Update on Engine Technologies and Emissions

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December 8, 2016

HEI Fuels Workshop
Chicago

Summary

- There are several low-CO_2 engine strategies being developed that can drop emissions by up to 40%.
  - Emissions and development challenges are summarized – LT, HC, lean NOx, PN
- Gasoline particulates are emerging as a major emissions issue
  - Difficult to remediate without filters
    - Rich zones during cold start, hot starts, accelerations, and LT ambient conditions
  - High PAH emissions
  - GPF solution
- Lean NOx solutions are focusing on lower-temperature and cold start
- LT oxidation catalysts are evolving – CH_4, HC, CO

Engines

MATURE ↑ DEVELOPING

Technology	CO_2 Benefit*	Challenges	Penetration	Implications for emissions
GDI	~ 3 – 5%		98% by 2022	PN
Atkinson cycle (+VVT)	3 – 10%	↓ peak power & torque	Primarily in hybrids	Cooler exhaust
Adv. start-stop	2 – 5%	Consumer acceptance Particulates at re-start	45% by 2025	Warm start PN
Dynamic cyl. deactivation (+ VVL)	2 – 10%	Noise & vibration	50% in 2025	Reduced idle emissions. Hotter exhaust Faster heat up for DPF regen
Lean-burn gasoline	15 – 25%	NOx, pSCR controls	Implemented EU	PN, NOx control, LT exhaust
High CR (~ 17) engines (+ S/B ~ 1.5, GDI, Atk.)	20 – 25%	Knock	Adv. Eng.	
2-stroke opp. piston Diesel	30 – 40%	Boost; new design	Development	Conventional DPF+SCR
Dedicated-EGR	20 – 25%	Durability	Development	
GDCI	20-30%	Transient control	Research	Lean NOx; High HC (→ adv. ox. Cat, HC trap)
Pre-chamber combustion	15 – 20%	Complexity (2 chambers), particulates	Research	Lean NOx
LTC (HCCI, RCCI)		Operating load range Complexity – dual fuels	Research	Low NOx and PM emissions. LT and high HC emissions.

*Compared to NA PFI engines

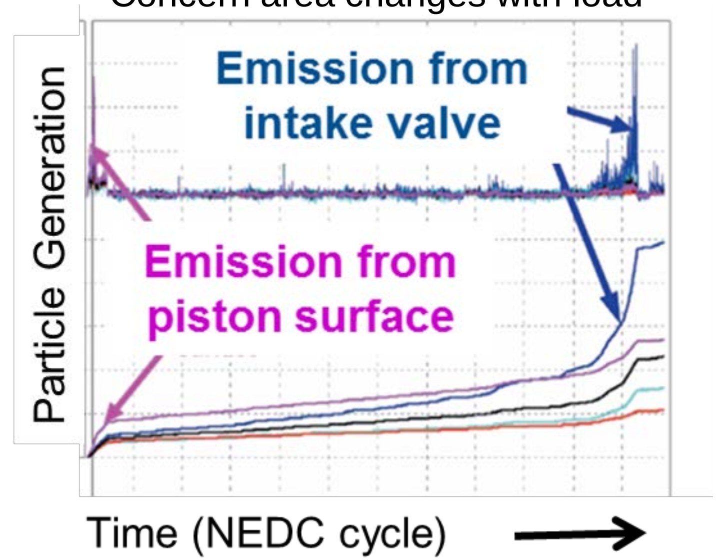
Gasoline particulates

Achieving PN reductions across all real world conditions and over vehicle lifetime is challenging

Progress made on in-cylinder particulate formation minimized via optimization of:

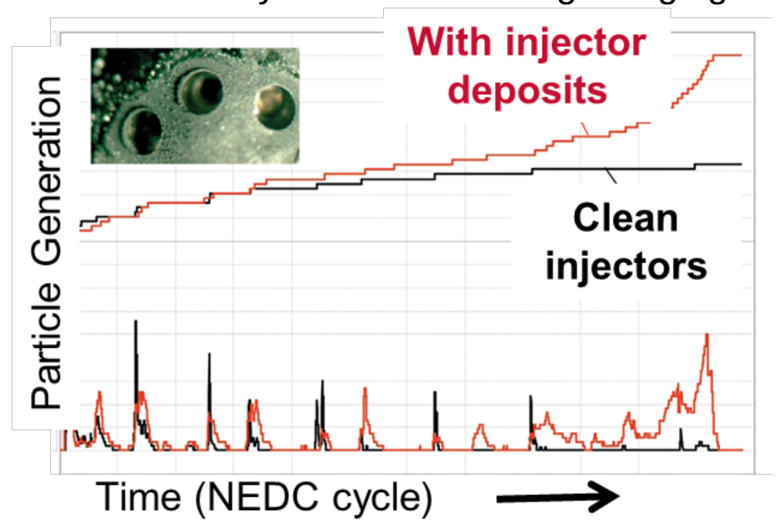
- Injection parameters (# injectors, timing, spray pattern, pressures, etc.)
- Combustion chamber geometry
- Valve events
- Charge motion, etc.

Fraidl et al. (AVL, 2012)



Challenge is to maintain sustainable low PN over real world conditions

- Variation in speed/load
- Ambient temperature
- Deposits – Injectors, combustion chamber, valves
- Production tolerances
- Wear, aging
- Variation of fuel, lube oil quality
- Variability across fleet
- Measurement challenges
- …



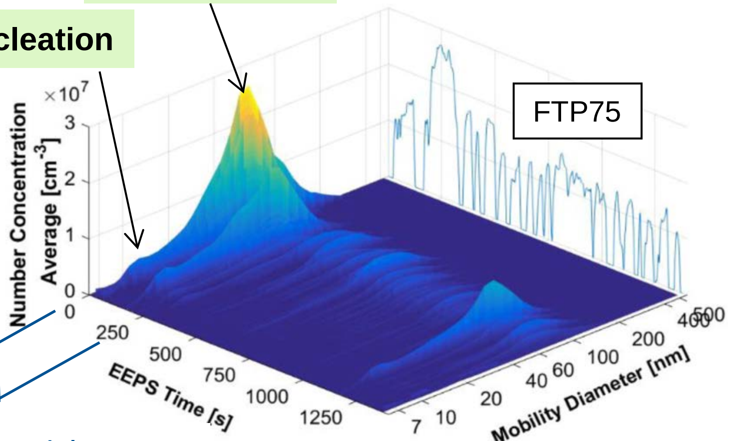
Test drive cycle has a significant impact on tailpipe emissions

Particulates driven mostly by cold start and hard acceleration events

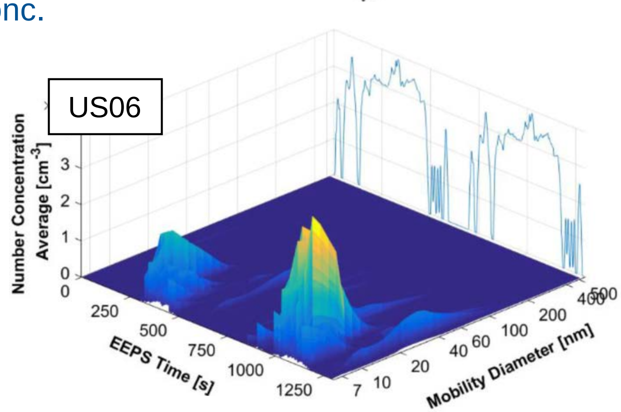
Reference: Koczak, J. et al. / SAE 2016-01-0992

Accumulation

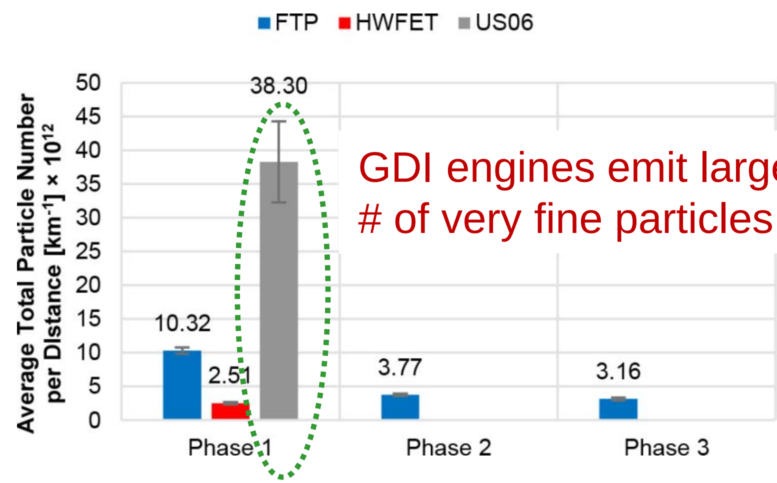
Nucleation



High particle conc. for t < 250 s

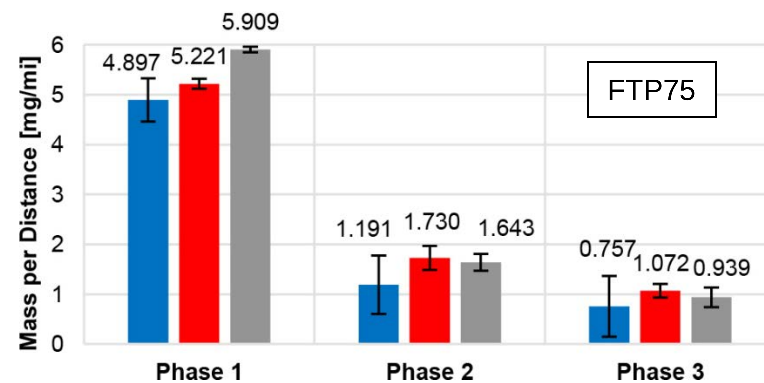


Unimodal, nucleation mode
Order of mag. higher conc.



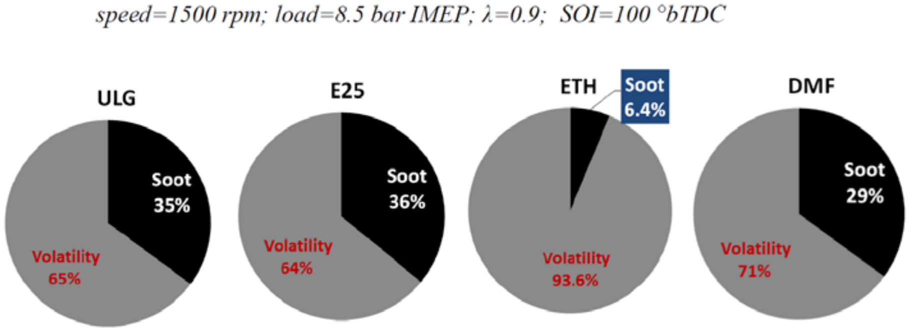
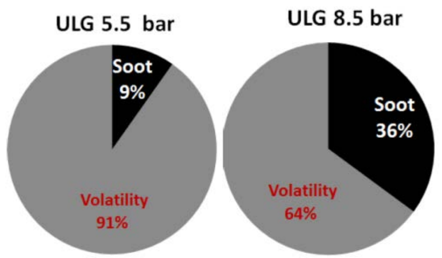
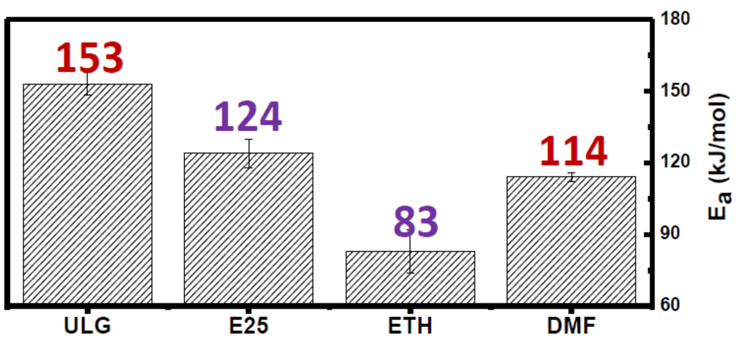
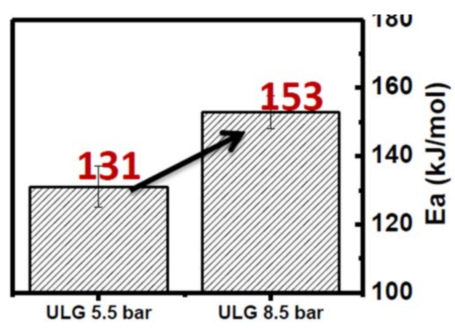
GDI engines emit large # of very fine particles!

Mass-based emissions are low (but still above CA limit of 1 mg/mi)



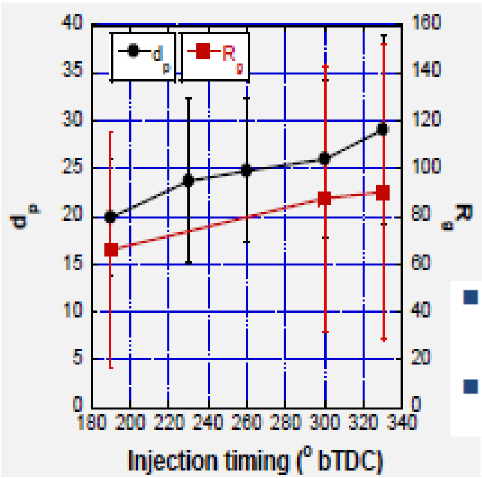
Soot composition & reactivity depend on fuel type and engine load

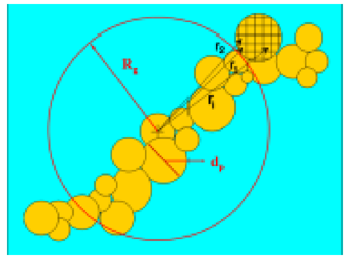
U. Birmingham, 2014 Cambridge Particle Meeting

	Impact of fuel	Impact of engine load
PM composition		
PM Reactivity		

GDI PN is characterized, and somewhat different from diesel.

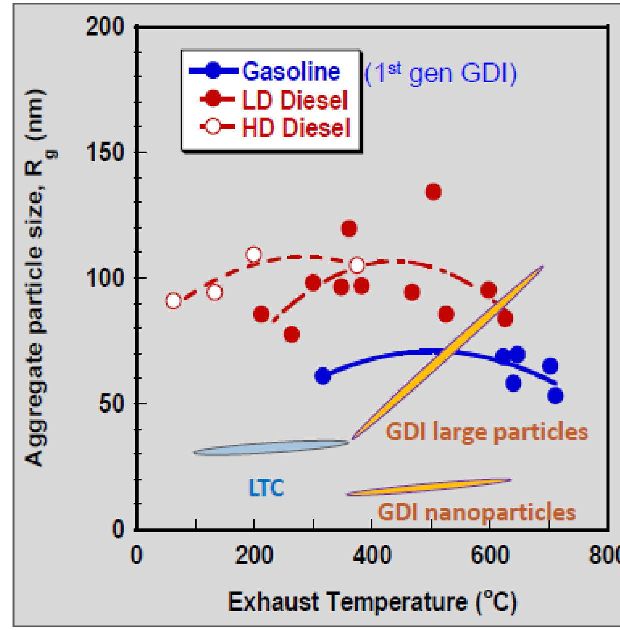
Smaller primary and aggregate size; less chrystalline. Oxidation catalyzed by ash.



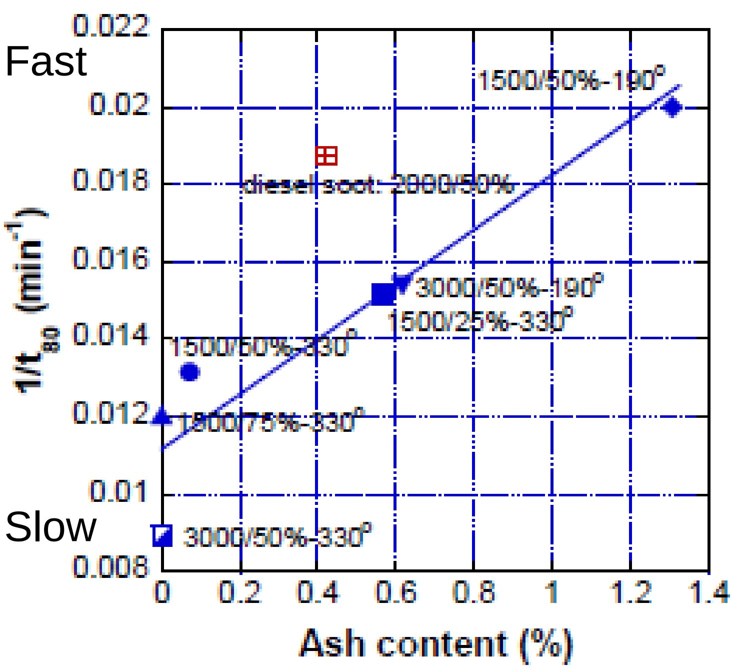


- Primary and aggregate particles tend to grow in size with advancing injection timing at the fixed spark timing.
- There emit a high population of sub 23 nm particles from GDI engines.

1500 rpm/50% load (spark timing fixed)



GDI PN aggregate size is bi-modal and much smaller than for diesel. Primary particle size is also ~10nm smaller.

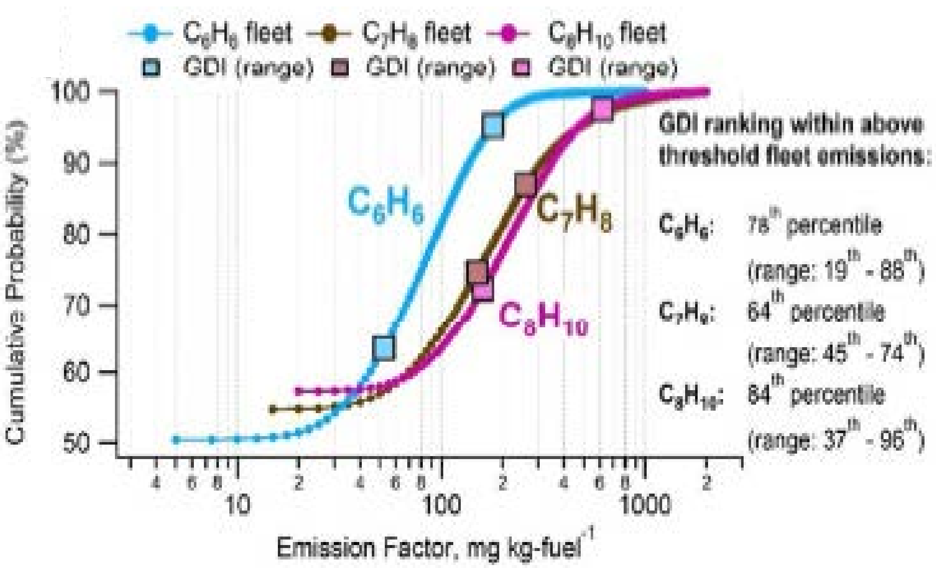


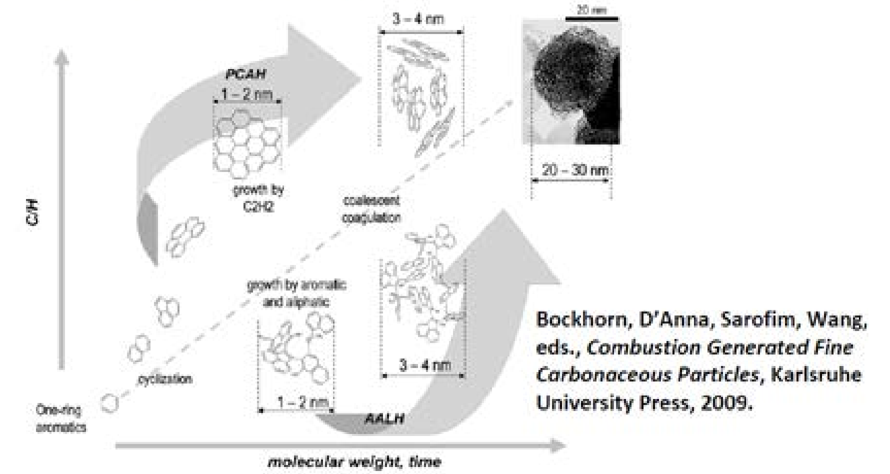
GDI PN oxidation rates depend on ash content. t_{80} is time to 80% oxidation.

Gasoline-derived GDI soot appears to be graphitic similar to diesel soot in TEM observation

- PDF data verify Raman results:
  - Degree of crystalline structures: GDI soot< Diesel soot
  - GDI soot shows no distinct change with engine conditions.

GDI engines have high PAH emissions.





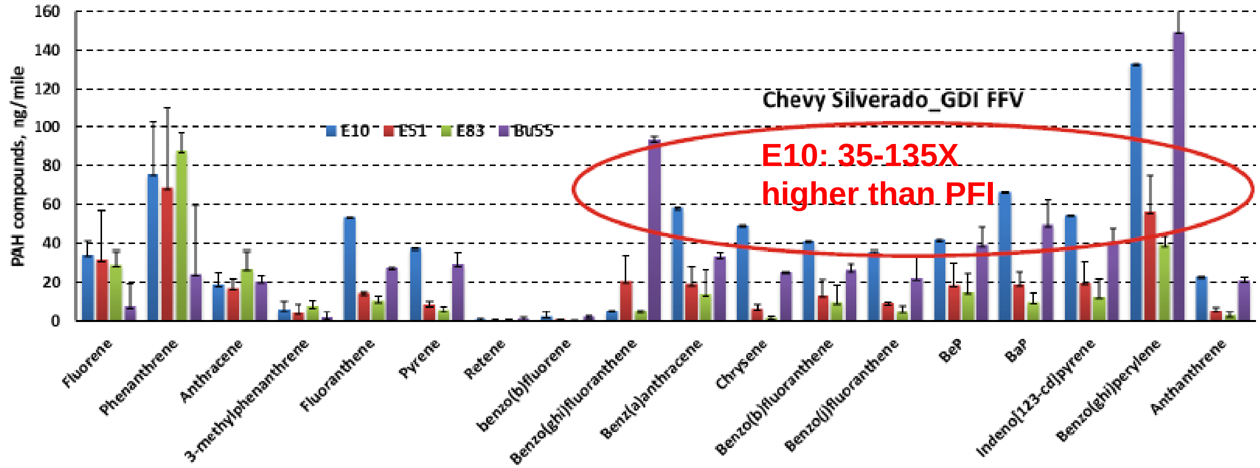
2013 Ford Focus GDI has PAH emissions in the upper percentiles of the whole Toronto fleet.

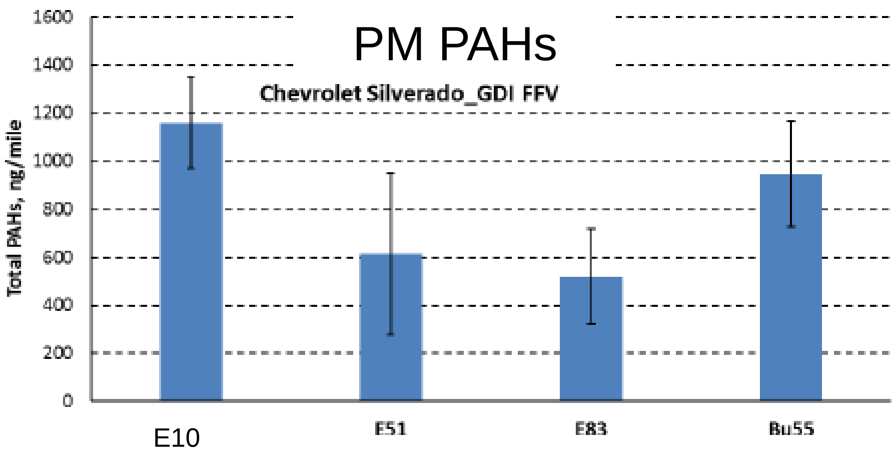
Univ Toronto, Environ Sci and Techn, 1/16

PAHs are soot precursors, so GDI soot may be “immature”.

E10 GDI PAH emissions ~4X higher on FTP-75 than for similar PFI pick-up truck. PM-based PAHs 14X higher. Large PAHs 35-135X higher.

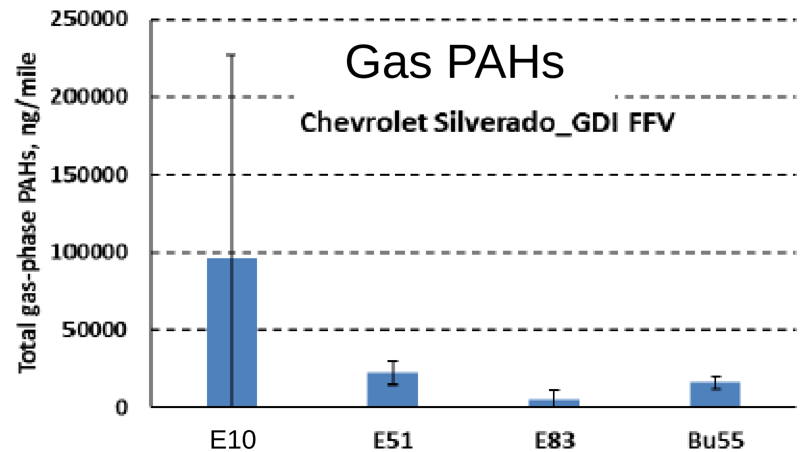
2012 MY Mazda 3	2013 MY Ford F150	2014 MY Chevrolet Silverado
Wall-guided, DI	PFI	Wall-guided, DI
2.0L	3.7L	5.3L
Inline, 4 cylinders	V6	V8
115 kW at 6000 rpm	225 kW at 6500 rpm	265 KW at 5600 rpm
203 Nm at 4000 rpm	377 Nm at 4000 rpm	519 Nm at 4100 rpm
13.0:1	10.5:1	11.0:1
California LEVII, SULEV	California LEV II, ULEV	California LEV II, ULEV
18,851	13,700	2,649





vs. Mazda (GDI) 5.1X 4X

vs. F150 (PFI) 14X 6X



vs. Mazda (GDI) 7.9X 0.7X

vs. F150 (PFI) 4.3X 1.2X

E10: GDI has up to 14X more PM-PAHs than similar PFI vehicle. Mazda GDI car has 2.7X more PM-PAHs than large PFI pick-up truck.

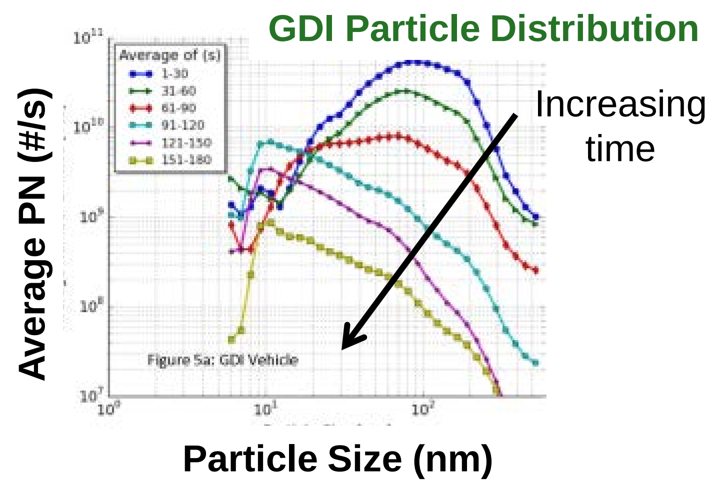
Gas + PM PAHs: GDI 4.3X higher than PFI

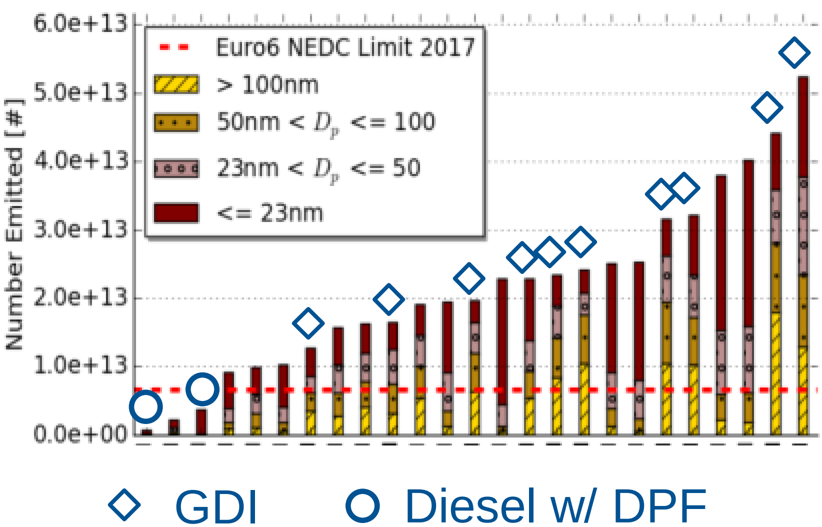
UC-Riverside, SAE PF&L, 10/16

Particulates during cold-cold start (7 °C) shown to exceed limits even for PFI vehicles

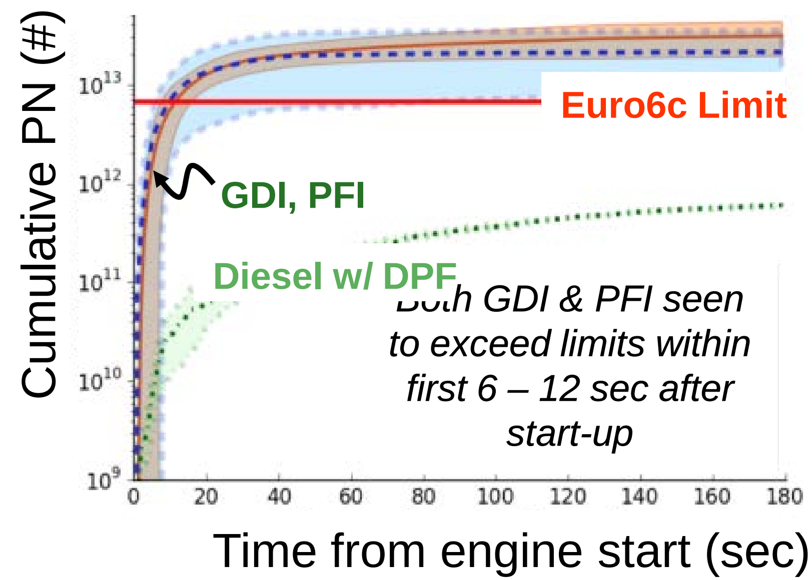
Reference: Badshah, H. et al. / SAE Int. J. Engines 9(3):2016

- PN from GDI mostly in accumulation > 50nm mode
  - Enrichment at low T, wall & piston wetting
- PN from PFI mostly < 50nm mode
- Particulates mostly “solid”
- Average PN over 180s: 3.1×10^{13} for GDI & 2.1×10^{13} for PFI
- Almost all vehicles exceed limit
  - DPF seen to be very effective for Diesels

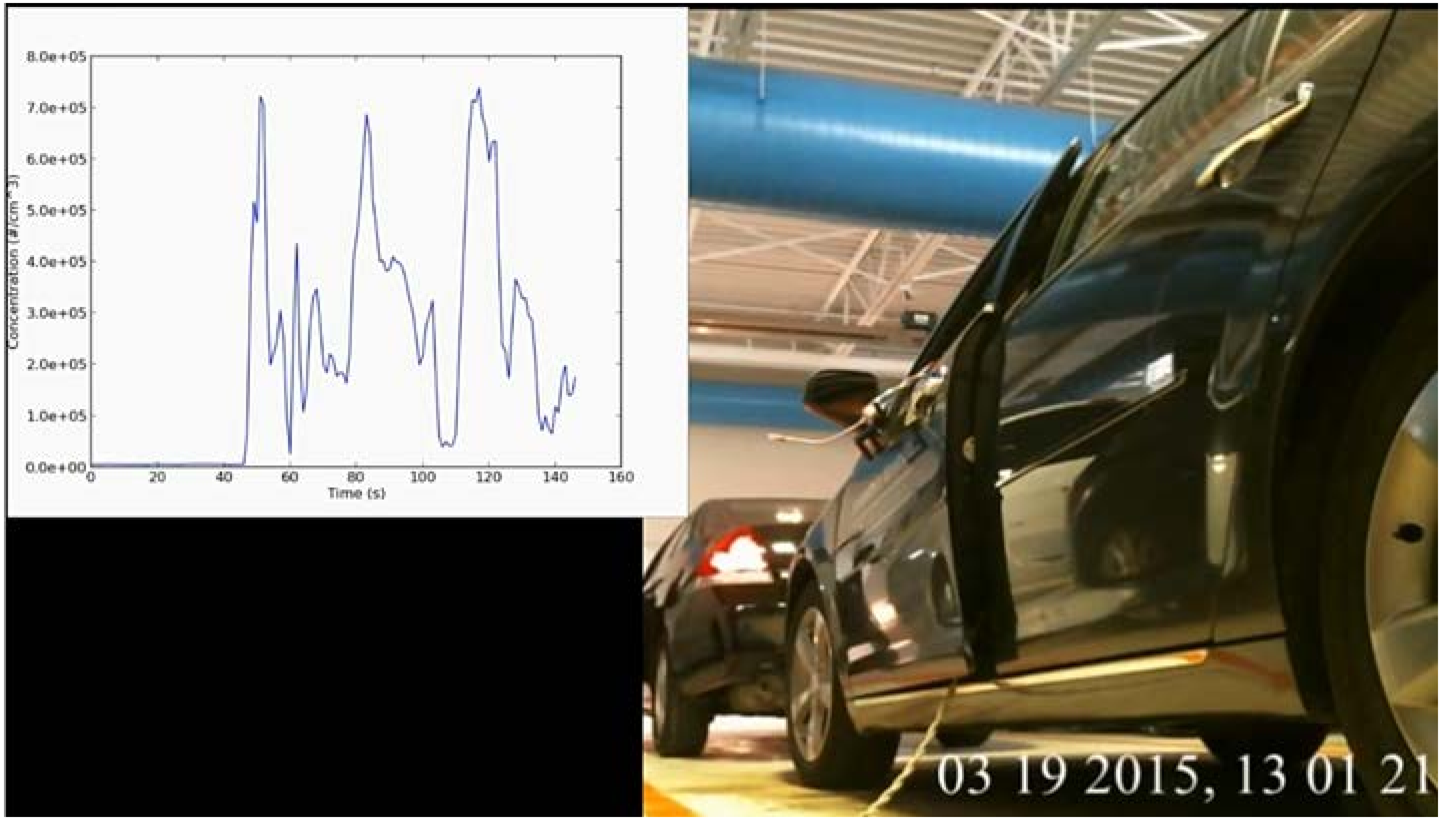




PN for different vehicles 180s after cold start at 7C.



PN exposures can be high in parking garages.

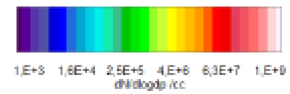


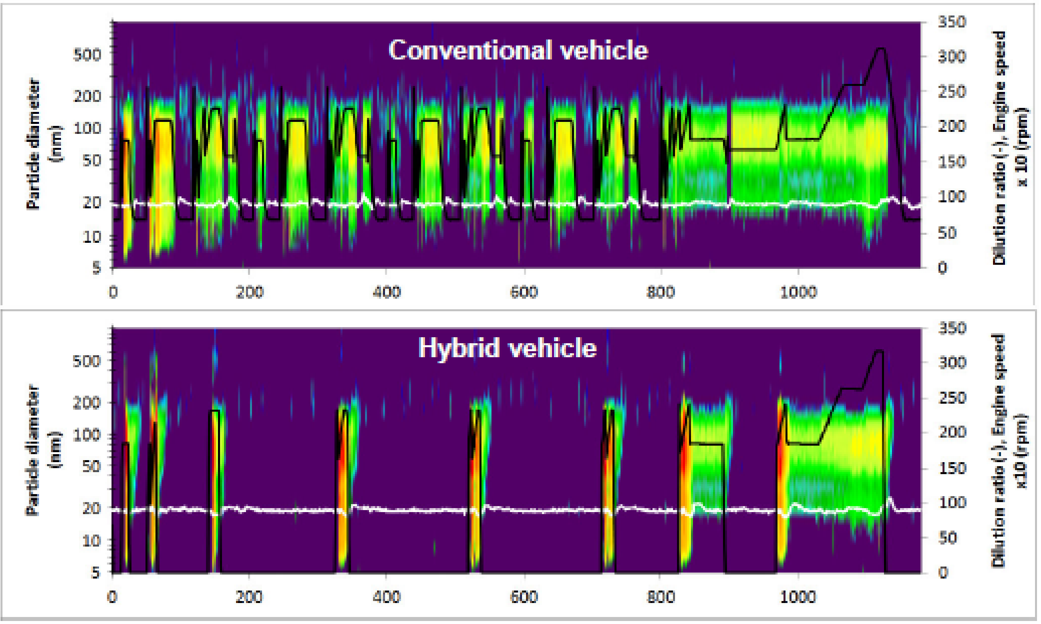
PN emissions from modern GDI car as measured by the trail car in a parking facility. 150,000 to 700,000/cm^3. Outside background is 3000/cm^3.Timeframe here is 100 sec.

Univ. of Minnesota, 4/15

Due to high hot-start PN emissions, an HEV might have higher PN emissions than a conventional vehicle.

- Comparison of conventional and hybrid driving operation at the engine test bench on NEDC cycle

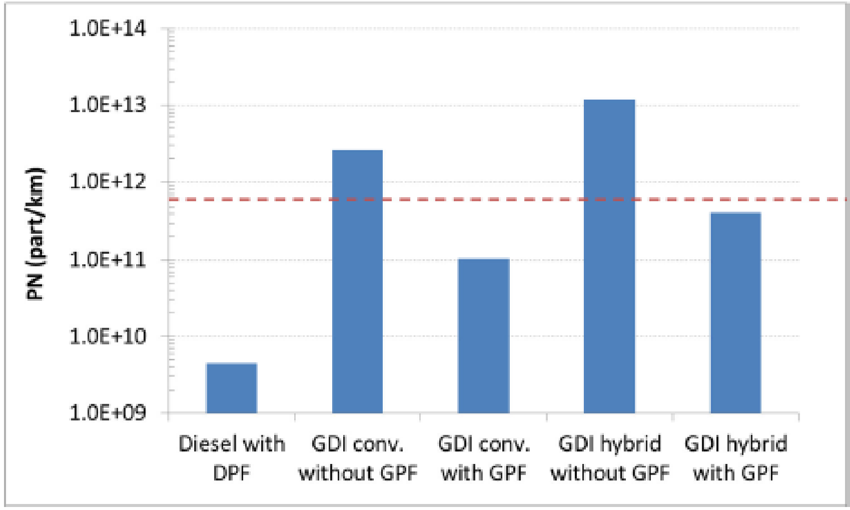




Tot. PN = 2.6. 10^{+12} part / km

Tot. PN = 1.2.10^{+13} part / km

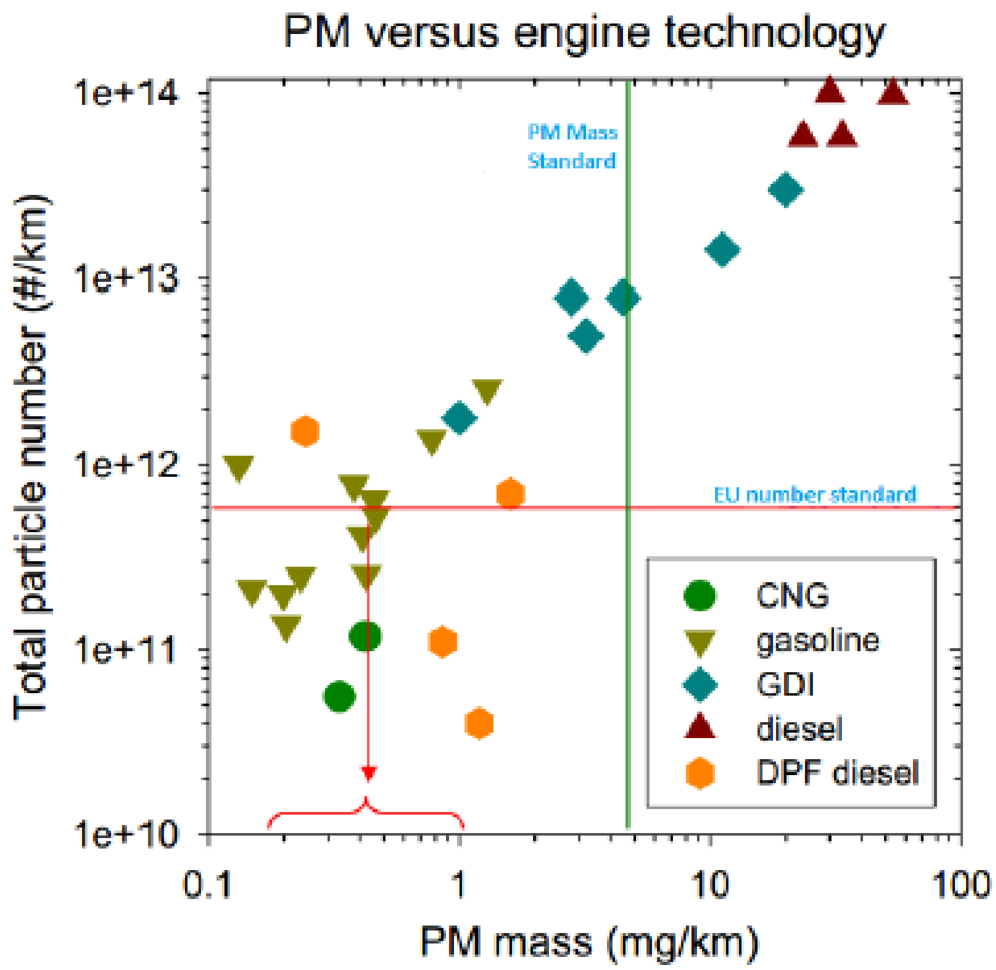
- B-segment vehicle
- 1.6 liter GDI
- Euro 5b
- Two close coupled TWC
- Uncoated GPF
- Fuel: EN 228, 4.8% EtOH, 31.7% aromatics, research octane 97.2, 3 ppm sulfur



- Engine bench simulation of D-segment HEV with 50 kW electrical system, 1.3 kW-hr battery
- Engine used only 28% of time during transients and high load.
- “HEV” on NEDC has 4.6X PN vs. conventional operation.
- Caution: Not calibrated nor optimized for HEV

IFP, SAE 2016-01-2283

Across engine types, PM may not be a good indicator of PN. At any given PM level, PN can vary up to 1.5 orders of magnitude.



Ford, HEI Annual Conf, 2009

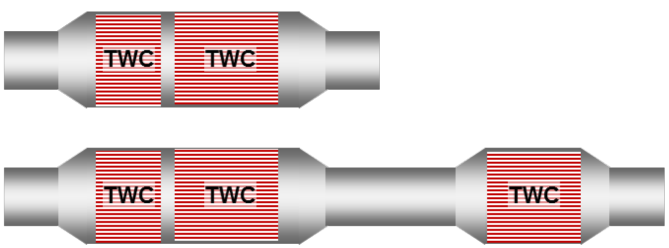
Evolution of light duty GPF architectures to meet particulate regulations

Broad introduction of GPF (uncoated and coated) – EU, Beijing and CARB

EU5/6b /
LEV II/III (@3-6mg/mi)

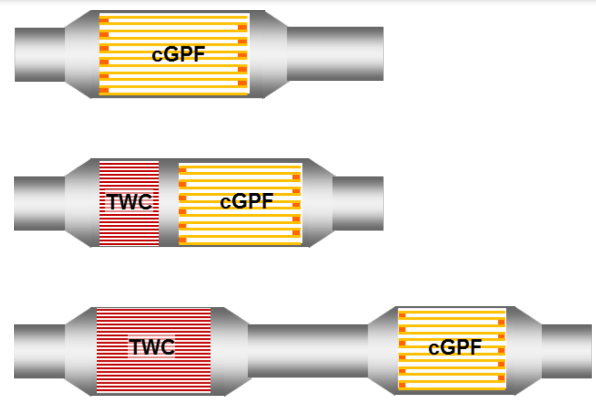
EU

US

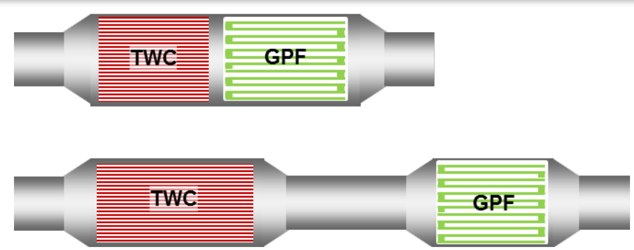


EU6c/7 / Beijing 6 /
LEV III (@1-3mg/mi)

TWC Integration into GPF

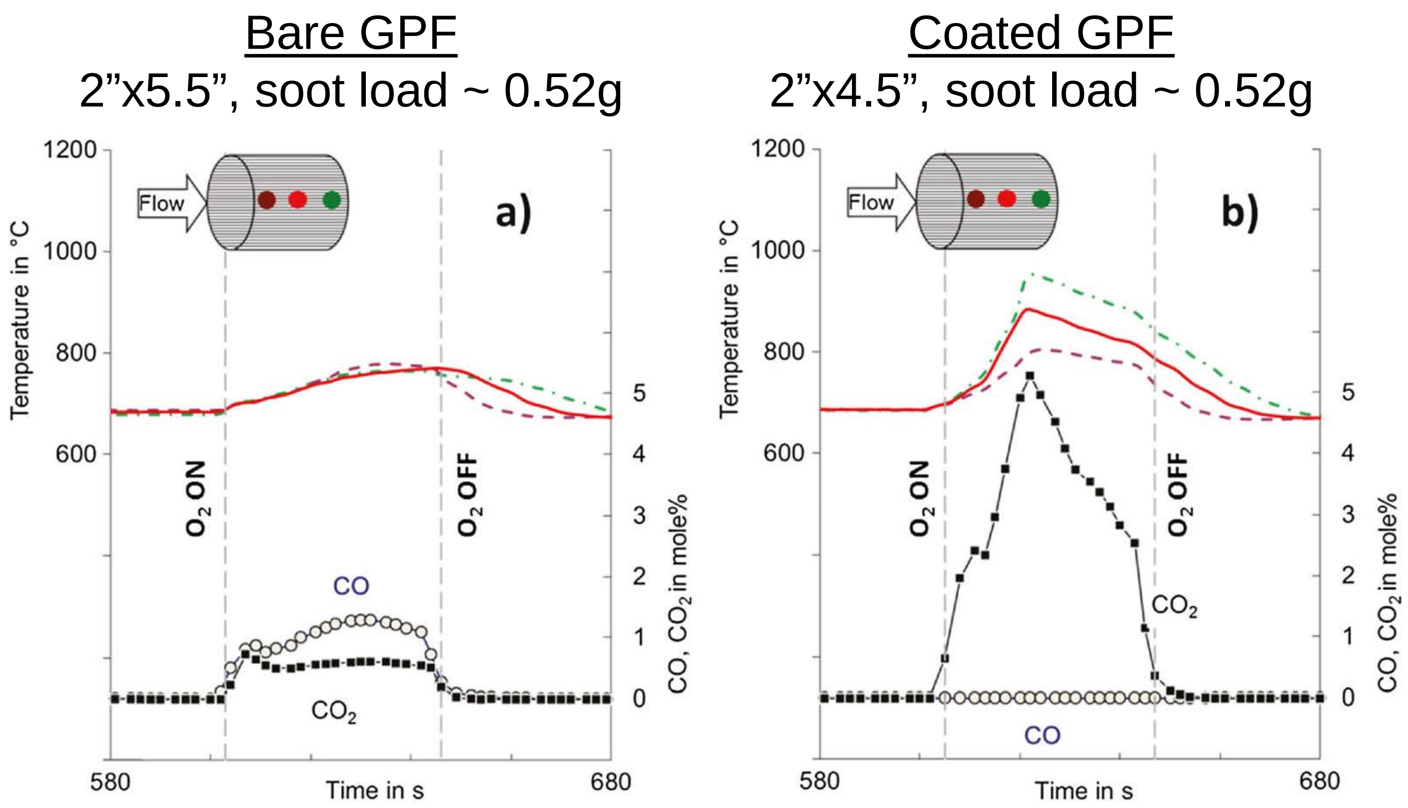


GPF for Filtration only



Comparison of soot oxidation on bare and coated GPF

T. Boger et al. Emiss. Control Sci. Technol. 1 (2015): 49–63



Complete oxidation to CO_2 on coated GPF due to PGM

PM characteristics from Lean GDI engines depends on combustion mode. GPFs effective for all conditions

Reference: Parks J. et al. (ORNL), SAE 2016-01-0937

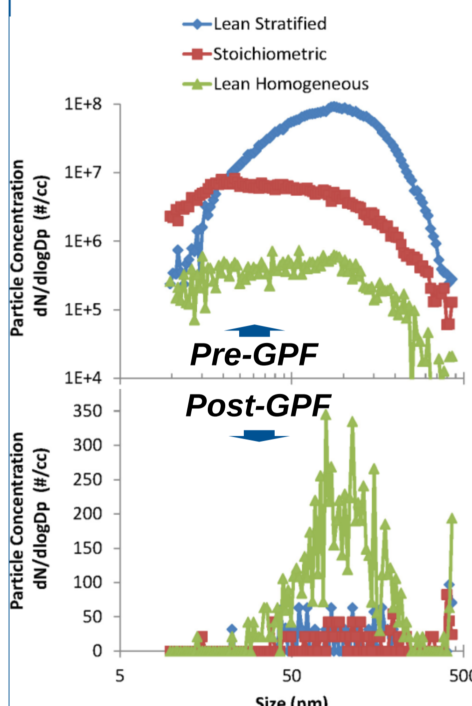
Engine	2008 BMW 1-series 120i, 2.0L, 4-cyl., naturally aspirated
Combustion modes	Lean stratified, Lean homogenous, Stoichiometric
GPFs	200/12, 5.66”x6”, Bare, Underfloor

PM depends on combustion mode (1)

- o Order of magnitude higher for lean stratified mode
- o Mean particle size smaller for stoichiometric
- o Organic C content PM: Lean stratified < stoichiometric < Lean homogenous

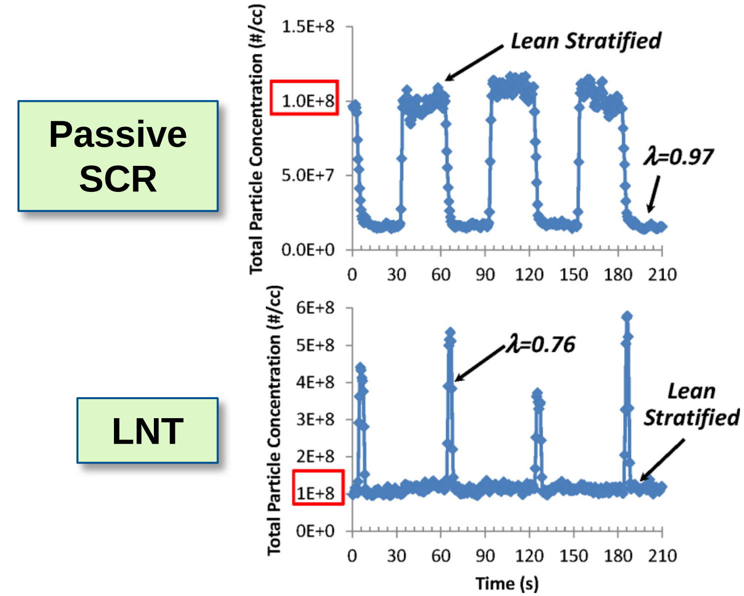
GPFs capture most particles in all cases

- o Filtration efficiency > 95% over wide operating range



PM depends on NOx control strategy (2)

- o LNT cycling produced higher PM than lean-rich cycling for passive SCR
- o GPFs highly effective even during transients



(3) **Organic content of PM primarily paraffins from engine oil**

- o Little/no PAHs found as reported in stoich. GDI engines

Lean NOx Control

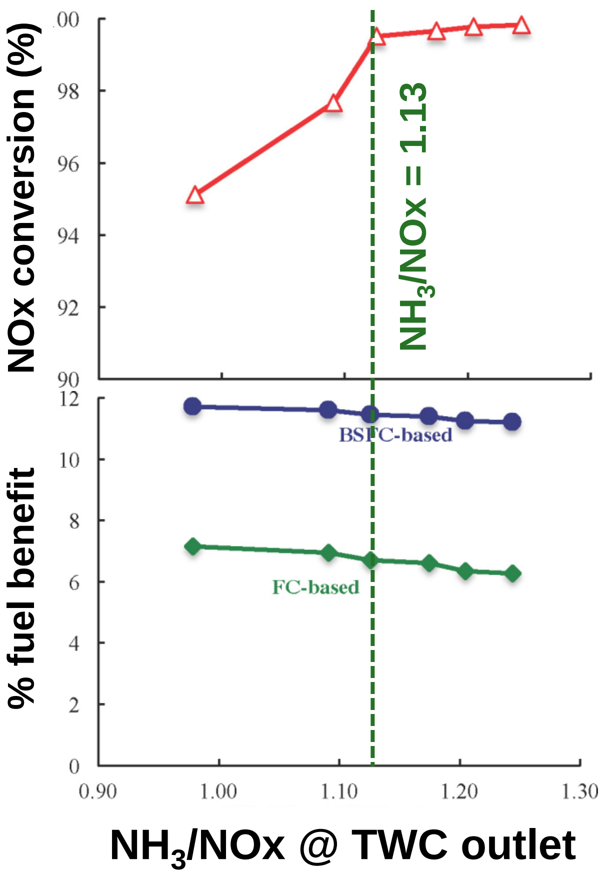
Passive SCR with lean gasoline engines shown to achieve > 99% deNOx and 11.5% fuel consumption benefit

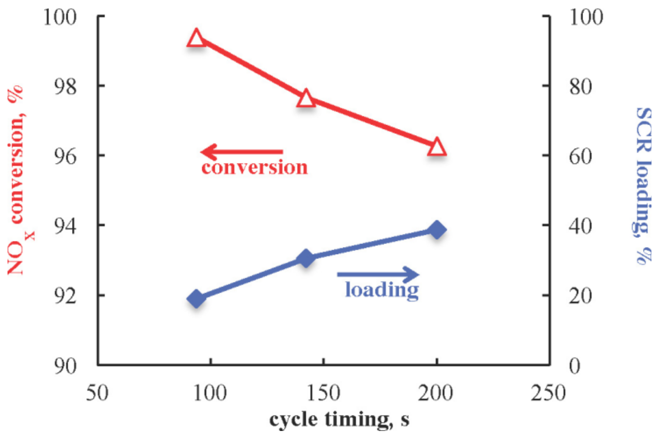
Reference: Prikhodko V. et al. (ORNL), SAE 2016-01-0934

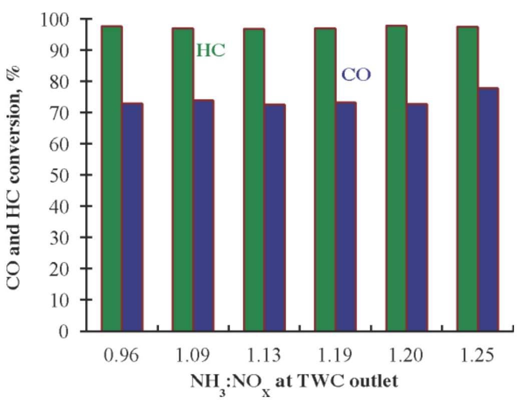
Engine: 2008 BMW 1-series 120i, 2.0L, 4-cyl., GDI, naturally aspirated
Test conditions: Load step conditions - Engine alternated between lean (λ = 2.0, 2 bar BMEP) and rich (λ = 0.97, 8 bar BMEP) operation

(1) At NH_3/NOx = 1.13:
- NOx conversion = 99.5%
- % fuel benefit = 11.5%

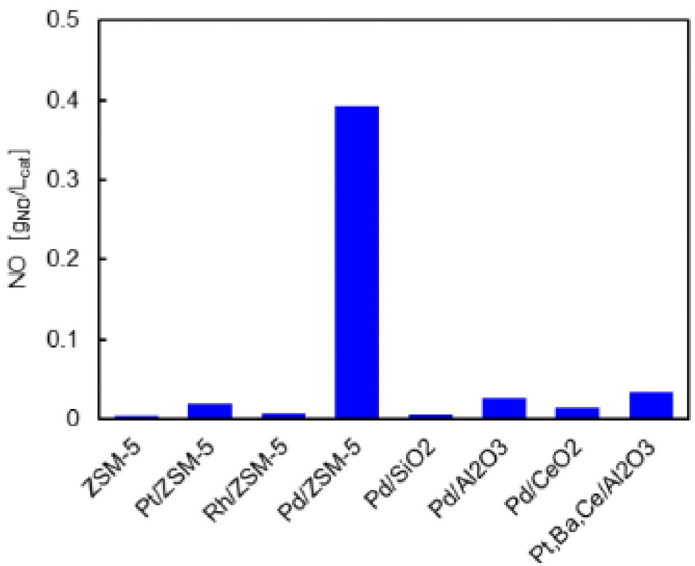
(2) Higher NH_3/NOx: NH_3 slip and decreased fuel benefit
(3) Increased cycle time leads to decreased NOx conversion (NH_3 oxidation during longer lean period)
(4) Low CO conversion still a challenge

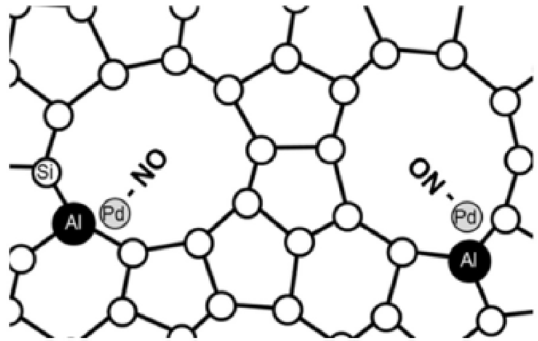


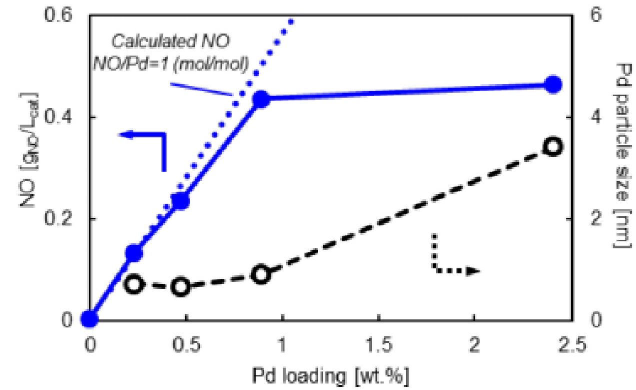




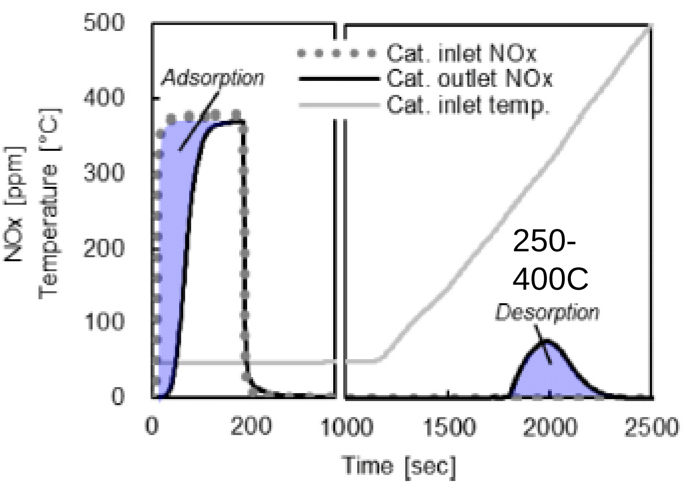
A new Pd-zeolite passive NOx adsorber has impressive cold-start NOx storage capacity. Desorbs at 250-400C.

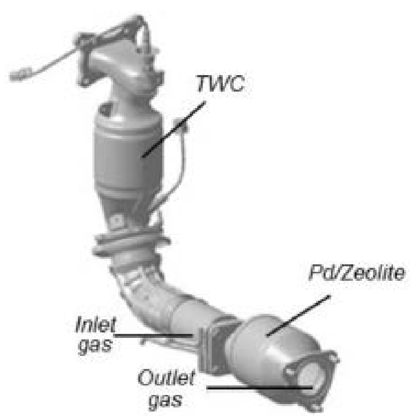


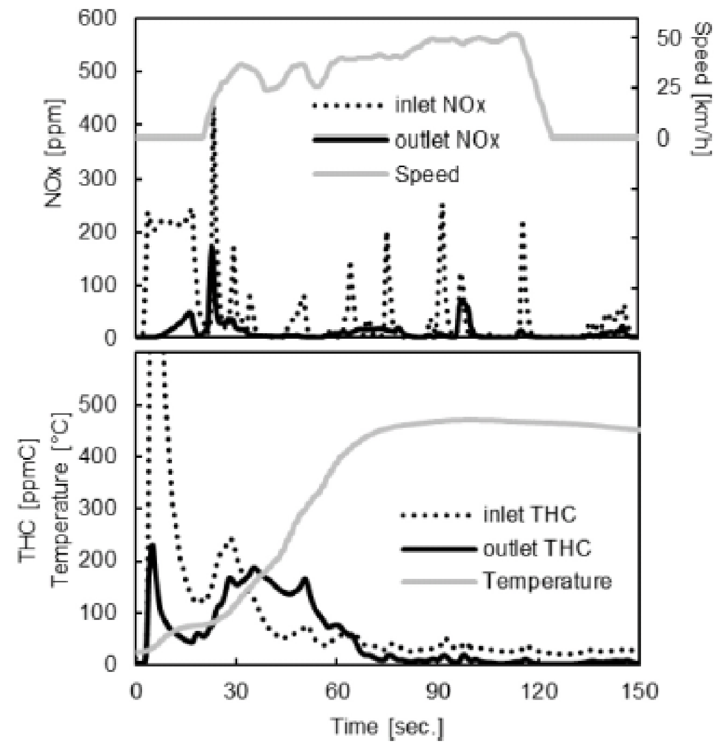




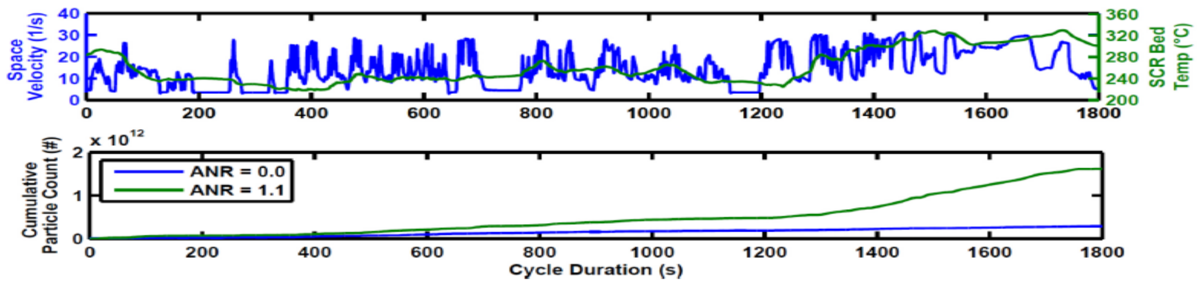
Zeolite with impregnated Pd has enhanced NO storage capacity

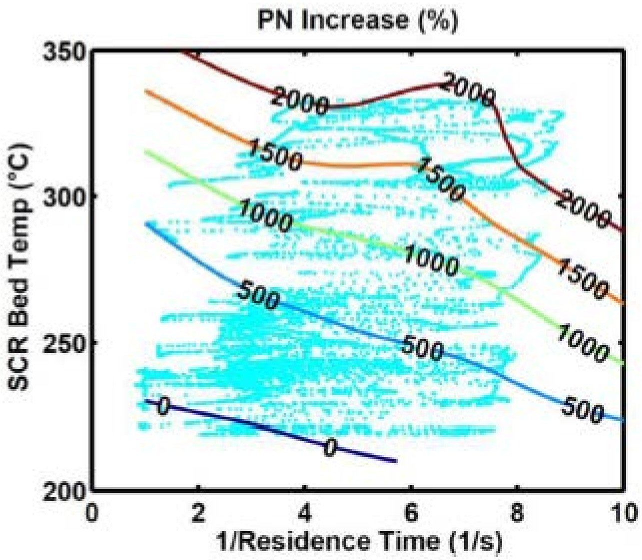






Urea dosing increases PN count by 3-5X. 80% of PN on WHTC from urea.

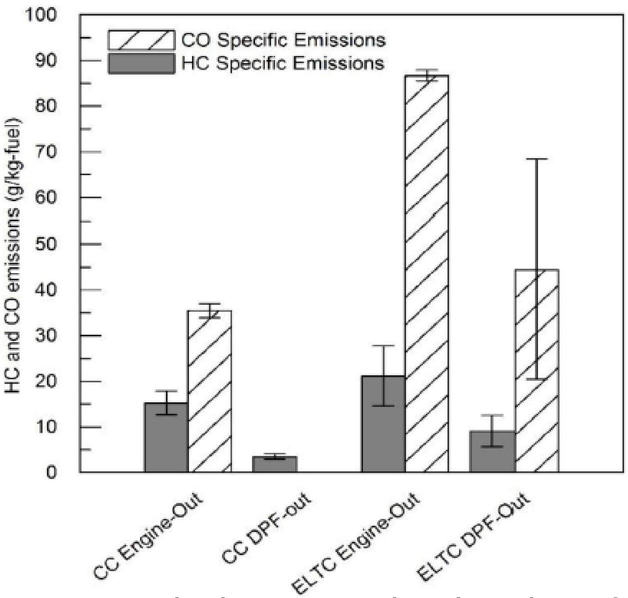




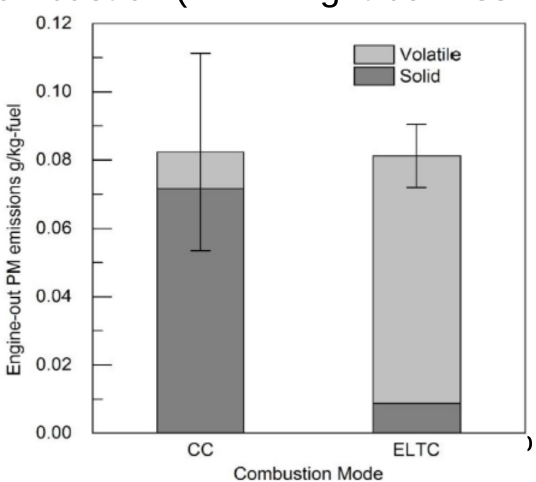
- DEF dosing increases particle count by 460% to 610% over the WHTC
- Propose HNCO polymerization, urea pyrolysis, and urea micro-explosions during evaporation as the leading causes
- Under normal urea dosing over 80% of the total particle count was found to be DEF-based.
- Increasing ET temperature from 300 to 400 °C decreased the DEF-based particle count by 15% for an ANR = 1.1.
- Coupled with the TGA results, it is plausible that this volatile fraction of the DEF-based particles were urea or biuret.

Oxidation Catalysts

DOCs and DPFs can capture LTC volatile PM via an adsorption mechanism. Lighter PM eventually breaks through. DOC efficiency also impacted by adsorption saturation.

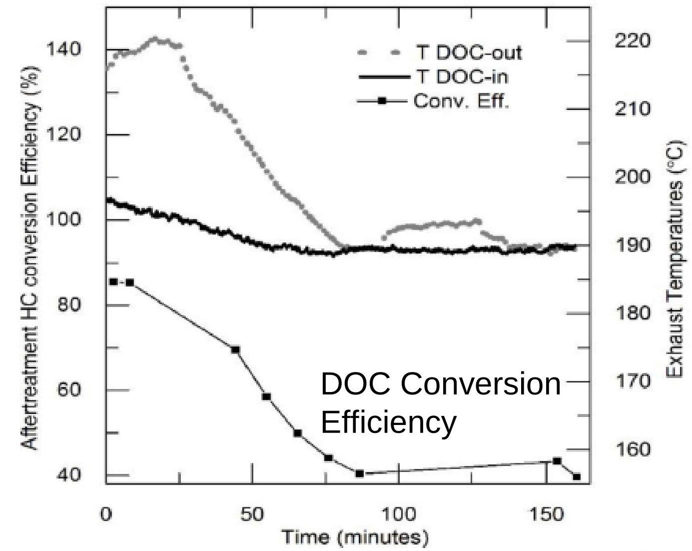


LTC HC emissions over the duration of the test is ~30% higher than for conventional combustion (FTIR might be missing species).

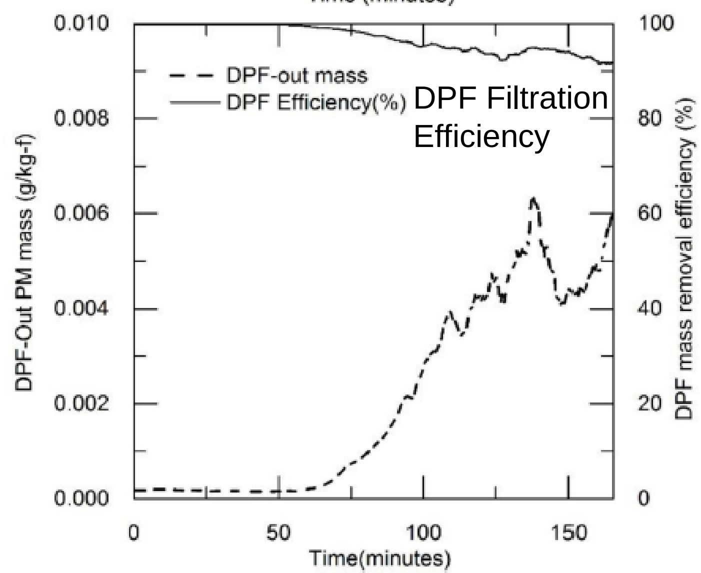


Most of LTC PM is volatile. Nearly all soot is captured by DPF.

DOC conversion efficiency in LTC mode drops with time from 85% to 40% then stabilizes after 80 minutes, despite T>190C. Zeolite HC adsorption and saturation.



LTC DPF PM emissions increase but with delay as it also becomes HC-saturated. DPF can remove LTC non-soot particles via adsorption.



Univ MN, SAE 2015-01-0835

Bimetallic catalysts on dual component support shows improved low-T CH_4 oxidation

Reference: A.I. Osman et al. / Applied Catalysis B: Environmental 187 (2016) 408–418

Context

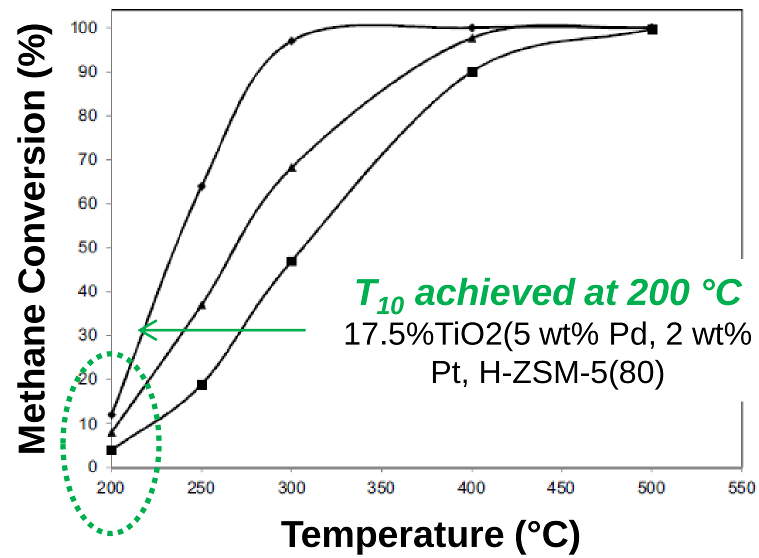
Natural gas is attractive as abundant and clean burning fuel <u>but</u> total combustion important due to global warming potential

Background

Pd known to be most effective for catalytic CH_4 combustion -
- Proceeds through (a) dissociation & (b) oxidation via PdO

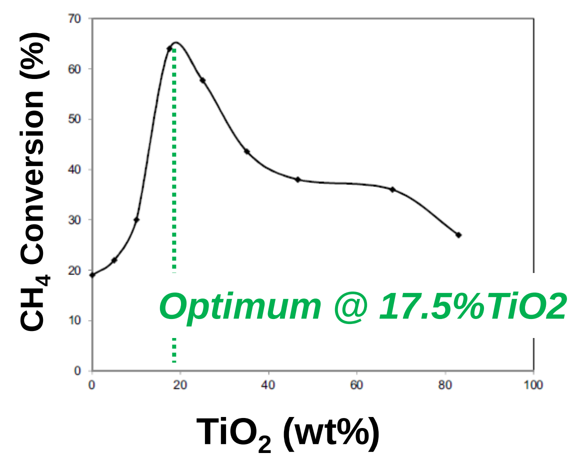
For enhanced activity:

1) Addition of an O_2 carrier → TiO_2
2) Support acidity → η-Al_2O_3 or H-ZSM-5
3) Reduced deactivation/sintering → CeO_2
4) Use of bimetallic catalyst → Pt



Improved low T activity achieved

- Optimized combination of four components – Pd, Pt, acidic support & O_2 carrier – shown to enable highly active and stable catalyst
  - Optimum at 17.5% TiO_2 on ZSM-5(80)
  - ***T10%was observed at only 200 °C***
- Role of bimetallic catalyst in improving catalyst stability confirmed
  - On addition of platinum, ***no decrease in the catalyst activity over 50 h at 250 °C***



Summary

- There are several low-CO_2 engine strategies being developed that can drop emissions by up to 40%.
  - Emissions and development challenges are summarized – LT, HC, lean NOx, PN
- Gasoline particulates are emerging as a major emissions issue
  - Difficult to remediate without filters
    - Rich zones during cold start, hot starts, accelerations, and LT ambient conditions
  - High PAH emissions
  - GPF solution
- Lean NOx solutions are focusing on lower-temperature and cold start
- LT oxidation catalysts are evolving – CH_4, HC, CO

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