Direct Injection Wasserstoffmotoren für Nutzfahrzeuge

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automotive engineering iav

IAV

Agenda

Introduction

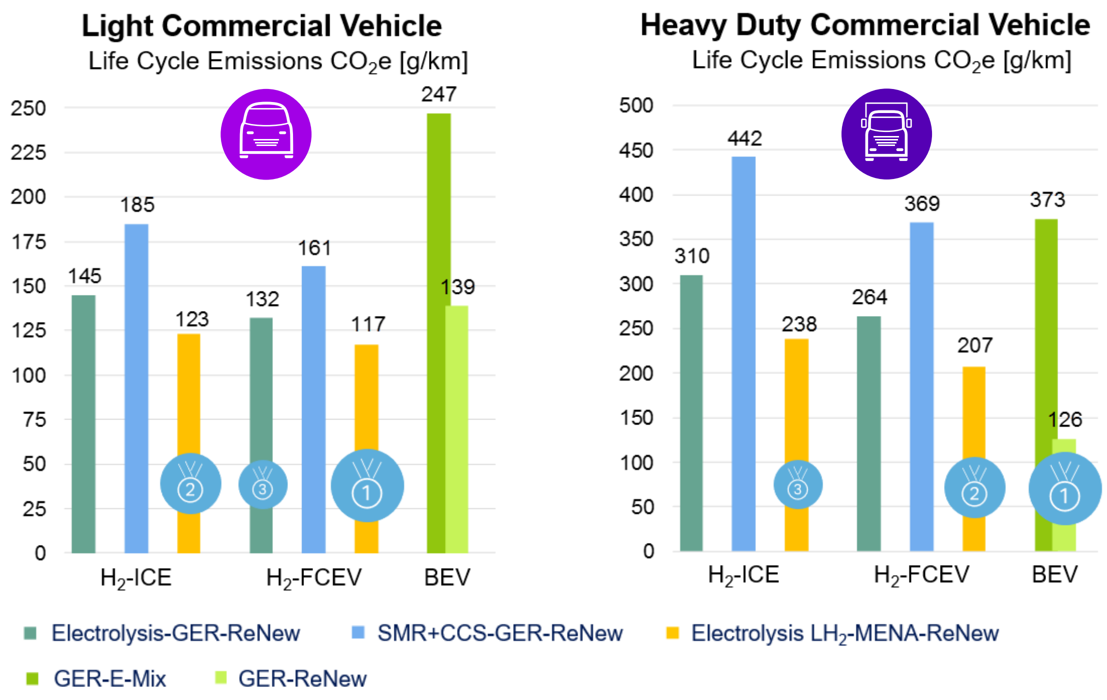
H2-ICE Development

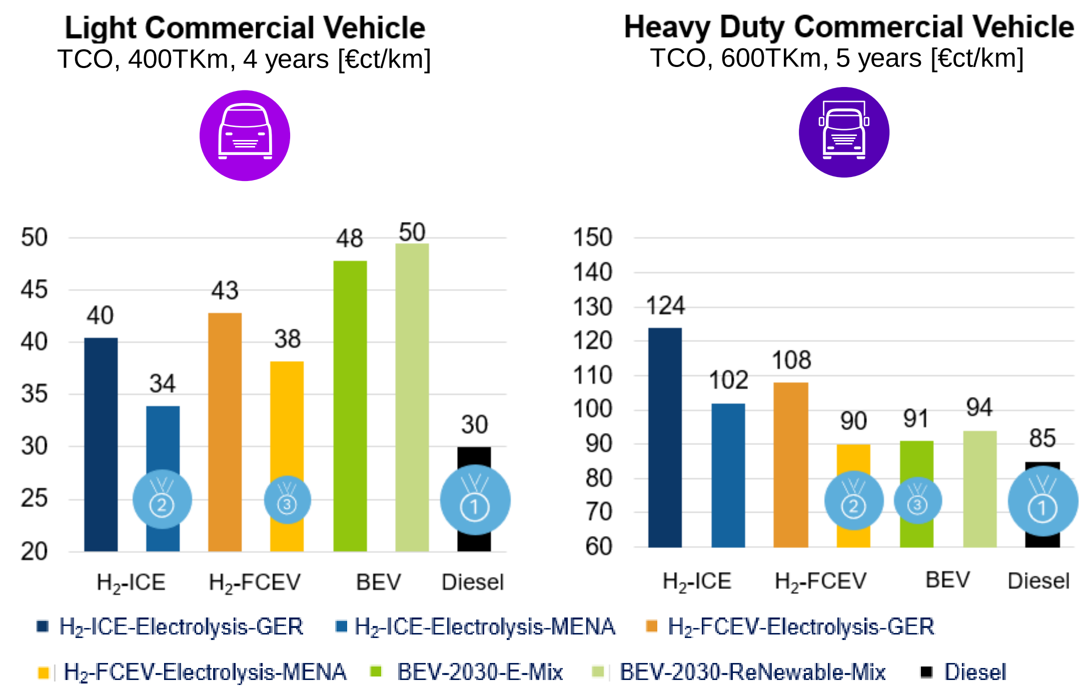
- PFI vs. LPDI
- LPDI mixture preparation
- Exhaust Aftertreatment

Summary and Outlook

Introduction and Motivation

Why H_2 ICE?





Sustainability – view*:

LCV: Fuelcell and H2-ICE are very close, while the BEV shows clearly the highest life cycle GHG emissions

HD: Usage phase with high mileage dominates the life cycle. This leads to an advantage of the BEV´s charged with 100 % renewable energy. So the battery CO2-backpack of the BEV pays off at the end of life.

TCO – view*:

LCV: ICE powertrains dominate the TCO ranking. H2-ICE will be competitive to Diesel beyond 2030.

HD: Usage phase with high mileage dominates the life cycle. This leads to an advantage of the BEV´s charged with 100 % renewable energy. So the battery CO2-backpack of the BEV pays off at the end of life.

* from: Hydrogen Powertrains in Competition to Fossil Fuel based Internal Combustion Engines and Battery Electric Powertrains; Vienna 2021, Sens et.al.

Introduction and Motivation

Why H_2 ICE?

Light Commercial Vehicle | Heavy Duty Commercial Vehicle | Light Commercial Vehicle | Heavy Duty Commercial Vehicle

- H2 ICEs are important ecological and economical alternatives to other Zero-CO2 propulsion concepts.
- On long term H2 FCEV may be in advantage over H2 ICE, however H2 ICE is important as short and midterm solution in LCV and HDV applications.
- Among all competing technologies, the (H2) ICE comes with the highest TRL and is based on a mature concept.

battery CO2-backpack of the BEV pays off at the end of life.

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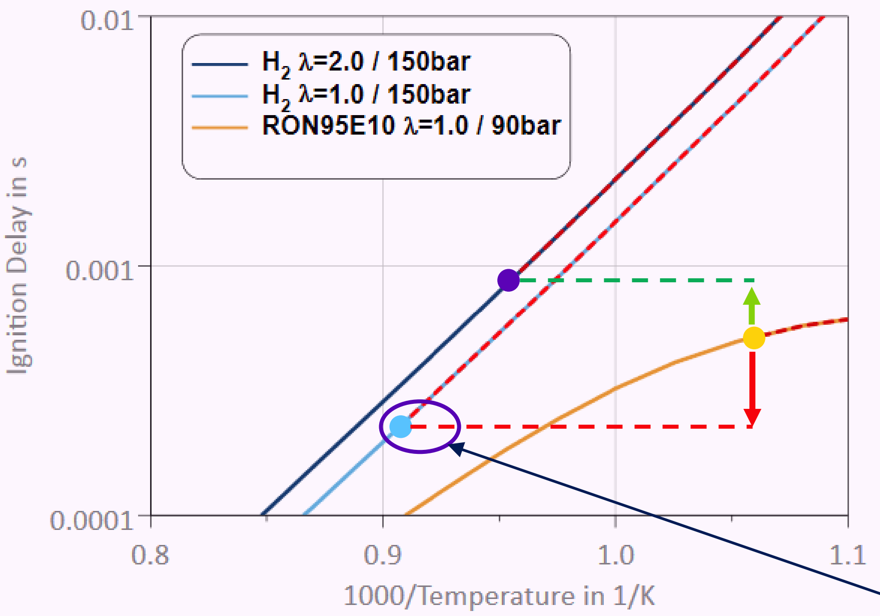
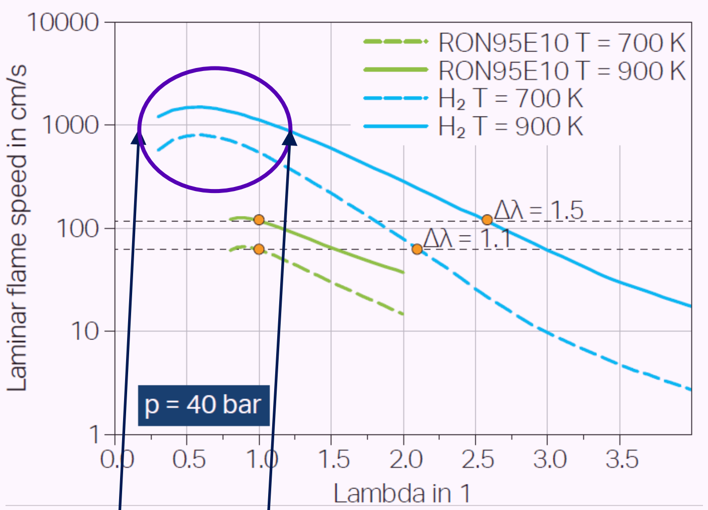
Introduction and Motivation

Challenges and Chances of H2 as ICE fuel

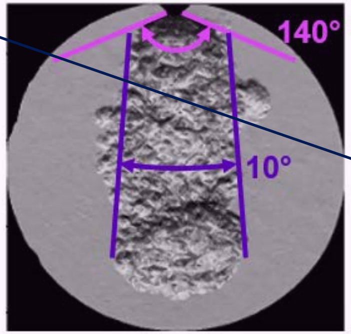
Auto-Ignition

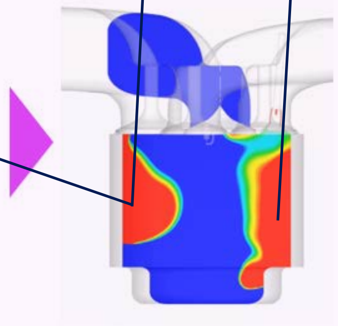


Combustion speed



Mixture Preparation

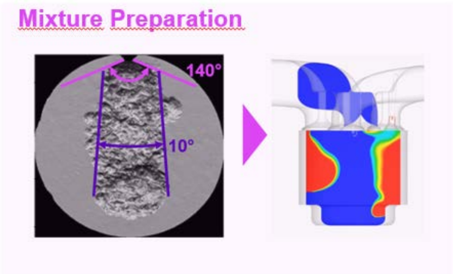




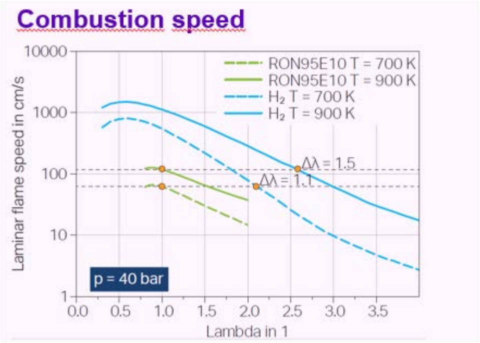
- Specifically LPDI mixture preparation is challenging due to spray contraction and short time interval, eventually leading to inhomogeneities.

Introduction and Motivation

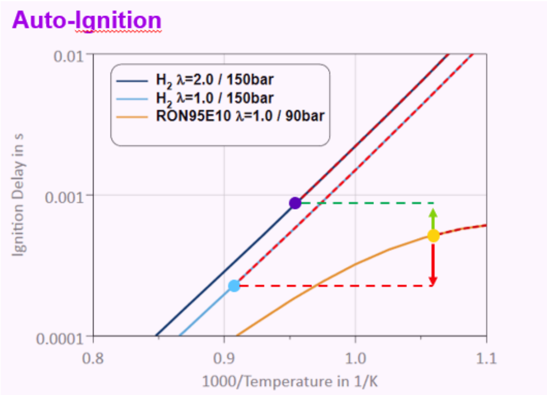
Challenges and Chances of H2 as ICE fuel



- Sufficient mixture preparation is the most crucial issue with H2-ICE
- Beneficial diffusion behaviour of H2 compared to other fuels playing only a minor role due to the relevant time scales.
- Deviations from good homogeneity comes with issues in combustion- and emissions performance.



- H2 features fast combustion even in diluted / lean conditions
- While this fast combustion is beneficial for efficiency and combustion stability, it also creates a high temperature in the flame area
- Minimum global lambda in the map shall be around ~2 with only small local deviations ($\sigma_{(\lambda)}$ < 0.1) in order to avoid severe NOx creation



- Faster H2 combustion leads to increased p_{cyl} and T_{cyl} compared to gasoline
- Ultimately, high p and T lead to drastically reduced ignition delay → auto-ignition
- Dilution (air / EGR) mitigates this issue and enable operation at higher spec power
- Poor homogeneity and rich spots need to be avoided (PI, Knock, Backfire)

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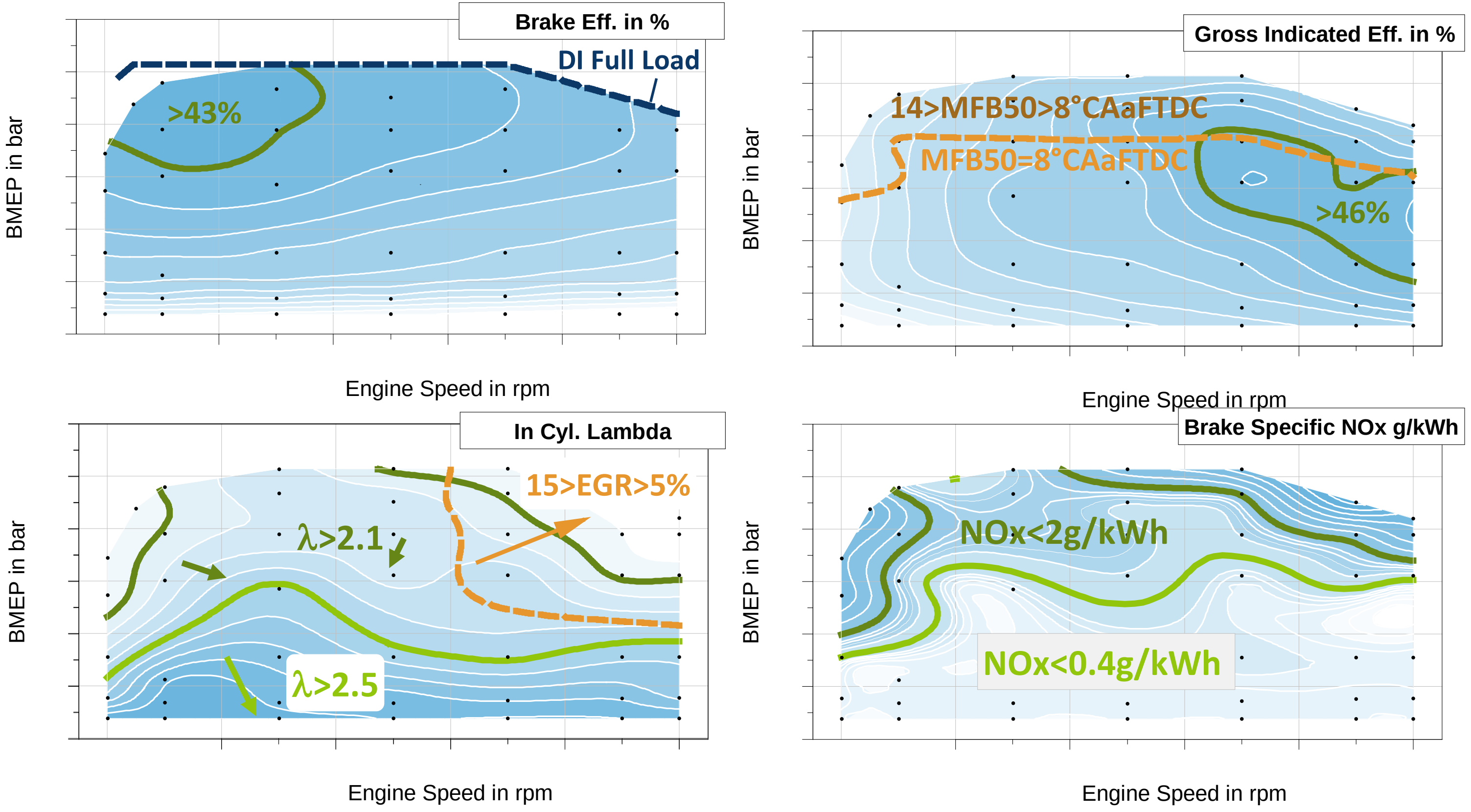
H2-ICE Development

Application Example of a PFI hydrogen engine

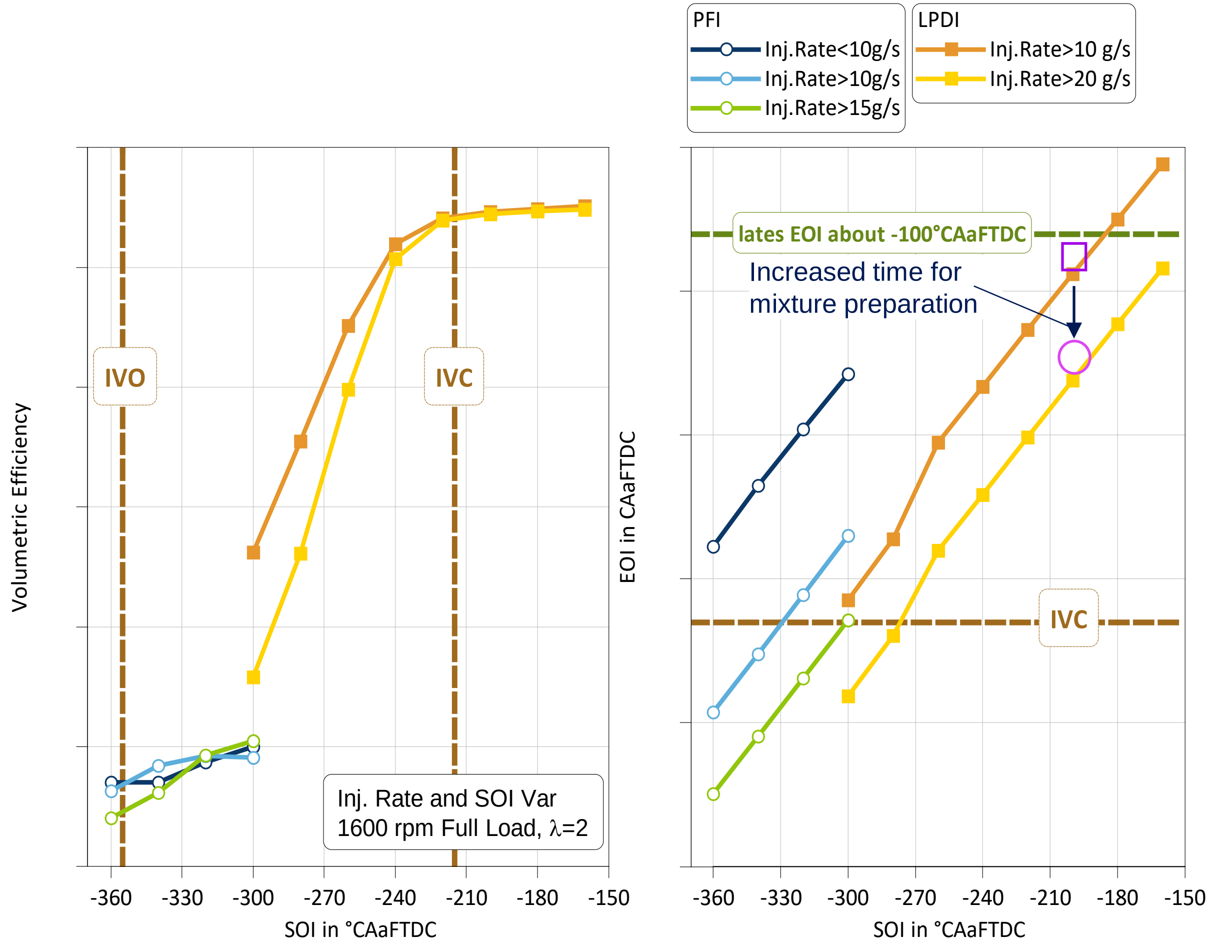


- Two stage-turbocharged
- High charge dilution potential (λ>2.1)
  - Caloric benefit (GIE>46%,BTE>43%)
  - Very low NOx emission level
  - Knock mitigation
- Cooled EGR (5… 15%) at rated power area with further benefits:
- Lower boost request (PMEP reduction)
- NOx reduction at “richer” charge
- Strong knock mitigation

- PFI System with benefits concerning mixture preparation but drawbacks in performance compared to LPDI due to lower volumetric efficiency

H2-ICE Development

Injection System Comparison PFI vs. LPDI

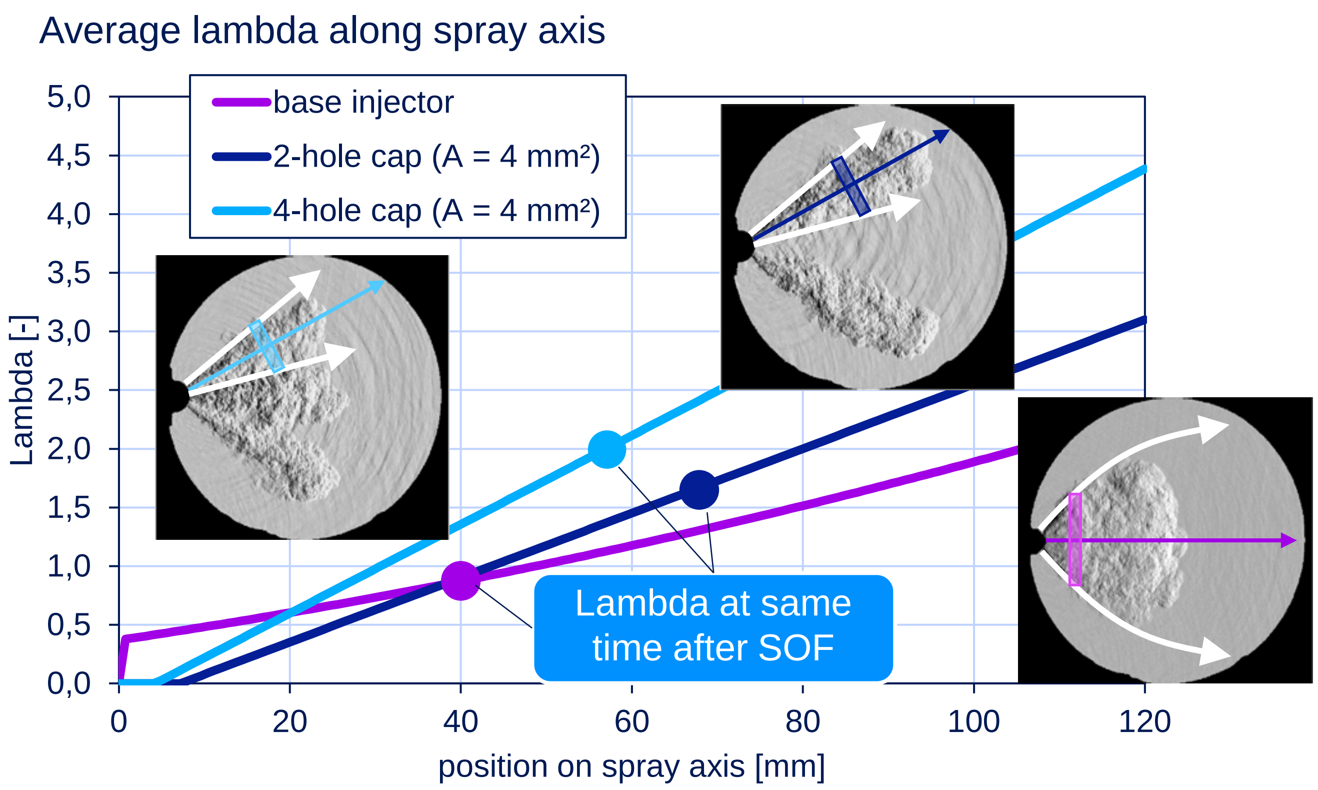


- LPDI: Later SOI increases volumetric efficiency when SOI gets closer to IVC and remains constant after IVC → reduced displacement effect of H2
- Higher injection rate increases time for mixture preparation
- PFI system has generally much more time and volume (flow distance from injector into cyl.) for a homogenous mixture preparation compared with LPDI
- High injection rate “also” for PFI system meaningful in order place entire mass during open valve phase:
- Ideal PFI injection time with SOI shortly after IVO; EOI well before IVC in order to avoid ignitable air-H2 mixture in intake port → **backfire risk!**

H2-ICE Development

LPDI Spray Formation

Comparison of air entrainment into the spray cloud: outward opening nozzle vs. multi hole nozzles



- At 40 mm (resp. 20 mm) distance the average lambda values are same for base injector and 2-hole (4-hole) cap sprays!
- Beyond that distances multi hole nozzles provide improved mixing quality in terms of air entrainment (lambda value) at spray front!
- Thus, multi hole caps provide
  - an improved spatial gas distribution within the combustion chamber,
  - best performance in terms of nozzle positioning at the cylinder head,
  - **best choice for big engines** (> 60 mm free penetration length at EOI).

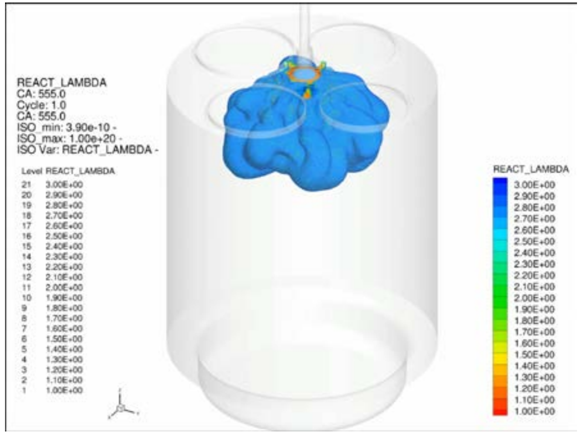
- A-Nozzle provides only poor penetration / air entrainment → Multihole caps needed for spray forming

H2-ICE Development

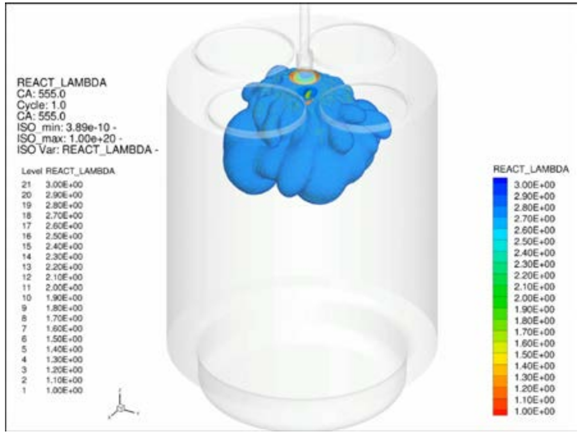
LPDI Mixture Preparation / Injector cap variation

1600rpm / FL

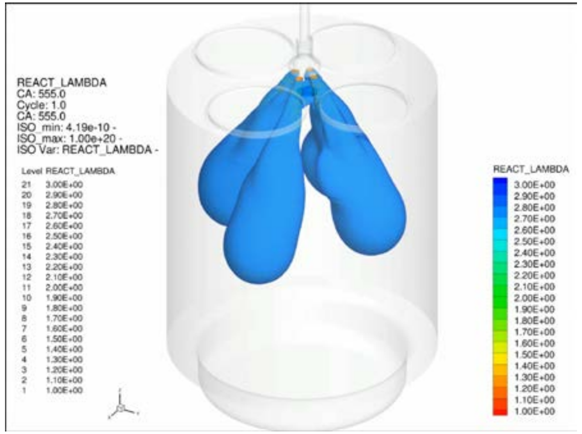
swirl = 0, no cap 0 mm



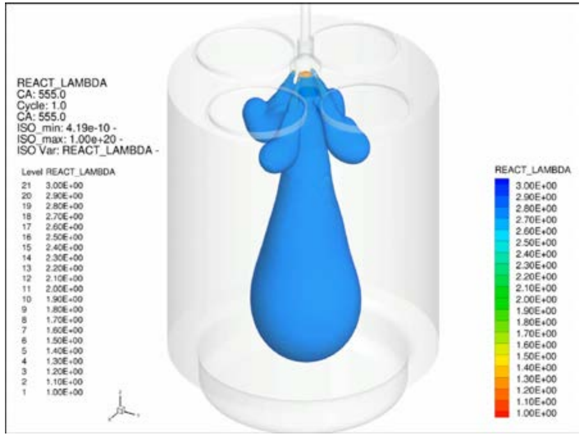
swirl = 0, no cap +1.6 mm



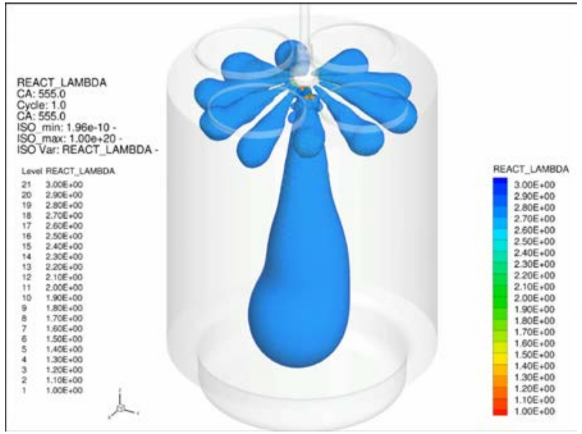
swirl = 0, 4-hole cap



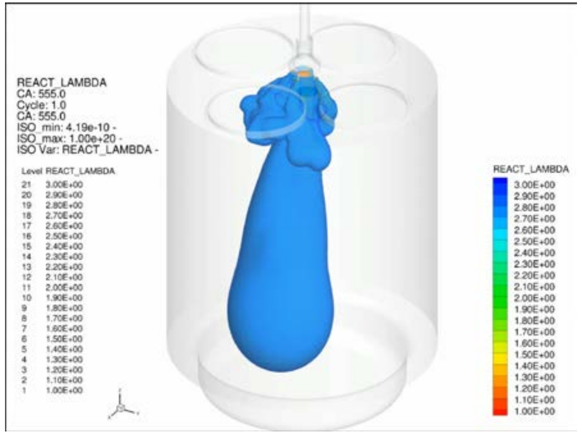
swirl = 0, 5-hole cap



swirl = 0, 11-hole cap



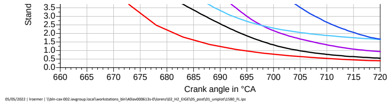
swirl = 5, 5-hole cap

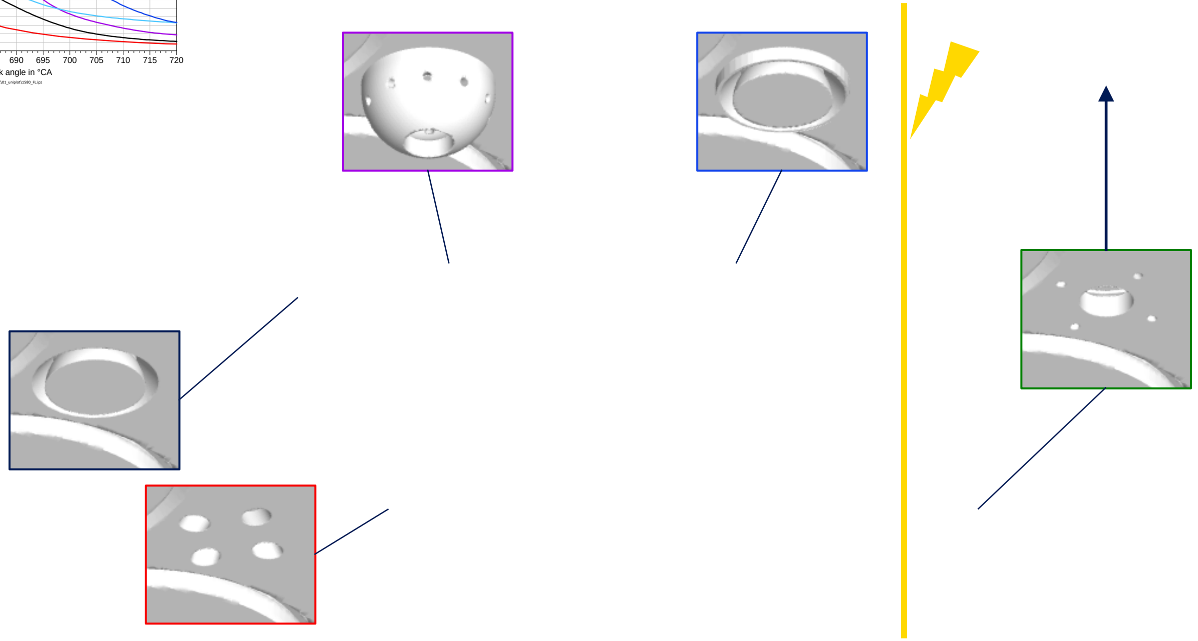


H2-ICE Development

LPDI Mixture Preparation / Injector cap variation

1600rpm / FL





- The standard deviation of lambda is a **homogeneity indicator**. The lower the value the better the mixture. Desired values here are **below 0.1**.
- Injector position +1.6 mm into the cylinder leads to a worse homogeneity.
- The 4-hole cap is showing the lowest standard deviation, i.e. the most homogenic mixture.
- The effect of the swirl is shown with the 5-hole cap, where increasing the swirl results in a significant homogeneity increase.

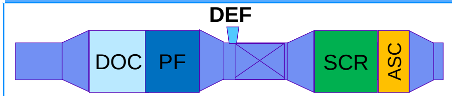
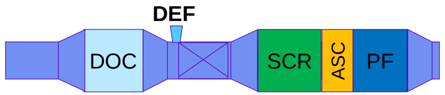
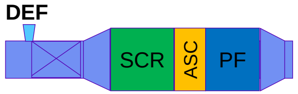
- Careful development of injector position and cap design needed to deliver good homogenization. Still, proper charge motion is greatest lever to improve homogeneity

H2-ICE Development

EAT layout investigations

Evaluation of different EAT layouts for HD engine

- Holistic investigation of 3 different EAT layouts via coupled simulation (Engine & EAT models)
- Optimization of transient engine control to allow fast engine load build-up with low NOx EO emissions:
  - throttle valve
  - boost pressure control (waste gate / VTG)
  - mixture enrichment
  - spark shift
  - EGR control
- Optimization of DEF dosing strategy to enable high NOx conversion with low NH_3 slip

	Fulfills proposed EUVII legislation		
EAT Layout	**NOx**	**NH3**	**N2O**
	✓	✓	✓
	✓	✓	✓
	✓	✓	✓

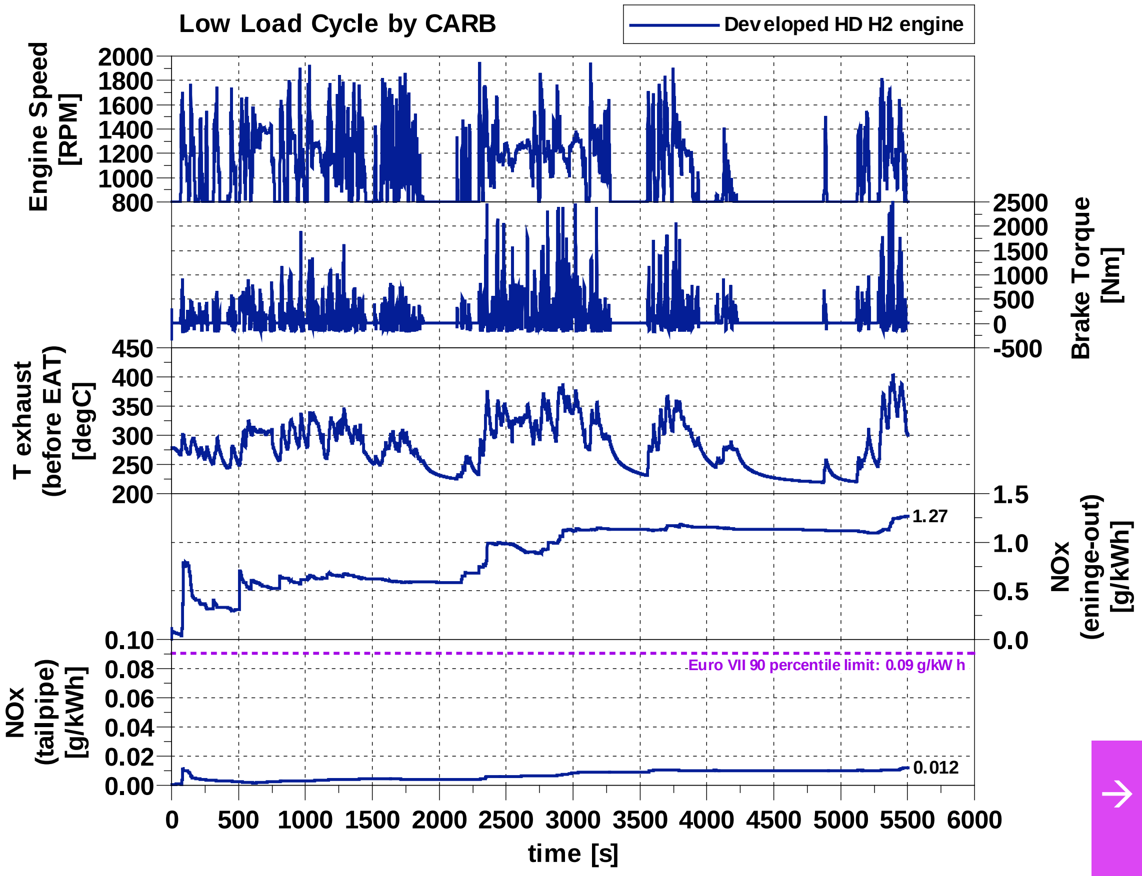
→ The considered emissions of all EAT configurations are below the proposed EUVII limits (100 and 90 Percentile).

→ Low engine out NOx emissions enable overall low tailpipe NOx emission

→ NOx and N_2O emission can be lowered significantly with the SCR-only layout due to lowered NO_2 generation

H2-ICE Development

NOx conformity of H2 ICE propulsion system



NO_x conformity for future ultra-low NO_x Hyd. engines

- Significant reduction in NO_x limits for future standards
  (CARB MY27, EPA planned standard, EURO VII)
- H_2 NO_x conformity demonstrated on CARB Low Load Cycle (LLC)
  - Engine-out NO_x emissions < 2.0 g/kWh
    → zero-emission aspect
  - Very low tailpipe NO_x emissions (~ 0.012 g/kWh)
  - SCR-only EAT used
    (No additional EAT heating required – no EHC)

→ The future ultra-low NOx regulation can be reached with advanced system development

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H2-ICE Development

IAV´s unique H2-ICE development methodology

Virtual

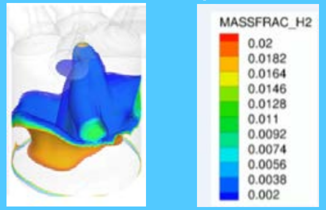
Component Level

Initial 0D / 1D / 3D CFD

- IAV H_2 Knock Prediction
- IAV H_2 Laminar Flame Speed Model
- Adapted Emission Models (NO_x, H_2,…)

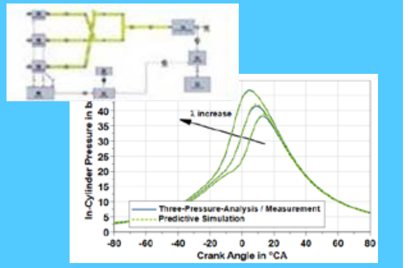
Subsystem Level

High fidelity 3D CFD
Driving design iterations for combustion improvement



System Level

1D Simulation



Validation / Calibration

Validation/ Calibration

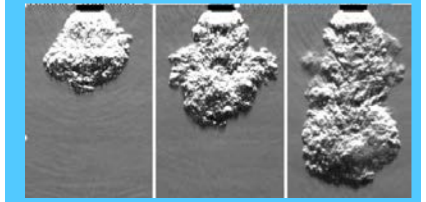
Validation

Parametrization (burn rate, in/ex pressure)

Validation

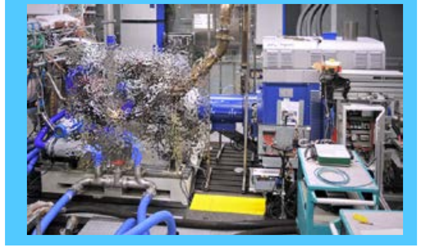
Experimental

Optical H_2 Spray Characterization



Single Cylinder Engine

2 H_2 Engine Dynos
660 kW / $p_{H2} \leq$ 100 bar

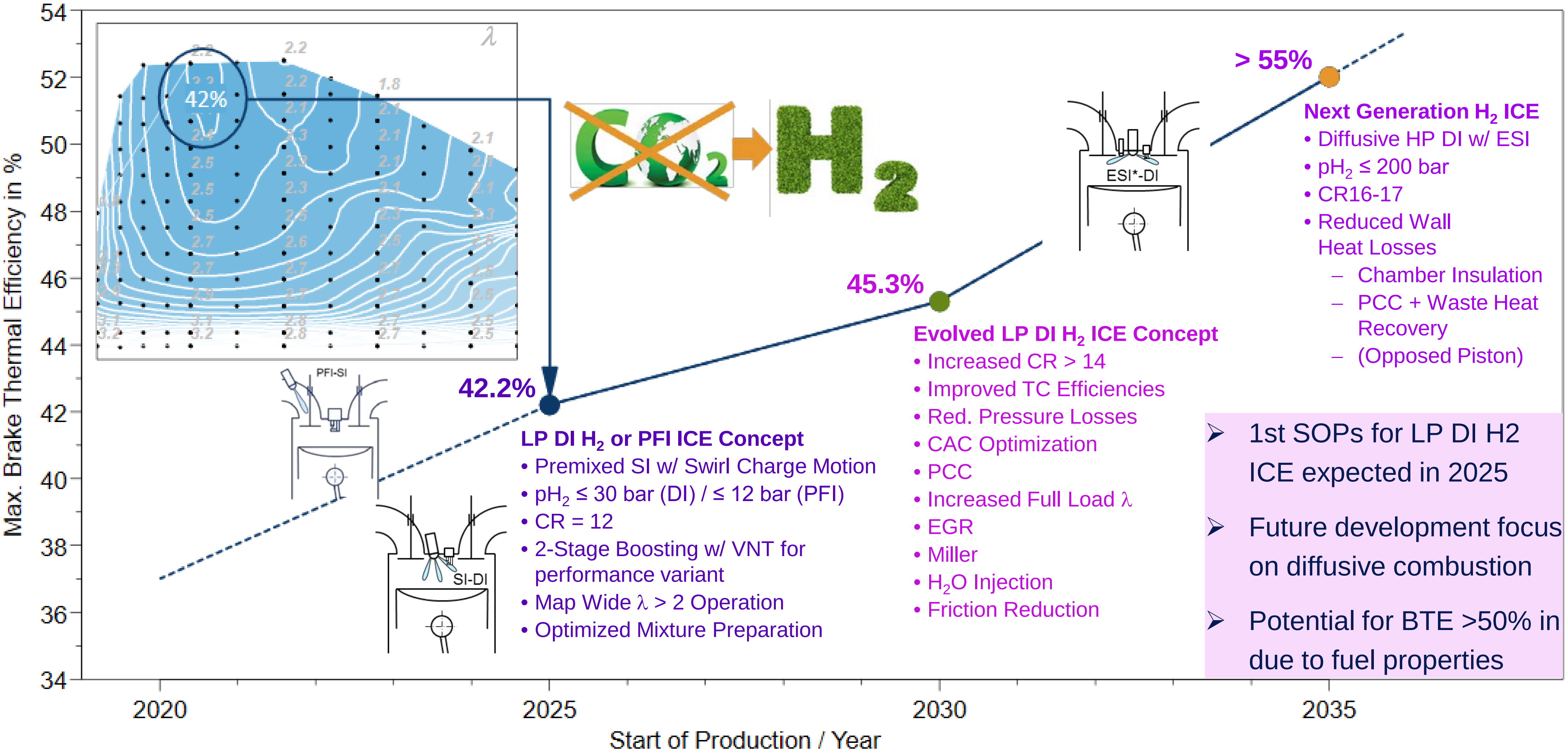


Rapid Prototyping by means of 3D print, e.g. pistons and cylinder heads

- In all development levels, IAV aims at employing own phenomenological models that enable predictive simulation of system behavior, e.g.
  - Ignition
  - Knock
  - Flame speed / burn rate
  - Engine–out emissions
  - Tailpipe emissions
- Validation of assumptions and simulation results on all levels (specific component testing or in-situ experiments) is part of IAV´s development process

Conclusion and Outlook

Technology Perspective of H2-ICE´s

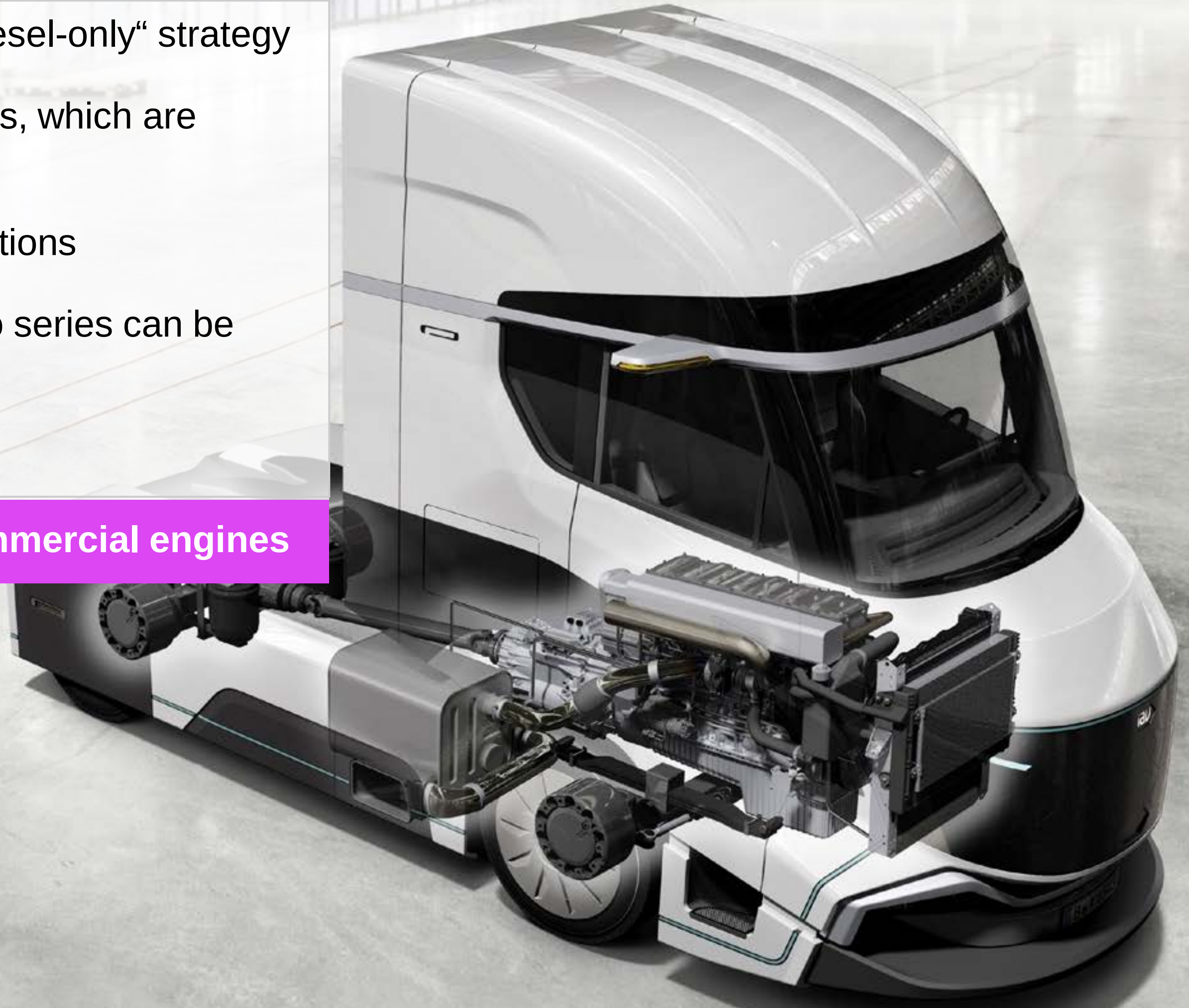


- 1st SOPs for LP DI H2 ICE expected in 2025
- Future development focus on diffusive combustion
- Potential for BTE >50% in due to fuel properties

Summary and outlook

- 30 % CO_2 reduction cannot be achieved with a „Diesel-only“ strategy
- There is a need for zero CO_2 alternative propulsions, which are available shortterm
- Hydrogen mobility (FC and ICE), e-fuels, electrifications
- HD Hydrogen system development from concept to series can be supported by IAV
- Retrofit, especially for large-bore engine

→ **Promising results in development of new commercial engines**



Thank you for your attention!

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Many thanks to all colleagues who have contributed to this presentation.