SAE INTERNATIONAL

WCX™ APRIL 9-11 2019 DETROIT

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# Review of Vehicle Engine Efficiency and Emissions

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CORNING

# Summary

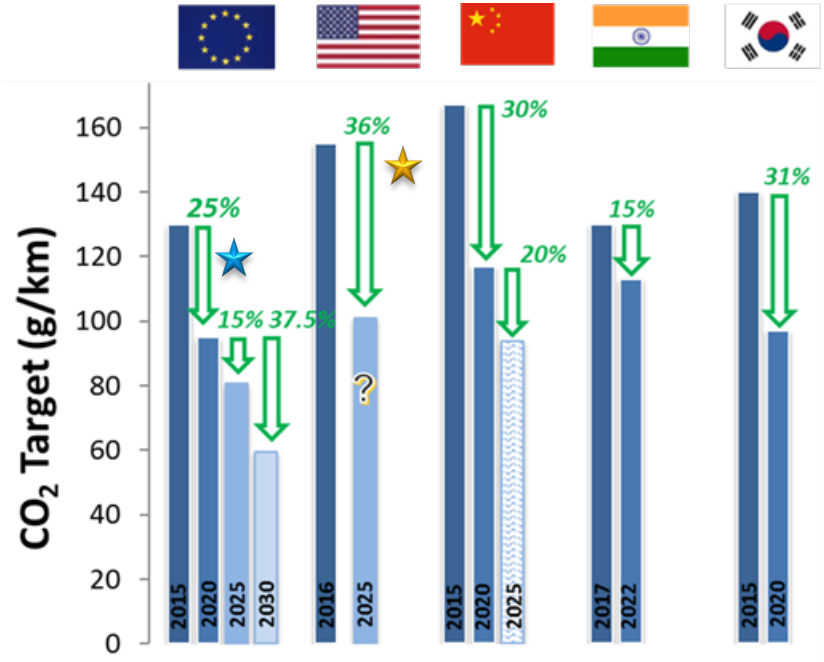
Light-Duty

- Europe has set the tightest $CO_2$ standards : 37.5% reduction by 2030, along with electrification mandates.
- There is still significant untapped potential for ICE technologies. Much more efficiency improvements to come. Synergistic gains with hybridization ahead.
- First emissions data from RDE compliant vehicles published. Both gasoline & diesels exceed Euro 6 norms.
- Gasoline particulate filters are being deployed in EU/China. Even some PFI and hybrids may require GPFs.
- Addressing cold start emissions critical to meet SULEV30. TWCs continue to improve, but may require addition of HC traps.

Heavy-Duty

- Europe has established its first-ever $CO_2$ standards : 30% reduction needed by 2030, compared to 2019
- SuperTruck II program is promising impressive gains in fuel efficiency – leading concepts reviewed
- Several filter-enforcing regulations in place : China VI, BS VI, non-road Tier 4, Brazil PROCONVE P8
- California is leading the development of an omnibus rule for lower in-use NOx emissions

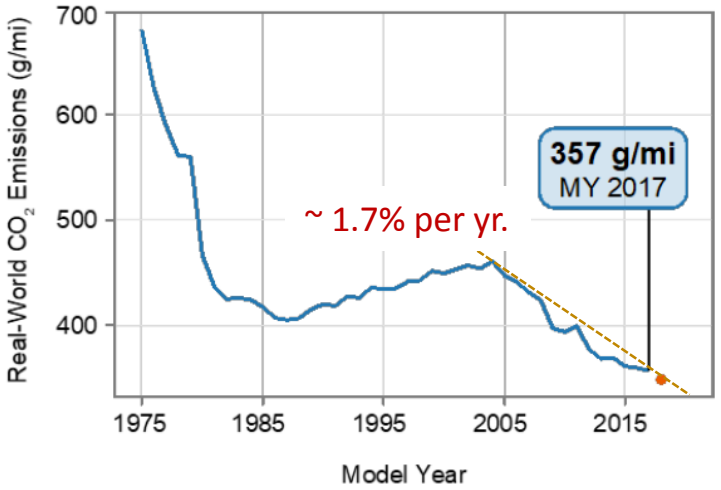
# Major markets have mandated 3 – 6% reductions in tailpipe $CO_2$ + Electrification targets in California, China and Europe




★ US 2017 compliance = 146 g/km (235 g/mi)

★ EU 2017 NEDC = 119 g/km

EPA 2018 Fuel Economy report




EU electrification mandate (ZLEVs) : $CO_2$ < 50 g/km

- Targets for ZLEV cars: 15% by 2025, 35% by 2030
- Vehicles count from 0.3 to 1 depending on TP $CO_2$
- BEVs count as full ZLEV, plug-ins from 0.3 to 1

# Gasoline Engines & After-treatment

## Fuel Economy and Advances in Engine Technology

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# There is significant untapped potential of advanced ICE technologies

EPA, SAE 2018-01-0319 & High Eff. ICE Conference 2018

- Early implement
- Nearing maturity
- Not implemented

## Benchmarking of Honda Civic 1.5L engine

6.7% improvement over MY 2013 1.6L T (VVT, CVT, ..)

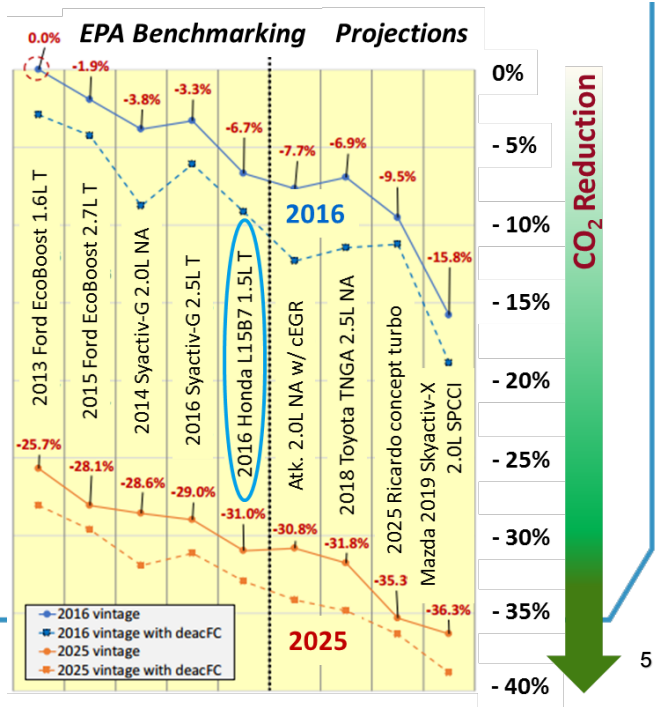
VVT, Integ. Exh. Man., High CR, Friction ↓, ↑ S/B ratio, Boosting, c-EGR, VVL, Miller Cycle, VNT/VGT, Cyl. Deac., Dyn. Cyl. Deac., VCR, SPCCI / Lean burn

| | | |
|---|---|---|
| Ford EcoBoost 1.6L | 2010 | |
| Ford EcoBoost 2.7L | 2015 | |
| **Honda L15B7 1.5L** | **2016** | |
| Mazda SKYACTIV-G 2.5L | 2016 | 4, 4 |
| VW EA888-3B 2.0L | 2018 | |
| VW EA211 EVO 1.5L | 2019 | ?[3] |
| VW/Audi EA839 3.0L V6 | 2018 | ?[3] |
| Nissan MR20 DDT VCR 2.1L | 2018 | +, ?[3], ?[3], ?[3], ?[3] |
| Mazda SKYACTIV-X SPCCI 2.0L SC[1] | 2019 | +, ?[3], NA |
| EPA/Ricardo EGRB24 1.2L[2] | N/A | |

-0314

## 2016 → 2025 (Mid-sized cars)

- 10% ↓ aero & rolling resistance
- Start/stop
- Higher eff. accessories
- Weight ↓ (7%)



# Advanced combustion technologies coupled with electrification are being adopted to reduce fuel consumption

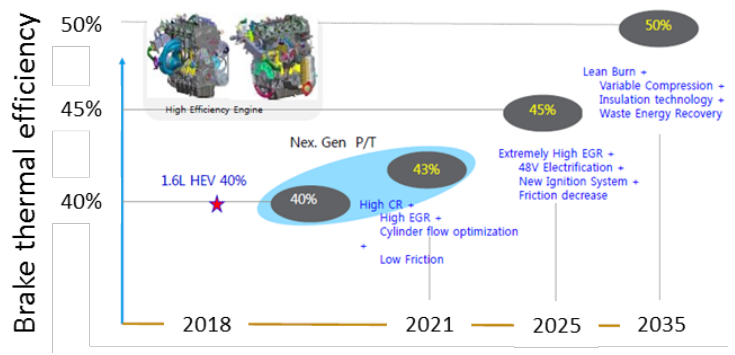
| Technology | Fuel Consumption / $CO_2$ Reduction |
|---|---|
| Direct Injection | 1.5% |
| c-EGR | 2 – 5% |
| High CR (Atkinson cycle, c-EGR, DI, VVT) | 10 – 14% |
| Miller cycle (Turbocharged Atk., c-EGR) | 12 – 20% |
| Variable CR | 10 – 15% |
| Dyn. cylinder deactivation (+ VVL) | 6 – 8% |
| Adv. turbocharging, e-boost | 5% |
| 2-stroke opp. piston (Diesel, GCI) | 30 – 50% |
| Dedicated-EGR | 10% |
| Water Injection | 5 – 7% |
| On-board separation of high RON fuel | 10 – 15% |
| Lean-burn gasoline | 10 – 15% |
| HCCI w/ spark assist | 20 – 30% |
| Low T Comb. (GDCI, RCCI) | > 35% |

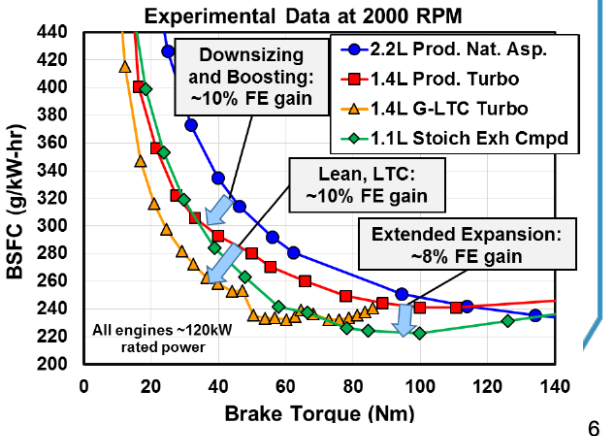
+3% synergy with mild hybridization

HMC : High CR, 48V, Low friction, VCR, WHR

GM : Downsizing, lean-burn, turbo-compounding

SAE High Eff. ICE Conference, 2018



# Technologies being explored to reduce exhaust T & enable λ = 1 operation without power loss

Fuel enrichment increases fuel consumption and high CO emissions

High CR for fuel efficiency

↓

High temp. at high loads

↓

Engine knock, thermal stress for downstream components

## Solutions

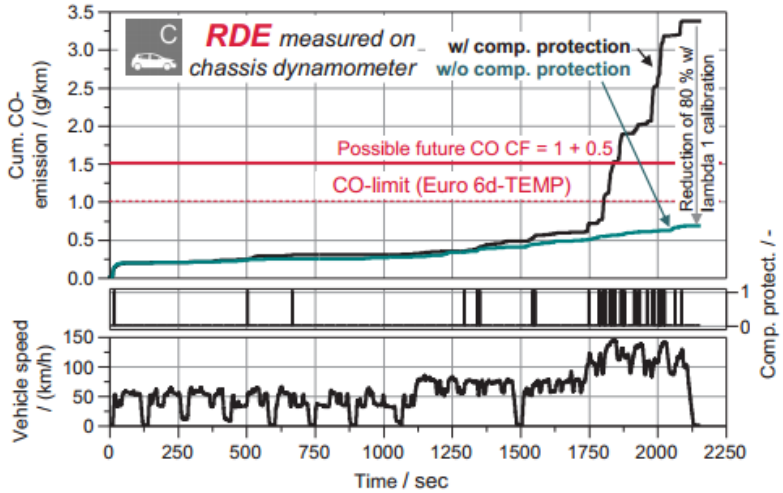
Variable compression ratio (VCR)

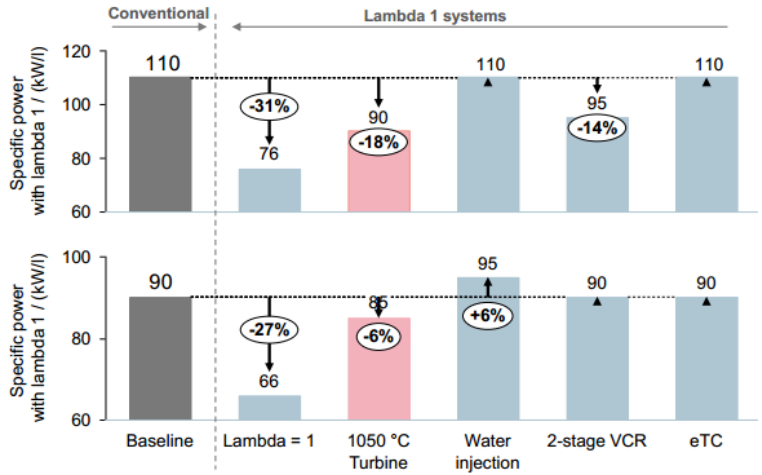
Improved turbines & catalysts

Water injection (WI)

Octane on demand (OOD)

FEV, Aachen Univ. 30th Int. AVL Conf. "Engine & Environment", 2018



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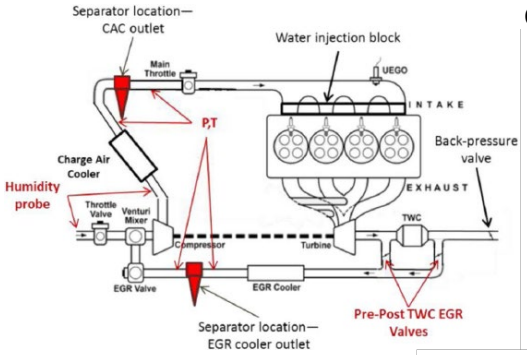
# Potential for water recovery from exhaust explored for water injection

Tenneco, SAE 2018-01-0369

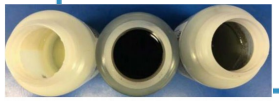
2.0L GDI, CR 9.5:1, LP-EGR, Water : port injected

Two locations for water separation:

1. Post EGR cooler
2. Post charge air cooler

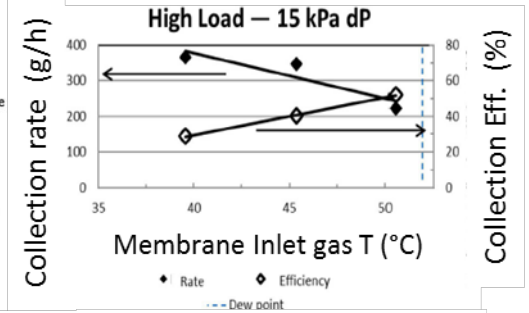



Water quality best for membrane separator



MEM Active Cyclone

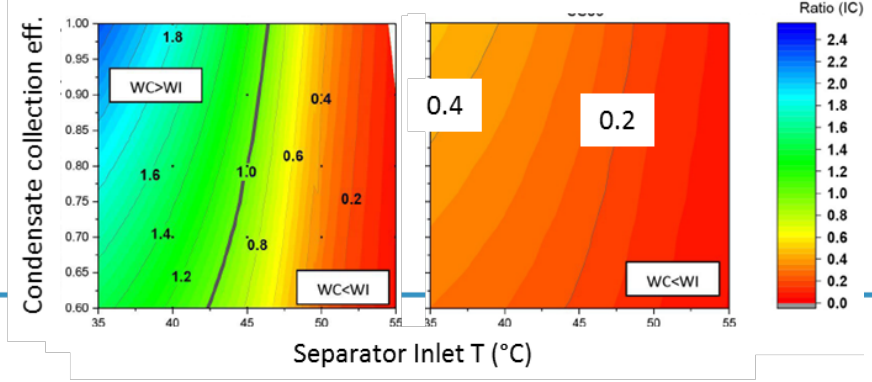
Condensate collection rate & efficiency is sensitive to inlet gas T




*Simulations*

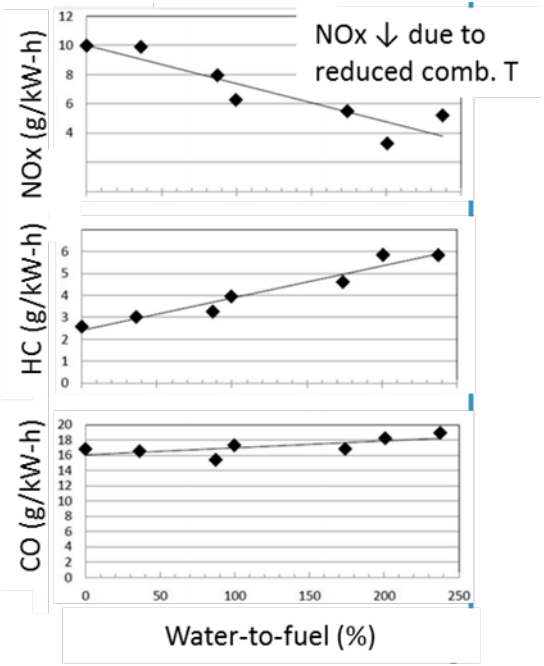
FTP : Sufficient water

US06: 40 – 70% of required water collected




## High Load

3000 rpm, 14bar BMEP, 10% EGR




Full load fuel economy improved by 13%

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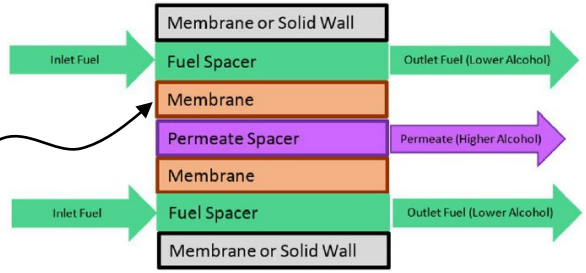
# "Octane on demand" : On-board separation of ethanol can deliver >20% improvement in fuel economy

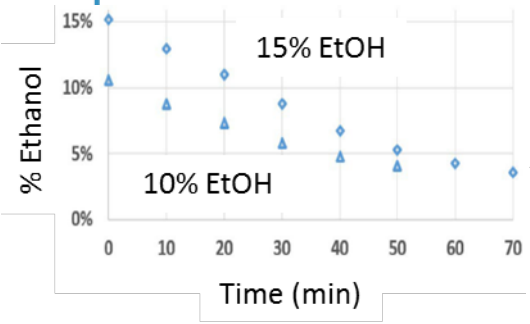
Honda, 3M SAE 2018-01-0882  MIT, 3M SAE 2018-01-0879

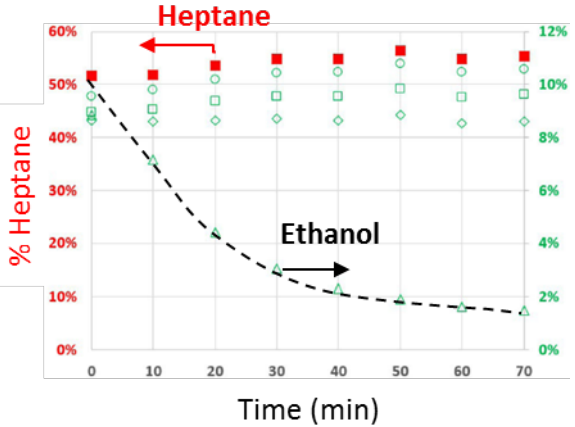
Separation of high & low octane components via pervaporation membrane

Organic membrane supported by porous polymer




## Concentrations in the retentate

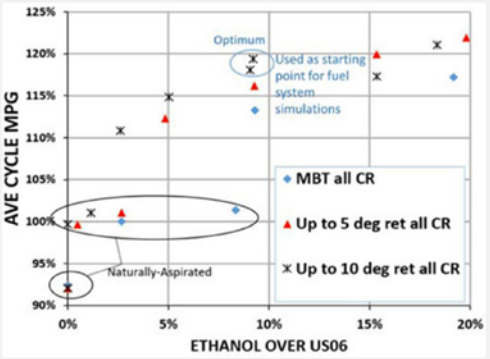


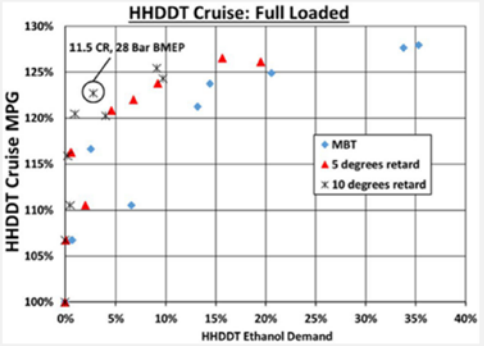

| 70 minute run | EtOH | Toluene | o-Xylene | TMB |
|---|---|---|---|---|
| Initial fuel | 8.9% | 8.6% | 8.9% | 9.5% |
| Final fuel | 1.5% | 8.6% | 9.6% | 10.6% |
| Permeate | 66.1% | 8.5% | 3.6% | 1.8% |

## Fuel economy simulations (GT-Power + Autonomie)

Toyota Camry
20% improvement over US06 compared to baseline NA engine with CR 11.5:1




Ford F550 Truck
(fully loaded)
25% improvement over HHDDT cruise cycle compared to baseline NA engine with CR 9.2:1



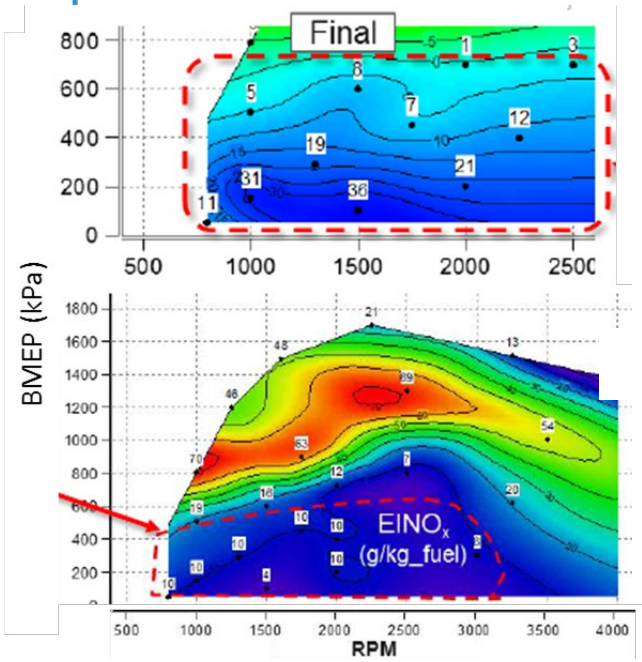
# Lean + Miller combustion : 18% fuel efficiency gains
# After-treatment complexity and cost needs to be addressed

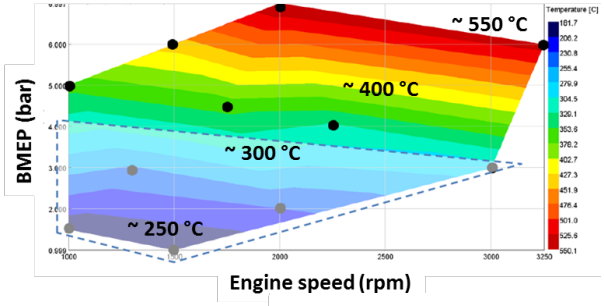
GM, DOE Annual Merit Review, 2018

## Reduction of fuel consumption

Lean Miller (LIVC) - 18%, 3.5L PFI → 2.5L DI

Turbo : - 8%, Stop-start : - 4%, Lean A/T : +1%




Temp. @ TWC inlet mostly < 300 °C

Active urea dosing for NOx control

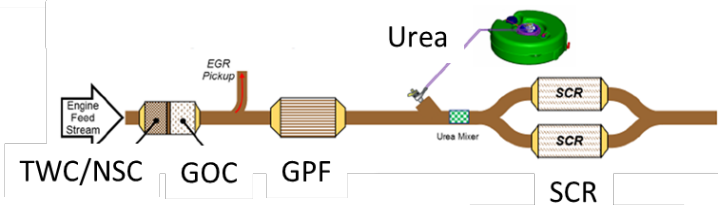
## Strategy

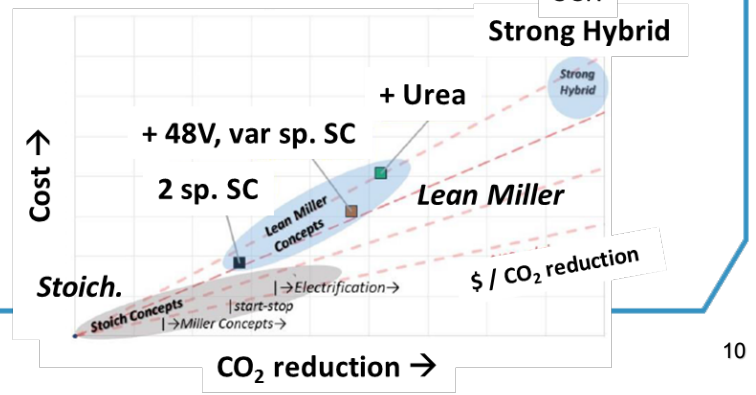
High-loads

Stoich-Miller

Part-loads (< 6bar BMEP, ~ 70% of FTP)

- Lean Miller
- Engine-out NOx ≤ 10 g/kg-fuel



# Light-Duty Regulations

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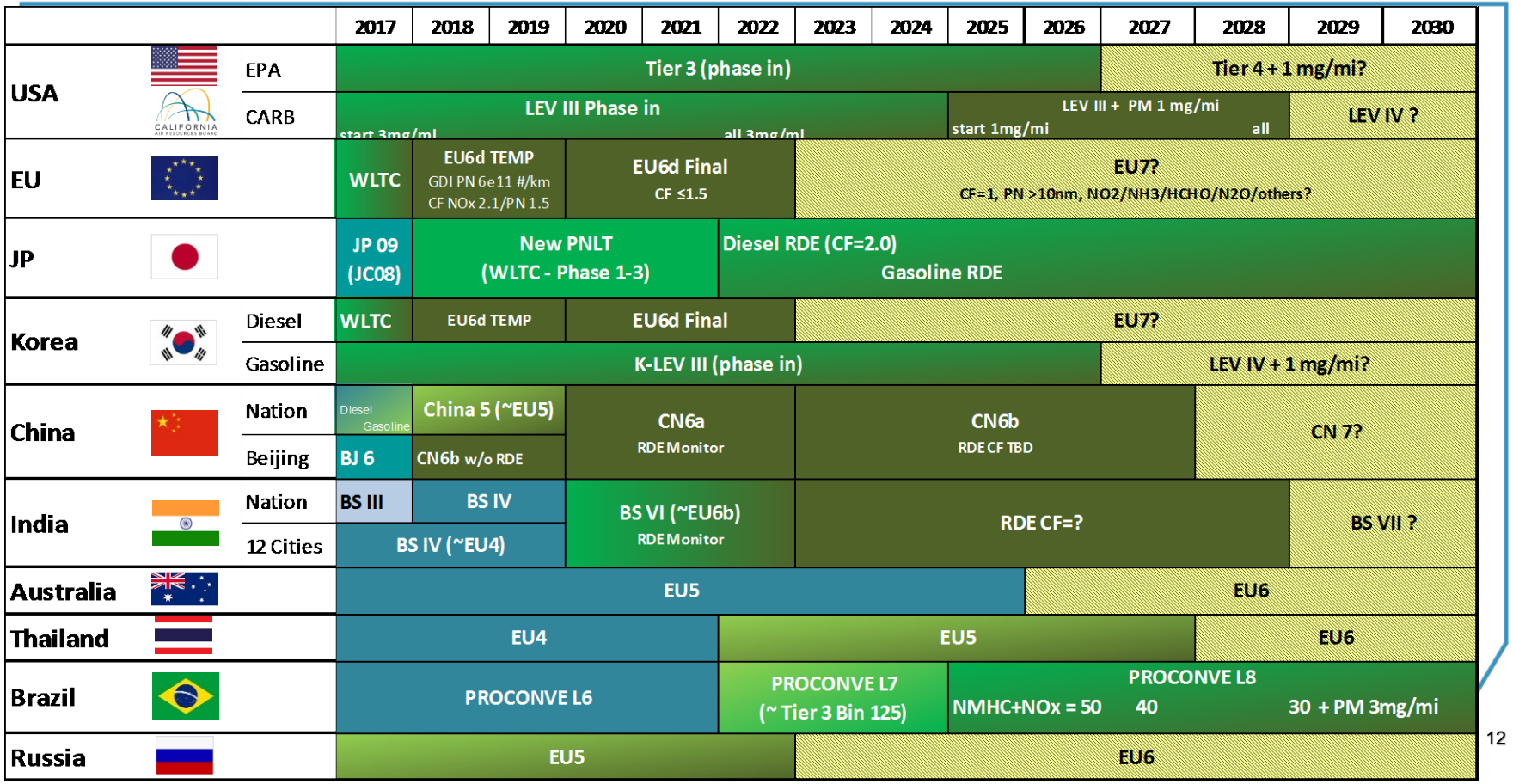
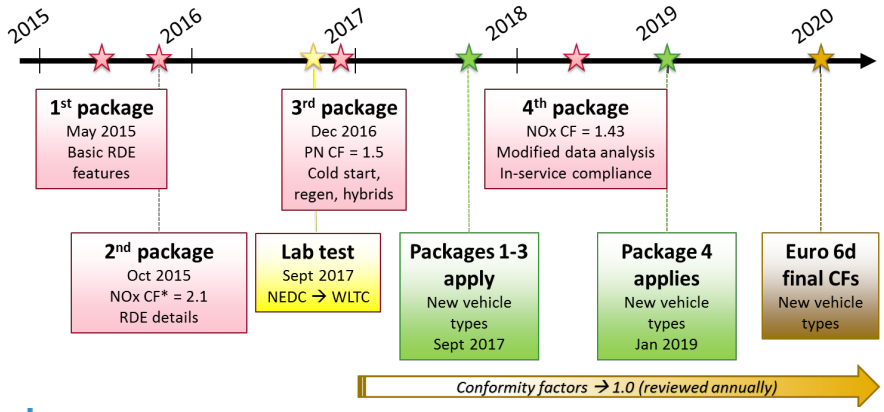
# Global Light Duty Regulations
## US Regs Drive Advanced Substrates, EU & CN Enforce Filters

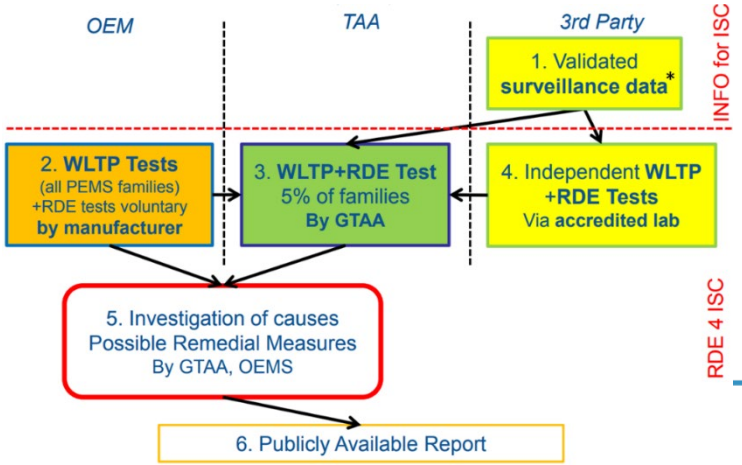


# Europe: 4th Real World Driving (RDE) package implemented in Jan 2019



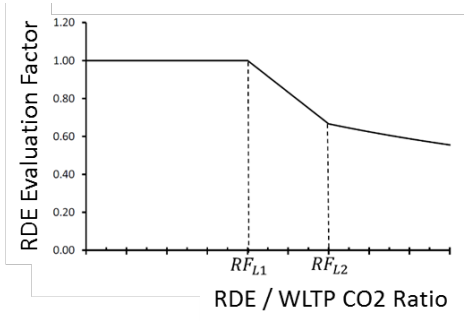

In service conformity (ISC) Up to 100,000 km or 5 yrs.

EU Commission
https://www.trueinitiative.org/media/597000/zlatko-kregar.pdf




## Key changes through 4th RDE package

- Data analysis using moving average window method
  - Power binning (CLEAR) discontinued
- Margin error for NOx lowered from 0.5 to 0.43 (CF = 1.43) starting Jan 2020
- RDE evaluation factors defined




- Type VI (low T) optional
- Data will be made public

# Emerging possibilities for Euro 7 / VII

**Tightening of criteria pollutant limits & inclusion of previously unregulated species**

(1) Fuel neutral standards: Diesel = Gasoline
(2) Further reduction of limits. Example: NOx = 40 mg/km (note: China6b limit is 35 mg/km)
(3) RDE limit for CO
(4) Inclusion of PN < 23 nm (down to 10 nm)
(5) Tightening of conformity factors (CF = 1.0 or “margin error = 0” for RDE/PEMS
(6) Limits on previously unregulated species – $NO_2$, $N_2O$, $NH_3$, HNCO, HCHO, PAHs
(7) Replace NMHC with THC and account for $CH_4$ with $CO_2$ equivalence
(8) Low temperature test ( - 7 °C) for type approval (type VI test)
(9) Other - fuel enrichment, evaporative, etc.

**Timing:** Likely > 2023

# Gasoline After-treatment

## Particulate Control

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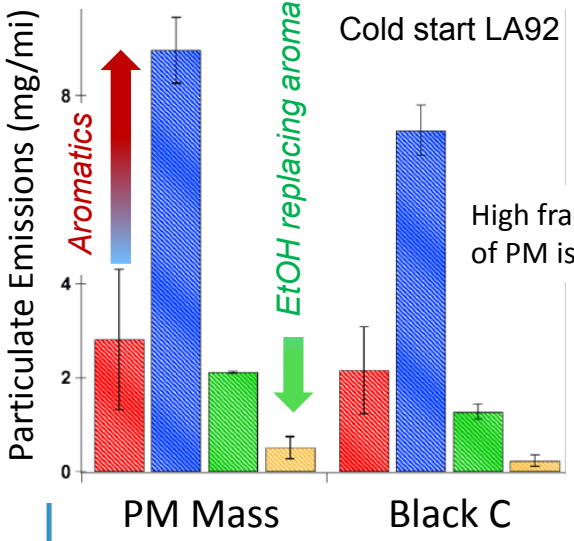
# Engine out particulate emissions continue to decrease with reduced aromatics in fuel and improved injection systems

## **Fuel** : Reducing aromatics

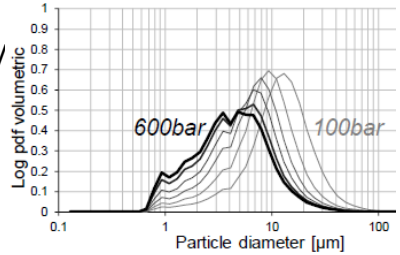
Fuels
- E10, 28% aromatics
- E10, 37% aromatics
- E30, 22% aromatics
- E78, 5.6% aromatics

MY2016 Flex-fuel, 2.0L
4-cyl. GDI w/ TWC
E30 : Splash-blended w/ E10




CE-CERT, UC Riverside, U. Maryland
Energy Fuels 2019, 33, 429−440

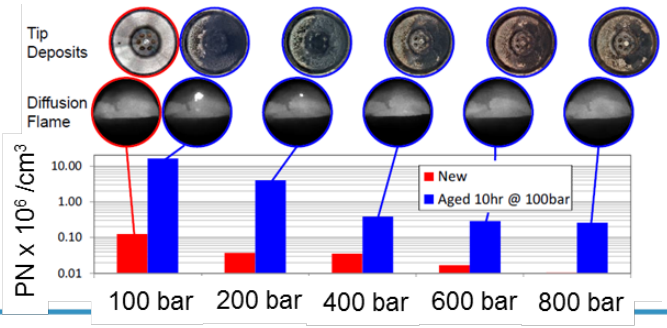
## **Injection pressure** >500 bar




Particle Diameter (μm)

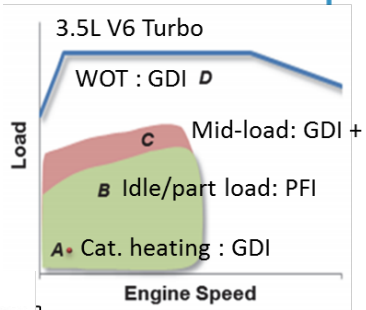
Smaller droplets, faster evaporation and air-fuel mixing

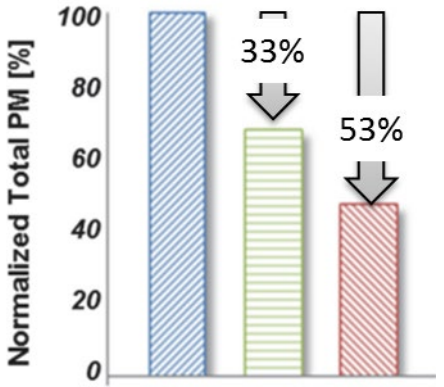
Reduces tip deposits




Delphi, 18th Hyundai Kia Powertrain Conf. 2018

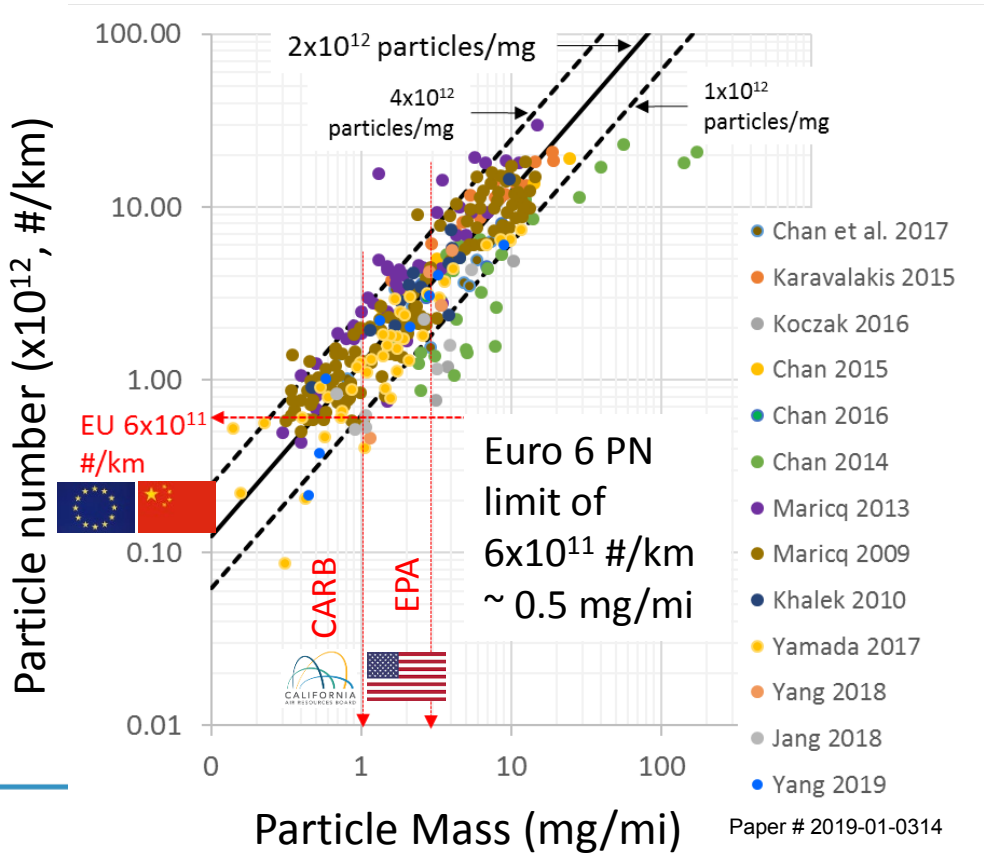
## **Dual Injection**
GDI + PFI

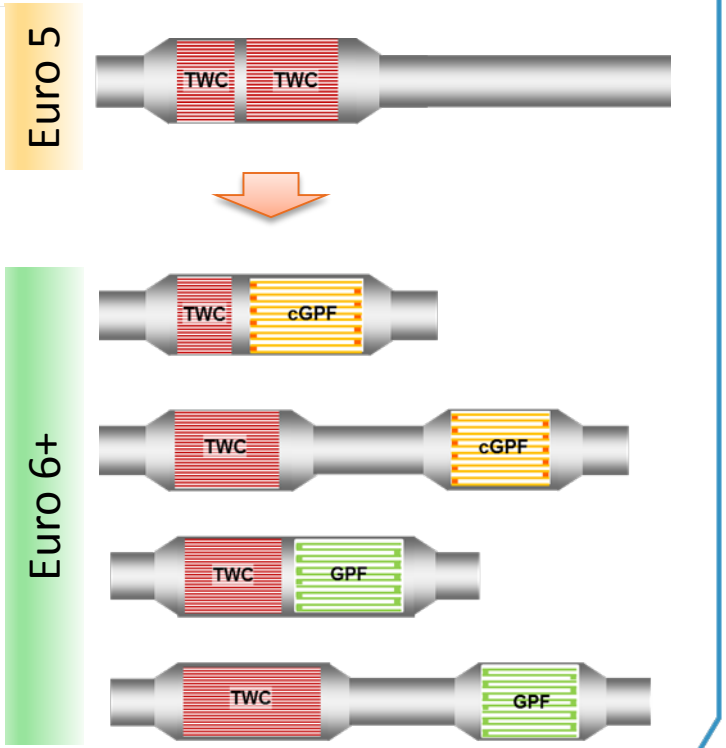





Hyundai, 27th Aachen Colloquium, 2018

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



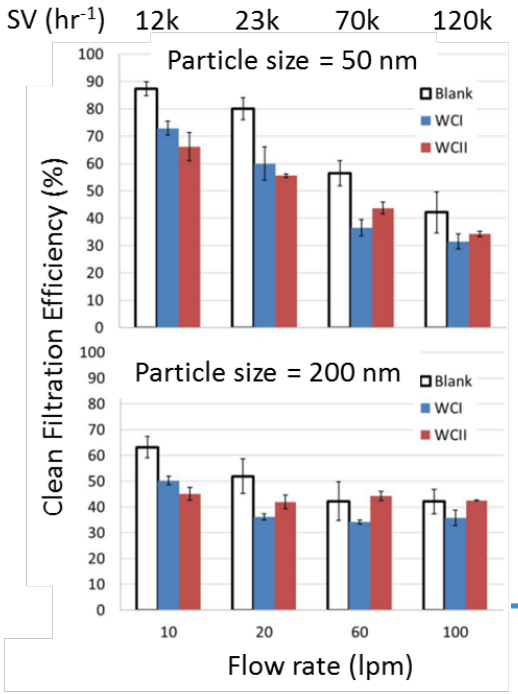

Paper # 2019-01-0314

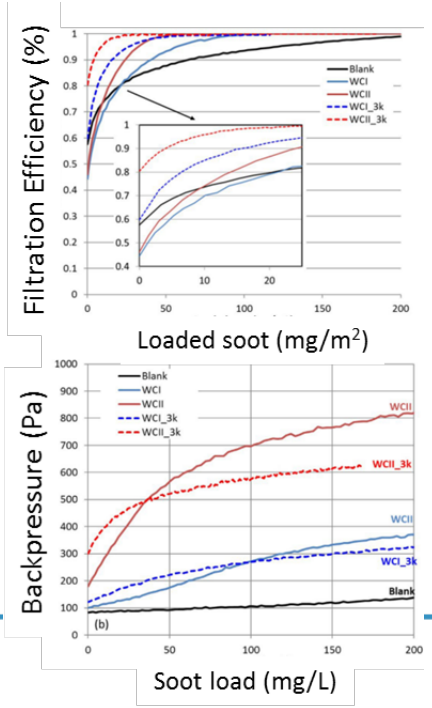
# Increase in filtration efficiency with soot and ash higher for coated filters. Ash membrane increases efficiency, reduces soot loaded ΔP

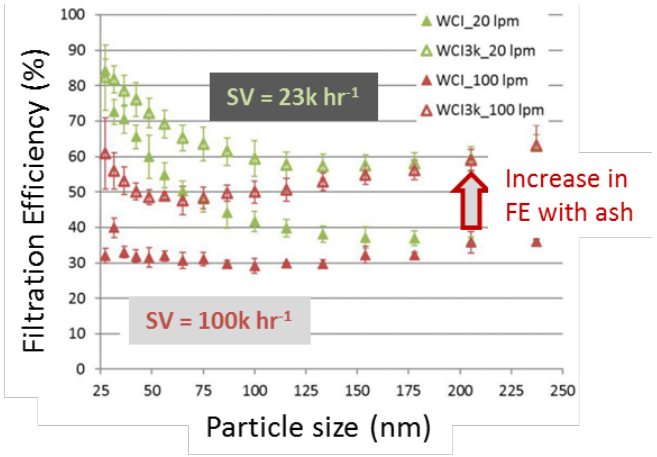
Ford, SAE 2018-01-1259

2.3L GTDI, GPFs in uF position
Washcoat loading WCI < WCII
Mileage accumulation : 3000 km on highway

- Coating: Reduces clean filtration efficiency but improves filtration in presence of small soot/ash
- Particle size: Higher efficiency for smaller particles (Brownian)
- Ash : Reduces soot loaded ΔP and improves filtration



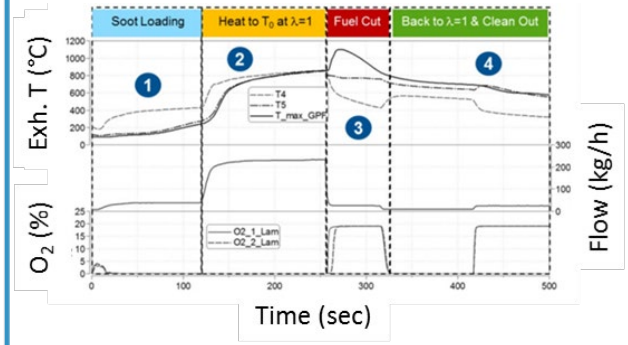



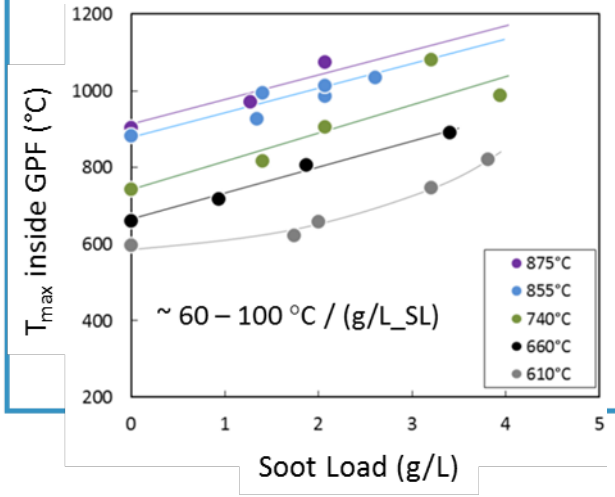

Ash accumulation after 3000 km driving (0.6 – 1 g/L) improves efficiency

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

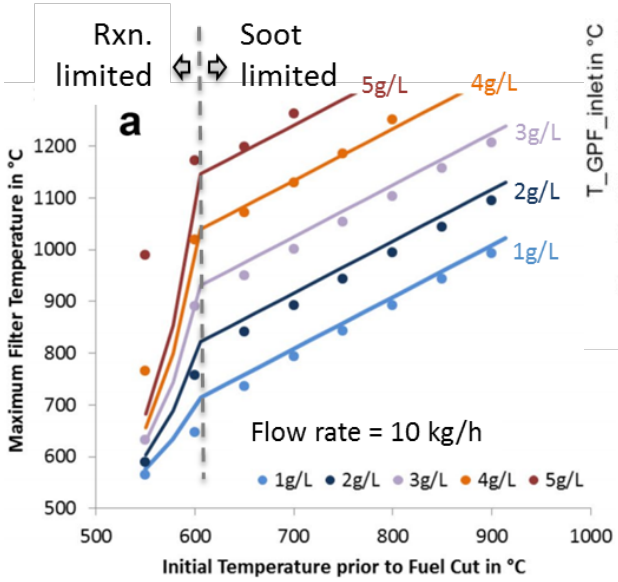
Corning, SAE 2018-01-1699

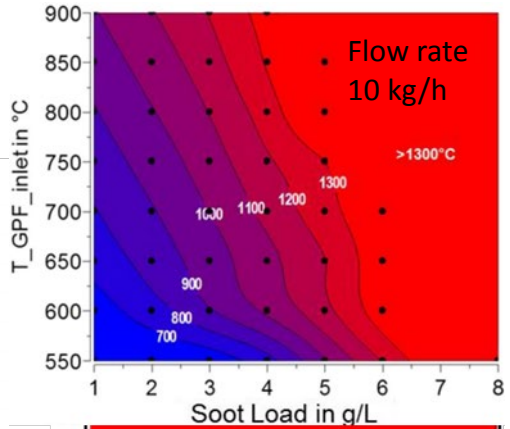
## Fuel cut testing

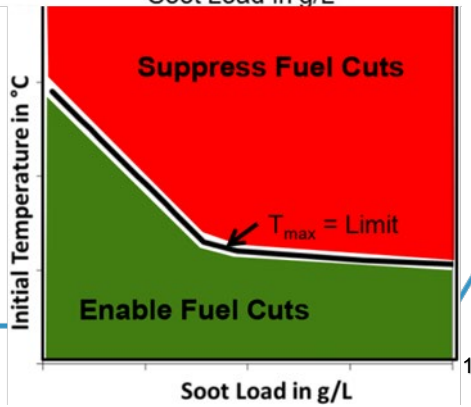



Simulations used to map response to soot load, inlet T and flow rate



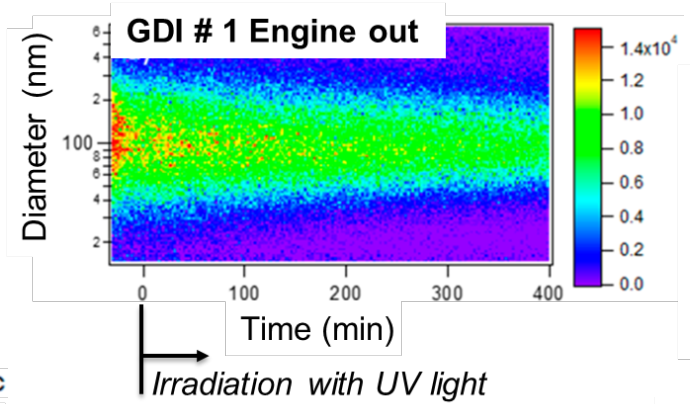



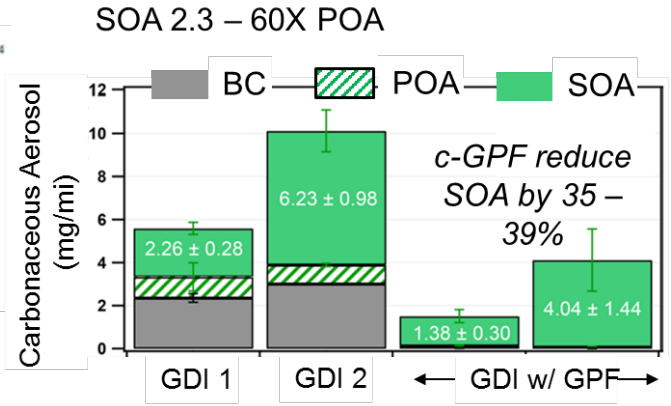



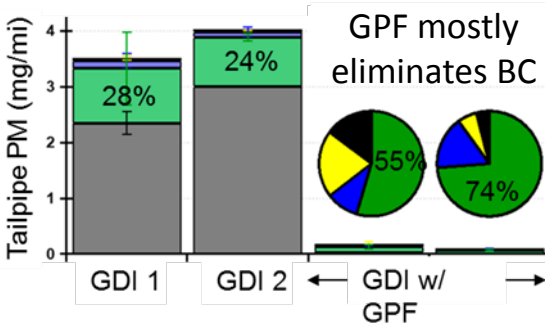
# Catalyzed GPFs reduce secondary organic aerosols from GDI vehicles

UC Riverside, MECA, Univ. Maryland *Environ. Sci. Technol.*, 2019

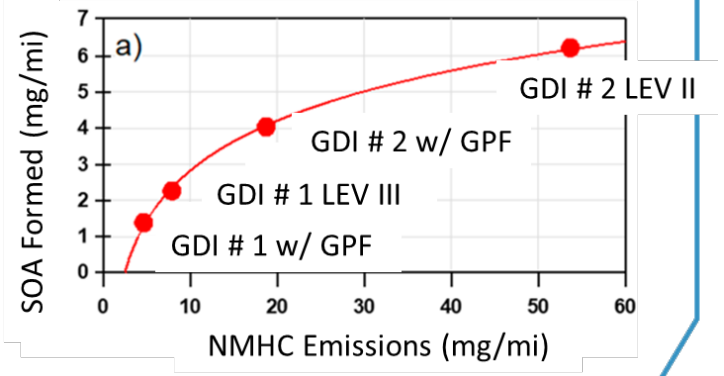
GDI#1
MY 2016 2.0L, LEV III
GDI#2
MY 2016 1.5L T, LEV II
After-treatment
cc-TWC + c-GPF






SOA emissions proportional to NMHC & PAH emissions



WCX APRIL 9-11 2019 DETROIT

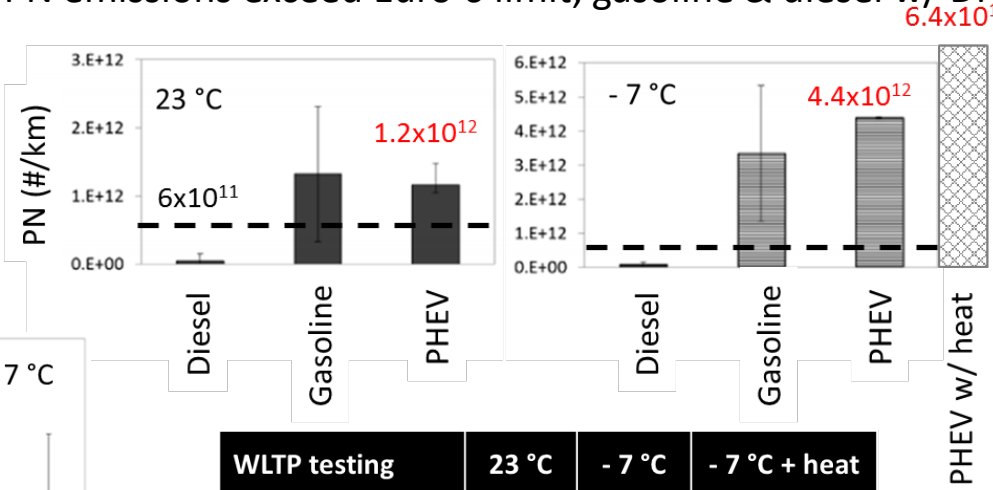
# Plug-in hybrids offer significant $CO_2$ reductions but reduction in electric range at low temperature increases particulates

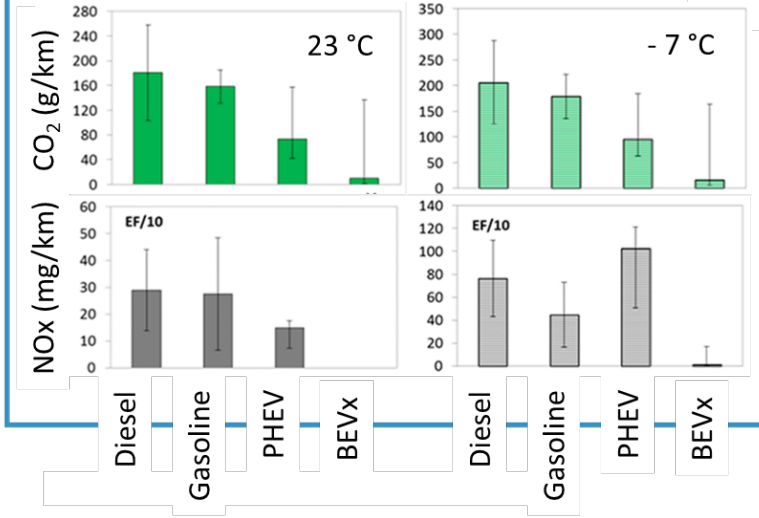
JRC ACS Omega 2019, 4, 3159−3168

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 |

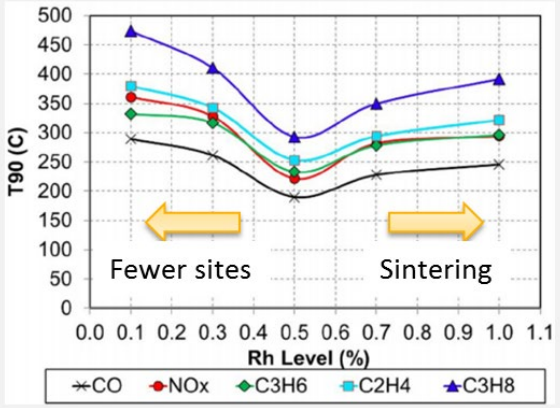
# Gasoline After-treatment

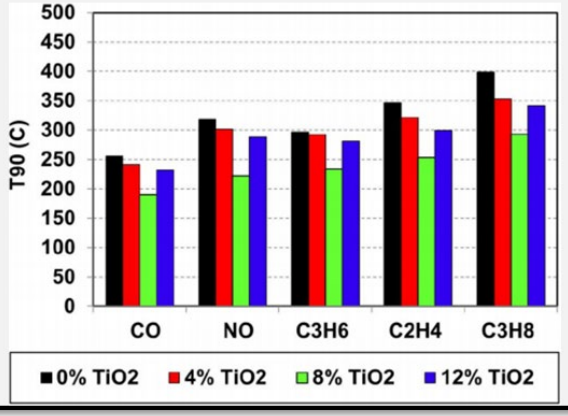
## Gas Emissions

# Improved TWC demonstrates 90% conversion at T < 300 °C

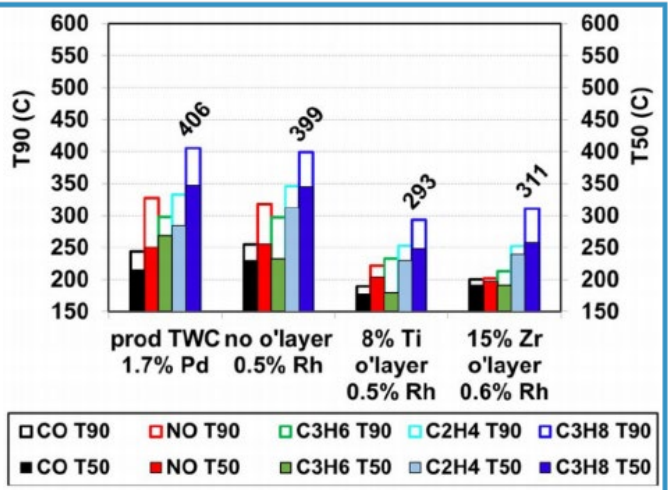
Ford, SAE 2018-01-0939

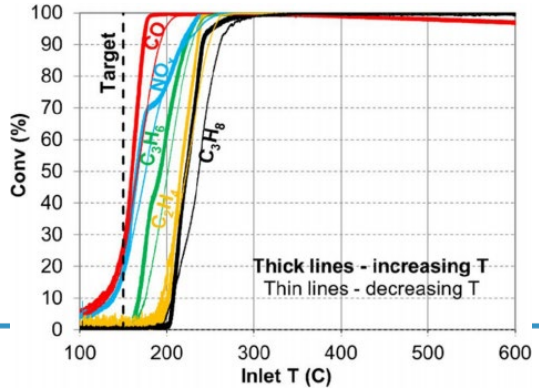
## Optimization of Rh and $TiO_2$ content




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



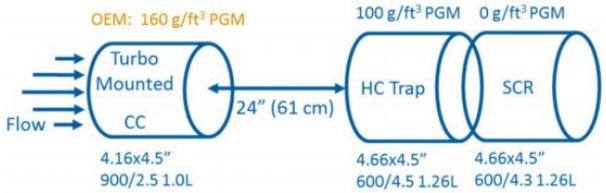

Exposure to 6 ppm $SO_2$ and desulfation at 650 °C → performance is fully recovered

# New HC trap technologies reduce cold-start emissions

Umicore, SAE 2018-01-0336

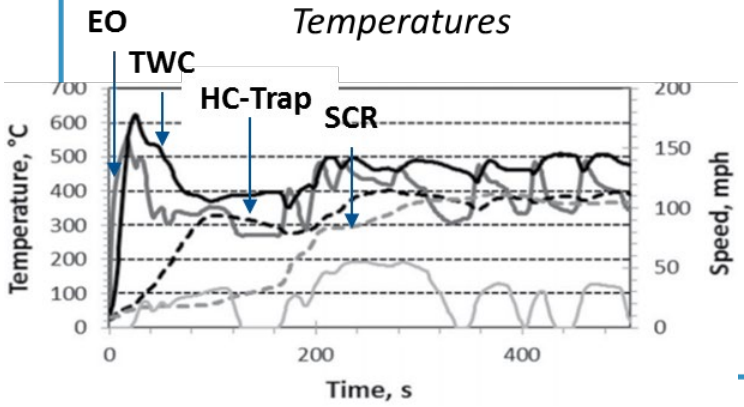
Vehicle : 2014 VW Jetta Hybrid, 4-cyl 1.4L GTDI

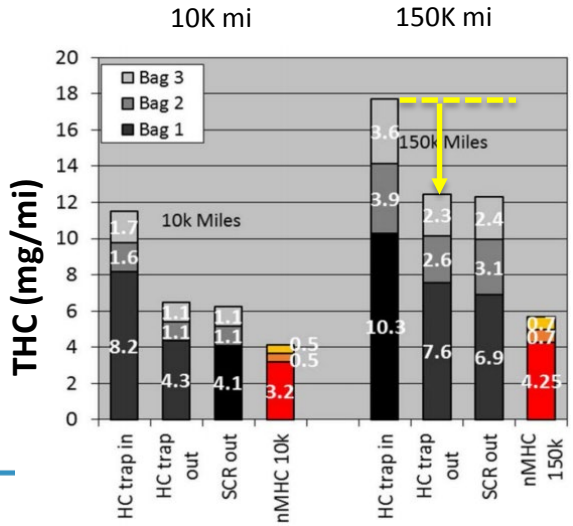
uF TWC replaced by HC trap & SCR

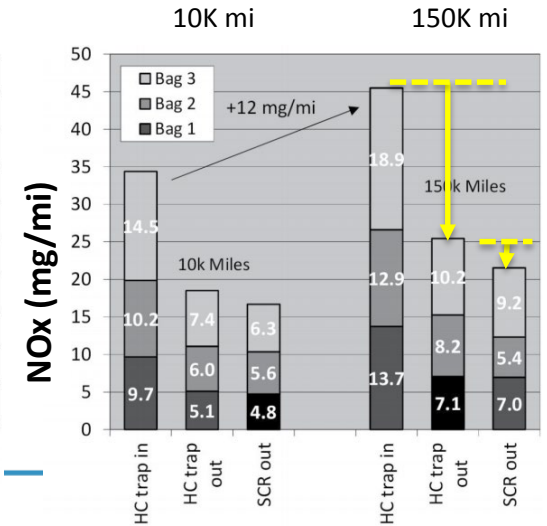



Emission reductions (150K mi aged, mg/mi)

| | HC Trap | pSCR |
|---|---|---|
| THC | 6 | 0 |
| NOx | 20 | 5 |



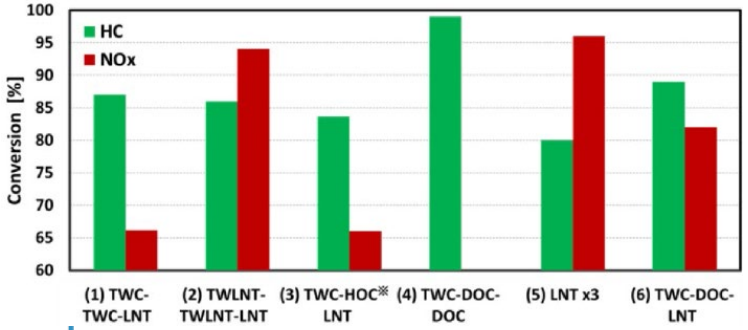



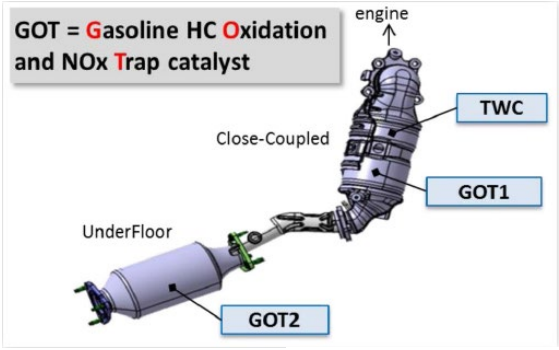
# Combined oxidation and trapping catalysts proposed for homogenous lean charge spark ignition (HLSI) engines

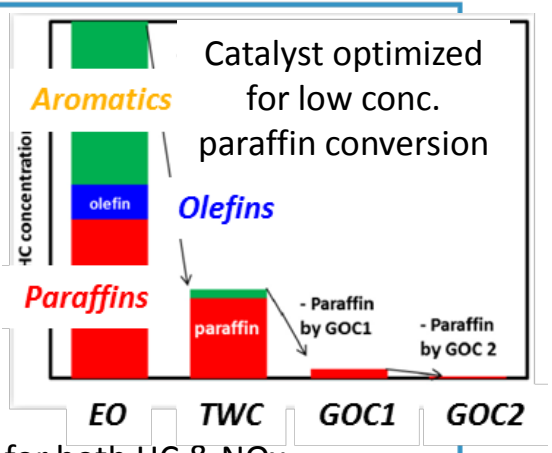
Honda, SAE 2018-01-0945

Various systems evaluated for low combined NOx and HC emissions




GOT Upper layer: HC ox. -- Lower: NOx trap



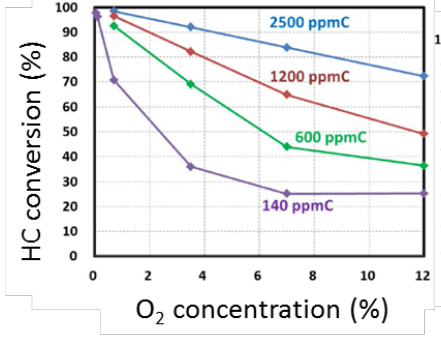



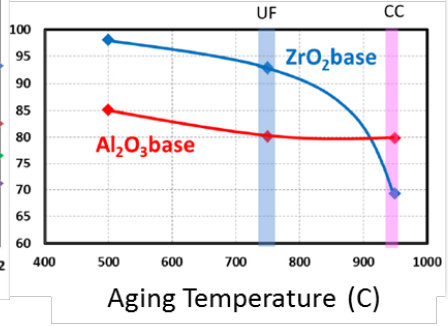

Catalyst optimized for low conc. paraffin conversion

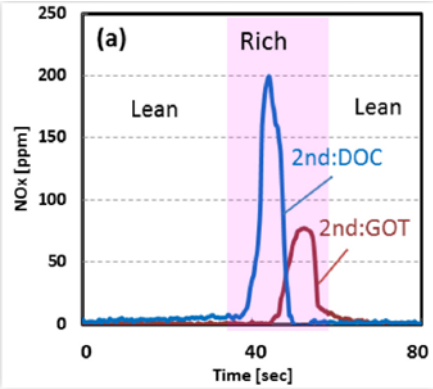
High conversion for both HC & NOx

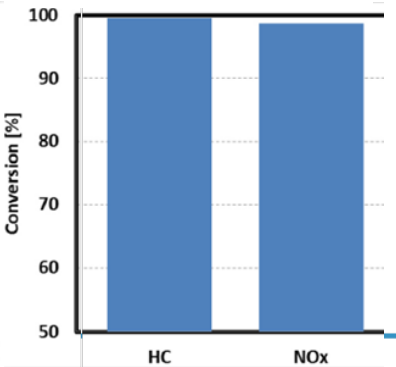
HC conversion limited by adsorbed O

Acidic supports to suppress O adsorption




3-cyl (1.0L), 1500 rpm IMEP 340 kPa, lean 210 sec, rich 20 sec

# Light-Duty Diesel

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

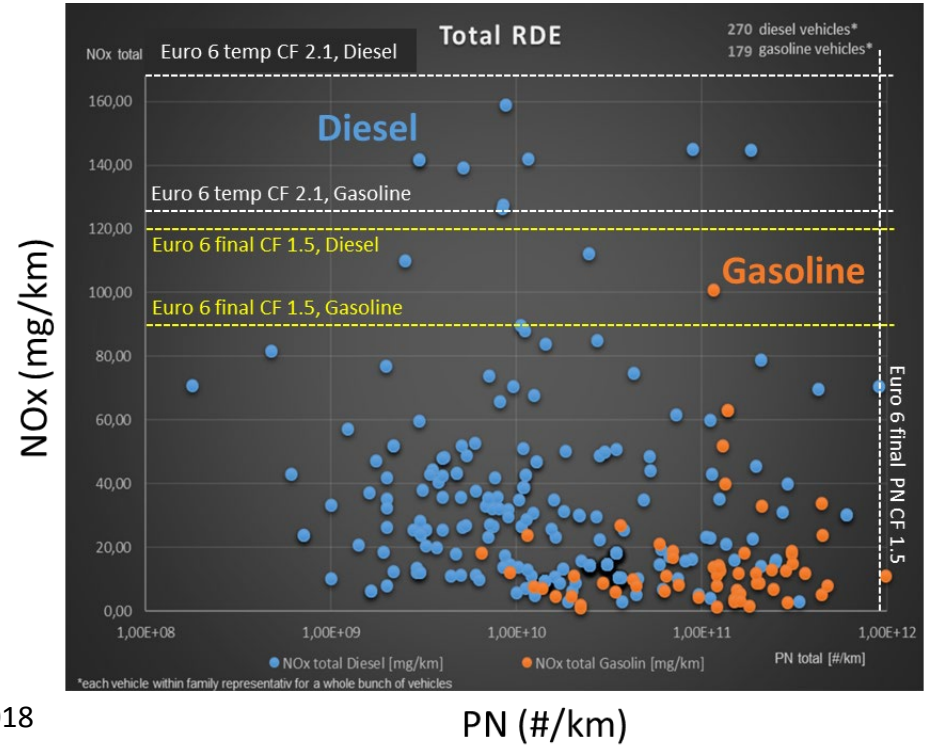
Data from Euro 6d temp vehicles

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



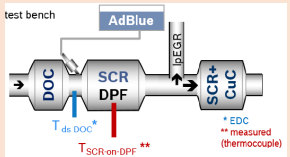

ACEA, EU Commission Stakeholder meeting Oct 24th, 2018

# Engine thermal management coupled with optimized after-treatment can enable low NOx under severe real-world driving

Bosch, Vienna MotorSymposium, 2018

## Technologies

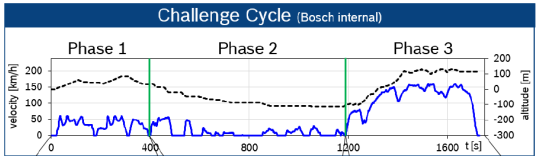
- Thermal mgmt: Retarded comb., ign. timing
- Air flow management for lower catalyst cool-down
- Optimized turbo for RDE (improved transients & low-end torque)
- SCR on DPF + SCR & HP- & LP EGR



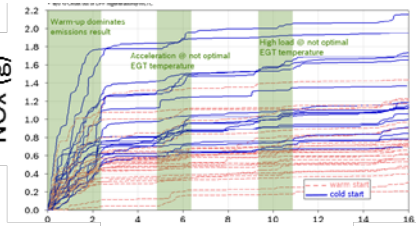

- NSC, double urea injection not seen to add much value, EHC led to 19% $CO_2$ penalty

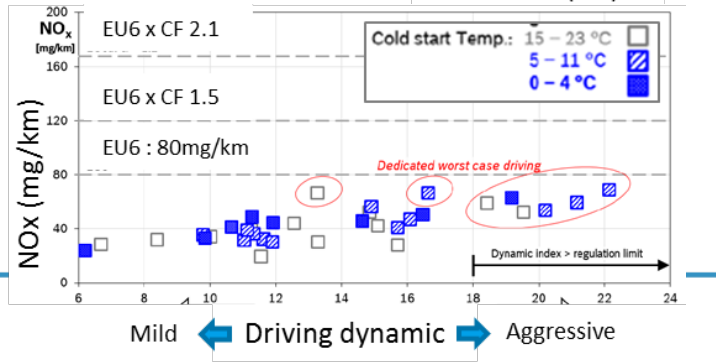
## Scenario 1

Cold start + low speed / high torque → high EO emissions



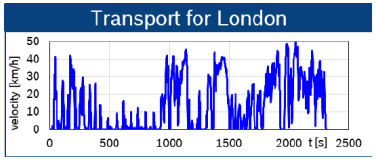

Cold start & accelerations dominate emissions

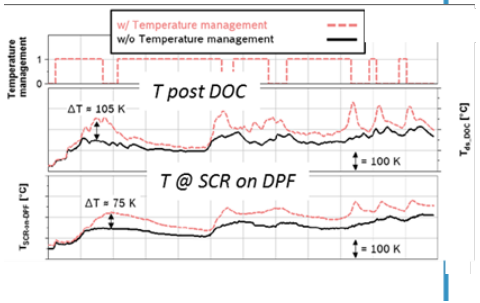


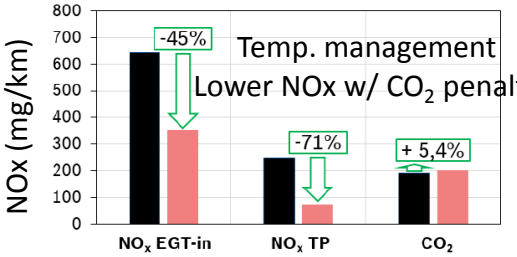




## Scenario 2

Cold start + stop/start → low A/T temp.



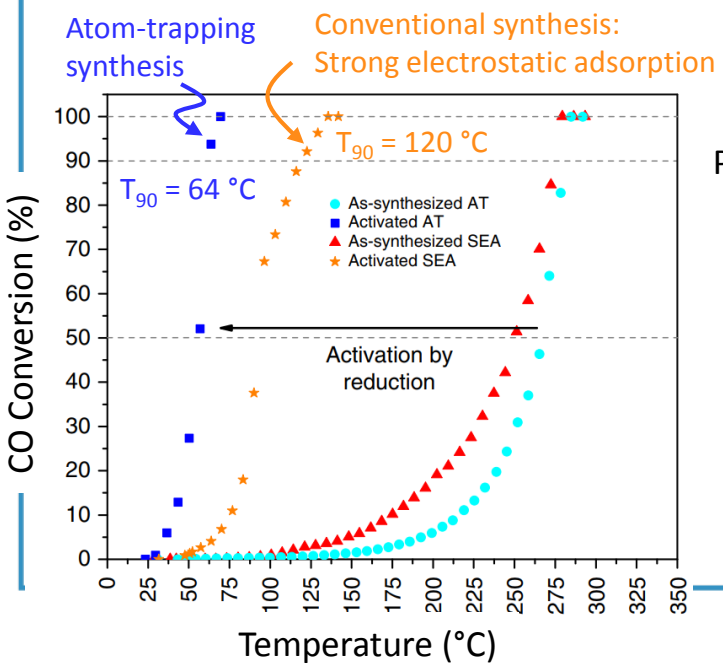



# New high T synthesis of Pt-CeO2 catalyst shows 90% CO conversion *at 64 °C*

Wash. St. Univ., Univ. of N Mexico, Eindhoven Univ., PNNL NATURE COMMUNICATIONS | (2019) 10:1358

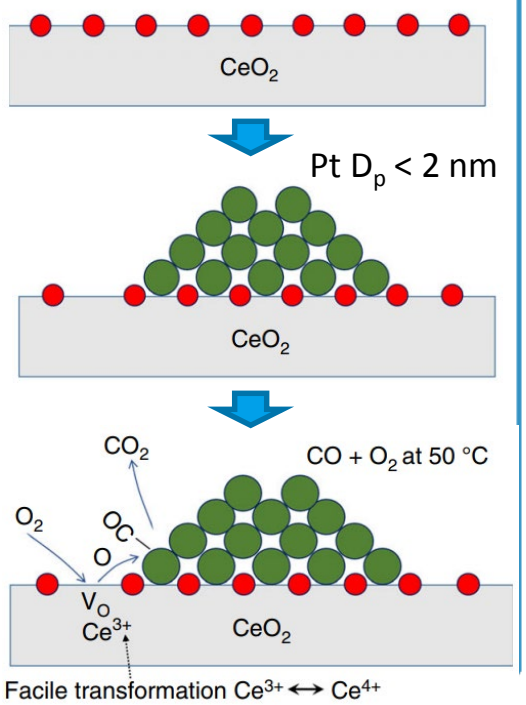
- High T vapor phase atom-trapping synthesis
- Pt trapped on $CeO_2$ in thermally stable form
- $CeO_2$ sites activated and provide O2 for rxn.
- Onset of CO oxidation near *room temp.*




❶ Synthesis : 800 °C in air
Stabilization of Pt single atoms on $CeO_2$

❷ Activation (CO @ 275 ° C) :
Pt single atoms → nanoparticles, active $CeO_2$

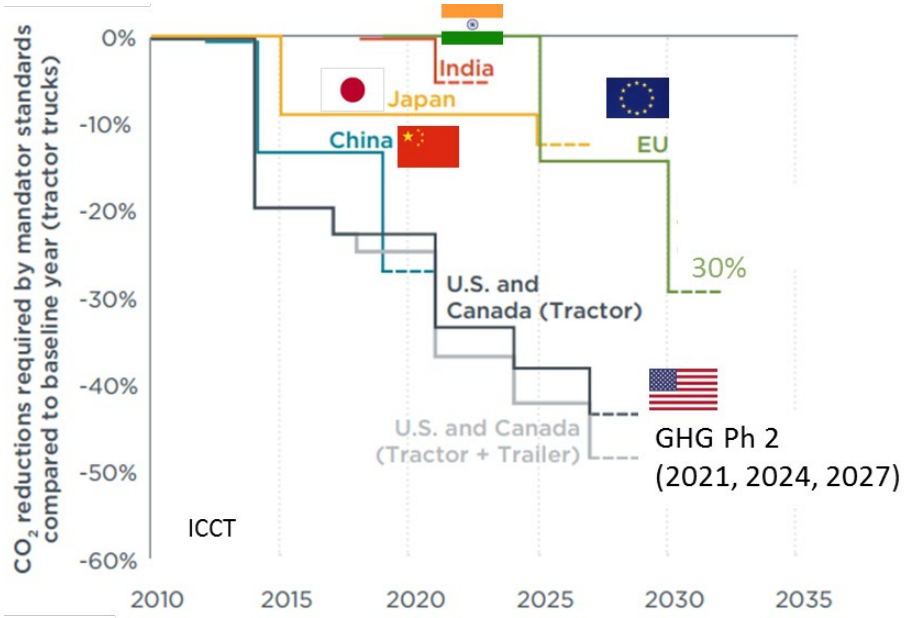
❸ CO oxidation : Conversion of $Ce^{3+} \leftrightarrow Ce^{4+}$ activates $O_2$

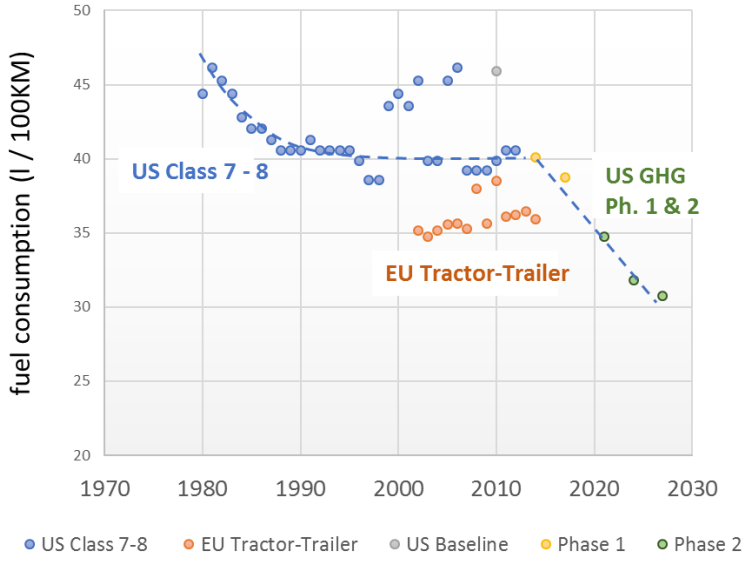


# Heavy-Duty

## Fuel Economy / GHG

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




US Data: Transportation Energy Data Book: Ed. 33—2014
https://info.ornl.gov/sites/publications/files/pub50854.pdf
EU Data : ICCT, Lastauto Omnibus

# SuperTruck II
## Some common themes emerging

**Goals**

**(1) > 55% BTE at 65 mph cruise on engine dyno**

**(2) Improve freight efficiency by 125% over SuperTruck I (Freight efficiency = mpg x tons)**

- Improved combustion and air handling

  Increased CR, HRR optimization, EGR optimization

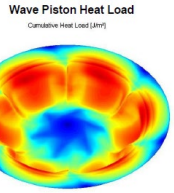
- Improved aerodynamics, weight reduction, lower rolling resistance, friction reduction
- Insulation, thermal barrier coatings
- Mild hybridization
- NOx control optimization
- Waste-heat recovery

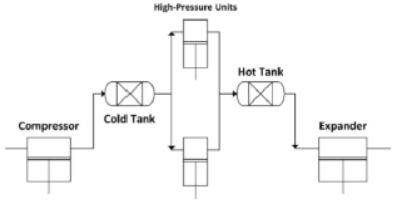
  But need to include low grade heat. Small improvements not sufficient to justify cost / complexity

# SuperTruck II
## Various approaches are being pursued

## Volvo

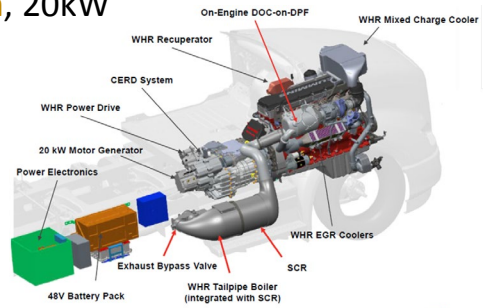
- Thermal barrier coated piston
- Turbocompounding
- Predictive energy management, idle free hotel mode
- Mild hybridization, 25 kW, P1 architecture
- Dual comp. / expansion engine



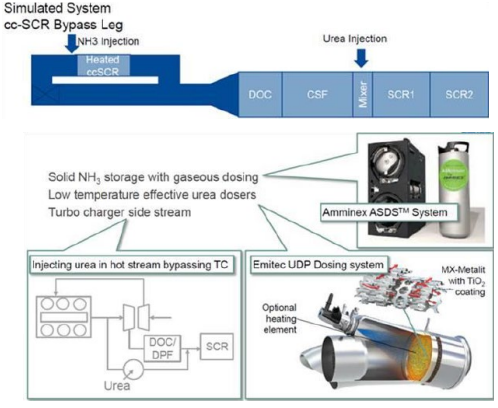

## Cummins / Peterbilt

48 V mild hybridization, 20kW
WHR BTE benefit > 4%



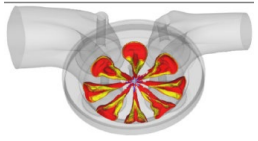

## Navistar

- GCI (w/ ANL)
- Improved NOx conversion
- Predictive cruise control
- Use of solar panels

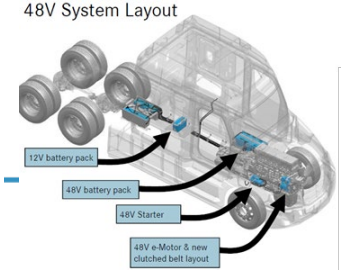



## Daimler

OAK RIDGE National Laboratory

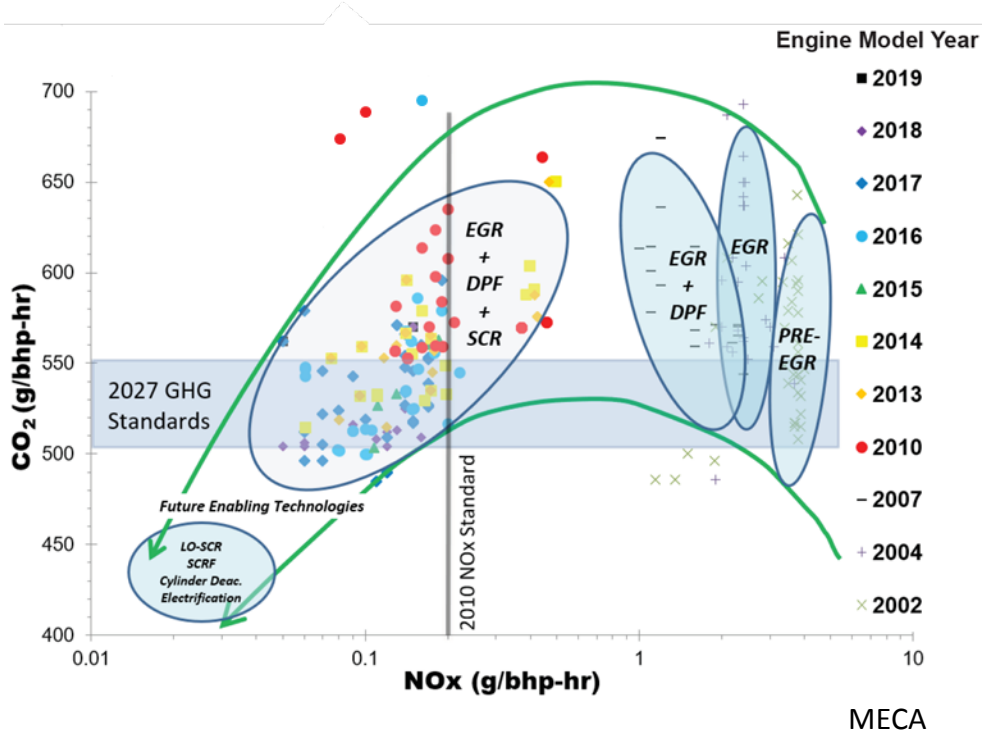


- Bowl redesign, thermal barrier coating
- 48 V mild hybridization
- WHR benefit insufficient to justify complexity
- Close-coupled SCR, model-based NOx controls



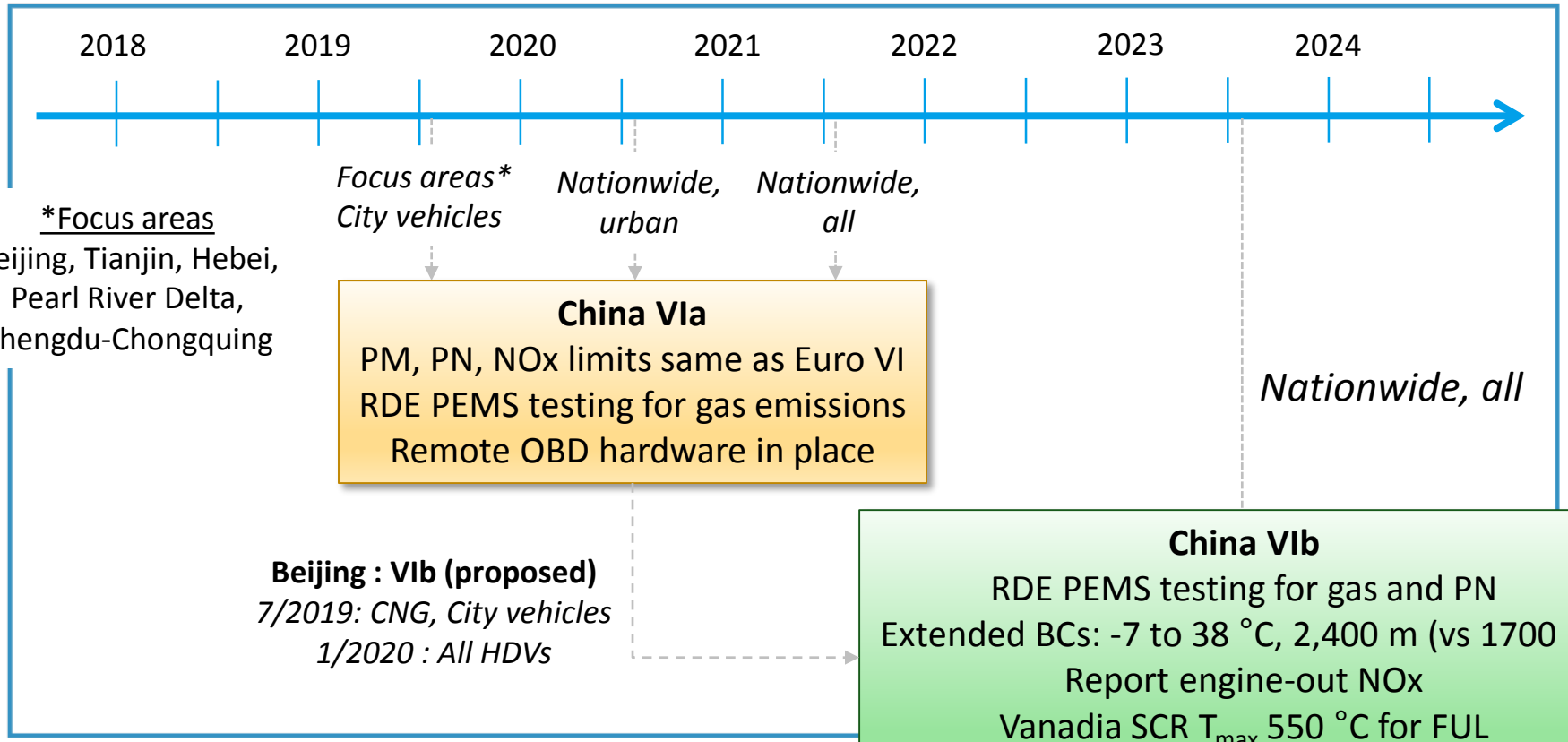
# Heavy-Duty

## Criteria Pollutants



WCX APRIL 9-11 2019 DETROIT

# China VI Heavy-Duty Regulations



# China Non-road Tier 4 Regulations

Timing: Nationwide Dec 2020, earlier in key areas

Emission limits over Non-Road Transient Cycle (NRTC)

| Engine Rating kW | CO g/kW-h | HC g/kW-h | NOx g/kW-h | HC + NOx g/kW-h | PM g/kW-h | PN #/kW-h |
|---|---|---|---|---|---|---|
| < 37 | 5.0 | - | - | 7.5 | 0.60 | - |
| 37 – 56 | 5.0 | - | - | 4.7 | 0.025 | $1x10^{12}$ |
| 56 – 130 | 5.0 | 0.19 | 3.3 | - | 0.025 | $1x10^{12}$ |
| 130 – 560 | 3.5 | 0.19 | 2.0 | | 0.025 | $1x10^{12}$ |
| > 560 | 3.5 | 0.40 | 3.5 | - | 0.10 | - |

- DPF and GPS mandated for 37 – 560 kW engines. GPS will be used for OBD3
- Not-to-exceed (NTE) requirements: 2 x cycle limit
- PEMS for gas emissions only. NOx limit = 2.5 x cycle limit, applicable over - 7 °C to 35 °C, Altitude < 2400 m
  - Work window based on NRTC, test duration 5 – 7 times window. Cold start excluded.
- Reporting of instantaneous engine-out NOx concentration required
- Cycle-averaged $NH_3$ slip < 25 ppm
- For V-SCR catalyst, SCR Temp must be < 550 °C under all conditions, monitored via OBD

# Brazil HD Regulations
## PROCONVE P8 (~ Euro VI-C) introduces DPF enforcing PN limit

**Timing**: 2022 for new models, 2023 for all vehicles

**Vehicles included** : All freight and passenger vehicles with GVW > 3,856 kg
Light commercial vehicles with GVW 3,500 and 3,856 can be certified under LD or HD

**Test procedures**: WHSC (steady state) & WHTC (transient) and WNTE (not-to-exceed)
Real-world driving testing included (urban, rural, highway), includes cold-start

**OBD strengthening**: Urea concentration monitored to ensure effective SCR

| Cycle | CO (mg/kWh) | THC[1] (mg/kWh) | NMHC[2] (mg/kWh) | $CH_4$[2] (mg/kWh) | $NO_x$ (mg/kWh) | $NH_3$[3] (ppm) | PM (mg/kWh) | PN (#/kWh) |
|---|---|---|---|---|---|---|---|---|
| WHSC[1] | 1,500 | 130 | - | - | 400 | 10 | 10 | $8.0 \times 10^{11}$ |
| WHTC[1] | 4,000 | 160 | - | - | 460 | 10 | 10 | $6.0 \times 10^{11}$ |
| WHTC[2] | 4,000 | - | 160 | 500 | 460 | 10 | 10 | - |
| OCE (WNTE) | 2,000 | 220 | - | - | 600 | - | 16 | - |
| ISC | 6,000 | 240 | 240 | 750 | 690 | - | - | - |

ICCT, Feb 2019

**Emission Durability**

GVW < 5 tons: 160K km / 5yrs | Freight > 3,856 kg & pass. vehicles ≤7.5 ton : 300K km / 6yrs | Freight vehicles > 16 ton & pass. vehicles >7.5 ton : 700K km / 7yrs

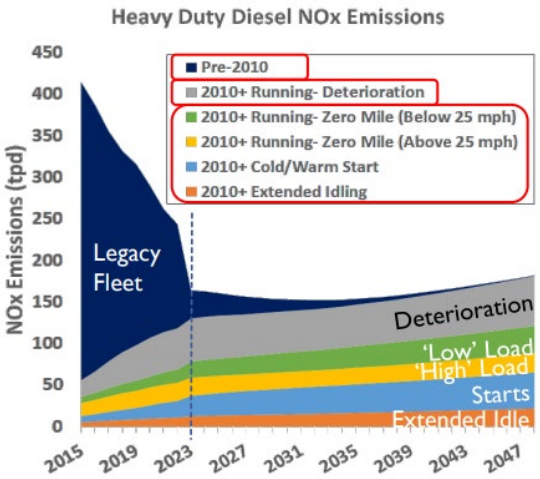
# US / EU : Emphasis on reducing in-use NOx emissions Coupled with significant cuts in $CO_2$ / GHGs

| | 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 |
| | GHG Phase 1 | | | | GHG Phase 2 | | | | | | | |
| CARB | Optional low NOx : 0.1, 0.05 & 0.02 g/bhp-hr | | | | | | | | | | UL NOx 0.0x g/hp-h, low load cycle | |
| EU | EU VI A, B, C ISC: Power threshold 20%, Max payload 50 - 60% | | | | 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 |

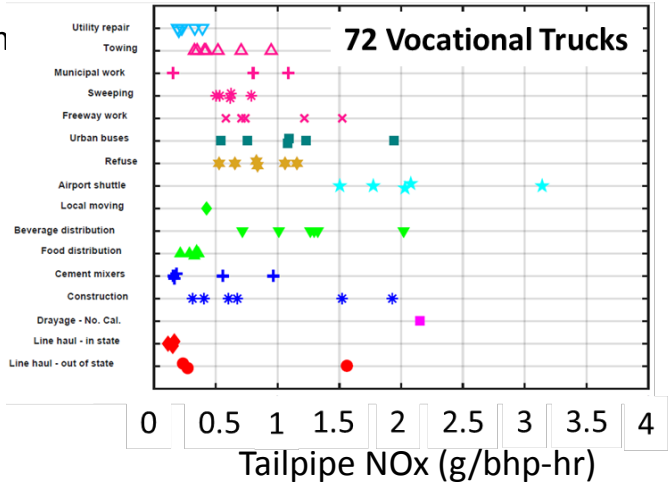
# > 90% reduction in NOx emissions needed to achieve CA ozone attainment

Significant emissions reductions achieved post 2010

But > 2023, emissions expected to increase due to in-use deterioration




In-Use NOx emissions vary widely depending on vocation / duty cycle




Most engines certified to 0.2g/bhp-hr, some <0.35g family emission limits

CARB, UC Riverside, 28th CRC Workshop (2018)

Various measures being considered to reduce NOx -

- Lower certification NOx limit on FTP (0.2 → 0.0x g/bhp-h)
- New low load test cycle
- Improved in-use emissions testing
- Increase warranty and useful life

# HD In-use testing : Move from Not-to-Exceed (NTE) to Moving Average Window (MAW) method

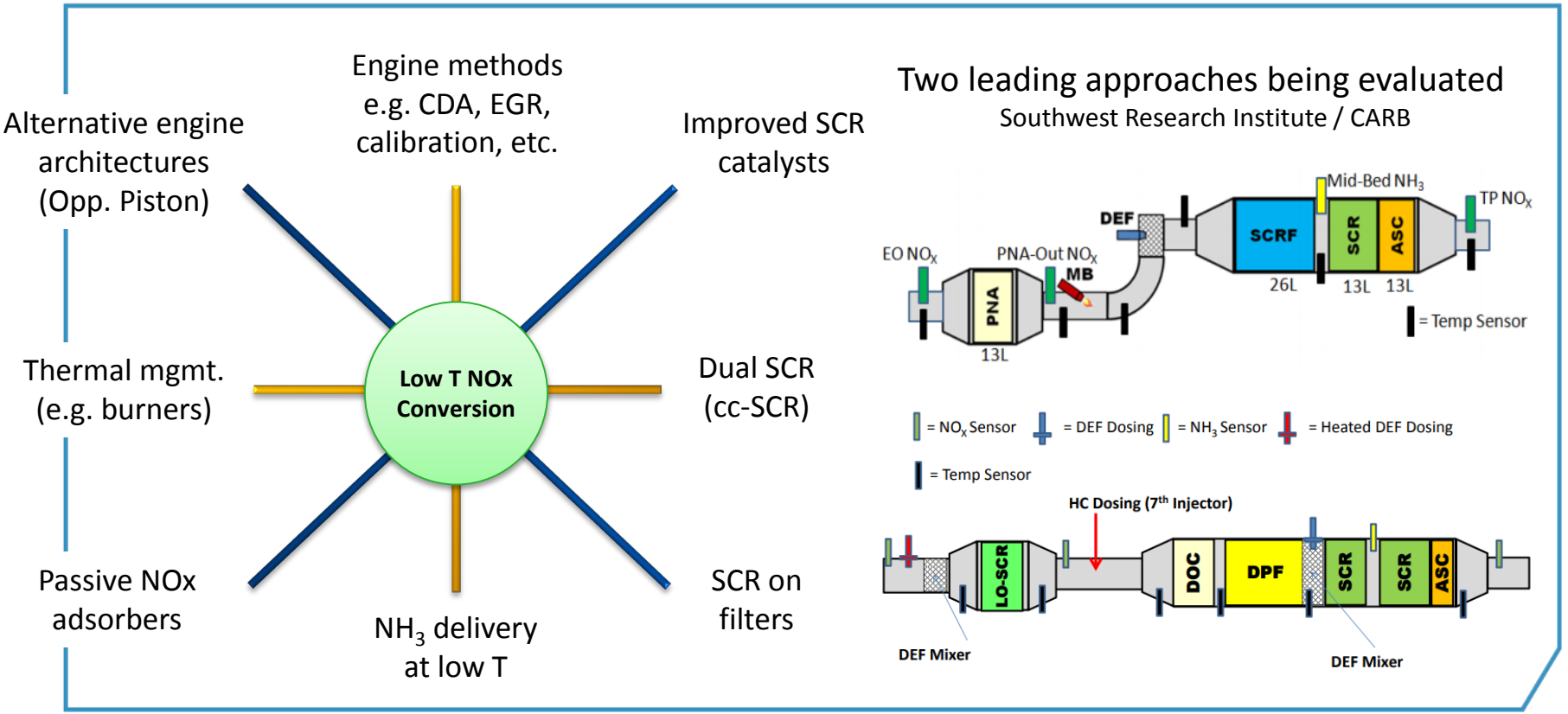
## HDIUT: FUTURE METHOD SUMMARY

Key:
Previous Requirements
New or updated Elements

| | MY 2022-2026 | MY 2027+ |
|---|---|---|
| Testing Request | • CARB & EPA | • CARB & EPA |
| Number of Families | • 25% EFs per year | • 25% EFs per year |
| Test Plan | • Mfr. Submitted for CARB approval | • Mfr. Submitted for CARB approval |
| Driver & Route | • Real world fleet driver and route for a full day or mfr. testing with prior CARB/EPA approval | • Real world fleet driver and route for a full day or mfr. testing with prior CARB/EPA approval |
| Method | • MAW Euro VI(d) | • TBD |
| Cold Start | • Cold start engine coolant temp. exclusion | • Include composite weighting ~ *Euro VI(e)* |
| Exclusions | • Extreme ambient conditions & PEMS checks | • Extreme ambient conditions & PEMS checks |
| Window size | • Work or $CO_2$ equivalent on an FTP cycle | • TBD |
| Window Validity | • Avg window power at or above 10% Power Threshold | • All operation *Expand operation to idle* |
| Test Validity | • 3 hours valid test data | • N/A (all valid operation considered) |
| Emissions metric | • Work or $CO_2$ specific | • $CO_2$ specific *Possibly new emission metrics* |
| Emissions Evaluation | • 90th percentile of valid window emissions | • 9X$^{th}$ percentile (TBD) of warm valid window emissions<br>• 100$^{th}$ percentile of cold start window emissions |
| Conformity Factor | • $CF_{final} = 1.5$ | • $CF_{final} = 1.5$ |
| Pass Criteria | • $\frac{e_{90th\ percentile}}{e_{FTP\ std.}} \leq CF_{final}$ | • $0.14\ x\ CF_{cold} + 0.86\ CF_{warm} \leq CF_{final}$ |

15

# A systems approach will be needed to address further reductions in NOx



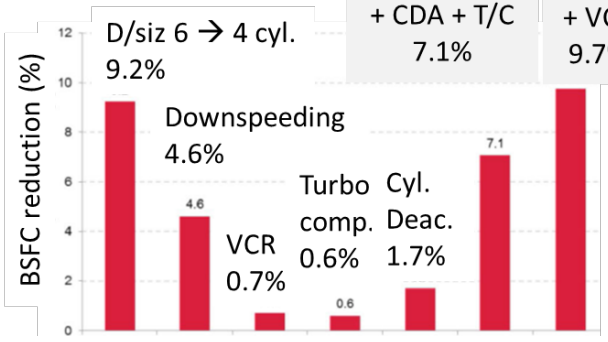
# Modeling study identifies packages for 5 - 7% reduction in fuel consumption and < 20 mg/bhp-h NOx

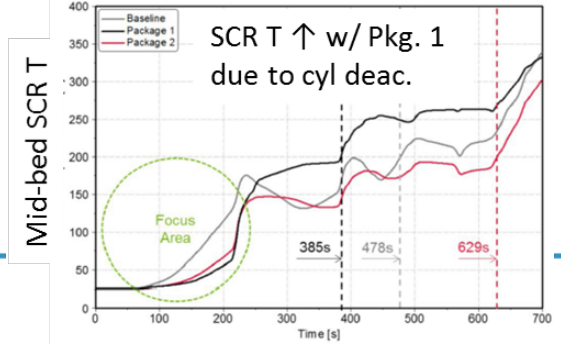
FEV, SAE 2018-01-1429

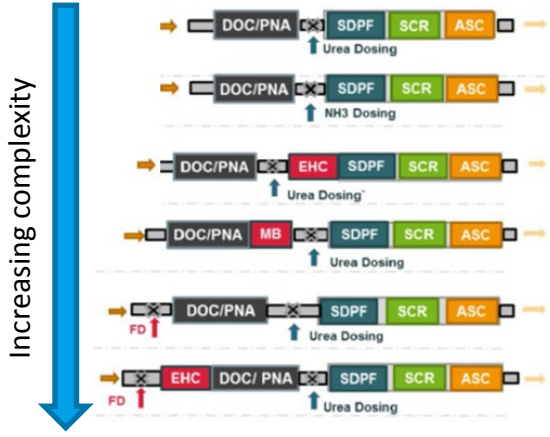
GT-Power modeling Baseline: US2010 7.7L 6-cyl.
MHD, CR 17.6, HP-EGR, DOC + DPF + SCR

HD-FTP, constant EO NOx

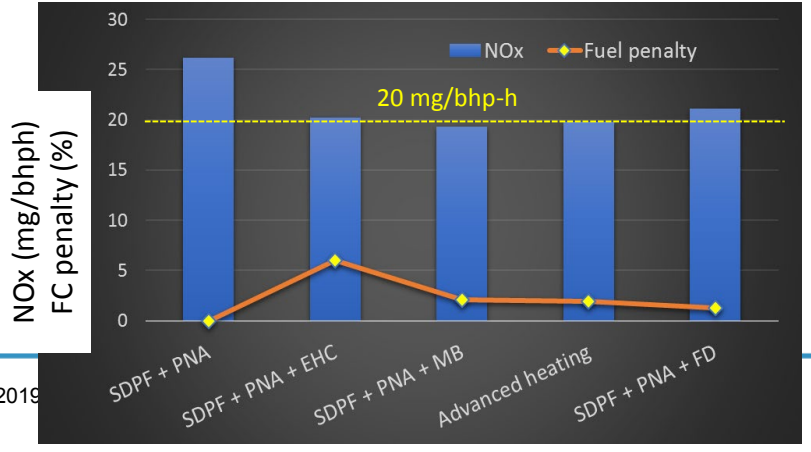
| Pkg. 1 | Pkg. 2 |
|---|---|
| D/Sp. + VCR + CDA + T/C 7.1% | D/Siz. + VCR 9.7% |



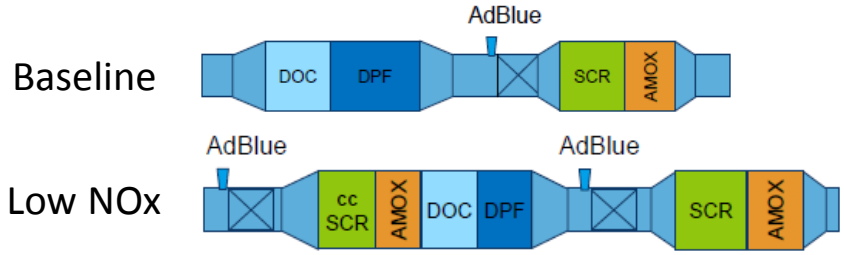




PNA = Passive NOx adsorber
SDPF = SCR coated DPF
ASC = Ammonia slip cat.
MB = Mini burner
EHC = Electrically heated catalyst
FD = Fuel dosing



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

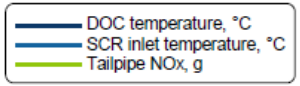
IAV, SAE HDD Symposium, Gothenburg 2018

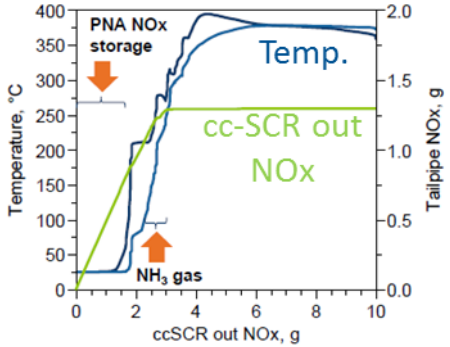



| Vol., l | ccSCR | ccAMOX | DOC | DPF | SCR | AMOX |
|---|---|---|---|---|---|---|
| EUVI | | | 11 | 26 | 28 | 4.4 |
| UL NOx | 8.7 | 4.3 | 11 | 15 | 28 | 4.4 |

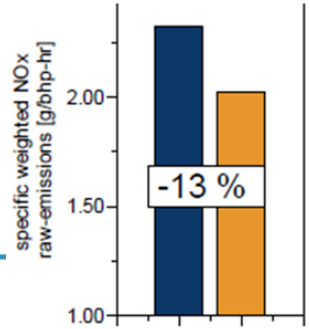
H. Rauch *et. al.*, 7th MinNOx, 2018

Potential for further improvement through PNA, gas $NH_3$

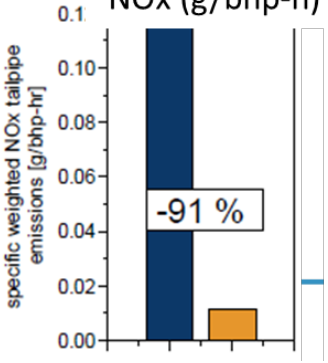


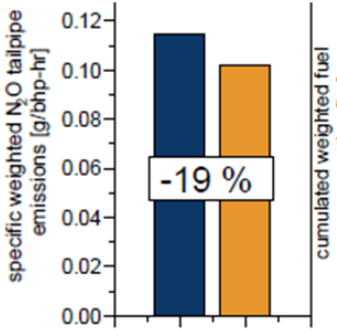

Weighted raw NOx (g/bhp-h)



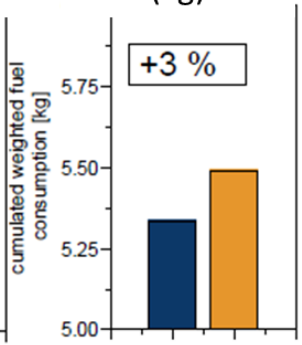

Weighted TP NOx (g/bhp-h)



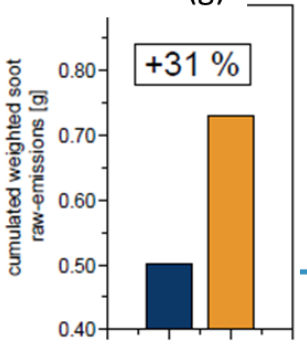

Weighted TP $N_2O$ (g/bhp-h)




Fuel cons. (kg)

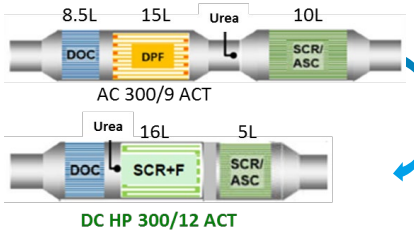



Soot raw emissions (g)

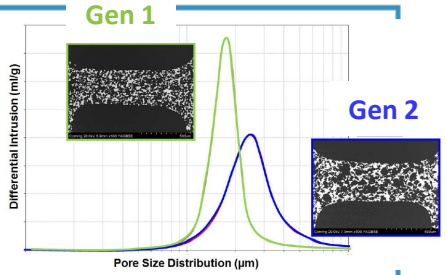


# High porosity filters enable integrated SCR & lower NOx
## Optimized μstructure for low ΔP & high FE, ACT for ash storage

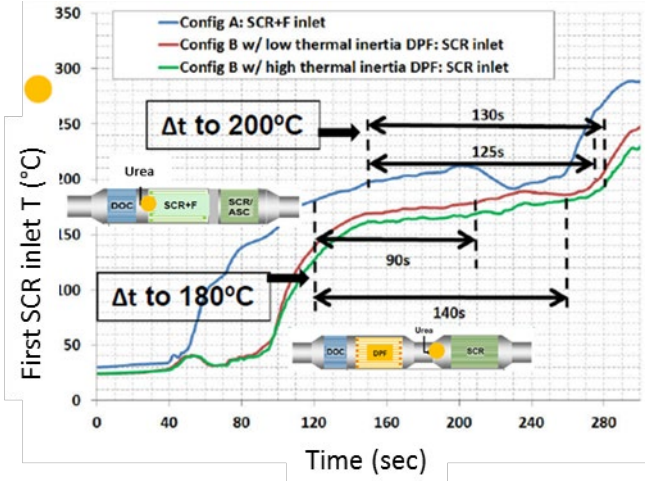
Corning, SAE 2018

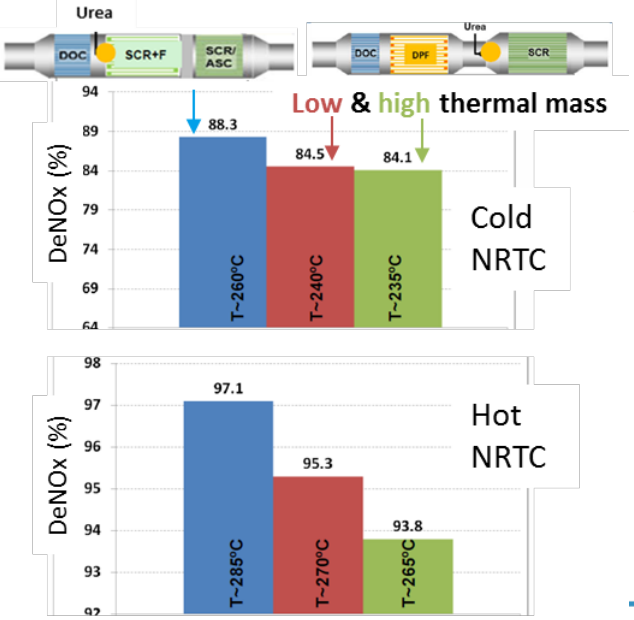


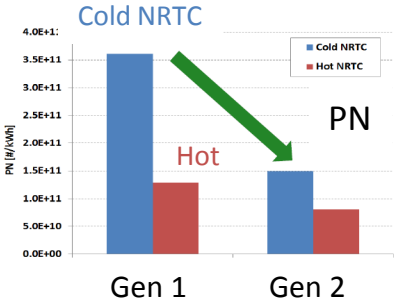

- Volume ↓ by 10 – 15%
- Faster heat-up & SCR light-off
- Improved NOx conversion
- Optimized microstructure for low dP and soot slip

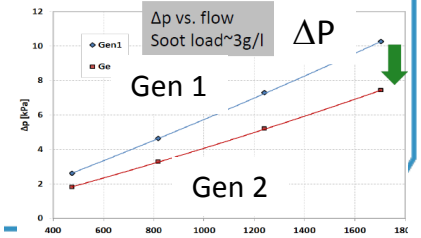



SCR+F reaches 180 °C 90 – 140 sec earlier



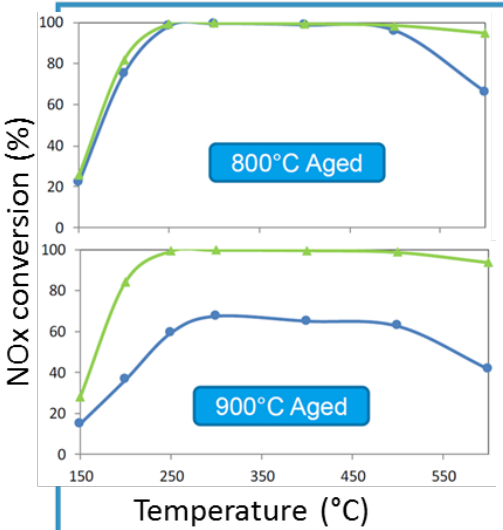



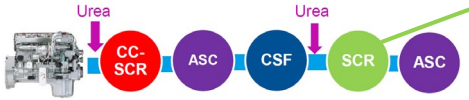

Tests on HD US EPA 2017 on-road engine
Procedure: Regen – 4xNRTC – Cool down – NRTC

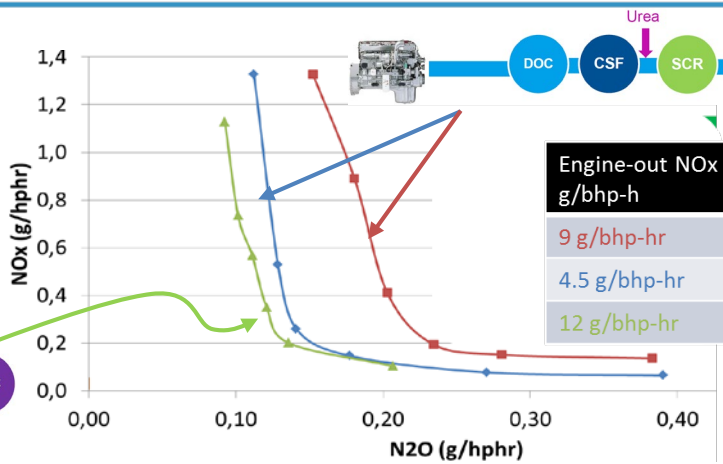
# Durability of SCR shown to 900 °C. Combination of close-coupled SCR and ASC shown to improve NOx-$N_2O$ trade-off

JM, SAE HDD Symposium, Gothenburg 2018



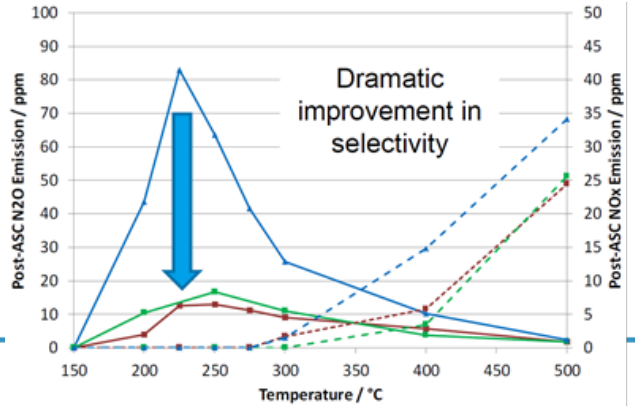

Close-coupled SCR :
Better tailpipe NOx / $N_2O$ trade-off even with 3X higher engine-out NOx → improved fuel economy

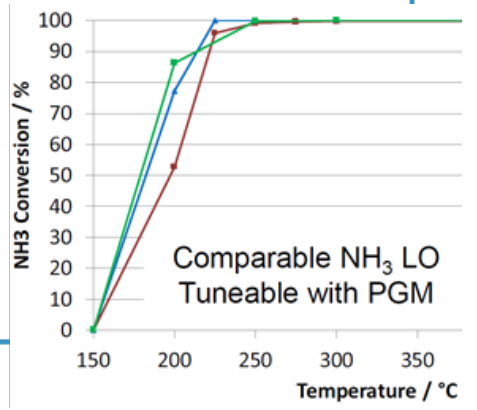



| Engine-out NOx g/bhp-h | After-treatment |
|---|---|
| 9 g/bhp-hr | SCRT® |
| 4.5 g/bhp-hr | SCRT® |
| 12 g/bhp-hr | SCR + SCRT® |

$N_2O$ emissions also reduced
NH3 conversion can be tuned with PGM

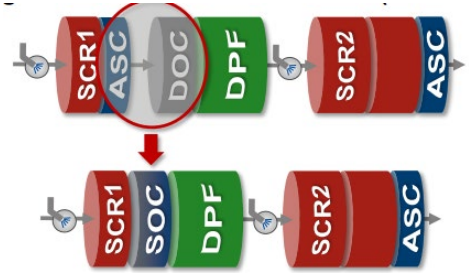


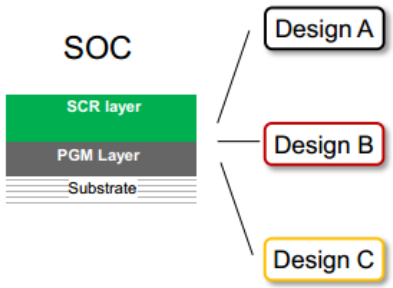



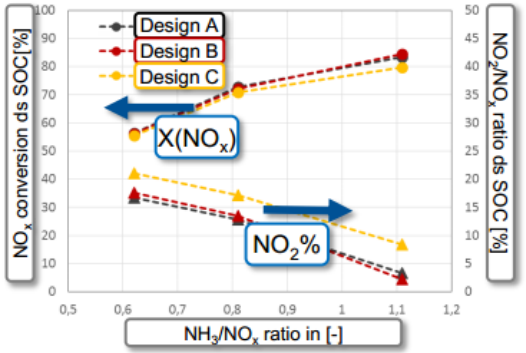
# New hybrid catalysts combining DOC and ASC being developed. Challenge is to make sufficient $NO_2$ with ammonia inhibition

SAE HDD Symposium, Gothenburg 2018

*Umicore*

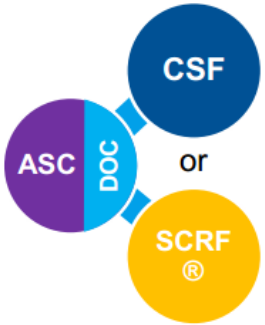


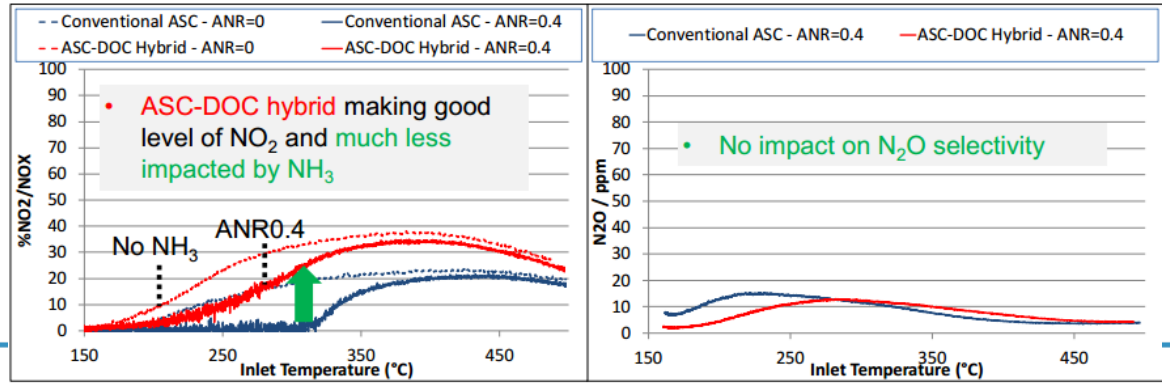




Increased Urea dosing shows negative impact on $NO_2$ formation
→ Competition with SCR reaction

*JM*

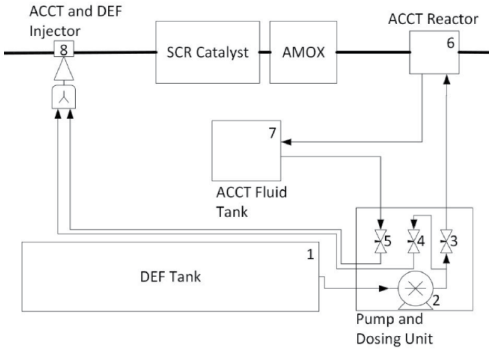



*500ppm NO feed, 55K SV*

# Solutions for ammonia delivery at low temperatures

Loughborough Univ., SAE 2018-01-0333




Ammonia creation & conversion technology (ACCT)

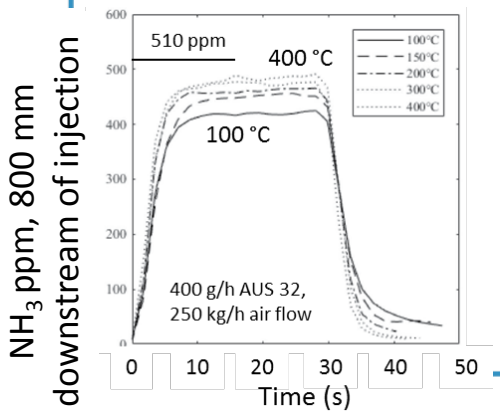
Exhaust waste-heat used to convert urea solution to ammonium carbamate

Thermolysis/hydrolysis of urea

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

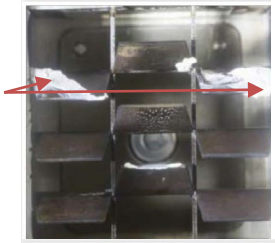
Products dissolve in steam

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

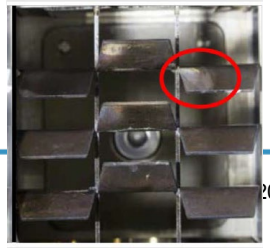



AUS 32

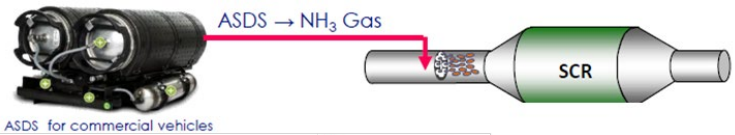
Deposits



ACCT

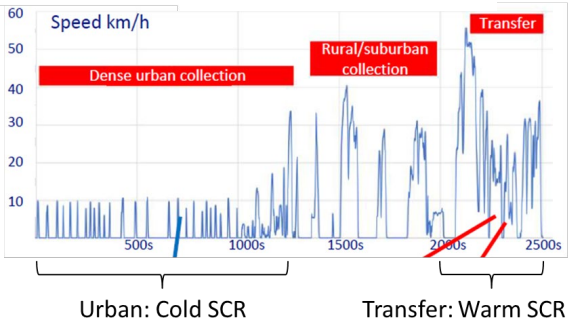


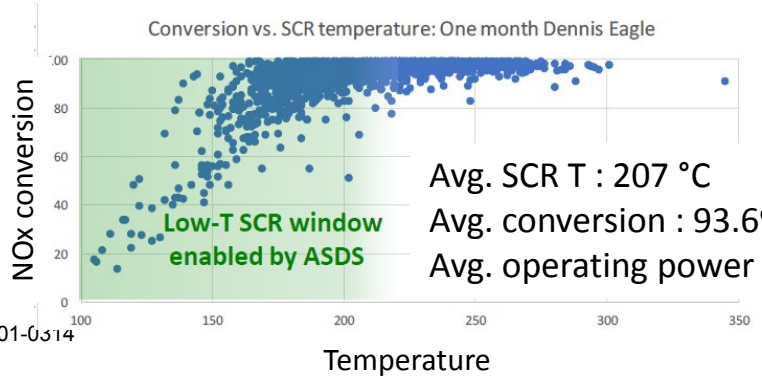
Amminex, Integer Emissions Summit USA, 2018




Refuse collection vehicle (RCV) route

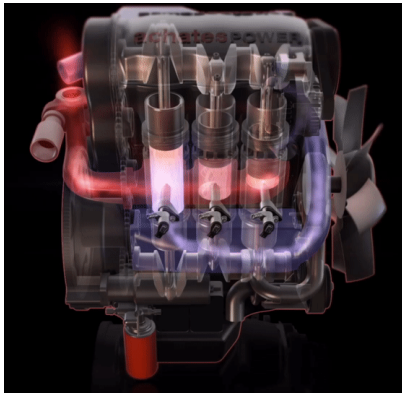
Depo → collection → empty at landfill → collection → depo



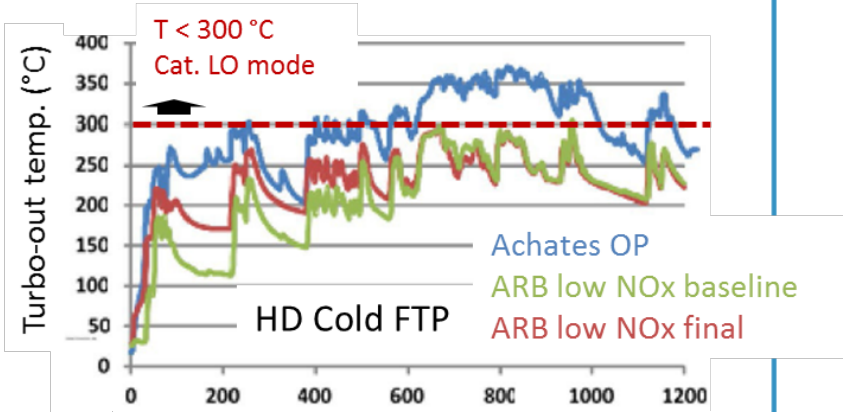
# HD opposed piston engine
# Simulations show path towards ultra-low NOx emissions

Achates, SWRI SAE 2018-01-1378

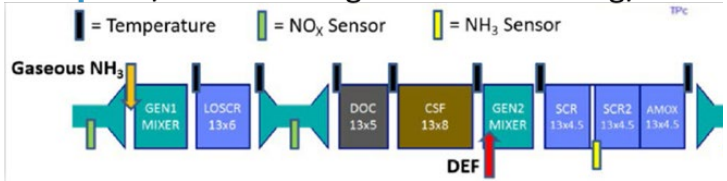


Data from 4.9L OP engine used to simulate 10.6L Class 8 engine

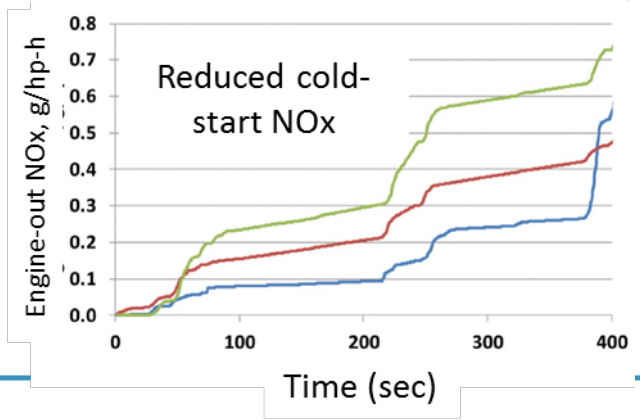
| | |
|---|---|
| Displacement | 10.6 L |
| Arrangement, number of cylinders. | Inline 3 |
| Bore | 120 mm |
| Total Stroke | 312 mm |
| Stroke-to-Bore Ratio | 2.6 |
| Compression Ratio | 17.5:1 |
| Nominal Power (kW @ rpm) | 336 @ 1700 |
| Max. Torque (Nm @ rpm) | 2373 Nm @ 950 |
| Exhaust mass flow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




A/T simulated gives NOx at 0.03 g/kWh



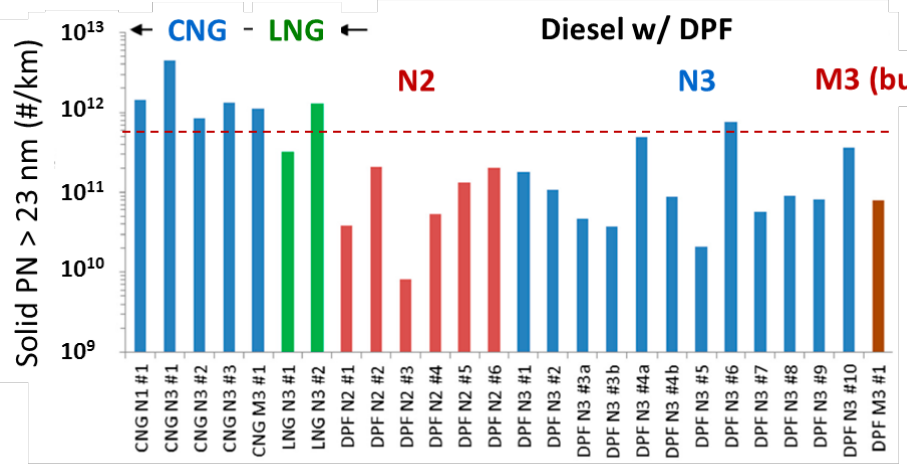

Elevated exh. T through increased residuals
With close-coupled SCR, deNOx can start in < 100 sec.



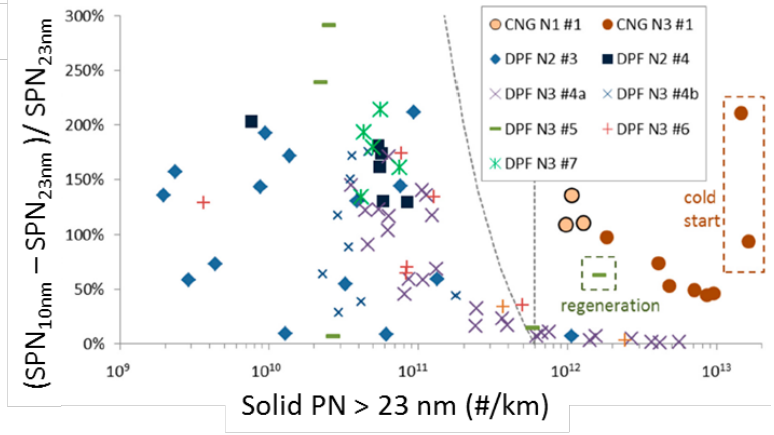
# CNG engines offer pathway to low NOx
# But PN emissions from stoich. NG trucks higher than Diesels w/DPF

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




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




PN measured under real world driving:
Stoichiometric NG trucks: $3.3 \times 10^{11} – 4.5 \times 10^{12}$ #/km
Diesels with DPF : $8.0 \times 10^{9} – 7.0 \times 10^{11}$ #/km

CNG vehicles emit > 50% of sub-23 nm particles

# Summary

Light-Duty

- Europe has set the tightest $CO_2$ standards : 37.5% reduction by 2030, along with electrification mandates.
- There is still significant untapped potential for ICE technologies. Much more efficiency improvements to come. Synergistic gains with hybridization ahead.
- First emissions data from RDE compliant vehicles published. Both gasoline & diesels exceed Euro 6 norms.
- Gasoline particulate filters are being deployed in EU/China. Even some PFI and hybrids may require GPFs.
- Addressing cold start emissions critical to meet SULEV30. TWCs continue to improve, but may require addition of HC traps.

Heavy-Duty

- Europe has established its first-ever $CO_2$ standards : 30% reduction needed by 2030, compared to 2019
- SuperTruck II program is promising impressive gains in fuel efficiency – leading concepts reviewed
- Several filter-enforcing regulations in place : China VI, BS VI, non-road Tier 4, Brazil PROCONVE P8
- California is leading the development of an omnibus rule for lower in-use NOx emissions

# Thank you

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