CORNING

Presented at ECMA workshops at ARAI & ICAT
PART 3

Vehicle Engine Efficiency and Emissions
Review of Regulations & Technology Trends

Sept 11th – 12th, 2019

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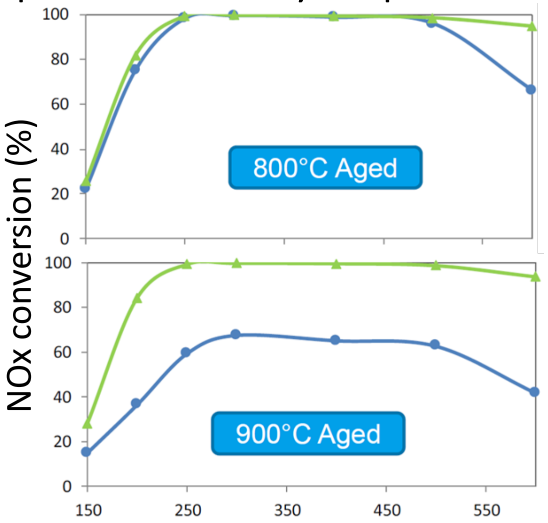
SCR
Some advances apply to both LD and HD

Durability of SCR shown to 900 °C. Combination of close-coupled SCR and ASC shown to improve NOx-N_2O trade-off

JM, SAE HDD Symposium, Gothenburg 2018

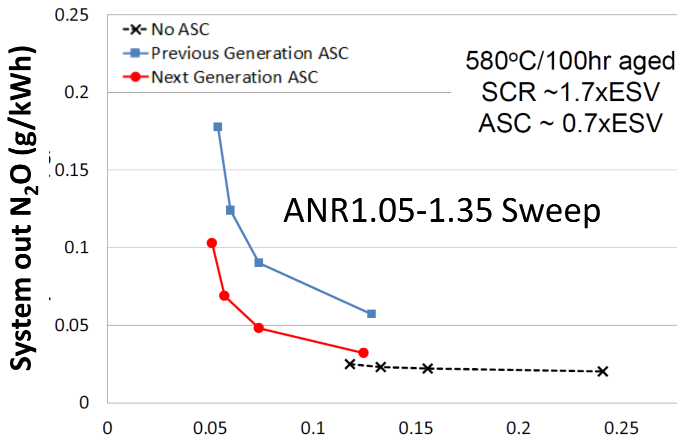
SCR on filters

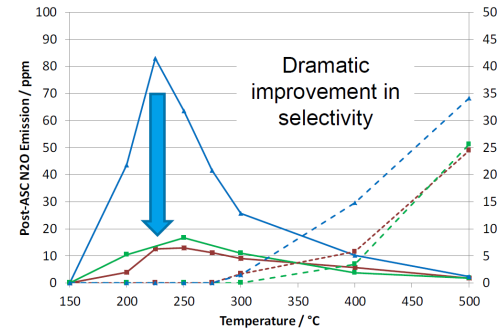
Improved durability & op. window

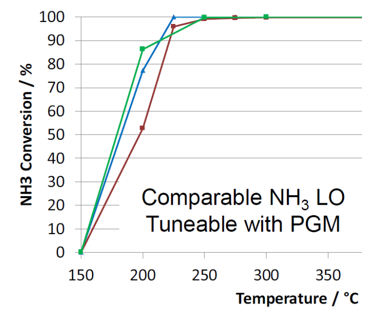


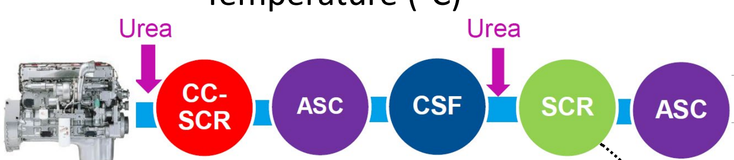
ASC

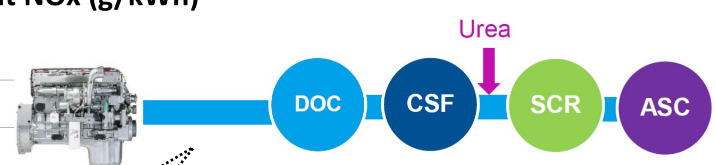
Improved selectivity - lower N_2O
While retaining NH_3 ox. performance





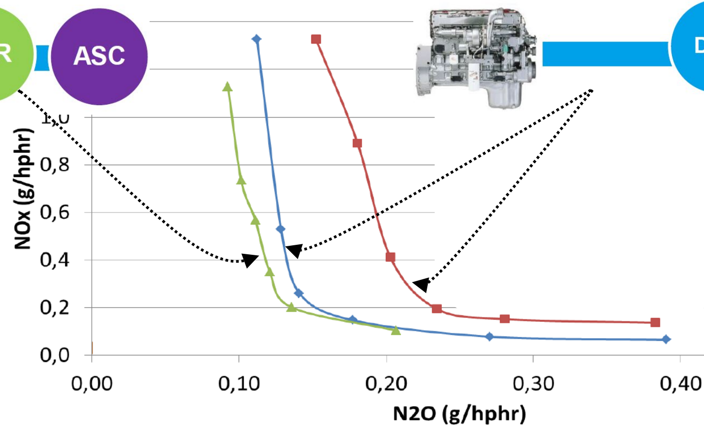






Use of close-coupled SCR

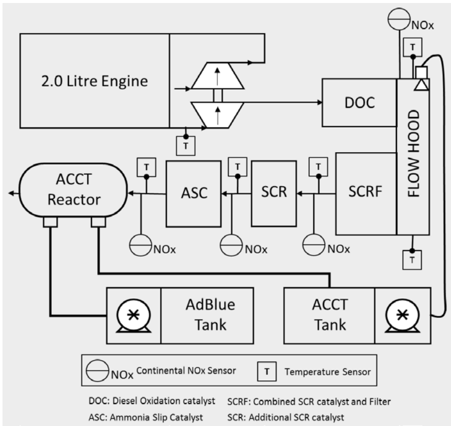
Better tailpipe NOx / N_2O trade-off even with 3X higher engine-out NOx → improved fuel economy



Engine-out NOx g/bhp-h	After-treatment
9 g/bhp-hr	SCRT®
4.5 g/bhp-hr	SCRT®
12 g/bhp-hr	SCR + SCRT®

Ammonia creation & conversion technology (ACCT) demonstrated on LD prototype vehicle

Loughborough Univ., SAE 2018-01-0333



Exhaust waste-heat used to convert urea to ammonium carbamate solution

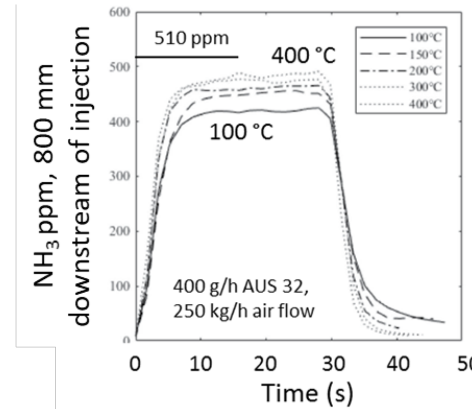
Ammonium carbamate solution decomposes to ammonia at T > 60 °C

Thermolysis/hydrolysis of urea

$CO(NH_2)_2 + 6.92H_2O \rightarrow 2NH_3 + CO_2 + 5.92H_2O$

Products dissolve in steam

$2NH_3 + CO_2 + 5.92H_2O \rightarrow NH_4(H_2NCO_2)_{(aq)}$



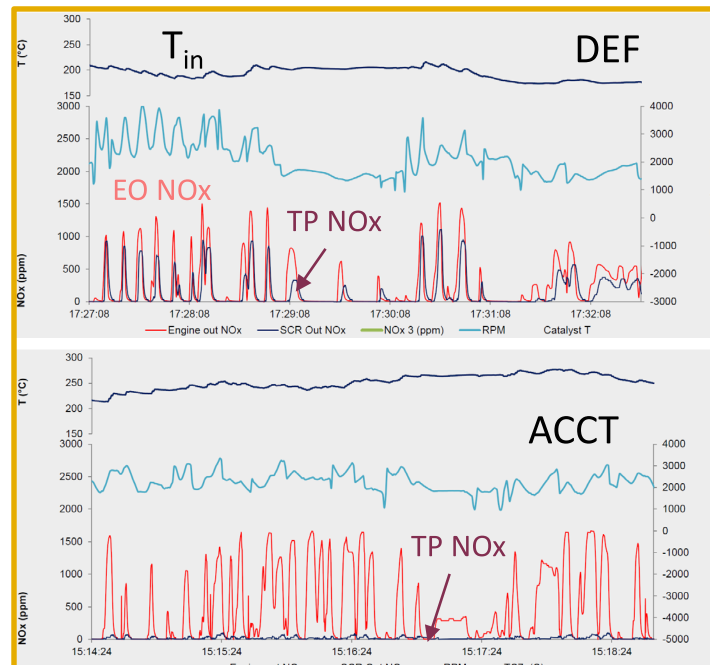
Prototype vehicle

- Euro 6 vehicle
- Works reasonably well for NOx emissions
- EQUA (AIR) Index C
  - 2.1 Conformity Factor Euro 6 RDE
- Retrofitted to be able to hot-swap between AdBlue and ACCT fluid.

10L/6000 mi, Conversion rate needed : 0.07L/h, Additional P = 10W

Example 2

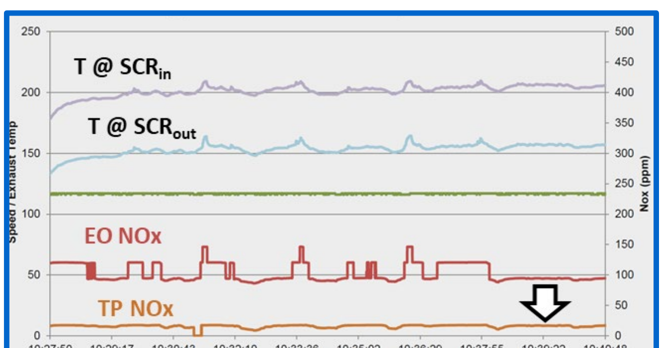
Mountain driving
→ Near complete conversion using ACCT



Example 1

Motorway driving

>75% conversion at ~ 160 °C

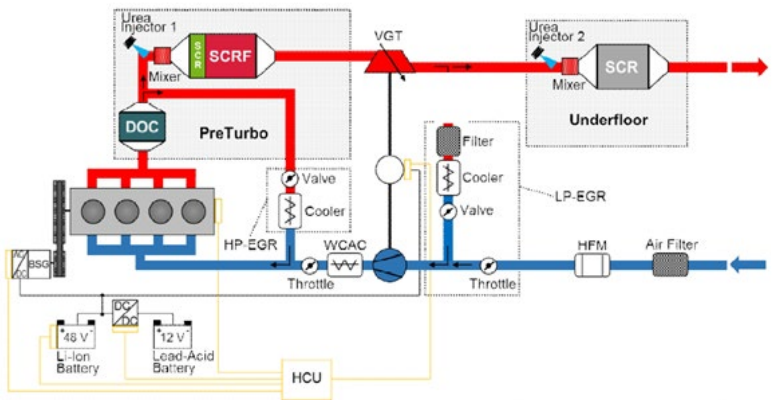


What next for Diesel ?

Pre-turbo catalyst combined with electrically assisted turbo < 35 mg/km NOx over a wide range of driving conditions

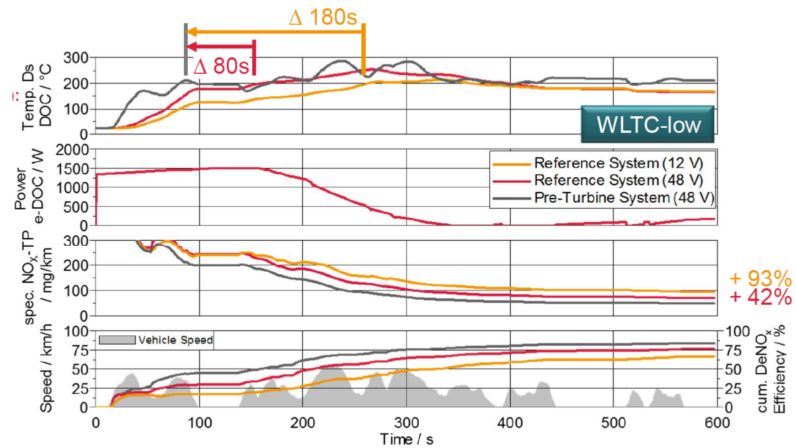
FEV FEV Diesel Powertrains 3.0, 2019

Vehicle : JLR F-Pace 2.0L EU6b

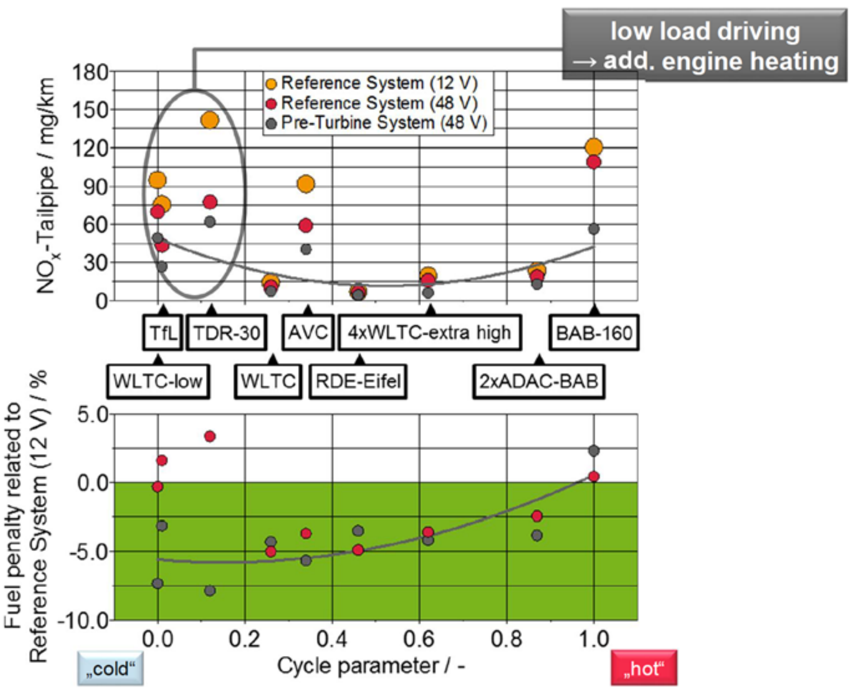


PTC reduced enthalpy at TC ~ 4% on WLTP
→ 11 kW e-TC added to overcome this loss

System	Battery	After-treatment
Ref 1	12 V	DOC 2.0 – SDPF 3.5 – SCR 5.0; HP – EGR, LP – EGR
Ref 2	48 V	Above and e-DOC
3	48 V	DOC 1.0 – SCR 1.0 – SDPF 2.0 – SCR 5.0; HP – EGR, LP – EGR



* w/o engine heating, w/ e-DOC heating



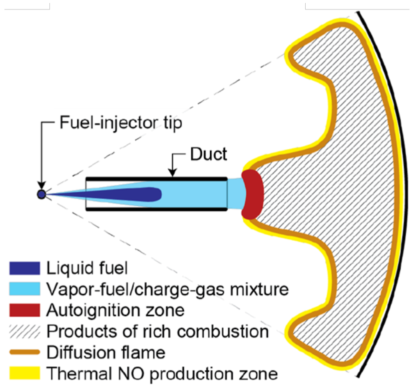
Ducted fuel injection (DFI) : Near soot-free Diesel combustion

Sandia Natl. Lab, SAE High Eff. ICE 2019

Concept

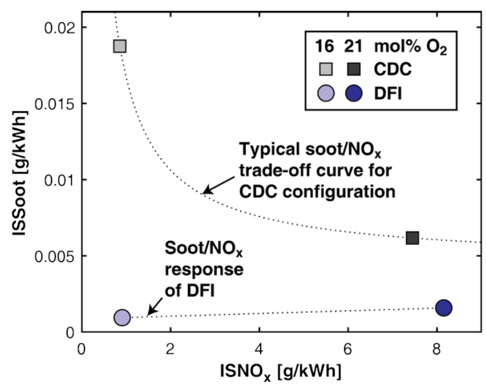
Fuel injection through small tube

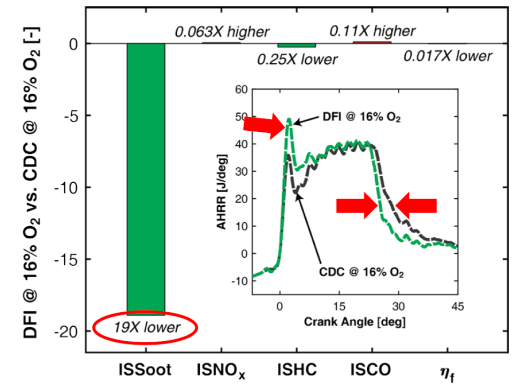
- Leaner fuel-rich mixture in autoignition zone
- "Leaner lifted flame combustion (LLFC)"



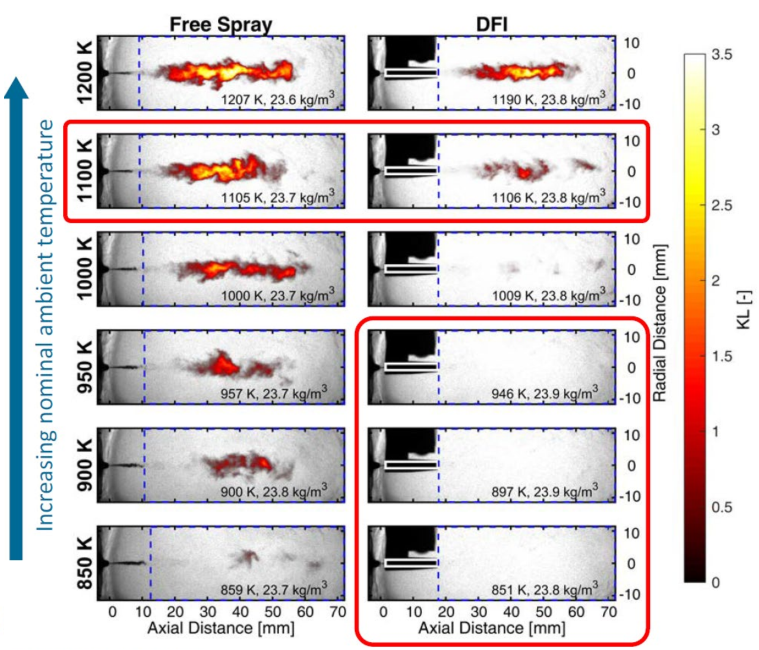
Single cyl. experiments

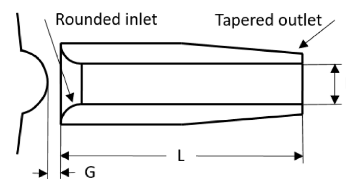
Speed 1200 rpm, Load 2.5 bar, Inj. P 180 MPa





Const. vol. combustion vessel experiments





Study of optimum duct geometry

Constant pressure vessel experiments

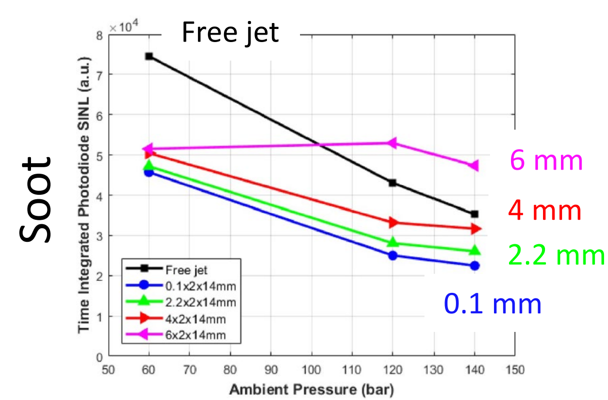
Caterpillar SAE 2019-01-0545

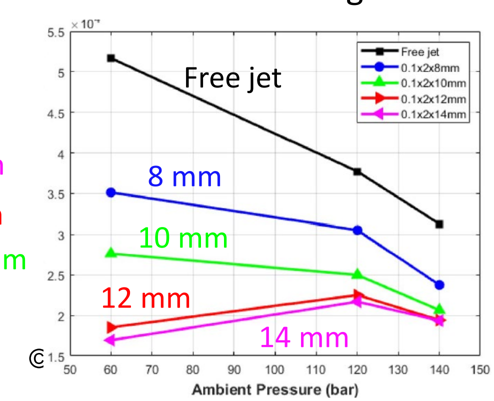
G = Dist. from injector orifice

Lower soot at smaller distance

L = Duct Length

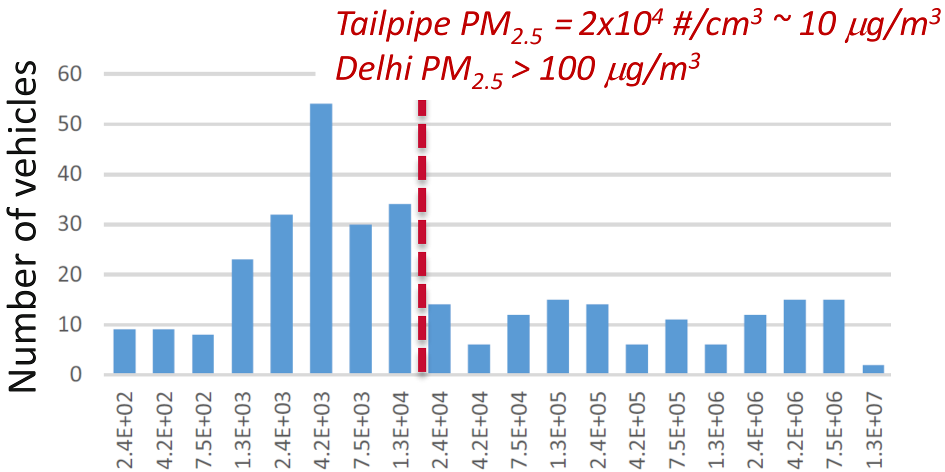
Lower soot with longer duct





Advanced after-treatment systems enable “negative emissions” But need to address cold start and high emitters

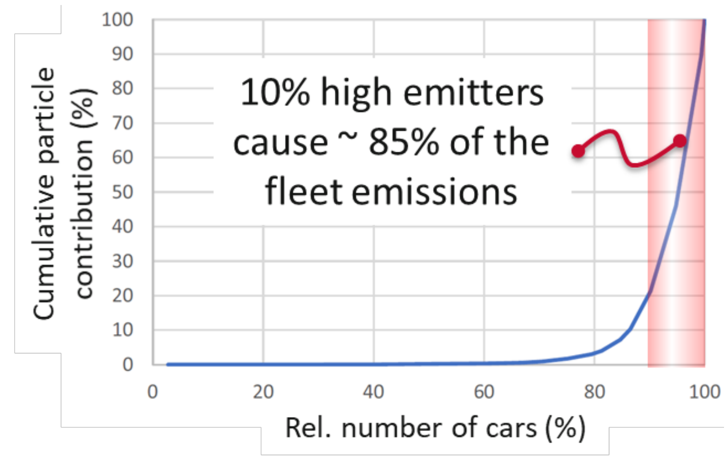
Fleet measurements in Zürich

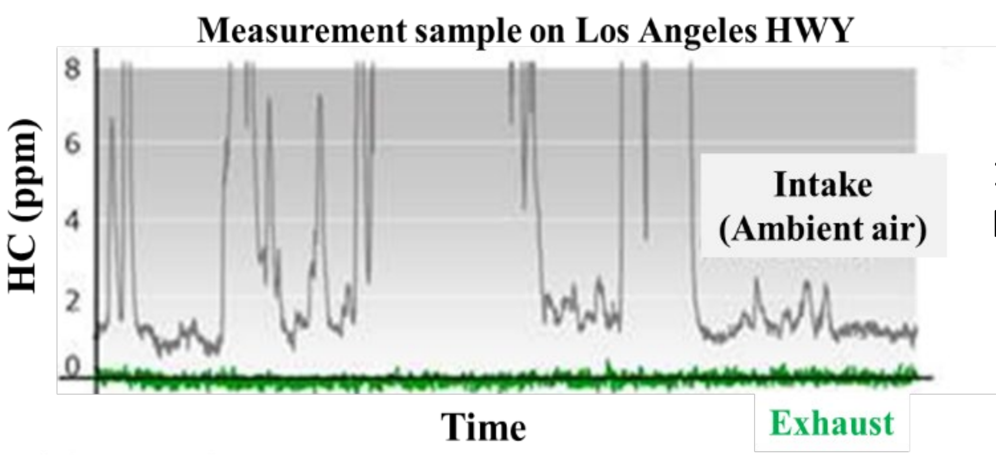


Tailpipe soot emissions of Diesels with DPF (# / cm^3)

Emission Control Sci and Tech (2019) 5:279–287

Most emissions today from a few vehicles with high emissions





1999 vehicle designed for 1/10 of ULEV: 4 mg/mi NMOG (non-methane organic gas) and 20 mg/mi NOx, or roughly SULEV

Honda, Hokkaido 2017

Summary – Light Duty

Fuel economy / CO_2 emissions

- CO_2 reduction targets across the world will require a 3 – 6% improvement in fuel economy per year
- Electrification mandates being proposed: China is now including hybrids in NEVs.

Technology trends / implications

- Various advanced ICE technologies still to be deployed. Pathways to 50% BTE outlined.
- Hybrids offer a 20 – 30% reduction in CO_2 today
- Lower comb. temperatures emphasize the role of advanced after-treatment systems

Criteria Pollutant Regulations

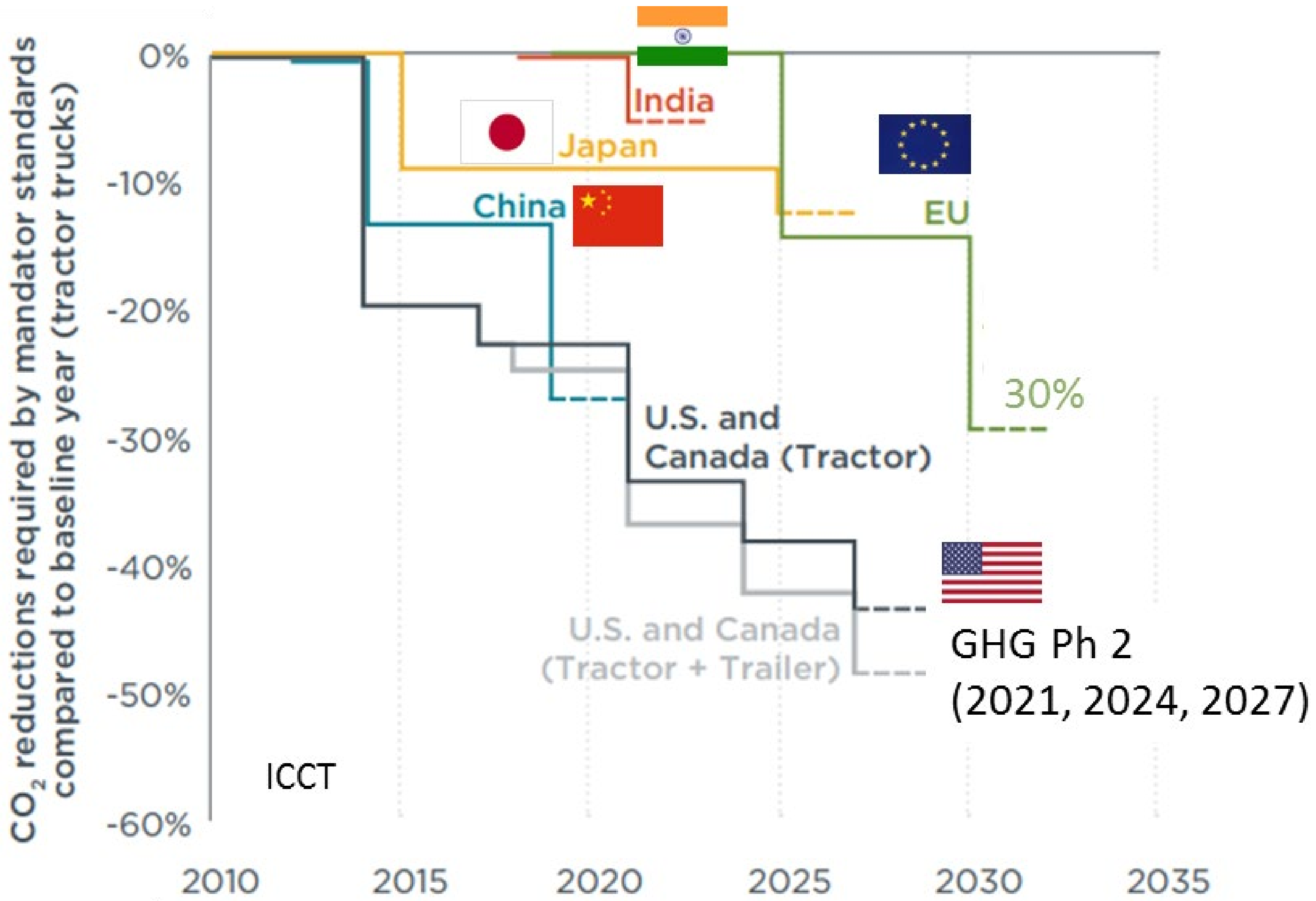
- Particulate emissions is a key health concern : PN regulations in EU/CN/IN
- US still the tightest for gas emission standards
- With tailpipe emissions approaching near-zero, focus now on real-world and in-use compliance
- Key elements of post Euro 6 regulations are being discussed

Technologies to reduce criteria pollutants

- Gasoline particulate filters (GPFs) widely being deployed in EU and China
- Reduction of cold start emissions is critical : TWC, HC-traps, SCR, DOCs are improving
- Euro 6 RDE compliant gasoline and Diesel vehicles certified and exceed the requirements
- Hybrids can have unique emission challenges which must be tackled

Heavy-Duty

Europe has first CO_2 targets for Heavy-Duty Vehicles
Fleet average reduction of 15% by 2025, 30% by 2030, compared to 2019



Global Heavy Duty Regulations

On-Road		2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
USA		US 2010 + ARB Optional low NOx						ARB Low load cert. cycle	ARB Low NOx 20 mg/bhp-hr			EPA CTI			
	CO2 / FC	GHG Phase 1				GHG Phase 2									
EU		EU VI - C	Euro VI-D		Euro VI-E					Euro VII ?					
	CO2 / FC				HD CO2 : 15% vs. 2019						30% vs. 2019				
JP		JP '16 (JE05 → WHTC)													
China		CN V		CN VI - Key areas	CN VIa (July 2020)			CN VIb (July 2023)				CN VII ?			
	CO2 / FC	Stage 2		Stage 3								Stage 4 ?			
India		BS IV (~ Euro IV)			BS VI Ph. 1			BS VI Ph. 2						BS VII ?	
Brazil		P-7 (~ Euro V)						P-8 (~ Euro VI-C)							
Mexico		Euro IV		US 2007 / Euro V		US 2010 / Euro VI								Low NOx / Euro VII ?	

Non-Road	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
USA	Tier 4F								Tier 5 (?)					
EU	Stage IV		Stage V											
China	Stage III (~ Euro IIIA)			Stage IV + PN limit						Stage V ?				
India	BS III (~ US Tier 2/3)			BS IV (Oct '20)				BS V (Apr '24)						

In-use NOx emission limits continue to reduce across major markets Coupled with significant cuts in CO_2 / GHGs

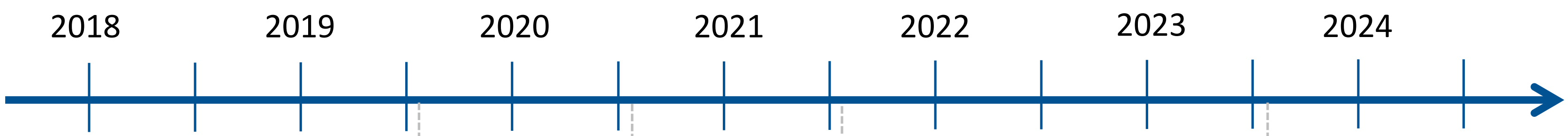
	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	> 2025
US EPA	EPA 2010 : NOx 200 mg/bhp-h, PM 10 mg/bhp-h									EPA Low NOx (CTI)		
	GHG Phase 1		GHG Phase 2									
CARB	Optional low NOx : 0.1, 0.05 & 0.02 g/bhp-hr								UL NOx 0.0X g/bhp-h Low load cycle, MAW			
EU	EU VI A, B, C ISC: Power threshold 20%, Max payload 50 - 100%				EU VI D ISC: Power threshold 10%, Max payload 10 - 100%			EU VI E Trip share (for N3): 30% urban (up from 20%), 45% motorway Include cold start PN CF = 1.63			EU VII ?	
	CO_2 measurements for 2019 baseline					15% reduction in 2025						30% by 2030

Emphasis on reducing cold-start NOx emissions without impact on fuel consumption
Various after-treatment system concepts being evaluated

HD Low NOx rule : CARB proposing 60-75% NOx tightening and MAW ISC testing for 2024. 2027: increased warranty and durability requirements, and use of telematics

Step	Timing	Proposed Change	Technology Implications
Step 1	MY 2022 – 23	**Minor modifications to NTE** • Min ambient T = 7°C • Min after-treatment T = 200°C	Hardware modifications not likely needed
Step 2	MY 2024 – 26	**Reduced limits for NOx** FTP / RMC-SET: 0.05 to 0.08 g/bhp-hr **New low load cycle (LLC)** NOx : 1 to 3 x FTP std **New HDIUT program** MAW method, CF = 1.5 ~ Euro VI-D PM: 0.005 g/bhp-hr on FTP / RMC-SET **Durability Demonstration Program**	Engine calibration + Some engine and aftertreatment hardware modifications
Step 3	MY 2027+	More stringent NOx standards 0.0x TBD HDIUT ~ Euro VI-E (incl. cold-start, etc.) Possible compliance using NOx sensors / telematics warranty and useful life requirements	Major hardware upgrades to engine & aftertreatment

China VI Heavy-Duty Regulations



Focus areas, Buses, garbage vehicles*

Nationwide, urban

Nationwide, all

Nationwide, all

<u>*Focus areas</u>
Beijing, Tianjin, Hebei, Pearl River Delta, Chengdu-Chongquing

China VIa
PM, PN, NOx limits same as Euro VI
RDE PEMS testing for gas emissions
Remote OBD hardware in place

Beijing : VIb (proposed)
7/2019: CNG, City vehicles
1/2020 : All HDVs

China VIb
RDE PEMS testing for gas <u>and</u> PN (CF = 2.0)
payloads 10% - 100% of rated weight
Extended BCs: -7 to 35 °C, 2,400 m (vs 1700 m)
Report engine-out NOx
Vanadia SCR T_{max} 550 °C for FUL
OBD III – Remote transmission

<u>Durability</u>: 700K km for heaviest vehicles

China's Clean Diesel Program

ICCT, 2019
https://theicct.org/sites/default/files/publications/ICCT_China_Clean_Clean_Diesel_2018_2020_20190529.pdf

Eliminate 1M pre-China IV diesel & NG trucks by 2020

<u>Environmental information disclosure</u>
- Agencies will check emission control devices, OBD against form, and conduct RDE tests

<u>Early China VI implementation in "Key Regions"</u>
Beijing, Tianjin, Hebei, Shanxi, Shandong, Henan, Shanghai, Jiangsu, Zhejiang, Anhui, Shaanxi, Nei Mongol, Sichuan, Chongqing

<u>July 1st 2019</u>

<u>In-use I&M program</u>
Remote OBD
Remote sensing
Transmission of data to authorities
Random roadside & onsite inspections

<u>NEVs</u> to power > 8% of new urban fleets (buses, sanitation trucks, postal vehicles, taxis, and commuting coaches)

<u>Fuel / urea quality</u>
> 95% compliance of Diesel fuel (10 ppm) and urea quality

<u>China IV Off-road</u> : Dec 1st 2020
OBD and telematics as key in-use compliance tools

NOx control

Systems

Euro VI HDD vehicles can meet NOx limits under real-world testing

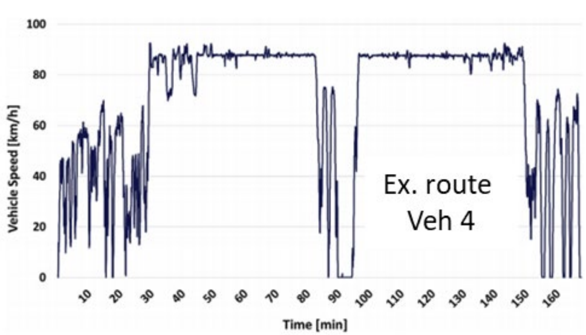
Emissions higher during low speed driving, low amb T. NO_2 fraction is a concern.

JRC, Univ. of Thessaloniki, Atm. Env. 201, 2019, 348-359

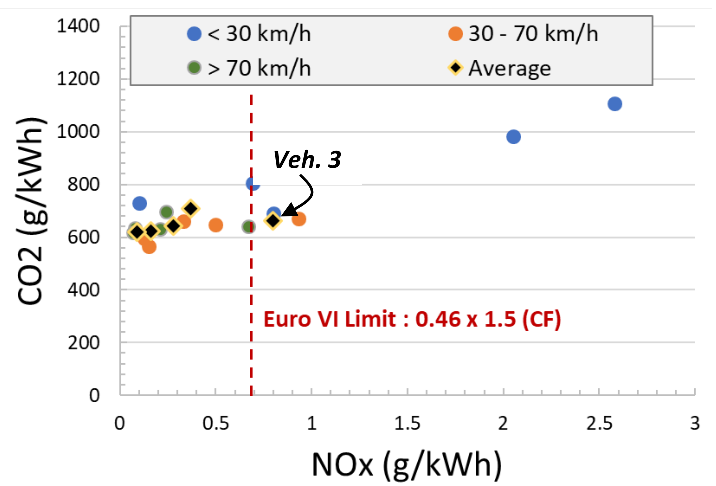
Specification	Vehicle #1	Vehicle #2	Vehicle #3	Vehicle #4	Vehicle #5
Type of Vehicle	Long–Haul	Regional	Long–Haul	Long–Haul	Coach
Engine Displacement [L]	13 ± 0.3	7.5 ± 0.3	13 ± 0.3	13 ± 0.3	13 ± 0.3
Rated Power Range [kW]	350 ± 10%	250 ± 10%	350 ± 10%	350 ± 10%	350 ± 10%
Gross Vehicle Weight [t]	34	26	34	34	25

After-treatment for all vehicles: DOC + DPF + SCR + ASC

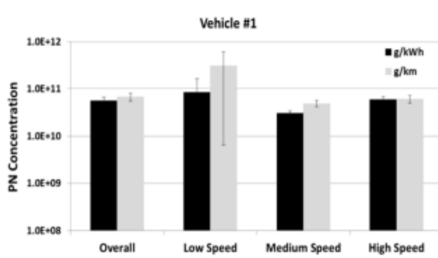
<u>RDE testing</u>:
200 km, urban, rural, hwy, 3 repeats
<u>Speed bins (km/h)</u>:
Low < 30, Med 30 – 70, High > 70
<u>Payload</u> : 60 – 65% of max.
Cold start excluded (30 min warm up



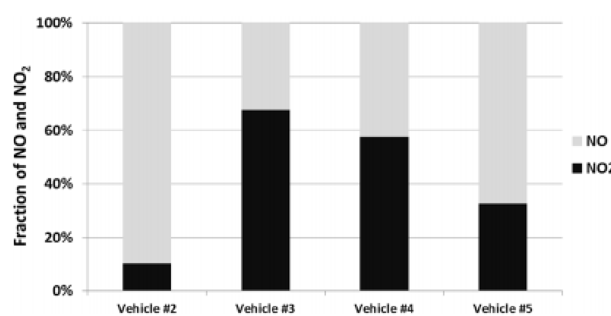
NOx/CO_2 for long haul : 0.15 – 0.25 g/kg

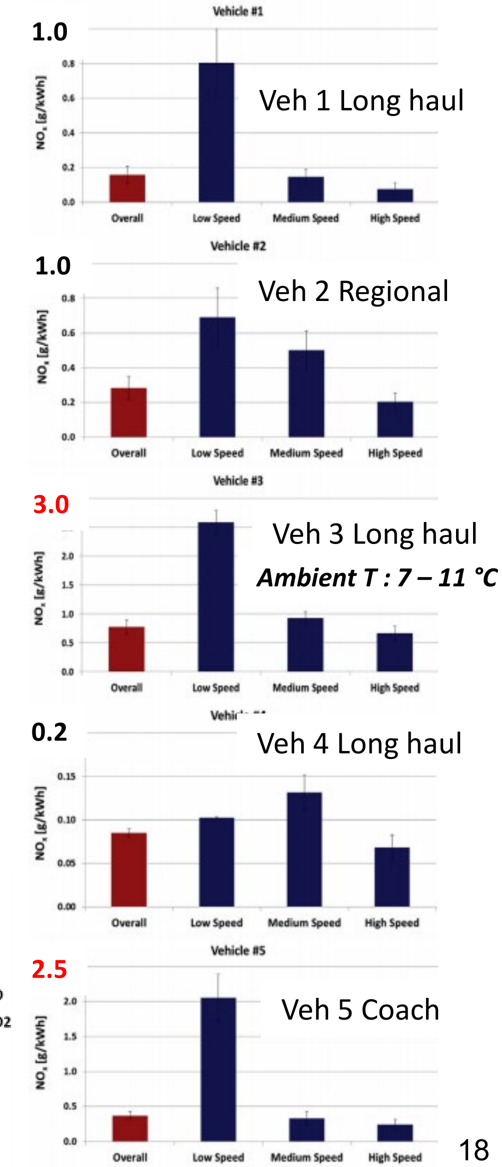


PN one order of magnitude below limit



Tailpipe NO_2 : 10 – 67% of total NOx





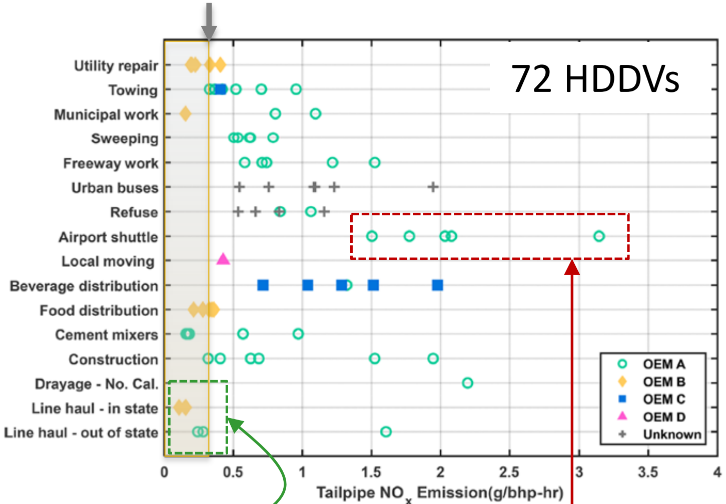
CARB : New test cycle proposed to include low load emissions

CARB, UC Riverside Env. Sci. Tech. 2019, 53, 5504 - 5511

In-use tailpipe NOx
0.11 – 3.14 g/bhp-hr

No data < 150 °C due to sensor limitations

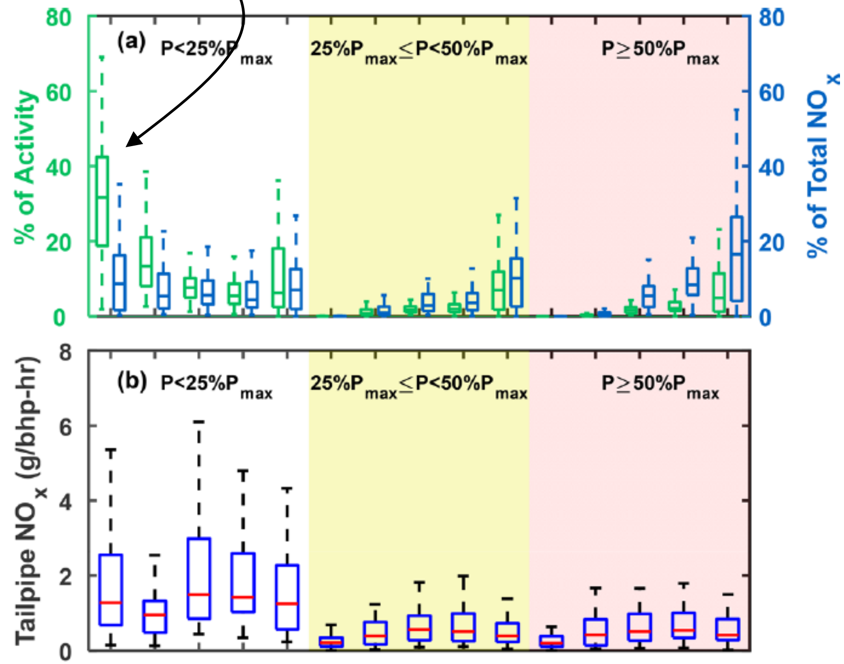
NTE limit = 1.5x0.2 = 0.3 g/bhp-h



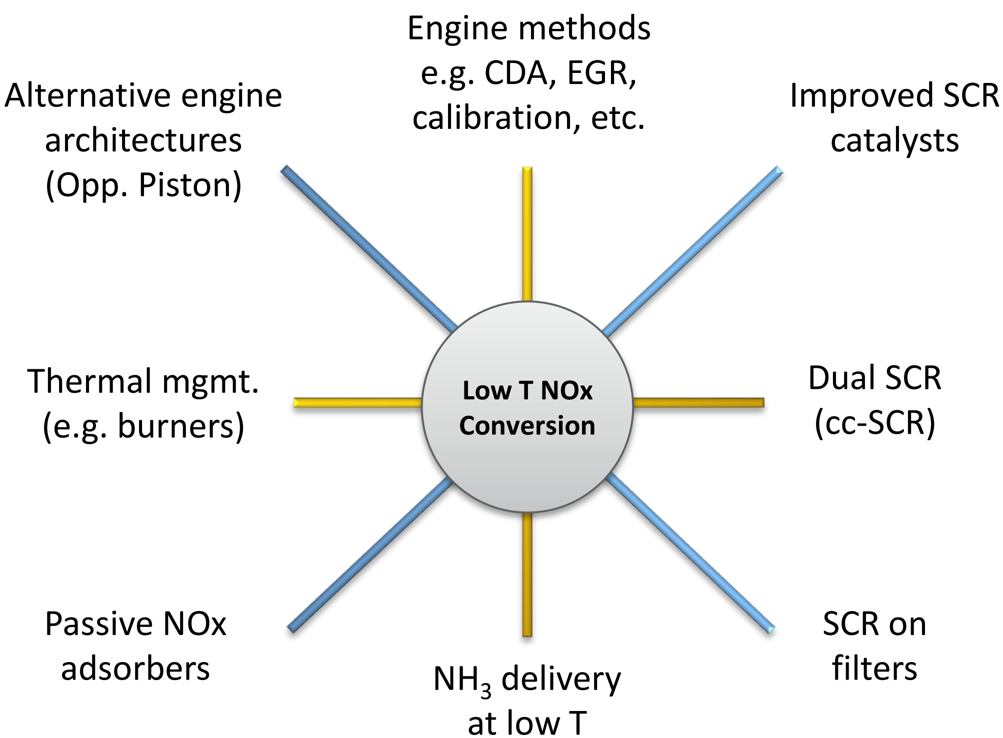
Line-haul
Generally cleaner
< 0.3 g/bhp-hr
(account for 2/3rd of VMT in CA)

Vocational
Some have very high NOx
> 60% VMT and NOx in urban areas

Low load idling is ~ 1/3rd of total activity
And accounts for 14% of total NOx emissions

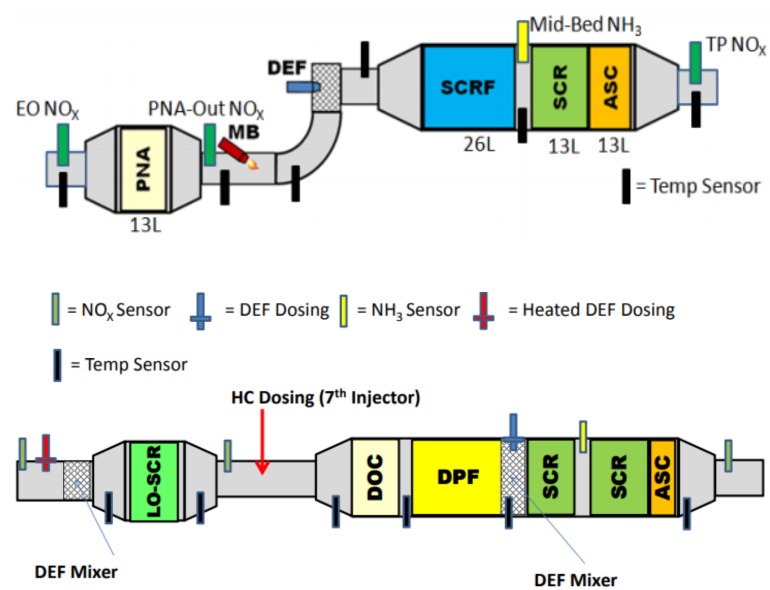


Various technologies are being developed to reduce NOx



Two leading approaches being evaluated

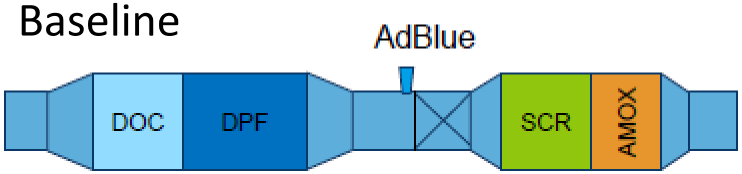
Southwest Research Institute / CARB



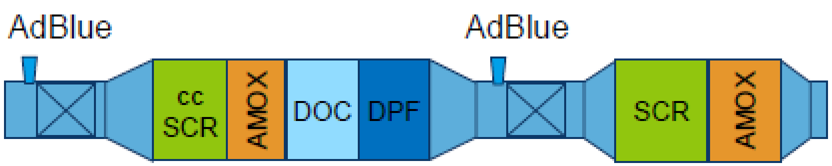
Combination of engine-out reduction & improved A/T necessary
Need to watch for N_2O, higher soot, fuel consumption penalty

IAV, SAE HDD Symposium, Gothenburg 2018

Baseline



Low NOx



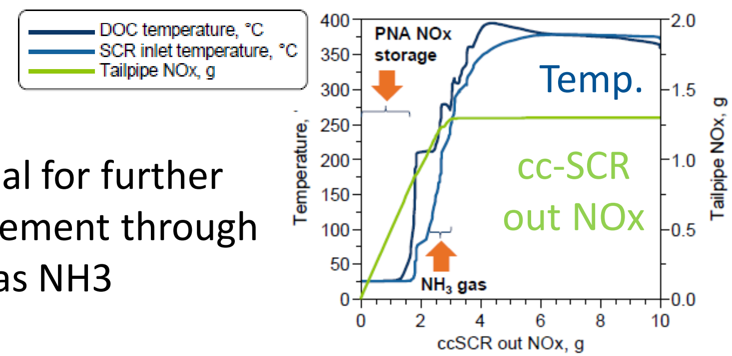
Vol., l	ccSCR	ccAMOX	DOC	DPF	SCR	AMOX
EUVI			11	26	28	4.4
UL NOx	8.7	4.3	11	15	28	4.4

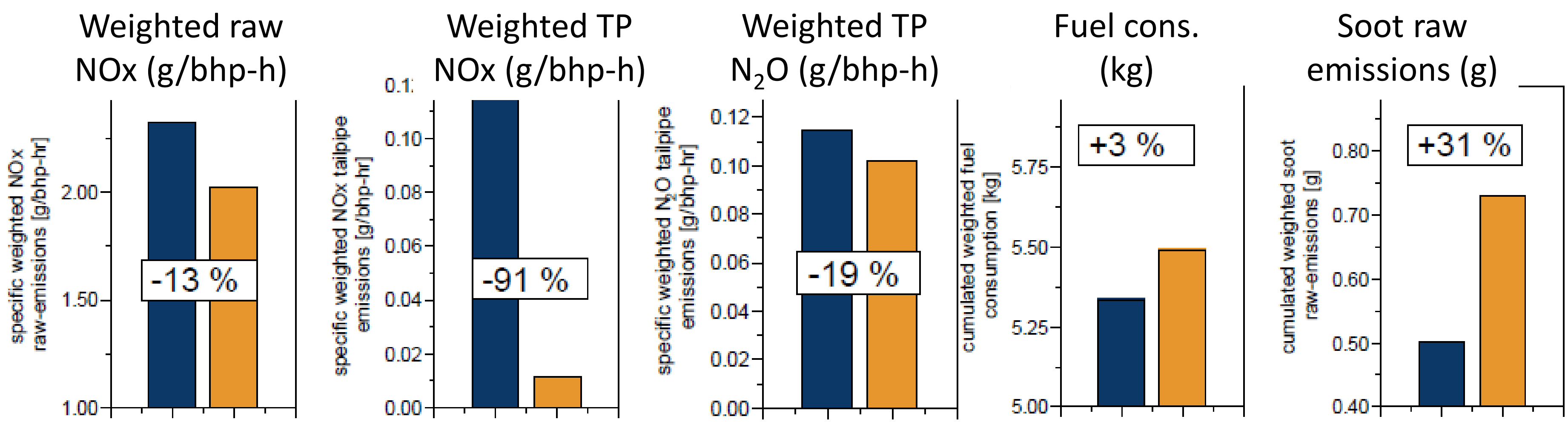
H. Rauch *et. al.*, 7th MinNOx, 2018

<u>Simulation study</u> : 6-cyl. HD EuroVI engine, EGR, 2-stage TC US HD FTP cold & hot

<u>Thermal management</u> : Early post injection + intake throttle idle + intake throttle in low load + retarded start of main inj. + exhaust throttle load + idle

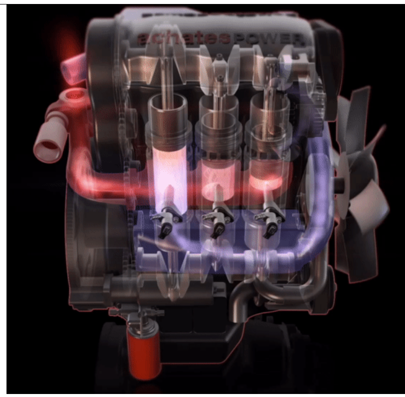
Potential for further improvement through PNA, gas NH3





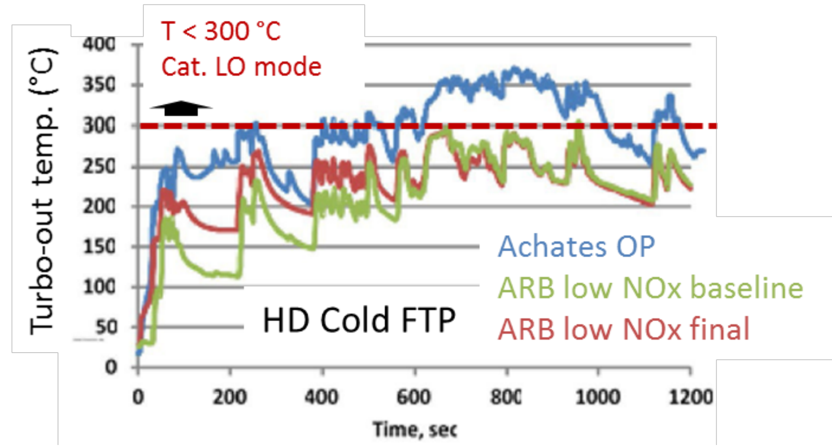
HD opposed piston engine simulations show path towards ultra-low NOx emissions

Achates, SWRI SAE 2018-01-1378



Data from 4.9L OP engine used to simulate 10.6L Class 8 engine

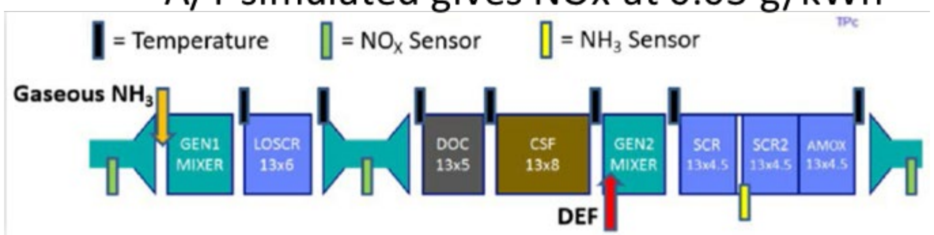
Displacement	10.6 L
Arrangement, number of cylinders.	Inline 3
Bore	120 mm
Total Stroke	312 mm
Stroke-to-Bore Ratio	2.6
Compression Ratio	17.5:1
Nominal Power (kW @ rpm)	336 @ 1700
Max. Torque (Nm @ rpm)	2373 Nm @ 950
Exhaust mass flow at rated power	1412 kg/hr

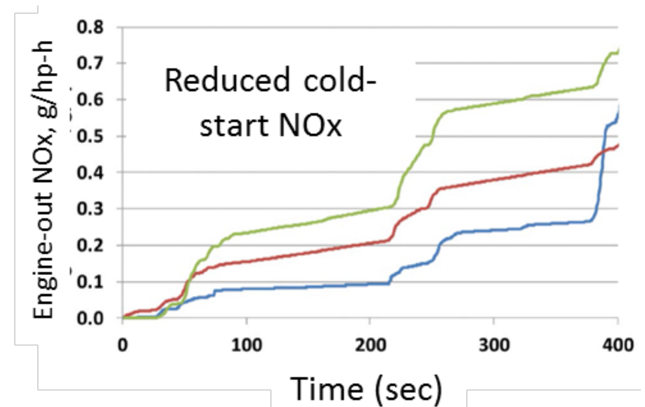


Elevated exh. T through increased residuals

With close-coupled SCR, deNOx can start in < 100 sec.

A/T simulated gives NOx at 0.03 g/kWh





In progress: The CALSTART and Achates contract with CARB to install 10.6 liter 2SOP engines into two Class 8 trucks to be placed in revenue service.

Objectives: 20 mg/hp-h NOx, at lower FC than standard diesel

Natural Gas

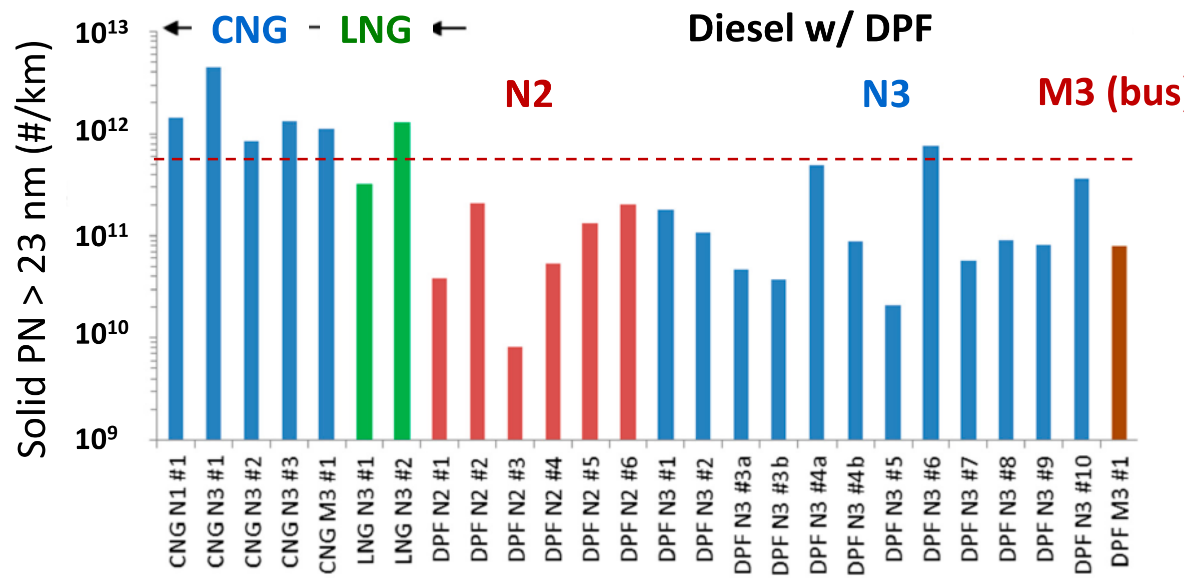
On-road emissions from Euro VI trucks
PN emissions from stoich. NG trucks higher than Diesels w/DPF

JRC, Int. J. Environ. Res. Public Health 2018, 15, 304

Solid PN emissions measured on RDE from 24 diesel, CNG, and LNG trucks and buses

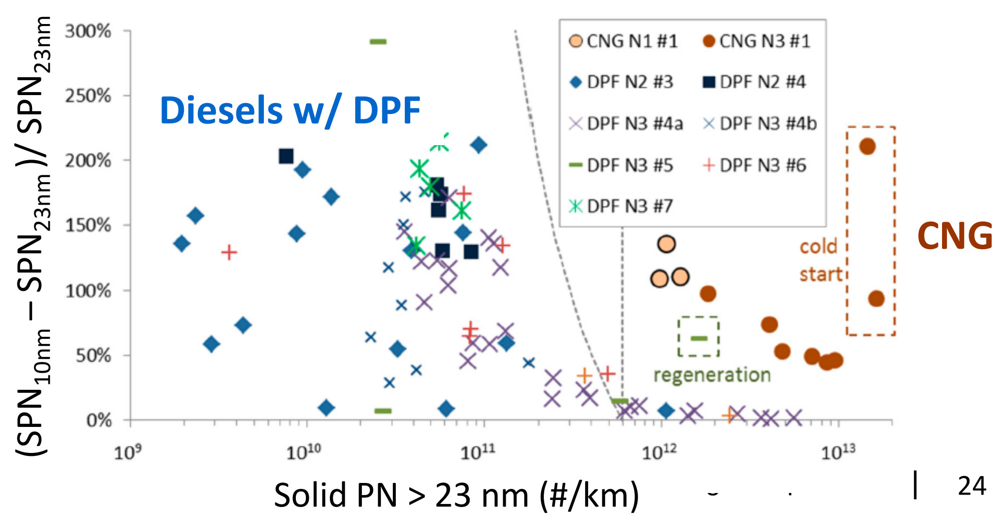
PN measured under real world driving:

- Stoichiometric NG trucks $3.3 \times 10^{11} – 4.5 \times 10^{12}$ #/km
- Diesels with DPF $8 \times 10^{9} – 7 \times 10^{11}$ #/km



Weighted PN : 14% cold start, 86% mean of urban, rural, motorway

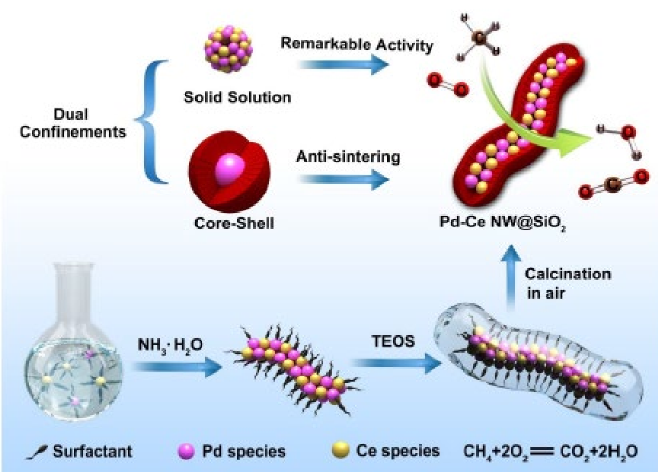
- CNG vehicles found to have > 50% of sub-23 nm particles
- Diesels with DPF also have high sub-23 nm particles, but total emissions are less than limit



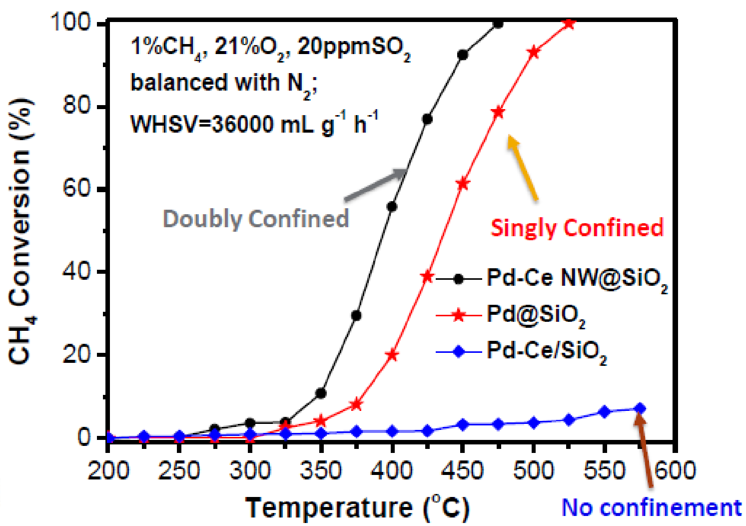
Pd-based catalysts for methane oxidation
Enhanced activity and improved stability, water resistance

ORNL DOE AMR 2019

Doubly Confined Pd-Ce NW@SiO$_2$ for enhanced methane activity and stability

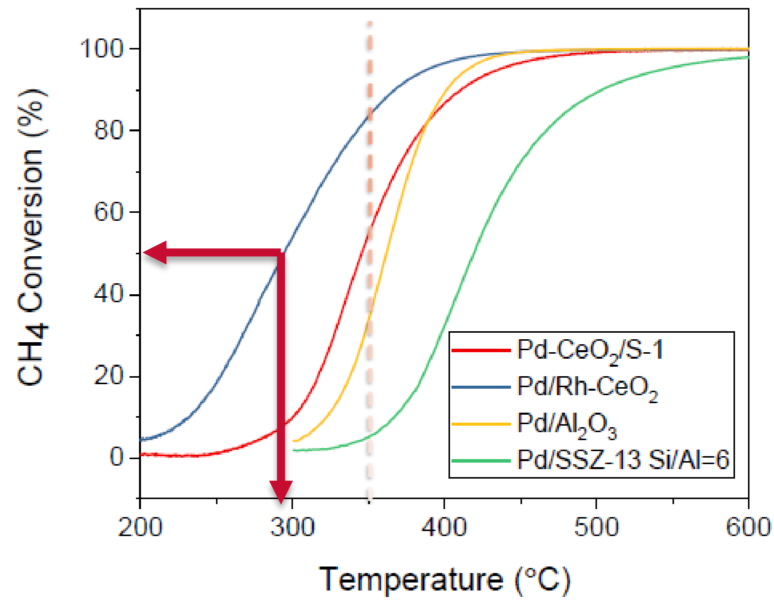


Peng, Zhang, Dai, et. al., *Angew. Chem.*, 2018, *57*, 8953-8957



Single Atom Pd/Rh-CeO2

Light-off < 300 °C, >80% at 350 °C



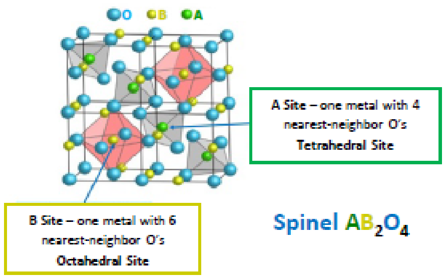
640 ppm CH$_4$, 14% O$_2$, 5% CO$_2$ and 2.5% H$_2$O, balanced with N$_2$.
SV = 300 L/g-h, 60 mg catalyst, ramp rate 3°C/min.

Other learnings (data not shown here)

- High Si/Al ratios → higher hydrophobicity → improved activity & stability
- PdO nanoparticles are more active than isolated Pd ions of PdOx clusters

Methane conversion : PGM activity can be enhanced by adding spinels, coupled with lambda modulation

U. Houston, CDTi, U. Virginia, ORNL DOE AMR 2019



Spinel AB_2O_4

Catalyst

PGM : 95% Pt, 5% Pd, 30 g/ft3

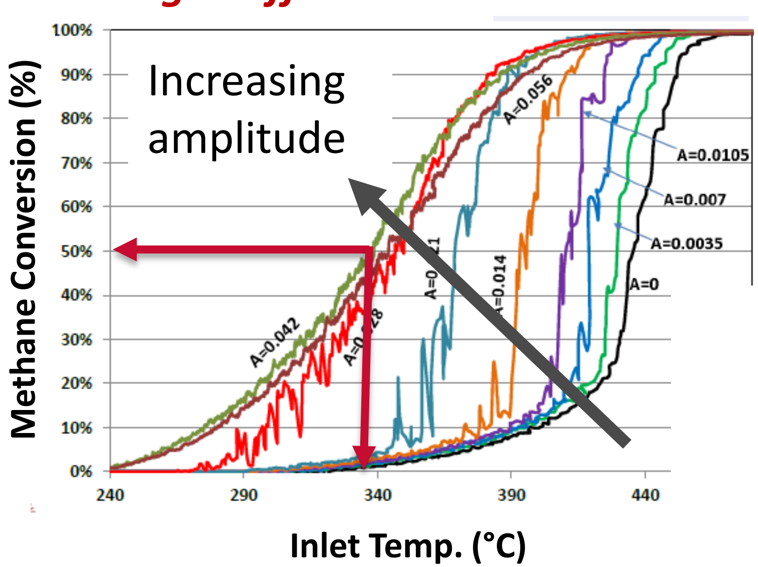
Spinel : $Mn_{0.5}Fe_{2.5}O_4$, 100 g/L

Flow reactor

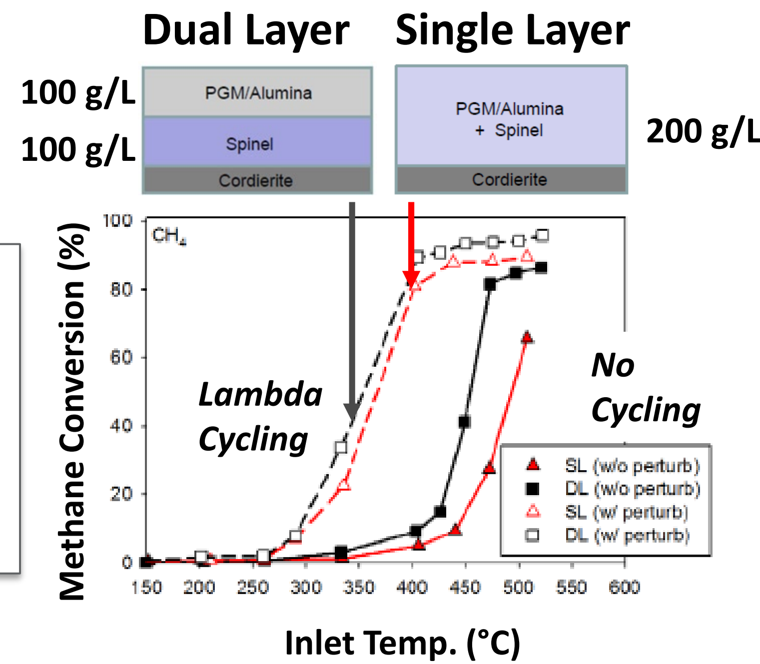
λ = 0.981 – 1.009, <λ> = 0.995

CH_4 = 1500 ppm, O_2 = 4500 ppm – 8900 ppm, CO 8000 ppm, H_2 2000 ppm, NO 1000 ppm, 10% H_2O, 10% CO_2, rest N_2

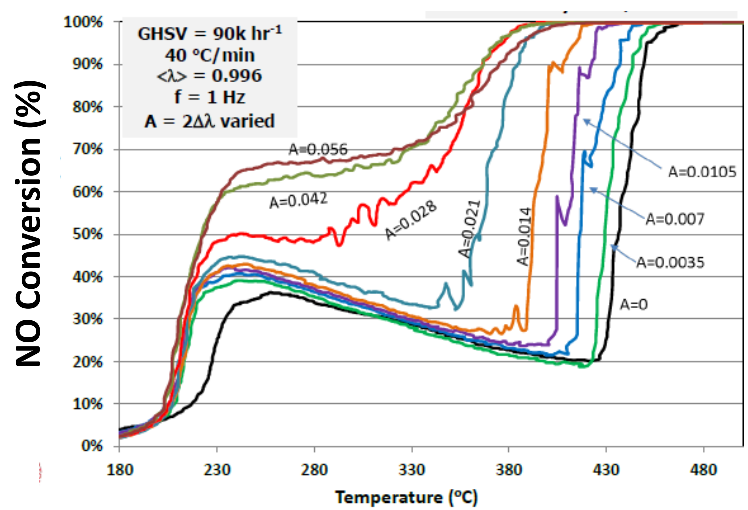
Light-off < 350 °C



Coating architecture does not have a significant impact on performance



NO conversion also improves with modulation



Summary – Heavy Duty

- Regulations are tightening in California; China VI beginning soon (?); Brazil in motion
  - CARB 2024: 50-80 mg/bhp-hr NOx and MAW; 2027: further NOx tightening and increased durability and warranty
  - Continued emphasis on in-use emissions in major markets
- Engine research aimed at 55% BTE under road load – impressive progress in SuperTruck 2 program. Mixed approaches with common themes.
- NOx control developments are targeting low-load and high efficiency, in line with CARB program. Durability is also topic.
  - EU success on WBW ISC;
- Oxidation catalysts advancing with LT CO control, consolidation of DOC and ASC, methane conversion getting to T_{50}~300-350^{o}C.
- Incremental PM control advances and understanding – stoichiometric NG truck PN, DOC+CSF integration

CORNING