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Vehicle Emissions Review – 2011 (so far)

Tim Johnson
October 4, 2011

DOE DEER Conference, Detroit

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Summary

- California LD criteria emission regs are tightening. Could signal another round in all sectors.
- CO_2 regs are present in both LD and HD markets. Tightening is just beginning. Paradigm shift.
- Engines are meeting the challenge
  - Downsizing, lean burn, new designs, HD deNOx
- deNOx is advancing
  - New sources of NH_3, new catalysts, new LNT+SCR architectures, new ways to run an LNT
- DPFs evolving
  - Low thermal mass, membrane effects, fundamentals on permeability
- DOC Pd:Pt ratios allow optimization
- Gasoline emission control is amazing
  - Zone coating
  - Lower PGM with better performance
  - Need low-sulfur fuel
  - GPFs give ultra-clean exhaust

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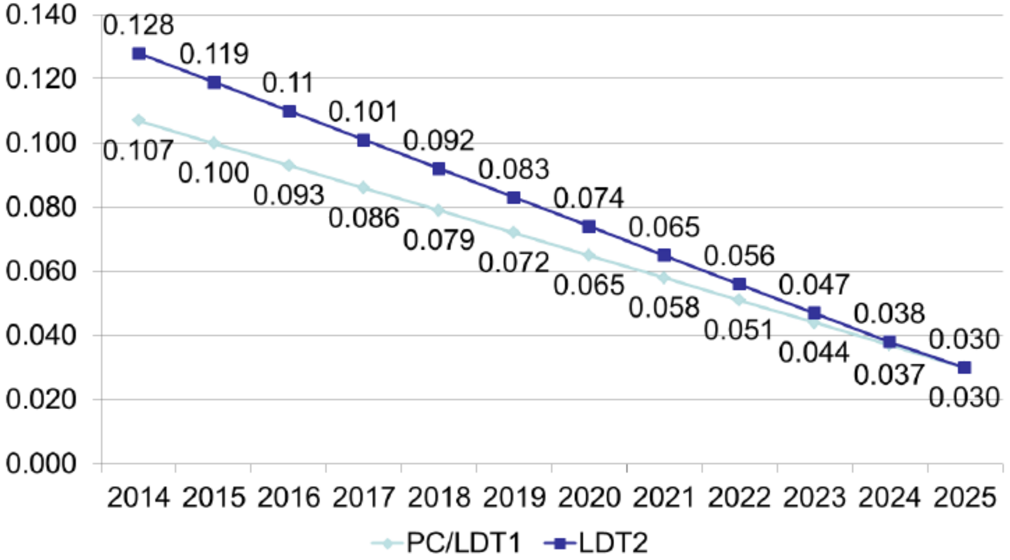
Regulations

CARB-Proposing LEVIII Standards for 2014-2022

SULEV Fleet Average NMOG+NOx.



Proposed fleet average NMOG+NOx standards.

•PM reduced 40% to 6 mg/mi, then phase-in to 3 mg/mi starting in 2017,and then to 1 mg/mi phase-in starting 2025, subject to 2020 review. Optional PN standard being considered for 2025.

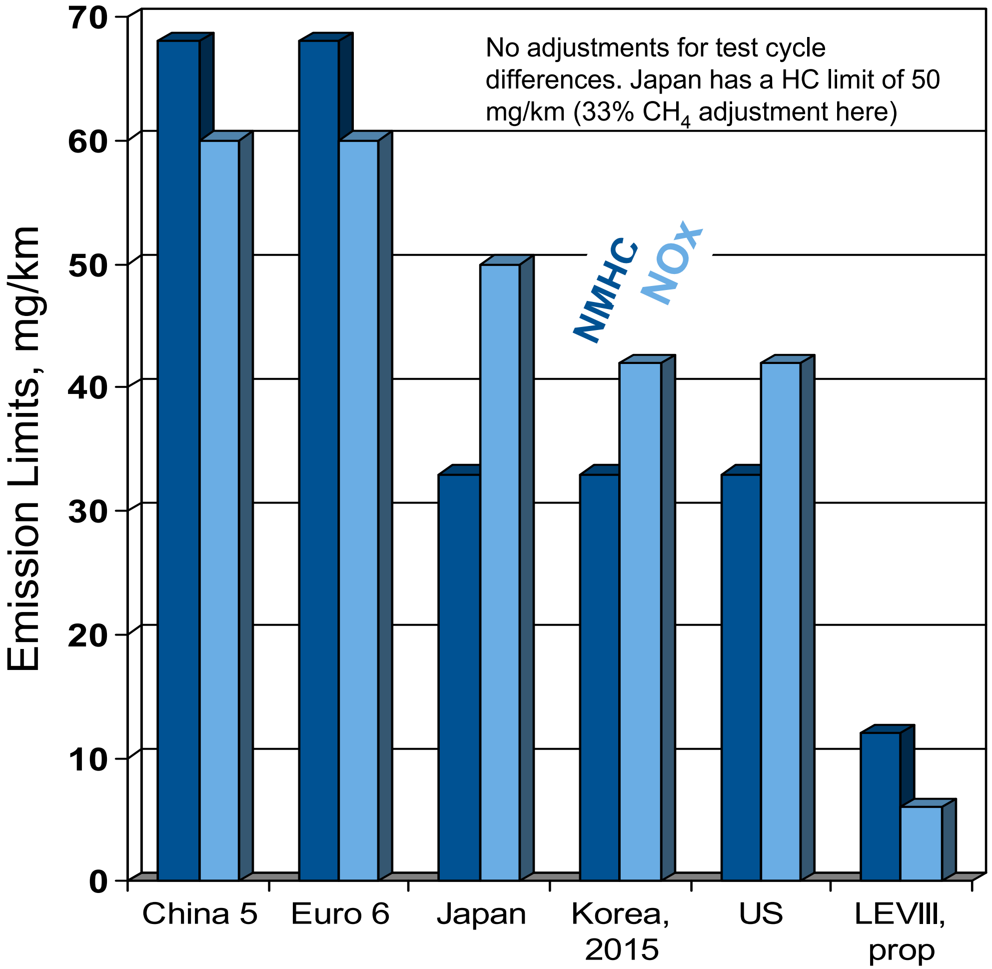
•Composite SFTP option using FTP, SC03 and US06 cycles. SULEV fleet limit values at full phase in .

•Will be proposed as part of CO_2 regulation in a month or two.

•EPA to follow CARB with a Tier 3 LD regulation.

Current Gasoline emissions limits require similar technologies.

We could see another round of tightening around the world as LEVIII is implemented.

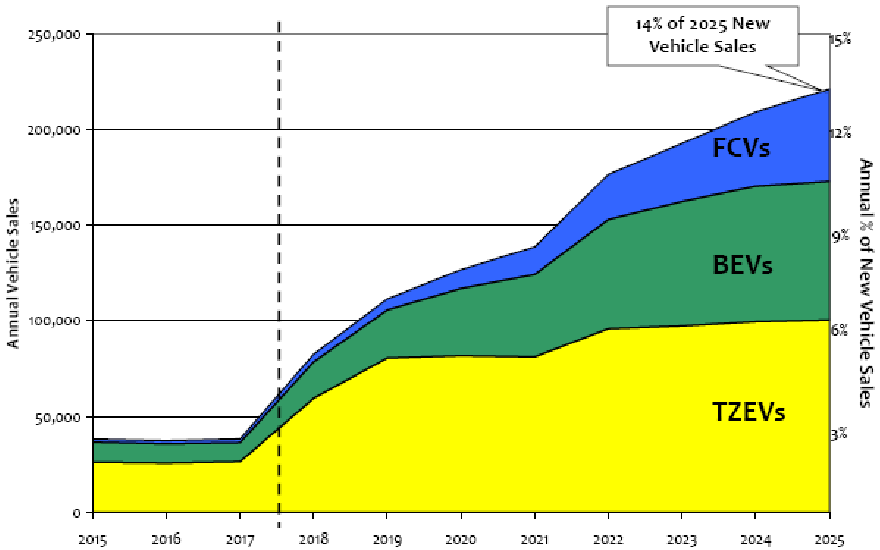


- Durability Requirements:
  - China 5 160,000 km
  - Euro 6: 160,000 km
  - Japan: 80,000 km
  - Korea: 192,000 km
  - US: 192,000 km
  - LEVIII: 240,000 km

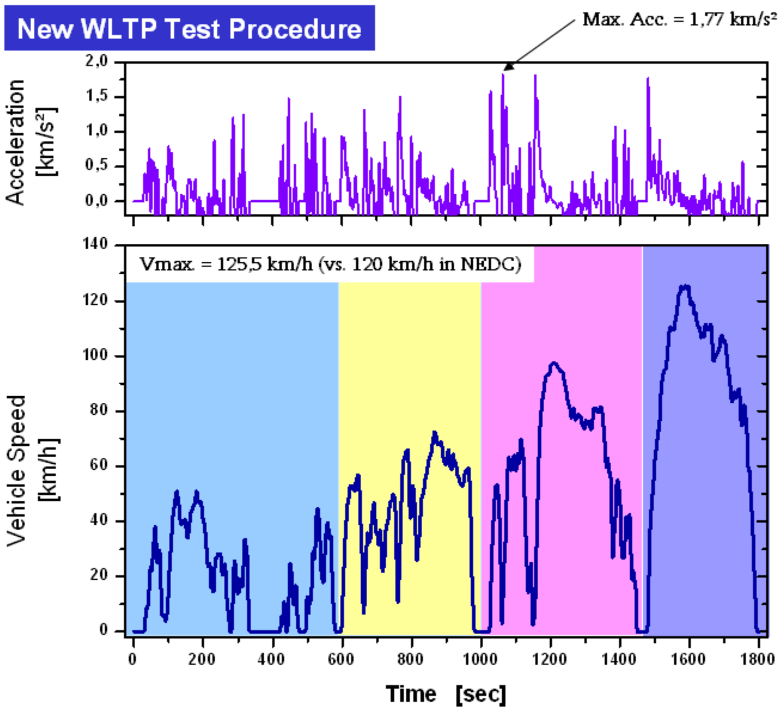
CARB shows some ZEV targets for 2014-17

Production requirements for auto manufacturers

- 2012 to 2014:
  – 12,500 ZEVs
  – 58,000 Plug-in hybrid EVs (“TZEV”)
- 2015 to 2017:
  – 50,000 ZEVs
  – 83,000 Plug-in hybrid EVs
- Advanced Clean Cars rulemaking will increase volumes 2018+ to launch sustainable market



Criteria toxic emissions issues in Europe



New test cycles being developed. WLTP

Four cycles to mix-and-match: LS (0-60 kph, incl CS), MS (0-80), HS (80-110 max), XHS (130-140 max)

May be part of Euro 6 (aggressive), but considering “Euro 6b”.

Main impacts: LDD NOx, and PI and CI CO_2

Gasoline PN limits are being developed

- European Automobile Manufacturers Association (ASEA) is recommending a limit of 60 X 10^{11} #/km; corresponds to 3 mg/km PM (vs. 4.5mg/km for diesel)
- Commission recently announced two options for further evaluation: 20 X10^{11}/km or 200X10^{11}/km, then to 6 X 10^{11}/km in 2017.

In-use emissions are being evaluated

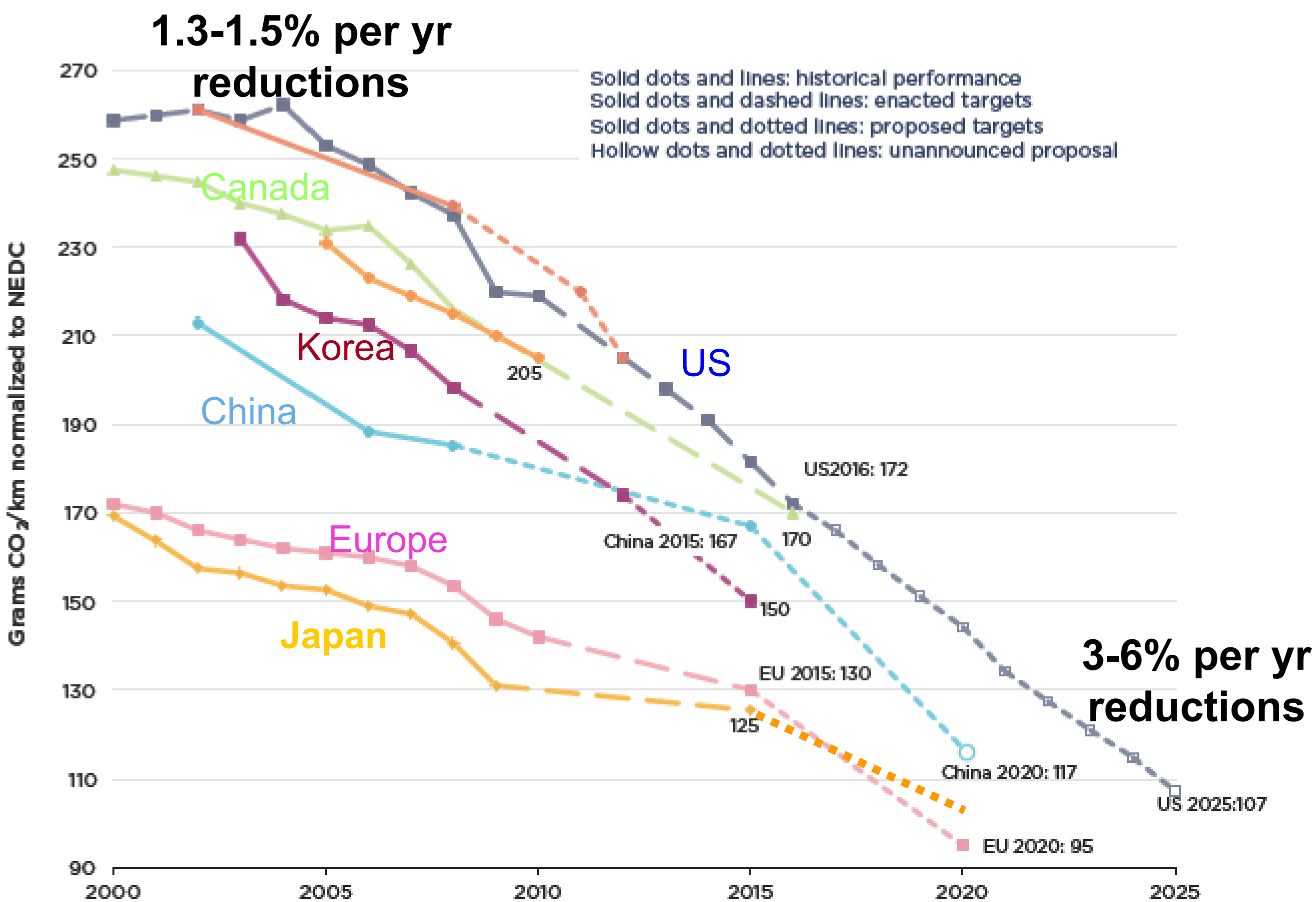
- JRC is testing vehicles now
- Two options being evaluated: random test cycle or the use of PEMS (portable emissions measurement systems)
- Decision coming year end on which approach to develop

Euro 7 is expected by the industry, but no formal movement yet from the Commission

Figure from FEV, ICE2011, Capri

Normalized CO_2 regulations are shown.

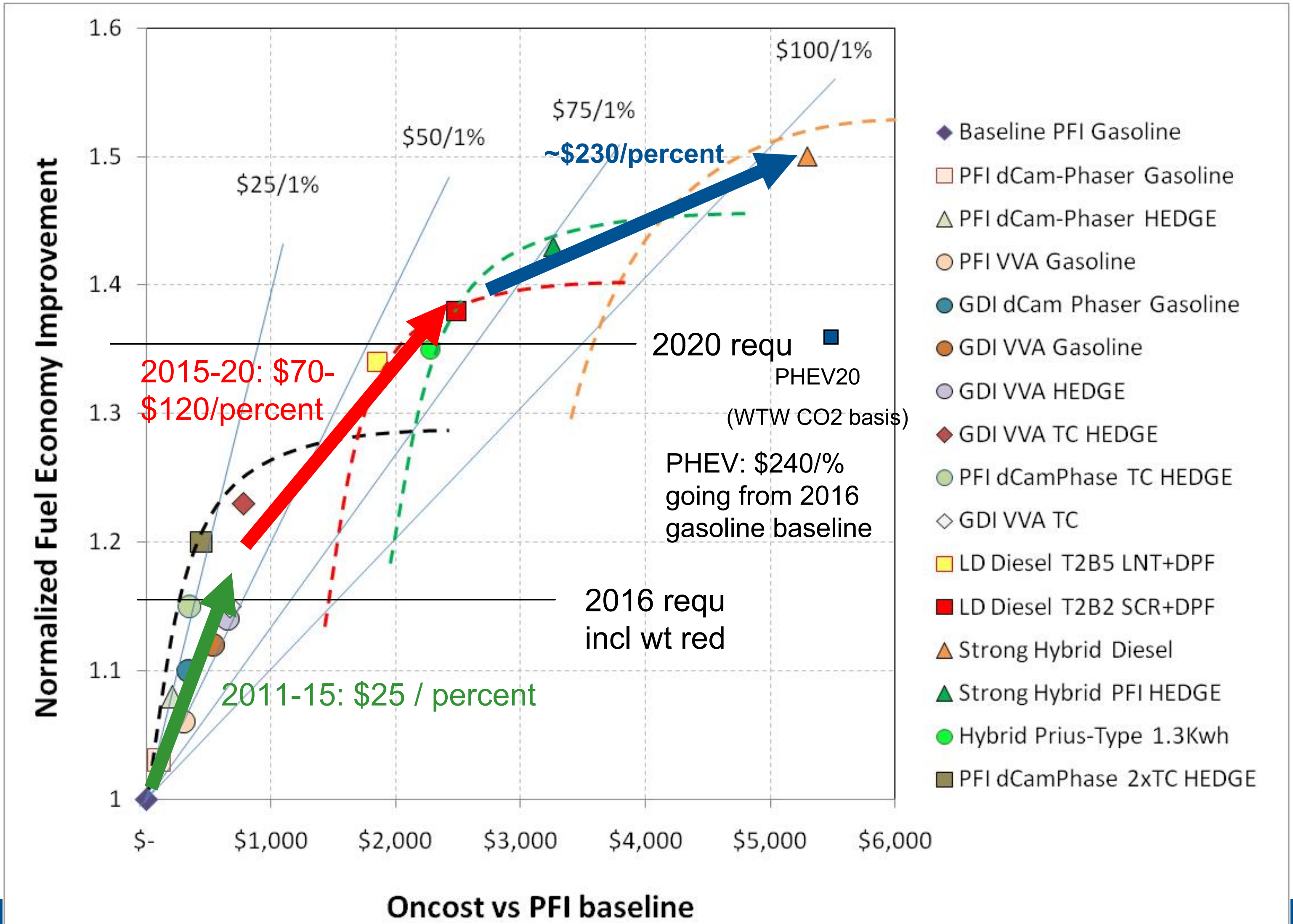
Most regulated countries are trending to <100 g/km in 2020+. Increasing rate of reductions relative to “unregulated period” signals paradigm shift.



[1] China's target reflects gasoline fleet scenario. If including other fuel types, the target will be lower.
[2] US and Canada light-duty vehicles include light commercial vehicles.

Incremental costs go up as higher fuel efficiency is required.

Grid CO_2 accounting and incentive factors can have a big influence on xEV effective cost for CO_2 compliance.



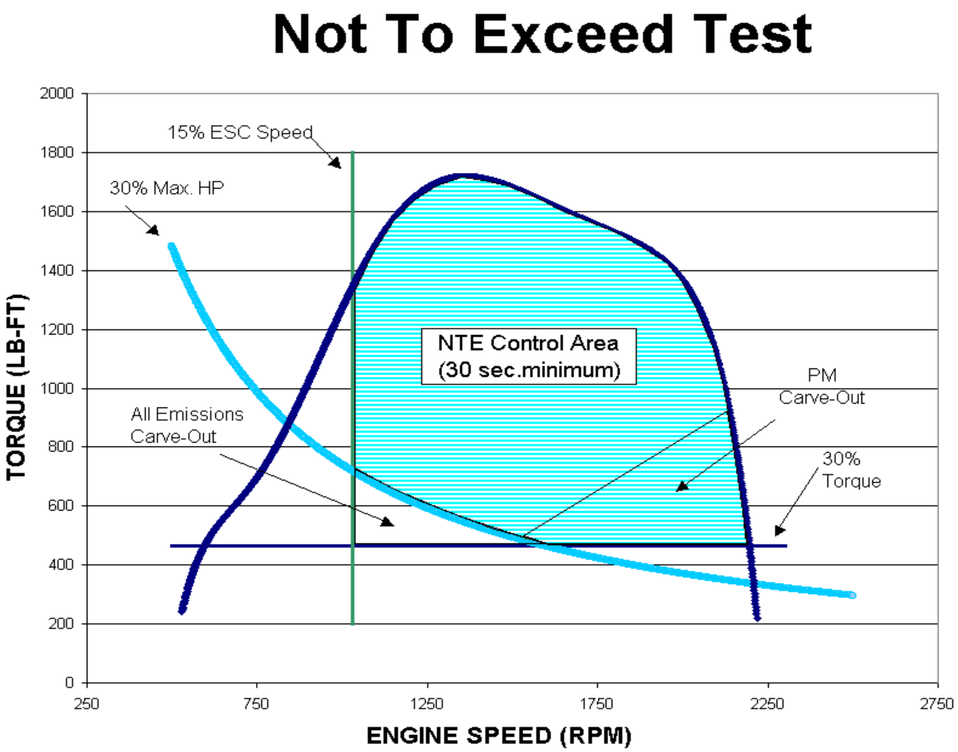
EPA is signaling zero grid CO_2 for xEVs, and a vehicle multiplication factor or 1.3-2.0X :

Effective cost of PHEV40 in 2016-20 is about $25-30 / % CO_2 from 2016 base.

FE data from SwRI Powertrain Consulting Service 8/10

Urban HD NOx is emerging as a key issue.

Can't inject urea at T<180C. Regs do not cover.



NTE does not cover <30% power, the regime of much urban driving.

Other HD regulatory developments on criteria pollutants

- The Euro VI comitology finished.
  - PN method quite tight if preconditioning is not used.
- Japan is considering the next round of tightening for 2016
  - Need to complete its FC regulation in 2015
  - Looking at Euro VI harmonization
- China scheduled to introduce Euro IV in January 2011.
  - Euro V being considered for 2015-16
- India is implementing Euro IV – few engines sold due to registration outside of controlled cities

HD engine CO_2 regulation calls for 3% reductions in both 2014 and 2017 for line haul (SET).

3-5% reductions for vocational (FTP) in 2014; 2-4% in 2017.

GVWR CLASS	FUEL	MODEL YEARS	CO_2 REDUCTION FROM REFERENCE CASE
HHD (8a-8b)	Diesel	2014-2016	3%
		2017+	6%
MHD (6-7) and LHD 4-5	Diesel	2014-2016	5%
		2017+	9%
	Gasoline	2016+	5%
LHD 2b-3	Gasoline	2016+	5%
	Diesel	2016+	9%

Total Vehicle Reductions

Line Haul:	20%
Vocational	6-9%
Small trucks	17%

General: Proposed engine CO_2 standards relative to the 2010 industry average. HHD: 3% drop in 2014 then additional 3% in 2017. MHD and LHD: 5% drop 2014, then additional 4% in 2017.

N_2O: 0.10 g/bhp-hr on FTP; 6% of carbon footprint;

CH_4: 0.10 g/bhp-hr;

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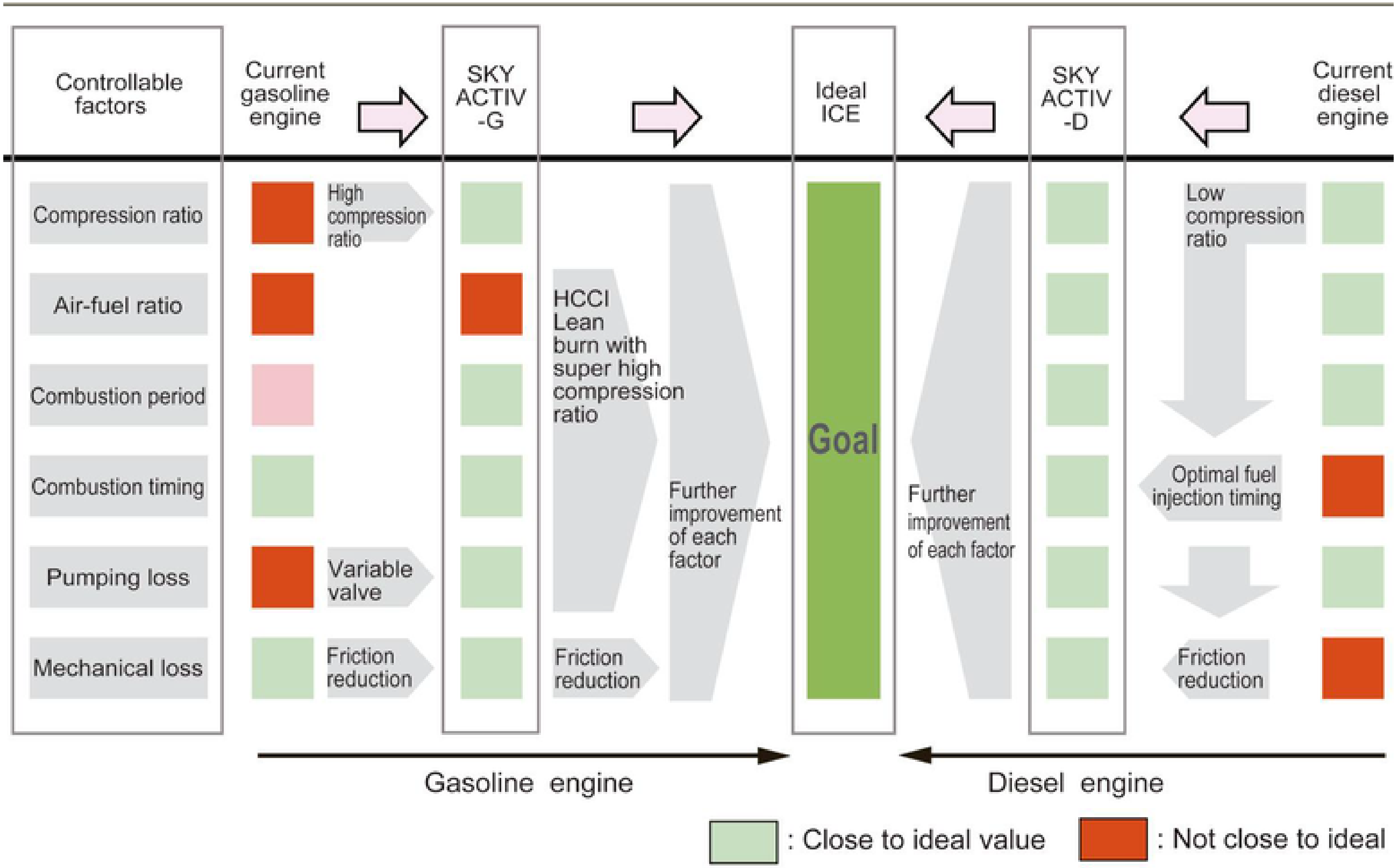
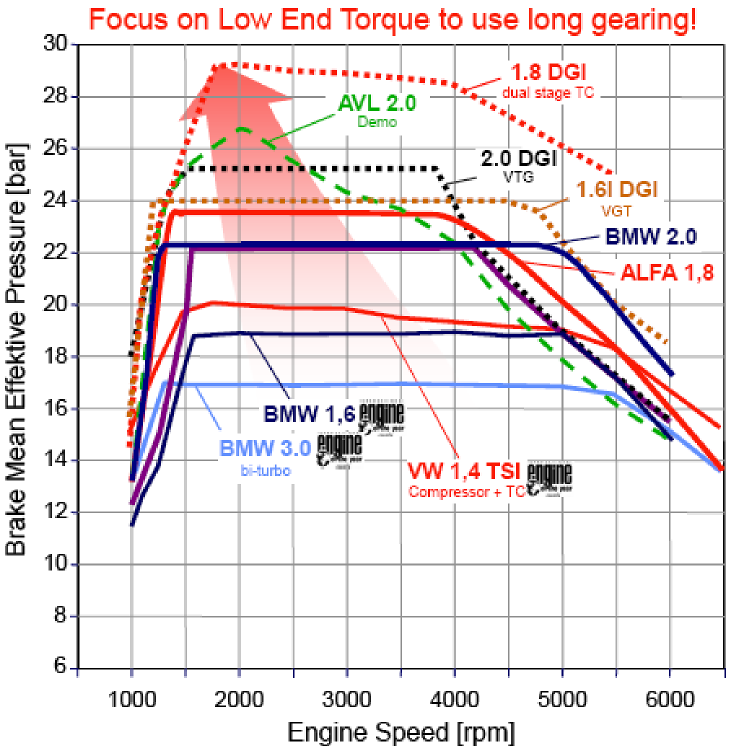
Engines and approaches

ICE trends show gasoline and diesel strategies merging

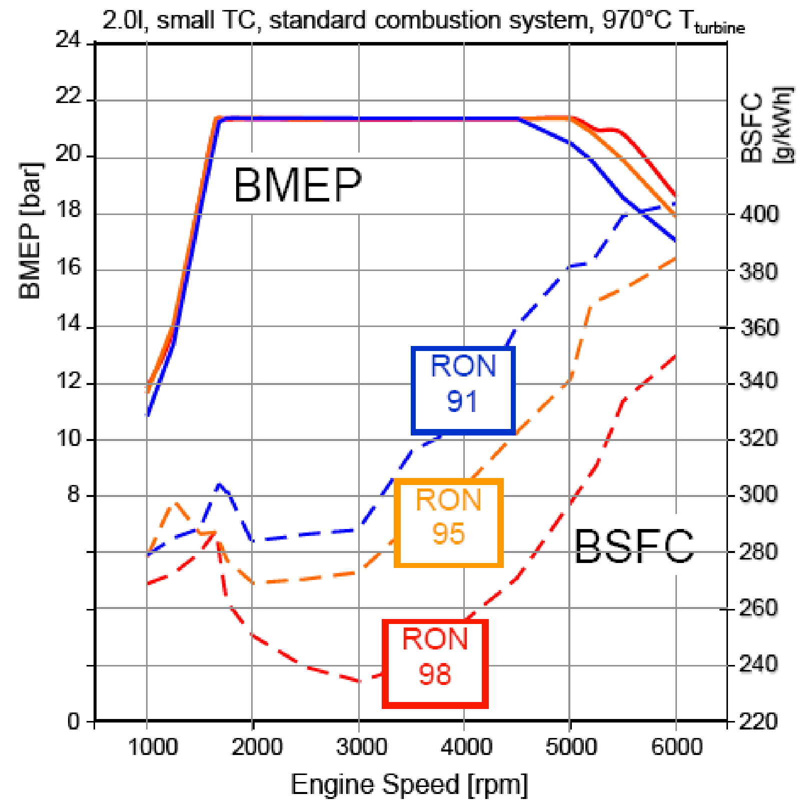


http://www.greencarcongress.com/2011/08/skyactiv-20110804.html

Boosted GDI BMEP is moving towards 30 bar. Low RON fuel is potential challenge.



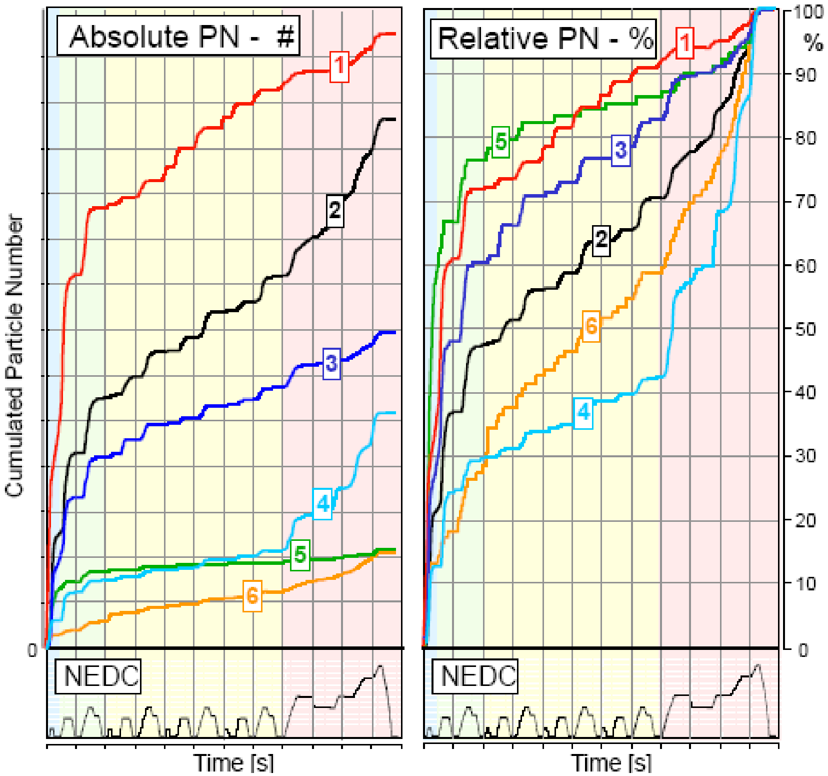
Low speed torque is improving. Affects gearing. Std today with 1-stage boost is 21-23 bar. VCR allows higher load (43 bar), but 30-35 bar is opt.



Low RON fuel requirement - more enrichment at HL. Managing for low RON fuel is challenge

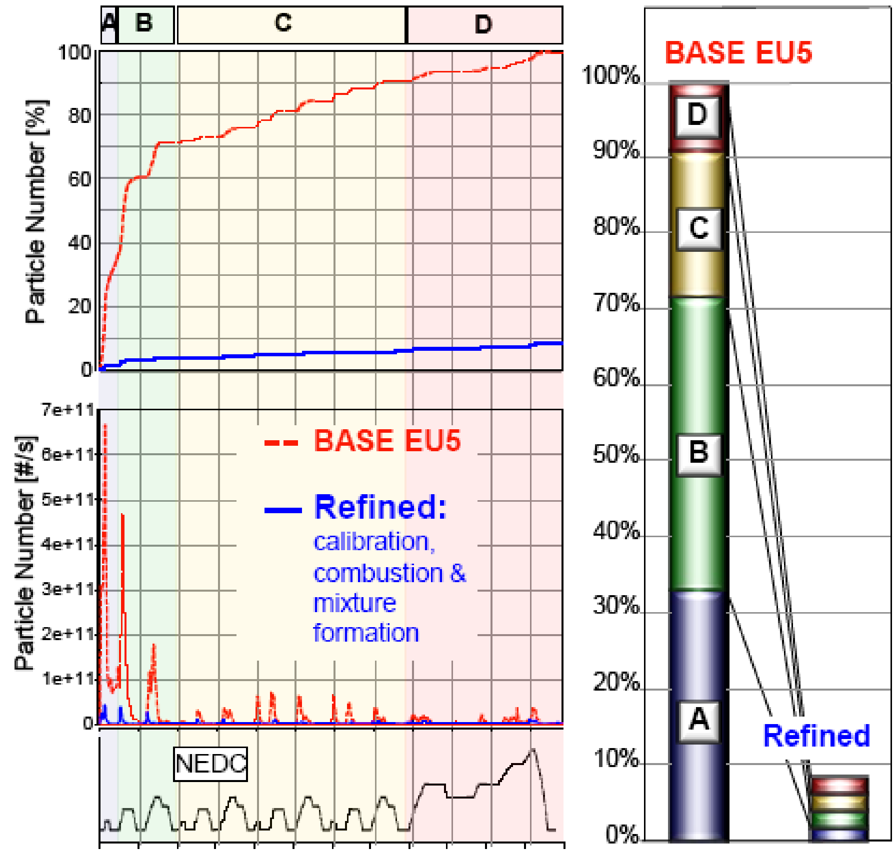
AVL, CTI Conf 5/11

PN emissions from a GDI can come from many sources.



Six different GDIs have six different causes of PN.

AVL, CTI Conf 5/11



- improved mixture formation
- refined combustion
- highly sophisticated detail optimization of calibration (e.g.: start & drive-off functions, cat heating, warm-up functions, valve-, injection- and spark–timing)

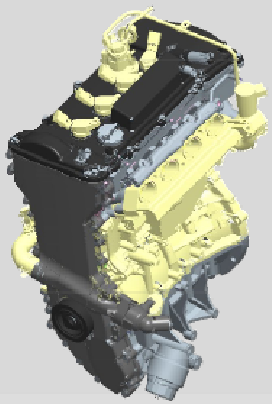
Toyota shows lean+EGR gasoline engine concept for 2020. Long stroke, low surface/volume

Next generation Prius engine concepts.

Cooled EGR Stoichimetric Concept

B=75mm
S=113mm
V=1996cc

- S.I. Direct Injection
- Long Stroke Design (Prototype Engine)
  Stroke / Bore = 1.5
- Cooled EGR (EGR Ratio ＞30%)
  High Tumble Ratio Intake Port TTR=3.0
  High Energy Ignition System 100mJ
- Lower Friction
  Lower Viscosity Oil
  Rolling Bearing

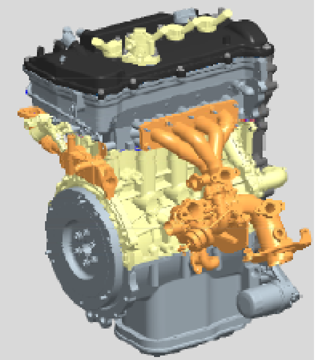


Later Prius engine concepts.

Turbo Lean Burn Concept

B=75mm
S=113mm
V=1996cc

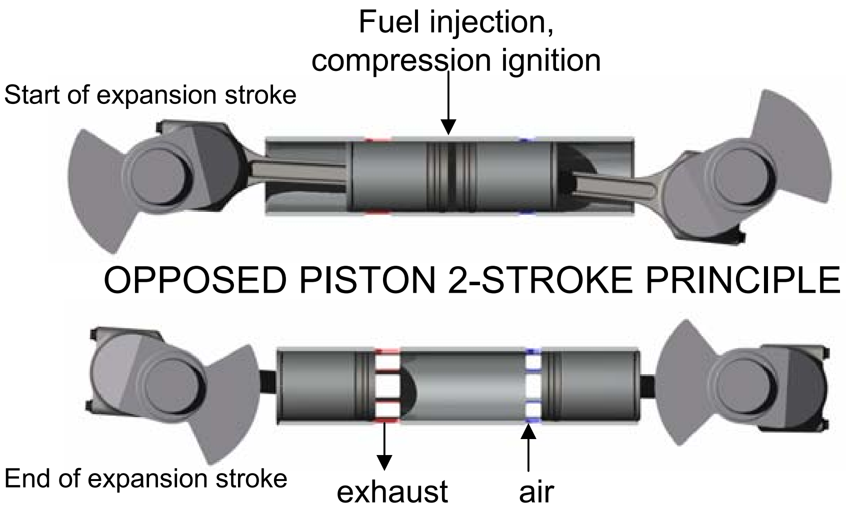
- S.I. Direct Injection
- Long Stroke Design (Prototype Engine)
  Stroke / Bore = 1.5
- Turbo Charged Air Lean with Cooled EGR
  High Tumble Ratio Intake Port TTR=3.0
  High Energy Ignition System 150mJ
  Lower NOx Emission



Toyota, SAE High Eff. ICE Symp, 4/11

New concept 2-stroke opposed-piston diesel engine is described. Enablers: New FIE, better cooling, and enhanced scavenging.

-15% BSFC, -10% cost, -30% weight; 2X NOx and oil consumption, but manageable

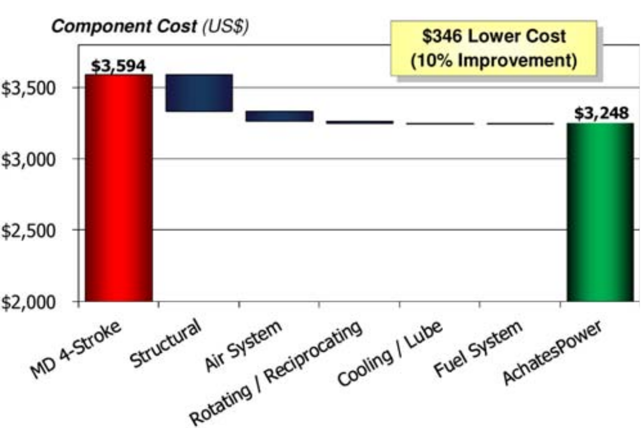


Near the bottom of the expansion stroke, exhaust exits and air enters. Decreased heat losses due to: Much higher vol:area ratio, and eliminates cyl head heat losses. No valve mechanisms. Lower BMEP (lower PCP) and higher power density for downsizing.

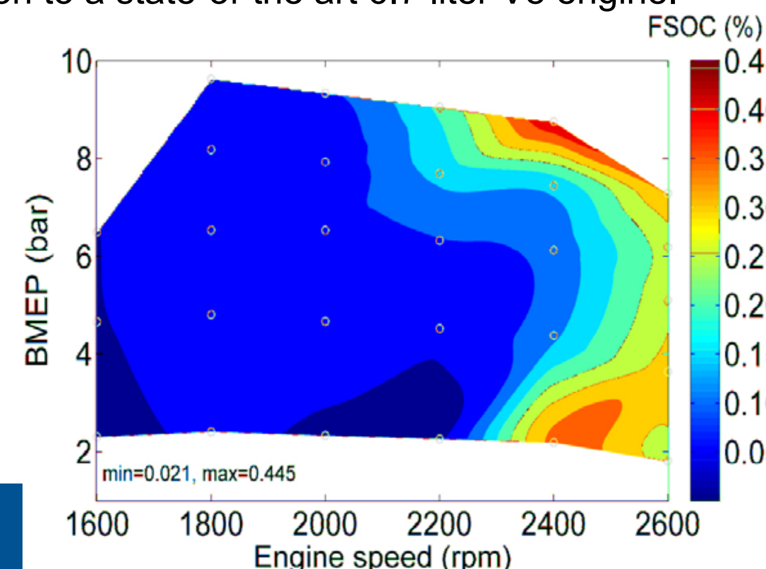
Engine Condition		Achates Power	Ref. [12]
BSFC	g/kWh	202.7	239.9
$BSNO_x$	g/hph	1.88	0.97
BSSoot	g/hph	0.052	---
BSCO	g/hph	0.47	---
BSHC	g/hph	0.38	---

Brake-specific fuel consumption and emissions values measured on a single cylinder (1.1 liter) research engine, but modeled to produce these multi-cylinder comparison to a state-of-the art 6.7 liter V8 engine.

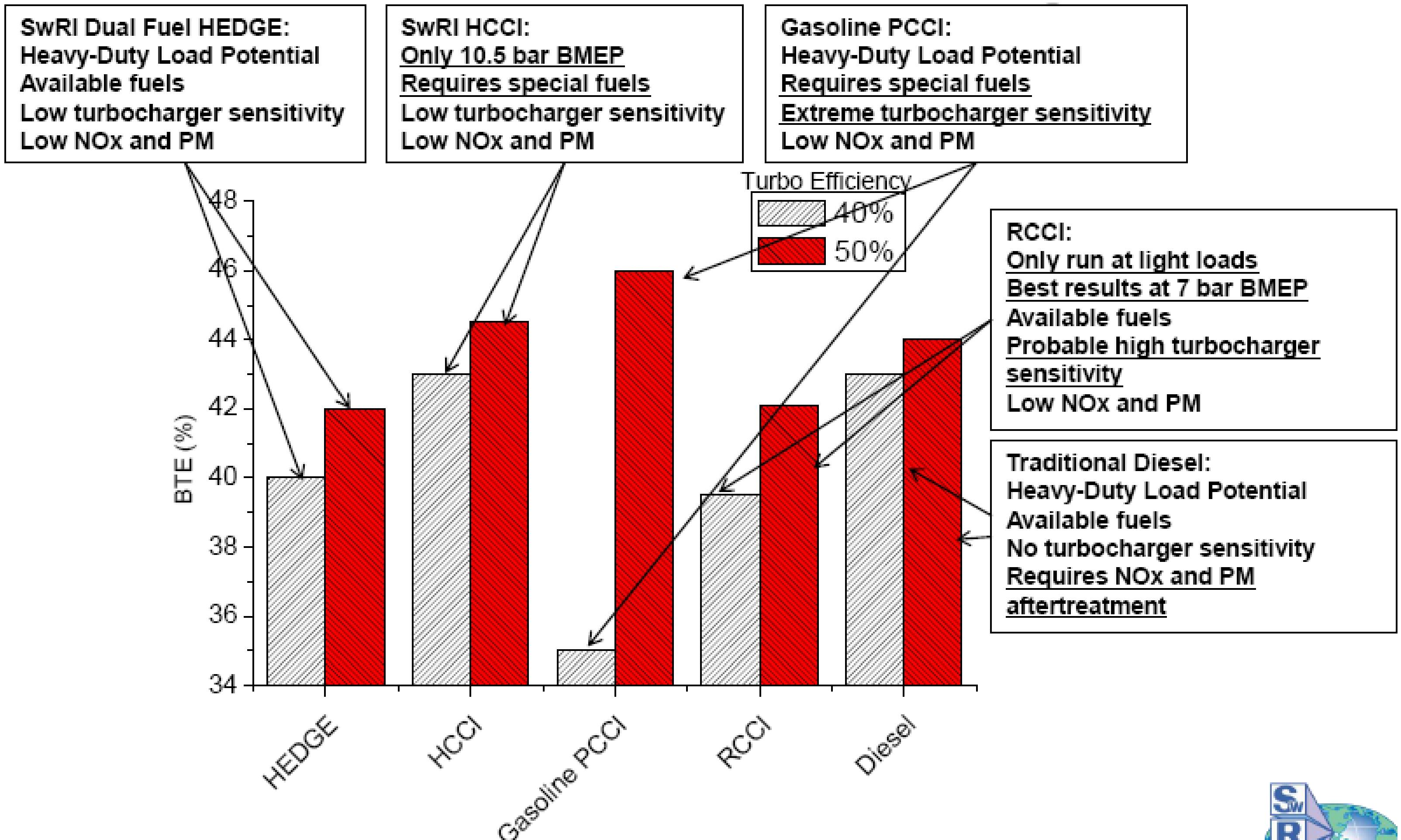
Achates, SAE 2011-01-2221.



The engine is expected to be about 10% cheaper than a conventional MDD engine; 40% fewer parts, 30% lighter.

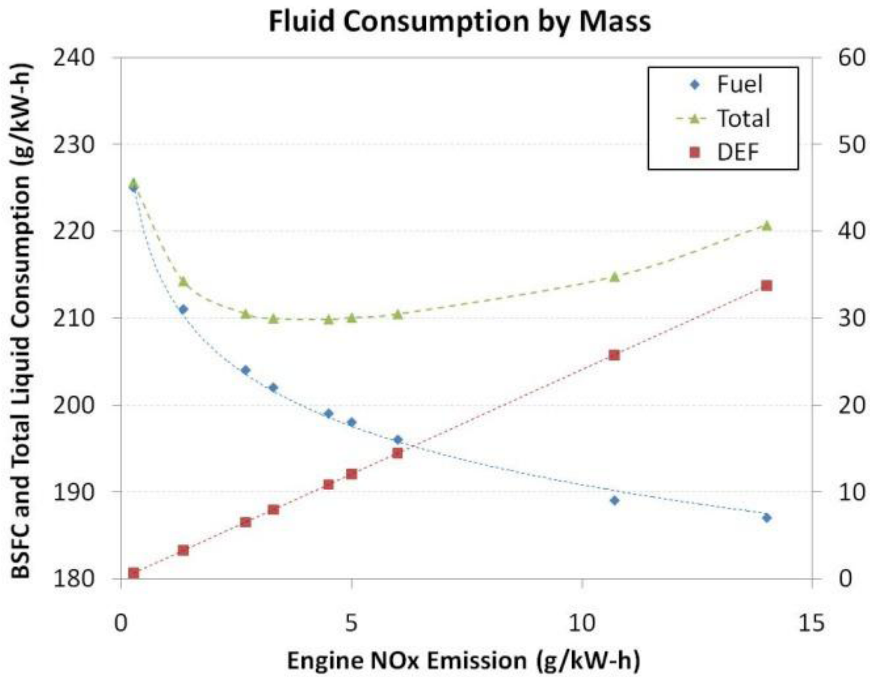


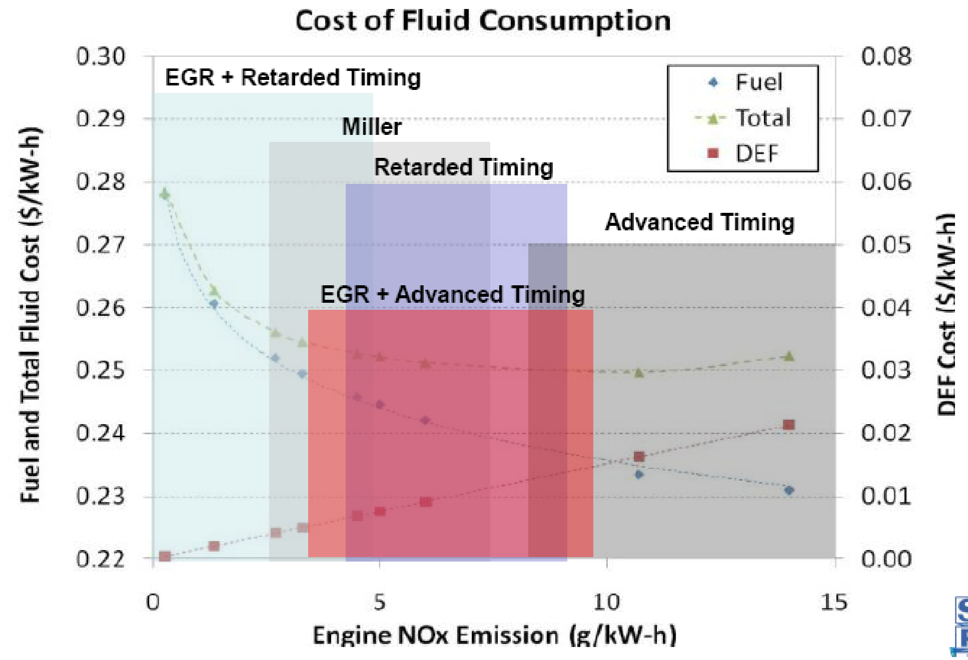
Critical assessment of emerging LD ICE technologies is provided. Boost is very important consideration. Emerging PCCI and RCCI interesting, but have trade-offs. HEDGE and diesel are most-robust.



SwRI Analysis of Engine Technologies - SAE 2011-01-0358

As the spread between urea and fuel increases, engine strategies will move to higher NOx levels.





On a mass basis, 2.5 to 5 g/kW-hr NOx is the optimum calibration. Note the significant slope of the BSFC vs. NOx curve at higher NOx levels. DEF consumption 1.1% DEF per g/kW-hr NOx

Economics will help drive choices of HD engine technology. Diesel fuel: $3.89, DEF: $2.59

SwRI, Emissions 2011, 6/11

Other opportunities in HD engine optimization: 20-50% fuel consumption reductions

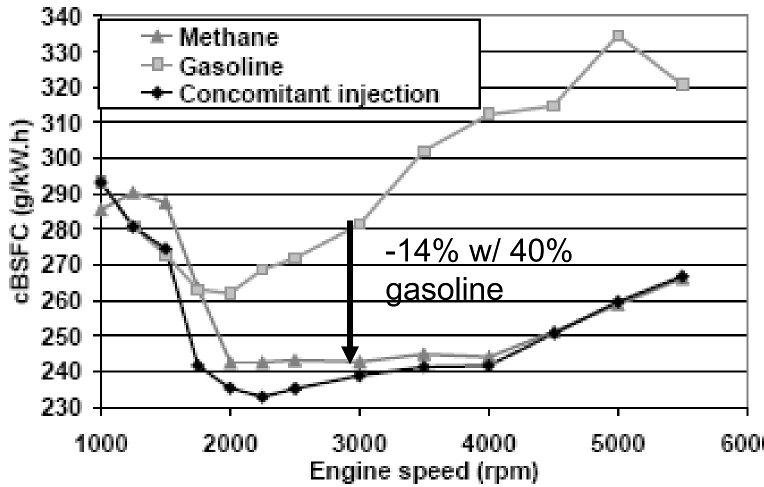
- Incremental improvements: more turbocharging, more flexible FIE, VVT, downsizing, controls – 5 to 10% fuel savings
- Waste heat recovery – 6 to 9% fuel savings
- Hybridization – 15 to 30% savings
- New combustion strategies – PPC, RCCI

Synergistic combustion of NG and gasoline.

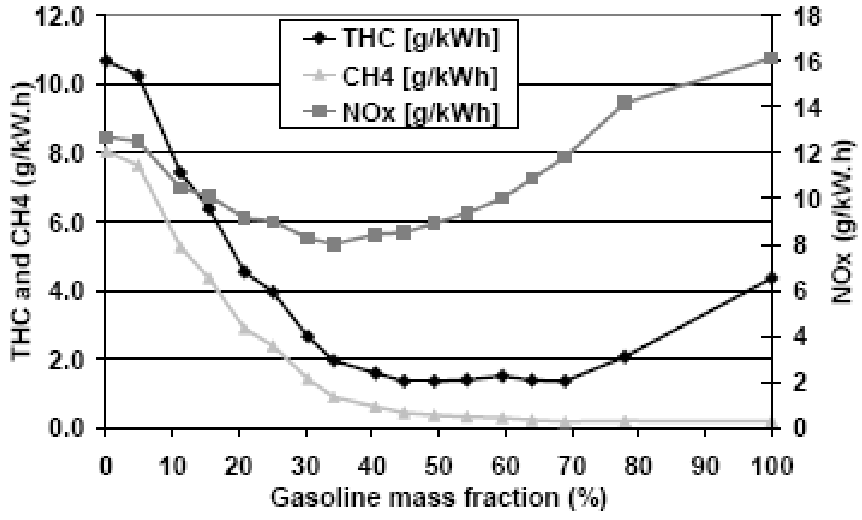
MPI natural gas, DI gasoline, 1.6 liter. 40% gasoline: BMEP +20%, BSFC -13%, emissions -50 to -65%. 36.5% BTE

	Difference compared to 100% methane operation	Difference compared to 100% gasoline operation
Maximum BMEP	+16%	+20%
cBSFC	+1%	-13%
Specific THC emissions	-85%	-64%
Specific CH4 emissions	-89%	n.s.
Specific NOx emissions	-34%	-48%

BSFC and emissions comparisons at 2000 rpm, full load for 40% gasoline – 60% methane mix.

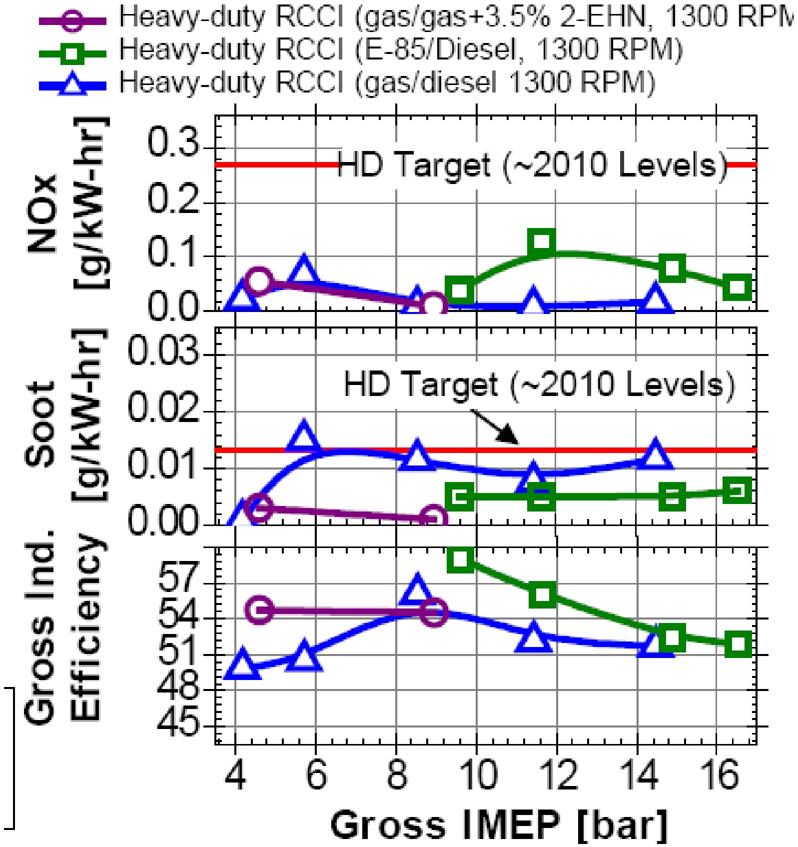


Gasoline-equivalent BSFC for mixed fuel combustion at full load using fuel mix shown at left.



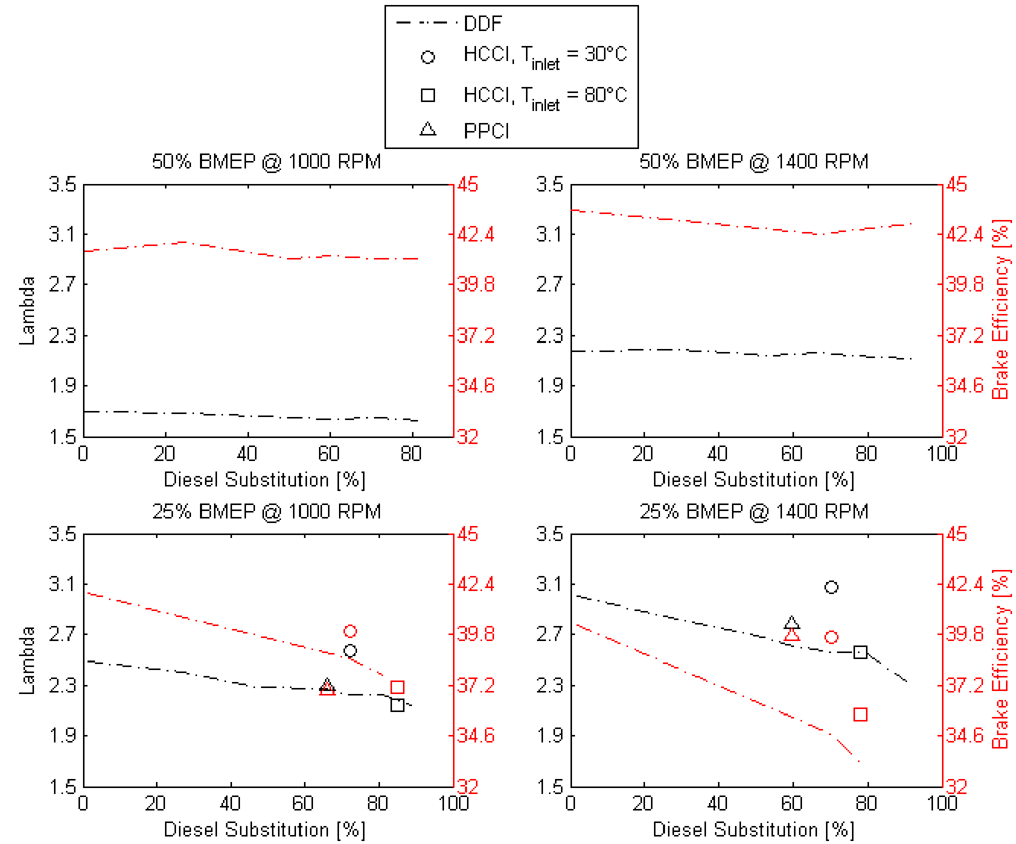
IFP/PSA, SAE 2011-01-1995

Diesel-NG combustion also shows some synergies. BTE is unaffected in preliminary work, NOx can drop 20%. RCCI shows promise for more synergy.



E85 (and perhaps NG) has the highest ITE (58%) and lowest NOx of the dual fuels reported for RCCI.

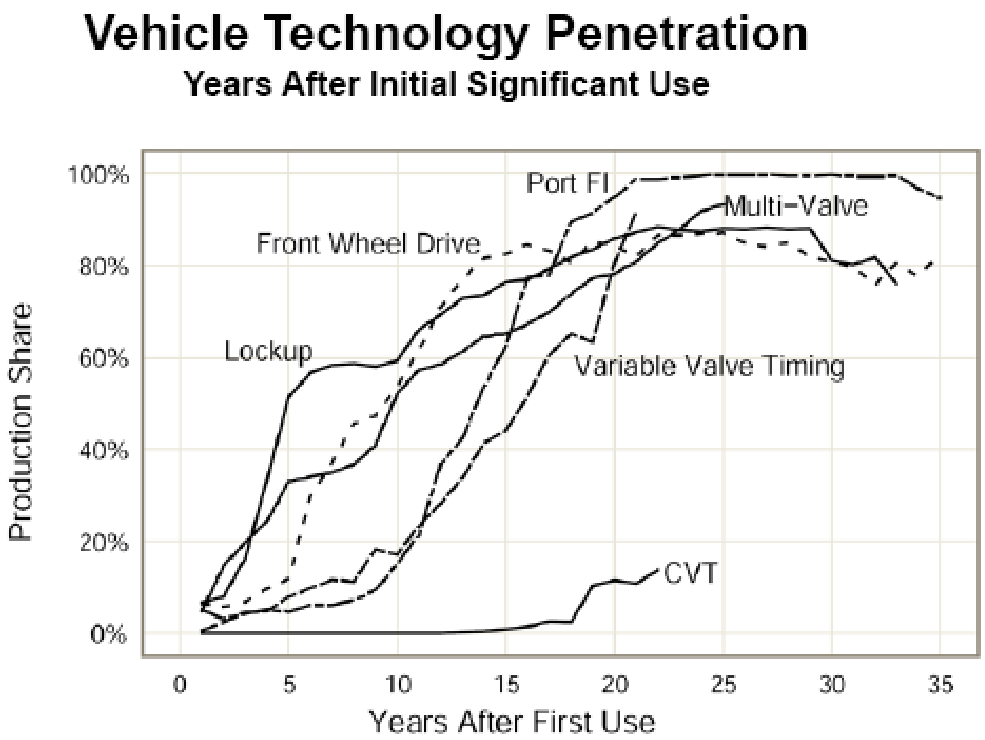
Univ WI SAE 2011-01-0363 and 2011-01-0361



BTE is constant with NG usage at 50% load. At 25% load, efficiency decreases with NG usage. Reduction of crevice volume will likely bring CNG to diesel levels.

AVL, SAE 2011-01-1962

It takes about 15-20 years for automotive technology to go from first introduction to 80% market penetration



It has taken about 15 – 20 years for a technology to reach maximum market penetration.

Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2010, EPA420-R-10-023, November 2010, p. 69

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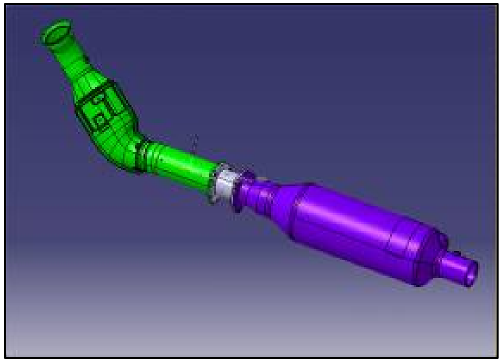
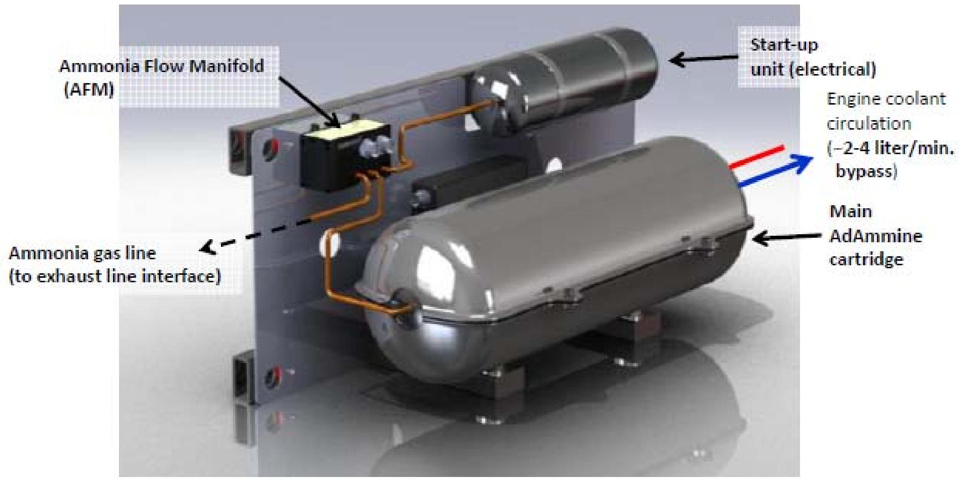
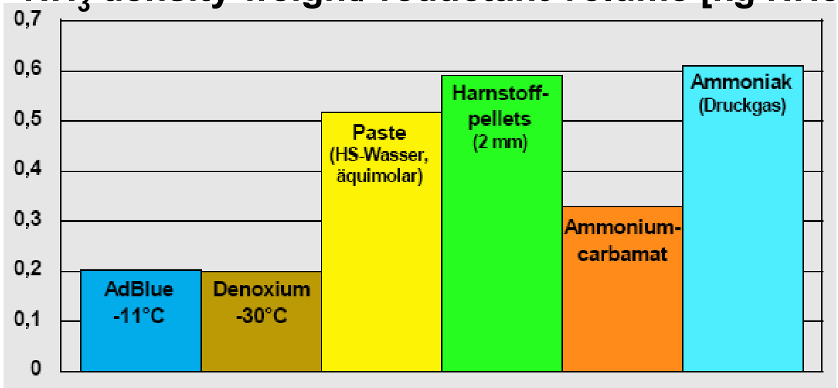
deNOx

Solid Ammonia Facilitates Low Temperature Operability





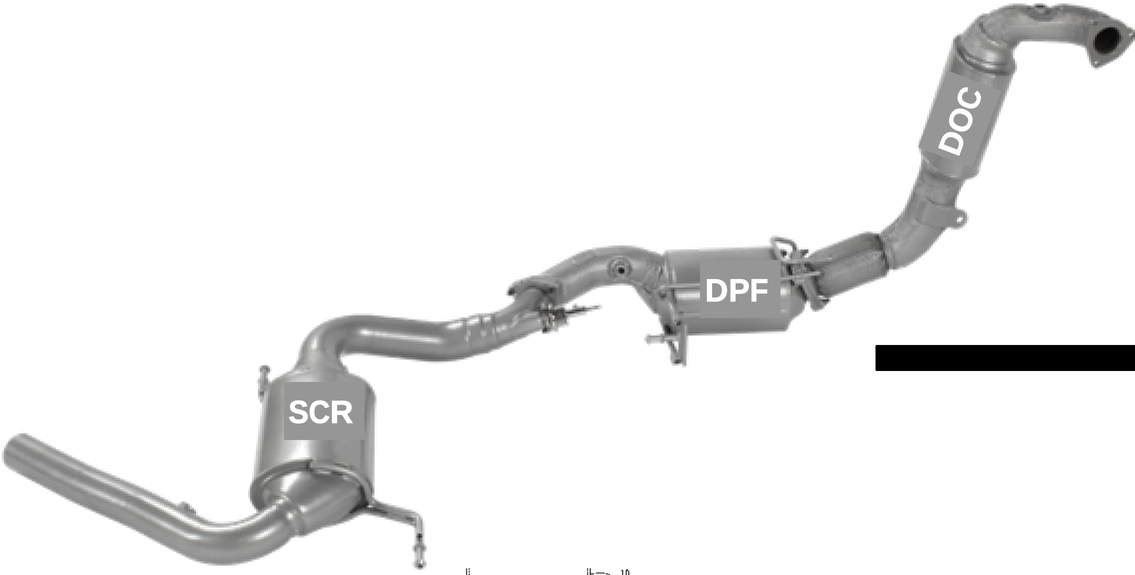
NH_3 density weight/ reductant volume [kg NH3/L]

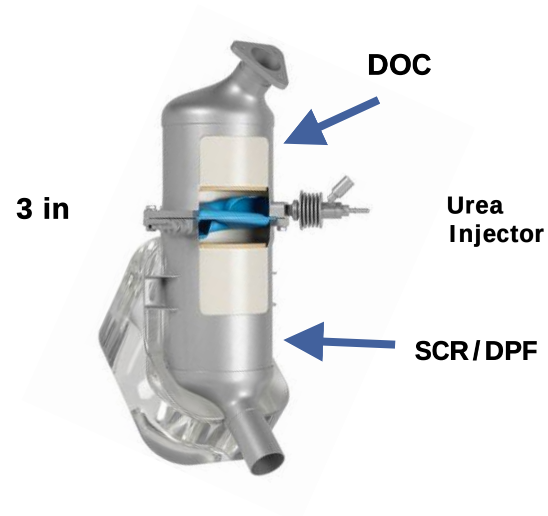


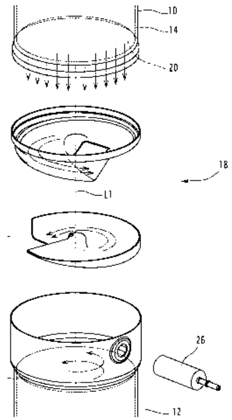
Ford, CTI, 7/11

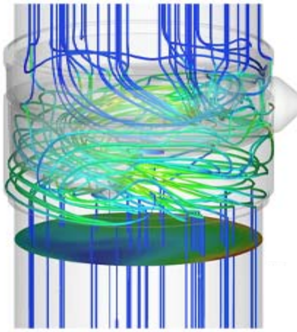
- Several systems being evaluated as alternatives to DEF
- Both offer higher ammonia concentrations
- Absence of hydrolysis enables lower temperature operability

New Packaging Designs Reduce Cold-Start Emissions



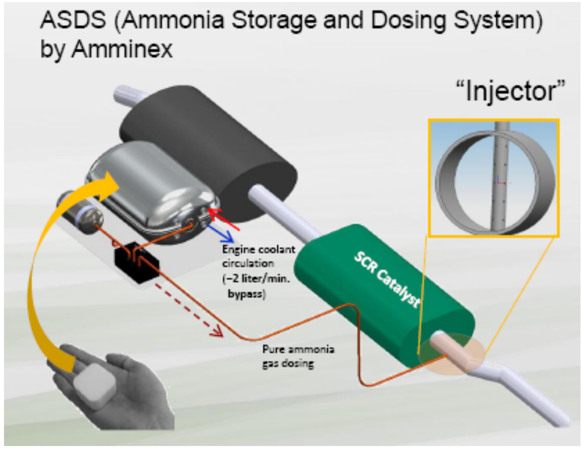


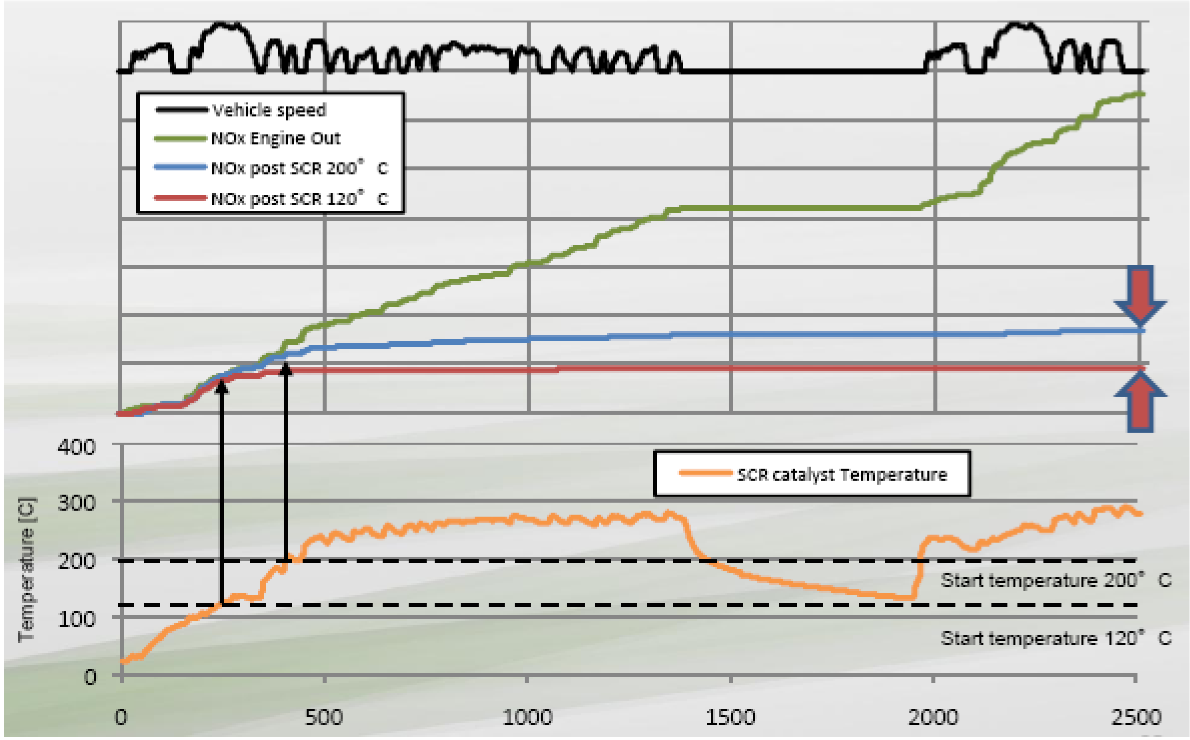


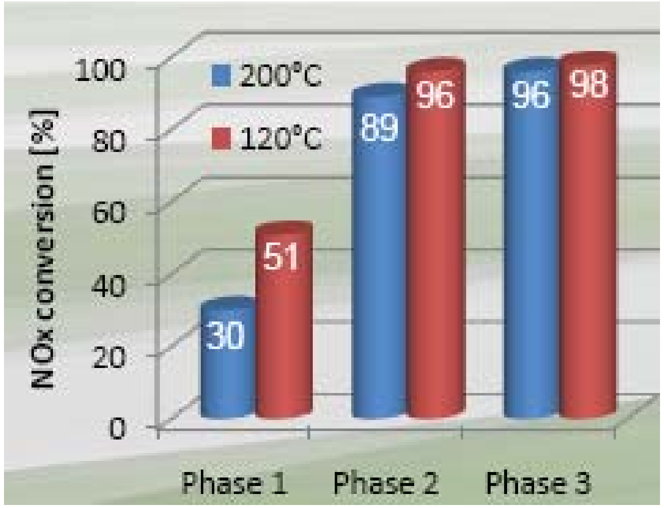


Reference: SAE 2011-01-1318

Gaseous NH_3 injection allows in better mixing and reduced low-temperature NOx emissions.

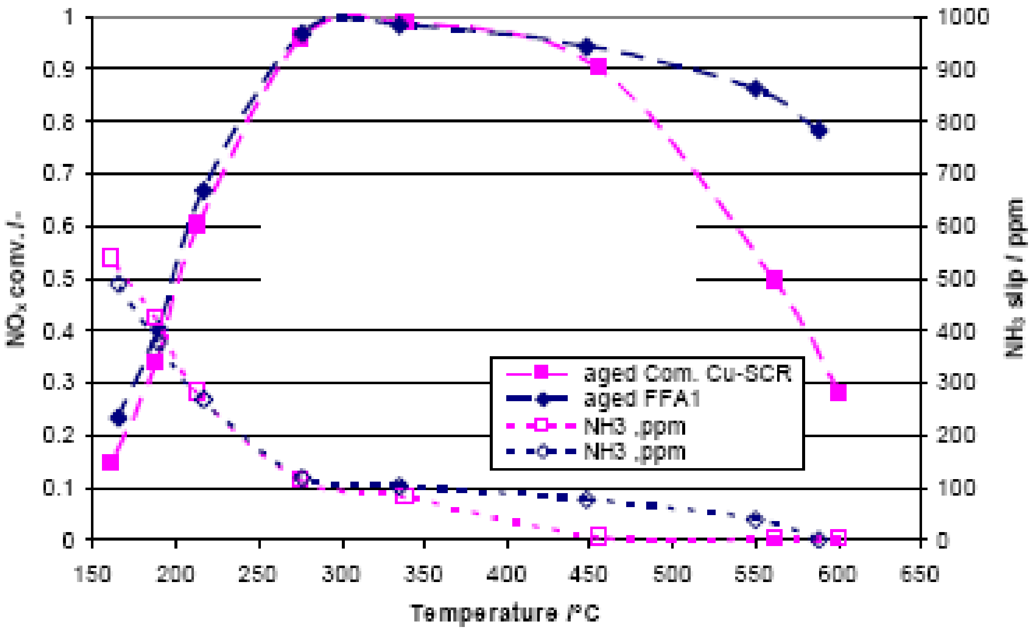






Injecting NH3 at 120 vs. 200C shortens light-off time by 45% and cuts cold start NOx by 40%

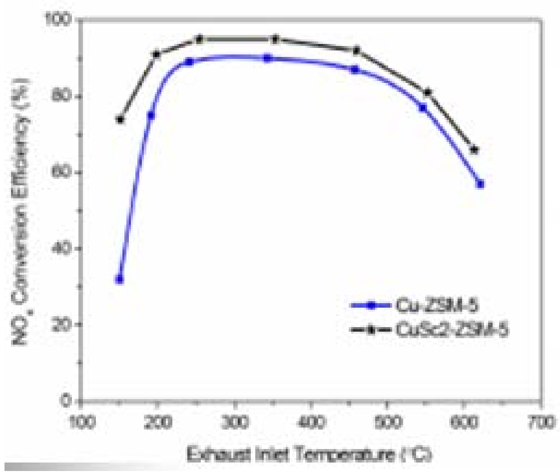
New SCR catalyst combines attributes of both Cu- and Fe-zeolites

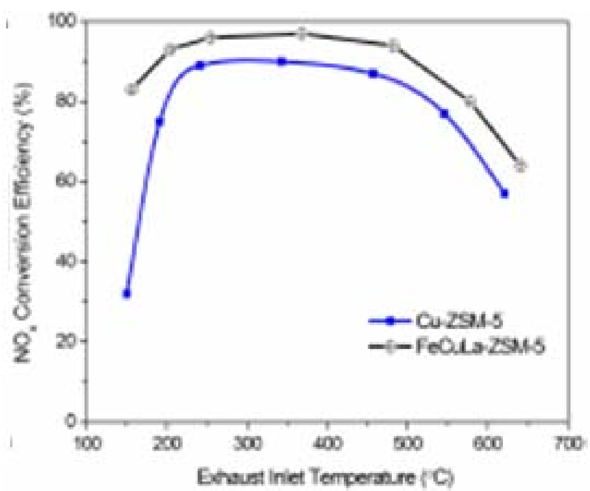


"FFA-1" combines advantages of Cu- and Fe-Z with good LT and HT aged performance.

LT light-off performance governed by NO-NO2 act energy

Ford, CTI, 7/11



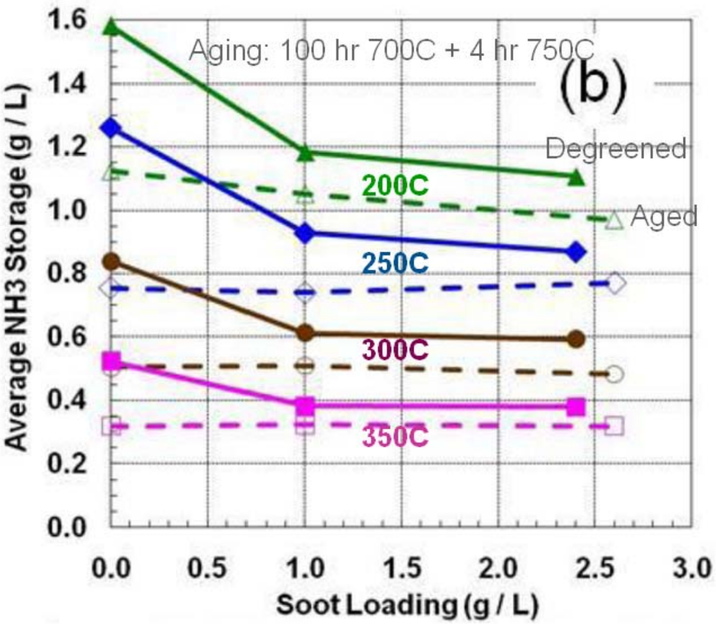


Other multi-metal formulations are being investigated. CuSc2 and CuFeLa show promise, among others. Aging issues.

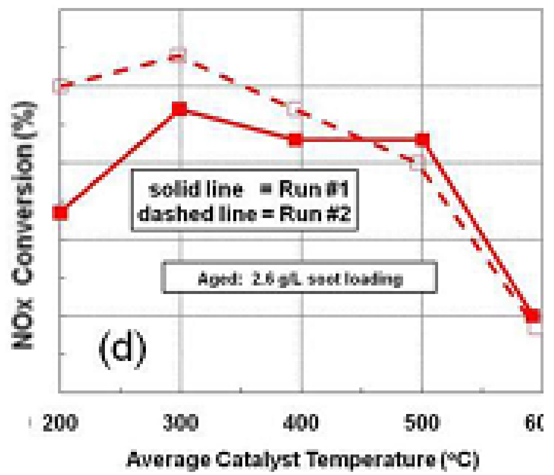
ORNL, DEER Conf poster, 9/10
SAE 2011-01-1330

New information is shown for DPF+SCR system.

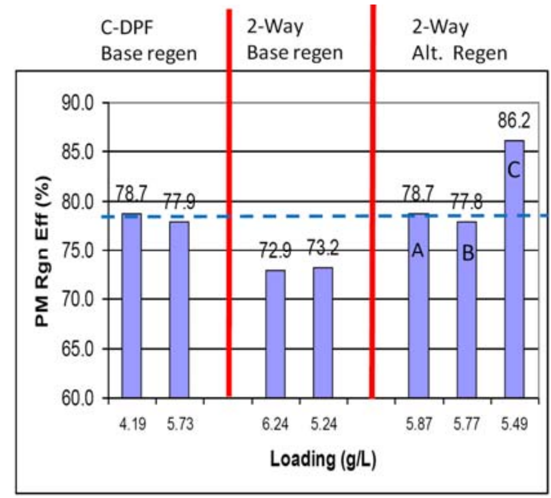
NH3 storage slightly impacted by soot, big impact at LT. Regeneration needs adjustment. Soot mass limit depends on substrate.



Aged NH3 storage capacity at 200C drops 14% with soot (2.5 g/l). No impact at higher test temperatures.



Run 1 with soot. Run 2 without soot. Soot effects LT deNOx performance, mostly due to NH3 storage. 1 g/liter has impact at T<300C.

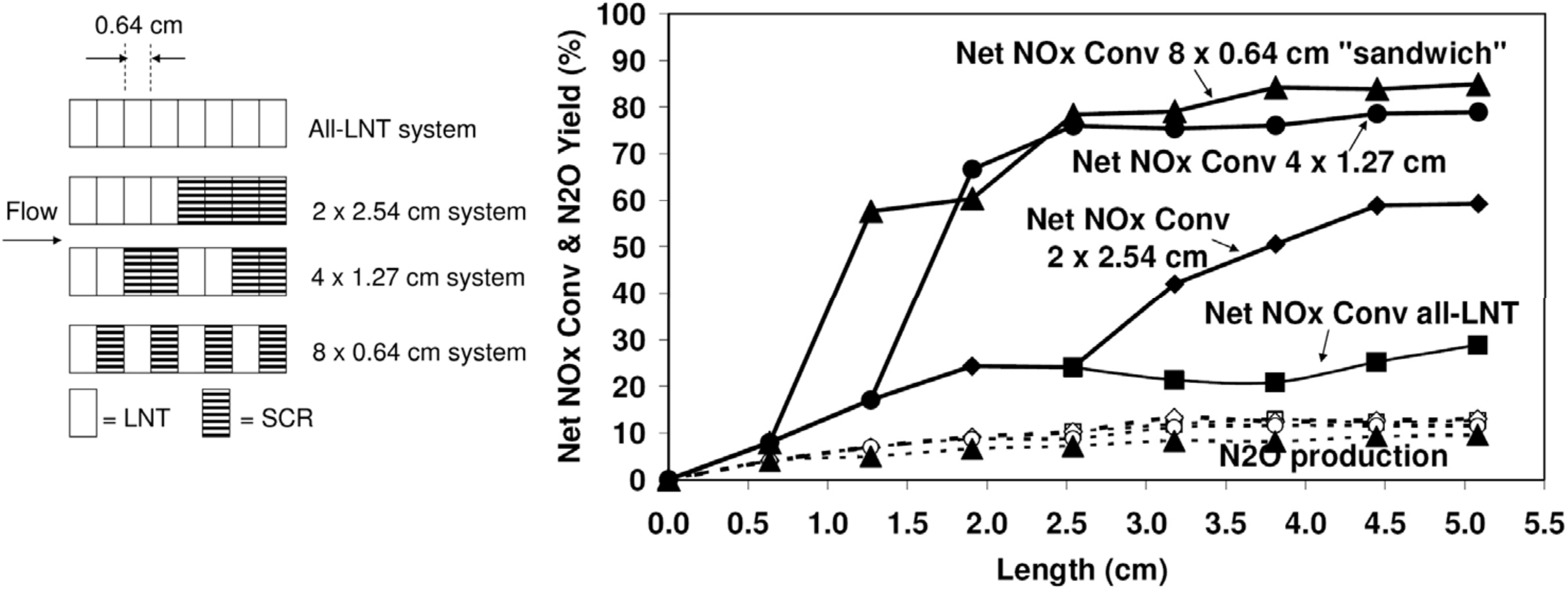


SCR effects active regen, but can be covered by incr T ~25C (A), or increasing time 4 min (B) or 8 min (C). 200kg/hr flowrate

System volume reductions:

44% for LD, 51% for HD

Alternating slices of LNT+SCR enhance system performance at reduced PGM. Better axial distribution of NO, NH3, and HC results in better performance.

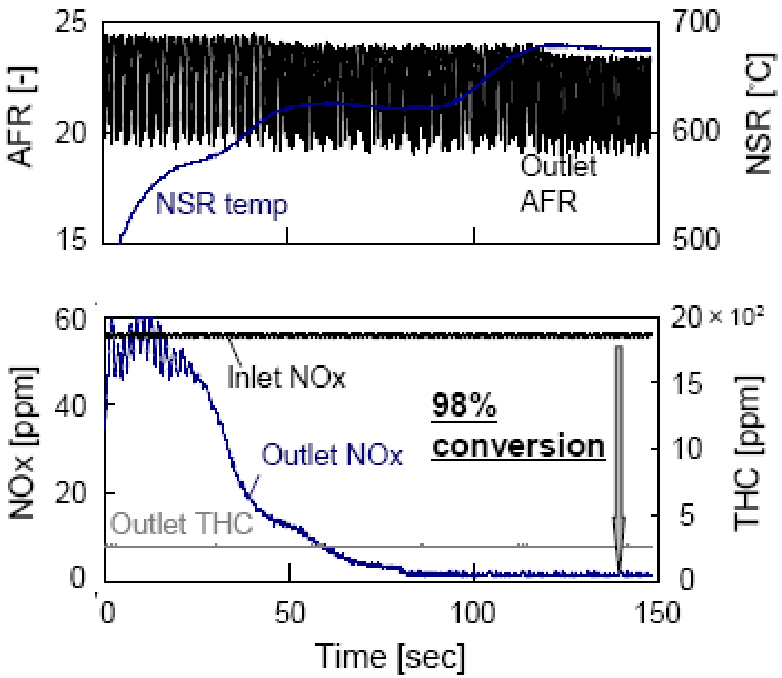


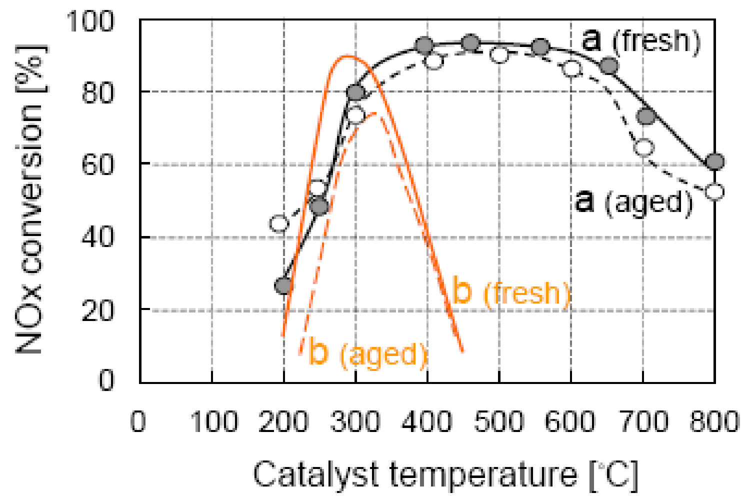
The LNT+SCR systems have the better net deNOx performance with lower N2O emissions as the LNT, but with half the PGM.

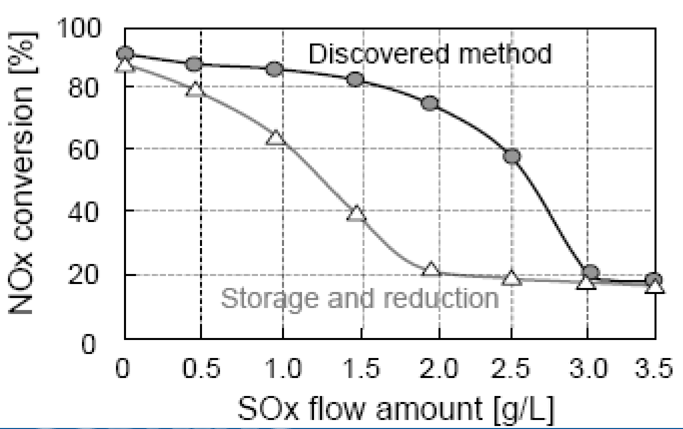
Ford, SAE 2011-01-0305

Toyota introduces a new DeNOx system.

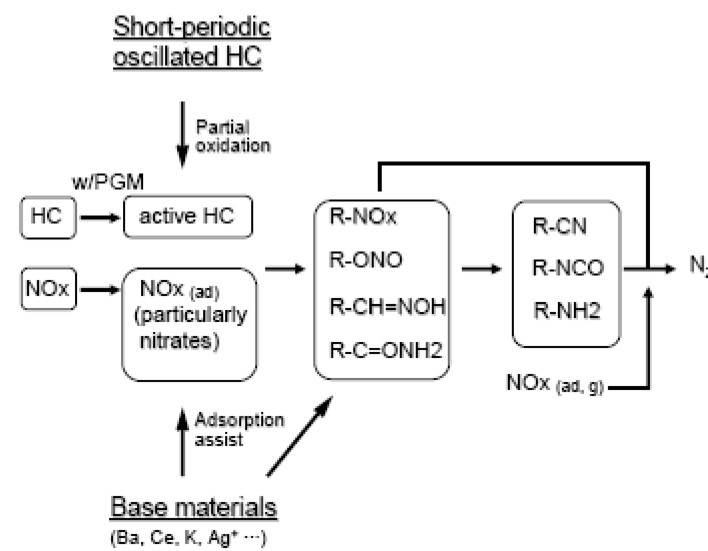
LNT run with rapid, lean AFR pulses to significantly extend HT range.







70% deNOx on high-speed drive cycle, vs. 20% for traditional LNT operation

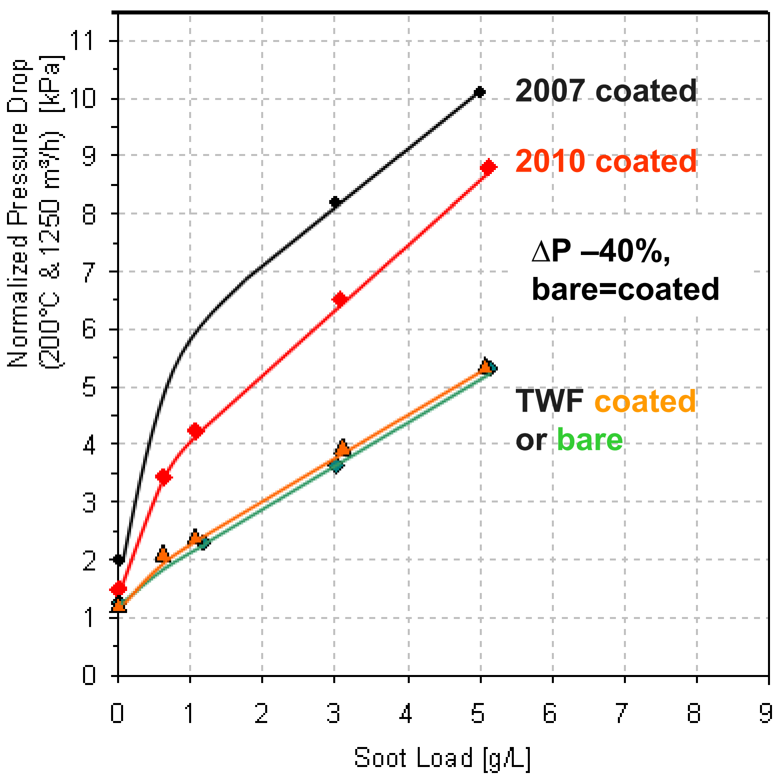


Toyota, SAE 2011-01-2089

CORNING

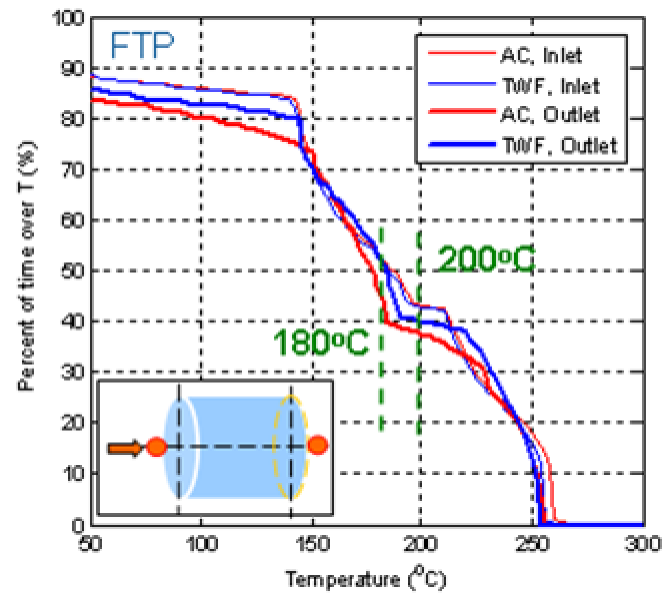
PM

More HD DPF passive regeneration means lower thermal mass DPFs. -40% ΔP, faster heat-up, better regeneration.



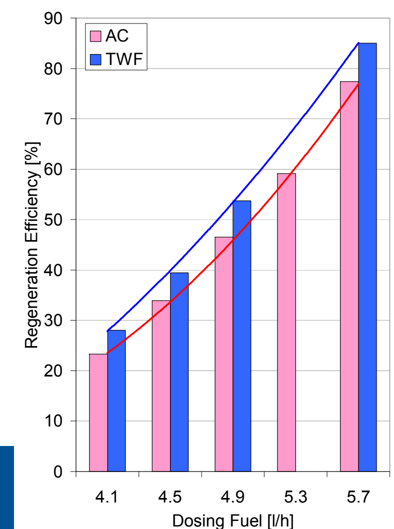
New cordierite thinwall filter (TWF) has 40% lower back pressure, very little depth filtration, and little coating back pressure impact.

Low thermal mass of TWF allows more earlier urea injection in the first 400s of the FTP. 50% of time at T>180C vs. 40% for 2010 filter. -15% NOx on cold FTP.



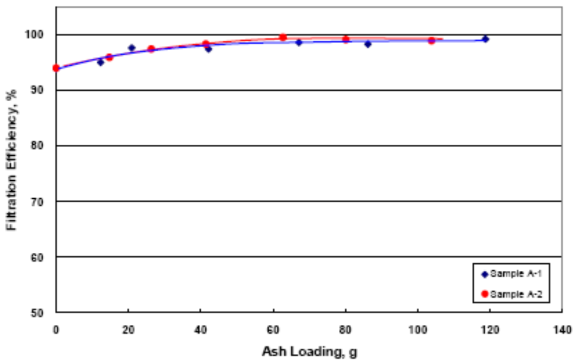
Corning, SAE 2011-01-0813

Improved DPT regeneration due to higher skin temperature and less heat absorption.



Active regeneration max. temperature similar to 2010 product up to ~4 g/liter soot.

Ash membrane related filtration efficiency depends on cell density, pore character, and regeneration strategy.



200 cpsi, 12 mil
50%, 15um (A-1)

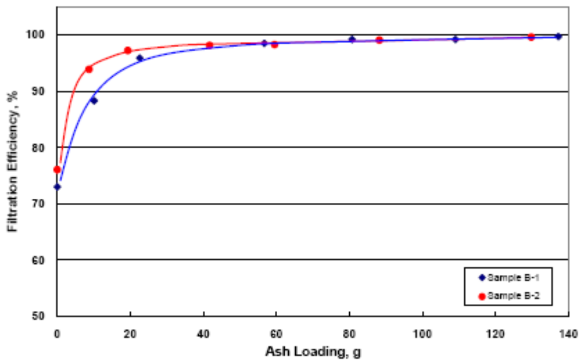
vs

300 cpsi, 12 mil
50%, 15um (A-2)

200 cpsi, 12 mil
65%, 20um (B-1)

vs

300 cpsi, 12 mil
65%, 20um (B-2)



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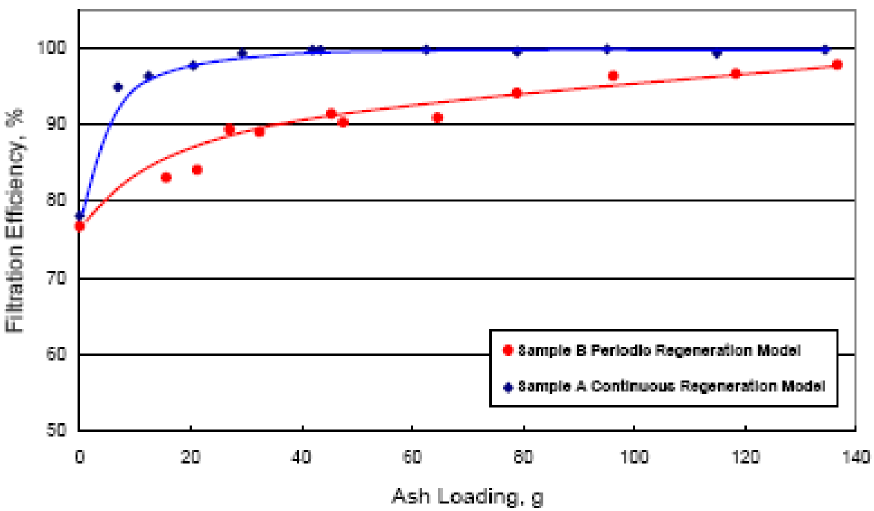
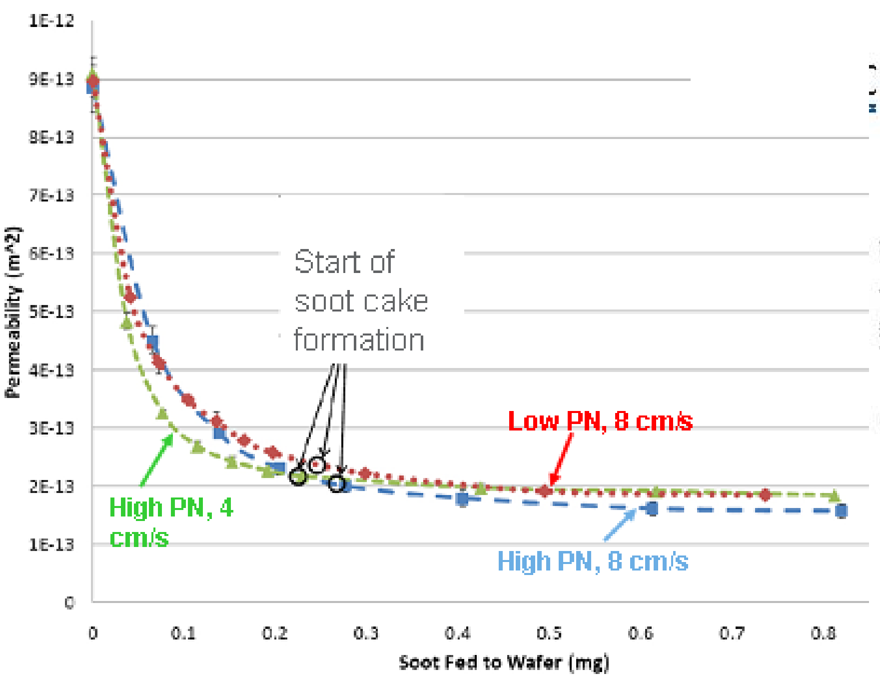


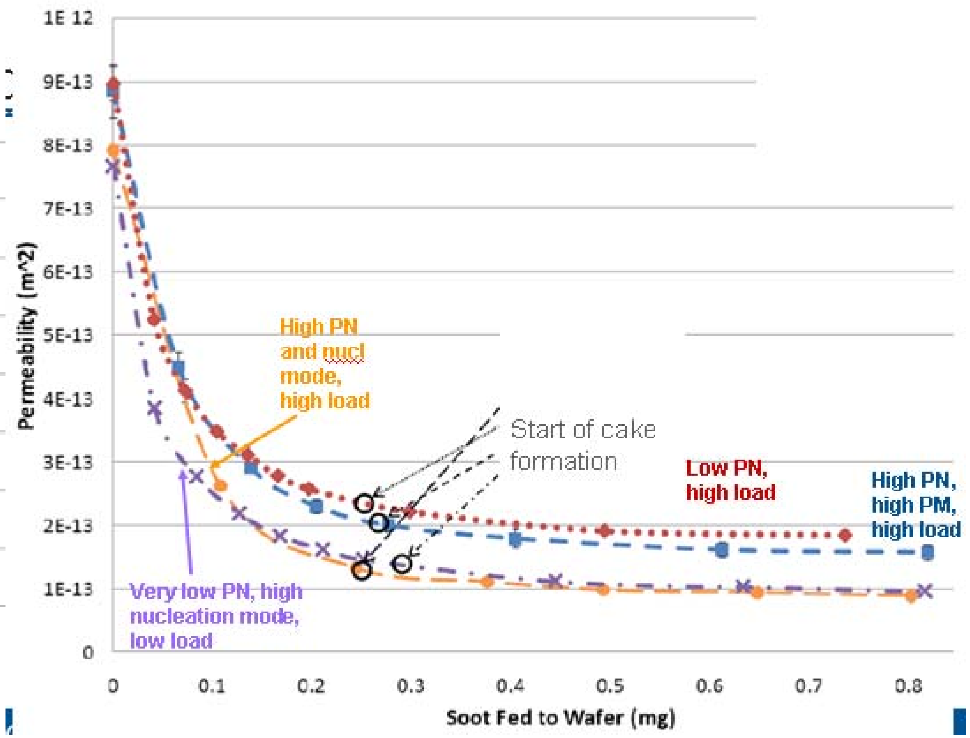
Continuous regen strategies build up an ash membrane faster than periodic regen, hence better efficiency.

With low-porosity medium diameter pores, efficiency independent of cell density (top). With high-porosity and larger pores, 300-csi has higher efficiency, perhaps due to thinner, more evenly distributed ash.

NGK, Emissions 2011, 6/11

Fundamentals on effect of exhaust flow rate and PN character are described. Results will be useful in improving soot models.





Similar curves: Most of the wall permeability impacts are due to substrate. Normalized wall permeability starts out similarly for high face velocity, indep of PN in exhaust (red and blue), but later low PN has higher permeability due to less PN going into wall and thinner cake. Low flow, high PN allows low cake density (higher end permeability), but thicker cake.

High nucl mode penetrate into wall and bridges early – fast drop in permeability and low final permeability.

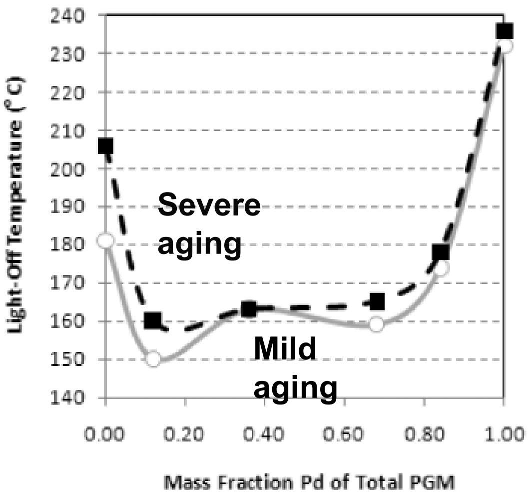
Univ of WI, SAE 2011-01-0815

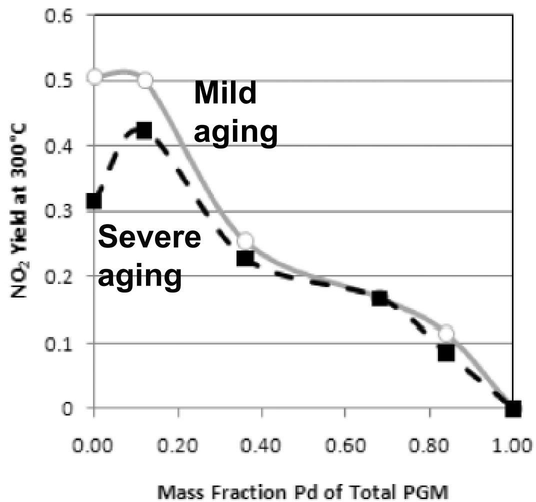
CORNING

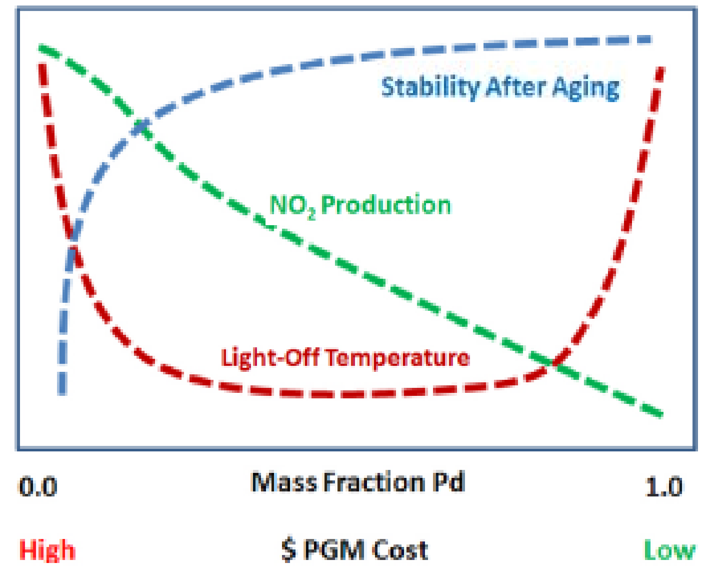
DOC

Effect of Pd substitution on DOC performance is characterized.

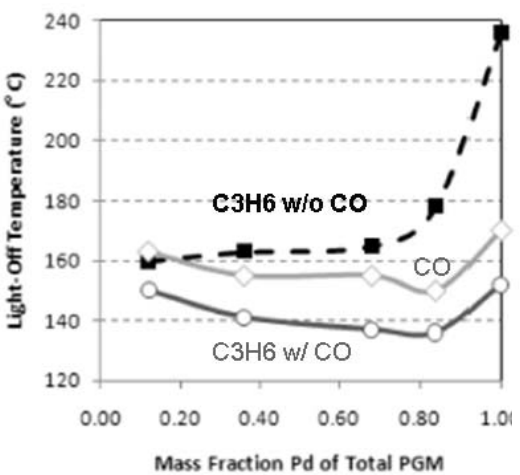
HC light-off improved, NO_2 decreases, durability increases.





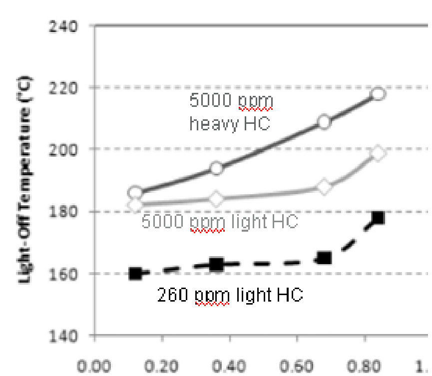


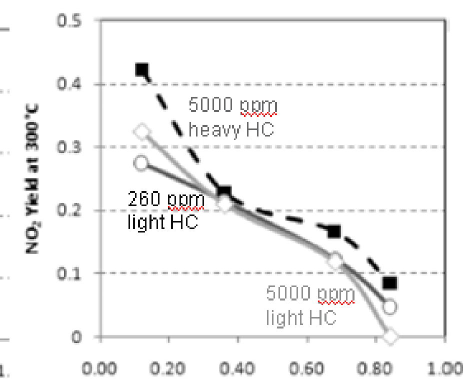
HC light-off and durability is favorably impacted by small to moderate substitution of Pd for Pt. NO oxidation is strongly dependent on Pt content. 1.8 g/liter catalyst, C_3H_6:C_3H_8=260:90, 30,000/hr



GM, SAE 2011-01-1134.

CO promotes HC oxidation at 300C. No impact on NO oxidation.



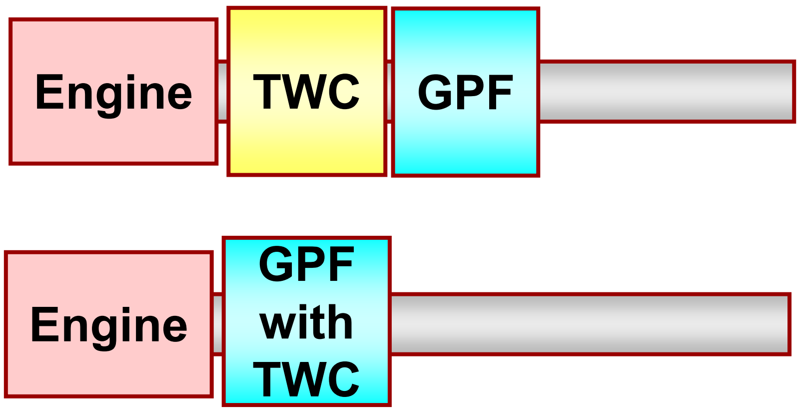


High concentrations of HC increase light-off temperatures. Heavy HC has greater impact. Minimal impact on NO2, except at lower Pd content.

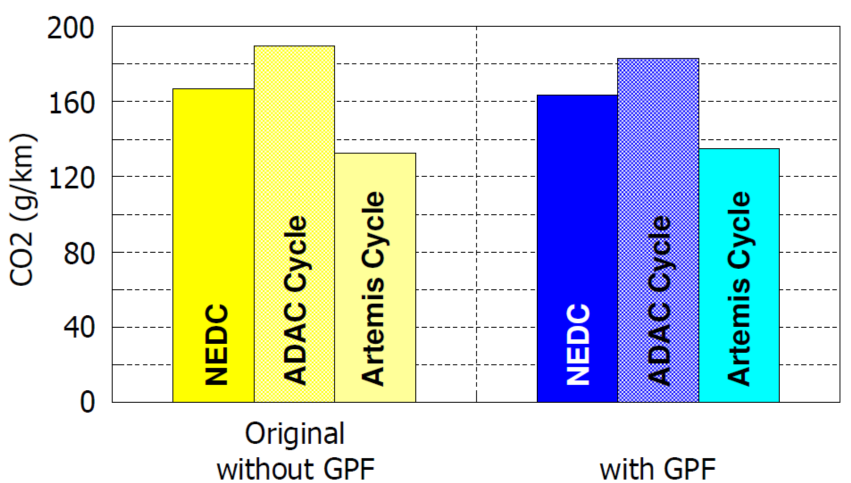
CORNING

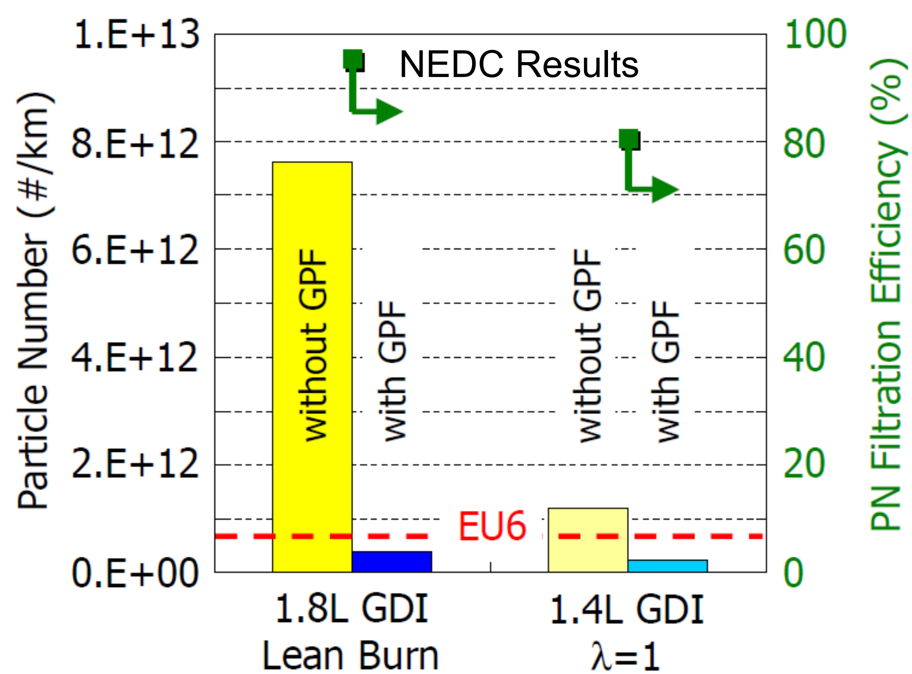
Gasoline

Benefits of filters being demonstrated on GDI engines



- GDI engines exhibit high PM emissions under high speeds and loads
- Wall-flow filters offer same benefits of PM number and mass reductions as with diesel engines





TWC system architectures being optimized for LEV III.

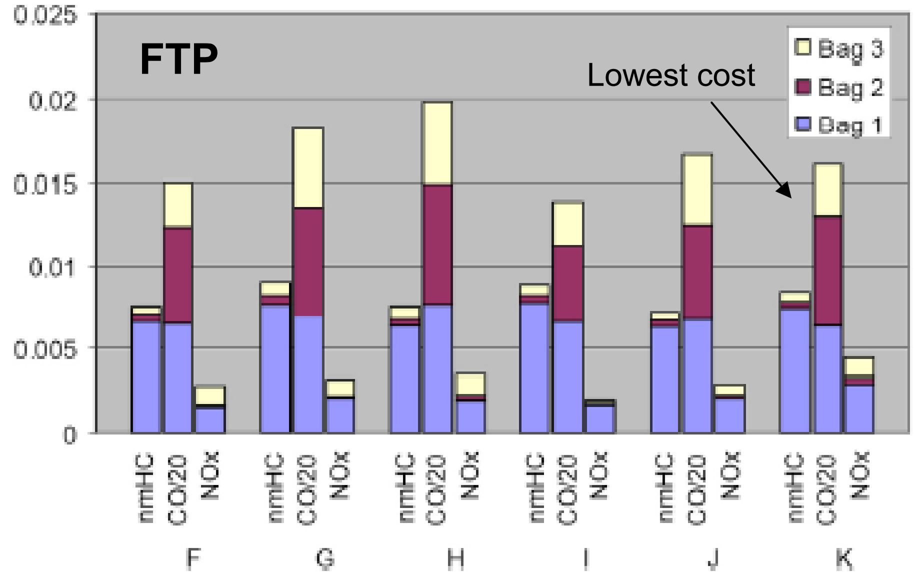
4-cylinder application with secondary air. Much reduced PGM.

Front Catalyst		Mid Catalyst		Rear Catalyst	
Vol (L)	Sub (cpsi/mil)	Vol (L)	Sub (cpsi/mil)	Vol (L)	Sub (cpsi/mil)
0.62	900/2.5	0.62	600/4.3	1.23	600/4.3

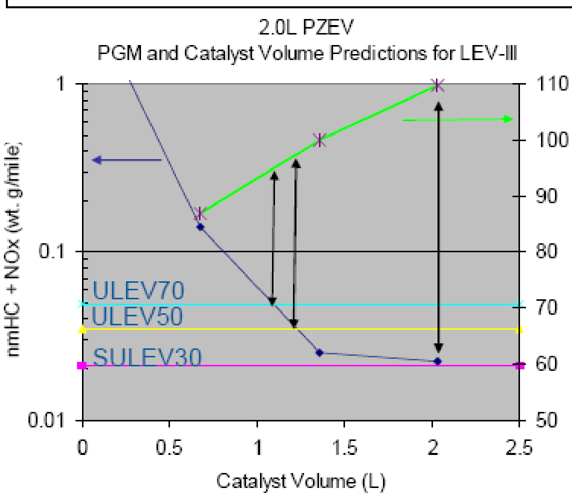
Production UBC put within CCC can in new design. SVR=1 for all CCC design. <u>In CCC, NMHC+NOx was 25% lower with a PZEV calibration.</u>

- New catalyst drops PGM by 25% at same emissions level, or emissions at same PGM.
- FTP 20 mg/mi NMHC+NOx is more difficult than US06 50 mg/mi for these catalyst designs.

	Front		Mid		Rear		
Design	Pd (g/l)	Rh (g/l)	Pd (g/l)	Rh (g/l)	Pd (g/l)	Rh (g/l)	PGM $
F	7	0.3	5	0.3	2	0.3	211.5
G	7	0.3	2	0.1	1	0.1	135.8
H	3	0.3	5	0.1	2	0.1	145.7
I	3	0.3	2	0.3	1	0.3	121.6
J	7	0.3	2	0.1	2	0.3	172.8
K	3	0.3	2	0.1	2	0.1	115.6



All catalyst designs were <20 mg/mi NMHC+NOx on the FTP, and all were below 50 mg/mi on the US06, including the cheapest one (k).

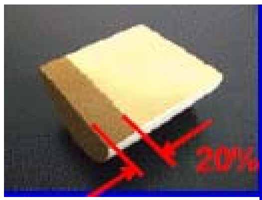


SULEV30 PGM could cost +15% vs. ULEV70, but could be 2X in size. Umicore, CTI 5/2011

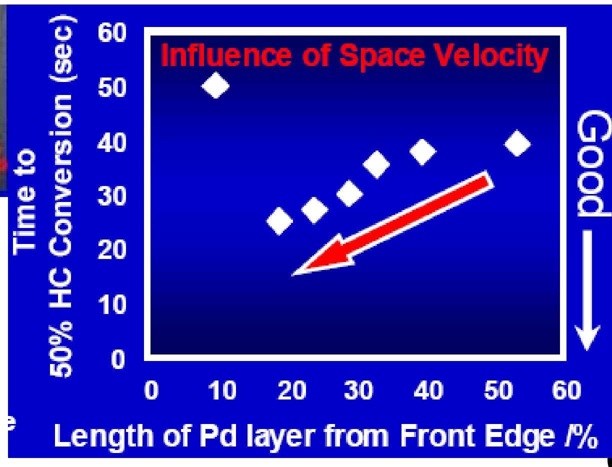
Umicore SAE 2011-01-0301

Gasoline catalysts show multiple zone coatings and PGM stabilization methods.

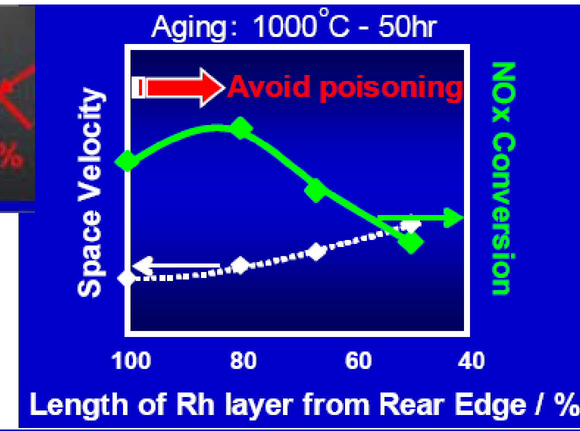
Pd in front, Rh behind, different OSC in front and back.

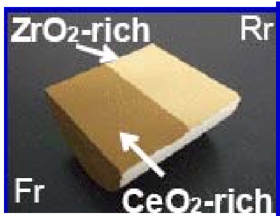


Pd is zoned in the front to give fast HC light-off

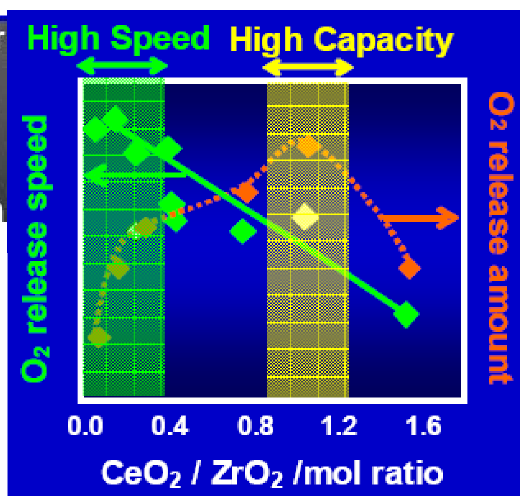


Rh is zoned in the back to protect again phosphorous





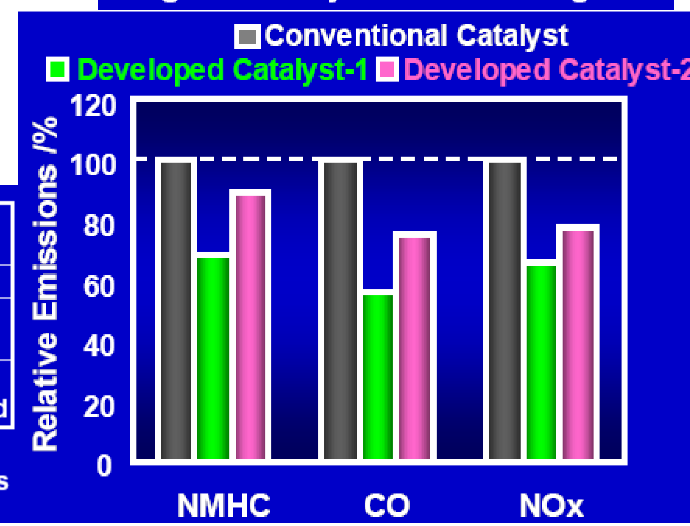
OSC is zoned to give optimum performance in front and back.



Catalyst w/ -45% Rh has -20% emissions

	Conventional	Developed Catalyst 1	Developed Catalyst 2
Coat	Double Layer	Zone-Coat	
Noble Metal	Pd/Rh	Pd/Rh	Rh45% reduced

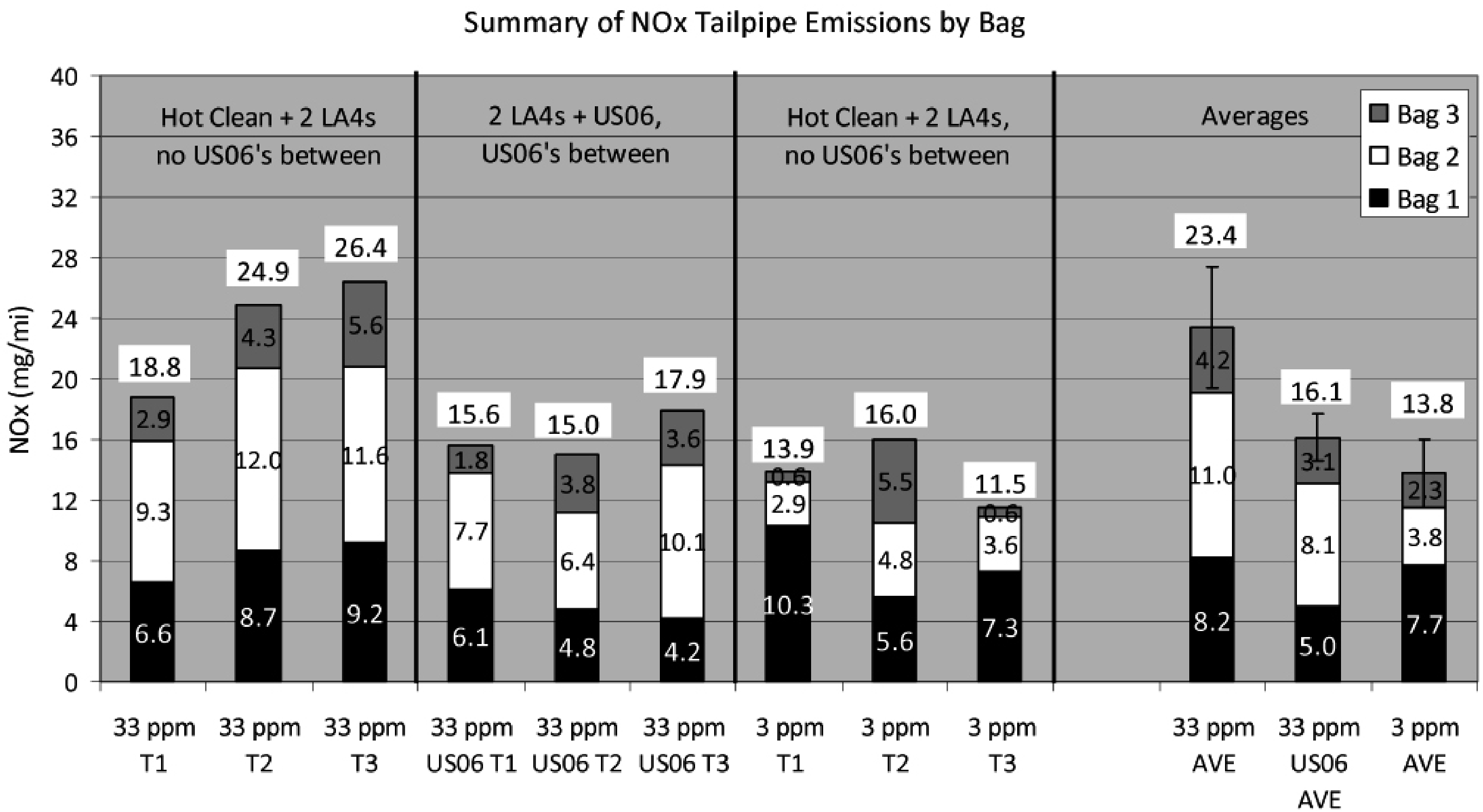
Substrate Volume: 0.9[L]
Aging: Equivalent of 120K miles
Vehicle: '05MY ULEV/CAMRY



Toyota, SAE 2011-01-0296

Other: Rh is better-dispersed with Al_2O_3 barrier to prevent ZrO_2 sintering; Nd_2O_3 pins Rh grains

30 ppm sulfur adversely affects TWC formulations. Hot driving partially recoups performance; 3 ppm sulfur lower NOx



Sulfur builds up on TWC, results in increased NOx emissions (left panel). Hot US06 partially cleans catalyst (2nd panel). 3 ppm sulfur does not have the issue (3rd panel), and has lower emissions all around.

Summary

- California LD criteria emission regs are tightening. Could signal another round in all sectors.
- CO_2 regs are present in both LD and HD markets. Tightening is just beginning. Paradigm shift.
- Engines are meeting the challenge
  - Downsizing, lean burn, new designs, HD deNOx
- deNOx is advancing
  - New sources of NH_3, new catalysts, new LNT+SCR architectures, new ways to run an LNT
- DPFs evolving
  - Low thermal mass, membrane effects, fundamentals on permeability
- DOC Pd:Pt ratios allow optimization
- Gasoline emission control is amazing
  - Zone coating
  - Lower PGM with better performance
  - Need low-sulfur fuel
  - GPFs give ultra-clean exhaust

JohnsonTV@Corning.com