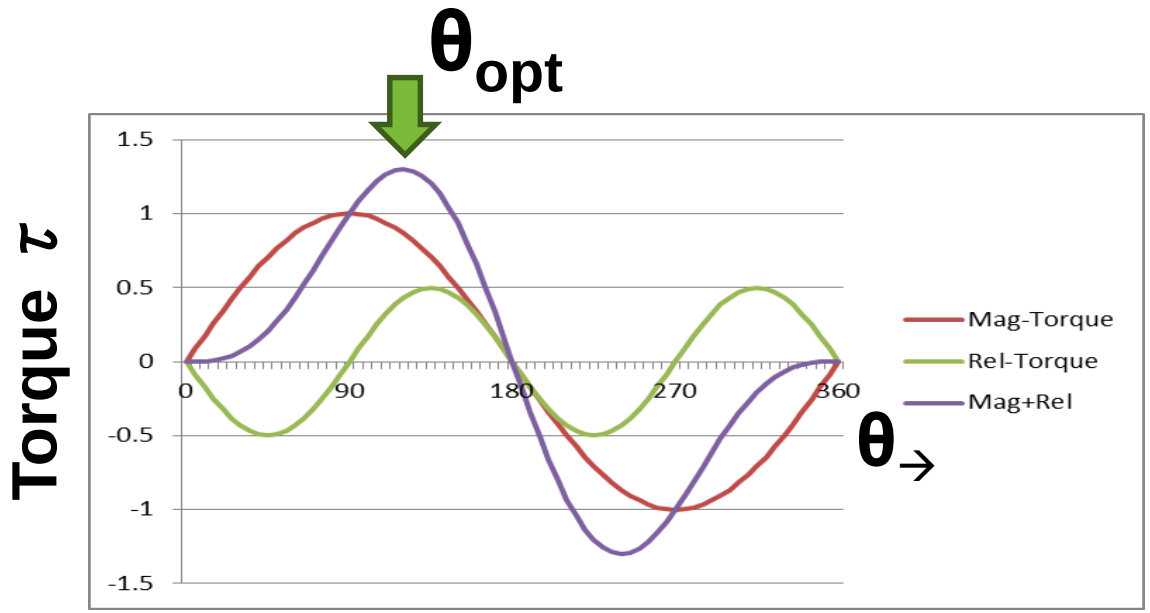


- Maximize efficiency of Inverter & Motor for all speed load conditions
- Vary the Angle **θ** to maximize the Torque
- Monitor Back EMF and Temperatures of rotor and stator

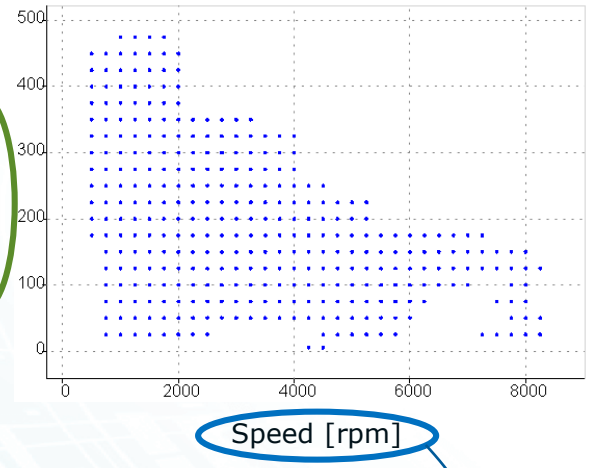


$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = I \begin{bmatrix} \cos \theta_{opt} \\ \sin \theta_{opt} \end{bmatrix}$$

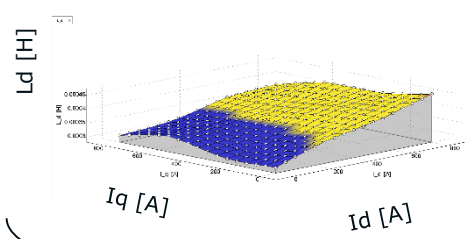
Stator's fixed coordinates: α, ß
Rotor's rotating coordinates: d, q

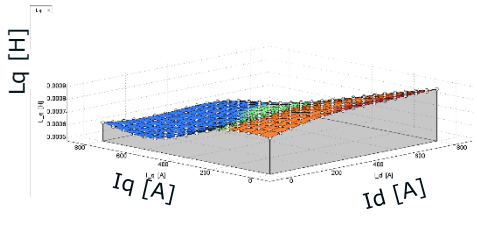


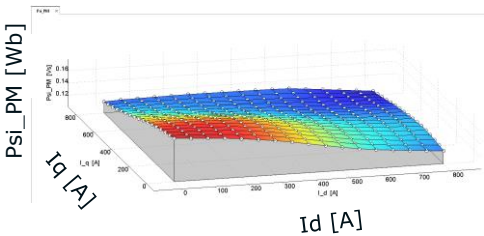
Parameter dependencies for the PESM:
n, **Tq/I_Amp**, **Theta** or **n**, **I_d**, **I_q**

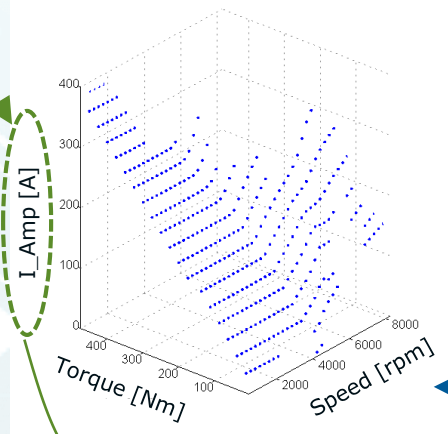


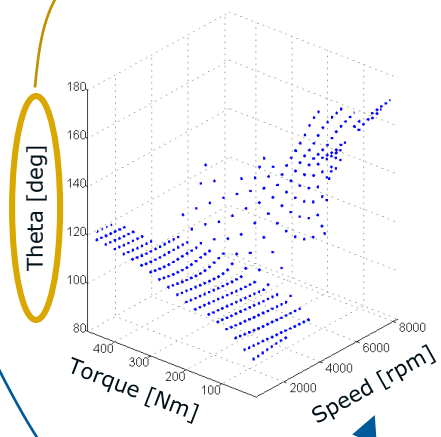
Used for Torque feed back and pre control



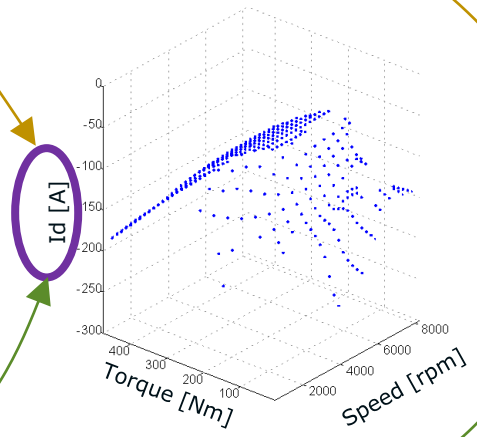


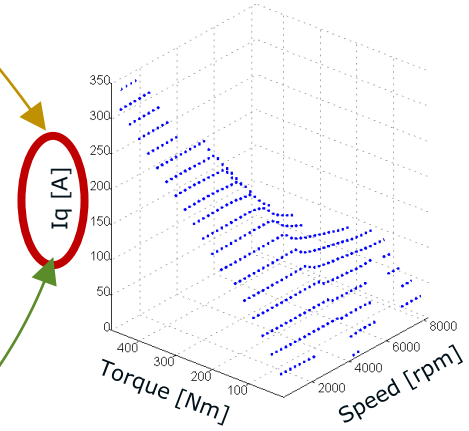




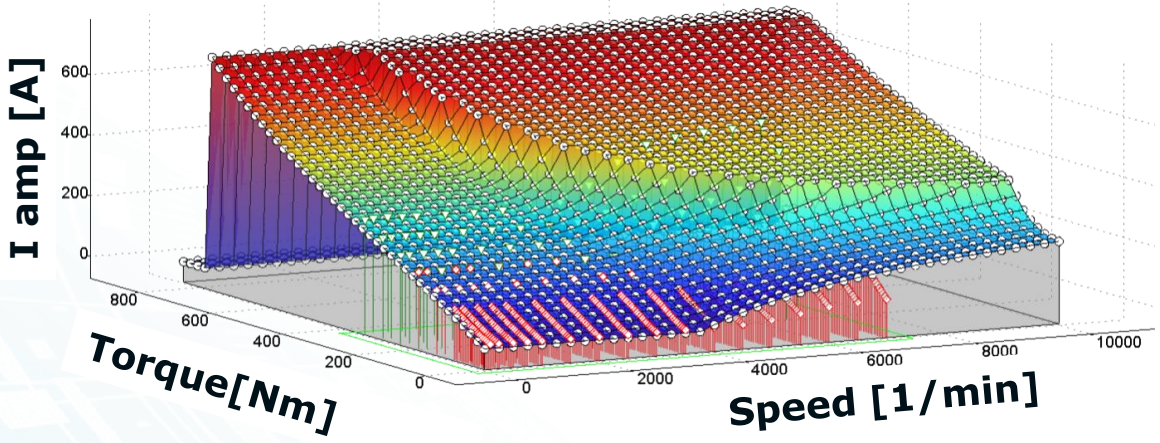


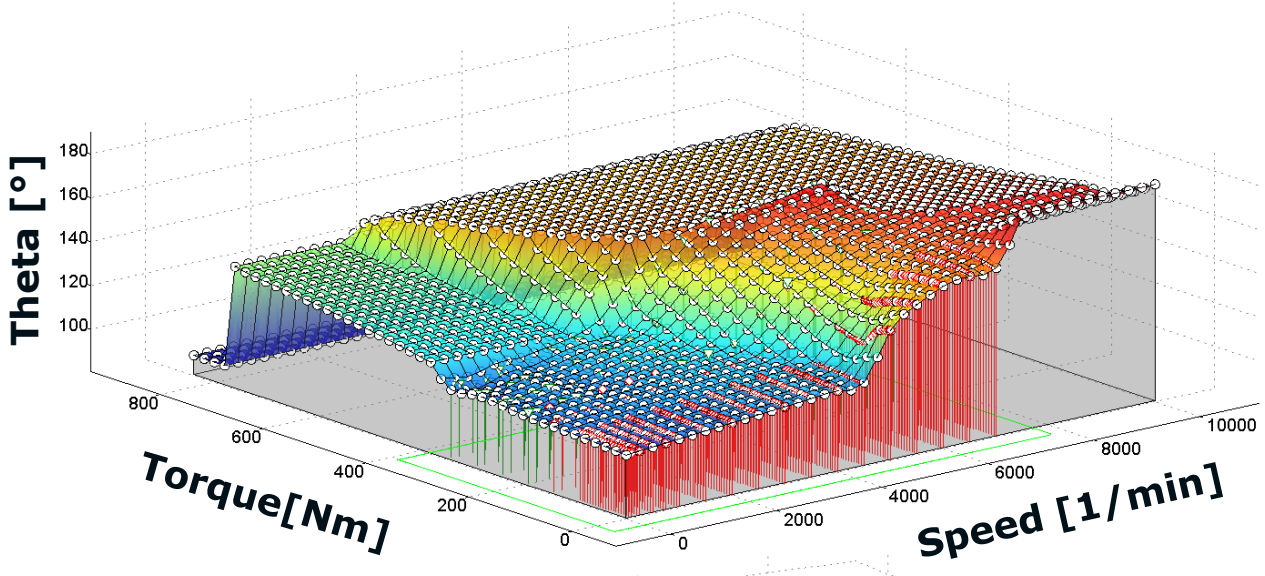
or

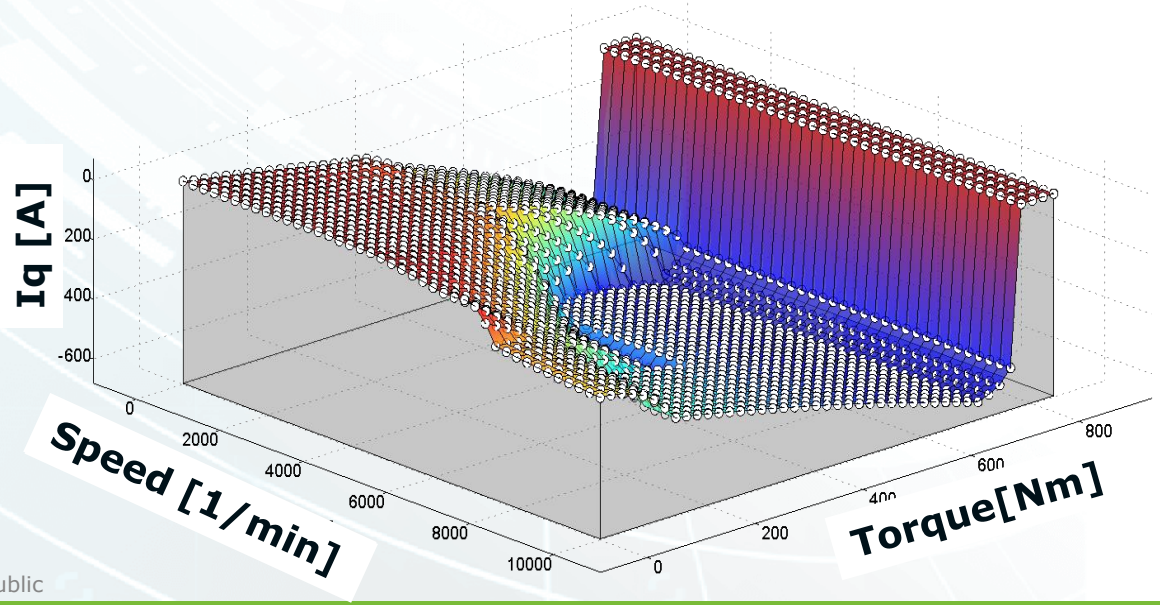


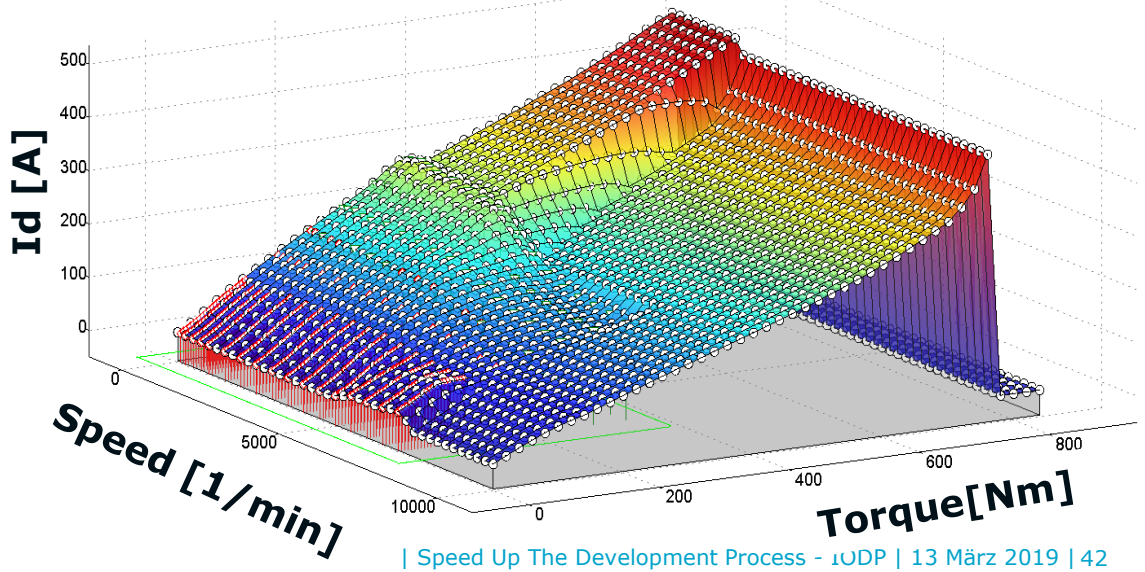


Automated Map Calculation









Proven Benefits

Fully Automated Process

- Up to **80% time reduction in calibration process** compared to manual approach
- Seamless tool chain integration on the testbed assures maximum testing efficiency

Reduction of cost

- Minimized UUT & testbed occupation time
- Reduction of measurement effort due to consequent DOE utilization

Increased product quality

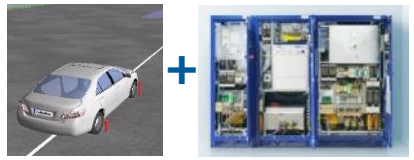
- High repeatability of measurement results
- Higher traceability of results
- Multi-parameter optimization in the whole operating range
- Optimized efficiency of E-drive **increases the electric range**

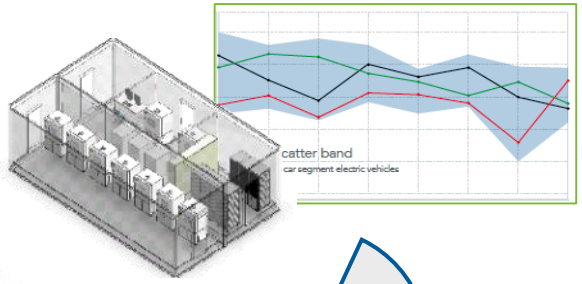
Battery

OVERVIEW of AVL´s BATTERY ACTIVITIES:

FROM Concept to Start of Production

- Test equipment for pack testing
- turnkey solutions for battery labs

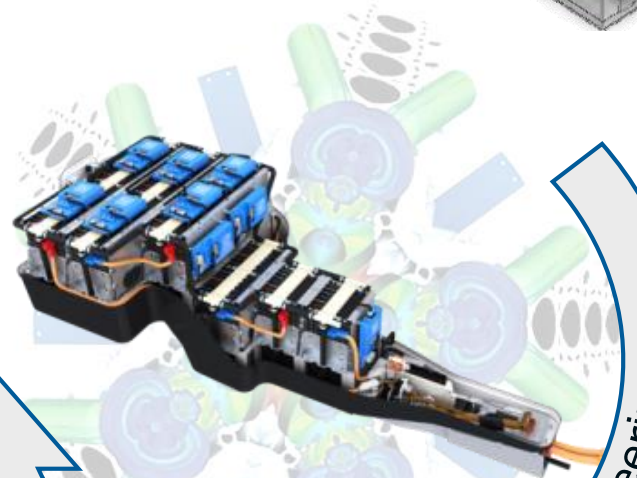


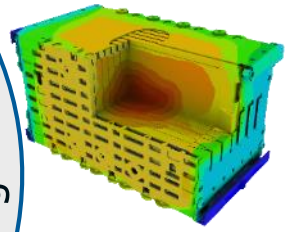


- Testing & Benchmarking

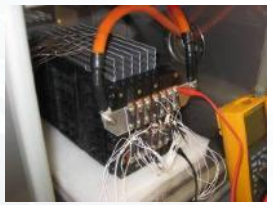
- System validation
- Planning, optimization & monitoring

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



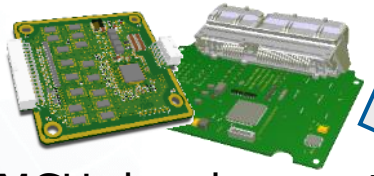


- Module integration
- Thermal Simulation
- Mechanical Simulation
- Cell Modeling



- Prototype build
- Generation 1&2 build-up

- Systems Engineering
- Electrical & Mechanical Design Engineering
- Design for Production

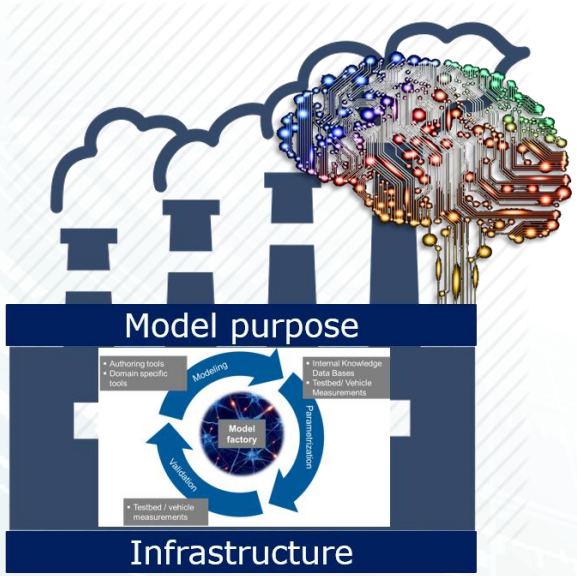


- BMS & MCU development (SW & HW)

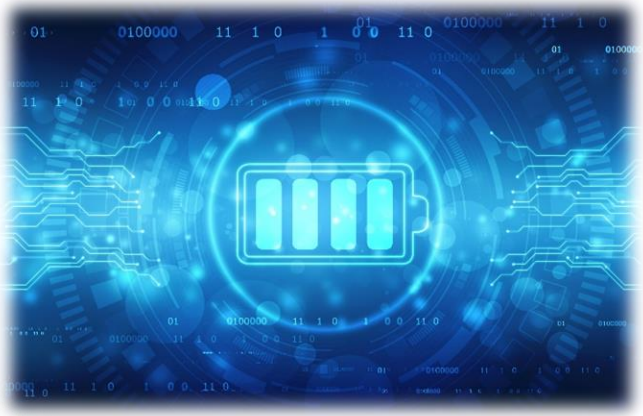
Production Engineering

Battery Focus Topics
Simulation, Tests & Data Handling

Battery Digital Twining

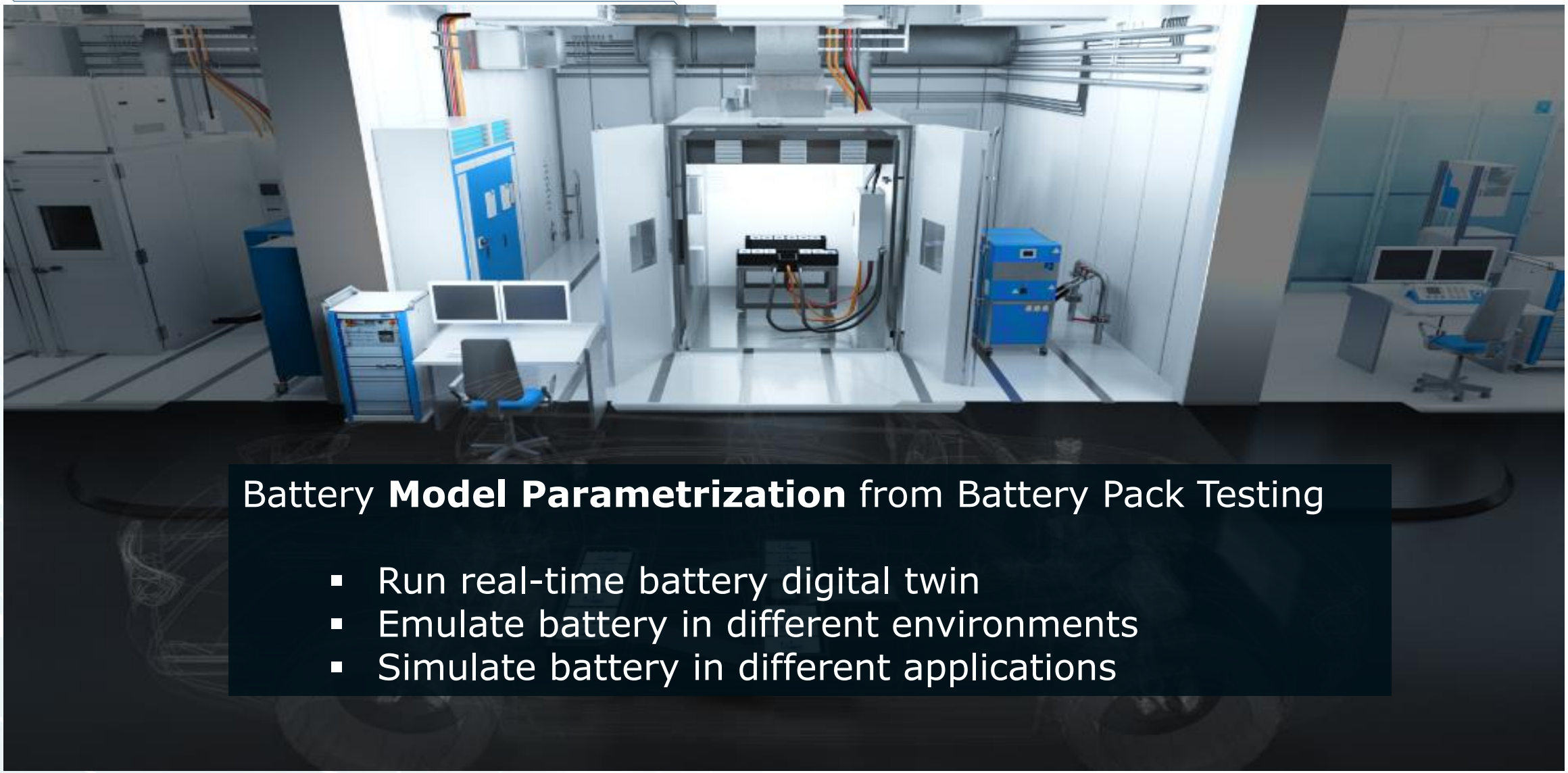


Battery Lifecycle



Battery Data Management

Battery Digital Twining

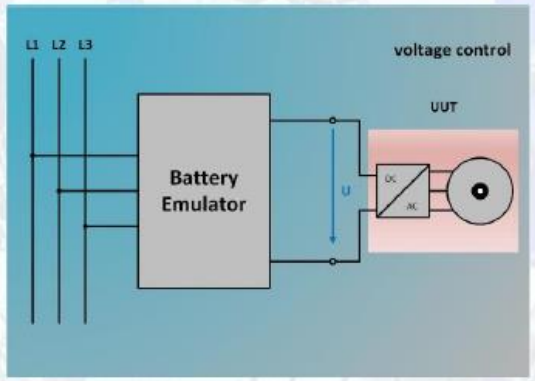


Battery **Model Parametrization** from Battery Pack Testing

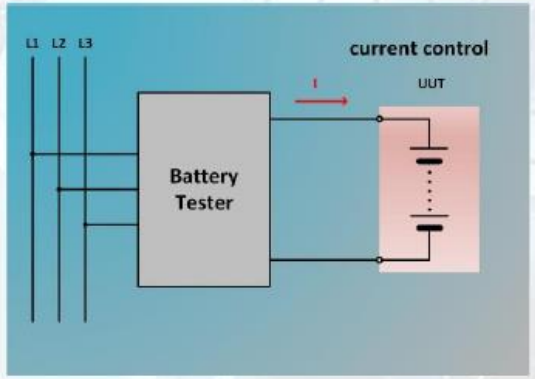
- Run real-time battery digital twin
- Emulate battery in different environments
- Simulate battery in different applications

Battery Digital Twining

E-STORAGE



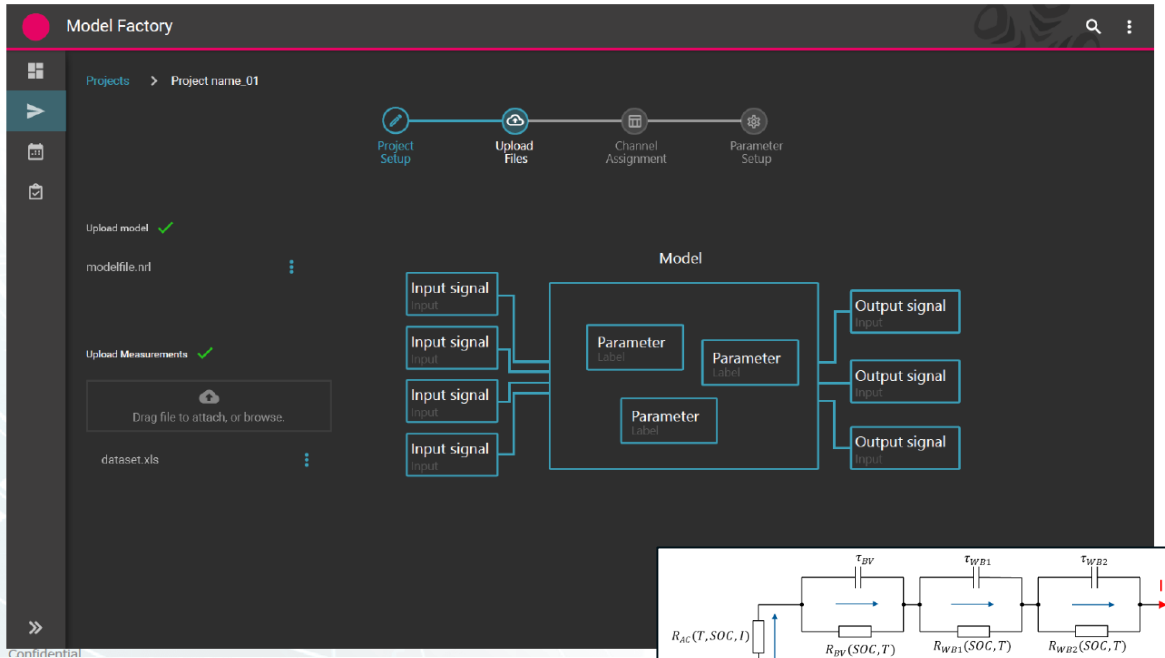
Emulation Operation



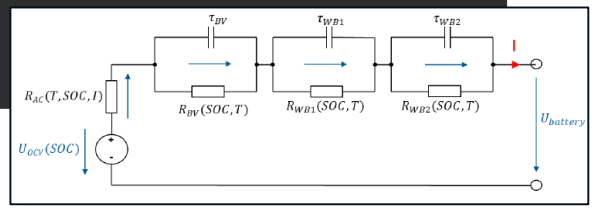
Testing Operation

Model Factory
Parameter Optimization Tool for Battery Models

Battery LAB



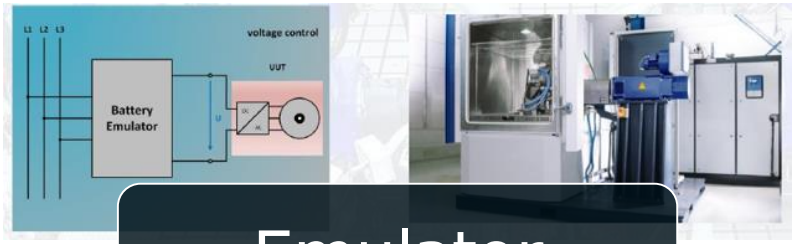
E - LAB



Optimized parameters can be saved and forwarded to all locations

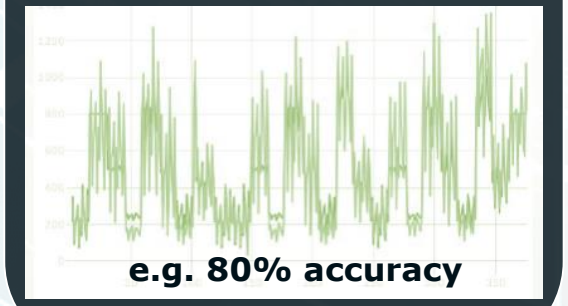
Model Factory
Parameter Optimization Tool for Battery Models

Measurements



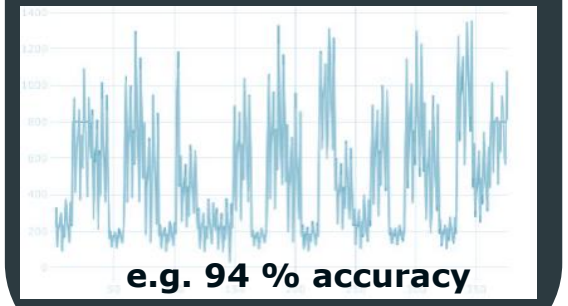
Emulator

Model
with ad-hoc parameters



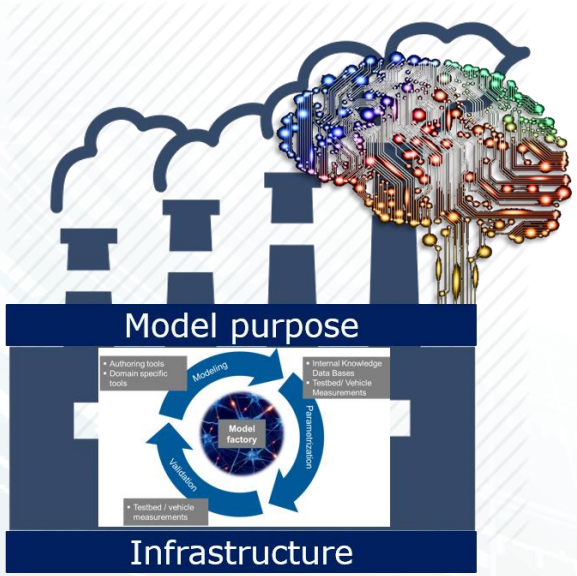
Model Factory
Automated Parameter Optimization

Model
with optimized parameters



Battery Focus Topics
Simulation, Tests & Data Handling

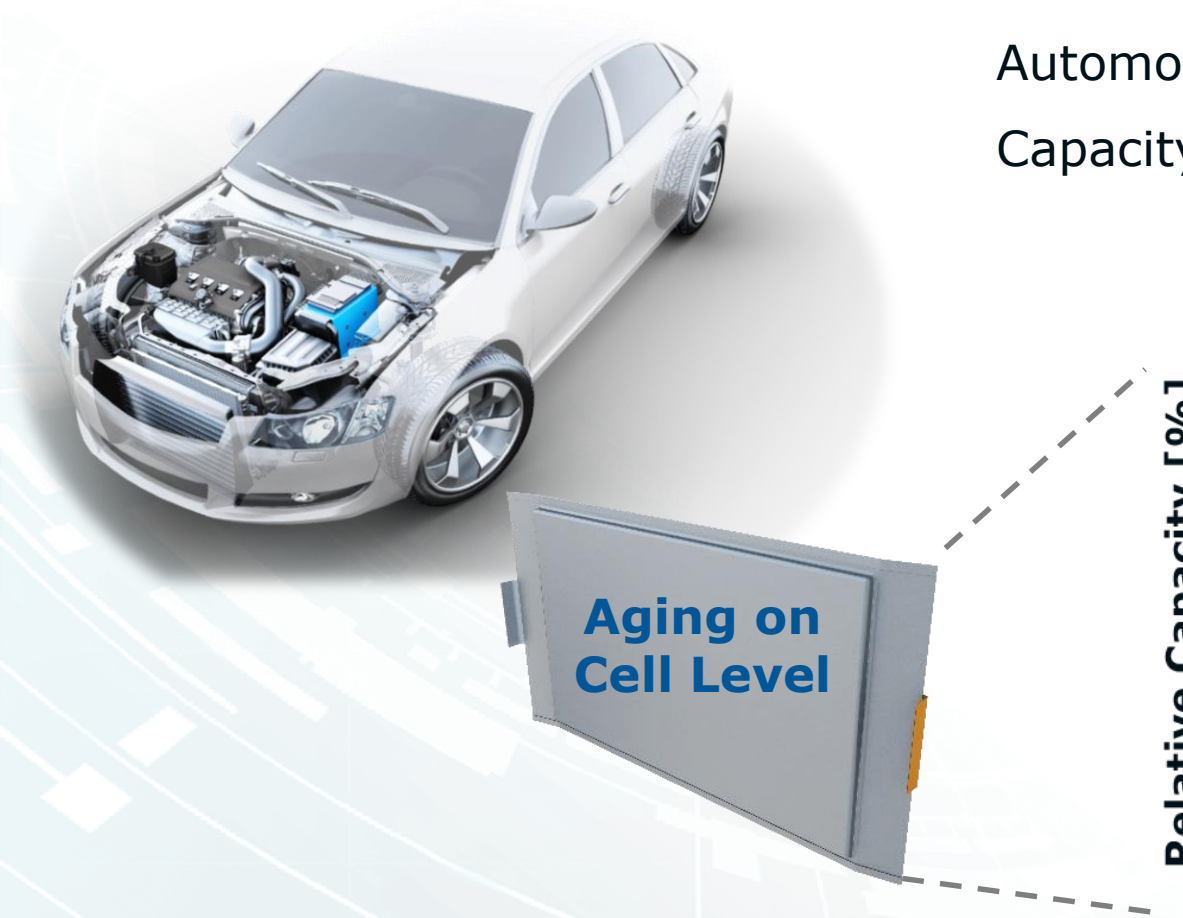
Battery Digital Twining



Battery Lifecycle

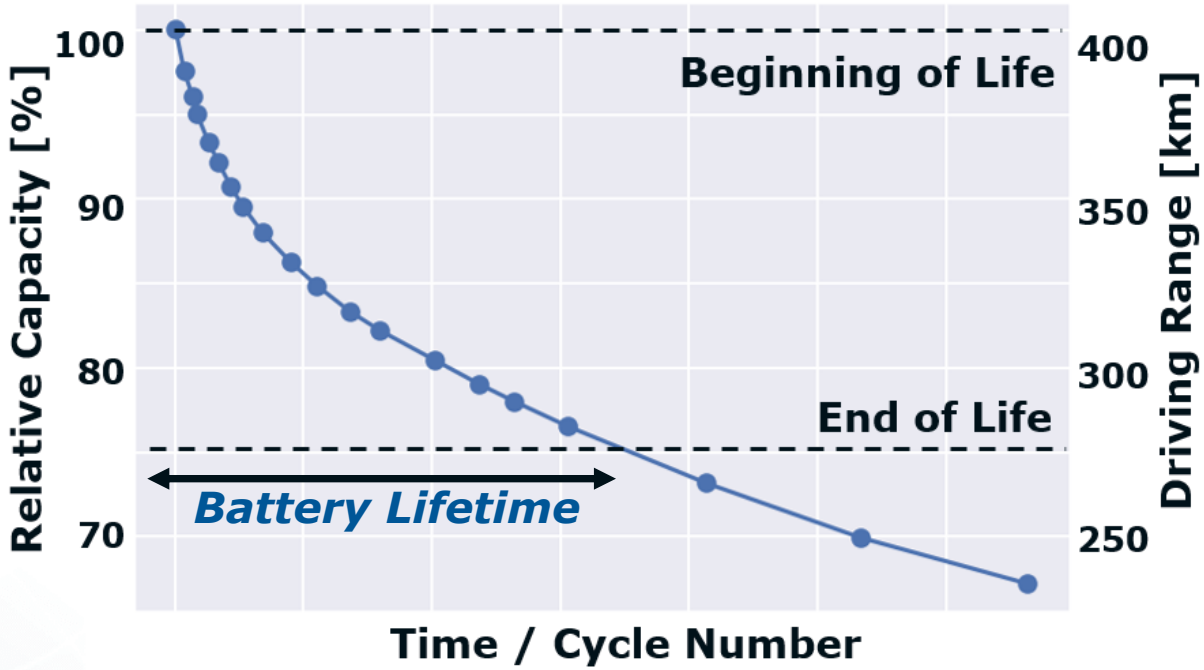
Battery Data Management

How is the Lifetime of a Battery defined?



Automotive **battery cells** age over time

Capacity loss leads to driving range reduction



Aging Drivers

- **Vehicle operation mode**

  Driving, parking, charging

- **Environment**

  Road profile, climatic condition

- **Battery pack design**

  Cooling system, electrical connection, mechanical load

- **Cell design and chemistry**

  Material degradation, chemical reactions

How Can Battery Aging be Modeled?

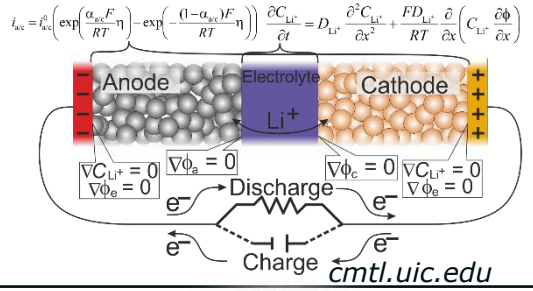
AVL is working on different modeling approaches:

Test Data Amount

Physical Chemical Details

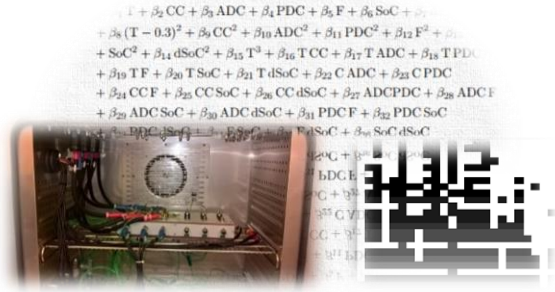
Physics - Based Model

- Physical, chemical, biological laws
- No aging experiments
- Electro-chemical modeling



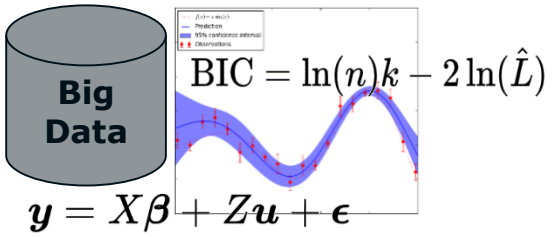
Half - Empirical Model

- Half-empirical data driven model
- Based on aging experiments
- Statistical methods



Data - Driven Model

- Purely data driven
- Based on many aging experiments
- Machine Learning, Neural Networks



Accuracy

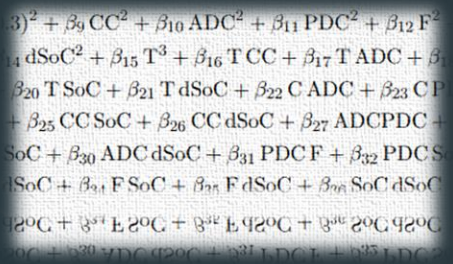
Complexity

Predicting Battery Lifetime

- Predict lifetime of each individual vehicle
- Gain knowledge **WHEN** and **WHY** the battery reaches its end of life
- Understand aging effects
- Identify most damaging operation modes
- Optimize operation strategy

Predicting Battery Lifetime

Battery Cell Aging Tests



Battery Aging Model Parametrization

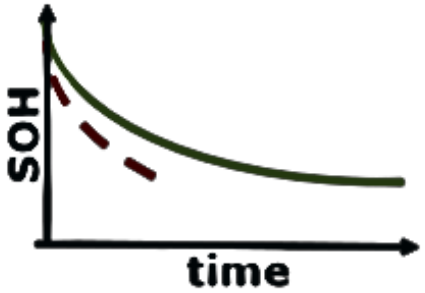
Vehicle In-Use Data

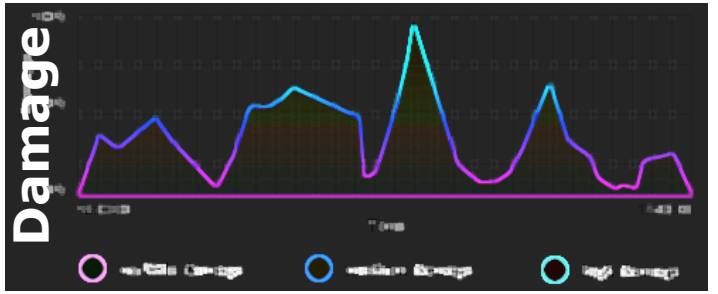
Vehicle & Battery Monitoring

Lifetime Prediction

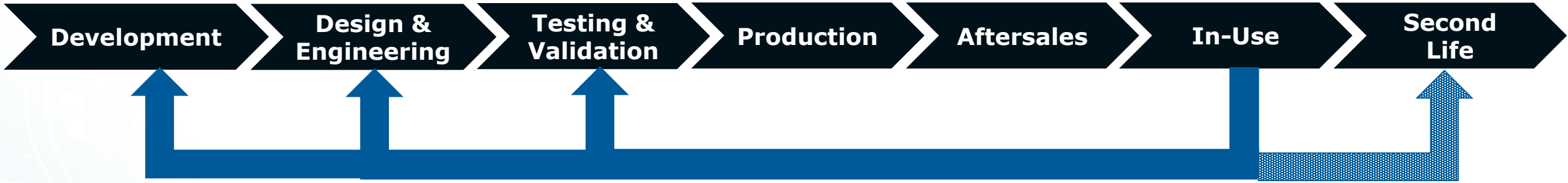
Analysis of Operation Strategy

Feedback to Development

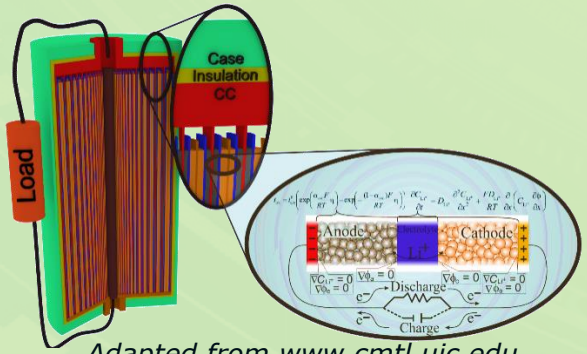




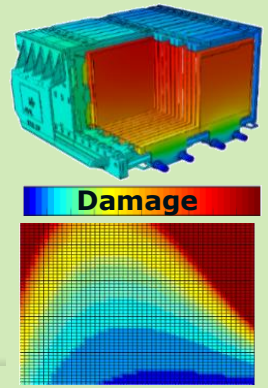
Use Cases along the Battery Life Cycle



AVL involved from Battery Development to Second Life

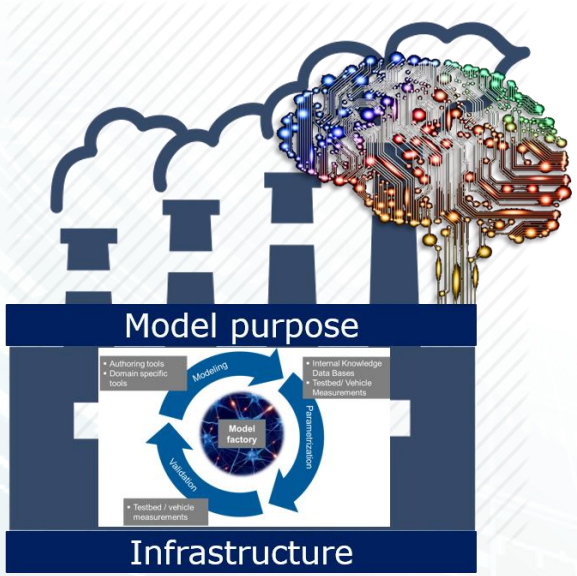


Adapted from www.cmtl.uic.edu

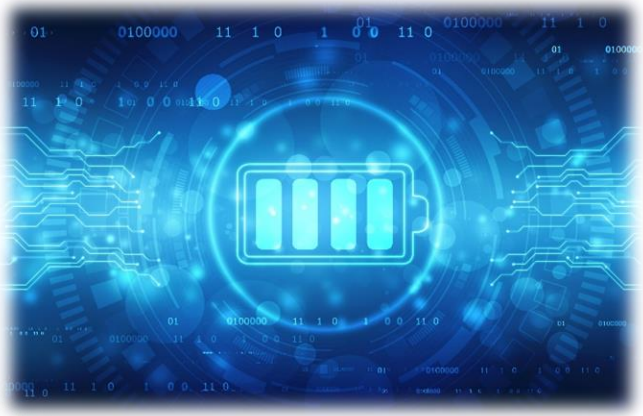


Battery Focus Topics
Simulation, Tests & Data Handling

Battery Digital Twining



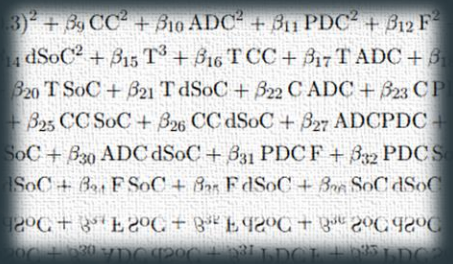
Battery Lifecycle



Battery Data Management

Battery Data Management

Battery Cell Aging Tests



Battery Aging Model Parametrization

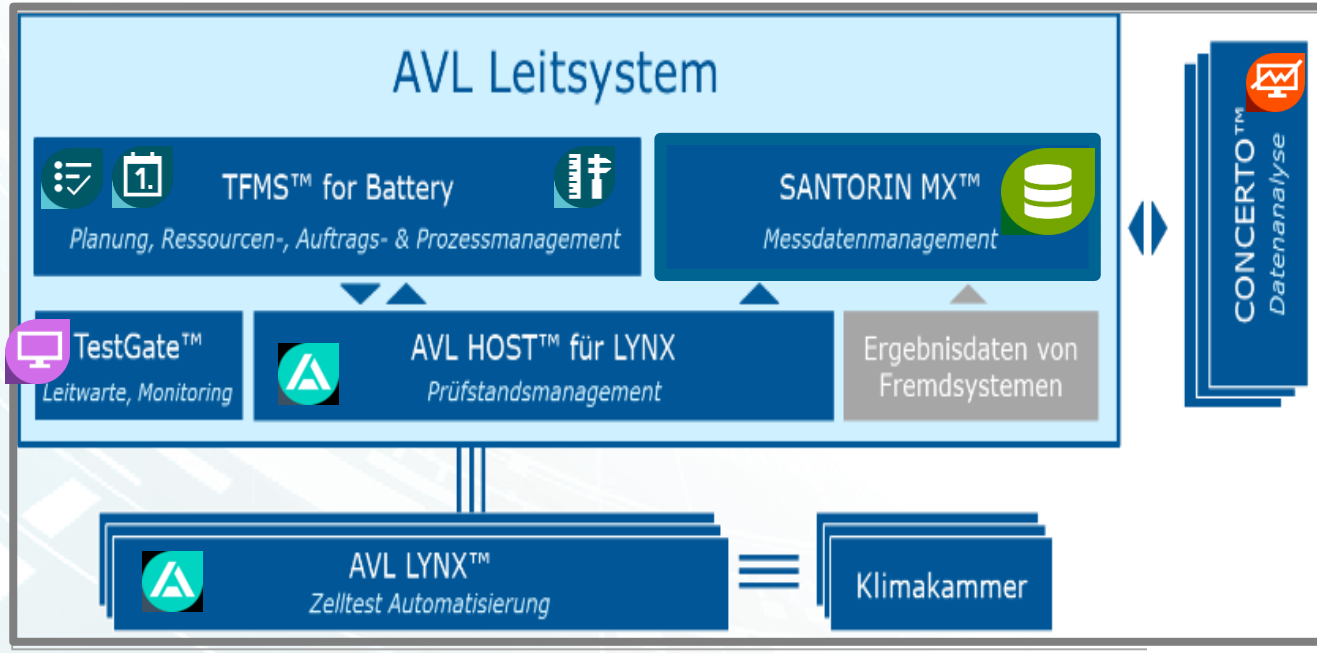
Challenge:

- high number of test samples in simultaneous test operation over long time
- high amount of test equipment in use
- high diversity of test methodology

AVL Battery Data Management

Reference: Cell-Lab Project for an OEM in Germany

Big Data Ready!
Conversion to big data formats enables the utilization of **Big Data** platforms for advanced/highly scalable analytics **after initial indexing**



Data Management

40 Mbyte/Day/Channel

4.000 Channels

151 GByte per day

Added Value

Efficiency gain by centrally processing all data independent of its source

Highest possible **time savings** by batch based data processing and exporting

System grows with your need

Full Traceability over the data life cycle

Summary

Efficient Electric Vehicle Development

Electrification causes big change in tools, method & testing solutions

Development relevant decisions in early stages are key for time to market targets

Consequent re-use of tools and testbeds combined with adaptation of proven & new methodologies enables big efficiency improvements

Combination of simulation, test and efficient data handling is key

Increase quality

reduce effort & costs

earlier in your process

is our target

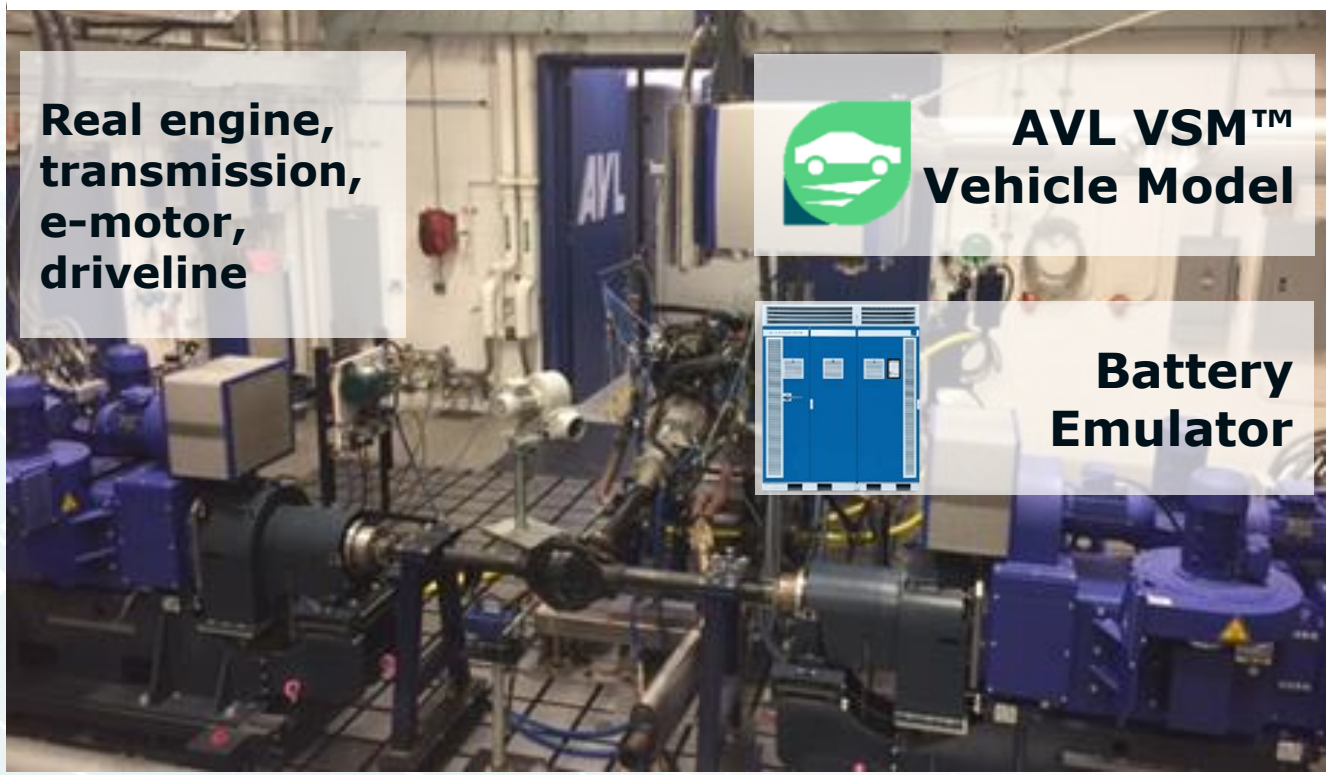

Thank You
AVL
www.avl.com

Appendix

Customer Reference
Ford US Hybrid calibration on Powertrain testbed

Calibration of hybrid functions before the first vehicle including regen braking, starts and drive-away

ROAD → POWERTRAIN TESTBED



Proven Benefits

Reduction of development and testing time	▪ Calibration started **6 months** before first vehicle was available ▪ High degree of automation in comparison to road
Reduction of cost	▪ **Reduced use of expensive vehicle prototypes** ▪ **Calibration procedures** designed to specifically to PTTB.
Increased product quality	▪ **Higher testing coverage** leading to higher product quality ▪ **More development iterations** possible before SOP

Customer Reference
European OEM BEV validation on Powertrain testbed

Benchmark of BEV driveability on Powertrain Testbed

AVL tool-chain

AVL Tool Contribution:

- **AVL VSM** Realistic vehicle dynamics simulation
- **AVL-DRIVE™** Objective driveability assessment

Scope of the project

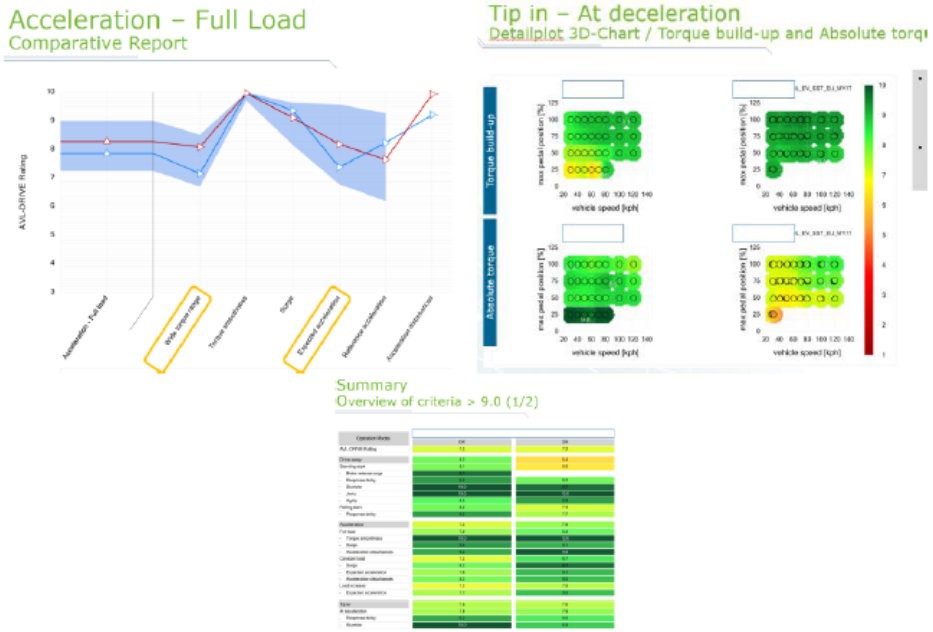
- **Battery electric vehicle driveability benchmark using Driveability Methodology and Toolchain in powertrain testbed environment**
  - Installation of the toolchain
  - Driveability manouvers to allow benchmark against AVL-DRIVE BEV scatterband and detailed comparison with Tesla Model X
- **Driveability maneuver testruns considering SOC**
  - **Tip-In / Tip-Out** at different speeds, pedal positions
  - **Part load and full load acceleration; driveaway**
  - **Hill climb with different friction/slopes** – on dedicated test track and comparison with PTTB
- **Verification regarding:**
  - AVL-DRIVE™ rating
  - Physical signal level (chassis acceleration, engine speed, engine torque, etc.)

Project results

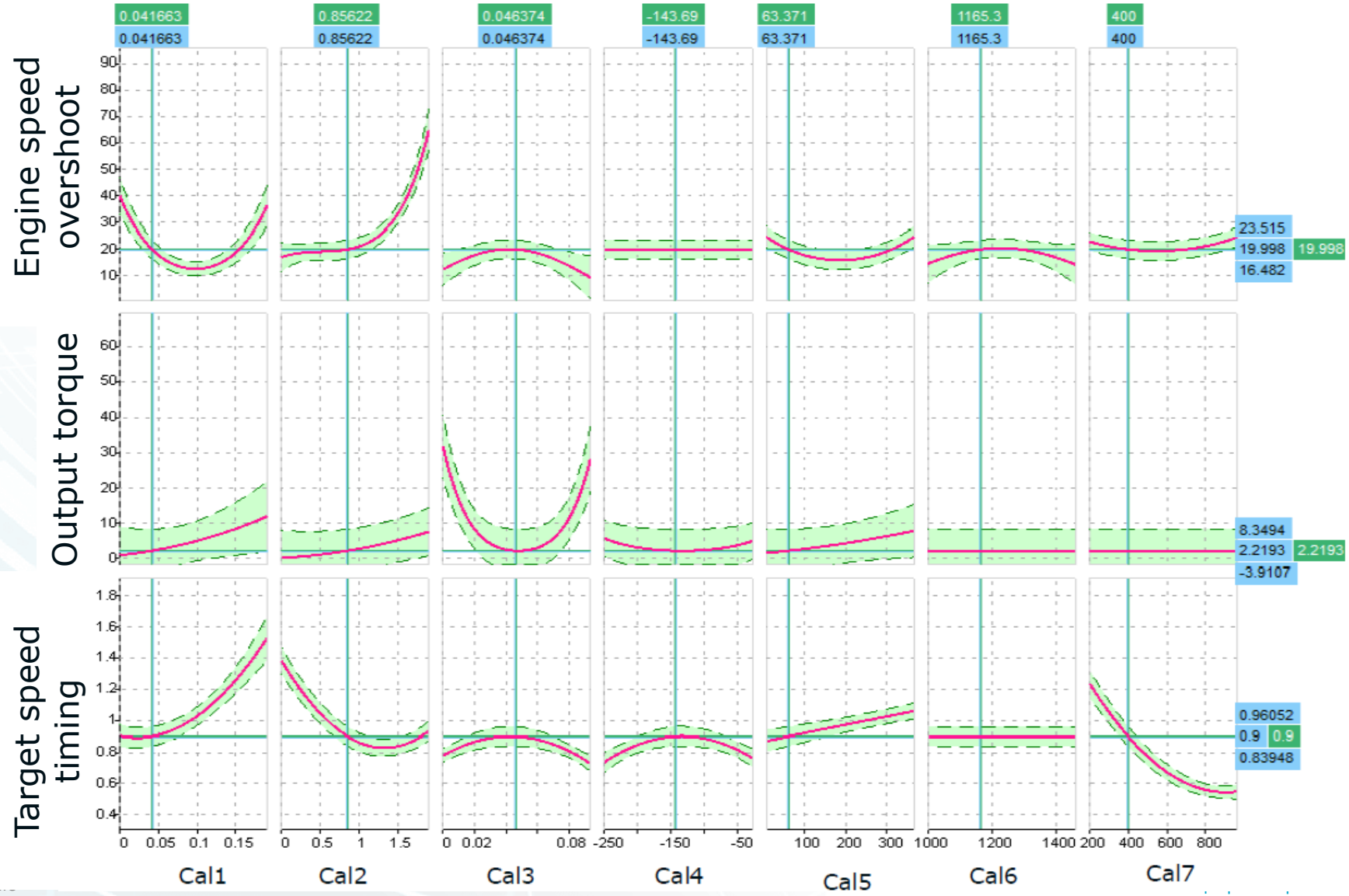
Jaguar Land Rover

JLR BEV SUV on powertrain test bed, low inertia dynos

Results of benchmark:



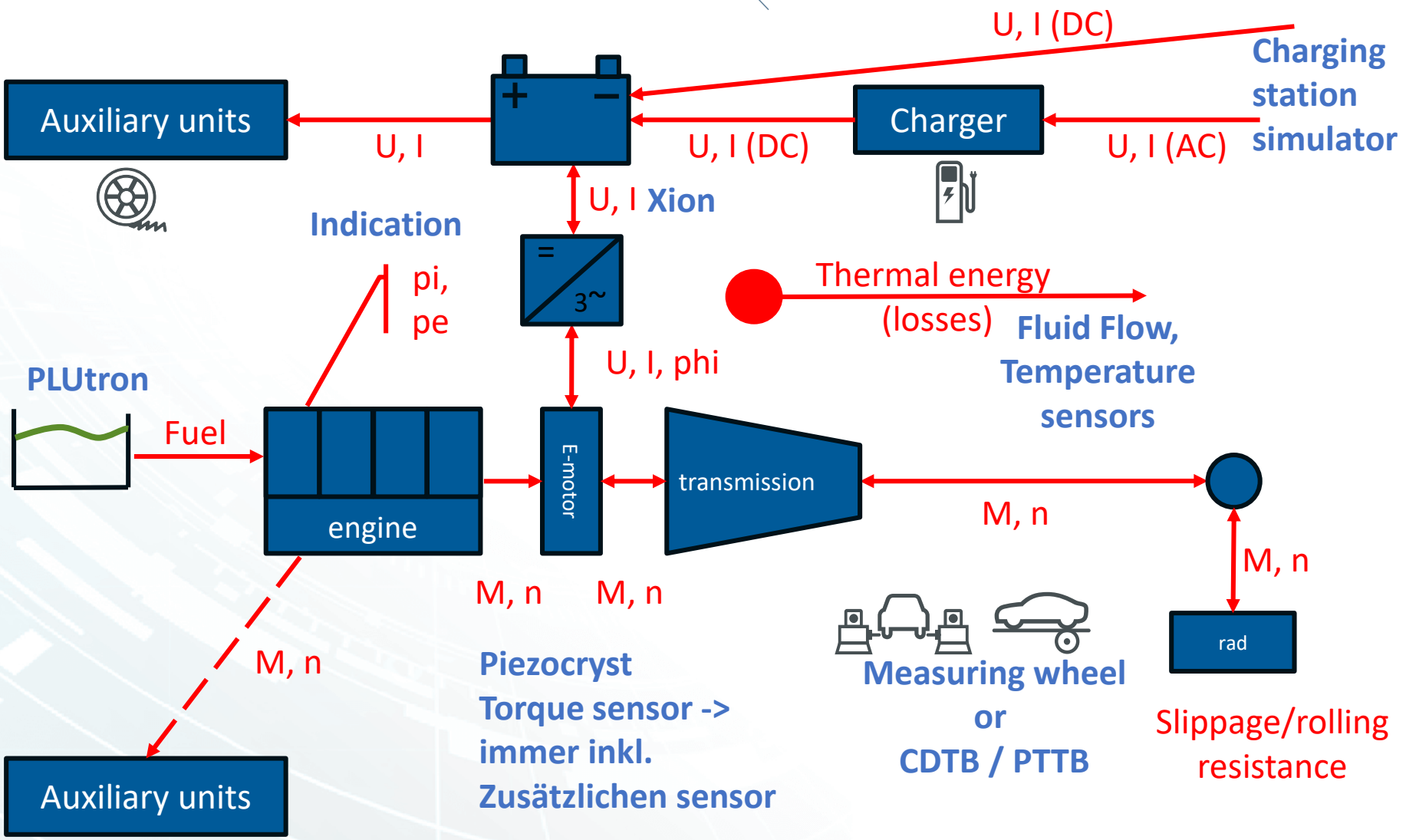
Example results



Engine Speed target during a restart at high speed

Energy flow- & efficiency factor analysis

In vehicle, on Chassis dyno & Powertrain testbeds



Test automation:

- Device handling
- Maneuver execution
- Dynamic testing (RDx)

Data Handling:

- Synchronization
- Storage
- Searching / finding

Data Processing:

- Calculation
- Simulation if (direct) measurement not possible
- Optimization
- xCU map calculation
- Report generation

Simulation:

- Model calibration with measurement data

Legend:
Physical value
Tools

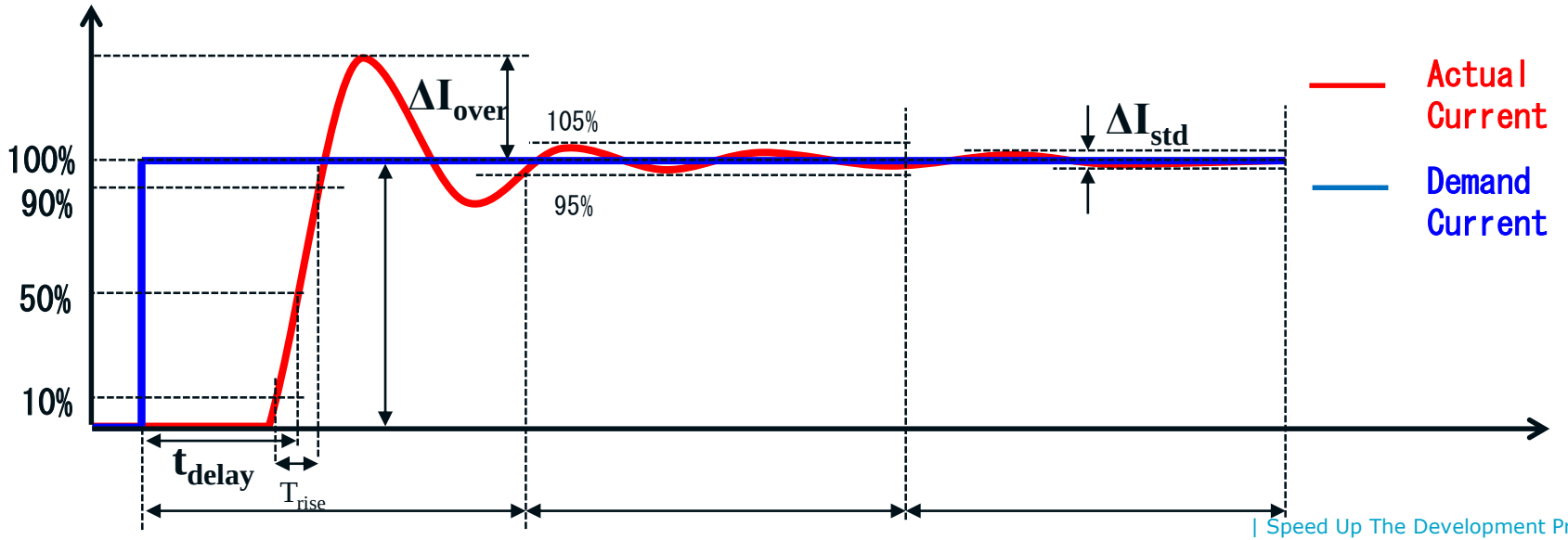
Calibration of Current Controller

Task: Optimize the current controller

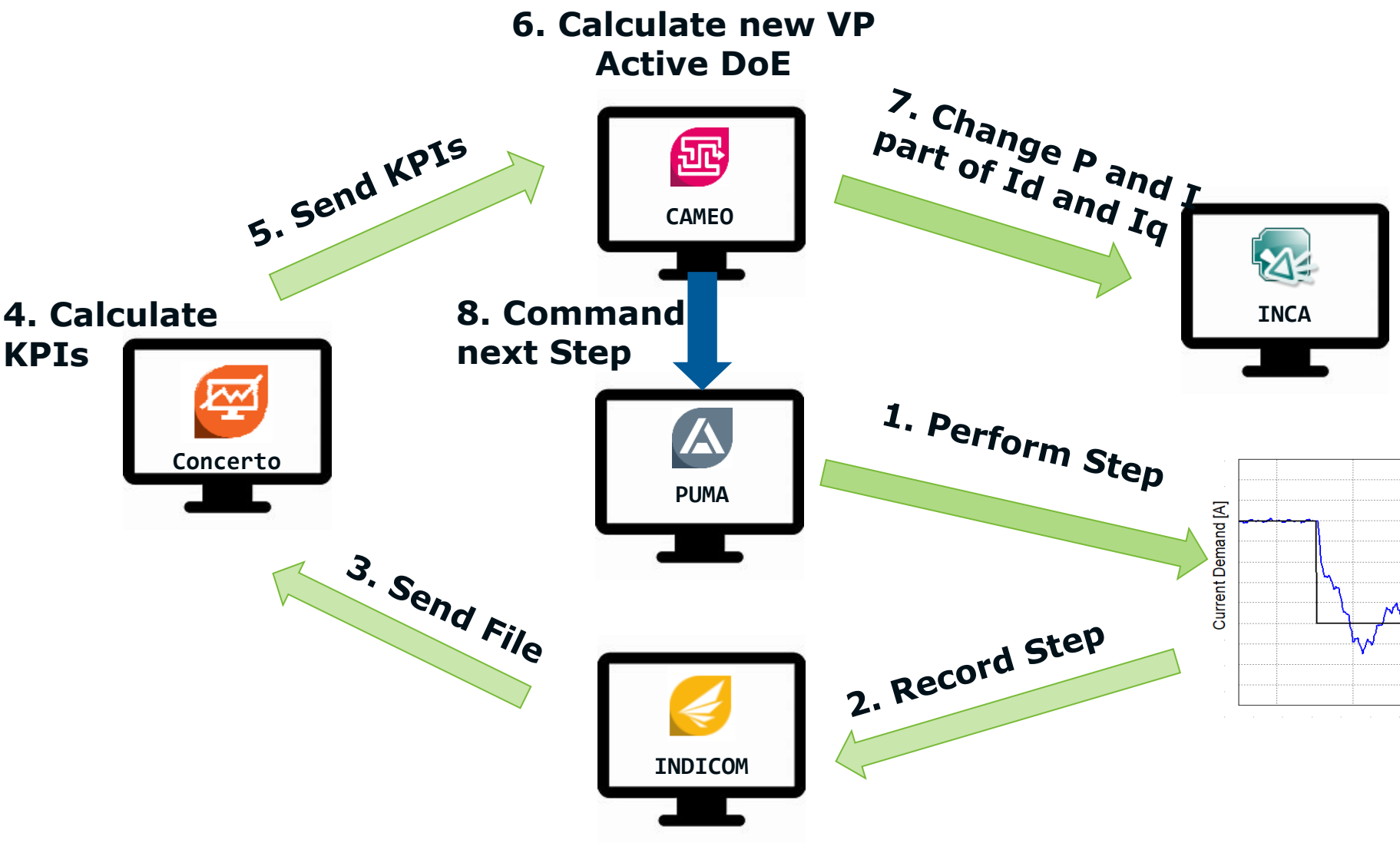
Factor definition: P and I part of $\mathbf{I_d}$ and $\mathbf{I_q}$ current

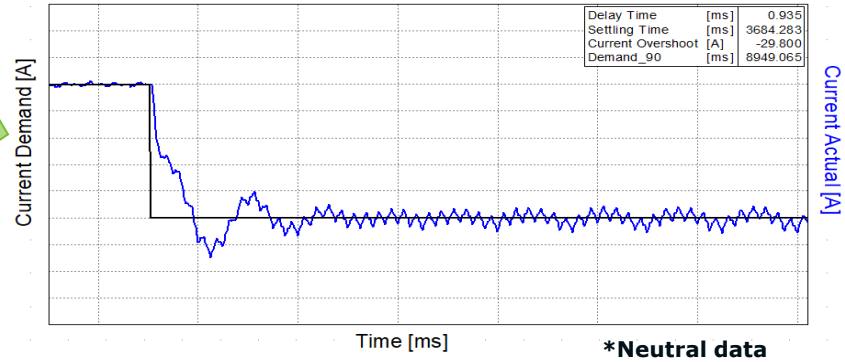
Method: Run a **transient test** with different P and I values for $\mathbf{I_d}$ and $\mathbf{I_q}$
Calculate KPIs from Recorder to optimize the controller

Response definiton: **KPI**s for Reponse delay ($\mathbf{t_{delay}}$), Current demand 90% reached ($\mathbf{t_{90\%}}$), Overshoot ($\mathbf{\Delta I_{over}}$) and Standard deviation ($\mathbf{\Delta I_{std}}$)



Calibration of Current Controller





*Neutral data

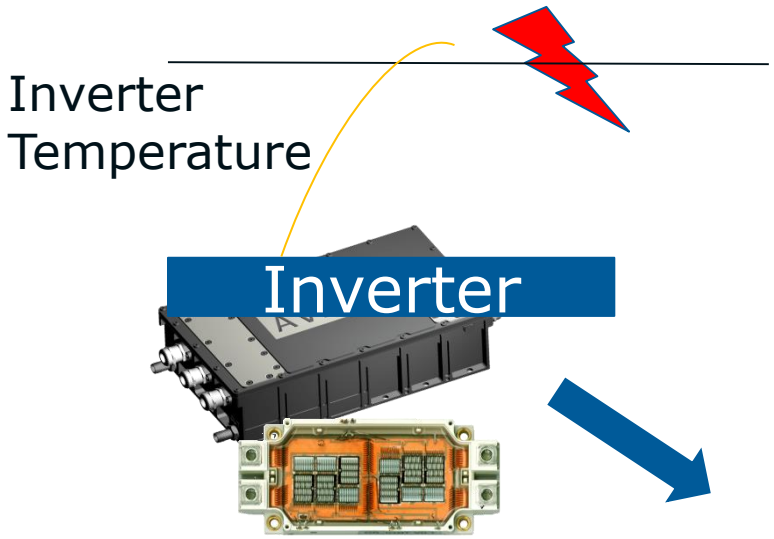
Calibration of Derating Functionalities

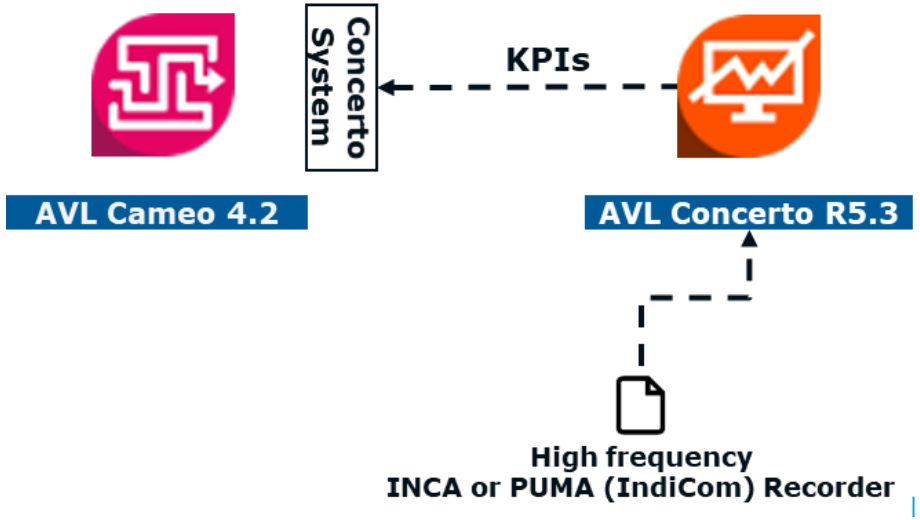
Task: Temperature/current derating in case of overheating of Inverter & E-Motor

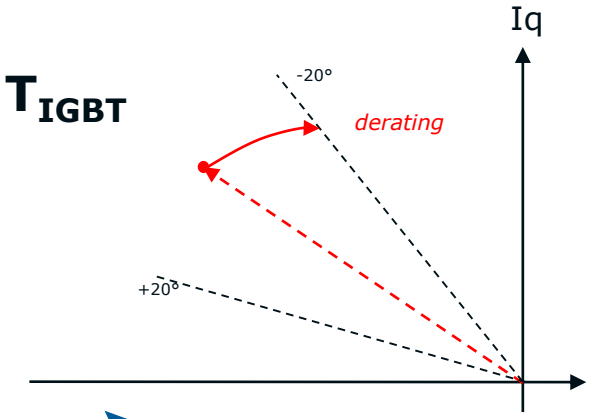
Factor definition: $\mathbf{I_d}$ and $\mathbf{I_q}$ current

Method: Check the temperature of Inverter. In case of overheat upon certain limit, smooth reduction of current $\mathbf{I_{Abs}}$ with AVL PI controller.

Response definiton: Derating function, Inverter Junction Temperature $\mathbf{T_{IGBT}}$



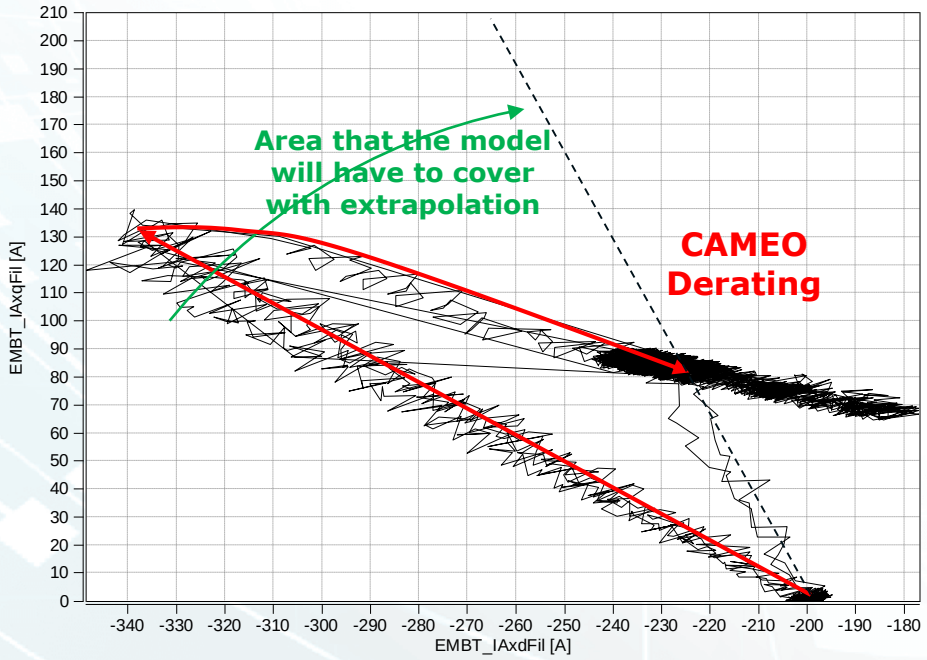


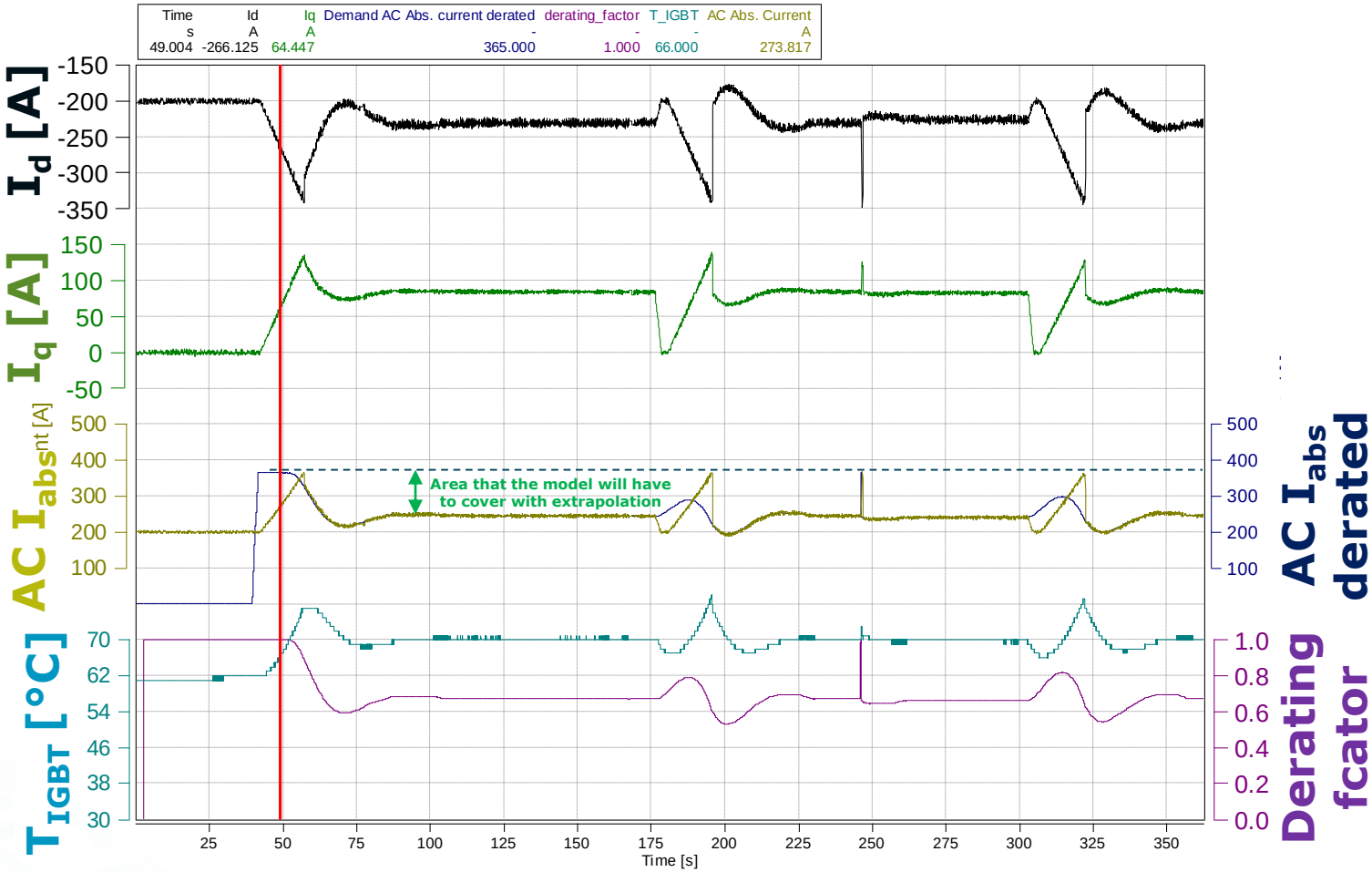


Calibration of Derating Functionalities

Example of Derating PI controller in CAMEO

$\mathbf{T_{IGBT}}$ = 70°C limit set in CAMEO for the activation of the derating factor



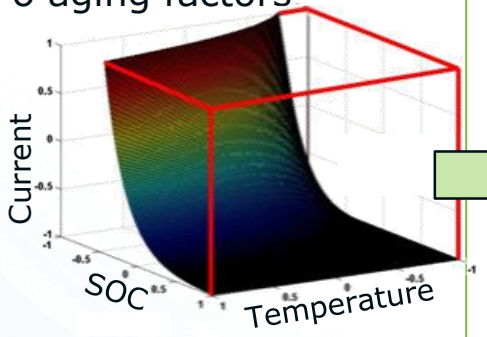


AVL Statistical Battery Lifetime Prediction

Cell testing

- Design of Experiment **DOE**
- On basis of 6 aging factors

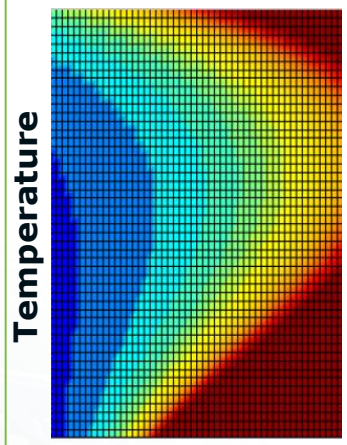
T, SOC, ΔSOC, CC, ADC, PDC

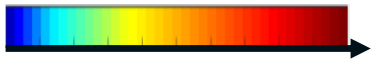


- Aging experiments
- 30-90 tests, 6 months to 2 years

Mathematics & Statistics

- Input: **Cell tests**, capacity fade, resistance increase, impedance change
- Output: Mathematical **model** for time until EOL & damage

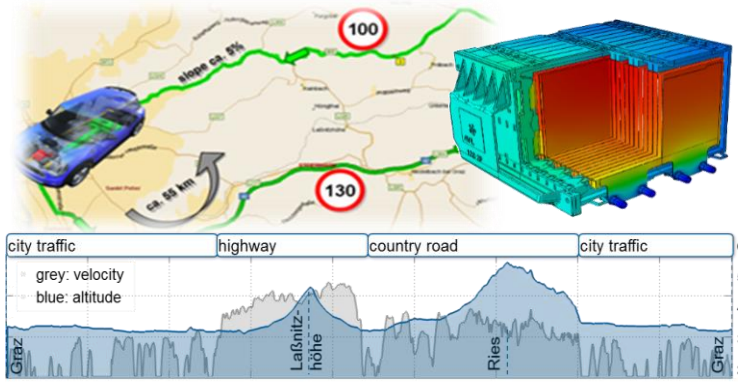




$$t_{EOL} = \sum_j \beta_j x_j$$
$$= \beta_1 T + \beta_2 CC + \beta_3 ADC + \beta_4 PDC + \beta_8 (T - 0.3)^2 + \beta_9 CC^2 + \beta_{10} ADC^2 + SoC^2 + \beta_{14} dSoC^2 + \beta_{15} T^3 + \beta_{16} T + \beta_{19} T F + \beta_{20} T SoC + \beta_{21} T dSoC + \beta_{24} CC F + \beta_{25} CC SoC + \beta_{26} CC dS + \beta_{29} ADC SoC + \beta_{30} ADC dSoC + \beta_{33} PDC dSoC + \beta_{34} F SoC + \beta_{35} F$$

python

Lifetime Prediction



Input: driving profile, battery temperature, statistical model

Output: **Lifetime**, distance until EOL, Detect parts of a driving profile that constitute the largest **damage**

python

Optimization of **driving, cooling, charging** strategy

Lifetime Prediction

- Apply mathematical aging model to real-world driving cycle
- Predict lifetime and driving distance until EOL
- Find parts of the driving profile that constitute largest damage