AVL List GmbH (Headquarters)

State of the Art Development Methodologies for Hybrids and e-Drives

29.11.2018 PDiM 18,
Chalmers Conference Centre

Andreas Volk

Public

Content

Introduction

Technology selection - *Do the right thing*

Validation of new design concepts – *Do the things right*

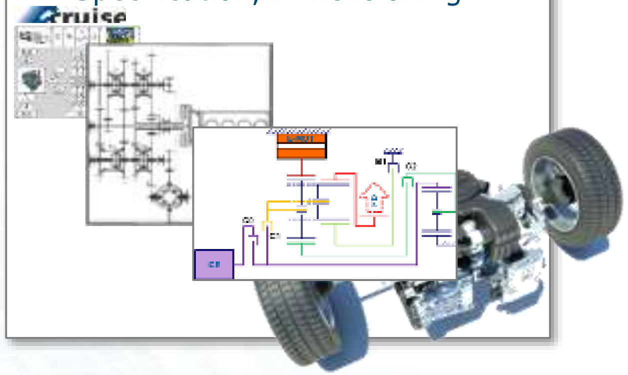
Integrated design verification

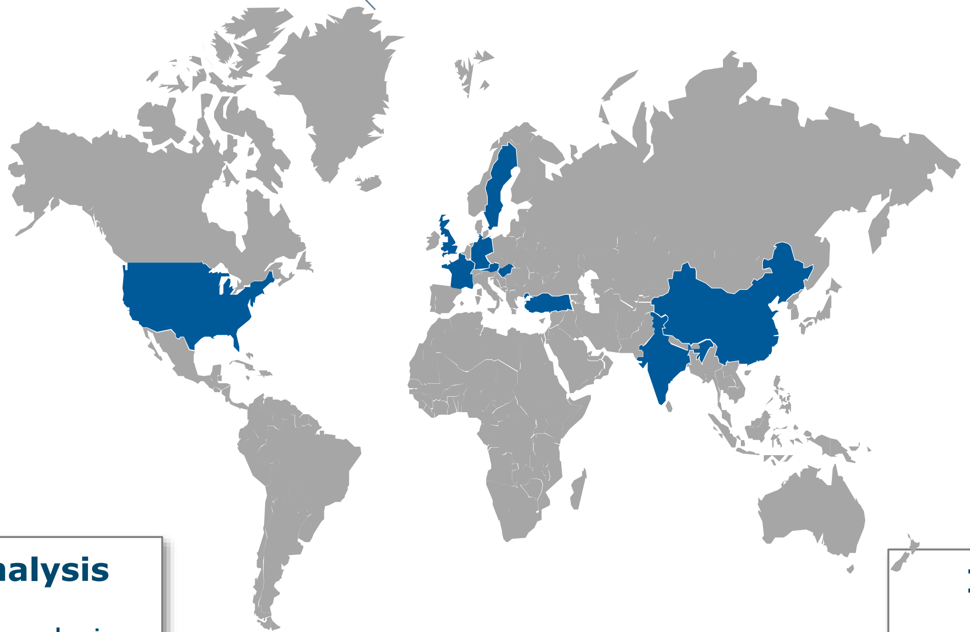
Summary and outlook

Content

AVL – Transmission Overview

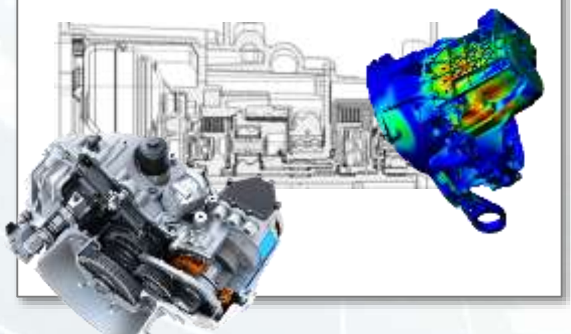
Concept / Structure
Transmission synthesis,
Specification, Dimensioning





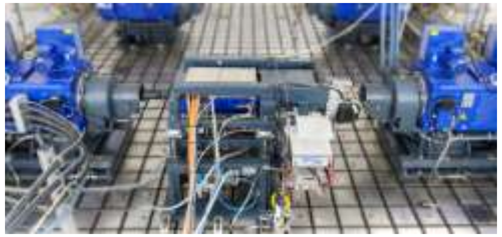
Calibration
ACT – test bed calibration
In-vehicle calibration
DRIVE™ evaluation

Detail Design & Analysis
CAD Design
Structural and dynamic analysis



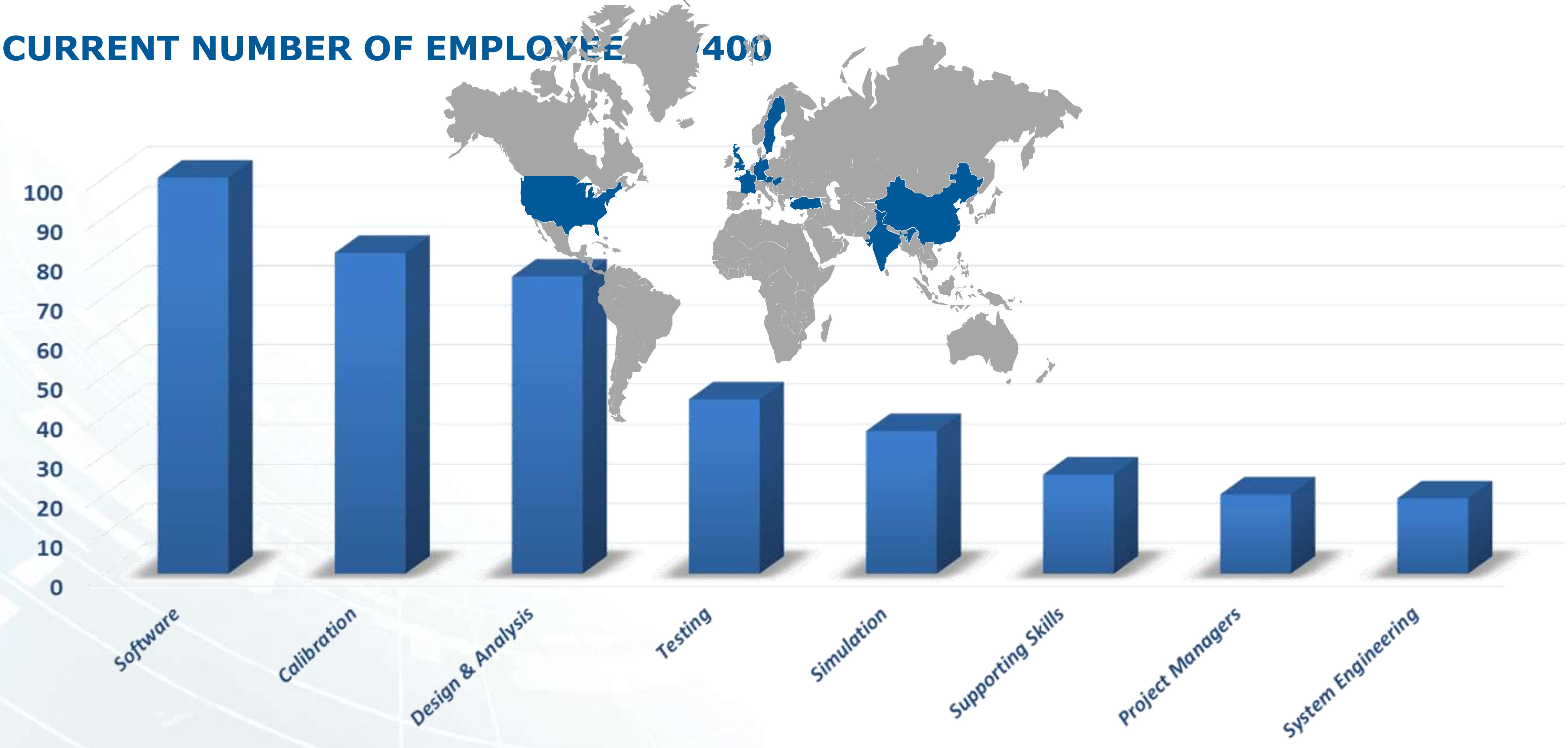
Software & Controls
Specification & coding
Safety

Integration & Testing
Rig and vehicle testing

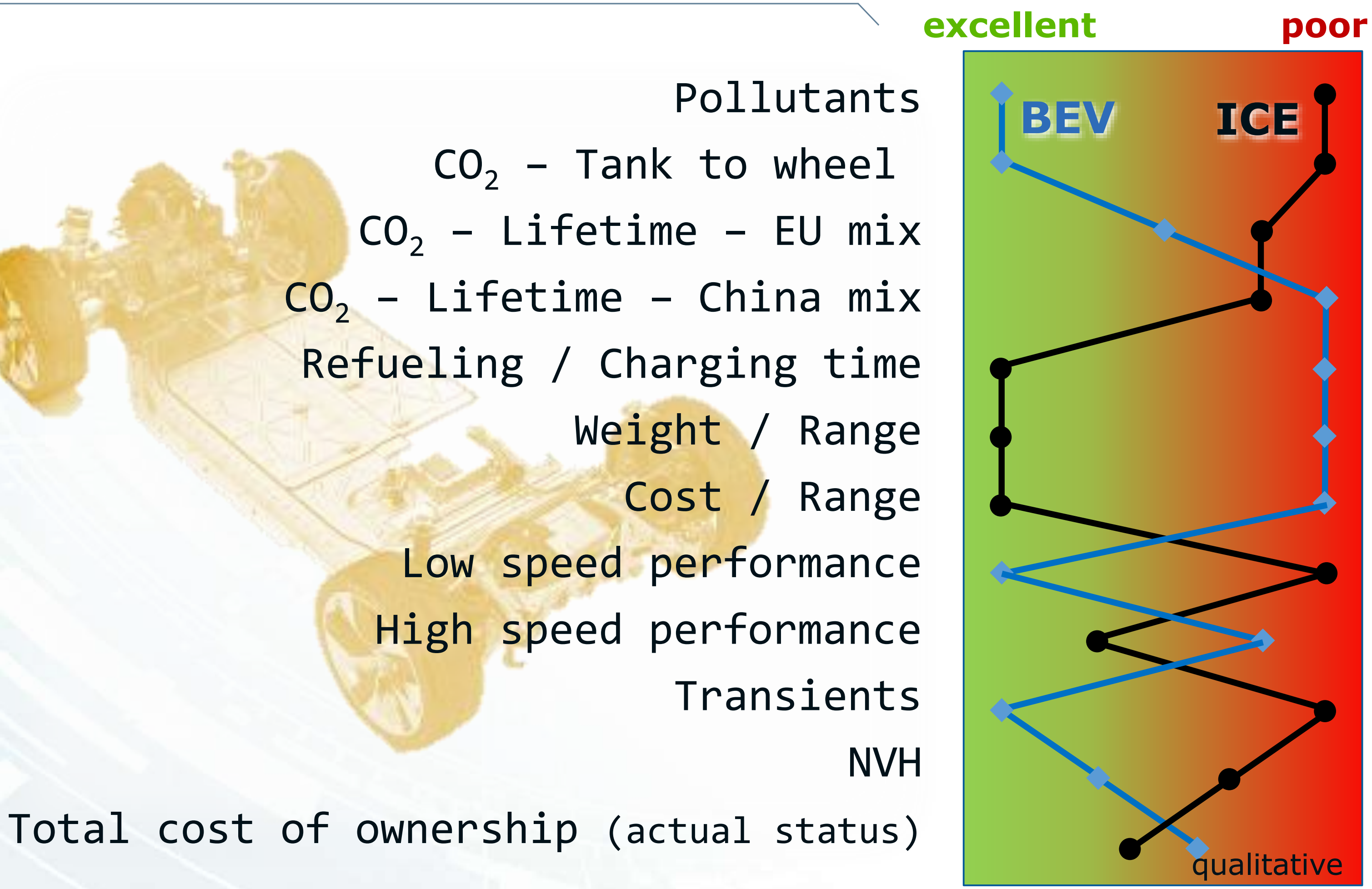


AVL – Transmission Overview

CURRENT NUMBER OF EMPLOYEE… 400



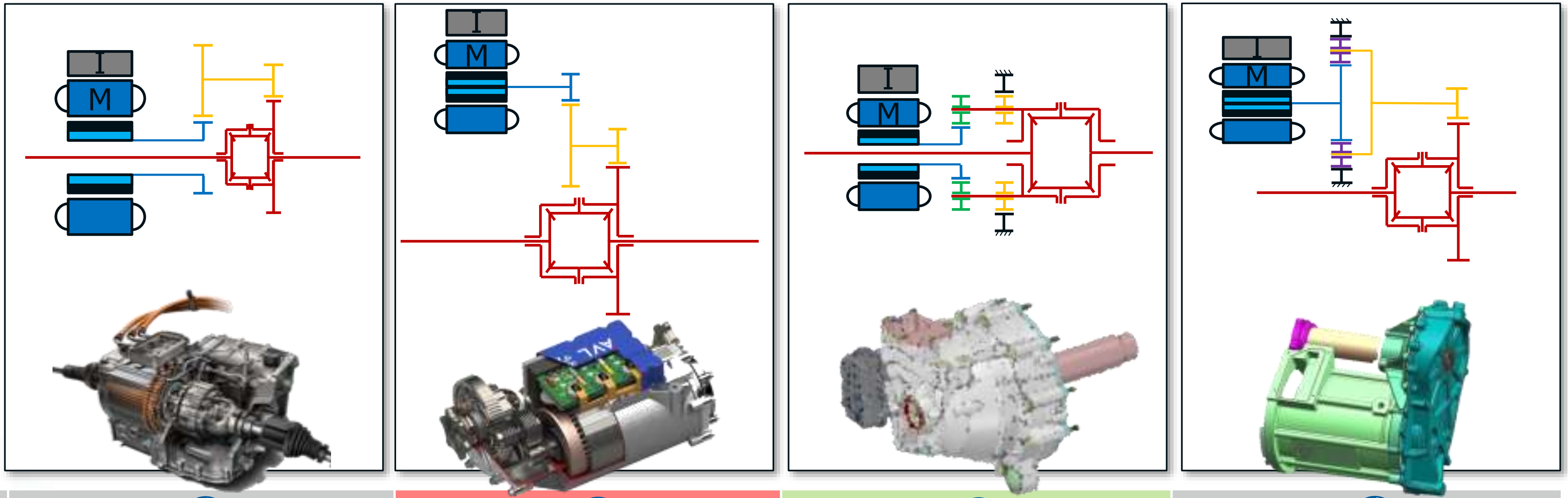
KEY FEATURES OF CONVENTIONAL (ICE) AND BATTERY ELECTRIC POWERTRAIN (BEV)



Electrification and ICE offer quite complementary characteristics

Content

Overview typical EV-Drive Architectures

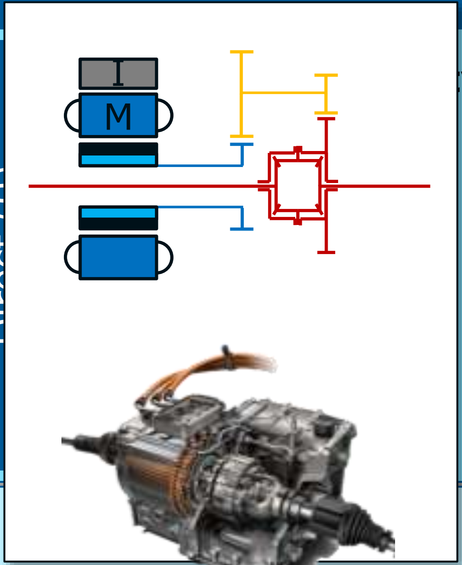


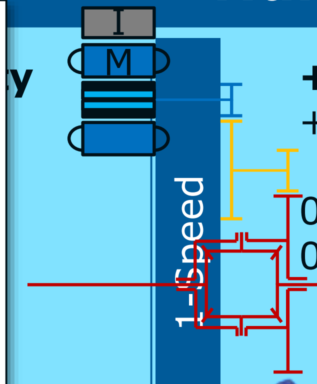
	LAYSHAFT Co-Axial	LAYSHAFT Offset	PLANETARY GEAR Co-Axial	PLANETARY GEAR Offset
Packaging	better	bad	best	good
Complexity	good	best	bad	better
Efficiency	better	best	better	good
NVH	better	better	good	better
Cost	good	best	bad	better

bad good better best

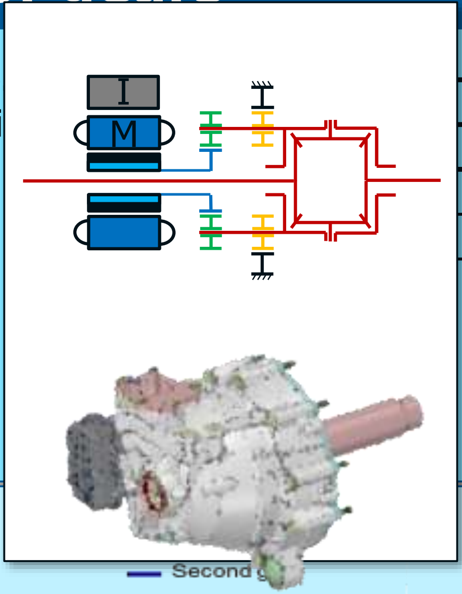
EV-Drive Transmissions
Influence of subsystem parameters

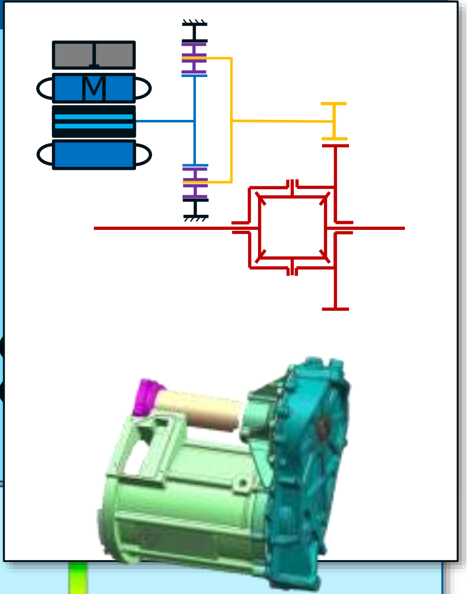
LAYSHAFT Co-Axial	LAYSHAFT Offset	PLANETARY GEAR Co-Axial	PLANETARY GEAR Offset





+ Low co
+ Low wei
0 Medium
0 Medium

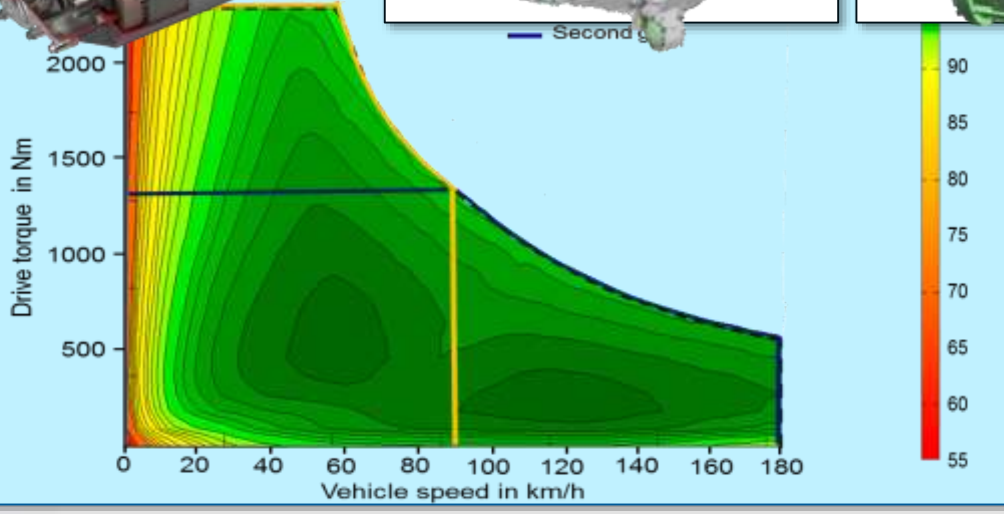




Example

E-motor for 1-Speed transmission:
- **max. torque 313 Nm**
- max. power 70 kW

E-motor for 2-speed transmission:
- **max. torque 170 Nm**
- max. power 70 kW



Challenges – Driveline & EV-Driveline

*Efficiently identify **product design parameters,** that perfectly meet **technological** and **monetary customer requirements***

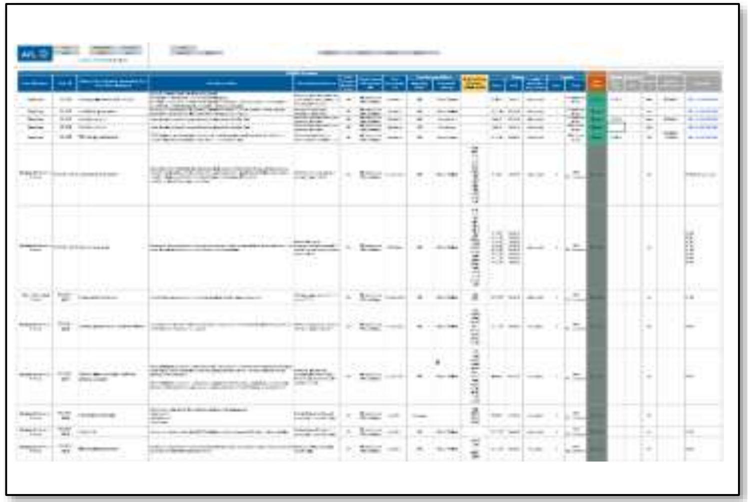
Minimize development time with maximum possible ***product maturity***

Content

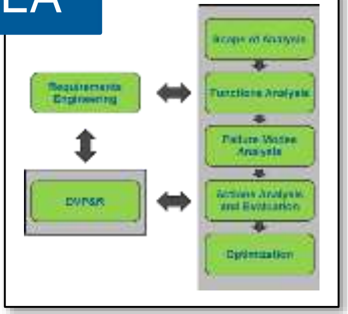
AVL Validation Methodology DVP&R

Requirements Engineering

Design Verification Plan & Report



FMEA



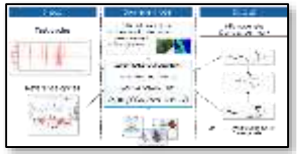
CAE

Reports

Failure mode analysis

System analysis on component level to determine failure modes and damaging operation

Damage Calculation



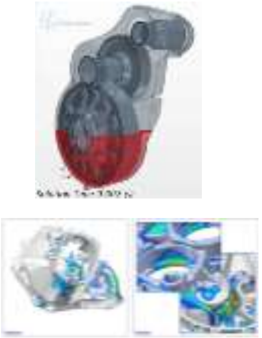
Failure mode based test program

Verification / Validation

Test specification

Testing

Simulation



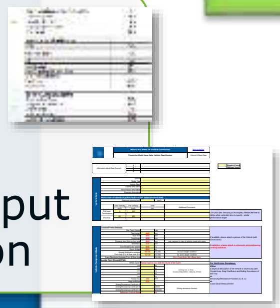
Duty Cycle Generation

Input definition

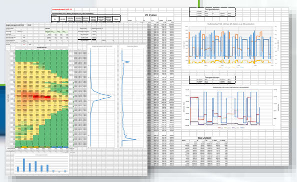
- Markets
- Lifetime targets

300.000 km

- Road profile distribution
- Vehicle simulation input data definition



- Reference customer load duty cycle

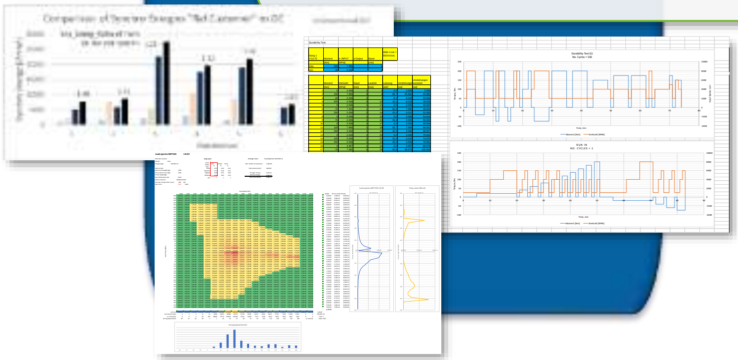


Load data generation

- Track Profile selection
- AVL CRUISE simulation
- System analysis
- Damage calculation

Duty cycle definition

- Evaluation & balancing of part specific damages
- Duty cycle definition
- Design duty cycle verification
- Test program generation



Duty Cycle Generation - WORKFLOW

REFERENCE CUSTOMER BEHAVIOR

TESTING BOUNDARIES for DC
- SYNTHETIC LOAD DATA
- SYSTEM and DYNO LIMITATIONS

LIFETIME TARGET
CONVENTIONAL DRIVING, WOT ACC., REVERSE DRIVING, …

DAMAGE CALCULATION

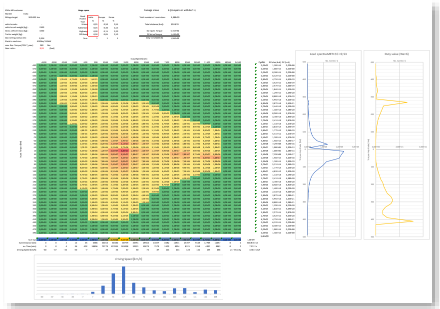
D_{REF} $\dot{D}_{DC}$

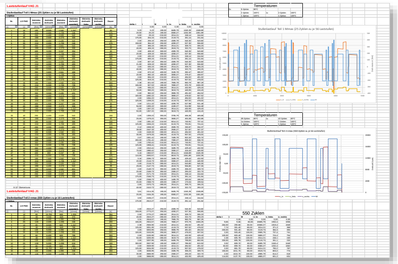
BALANCING
DETERMINATION OF TEST TIME FOR EACH DC LOAD POINT TO CAPTURE THE REFERENCE DAMAGE

$$D_{DC} = \dot{D}_{DC} \cdot t_{DC}$$

DUTY CYCLE

Abbreviation:
DC … duty cycle
D_{REF} … reference damage
D_{DC} … duty cycle damage
$\dot{D}_{DC}$ … duty cycle damage rate
t_{DC} … time to reach





- Design verification
- Testing

Duty Cycle generation
Detail Reference Customer

Customer Input:

Life time target: 300.000 km

Road Condition & % of utilisation	%
Rough City road	20%
Smooth City road	50%
Highway/ Good roads	20%
Non Paved	10%
Terrain & % of Utilisation	
Plain	70%
Ghat type Drive	10%
Hill	15%
Desert Drive	5%
Mine/Construction site Drive	0%
Drive distribution	
Day Drive	60%
Night Drive	40%
Drive pattern discription	
Steady state Drive	30%
Frequent Acceleration	40%
Clutch riding	0%
Brake application	20%
Cornering / Ghat Drive	10%

Additional – Korea Market

S.no	Item	Percentage distribution	Percentage distribution
1	City	30% (Rough city)	20% (Rough city)
2	General road (Included up and down hill curve road)	40% (Smooth city)	50% (Smooth city)
3	High way	20%	20%
4	Off road	10% (Non paved)	10% (Non paved)

Percentage split into Urban and Sub Urban

Highway directly transferred

Non Paved directly transferred in Off-Road percentage

Altitude profiles are included in some of the used track profiles

Day and night operation is not considered in simulation

AVL Usage Space Definition

Road Profile Type	India %	India Distance [km]	Europe %	Europe Distance [km]	Korea %	Korea Distance [km]
Urban	55%	165000	50%	150000	55%	165000
Sub Urban	15%	45000	30%	90000	15%	45000
Highway	20%	60000	15%	45000	20%	60000
Off-Road	10%	30000	5%	15000	10%	30000
Sum	100,0%	300000	100,0%	300000	100,0%	300000
Special Maneuvers	**Total Number**	**Distance [km]**	**Total Number**	**Distance [km]**	**Total Number**	**Distance [km]**
WOT_0-v_max kph	5000		5000		5000	
Driving - R		50		50		50
µ-Transient	500		150		750	
Hill-Start	250		250		250	

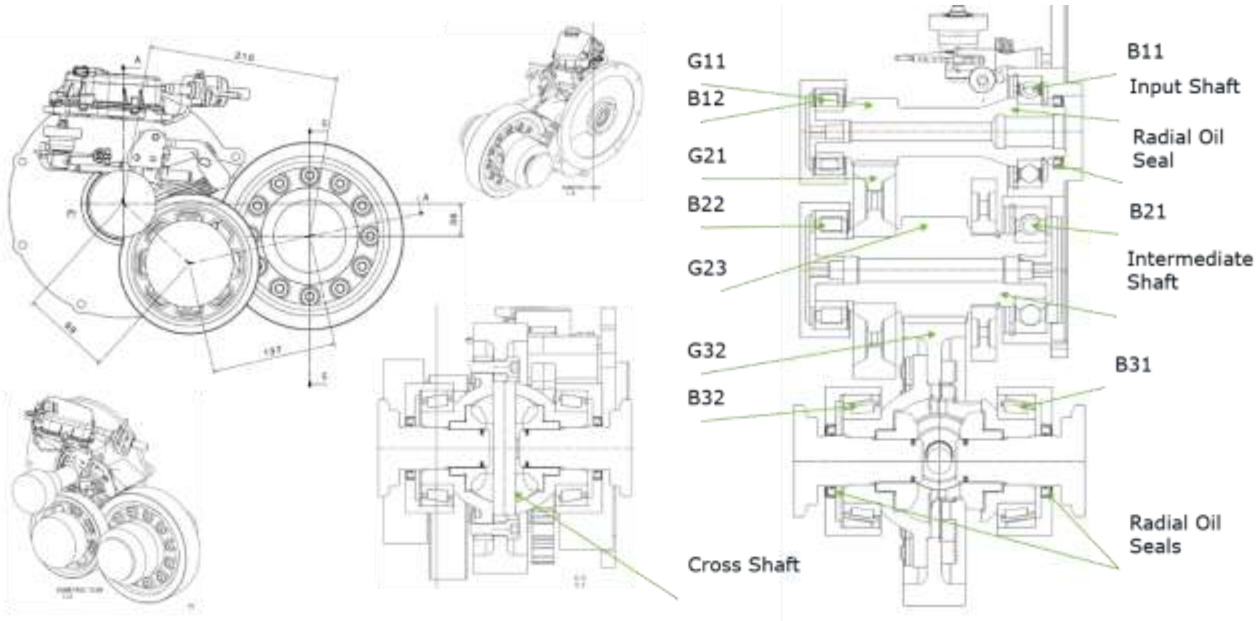
Percentage split into Urban and Sub Urban

Highway directly transferred

Non Paved directly transferred in Off-Road percentage

Duty Cycle generation
Detail Damage calculation models

System analysis



Failure mode definition

Failure Modes	
[311-1] HCF - bending input shaft S1	[412-2] Wear coast - tooth flank gear G23
[312-1] HCF coast - toot root gear G11	[412-3] HCF drive - toot rooth gear G23
[312-2] Wear coast - tooth flank gear G11	[412-4] Wear drive - tooth flank gear G23
[312-3] HCF drive - toot root gear G11	[416-1] HCF - ball bearing B21
[312-4] Wear drive - tooth flank gear G11	[416-2] Wear - ball bearing B21
[312-1] HCF - ball bearing B11	[417-1] HCF - roller bearing B22
[312-2] Wear - ball bearing B11	[417-2] Wear - roller bearing B22
[313-1] HCF - roller bearing B12	[681-1] HCF coast - toot rooth gear G32
[313-2] Wear - roller bearing B12	[681-2] Wear coast - tooth flank gear G32
[411-0] HCF - bending intermed shaft S2	[681-3] HCF drive - toot rooth gear G32
[411-1] HCF coast - toot rooth gear G21	[681-4] Wear drive - tooth flank gear G32
[411-2] Wear coast - tooth flank gear G21	[682-1] HCF - roller bearing B31
[411-3] HCF drive - toot rooth gear G21	[682-2] Wear - roller bearing B31
[411-4] Wear drive - tooth flank gear G21	[683-1] HCF - roller bearing B32
[412-1] HCF coast - toot rooth gear G23	[683-2] Wear - roller bearing B32

Example: Failure mode activation methodology

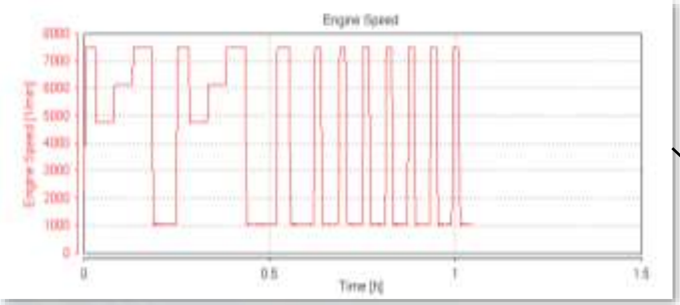
SUBSYSTEM	FAILURE MODE	FAILURE LOCATION	CAUSE OF FAILURE	EFFECT ON SYSTEM	ACTIVATION
Input Shaft / Gear in	Wear (fracture fatigue)	Tooth flank	Mech. load (poor lubrication, pitting)	NVH → Damage of transmission	High load operation

DVP Input - Damage Calculation

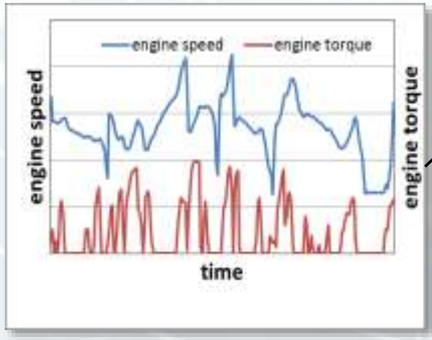
Input	Damage model	Output

Input

Test cycles



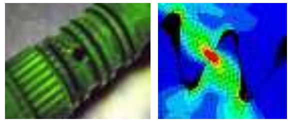
Reference cycles



Damage model

Model calibration

- "Real world" damage measurement
- Simulations



LOAD TRANSFER FUNCTION:

$$Contact\ Stress = f\,(Torque_{EM})$$

DAMAGE CALCULATION

$$D_i = f\,(Contact\ Stress)$$

Output

$\dot{D}$ Damage rate
(Damage per hour)

$$\dot{D}_{Test} = \frac{1}{t_{Test}} \sum D_i$$

$$AF = \frac{\dot{D}_{Test}}{\dot{D}_{Ref}}$$

$$\dot{D}_{Ref} = \frac{1}{t_{Ref}} \sum D_i$$

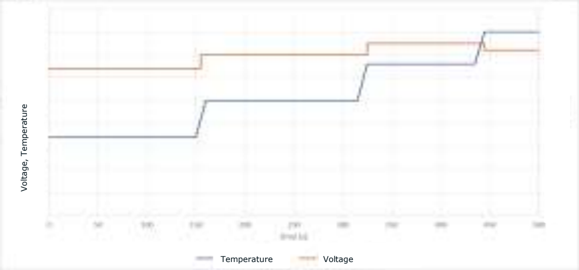
AF ... Acceleration factor
$\dot{D}$ ... Damage rate

Online Target Monitoring

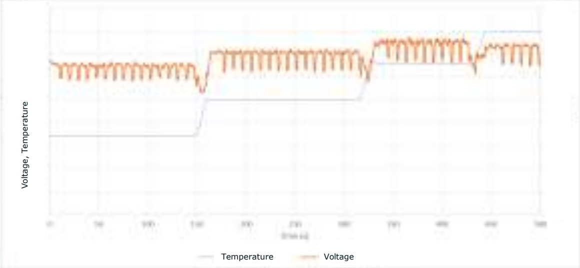
Test procedure / measured test cycle vs. reference

Input

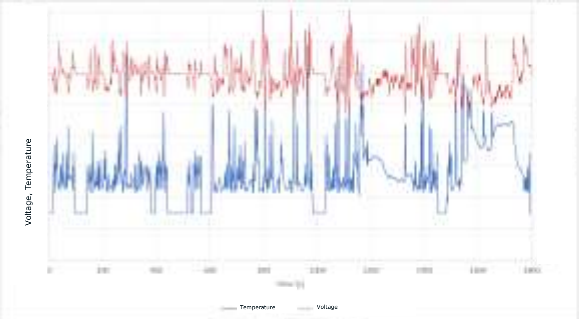
Test procedure



Test cycle on test bed



Reference cycles



Damage model

Model calibration

- “Real world” damage measurement
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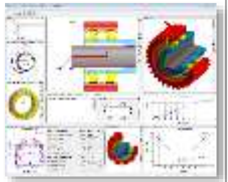


MATHEMATICAL EXPRESSION

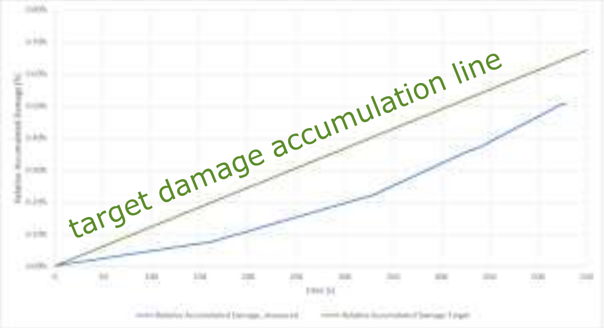
$$D_i = f\left(U_i, M_i, T_{amb_i}, \dots\right)$$

Online comparison of damage from reference (target damage) to test cycles

Output

Rel. accumulated Damage

test cycle does not reach the validation target, test cycle has to be modified

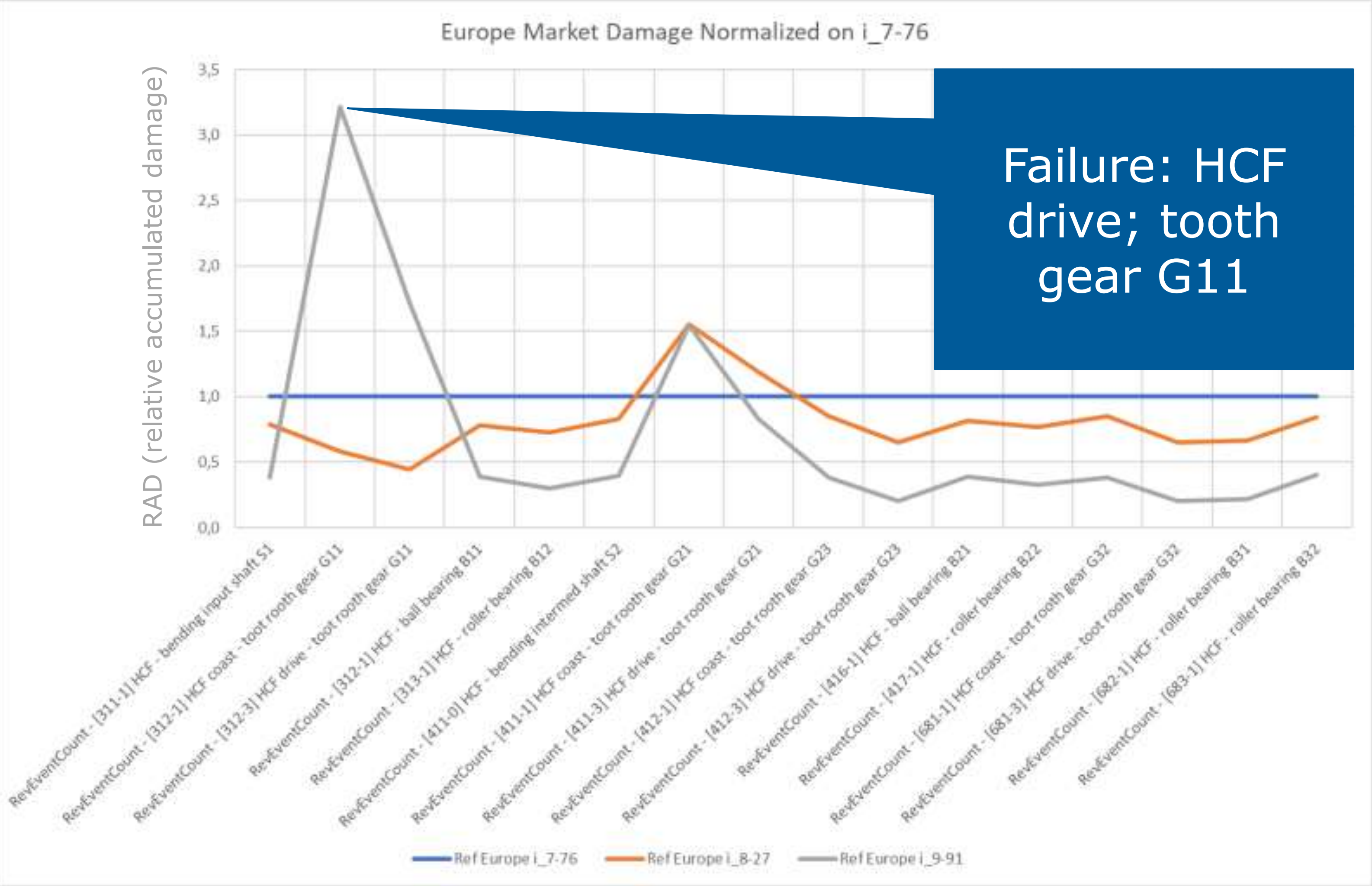


test cycle modification

test cycle reaches the validation target

target reached!

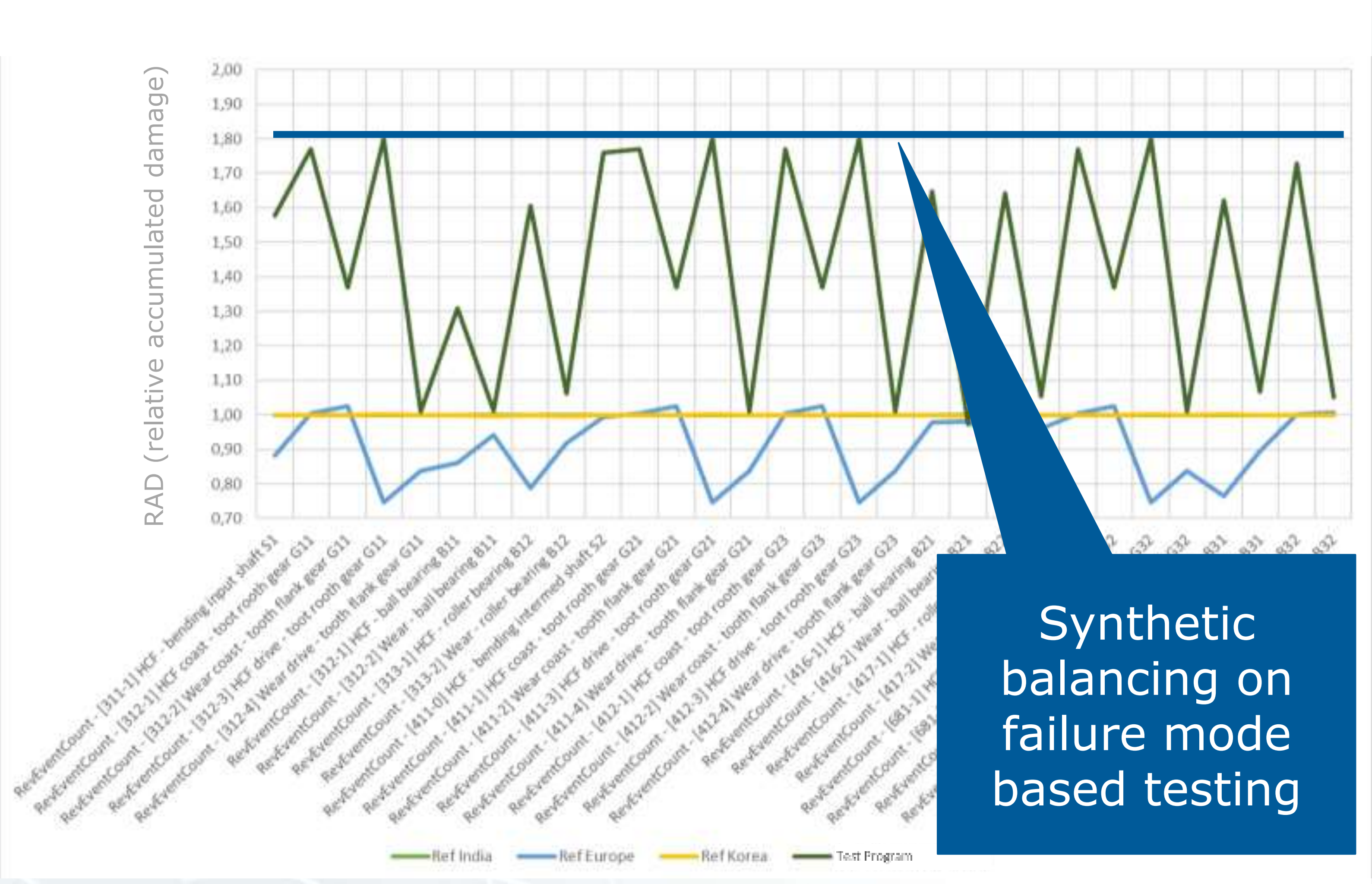
Result – Comparison Normalized damage



The lowest ratio is most demanding for the design. Excepting damage modes are:

- Ratio 9,91 HCF tooth root G11 drive/coast
- Ratio 9,3 HCF coast tooth root G21
- Ratio 8,27 HCF tooth root gear G21 drive/coast.

Result – Test Program
Damage normalized on market



The comparison is based on the calculated damage

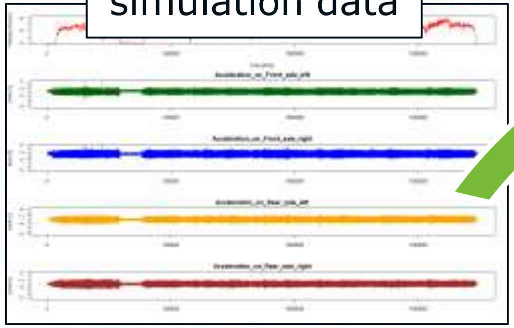
LP	Time	Input Speed	Input Torque	Power
	[h]	[rpm]	[Nm]	[kW]
LP1	90	12500	110	144
LP2	55	5500	-250	-144
LP3	14	3500	400	146,6
LP4	5	15000	50	78,5
LP5	120	5500	150	86,4
LP6	30	9500	-150	-149,2
LP7	390	9500	150	149,2
LP8	10	-1500	-270	42,4
Test Time:	714	h		

Test Program balancing was carried out respecting the following boundary conditions:

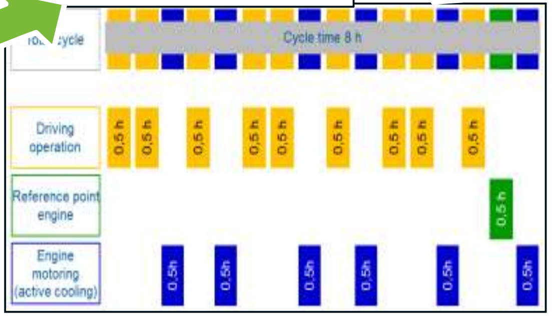
- Max. RAD < 1,85
- Min. RAD < 0,85

Correlation between RIG Testing, DVP&R and FMEA

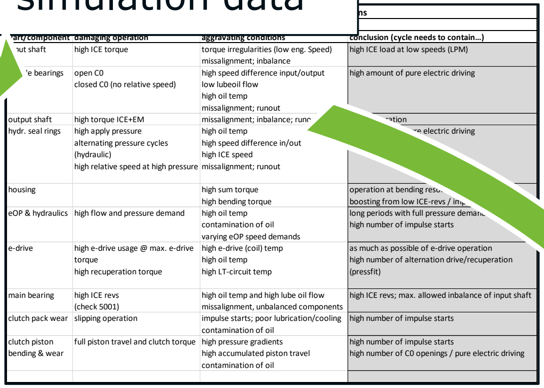
1. Collection of simulation data

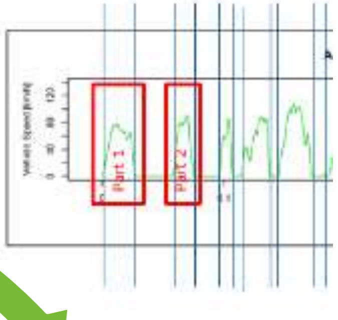


2. Definition of test cycle structure *)



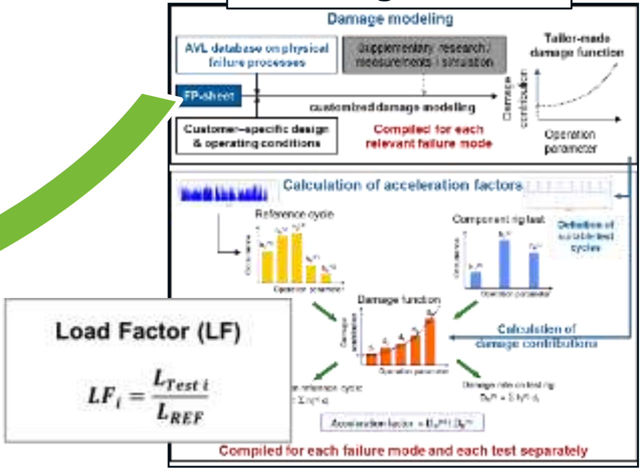
3. Segmentation of simulation data



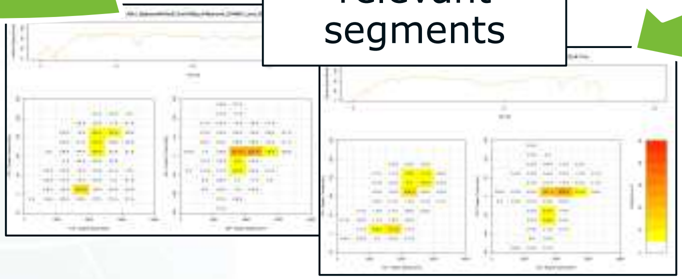


4. Load analysis

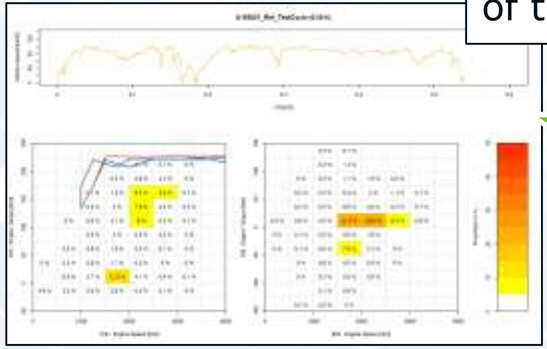
Characterization of segments



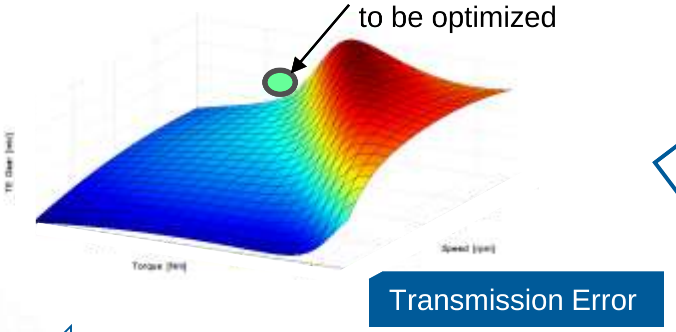
5. Selection of relevant segments

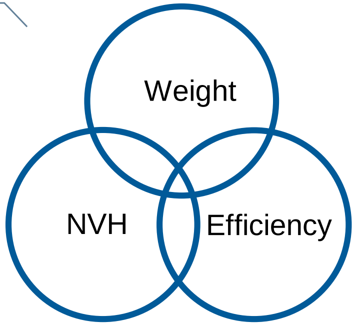


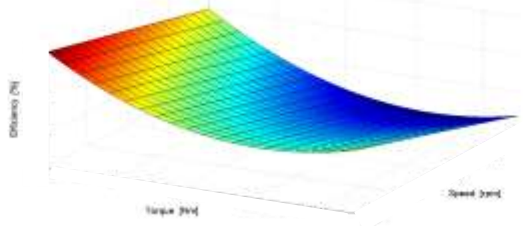
6. Assembly of test cycle



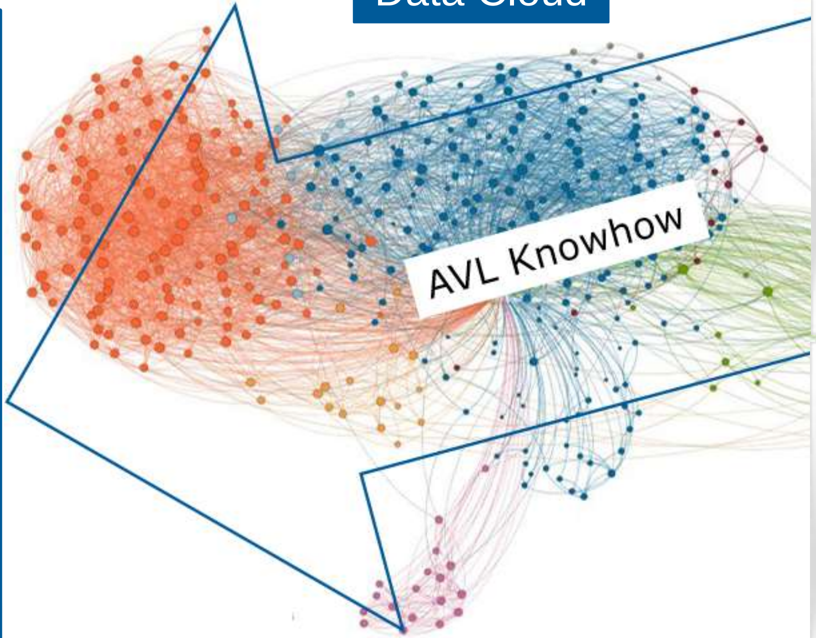
Transmission - Variation of subsystem parameters (DoE)

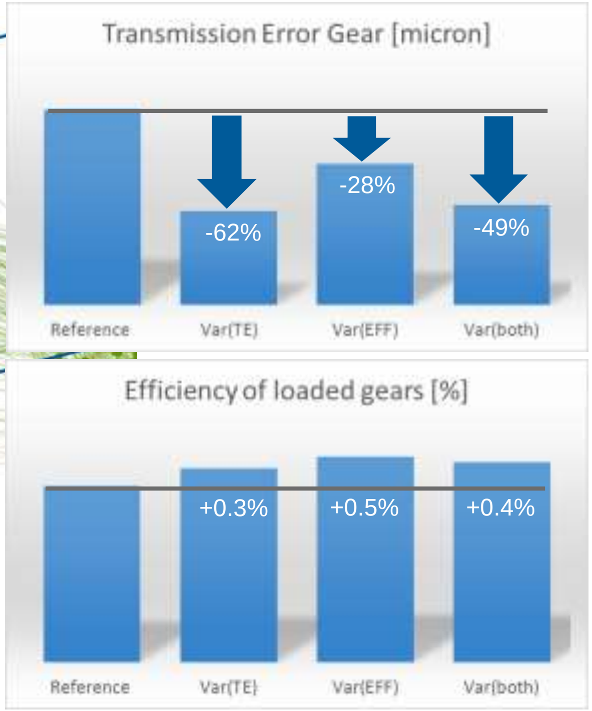






Data Cloud





AVL CAMEO

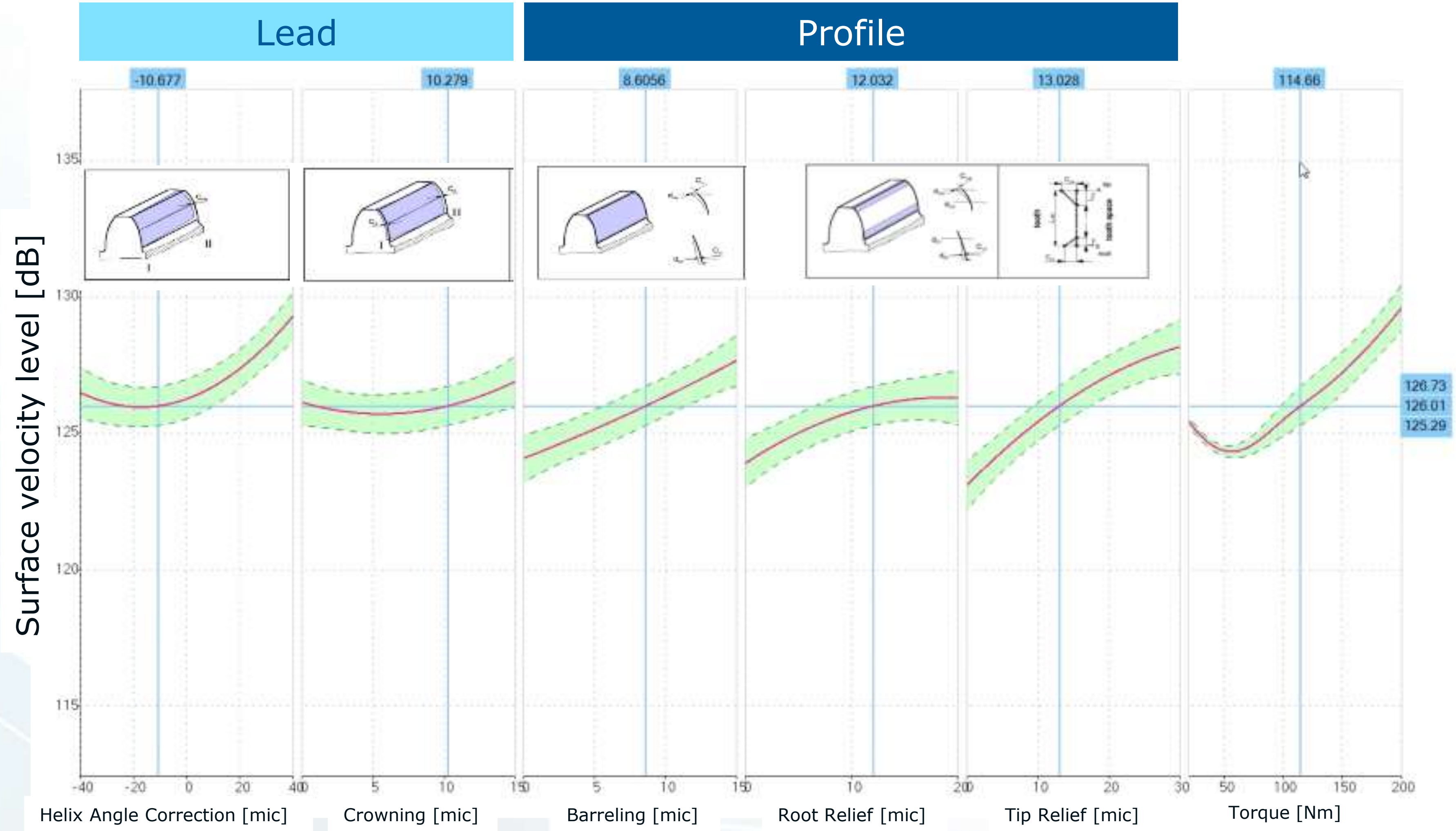
CAMEO- Optimization:

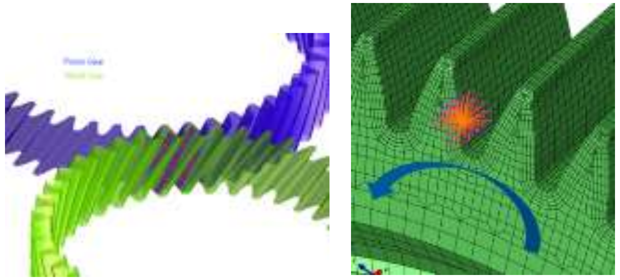
- Optimization is done by an evolutionary algorithm
- Single correlations between the parameters can be shown
- Optimized micro geometry parameters regarding Transmission Error can be estimated for specific operating points.

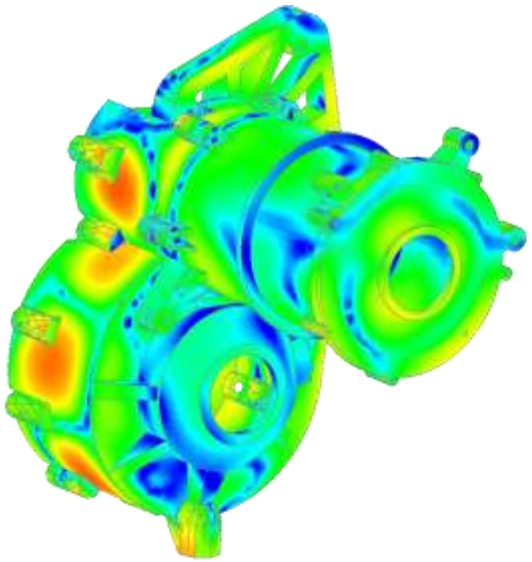
Driveline NVH-Performance
Variation of subsystem parameters (DoE)

MECHANICAL NOISE

Influence of **micro geometry parameters** on **surface vibrations**



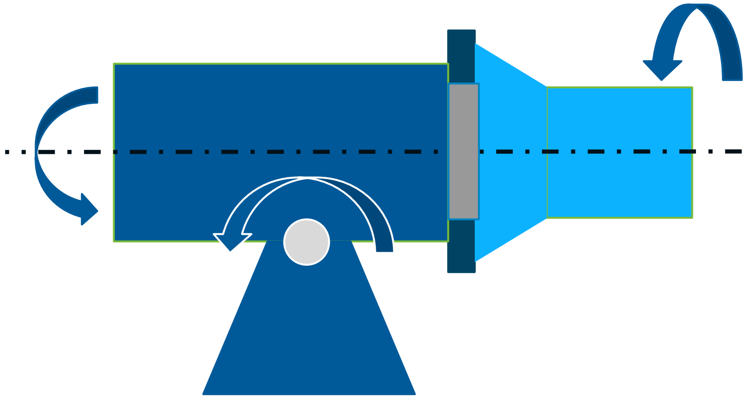




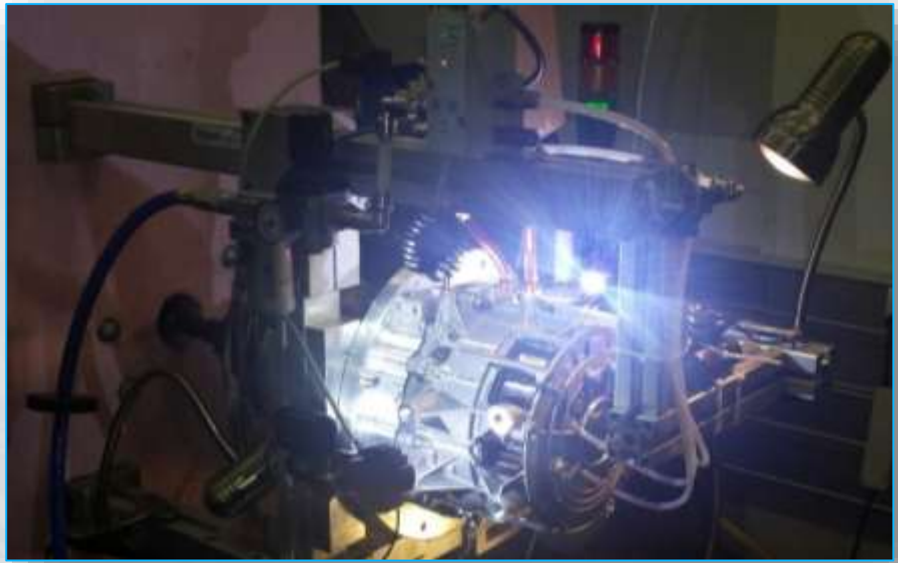
Content

Tilt Test Bed - ONE dyno configuration

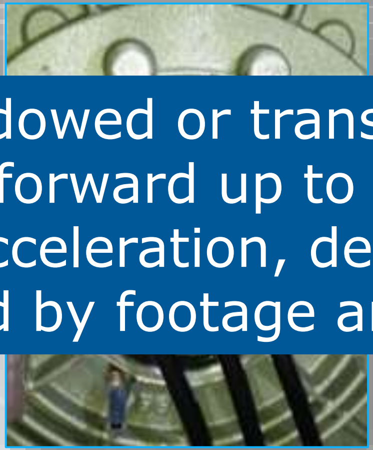
	1 Dyno (Tilt rig)
Power	41,5 kW
Rotational Speed	12.000 rpm
Torque	100 Nm
Max. tilting speed	30 °/s
Max. tilting position	60 °
Additional facts	• Climatic chamber with temperature range -72 to +180 °C • 8-Channel high resolution camera system

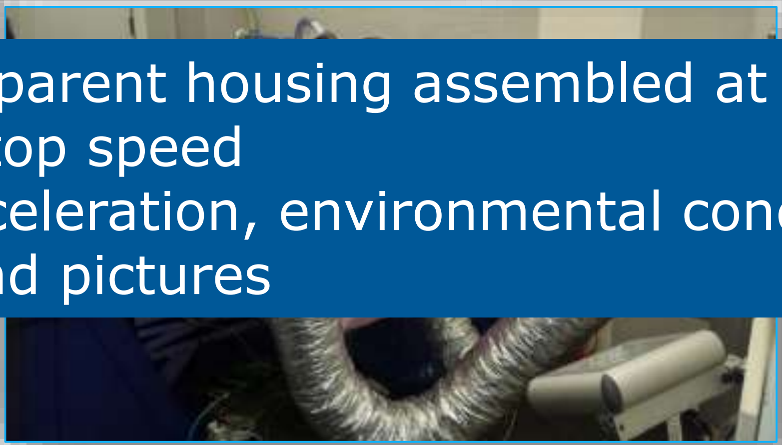


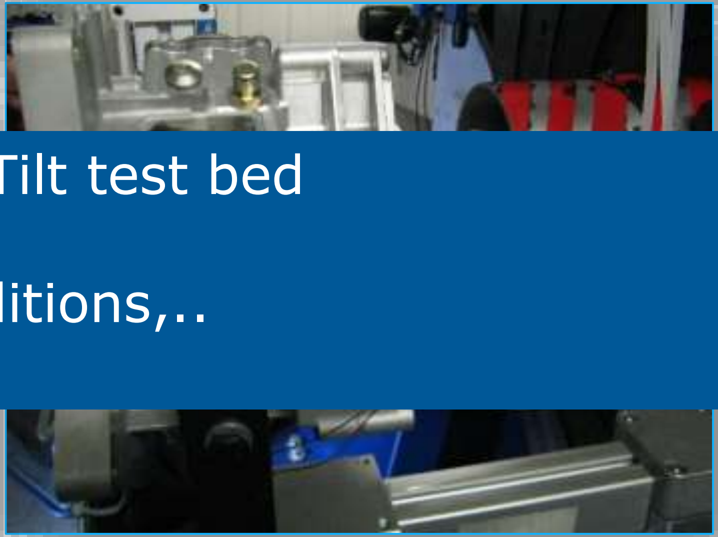
Tilt test bed - Test assembly



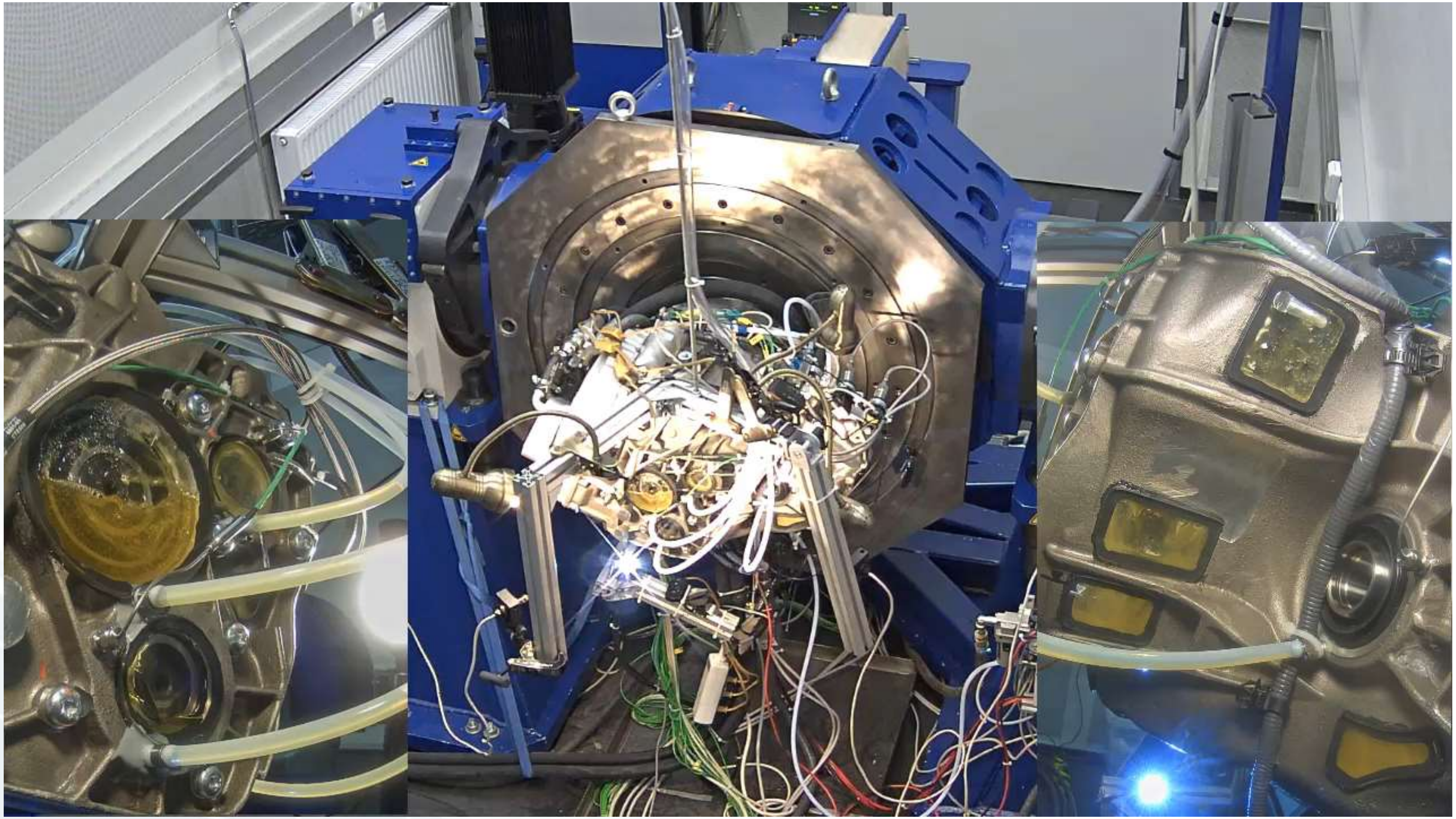
- Transmission – Windowed or transparent housing assembled at Tilt test bed
- Driven reverse and forward up to top speed
- Tilted to simulate acceleration, deceleration, environmental conditions,..
- Oil flow documented by footage and pictures



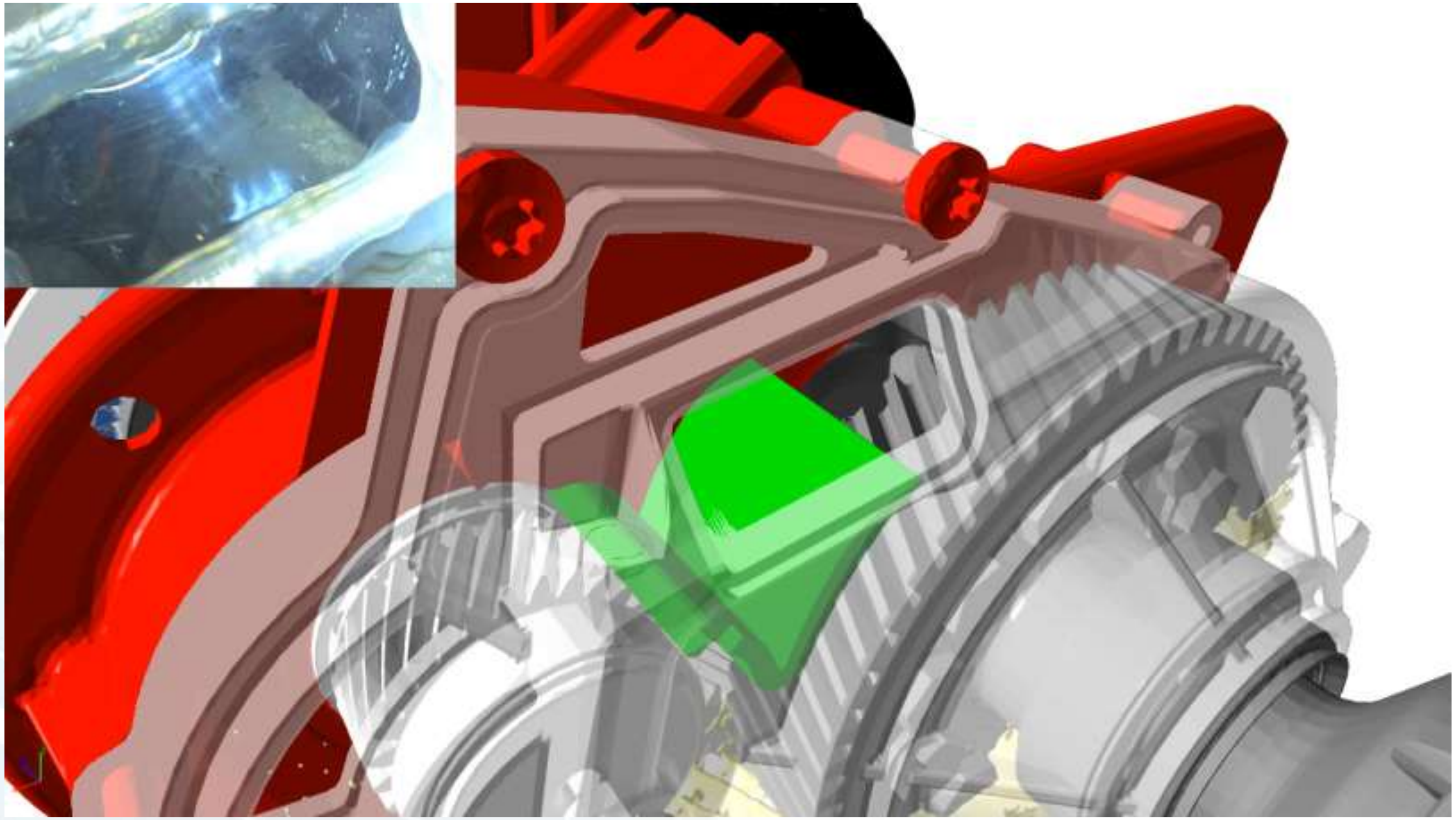


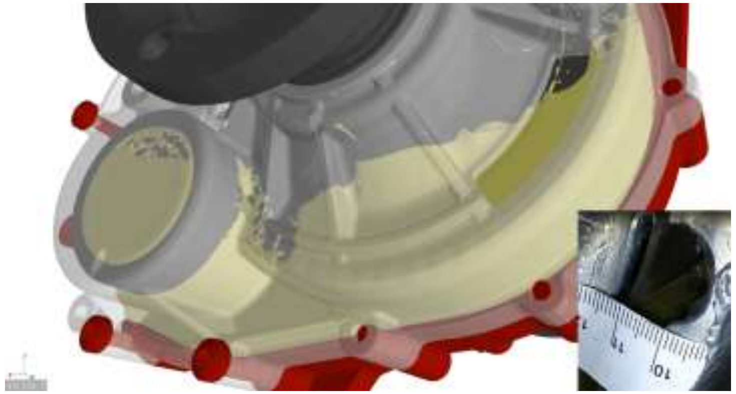


Tilt test bed - Action



Virtualization of Testing

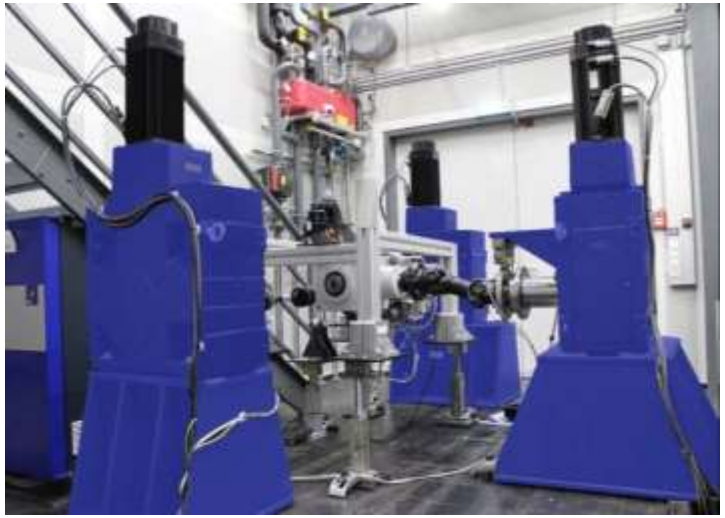




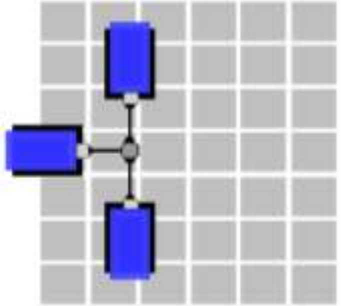
Drive Testbeds

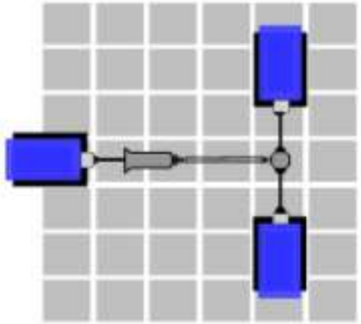
Three dyno High Load configuration

	3 Independent Dynos
Power	13,2 kW
Gear Ratio	1:320
Rotational Speed	11 rpm
Torque	10.000 Nm
Additional facts	• Flexible installation of intermediate reduction transmissions



Test of a differential gear / e-axle, transversal engine installation

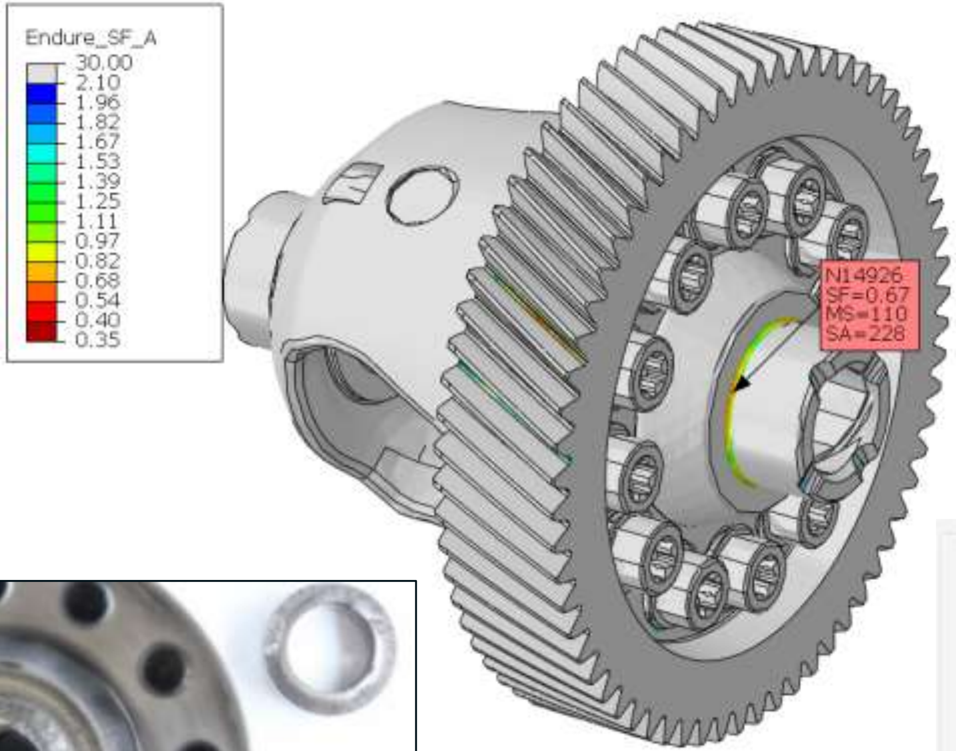




Test of a powertrain Rear drive, longitudinal engine installation

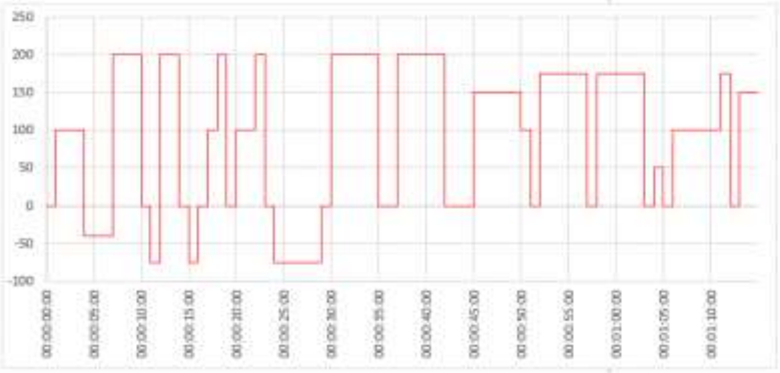
Specialized Rig Approach – Single failure activation → Fatigue (HCF)

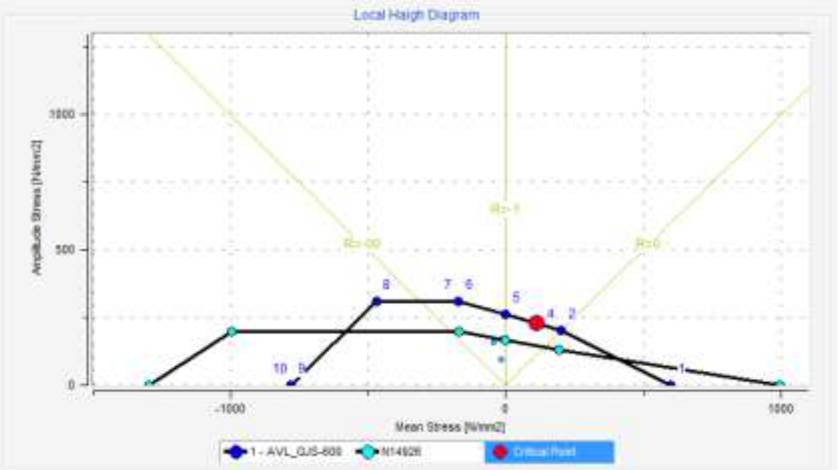
HCF - Simulation



Damage - Calculation

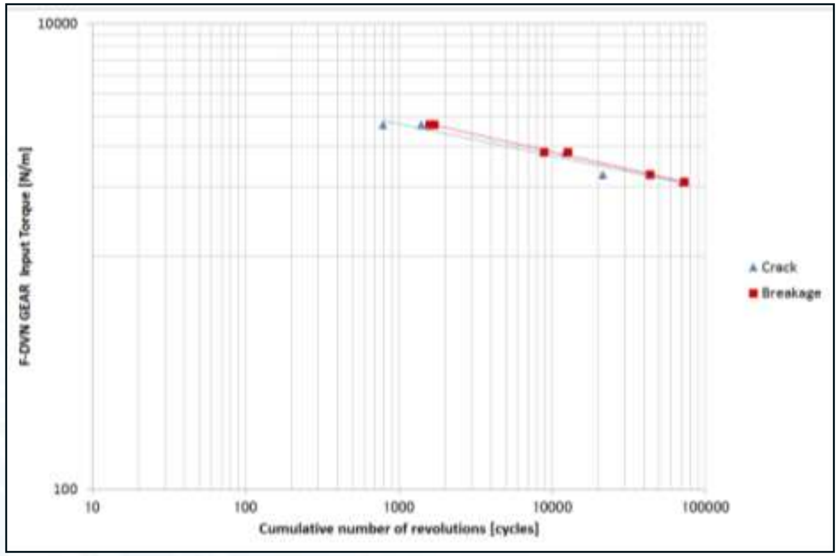
Duty Cycle First Gear from 3b		
Time	eM Speed	eM Trq
Hrs	RPM	Nm
200,44	10.000	-75
190,29	12.000	-50
270,29	12.500	-25
430,82	12.500	-
438,79	12.500	25
391,40	12.000	50
254,30	10.000	75
181,95	8.000	100
83,30	6.750	125
42,52	5.500	150
11,43	4.500	175
5,05	4.000	200

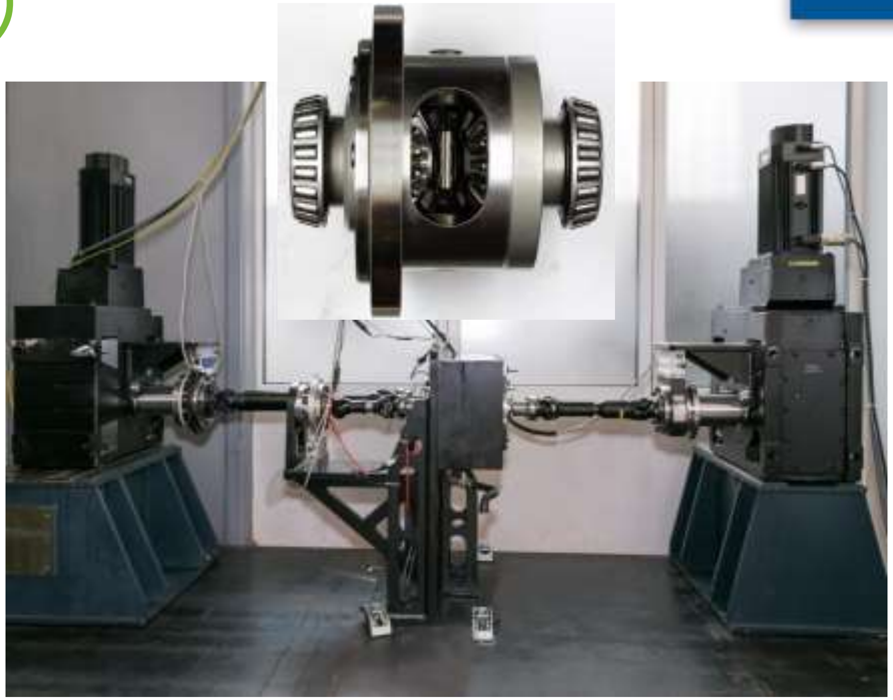


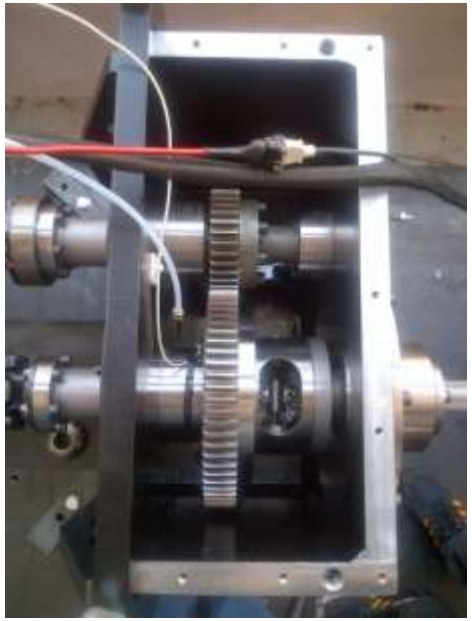


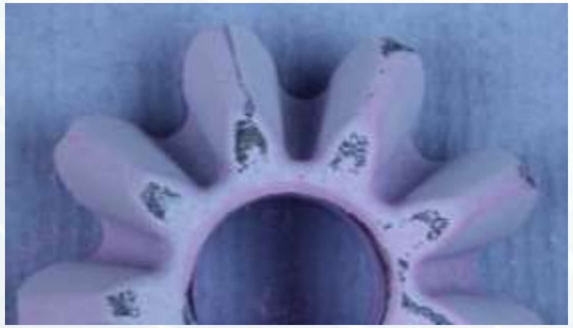
Node		# 14926
torque	cycles	-
Overrolling_driving	-	-
-75	8163265	8.16E-24
-50	9306122	9.31E-24
50	19151020	1.92E-23
75	10367347	1.04E-23
100	5910204	0.08535103
125	2295000	0.24655415
150	954531	0.25316739
175	209939	0.11160441
200	82449	0.07831666
Total sum	-	0.85

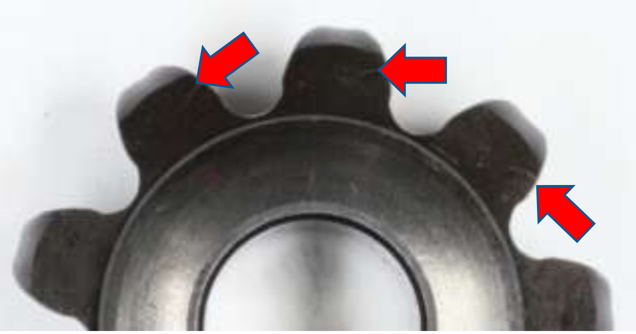
Specialized Rig Approach – Single failure activation → Fatigue (HCF)



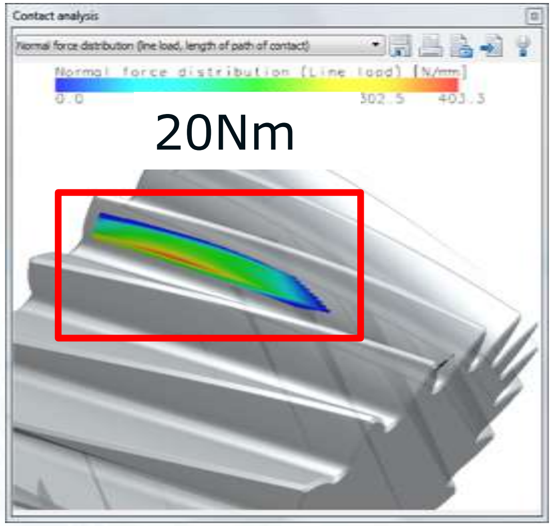




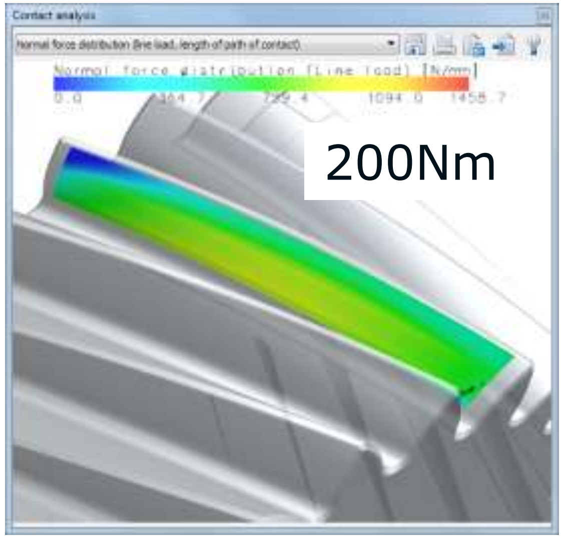




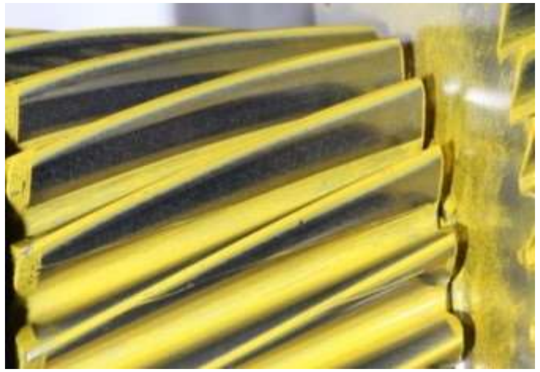
Specialized Rig Approach – Single failure activation → Tooth contact

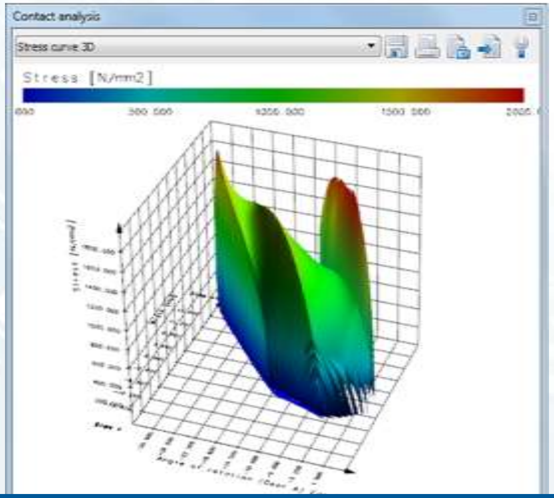


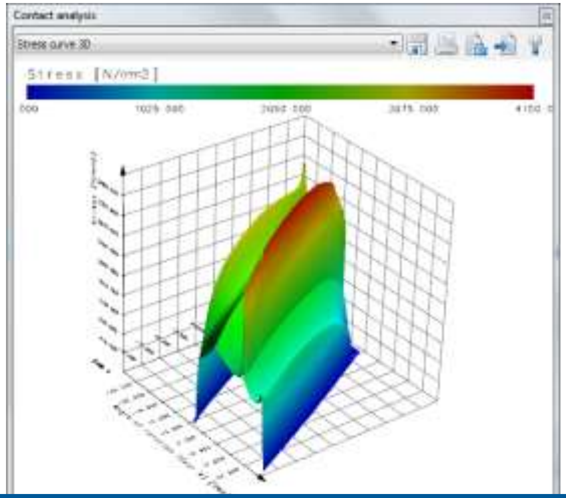
20Nm



200Nm

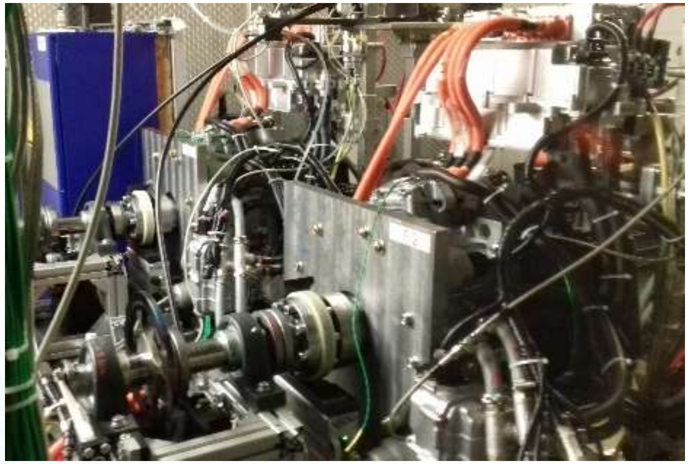


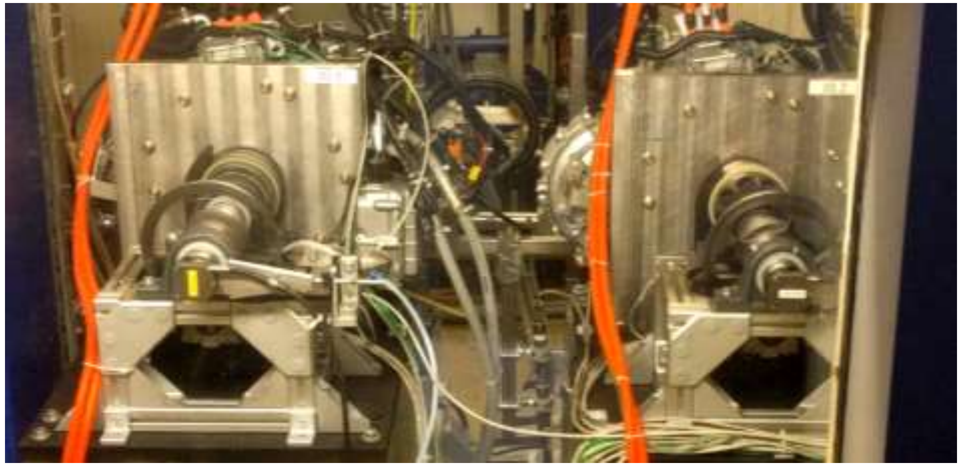


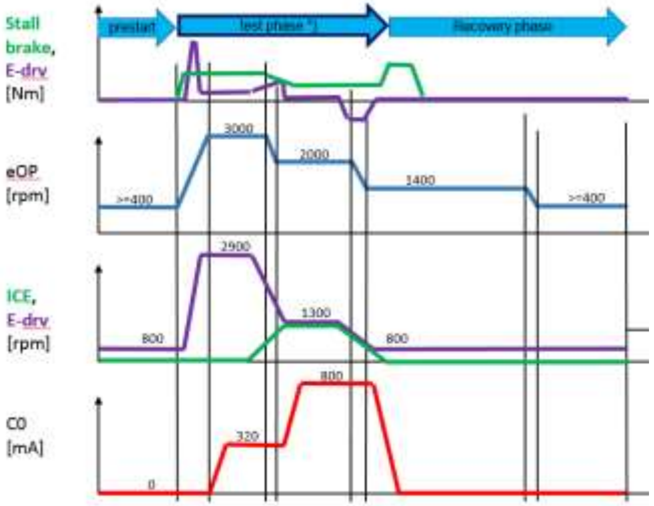


Similar contact pattern can be observed between simulation and testing

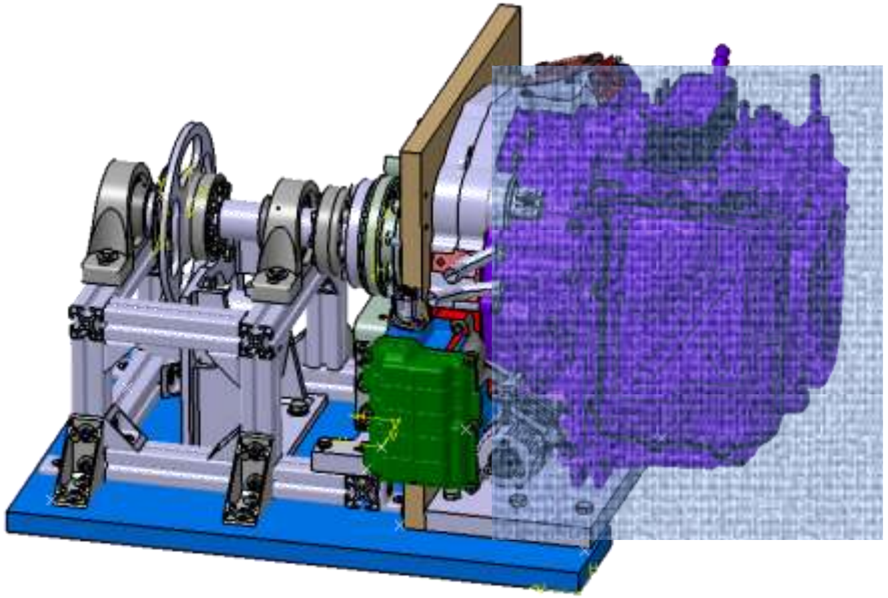
Specialized Rig Approach – Single failure activation →Lifetime hybrid P2 module





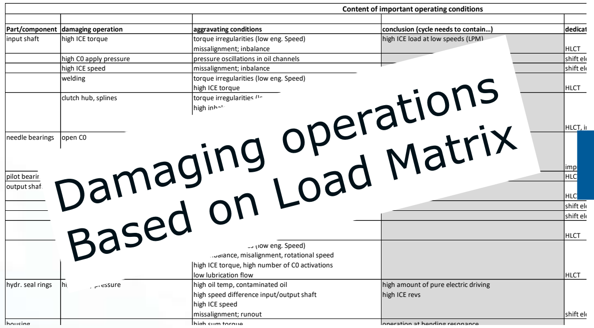


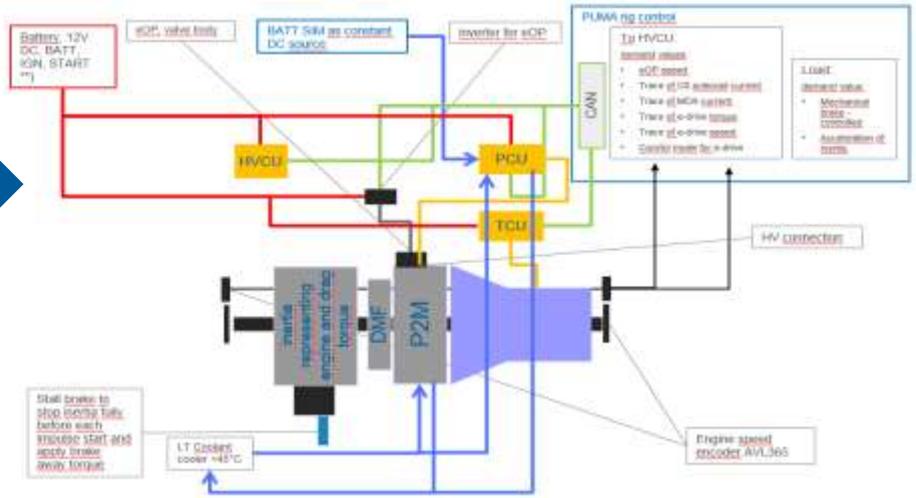
Testing Target:
Prove of C0 clutch component life time
Execution:
Run 450 000 impulse starts on component rig

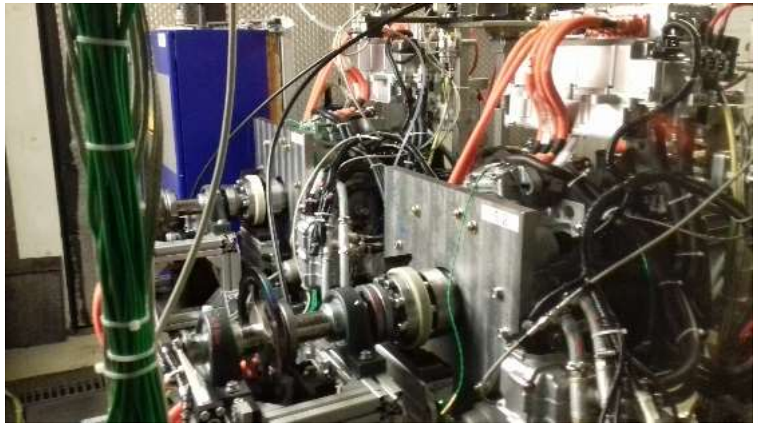


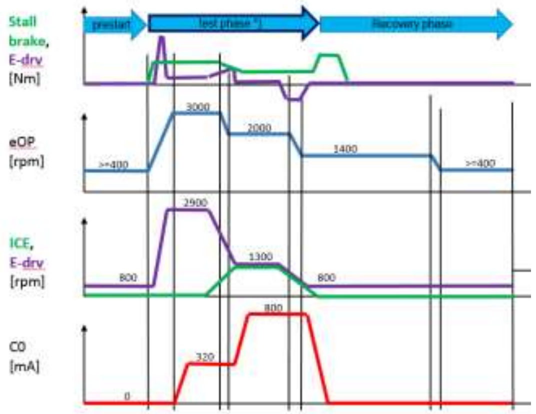
Public

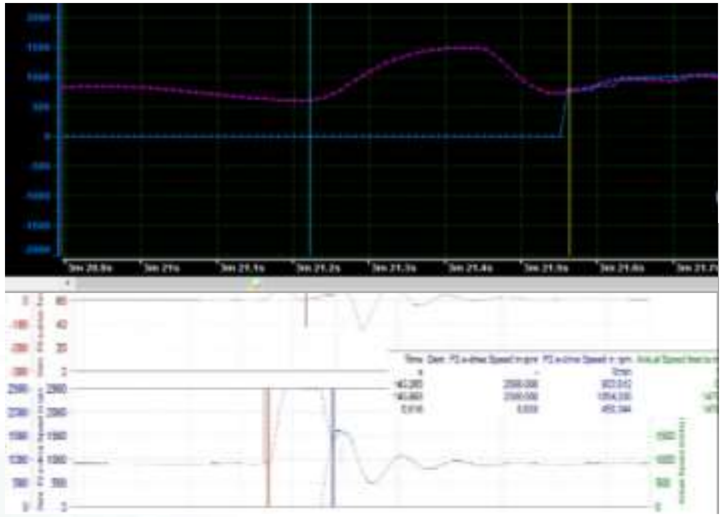
Specialized Rig Approach – Single failure activation →Lifetime hybrid P2 module



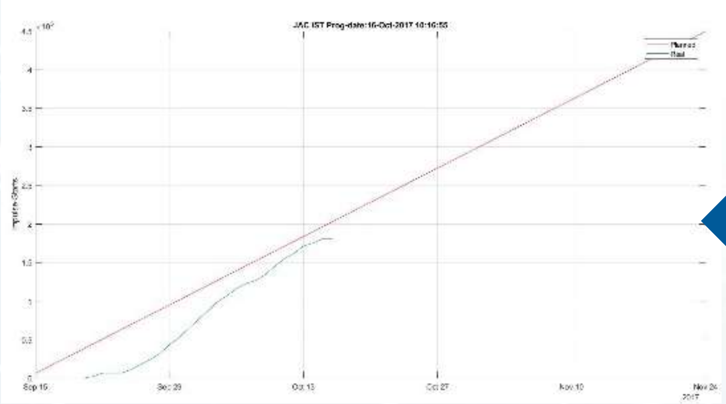








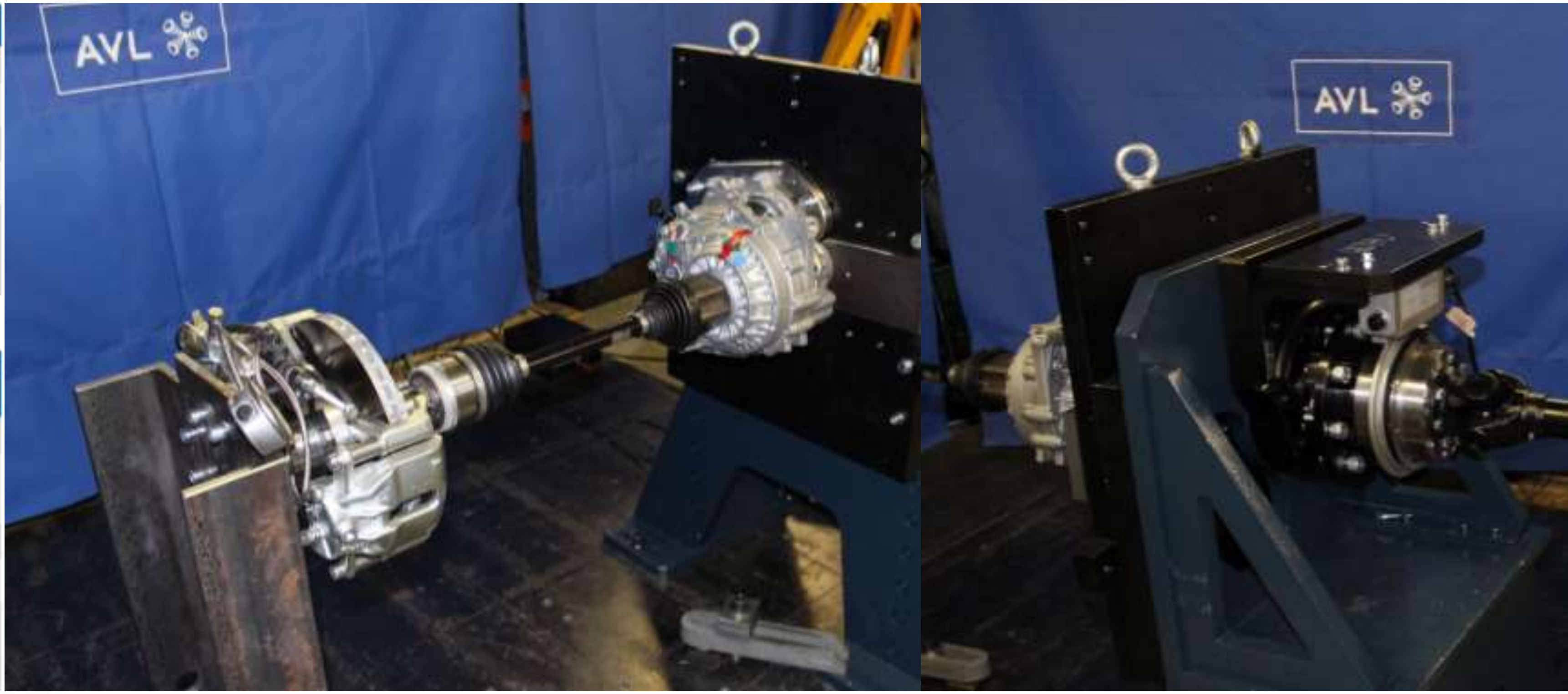
Status:
Online damage calculation from test bed data



Specialized Rig Approach – Single failure activation →Tooth contact, abuse

	3 Independent Dynos
Power	13,2 kW
Gear Ratio	1:320
Rotational Speed	11 rpm
Torque	10.000 Nm
Additional facts	• Flexible installation of intermediate reduction transmissions

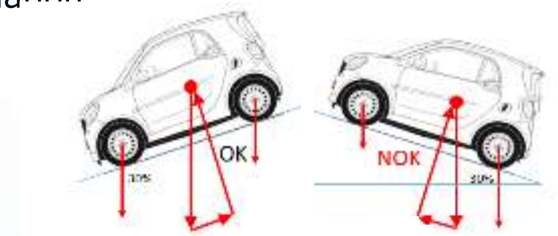
	1 x Dyno Prime	2 x Dyno Train
Power	370 kW	220 kW
Rotational Speed	10.000 rpm (max. 20.000 rpm*)	3.000 rpm
Torque	650 Nm	3.250 Nm
Overload torque	820 Nm	4.850 Nm
Additional facts	• HV-Emulator up to 320kW • *with step up transmission	



According to load profiles multi configuration setup

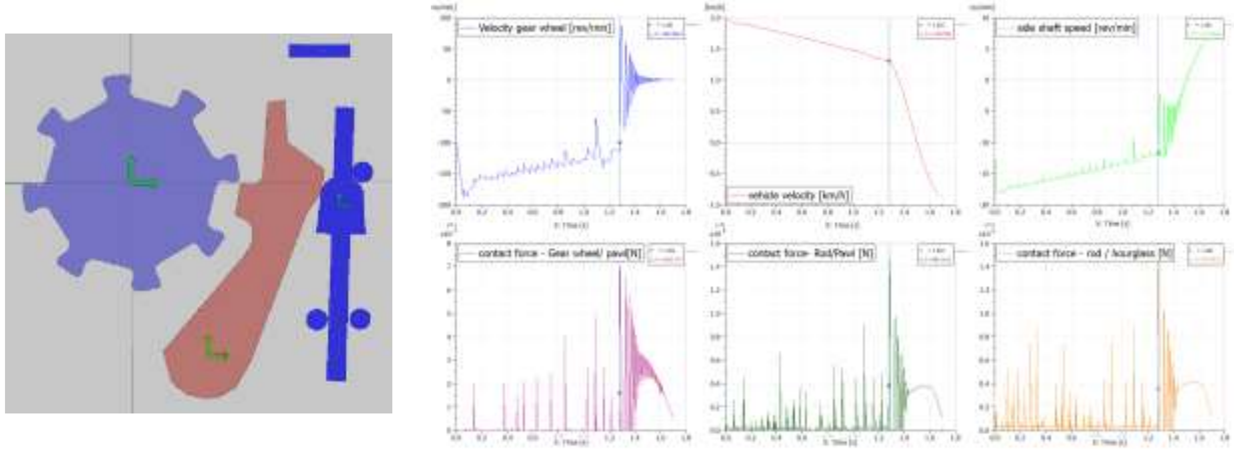
Validation & Verification
Seamless integration Testing & Simulation

- Retching of park lock system of BEV in slope situation

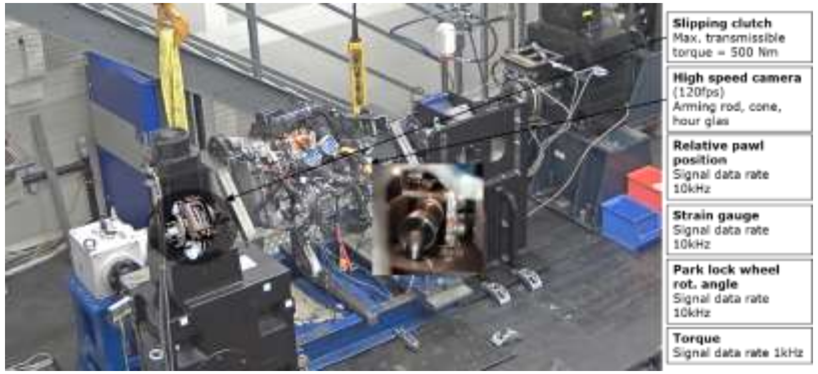


- Short reaction time by combine of simulation and testing strength
- Simulation input for testbed setup and test strategy → Test specification (speeds, loads)
  - Frontloading approach
  - Validation and tune of simulation by test results
  - Information gained without real HW
  - Fast results & variants conducted in virtual world
  - Maturity level checked virtual before HW

Simulation



Testing

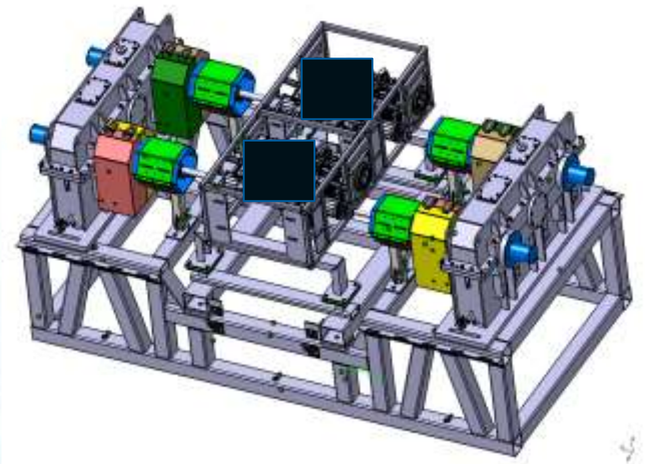


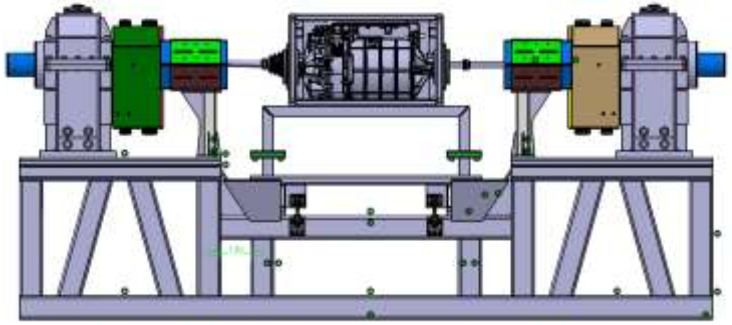
VDA – Overview Back to back testing

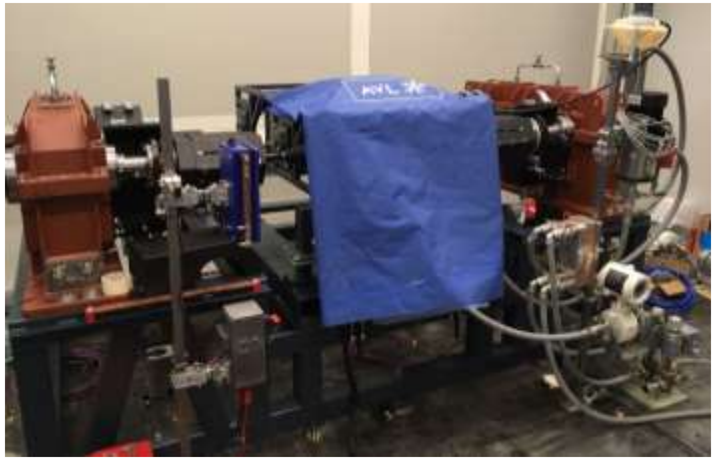
- Use of UuT´s
  - Customized gearboxes wheel side
  - Inverter and cables from customer
  - Condition monitoring system (additional from STD I, A, Ohm, mm/sec)
- Powerful coolant devices
  - Air: -40°C – 160°C
  - Coolant: -35°C – 120°C
- Small Footprint (1,8m x 1,5m x 1,5m)
- Scalable system , multi stage

  (room size 5m x 3m)

Back to back – Customer Application

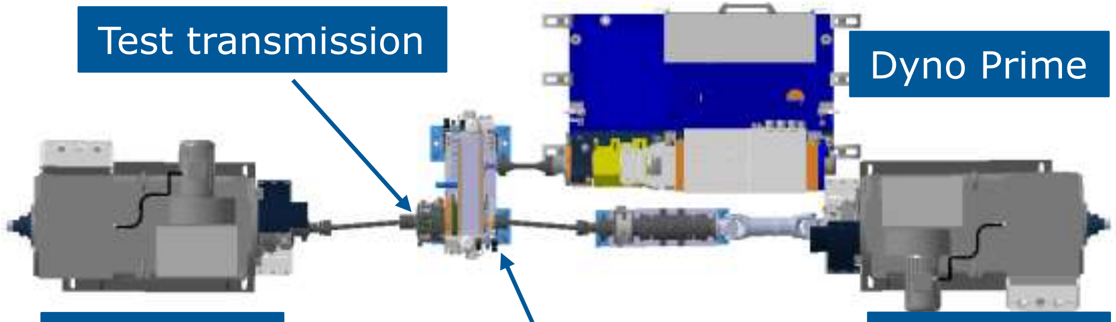


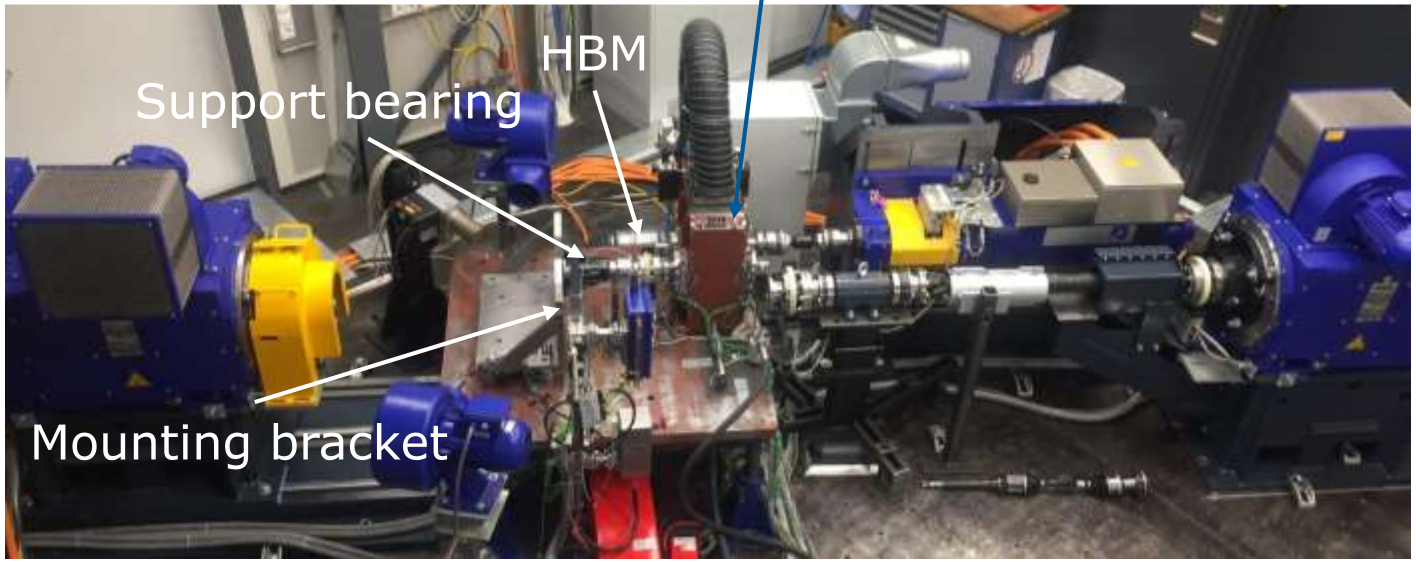




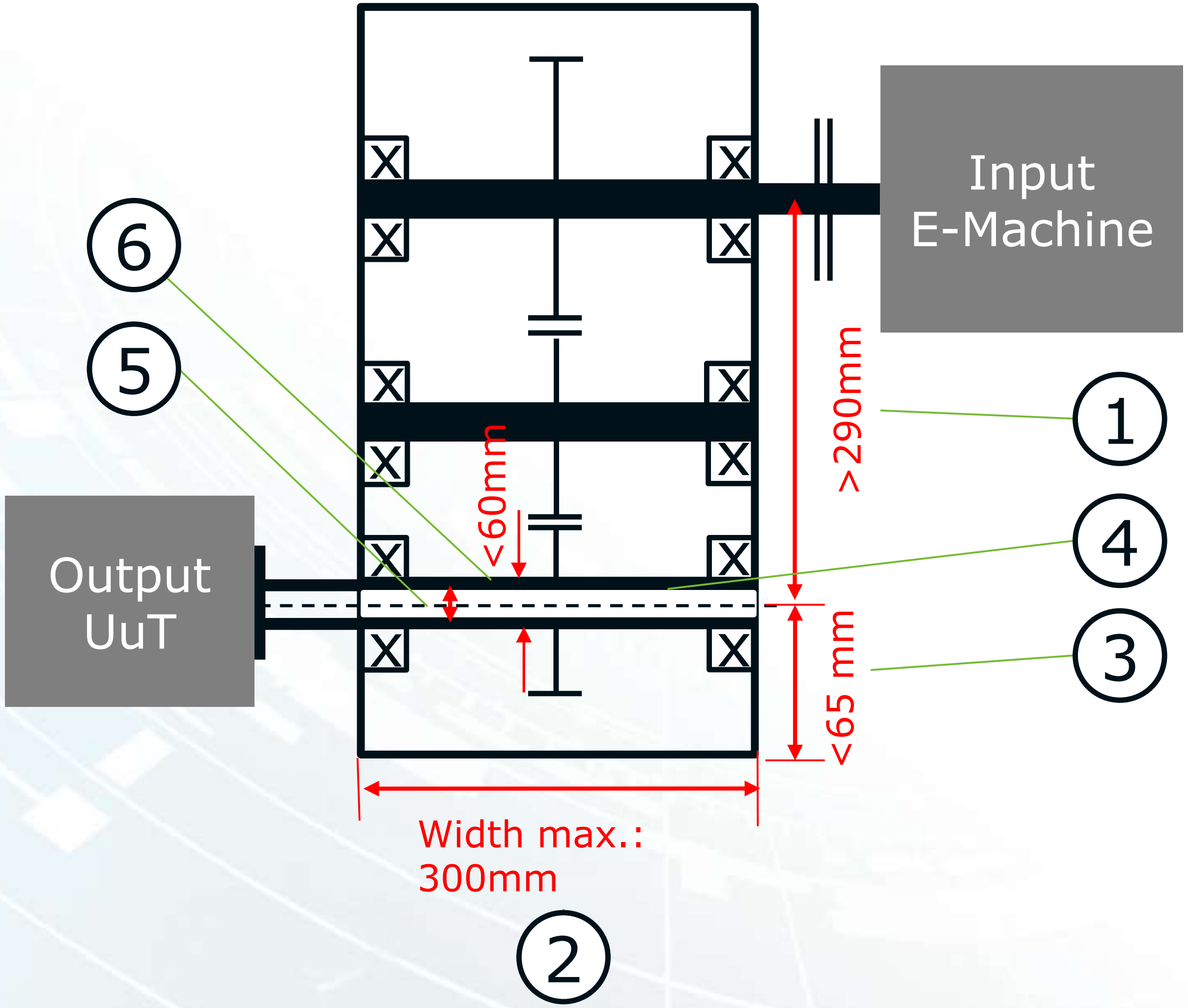
3M Test bench E-Motor use cases – Transmission approach

	1 x Dyno Prime	2 x Dyno Train
Power	400 kW	220 kW
Rotational Speed	20.000 rpm	3.000 rpm
Torque	700 Nm @ 2.650rpm*	4.850 Nm
Additional facts	• HV-Emulator up to 500kW • Test bed transmission speed up (ratio *2,1 and 3,6 available)	



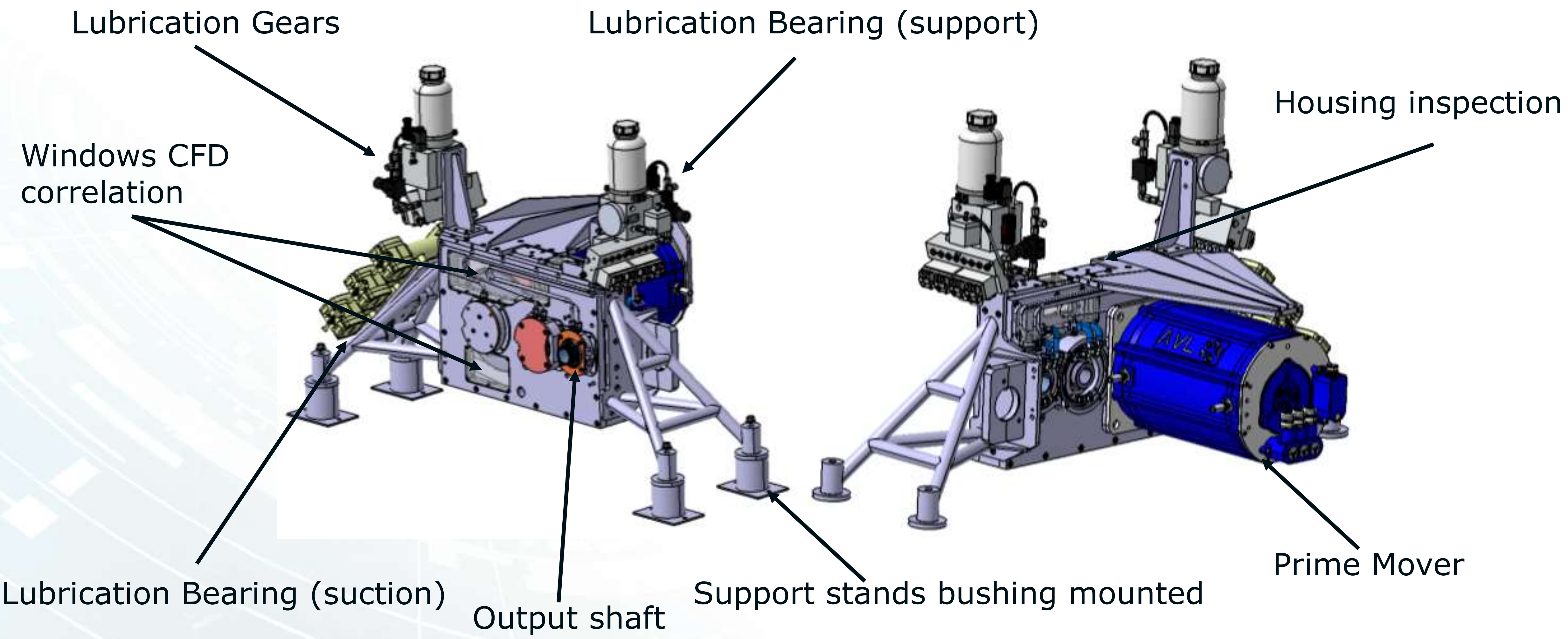


Schematic Structure and Specification high speed transmission

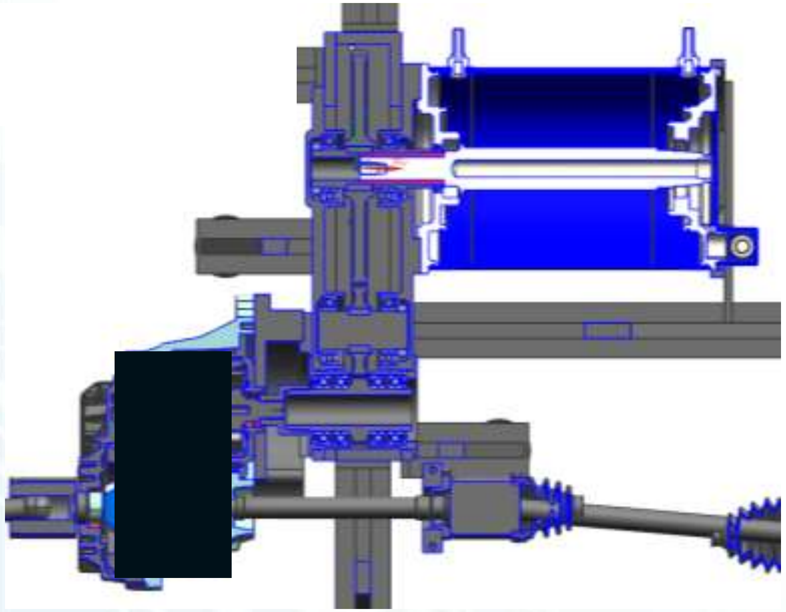


POS	Specification	Limits/Targets	Additional information
	Design	2 stage gear box	
	Input speed	10000[rpm]	
	Output speed	20.000 & 35.000[rpm]	
1	Center distance (input shaft - output shaft)	>290[mm]	
2	Width of gearbox housing	<300mm	As slim as possible
4	Output shaft	Hollow shaft	Coaxial and axially parallel operation possible
5	Inner diameter output shaft	40mm	
6	Outer diameter output shaft	<60mm	Directly influences limits of possible speed
3	Distance center output shaft – gearbox housing	<65[mm]	

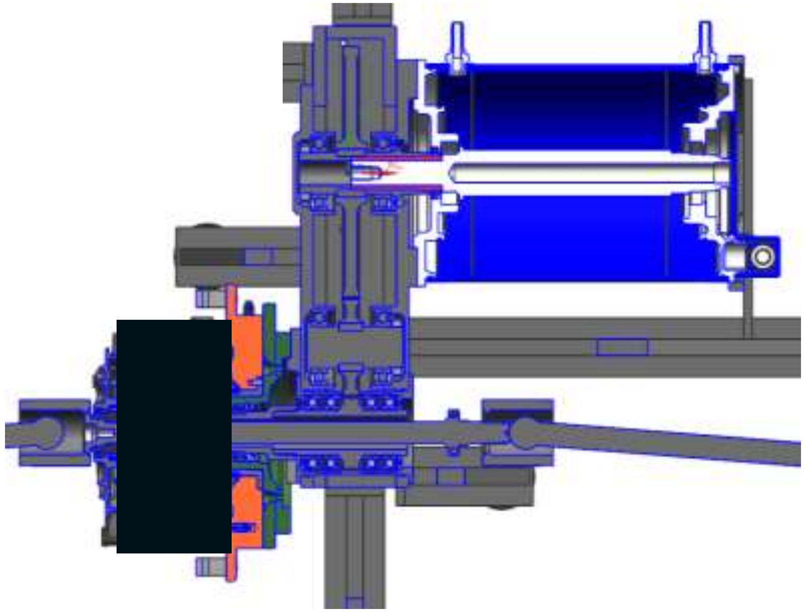
Overview high speed transmission



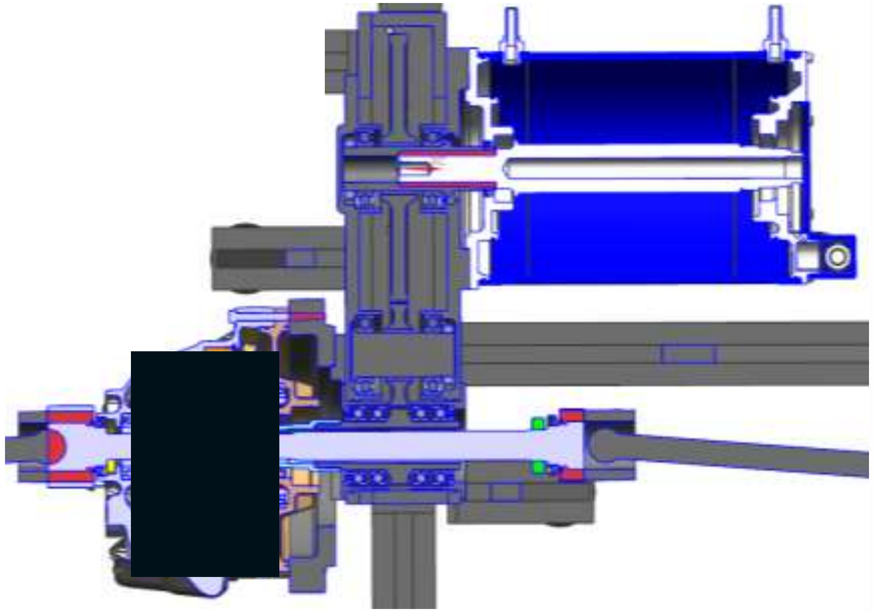
Overview high speed transmission – Different application



Off axis



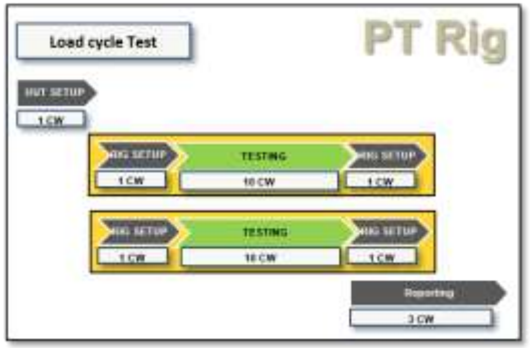
Coaxial



layshaft/Coaxial

Cycle based validation approach - Mechanical Development

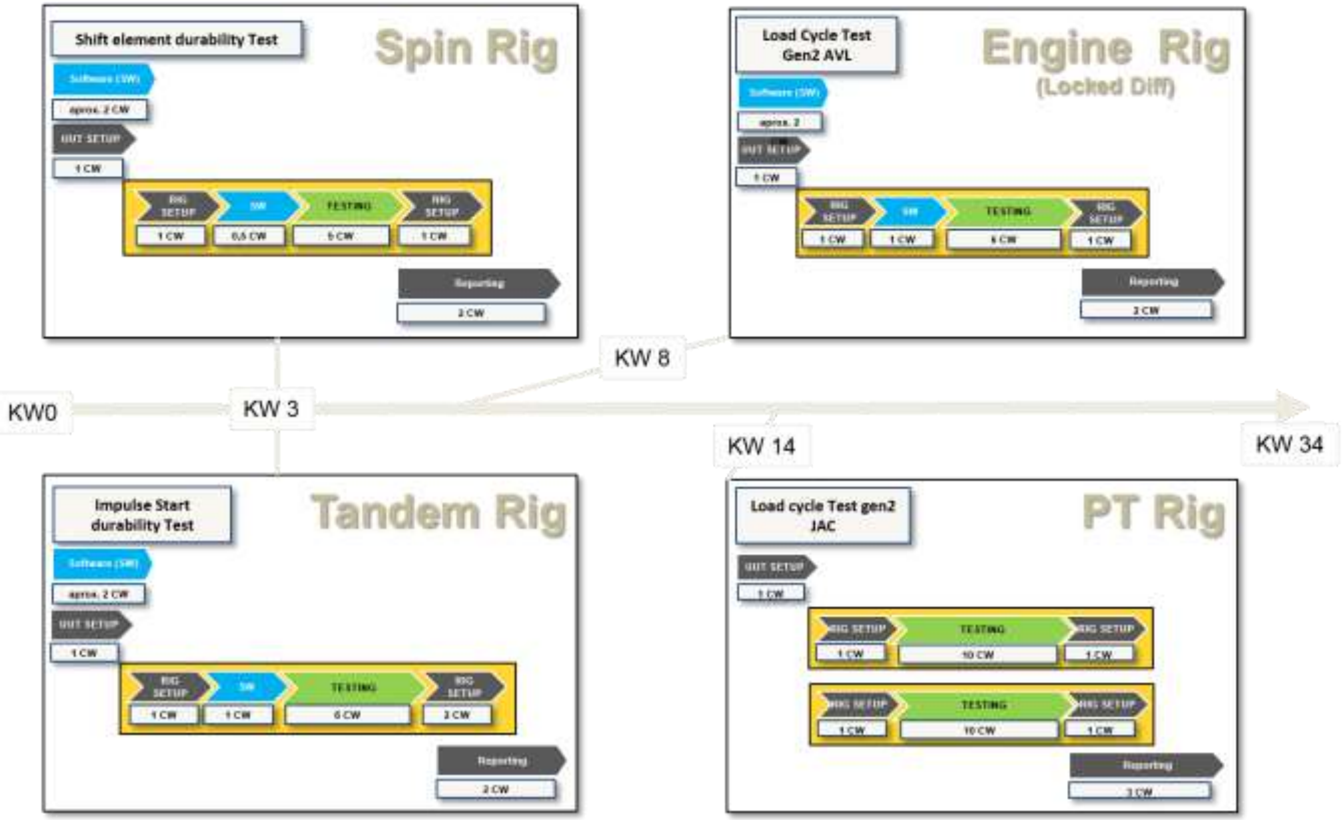
needle bearings	open C0 closed C0 (no relative speed)	high speed difference input/output low lubeoil flow high oil temp missalignment; runout	high amount of pure electric driving	PT test	☑
output shaft	high torque ICE+EM	missalignment; inbalance; runout	boost operation	Component Test	?
hydr. seal rings	high apply pressure alternating pressure cycles (hydraulic) high relative speed at high pressure	high oil temp high speed difference in/out high ICE speed missalignment; runout	high amount of pure electric driving high ICE revs	Component Test	☑
housing		high sum torque high bending torque	operation at bending resonance boosting from low ICE-revs / impulse starts	Component Test	?
eOP & hydraulics	high flow and pressure demand	high oil temp contamination of oil varying eOP speed demands	long periods with full pressure demand (ICE-torque) high number of impulse starts	Component Test	?
e-drive	high e-drive usage @ max. e-drive torque high recuperation torque	high e-drive (coil) temp high oil temp high LT-circuit temp	as much as possible of e-drive operation high number of alternation drive/recuperation (pressfit)	LPC, Component Test	?
main bearing	high ICE revs (check 5001)	high oil temp and high lube oil flow missalignment, unbalanced components	high ICE revs; max. allowed inbalance of input shaft	PT test	?
clutch pack wear	slipping operation	impulse starts; poor lubrication/cooling contamination of oil	high number of impulse starts	PT test	?
clutch piston bending & wear	full piston travel and clutch torque	high pressure gradients high accumulated piston travel contamination of oil	high number of impulse starts high number of C0 openings / pure electric driving	Component Test	☑



- Not all damage figures sufficient activated at validation phase → only 20% sufficient!
- 16 CW of powertrain testing at full assembly

Failure mode based validation approach - mechanical development

Content of important operating conditions					
Part/component	damaging operation	aggravating conditions	conclusion (cycle needs to contain...)	dedicated test Gen2	durability Cycle @ JAC
input shaft	high ICE torque	torque irregularities (low eng. Speed) missalignment; inbalance	high ICE load at low speeds (LPM)	HLCT	
	high C0 apply pressure	pressure oscillations in oil channels		shift element durability	
	high ICE speed	missalignment; inbalance		shift element durability	
	welding	torque irregularities (low eng. Speed) high ICE torque		HLCT	
	clutch hub, splines	torque irregularities (low eng. Speed) high inbalance, misalignment, rotational speed high ICE torque, high number of C0 activations low lube flow		HLCT, impulse start test	vehicle driving high speed
needle bearings	open C0	high speed difference input/output low lubeoil flow / high lube oil flow high oil temp missalignment; runout, contaminated lube oil	high amount of pure electric driving	impulse start test	
pilot bearing	high travel of DMF	oscillating / torque irregularities (low eng. Speed)		HLCT	
output shaft	high torque ICE+EM	missalignment; inbalance; runout	boost operation	HLCT	vehicle driving @ WOT acceleration
	high C0 apply pressure	pressure oscillations in oil channels		shift element durability	vehicle driving @ WOT acceleration
	high EM/ICE speed	missalignment; inbalance		shift element durability	
	weldings	torque irregularities (low eng. Speed) high ICE&EM or EM torque		HLCT	vehicle driving @ WOT acceleration from standstill
	clutch basket, splines	torque irregularities (low eng. Speed) high inbalance, misalignment, rotational speed high ICE torque, high number of C0 activations low lubrication flow		HLCT	vehicle driving @ WOT acceleration from standstill
hydr. seal rings	high apply pressure	high oil temp, contaminated oil high speed difference input/output shaft high ICE speed missalignment; runout	high amount of pure electric driving high ICE revs	shift element durability	
housing		high sum torque high bending torque unbalanced thermal load	operation at bending resonance boosting from low ICE revs / impulse starts	vehicle driving, rough road	
eOP & hydraulics	high flow and pressure demand	high oil temp, contamination of oil varying eOP speed demands high oil pressure levels, varying pressure levels foaming of oil, contaminated suction filter (pressure drop)	long periods with full pressure demand (ICE-torque) high number of impulse starts	vehicle test	
e-drive	high e-drive usage @ max. e-drive torque high recuperation torque	high EM speeds high e-drive (coil) temp, high oil temp high LT-circuit temp; frequent change of LT temp level	as much as possible of e-drive operation high number of alternation drive/recuperation (presift)	vehicle test	high recuperation power
main bearing	high ICE revs	high oil temp and high lube oil flow missalignment, unbalanced components	high ICE revs, max. allowed inbalance of input shaft	shift element durability	
clutch pack wear	slipping operation	impulse starts; poor lubrication/cooling contamination of oil, frequently repeated starts	high number of impulse starts	impulse start test	
clutch piston bending & wear	full piston travel and clutch torque	high pressure gradients, high revs, high oil temperature high accumulated piston travel contamination of oil	high number of impulse starts high number of C0 openings / pure electric driving	shift element durability	



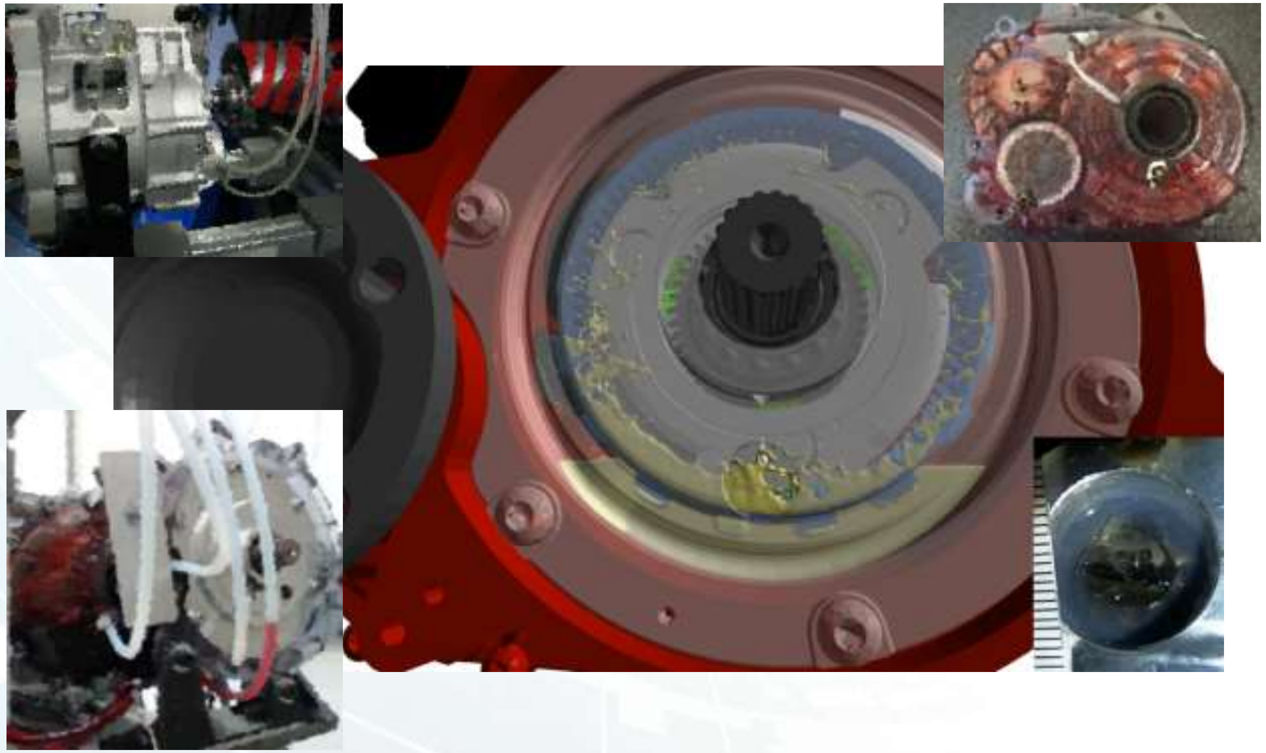
- All damage figures sufficient activated at validation phase
- Big data analytics load profile corrections on damage figure calculations → 100% controlled
- 14 CW of component testing @ #3 different rigs

Content

Integrated design verification - Transmission lubrication system

Lubrication system check

ROAD → Tilt Rig → Simulation



Several variants of housing, e-Motor designs, cooling layouts and baffle plates.

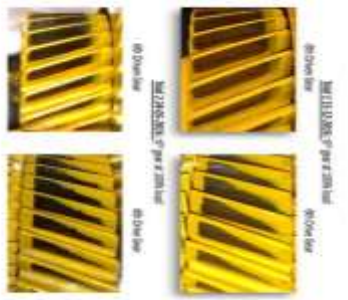
Proven benefits

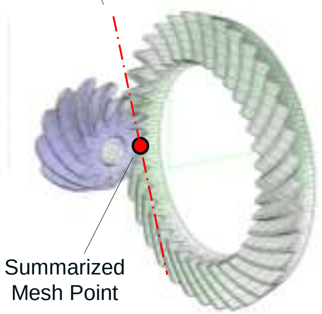
Reduction of development time	▪ Concept layout validated before trying in vehicles. ▪ Overnight validation of new HW variants to prove simulation results.
Reduction of cost	• Multiple HW variants validated short period. • Reduced time on costly test environments (Powertrain, climate, vehicle).
Increased product quality	• Regular reference cycles and measurement point checks to find design improvements and reduce errors.

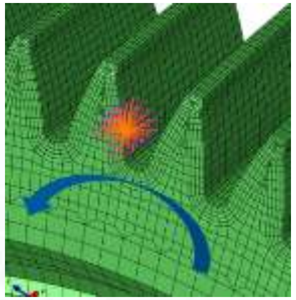
Integrated design verification - Transmission gear train

Gear optimization

ROAD → Specialized Gear Rig → Simulation







Test beds dedicated ONLY for model validation by isolating gear pair failures

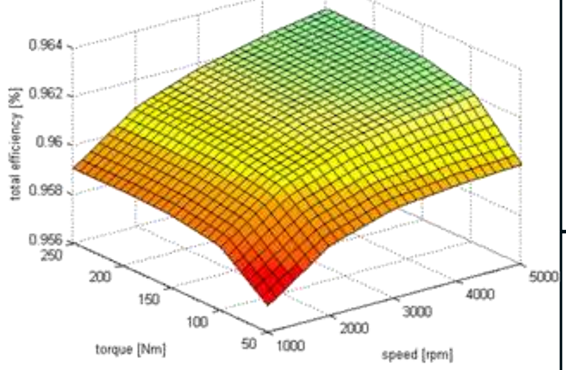
Proven benefits

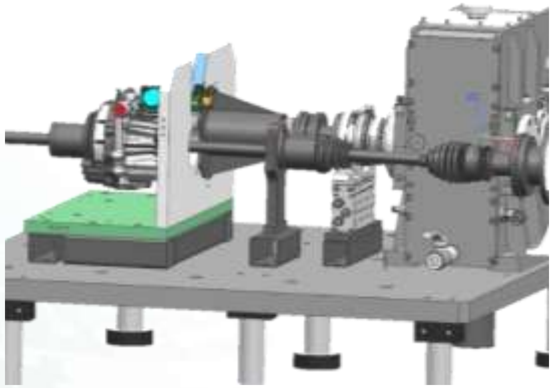
Reduction of development time	▪ High model maturity in an early design phase reduces efforts in later development phases. ▪ Reduce validation time in case of design changes.
Reduction of cost	• Reduced cost risks in case of design changes over all development phases. • Potential for reduced number of prototypes.
Increased product quality	• Knowledge of influence parameters on different attributes (NVH, strength, efficiency) gained with manageable efforts.

Integrated design verification - Transmission efficiency

Sub-System Efficiency

Powertrain → Transmission test bed → Simulation





Isolated assessment of EV-Drive reducer on high-speed transmission test bed.

Proven benefits

Reduction of development time	▪ Reduced development risk by assessment of sub-system performance in an early stage of development.
Reduction of cost	▪ Reduced testing costs by shifting test to on sub-system environment.
Increased product quality	▪ Detailed knowledge of sub-system performance helps to set development targets.

Integrated design verification - Failure mode based durability testing

System durability testing

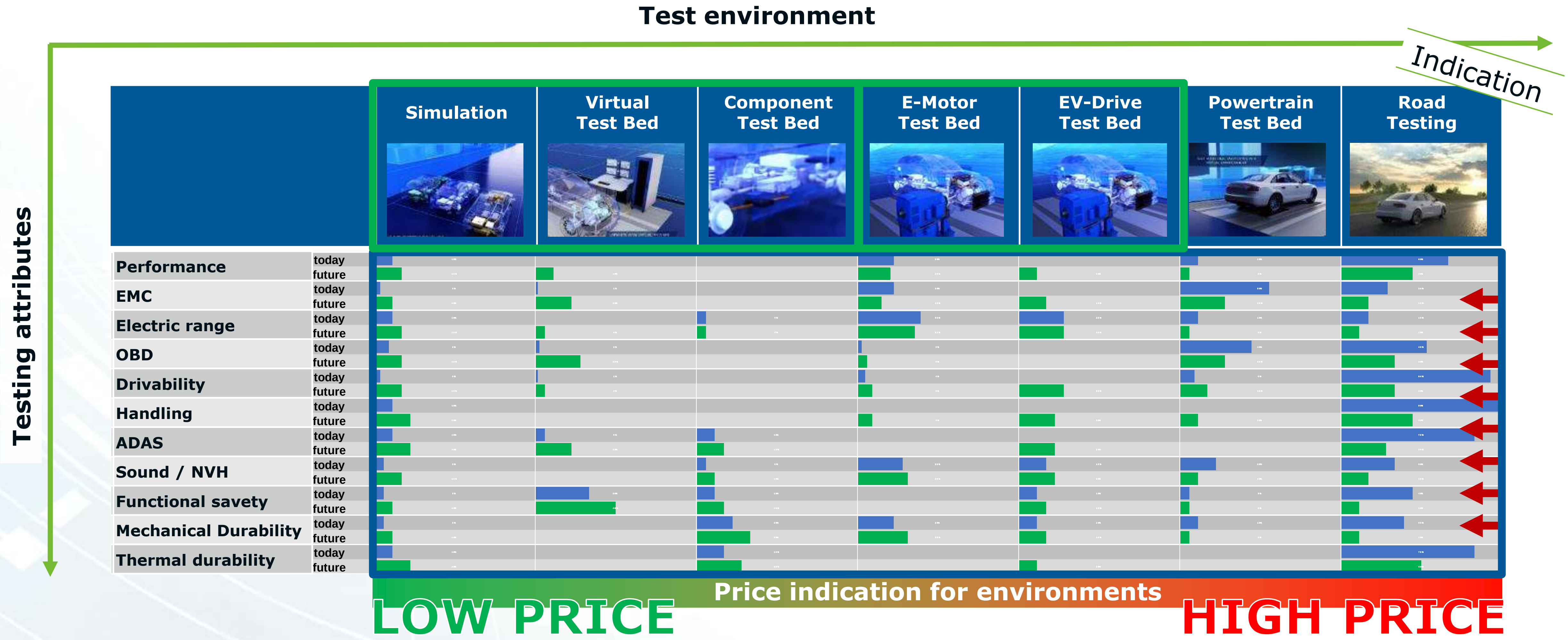
ROAD → EV-Drive test bed → Simulation

Online damage monitoring during the complete durability run

Proven benefits

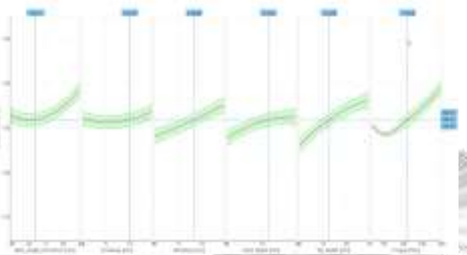
Reduction of development time	▪ Potential reduction of duration and number of durability runs due to specific damage of components / failure modes.
Reduction of cost	▪ Reduced development time and number of test samples. ▪ Potential for decrease of design safety factors.
Increased product quality	▪ Damage figures over the complete durability run helps to improve product robustness.

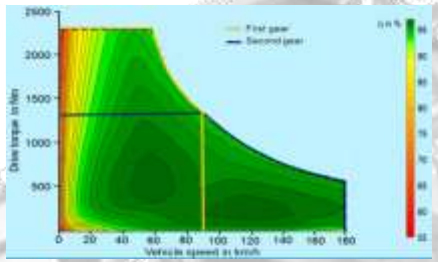
State of the art test environments

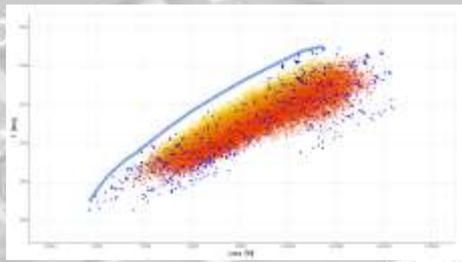


Summary and Outlook

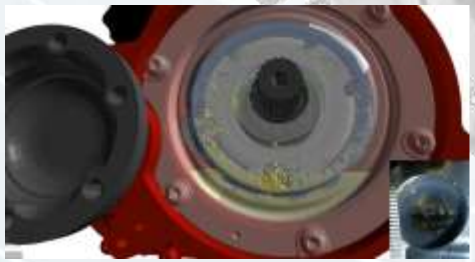
*The deep knowledge of **sub-system influence parameters** and respective **cross influences** are mandatory to meet the **target requirements***

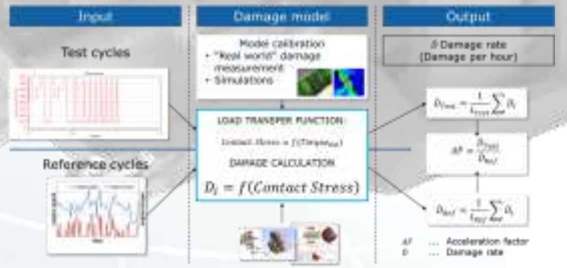


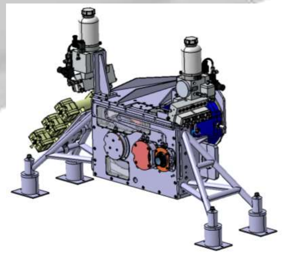




*By **increasing the productivity** within existing testing environments (failure mode based testing) and **shifting** to **other testing environments** (integrated design verification) **time to market requirements** can be met.*







Thank You

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