Smart ways to leverage power density and thermal efficiency of 2nd Gen. H2 ICE’s

National Motorcycle Museum,
Solihull/UK, March 13th, 2025

H. Busch / FEV Vehicle GmbH

Prepared for

FPC2025
Future Propulsion Conference

PUBLICATION

AGENDA

INTRODUCTION AND STATUS

ENGINE DESIGN AND MECHANICS

THERMODYNAMIC OPTIMIZATION

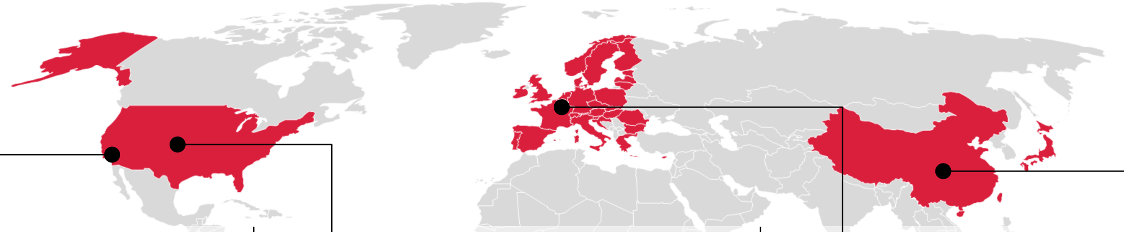
RESULTS AND ACHIEVEMENTS

SUMMARY AND COCLUSIONS

All major markets stipulate regulations pushing for low and zero (CO_2) emission in the transport sector; EU and California regulations most challenging

FEV

CO_2 EMISSION REGULATION FOR HD[1)] COMMERCIAL VEHICLE FLEETS – OVERVIEW



	California	USA	Europe	China
Regulatory metric / KPI	**Zero emission vehicle sales: in % of total sales**	**CO_2 emissions: Fleet average**		**Fuel consumption: Individual vehicle**
Reference	**N/A**	**Relative to 2017**	**Relative to 2019**	**Relative to 2015**
Targets (2020 – 2025 – 2030)	2025: **7%** ZEVs (class 7/8 tractors) **11%** ZEVs (class 4-8) 2030: **30%** ZEVs (class 7/8 tractors) **50%** ZEVs (class 4-8)	2021: **6-14%** reduction[1)] 2024: **11-20%** reduction[1)] 2027: **12-27%** reduction[1)] Post 2027 targets under discussion	2025: **15%** reduction More stringent target currently under discussion (decision expected in 2025) 2030: **30%** reduction	2019 / 2021: **15%** reduction Stage IV fuel consumption targets (for 2025/26) targets under discussion

1) depending on truck class
Source: FEV, Public domain,

If both main solutions – battery electric as well as H2-fueled propulsion systems – feature Zero CO2 classification other criterions gain relevance

Hydrogen based vs BEV powertrain

+

- High energy storage density
- Fast refueling

−

- Fuel cost (nowadays)
- Maintenance effort

H2 ICE based vs FC/BEV powertrain

+

- Lower development and production effort, hence quicker introduction to the market
- Proven powertrain durability and less sensitive to environmental impacts
- Less stringent requirement to hydrogen purity
- Beneficial efficiency in high load operations

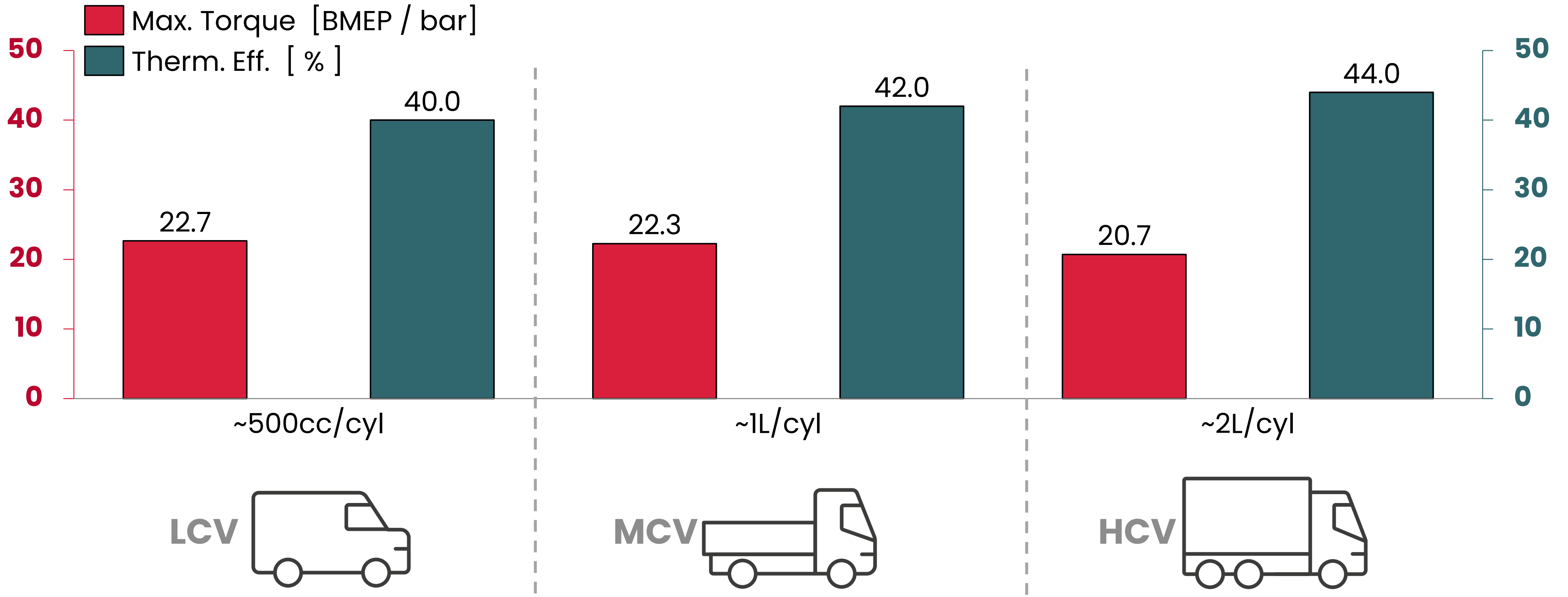
−

- Engine-out NO_x emissions require EATS, but zero-impact emission behavior
- Powertrain noise level

1st Generation LP-DI H2 ICE's summarize all powertrain attributes and features to meet key commercial application demands with carbon neutrality

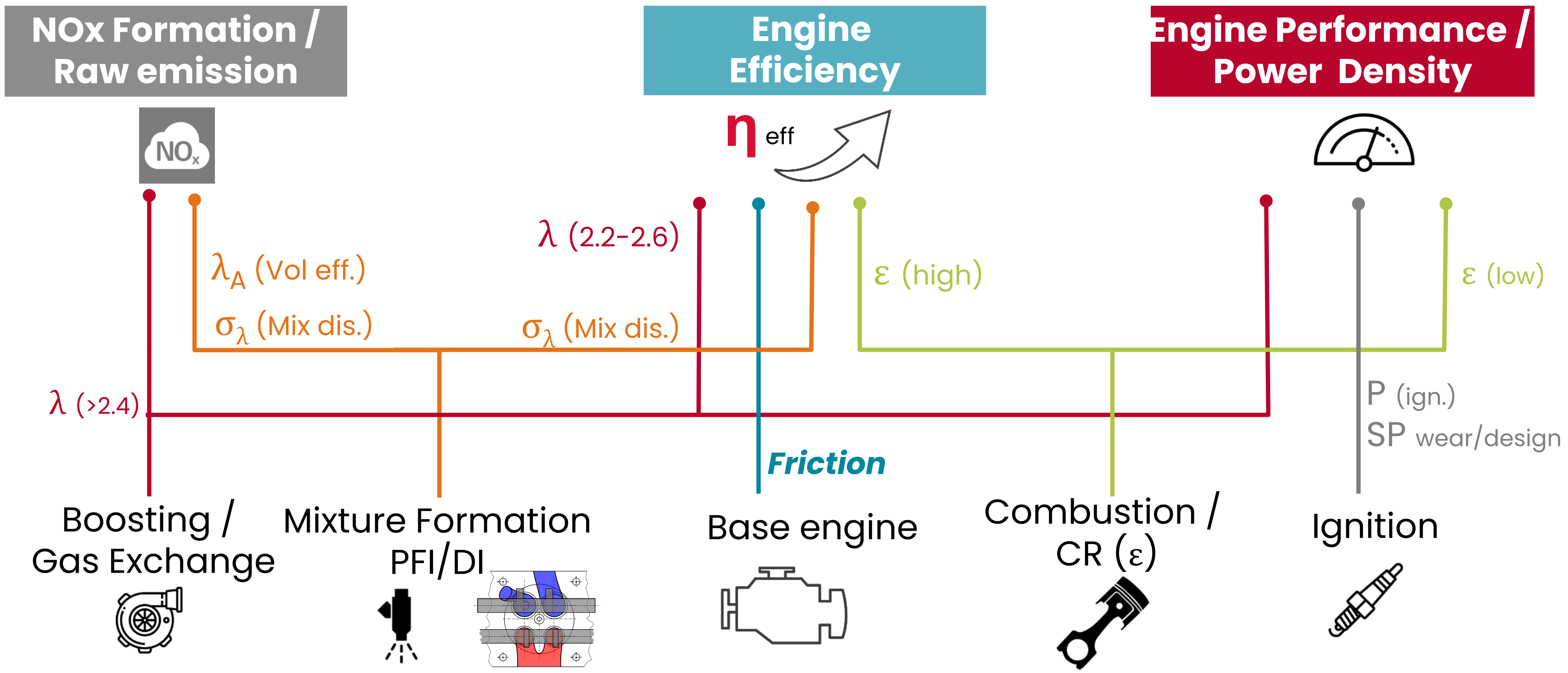
BASE DIESEL ENGINE ARCHITECTURES REPRESENT A FAVORABLE PLATFORM FOR H2 CONVERSION

H2-ICE's
High Torque – High Efficiency



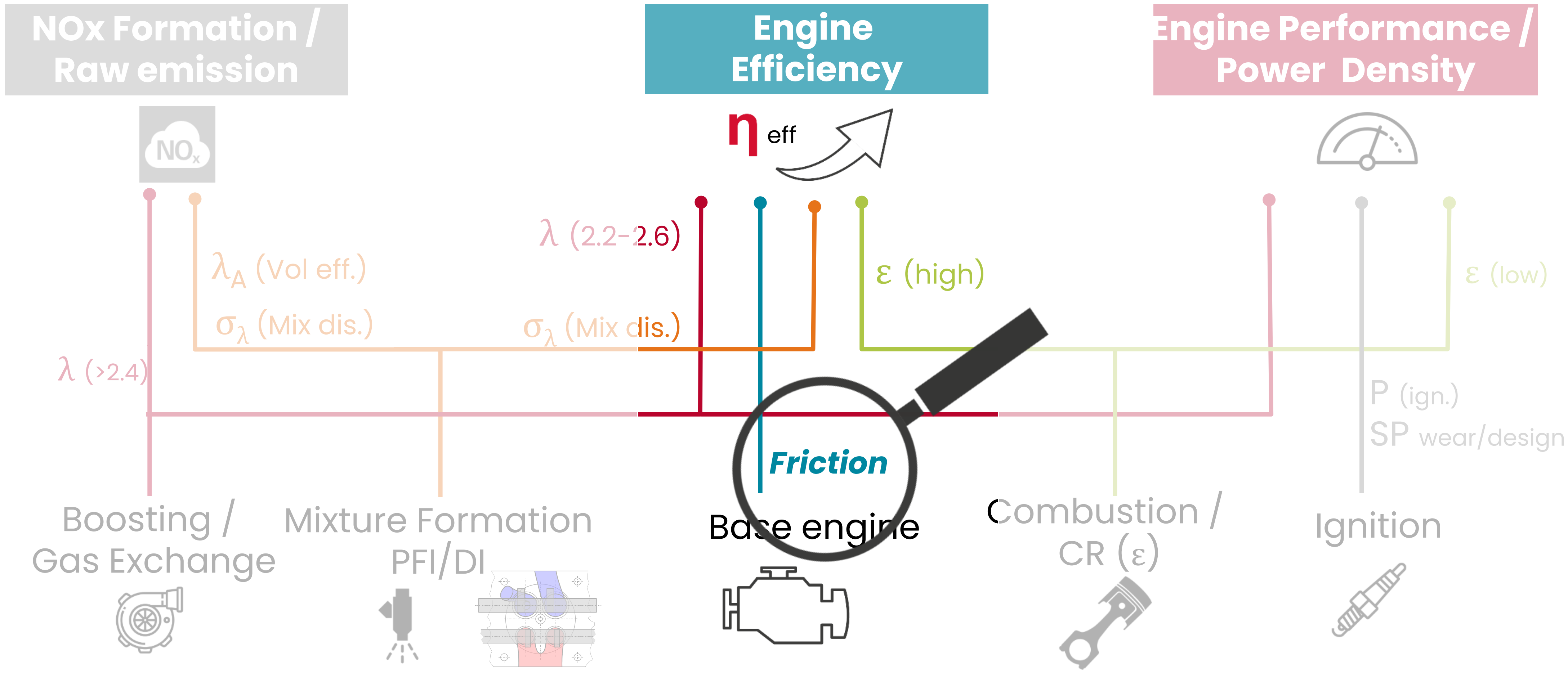
AGENDA

Three main output parameters performance, emissions and efficiency are mainly influenced by five major components or sub-systems



SP: spark plug, PFI: Port fuel injection, DI: Direct injection, AFR: Air fuel ratio, Mix dis.: mixture distribution, Vol. eff.: Volumetric efficiency

Three main output parameters performance, emissions and efficiency are mainly influenced by five major components or sub-systems



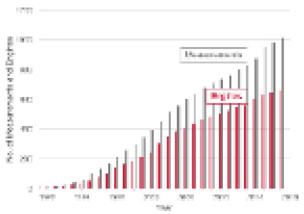
SP: spark plug, PFI: Port fuel injection, DI: Direct injection, AFR: Air fuel ratio, Mix dis.: mixture distribution, Vol. eff.: Volumetric efficiency

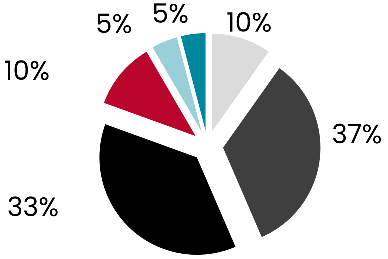
Reduction of Friction and Minimization of Losses characterize since decades a continuous optimization approach for increased thermal efficiency

FEV

Friction Estimation

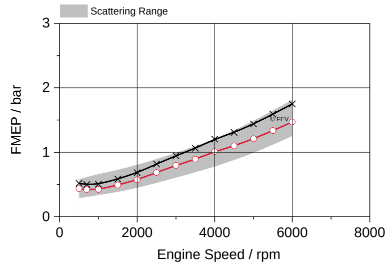
- FEV data base and bench (> 700 engines)
- Validated FEV friction estimation tool

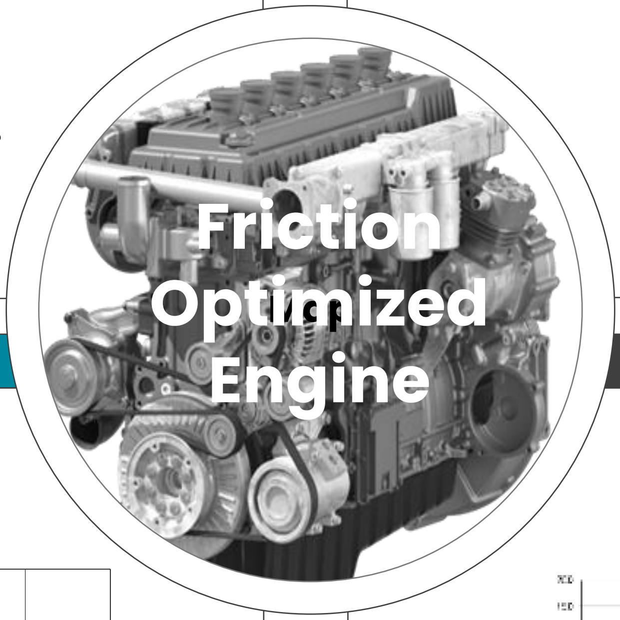




Motored Friction Investigations

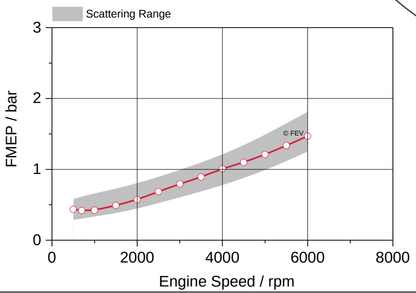
- Strip-down
- Supercharged
- Cold start behavior
- Cold strip-down
- FEAD optimizations under load





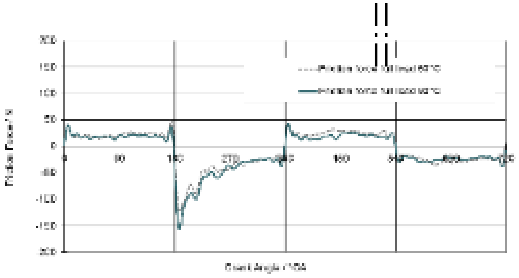
Fired Friction Investigations

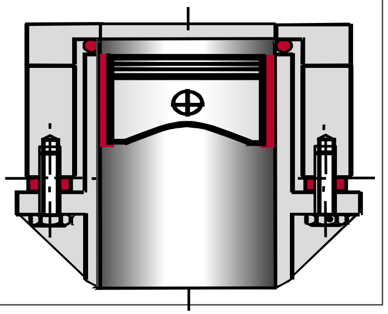
- Complete engine friction determination by cylinder pressure indication
- Cold fired friction for hybrid powertrains



PIFFO

- Dynamic Piston Friction Force
- Floating liner concept





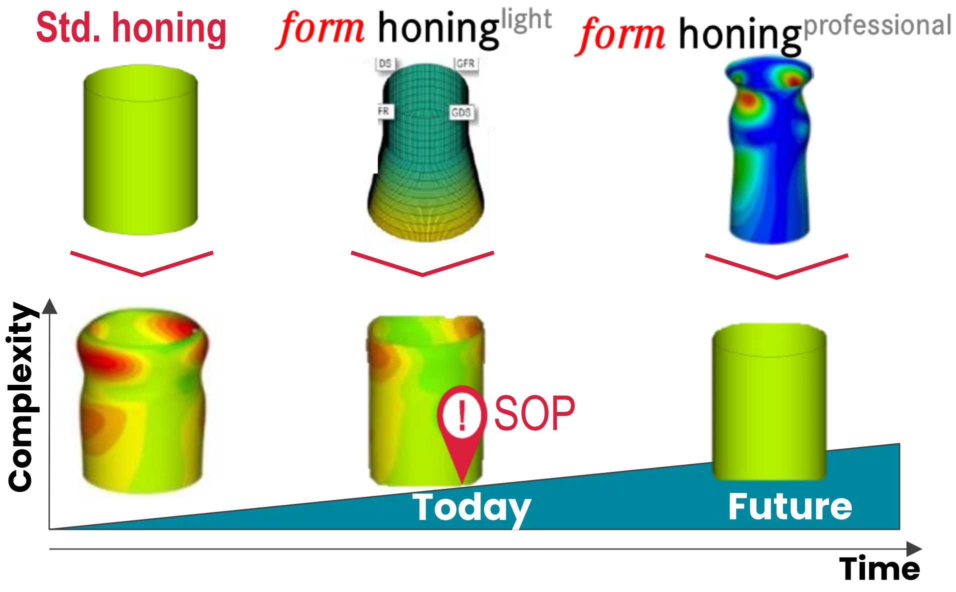
Advancements in fabrication of cylinder liners due to optimized layout and machining processes offer potential for better matching of clear

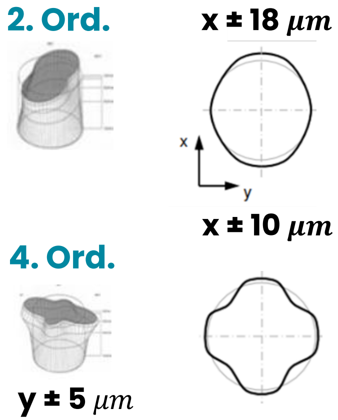
FEV

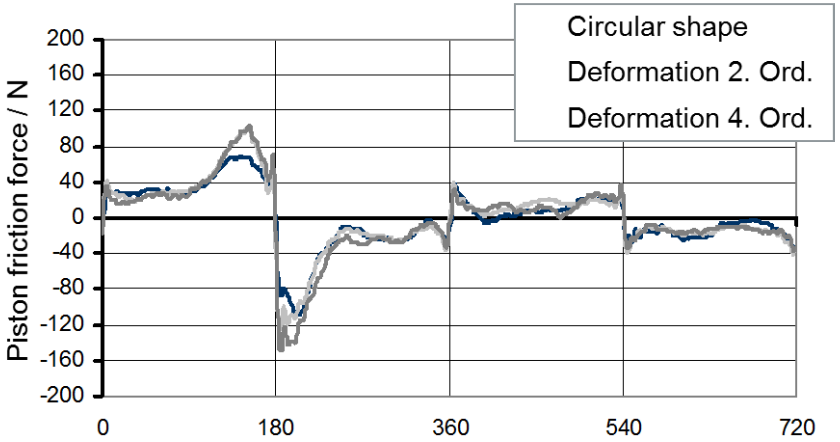
Machined state

ASSEMBLY & THERMAL DISTORTION

Shape in operation



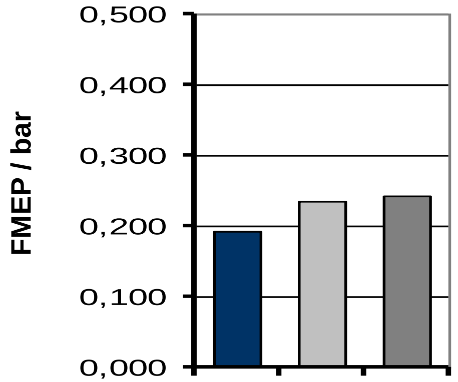




Source: Gehring; FEV

Form honing process & targets

- Compensation of assembly and thermal distortion
- Optimized liner shape for relevant engine operating conditions to:
  - Optimize piston clearance for low friction
  - Decrease piston ring tension for low friction w/o increasing oil consumption
  - Reduce oil consumption w/o increasing friction due to increased piston ring tension

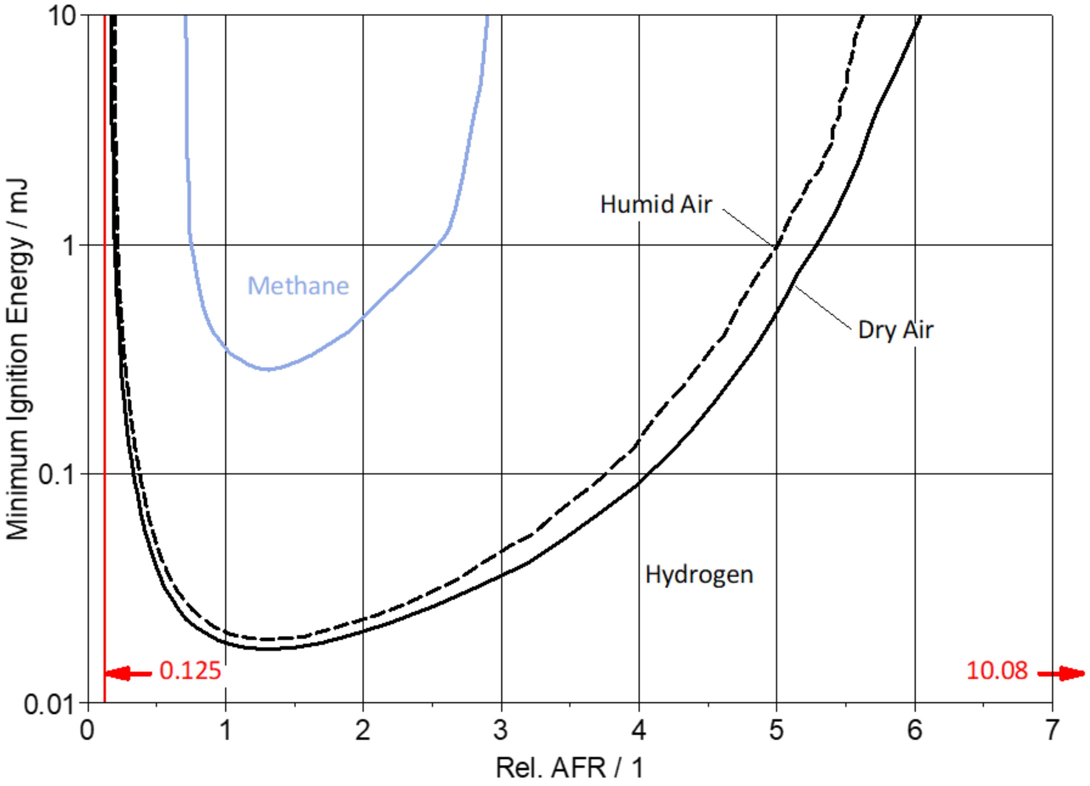


Hydrogen, often called the „Champagne“ of the energy transition, features multiple beneficial and some „challenging“ properties

FEV

Fuel Properties

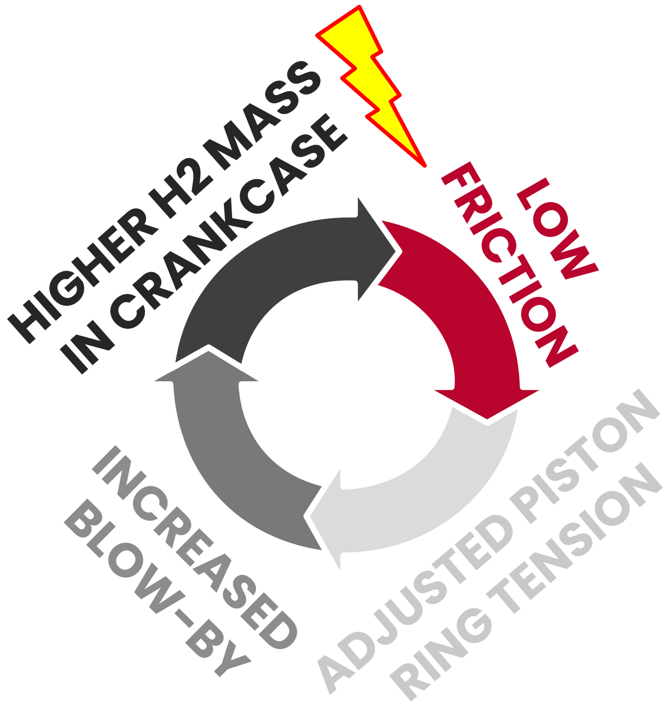
Property	Unit	Gasoline	Diesel	Methane	Hydrogen
Density @ 15°C	kg/m³	≈ 760 (l)	≈ 835 (l)	0.68 (g)	0.09 (g)
Stochiometric air demand	kgA/kgF	14.0	14.5	17.2	34.3
Lower heating value	MJ/kg	42.5	42.8	50.0	120.0
Gravimetric energy content	kWh/kg	11.1	11.7	13.9	33
Volumetric energy content	kWh/L	9.25 *liquid, 20°C, 1013mbar*	9.74 *liquid, 20°C, 1013mbar*	2.25 *gaseous, 20°C, 200bar*	0.85 *gaseous, 20°C, 350bar* 1.42 *gaseous, 20°C, 700bar* 2.34 *liquid, -253°C, 1013mbar*
Auto ignition temp.	°C	230-450	> 225	595	585
Minimum ignition energy	mJ	0.24	0.24	0.29	**0.02**
Flammability limits	λ	0.4-1.4	0.5-1.4	0.6-2.1	0.13-10
Laminar flame speed	cm/s	< 40	< 40	≈ 42	≈ 230



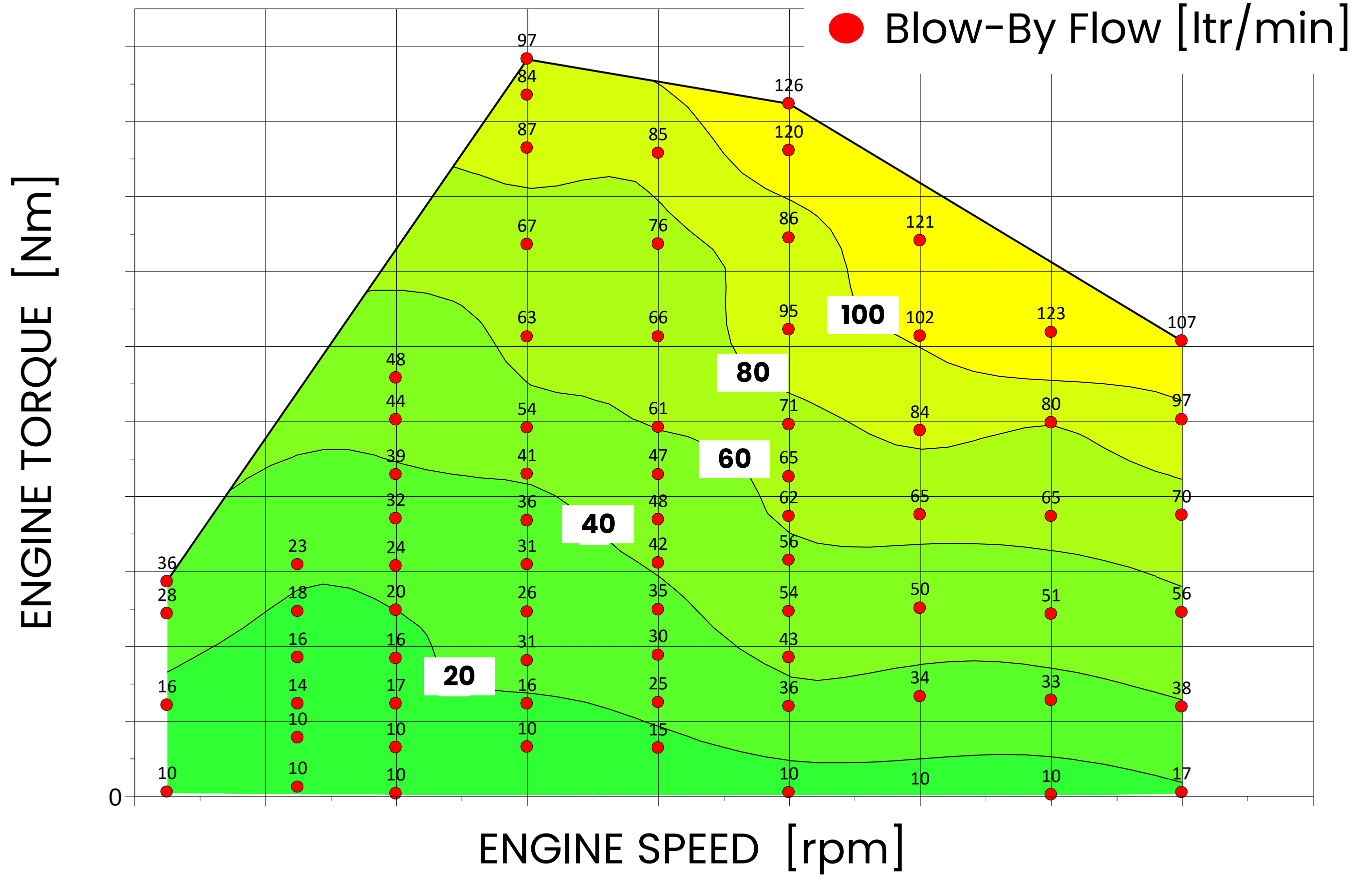
Efficiency Optimization covers multiple technical areas with contrary effects and consequences – careful evaluation mandatory

FEV

BLOW-BY MAPPING



REPRESENTATIVE ENGINE MAP



Values under 10l/min set to 10l/min

Two methodologies for the suppression of pre-ignition in hydrogen engines can be applied

REDUCTION OF PROVIDED IGNITION ENERGY

Identify possible sources for pre-ignition

- **Hotspots**
- **Oil droplets**

Find measures to reduce ignition energy

- **Improve cooling or heat transfer**
- **Optimize piston rings**

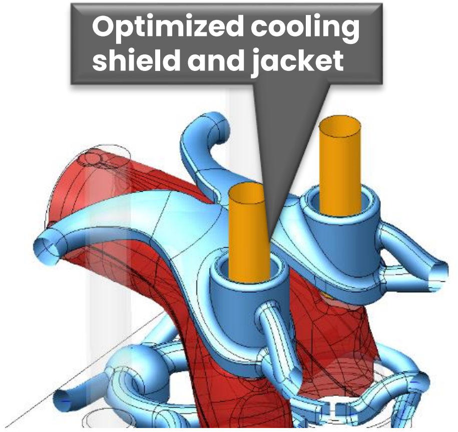
INCREASE OF REQUIRED IGNITION ENERGY

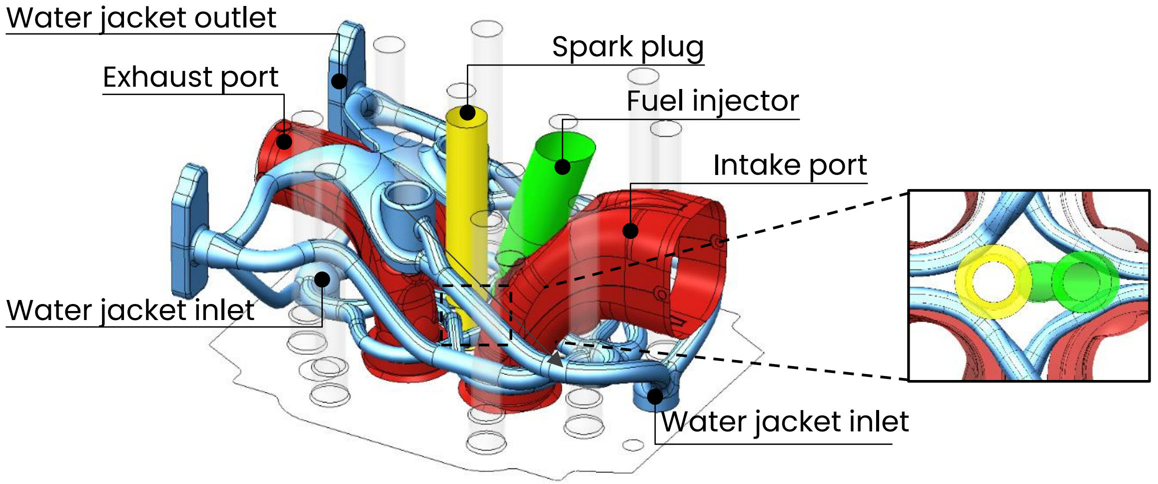
Influence air/fuel mixture to increase required ignition energy

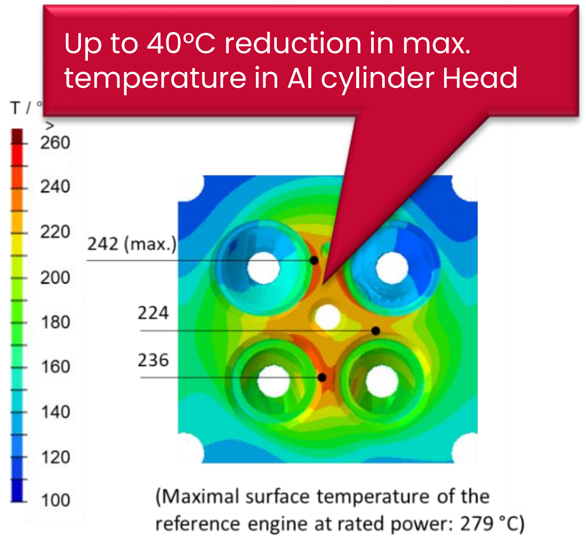
- **Mixture temperature**
  - **Improved charge air cooling**
- **Mixture composition**
  - **Enleanment**
  - **EGR**
  - **Water injection**

Precise cooling with increased flow velocities due to small channel diameter allowing improved cooling capability of hot zones

FEV ARTERY COOLING CONCEPT IS SECURED BY A PATENT







- Increased exhaust valve cooling due to special cooling jacket of valve stem for cooled exhaust valves
- Optimized cooling shield of exhaust port for maximizing exhaust enthalpy

- Manufacturing method:
  - Water jacket produced with additive manufacturing for 3D sand core and maintaining average artery diameter of 8mm enables conventional casting process for cylinder heads (cast iron and aluminum)
- Cooling method:
  - Increased flow velocities at the coolant channels due to small channel diameter allowing increased cooling capability of hot zone e.g. spark plug & DI injector

- Superior flame deck cooling of spark plug & DI injector
- High cooling performance due to close arteria guidance
- Precise cooling w/ small channel diameters leads to higher stiffness of cylinder head and allows usage of optimized materials

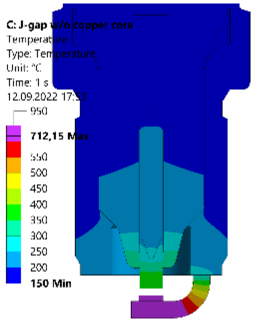
Source: FEV

For enhancement of thermal efficiency high temperature components demand optimization and refinement in order to mitigate pre-ignition tendencies

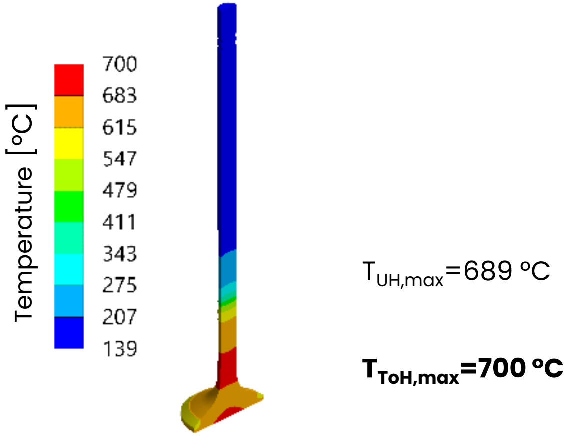
FEV

Hot

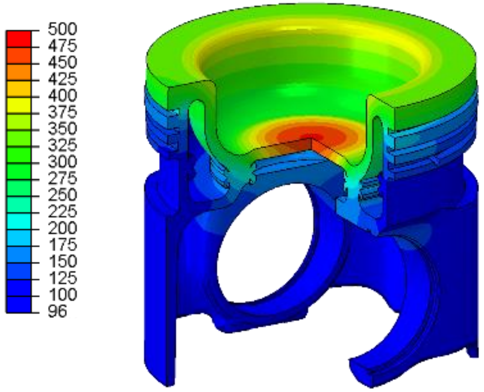
J-GAP SPARK PLUG, **MAX 712°C**



SOLID VALVE, **MAX 700°C**

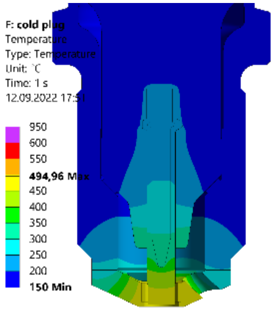


STEEL W/ SINGLE OIL JET, **MAX 478°C**

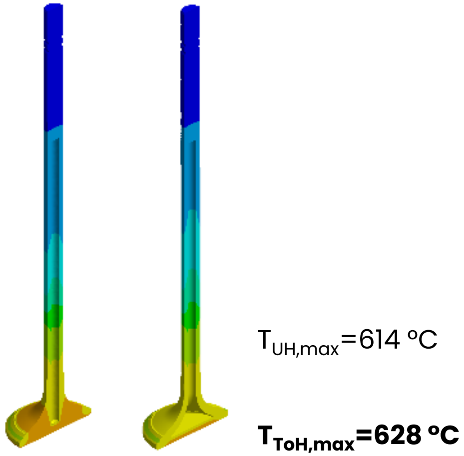


Cold

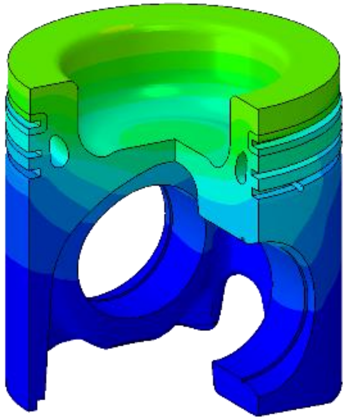
COLD SPARK PLUG, **MAX 495°C**



HOLLOW VALVE, **MAX 628°C**



ALU W/ DUAL OIL JET, **MAX. 335°C**



Source: Tenneco

AGENDA

INTRODUCTION AND STATUS

ENGINE DESIGN AND MECHANICS

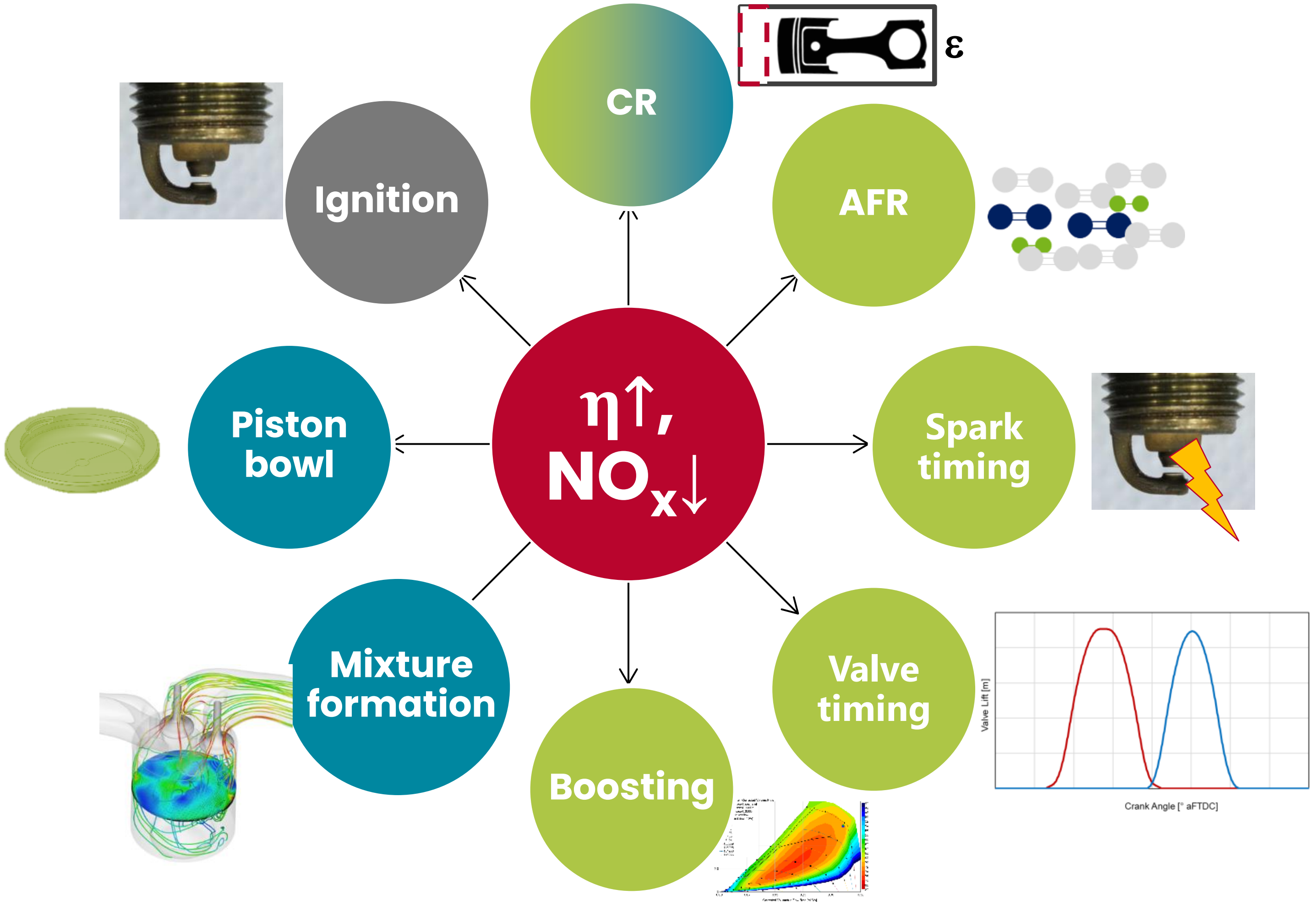
THERMODYNAMIC OPTIMIZATION

RESULTS AND ACHIEVEMENTS

SUMMARY AND COCLUSIONS

High efficiency, low NOx emissions and knock mitigation summarize the main engineering activities for optimization by usage of advanced CAE tools

POWERFUL TOOL CHAIN FOR LAYOUT AND OPTIMIZATION – VALIDATED BY MEASUREMENTS AND ANALYSIS



1-D Simulation

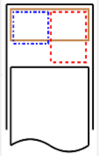
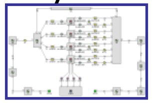
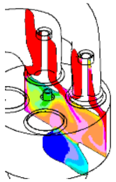
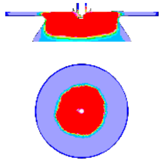
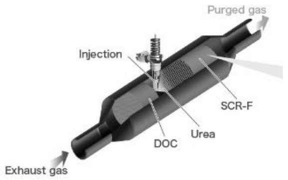
3-D Simulation

Peripheral systems

For leveling up of hydrogen-fueled internal combustion engines FEV applies an advanced and tailored 0D to 3D simulation tool chain

FEV

INTEGRATED TOOL CHAIN SUPPORTS ACCELERATED DEVELOPMENT FROM CONCEPT DEFINITION TO SOP

Input	▪ Bore, Stroke, operation parameters ▪ Reaction Kinetics & sL	▪ Air path geometry ▪ TC maps	▪ Port & camshaft variants ▪ H2 injector	▪ In-Cylinder Reaction Kinetics	▪ EATS Reaction Kinetics
Model	0-D Entrainment  Matlab + Cantera	1-D Gas exchange Simulation/TC layout  GT-Power	3-D CFD Mixing simulation  Converge CFD	3-D CFD Combustion  Converge CFD	1D /3-D CFD Aftertreatment 
Output	▪ Heat release rate	▪ Intake and exhaust pressure ▪ Valve timings	▪ Conditions at IVC, gas, flow, turbulence, distribution	▪ Knock ▪ HTC ▪ EO-NOx	▪ TP-NOx
H/W Definition	▪ Compression Ratio	▪ Valve timings ▪ TC ▪ Air-exhaust path	▪ Injector specifications and location	▪ Spark plug location and piston bowl	▪ Catalyst Volume/Spec ▪ Positioning

FEV Signature Solutions
CMD Process for H_2 ICE

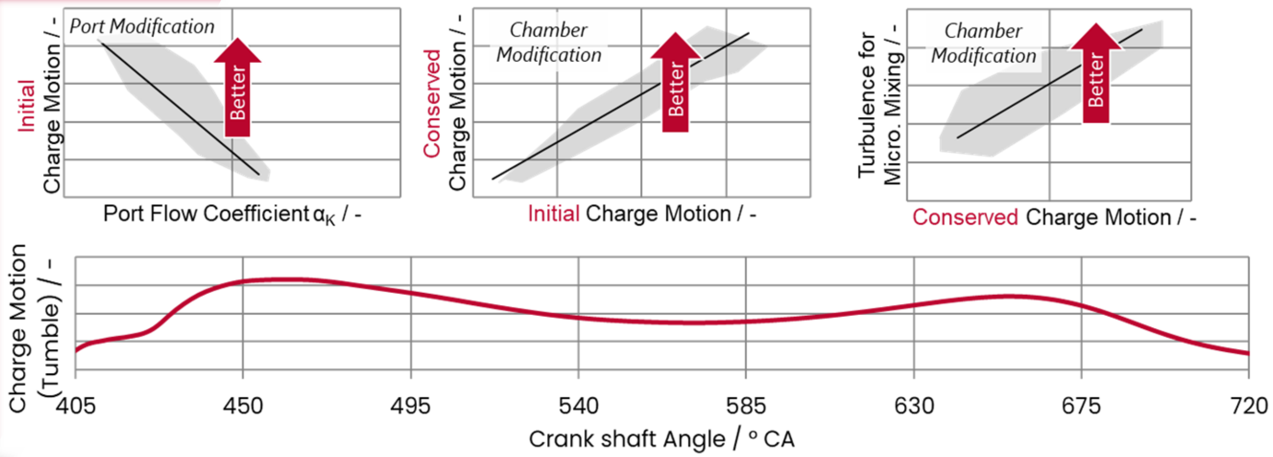
Charge Motion Design (CMD) process enables effective mixture formation for H_2 ICE based on charge motion & turbulence

FEV offers

- Determination of port quality and comparison to benchmark
- Evaluation of charge motion & turbulence level in pre-development stage
- Estimation of burn duration for HRR estimation
- Optimization of mixture formation layout via 3D CFD simulations
- Comparison of customer layout with FEV benchmark

Why FEV

- >30 scatter bands from previous engine developments to identify weak points
- More than 80 different premixed engine concepts ranging from pass-car to heavy duty applications (see reference slides)
- Optimization of relevant design parameters based on scatter band data



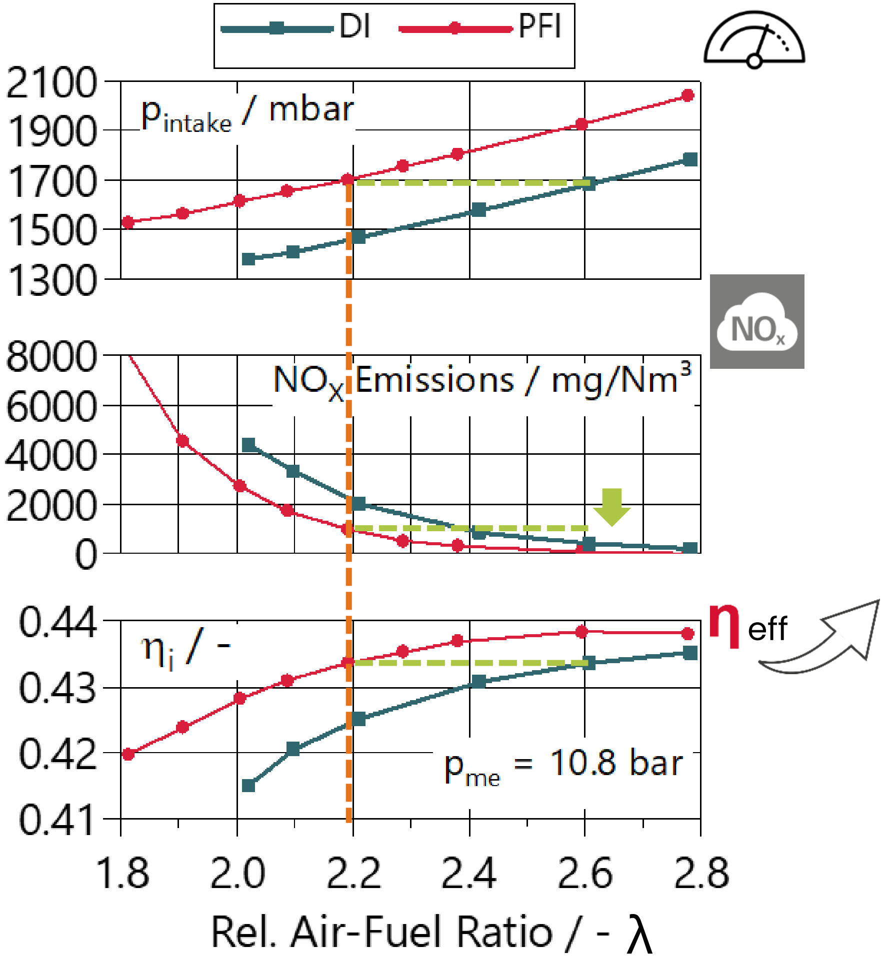
Challenge for DI technology is providing "PFI like" mixture homogeneity for low NO_X raw emissions while maintaining key benefits of DI technology

FEV

HYDROGEN DI APPLICATION REACHING EFFICIENCIES OF 44 %

HD SCE 2.13l

- Base engine:
  - OM471 diesel engine
  - No charge motion
- For hydrogen operation:
  - Reduced CR



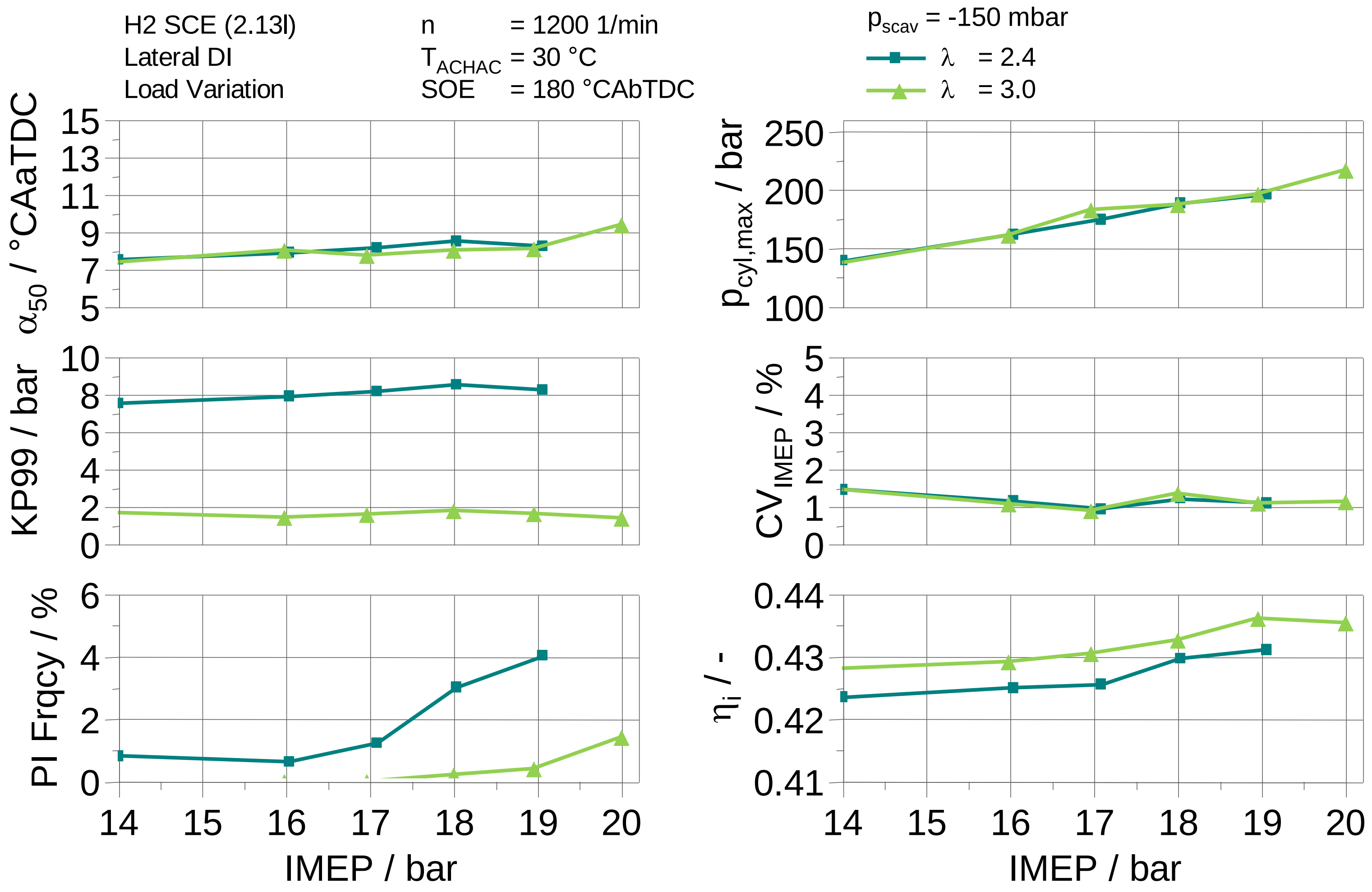
- For comparison on constant BMEP level and constant lambda, DI technology has drawback on engine NOx emissions and engine efficiency
- For real engine operation comparison on same boost pressure level more realistic, here DI offers benefit in NOx at same engine efficiency level
- Further improvement in mixture homogeneity will even raise DI benefits

CoC: Center of Combustion

Lean H2 combustion and boosting concepts
Dilution Strategies for H2ICE – Ultra Lean Operation

FEV

ULTRA LEAN STRATEGY



KEY FINDINGS

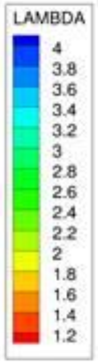
- Maximum peak pressure of all recorded cycles on a similar level
- KP99 (99th percentile of knock peak-to-peak value) is significantly reduced by enleaning the mixture
- Enleanment has no measurable effect on combustion stability
- PI are significantly reduced when further enleaning the mixture
- Enleaning the engine positively impacts the efficiency

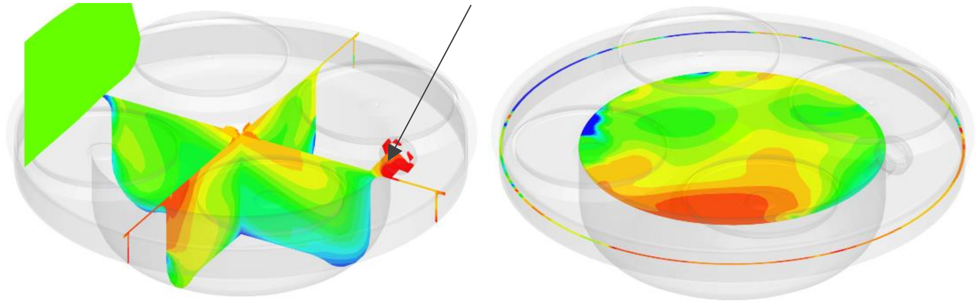
Introduction of tumble blends, asymmetric bottom chamfers and central injectors reduces the rich zones and improves homogeneity

FEV HD SCE
Rated power

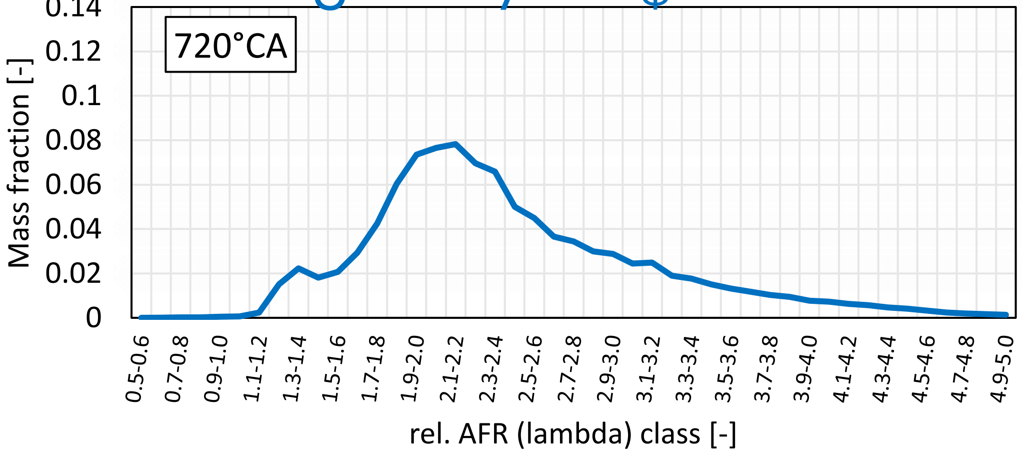
BASE GEOMETRY

- Side injector, FEV patented integrated spray cap



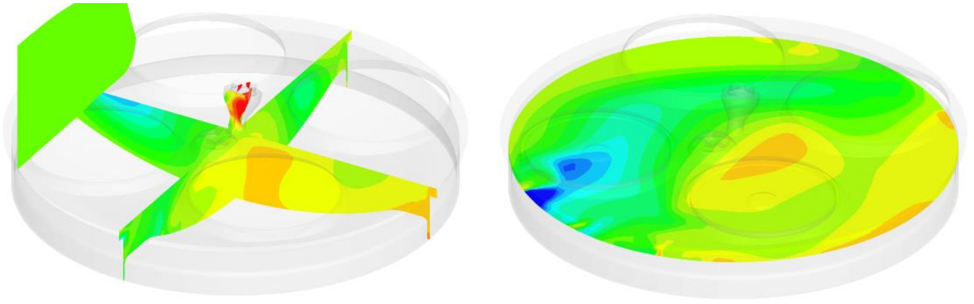


Homogeneity $\mathrm{Rel}\sigma_{\Phi}$ = 29%

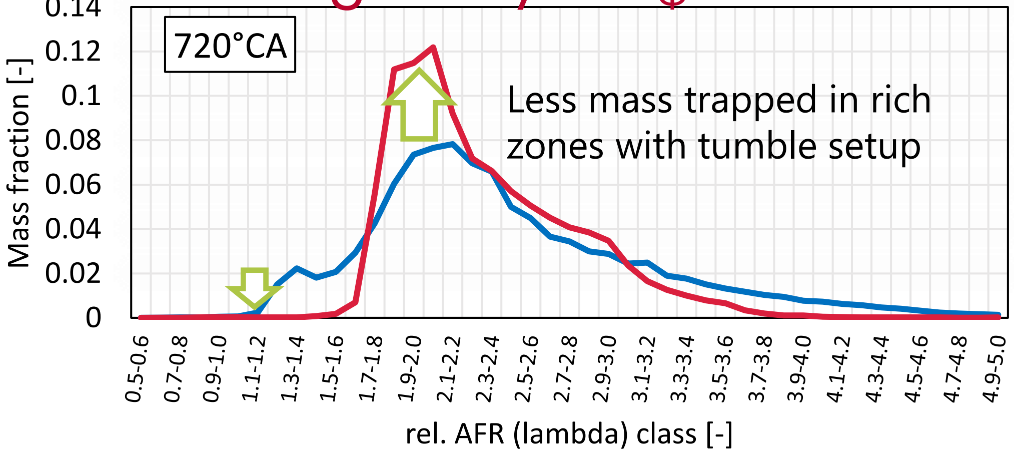


OPTIMIZED GEOMETRY

- Central injector, tumble blends, bottom chamfers & lens piston



Homogeneity $\mathrm{Rel}\sigma_{\Phi}$ = 18%

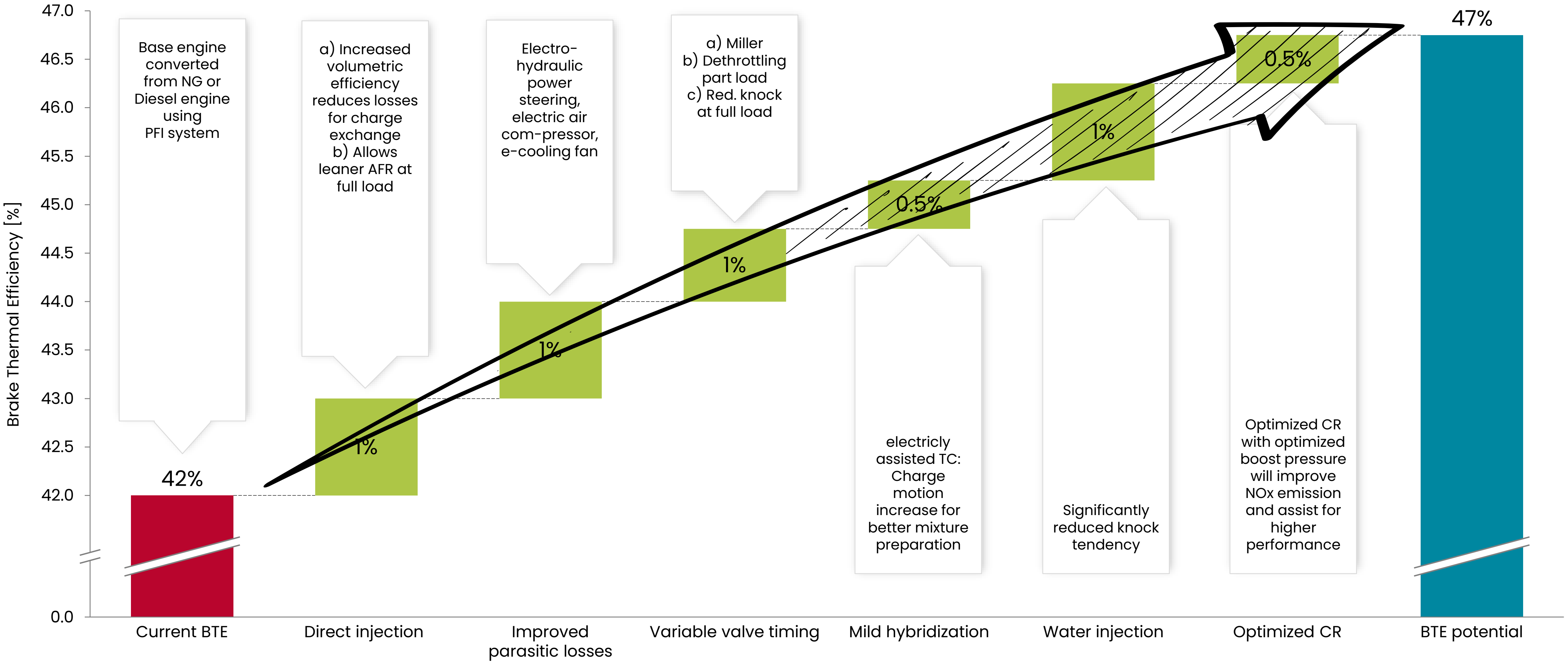


Simulation results at rated power, SOI 540°CA, cut sections at 720°CA
$\mathrm{Rel}\sigma_{\Phi}$ = Relative standard deviation of equivalence ratio. Smaller values denote better mixing and homogeneity

AGENDA

H2 ICE: Thermal efficiency of ~47% for future high tech package DI possible

HYDROGEN COMBUSTION ENGINE – OUTLOOK



Source: FEV

AGENDA

INTRODUCTION AND STATUS

ENGINE DESIGN AND MECHANICS

THERMODYNAMIC OPTIMIZATION

RESULTS AND ACHIEVEMENTS

SUMMARY AND COCLUSIONS

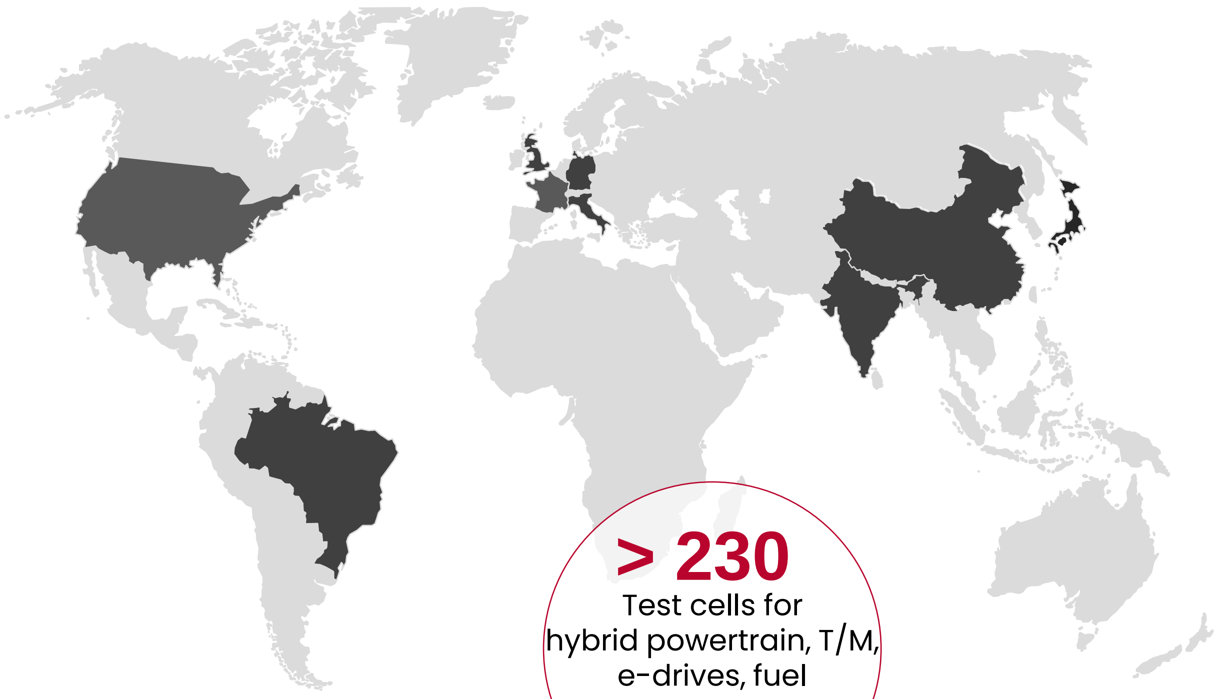
SUMMARY

H2-ICE features the potential to power short- and mid-term applivcations with a high thermal efficiency

- **Existing as well as Upcoming Fleet** determines GHG reduction potential in the oncoming years
  - **Renewable Energy Directive** – RNFBO share key enabler to achieve the agreed Fit for 55% Ambition
  - **Fast transition** towards **sustainable** propulsion concepts mandatory
- ICE w/ renewable fuel is one mature solution with a **fast-to-market** approach
- H2-ICE needs to perform at **same transport efficiency** as currently available in the market, therefore objectives for on-going developments are to **improve performance** and **efficiency** of H2-ICE, while maintaining reliability and ultra-low emission behavior
- **Pre-ignition** represents a main challenge for H2-ICE, and impacts further efficiency achievements, but with **solutions** available in the areas of
  - Reduction of Engine Losses and Mechanical Friction
  - Optimization of fuel introduction and mixture formation towards **maximum (PFI-like) homogeneity**
  - **Lubrication and component development** to reduce pre-ignition by hot spots and 'oil droplets'
  - Improvement in the areas of **heat transfer** and **local cooling** by implementation of steel piston and **thermal swing coatings**, critical component **temperature reduction** and the use of the **FEV's Artery Cooling Concept** cylinder head

Hydrogen propulsion system testing facilities close to our customers

OVERVIEW OF KEY FEV HYDROGEN TEST CENTERS



> 230
Test cells for hybrid powertrain, T/M, e-drives, fuel cells & battery packs

1	HQ Aachen, GER		14 H_2 test cells
2	Coventry, UK		5 H_2 test cells
3	Trappes/Rouen, FRA		3 H_2 test cells
4	Pune, IN		2 H_2 test cells
5	Auburn Hills, USA		2 H_2 test cells
6	Beijing, CN		1 H_2 test cell

Smart ways to leverage power density and thermal efficiency of 2nd Gen. H2 ICE's

FEV

National Motorcycle Museum,
Solihull/UK, March 13th, 2025

H. Busch / FEV Vehicle GmbH

Prepared for

FPC2025
Future Propulsion Conference

PUBLICATION