For a copy of the slides, connect on LinkedIn or email @ joshia@corning.com

WCX Digital Summit

Review of Vehicle Engine Efficiency and Emissions

Based on SAE 2020-01-0352

Dr. Ameya Joshi

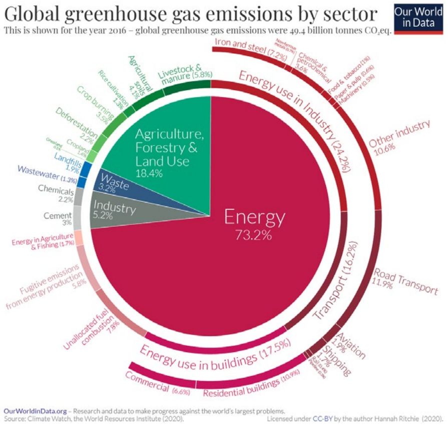
April 15th, 2021

CORNING

joshia@corning.com https://www.linkedin.com/in/joshiav/

What are the problems we are trying to solve ?

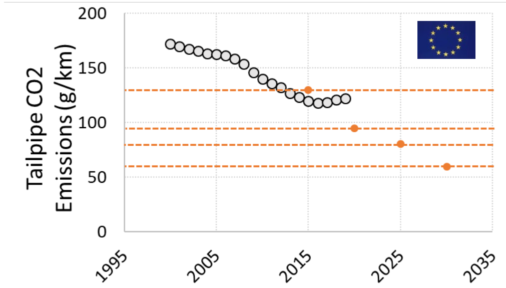
GHG emissions

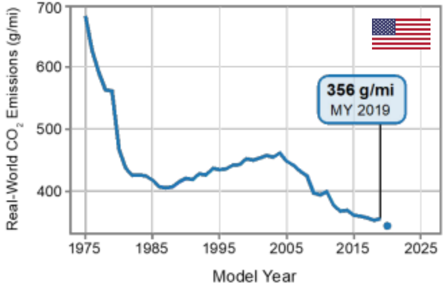


Road transport accounts for ~ 1/5th of GHG emissions associated with energy use

Source: Visual Capitalist

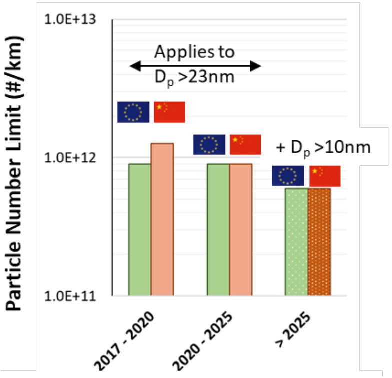
Reductions in tailpipe CO_2 have stalled in the recent years

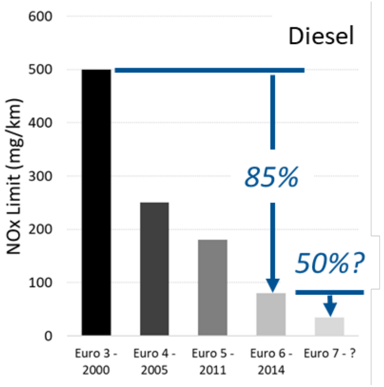




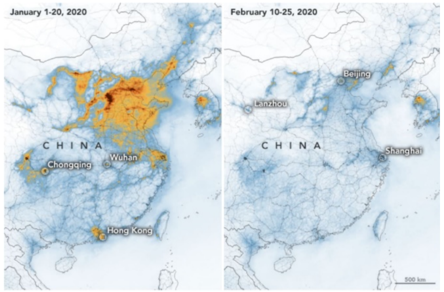
Criteria Pollutants

Regulations focused on NOx and particulate reduction

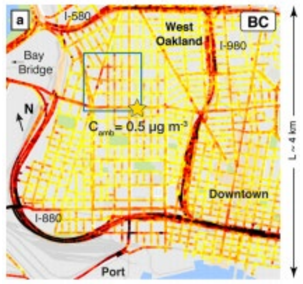




High emissions in real-world, urban driving conditions



NO_2 concentrations before / after Covid lockdowns



NO_2 concentrations in an urban center

What are the options to solve these problems ?

R & D → TECH MATURITY & CONSUMER ACCEPTANCE → EXISTING INFRASTRUCTURE

Correct

CO_2 capture

Synthetic or e-fuels

Covered in this talk

Avoid

Telecommuting

Geo-fencing

Covered in this talk

Electrification

Green H_2, NH_3, etc.

Recycling

Shift

Public transportation

Rail & marine for goods

Ride-sharing

Renewable fuels

Cycling

Improve

Covered in this talk

Improved ICE efficiency

Hybridization

Improved aftertreatment systems

Light-weighting, aerodynamics etc.

Waste heat recovery

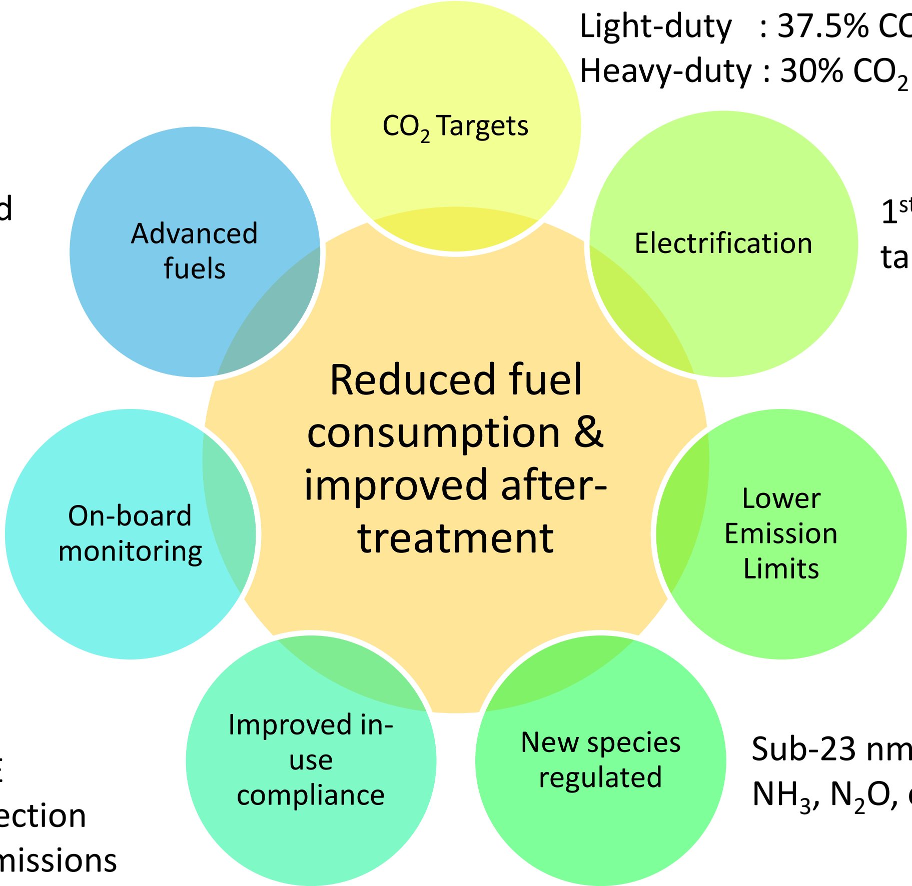
Automation, connectivity, predictive control

Our industry is adapting to various new – and often conflicting – regulatory drivers

Light-duty : 37.5% CO_2 reduction by 2030
Heavy-duty : 30% CO_2 reduction by 2030

Renewable and synthetic fuels

1^{st} heavy-duty electrification targets by CARB



CARB : HD I&M program with telematics (already started for HD in China)

LD : Euro 7, China 7
HD : 90% reduction in NOx

Low T testing, improved RDE
New Periodic Technical Inspection
HD : Cold start & low load emissions

Sub-23 nm PN
NH_3, N_2O, etc.

Outline

For a copy of the slides, email @ joshia@corning.com

Light-duty

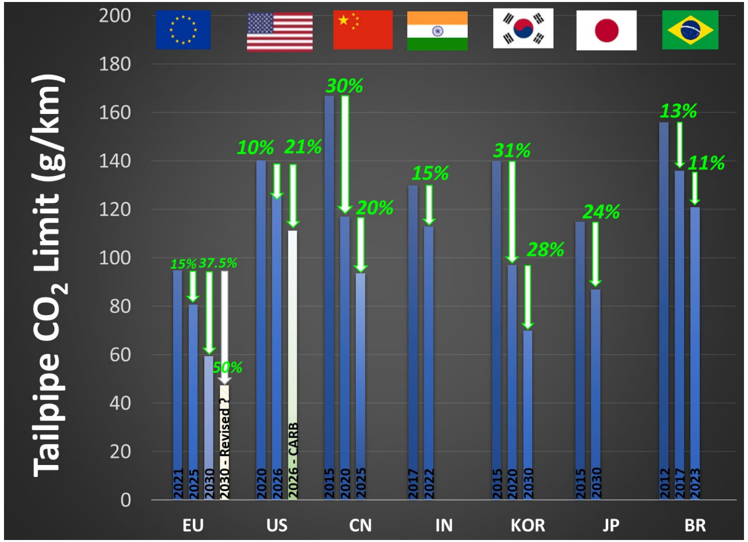
- GHG/Fuel Economy
- Criteria pollutant regulations & emission control technologies

Heavy-duty

- GHG/Fuel Economy
- Low NOx regulations & technology pathways

CO_2 / Fuel Economy Regulations …

… And ICE ban announcements



Changes since the last review (2020)

- EU : Further reduced limits likely following Climate Law
- China : 2025 standards published (FC = 4L/100km)
- US: Revision of MY 2026 nationwide standards likely
- Korea : Standards set to 2030

California Bans the Sale of New Gas and Diesel Cars by 2035

"Cars shouldn't give our kids asthma. Make wildfires worse. Melt glaciers. Or raise sea levels," Governor Newsom said.

The Drive, Sept 23, 2020

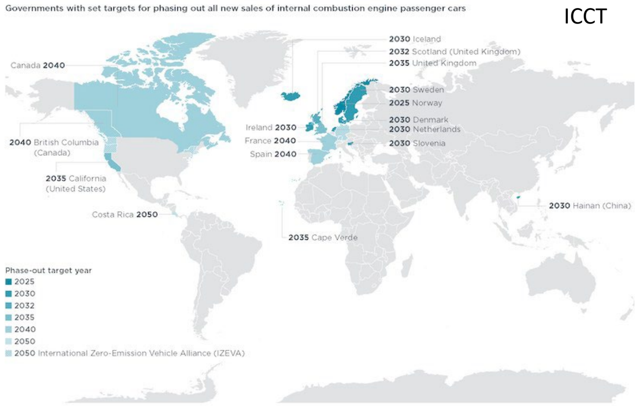
Just-auto.com, Nov 18, 2020

UK government confirms 2030 ICE ban

Autoweek.com Dec. 7, 2020

Japan Plans to Ban Gasoline Car Sales by 2035, but Hybrids Will Remain

ICCT

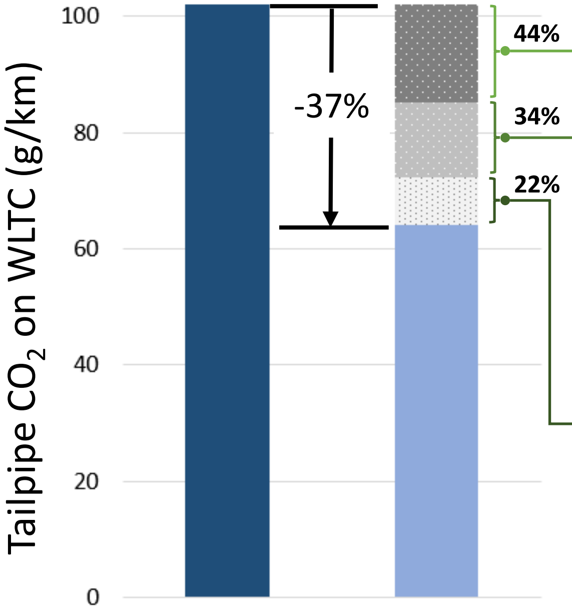


Road to 59 g/km fleet CO_2 by 2030

– FEV, Aachen Univ. 29th Aachen Colloquium, 2020

C-segment, 1400 kg

2020 102 g/km | 2030 64 g/km



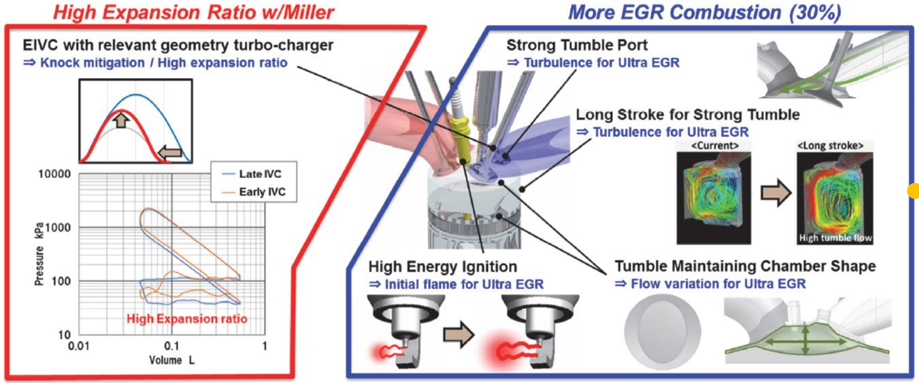
	2020	2025	2030	Enabling Technologies
Vehicle drag & tires				
Drag	Ref.	- 5%	- 15%	Shape optimization, lowering of vehicle at higher sp., mirrors → cameras, etc.
Rolling R.	Ref.	- 20%	- 27%	Improved materials, narrow tread
Hybridization				
	48V Mild	400V Full		Oil cooling of e-machine components, SiC inverters
“Dedicated hybrid engine”				
Displ.	< 1.5L	< 1.2L		Miller cycle, cEGR, adv. Turbocharger, long stroke, electric intake cam phaser, low friction, VCR, pre-chamber, water injection, lean combustion, …
S/B	< 1.2	> 1.3		
Peak BTE	>42%	>43%	>43.5%	

Pathway to 50% brake thermal efficiency outlined : High EGR, Lean combustion, Waste heat recovery and fixed speed/load operation for charging battery

Nissan, 29th Aachen Colloquium, 2020

1.5L 3-cylinder

STARC combustion concept – **S**trong **T**umble and **A**ppropriately stretched **R**obust Ignition **C**hannel



Knock mitigation using EIVC Miller

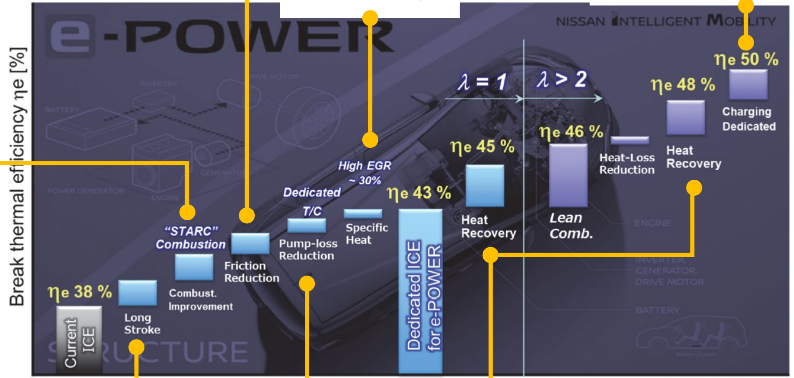
Stable combustion with high dilution - Strong tumble, High energy ignition

Stoichiometric η = 43%	Lean (λ > 2) η = 50%

Friction reduction by 46%

EGR ~ 30%

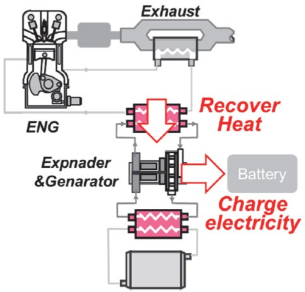
Larger battery – fixed. speed charging



Stroke / Bore = 1.26

Dedicated FGT

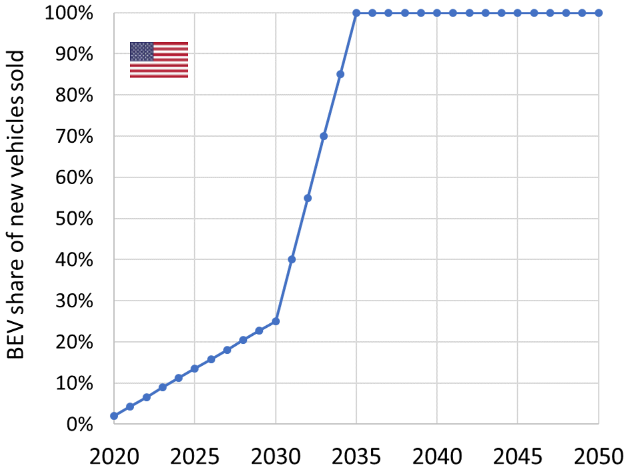
Waste heat recovery : Rankine cycle ~ 4.5% fuel economy ↑ on WLTC Extra High mode



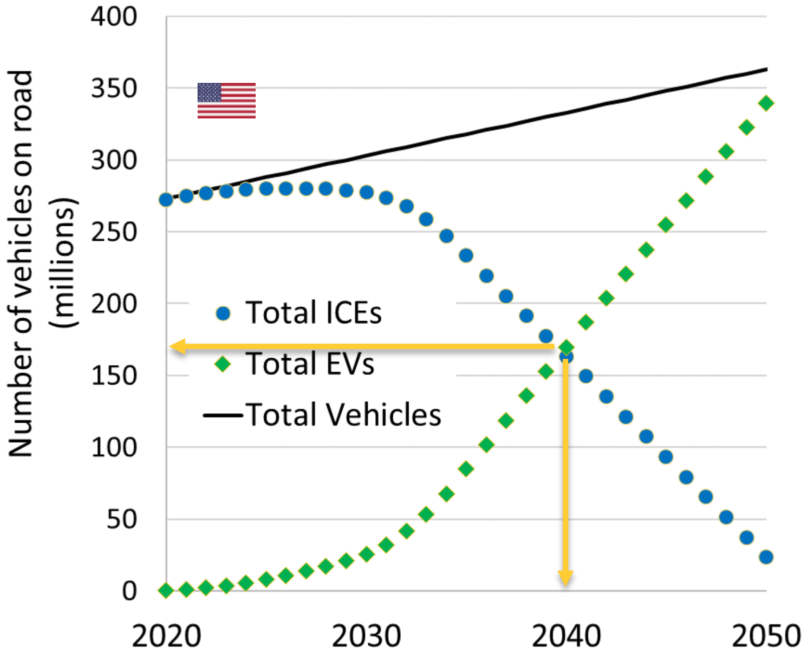
Green Car Reports, March 2nd, 2021

Hundreds of millions of ICE vehicles will be on the road for decades
… *even with rapid electrification*

Scenario (US only)
100% BEVs sold after 2035



Total BEVs exceed ICEs only after 2040



It is imperative that we continue to improve upon the ICE technology

Outline

For a copy of the slides, email @ joshia@corning.com

Light-duty

- GHG/Fuel Economy
- **Criteria pollutant regulations & emission control technologies**

Heavy-duty

- GHG/Fuel Economy
- Low NOx regulations & technology pathways

Light-Duty Criteria Pollutant Regulations

Confirmed
Speculation

Region	Category	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
USA	EPA	Tier 3 (phase in)							Tier 4 + PM 1 mg/mi?			
USA	CARB	LEV III Phase in					LEV IV NMOG + NOx: NZEV SULEV 30 --> SULEV 20 ? US06 3 mg/mi					
							FTP 1mg/mi phase-in			All FTP 1 mg/mi		
EU		EU6d : PN 6e11 #/km GDI RDE CF NOx 1.43, PN 1.5		CF NOx 1.0, PN 1.5			Euro 7 : Technology neutral, NOx < 35 mg/km, PN limit reduction, RDE modification CF = 1.0, PN down to 10nm, NH3/HCHO/N2O/others					
JP		New PNLT (WLTC - Phase 1-3)		Diesel RDE (CF=2.0) Gasoline RDE		Diesel PN 6e11 #/km ?	GDI PN 6e11 #/km (WLTC)?					
Korea	Diesel	EU6d Final					Euro 7 ?					
Korea	Gasoline	K-LEV III (phase in)							LEV IV + 1 mg/mi?			
China	Nation	CN 5 (~EU5)	CN6a PN 6e11 #/km RDE Monitor		CN6b RDE CF TBD CF tightening				CN 7 (possibly earlier in key areas) ? CF = 1.0 ? PN down to 10 nm			
China	Beijing	CN6b w/o RDE										
India		BS VI (~EU6b) RDE Monitor		RDE CF=?							BS VII ?	
Brazil		PROCONVE L6		PROCONVE L7 (~ Tier 3 Bin 125)			PROCONVE L8 NMHC+NOx = 50		40		30 + PM 3mg/km	
Chile		US Tier 2 Bin 5 AND Euro 5		Euro 6b (Tier 3 bin 125)		Euro 6c (Tier 3 bin 70)					Euro 6d ?	
Russia		EU5			EU6							
Thailand		EU4				EU5		EU6				
Australia		EU5						EU6				
African nations (SADC, ECoWAS)		~ EU2		EU4							EU5 ?	

California : Possibilities for LEV IV
"Advanced Clean Cars II" workshop - Sept 16th, 2020

1. Further reduction of NMOG + NOx limits
   - Separate fleet average limit for non-ZEVs
   - Possible reduction to 20 mg/mi (SULEV 20)

2. Elimination of SFTP and certification to separate FTP, US06, SCO3 standards

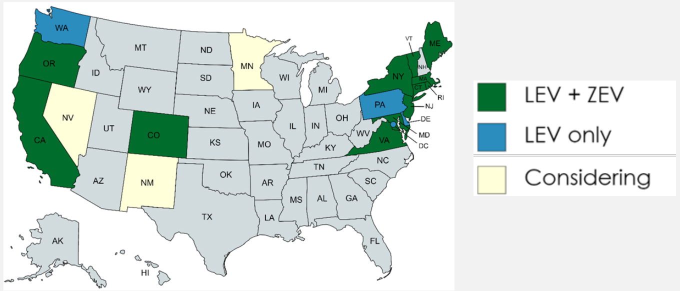
3. Testing over various cold soak durations

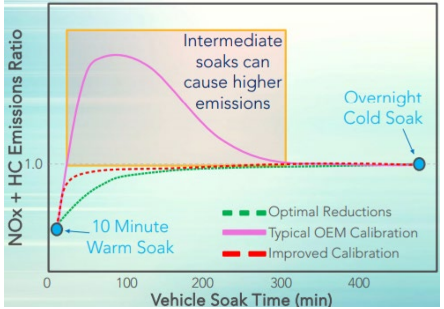
4. Shorten FTP idle time to 5 sec and limit on idling emissions

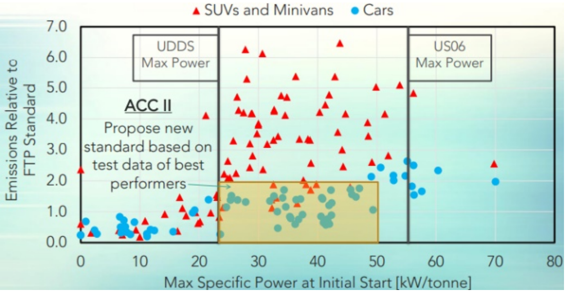
5. Standard for high powered cold start emissions from plug-ins

6. PM limit reduction to 3 mg/mi on US06 cycle (aggressive driving)

California section 177 states
(~ 30 – 40% of the US market)







Source: AGVES meeting, April 2021

Euro 7 proposals

Expect broad changes : Reduced PN & NOx limits, modified RDE, no CF, …

Euro 7: Technology & fuel neutral (Diesel = GDI = PFI = CNG …)

Reduced limits (CO, NMOG, NOx, PM, PN) — New species regulated (NH_3, CH_4, N_2O, HCHO)

PN : #/km Rest: mg/km	CO	NMOG	NOx	PM	PN	NH_3	CH_4	N_2O	HCHO
Euro 6	1000	68	60 CF = 1.5	4.5	$6x10^{11}$ >23nm	-	-	-	-
Euro 7 scenario	400	45/25	30/20 CF = 1.0	2	$1x10^{11}$ >10nm	10	10	10	5

RDE limit for CO

Conformity Factor → 1.0

Modified boundary conditions

Euro 6 extended: -7 to +35 °C

Normal conditions : - 7 to +35°C
Extended conditions: - 10 to +45°C
(Limits may be higher for extended)

Modified test conditions

No urban/rural/motorway → testing under any "normal" driving routes

Regen emissions included through on-board monitoring of regen intervals

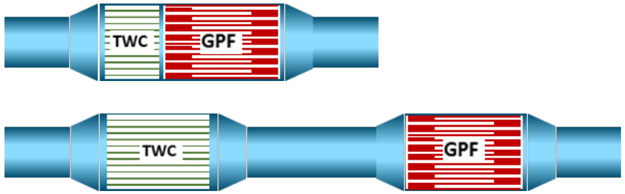
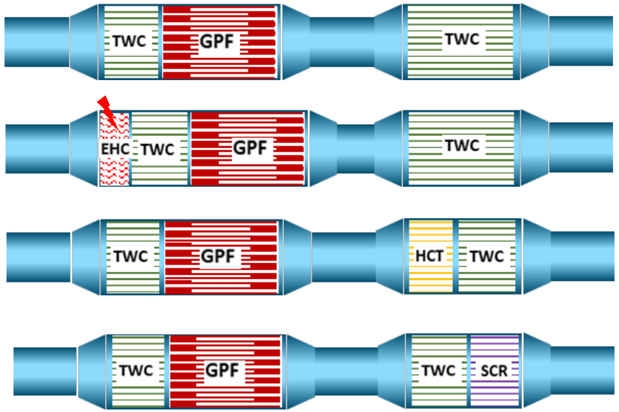
Cold start emissions

Cumulative budget for first 16 km

Fixed limit at > 16 km

Gasoline after-treatment architectures

TWC = three-way catalyst, GPF = gasoline particulate filter, EHC = electrically heated catalyst, HCT = hydrocarbon trap, SCR = selective catalytic reduction

Euro 5 Tier 3 / LEV III	
Euro 6d CN 6b BS 6 w/ RDE LEV III + 1 mg/mi	
Euro 7 CN 7 LEV IV (?)	

+ GPF for PN control

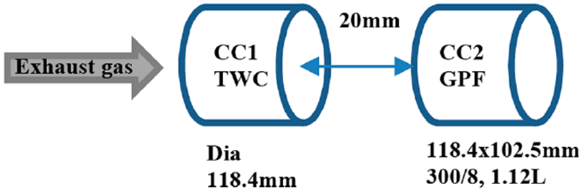
Advanced cold start strategies

Passive SCR for NOx / NH_3 reduction

Meeting China 6b / Euro 7 limits

Larger TWC, high PGM and high washcoat loading for GPF

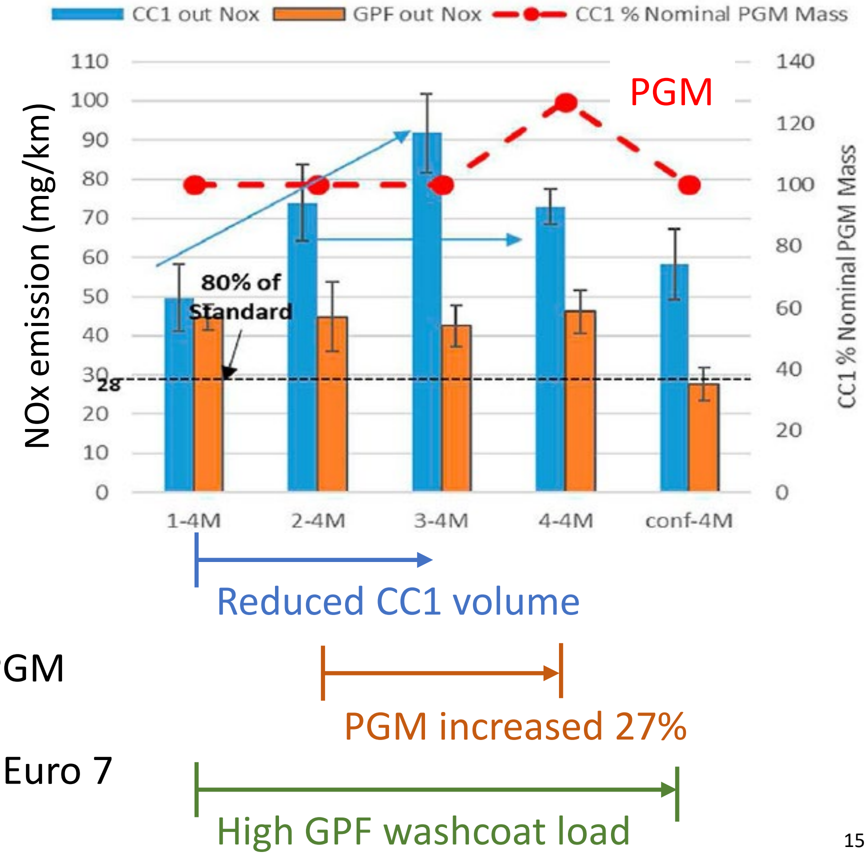
Umicore, SAE 2020-01-0654 doi:10.4271/2020-01-0654



Example: China 6b,1.6L GDI

System No.	TWC @CC1 Vol (liter))	CC1 PGM Mass (Relative %)	Pd/Rh (g/ft3)	GPF @CC2 Washcoat (Relative)
1-4M	1	100	36	Medium-A
2-4M	0.76	100	36	Medium-B
3-4M	0.6	100	36	High
4-4M	0.76	127	36	Medium-C
Conf-4M	1	100	36	High

- Larger TWC volume is more important than higher PGM
- High washcoat GPF essential for meeting China 6b / Euro 7 limits



Lower thermal mass substrates : up to 20% ↓ in NMHC & NOx

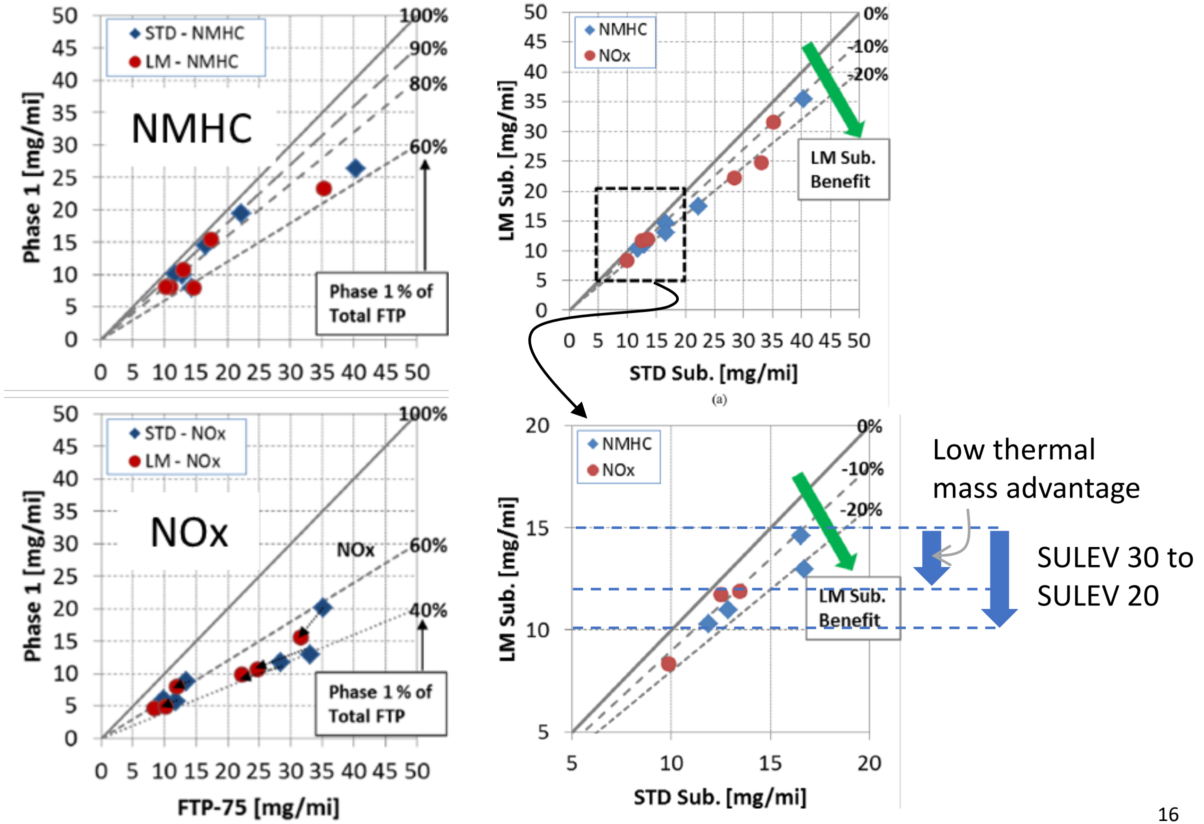
Test-to-test variability needs to be controlled as we approach near-zero emissions

Corning SAE 2020-01-0652 doi:10.4271/2020-01-0652

Vehicle Platform	Engine	Emissions Cert.	Cold-start Strategy
Vehicle A	1.6L Turbo	LEV II - PZEV	Lean-start idle
Vehicle B	2.4L	LEV II - SULEV	Lean-start idle
Vehicle C	2.0L Turbo	LEV II - ULEV	Rich-start idle
Vehicle D	1.5L Turbo	T3B30	Rich-start idle
Vehicle E	2.0L	T3B70	Lean-start idle

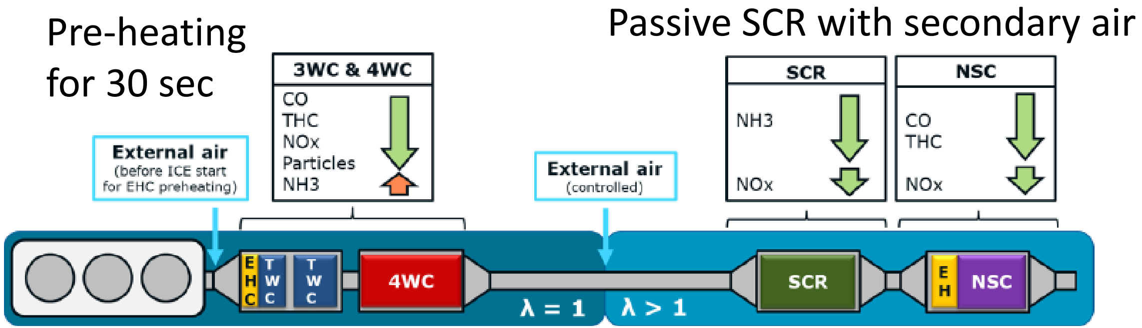
Bag 1 cold-start emissions account for 60 – 90% of total emissions

Low thermal mass
=
Early catalyst light-off
=
Lower cold start emissions



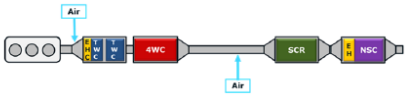
“Zero-impact” emitting vehicles
Combination of hybridization, pre-heating, SCR and slip catalysts

AVL, TU Darmstadt 32nd Intl. AVL Conference Engine & Environment, 2020

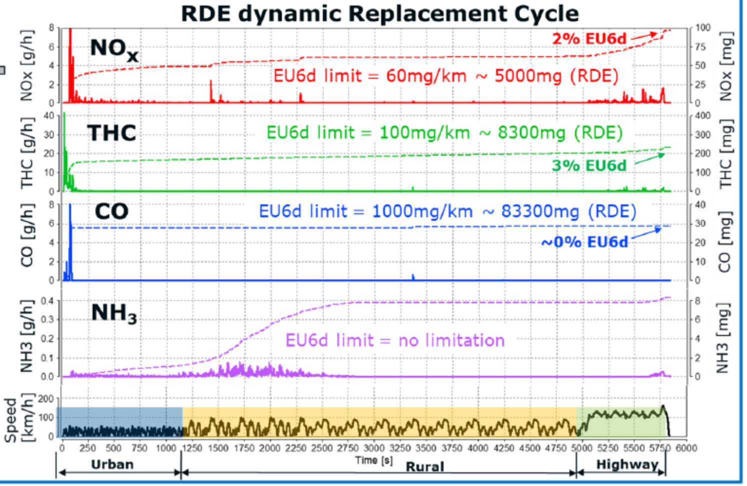


Engine : 1L TGDI,
48V P2 mild hybrid
(15 kW, 1.8 kWh)

Pure ICE Mode, 30sec. main e-cat Pre heating, heating stops with the start of the ICE (30/0)



		NO_x	THC	CO	NH_3
Urban	mg/km	6,27	21,68	3,56	0,17
	CF_{EU6d}	0,1	0,21	0,004	-
Rural	mg/km	0,27	0,7	0,015	0,13
	CF_{EU6d}	0,004	0,007	0	-
High-way	mg/km	1,31	1,2	0	0,022
	CF_{EU6d}	0,021	0,011	0	-
Total	mg/km	1,17	2,8	0,34	0,1
	CF_{EU6d}	0,02	0,028	~0	-



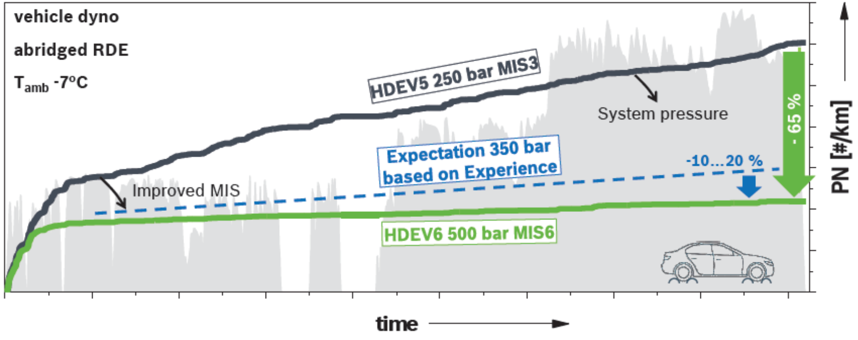
Results
NOx : 1.2 mg/km
THC : 2.8 mg/km

Euro 7 regs will require very high filtration efficiency

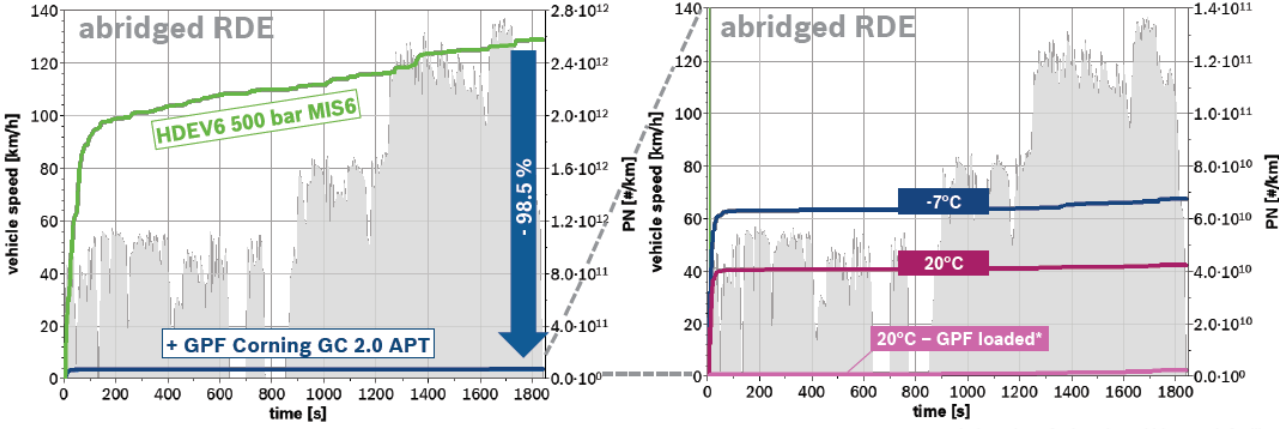
Bosch, 32nd Intl. AVL Conf. Engine and Environment, 2020

High P injection will help reduce engine out PN

PN reduced by 65% when moving from 250 bar → 500 bar



In addition to engine improvements, a high filtration GPF will be needed to meet future standards



* shot trip to fuel station within Bosch facility

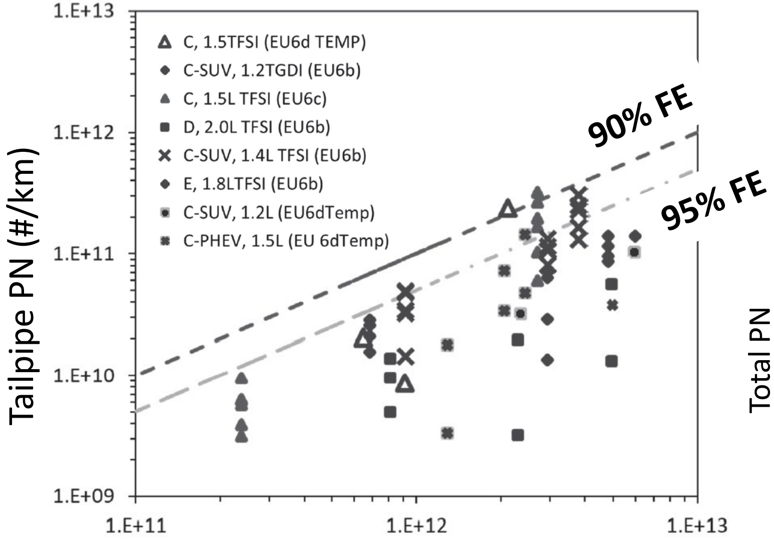
Next generation GPFs are delivering very high (> 95%) filtration efficiency

Corning 29th Aachen Colloquium Sustainable Mobility, 2020

Accelerated Purification Technology

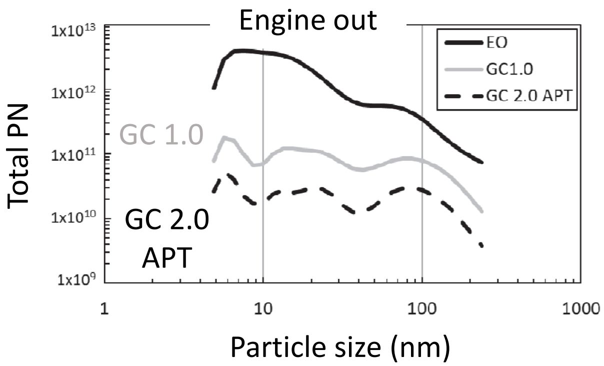
Surface modification in inlet channels delivers very high FE with little pressure drop penalty

All GPFs 200/8, uncoated

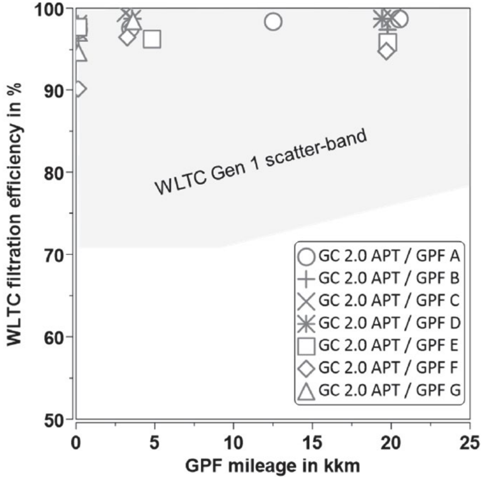


Very high filtration of sub-23 nm particles

Euro 6d-Temp vehicle, WLTC



High filtration at "0" km

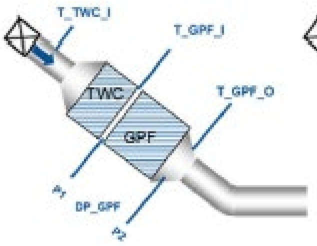


Various parameters affect GPF performance : GPF location, pore structure, coating technology, washcoat loading, …

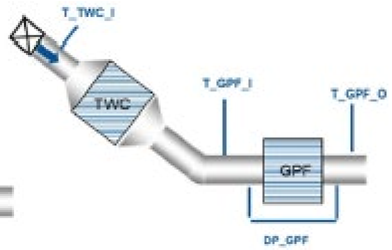
Corning, Kunming Sino-Pt., SAIC-GM-Wuling SAE 2020-01-0387

Vehicles & After-treatment

T-MPI 1.5L, China 6b
cc-GPF

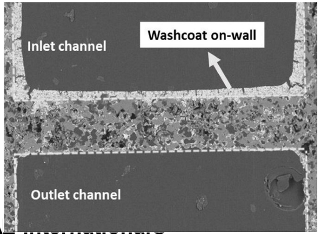


T-GDI 1.8L, China 5
uF GPF

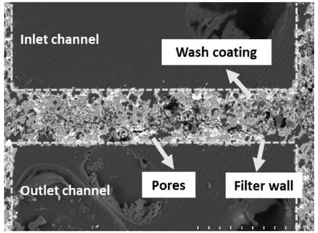


Coating technologies

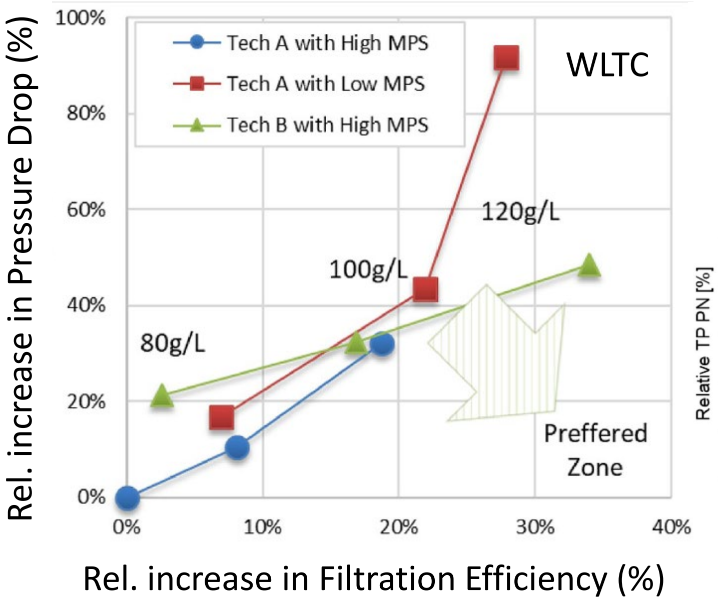
A: Mostly in-wall



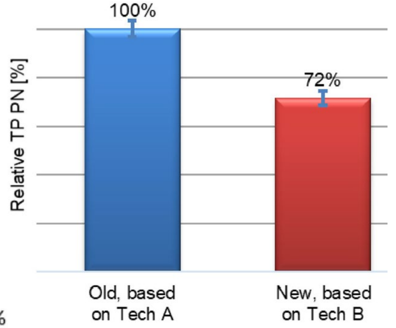
B: Mostly on-wall



- Filtration improves with increased washcoat loading
- Filtration improves with lower mean pore size
- Proper selection of filter pore structure and coating technology is critical to manage FE – ΔP trade-off



Filtration of cc-GPF improved by moving to new coating technology

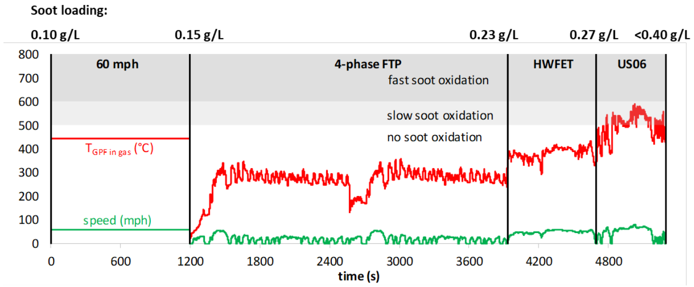


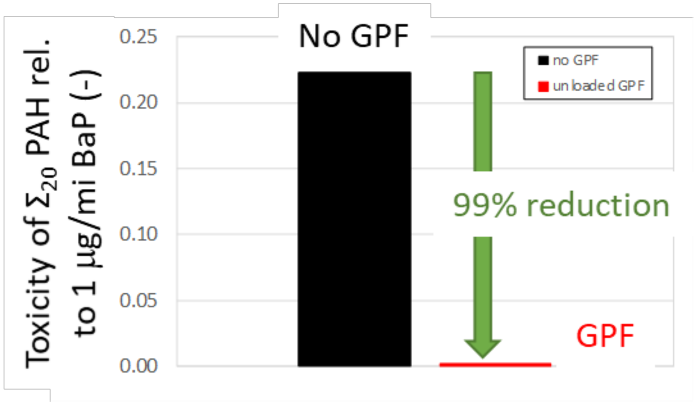
Catalyzed GPFs (cGPF) are very effective at reducing cancer toxicity of PAHs associated with engine soot

U.S. EPA, CSS, 30th CRC Real World Emissions Workshop, 2021

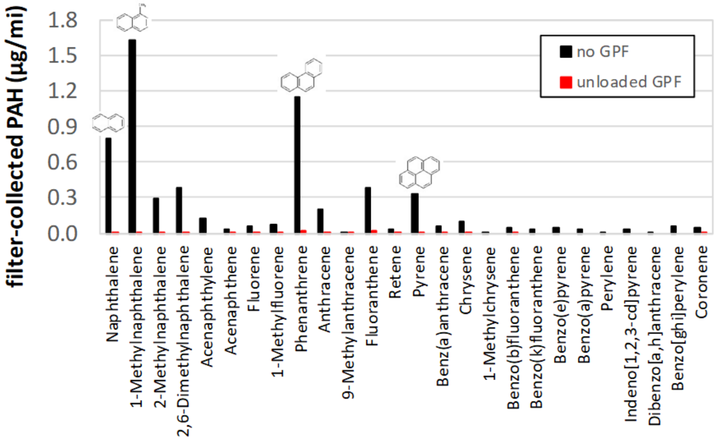
<u>Vehicle</u>: 2011 Ford F150, 3.5L Ecoboost, wall-guided GDI

cGPF in place of resonator: Ø5.66" x 4", 300/12, Pd/Rh coated

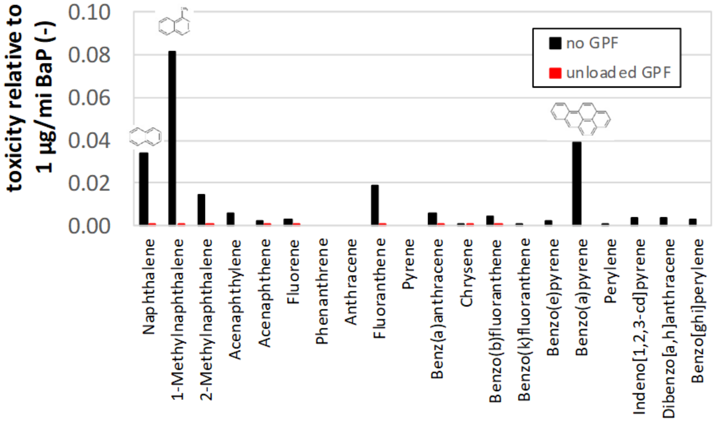




cGPF greatly reduce the amount of PAHs emitted

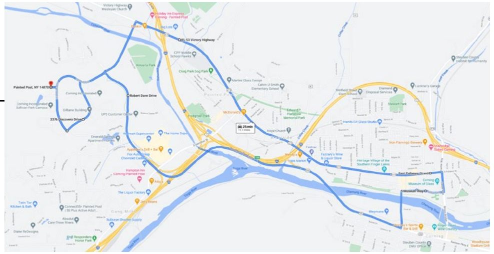


And the related cancer toxicity of these PAHs



SAE Int
WCX Di

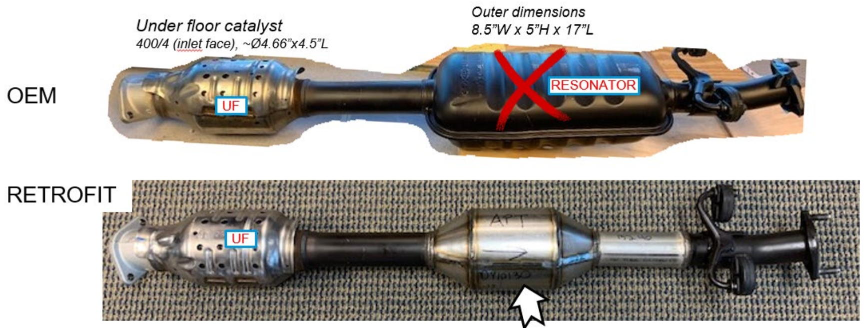
Test route (at Corning, NY) ~ 11 miles



The coolest car in the US

My MY2015 Sonata – with a GPF !

3 tests done, one with a hot start and two with cold starts

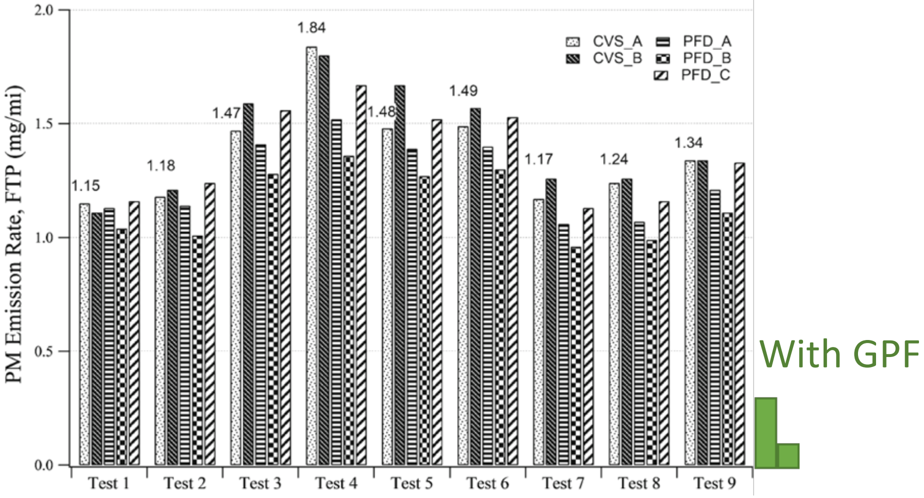


Uncoated GC 2.0 APT 200/8, 5.2" x 4.7"

With GPF, tailpipe PM at 0.1 – 0.3 mg/mi

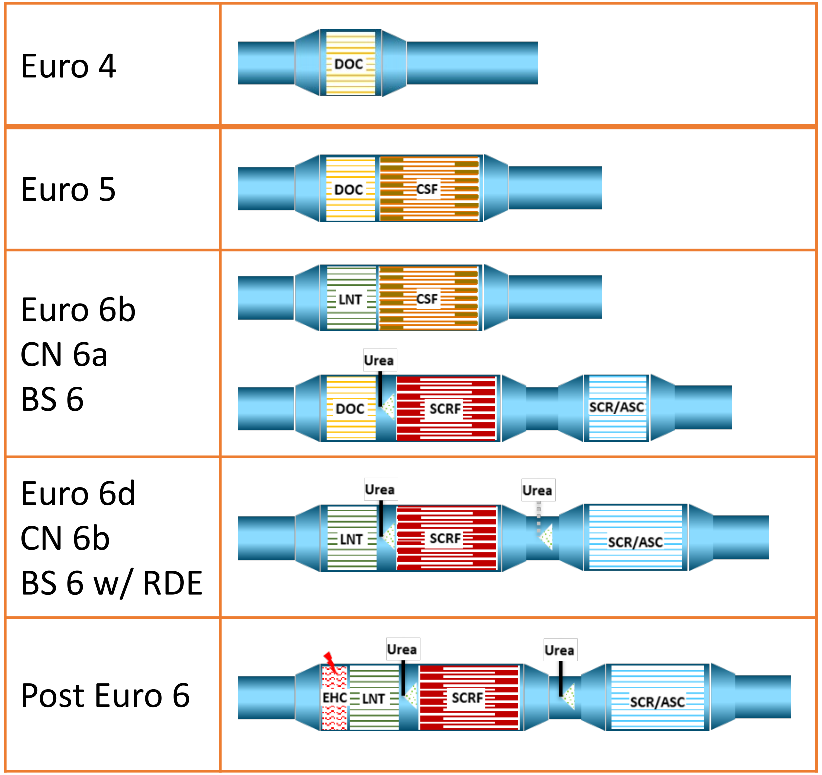
78 – 93% reduction in PM

Emissions measured after 3000 mi driving (ash accumulation helps)



PM emissions on FTP from MY 2016 Sonata
UC Riverside, U. Minnesota Emiss. Control Sci. Technol. (2018) 4:247–259

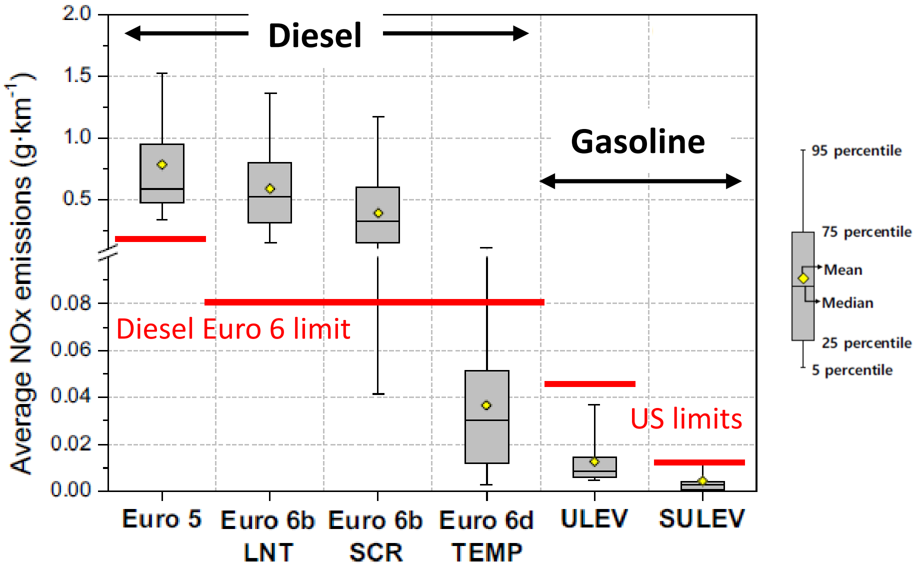
Diesel After-treatment systems
Real-world driving regulations are resulting in NOx emissions well below limit



Natl. Institute of Env. Res. (NIER), Korea Science of the Total Env. 767, 2021, 144250 https://doi.org/10.1016/j.scitotenv.2020.144250

Average on-road NOx emissions

74 diesels and 35 gasoline, model years 2012 - 2019

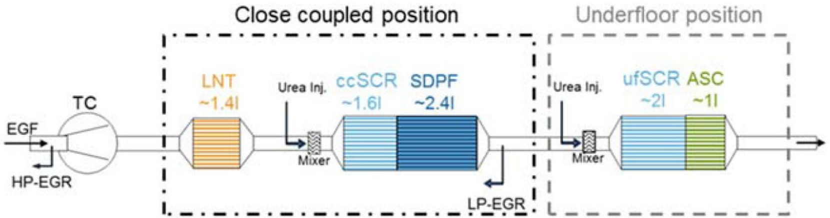


DOC = Diesel oxidation catalyst, CSF = Catalyzed soot filter, SCR = Selective catalytic reduction (of NOx)
SCRF = SCR on filter, ASC = Ammonia slip catalyst, LNT = Lean NOx trap

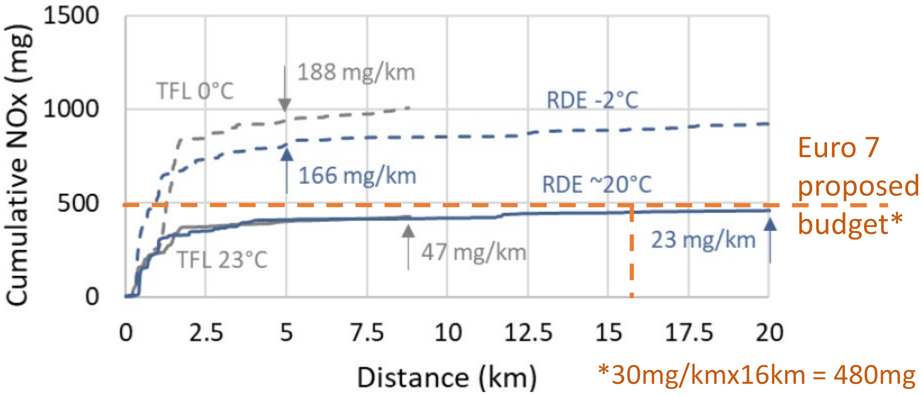
Diesels: Very low NOx emissions demonstrated. Meeting the limits at T < 0 °C will require further improvements. Low C fuels can help reduce WtW CO_2.

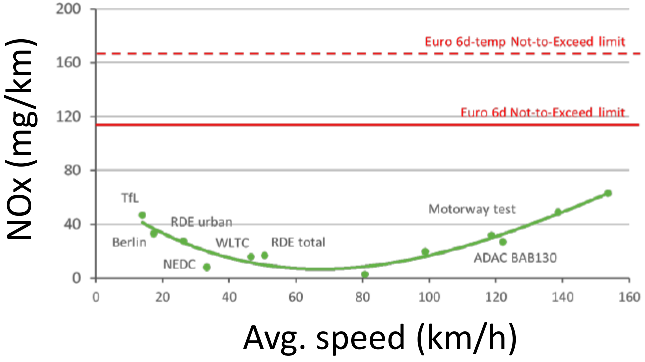
AECC, 11th VERT forum, 2021

48V P0 mild hybrid, 10kW motor, 140 Wh Li-ion battery

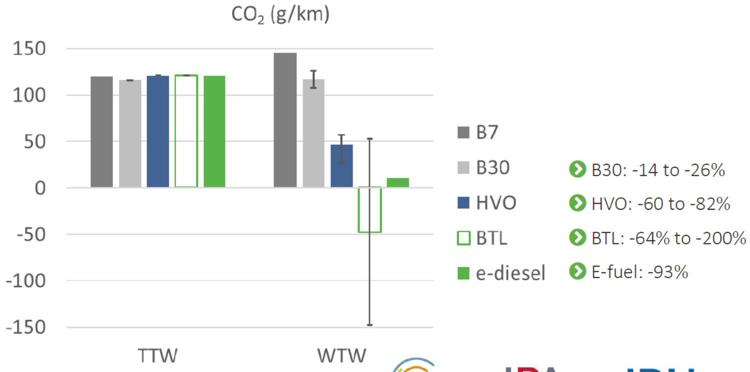


Opportunity to further improve cold start emissions at low T





< 10 ppm NH3 slip, Urea 1.5L/1000km



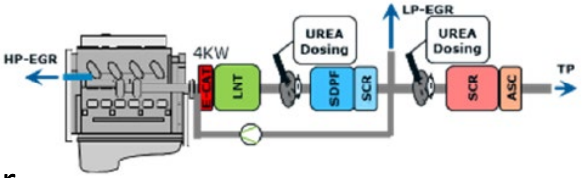
11th VERT Forum – 25 March 2021

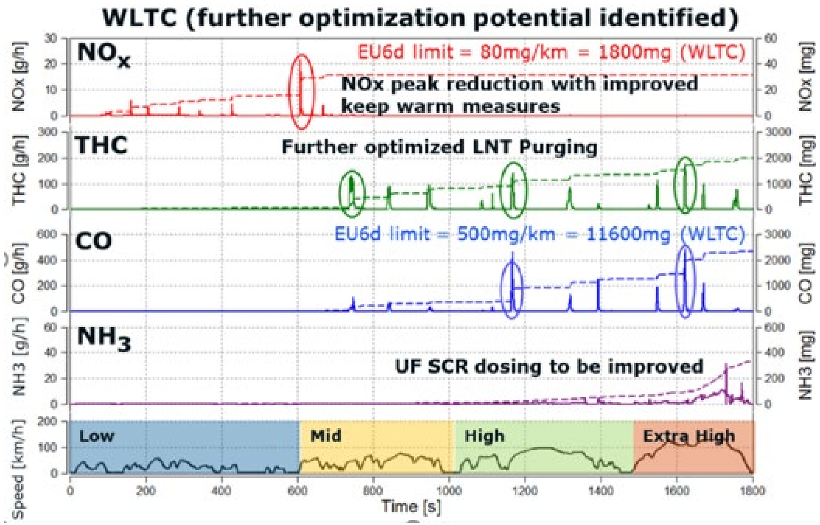
"Zero impact" vehicle demonstrations are underway
EHC with pre-heating seen as one pathway

AVL, 32nd Intl. AVL Conf. Engine & Environment, 2020

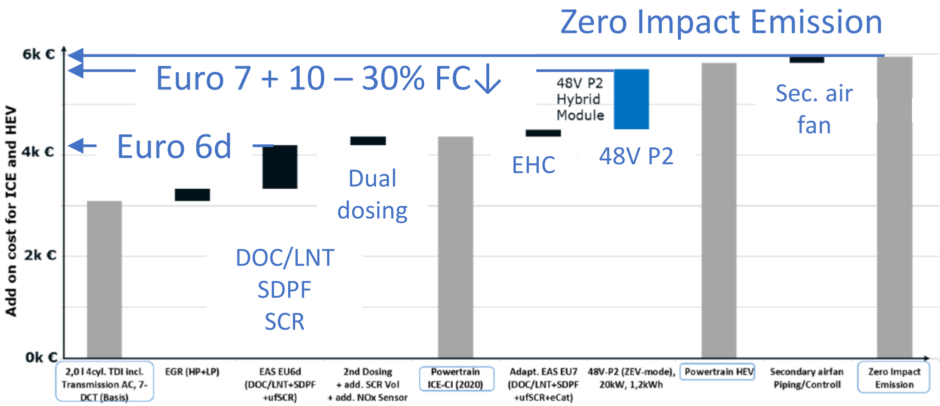
Vehicle: 2.2L diesel, Mild hybrid: 48V P2, 30 kW peak P

Emissions control
HP + LP EGR,
Dual dosing SCR
EHC, LNT, SCR on filter
Pre-heating by 30 sec + sec. air fan





Euro 6d to Euro 7 : Incremental cost of ~ €1,500



NOx 1.3 mg/km
THC 96 mg/km

		NOx	NOx+ THC	CO	NH3
Low	mg/km	4,2	22	5,0	0,5
	CF_{EU6d}	0,053	0,13	0,01	-
Mid	mg/km	3,5	170	71,3	1,0
	CF_{EU6d}	0,044	1,00	0,14	-
High	mg/km	0,07	91	150,4	6,8
	CF_{EU6d}	0,001	0,54	0,30	-
extra High	mg/km	0	84	128,7	31,6
	CF_{EU6d}	0,000	0,49	0,26	-
Total	mg/km	1,3	96	107	13,5
	CF_{EU6d}	0,017	0,56	0,21	-

Outline

For a copy of the slides, email @ joshia@corning.com

Light-duty

- GHG/Fuel Economy
- Criteria pollutant regulations & emission control technologies

Heavy-duty

- **GHG/Fuel Economy**
- Low NOx regulations & technology pathways

On-road criteria pollutant regulations

On-Road		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
USA	Nationwide	US 2010 + ARB Optional low NOx				CA Low NOx Ph 1			CA Low NOx Ph 2			
	CA								US Cleaner Trucks Initiative			
	GHG / FC	GHG Phase 1	GHG Phase 2									
EU		Euro VI-D	Euro VI-E							Euro VII ?		
	GHG / FC					CO2 15% Lower vs. 2019					CO2 30% Lower vs. 2019	
JP		JP '16 (JE05 → WHTC)										
China	Nationwide	CN VIa City	All		CN VIb (July 2023)				CN VII ?			
	Key Areas	BJ VIb										
	GHG / FC	Stage 3							Stage 4 ?			
India		BS VI Ph. 1			BS VI Ph. 2						BS VII ?	
Brazil		P-7 (~ Euro V)			P-8 (~ Euro VI-C)							
Mexico		US 2007 / Euro V		US 2010 / Euro VI								

Heavy-duty trucks will incur significant penalties for CO_2 exceedance

HD CO_2 Targets in Europe

15% & 30% reduction by 2025 & 2030, respectively compared to 2019 baseline

ACEA, March 2020

	Q3-Q4 share	Configuration	GCW [T]	Engine [kW]	Cabin	Avg. CO_2
4-UD	0.4%	R 4x2	>16	<170	All	
4-RD	7.9%	R 4x2	>16	≥170 day cab ≥170 <265 sleeper cab	Day & sleeper	
4-LH	1.9%	R 4x2	>16	≥265	Sleeper	103
5-RD	0.8%	T 4x2	>16	All-day cab <265 sleeper cab	Day & sleeper	
5-LH	62.8%	T 4x2	>16	≥265 sleeper cab	Sleeper	56
9-RD	7.2%	R 6x2			Day	
9-LH	9.2%	R 6x2			Sleeper	65
10-RD	0.1%	T 6x2			Day	
10-LH	9.7%	T 6x2			Sleeper	59

Penalties

4,250 €/gCO_2/tkm in 2025, 6,800 €/gCO_2/tkm in 2030

Categories 5, 9, 10: Avg. CO_2 emissions ~ 60 g/tkm

→ €38,000 in 2025 if no improvement

Pathway outlined to meet 2030 targets

FEV 41st Intl. Vienna Motorsymposium, 2020

Topic	Improvements	CO_2 reduction	Total CO_2 reduction
Vehicle aero/tires	Incr. vehicle length (80 cm)	4%	6%
	Low resistance tires	2.5%	
Engine 45 → 50% BTE	CR increase by 3 units (VCR, piston redesign)	1.5%	5%
	LP EGR	1.5%	
	Friction & parasitic losses	2%	
Predictive powertrain control	Route & driving opt., gear shifts, re-fueling, energy & power mgmt., after-treatment etc.	5%	5%
48V mild hybrid (25kW)	Regenerative braking, transients	1%	3%
	e-WHR	2%	
Sub-total			**18%**
Full hybrid (100 kW) + H_2 ICE		12%	30%

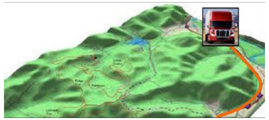
Cost Effectiveness : € / %-CO_2 — 400, 600, 750

2019 level; 2025 target: 15%; 2030 target: 30%

Super-Truck II : Various technologies being deployed to meet targets

https://www.energy.gov/eere/vehicles/annual-merit-review-presentations

Model-based control



Improved combustion

High CR + 0.3 – 0.8 BTE

Thermal barrier coatings (- 1% BSFC)

CLEMSON UNIVERSITY

SOLUTION SPRAY TECHNOLOGIES

OAK RIDGE National Laboratory

MICHIGAN ENGINEERING

Weight reduction

Volvo: Lightweight trailer - 2,000 lbs

Peterbilt: Lightweight chassis - 500 lbs

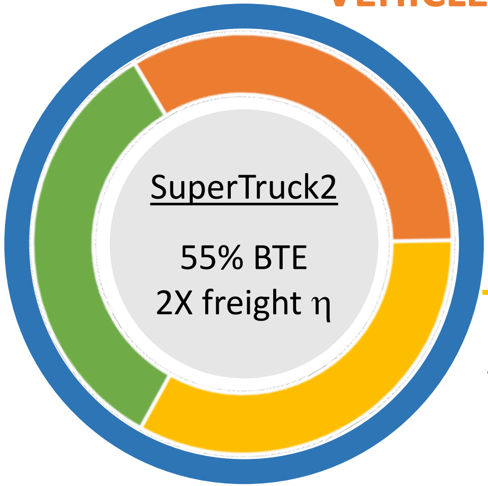
Improved air handling

Eaton

EGR pump (+0.9 BTE)

Miller cycle LIVC (0.3 – 0.7 BTE)

Optimized turbochargers



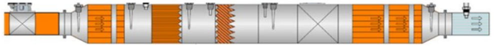
Aerodynamics & tires

Peterbilt: 63% aero drag ↓

Chassis height control

33% RR ↓

Improved after-treatment



Navistar

Low ΔP design

cc-SCR, high cell density, thin wall

48V mild hybridization, 7 – 14 kWh Li-ion battery

Electrification: HVAC, Power-steering, coolant pumps, CAC, etc.

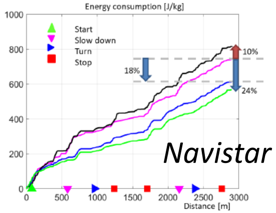
Waste heat recovery

~ +3 – 4% BTE

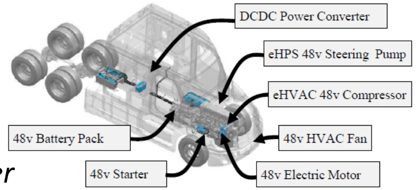
ORC/Phase change cooling

Dual entry turbine

Predictive cruise control



Navistar



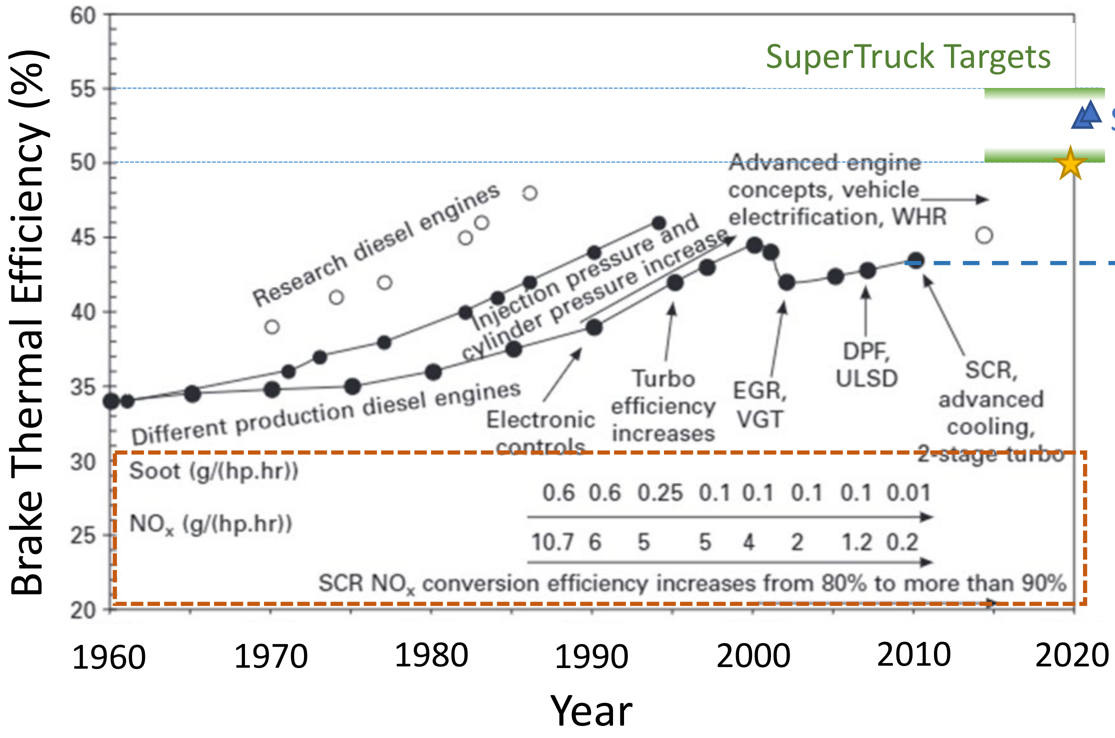
Daimler

Strategies from Super-Truck II participants for 55% BTE engines

https://www.energy.gov/eere/vehicles/annual-merit-review-presentations

	Daimler 	Volvo 	Cummins / Peterbilt 	Navistar 	PACCAR / Kenworth 
Combustion & Air Mgmt.	• Thermal barrier coating • High CR • Miller cycle • 2 stage EGR cooling	• Thermal barrier coating • High CR 20:1, wave piston • LIVC Miller • Turbo-comp.	• Low heat transfer • Reduced friction • High efficiency turbo.	• High T pistons • Gasoline comp. ignition (GCI) : +0.7 – 1.3% BTE • Cyl. deac. 2.9% FC ↓ on city cycle	• LIVC Miller • High efficiency turbo.
Waste heat recovery	Phase change cooling, Est. +3.5% BTE	Dual-loop : Coolant + exhaust Est. +2 – 3 % BTE	Dual-entry turbine +4.1% BTE	ORC : Expander eff. optimization >2.5% BTE to date	4% BTE target, coolant + exhaust
After-treatment	cc-SCR Model predictive controls	High cell, thin wall subs., low ΔP short DPF/SCR	Dual loop EGR	cc-SCR/AMOX for low NH_3/N_2O slip Heated DEF injector	cc-SCR
Status	52.9% BTE		53.5% BTE		

Putting brake thermal efficiency improvements in perspective



UL NOx regs will require > 98% SCR conversion and another factor of 2 reduction in soot emissions

Navistar, Book chapter in “Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance”, 2014
doi: 10.1533/9780857097422.2.225

Outline

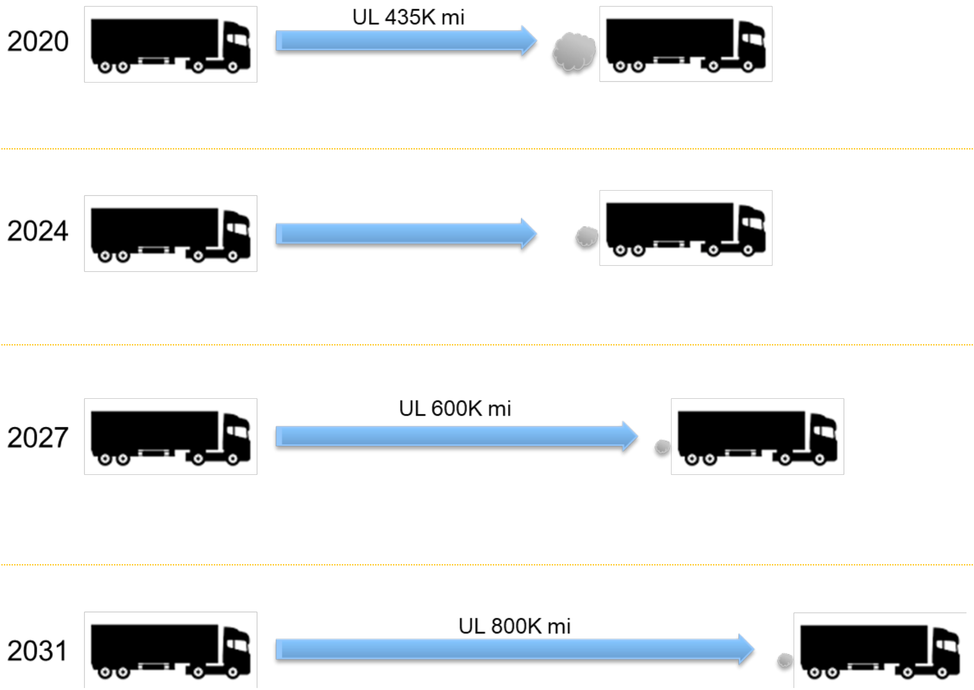
Light-duty

- GHG/Fuel Economy
- Criteria pollutant regulations & emission control technologies

Heavy-duty

- GHG/Fuel Economy
- **Low NOx regulations & technology pathways**

California Ultra-Low NOx Omnibus Rulemaking
Reduced NOx/PM, Strengthened in-use compliance, Extended durability



Regulatory Change

Reference
NOx 200 mg/bhp-h on FTP
PM 10 mg/bhp-h on FTP
IUC : NTE method

NOx 75% ↓, PM 50% ↓
New: Low-load cycle
IUC : MAW method
OBD data transmission

NOx 90% ↓
IUC : Cold-start included
NOx sensor-based
GHG Phase 2: CO_2 25% ↓

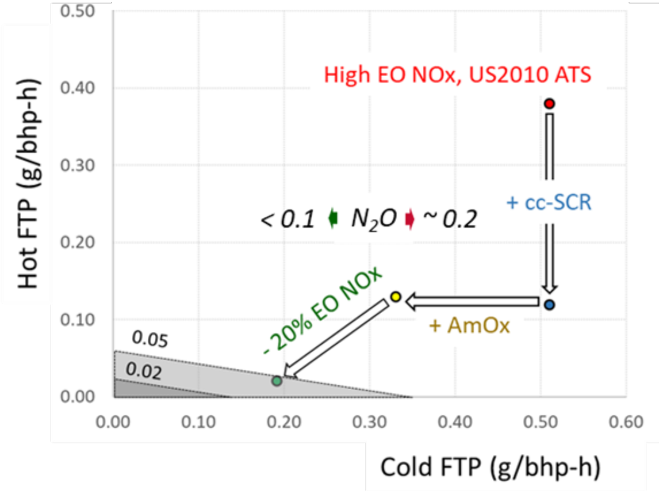
All of above
+ reduced deterioration

IUC = In-use compliance, NTE = Not-to-exceed, MAW = Moving avg. window, GHG = Greenhouse gas, UL = useful life

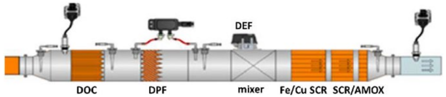
Challenges for meeting UL NOx targets : Very high NOx conversion, passive regen, low N_2O, low CO_2 and robust performance to EOL

Navistar SAE 2020-01-1403

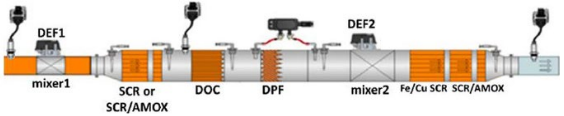
Diesel engine: Navistar
A26™ 12.4L, 6-cyl. 475 hp
CR 18.5:1, VGT, 2500 bar

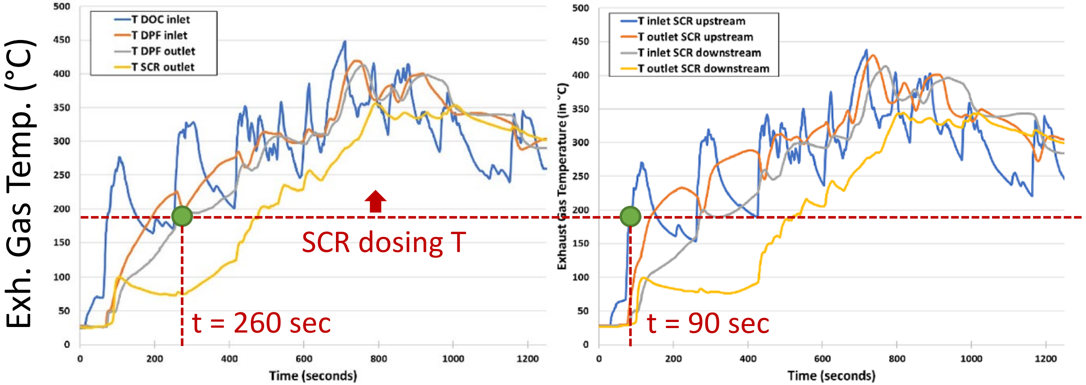


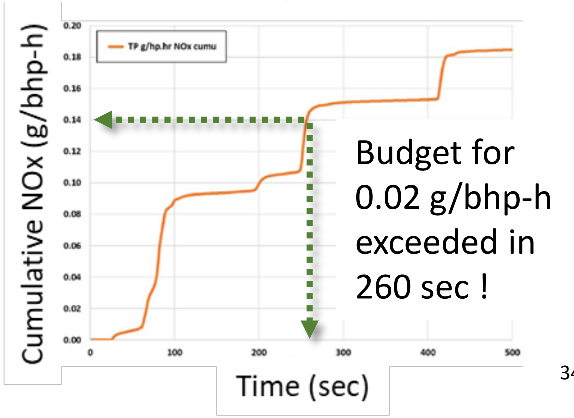
2010 ATS
DOC + DPF + SCR

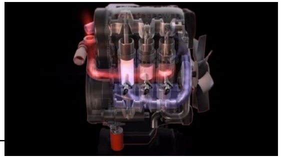


UL NOx
cc-SCR + DOC + DPF + SCR





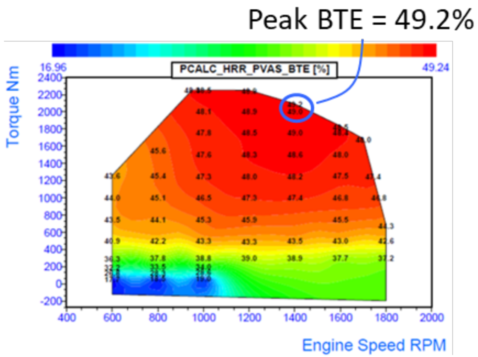


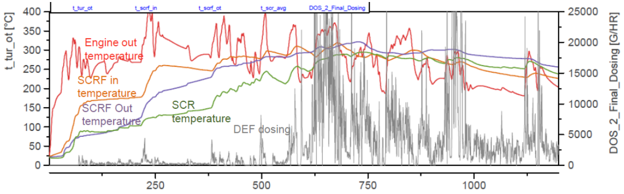


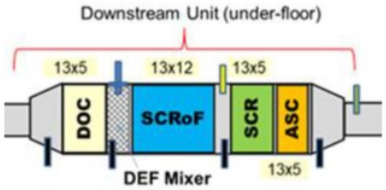
Opposed piston engines

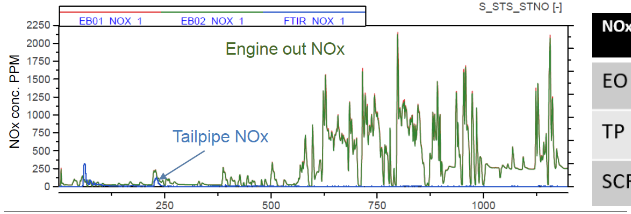
Meeting 2027 GHG targets + Ultra-low NOx -- without dual SCR ?

Vehicle demonstration : 10.6L OP, 3-cyl. + Peterbilt 579



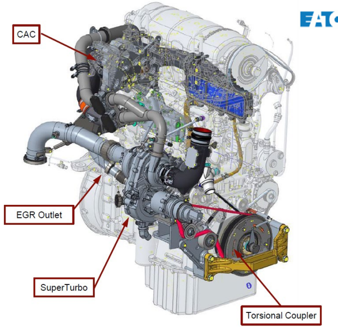






NOx in g/bhp-h	Cold	Hot	Combined
EO NOx	2.72	3.09	3.03
TP NOx	0.67	0.008	0.016
SCR conversion	97.5%	99.7%	

Further improvements in CO_2 and NOx



CO_2

415 g/bhp-hr on SET cycle,

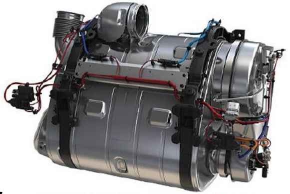
465 g/bhp-hr on FTP cycle

4% - 7.5% below 2027 limit

After-treatment

DOC/DPF + SCR + SCR/AMOX

+ Advanced catalyst technology



2021 Volvo Single Box Aftertreatment

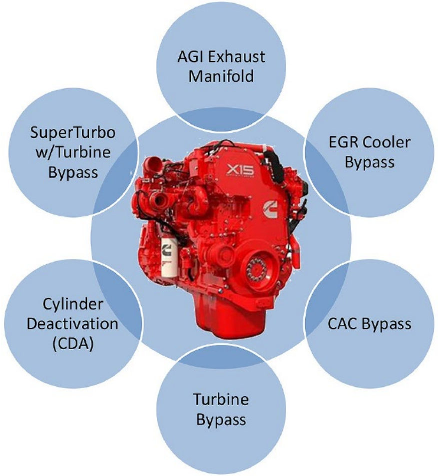
Simulations for HD-FTP cycle:

NOx : 0.007 g/hp-hr

Pathways to CARB UL NOx – without CO_2 penalty – being evaluated
Engine calibration, cylinder deactivation & light-off SCR

SWRI, SAE 2020-01-0318

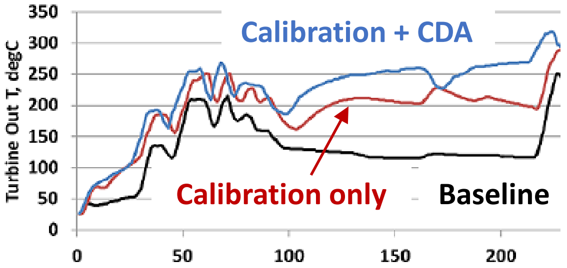
Engine : Cummins 2017 X15 6-cyl.
+
Modified engine calibration (incr. EGR, idle speed)
+
Various engine technologies evaluated



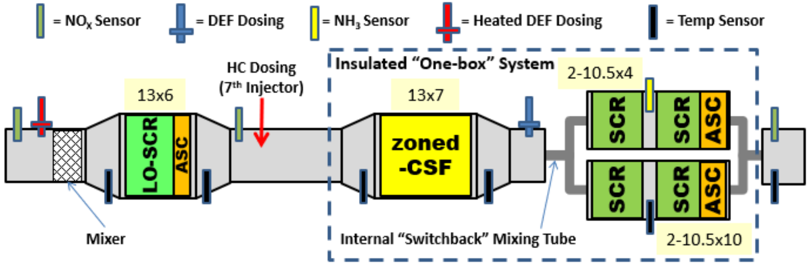
Eaton CDA

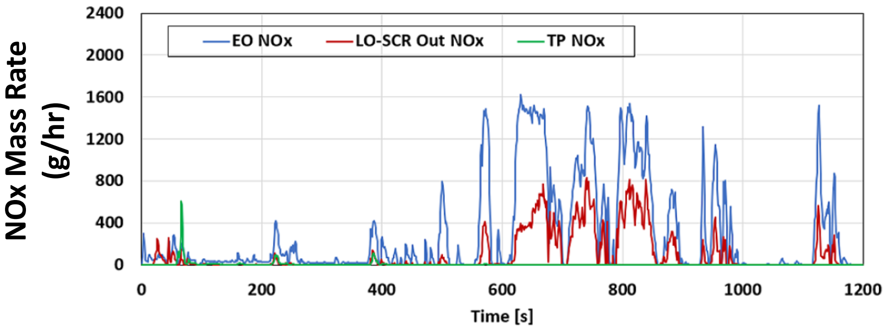
SAE International®
WCX Digital Summit

Turbine out temperatures



SWRI, SAE 2020-01-1402





Degreened performance

Emissions (g/bhp-hr)	Baseline NOx	Stage 3 NOx	Baseline CO_2	Stage 3 CO_2
Composite FTP	0.16	0.017	511	502
Low load cycle	1.0	0.020	609	603

Dynamic cylinder deactivation can help reduce NOx and CO_2 simultaneously

April 13th press release

– Cummins, Tula 41st Intl. Vienna Motorsymposium, 2020

Cummins and Tula Study of Diesel Dynamic Skip Fire (dDSF™) Shows 74% Reduction in NOx Emissions

5% Reduction in CO_2 Emissions Also Verified in Low-Load Cycle

Engine: Cummins X15 6-cyl. with VGT, high P EGR

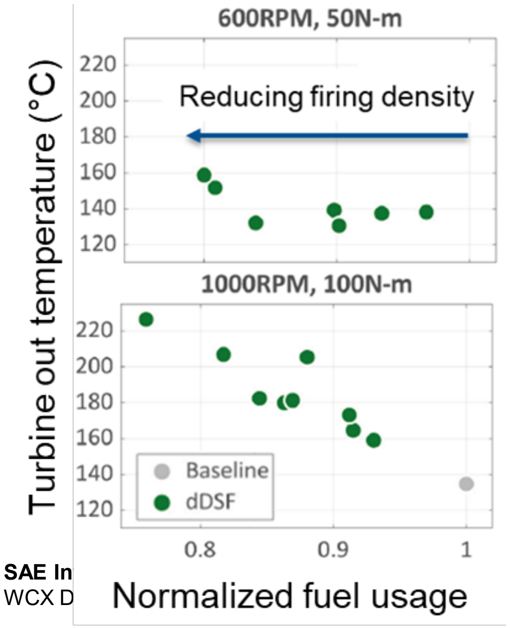
Results during idling at 600 & 1000 rpm

» Turbine out temp : ~ 40 – 100 °C ↑ » Fuel consumption : ~ 20% ↓

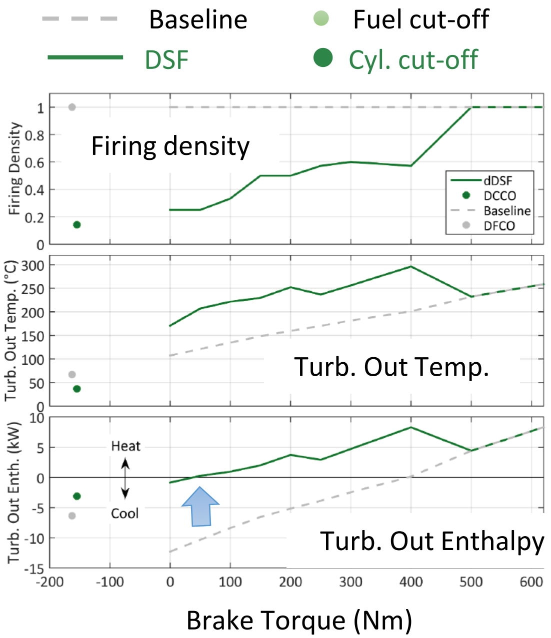
» Reduced exhaust cool-down during fuel cut-off

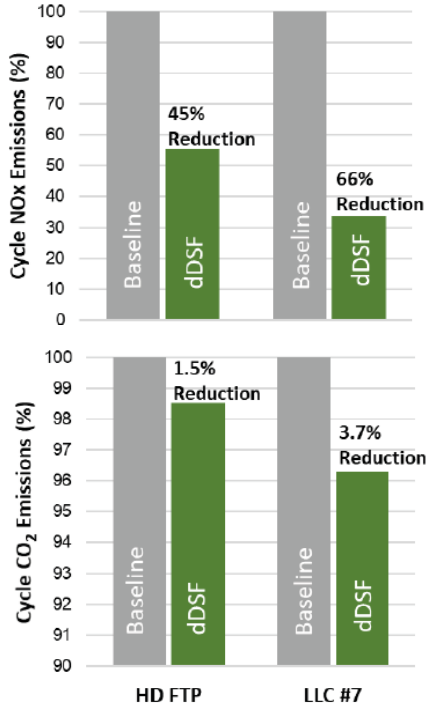
Simulations

NOx: 45 – 66% ↓ CO_2 : 1.5 – 3.7% ↓



SAE In
WCX D





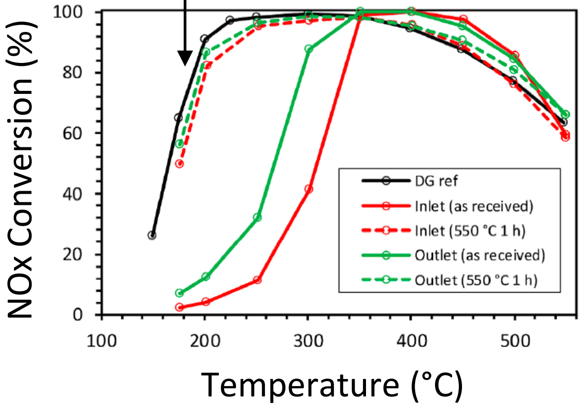
S poisoning of Cu-SSZ-13 : Thermal treatment up to 550 °C can recover much of the activity, but with CO_2 penalty

Cummins SAE 2020-01-1319

Comparison of SCR activity of degreened and field aged samples in lab

Degreened

Solid: Field aged
Dashed : 550 °C @ 1 hr



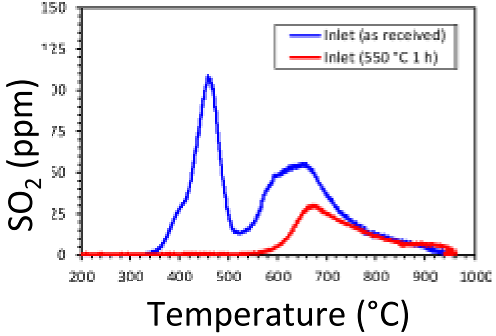
Reactor inlet: NOx = NH_3 = 200 ppm, H_2O 7% , CO_2 8%, O_2 10% , SV = 60K hr-1

TPD experiments

Physically bound S released at 350 – 500 °C

Expected to be ammonium bisulfate (NH_4HSO_4)

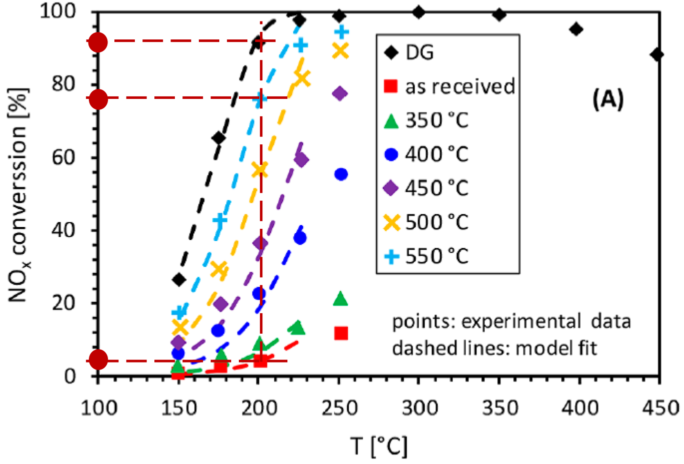
Field aged 550 °C @ 1 hr



Note that strongly bound sulfur is not removed till higher temperatures

Thermal treatment up to 550 °C recovers NOx conversion from ~4% to 76% at 200 °C

Still not fully recovered - 96% conversion for degreened

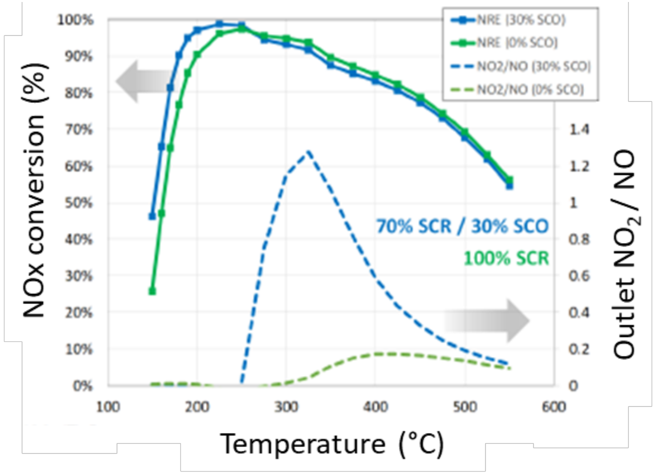


Improved SCR on DPF performance : Selective catalytic oxidation (SCO) of NO → NO_2 using Mn-based catalyst

PNNL, PACCAR DOE Annual Merit Review 2020

Catalyst:
SCO : 10% Mn/ZrO_2, SCR = CuCHA
Physically mixed 30% SCO + 70% SCR

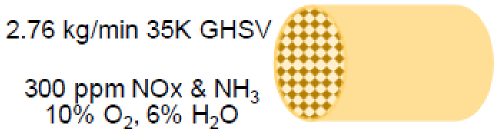
Higher NO_2 in outlet
NO → NO_2 oxidation increased by SCO

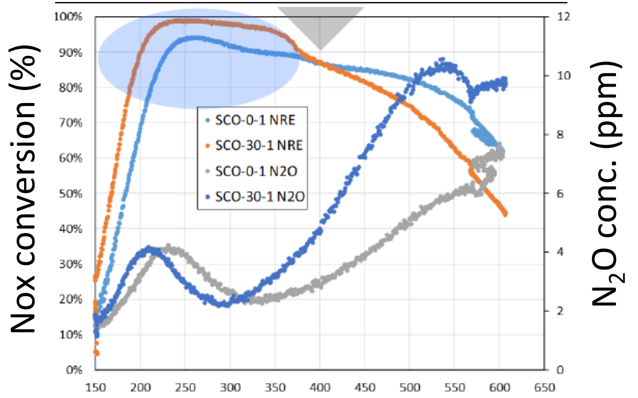


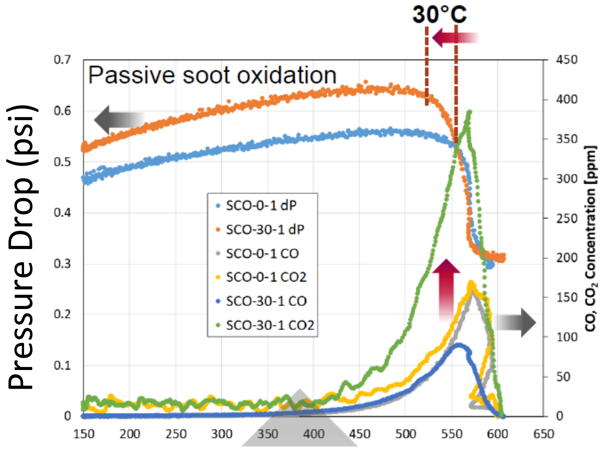
Std SCR : 300 ppm NO, 10% O_2, 6% H_2O, SV=35K/hr

Combined SCR & passive soot regen, soot load 4 g/L

- NOx conversion increased from ~ 70% → 90% at 200 °C
- Passive soot oxidation initiated ~ 30 ° C earlier
- Higher fraction of complete soot oxidation (CO_2 vs CO) with SCO catalyst







Euro VII : Expect lower limits coupled with broad changes in in-use testing

Key changes under consideration

Tailpipe Limits

Separate limits based on short vs. long trips : fixed “budget” for short trips

Reduced limits for most species. (focus on NOx and particulates)

Reduced PN limit. Inclusion of sub-23 nm particles (down to 10 nm).

N_2O and CH_4 to be accounted as GHGs

In-use testing

All driving conditions included - No minimum trip distance, no weightage for cold start emissions, inclusion of regen emissions.

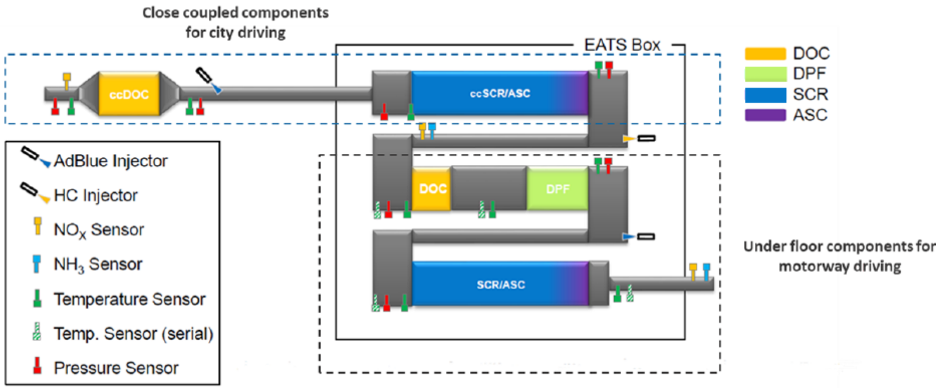
Extended boundary conditions : T down to – 10 °C, Altitude up to 2,200 m

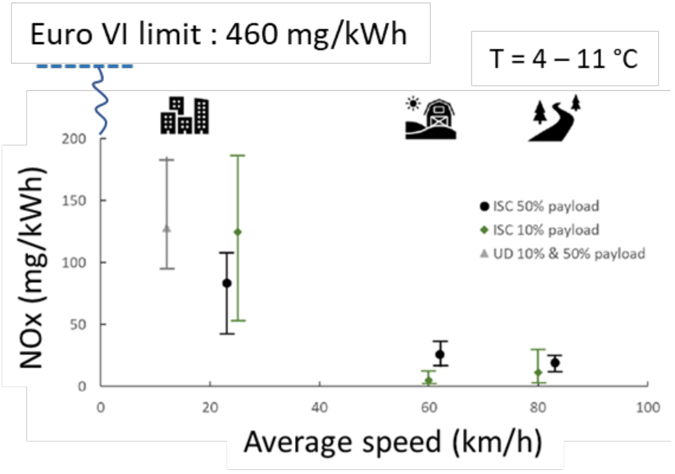
Increased durability

Low NOx emissions demonstrated on European truck

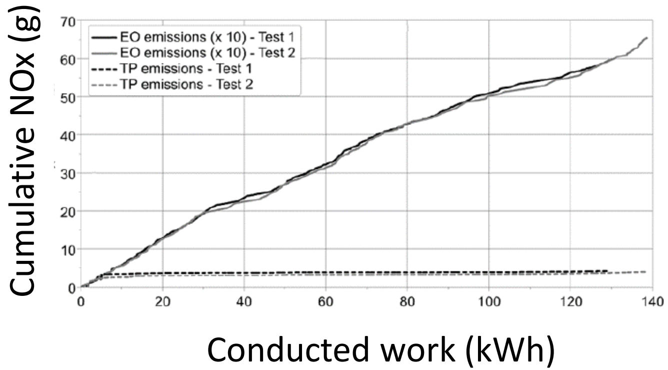
AECC, 11th VERT forum, 2021

Vehicle demonstrator: MB Actros 1845 LS 4x2
Euro VI C, 12.8 L, 6 cyl., HP EGR. Parts aged to 500K km target





High emissions during cold start. Near zero emissions under hot conditions. Further reductions possible using cc-SCR, thermal mgmt. etc.



Stoichiometric natural gas engines
Already below UL NOx levels, need to address high PN & CH_4

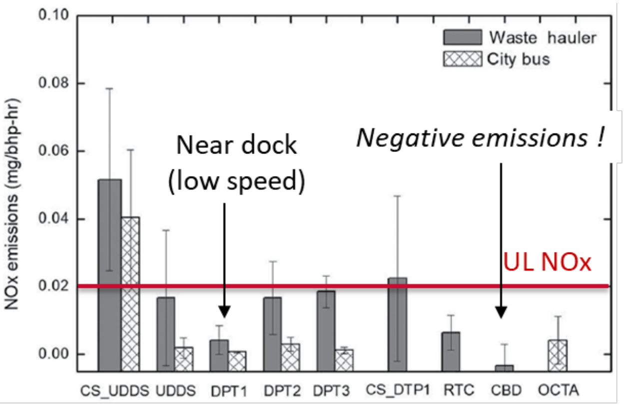
UC Riverside SAE 2019-01-0751

Engine L9N NZ CWI 8.9L w/ TWC & EGR
Cert. to 0.02 NOx
9% lower GHG rel. to ISL G 8.9 NG

Applications City transit bus & Waste hauler

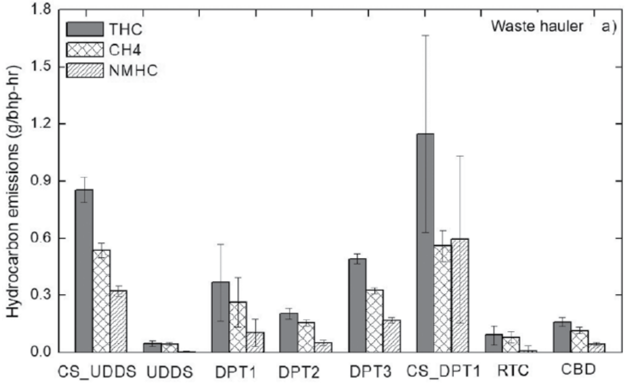
Testing Engine dyno, various test cycles

NOx emissions below 0.02 g/bhp-h, even for low speed drayage cycle

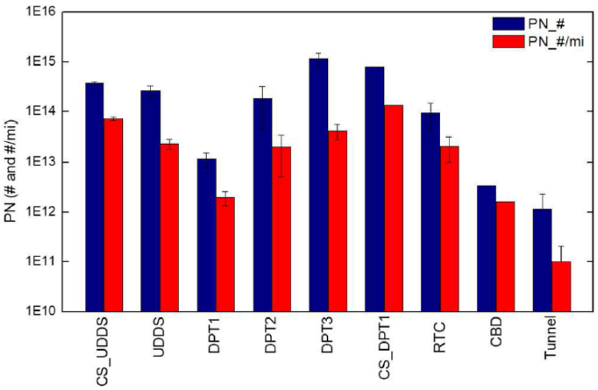


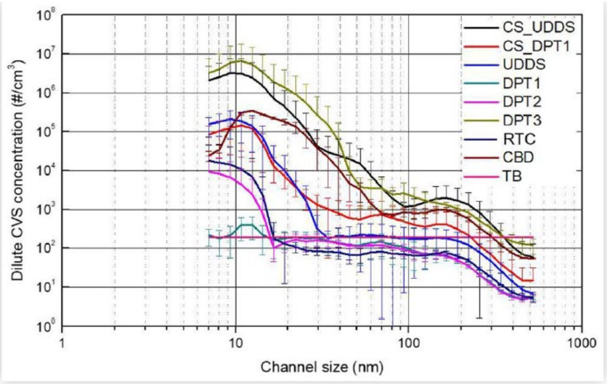
Drayage Waste truck Bus

HC & CH_4 emissions meet limits but CH_4 is significant fraction of THC



PM 90% below limit but PN emissions very high. Sub-23nm particles dominate



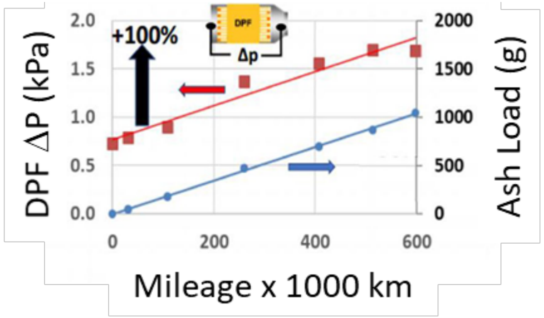


Next generation DPFs will address high ash storage and low ΔP

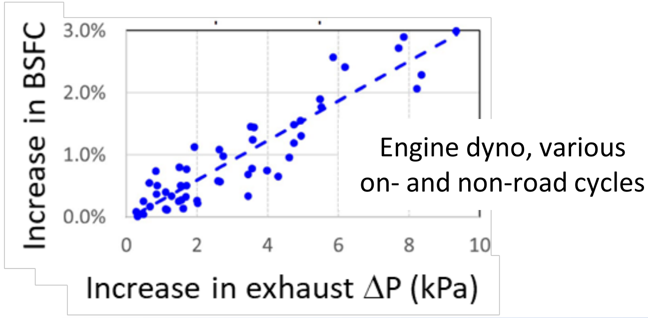
Corning, SAE 2020-01-1434

Longer useful life
→ Need to address lifetime ΔP & fuel penalty with ash accumulation

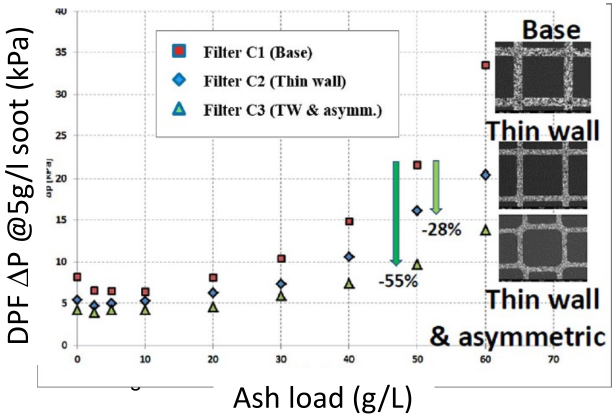
Increase in DPF ΔP with ash (no soot). Line haul operation.



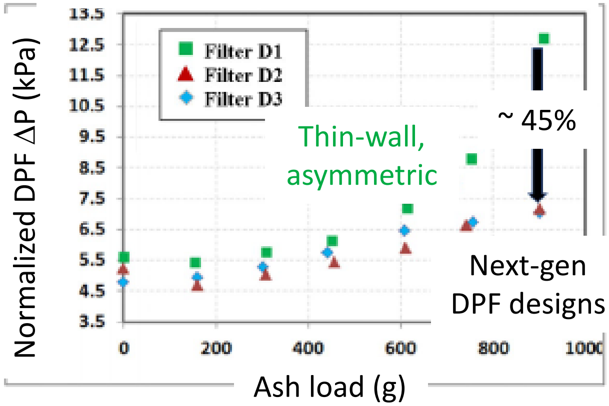
Increase in fuel consumption with exhaust system backpressure



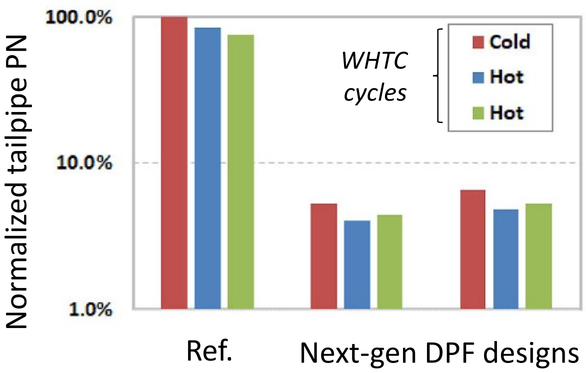
Thin-wall, asymmetric channels increase ash capacity & lower ΔP



Novel cell designs with increased OFA can greatly reduced ΔP



While also offering an order of magnitude PN reduction

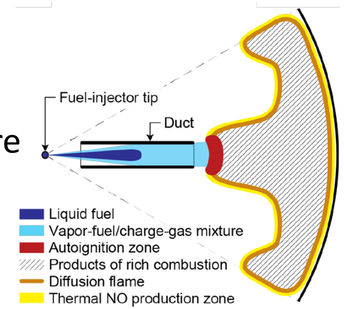


Ducted fuel injection (DFI) promises to break the soot-NOx trade-off

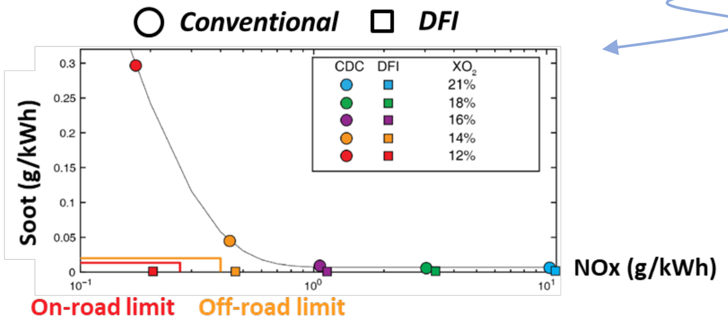
Sandia Natl. Lab, *SAE Int. J. Engines* 13(3):345-362, 2020

Concept: Fuel injection through small tube

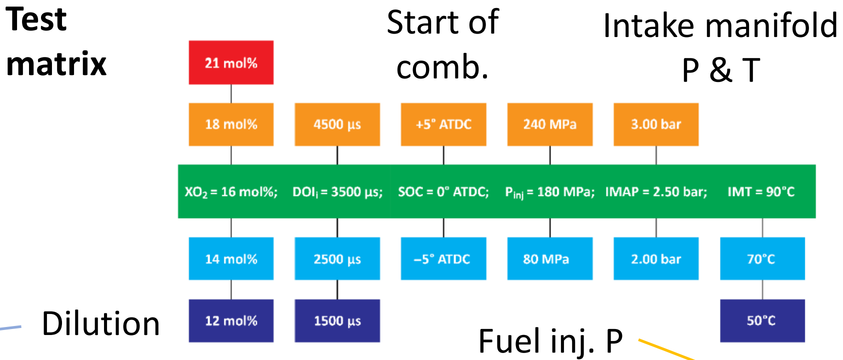
- Leaner fuel-rich mixture in autoignition zone
- Leaner lifted flame combustion (LLFC)

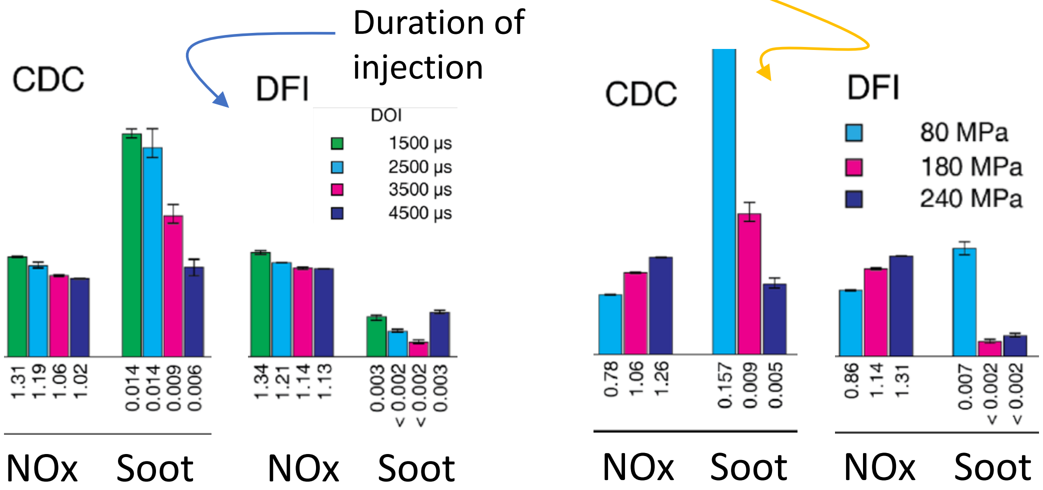


Four-duct DFI in optical engine @ 1200 rpm



- > 90% reduction of soot emissions
- Ability to increase dilution → simultaneous NOx reduction

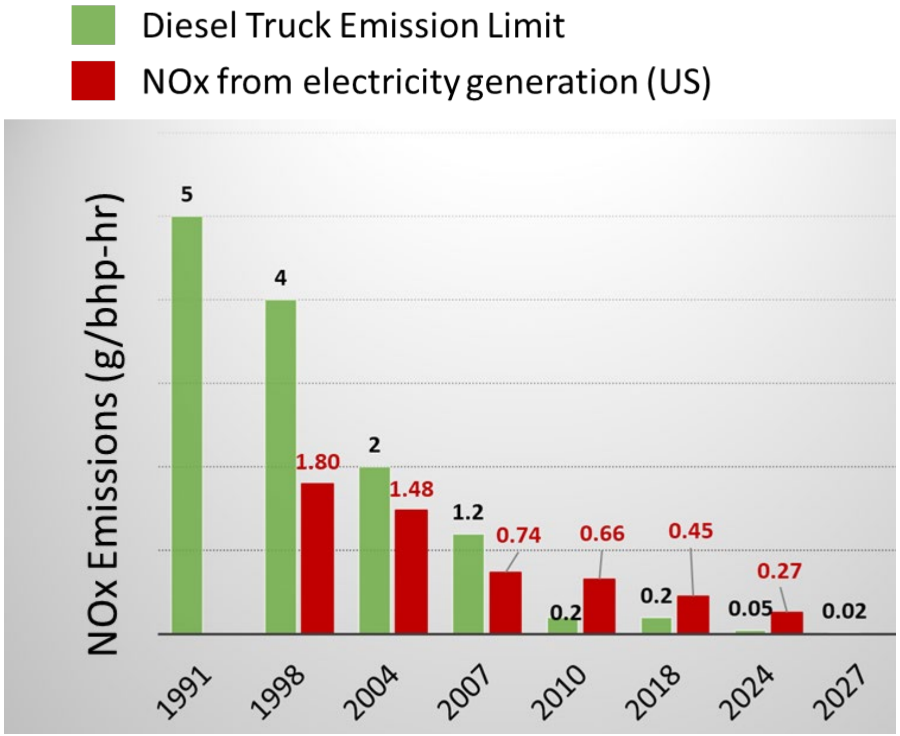




Diesel trucks will emit lower NOx compared to electric trucks when including upstream emissions

To BE or not to BE ..

Model Year	Class 2b-3*	Class 4-8	Class 7-8 Tractors
2024	5%	9%	5%
2025	7%	11%	7%
2026	10%	13%	10%
2027	15%	20%	15%
2028	20%	30%	20%
2029	25%	40%	25%
2030	30%	50%	30%
2031	35%	55%	35%
2032	40%	60%	40%
2033	45%	65%	40%
2034	50%	70%	40%
2035 +	55%	75%	40%



Electricity NOx emissions
https://www.eia.gov/electricity/state/unitedstates/

What to look for in 2021

For a copy of the slides:

joshia@corning.com https://www.linkedin.com/in/joshiav/

Policies set by the Biden administration and the new EPA
California waiver, new CO2 targets, incentives for electrification, etc.

Heavy-duty Cleaner Trucks Initiative (national version of California's Low NOx)
Expect some alignment with California standards

Euro 7 / VII
Proposal expected by end of year after stakeholder inputs.

China 7 / VII ? (no public announcements so far)

Climate Law in Europe and potential revisions of CO_2 targets
Possible revision to the already stringent CO_2 tailpipe limits, both for light- and heavy-duty.

EPA Tier 4 / CARB LEV IV
SULEV 20, PM 1 mg/mi (nationwide)

Non-road low NOx rulemaking (US) ?

Non-exhaust emissions – new data and some progress towards regulatory actions