SCR on Filter Based Aftertreatment for High Efficiency Engine Systems

BUILT FOR IT.

A UK based Energy Technologies Institute Funded Project

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energy technologies institute

Johnson Matthey

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Outline

- Introduction
  - Global, collaborative project

- Results for NRTC and WHTC legislative cycles
  - System design impact
  - Summary of GHG Emissions

- Results for in-use vocational cycles
  - Work Based Windows Analysis

- Conclusion

Introduction

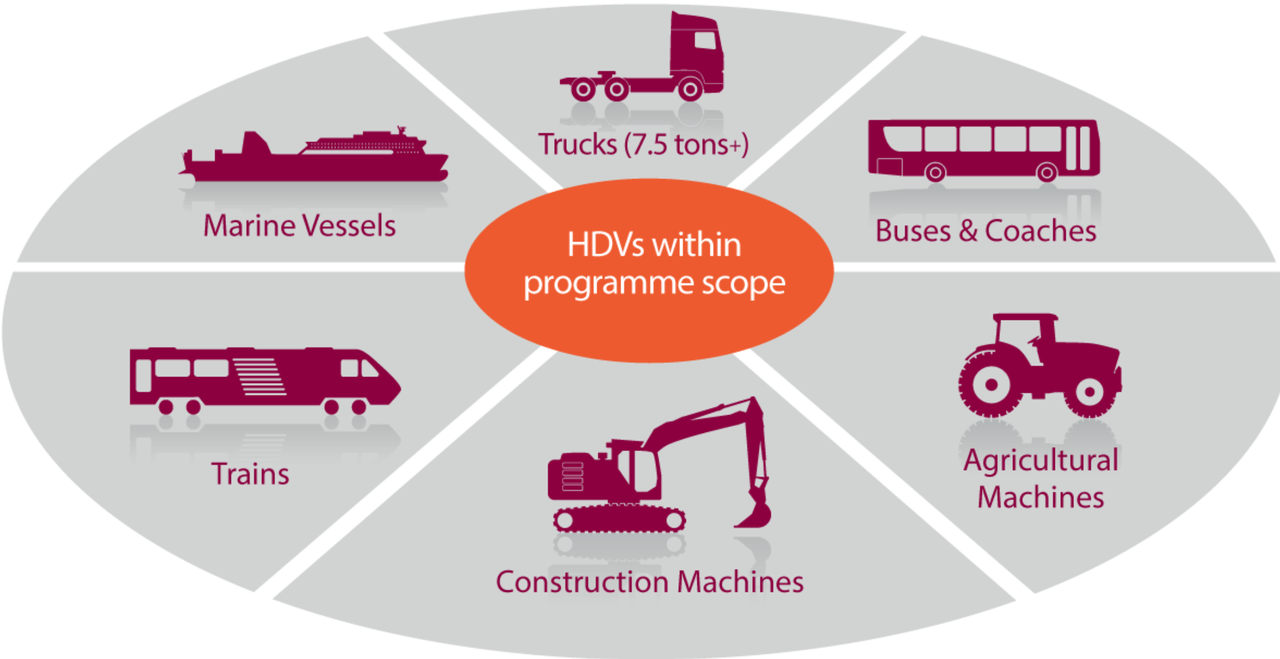
What is the ETI?

- Public-private partnership between global energy and engineering companies and the UK Government.
- Develop, demonstrate and de-risk new technologies for affordable and secure energy, and lower GHG emissions
- Global consortium between Caterpillar, Johnson Matthey, and Loughborough University to develop aftertreatment for next gen HDD engines

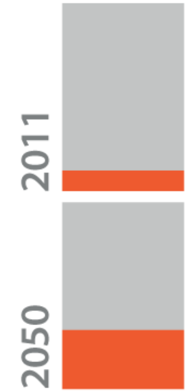
ETI members

ETI programme associate

ETI Heavy Duty Vehicle (HDV) Programme Overview



Why is HDV efficiency so important?



8% of current UK CO_2 emissions are from HDVs

Proportion is set to increase to approx 30% as other sectors reduce CO_2

Limited options for low-carbon fuel alternatives

Modelled scenarios consistently point to HDV efficiency as cost-effective way to reduce emissions

Objectives

Develop new **vehicle concepts**

Develop new **technologies** to support concepts

Produce **demonstration vehicles** that are 30% more efficient

Develop supply chain to enable meaningful market deployment

Enable substantial reduction in CO_2 emissions across sector

Goal: Meet Both On Road and Off Highway Regulations

Regulations On-Road:

Stage	Test Cycle	CO	THC	NO_x	PM	PN	NH_3
		g/kWh				#/kWh	ppm
Euro V	ETC	4	0.55*	2	0.03	-	-
Euro VI	WHSC	1.5	0.13	0.4	0.01	8.0×10^{11}	10
Euro VI	**WHTC**	**4.0**	**0.16**	**0.46**	**0.01**	**6.0×10^{11}**	**10**

*NMHC

Regulations Off-Highway Engines 130 – 560 kWh:

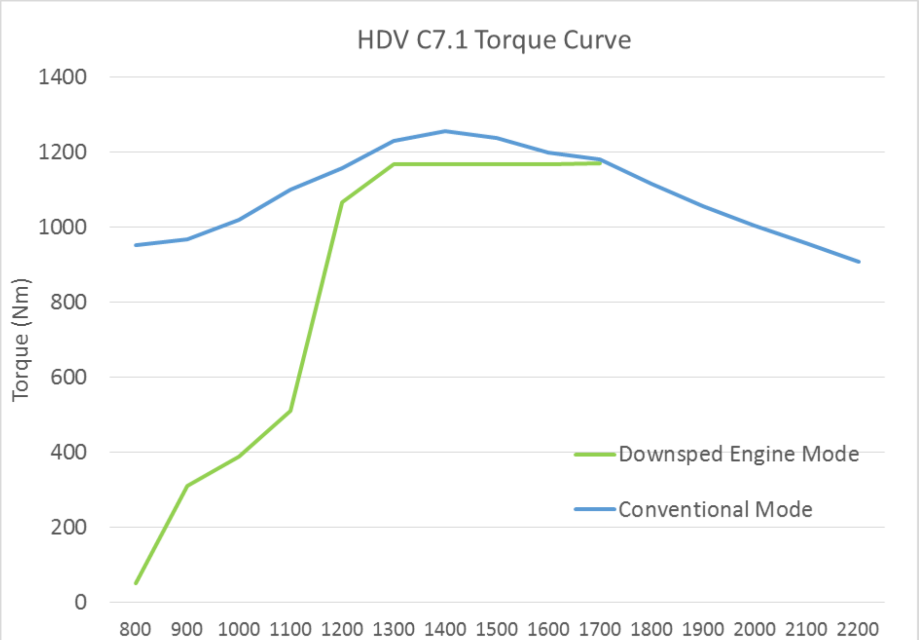
Stage	CO	NO_x	HC	PM	PN
	g/kWh				#/KWh
EU Stage IV	3.5	0.4	0.19	0.025	none
EU Stage V	**3.5**	**0.4**	**0.19**	**0.015**	**1×10^{12}**

Baseline Engine and Modifications

Baseline engine = 7 liter Cat® EU Stage IV compliant non-road engine.

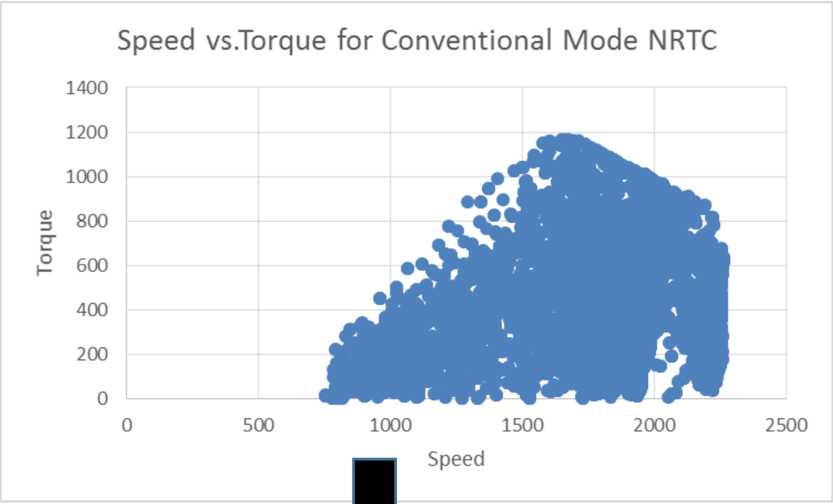
Engine modifications made to improve BSFC:

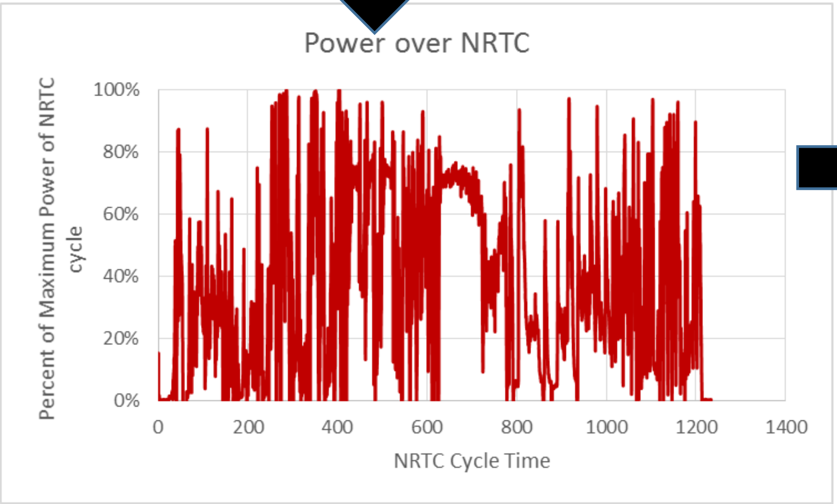
- Remove EGR
- Adjust combustion timing
- Optimizing the air system
- 9 g/kWh Engine out NOx calibration
- 2 operating modes evaluated:
  - Conventional
  - Downsped



Engine Calibration	Average NRTC Turbine Out Temperature (°C)	Typical Engine out NOx levels (g/kWh)
Tier 4 Final Baseline	304.7	~ 3.5
ETI Conventional	289.8	9.3
ETI Downsped	300.4	8.5

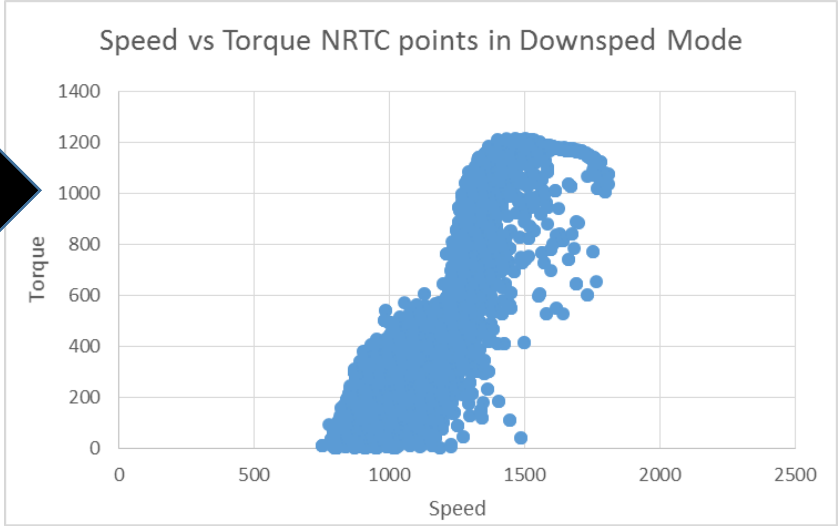
Translating NRTC Test Points to Downsped Operating Mode





Speed vs. Torque data points from every second of NRTC cycle with an engine running conventional mode are translated into a power vs. time curve.

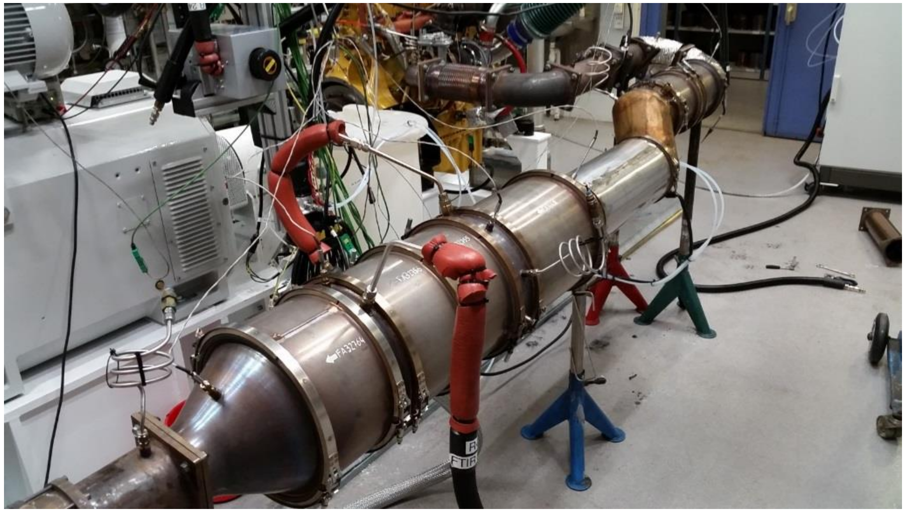
The power vs. time data points are then converted back to speed vs. torque data points for the engine in Downsped Mode

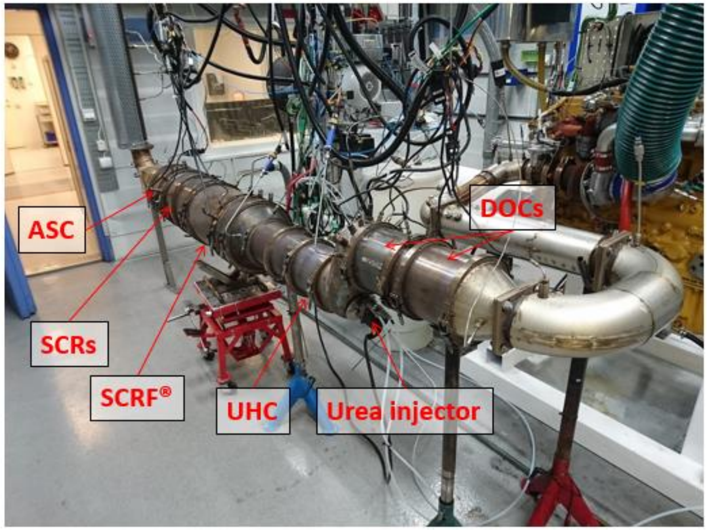


Aftertreatment System Installation

- Modified Cat® C7.1 engine installed in JM HDD Test Cell
- Aftertreatment initially installed in a ”straight” line from DOC to tailpipe
- Insulated pipe used between turbo out and DOC to reduce heat losses of catalyst system
- All catalysts provided by Johnson Matthey (JM)
- Aged catalysts (650°C/100h)

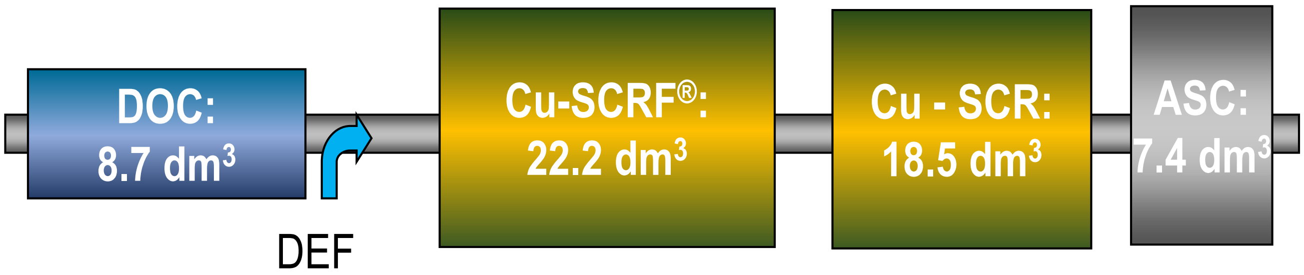
JM





NRTC Results on Linear System Layout

System Cu-SCRF®

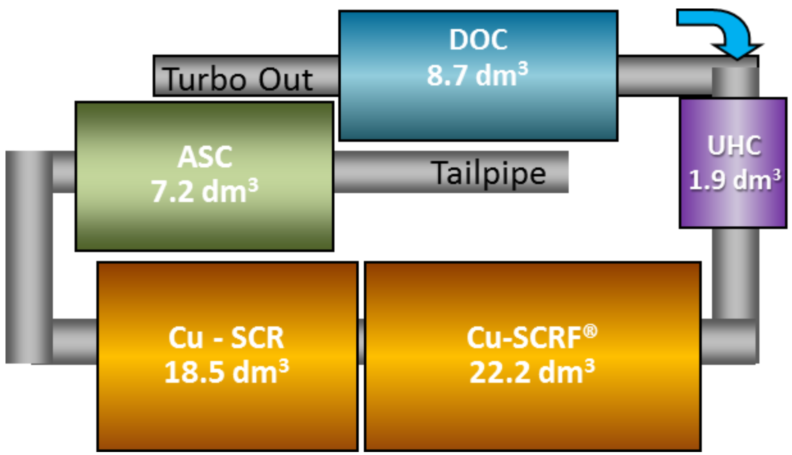


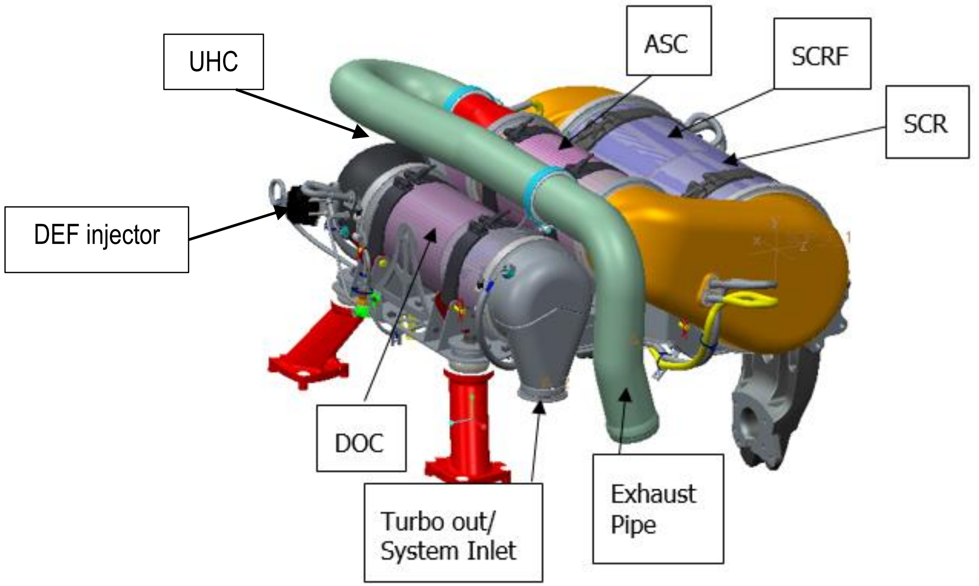
Aged at 650ºC for 100 hours prior to evaluation

- NO_2/NOx > 25%
- ANR = 1.2

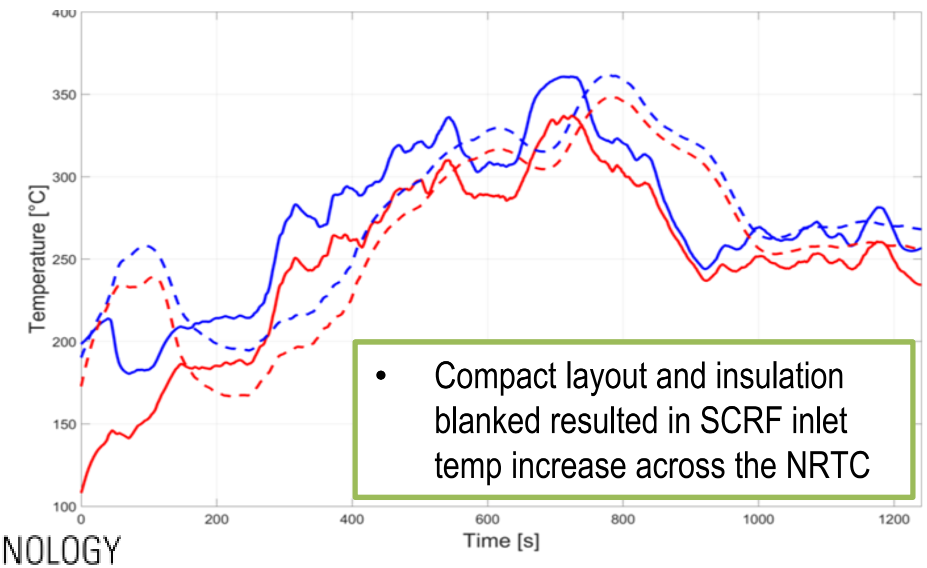
	Linear System Engine Test results (Weighted)			
Engine Mode	Turbo Outlet Average Cycle T (°C)	NOx Conv. (%)	Tailpipe (TP) NOx (g/kWh)	Tailpipe (TP) N_2O (g/kWh)
Conventional	290	**96.7**	0.29	0.26
Downsped	300	**98.3**	0.15	0.36

Compact System Layout with Urea Hydrolysis Catalyst (UHC)



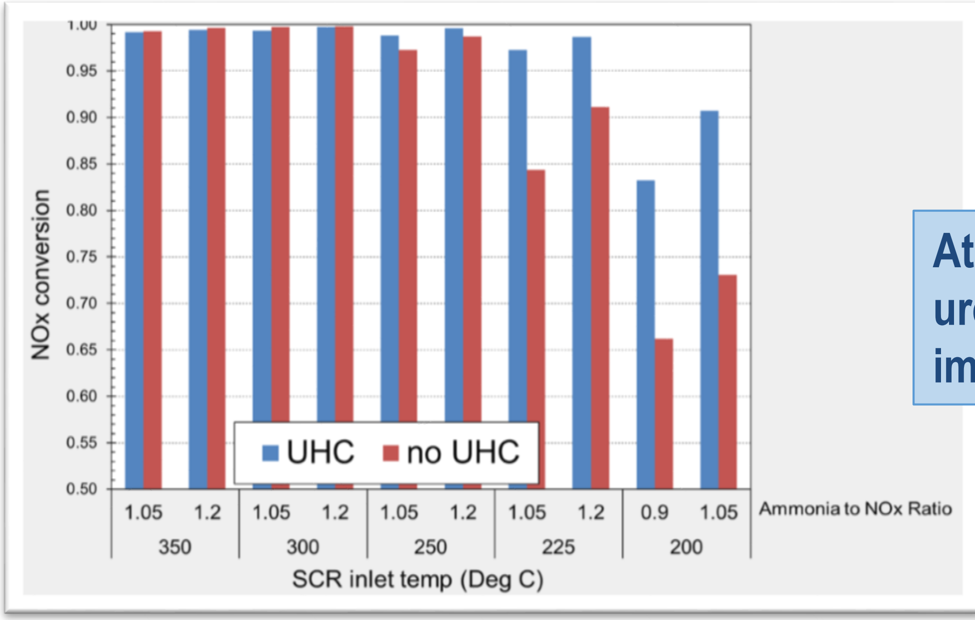


Linear (red) vs. compact design (blue) NRTC Temperature Profile



- Compact layout and insulation blanked resulted in SCRF inlet temp increase across the NRTC

NRTC Results for Conventional Mode Using Compact Design



At low temperatures the urea hydrolysis catalyst improves the NOx reduction.

	Conventional mode NOx [g/kWh]				Max.TP NH_3 (ppm)*	PN #/kWh	N_2O (g/kWh)
Layout	Cold	Warm	**Weighted**	**% NOx**			
Linear	0.94	0.22	0.29	**96.8**	4.3	9.0e9	0.26
Compact Design	0.60	0.05	0.11	**98.8**	3.3	2.2e9	0.32

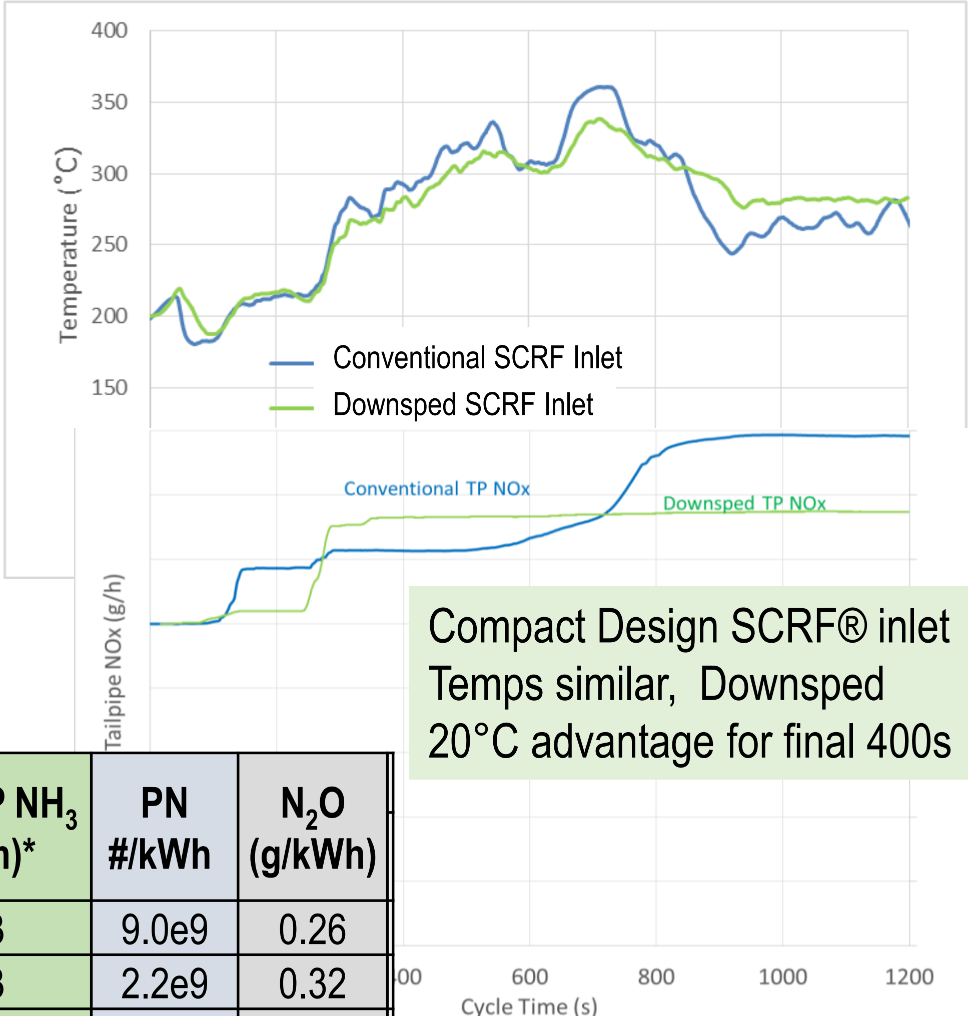
*Model Predictive Controls used in compact design to maximize use of available NH_3, and minimize slip.

Regulation: NOx< 0.4, NH_3 < 10, PN < 1e12

NRTC Results for Downsped Mode Using Compact Design

Aftertreatment Controls Calibration Unchanged between Engine Operating Modes

Compact Design Conventional (blue) vs. Downsped (green) Operating Mode Warm NRTC Temperature and Cumulative

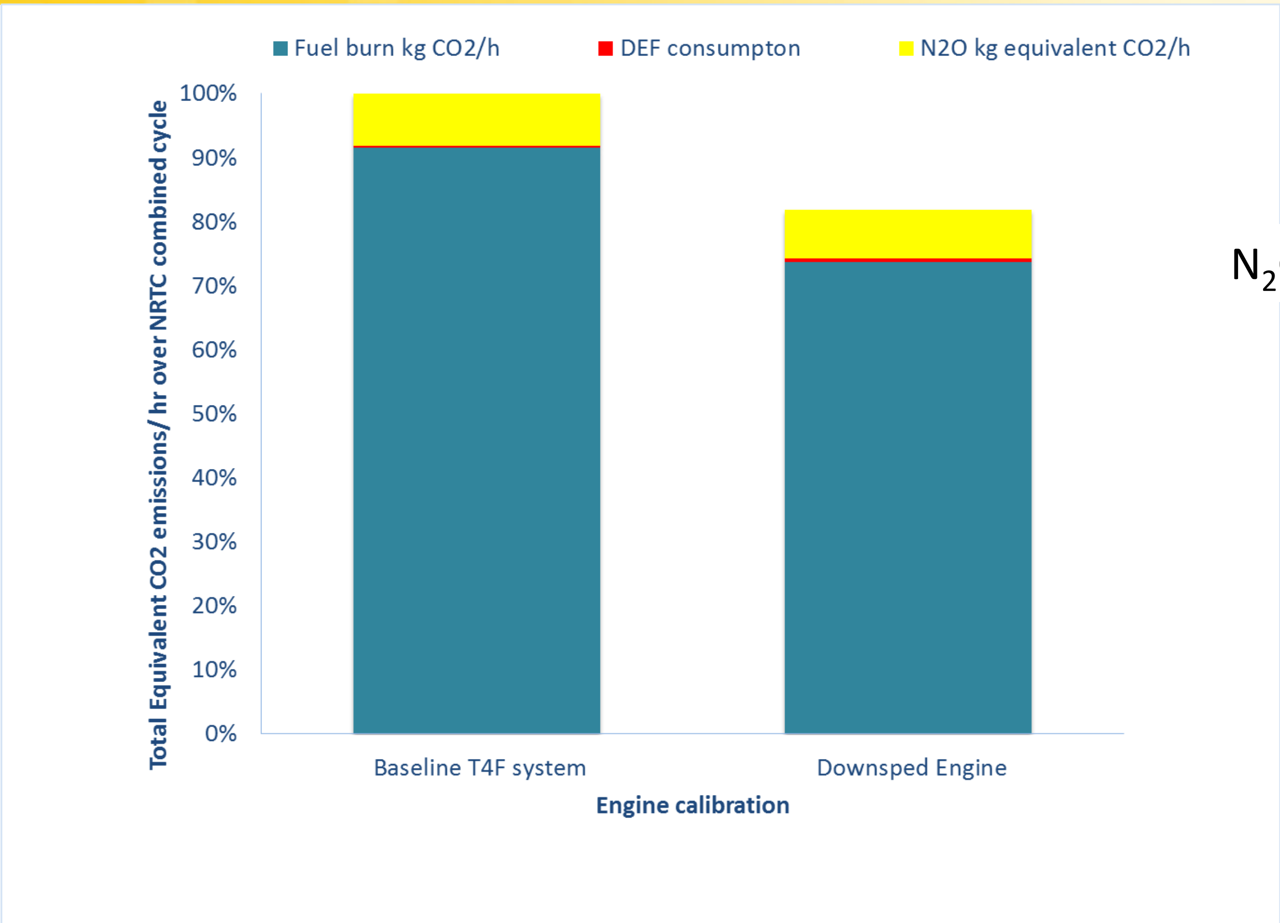


Compact Design SCRF® inlet Temps similar, Downsped 20°C advantage for final 400s

		NOx [g/kWh]		Max.TP NH_3 (ppm)*	PN #/kWh	N_2O (g/kWh)
Mode	Layout	**Weighted**	**% NOx**			
Conventional	Linear	0.29	96.8	4.3	9.0e9	0.26
Conventional	Compact	0.11	**98.8**	3.3	2.2e9	0.32
Downsped	Compact	0.08	**99.0**	2.9	2.2e9	0.22

Regulation: N0x< 0.4, NH_3 < 10, PN < 1e12

GHG Emissions over NRTC Using Downsped Mode



$N_2O = 298^* \; CO_2$

- ✓ About 10% of total GHG was N_2O made by the SCR system
- ✓ Increased NOx conversion over ETI engine did not increase N_2O
- ✓ 20% Lower GHG obtained using new SCR system on downsped engine

Additional Cycles for Simulated In Use Work Analysis

✓ Remainder of presentation to focus on 3 of these applications:

Backhoe

On-road Truck (WHTC)

Braunschweig (bus)

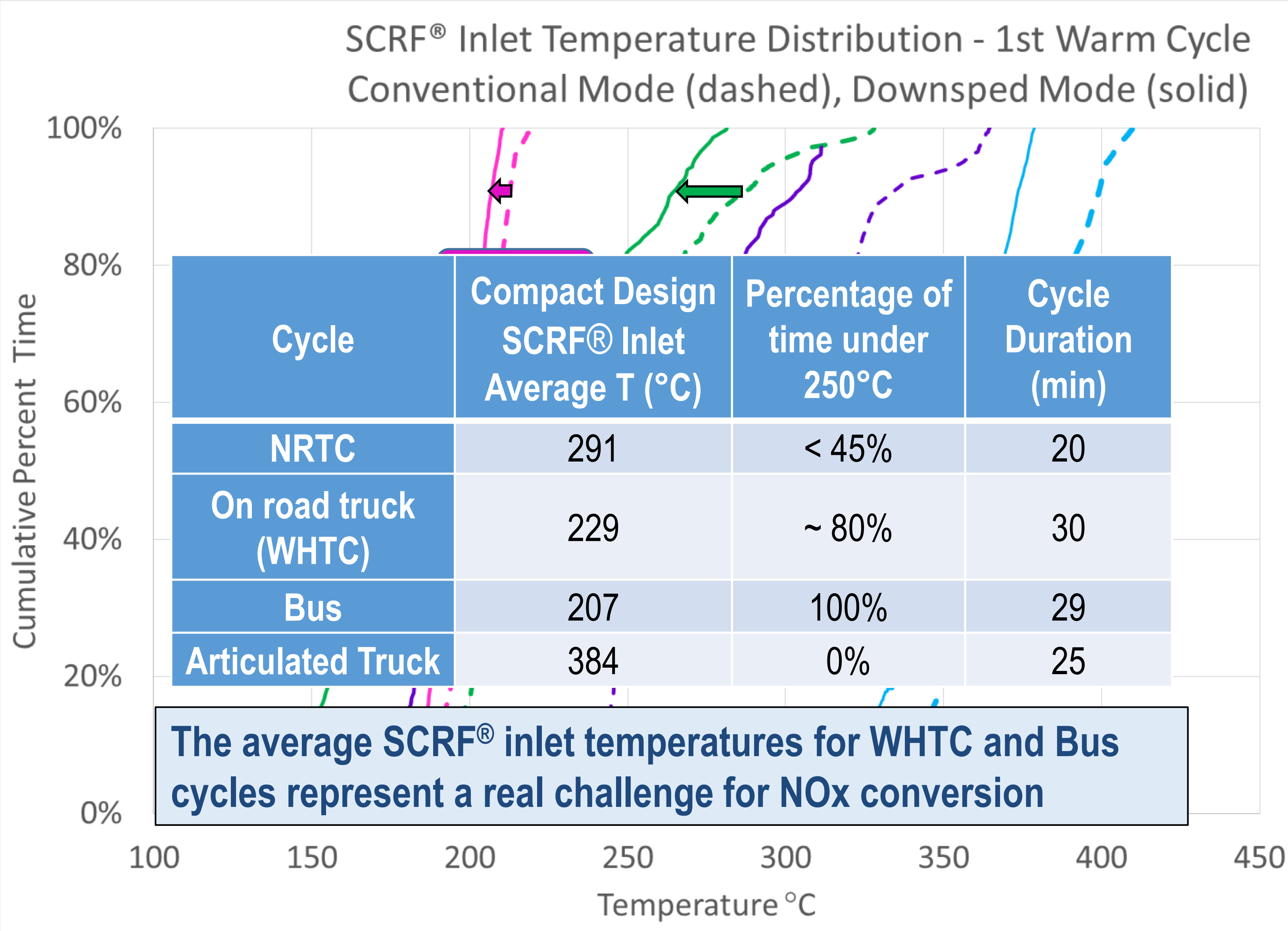
Wheel Loader

Articulated Truck

Ag (tractor)

➢ **Wide variety of cycles represent the range of uses of HDD engines on mobile applications.**

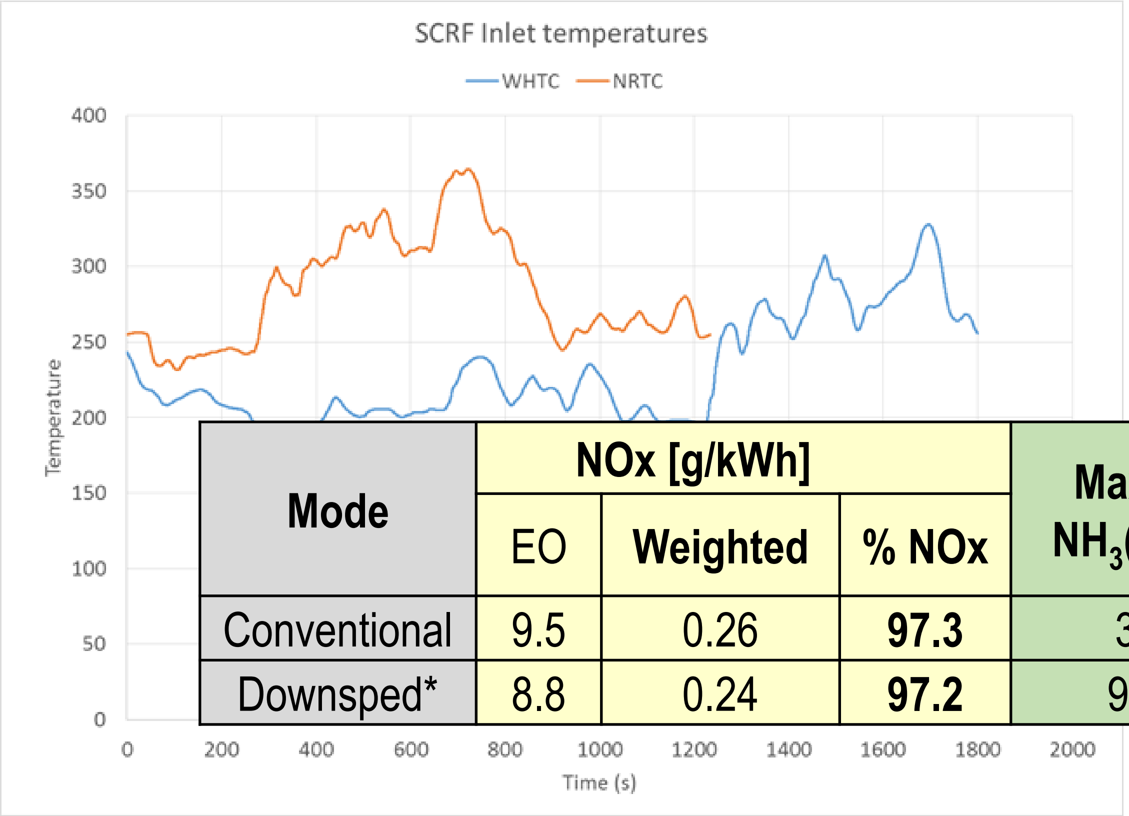
Comparison Between Regulatory and Vocational Cycles



Cycle	Compact Design SCRF® Inlet Average T (°C)	Percentage of time under 250°C	Cycle Duration (min)
NRTC	291	< 45%	20
On road truck (WHTC)	229	~ 80%	30
Bus	207	100%	29
Articulated Truck	384	0%	25

The average SCRF® inlet temperatures for WHTC and Bus cycles represent a real challenge for NOx conversion

WHTC Performance using Compact Design



Mode	NOx [g/kWh]			Max.TP NH_3(ppm)	PN #/kWh	N_2O (g/kWh)
	EO	Weighted	% NOx			
Conventional	9.5	0.26	**97.3**	3.5	3.9e9	0.29
Downsped*	8.8	0.24	**97.2**	9.4*	2.2e9	0.43*

- ✓ Colder exhaust of WHTC vs. NRTC, increases challenge to AT performance
- ✓ >97% NOx conversion

Simulated In Use Testing Using Compact Design

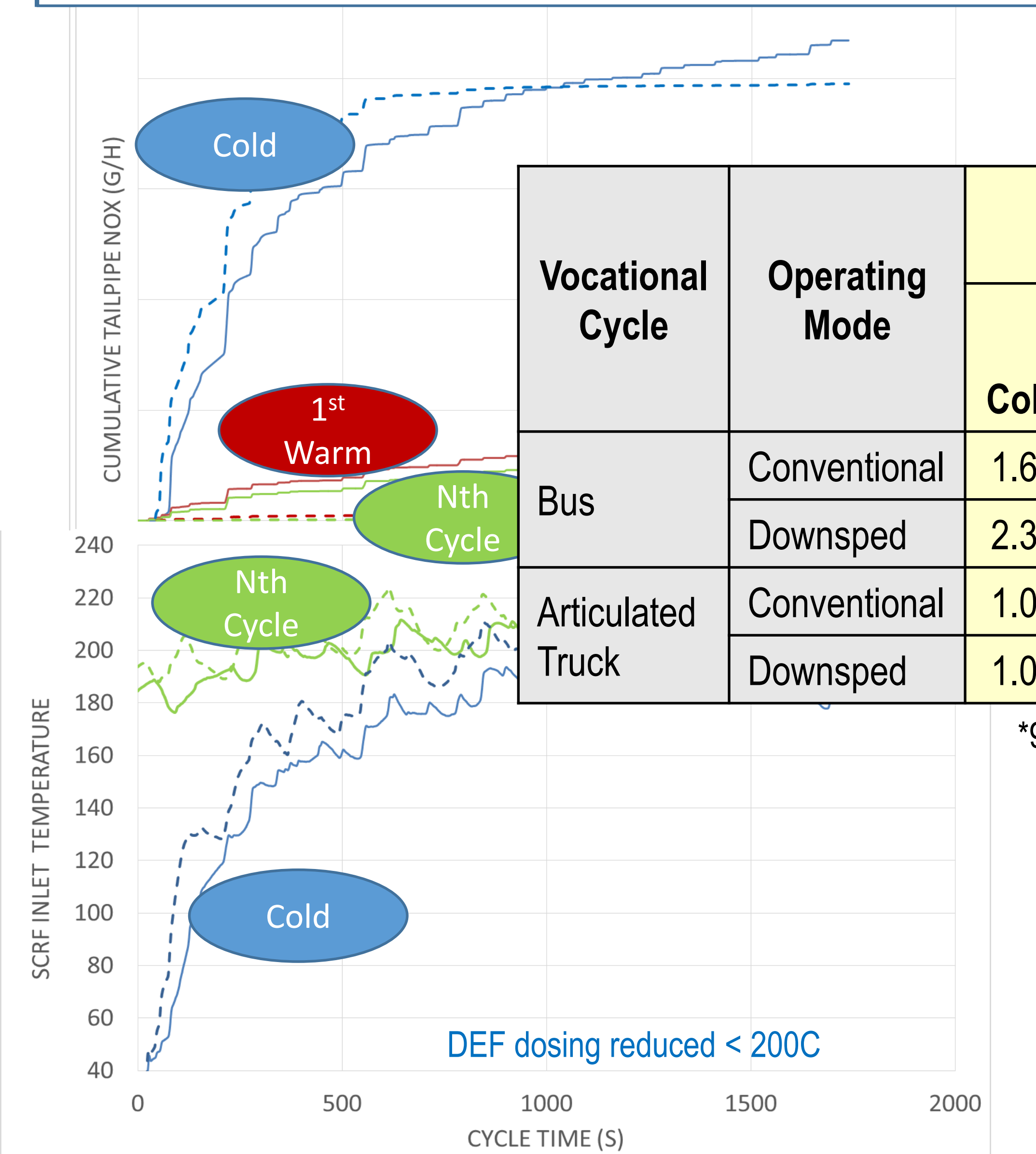
- ✓ Local transit bus done in Braunschweig, Germany
- ✓ Cat® 725 Articulated Truck in Peterlee, UK

Procedure:

- ✓ Run engine in test cell following simulated vocational cycle
- ✓ Follow cold start procedure of NRTC for first test of the day using vocational cycle (“Cold Cycle”)
- ✓ Repeat the vocational cycle immediately after completing the cold cycle (“Warm Cycle”) – no soak time
- ✓ Continue repeating vocational cycle until change in NOx tailpipe levels < 5% between two contiguous runs (“Nth Cycle”)
- ✓ Replicate Nth cycle to fill out 8 hours of operation data
- ✓ Generate a set of “work based windows” for analysis based on this combined data set

Performance Evaluation Using Simulated In Use Testing

Bus Cycle Cumulative TP NOx Improves With Repetition; Conventional (Dashed Lines) < Downsped (Solid Lines)



Vocational Cycle	Operating Mode	NOx [g/kWh] Cold	NOx [g/kWh] 1st Warm	NOx [g/kWh] Average Warm	NOx [g/kWh] 90th percentile*	Relevant Regulation for Conformity factor
Bus	Conventional	1.60	0.03	0.01	**0.014**	0.46
	Downsped	2.36	0.46	0.38	**0.39**	
Articulated Truck	Conventional	1.06	0.25	0.30	**0.35**	0.40
	Downsped	1.08	0.25	0.29	**0.25**	

*90% of all Work Based Windows have TP NOx < this value

- ✓ Coldest (Bus) and Hottest (Articulated Truck) Cycles pass WBW type NOx requirements
- ✓ All other vocational cycles evaluated passed WBW type NOx requirement

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Summary and Conclusions

- ✓ An SCR on Filter (SCRF®) based aftertreatment system was evaluated using a high efficiency engine operating in either conventional or downsped mode.
- ✓ EU Stage V and Euro VI regulations for NOx, PN, and NH_3 slip were met over each operating mode.
- ✓ In-use compliance was demonstrated using WBW type analysis over relatively hot (Articulated Truck) and cold (Bus) vocational cycles over each operating mode.
- ✓ The downsped mode reduces GHG emissions due mainly to lower BSFC while simultaneously holding N_2O formation constant over the AT system despite increased NOx conversion.
- ✓ >97% NOx conversions for most applications were similar over both operating modes, despite downsped mode exhaust being colder. Conversions over the downsped bus cycle were lower than conventional mode due to increased %cycle time spent below 200°C (50% vs. 70%), where urea dosing was limited.
- ✓ A versatile Cu SCRF® based aftertreatment system has been developed to provide high NOx conversion and PN reduction to meet future emission regulations on advanced engine technologies.

Thank you for your attention – Any questions?

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