eFuels in Internal Combustion Engines (ICE) for Commercial Vehicles - State of Art and Future Perspectives

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eFuels in Internal Combustion Engines for Commercial Vehicles
Agenda

CV Commercial Vehicle ICE Internal Combustion Engine

1

Introduction

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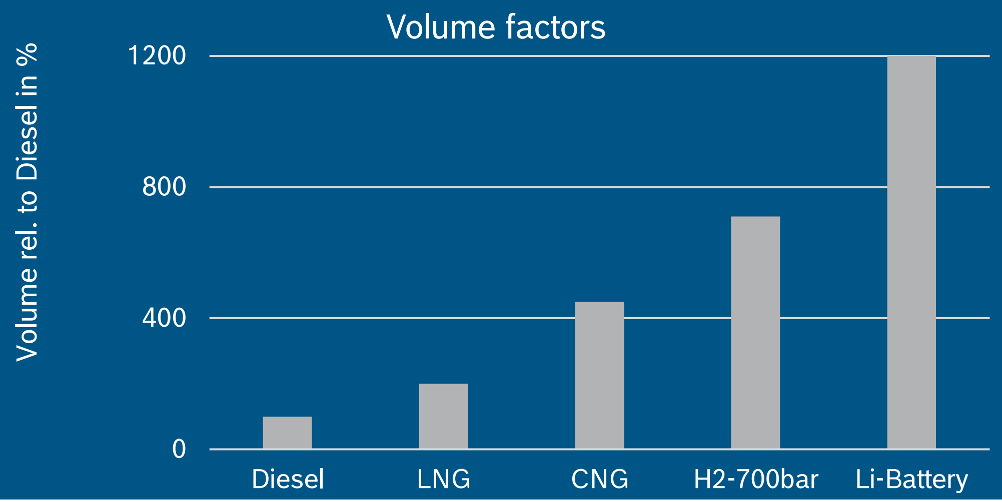
Introduction

Energy storage

- Volumetric integration / packaging challenge



Assessment of different energy carriers based on volumetric energy density only shows already very big differences with high relevance for CV applications

Several other relevant assessment criteria such as e. g. availability, infrastructure, GHG and pollutant emissions “well to tank”, costs have to be included

As a consequence a “one fits all” solution for all CV applications is currently not apparent

Several energy carriers for CV are available, but a wide range of CV applications has to be covered
Technology openness is needed for development of powertrain solutions

CV Commercial Vehicle GHG Greenhouse Gases

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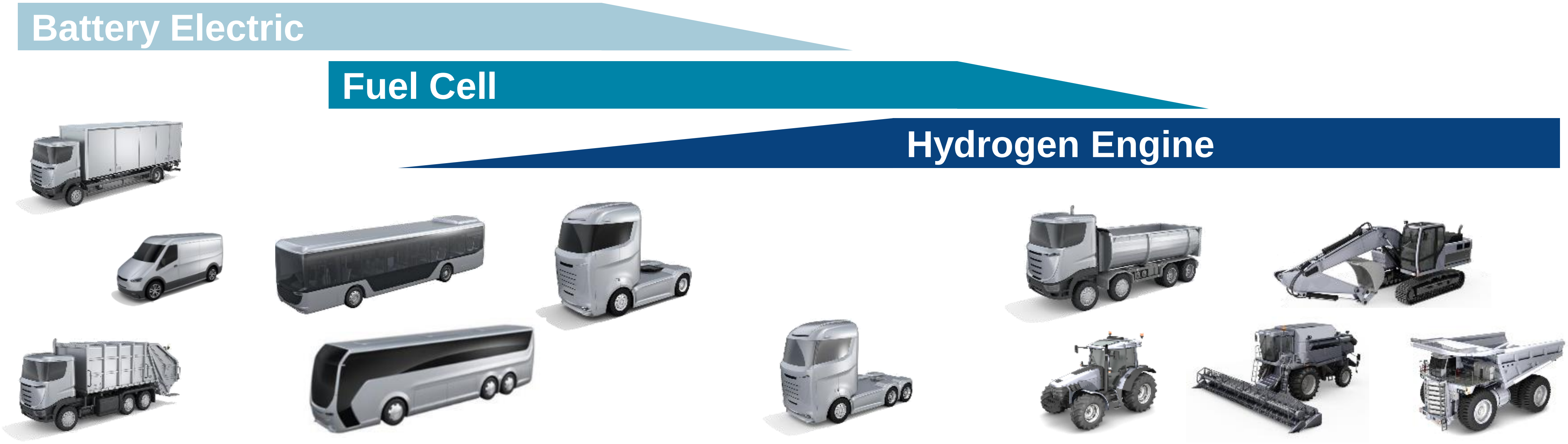
Variety of Commercial Vehicles and Associated Powertrains

Diesel Engine* (further potential for CO_2-reduction via η and e-fuels)



Commercial vehicles / machinery have a wide range of applications with very different operation requirements. In the future, all propulsion technologies will be required to meet customer and social needs. There is no single solution that optimally fulfills all requirements. The development of CO_2-neutral / minimized propulsion technologies is a main innovation driver

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Focus CV with ICE

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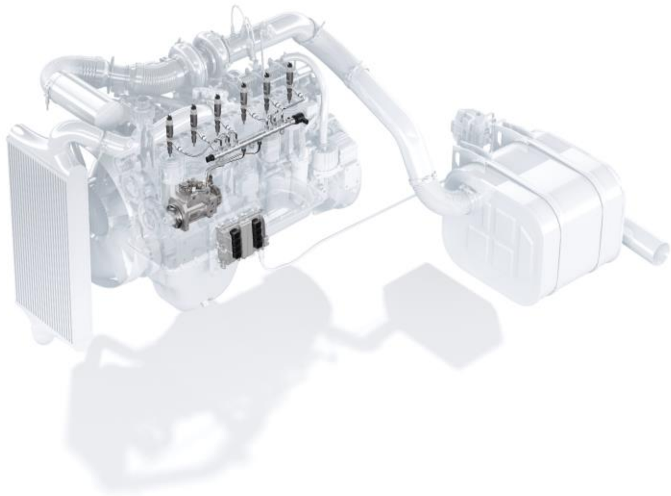
Key Requirements on ICE for CV

EXHAUST EMISSIONS

FUEL CONSUMPTION

POWER & TORQUE



DURABILITY

ROBUSTNESS

COMPETITIVNESS

Different key requirements regarding sustainability, technical performance and economic efficiency to be fulfilled

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Diesel-ICE

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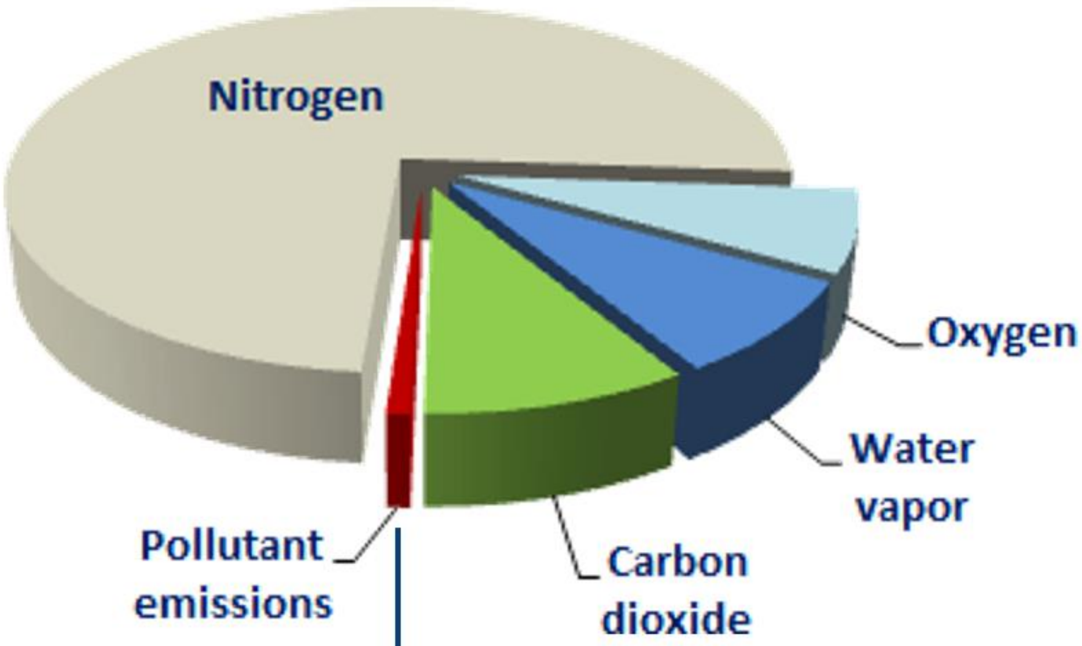
Diesel-ICE: Exhaust Gas Composition Engine-Out



<< 1 % of Engine-Out Emissions

- Particulates – PM
- Nitrous Gases – NO_x
- Carbon Monoxide – CO
- Hydrocarbons – HC
- Sulfur Dioxide – SO_2

Limited non-GHG emissions represent only a very small proportion of the engine-out Diesel exhaust gas (<< 1%)

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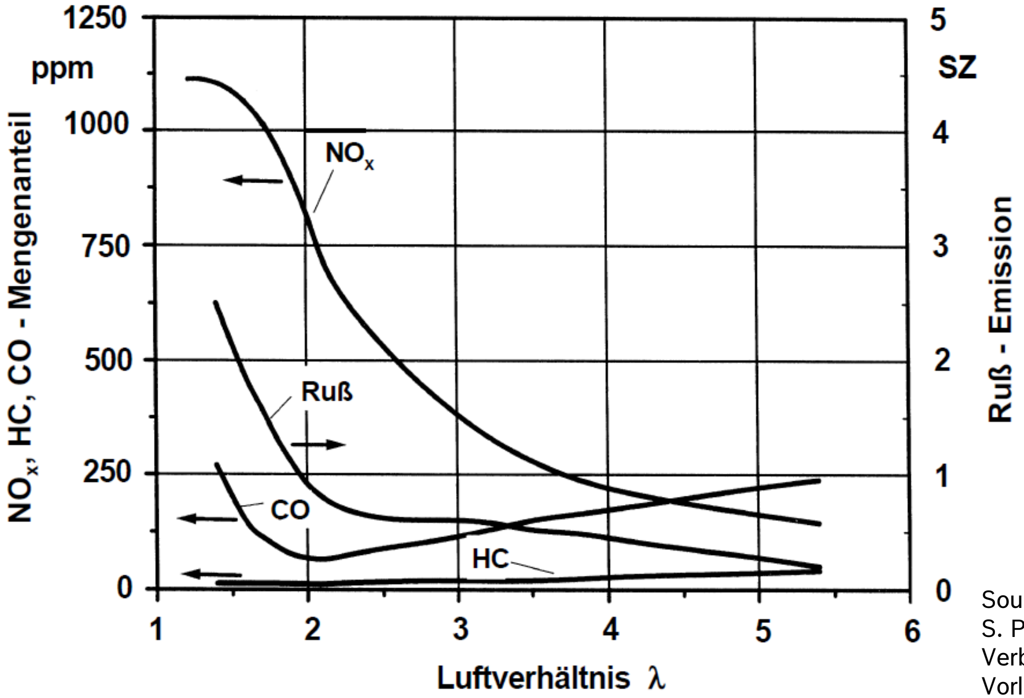
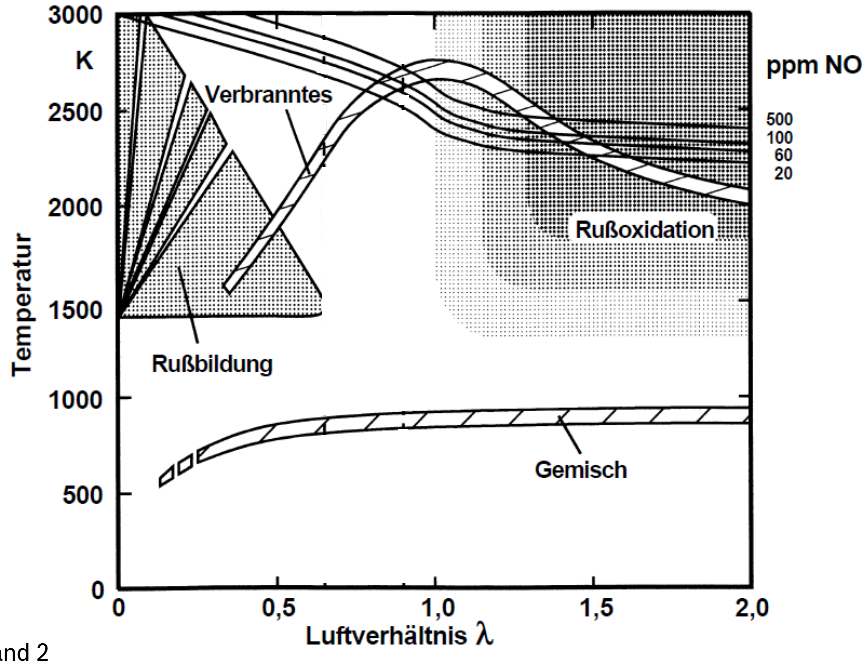
Diesel-ICE: Exhaust Emissions Engine-Out

Influence of Air-Ratio λ on Engine-Out Exhaust Emissions



Influence of Temperature and Air-Ratio λ on Soot Formation / Soot Oxidation



Source:
S. Pischinger
Verbrennungsmotoren Band 2
Vorlesungsumdruck 21. Auflage

(Local) Air-ratio λ is a key influencing parameter on Diesel engine-out emissions

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ICE Internal Combustion Engine

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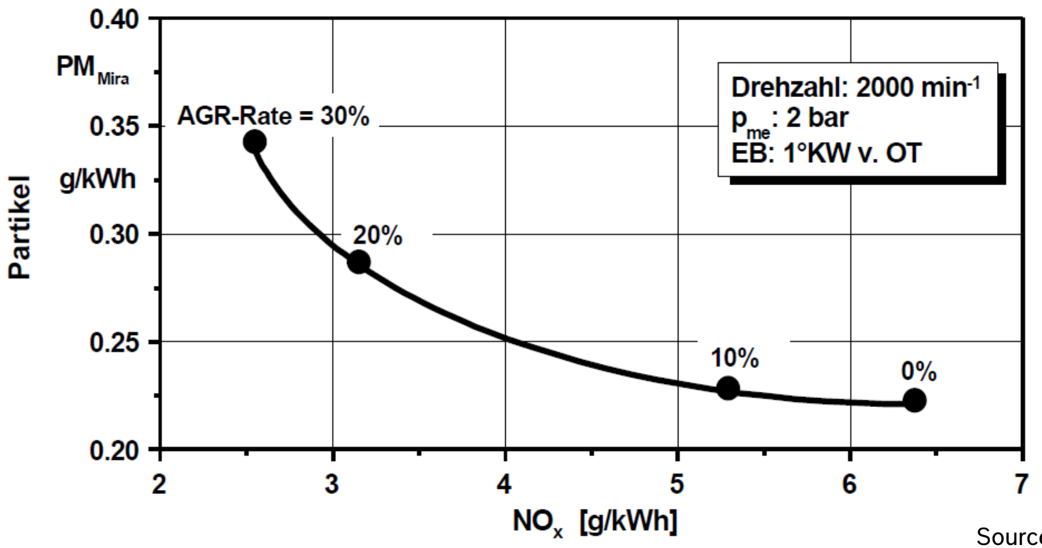
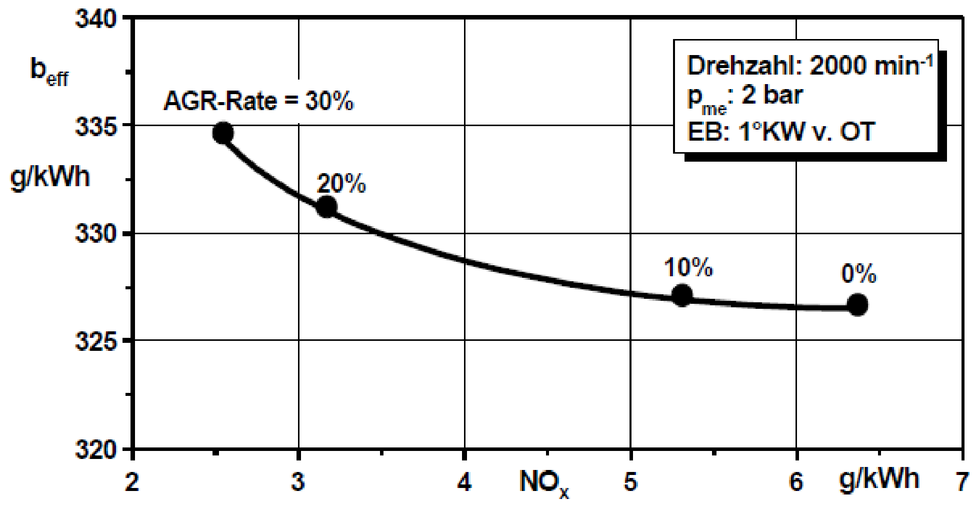
Diesel-ICE: Exhaust Emissions Engine-Out

Influence of EGR on Engine-Out Exhaust Emissions PM and NO_x



Influence of EGR on Engine-Out NO_x and Specific Fuel Consumption



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In addition to air-ratio λ also EGR is a key influencing parameter on Diesel engine-out emissions

ICE Internal Combustion Engine EGR Exhaust Gas Recirculation

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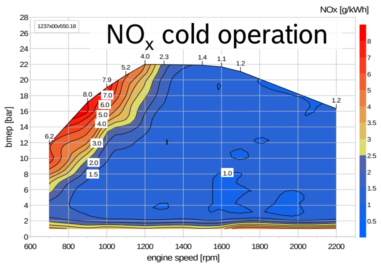
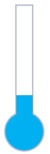
Diesel-ICE: State of the Art Engine Measures

CRSN Modular System
- Moderate nozzle flow
- Faster injector opening setting
- Up to 2500 bar

Improved fuel-injection

Optimized NO_x raw emissions





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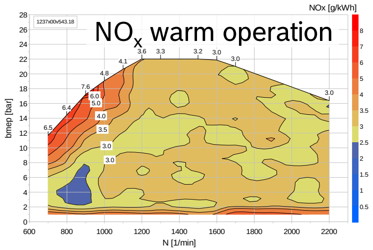
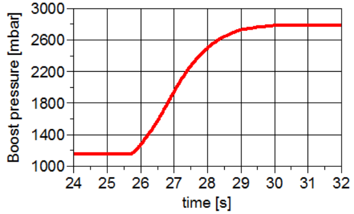
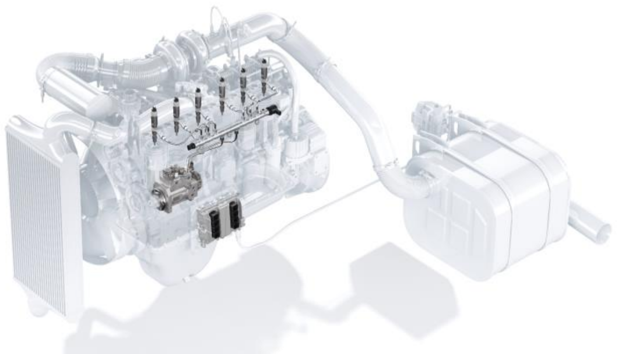
Efficient temperature management



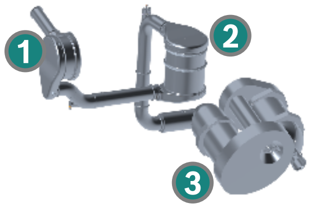
e.g. faster boost pressure build → more EGR in transient operation



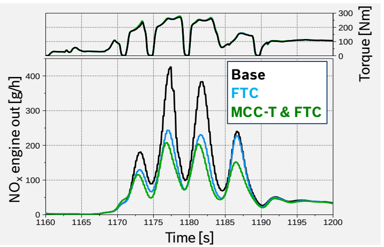
Improved turbocharging



Optimized exhaust-gas treatment

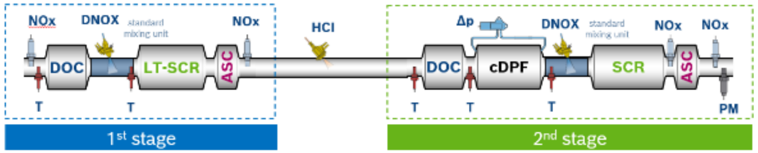


e.g. transient correction function air and fuel path



Extended software functions

Engine	7.8 l / 6 cyl.
Power	230 kW
Torque	1400 Nm
Fuel injection equipment Pressure	CRIN C 2500 bar
Exhaust gas recirculation	HP-EGR



Development of Diesel CV ICE towards lowest exhaust emissions requires a complete system approach

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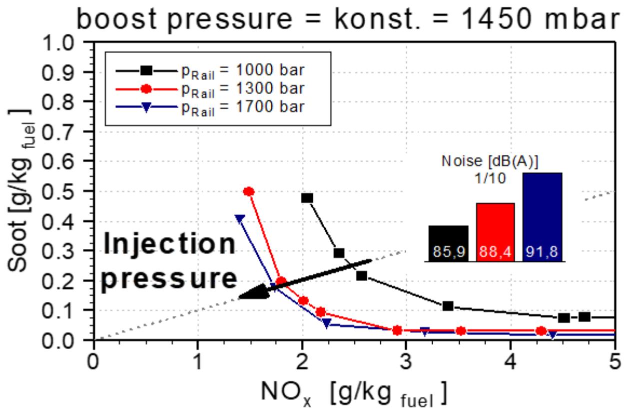
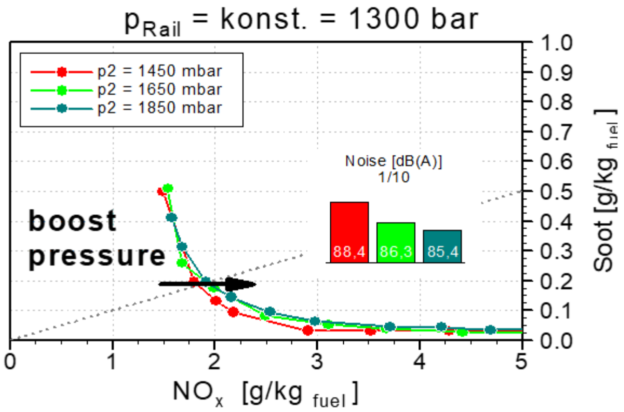
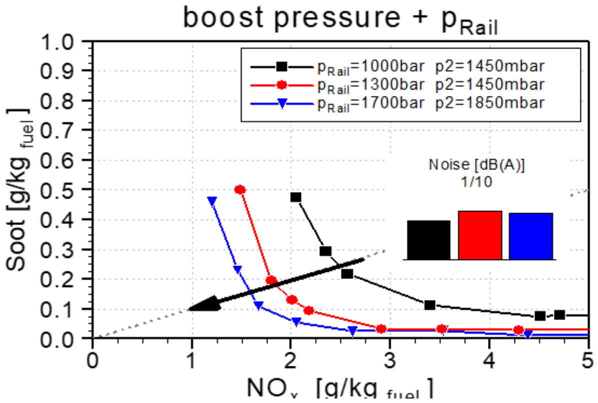
Diesel-ICE: Key Engine Measures for Exhaust Emission Reduction





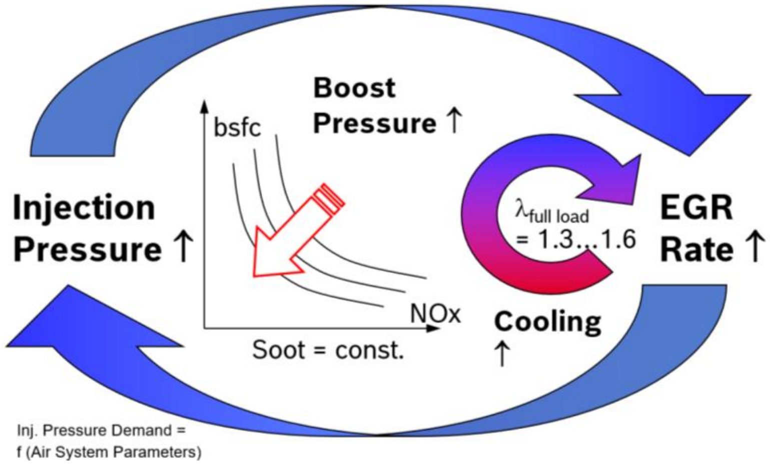
NO_x reduction



Noise reduction

SCE 538 cm^3
n = 2000 rpm, IMEP = 8 bar

Interaction of Key Engine Measures



Optimized setting of engine control parameters leads to strong reduction of engine-out emissions

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ICE Internal Combustion Engine EGR Exhauts Gas Recirculation SCE Single Cylinder Engine IMEP Inner Mean Effective Pressure

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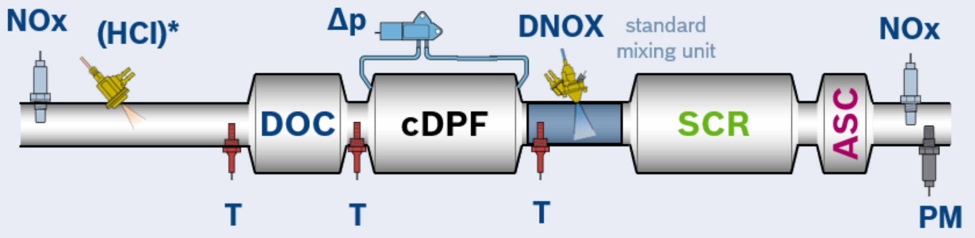
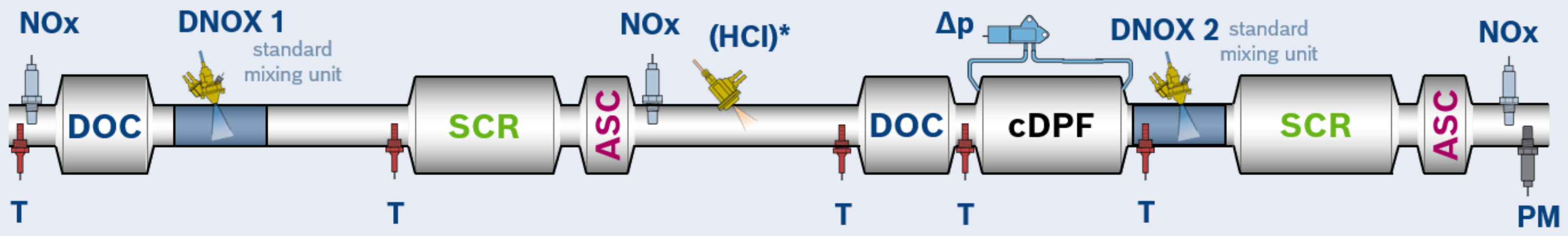
Diesel-ICE: Exhaust Gas Treatment (EGT)

EGT
Base Design 1
- Euro VI
- Baseline Euro 7



EGT
Base Design 2
- Euro 7
- CARB Low NO_x



* optional

EGT systems of modern Diesel ICE consist of specific exhaust gas treatment components, actively managed by electronic control to ensure high emissions conversion over a wide range of boundary / operation conditions

ICE Internal Combustion Engine DOC Diesel Oxidation Catalyst cDPF coated Diesel Particle Filter SCR Selective Catalytic Reduktion
ASC Ammonia Slip Catalyst HCI Hydrocarbon Injection

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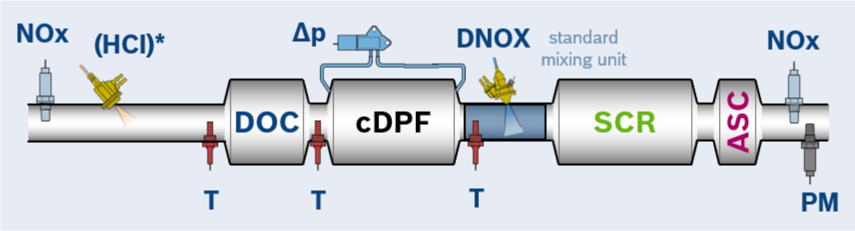
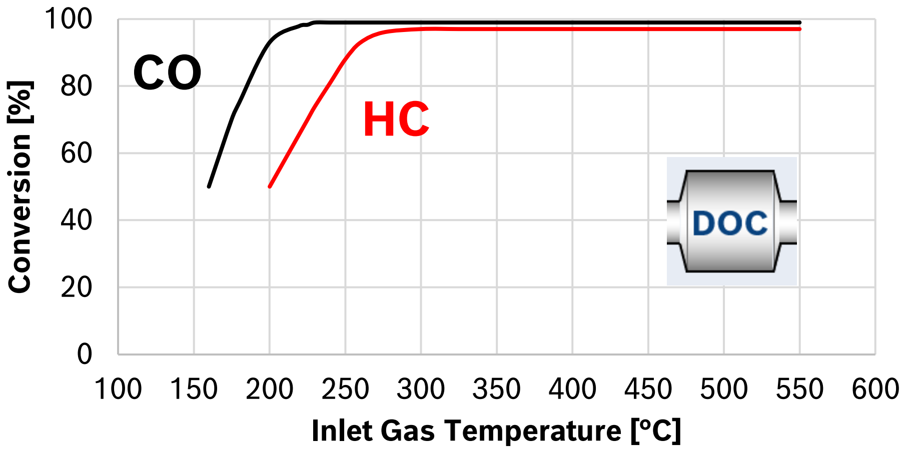
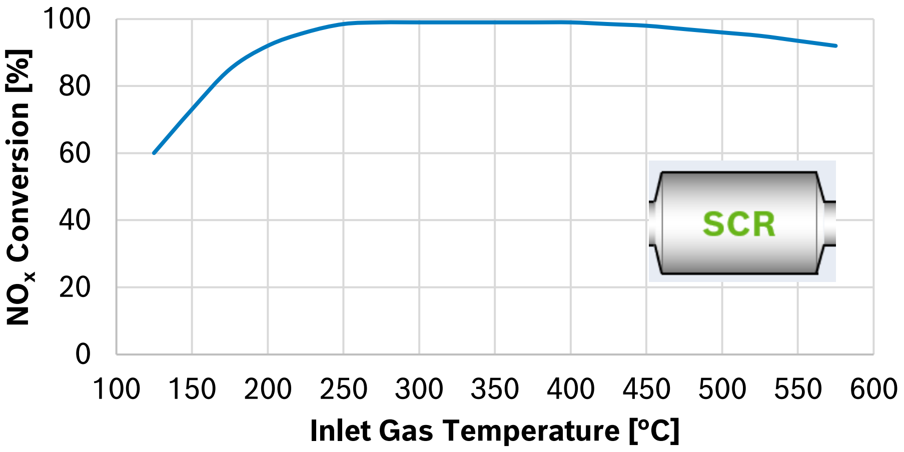
Diesel-ICE: Exhaust Gas Treatment (EGT)



DOC: CO and HC Conversion (schematic)



SCR: NOx Conversion (schematic)



Very high emissions conversion up to > 98 % as long as catalysts are in right temperature condition

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ASC Ammonia Slip Catalyst

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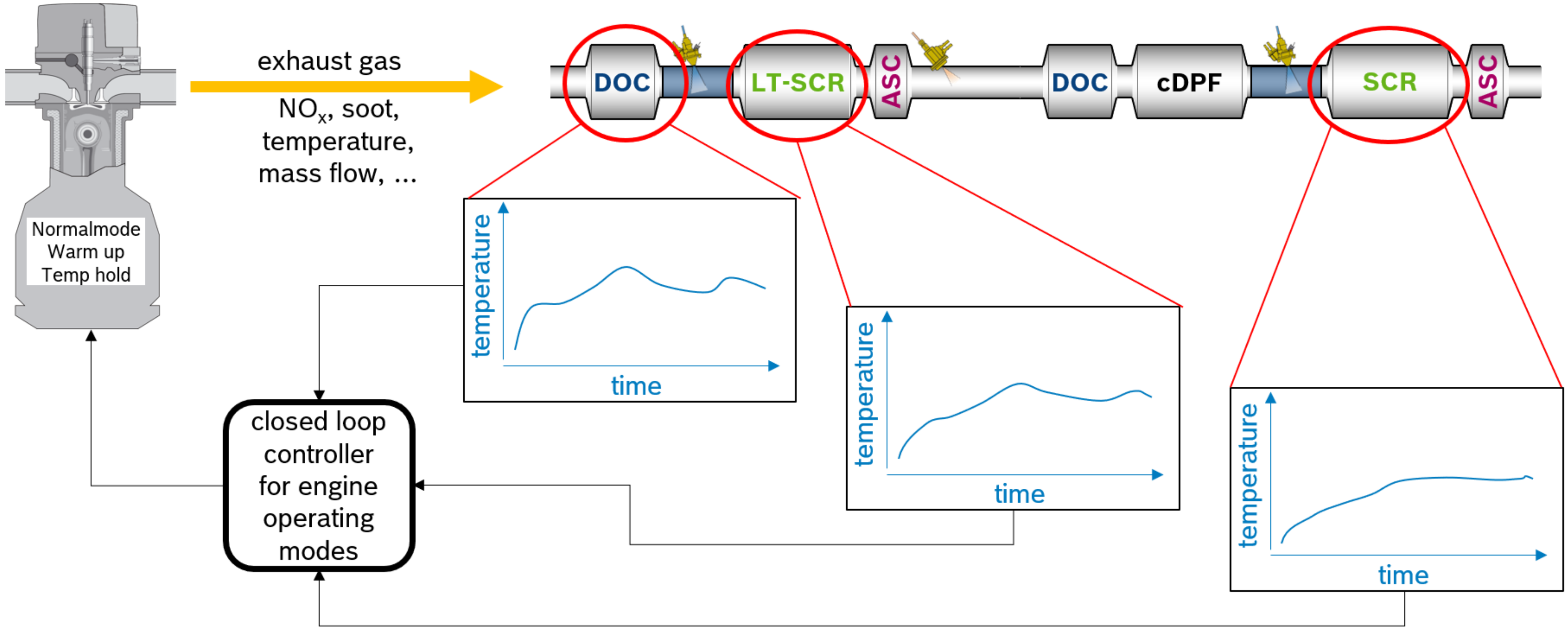
Diesel-ICE: Exhaust Gas Treatment



Thermal management of exhaust gas treatment system – a mandatory element for low exhaust emissions

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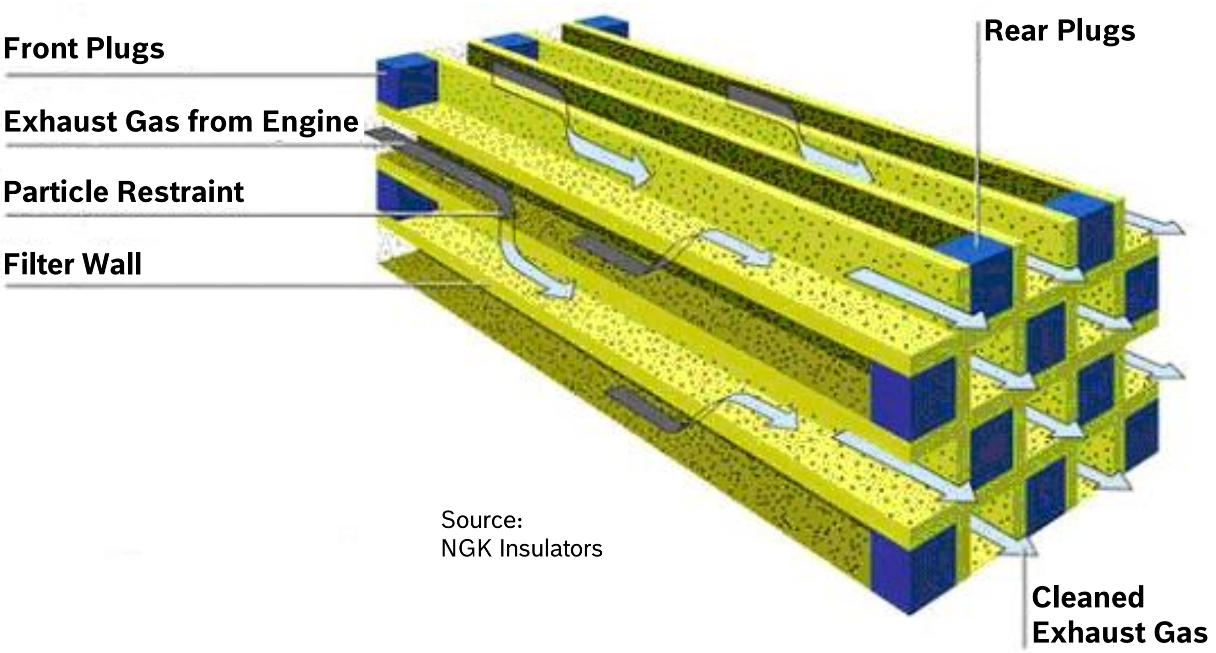
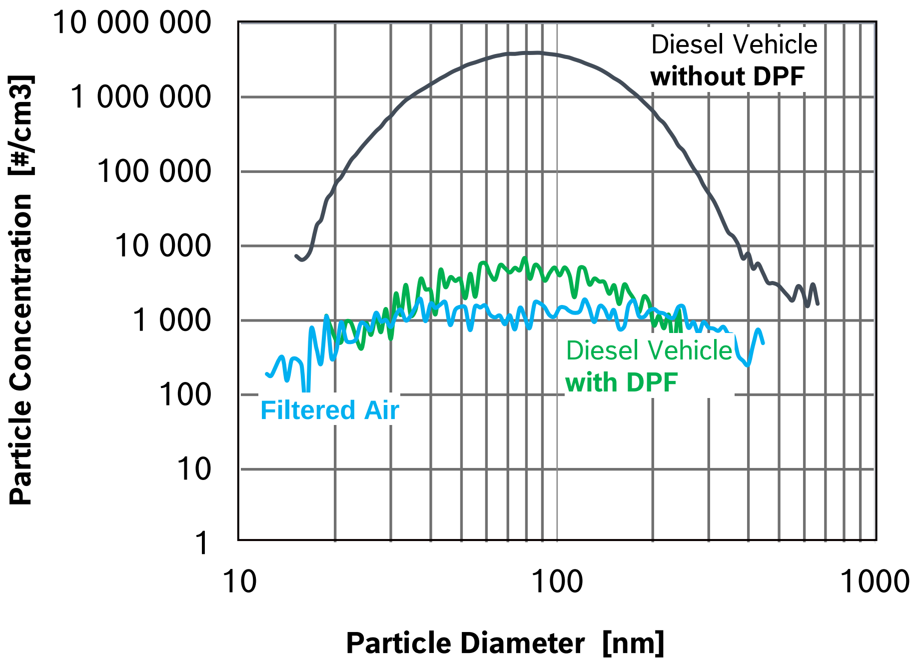
Diesel-ICE: Exhaust Gas Treatment

Diesel Particle Filter (DPF)



Source:
NGK Insulators

Particle Concentration



Emissions of particulate mass and particle number are very effectively reduced by the Diesel particle filter DPF

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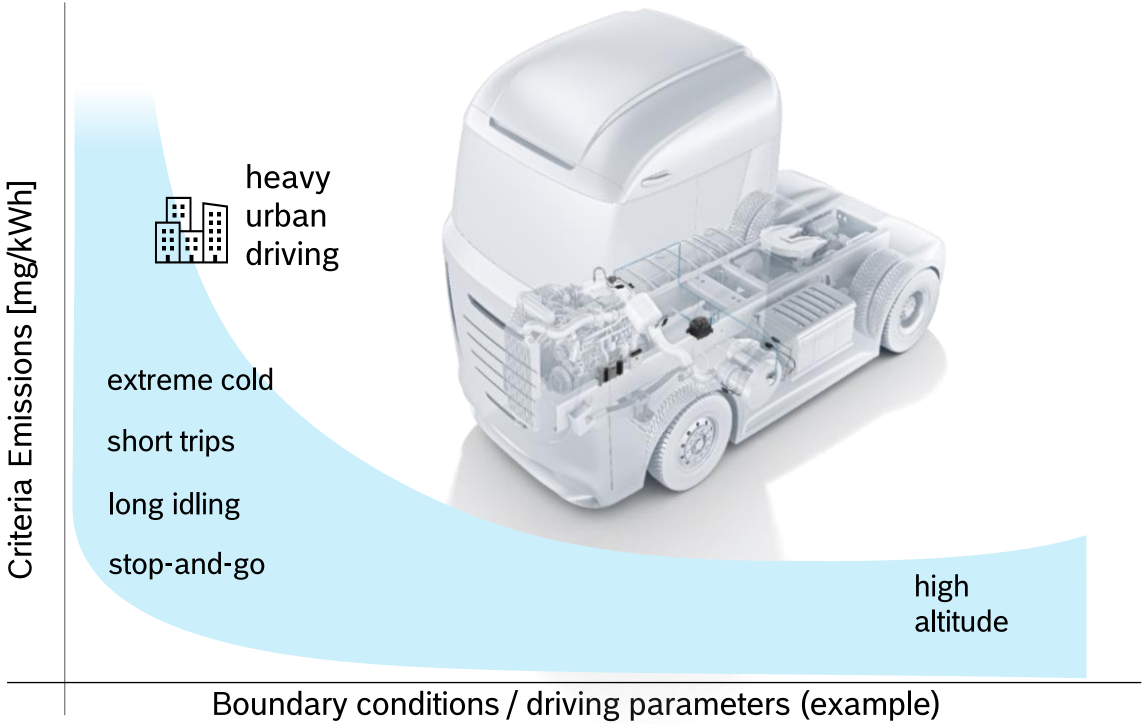
Diesel-ICE: Exhaust Gas Emissions



- **Modern Diesel CV are characterized by low exhaust emissions in a wide range of boundary conditions / driving parameters**
- Additional technologies would be required to keep exhaust emissions low even in very extreme cases of boundary conditions / driving parameters

Covering extreme cases of boundary conditions / driving parameters has to be balanced with regard to real driving relevance and resulting effectiveness of air quality improvement

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CV Cmmercial Vehicle ICE Internal Combustion Engine

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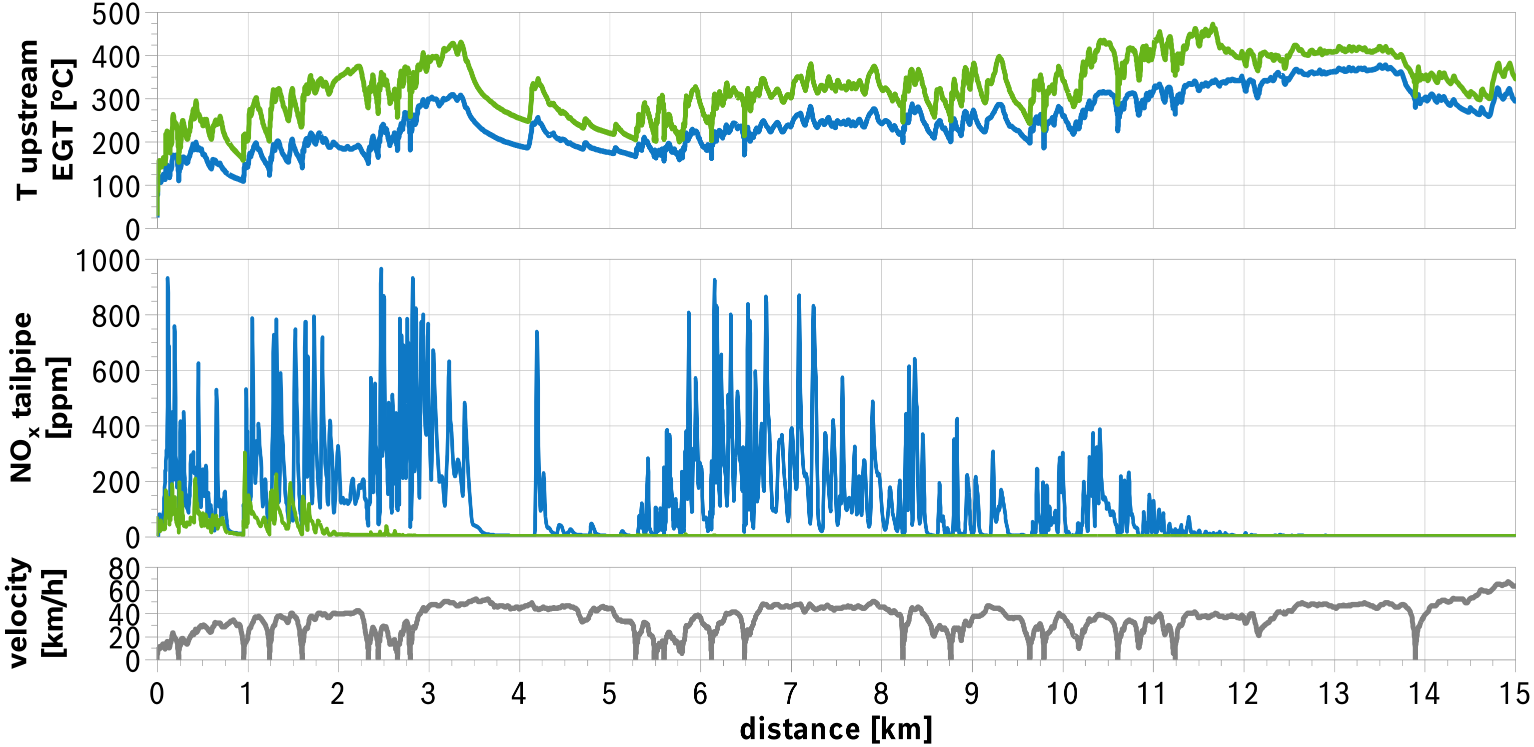
Stuttgart Urban with HDV, example: EUVI vs. CARB



Example of different emission concepts
for HDV application
on same route (Stuttgart urban, cold started).

EU VI

Demo CARB MY´27

Heat up @ CV applications is generally more challenging compared to PC due to:

- Higher mass of components (durability requirements)
- Higher volume of catalyst and higher thermal mass (absolute full load capability)

CARB represents an extreme example with massive heating measures and raw emissions requirements (w/o heater or burner) → excessive, requirements recently lowered.

Heat Up and Keep Warm Strategy are the enabler for emission reduction @ urban and cold start conditions.

CV Commercial Vehicle HDV Heavy Duty Vehicle PC Passenger Car

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Diesel-ICE: Comparison of Fuel Properties

Fuel Property	Fuel Quality Commercial Grade Diesel*	Fuel Quality eFuel ARAMCO R75*
Density @ 15°C [kg/m³]	839,2	821,4
Lower Heating Value [MJ/kg]	43,13	43,48
Cetane Number [-]	51,5	64,3
Sulfur Content [mg/kg]	6,2	2

* examples of respective fuel types

eFuel R75 especially has a higher Cetane Number – thus higher combustibility - than typical commercial grade Diesel

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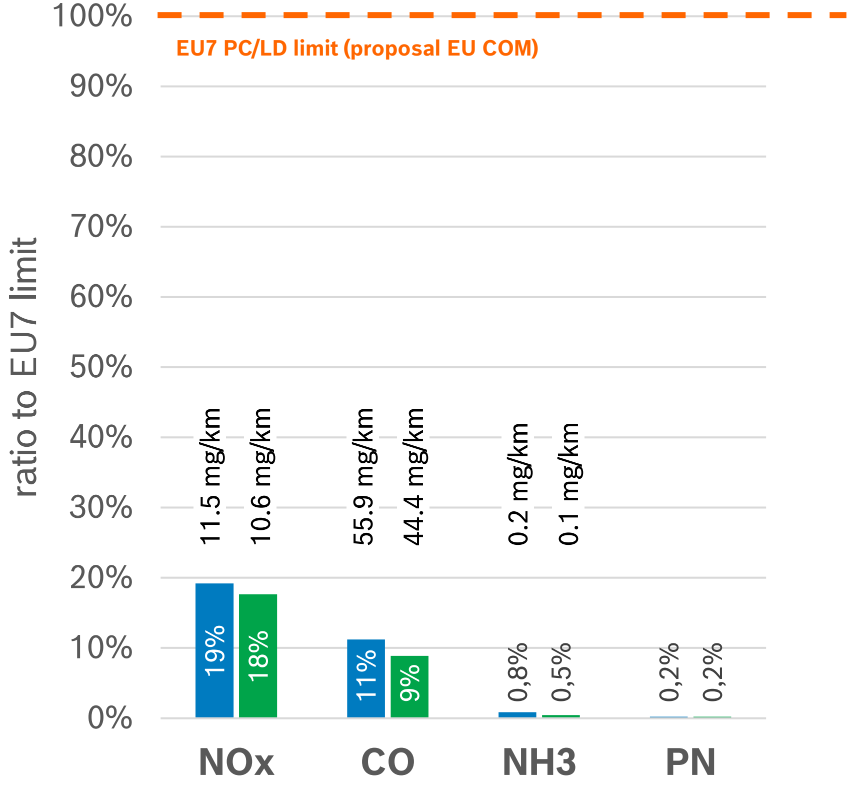
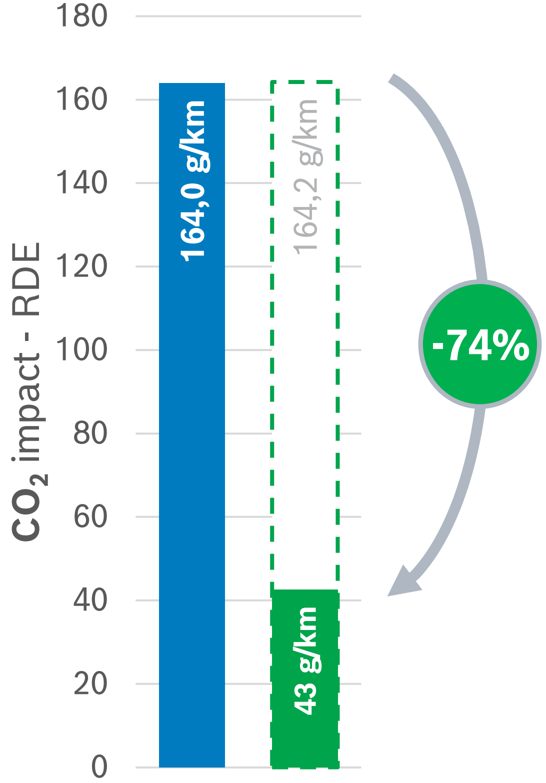
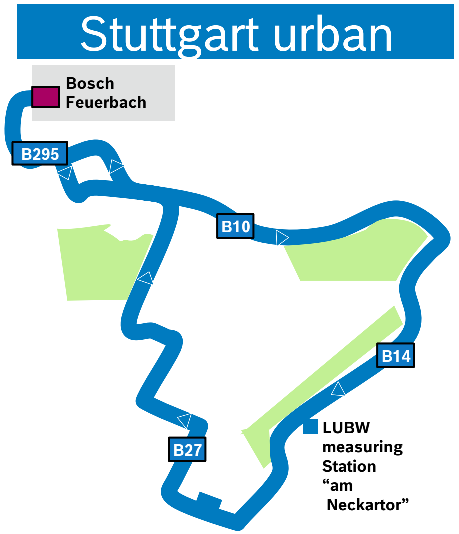
Tailpipe emissions Diesel / R75 @Stgt Urban





Test-Variant	No. of tests
Stuttgart-Urban, EN590 standard Diesel	**11**
Stuttgart-Urban EN590 R75 (75% e-blend)	**12**



Tailpipe emissions: Comparable low emission level / Big step in CO_2 impact of R75

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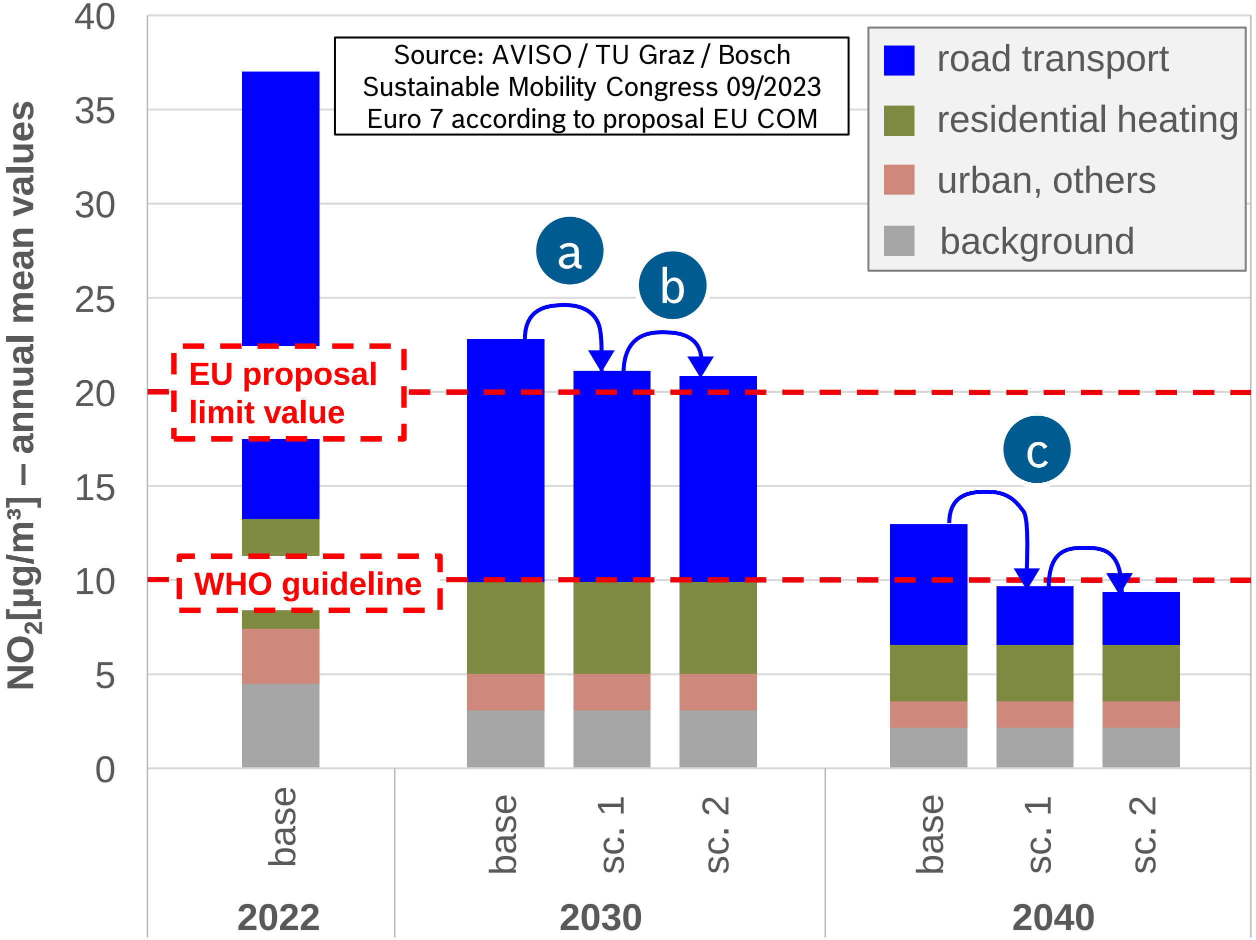
Impacts on Air Quality: NO_2



Air-quality view on NO_2 shows comparable dependencies like NO_x emission view

a
- Stringent exhaust emission regulation as a relevant step towards achieving EU air-quality targets.
- Limit value compliance 2030 without stringent exhaust emission regulation critical

b
Higher electrification share has no noticeable advantage for NO_x

c
Assuming an alignment with the WHO proposal in 2040, the perspective shows a similar picture as in 2030

base: Baseline + renewal with current EU6/EUROVI
sc. 1: base + EU7 (EU COM-proposal)
sc. 2: sc. 1 + fast ramp up of BEV (15 mio. BEV in 2030)

BEV Battery Electric Vehicle

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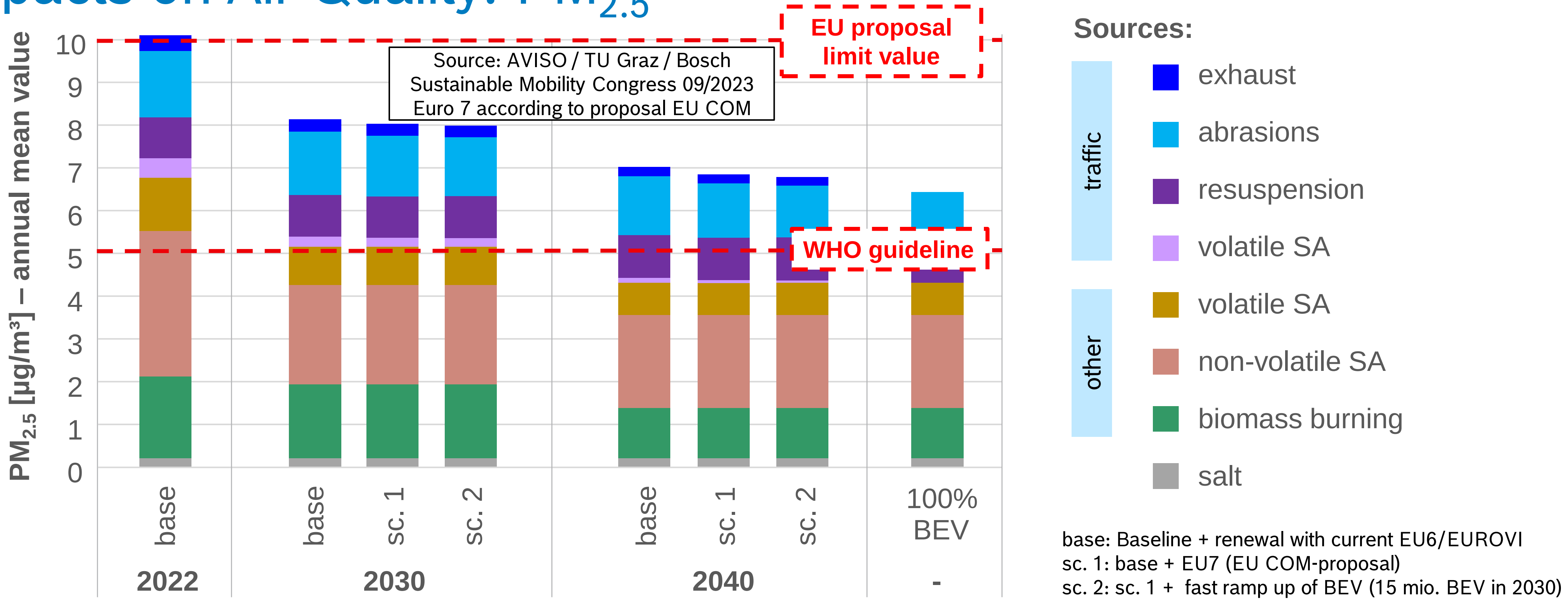
Impacts on Air Quality: $PM_{2.5}$



base: Baseline + renewal with current EU6/EUROVI
sc. 1: base + EU7 (EU COM-proposal)
sc. 2: sc. 1 + fast ramp up of BEV (15 mio. BEV in 2030)

- Traffic contribution to $PM_{2.5}$ is largely not exhaust-related → influence of the powertrain is small
- WHO AQG is not to be fulfilled by any of the scenarios in 2040, this also applies with a 100 % BEV scenario

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BEV Battery Electric Vehicle

2.2

H_2-ICE

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H_2-ICE: Fuel Characteristics compared to Diesel

Property	Unit	Diesel	Hydrogen
Stoichiometric Air Demand	kg/kg	14,7	34,3
Lower Heating Value	MJ/kg	42,9	120
Energy Density	MJ/dm³	35,8 (liquid) [a]	3,0 (gaseous) [c]
Mixture Heating Value (air aspirating) [a,b,d]	MJ/m³	3,77	4,52
Ignition Limits [a,e,f]	Vol.-%	0,6 – 5,5 (λ = 1,35 – 0,48)	4 – 76 (λ = 10 – 0,13)
Self Ignition Temperature [a,f]	°C	250	585
Minimal Ignition Energy [d,f]	mJ	0,24	0,017
Laminar Flame Speed [a,e,d,f]	cm/s	≈ 40	≈ 230
Adiabatic Combustion Temperature [d]	°C	≈ 2100	≈ 2260

[a] 1,013 bar [b] 0°C [c] 350 bar 280 K [d] λ = 1 [e] at 25°C [f] in air

Source:
ATZ/MTZ-Fachbuch „Wasserstoff in der Fahrzeugtechnik“
4. Auflage, Springer Vieweg

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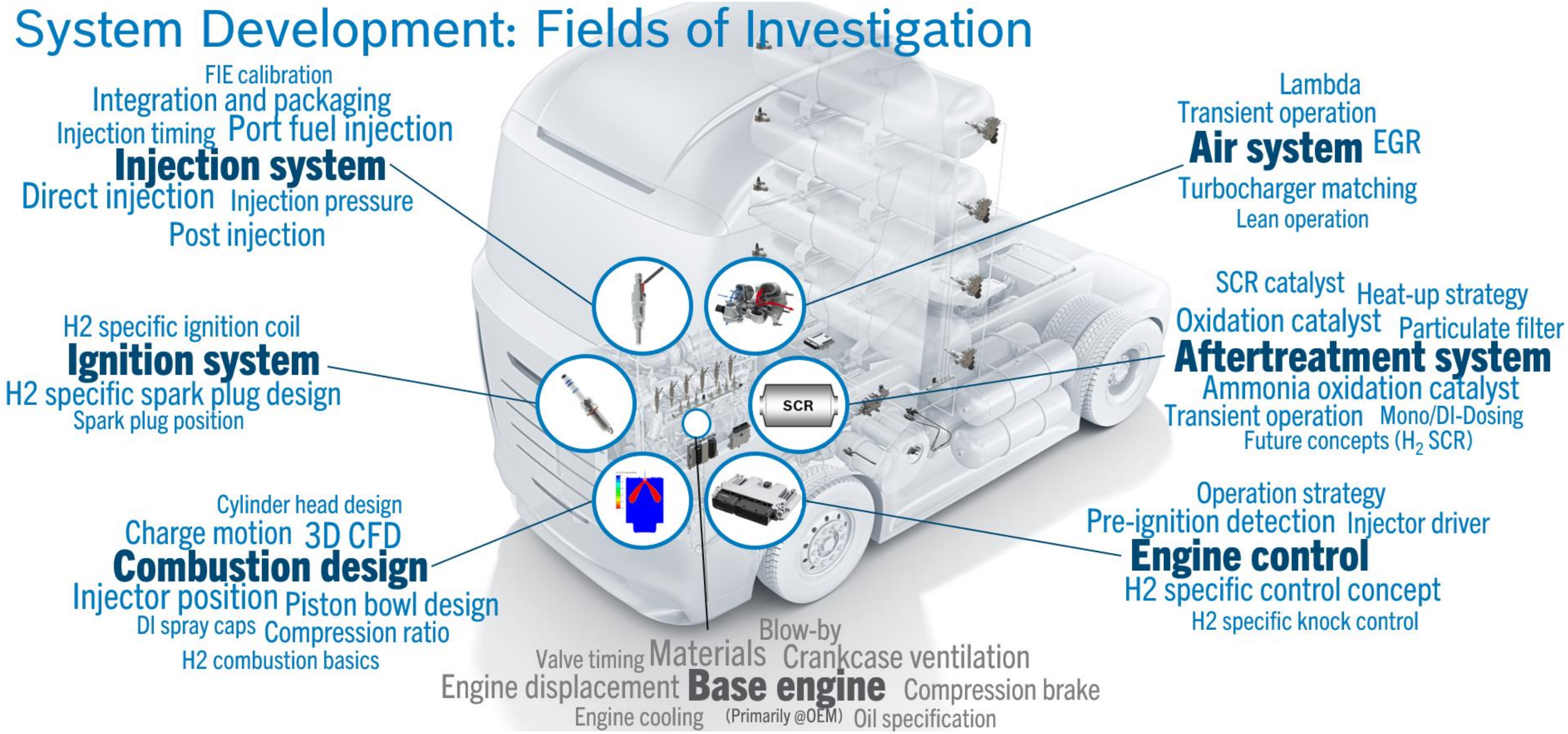
H_2-ICE: Engine Measures



ICE Internal Combustion Engine

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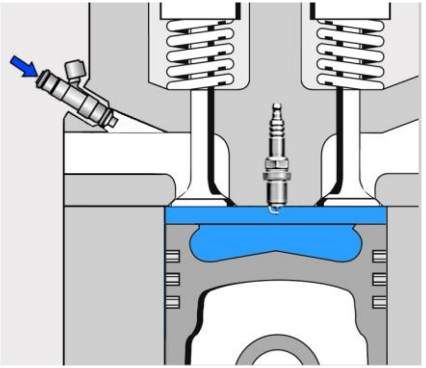
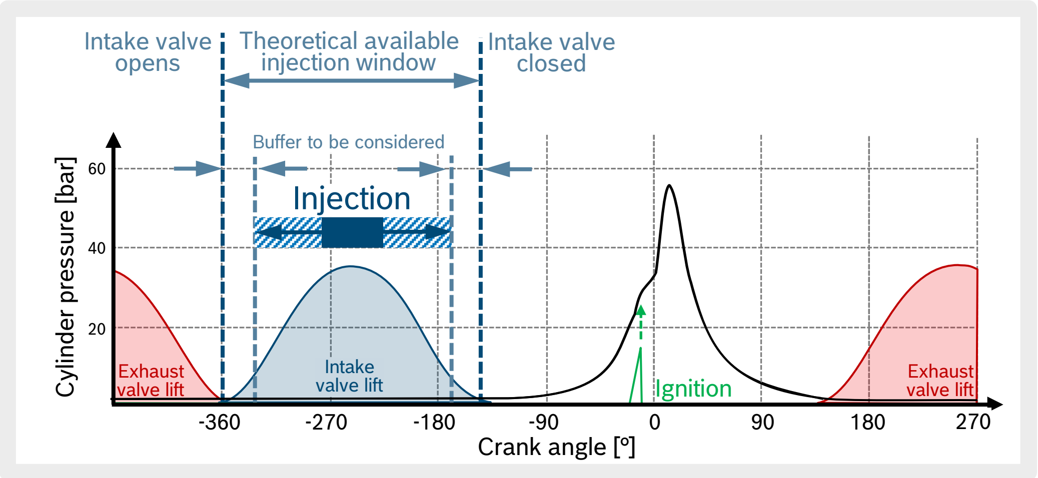
H_2-ICE: Injection System PFI vs. DI

Port Fuel Injection

- Injectors: MPGI and HIPI
- System pressure up to 15 bara

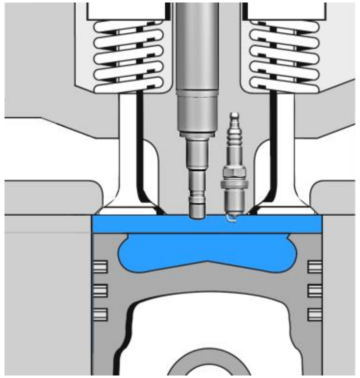


- \+ Low integration effort
- \+ Good homogenization
- \- Risk of backfire
- \- Reduced cylinder charge
- \- Transient load steps (time to torque, NO_x-emissions)

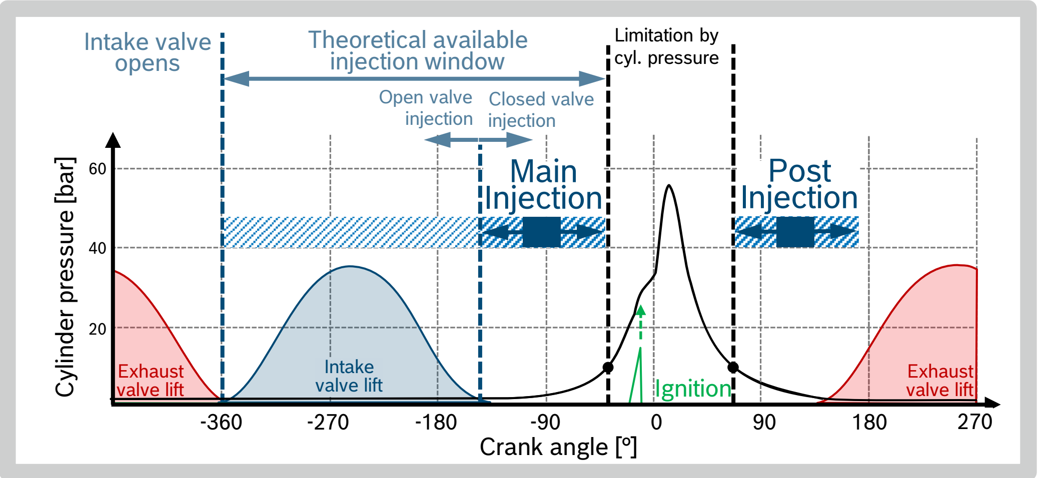


Direct Injection

- Injector: HIDI
- System pressure up to 40 bara



- \+ No risk of backfire
- \+ Max. cylinder charge (closed valve inj.)
- \+ Post Injection for transient load step
- \- Higher integration effort
- \- More complex homogenization process



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ICE Internal Combustion Engine PFI Port Fuel Injection DI Direct Injection

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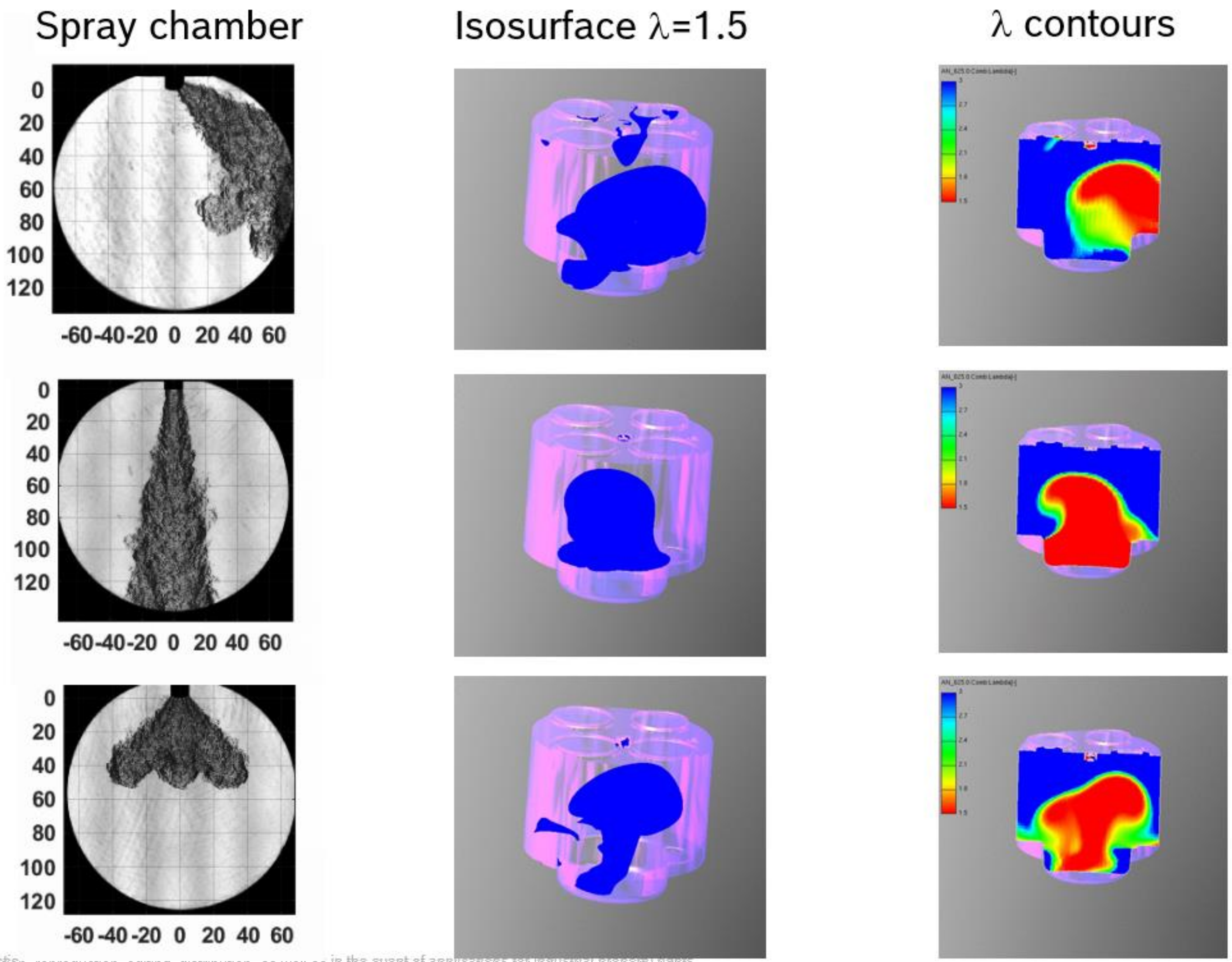
H_2-ICE: DI Mixing process and cap design

1-hole cap
w/ inclination

1-hole cap
vertical spray

6-hole cap



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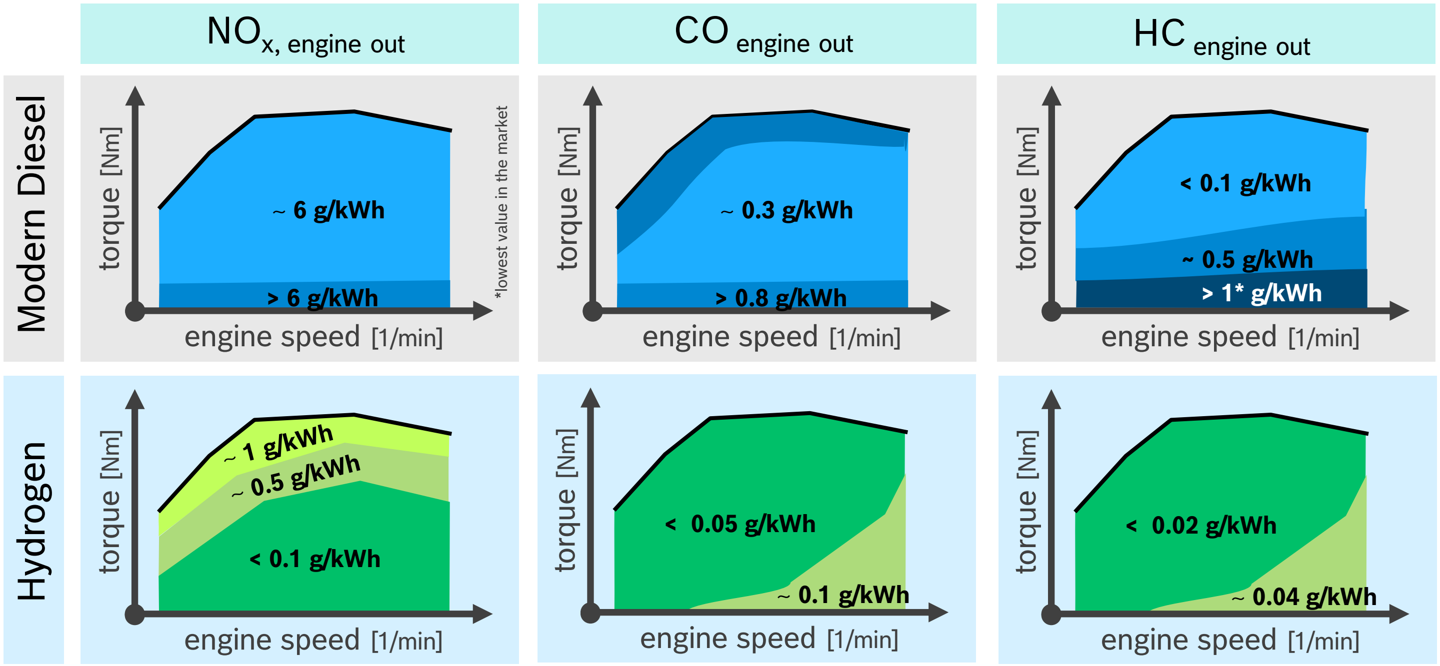
H_2-ICE: Emissions Engine-Out compared to Diesel

Criteria Emissions (schematic)



GHG Emissions

- Direct CO_2 – sources reduced > 99% due to non-carbon fuel
- N_2O formation by EGT expected much lower compared to Diesel

$$2\,NH_3 + 2\,NO_2 \rightarrow N_2O + N_2 + 3\,H_2O$$

$$2\,NO + H_xC_y + ½\,O_2 \rightarrow N_2O + H_xC_yO_2$$

Simplified reaction scheme for N_2O formation with main/relevant reaction pathways

H_2-ICE has much lower engine-out emissions NO_x, CO, HC than Diesel ICE

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ICE Internal Combustion Engine GHG Greenhouse Gases

ICE: Internal Combustion Engine | DI: Direct Injection | PFI: Port Fuel Injection | GHG: Green House Gas | EGT: Exhaust Gas Treatment

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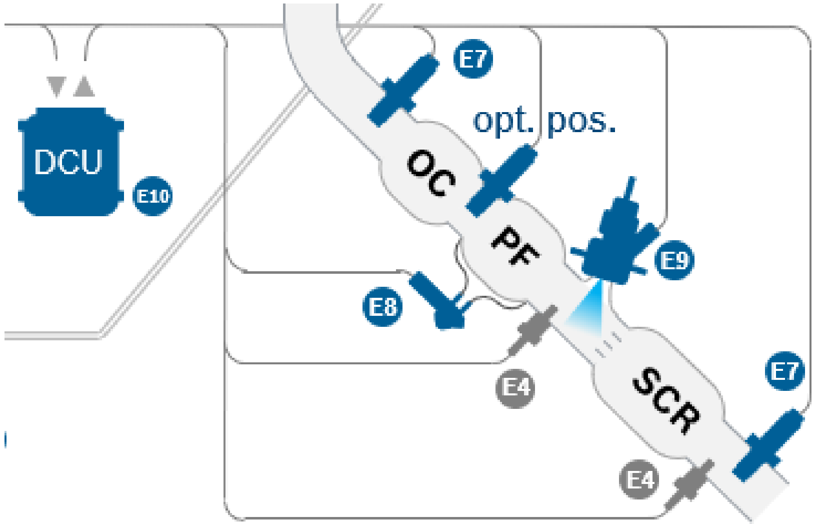
eFuels in Internal Combustion Engines for Commercial Vehicles

H_2-ICE: Exhaust Gas Treatment (EGT)

- **Operation conditions for EGT compared to Diesel**
  - Significant lower NO_x emissions in lean operation expected
  - Challenge may be high NO_x peaks in transient operation
  - Exhaust temperatures close to Diesel operation, maybe even lower. At low load higher temperature expected due to throttling
    → improved operation conditions for EGT in comparison to Diesel
  - Neglectable HC, CO and CO_2 emissions
    → Combustion of engine oil, carbon from AdBlue, carbon of hydrogen contamination
- **General EGT layout**
  - For lean operation classic aftertreatment components will be needed: oxidation catalyst, SCR catalyst & particulate filter (oil combustion, particulates from SCR system)
  - Development basis H_2-EGT will be close to future Diesel design



Further components (e.g. cooling, Ad-Blue supply, ...) are not shown

- E4 Exhaust temperature sensor
- E7 NO_x sensor (under evaluation)
- E8 Differential pressure sensor
- E9 SCR dosing module
- E10 SCR dosing control unit

ICE Internal Combustion Engine EGT Exhaust Gas Treatment SCR Selective Catalytic Reduction OC Oxidation Catalyst PF Particle Filter

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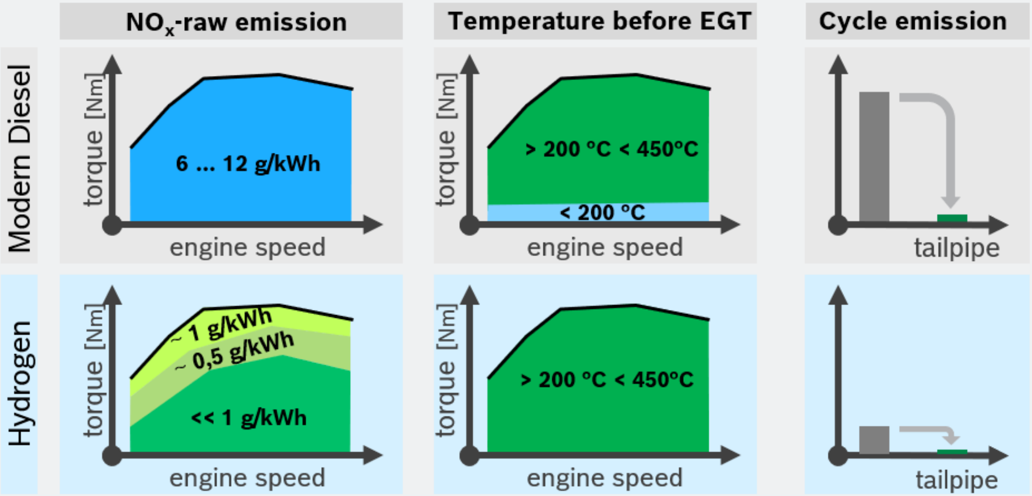
H_2-ICE: Exhaust Gas Emissions

NO_x



- Low engine out emission level supportive for EGT
- Proven robust SCR-system as first choice

PM/PN HC CO

- Very low values due to C-free fuel
- Oxi-catalyst / particle filter as mandatory part for EGT-system (lifetime robustness)

CO_2

N_2O CH_4

- No relevant emission source for N_20 and CH_4

H_2-ICE offers the potential for lowest exhaust emissions

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ICE Internal Combustion Engine EGT Exhaust Gas Treatment SCR Selective Catalytic Reduction

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Summary

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eFuels in Internal Combustion Engines for Commercial Vehicles
Summary

- The segment of commercial vehicles (CV) has a broad spectrum of transportation requirements and corresponding adapted vehicle applications. There are several technology pathways to meet future requirements on CV powertrains, e. g. usage of efuels for ICE, fuel cell power modules, battery electric powertrains.
- CV equipped with available and affordable Diesel engine and exhaust treatment technologies are capable to meet stringent exhaust emission legislations worldwide, e. g. Euro 7, CARB Low NO_x. The impact of such modern Diesel exhaust gas emissions on air quality is very small.
- Reduction of CV GHG emissions can be achieved by ICE combined with the usage of efuels. The usage of efuels typically leads – besides drastic reduction of the greenhouse gas exhaust emissions - to even lower exhaust pollutant emissions.
    - Usage of hydrogen is a quick path to reduce greenhouse gas emissions and achieve lowest exhaust gas emissions in general
    - Usage of liquid efuels would be beneficial with regard to energy density and handling

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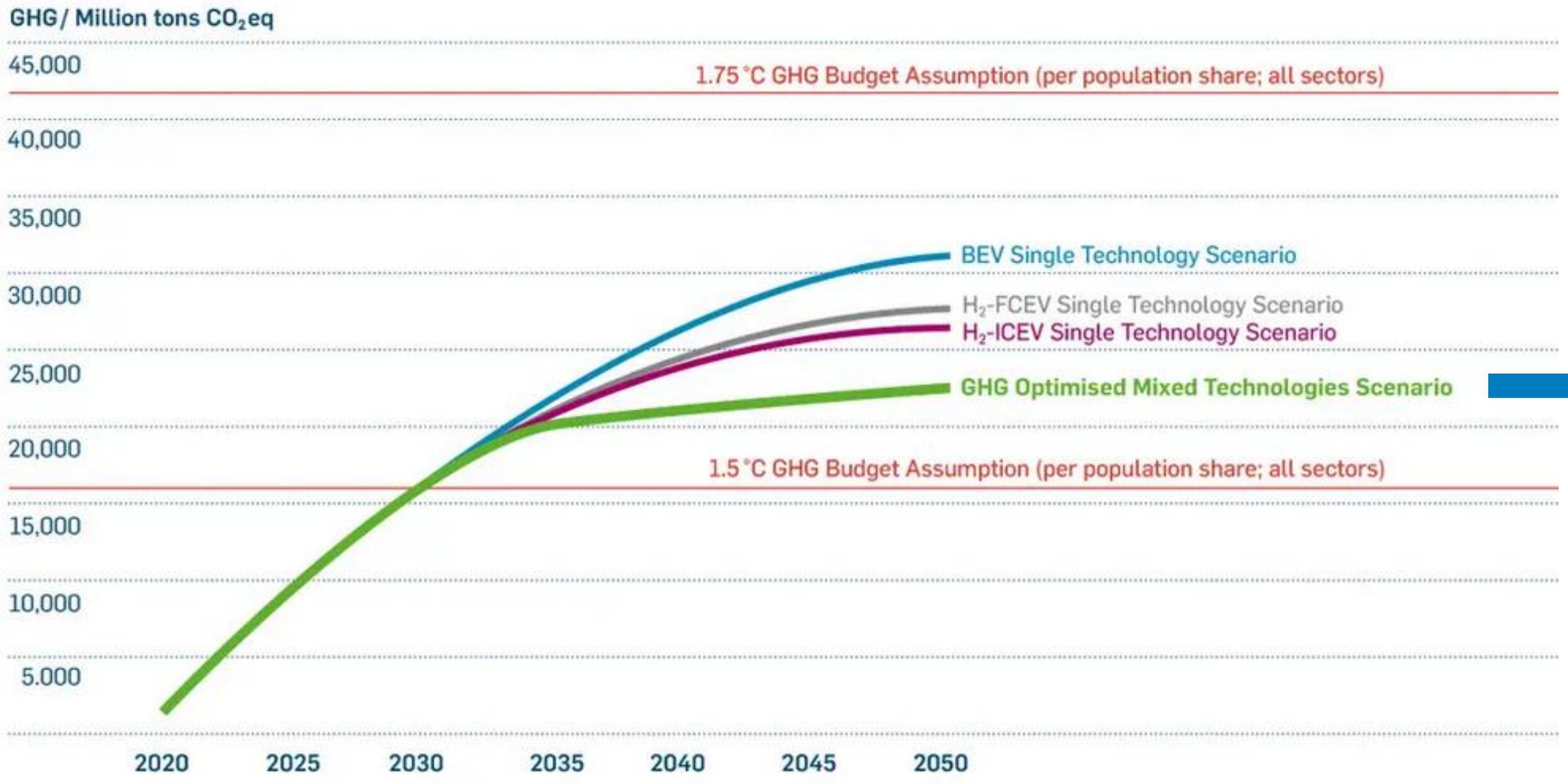
Greenhouse gas neutrality of transportation sector
Technology openness as key for fast goal achievement



Source:
FVV Fuel Study IVb
„Transformation of mobility to the GHG neutral post fossil age“
Report H1313 | 2022

Includes all Powertrain Types: BEV, FCEV, H_2-ICE, eFuels

To sustainably reduce cumulative CO_2 in earliest timeframe, a holistic approach is mandatory

No legal advice - provided for informational purposes strictly on a non-reliance basis.

ICE Internal Combustion Engine   GHG Greenhouse Gases   BEV Battery Electric Vehicle   FCEV Fuel Cell Electric Vehicle