Nfz – Prüfstandskonzept für die Motorenentwicklung und Homologation (Emissionsmessungen, H2-ICE-Prüfstand)

Leimen, 25. Mai 2023

T. Kauffeldt

Kurzvorstellung:

33 years in measurement technology
19 years at AVL

- Business unit sales support team leader
- Global accounts support
- Emission and energy measurement application management with focus on heavy-duty and non standard applications

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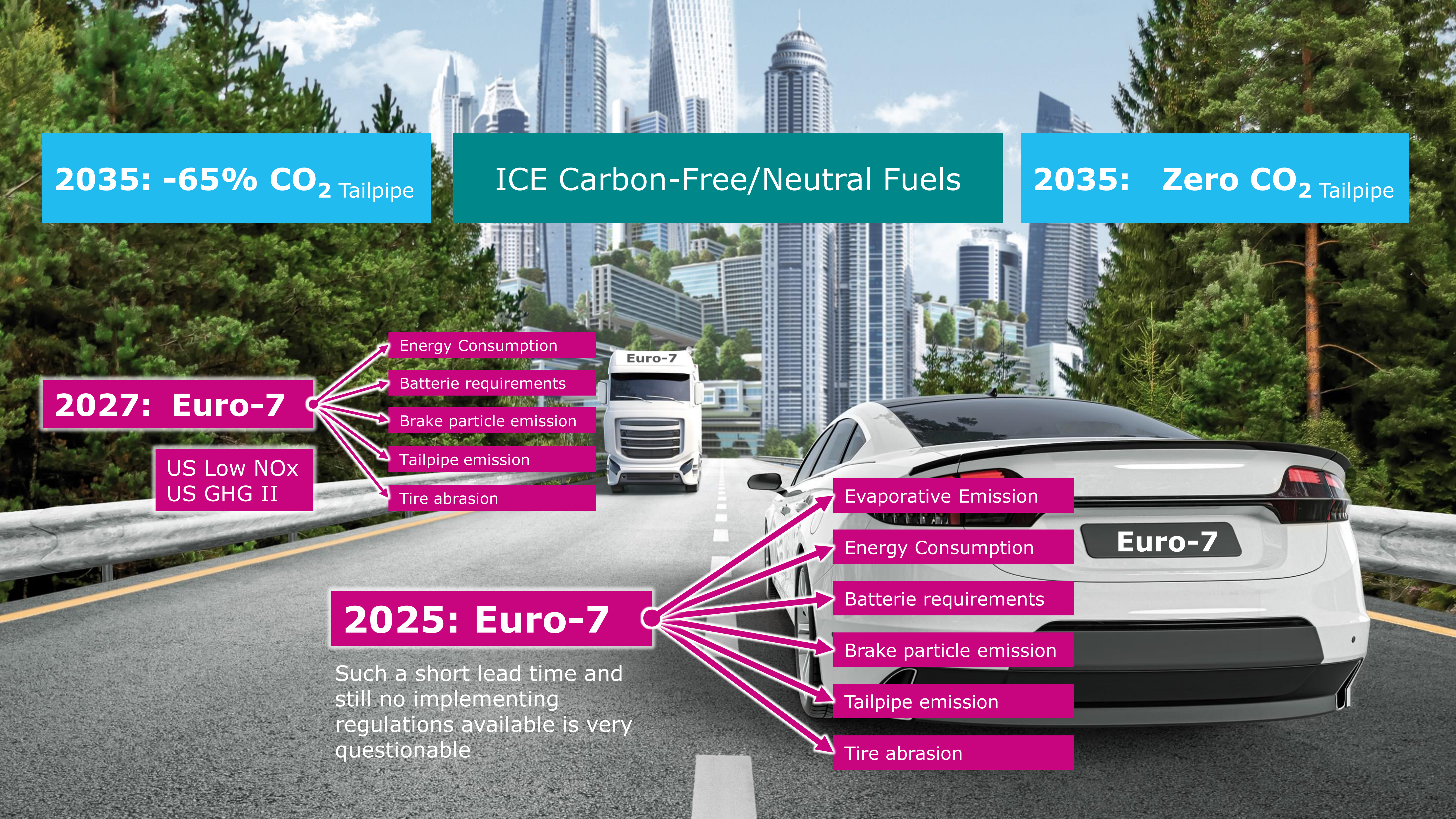
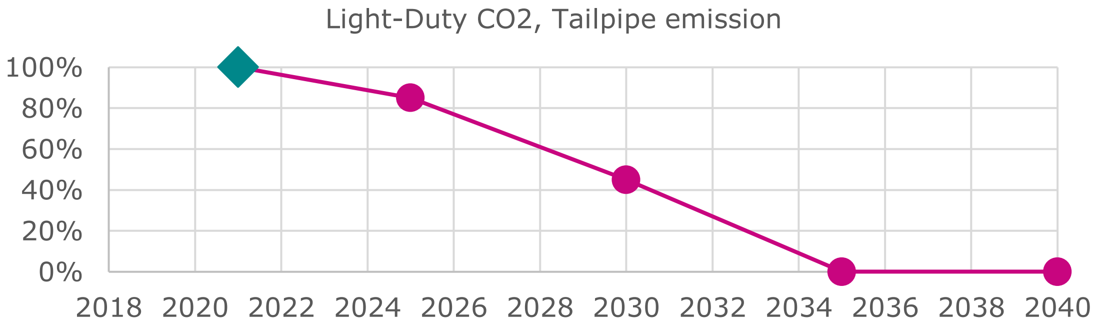

2035: -65% CO_2 Tailpipe
ICE Carbon-Free/Neutral Fuels
2035: Zero CO_2 Tailpipe
2027: Euro-7
Energy Consumption
Batterie requirements
Brake particle emission
Tailpipe emission
Tire abrasion
US Low NOx
US GHG II
Euro-7
2025: Euro-7
Evaporative Emission
Energy Consumption
Batterie requirements
Brake particle emission
Tailpipe emission
Tire abrasion
Euro-7
Such a short lead time and still no implementing regulations available is very questionable

EU CO2 reduction targets "Fit for 55"

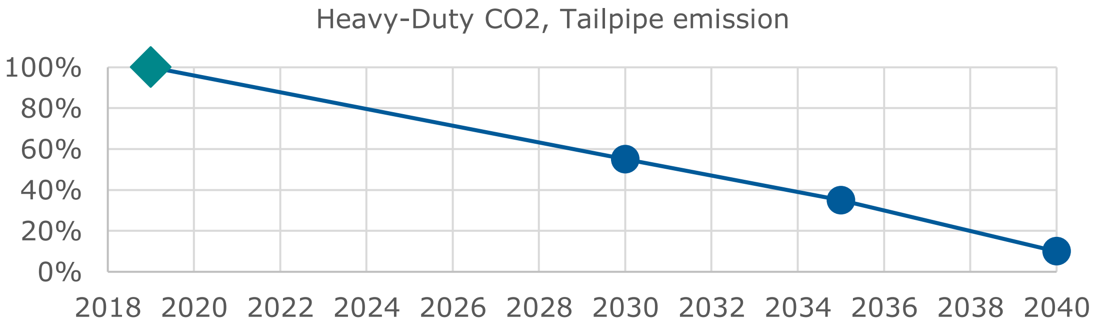
EU targets for Light-Duty vehicles

- 2025 tailpipe CO2 fleet average -15% in reference to **2021**
- 2030 tailpipe CO2 fleet average -55%
- **2035** tailpipe CO2 fleet average **-100%**
- H2, e-Fuels and Bio-Fuels are currently not considered as Zero.



EU targets for Heavy-Duty vehicles

- 2030 tailpipe CO2 fleet average -45% in reference to **2019**
- **2035** tailpipe CO2 fleet average **-65%**
- **2050** tailpipe CO2 fleet average **-90%**



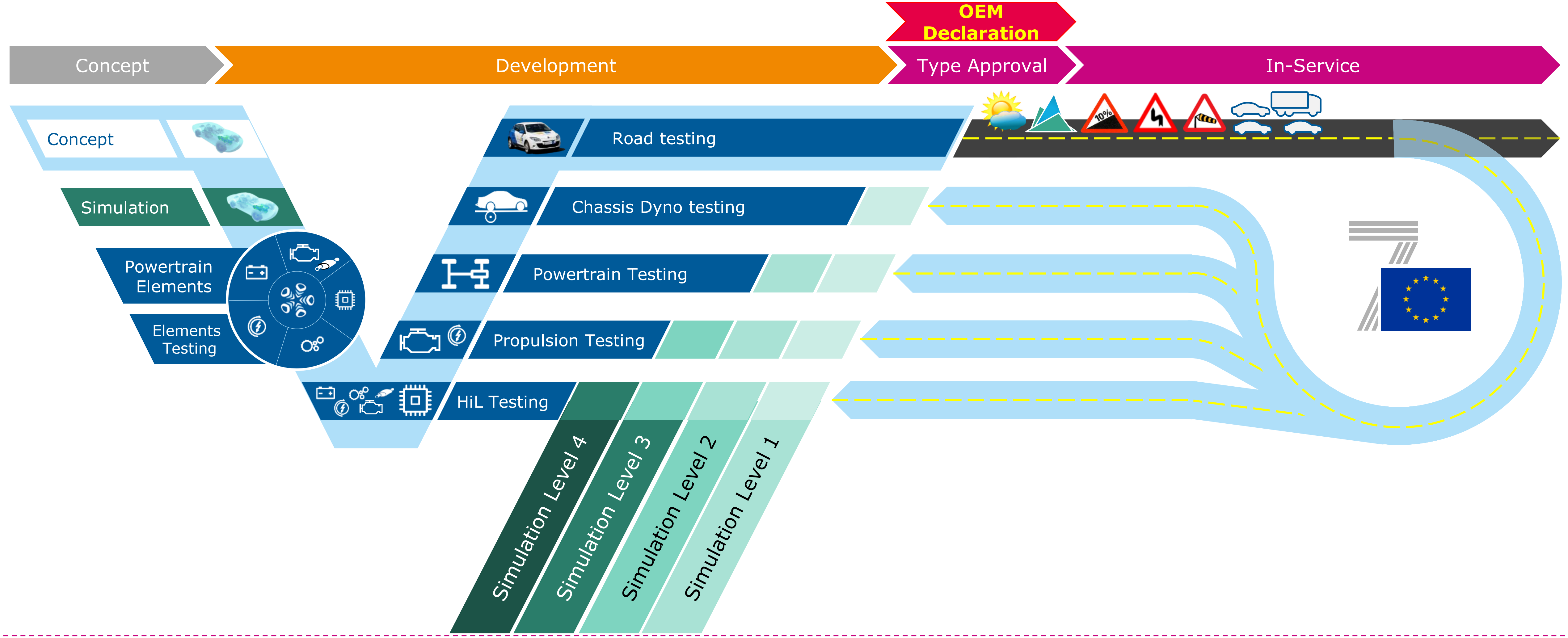
"ONLY" - $CO_{2,\ Tailpipe}$

Not fully environmental relevant and "Green washing of BEV"

Nov. 2022: EU Commission published the Euro-7 proposal

- Which gives a first indication what Euro-7 “Legislation” will be.
- Euro-7 is one common legislation for Light- und Heavy-Duty vehicles, brakes and tires.
- In 2023 the technical details will be defined (implementing regulations, which will be different for LD and HD).
- Euro-7 defines how CO2 is measured but does not regulate CO_2.

Powertrain Development Process



Not all cases can be covered on the road, need to use all simulation levels to prepare OEM declaration

Euro 7$_{\text{Heavy-Duty}}$: Limits

EURO 7 EMISSION LIMITS

Table 2: Euro 7 exhaust emission limits for M_2, M_3, N_2 and N_3 vehicles with internal combustion engine and internal combustion engines used in those vehicles

Pollutant emissions	Cold emissions[2]	Hot emissions[3]	Emission budget for all trips less than 3*WHTC long	Optional idle emission limits[4]
	per kWh	*per kWh*	*per kWh*	*per hour*
NO_x in mg	350	90	150	5000
PM in mg	12	8	10	
PN_{10} in #	$5x10^{11}$	$2x10^{11}$	$3x10^{11}$	
CO in mg	3500	200	2700	
NMOG in mg	200	50	75	
NH_3 in mg	65	65	70	
CH_4 in mg	500	350	500	
N_2O in mg	160	100	140	
HCHO in mg	30	30		

2 Cold emissions refers to the 100th percentile of moving windows (MW) of 1 WHTC for vehicles, or $WHTC_{cold}$ for engines
3 Hot emission refers to the 90th percentile of moving windows (MW) of 1 WHTC for vehicles or $WHTC_{hot}$ for engines
4 Applicable only if a system is not present that automatically shuts down the engine after 300 seconds of continuous idling operation (once the vehicle is stopped and brakes applied)

Tests with more than 3 WHTC windows must fulfill both limits, Cold and Hot. However, there will be no separate hot or cold test.

- Cold limit is 100% percentile, so including cold start peaks.
- Hot limit is 90% percentile, so excluding cold start peaks.

RDE tests up to 3 WHTC windows must fulfill the Emission Budget limit.

0 km/h

Idling (hoteling): Automatic engine off after 300s or Idle emission limit of 5000mg/h.

Engine fuel mapping cycle for VECTO CO2 simulation.

In discussion if an engine pollutant WHTC cycle is needed. EU Commission cares only for vehicle, OEMS prefer a testbed test for **multi stage vehicle** applications.

Based on original Document of EU Commission proposal for Euro-7, 10.11.2022

Criteria Emissions – Heavy-Duty Euro-VII limits

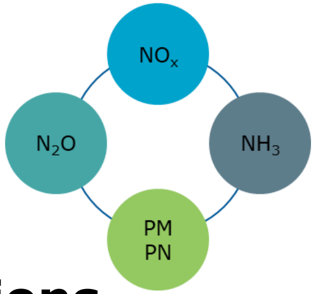
Component Candidates	Light-Duty	Unit	EU-VII Heavy-Duty M2, M3, N2 and N3			
			Cold emissions 100th percentile	**Hot emissions** 90th percentile	**Emission Budget < 3xWHTC**	**Idle emission** if no 5min automatic engine shut off
CO_2	✓	mg/kWh	✓	✓		
$CH_4 + N_2O$		mg/kWh	-	-		
CO	✓	mg/kWh	3500	200	2700	
NO_x	✓	mg/kWh	350	90	150	5000 mg/h
THC	✓	mg/kWh	-	-		
NO_x + THC		mg/kWh	-	-		
CH_4	✓	mg/kWh	500	350	500	
NMHC	✓	mg/kWh	-	-		
Alcohols		mg/kWh	Needed for NMOG	Needed for NMOG	Needed for NMOG	
NMOG		mg/kWh	200	50	75	
PM	✓	mg/kWh	12	8	10	
PN_{10nm}	✓	#/kWh	5E+11	2E+11	3E+11	
N_2O		mg/kWh	160	100	140	
NH_3	✓	mg/kWh	65	65	70	
HCHO		mg/kWh	30	30		

New

EU VII Legislation HD
AVL Interpretation

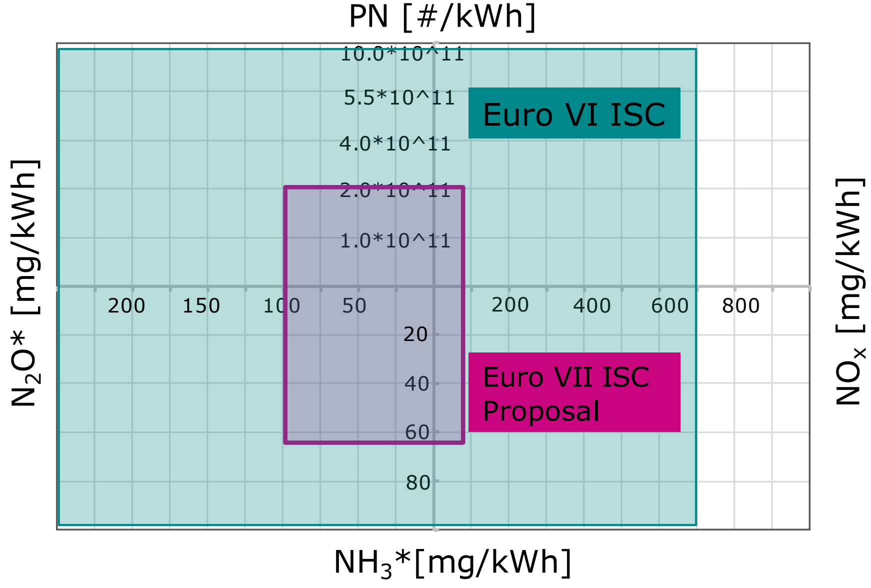
- **Transition** from **Lab Testing** to **Road Testing**
- **Emission** reduction down to
  - **350 mg/kWh NO_x** for **cold start**
  - **90 mg/kWh NO_x** in **hot condition**
- **Limits for HCHO, N_2O, CH_4, PN_{10}** and **NH_3** in **RDE**

→ **Balancing** of **conflicting targets**



- **Emission compliance** under **all RDE conditions**
  - Almost **no boundaries** on **test conditions** (ambient temperature, altitude, vehicle mileage, engine load, …)
  - **No** dedicated **preconditioning**
  - **No separate weighting** of **cold start**

Proposed Limits for ISC



*: Euro VI no NH_3 and N_2O limit in ISC

Main topics for HD EU7 – ICE Emission Testing

CHALLENGES from EU7

- Reduced Limits
- New components
- Environmental conditions
- OEM Declaration
- OBM-Limits

DEVICE REQUIREMENTS

- Particle Counter - APC
- SESAM i60 FT
- AMA SL (CLD)
- Emission Automation iGEM2

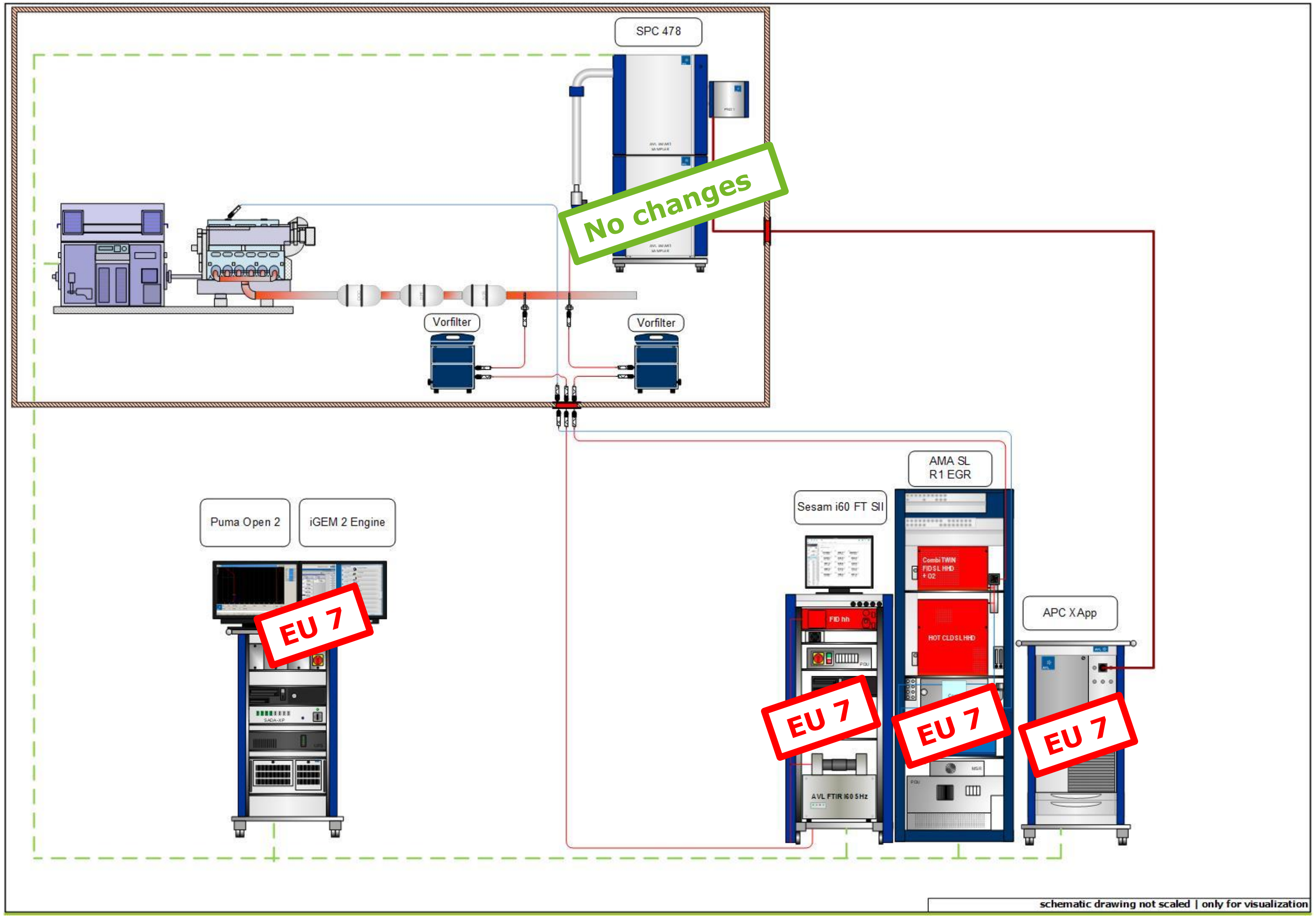
TEST CELL REQUIREMENTS

- Climatic range
- Altitude range

CO2 neutral FUELS

- H2
- ……….

Overview HD Engine Test Cell – Partial Flow Dilution



EU7 requirements & readiness

Automation iGEM2	
FTIR Analyzer SESAM FT	
Analyzer AMA SL	
Particle Counter APC	

AVL

Emission Automation – iGEM 2

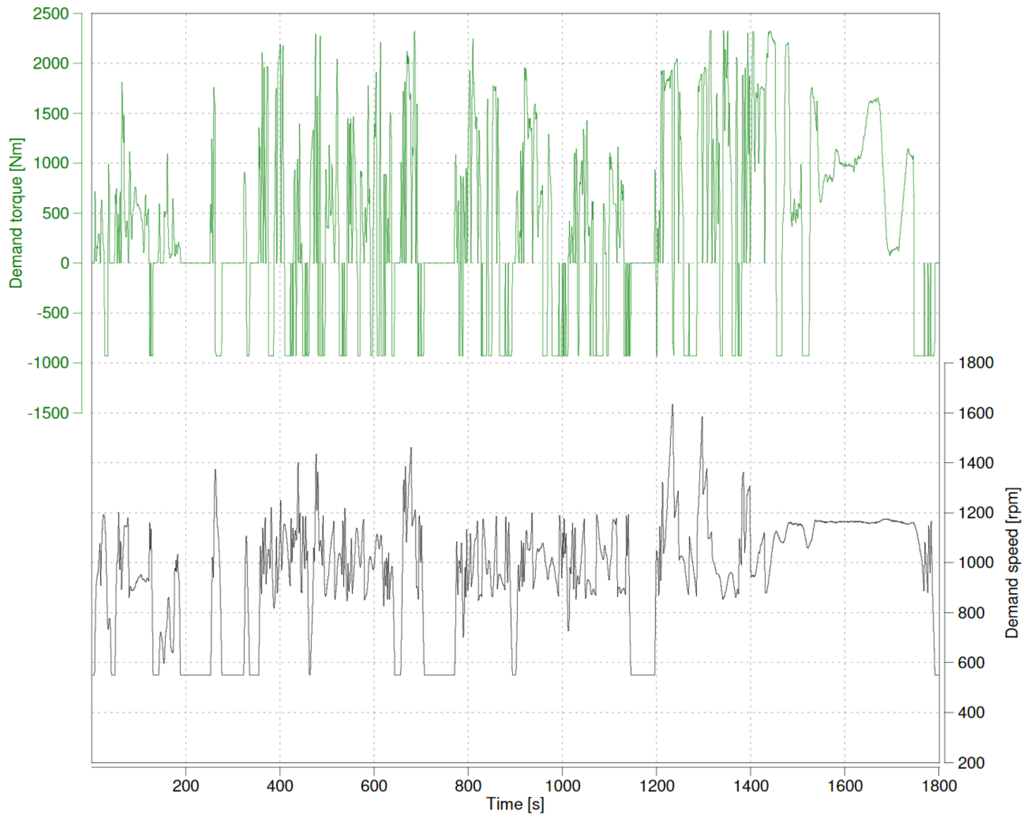
Changes to the standard regulatory test application (so far known as of today)

1 | **No combined weighted result of cold and hot WHTC**
WHTC cold and WHTC hot as two test cycles and/or one cycle with 2 evaluations

2 | **Additional test applications and calculation packages (R&D mainly)**

3 | **New Limits**

4 | **New Components measured, calculated and reported:**
NMOG, CH_4, N_2O, NH_3, HCHO



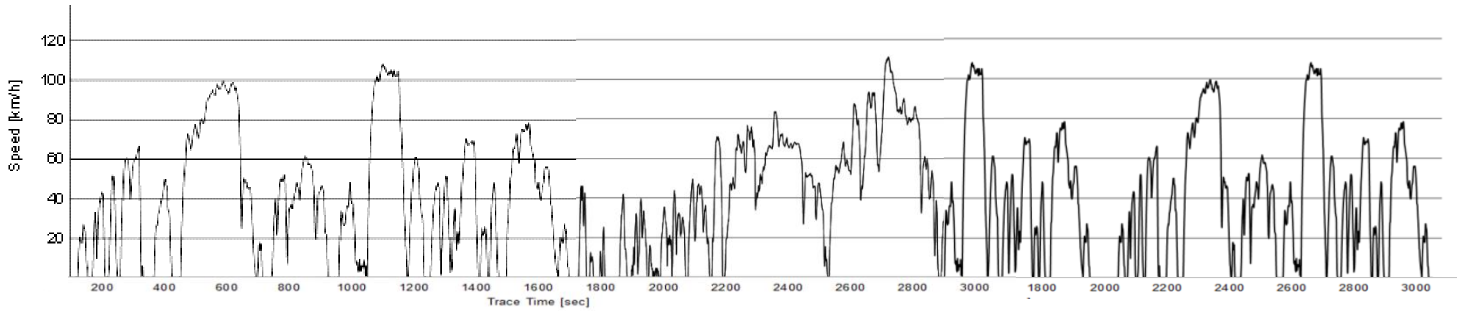
Emission Automation – iGEM2

R&D requirements expected based on first discussion with HD customers and PTE

Tests and requirements at initial emission type approval
Required demonstration tests for all fuels for which the type approval is granted per vehicle type and a declaration of compliance for all fuels, all payloads and all applicable vehicle types

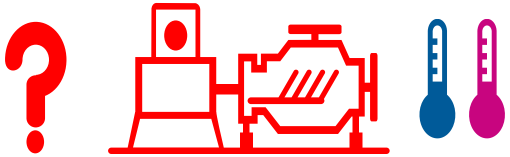
R&D requirements expected:

- ➢ Worst Case Cycle Generator
- ➢ Road to Lab Importer: Torque/Speed profile at the test cell. Result calculation as MOVE systems.



Schematic Worst-Case-Cycle

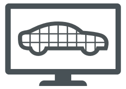
Testbed automation – PO2 & iGEM2



In discussion if an engine pollutant WHTC cycle is needed. EU Commission cares only for vehicle, OEMS prefer a testbed test for **multi stage vehicle** applications.

Extended Vehicle Simulation on the engine / powertrain test bed
Additionally advanced VTB needed.

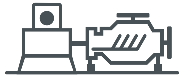
Simulation:



SIL Simulation

HIL Simulation

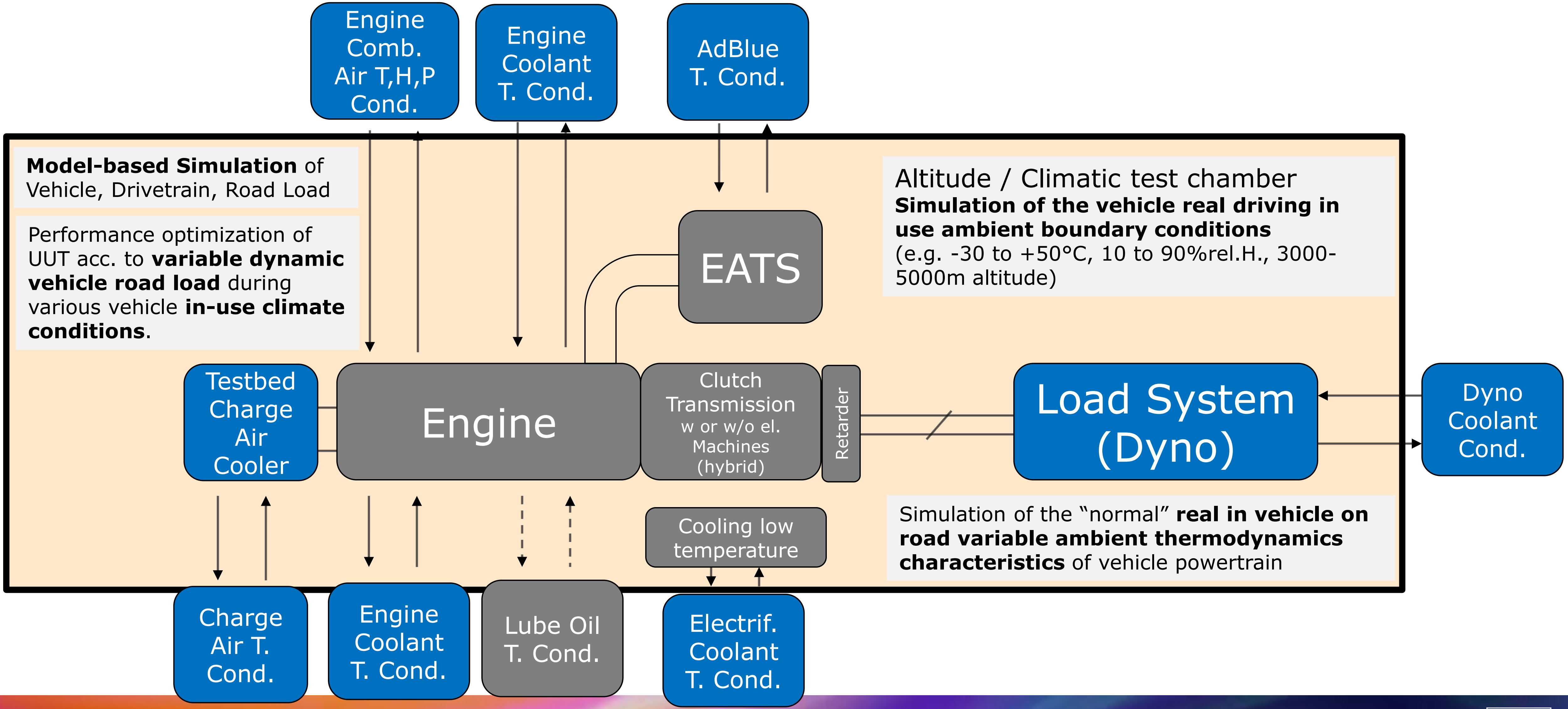
Laboratory:



Engine testing

24/7 Powertrain testing

EU7 HD- in Laboratory Real Driving „Vehicle" Testing - Possible Test System approach



CO2 & Fuel Consumptions – Best guess February 2023

Fuel cycle test delivers the input dada for the **VECTO** tool. VECTO (Vehicle Energy Consumption Calculation Tool) is a simulation tool developed by Graz University of Technology (TUG) to calculate HD vehicle fuel consumption and CO_2 emissions based on engine testbed data. This test will remain as it is already for Euro 6. Regeneration of exhaust aftertreatment systems shall be included by a weighting factor.

FCMC Will be required for Euro 7. Basically Euro 6 provisions will be taken over (up to 110 points, same map). Possible changes to Euro 6: Emissions will be measured in every point of the FCMC, the average emissions over the whole map must be below the WHTC hot limit. Actually, there is a control area where emissions must be below the NTE limit.
Final decision open.

iGEM2 solution for Euro-7

EU Emission

European Commission, Picture Engeljehringer 2015

Temporary Euro-7 solution	Supported by iGEM 2
① **WHTC changes** • Single evaluation • 1x WHTC -> 2 results: 100% and 90% percentile • New limits • New components	Q2 / 23
② **R&D requirements** • Worst Case Cycle Generator • Road to Lab Importer • ………	To be done / 2023

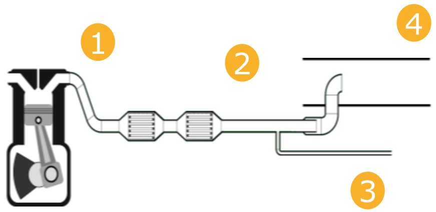
APC Variants

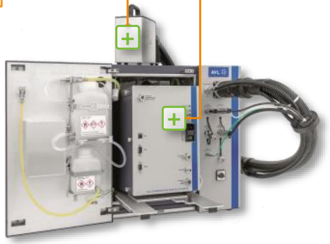
Section 1:

Particle pre-treatment: **V**olatile **P**article **R**emover

Section 2:

Core Sensor: **C**ondensation **P**article **C**ounter





	APC xCert	APC xCert 10	APC xApp	APC xApp 10	APC xApp Dual
		New			
(1) Engine Out			✓	✓	✓
(2) Tailpipe			✓	✓	✓
(3) PFDS	✓	✓	✓	✓	✓
(4) CVS	✓	✓	✓	✓	✓
Volatile Particle Remover	Evaporation Tube	Catalytic Stripper	Evaporation Tube	Catalytic Stripper	Catalytic Stripper
Number of PCRF	3	3	16	16	16
AVL CPC	23nm	10nm	23nm	10nm	1x 10nm, 1x 23nm

Criteria Emissions: New emission components

Gas component	Accepted analyzer types, as defined in GTR-15 (WLTP)													Notes
	☆ FTIR	NDIR	QCL	LDS	GC-ECD	PAS	Impinger	DNPH Catr.	PTR-MS	Direct GC	FID	NMC-FID	GC-FID	
N2O Nitrous oxide	✓	✓	✓		✓									• Batch sample for GC-ECD
NH3 average conc. Ammonia	✓		✓	✓										• raw sample for average NH3 concentration.
NH3 mass Ammonia	✓		✓	✓										• sampling method to be defined
HCHO Formaldehyde Acetaldehyde	✓							✓						• cont. diluted or • cartridge sample
Alcohols	✓					✓	✓		✓	✓				• only when the HC limit will be based on NMOG
NMOG	✓					✓	✓		✓	✓	✓	✓	✓	• NMOG = THC + Aldehydes + Alcohols – CH4

+ others

AVL SESAM i60FT D1

NMOG	= Non-Methane Organic Gases
FTIR	= Fourier Transform Infra-Red multi component analyzer
NDIR	= Non-Dispersive Infra-Red analyzer
QCL	= Quantum Cascade Lasers analyzer
LDS	= Laser Diode Spectrometer
GC-ECD	= Gas Chromatograph Electron-Capture Detector
PAS	= Photo-Acoustic analyzer
Impinger	= Alcohol sampler with High-Pressure Liquid Chromatography (HPLC)
DNPH Cart.	= Dinitrophenylhydrazine impregnated cartridges with Gas Chromatography
PTR-MS	= Proton Transfer Reaction - Mass Spectrometry
Direct GC	= direct measuring Gas Chromatograph
FID	= Flame Ionization Detector
NMC-FID	= Non-Methane Cutter - Flame Ionization Detector
GC-FID	= Gas Chromatograph - Flame Ionization Detector

SESAM FT

New Components EU7 HD

NH_3 (mg / kWh instead ppm)
CH4
N2O
HCHO
NMOG = THC + Aldehyde + Alcohol – CH4 (as CARB)
= THC + Aldehyde – CH4 + F_{fuel} (actual discussion @ CLOVE)

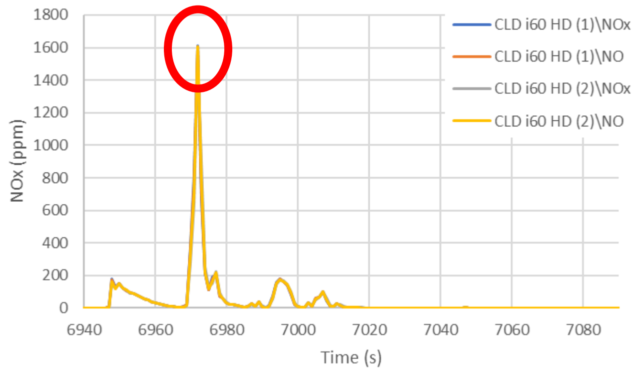
Measured Gas Components			
CO - Carbon monoxide	CH_4 - Methane	C_2H_5OH - Ethanol	NC_5 - n-Pentane
CO_2 - Carbon dioxide	C_2H_2 - Acetylene	CH_3OH - Methanol	NC_8 - n-Octane
H_2O - Water	C_2H_4 - Ethene	CH_3CHO - Acetaldehyde	HNCO - Isocyanic acid
NO - Nitrogen monoxide	C_2H_6 - Ethane	HCHO - Formaldehyde	HCN - Hydrogen cyanide
NO_2 - Nitrogen dioxide	C_3H_6 - Propylene	HCOOH - Formic acid	COS - Carbonyl sulfide
N_2O - Nitrous oxide	C_3H_8 - Propane	SO_2 - Sulfur dioxide	AHC - Aromatic HC
NH_3 - Ammonia	C_4H_6 - Butadiene	IC_5 - iso-Pentane	

CLD analyzers for Low NO_x measurements

Decreasing $NO_{(x)}$ emissions lead to a need for lower measuring ranges:

- Raw measurements with **0…3 ppm** range
- Dilute measurements with **0…1 ppm** range

However, in the cold start phase much higher concentrations occur. A measuring range of 1,000 ppm will not cover the cold start phase. Here, values up to 3,000 ppm are expected.



New/adapted CLD SL analyzers:

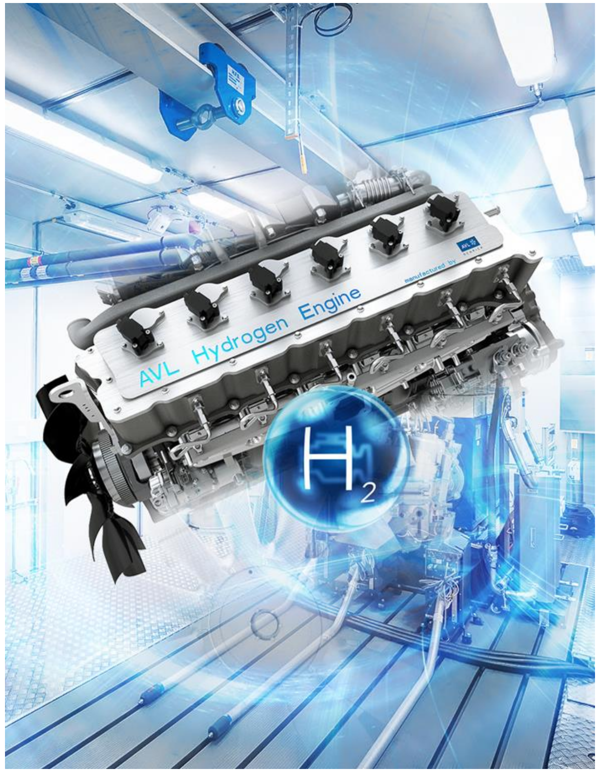
CLD type	Highest range	Lowest range	Linearity limit	Quench	Temp.
(DUAL) CLD SL low/high * switchable	0 … **3,000 ppm** 0 … 10,000 ppm	0 … 3 ppm 0 … 10 ppm	0.3 ppm 1 ppm	< 1% < 1%	180°C 180°C
(DUAL) CLD SL super low **	0 … 500 ppm	0 … **1 ppm**	0.1 ppm	~0,25% per % H_2O	180°C

* The switchable CLD is optimized for Low NO_x applications.
The range specific parameters are stored in the AMA. For switching a reboot of the analyzer is required.
It secures your investment by allowing to cover older applications with higher concentrations.
One CLD Type for the complete test field.

** To come down to a range of 1 ppm a higher flow rate is required.
This leads to a worse quenching behavior than standard CLD SL analyzers:


2035: -65% CO_2 Tailpipe
ICE Carbon-Free/Neutral Fuels
Heavy-Duty Vehicles

H_2 (Carbon free fuel) in Emission Regulations:



Carbon free fuel ICE Emission Regulations	UN-ECE / EU	USA	ISO
Use cases	(Very) Lean Proposal	All use cases	All use cases
Fuel	H_2	All Carbon-free fuels (H_2, NH_3)	All Carbon-free fuels (H_2, NH_3)
Fuel type	Mono fuel	Mono and Dual fuels	Mono and Dual fuels
Emissions measured	All limited components	Criteria emissions plus H_2O, H_2, and NH_3	Criteria emissions plus H_2O, H_2, and NH_3
Measurement method:			
Raw exhaust	✓	✓	✓
Continuose diluted	X	✓	✓
Bag diluted	X	✓	✓
Exhaust flow rate determination	• measured	• Measured or • Calculated out of 2 quantities of O_2, H_2O or H_2 plus NH_3 for NH_3 fuel.	• Measured or • Calculated out of 2 quantities of O_2, H_2O or H_2 plus NH_3 for NH_3 fuel.
Dry-to-Wet correction	✓	✓	✓
CVS Background correction	No (No CVS measurement)	✓	✓

EPA – 40 CFR 1065

Draft for new 1065 Sections and Section Modifications for ZCF (**Zero Carbon Fuels**)

§1065.25X **H_2 measurement** devices.
(1) Magnetic sector mass spectrometer.

§1065.257 Fourier transform infrared analyzer for **H_2O measurement**.

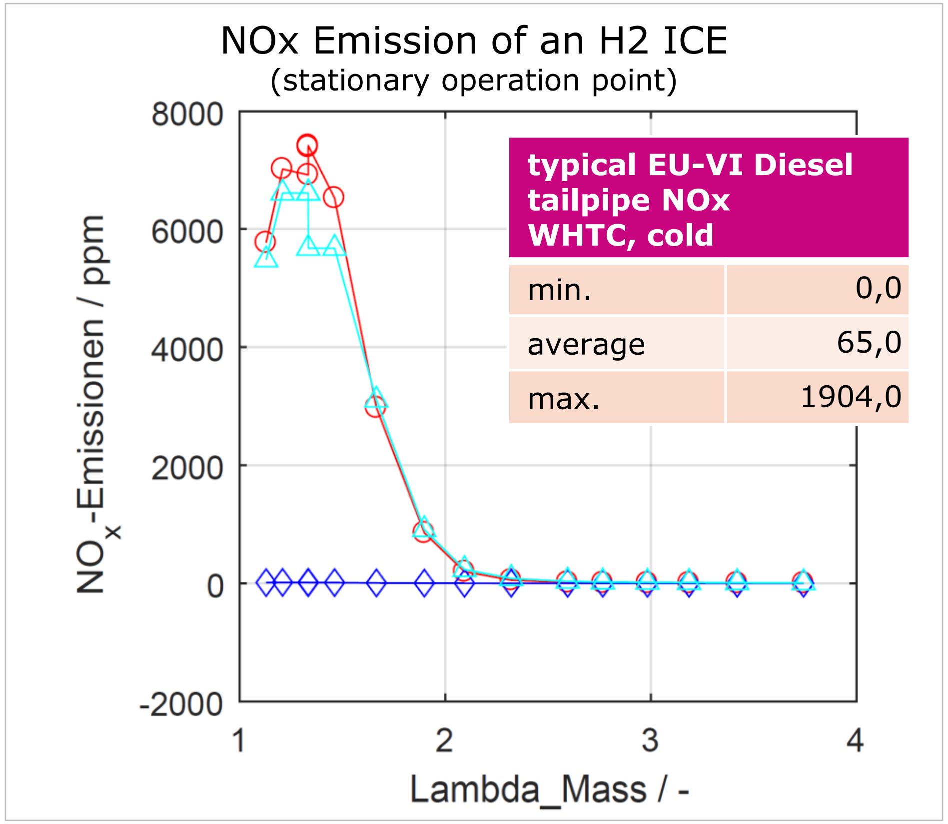
Challenge for Cal. gas

§1065.357 CO_2 interference verification for H_2O FTIR analyzers.

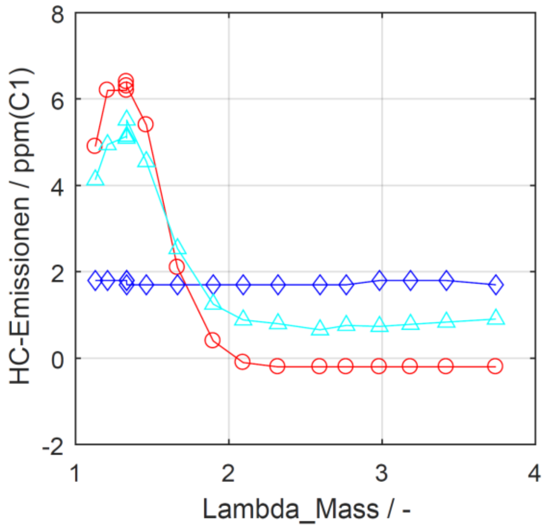
§1065.277 **NH_3 measurement** devices.
(2) Fourier transform infrared (FTIR) analyzer.

§1065.657 Chemical balances of zero-carbon fuel, DEF, intake air, and exhaust.

H2 ICE: exhaust gas

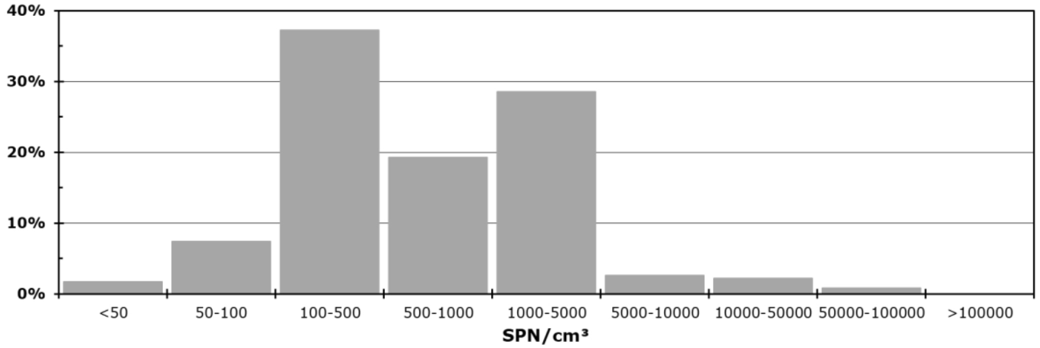


typical EU-VI Diesel tailpipe NOx WHTC, cold	
min.	0,0
average	65,0
max.	1904,0



HC

Snapshot data from a H2 ICE pilot project at TU Graz

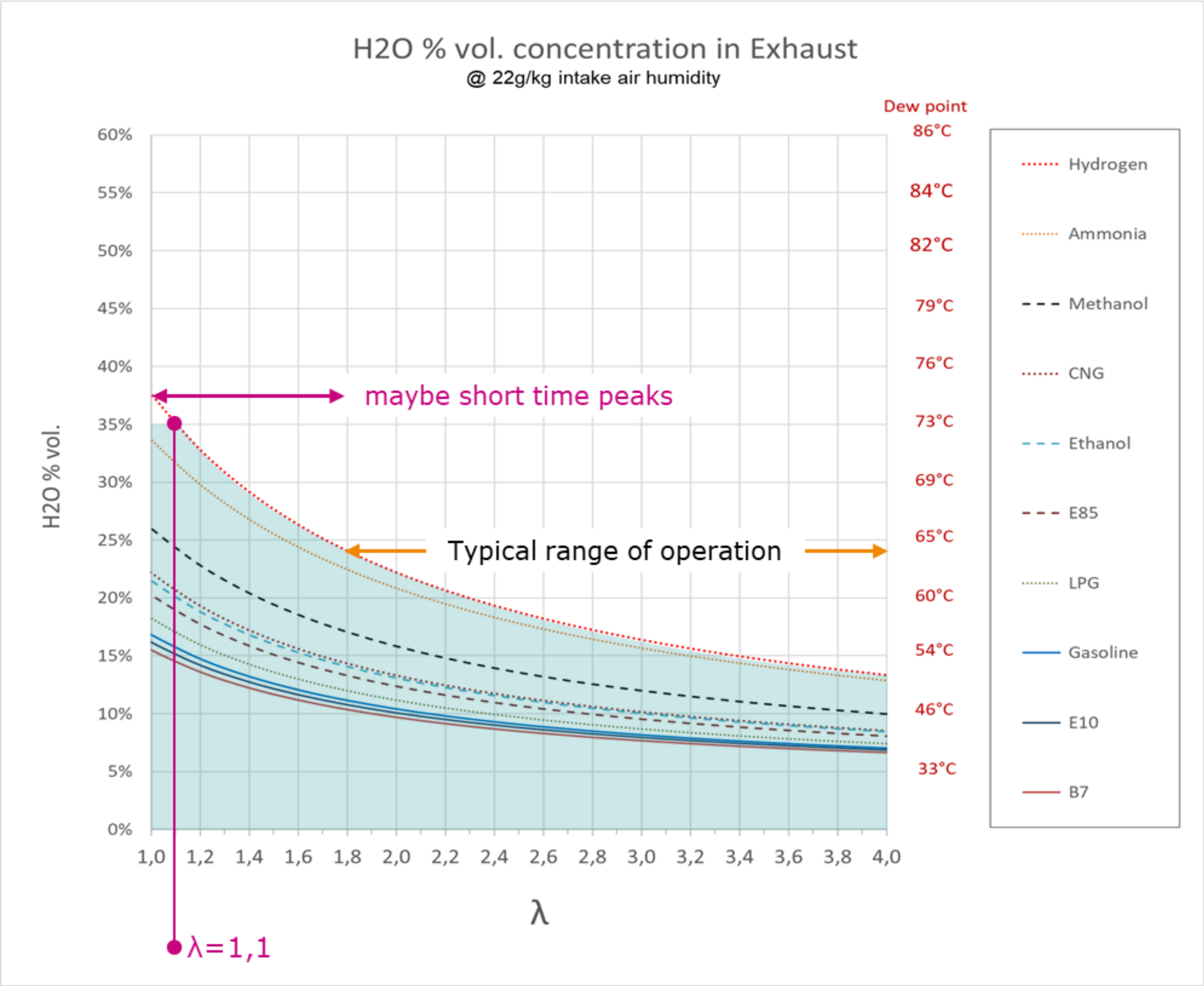


PN

$$H_2 + O_2 + N_2 \rightarrow \underbrace{H_2O + O_2 + N_2}_{\text{ideal combustion}} + \underbrace{H_2}_{H_2\ \text{slip} < 1 - 2\%} + \underbrace{NO + NO_2 + HC + Soot}_{\text{Pollutants}}$$

Coming from oil / lubricants

H2 ICE: Water load in the exhaust (impact on analytical system)



Chiller capacity

AMA SL: H_2O < 35% using one chiller circuit, peak wise above

AMA i60: H_2O < 25% with one, < 45% with two**

CLD Quench

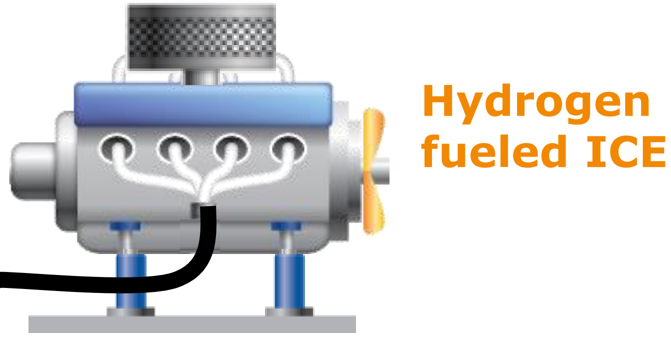
Regulation requirements fulfilled for all H_2O ranges with AVL Hot (SCR) CLD

H_2O Interference

Critical for H_2 mass spectrometer (magnetic sector field) so far not compensated.

Standard Solution for H_2-ICE

AVL H2D in Combination with the AVL SESAM i60 FT



- Standard solution consisting of:
  - SESAM for diverse components
  - H2D for H_2 measurement
- SESAM correcting for H2D H_2O interference for accurate H_2 measurement:

$$H2_{corr} = H2_{H2D} - H2O_{SESAM} * C$$

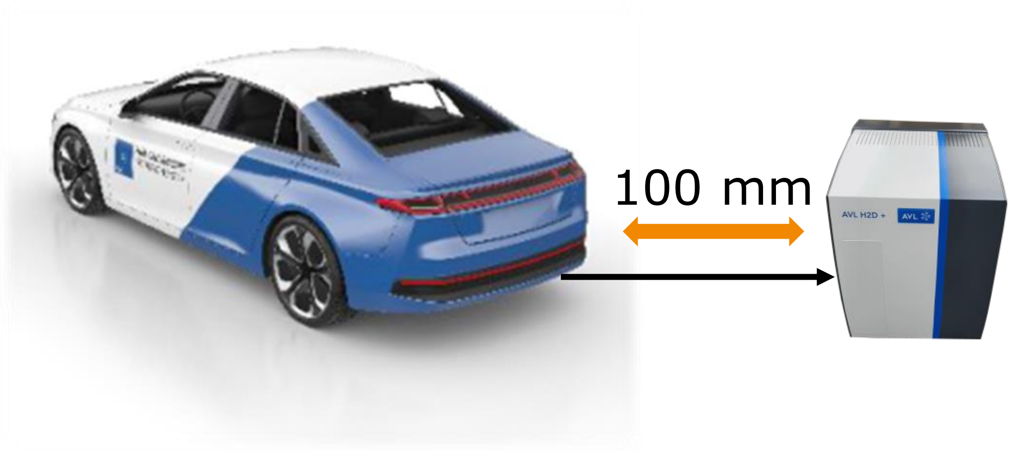
H2 < 20 ppm / 1 Vol.% H2O
e.g. < 700 ppm @ 35 Vol.% H2O

UNR 134 Approval of hydrogen-fuelled vehicles with regard to the safety-related performance

- Part I and II are about type approval tests for hydrogen storage systems and its components (e.g. fire, leak, corrosion tests)
- Part III is defining type approval tests for vehicles:
  – max. allowed H_2-emissions of the exhaust:

(a) **≤ 4 % average** by volume during any **moving 3 sec. time interval** during normal operation (including start-up and shut-down)

(b) **< 8 % at any time**



- ➢ vehicle and measuring device are fully warmed up
- ➢ continuous measurement of H_2-conc. during:
  - complete shut-down procedure with a restart
  - idle for 1 minute followed by a complete shutdown
- ➢ measurement response time **< 300 ms**

Thank you

AVL

www.avl.com