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Advanced Catalyst Systems for HDD On-Road BS VI and Off-Road Trem IV

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Mobile Emissions Catalysts Asia Pacific

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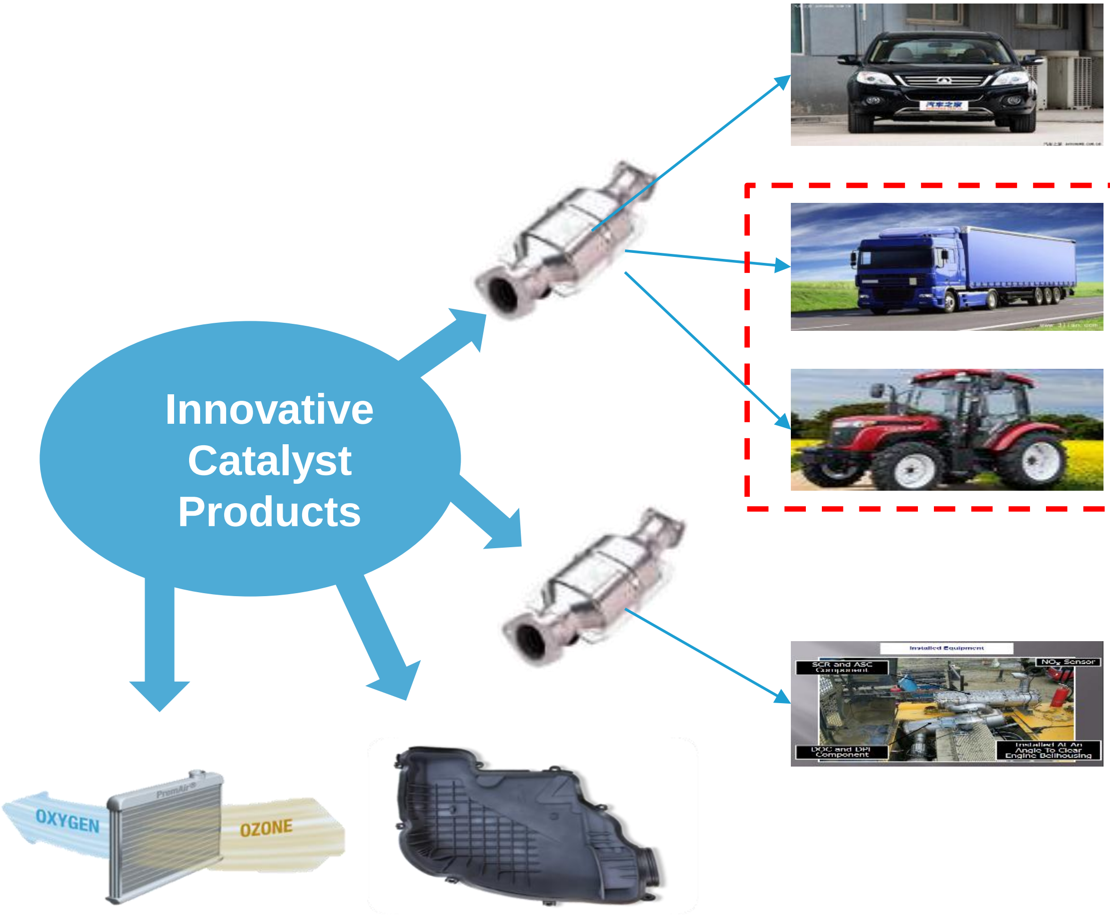
BASF Provides Broad Catalyst Products to Help Reduce Pollutions



- Control tail-pipe emissions for new LDV vehicles
- Control tail-pipe emissions for new HDV vehicles
- Control tail-pipe emissions for new off-road equipment
- Control tail-pipe emissions for used on- and off-road vehicles

- Reduce ground-level ozone
- Reduce evaporative emissions

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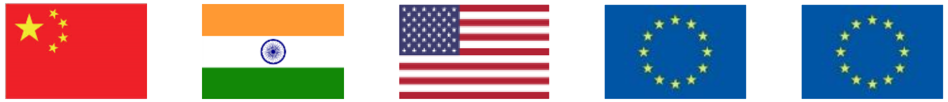
Agenda

- Regulation review and market trend
- System design and validation for BS VI HDD on-road
- Aftertreatment pathways for Trem IV off-road
- Summary

Regulation Comparison

	HDD (g/kwh)				
Norm	NS V	NS VIa	NS VIb	BS VI	EU VI
CO	4.0	4.0	4.0	4.0	4.0
HC	0.55	0.16	0.16	0.16	0.16
NO_x	2	0.46	0.46	0.46	0.46
NH_3	25ppm	10ppm	10ppm	10ppm	10ppm
PM	0.03	0.01	0.01	0.01	0.01
PN	–	$6x10^{11}$	$6x10^{11}$	$6x10^{11}$	$6x10^{11}$
Cycle	ETC	WHTC	WHTC	WHTC	WHTC

- Same between India and China as Europe



	Off-Road (g/kwh) (56-129kw range)				
Norm	NS IV	Trem IV	US T4F	EU IV	EU V
CO	5.0	5.0	5.0	5.0	5.0
HC	0.19	0.19	0.19	0.19	0.19
NO_x	3.3	0.4	0.4	0.4	0.4
PM	0.025	0.025	0.02	0.025	0.015
PN	$5x10^{12}$	–	–	–	$1x10^{12}$
Cycle	NRTC	NRTC	NRTC	NRTC	NRTC

- Variations seen between India and China
- <56kw EU IIIB, >56kw EU IV

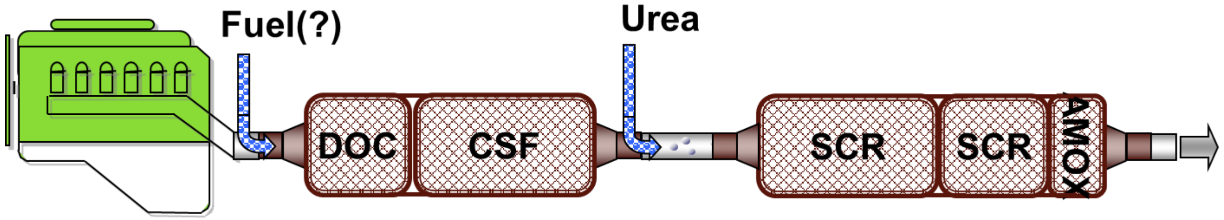
Market Trend

- HDD
  - US: ULNOx is likely moving forward with implementation target of 2023
  - EU: EU VI D focus on ISC (in-service conformality) and EU VII under discussion
    - Market sees a mixture of Vanadia and zeolite SCR systems
  - China: Vanadia SCR in Stage IV and V and Cu-zeolite SCR system in Stage VI

- Off-Road
  - US: EPA Tier 4F no PN requirement, exploratory SCRoF development
  - EU: SCRoF system for meeting Europe off-road Stage V in 2019
  - China: Split into DPF solutions for smaller displacement and SCR solutions for larger displacement

Aftertreatment Systems for India and China

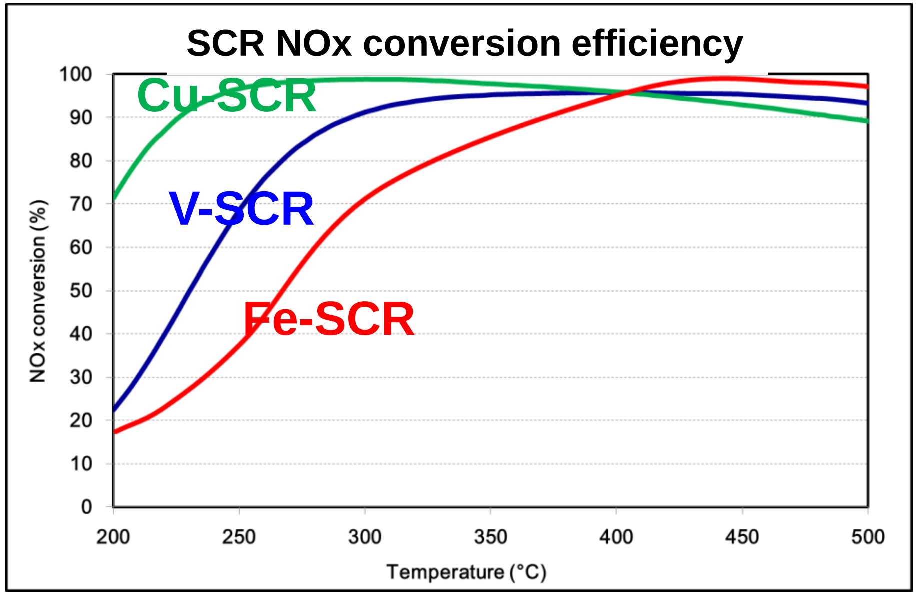
- Europe (SCR route)
  - DOC and V-SCR in Y2005
  - DOC-DPF-SCR started 2013
  - Non-EGR high efficiency SCR
- United States (EGR route)
  - DPF in 2007 and 2011
  - DOC-DPF-SCR started 2010
  - Volume reduction, higher E/O, N_2O

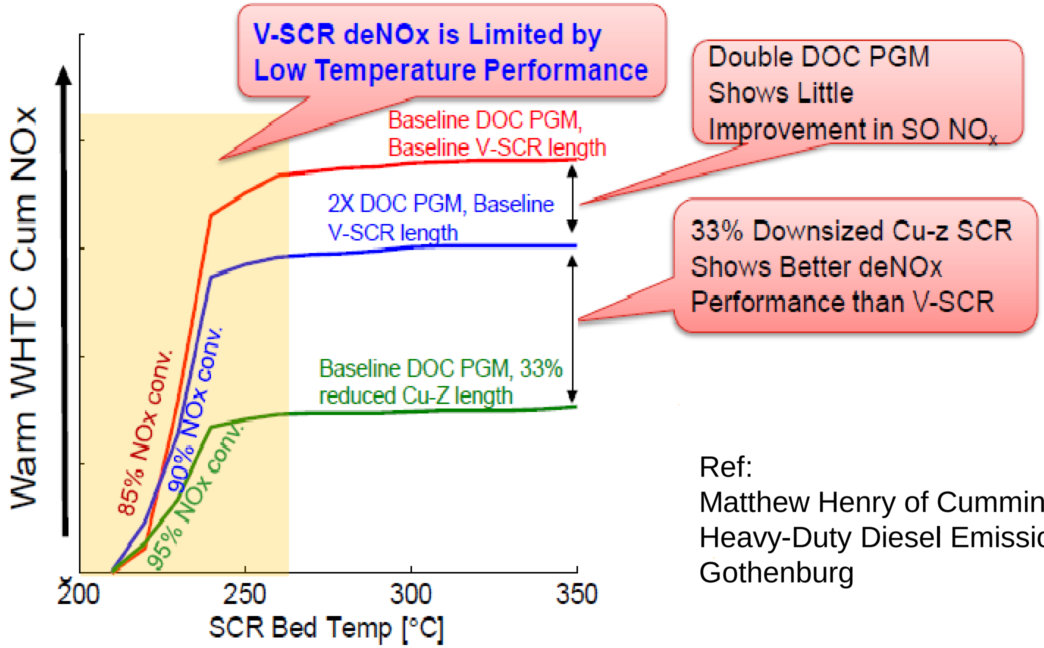


Key design consideration (for India and China):

- How much should the E/O BSNOx be? ***EGR vs. Non-EGR***
- How should the soot in DPF be regenerated? ***Active vs. Passive***
- What type of SCR catalyst should be used? ***Cu vs. V***

Cu-Zeolite vs. Vanadia SCR





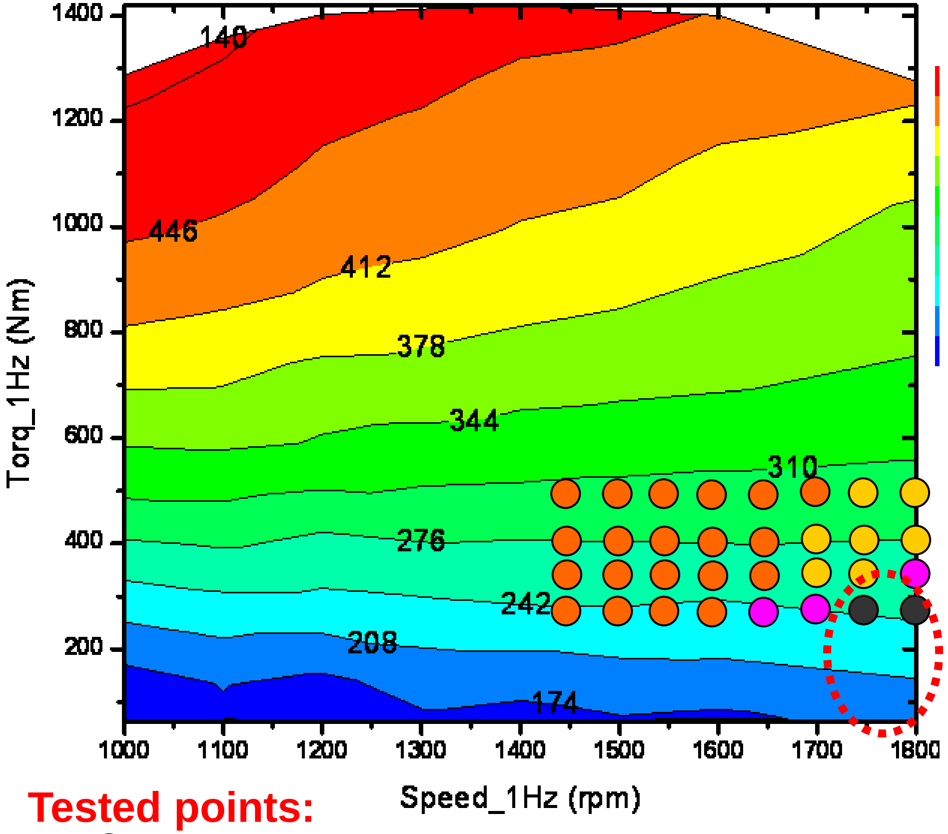
Ref:
Matthew Henry of Cummins at the SAE 2016 Heavy-Duty Diesel Emissions Control Symposium Gothenburg

Catalyst Type	Active Component	Low Temp Activity	High Temp Stability	HC Impact	Sulfur Effect
V-W-Ti	V_2O_5	0	--	0	+
Zeolite	Fe	-	+	-	-
Zeolite	Cu	++	++	+	-

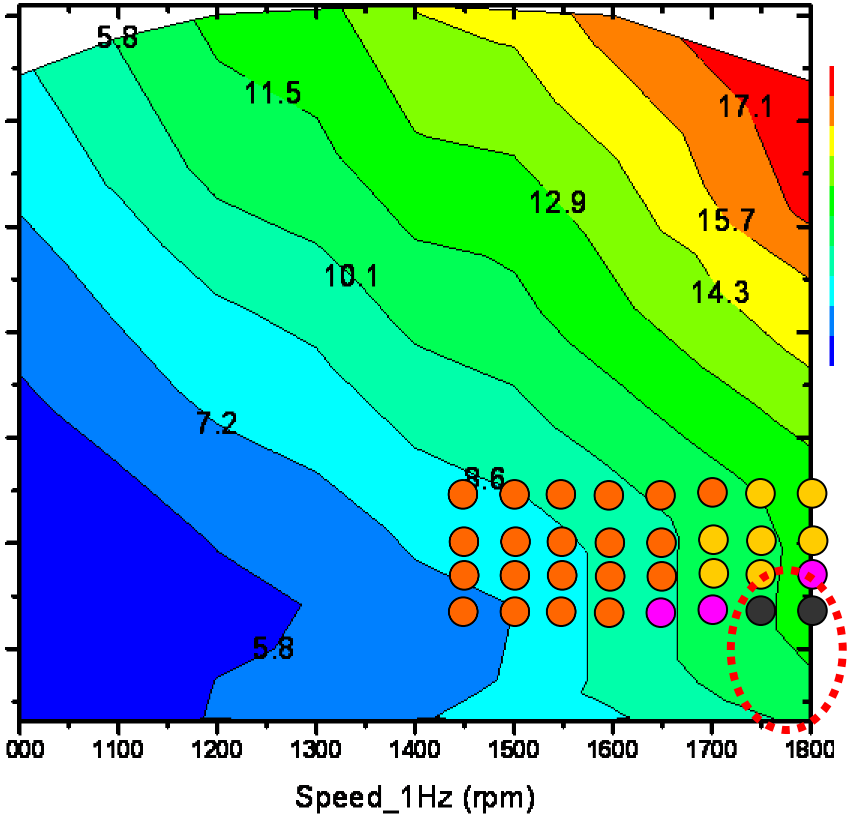
DOC Design and Validation

- DOC inlet temperature and space velocity are two key design factors

DOC inlet temperature, °C



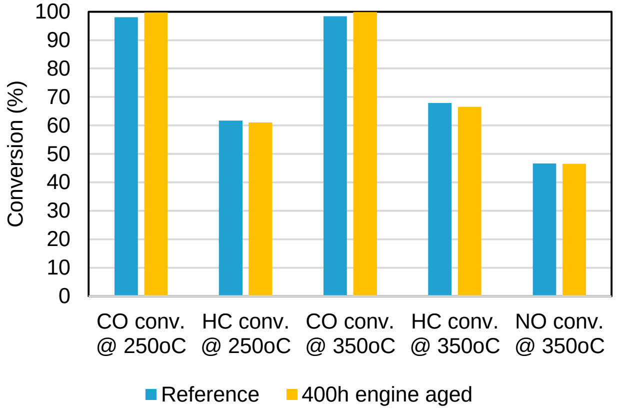
Exhaust flow rate, kg/min

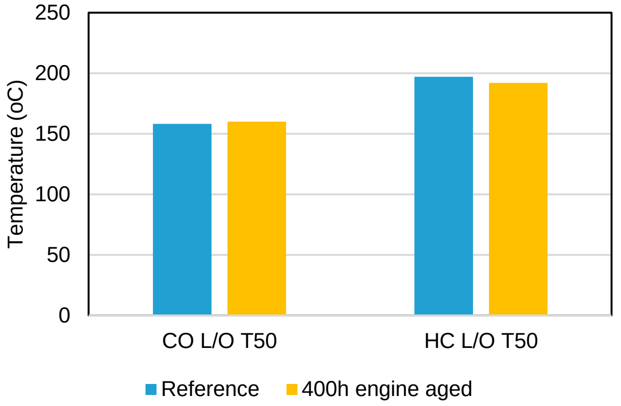


Tested points:

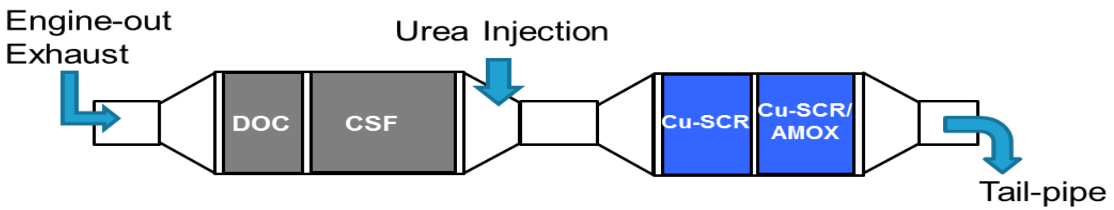
- **Unable to L/O**
- **Stable L/O (w/ high HC slip)**
- **Stable L/O (w/ medium HC slip)**
- **Stable L/O (w/ low HC slip)**

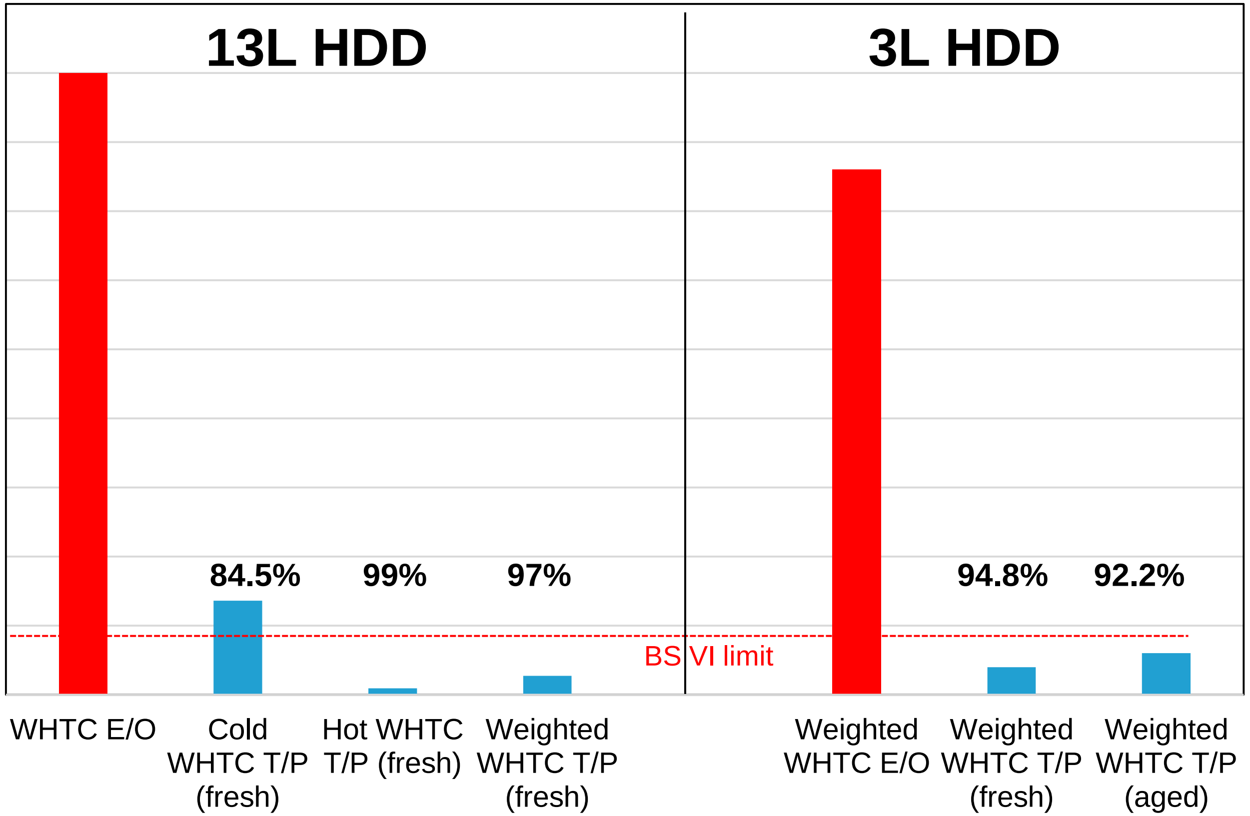
- Analysis of 400h engine aged part





System Design and Validation





Typical design

- SCR to engine displacement ratio: 1.8-2.5
- DOC PGM loading: 20-35g/ft^3
- CSF PGM loading: 3-5g/ft^3

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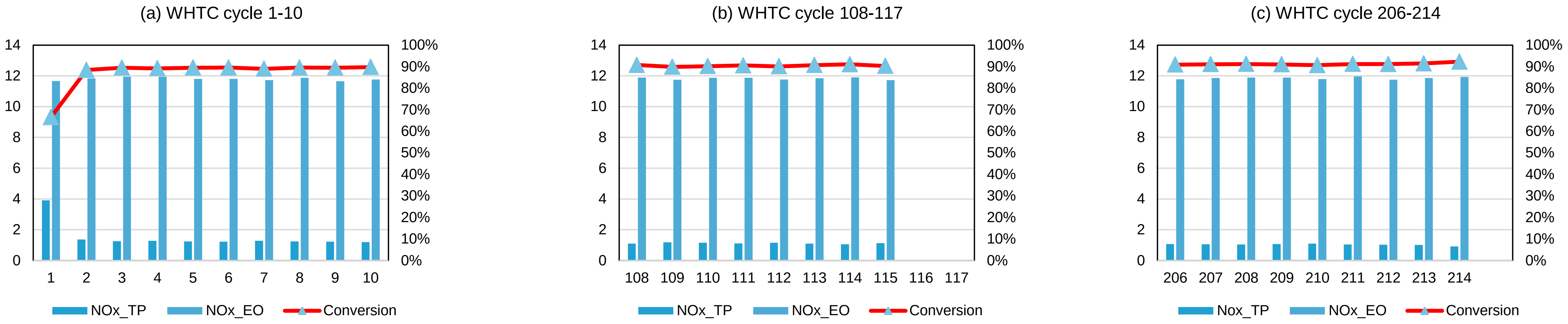
System Endurance and Robustness



- No measurable loss of system NOx conversion capability after 100h continuous WHTC engine runs

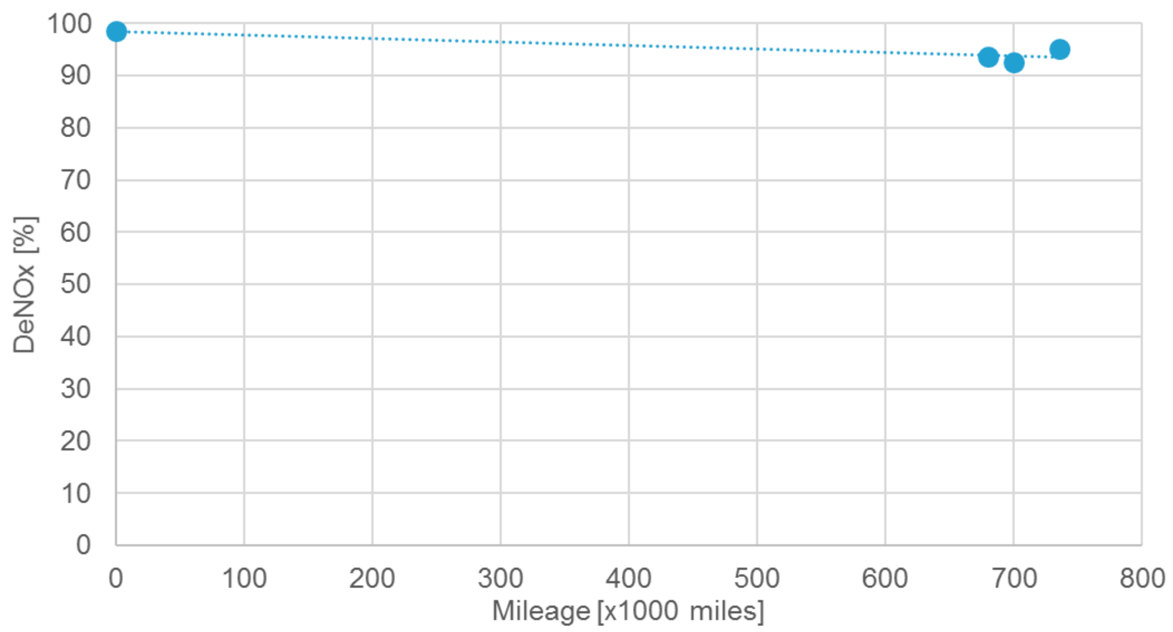
Sequence	Description
Step 1	Evaluate system performance using 10ppm S fuel
Step 2	Switch to 395ppm S fuel, run transient cycle for 28h, with performance measurements in the beginning, middle and end of it, followed by active regenerate event and system performance evaluation
Step 3	Continue 395ppm S fuel, ditto step 2, also for 28h
Step 4	Continue 395ppm S fuel, ditto step 2, for 25h
Step 5	Continue 395ppm S fuel, ditto step 2, for 28h
Step 6	Switch back to 10ppm S fuel, system performance evaluation before active regenerate event followed by another performance check

Sequence	Cycle cumulative NOx conversion result
Step 1	94.6% (ca. 0.32 on cycle average SCR in NO_2/NOx)
Step 2	90.4% → 61.4% (@14h) → 38.2% (@28h) → 90.6% (after the 500°C regen event)
Step 3	90.4% → 64.4% (@14h) → 37.7% (@28h) → 90.8% (after the 500°C regen event)
Step 4	89.1% → 66.4% (@12.5h) → 41.2% (@25h) → 90.4% (after the 550°C regen event)
Step 5	89.6% → 69.4% (@14h) → 38.2% (@28h) → 89.3% (after the 500°C regen event)
Step 6	90.0% → 93.1% (after the 500°C regen event) (ca. 0.24 on cycle average SCR in NO_2/NOx)

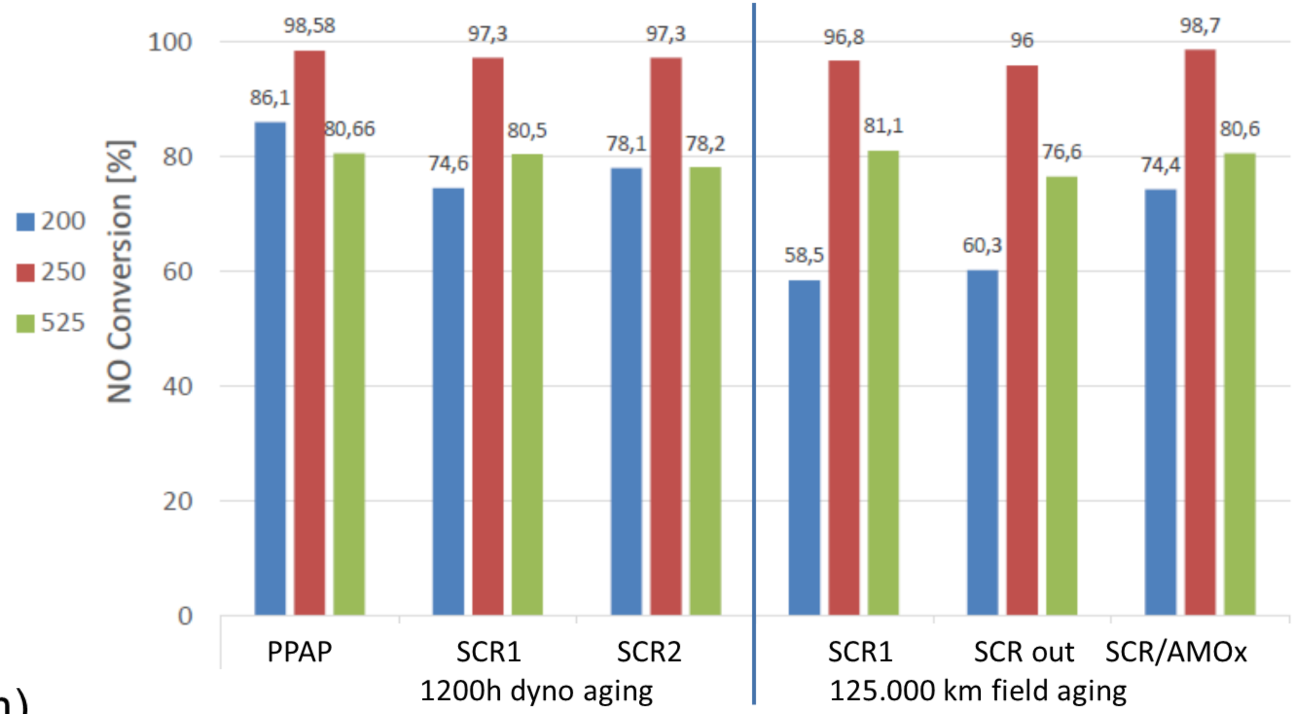
- Simulation experiment of fuel quality impact: system can recovery from refilling with high sulfur fuel

EU6 System Durability Experience

13L HHDD



3L LHDD



- High DeNOx activity even after >700k miles (~1 mio km)

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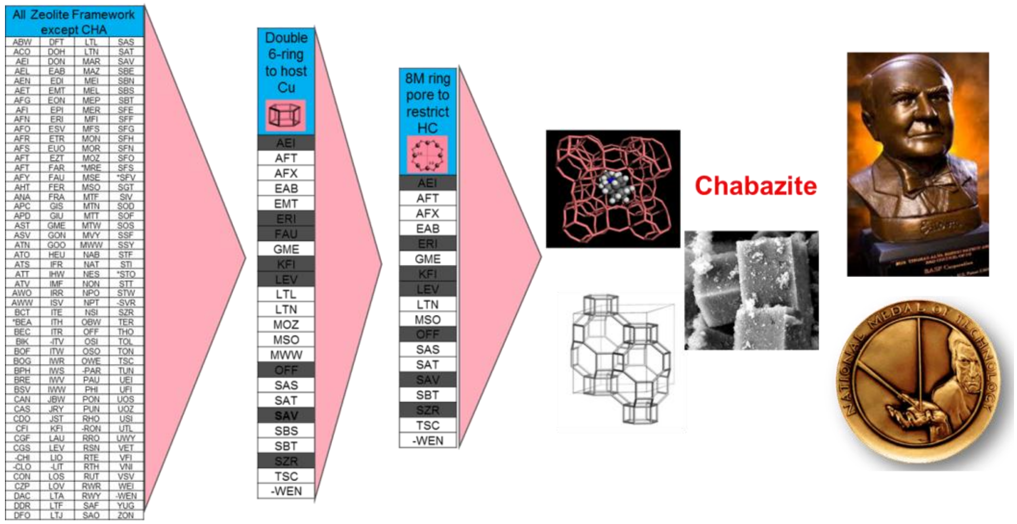
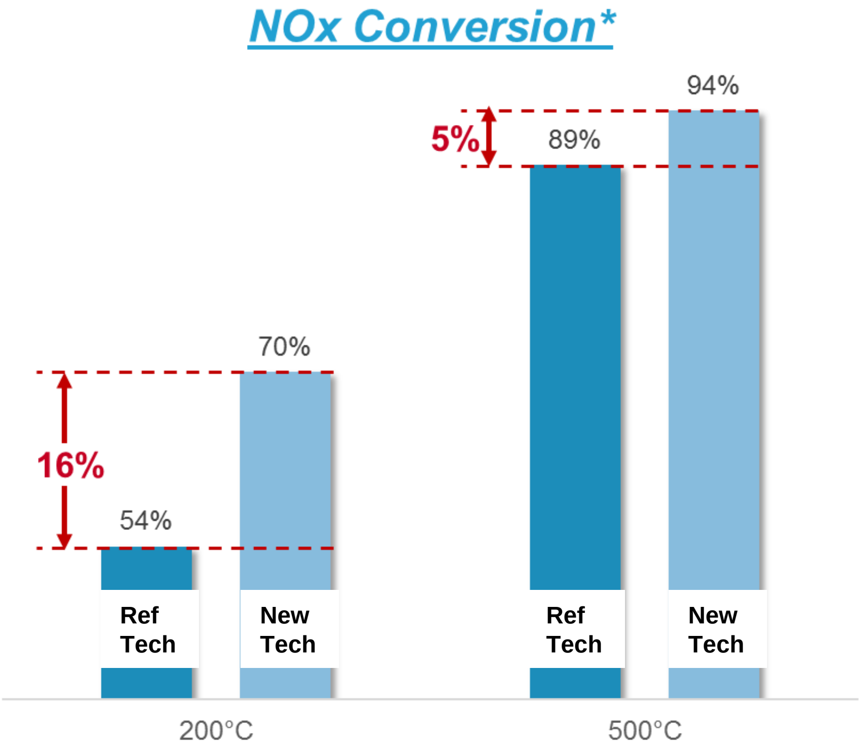
BASF Cu-SCR Pipeline

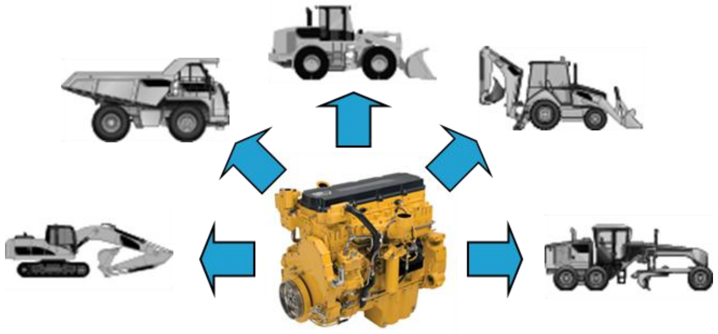


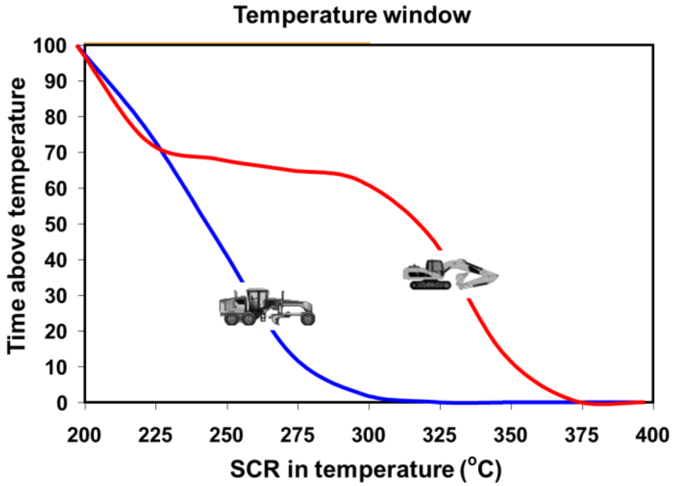


* 650°C/50 h hydrothermal aging
Testing w/ 1000 ppm NO, NSR=1, 120k SV

Off-Road Challenges

- Tier 4 (a & b) further classified into 6 engine families (ranging between 11 < hp ≤ 750) with different emission limits
- U.S. Off-road sector includes
  - 60 engine manufacturers
  - 600 equipment manufacturers
  - 6,000 different engine models
- Most OEMs not experienced in emissions after treatment
- Packaging and operator 360° visibility constraints
- Full useful life of 8,000 hours or 10 years - simulation undefined





Similar challenges are anticipated for India Trem IV off-road ATS development

Trem IV Aftertreatment Roadmap

w/o NOx abatement

w/ NOx abatement

56-75kw

Trem IV Off-Road Product Strategy

Design Consideration

- Most likely splitting into EGR and non-EGR engines
- ATS design
  - Compared to SCR, CSF/PFC is the preferable solution for smaller displacement engines
  - For larger displacement, SCR solution is more suitable to achieve a better TCO
- Technology maturity level and system cost are two key factors to most OEMs

BASF Offering

- EGR route
  - DOC+CSF // DOC+POC
    - SOF reduction DOC
    - On-road DOC for fuel L/O and NO_2-make
  - Zoned CSF (DOC on filter)
    - Co-development opportunity
- SCR route
  - Cu-SCR
    - Robustness demonstrated
  - Cu-SCRoF
    - In launch for EU Stage V application
    - Regional prototype capability
  - V-SCR
    - Improved low temperature $deNO_x$

An Example: SOF Reduction DOC for Off-Road

Superior SOF Reduction DOC + Unique Dual DOC Layout Design

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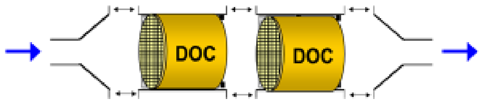
4JB1 2.8L Engine ESC 原排		
NOx [g/kWh]	8.473	
HC [g/kWh]	0.249	
CO [g/kWh]	1.303	
PM [g/kWh]	0.041	
Engineering Target of PM [g/kWh]	0.0175	
SOF Composition [g/kWh]	0.029	70%
Required SOF Conversion [%]	82.2%	
Required TPM Conversion [%]	57.6%	

Dual DOC Layout



- DOC tailored formulated with optimized PGM loading.
- Highest PM conversion achieved in benchmark tests.
- Segmented dual brick engineered to maximize SOF removal efficiency.
  - Design concept already copied by our competitor

Engine bench result of PM emission (g/kw-h)

Engine	NS V	E/O	T/P	(%)
4JB1 ESC	0.02	0.04	0.0139	65%
4JB1 ETC	0.03	0.041	0.02	51%
493 ESC	0.02	0.042	0.0111	74%

JAC 江淮汽车 DFAC FOTON ISUZU 庆铃汽车 JMC

On-road experience applied for off-road

Off-Road DOC Solution: SOF DOC Testing On An Off-Road Engine

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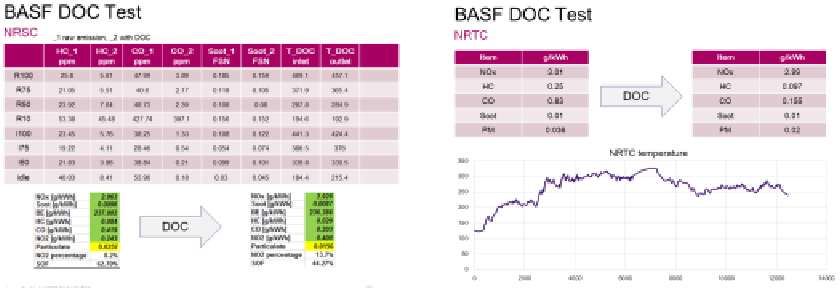

Items [g/kWh]	NRSC Raw	NRSC tailpipe	NRTC (hot) Raw	NRTC (hot) tailpipe	Limit
NOx	[illegible]	[illegible]	[illegible]	[illegible]	3.3
HC	[illegible]	[illegible]	[illegible]	[illegible]	0.19
CO	[illegible]	[illegible]	[illegible]	[illegible]	5
PM	0.032	0.02	0.04	0.021	0.025
Soot	0.011	0.011	0.012	0.012	-
BE	243	243	254	254	-

57%

68%

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Summary

- Both India and China follow Europe on HDD on-road regulations
  - Variations are seen in the off-road Stage IV standard (aka PN)
- Proven US 2010 / EU VI catalyst technologies are strongly recommended
- System design and validation should consider unique market application
  - Low temperature operation, uneven fuel quality, etc.
- New Cu-SCR technology provides cost reduction opportunity in the future
- Off-road Term IV will likely see split between EGR and SCR solutions
  - 56-75kw is the broadline for the split

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