CORNING

Presented at ECMA workshops at ARAI & ICAT
PART 2

Vehicle Engine Efficiency and Emissions
Review of Regulations & Technology Trends

Sept 11th – 12th, 2019

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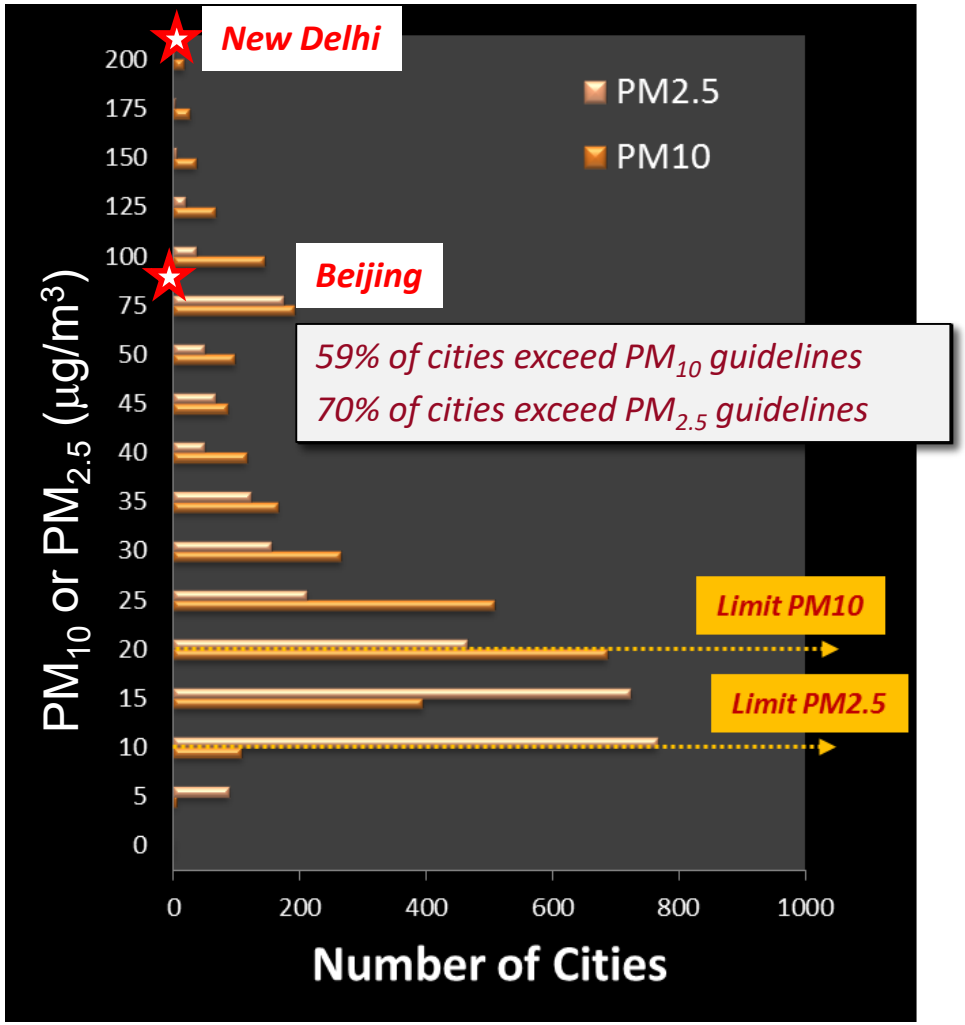
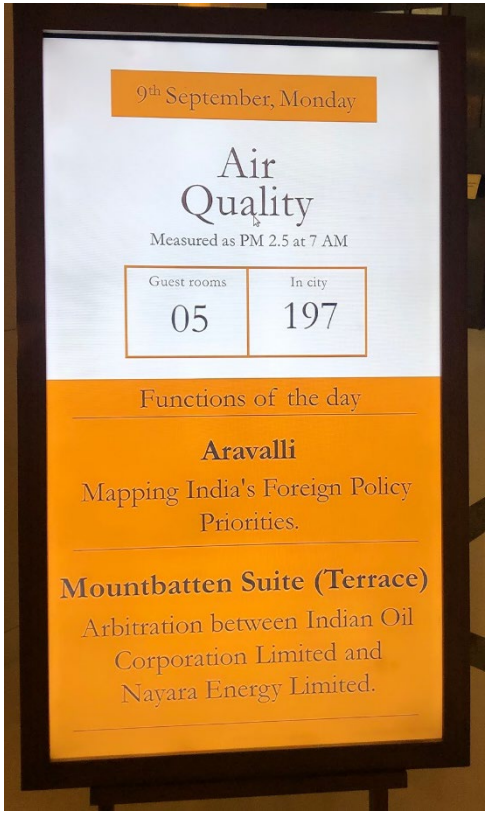
Technologies to reduce criteria pollutants

Gasoline Particulate Filters

Improving air quality has become a priority across the world

WHO Global Urban Ambient Air Pollution Database
~ 3000 cities, 2012 – 2015





Ultrafine particle deposition and transport mechanisms within the human body summarized

U. Of Rochester, S. Methodist Univ., Bayer CropSci. Environ Health Perspect 113:823-839 (2005)

Ultrafine particles have higher surface area and number count and have unique transportation pathways into various parts of the human body

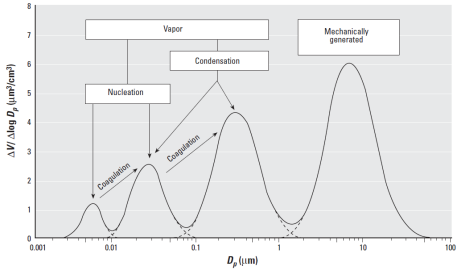
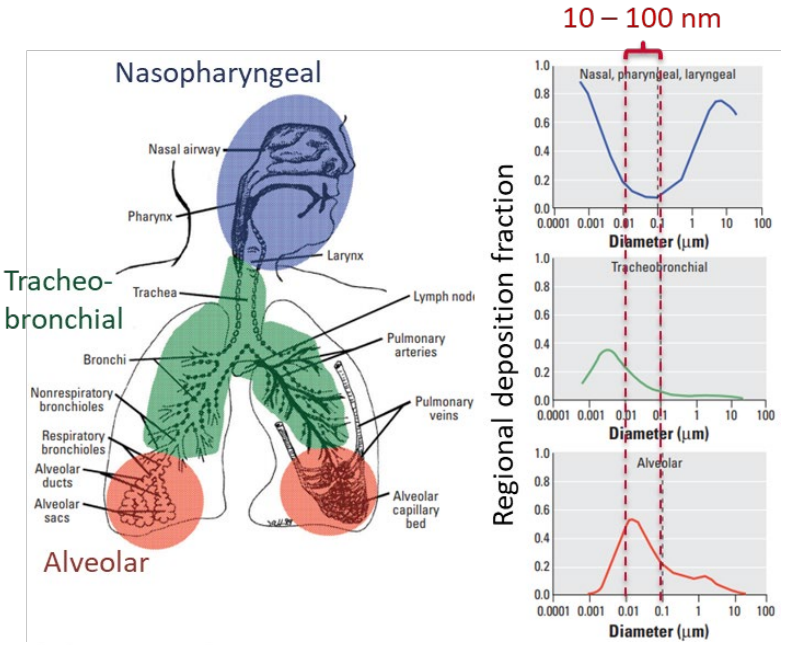


Table 2. Particle number and particle surface area per 10 μg/m³ airborne particles.

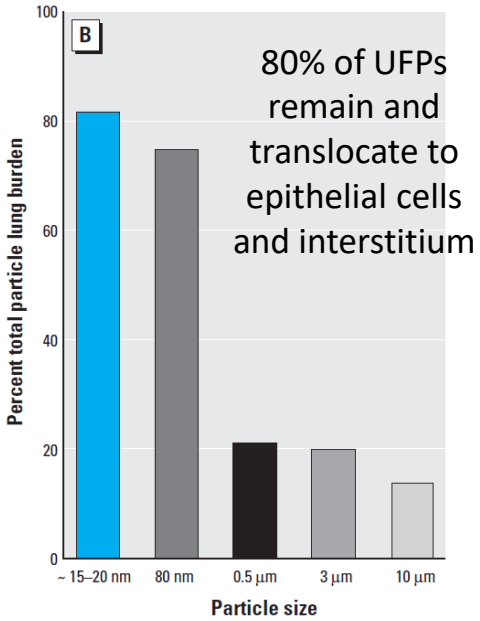
Particle diameter (μm)	Particle no. (cm^{-3})	Particle surface area ($\mu m^2/cm^3$)
5	153,000,000	12,000
20	2,400,000	3,016
250	1,200	240
5,000	0.15	12

UFPs deposit in various regions of the lung

Transport to bloodstream and nervous system

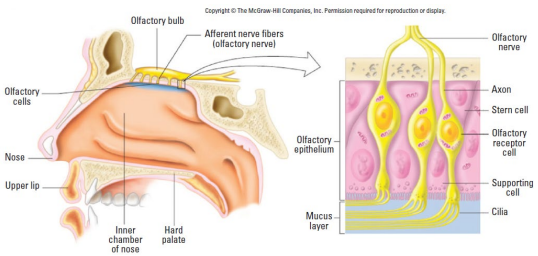


Retention of particles after clearance by alveolar macrophages



80% of UFPs remain and translocate to epithelial cells and interstitium

UFPs deposit on sensory nerve endings of olfactory nerves

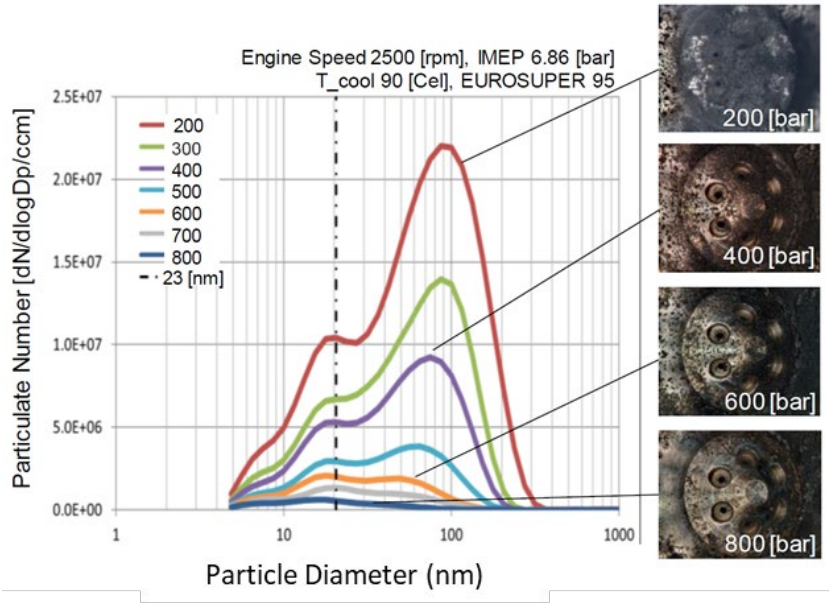


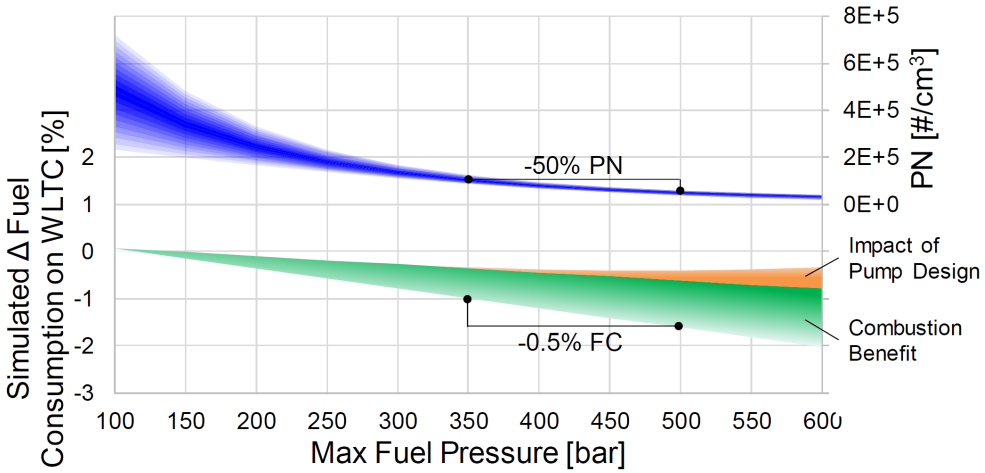
Translocation into deeper brain structures possible

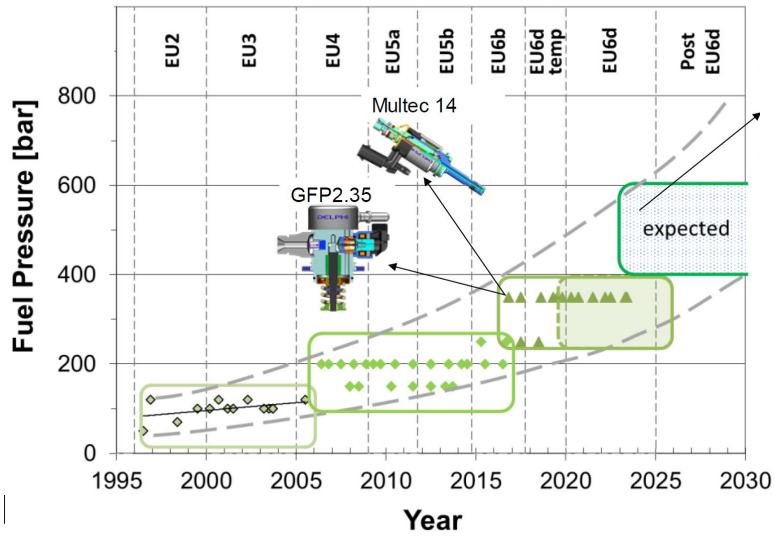
Distribution to heart, kidney, spleen, bone marrow reported

Engine out particulate emissions continue to decrease with improved injection systems

Delphi, Int. Vienna Motor Symposium, 2019





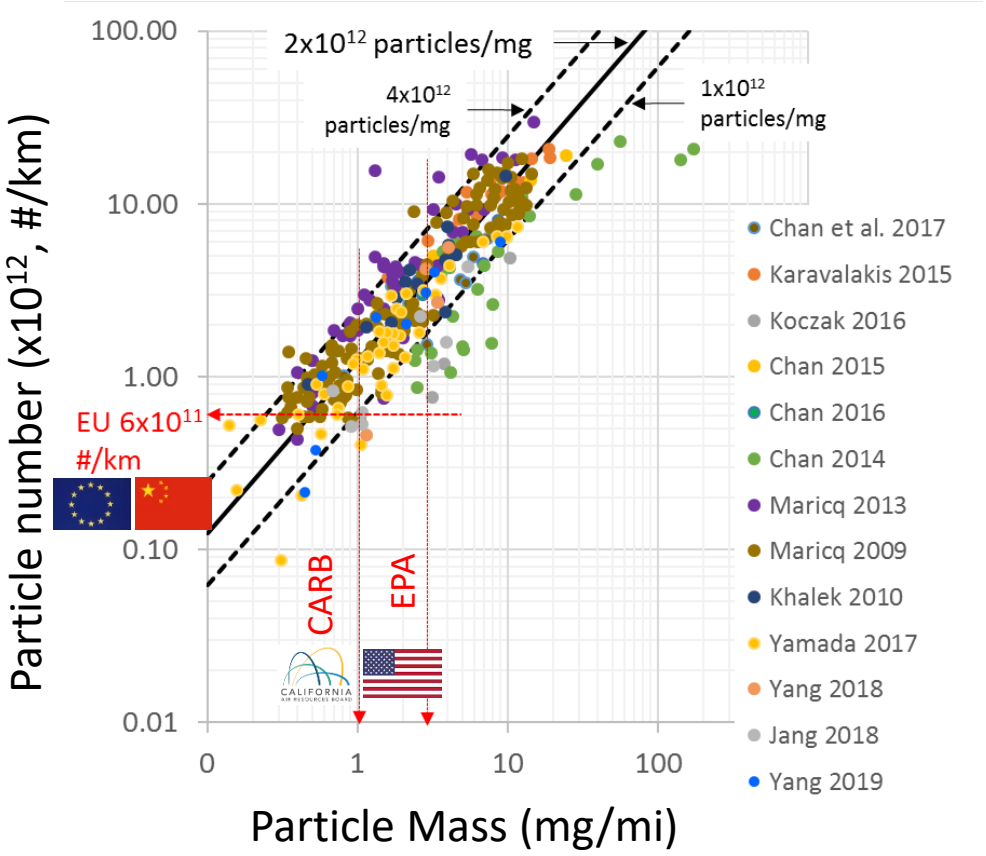


Injection pressures expected to increase from 350 bar (current) to 400 – 600 bar

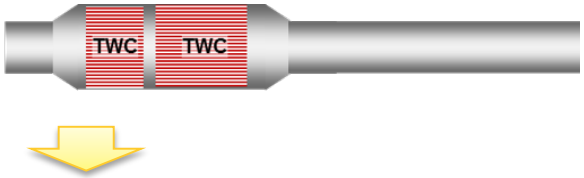
- ✓ Reduced overall PN
- ✓ Reduced sub-23 nm particles
- ✓ Reduced injector tip deposits

Particle number limits and RDE testing in Europe and China are driving rapid adoption of gasoline particulate filters (GPFs)

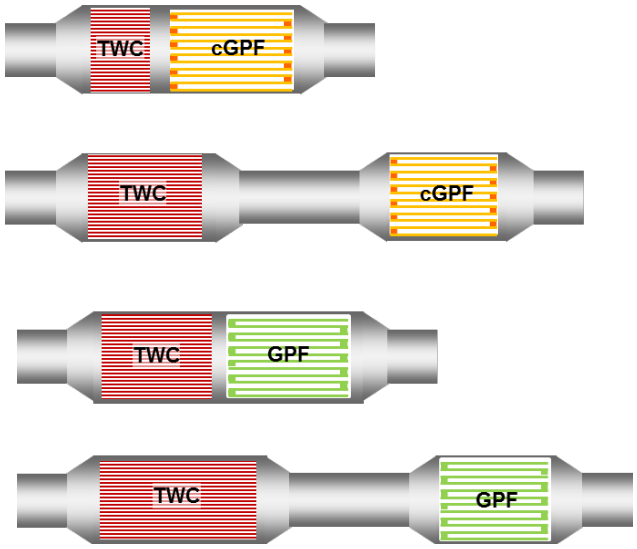
Euro 6 PN limit of $6x10^{11}$ #/km ~ 0.5 mg/mi



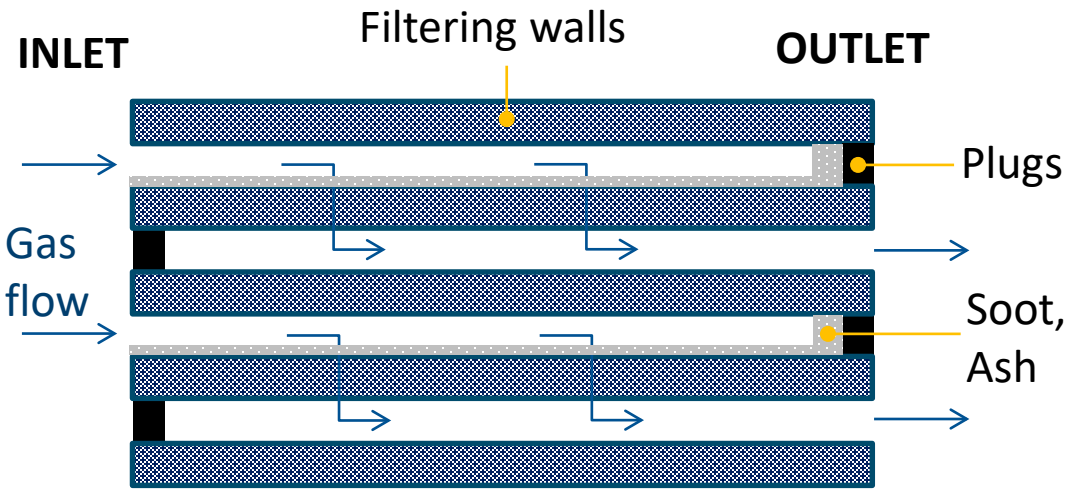
Euro 5



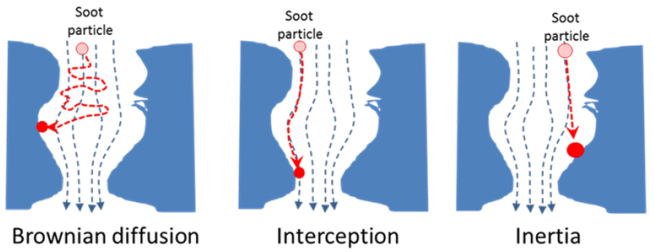
Euro 6+



Design considerations of particulate filters



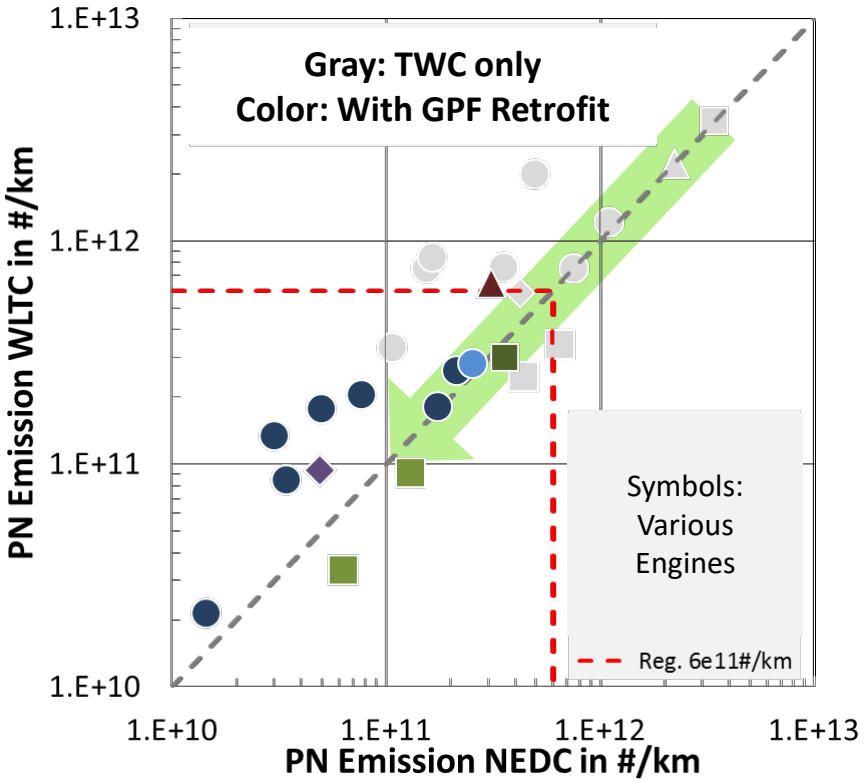
Relevant Filtration Mechanisms



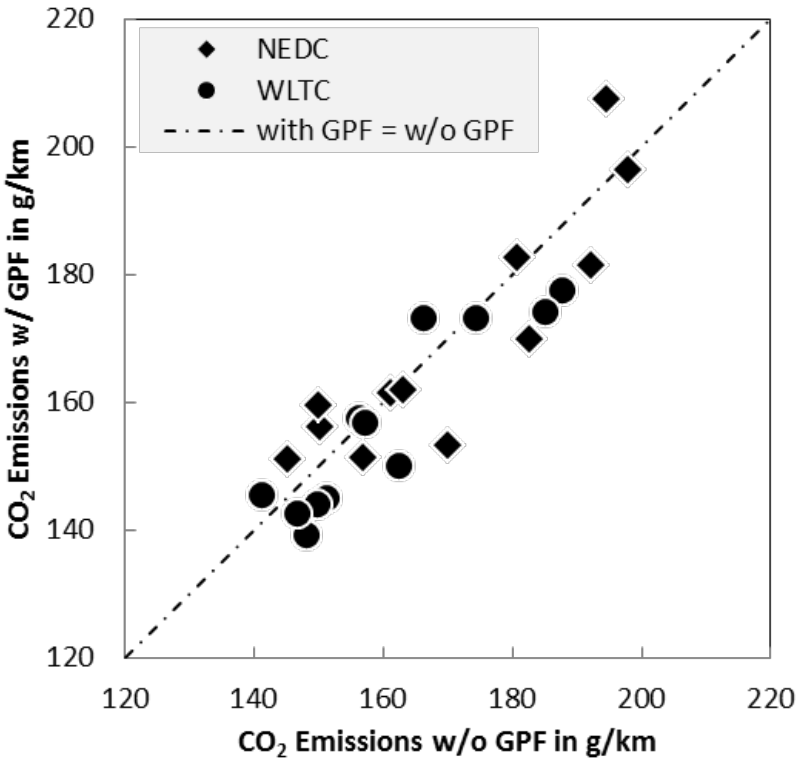
Need	Design Considerations
High filtration efficiency	Engineered pore size & Optimized cell design
Low pressure drop - Coated, soot/ash loaded	
Soot management	Thermal durability and regeneration strategy
Ash capacity	Inlet channel size
Catalytic performance	Adequate porosity for catalyst
Durability & strength	High material strength, low CTE, chemical resistance, etc.

Extensive vehicle fleet experiments confirm robust filtration performance of GPF with minimal Δp penalty

- PN Filtration studied using large Vehicle Fleet with GPF retrofits
  - 12 GDI vehicles (EU5/6b), Engines 1.4 – 3.0L, various segments (C,D,E, SUVs)
  - GPFs uncoated and some TWC coated



No clear trend for impact of GPF on CO_2 emissions observed



Artificial ash for increased filtration efficiency
~ 2.5g ash increases cold-start FE up to 20%

Ford, 2019-01-0974

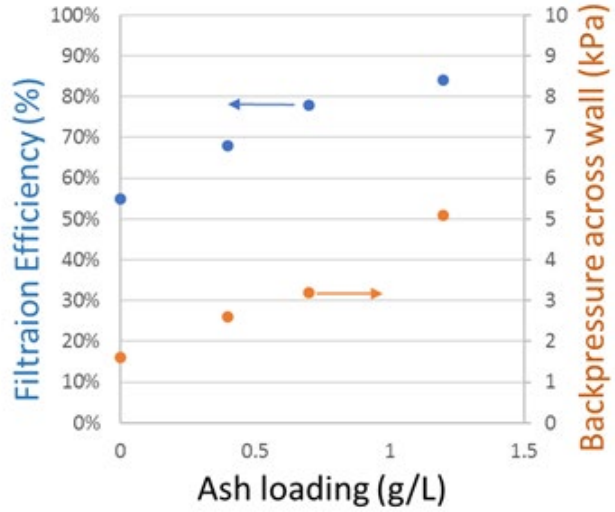
- GPF: Bare 300/12, 65% porosity
- Artificial ash : Alumina, d_{50} = 80 nm (10 – 500 nm)

Lab testing : GPFs : 1” (D) x3” (L), SV = 30K hr^{-1}

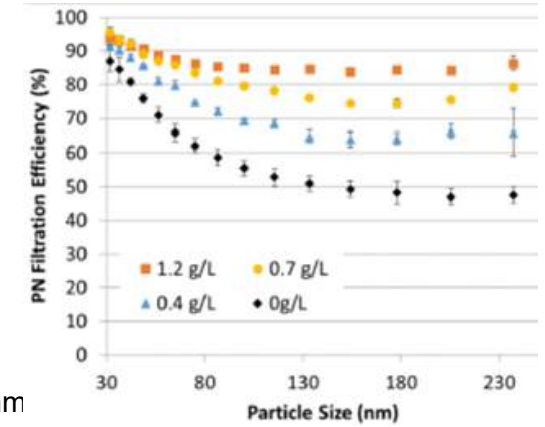
Filtration

~ 30% increase in FE with 1.2 g/L ash

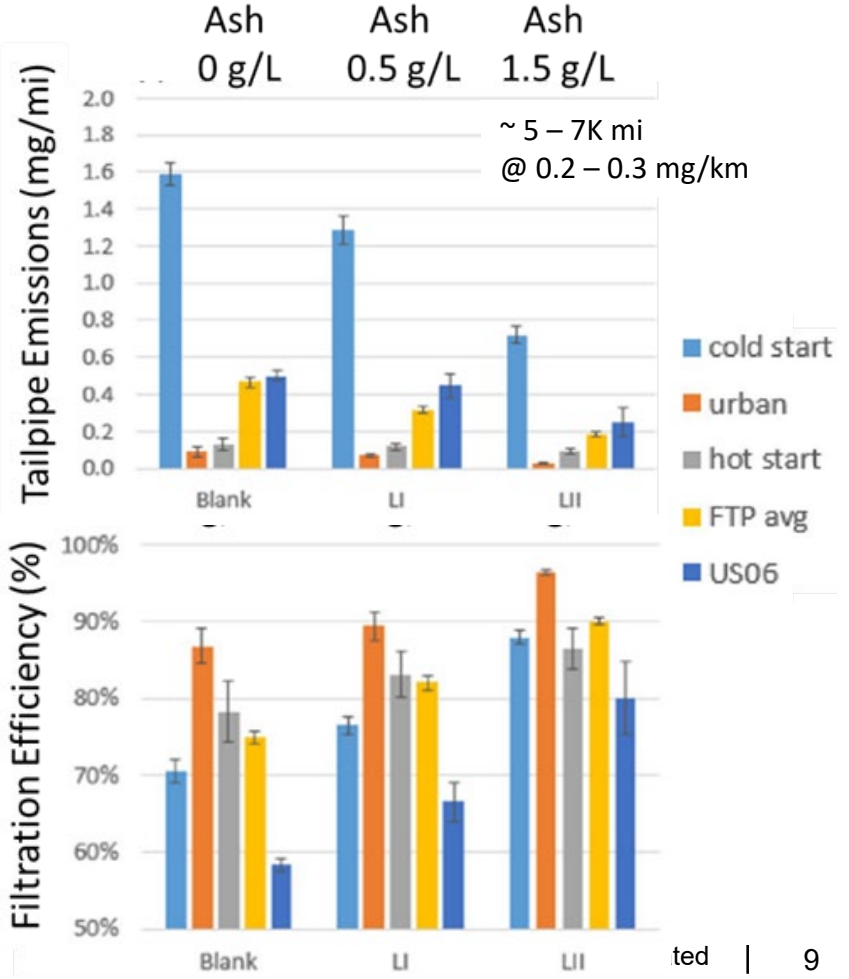
Diminishing gains with increased ash loading



Increase in FE is larger for bigger particles



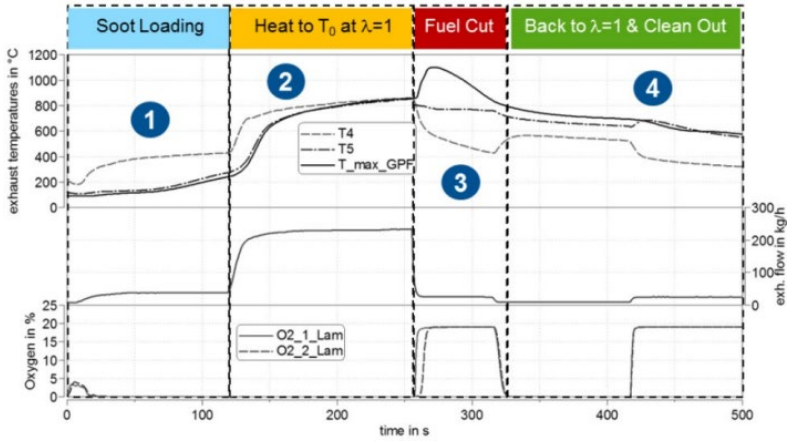
Vehicle testing : FTP75, US06 and WLTC
Vehicle: 2017 2.3 L GTDI with 3,800 mi
GPFs : 5.66” (D) x 4” (L). Ash loading : 0.5 and 1.5 g/L



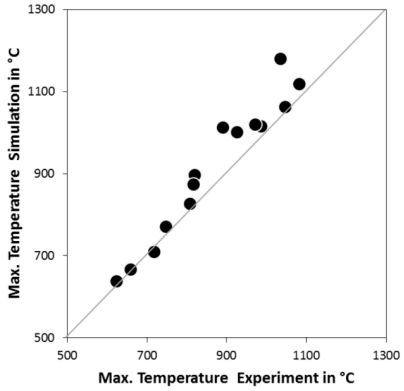
GPF temperatures mapped as function of inlet conditions and soot loads to manage regeneration

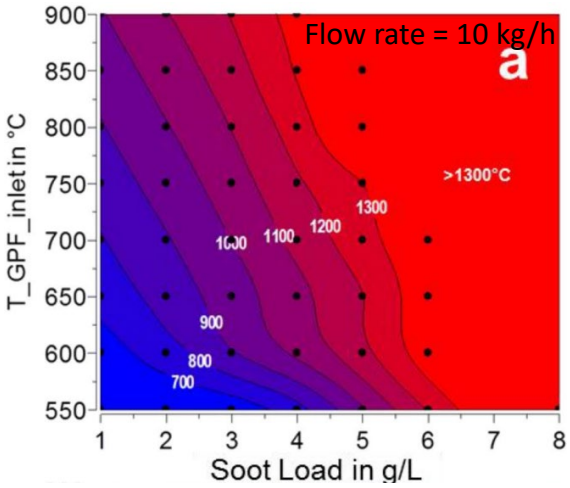
Corning, SAE 2018-01-1699

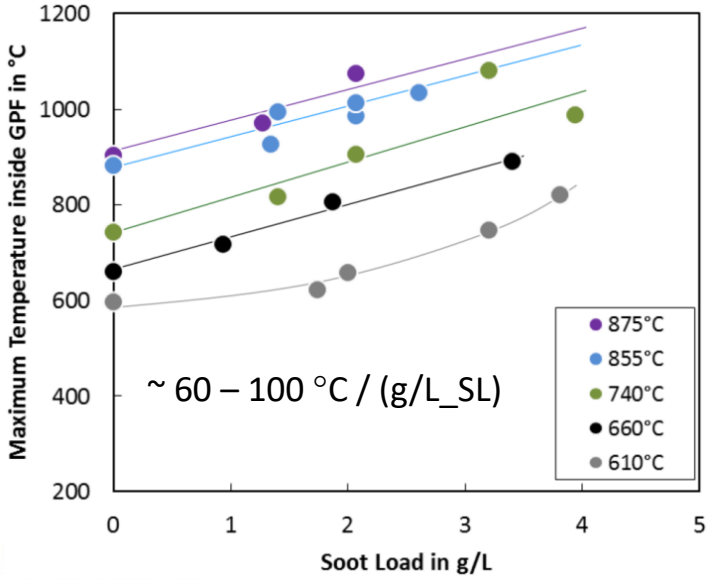
Fuel cut procedure on engine bench

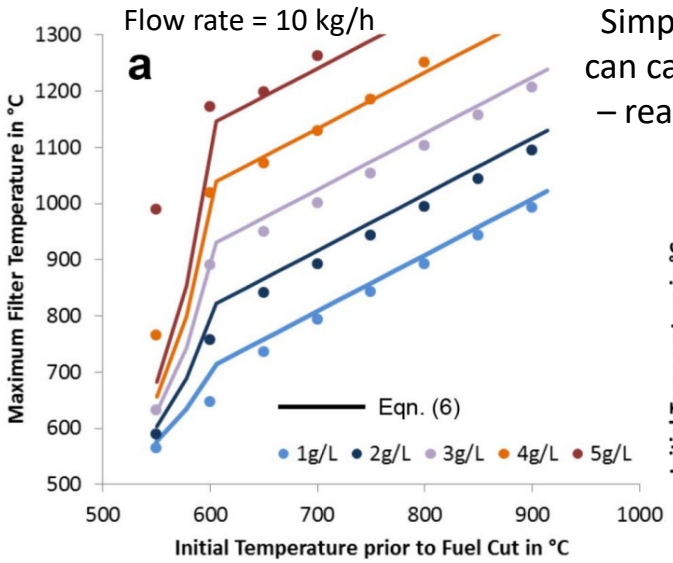


Simulations used to map response to soot load, inlet T and flow rate

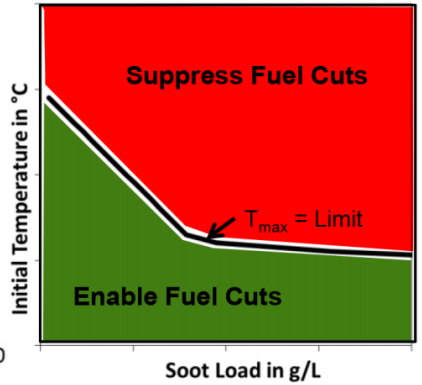






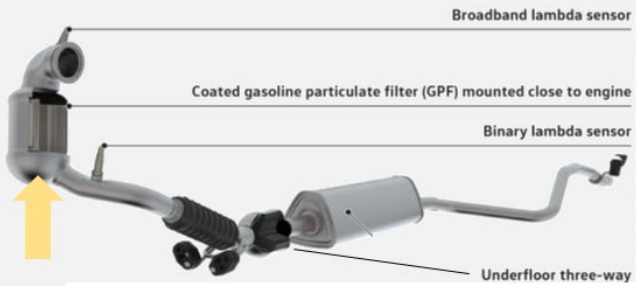


Simplified algebraic model can capture the two regimes – reaction and soot limited

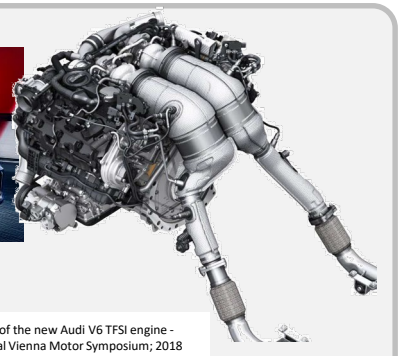


GPFs have been commercialized and are working effectively under real world operating conditions

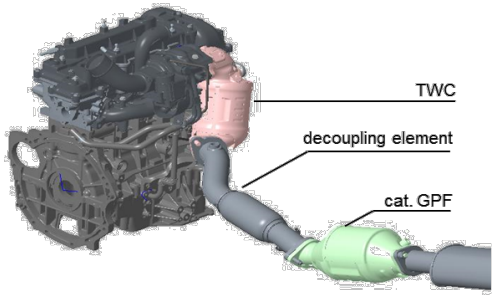
Source: Press Release PSA Group; POWERTRAIN GROUPS AT THE FOREFRONT OF TECHNOLOGY; Rueil-Malmaison; France; May 11th 2017



Source: Hentschel, L. et al.; The New 1.0 l TSI with 85 kW and Petrol Particulate Filter – Clean, Efficient Performance for the Up! GTI; 26th Aachen Colloquium; 2017



Source: Königstedt, J. et al.; The continued development of the new Audi V6 TFSI engine - The next milestone in TFSI Technology -; 39th International Vienna Motor Symposium; 2018



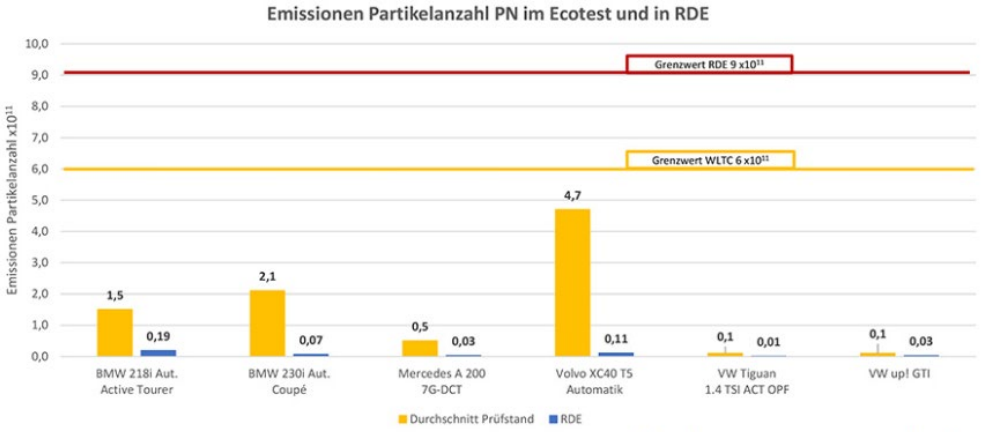
Source: Hyundai Motor Company

Exhaust Gas Test: First gasoline with particle filter - they are really clean

07/31/2018

In order to comply with the limit values of the Euro 6d-Temp emission standard, more and more gasoline engines with particle filters are coming. We reviewed six current models in the Ecotest. How clean are the exhaust fumes of BMW Active Tourer, BMW 2 Series Coupe, Mercedes A-Class, Volvo XC40, VW up and VW Tiguan actually? The results are surprising.

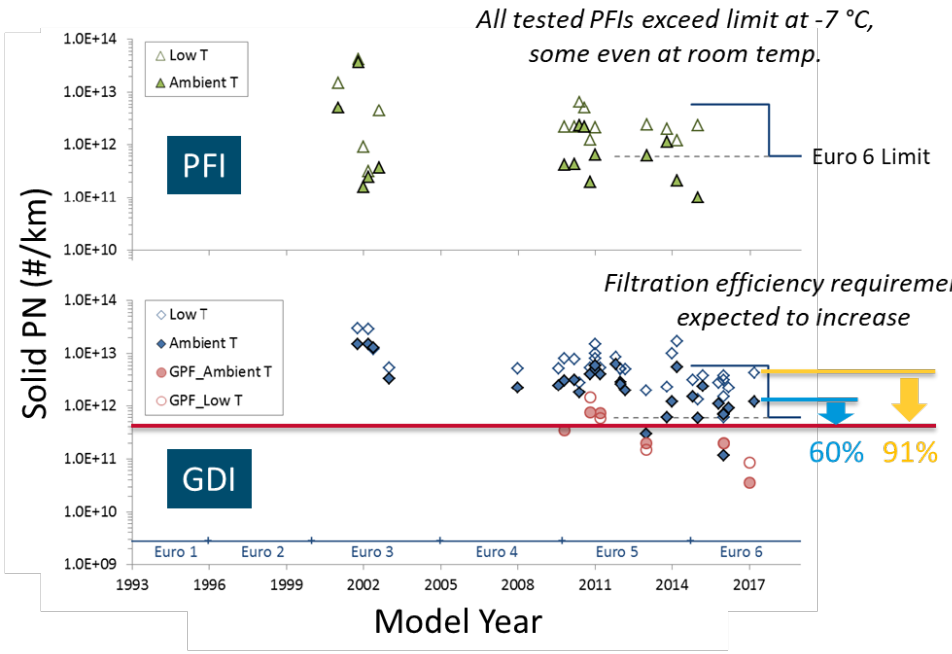
The Mercedes A200 on the ADAC exhaust test bench



Current limits and measured particulate emissions in the ADAC Ecotest

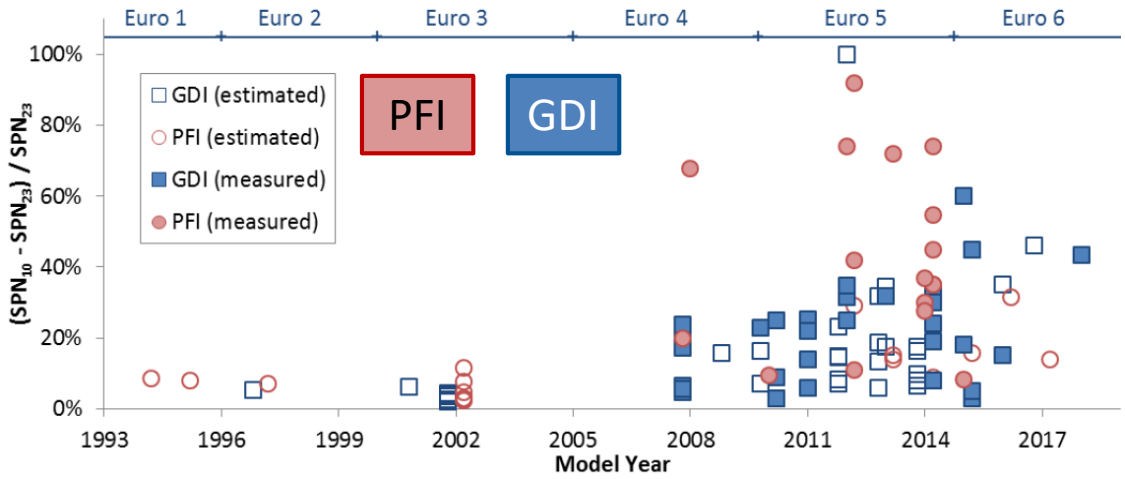
Port fuel injected (PFI) vehicles can also exceed PN limit

JRC, Corning, Aristotle University Catalysts 2019, 9, 586



Solid symbols : ~ 23 °C
Open symbols : - 7 °C

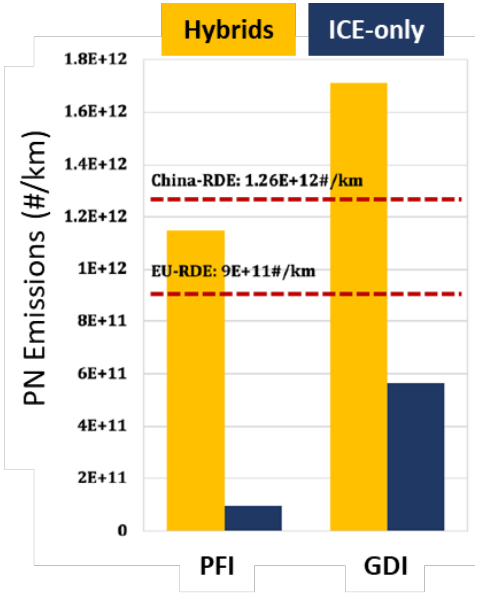
Up to 75% higher PN for PFI when including 10 – 23 nm particles



Hybrids – even PFI – can emit high PN due to engine stop-starts

Beijing Inst. of Technology, U. of Leeds Atmospheric Environment 199 (2019) 70–79

Car No.	Engine type	Model year	After-treatment	Mileage (km)	Emission category
1	In-line, 4 cyl, Atkinson-cycle, 1.8L NA PFI, 73kW	2017/18	Stoichiometric TWC	6065	China-6
2	In-line, 4 cyl, Atkinson-cycle, 2.0L NA GDI, 115kW,	2017/18	Stoichiometric TWC	13722	China-6

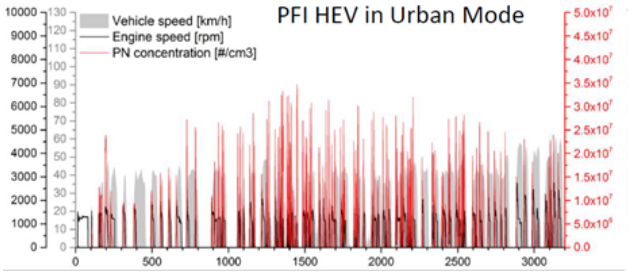


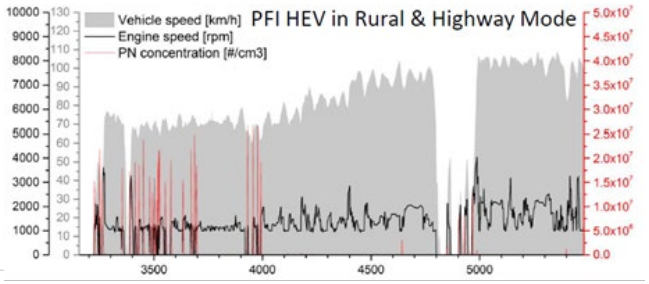
Overall higher PN for hybrids due to stop-start emissions

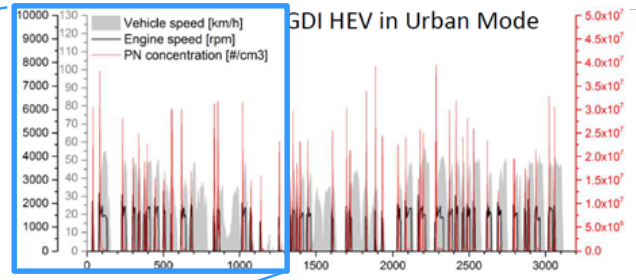
Higher PN for PFI during urban driving

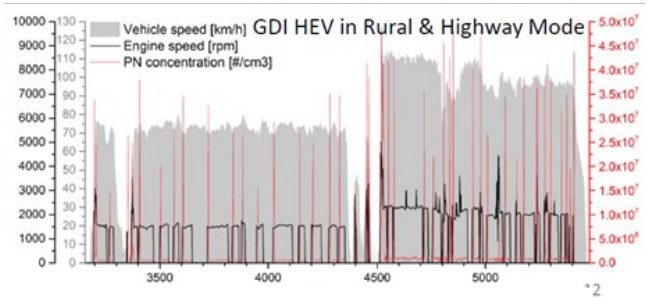
Urban driving

Rural / highway driving







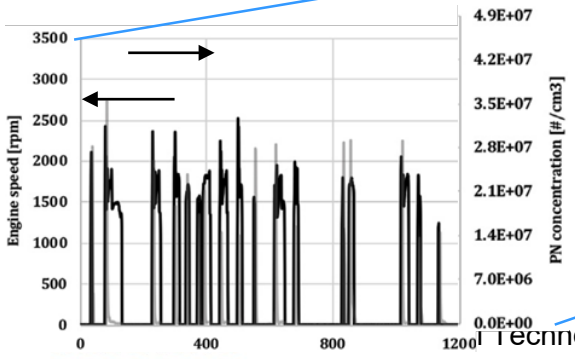


PN (#/cm^3)

PN (#/cm^3)

Time (sec)

Time (sec)



Emissions associated with frequent engine starts

Plug-in hybrids offer significant CO_2 reductions but reduction in electric range at low temperature increases particulates

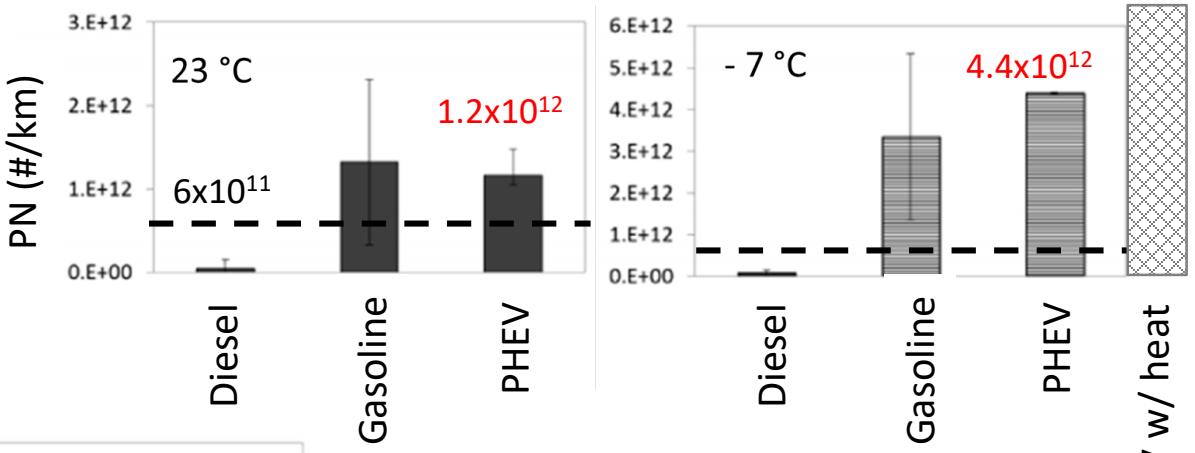
JRC ACS Omega 2019, 4, 3159−3168

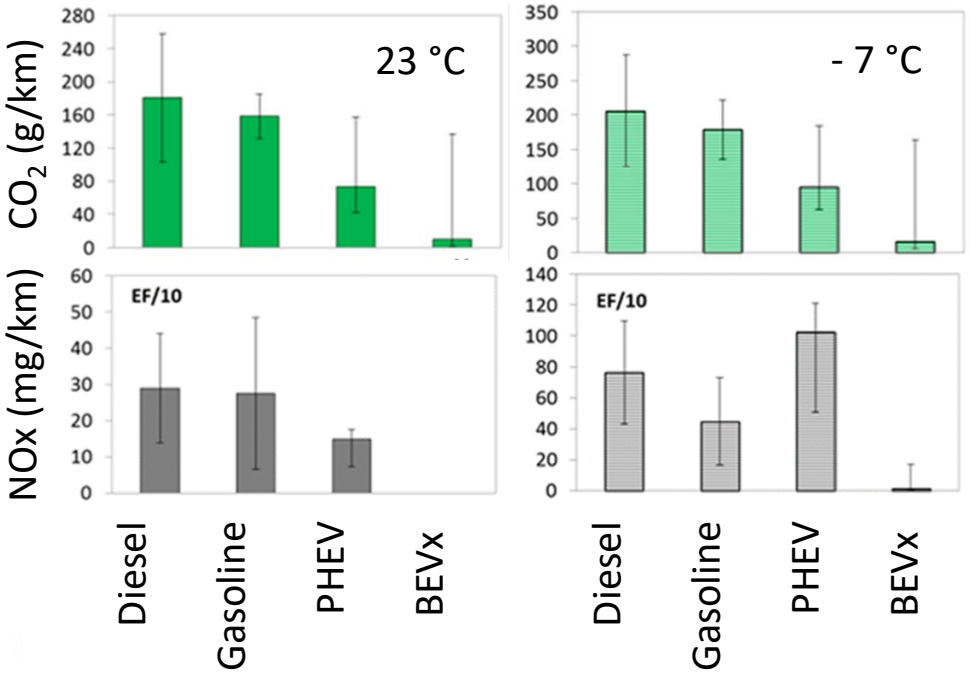
WLTP Testing on CS & CD modes

(1) Euro 6a Parallel PHEV. 1.4L, 110 kW engine.
Battery: 25 Ah, 345 V

(2) US range extender (BEVx) : 0.65L, 25 kW engine.
Battery: 60 Ah, 360 V

PN emissions exceed Euro 6 limit, gasoline & diesel w/ DPF





WLTP testing		23 °C	- 7 °C	- 7 °C + heat	
PHEV	AER (km)	20.1	16.4	15.5	↓ 23%
	CO_2 (g/km)	73	95	126	
BEVx	AER (km)	123	100	73	↓ 41%
	CO_2 (g/km)	10	15	29	

Technologies to reduce criteria pollutants

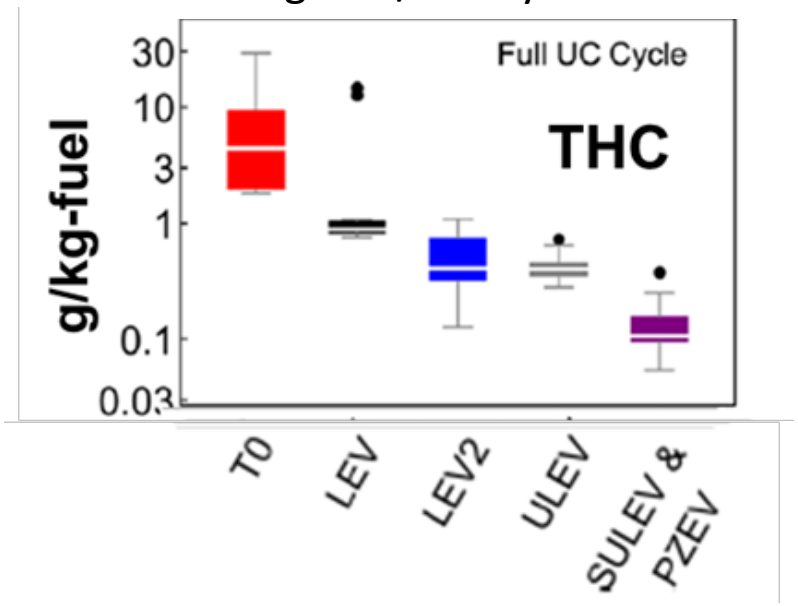
Gas Emissions

Gas emissions: Cold-start is the biggest challenge

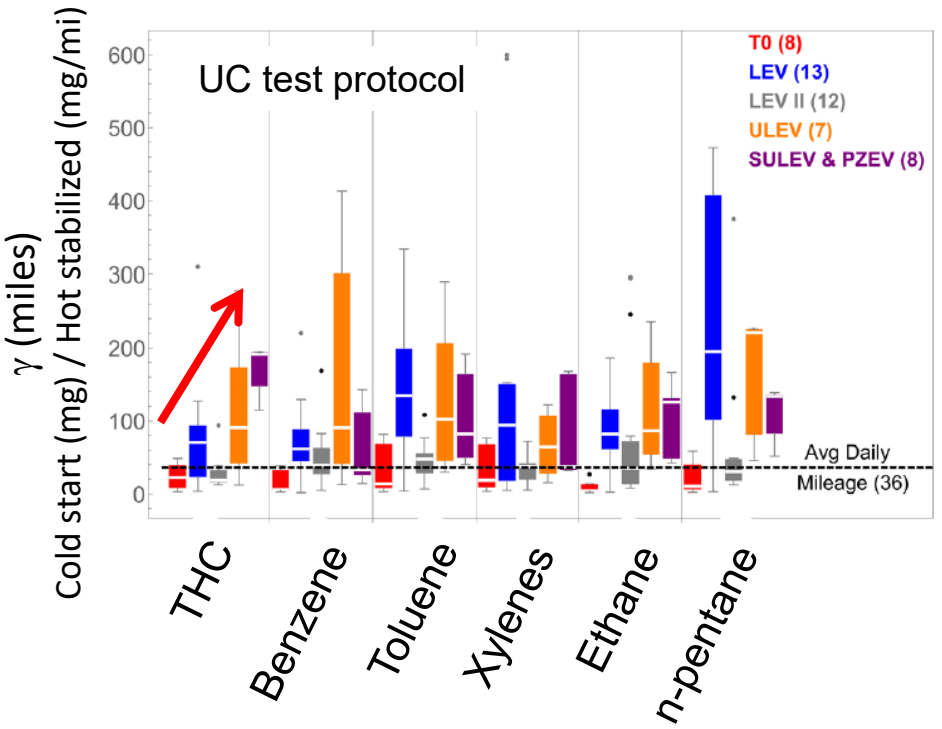
UC Berkeley, Carnegie Mellon, CARB, Env. Sci. Tech, 2016

Legend:
Tier0 **LEV** **LEV II** **ULEV** **SULEV & PZEV**

Emissions have decreased over the years with improved engines / catalysts



<u>But contribution from cold-start is increasing</u>
Hot-stabilized emissions over *200 miles* equal emissions from a single cold start



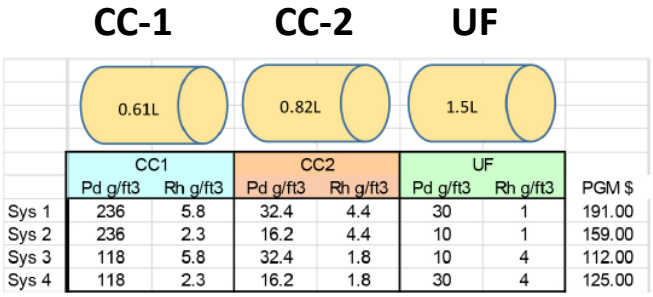
Meeting future regs will require advanced substrates and catalysts
<u>Approach 1</u>: Optimize current catalysts (composition, location, total precious metal content)
<u>Approach 2</u>: Innovative catalyst, substrate and packaging designs

PGM location and fuel S are critically important for lower emissions

Umicore SAE 2017-01-2404

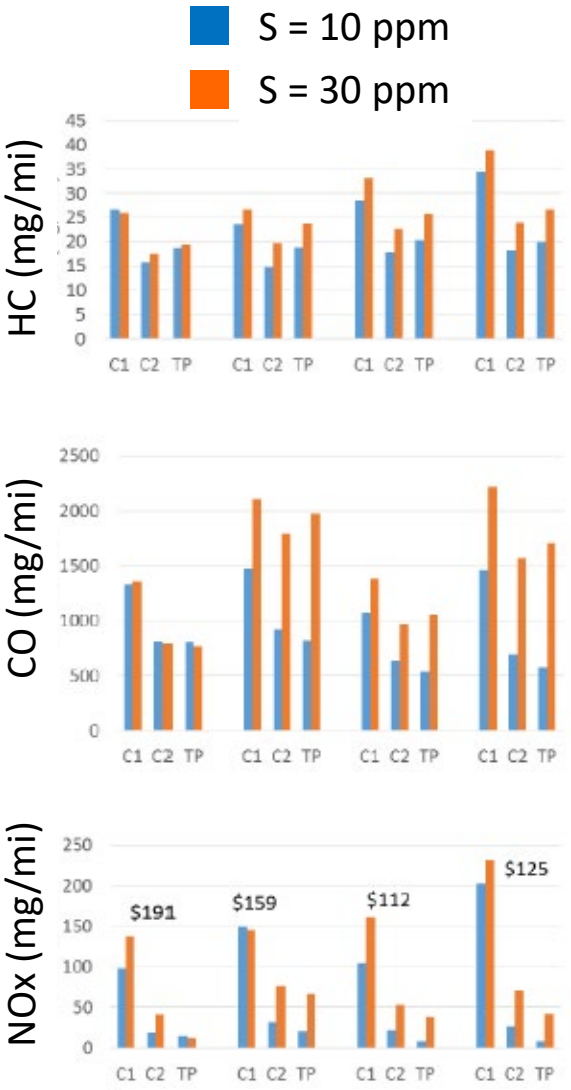
Vehicle: 4-cyl, 2.4L PFI 2009 Malibu
Close-coupled + Underfloor catalysts

- Varying levels of Pd/Rh
- Varying sulfur levels in fuel

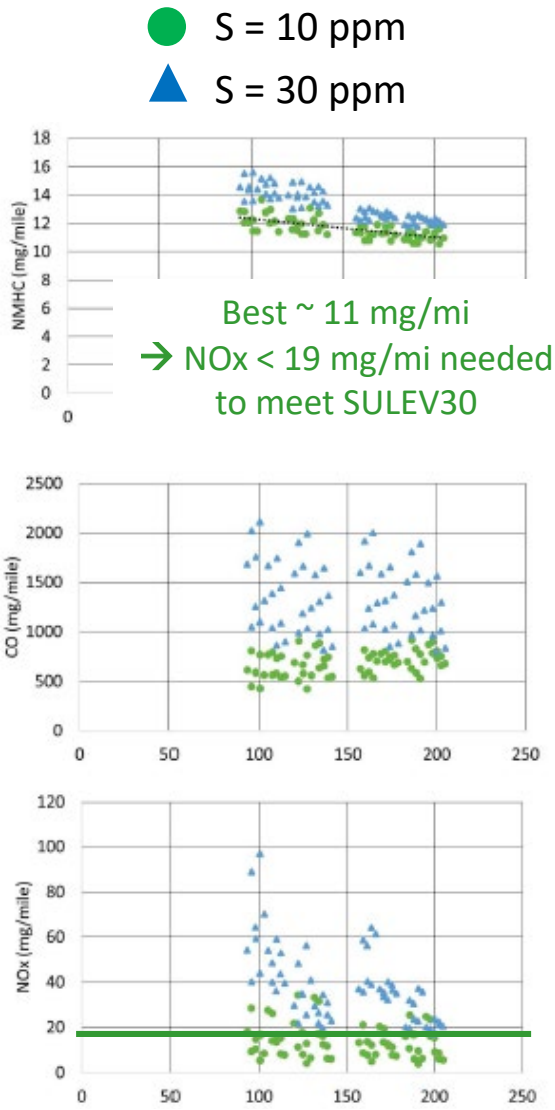


	CC1		CC2		UF		
	Pd g/ft3	Rh g/ft3	Pd g/ft3	Rh g/ft3	Pd g/ft3	Rh g/ft3	PGM $
Sys 1	236	5.8	32.4	4.4	30	1	191.00
Sys 2	236	2.3	16.2	4.4	10	1	159.00
Sys 3	118	5.8	32.4	1.8	10	4	112.00
Sys 4	118	2.3	16.2	1.8	30	4	125.00

- 10 ppm S allows for lower tailpipe emissions with lower PGM
- With 30 ppm S, SULEV30 can barely be met, and requires high PGM loadings ($$)
- PGM placement is critical



Systems 1 – 4



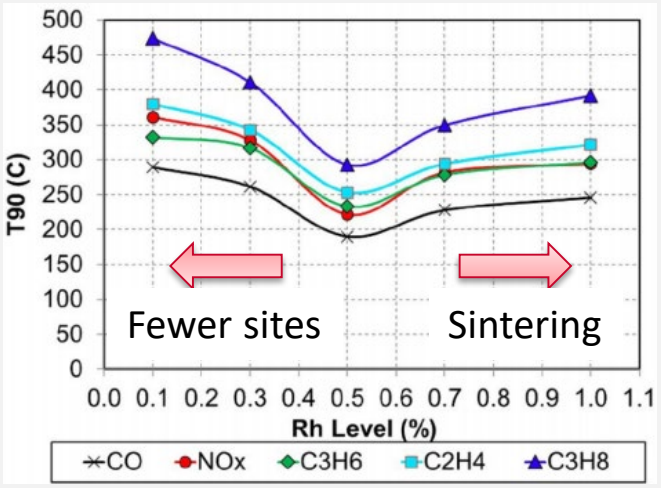
Best ~ 11 mg/mi
→ NOx < 19 mg/mi needed to meet SULEV30

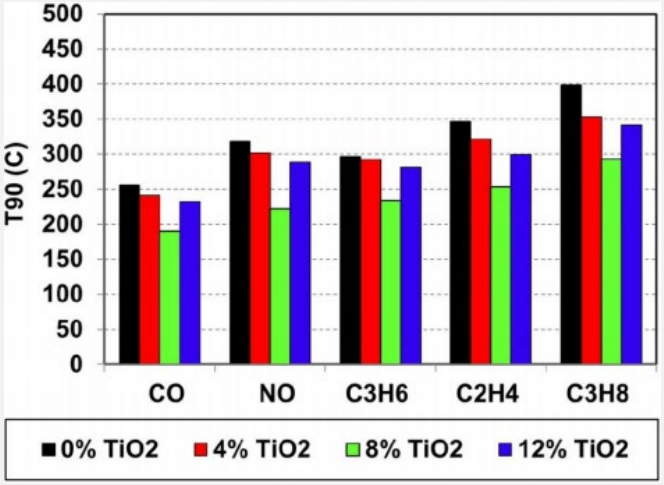
PGM ($)

Improved TWC demonstrates 90% conversion at T < 300 °C
Best: 8% titania overlayer on silica-stabilized alumina with 8% Rh

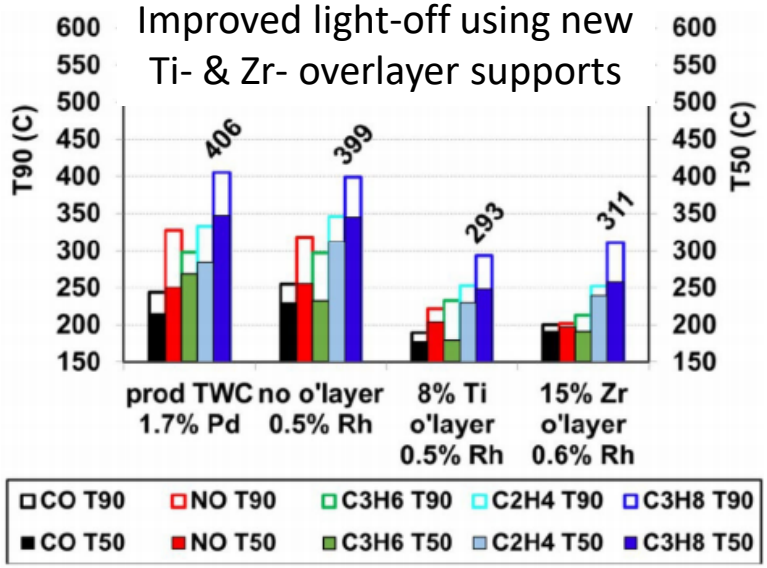
Ford, SAE 2018-01-0939

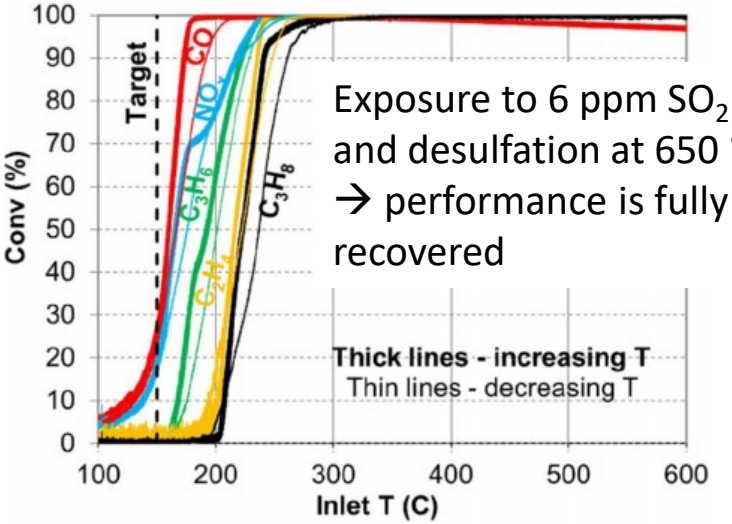
Optimization of Rh and TiO_2 content





Improved light-off using new Ti- & Zr- overlayer supports





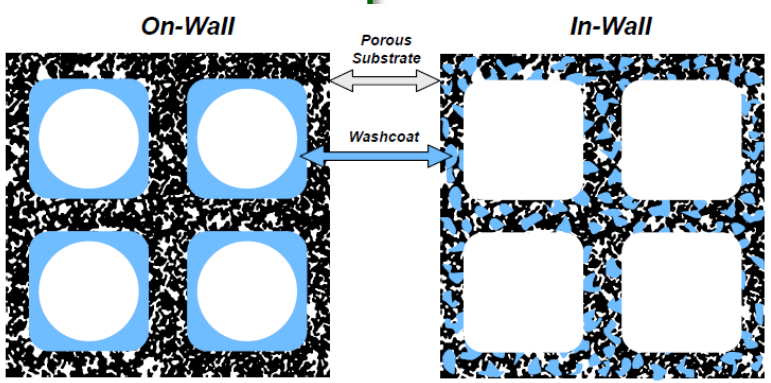
Exposure to 6 ppm SO_2 and desulfation at 650 °C → performance is fully recovered

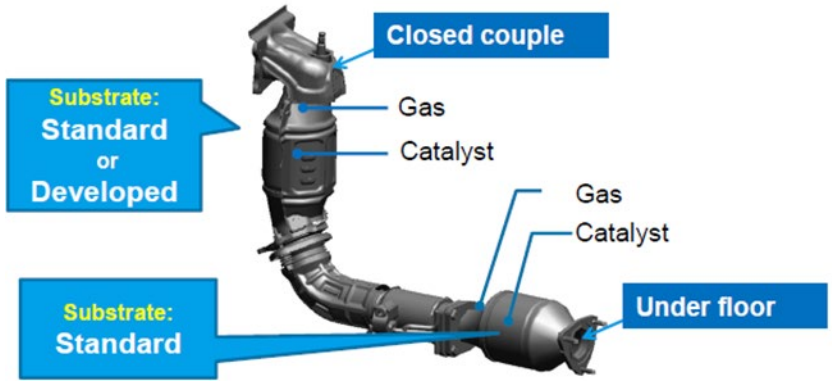
Low thermal mass substrates enable early light-off

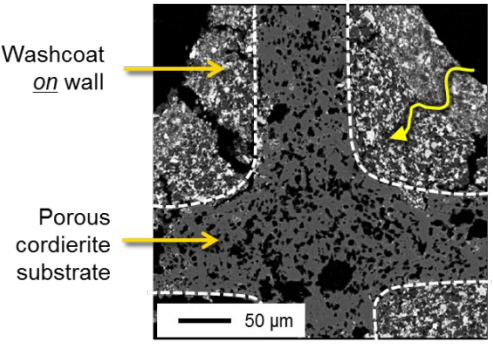
Corning SAE 2015-01-1009, Honda SAE 2015,01-1001

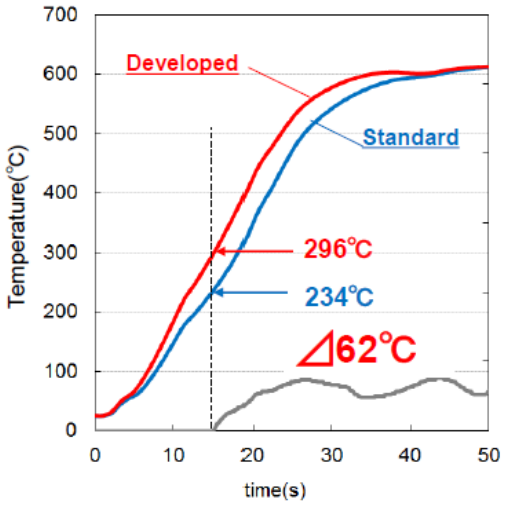
Low thermal mass for early light-off

Large pores for in-wall coating

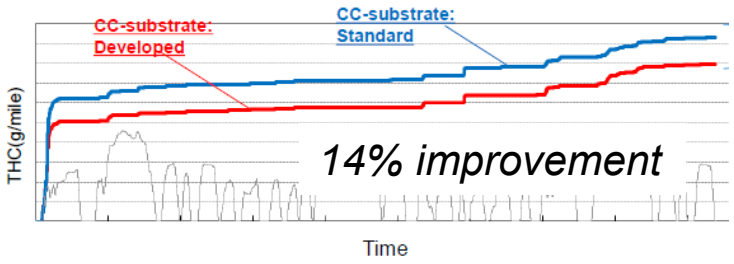




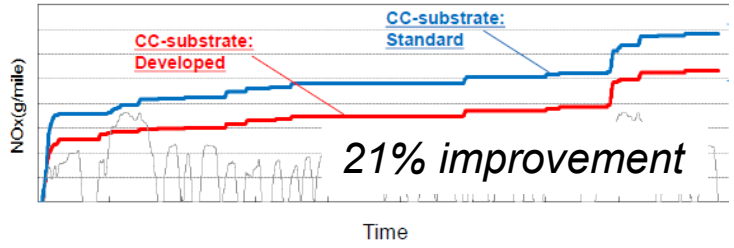




THC



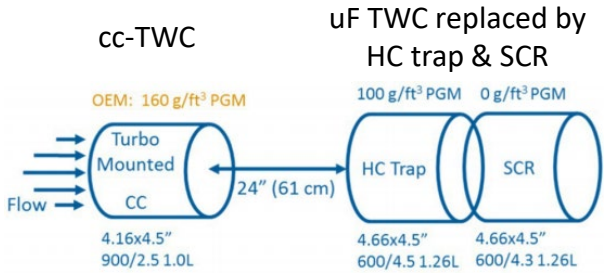
NOx

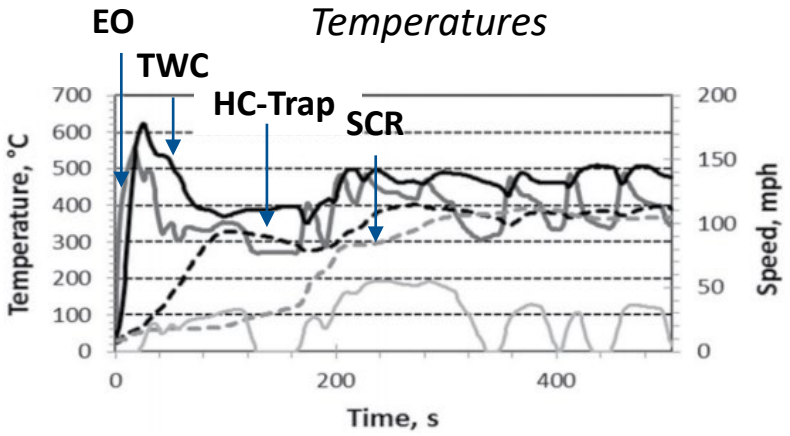


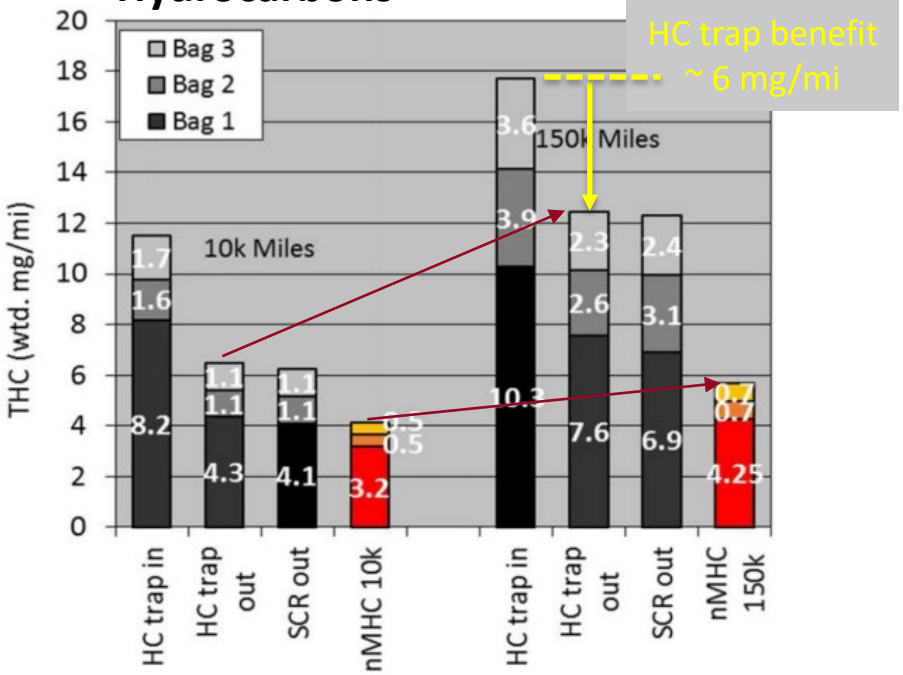
cc-TWC + Underfloor HC trap + pSCR system can meet SULEV30

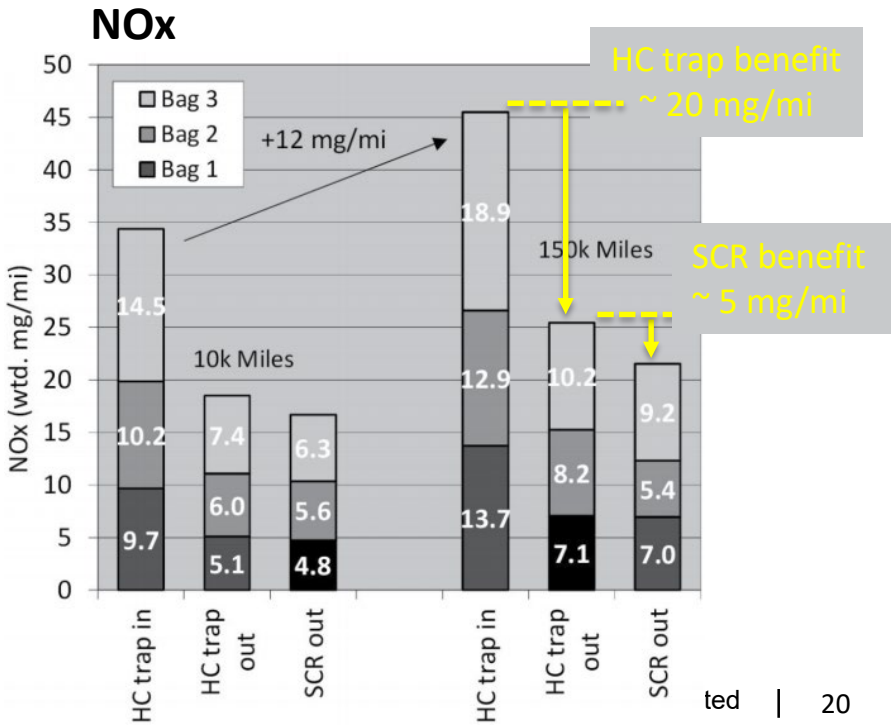
Umicore, SAE 2018-01-0336

Vehicle : 2014 VW Jetta Hybrid, 4-cyl 1.4L GTDI







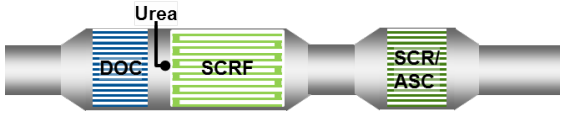
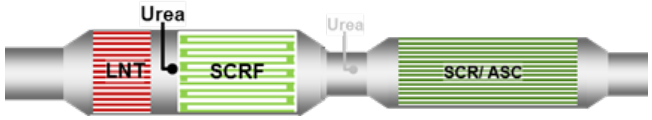
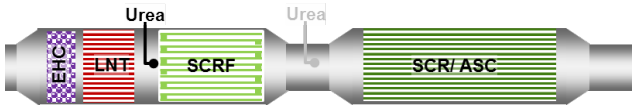


Most loss in performance with aging is associated with CH_4

Technologies to reduce criteria pollutants

Diesel

System architectures are converging across markets

Euro 4		
Euro 5		Introduction of DPFs
Euro 6b CN 6a BS 6	 	NOx control via SCR, LNT Some SCR integration with filters
Euro 6d CN 6b BS 6 w/ RDE		Combining all LNT, SCR on filter and downstream SCR. Possibly dual dosing.
Post Euro 6	 	Larger SCR, active heating measures Close-coupled SCR, dual dosing

First RDE data set indicates significant reductions in real world driving emissions

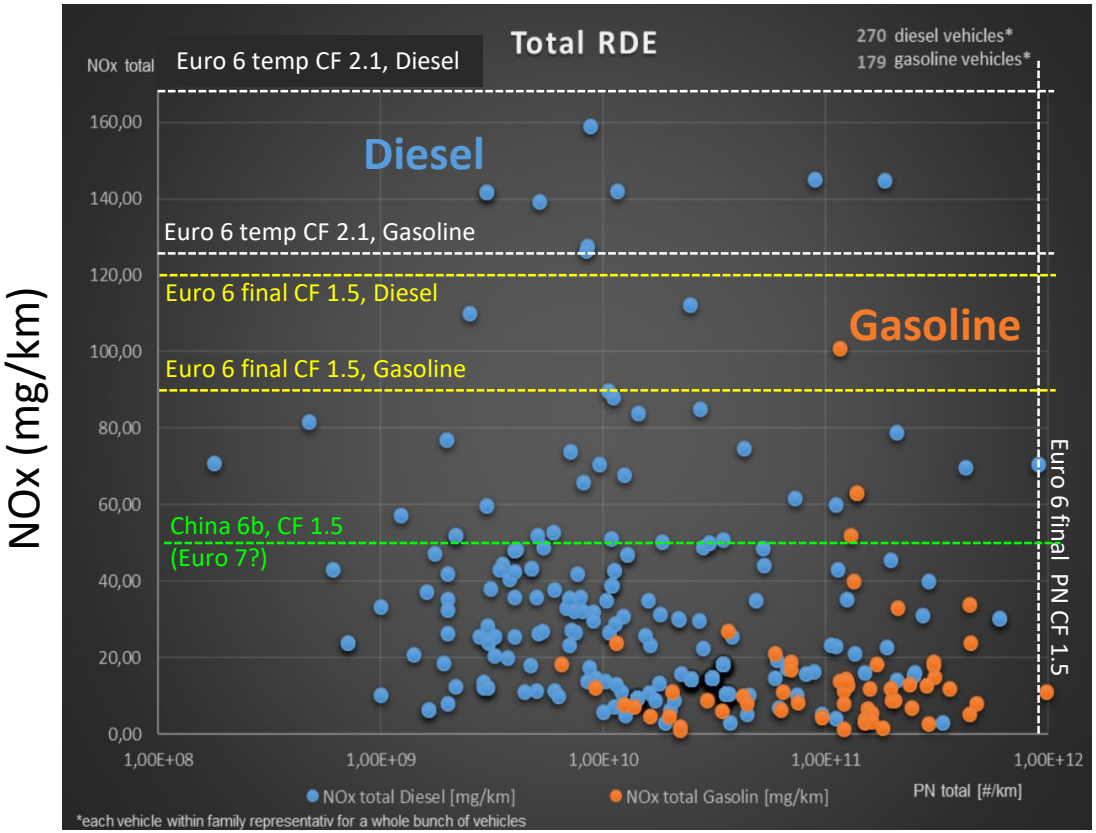
ACEA, EU Commission Stakeholder meeting Oct 24th, 2018

Data from Euro 6d temp vehicles

Emissions within the temp CF of 2.1

- Majority already meet final NOx and PN conformity factor of 1.5
- > 85% diesels and 98% gasoline already meet China 6**b** limit of 35 mg/km with potential CF = 1.5

Total RDE trip emissions
270 diesels, 179 gasoline



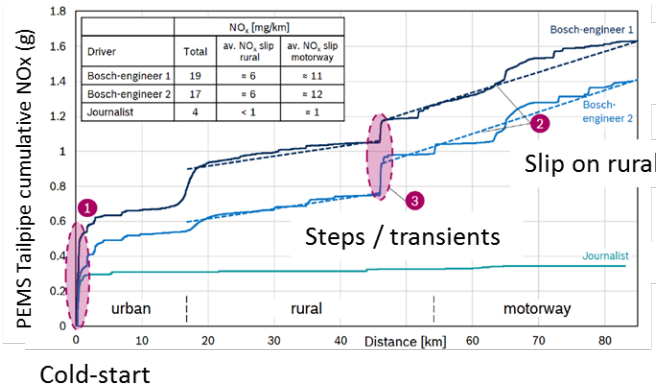
NOx (mg/km)

PN (#/km)

Pathway to < 10 mg/km NOx on RDE demonstrated

Bosch, 19th Stuttgart Int. Symp. 2019

Targets for further NOx reductions



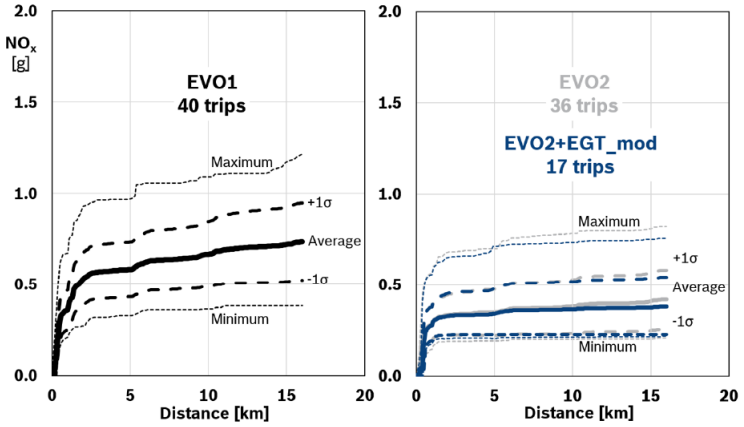
19 mg/km

17 mg/km

Slip on rural / motorway

4 mg/km

Avg. TP NOx ↓ by 30 – 35% on RDE over previously reported average of 13 mg/km

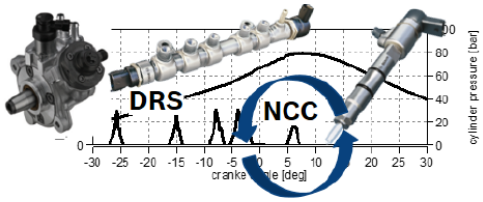


Cold-start + full-load acceleration

Lower engine-out emissions

Fuel injection optimization

Higher inj. P + needle closing control



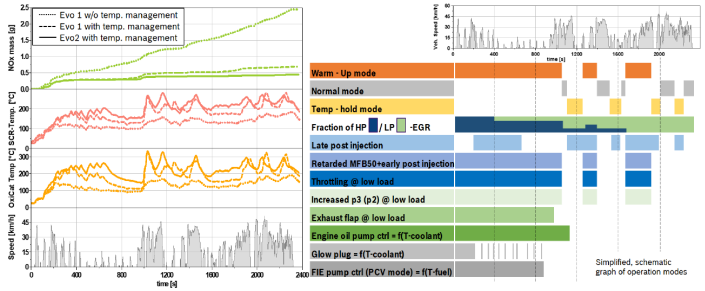
2500 bar FIE + NCC

Cold-start + slow driving

Thermal management

Improved engine calibration

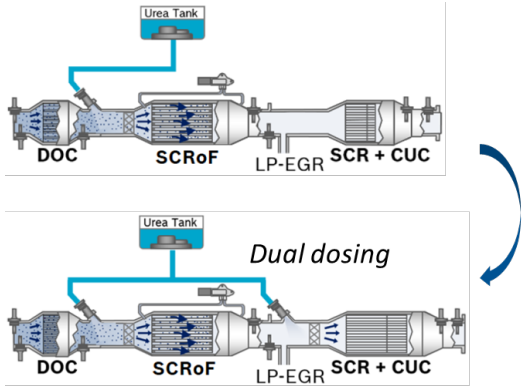
New turbocharger design, HP/LP EGR opt.



Slip during transients, high speed driving

Advanced After-treatment

Dual dosing, Increased uF SCR volume

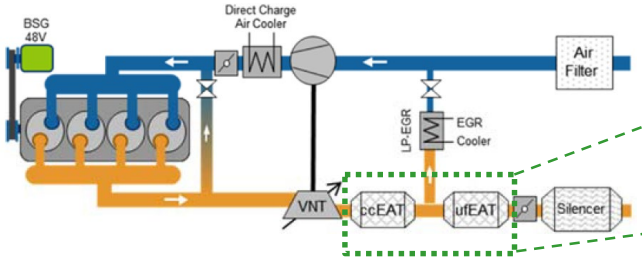


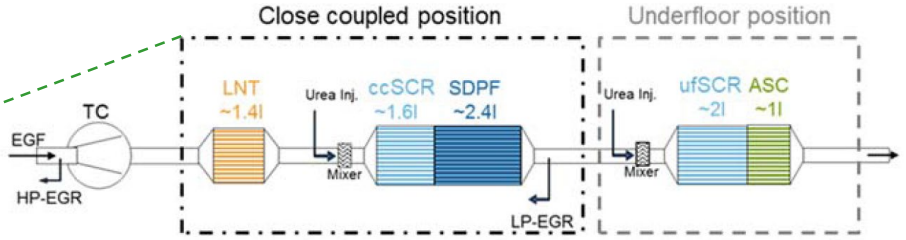
Larger uF SCR

Diesel mild-hybrid and advanced after-treatment offers ultra-low NOx under wide range of driving speeds

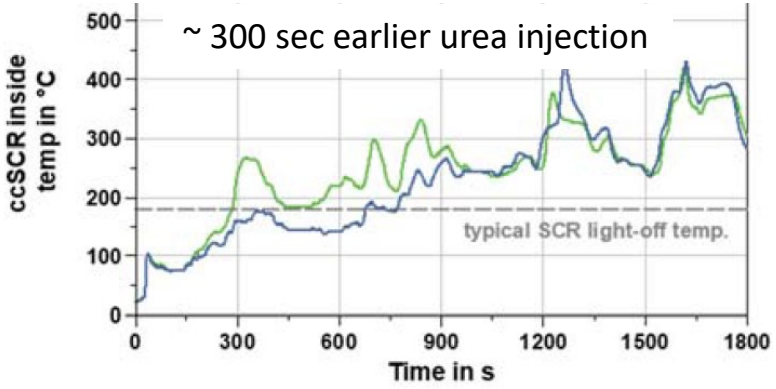
AECC, IAV Int. Vienna Motor Symposium, 2019

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

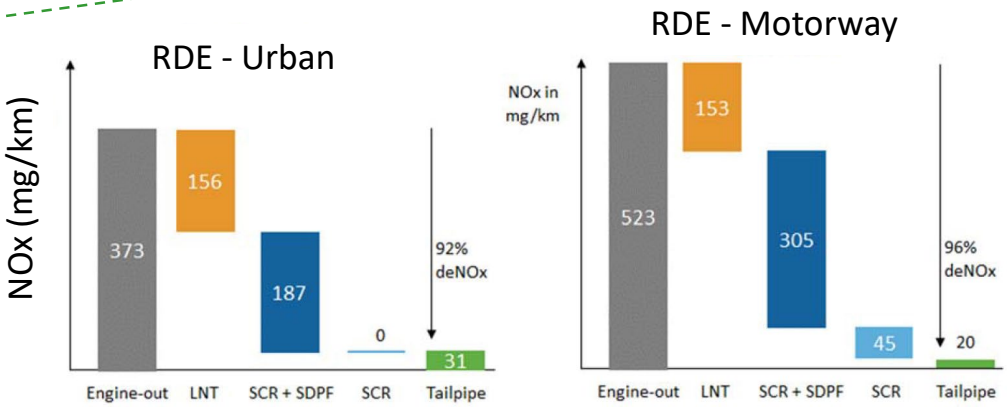


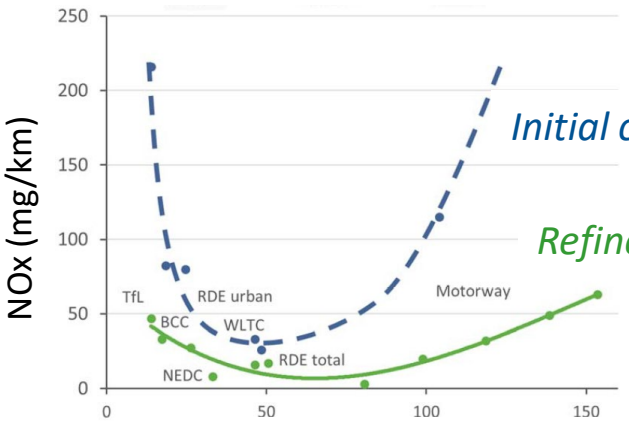


- Active thermal management – electric motor as generator to add load + late post injection for exotherm on LNT
  < 3% fuel penalty



- Electric motor manages transients (high NOx) and prevents LNT regen interruptions





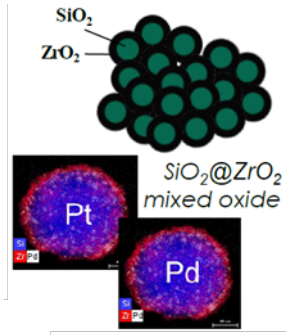
Other
< 10 ppm NH3 slip
Urea 1.5L/1000 km

Diesel Oxidation Catalyst

Some advances apply to both LD and HD

Core-shell DOC being developed for 90% conversion at T < 150 °C

Oak Ridge Natl. Lab, DOE Annual Merit Review 2019



Core-shell catalyst : ZrO_2 on SiO_2 - Pt/Pd supported on shell of ZrO_2

T90 ~ 175 °C for CO

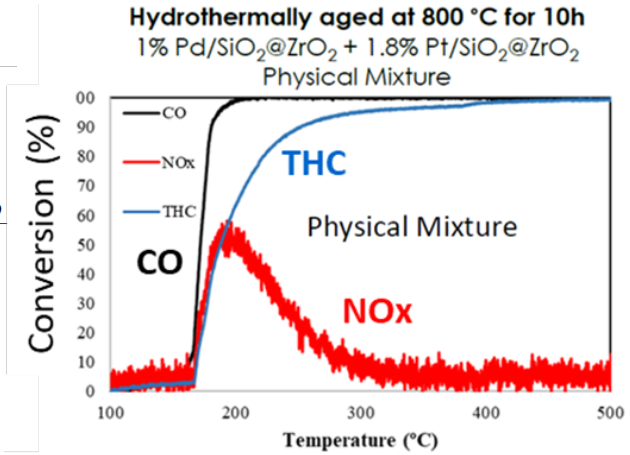
High reactivity for HC but

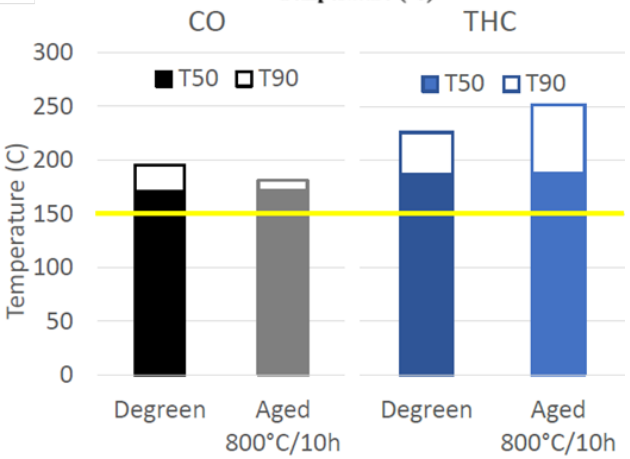
T90 ~ 250 ° C

Conditions during 2ºC ramp

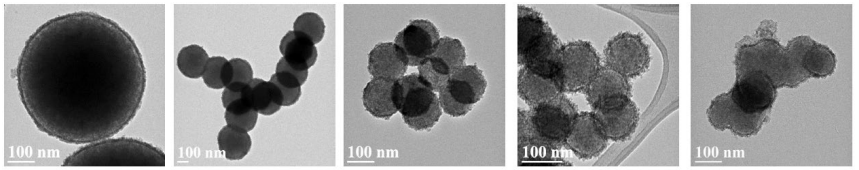
total HC_1:	*3000 ppm*
C_2H_4:	*500 ppm*
C_3H_6:	*300 ppm*
C_3H_8:	*100 ppm*
$C_{10}H_{22}$:	*2100 ppm*
CO:	*2000 ppm*
NO:	*100 ppm*

Also H_2, O_2, H_2O and CO_2





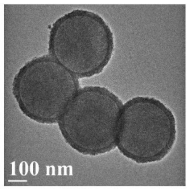
Next: Focus on 150 – 200 nm SiO_2@ZrO_2 particles



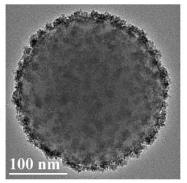
~490 nm ~290 nm ~150-200 nm ~120 nm <100 nm

3.9% 24.1% Pd dispersion

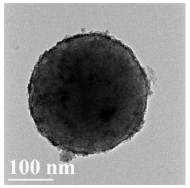
29 nm 4.6 nm Pd size



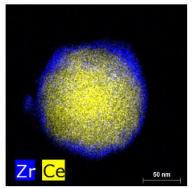
- SiO_2@ZrO_2 core@shell
  - Average diameter: 340 nm



- SiO_2@CeO_2 core@shell
  - Average diameter: 260 nm



- SiO_2@CeO_2-ZrO_2 core@shell
  - Average diameter: 260 nm

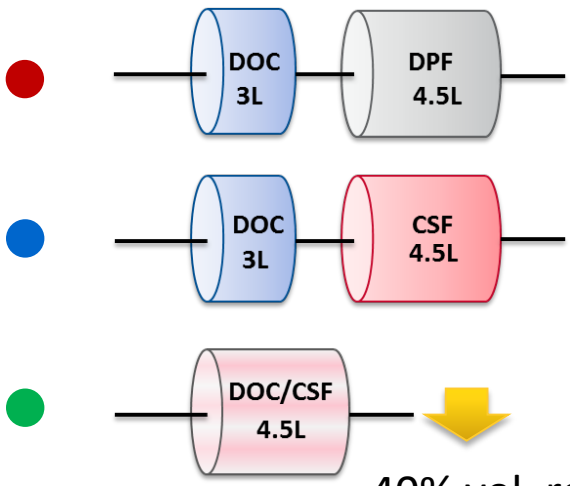


- CeO_2@ZrO_2 core@shell
  - Average diameter: 150 nm

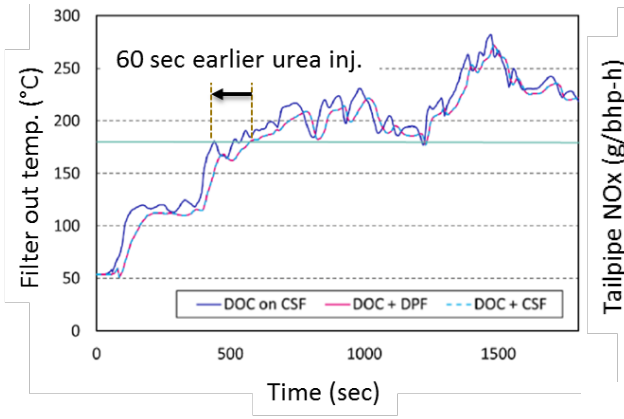
OAK RIDGE National Laboratory | NATIONAL TRANSPORTATION RESEARCH CENTER

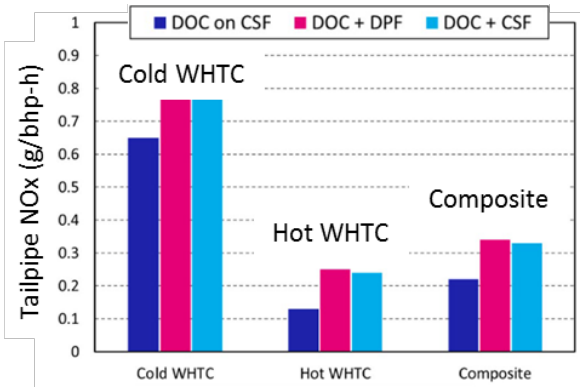
Combination of DOC and catalyzed DPF : Lower thermal mass = faster warm-up & earlier urea injection

JM, SAE 2019-01-0586



Simulations: 40% vol. reduction leads to faster warm-up → earlier urea injection

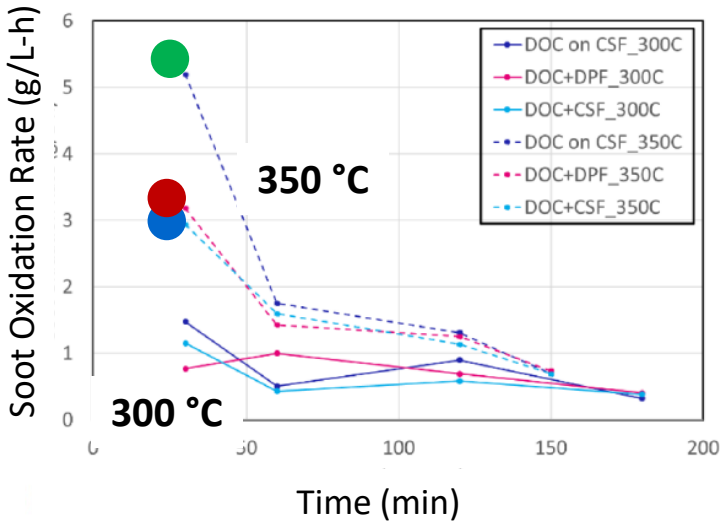




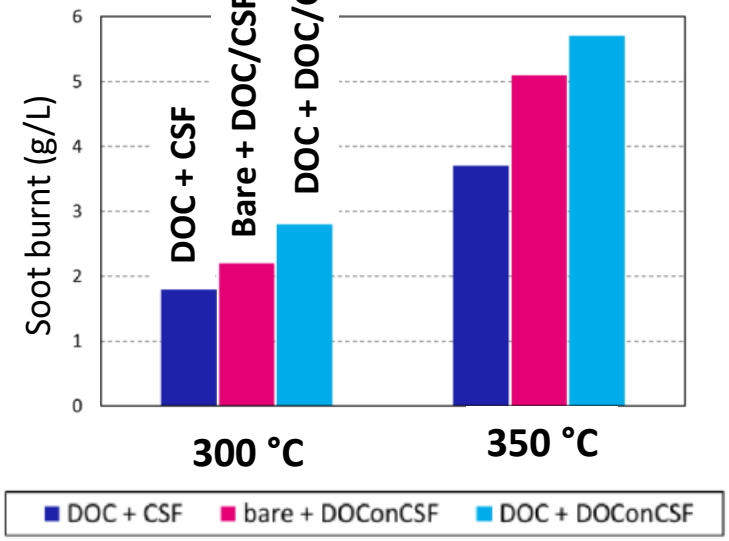
Most oxidation due to NO_2 back-diffusion

Passive soot oxidation

Initial SL = 5 g/L, SV = 100K hr^{-1}



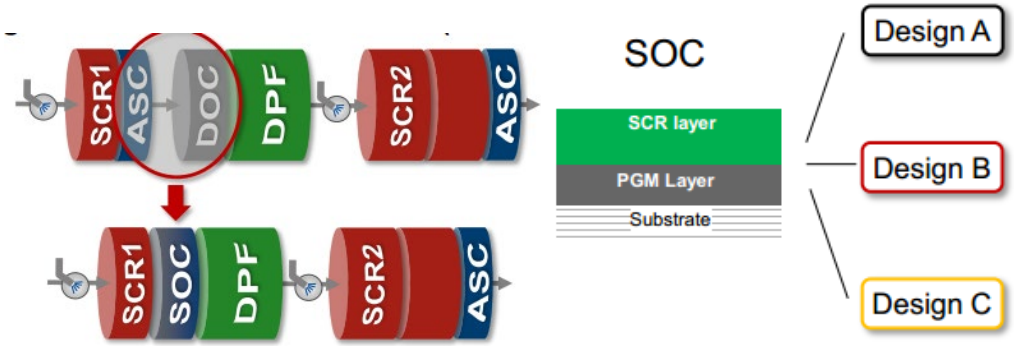
Higher soot oxidation rate for DOC/CSF due to higher PGM on filter

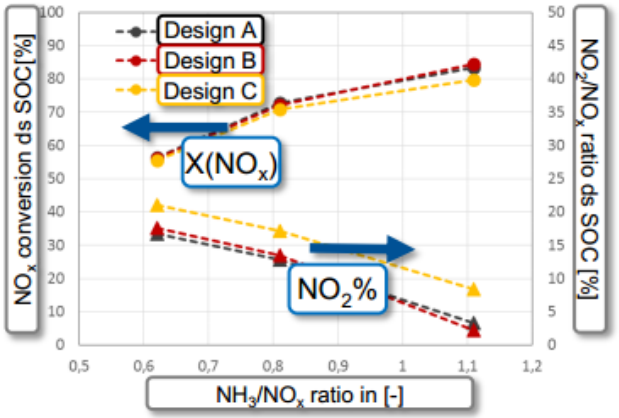


New hybrid catalysts combining DOC and ASC functionality are being developed. Challenge is to retain NO_2 with ammonia inhibition.

SAE HDD Symposium, Gothenburg 2018

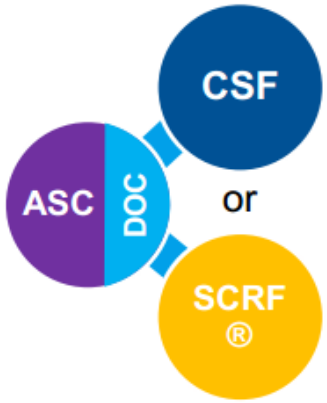
Umicore

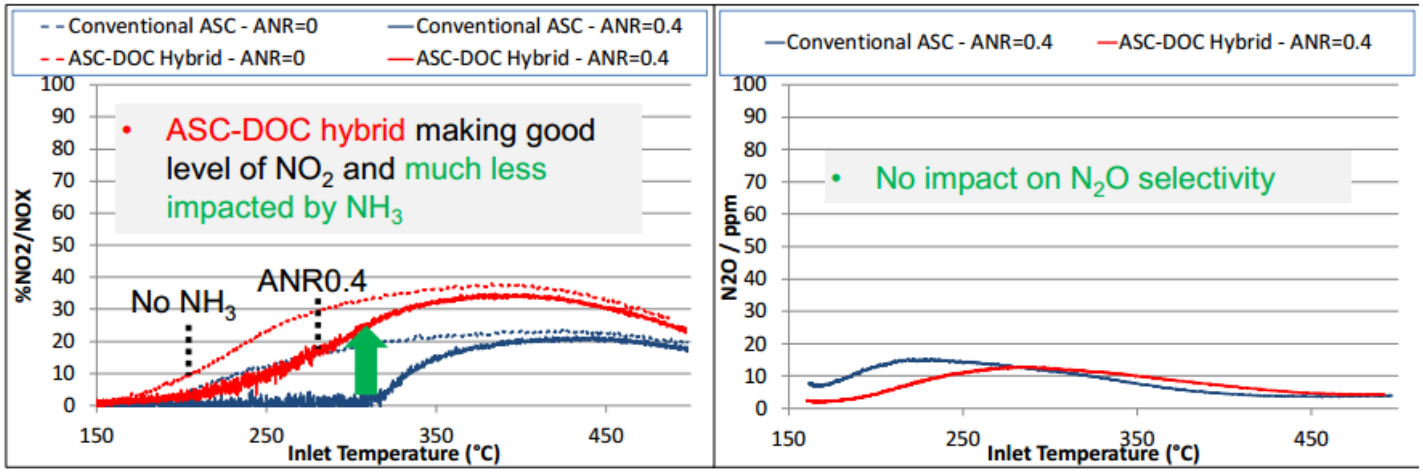




Increased Urea dosing shows negative impact on NO_2 formation
→ Competition with SCR reaction

JM





500ppm NO feed, 55K SV

CORNING