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CORNING

Engine Efficiency and Emissions Trends

Tim Johnson

May 14, 2015

Summary

Back Drop

- Criteria pollutant and GHG standards continue to tighten
- Significant measures are needed to hit 80% GHG reductions by 2050
- EVs are center stage for achieving goals, but not exclusively
- Connected vehicles will add value to the auto industry, drop emissions and congestion, and bridge an inevitable cost / consumer value gap

Engine technologies developing for significant fuel reductions

- LD potential CO_2 reductions up to 30% reductions from best LD engine today.
- -10% for HD

Emission control technology is delivering clean vehicles

- NOx control is achieving 98% reductions
- PM is or can be essentially eliminated from vehicles
- TWC is impressive and still evolving

Possible: 70-100% carbon-free petroleum and negative CO_2 vehicles

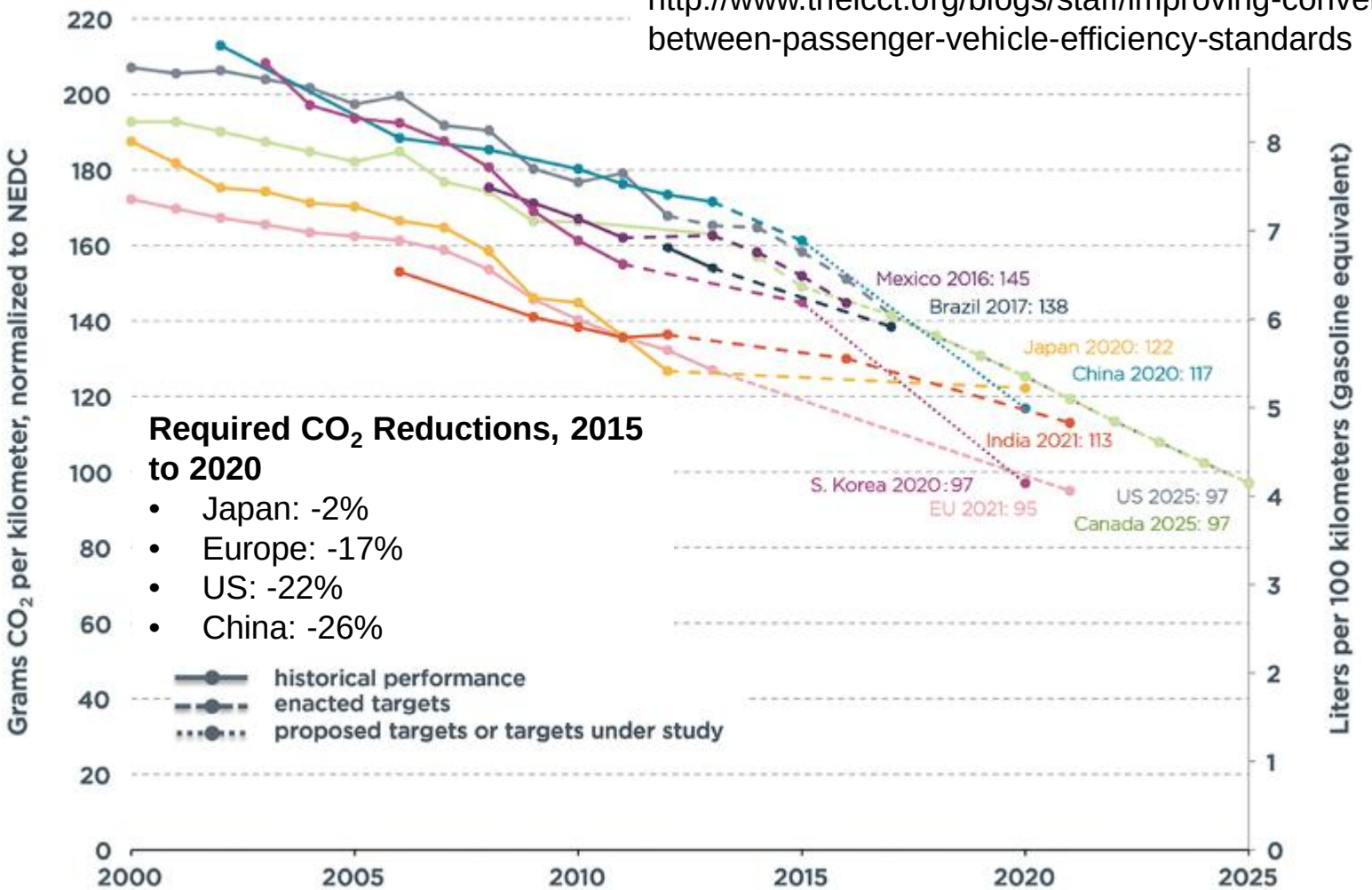
Back Drop

Future Directions

NEW ADJUSTMENT FACTORS

Major LDV automotive markets are moving to ~100 g/km CO_2. Nominally 20-25% reductions from today by 2020.

http://www.theicct.org/blogs/staff/improving-conversions-between-passenger-vehicle-efficiency-standards



Required CO_2 Reductions, 2015 to 2020

- Japan: -2%
- Europe: -17%
- US: -22%
- China: -26%

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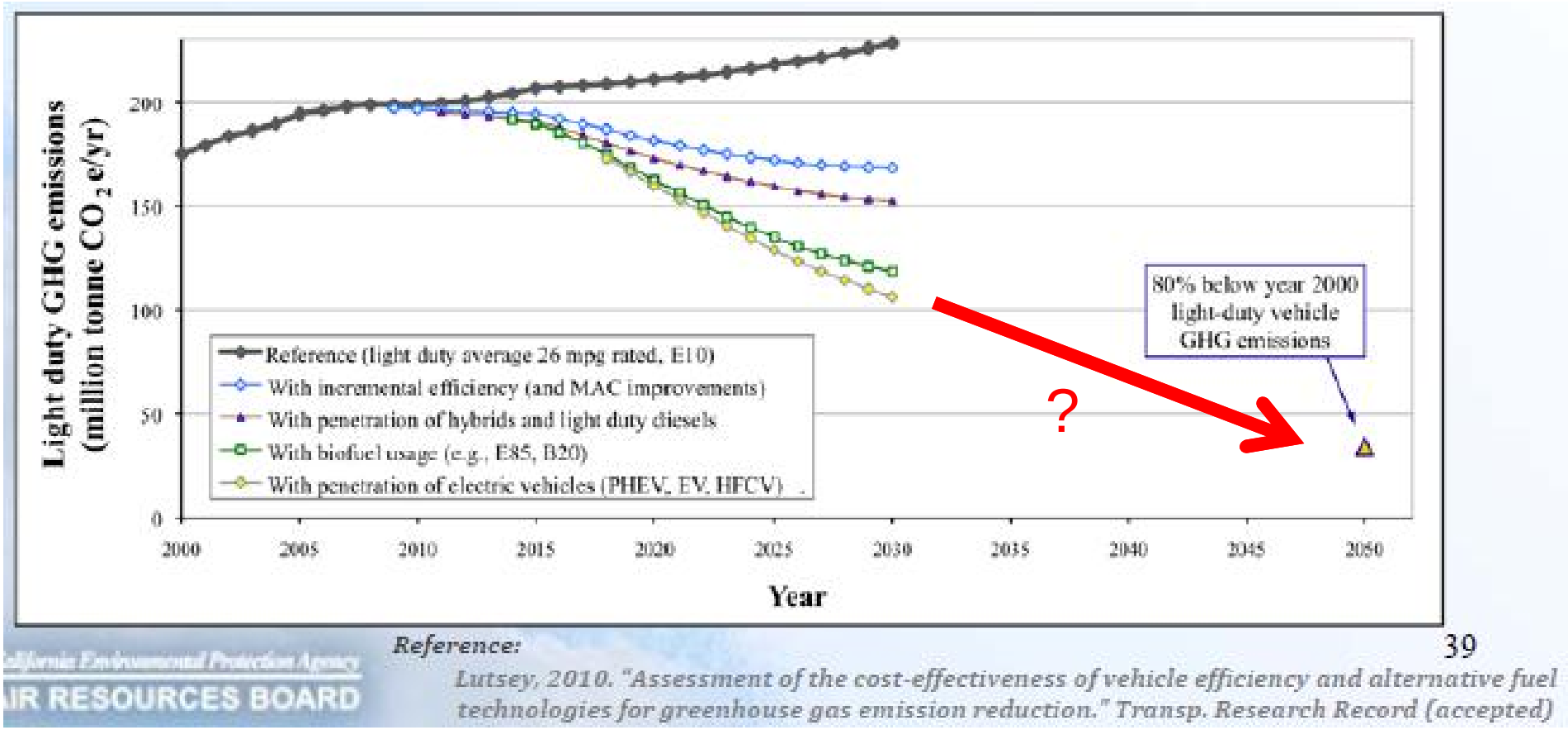
Some directions can be obtained from the California CO_2 roadmap. Perhaps biofuels and full-HEVs can do it. EV added for assurances.

CARB Workshop 3/10



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California Environmental Protection Agency
AIR RESOURCES BOARD

Reference:
Lutsey, 2010. "Assessment of the cost-effectiveness of vehicle efficiency and alternative fuel technologies for greenhouse gas emission reduction." Transp. Research Record (accepted)

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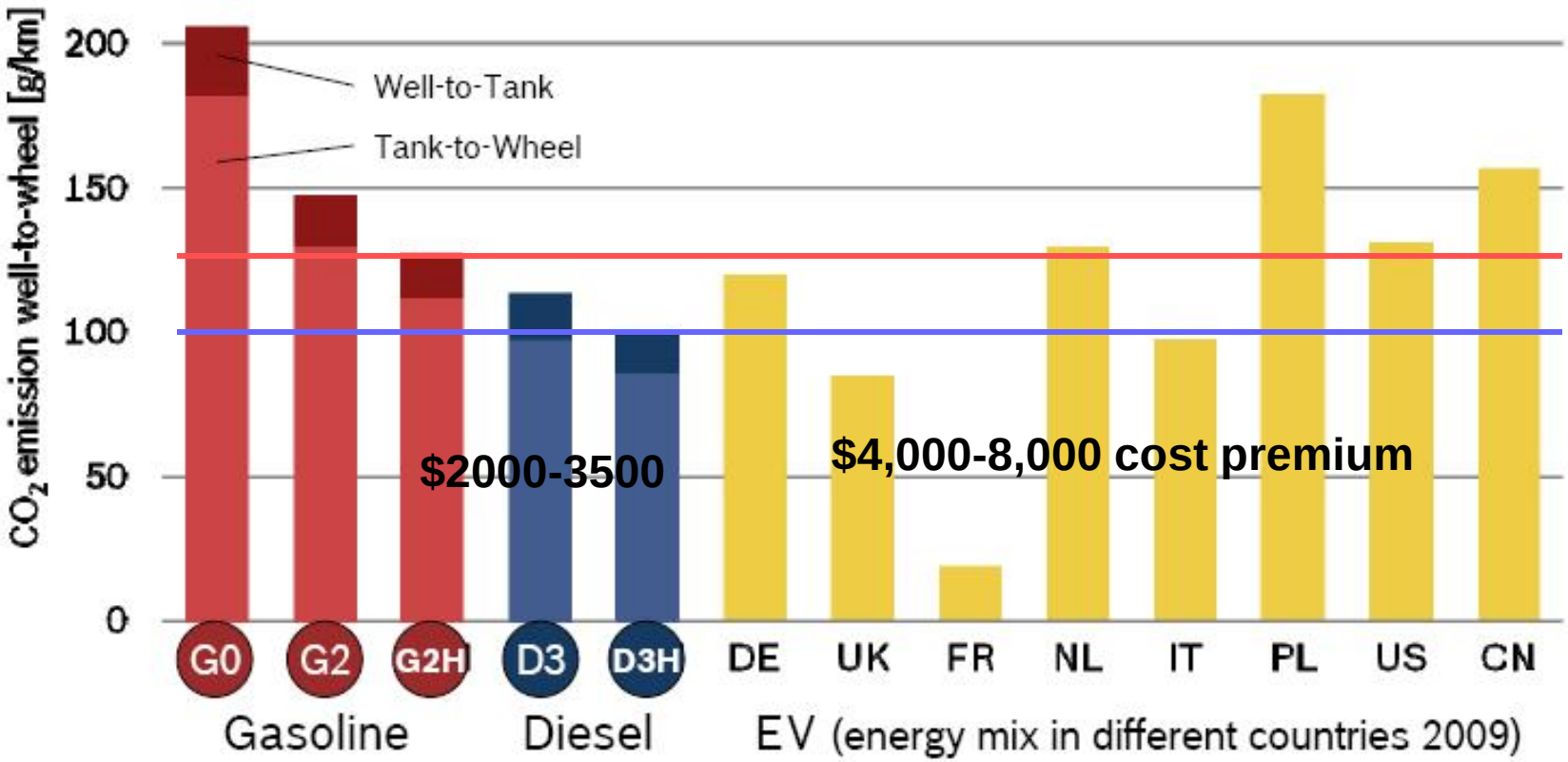
Gasoline and diesel HEV quite competitive with BEVs on well-to-wheel CO_2 basis. BEVs much more expensive.



* Assumption EV: Power generation includes net losses, 9% charging loss & 18.8 Wh/km

HEV: 1 kW-hr battery, 25 kW motor

Source: Bosch 10/11, NRC review, EPA cost teardown

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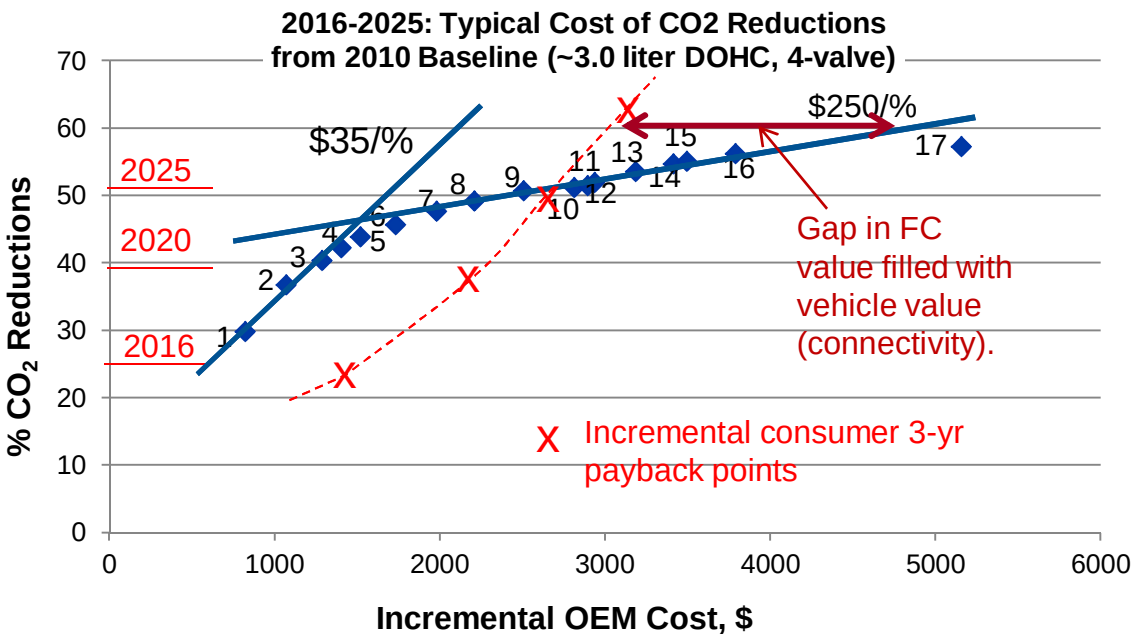
Analyses of EPA cost and CO_2 reduction estimates show incremental <3 yr customer payback to 2025. $4.50/gal



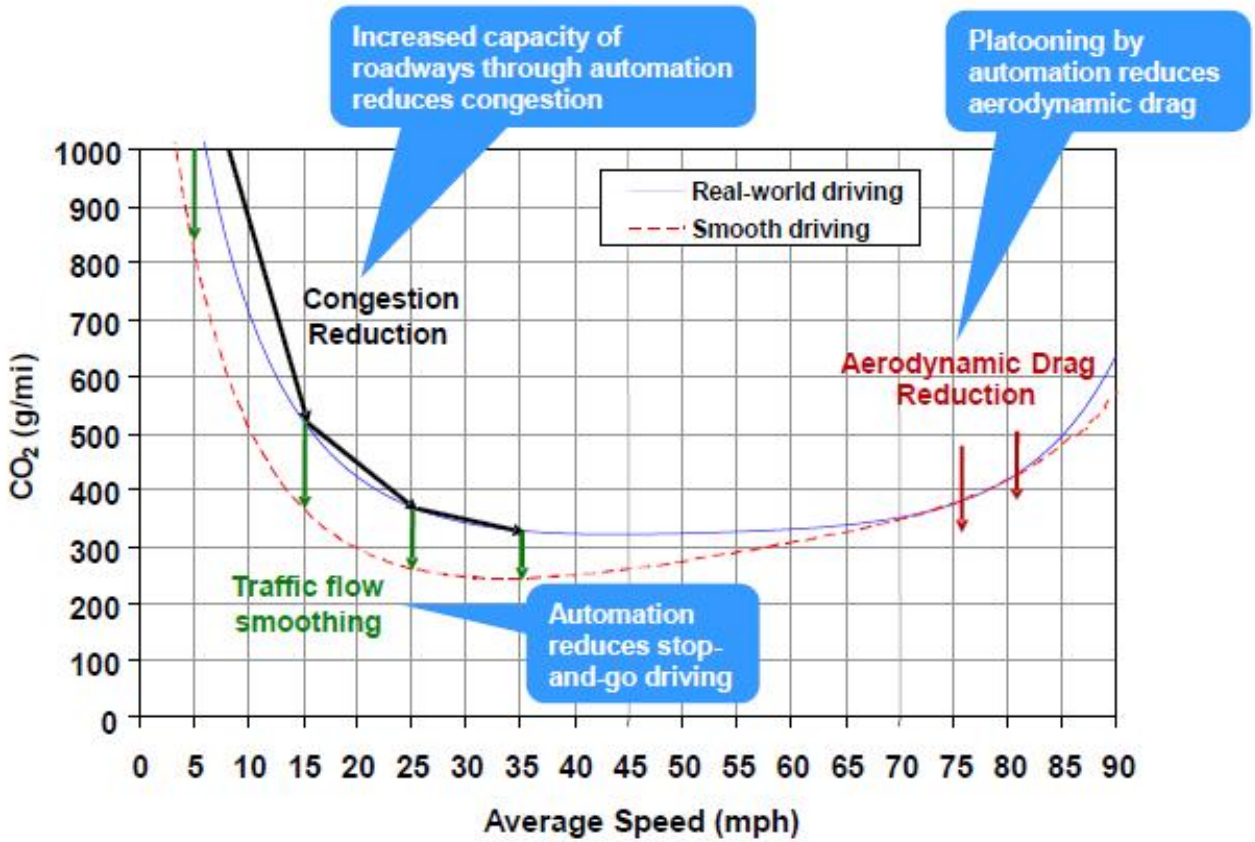
Incremental 3 yr payback points assume $4.50/gal and 12,000 mi/yr; $ are sticker price assuming 15% margin on hardware and dev cost

EPA420-R-12-016, 2017-25 GHG RIA; Table 1.3-8

1. Aggr frict red, aggr shift, low drag brake, impr eff accessories, elect PS, aero, LRR tires, high eff gearbox, dual cam phase, 5% WR, 6-sp wet DCT
2. 1 + TC GDI 18 bar BMEP
3. 2 + more aero, accessories eff., LRR tires
4. 3 + 8-sp wet DCT
5. 4 + 5% weight reduction
6. 5 + TC GDI 24 bar BMEP
7. 6 + cEGR
8. 7 + 5% weight reduction
9. 8 + 5% weight reduction
10. 9 + start-stop
11. 10 + secondary axle disconnect (SAX)
12. 11 + MHEV, +10% wt added, -EGR, -SAX
13. 12 + cEGR
14. 13 + 5% weight reduction
15. 14 + SAX
16. 15 + 5% weight reduction
17. 16 + discreet var valve lift + ATKCS (?)

- 2010 baseline 27 mpg (8.8 l/100 km), 3 liter DOHC, 4 valve, 3554 pounds (1615 kg)
- Costs are hardware + development costs

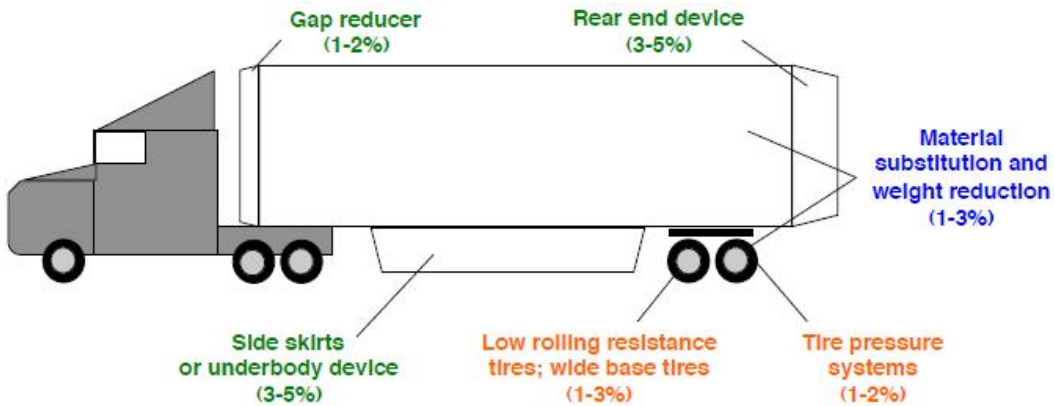
Connected cars can drop congestion and fuel consumption by 10-20%. And, may add a more relaxing trip.



- Minima in FC (blue line) is ~30-70 mph (50-115 kph)
- Automation can drop FC ~20% at urban speeds
- Provides a more-relaxed trip

M. Barth, K. Boriboonsomsin, G. Wu, "Vehicle Automation and its Potential Impacts on Energy and Emissions", Road Vehicle Automation, Gereon Meyer, Sven Beiker (Ed.), ISBN 978-3-319-05989-1, Springer International Publishing, 2014.

US EPA is investigating more HD CO_2 reductions for 2021+.



ICCT, SAE Gov&Ind 1-14

- 80% of van trailers made by 3 companies
- 2.5 to 3 trailers per truck
- Skirts: $900
  Boat tails: $1300

- Proposal is at the White House for review. Expected out within a month
- Final Rule by March 2016

- Separate engine standards
- Continuous tightening 2021, 2021, and 2027
  - 2027 perceived to be “stretch” goal
- Significant trailer reductions – new regs
- N_2O tightening; CH_4 crankcase closing
- SI CNG with gasoline; CI CNG with diesel

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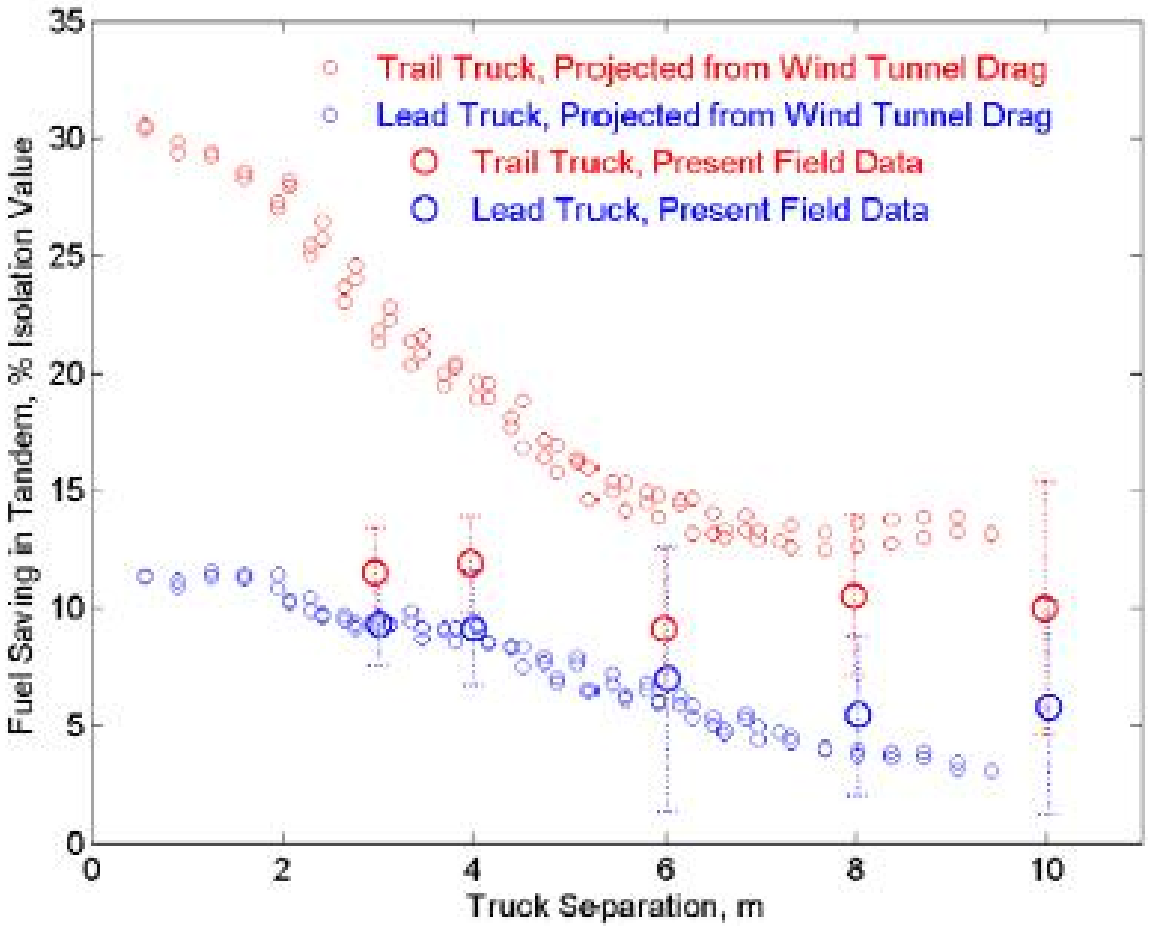
Platooned trucks can save 10-15% fuel.



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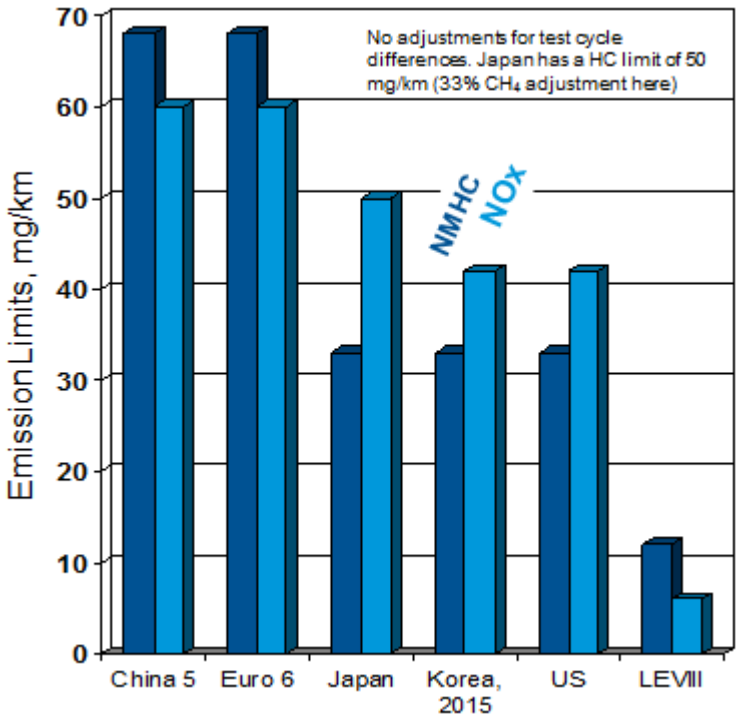
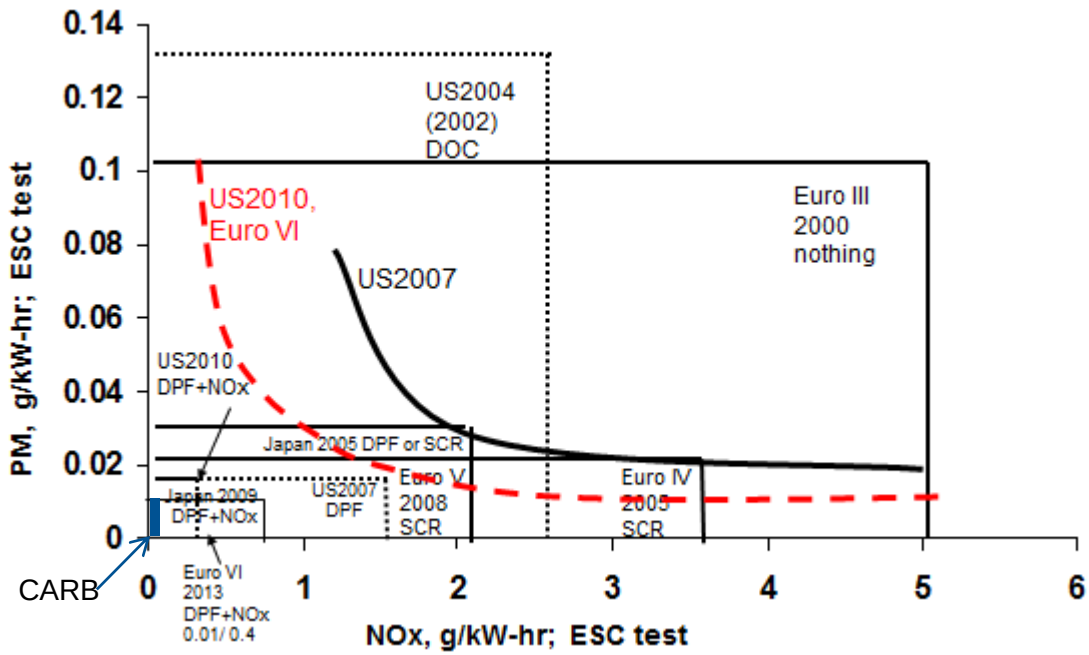
Regulators are continuing tightening of vehicular emissions in response to the health effects. LEVIII (US Tier 3) is 1/10 of Euro 6.

CARB looking at 0.065 g/kW-hr HD NOx.



Representative gasoline vehicle NMHC and NOx limits.



Representative HD truck PM and NOx regulations. Dashed and solid black curves represent best feasible engine out emissions.

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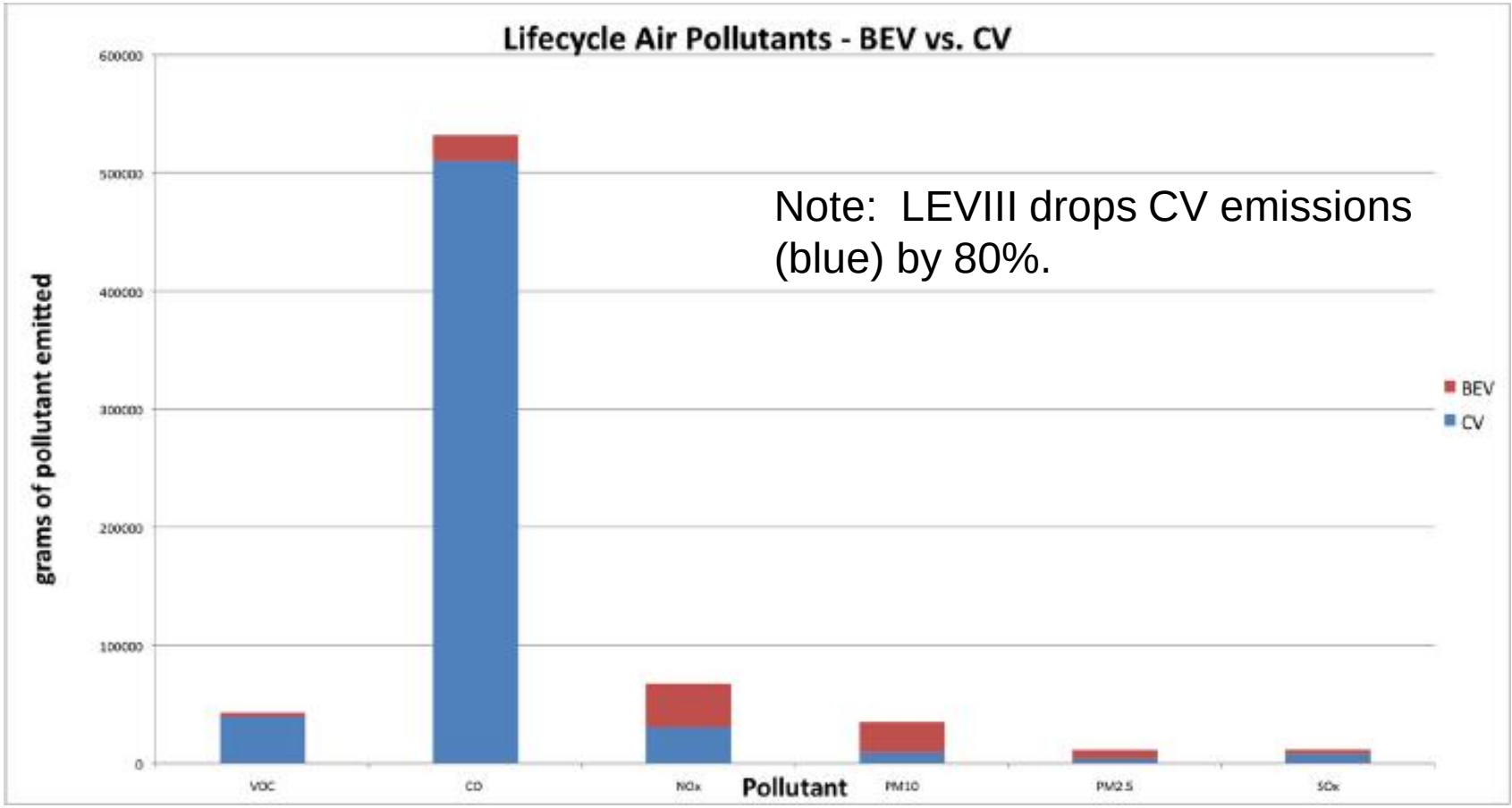
WTW EVs are not necessarily cleaner. California BEV power plant emissions are compared to conventional gasoline vehicle. PM much higher for BEV. NOx similar. VOC much lower. BEVs can drop urban pollution and are durable, but power plants need addressing.



NOx emissions from a conventional LEVII (US Tier 2 Bin 5) vehicle are similar to BEV on current California grid. PM is much higher for BEV. VOC much lower for BEV.

CARB, 2010

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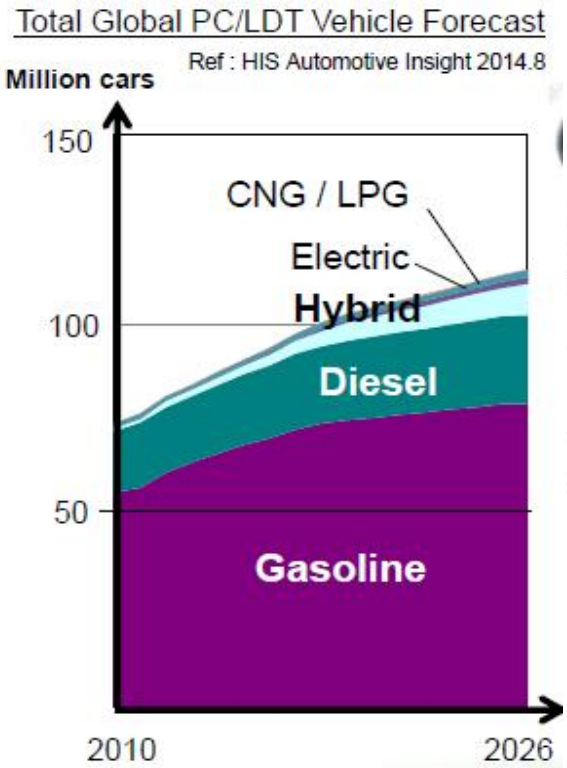
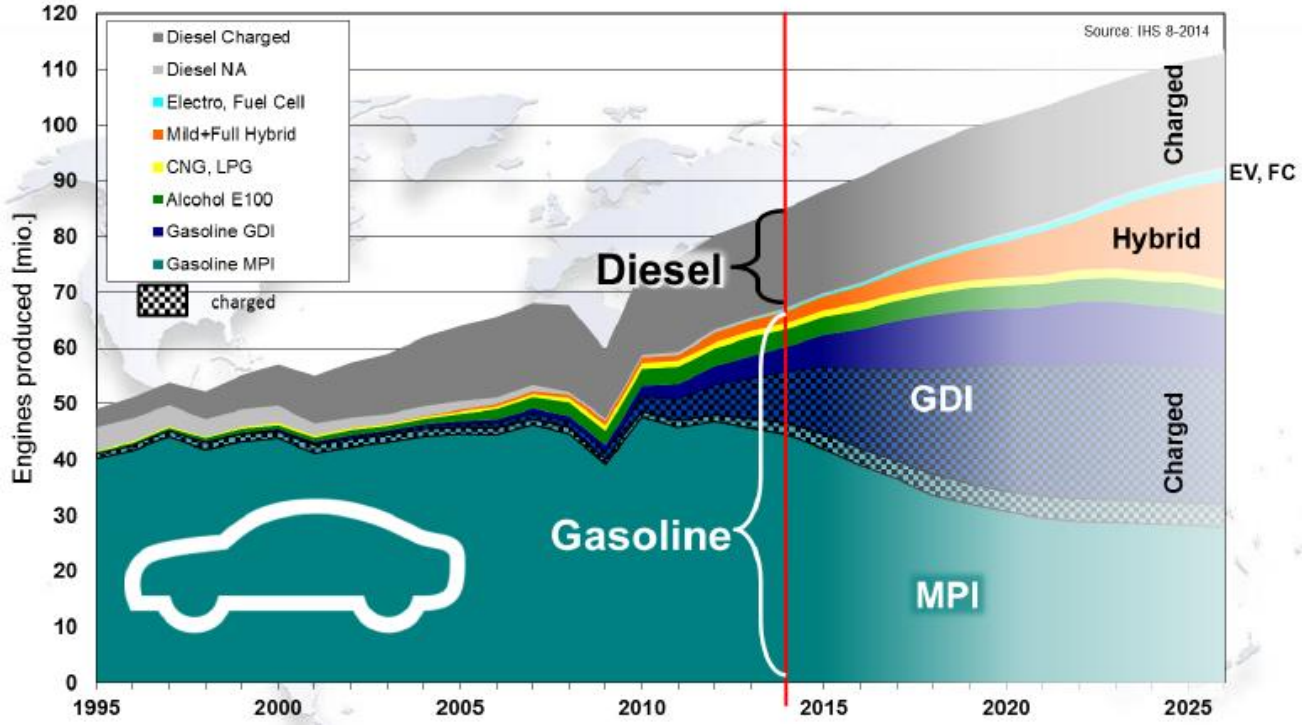
Engines

LD CO_2 reduction strategies are at various stages of development and effectiveness

	CO_2 Reduction	Emissions Issues	Status
GDI base, turbo, stoich	0	PN	Implemented
Stratified GDI	5-8%	PN	Implementing
Cylinder de-activation	5-8%	-	Implemented
Spark assist CI gasoline	5-10%	-	Research
Homogeneous Lean SI	5-10%	Lean NOx	Development
HEV (additive to others)	7-15%	-	Implemented
Downsize GDI, 18 →24 bar BMEP high CR, Miller stoic	10-15%	PN	Implementing
d- and c-EGR	10-15%	Cold start, controls	Implementing
CR~17, S/B~1.5, c-EGR, 2-stage boost,stoich, Miller.	15-20%	-	Adv Eng
Lean-burn GDI	10-20%	Lean NOx, PN	Implementing
Light-duty diesel	15-20%	Lean NOx	Implemented
GDCI	15-25%	Lean NOx, LT HC	Adv Eng
2-stroke opposed piston diesel	25-35%	Lean NOx	Development

Projections to 2025 show very small EV penetration, slightly growing diesel, and moderate growth in gasoline and HEV, with large growth in GDI.





Denso

AVL

HKIPC, 10/14

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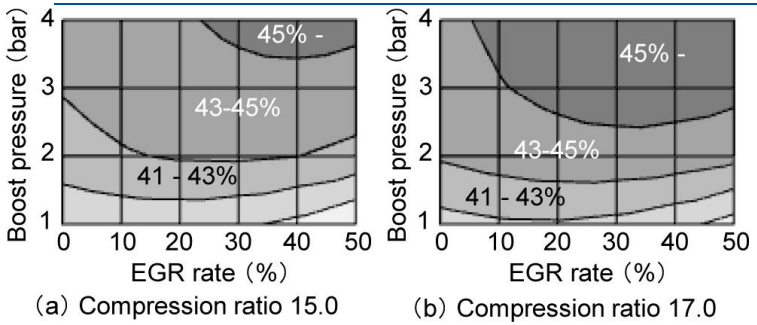
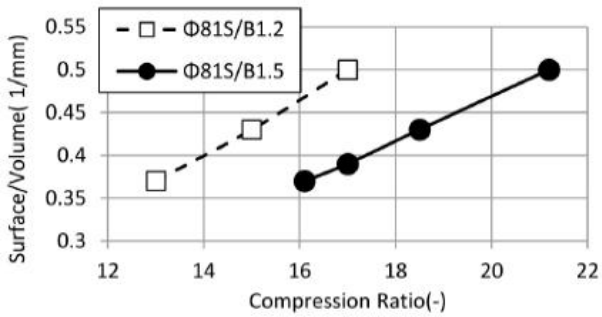
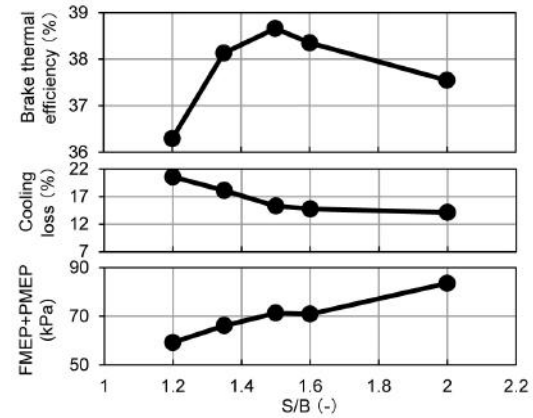
45% BTE on ~2.5 liter stoich gasoline engine. CR~17, S/B=1.5, MPI and DI, late IVC, 30% EGR, two-stage boost, strong ignition.



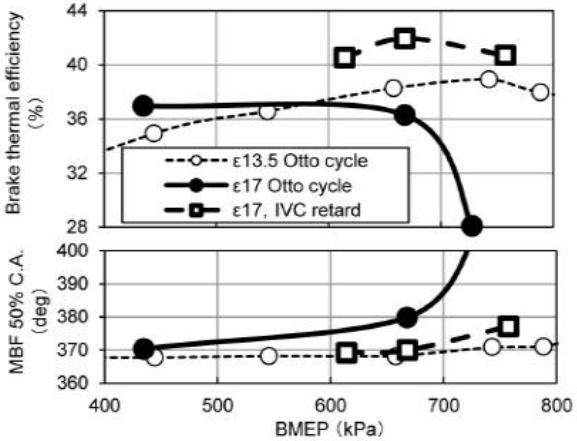
Model results. 45% BTE is possible at CR~17, 2.5 bar boost, and 30% EGR. Minimum-advance for Best Torque (MBT) used; 2000 RPM



S/B=1.5 gives CR=17 at same S/V ratio

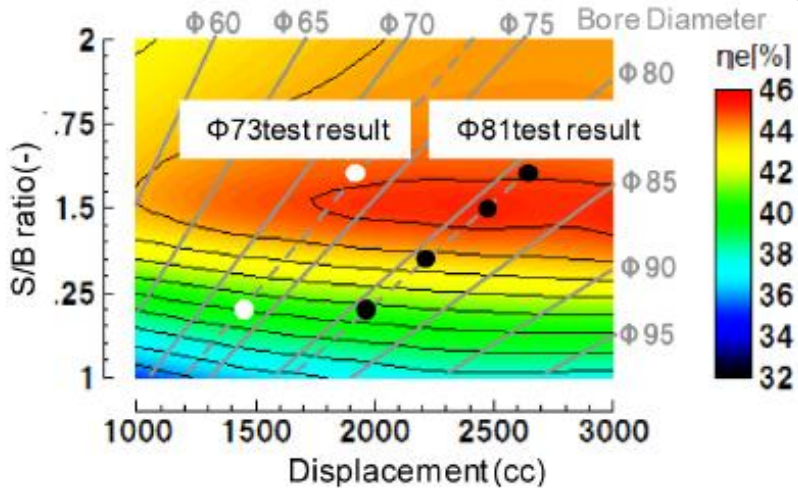


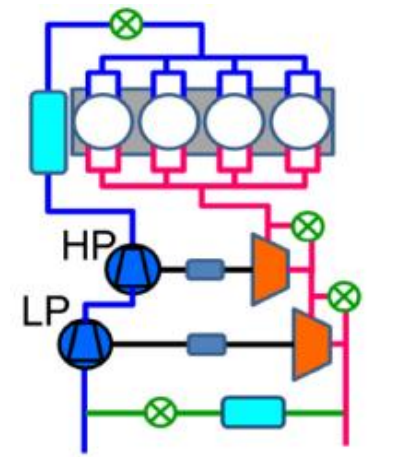
S/B=1.5 balances pumping and friction loss at CR=13.5. 2000 rpm, IMEP=720 kPa, MBT



Late IVC gives effective CR=12.5 with similar phasing as current engines but maintaining CR=17 expansion. 20% EGR, 2000 RPM

Multi-cylinder results





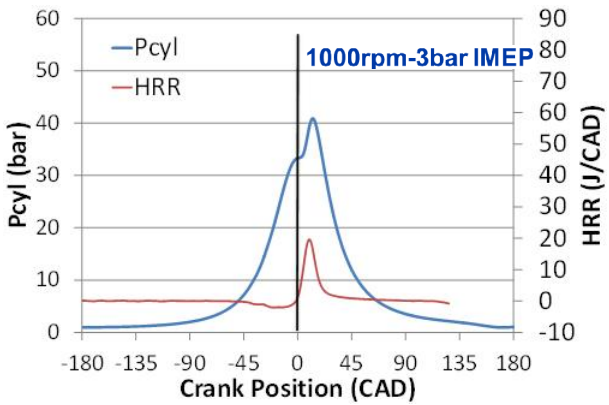
Combined boosting system

Honda, SAE 2015-01-1263

Gasoline Direct-Injection Compression Ignition (GDCI) is moving forward. MCE tests: Calibration, emissions, efficiency.

- Gasoline Partially Premixed CI
- Fuel Injection
  - Central Mounted
  - Multiple-Late Injection
  - GDi-like injection pressures
- Valvetrain – cont.-var. mechanical (exhaust rebreathing)
- Adv EMS – Cyl Pres Based Cntrl
- No classic SI Knock or Preignition
- Down-sized, down-speeded, & boosted
- High CR, Lean, Unthrottled

Engine Type	4-valve Comp. Ignition
Fuel	RON 91 E10
Displacement	1.8 L
Bore × Stroke	82 × 85.2 mm
Comp. Ratio	~ 15
Piston	GDCI Texan
Cyl Pres Rating	200 bar
Injection	Multi-hole GDI Central Mount
DOHC Type II Valvetrain	Intake & Exhaust Cont.-Var Mechanical
Swirl & Squish	Minimal Mixture Motion
Boost	2-Stage (Super & Turbo)
EGR	Low-Pres-Loop w/Cooler

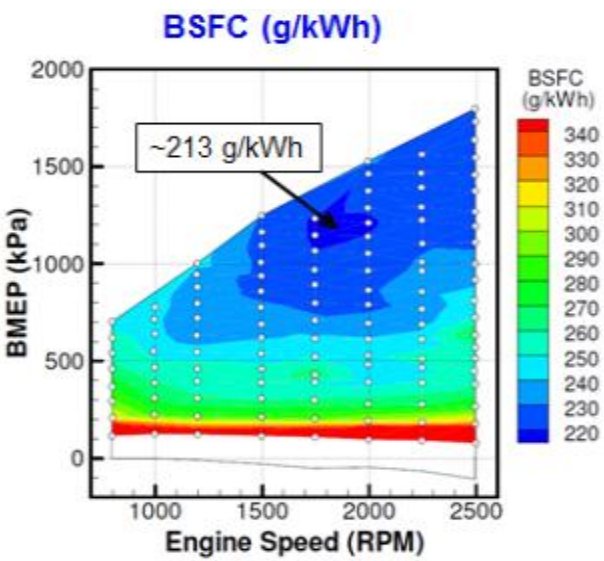


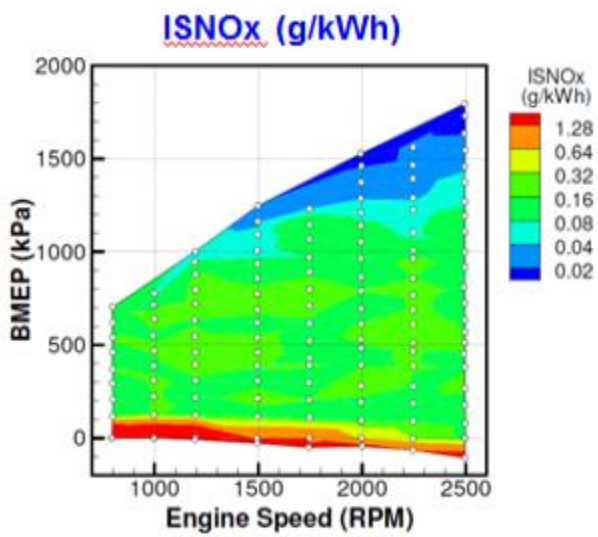
Start-of-Combustion at TDC for full expansion

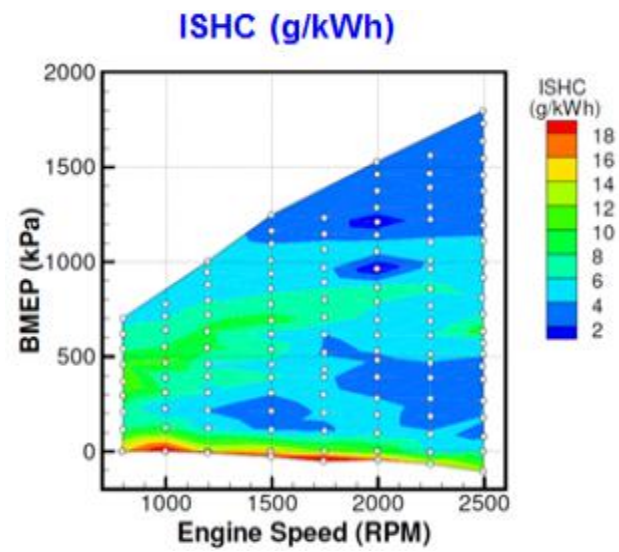
Short burn duration with low comb. noise

Low PMEP – rebreathing during intake stroke

Stable, low-temperature combustion with good T_{exh}







- FSN <0.05 typical
- NOx decr w/ load; 0.03 g/kWh full load
- 30% HCs aldehydes and ketones
- CO <20g/kWh

- Comb eff. 94-98% (96-97% typ)
- CoV IMEP 1-3%
- Low load Temp >230C
- High load Temp <700 C

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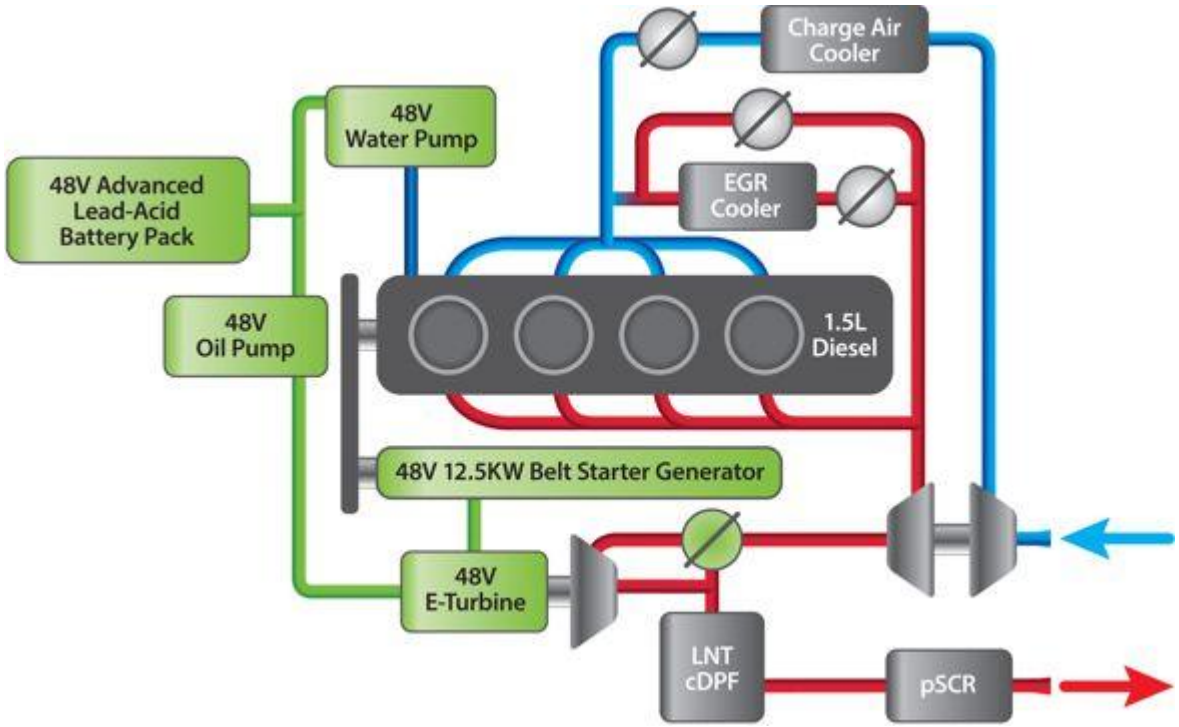
48 v stop-start diesel with turbo energy recovery targeting 70 g/km on a Ford Focus platform. Full HEV performance for lower cost.



Ricardo CTI 9/14

- Ford Focus Estate
- 48V electrical architecture
- SpeedStart 10kW (later to be upgraded to 12.5kW) belt integrated starter generator
- TIGERS turbine integrated exhaust gas energy recovery system
- Advanced lead carbon battery pack
- 12V-48V DC-DC converter and a Ricardo hybrid supervisory controller
- Targeting less than 70 g/km CO2 emissions as measured over the European Drive Cycle
- Planned completion of early 2016,

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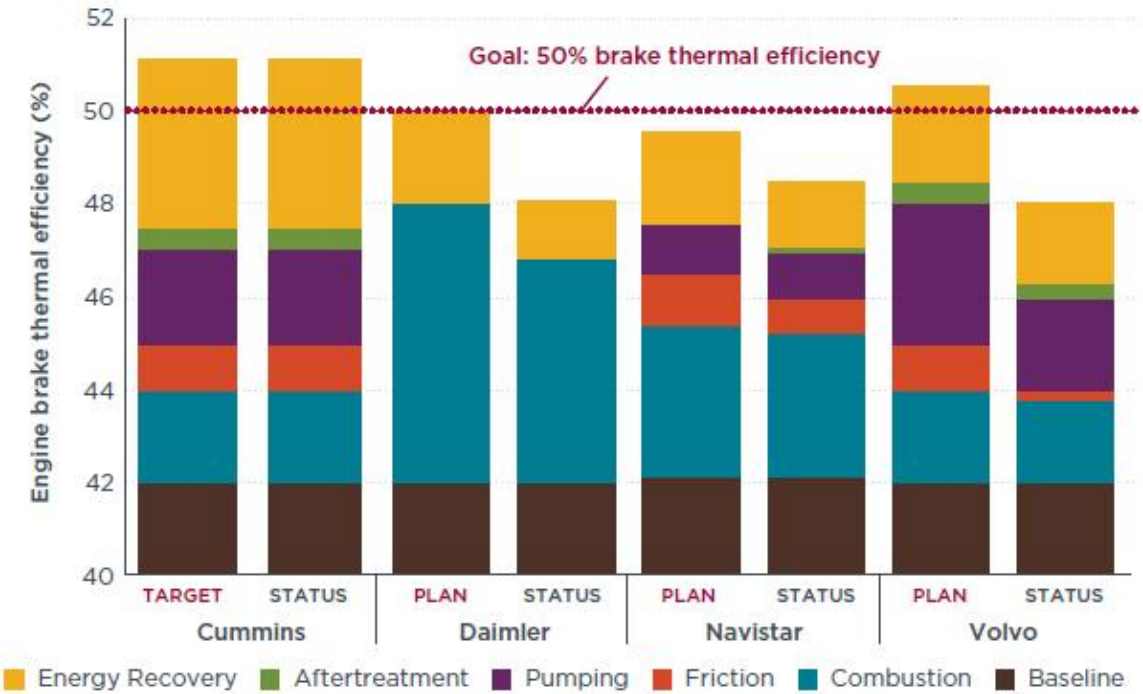
DOE SuperTruck engine approaches and results are summarized.



Strategy	Cummins	Daimler	Navistar	Volvo
Engine downsizing	No	Yes	No	Yes
Engine downspeeding	Yes	Yes	No	Yes
Transmission	Automated manual	Automated manual	Dual-mode hybrid	Dual-clutch automated manual
Hybridization*	No	Mild	Full (series/ parallel)	No
Organic Rankine cycle	Yes (mechanical)	Yes (electric)	No	Yes
Turbocompounding	No	No	Yes (electric)	Yes (mechanical)

* Hybridization can be described in terms of a "mild" or "full" relative power rating of the electric motor with respect to the internal combustion engine.

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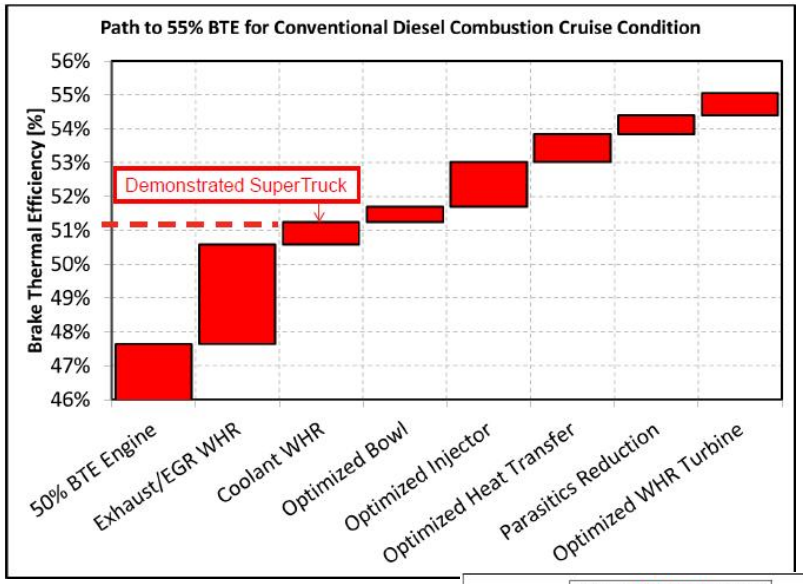
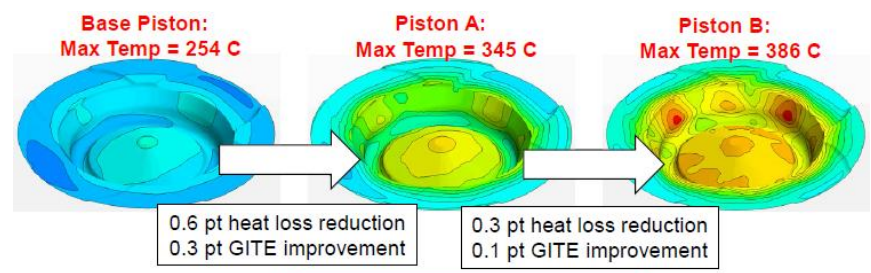
Pathways to 55% peak BTE proposed. Optimized WHR, injectors, bowl design, friction and parasitics, reduced heat loss. GPS engine control.

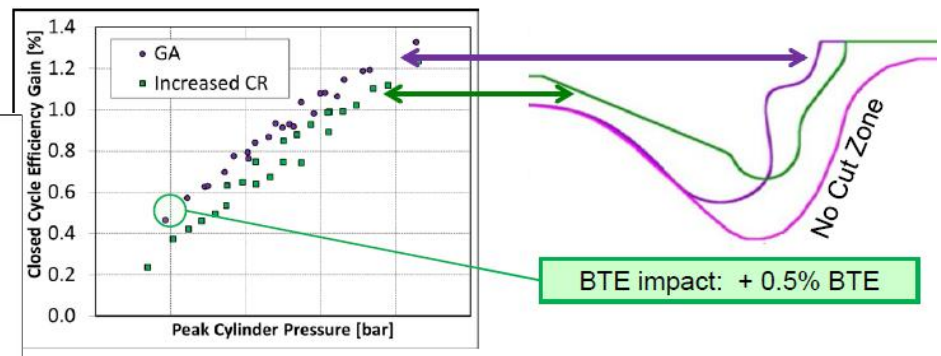


55% BTE technologies

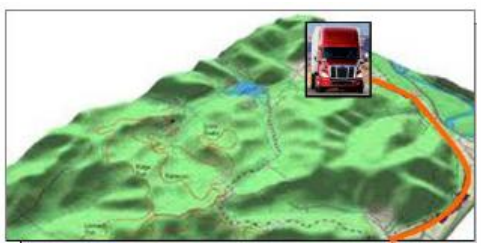


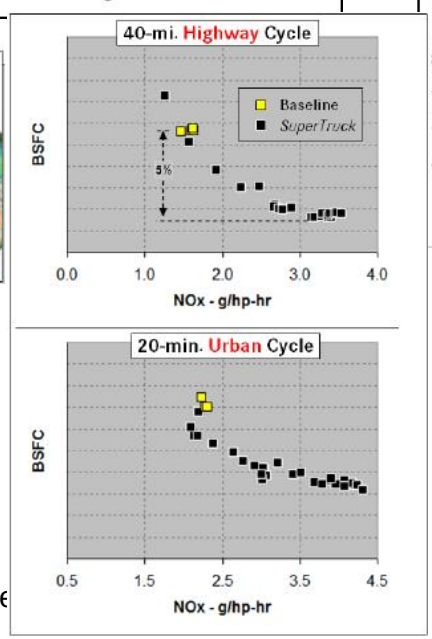
BTE impact: + 0.8% BTE

Cummins DOE AMR 6/14



BTE impact: + 0.5% BTE





Predictive controls using GPS enables a highway vs. urban calibration.

DDC, DOE Peer Review May 2012

- Friction and Parasitic reduction
  - Piston/ring pack/liner changes
  - Piston cooling flow reduction
  - Main & rod bearing

BTE impact: + 0.6% BTE

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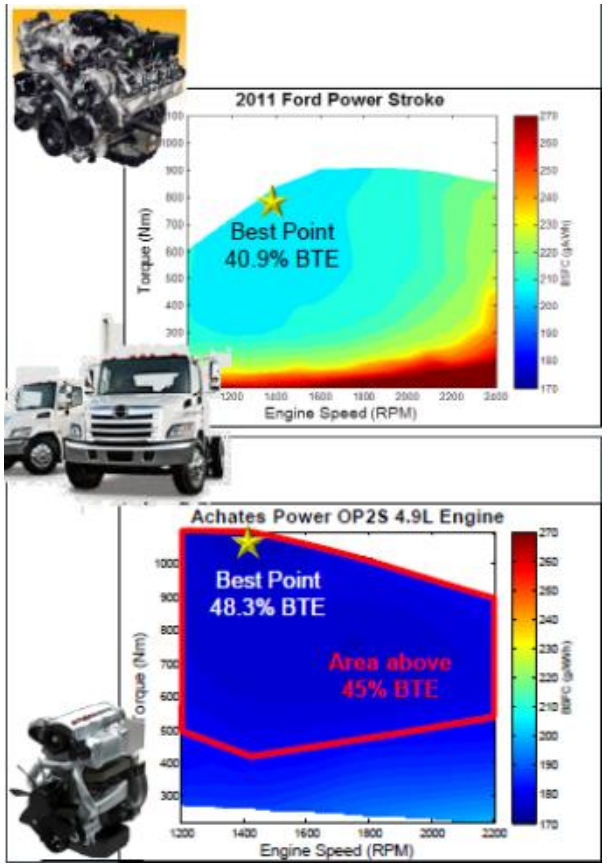
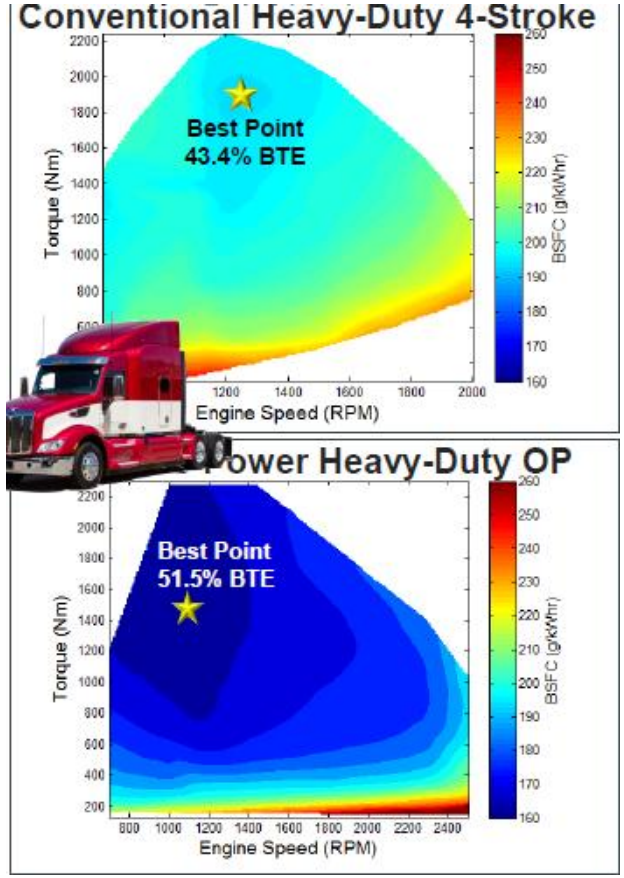
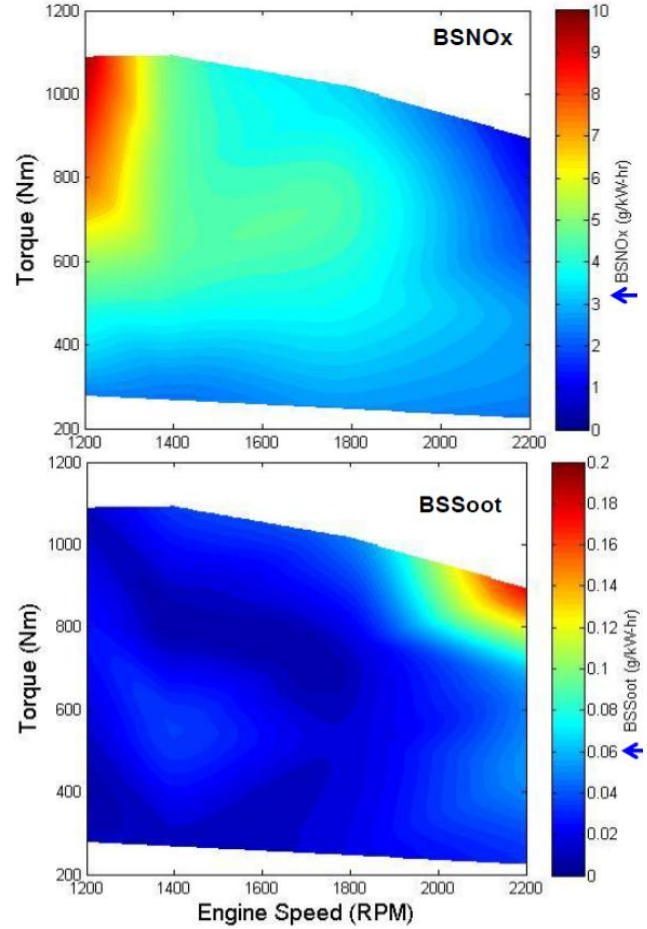
The multi-cylinder 2-stroke opposed piston 4.9 liter MD engine is evaluated. Projections are met. 24% lower FC vs commercial engine. Emissions seem addressable.



24% cycle-average FC than conventional 4-stroke MD diesel engine.



Projections into the HD engine show >50% BTE without VVT, high PCP, WHR, low-friction package, etc.



Near the sweet spot NOx/soot>100. DPF issues at high speed and load.

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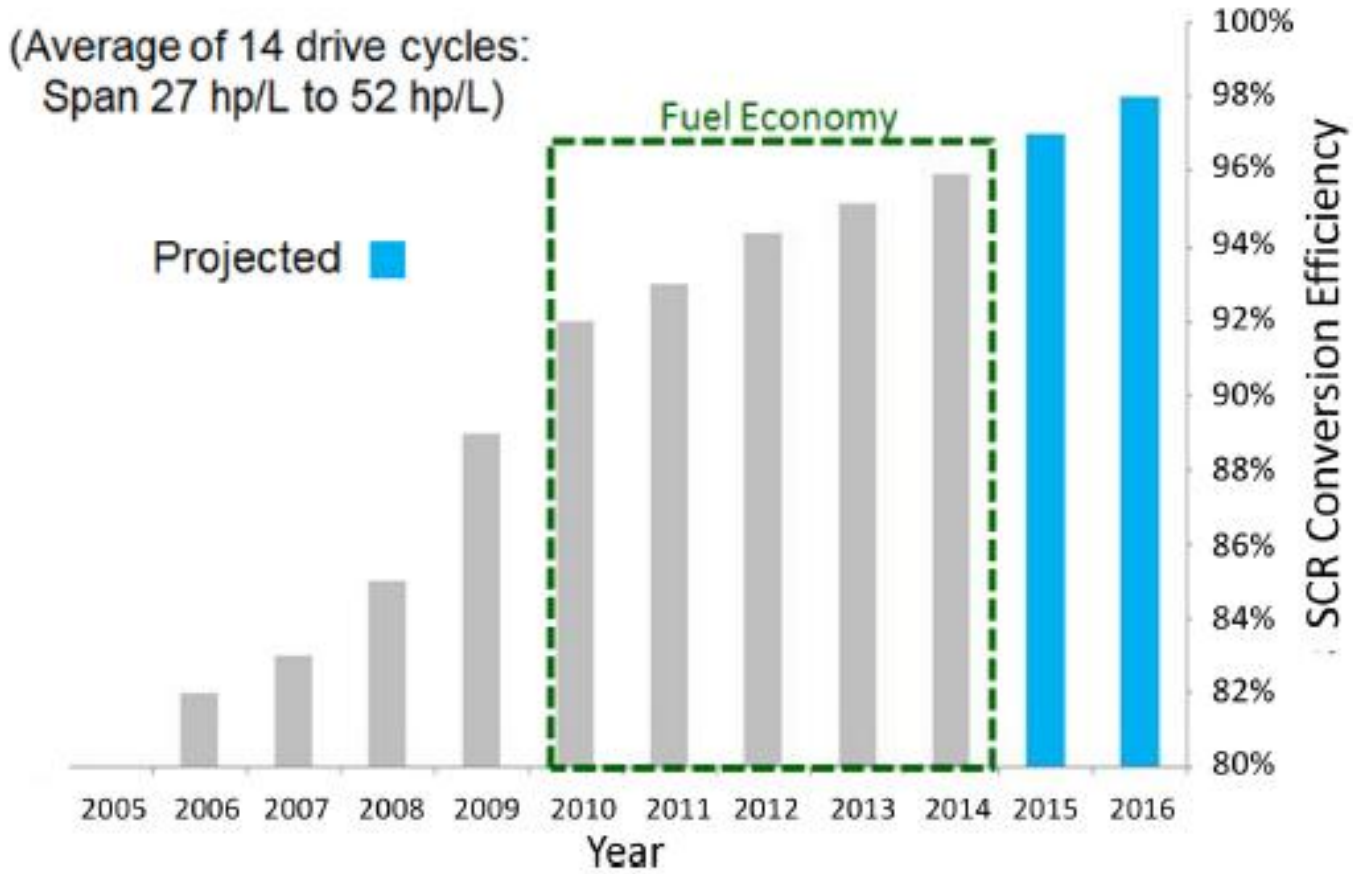
Emissions Reductions

Cycle-averaged SCR system deNOx efficiency has improved from 94% in 2012 to 96% today, and is projected to reach 98% in 2016.



Cummins SAE 2013-01-2421

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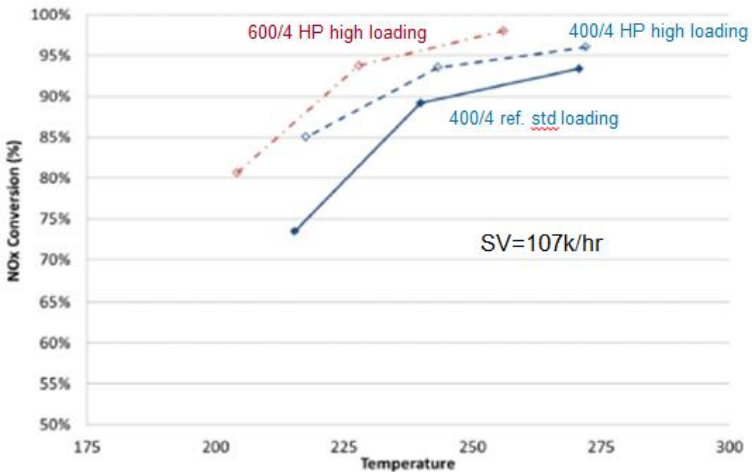
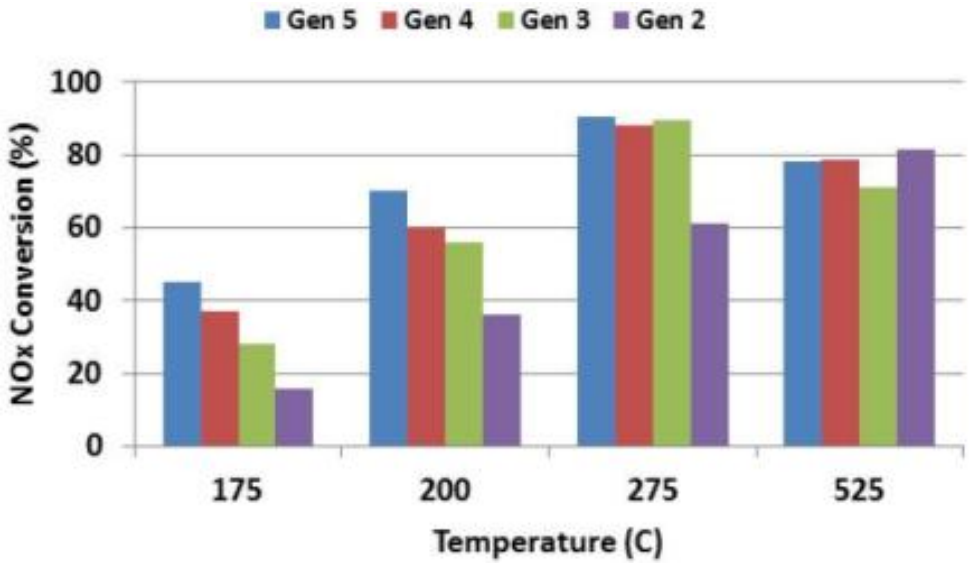
SCR deNOx technology is continuing to advance. Better performance over all temperature ranges.

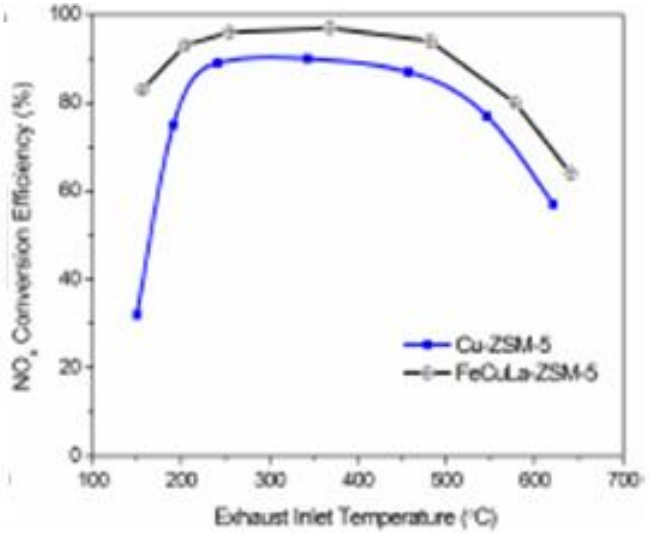


High Cu-Z catalyst loadings help NOx conversion at LT. High csi helps HT. Engine results. JM SAE 2014-01-1521



Cu-zeolite catalysts have improved markedly. Recent emphasis has been on LT performance and thermal durability.

JM, SAE HDDE Symp. 9-12

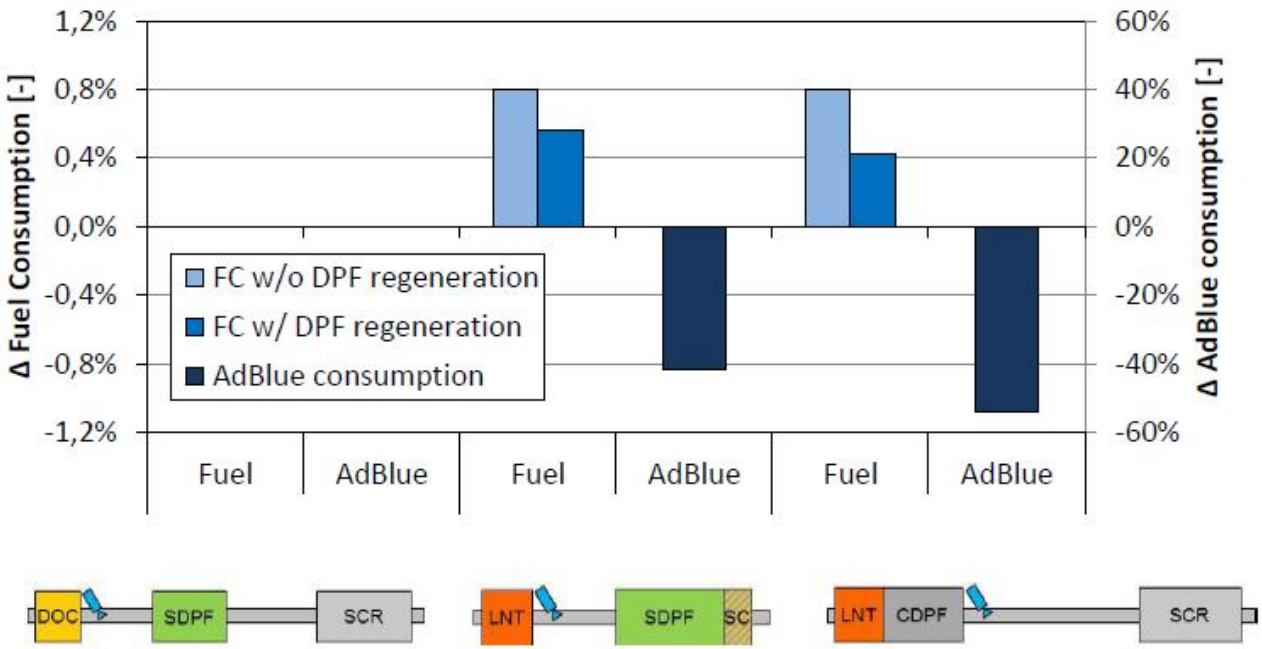


New multi-metal zeolite SCR formulations are being investigated. CuSc2 and CuFeLa show promise, among others

ORNL, DEER Conf poster, 9/10

s

LNT+SDPF systems are evaluated. Urea SCR NOx less sensitive to drive cycle. LNT adds up to 0.8% FC, but drops urea 40%.



Compared to DOC+SCR, LNT adds 0.4-0.8% FC but drops AdBlue by 40-55%. Diff in urea consumption for #2 vs. #3 is due to LPL EGR coming after the SCR in case #2.

Watchouts:

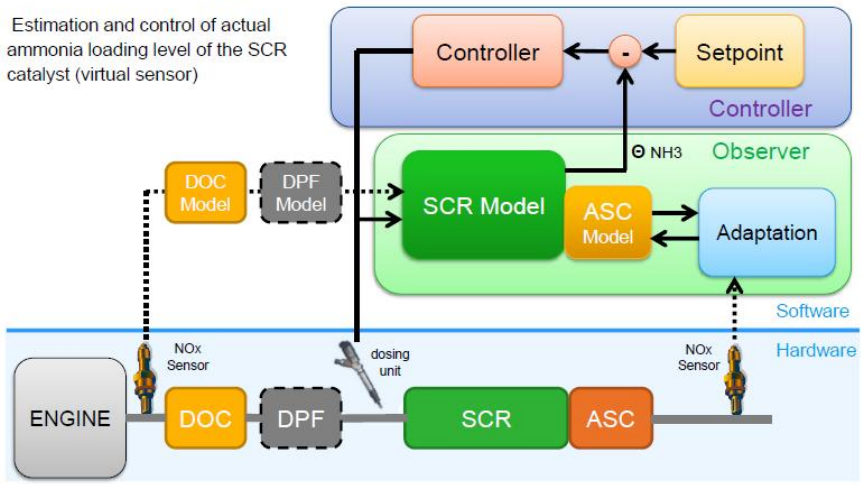
- HP DPFs can have NEDC PN emissions: 450E11/km at 0 g/l soot, 0.17E11 at 0.8 g/l, 0.04E11 at 2 g/l
- LNT can have high N_2O; ~50-60% from rich regen

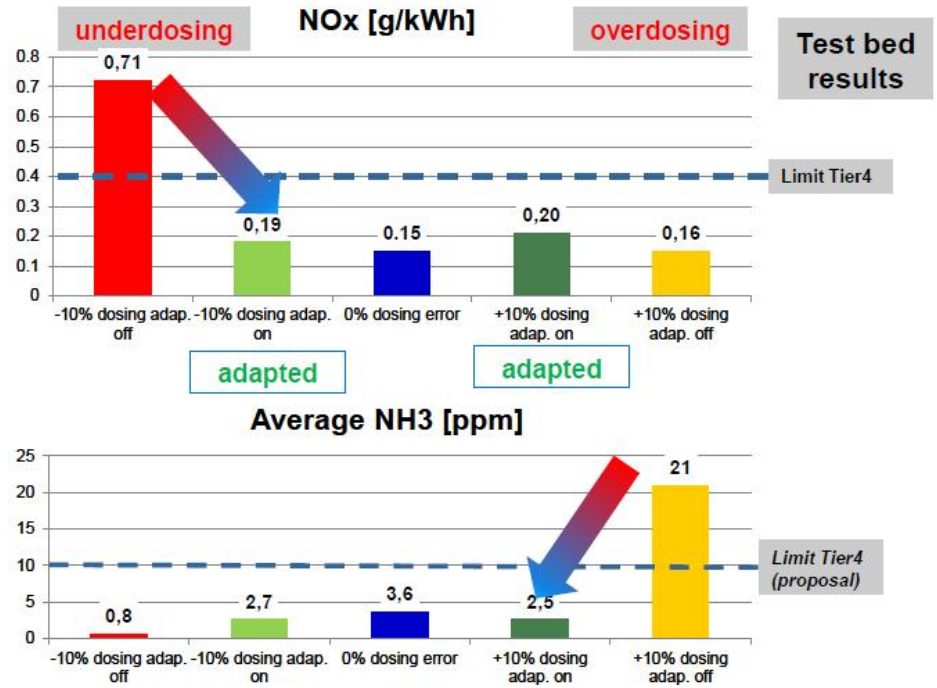
© Corning Incorporated

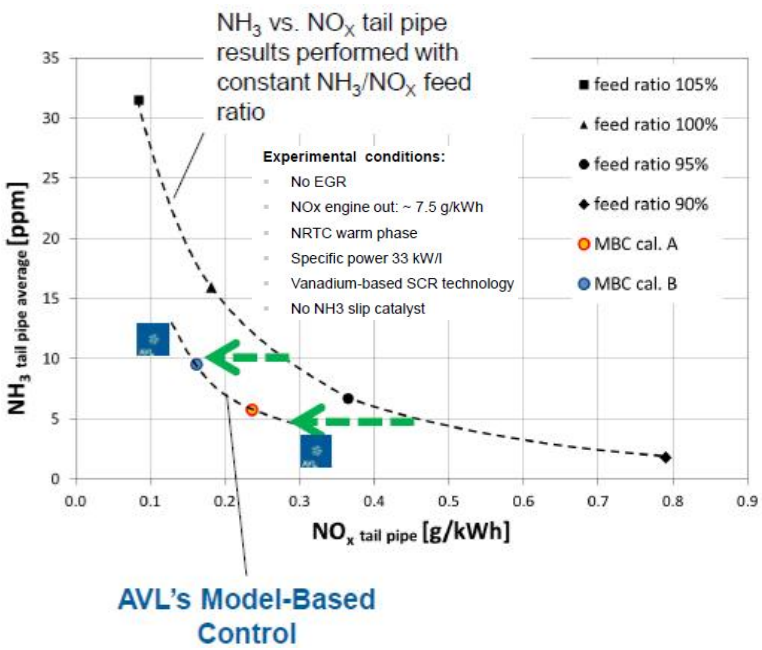
Attributes of model-based control are outlined.

Precise control, reduced time, virtual sensors, off-line calibration, HIL

- Observer - based control approach
- Estimation and control of actual ammonia loading level of the SCR catalyst (virtual sensor)

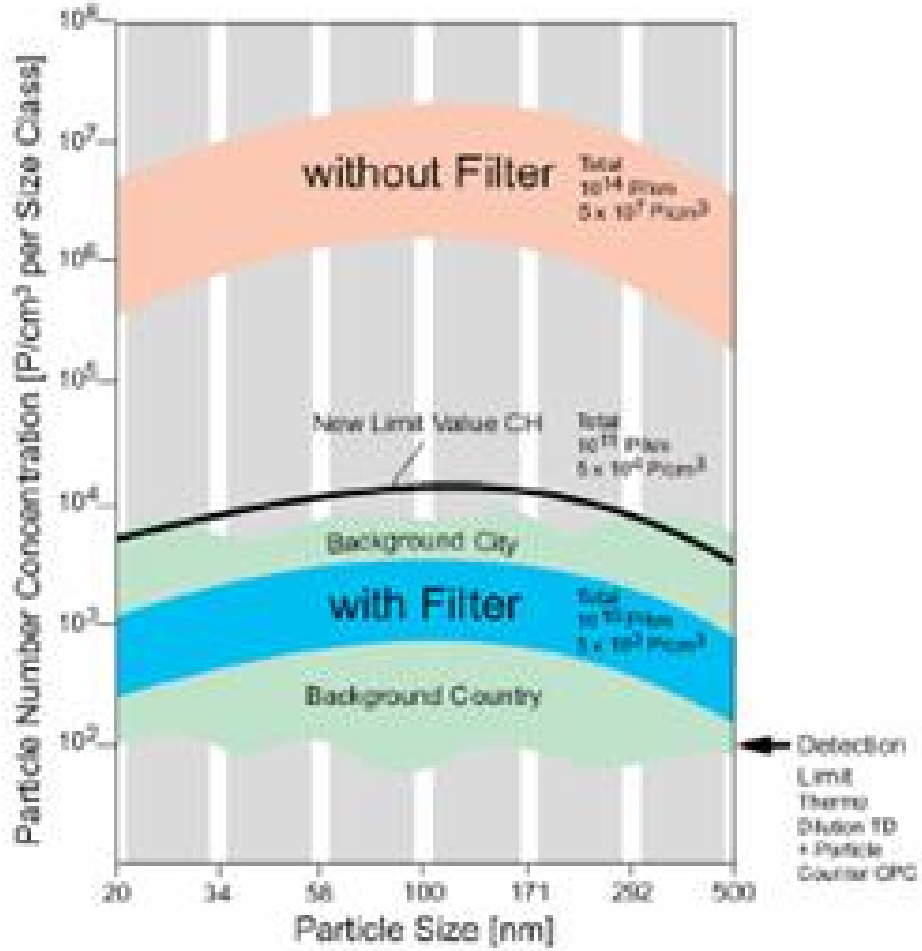






1. Precise control of AdBlue dosing with SCR catalyst NH3 loading control
   - •High NOx conversion without overdosing
   - •Reduced AdBlue consumption
   - •Reduced NH3 slip after SCR
   - ASC volume can be reduced
- 2. Reduced application & variant specific calibration effort
- 3. Virtual sensors inside the catalyst available (T, NH3 loading, gas concentrations)
- •Supports development & calibration work
- 4. Same EAT models can be used for off-line calibration
- •Reduces needed test bed time
- 5. Same catalyst models can be used in HIL simulators
- •Supports software testing

Europe is implemented a particle number standard (particles/km). Filtered tailpipe emissions are lower than city ambient levels (vehicle is vacuum cleaner”)



Particle number limit value

Number

Health related emission limit

for diesel cars

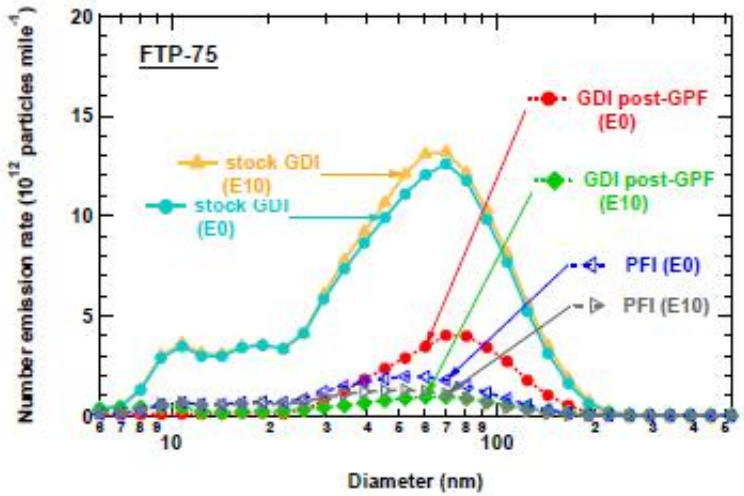
(total particles 20-500 nm)

Without filter	**10^{14} P/km**
With filter	**< 10^{10} P/km**
Detection limit	**10^{8} P/km**
New emission limit	**6 X 10^{11} P/km**

Buwal, ETH Ultrafine Conf. 8/2005

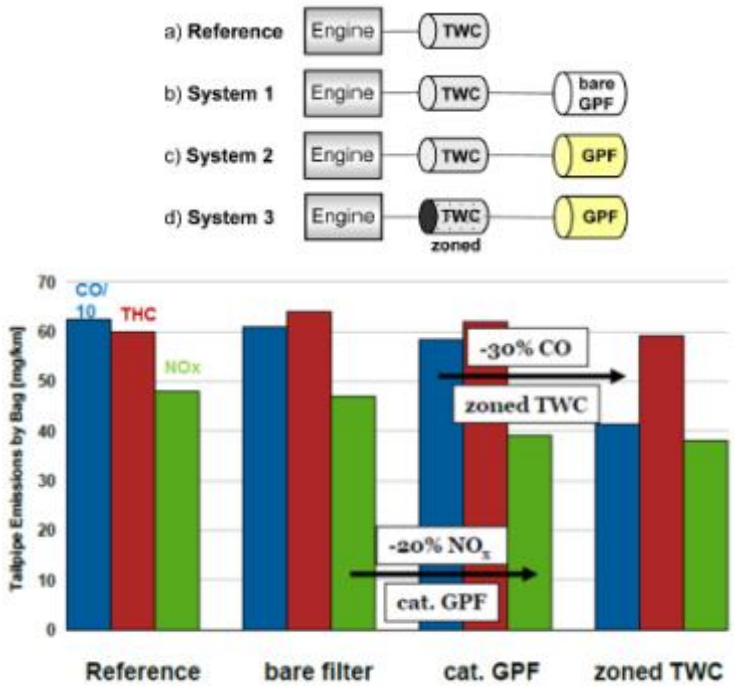
© Corning Incorporated

GPFs are progressing. High PN removal efficiency, synergies with TWC, and passive regeneration on coated filters.



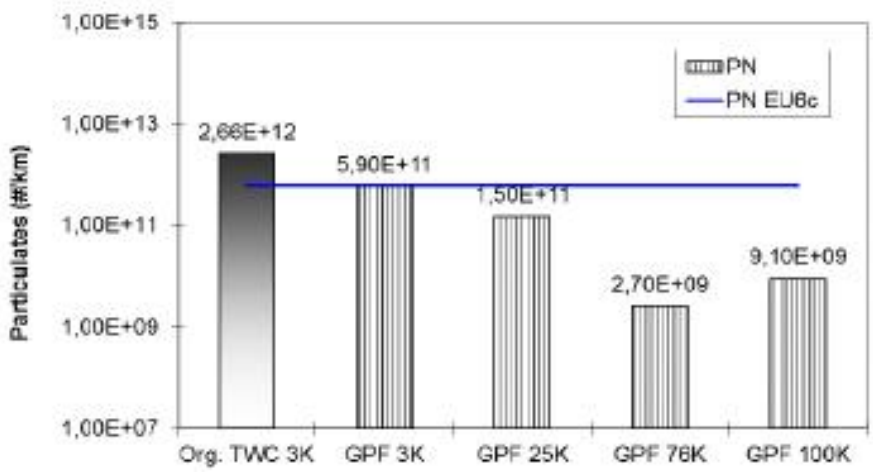
GDI and PFI solid PN size distributions for E0 and E10 on the FTP-75. 75-85% PN removal

Environ Canada, SAE 2012-01-1727



Moving TWC from flow-through to GPF drops NOx 20% on NEDC . Zone coating on TWC drops CO by 30%

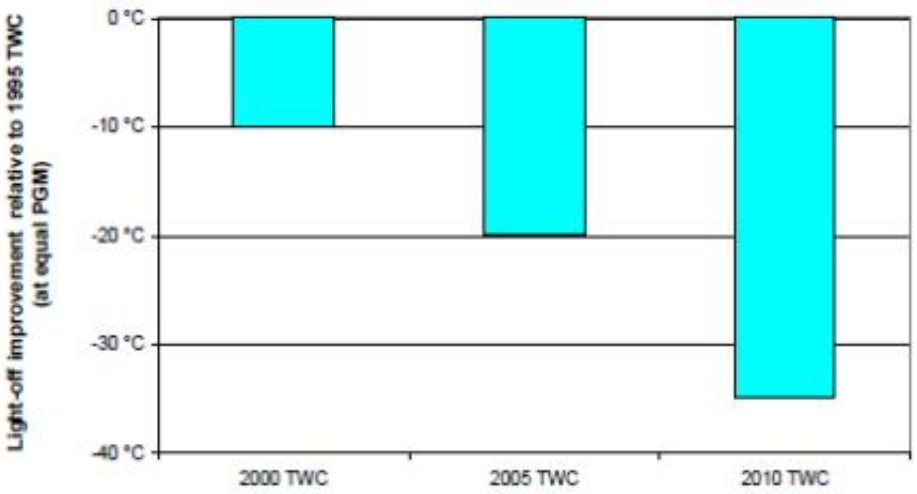
Umicore, SAE 2012-01-1244

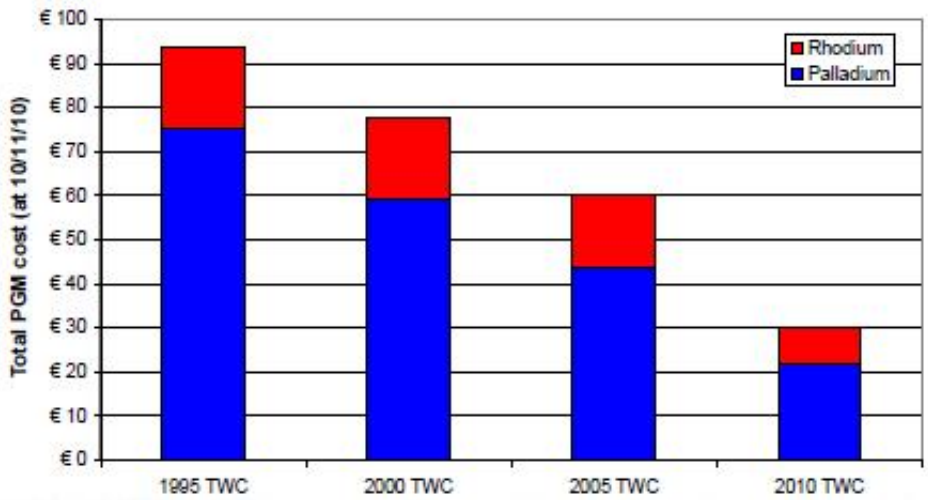


PN emissions drop with aging.

Umicore, SAE 2014-01-1513

The track record of TWC is impressive





Since 1995, regulated gasoline emissions have dropped 95%, light-off temperatures have dropped 35C, and PGM costs have dropped 70%.

JM, SAE Convergence Conf, 11/12

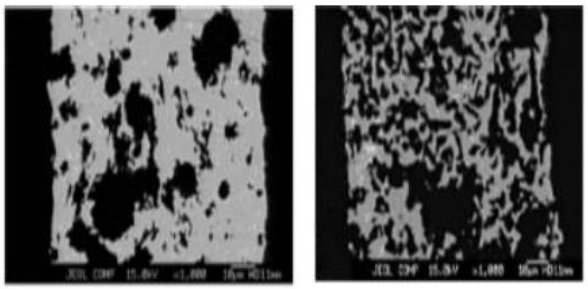
Similar SCR story:

- 2003: 75-80% efficiency; SVR=4:1
- 2012: 95-95% efficiency; SVR=2.5:1

© Corning Incorporated

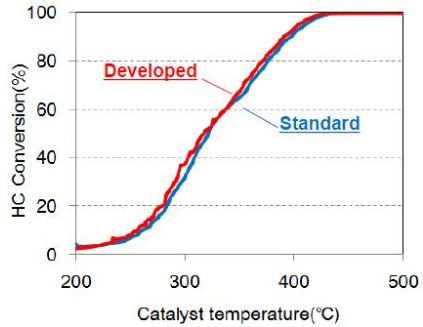
A new catalyst system was developed that drops cold start emissions 14-21% due to better thermal response.

Standard Developed

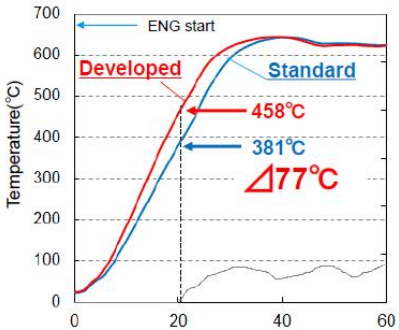


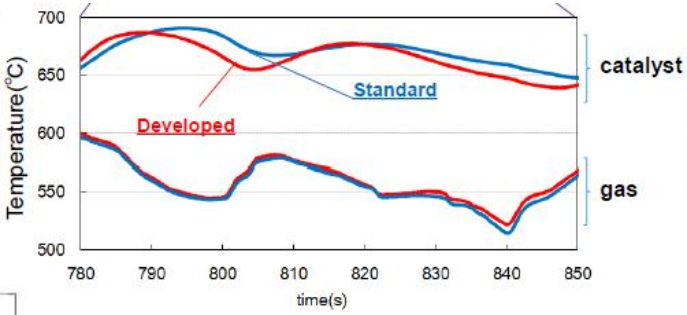
New substrate is 31% lighter with +20% porosity

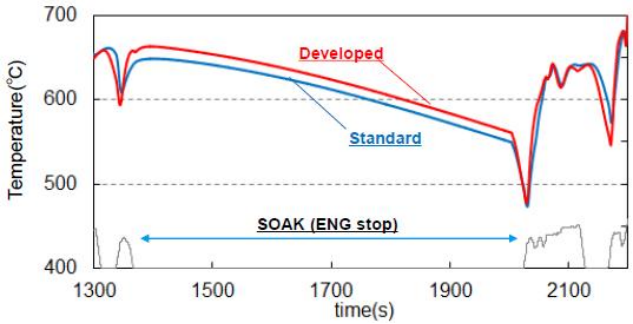
Honda, SAE 2015-01-1001

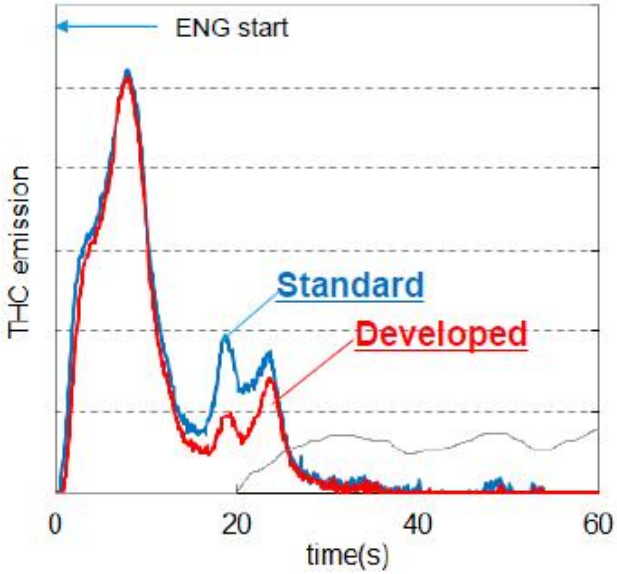


Although the light-off curves are the same, FTP thermal behavior of developed system is better.



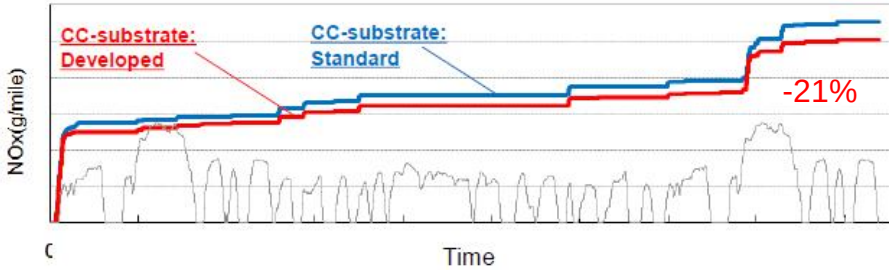


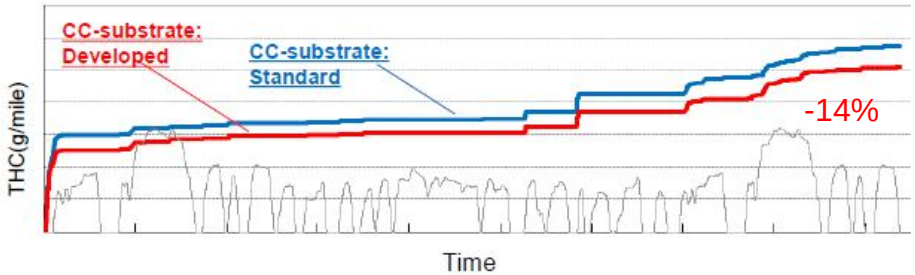




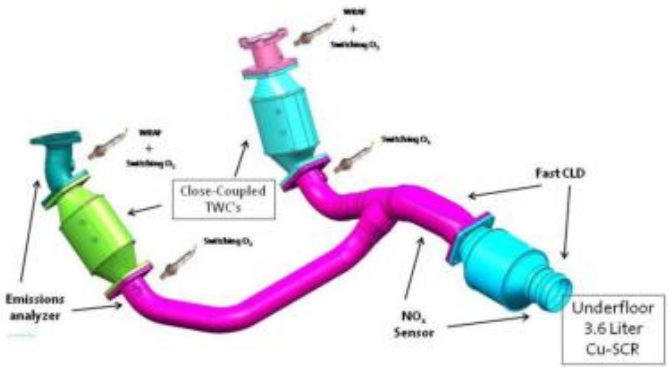
To simulate future colder exhaust, the first hill started earlier. The developed system dropped both NOx and HCs.

Cold start THC emissions are reduced

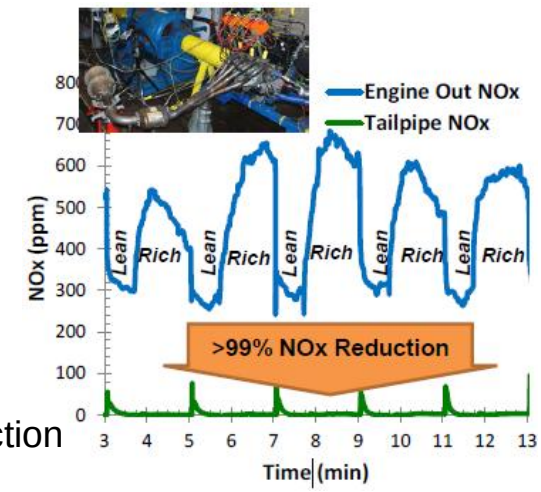


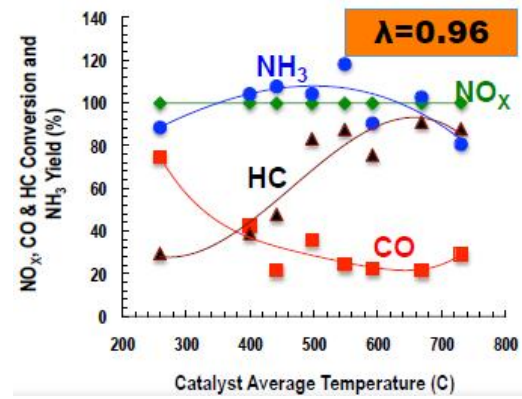


Lean-burn gasoline NOx work is now on an engine. Bench conditions duplicated. 99+% deNOx. Moving now into transient.

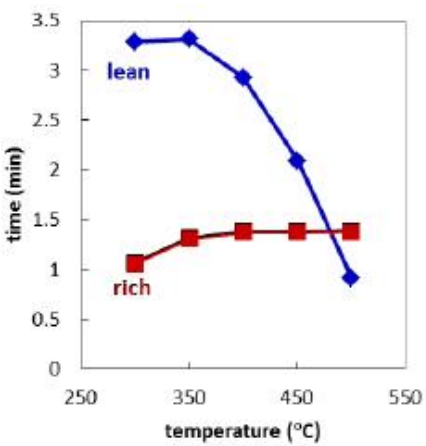


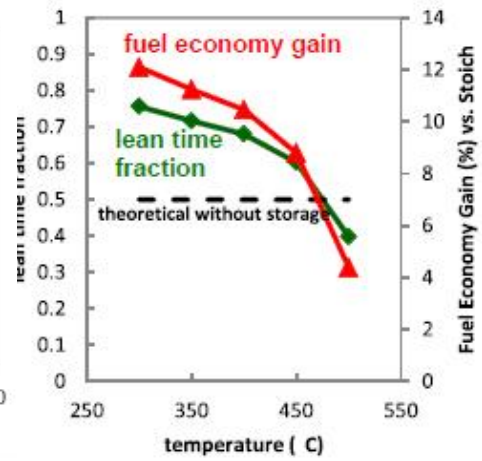
The TWC+SCR system is run in rich/lean oscillation to create NH3 for lean NOx reduction





λ=0.96 delivers good balance between NH_3 over wide range of operations, balancing FC.





Adding NOx storage material to the TWC increases lean time and decreases rich time. There is a delay in NH_3 production, however.

Transient test modeling shows 10.8% FE gain with lean modes. Stoich operation provides more ~30% more NOx, which might result in more NH_3 in transient testing.

ORNL DOE AMR 6/14

The route to a negative CO_2 ICE?

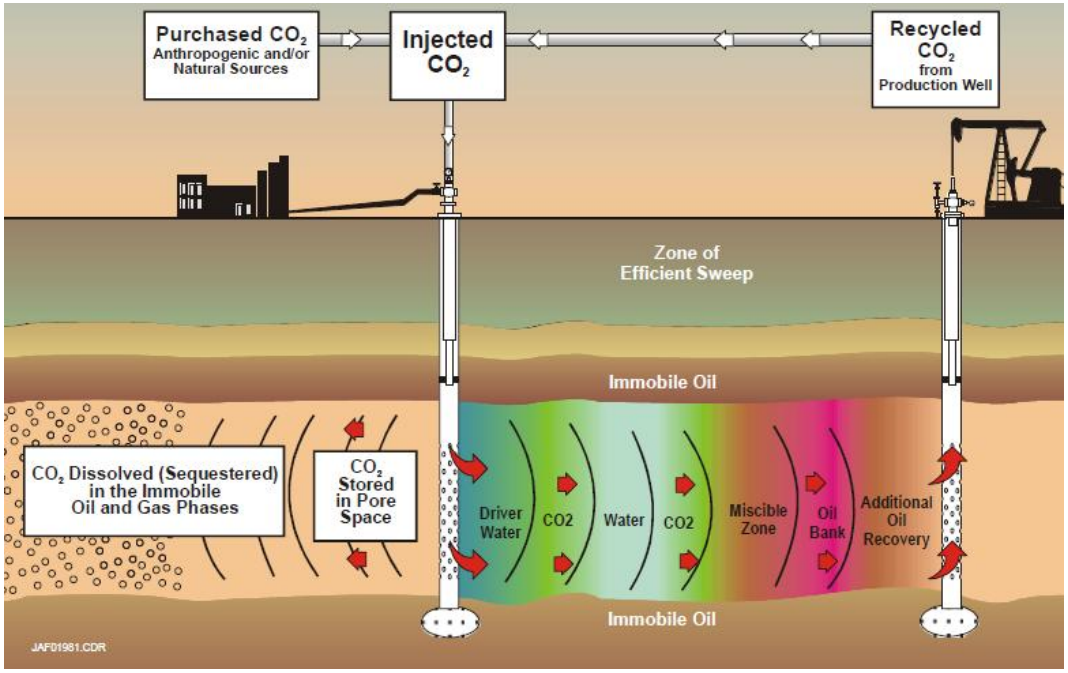
Soon to be demonstrated:

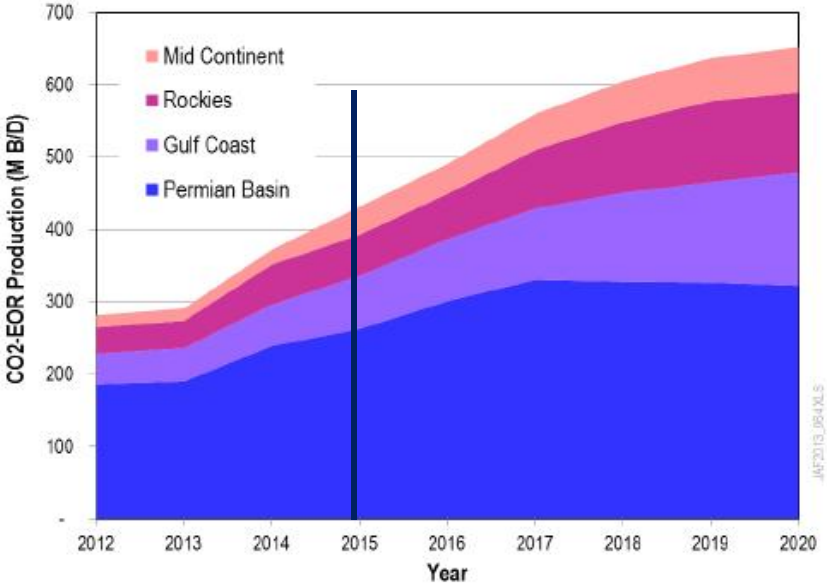
- 70-100% CO_2 reductions from in-use fleet

Technology is demonstrated in pieces and feasible. Now it's a matter of degree.

- New ICEs removes CO_2 from the air

Route to 70-100% carbon-free oil. It's happening, and it's big.





Method is producing 360Mb/d, going to 650Mb/d in 2020. source: ARI 2014

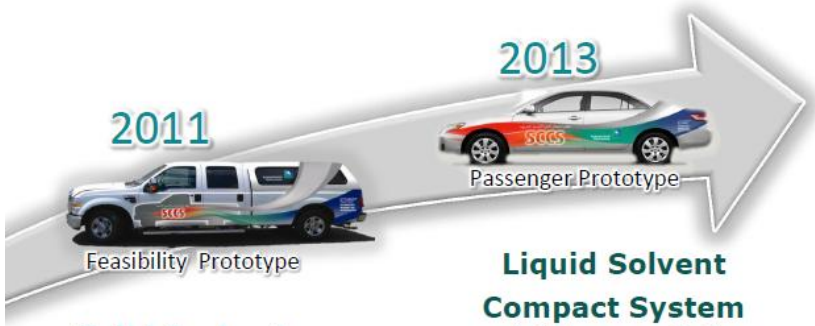
Region	Technical CO_2-EOR Oil Recovery (Billion Barrels)
1. Asia Pacific	47
2. C. & S. America	93
3. Europe	41
4. FSU	232
5. M. East/N. Africa	595
6. NA/Other	38
7. NA/U.S.	177
8. S. Africa/Antarctica	74
TOTAL	1,297

Production of 1.3T barrels of oil is technically possible. ~35 yrs of coal CO_2 emissions storage capacity. ARI 2014

"The oil produced with injection of captured CO_2 emissions is **70% "carbon-free"**. …The oil produced by EOR could be 100+% "carbon free"."

DOE, Energy Procedia (2009)

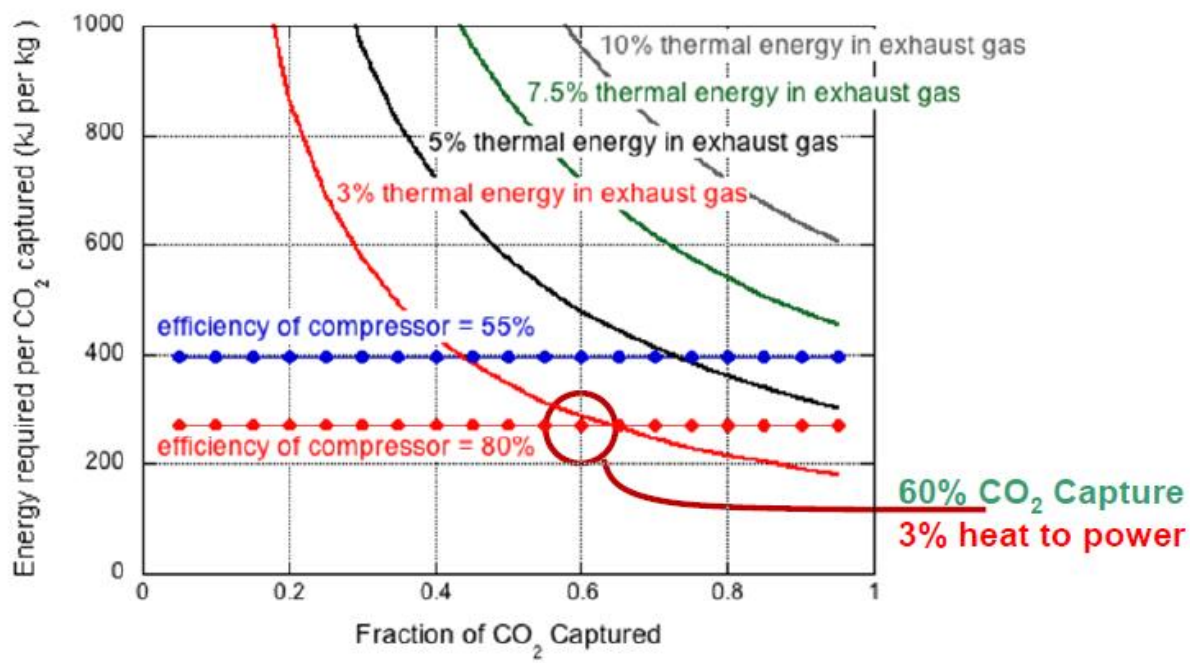
Going from 70-100% CO_2 reductions to negative: On-vehicle carbon capture has been demonstrated. 20-30% net capture. project ~3% fuel penalty for 60% capture



Solid Sorbent
High Regeneration T
(Heat from Exhaust Gas)
Road Driving Tests
10% CO2 Avoidance

Liquid Solvent
Compact System
(~8 times smaller)
Low Regeneration T
(Heat from Hot Coolant)
Drive Cycle Tests
20-30 % CO_2 Avoidance

Available Energy for CO_2 Compression, Thermal Electrics



Aramco, Emission 2014 6/14

Summary

Back Drop

- Criteria pollutant and GHG standards continue to tighten
- Significant measures are needed to hit 80% GHG reductions by 2050
- EVs are center stage for achieving goals, but not exclusively
- Connected vehicles will add value to the auto industry, drop emissions and congestion, and bridge an inevitable cost / consumer value gap

Engine technologies developing for significant fuel reductions

- LD potential CO2 reductions up to 30% reductions from best LD engine today.
- -10% for HD

Emission control technology is delivering clean vehicles

- NOx control is achieving 98% reductions
- PM is or can be essentially eliminated from vehicles
- TWC is impressive and still evolving

Possible: 70-100% carbon-free petroleum and negative CO2 vehicles