Development of Reliable & Future Proof Combustion Engines

Gerhard Buschmann, April 2021
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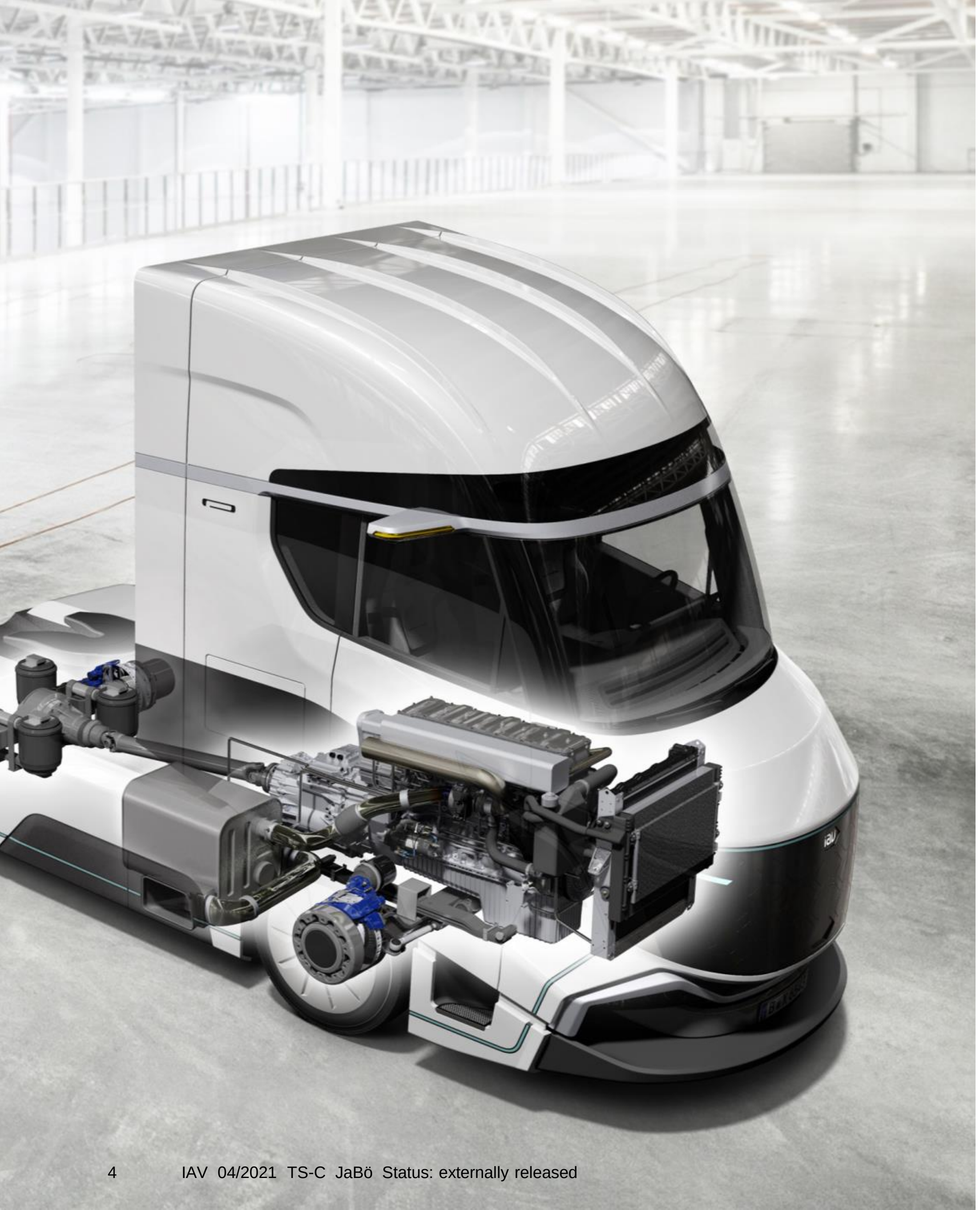

Outline of the Presentation

- Trends in Emissions-and CO_2-Legislation
- Future-Proof Combustion Engine
- Road to 55% BTE
- Modularity for Alternative Fuels
- IAV Virtual Release
- Conclusions and Outlook

Heavy-duty On-Highway Exhaust Gas Emission Legislation

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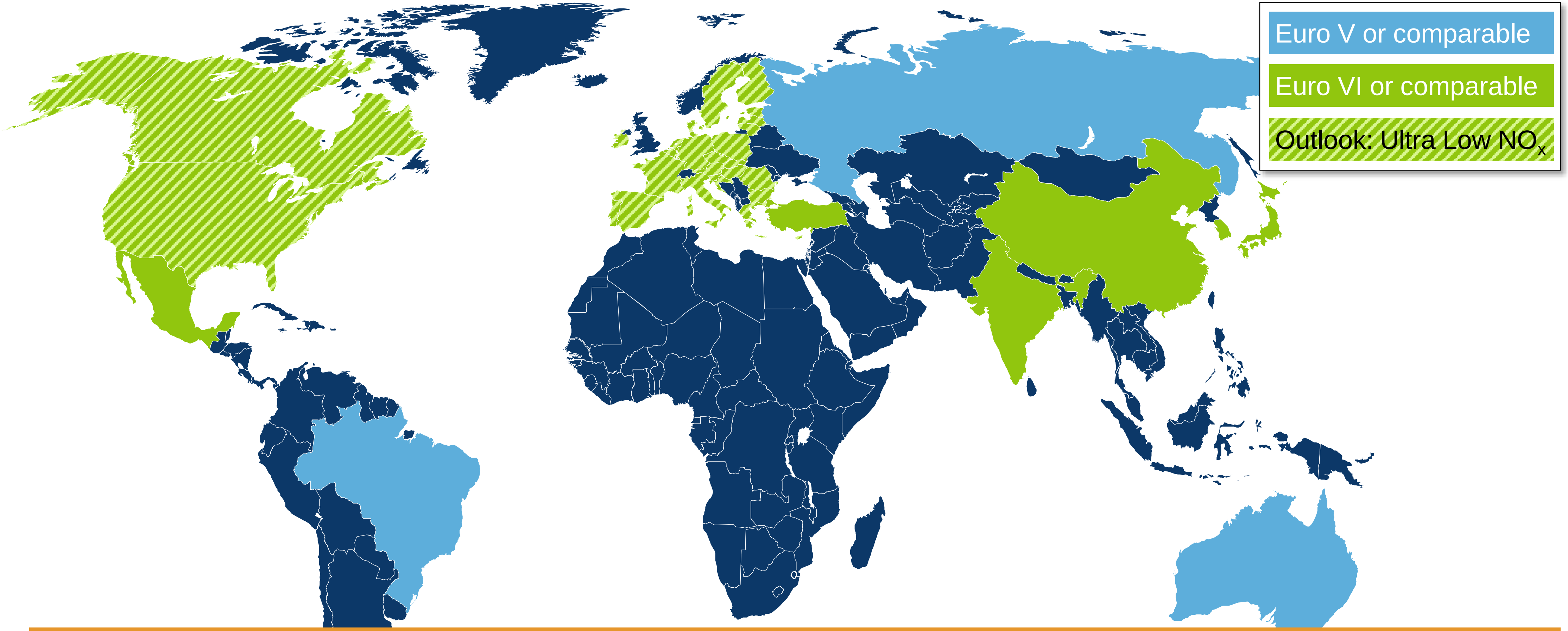

→ **The world is shifting towards China VI / Euro VI or comparable legislation**

→ **Ultra Low NO_x, real driving emissions, PEMS & online in-use-compliance are becoming more relevant**

→ **Next important exhaust gas emission legislation step expected from 2027**

CO_2 Is Our Major Challenge

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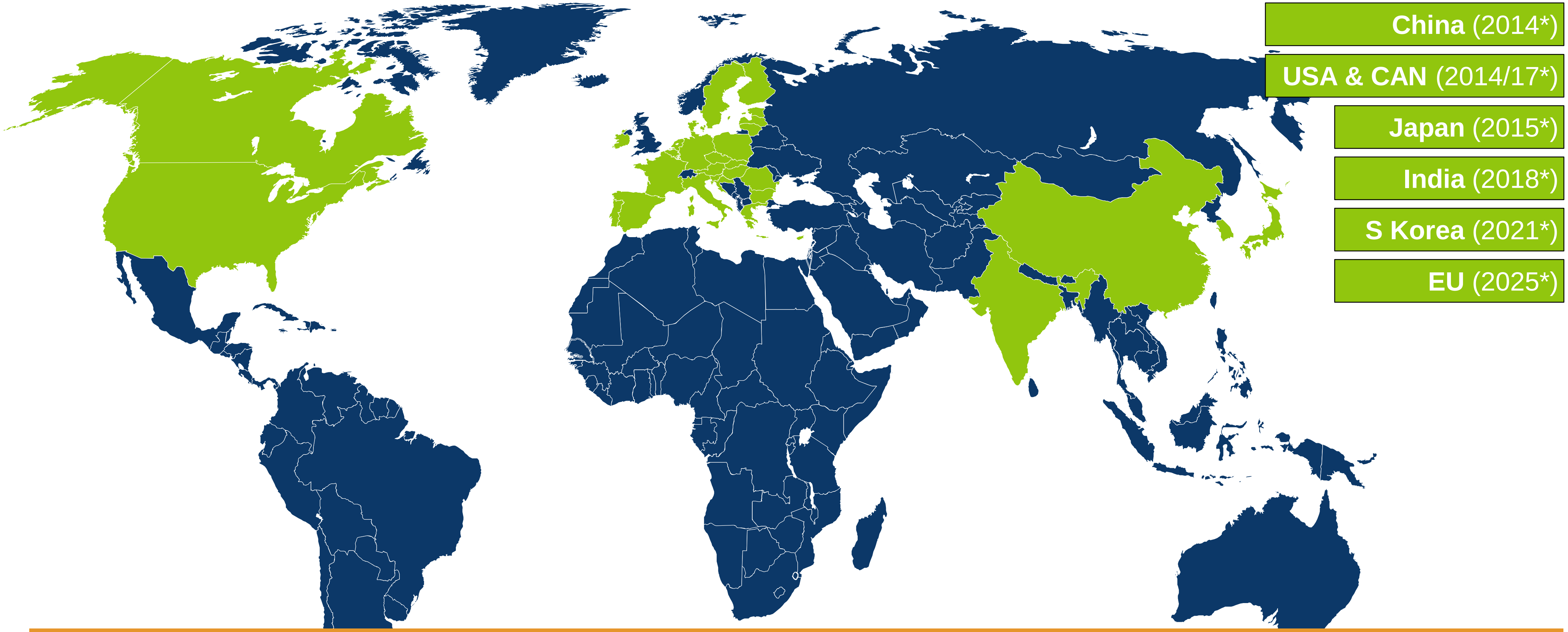

- → **Heavy-duty CO_2 regulation in place in all leading markets, China is the forerunner**
- → **China committed to reach the peak in CO_2 emissions by 2030 and to become carbon neutral by 2060**
- → **China targets 3 paths to reach CO_2 targets: (1) Fuel saving ICE, (2) BEV, (3) H_2**

** 1st year with binding limits*

Requirements of a Future Proof Combustion Engine

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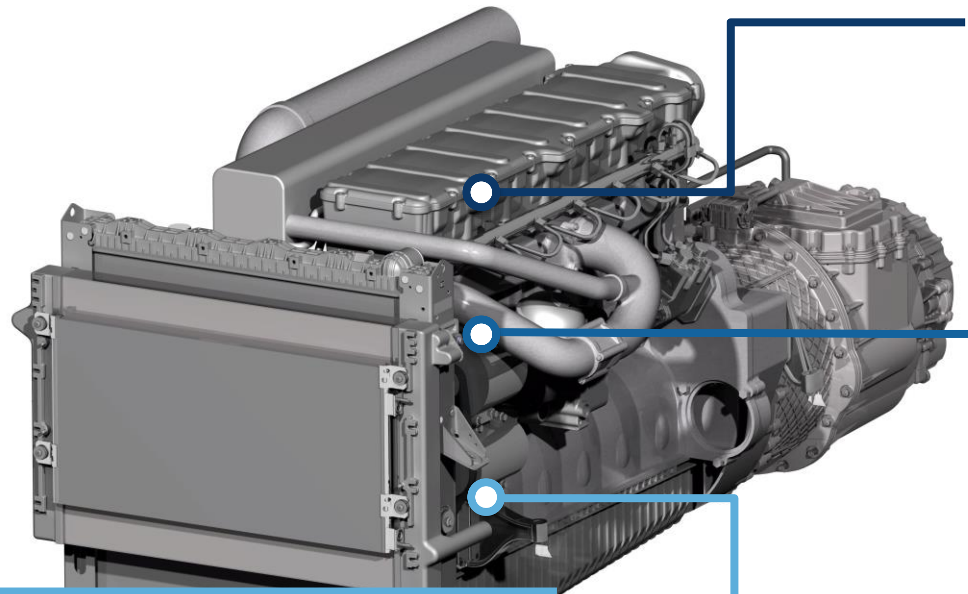

Design & Validation

- Main dimensions
- Reliability & robustness
- Ambient conditions

IAV's Virtual Release

- Linking data from design, simulation and testing
- Test 15% / Special Test 25%
- Simulation 60%

Characteristics

- Efficiency & performance
- Emission
- NVH
- Weight & package

IAV's Road to 55% BTE

- Cooling & recuperation
- Crank drive
- Gas exchange
- Electrification

Production

- Engine cost
- Quality & LCA
- TCO
- Worldwide production

Modularity

- Use case
- Fuel (Diesel, LNG/CNG & H_2)
- Electrification

→ The ambitious sub systems determine a modular architecture

→ Best in class BTE

→ A global future-proof engine needs to be best in class: efficiency, robustness, NVH and weight

IAV's Road to 55% BTE

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Holistic Combustion & Emission Development

→ 2 - 3% BTE*

Crank Drive Optimization

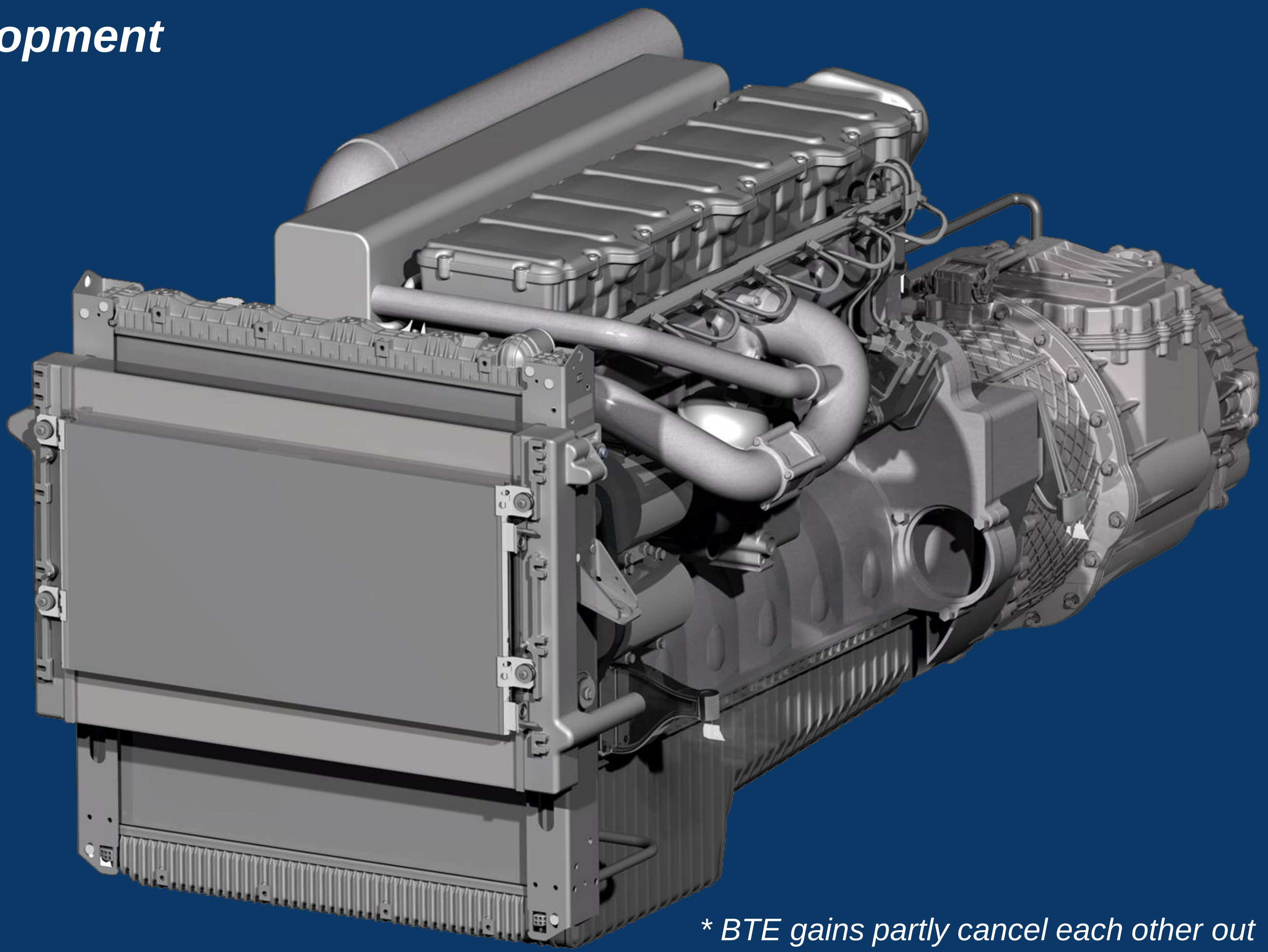
→ 0.5 - 1% BTE*

Improved Cooling & Recuperation

→ 4 - 5% BTE*

Smart Electrification

→ 1 - 2% BTE*



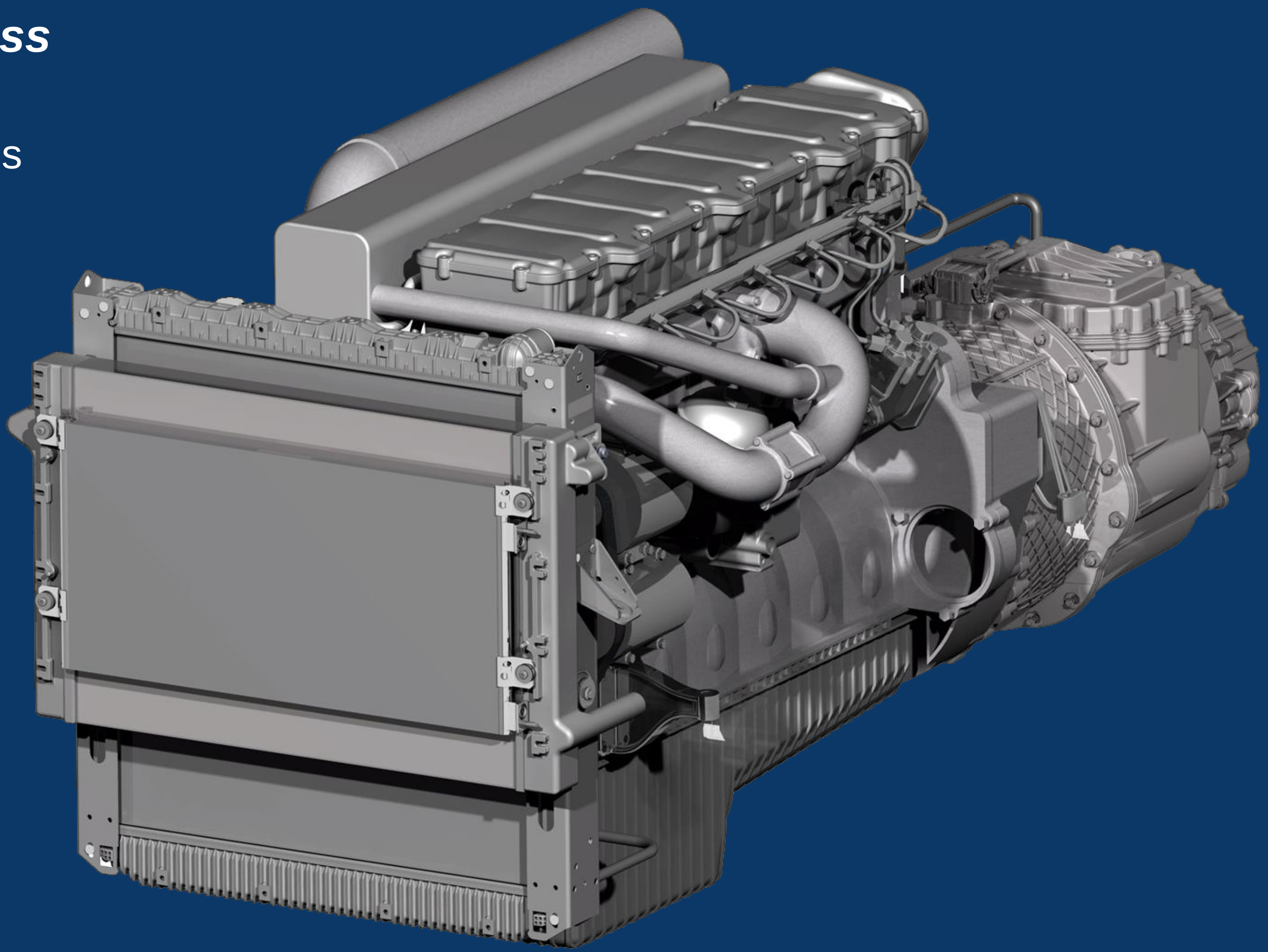
** BTE gains partly cancel each other out*

→ High efficiency is the key to cope with future legislation and global challenges

IAV's Road to 55% BTE

Holistic Combustion & Emission Process

- Combustion "at the technological limit"
- Gas exchange and valve train/ Miller process
- EGR, turbocharging & intercooling
- Thermal management and emission control



Holistic Engine and EAT Optimization (IAV's Model-based Approach)

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Holistic engine & EAT concept development

- Coupling of physical engine model to EAT system for considering fuel consumption and tail pipe emissions
- Simulation platform for model-based optimization of engine and EAT system

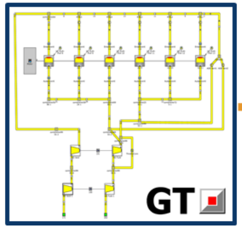
EAT modeling

- Set-up of complete EAT model (e.g. GT, Axisuite can be used to meet functionality and accuracy requirements, also compatible with engine model)
- Validation with SCAT and engine test data
- Tail pipe emission prediction

Engine modeling

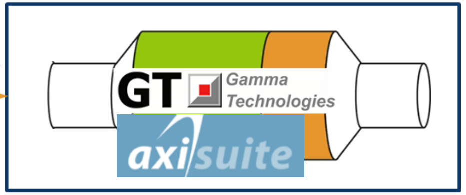
- Physical air-path model
- Phenomenological combustion model
- IAV novel hybrid emission model
- Validation using IAV test data

Predictive engine model



Coupling engine to EAT models

EAT (DOC, DPF, SCR, ASC) models



SCAT and engine testing

- Calibration of EAT model with synthetic gas testing of samples and fine tuning on engine bench
- IAV's global top physico-chemical labs (PCL) can perform all kinds of EAT component + sensor functional tests and physical data acquisition independently

Engine test bench data

- Validation and training of the engine model incl. novel hybrid emission model

Engine optimization:

- Air-path / TC system
- EGR concept
- Peak firing pressure and compression ratio
- NO_x and CO_2 emissions
- Fuel injection

EAT optimization:

- Architecture
- Technology and coating
- DEF dosing strategy

→ Achievement of legislation under all boundaries required holistic concept definition approach

→ Optimization of emissions and efficiency considering counter effects of EAT concept and technology

IAV’s Road to 55% BTE

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Holistic Combustion & Emission Process

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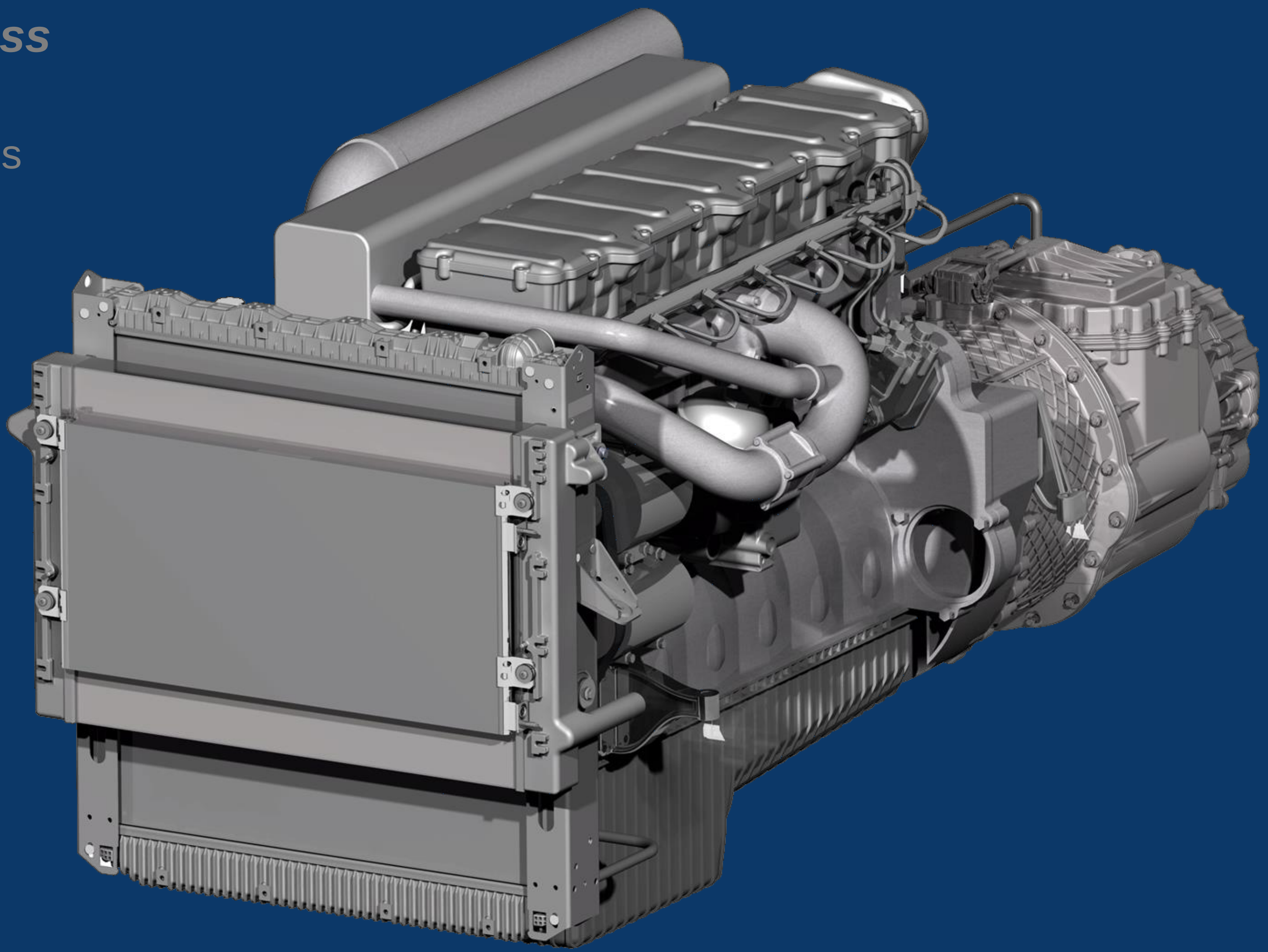
Crank Drive Optimization

- Crankshaft optimization
- Friction reduction



Crank Train Optimization

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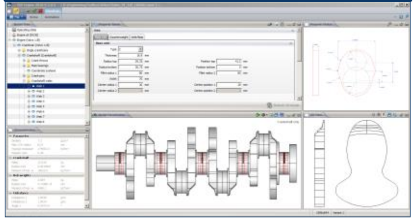
Targets

- Efficiency
- Future proof fuels
- Load & profiles & durability

Start Configuration



Parameters

List of free parameters

No.	Free Parameter	Unit	Interval
1	Main bearing diameter	mm	47 … 54
2	Main bearing width	mm	16.6 … 18.4
3	Conrod bearing diameter	mm	50 … 60
4	Conrod bearing width	mm	16 … 19
5 - 10	Opening angle of CW 2 to 7	deg.	30 … 160
11	Counterweight radius, big CW	mm	70 … 80
12	Counterweight radius, small CW	mm	48 … 60
13 - 16	Web width of crank 1 to 4	mm	70 … 90
17 - 18	Additional masses front / rear	g	60
19	Heavy metal inserts for CW 4 / 5	g	50
20	Inertia TV-damper	g*m²	2.2 … 3.5
21	Stiffness TV-damper	kNm/rad	10 … 42

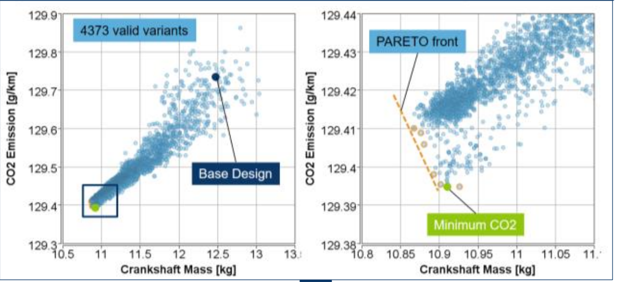
Optimization Targets

Optimization targets and restrictions

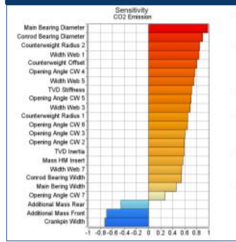
No.	Optimization targets	Direction
1	Cranktrain mass	Minimum
2	CO2 Emission (NEDC)	Minimum

No.	Restrictions	Unit	Limit
1	Crankshaft safety factor	-	> 1.4
2	Degree of utilization, main bearing	-	< 1
3	Degree of utilization, conrod bearing	-	< 1
4	Remaining unbalance	g*mm	500
5	Damping power, TV damper	W	< 500

Assessment of Results

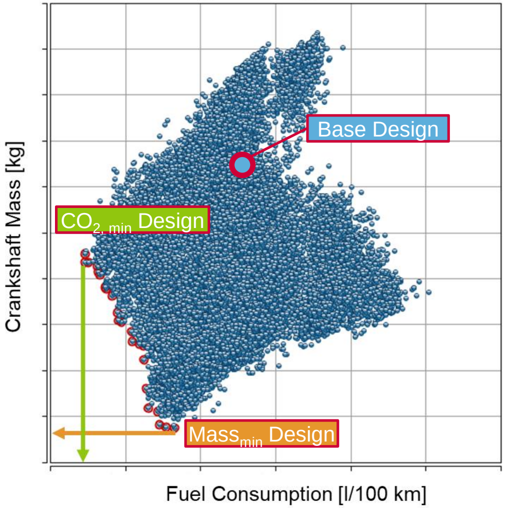


Rating



- IAV multi-criteria optimization method can be used for the assessment of cranktrain design variants
- 'IAV Engine Toolbox' calculates hundreds of cranktrain variants automatically, using mathematical optimization methods
- High number of free parameters possible (up to ~40)
- Operational safety limits are respected during the optimization process
- Cranktrain characteristics and fuel consumption can be assessed at the same time
- By means of parallelization on multi-core machines and in networks, the optimization process can be accelerated considerably (e.g. 10 s per variant)

Crankshaft Optimization @ IAV Engineering Toolbox

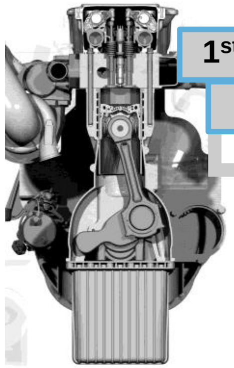


→ **Best in class crank train with IAV Engineering process**

→ **Ready for challenges of future fuels (e.g. H_2)**

Friction Reduction vs. Reliability: Engine Wear

Engine Development with Wear Measurement and Wear Simulation



1st Design

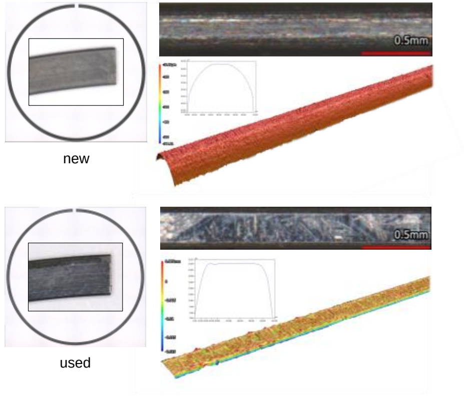
Simulation

Testing + Design loop

Commercial Vehicle Engine
up to 3500 h per run

Engine durability runs

Launch new piston rings



IAV's Engine Wear Optimization

Time & cost saving of minimum 25%

Engine Wear Measurement + Simulation

- High-precision online measurement
- Radioactive Nuclide Technology (RNT)
- Up to 5 marked surfaces (e.g. piston rings, cam- and crankshaft bearing) measured simultaneously
- Fast determination of the wear rate for predictive lifetime forecast

Shortening statement of robustness and reliability

- Cost down programs
- Release of new designs, materials and compositions
- Parts release of new suppliers

→ **IAV Approach: significantly reduce endurance testing time by wear simulation based on validated wear models**

→ **Application-specific validation of robustness and reliability by IAV's engine optimization**

IAV's Road to 55% BTE

Holistic Combustion & Emission Process

- Combustion "at the technological limit"
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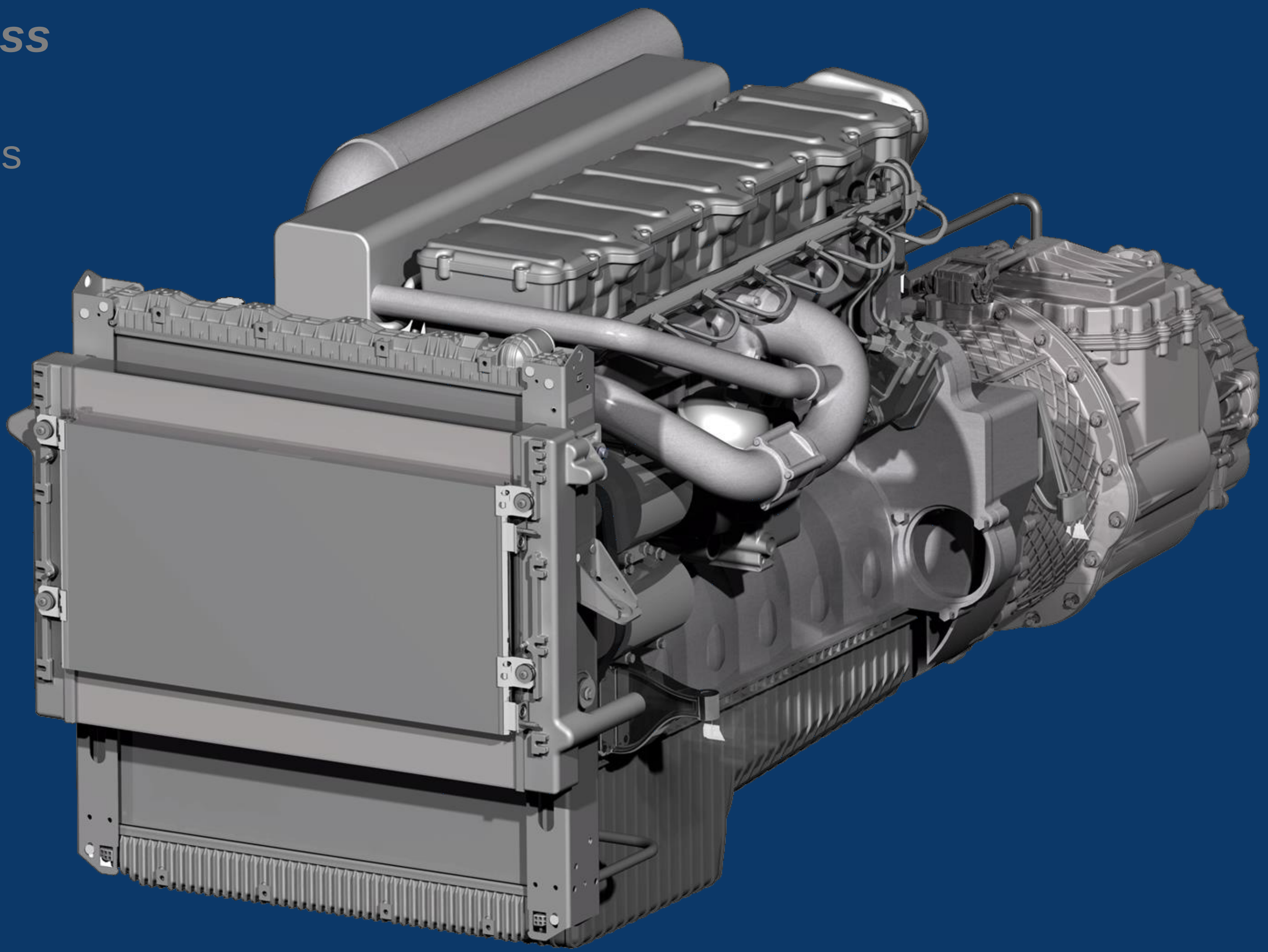
Cooling & Recuperation

- Phase Change Cooling (PCC)
- Waste Heat Recovery (WHR)



Phase Change Cooling (PCC) + Waste Heat Recovery (WHR)

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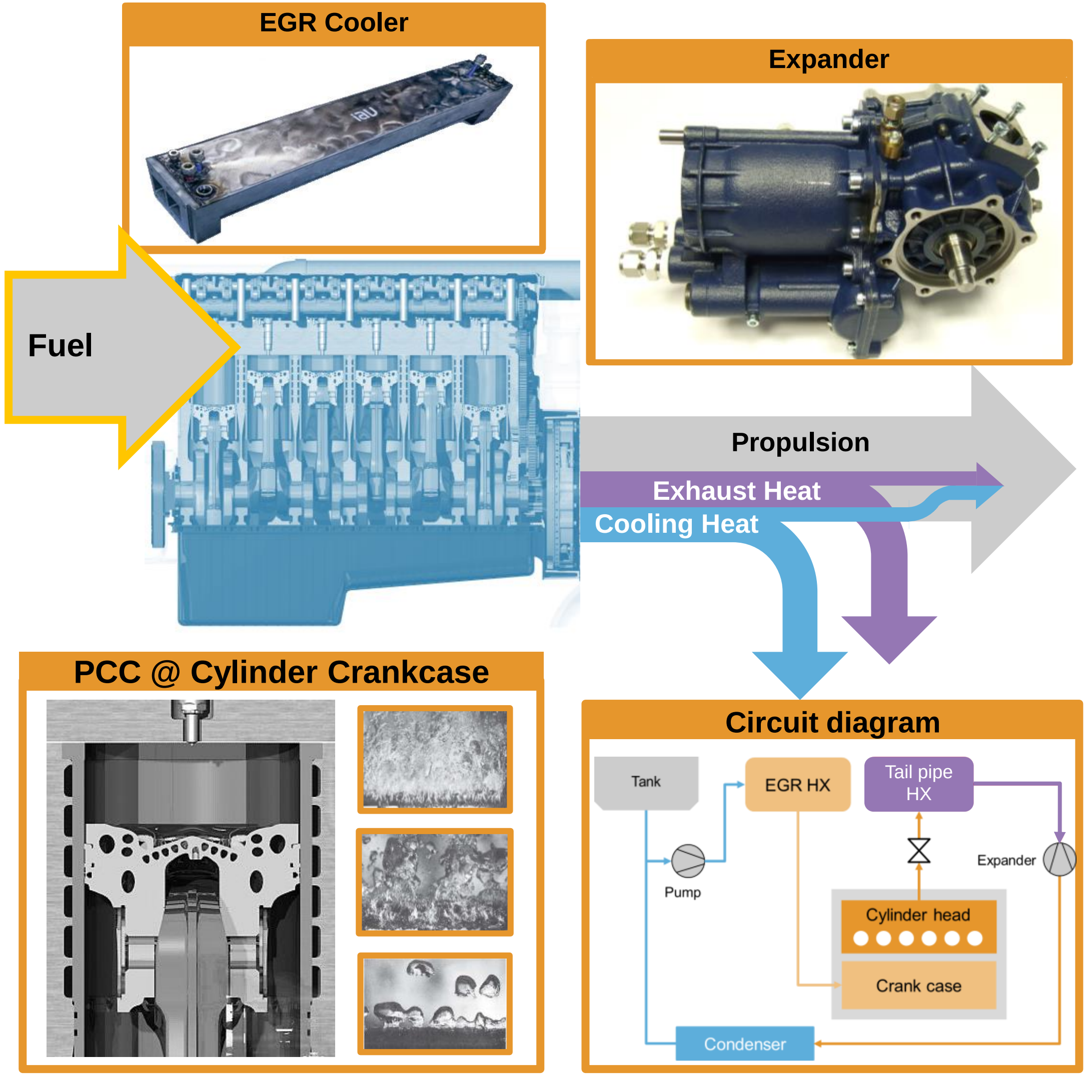

Phase Change Cooling (PCC)

- **Reduced thermal losses at part load** due to high temperature of cooling liquid
- **High energy absorption at full load** by phase change of cooling liquid
- **Reduced pump power** (approx. 98% mass flow reduction)

→ Engine cooling on demand or load applied cooling

→ Thermalmechanic simulation incl. design loop by IAV

→ Virtual release with final CFD & FE analysis by IAV

PCC in combination with Waste Heat Recovery (WHR)

- Exhaust gas recuperation + EGR heat recuperation + PCC engine cooling heat in one system with one fluid

→ Increased BTE potential of WHR system without additional circuit

→ EGR cooler & expander design made by IAV

→ IAV has simulated, developed and tested the new cooling successfully, also gains acknowledgement from European OEMs

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Cooling & Recuperation

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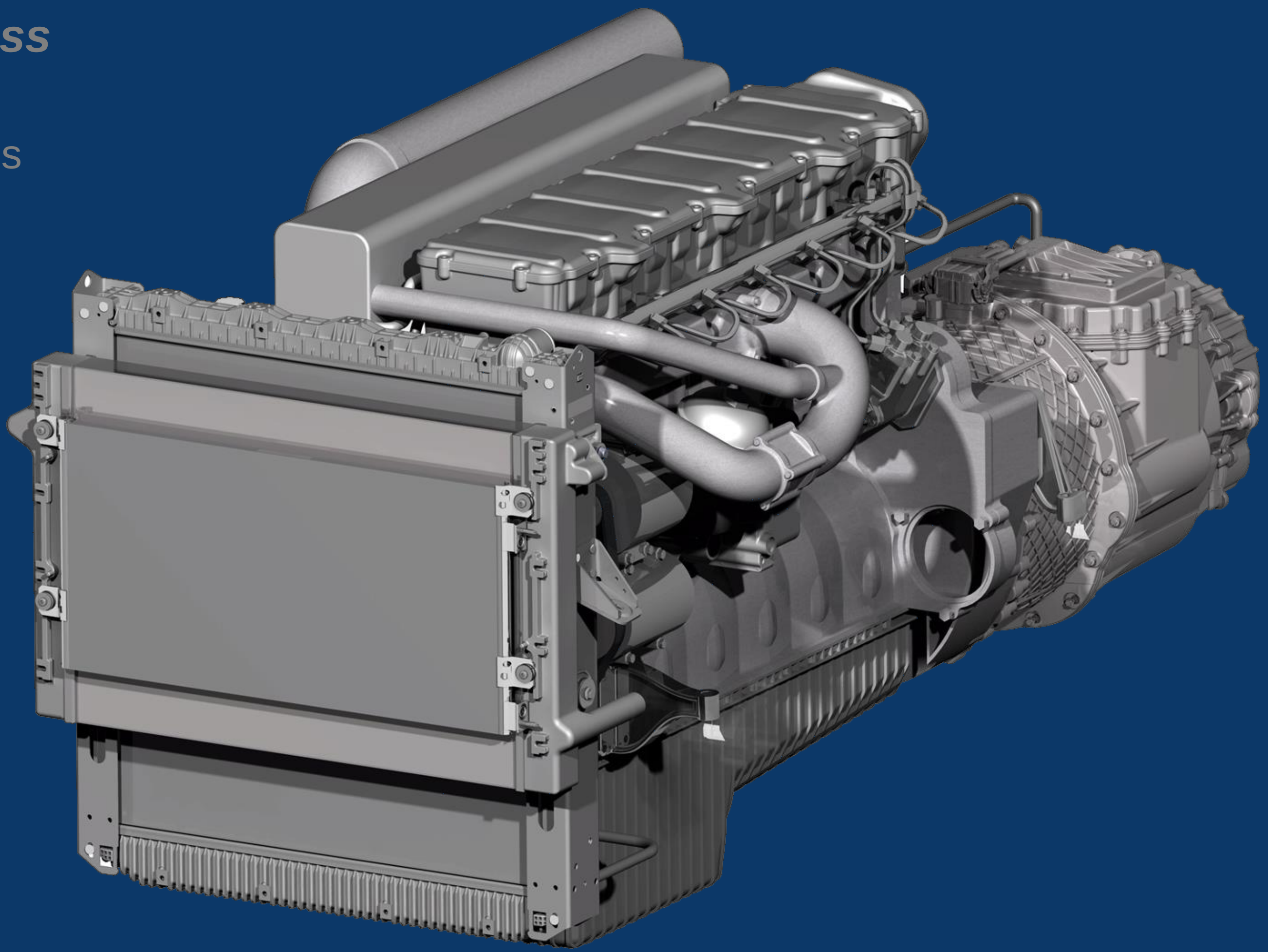
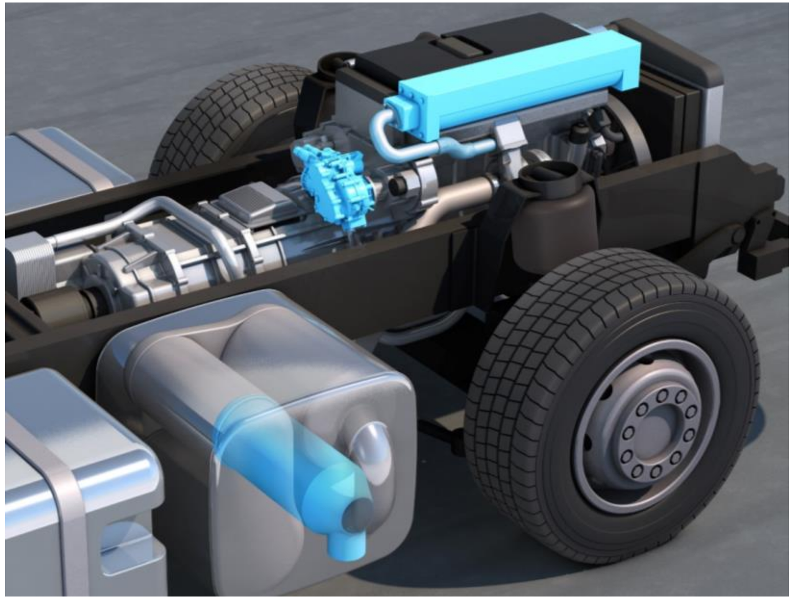
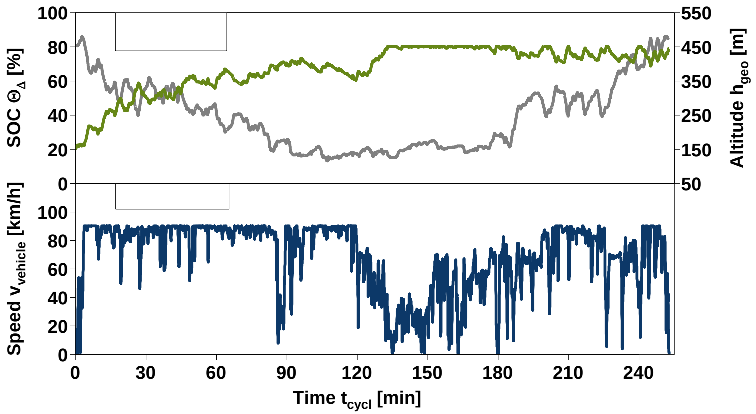
Smart Electrification

- Electric driven auxiliaries
- Motor/generator



Smart Electrification to Reduce Parasitic Losses





Electrification of auxiliaries

- **Demand-driven supply pumps** (coolant, oil, fuel, …) can be driven electrically, depending on the degree of electrification
- Main **recuperation** potential leveraged during engine braking and driving downhill

Recuperation principle

- Using kinetic energy that is usually transferred into heat using an engine brake or retarder
- 48V sub system or crank-driven recuperators can power electric supply pumps and reduce parasitic losses
- Electrification layout and potential depends on use-case and has to meet TCO requirements

→ Modularity of the vehicle architecture sets the framework for electrification

→ IAV develops tailor-made and energy-efficient solutions

Modularity is the Key, especially for Alternative Fuels like H_2

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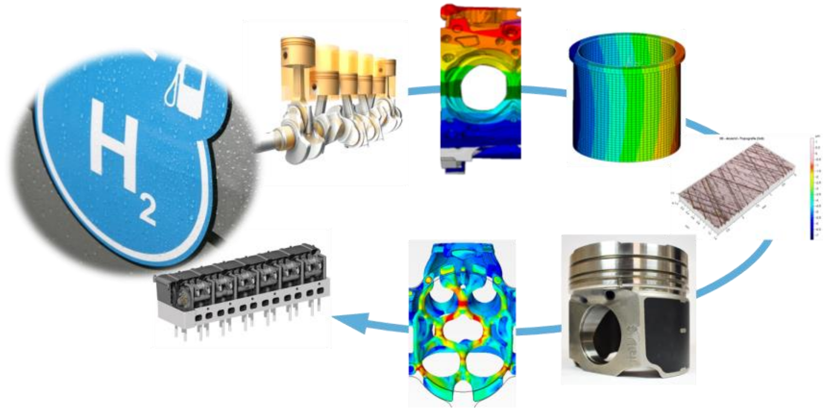
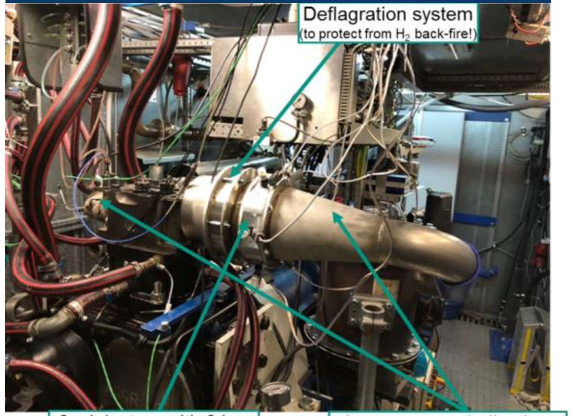
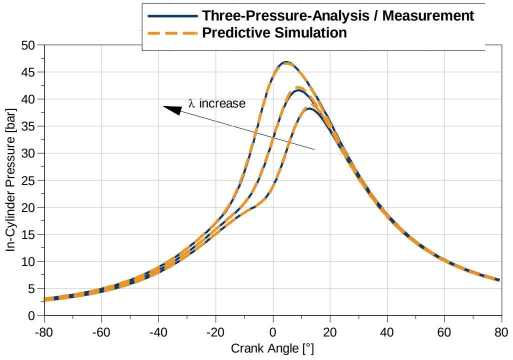


IAV H_2 HD Single Cylinder



In-cylinder pressure simulation vs. measurement



Challenges in H_2 combustion engine development

Ignition limit ↑	Turbocharging demand ↑
Burning rate ↑	FIS: H_2 gas volume ↑
Irregular combustion and hot spots	FIS: homogeneous mixture
Oil in combustion chamber: Sensitivity ↑	Hydrogen embrittlement
Ultra Low NO_x at λ > 2.3	Design space within cylinder head ↓
H_2O gas content in exhaust gas ↑	Engine oil: Lubrication effect ↓

→ **Specific requirements (power density & emission concept) require an extensive adaptation process**

→ **IAV has solution approaches to cope all of the base engine challenges (partly pre-developed)**

Crucial for Success: Virtual Release using IAV Virtual Field Testing

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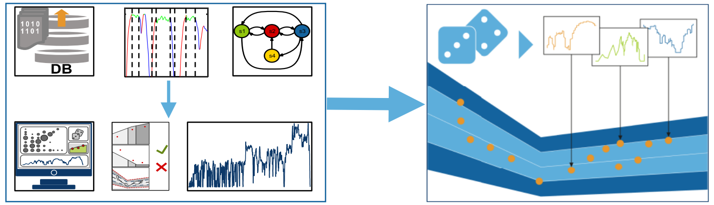
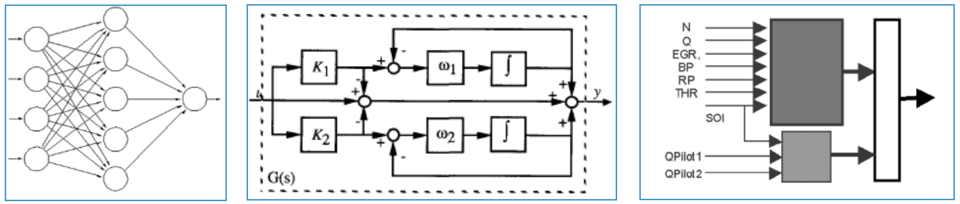
Data analysis, cycle generation & objective assessment

~200.000…300.000 cycles

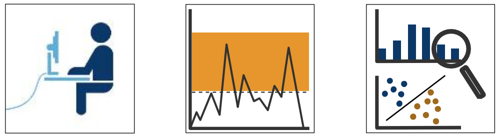


Statistical data evaluation and cycle generation (Monte-Carlo)



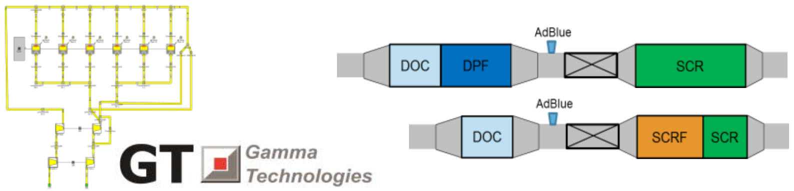
Virtual testing using AI based fast running simulation models

Evaluation & physical-based root cause containment



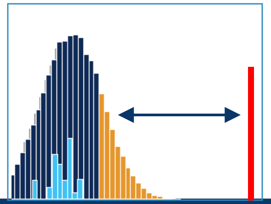
Result evaluation based on expert knowledge

~200…300 cycles



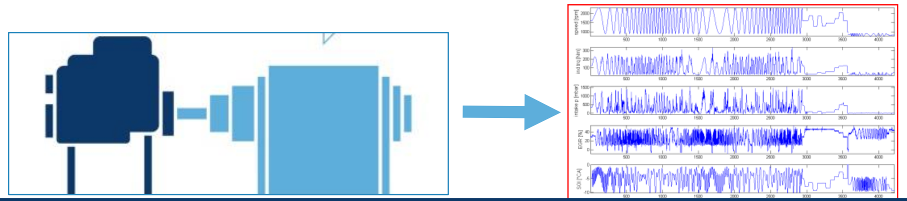
Holistic simulation approach using physical simulation models for engine and aftertreatment systems

Definition & validation



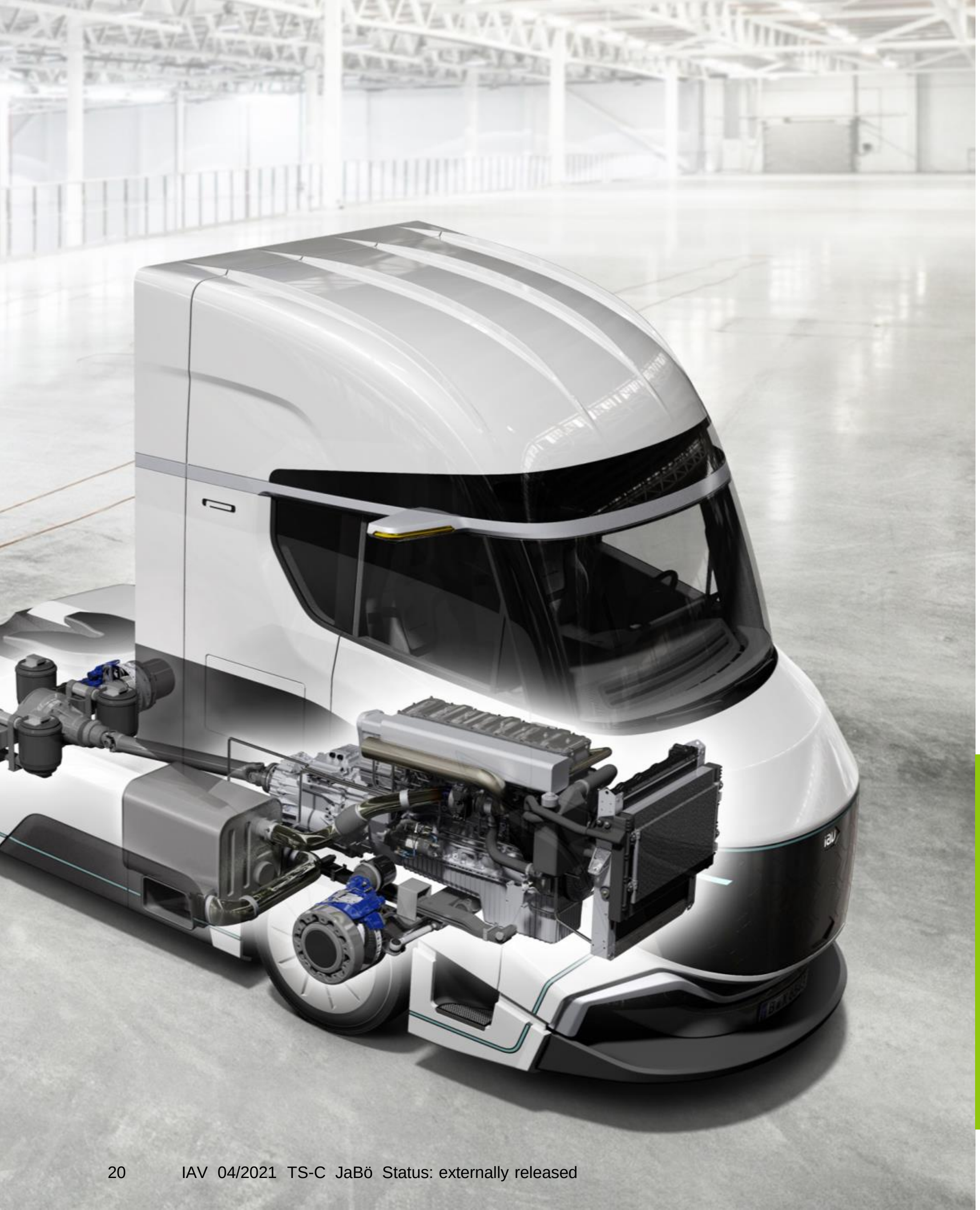
Result evaluation and worst-case definition

~10 cycles



Final validation with HiL and/or engine testbench

→ Time and cost saving: virtual release using AI drives the model based development



Summary and Outlook

Key challenges for future engines are:

- Emission compliance under all conditions
- Highest efficiency to reduce CO_2
- Modular design as a key especially for alternative fuels like hydrogen
- Virtual development to reduce time and cost

Outlook:

→ Future proof engines need to fulfil even more challenging requirements

→ IAV is well prepared and works on all these topics for its customers already

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