Shaping Our Tomorrow with Advanced Catalytic Solutions for Cleaner Air

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Senior Vice President
R&D and Application

BASF Environmental Catalyst and Metal Solutions

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BASF – We create chemistry for a sustainable future

- Global leading chemical supplier with >150 years experience
- Our chemistry is used by ~90,000 customers from various sectors in almost every country in the world
- We aim to achieve net zero emissions by 2050
- We combine economic success, social responsibility and environmental protection

BASF key facts (2022)

6 Verbund sites & 241 other production sites

110,302 employees

€87.3B sales
15% higher than last year

Around 950 new patents filed world-wide

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A new BASF company has taken shape

BASF Environmental Catalyst and Metal Solutions (ECMS)

Mobile Emissions Catalysts

Emissions control catalysts for cars, trucks, motorcycles, non-road vehicles

Catalysts for ozone and VOC removal for aviation industry

Catalysts and adsorbents for indoor air purification

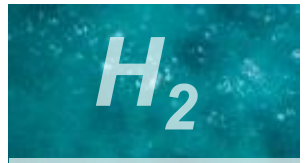
Precious Metal Services & Products

Trading

Recycling

Precious Metal Chemicals

Temperature Sensing



Solutions for the hydrogen value chain

4.350 employees

30 Sites

- 17 Manufacturing
- 8 R&D
- Others

in **12 countries** globally

14.5bn € sales 2022

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BASF Environmental Catalyst and Metal Solutions global presence

1) Typically includes some non-production personnel and lab activities (e.g., QC) | 2) Includes several sites in Shanghai and Greco JV | 3) Includes ECMS offices as well as JV manufacturing activities in Japan / Korea.

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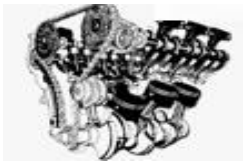
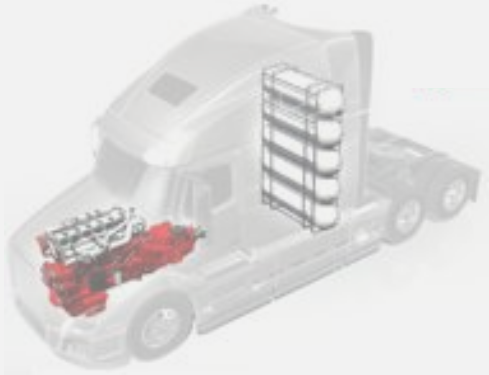
Agenda

Cleaner ICEs



Alt. Fuel ICEs



Green Hydrogen

We help improve air quality with our innovative catalysts solutions

BASF EMCS invented the TWC (Three-Way Catalyst) automotive catalytic converter enabling clean air

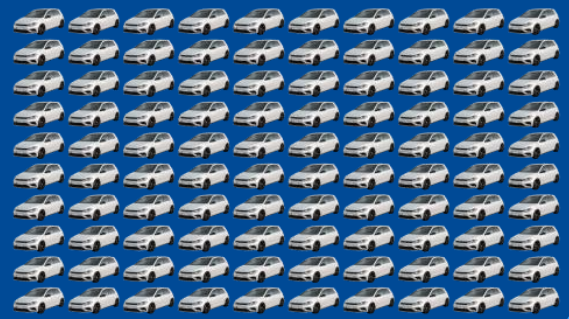
BASF received UN Award of the Decade & National Medal of Technology for the invention of automotive TWC.

1975

x1

Three-Way-Catalyst

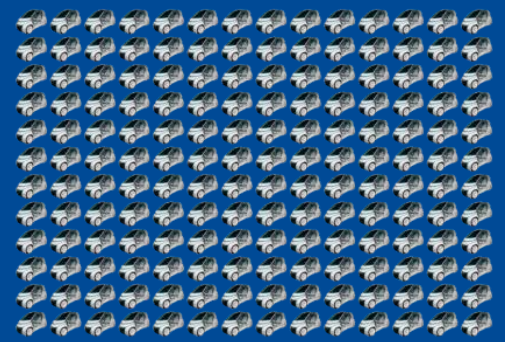
2018



x100

Four-Way-Catalyst
SCR - Catalyst

Tomorrow



x100+

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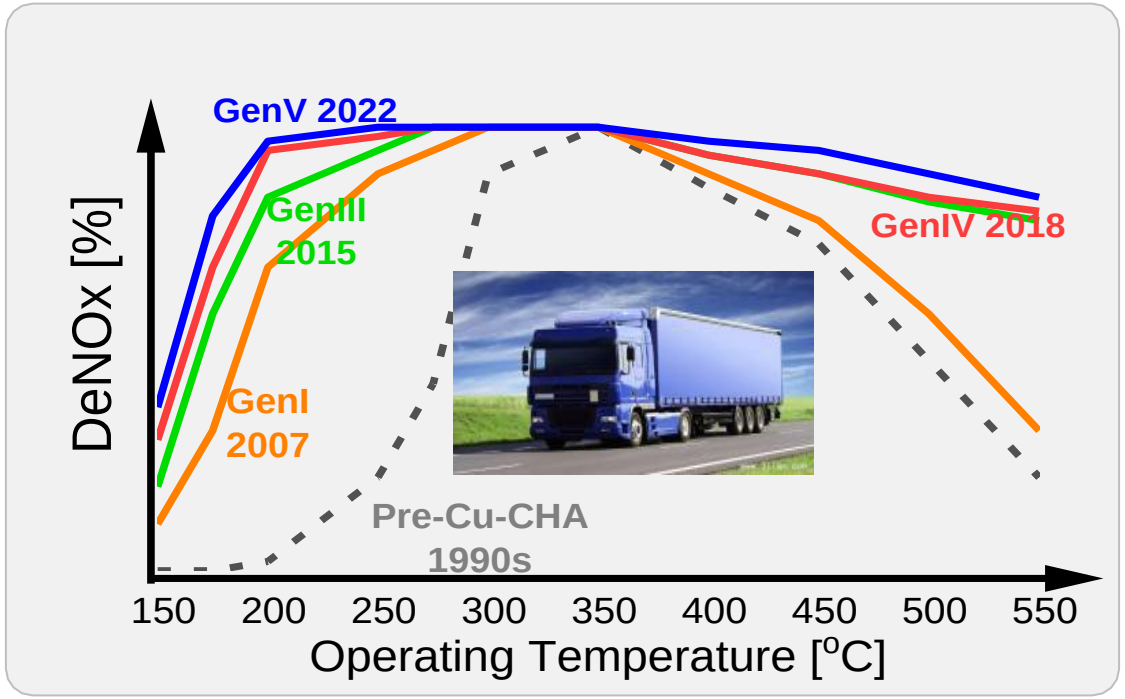
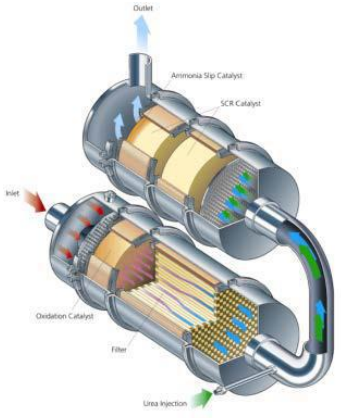
Cu-Zeolite SCRs advancement over the years

Continuous advancement of Cu-zeolite SCR with better DeNOx conversion & lower N_2O selectivity over wide temp. window

Cu-SCR Technology Evolution





Evolution of HDD emission control since US 2010

Aftertreatment systems are 40% lighter, 60% smaller, and substantially less expensive compared to US2010 system*

*MECA June 2019 report on meeting HDD Low NOx standards in the US. (www.meca.org)

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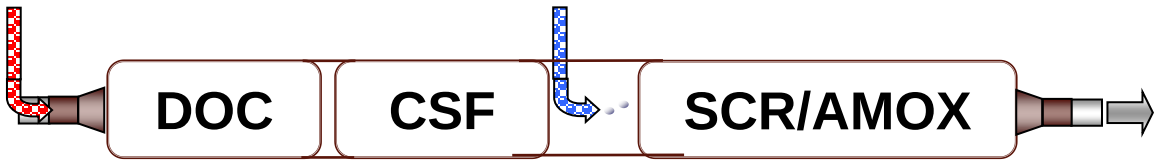
Fifteen Years of Design Innovation and Partnership:

Catalyst Systems for 11-13L Engines



	PGM Cost (Relative)	System Size (Relative)	Catalyst Levers	Know-How Levers
2010	100%	100%	Copper Chabazite Zeolite SCR	--
2013	81%	91%	New DOC designs SCR and AMOX improvements	Urea dosing strategy
2017	50%	70%	New DOC Formulation Improved SCR	Component aging Calibration and dosing strategy
2020 (NA/Eu)	50%	70%	Iron Chabazite SCR	
2020 (AP)	46%	56%	Localized SCR	Zeolite manufacturing and development
2024	51%	70%	DOC improvement	PGM effectiveness
2027	45%	106%	Low N2O Cu-CHA	Zeolite improvements

Increasing Regulatory Challenges

Technology innovations reduced PGM usage while enabling aftertreatment systems to meet more stringent regulations

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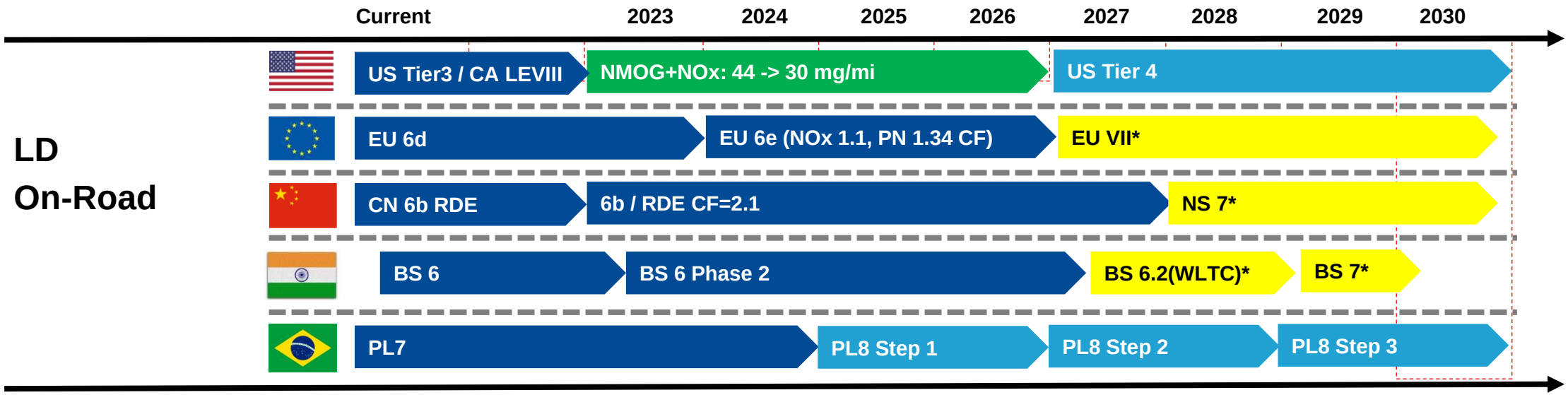
Global Regulation & System Trends - LD



*: Assumption

- EPA proposal for new LD Multipollutant NPRM published
  - → NMOG+NO_x fleet limit reduction by 60%
  - → No fuel enrichment allowed → increase of aging temperatures
  - → New PM limits (0.5mg/mi) will require Filter, FWC and non-catalyzed filter in discussion

- Euro 7 proposal with introduction in mid 2025 by European Commission was mostly rejected by European Council – positioning of European Parliament pending. Implementation later than 2025 expected - weaker requirements than initially proposed likely
- Final compromise on Emission limits, RDE boundary conditions and secondary emissions (NH_3) will have big impact on required components and system layout complexity for LDD and LDG

- High share of ethanol fueled engine (72% in Brazil) as low emission fuel alternative – only slow increase of BEV market expected
- PL8 regulation defined with stepwise introduction until 2029, PL9 expected after 2032

Gasoline After-Treatment Systems for Future Legislations

Specialized components focus on different Pollutant Species

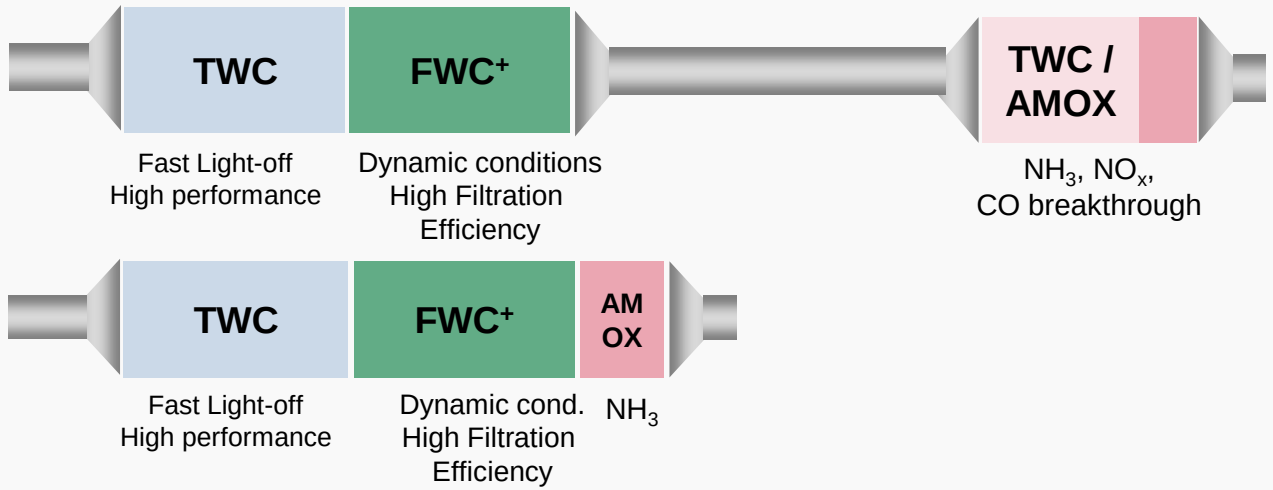
Challenge

§ New legislations
Euro 7
China 7
BS 7

NH_3
PN_{10} New pollutants

Extended RDE

BASF has dedicated technologies and co-development capabilities to tackle the challenges of future emission legislation



Together

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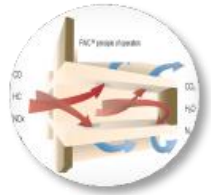
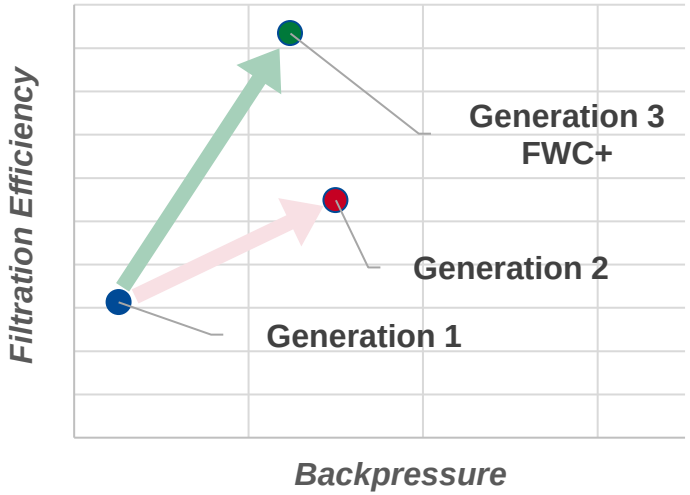
Four Way Catalyst (FWC)

Filtration Efficiency Maximization and PGM Content Optimization



Filtration and dp



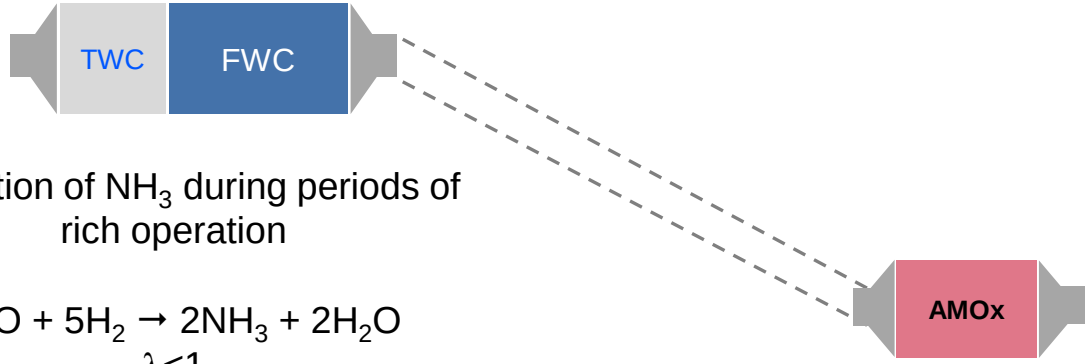
- **FWC+** developed and implemented:
  - ▶ High and super high FFEs reached
  - ▶ Δp and Δp with soot minimized
- **Filtration/dp can be tailored according to customer need**

Three-way-functionality

- FWC contributing to ultra-low emissions especially under RDE conditions
  - ▶ Improving system robustness
- Improved coatings with Pd-Rh and Pt-Rh developed and available

Secondary Emissions : Ammonia

AMOx for Euro 7 Gasoline



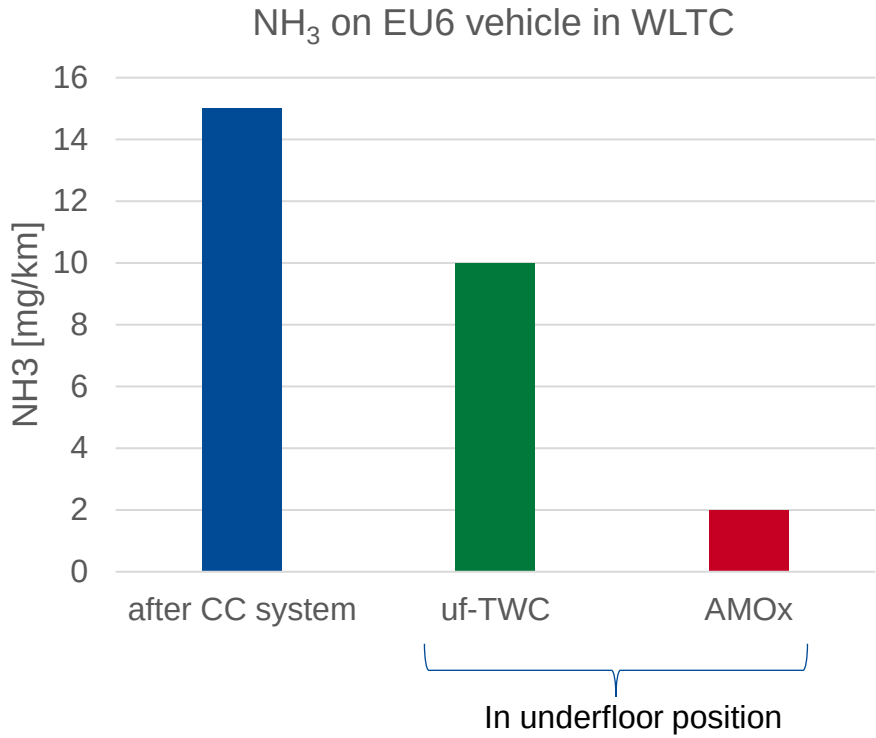
Formation of NH_3 during periods of rich operation

$2NO + 5H_2 \rightarrow 2NH_3 + 2H_2O$
$\lambda<1$

NH_3 emissions **strongly** depend on calibration

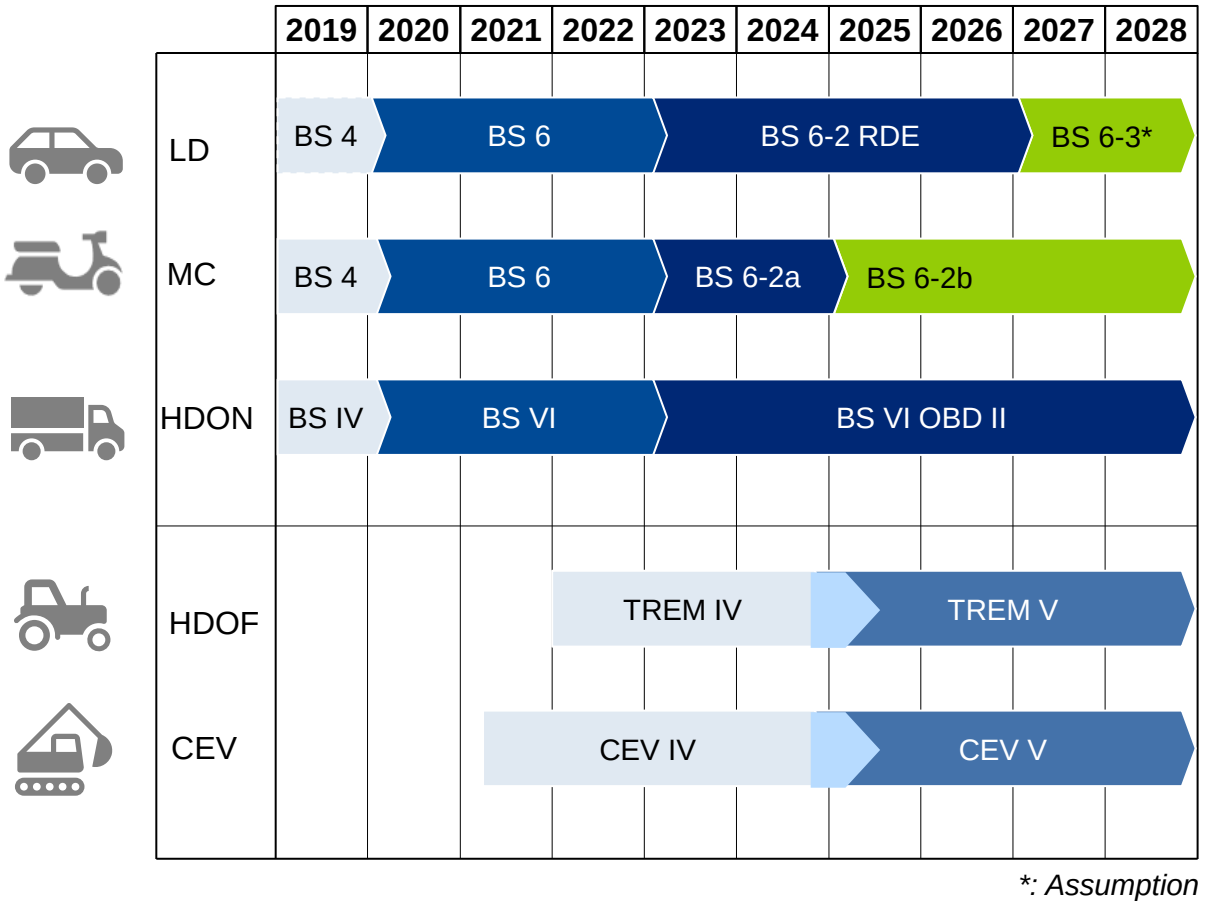
AMOx can oxidize NH_3 to N_2

$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$
$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$



- NH_3 emissions are strongly depending on Lambda profile of car NH_3
- BASF **AMOx** for gasoline conditions can reduce NH_3 emissions significantly

India Regulation Outlook



*: Assumption

Legislation

- BS7 to be based on Euro7 legislation
- Delay in Euro7 adoption leading to uncertainties in the Indian context.
- BS6-3 → Cycle change to WLTC from current MIDC being contemplated as an intermediate stage, possibly from 2027.

Future Fuels – 'Atmanirbhar' approach of the Indian Government

- E20 Gasoline mandated for introduction from Apr'2025,
- Availability of E85*/E100* fuels from 2025, Flex fuel vehicles being introduced
- Focus on widening CNG distribution network
- Hydrogen blending in CNG being explored
- Bio-CNG from Crop waste
- Ethanol/Methanol blending in Diesel
- Acceleration of H_2 ICE development

India regulatory outlook, market trend and technical needs

Market Outlook

- BS 6-2 rolled out on schedule
- Growing impact of CNG fuels, Bio-CNG fuels
- Fuel blending with Ethanol & Flex fuels
- H_2-CNG, H_2 based IC engines and ultimately Fuel cell solutions
- BS-7 to follow Euro-7, uncertainties in implementation timelines. MIDC change to WLTC expected as interim measure
- Expect TREM-V and CEV-V notified

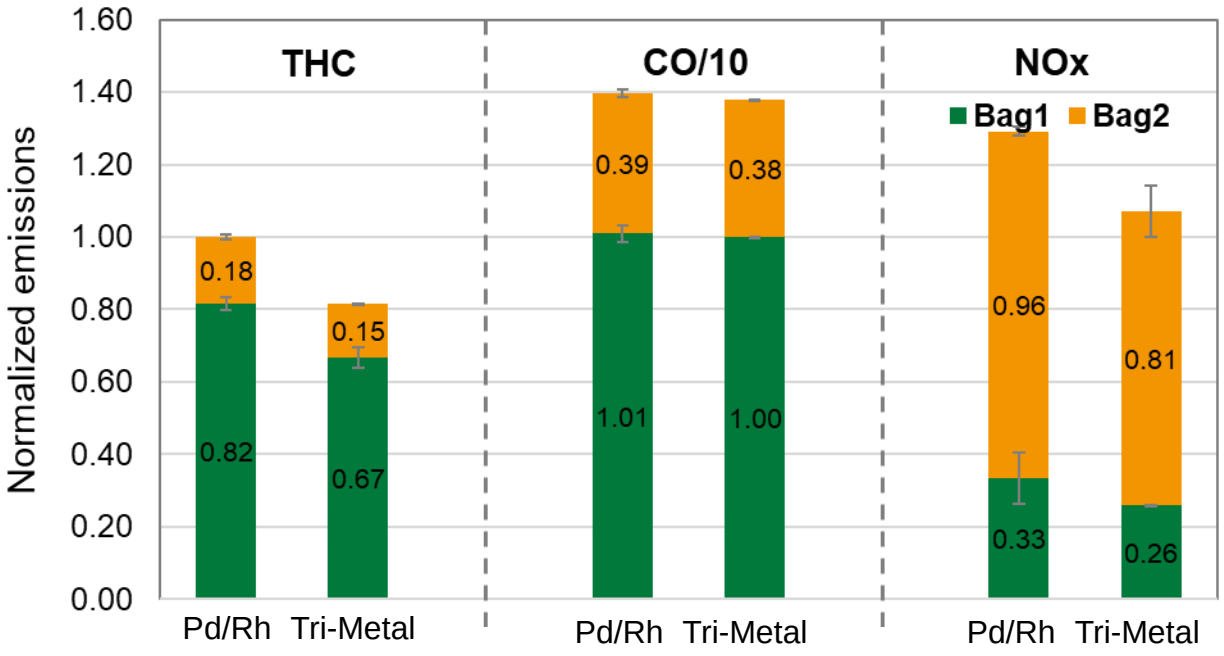
BASF ECMS Solutions

- Tailored technologies for Indian market
- Optimize the PGM loading in response to PGM price trend in near future
- Focus on ethanol and methanol blended Diesel fuels, ED5 and MD15.
- Particulate emissions
- Advanced fresh filtration efficiency
- Improved SCR technology
- Technologies for H_2 ICE engines

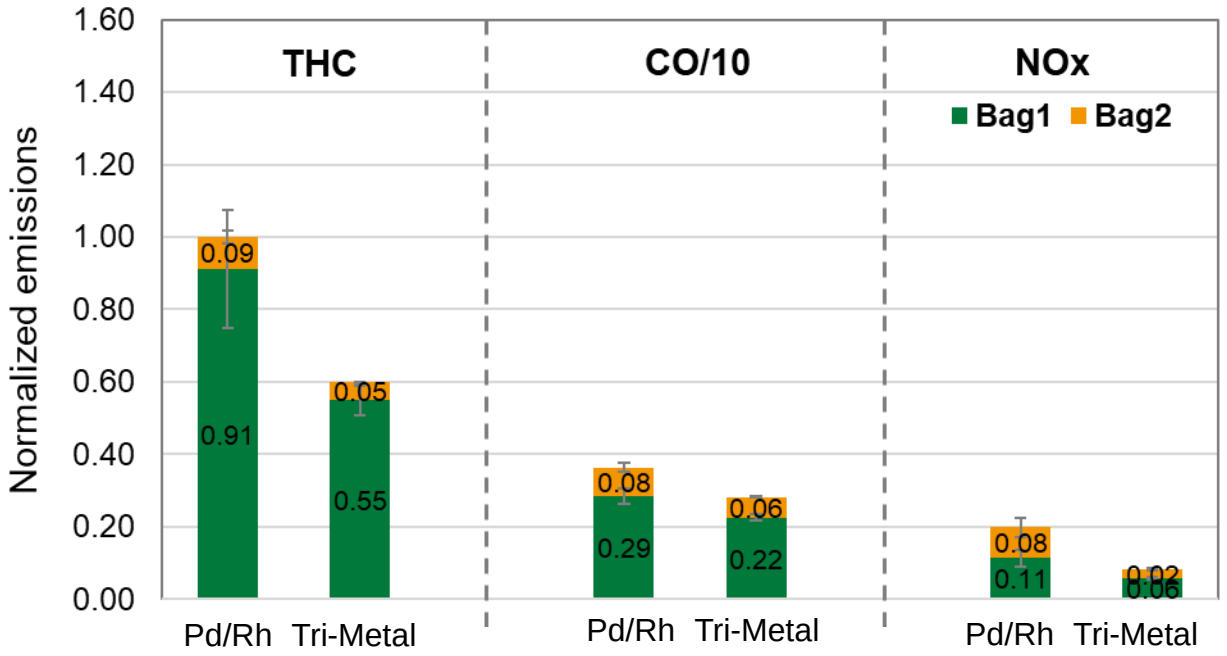
CNG Bifuel Passenger Cars : Focus on PGM Cost Optimization

- **Technology Optimization & use of Pt for Bifuel applications, lead to >25% savings in PGM cost compared to BS6-1 launch technologies.**

MIDC CNG Mode
Fresh catalyst



MIDC CNG Mode
Aged catalyst



L/R aging at 950°C for 30h

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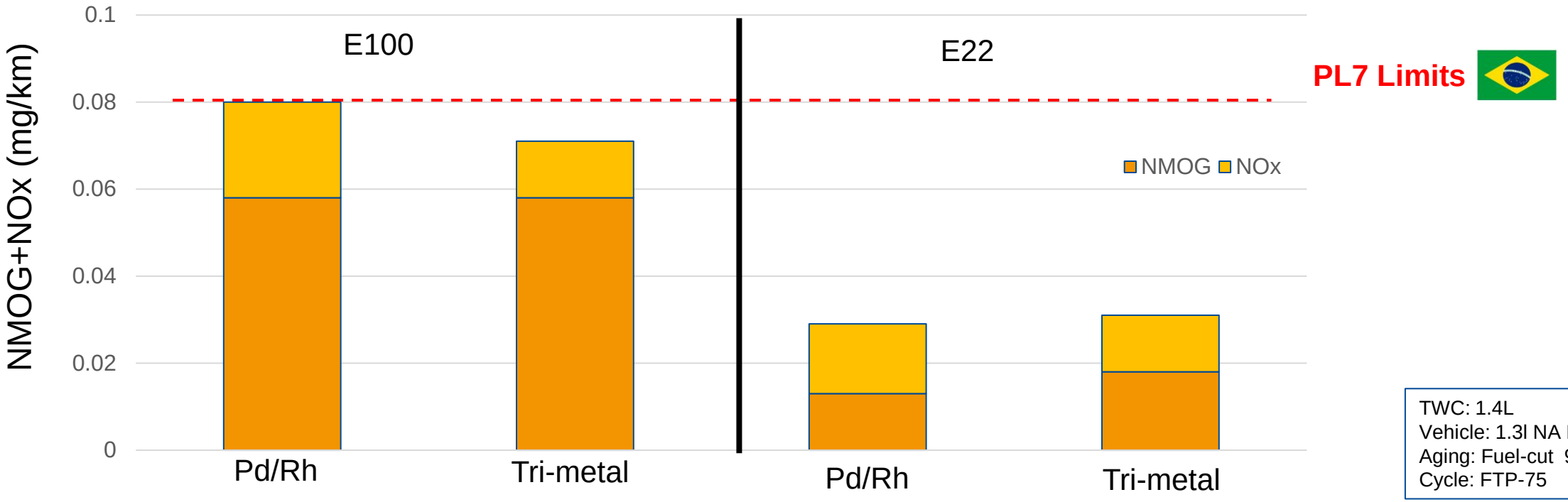
TWC Catalysts for Ethanol Flex Fuels

Advanced TWC Catalysts help meet emissions both in Gasoline & Ethanol modes



TWC: 1.4L
Vehicle: 1.3l NA PL6 cal.
Aging: Fuel-cut 970°C, 100h
Cycle: FTP-75

- 50% Pd substitution shows equivalent performance to reference and cost reduction opportunity after full durability aging

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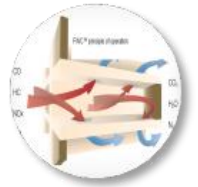
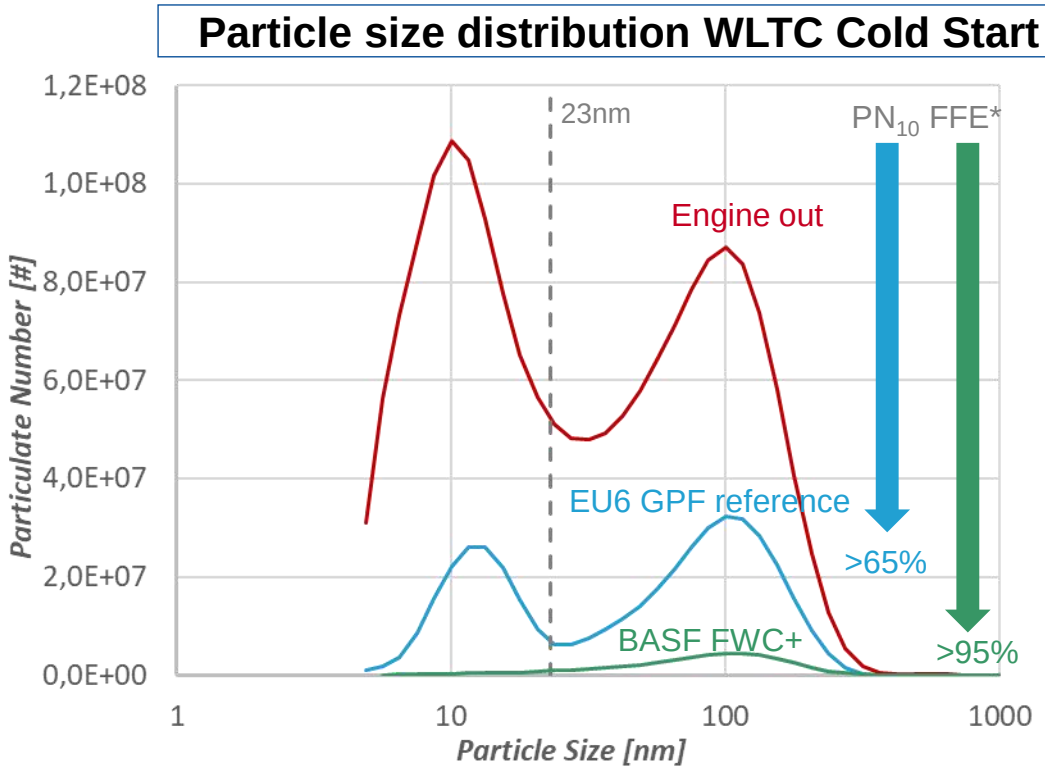
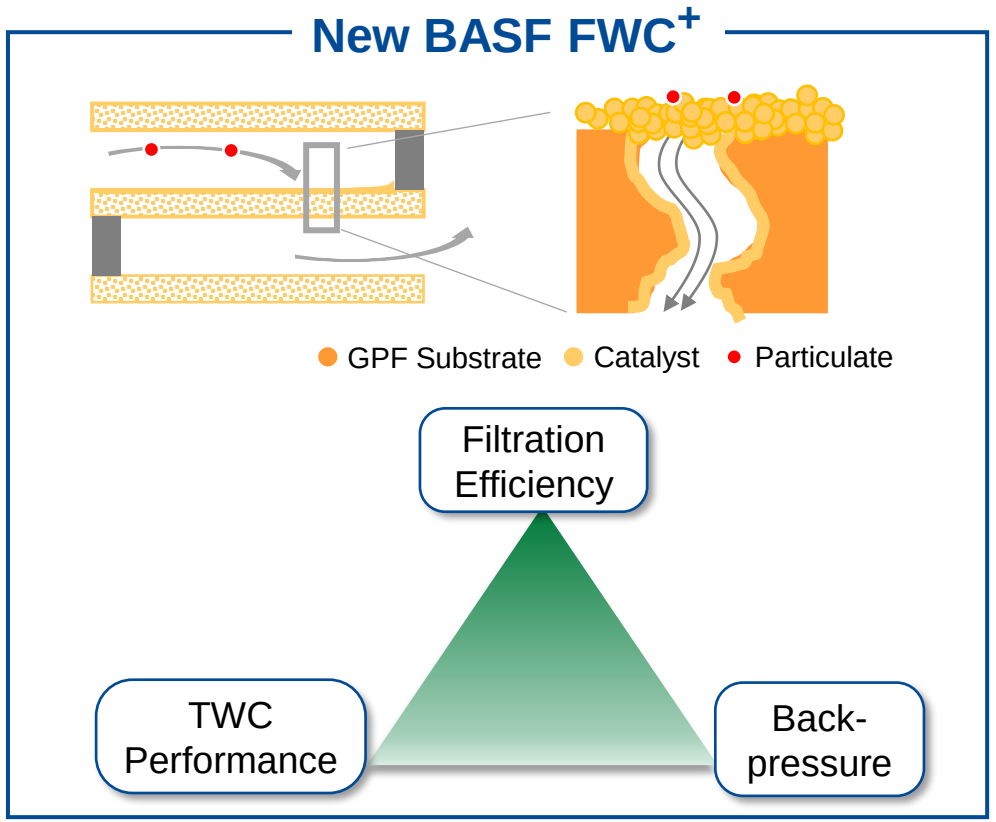
Gasoline Particulate Filters : FWC+

New Technologies show very High Filtration Efficiency without impact on back-pressure





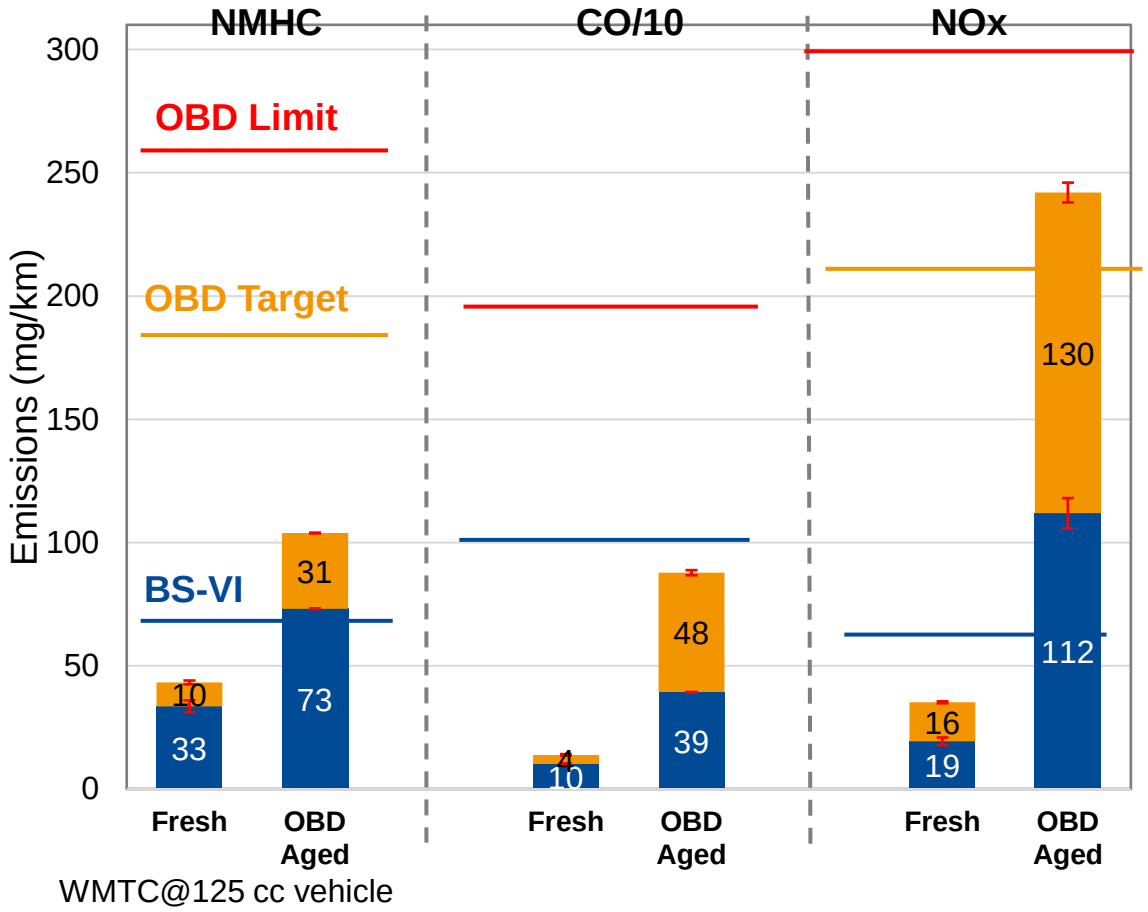


- New FWC⁺ exhibits excellent FFE* also in PN_{10} size range with overall FFE* >> 95 possible
- State-of-the-art BASF ECMS Filter Technology FWC⁺ balancing catalytic activity, backpressure and FFE*
- Serial production in India in preparation

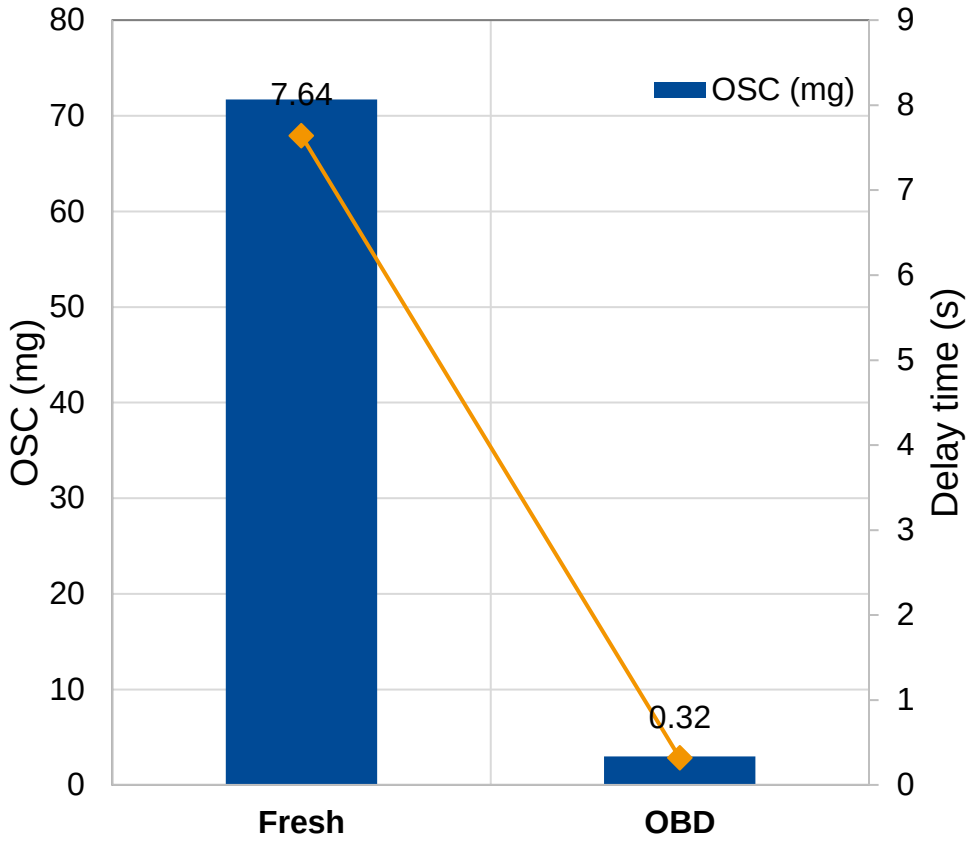
* FFE = Fresh Filtration Efficiency

Motorcycles : Catalyst Monitoring for BS6-2b

- Modified New Technologies for Motorcycle catalysts enable catalyst monitoring, with sufficient Emission and OSC gap between Fresh & Deteriorated catalysts



WMTC@125 cc vehicle



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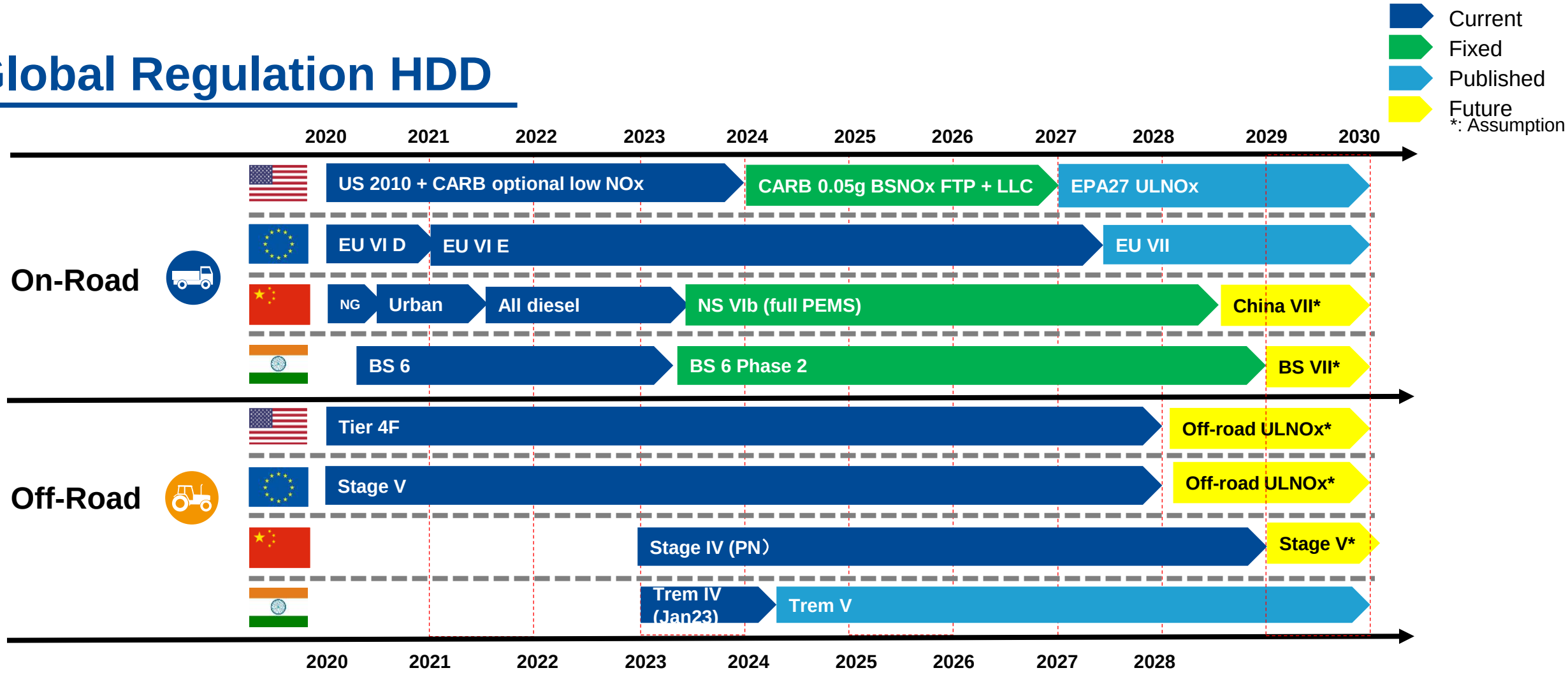
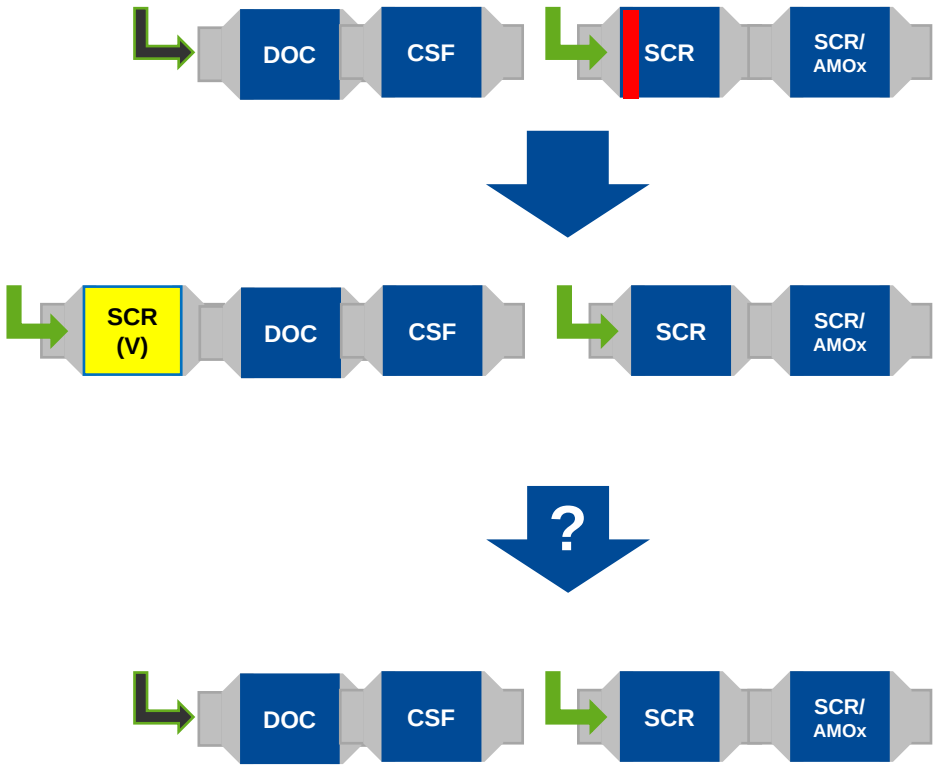
Global Regulation HDD



- NA: EPA MY27 rule-making announced Dec 20, 2023. ARB & EPA Off-road ULNOx under development.
- EU: Euro VII proposal announced November 10, 2022. Latest major announcement on Sep 25, 2023.
- CN: China NS VII pre-study ‘work groups’ formed by VECC of MEE, phase-II kicked-off Sep 30, 2022.
- IN: Likely delay for Trem V Off-Road; On-Road BS VII no early than 2029.

HDD aftertreatment system evolution

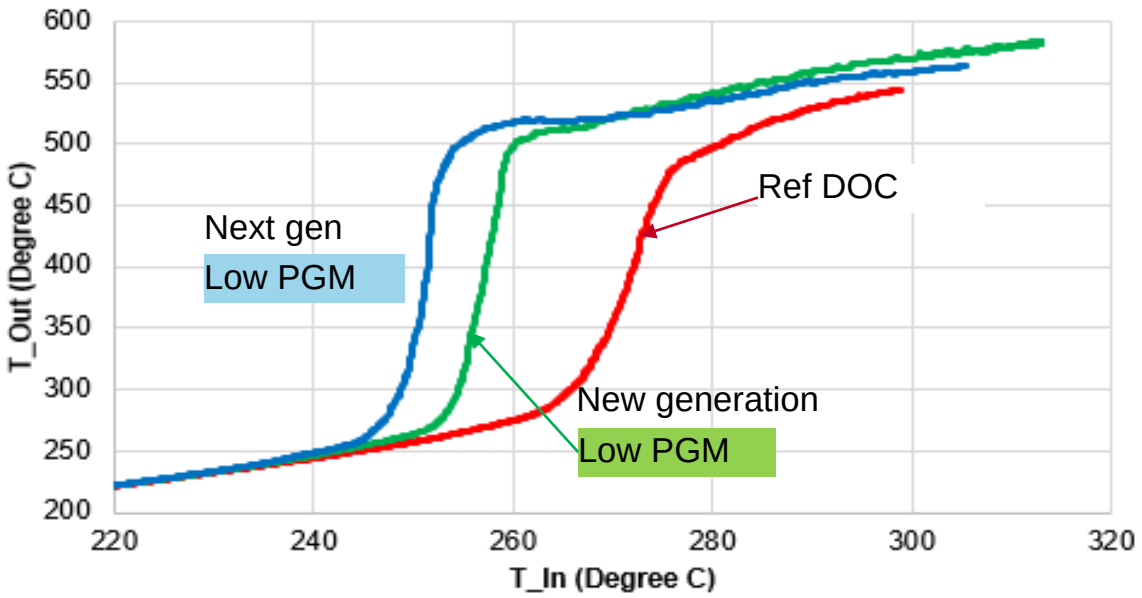


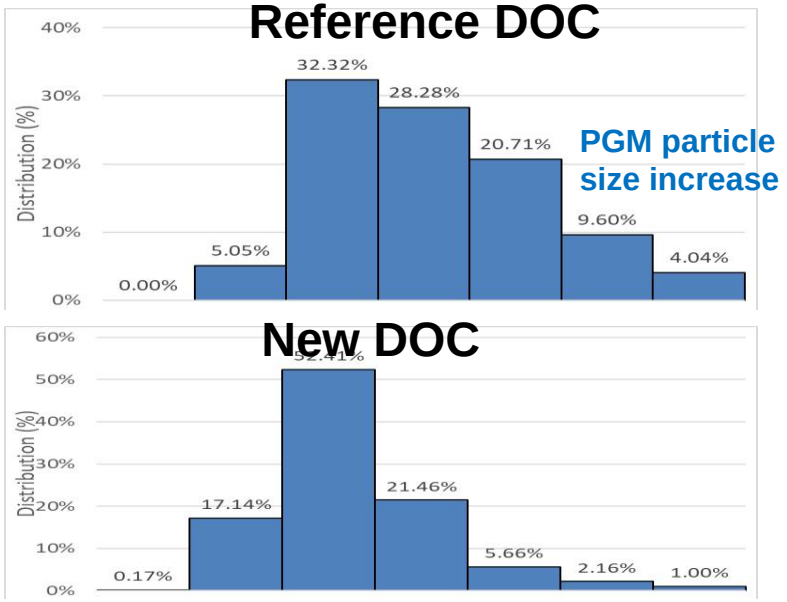
- **Euro VI**
  - Single urea dosing
  - Comparable share of Zeolite and V SCR systems
- **Euro VII** (CLOVE proposal)
  - Dual urea dosing mainstream
  - Higher share of V-SCR system (vs. Euro VI)
  - Both CSF+ and advanced substrates were evaluated
  - 2nd filter as back-up solution
- **Euro VII** ("light")
  - Dual dosing for 45% CO_2 reduction in 2030
  - Single urea dosing
    - Euro VI "refresh" by use of latest catalysts, heating
    - Low N_2O Cu-SCR instead of Fe zone
    - No need for a second filter

Next Generation DOC Enables PGM Reduction

- **Demonstrated improved performance in fuel burning test with even lower PGM attributed to improved PGM dispersion**
- **New generation DOC with 25% PGM reduction**
- **New generation in serial production; next generation under evaluation**

Fuel Burning on engine High HC Flux
(SV=120k/h, diesel fuel = 20000 ppm C1)





Aged sample
≥ 200 counts in each sample

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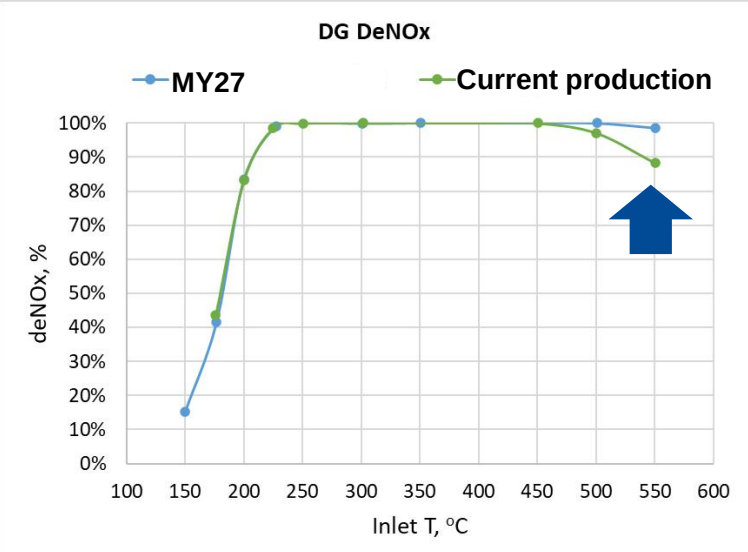
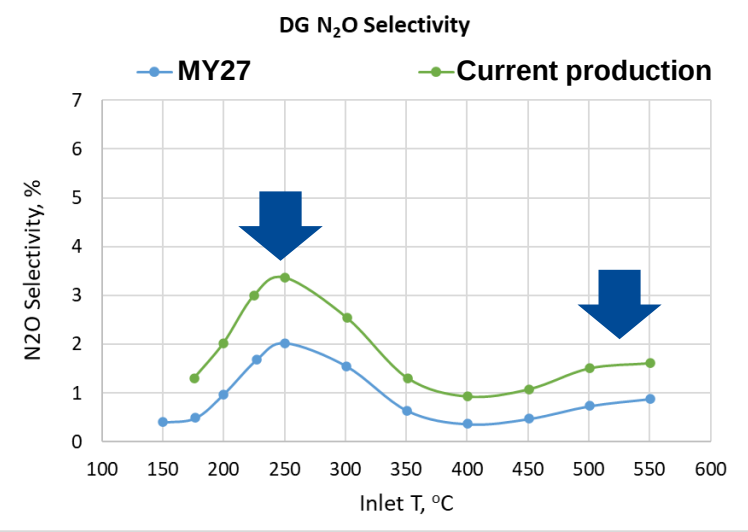
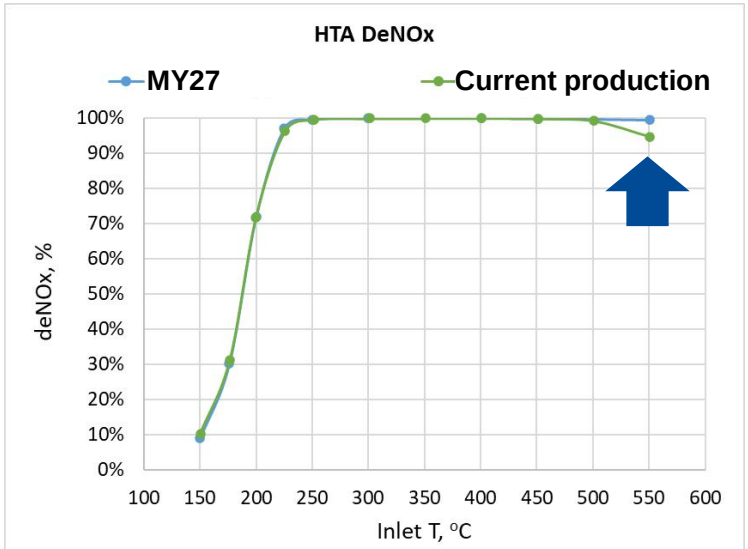
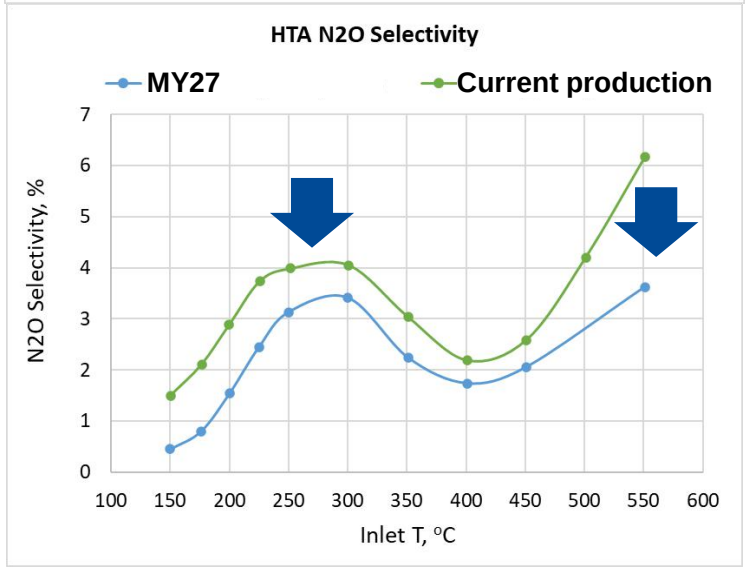
Next Generation Cu-SCR Technology for Heavy Duty









- SCR Performance improvement achieved by innovative zeolite and catalyst design
- Significant N_2O reduction with improved high temperature deNOx performance

Degreening: 550°C 4h 10% O_2, 10% H_2O, 20lpm
Aging: 650°C 100h 10% O_2, 10% H_2O, 20lpm

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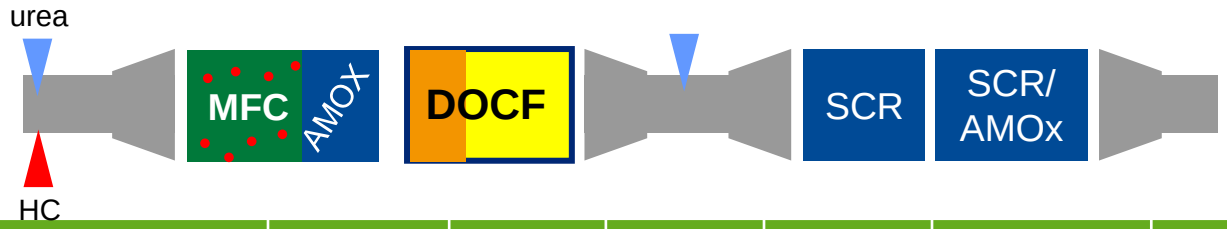
Tier 5 and Stage VI off-road development

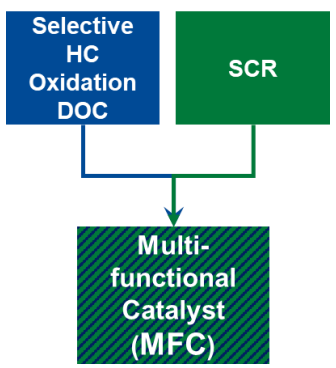
- BASF is working with SWRI on Tier 5 demonstration project
- Packaging in focus more than On-Road
- BASF MFC system offering excellent performance

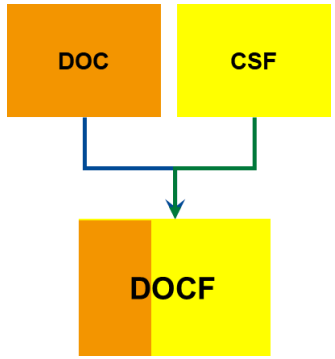


Cycle	EO NOx	TP NOx	DeNOx	CO2	Baseline CO2	TP N2O
	g/kw-hr	g/kw-hr	%	g/kw-hr	g/kw-hr	g/kw-hr
Cold NRTC	3.5	0.080	97.7	723	761	0.036
Hot NRTC	3.9	0.003	99.9	702	747	0.049
Composite NRTC	3.9	**0.007**	99.8	703	748	**0.049**
CARB Proposed Interim		**0.22**				**0.15**
CARB Proposed Final		**0.04**				**0.15**

*130 < kW < 560

BASF innovative 2-in-1 catalyst solutions help address packaging constraint often seen in off-road applications





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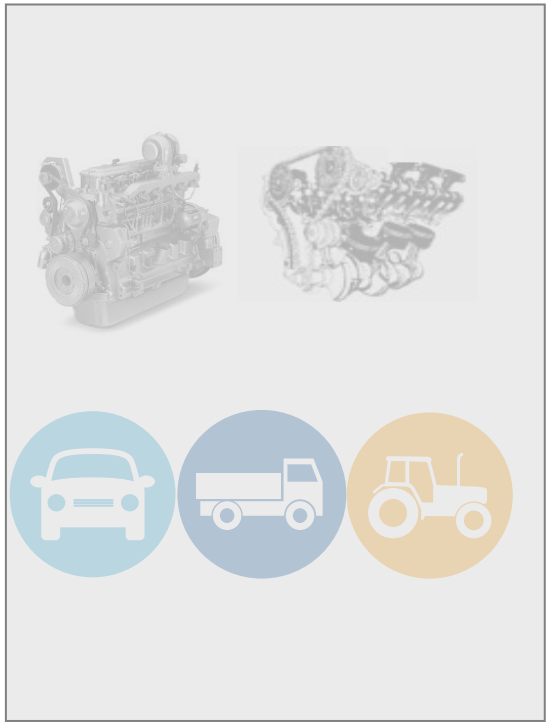
Agenda

Cleaner ICEs



Alt. Fuel ICEs

Green Hydrogen

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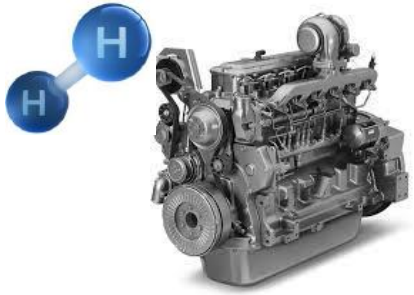
H_2-ICE: Application boundaries should be considered in designing EATS

EATS **for NOx, H_2, PM/PN control**

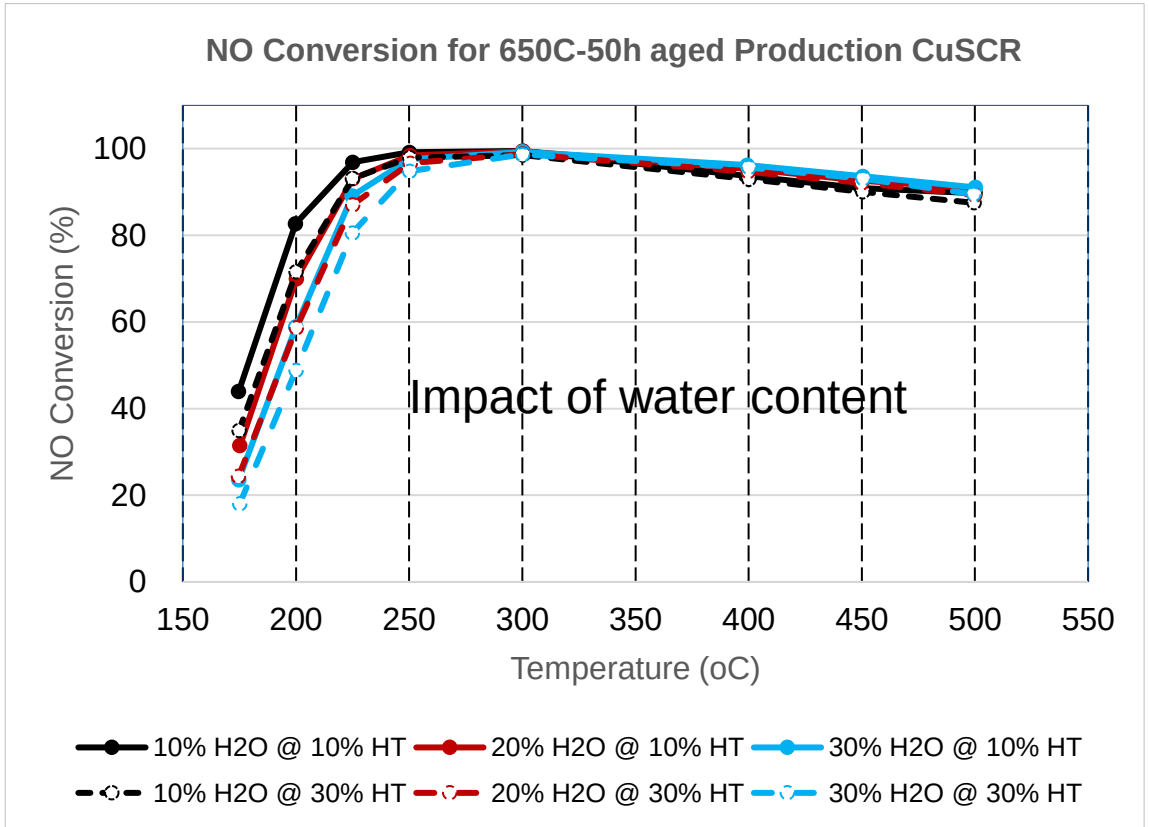


$H_2+O_2+N_2 = H_2O+NO_x$

	Diesel ICE	H_2 ICE
Exhaust Temperatures	Normal operation: amb. – 450°C Regeneration mode: up to 650°C	Depending on engine operation, but possibly no regeneration modes needed
Exhaust H_2O level	5 – 10%	**15 – 35%**
Exhaust H_2 level	Almost none	**~200 ppm - 2%**
Engine out NOx level	Typical range of 10 g/kWh	0.2 – 2 g/kWh (Depending on calibration)
PN Emissions	E/O of 10^{13} – 10^{14} #/kWh needs PN control	Significant lower PN, main contributor: oil
Chemical poisoning	Sulfur and lubricant/fuel ash components must be considered	Potential to use S-free lubricants to eliminate S poisoning and focus on ash components

H_2-ICE: Detailed parameter studies enable effective aftertreatment

- Higher water content in exhaust gas affects:
  - SCR reaction selectivity
  - SCR reaction rate
  - Catalyst deactivation rate
- Presence of H_2 in exhaust gas
  - Accelerates catalyst deactivation
  - Alters NH_3-SCR reaction kinetics
- Catalytic reduction of NO_x by H_2 causes N_2O make



NOx conversion is affected at low temperatures. Impact insignificant for temperatures above 225ºC
Either Cu-CHA or V-SCR technologies can work well for H_2-ICE

Join 2024 SIAT: BASF ECMS catalyst study for H_2-ICE applications

BASF ECMS partners with customers to develop a portfolio of solutions

Technology

Fossil Fuel

Renewable / Sustainable Fuel

1 **Advanced components**

2 **PGM optimization**

3 **Reduced PN emissions**

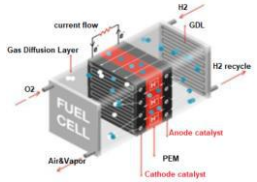
4 **H_2-ICE**

5 **H_2 Fuel Cells**

ICE Non-Diesel Fuel

Biofuels; e-fuels

Alternate Powertrains



ICE Fossil Fuel

- CO_2 reduction
- Euro 7 + EPA 27

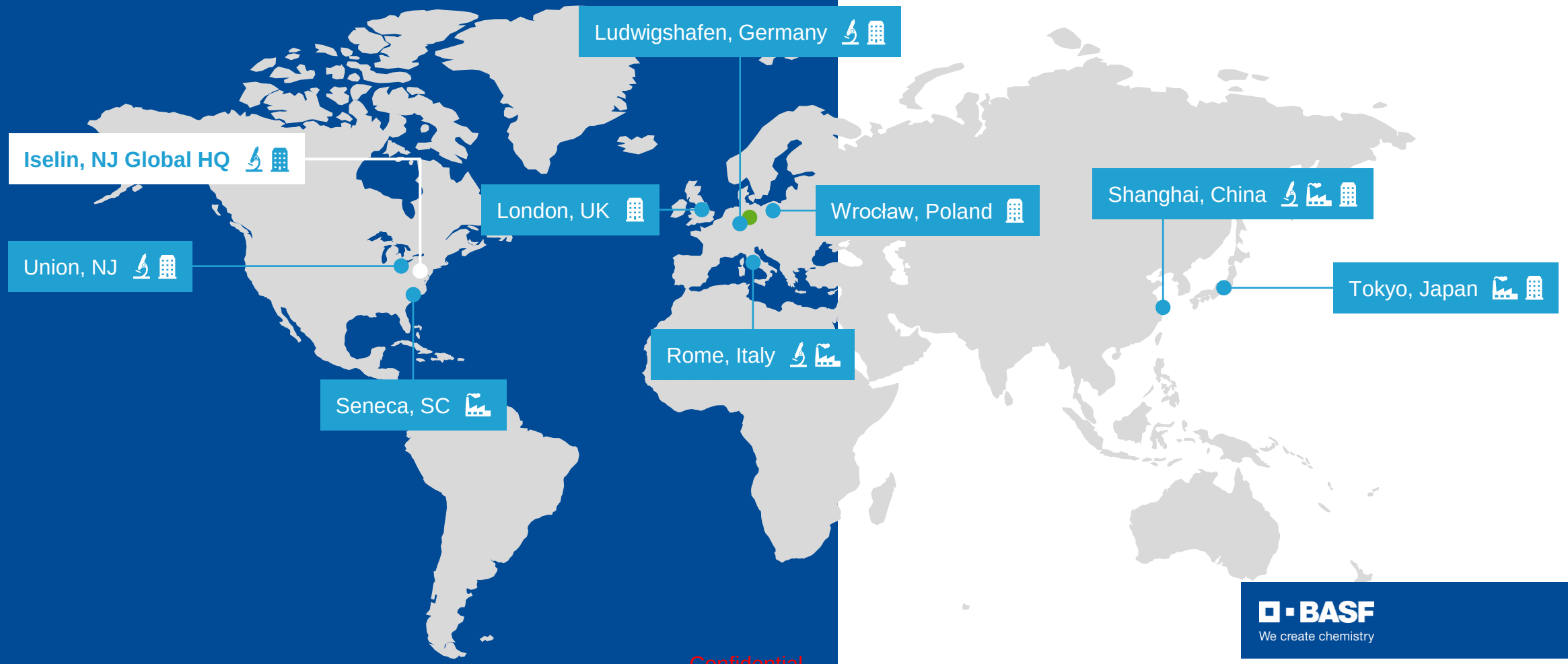
Towards zero carbon emissions

BASF
We create chemistry

BASF Environmental Catalyst and Metal Solutions

Hydrogen Solutions Business has a global presence

Manufacturing R&D Sales / Trading / Administration



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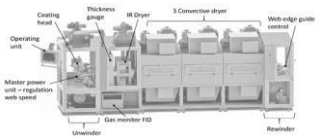
BASF ECMS offerings for Electrolyzer & Fuel Cells

PGM – Platinum Group Metals	BASF Metals: market insight and decades of sourcing, trading and hedging expertise for PGMs to support BASF mobile emission catalysts	
High Performance Catalysts	Electrolyzer and fuel cell catalyst development & production. Portfolio of Pt black, Pt/carbon, Ir black, IrO_2 and core shell catalysts	
Tailor made Ink Formulations	BASF Formulation Platform to ensure catalyst specific development and adaptation of inks for all membrane coating methods	
Catalyst Coating Expertise	BASF coating capabilities for spray- and decal-coating in lab and pilot scale – synergies with BASF Battery Materials - CAM coatings	
CCM Testing - single cells/short stack	BASF in-house testing in single-cells Ludwigshafen and Shanghai & cooperation with ZSW, Ulm for CCM development & testing	

Summary

- New advanced emission control catalyst technologies can cost effectively meet strictest Euro 7 and EPA 27 regulations
- These technologies can be customized for BS 7 regulations
  - Indian specific fuel and driving conditions and market trend should be taken into consideration for customized aftertreatment solutions
- Catalyzed solutions for Hydrogen ICE and other alternate fuels provide viable paths to serial launch of such platforms
- Electrolyzer and PEM fuel cell technologies enable energy and powertrain transformation for the automotive industry

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