Summary

- Diesel exhaust is a proven carcinogen, requiring maximum control in high-exposure environments.
  - Very fine particles are emerging as the main impact. ~90% of PM2.5 toxicity resides in the <0.1 µm fraction.
- New engine designs and strategies are making impressive gains
  - HD engines are close to 50% BTE with realistic technologies and very low emissions
    - Combustion, pumping, friction, WHR
    - Pathway to 55% BTE outlined
- NOx
  - LT NOx control, better catalysts, system integration
- PM control being optimized for diesel
  - SCRF advancing in LD
  - Fundamental ash behavior
- DOCs: Higher CO+HC a real challenge, and gap for DOCs

Criteria Pollutant Health Effects and Regulations

WHO has identified diesel exhaust as a proven human carcinogen.

- Diesel exhaust causes lung and bladder cancer.
- Low-sulfur fuel, diesel oxidation catalysts, diesel particulate filters, and clean combustion can reduce exposure.
- Earlier, California identified diesel PM as a carcinogen.

Diesel engine exhaust carcinogenic

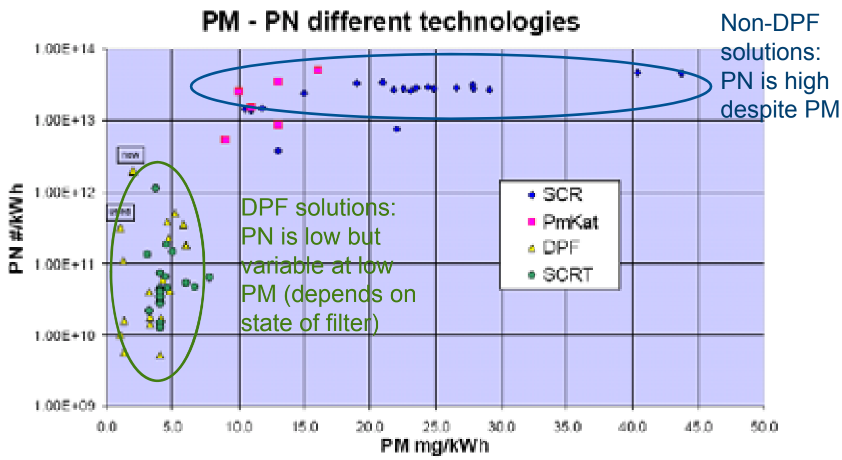
12 June 2012 -- After a week-long meeting of international experts, the International Agency for Research on Cancer (IARC), which is part of the World Health Organization, today classified diesel engine exhaust as carcinogenic to humans (Group 1), based on sufficient evidence that exposure is associated with an increased risk for lung cancer.

Read the press release from IARC on diesel engine exhaust

World Health Organization

Courtesy of ICCT

Low PM through Non-DPF technology does little to reduce PN



Daimler, SAE HD Emissions Symp, 9/14

The ultra-fine particle fraction has 8X more toxicity associated to it than the whole of PM2.5.

Put another way, 89% of the toxicity of PM2.5 resides in the UFP fraction.

Short term cardiovascular disease

Study	City, Year	CVD [%] per PN P/cm3	CVD - PNC 10'000 P/cm3	CVD - PM 2.5 per 10 µg/m3
Atkinson	London 2010	2.2/10199	2.2 %	0 - 0.5 %
Stolzel	Erfurt 2007	3.1/9748	3.2 %	0 - 1.5 %
Breitner	Beijing 2011	7.3 / 6250	11.7 %	NA
Branis	Prag 2010	1.1/1000	11 %	0 - 0.4
Forastiere	Rom 2006	7.6/27790	2.7 %	0.1-3.1 %
Kettunen	Helsinki 2012	8.5/4979	17 %	2.1 - 23 %
Average			7.9 %	3.1 %

CVD increases 7.9% per increase in UFP of 10,000/cm^3

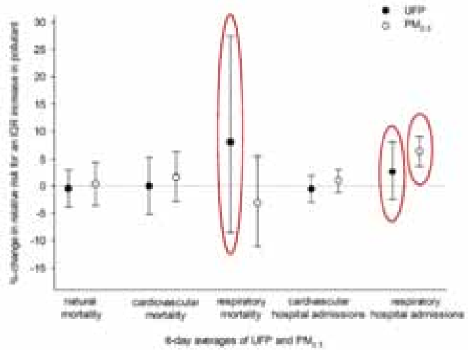
Study	City, Year	CVD - PNC 10'000 P/cm3	converted to 10 µg/m3	CVD - PM 2.5 per 10 µg/m3
Atkinson	London 2010	2.2 %	6.8 %	0 - 0.5 %
Stolzel	Erfurt 2007	3.2 %	9.9 %	0 - 1.5 %
Breitner	Beijing 2011	11.7 %	36.5 %	NA
Branis	Prag 2010	11 %	34.1 %	0 - 0.4
Forastiere	Rom, 2006	2.7 %	8.4 %	0.1-3.1 %
Kettunen	Helsinki 2012	17 %	52.7 %	2.1 - 23 %
Average		7.9 %	24.7 %	3.1 %

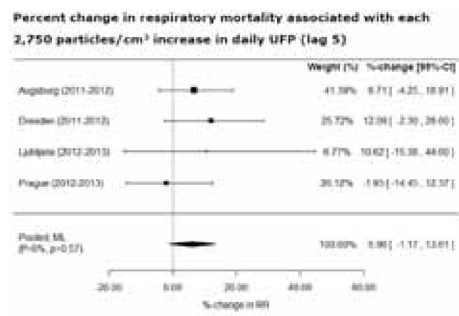
Assumption: Particles 70 nm, Density 1, mass [illegible] / 10'000 P/cm3 = 3.2 µg/m3

When UFP is converted to mass, its specific CVD increases 24.7% per 10 µg/m^3 increase in PM. This is ~8X higher than the mortality due to PM2.5.

UFPC Brussels, 2013
Katsuyanni, ETH 6-12

New data suggests the ultra-fine particle (UFP) fraction of PM2.5 contributes most of the respiratory health hazard.





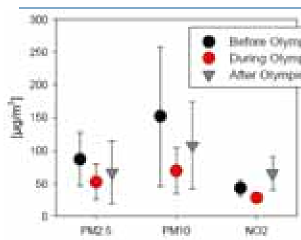
To convert PN (#/cm^3) to PM (µg/m^3) in this case, use 10X multiplier. The PN fraction is much more toxic than the PM.

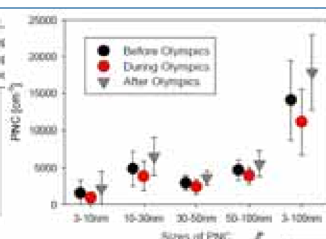
The "IQR" for UFP is 2606/cm^3; for PM it is 12 µg/m^3. The UPF multiplier to the equivalent PM IQR is ~10X, so respiratory disease risk due to the UFP fraction is much higher than for the whole PM2.5 population. 80% of the hospitalization rate of PM2.5 is due to the UFP fraction.

Converting the UFP to PM gives an 11% increase in respiratory mortality for every 10 µg/m^3 increase in the UFP. This is ~50-70% higher than PM2.5 as a whole.

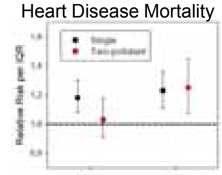
Helmholtz Zentrum, KIT UFP Conf 5/15

Beijing Olympics offered a unique opportunity to assess health dangers of air pollution.

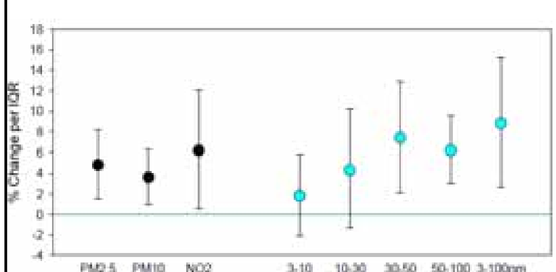


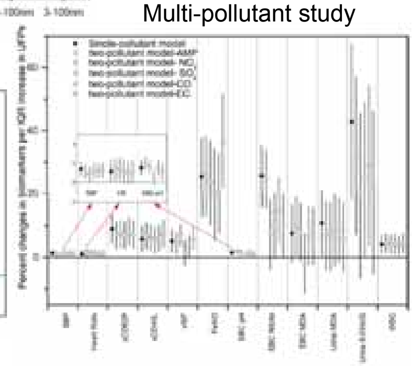


Heart Disease Mortality



Multi-pollutant study





Helmholtz Zentrum, KIT UFP Conf 5/15

NRMM Stage V proposal from European Commission formalized recently

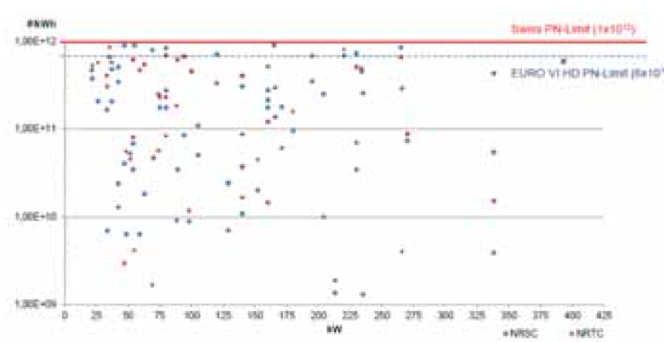
15 mg/kWh PM, PN on <560 kW, in-use conformity monitoring

- PN regulation harmonizes with Switzerland at 1 X 10^{12} particles/kW-hr.
  - PM for CI engines lowered from 20 down to 15 mg/kWh.
    - No PN limit for engines >560 kW because there is no data nor experience.
- Covers large marine engines (>300 kW) used on inland waterways and for trains
- Timing is 2018-21
  - 2019/2020 (new type approvals/market placement) for most engines with rated power of 56-130 kW
  - 2018/2019 for most engines in other power categories
  - 2020/2021 for certain categories of large inland marine and rail engines
- First-of-its-kind provisions for in-use testing
  - Report on results in 2025
- 2020 report on feasibility of further reductions
- Details on technical specifics by year-end 2016

EU Stage V NRMM regs will include PN regulation. Swiss show many certifications at 1 X 10^{12} / kWh.

Engines other than: SI Engines <56kW / IWV / Rail; emissions in g/kWh			Limit values proposed: CO	NOx	HC	PM	PN	A
CI engines 0 - 8 kW	variable & constant speed		8	7,5		[illegible]	-	1,1
CI engines 8 - 19 kW	variable & constant speed		6,6	7,5		0,4	-	
CI engines 19 - 37 kW	variable & constant speed		5,0	4,7		0,015	1x10^12	
CI engines 37 - 56 kW	variable & constant speed		5,0	4,7		0,015	1x10^12	
Engines 56 – 130 kW	variable & constant speed		5,0	0,4	0,19	0,015	1x10^12	
Engines 130 – 560 kW	variable & constant speed		3,5	0,4	0,19	0,015	1x10^12	
Engines P > 560 kW	variable speed		3,5	3,5	0,19	0,045	-	6,0
Engines P > 560 kW	constant speed	other than Gen-Sets	3,5	3,5	0,19	0,045	-	
Engines P > 560 kW	constant speed	Gen-Sets	3,5	0,67	0,19	0,035	-	

Swiss FOEN, Bosmal 5/14



Euro Commission is evaluating non-road In-Service Conformity (ISC). Framework described.

Purpose and Overview

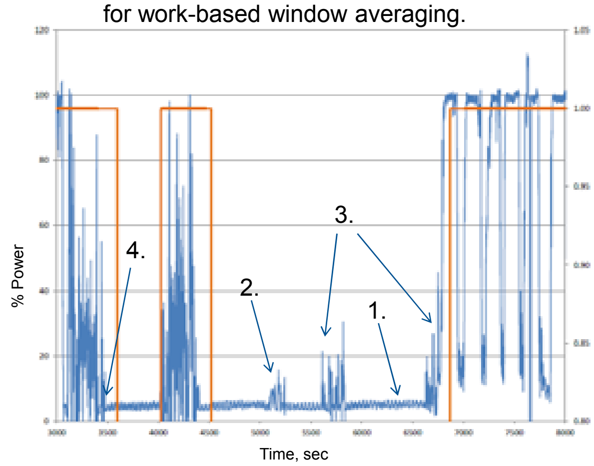
- Purpose is to screen out 56-560kW engines that should be removed and dyno evaluated
- Included periods will be averaged by working window (ala. E-VI)
- Windows <20% avg power rejected

Periods excluded and included in moving average:

1. Exclude periods <10% power and longer than 2 min excluded.
2. Exclude events shorter than 2 min are merged with surrounding idles >2 min
3. Exclude first period of stability after >2 min idle until 250C reached.
4. Include last 2 min of working period.

JRC, EU Integer Conf 6-13

Example of exclusions and inclusions for work-based window averaging.



US NR regulative considerations (2020+ timeframe)

- EPA will extend in-use testing to non-road (HD program finished ‘13)
  - Large number of non-DPF T4F certs
  - Relatively small engineering margin
- CARB is looking at taking on more of a role – NOx SIP reductions where ever they can get them.
- V SCR catalyst approval procedures further developing to prevent any loss of V in systems
- Tighter NOx (towards HD levels)
  - Will also impact PM (DPF?)
- N_2O and CH4 standards similar to HD expected
- Eliminate Emergency Use category for stationary engines

Non-road regulations are evaluated and rated.

China and India are the largest (5.4M combined engines) but are not harmonized on type approval nor timing.

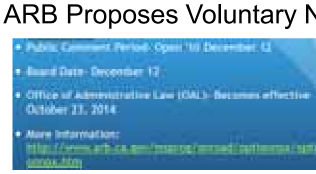
Deere; Knibb and Gormezano; Integer Euro 6-13

Demo plan being proposed for HD 0.020 g/bhp-hr NOx

- SwRI program manager. Q1 2015. Draft report mid-2016
- 2014 Volvo 13 liter base engine
- Maximum emissions technology to attain 0.020 g from engine-out of 3 g/bhp-hr
  - 95.7% efficiency for cold start
  - 99.5% for hot start
  - 99.6% SET
- Plug-and-play concept from 5 EAT packages from MECA
  - SwRI burner rig screening
- SI NG also being evaluated
- Issues: OBD? CO_2 impact? Technologies are cold start and can't be used for FC. Durability?

NOx Level g/bhp-hr	% Below Current Standard
0.2 (Current)	
0.1	-50%
0.05	-75%
0.02	-90%

ARB Proposes Voluntary NOx Standard



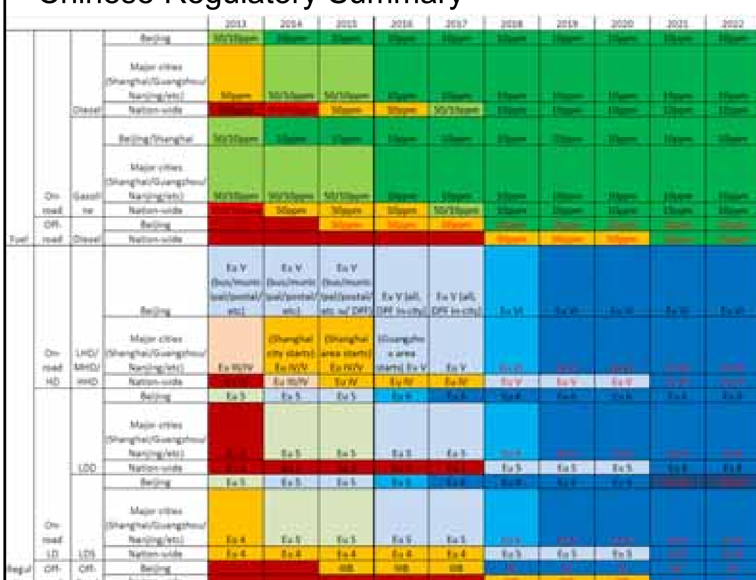
CARB US Integer Conf 10/13

China moving forward, and fast

- Government is getting serious
  - New compliance authority to MEP
  - New Minister. Former #2 guy is charged with environmental corruption
  - New fuel quality agreement

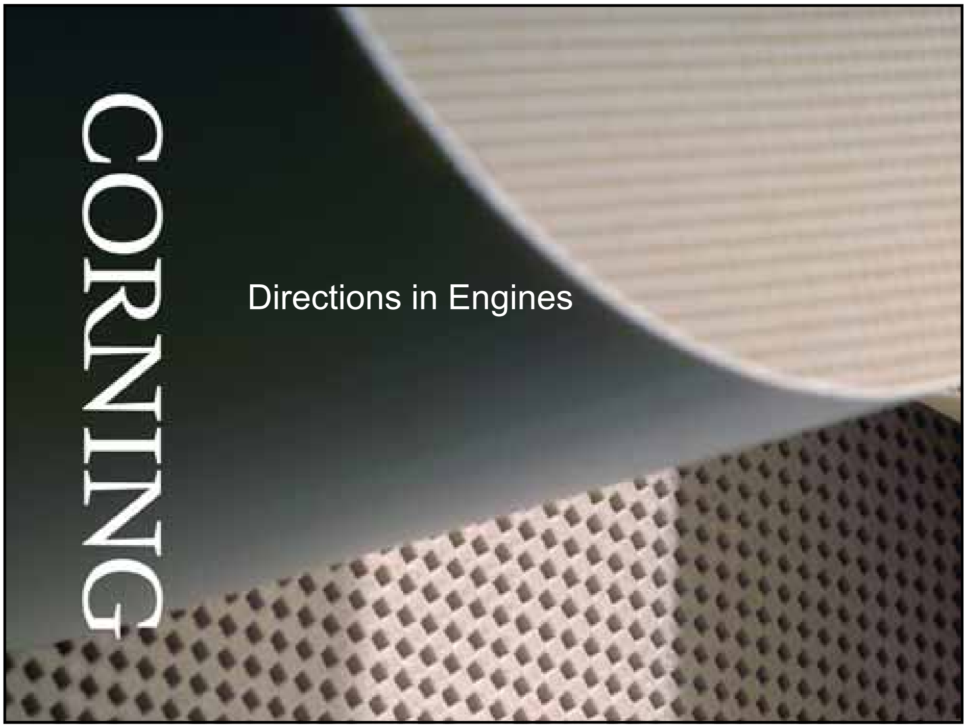
- Beijing looking at Beijing VI/6 in 2017
  - Wants to follow the US model but add PN standard
    - Breaking away from MEP – “Let the State Council decide.”
    - Need to develop PN standard on FTP, US06, SC03
- MEP looking at national VI/6 two to three years later
  - Wants to maintain EU model, but maybe go tighter, eventually (EU gasoline NOx regs change little from Euro 4→5→6
    - Wants one protocol and regulation across country
  - PN standard applicable to all gasoline vehicles
  - More reliance on Conformity of Production and in-use emissions rather than dyno certification. Considering OBD-III (real time gov tracking); HD (LD?)

Chinese Regulatory Summary

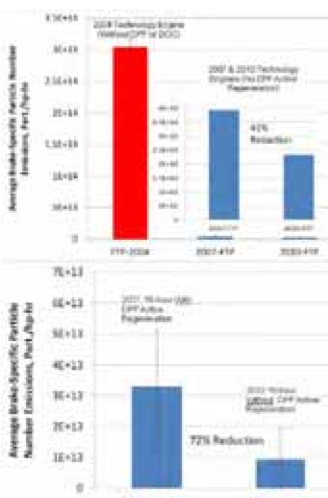


- LT WHTC is required for all city-use HD vehicles like bus/municipal/postal/school/etc. no matter how big the city is, for CN V and CN IV.
- Beijing has additional requirements to install a DPF in city vehicles starting 2015. If DPF is not used, then 6e12 #/kw.hr PN limit applies.
- Fuel readiness is a trigger point. The three regions all plan to have CN V fuel ready by end of 2015. Nationwide CN IV fuel is ready by end of 2014.
- There are a lot of complains of urea readiness.

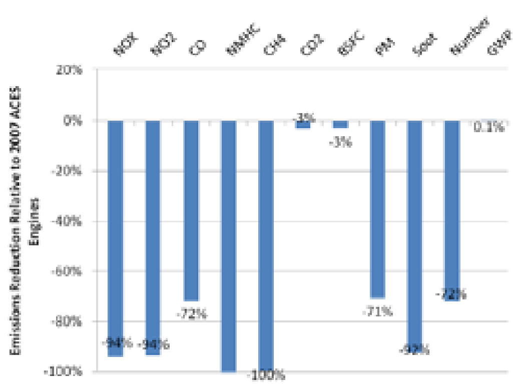
June 2014



US2010 engines (DOC+DPF+SCR+EGR) have greatly reduced PN and criteria pollutants vs. US 2007 (DOC+DPF+EGR). No DPF regeneration needed, reducing emissions. SCR reduced NOx and NO_2



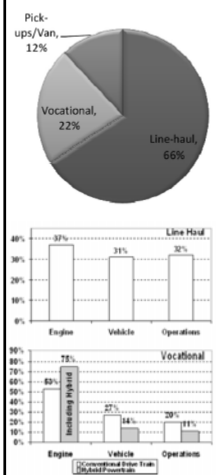
US 2010 PN emissions are 41% lower than US2007 without DPF regen. Including regens, they are 72% lower. US2010 DPFs did not regen.

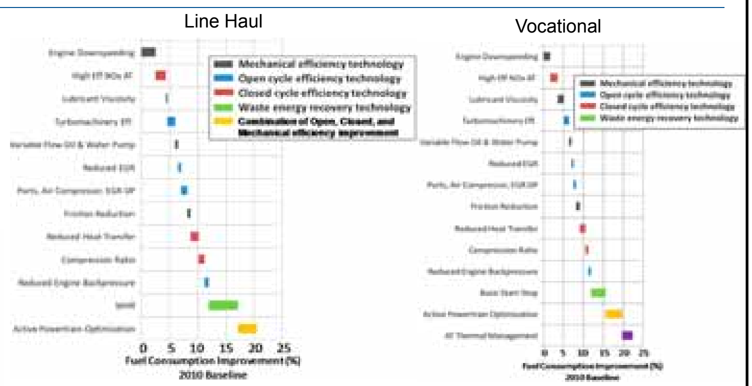


US 2010 engines have greatly reduced criteria emissions vs. US2007 engines.

SwRI, CRC 4/13

Line haul and vocational engine CO_2 reduction opportunities are compared. 20-22% total reductions are outlined.



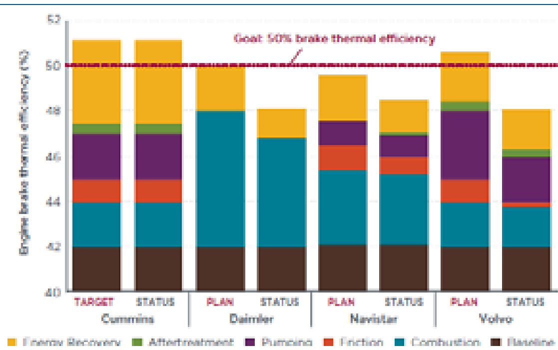


Engine methods to drop fuel consumption. Common themes return similar benefits. Differences: WHR for line haul (5-6%) and stop-start for vocational (3-4%).

Cummins, SAE 2013-01-2421

ICCT, 6/14

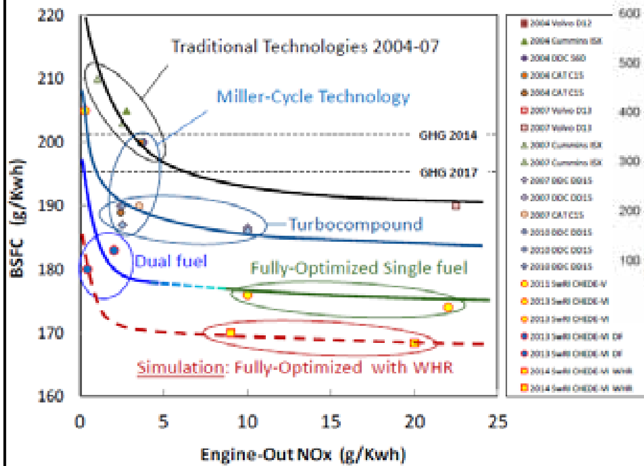
DOE SuperTruck engine approaches and results are summarized.

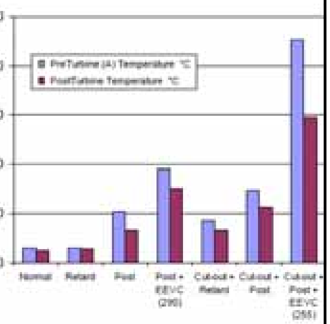


Strategy	Cummins	Daimler	Navistar	Volvo
Engine downsizing	No	Yes	No	Yes
Engine downspeeding	Yes	Yes	No	Yes
Transmission	Automated manual	Automated manual	Dual-mode hybrid	Dual-clutch automated manual
Hybridization*	No	Mild	Full (series/ parallel)	No
Organic Rankine cycle	Yes (mechanical)	Yes (electric)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

A range of HD engine technologies is shown with regard to the BSFC vs NOx tradeoff. -10% reductions possible vs. US2017 CO_2 goal.





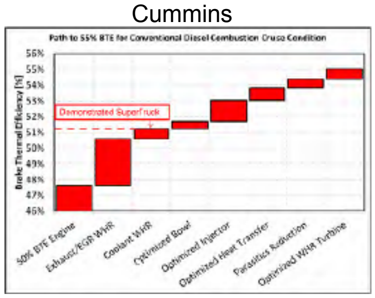
Key to low NOx is SCR temperature control.

Engine technologies will continually shift the BSFC vs. NOx curve downward.

SwRI, US Integer Conf 10/13

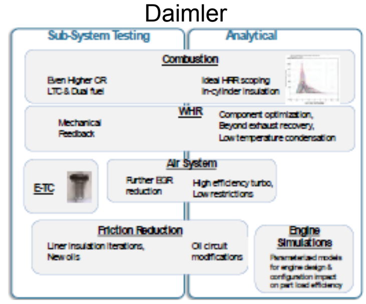
Roadmap approaches to 55% BTE are outlined.

Cummins

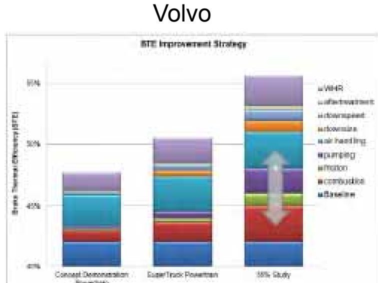


NRC 21st Century Truck Review , 9/15

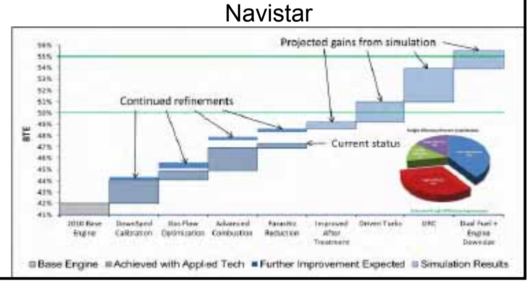
Daimler



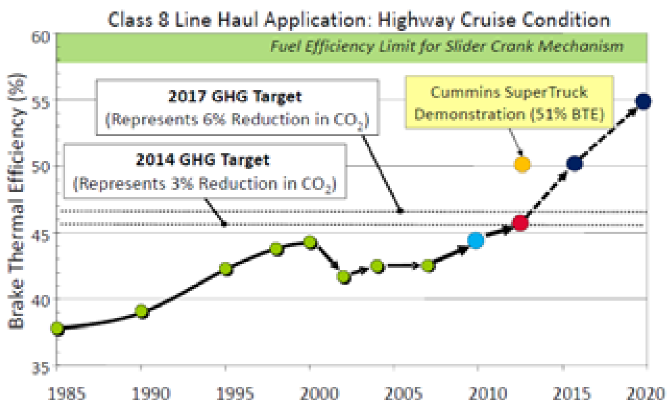
Volvo



Navistar



Progress is well-on the way to demonstrate 55% BTE by 2020.



55% BTE can be demonstrated in 2015 with

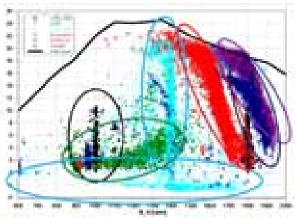
- Reduced heat transfer losses
- Better EGR delivery
- On-engine fuel blending

Cummins, 2013-24-0094

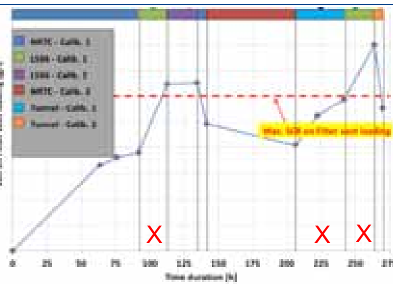
Diesel PM Control

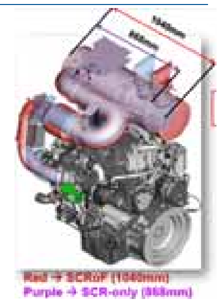
Liebherr, SAE HD Emissions, 9-14

SCRoF developed for NR applications. Replaces SCR-only (20% longer), passive regen and NOx durability satisfactory.

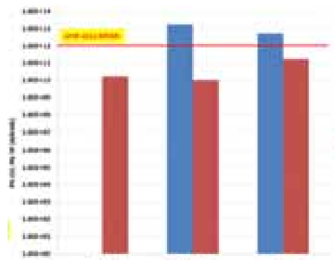


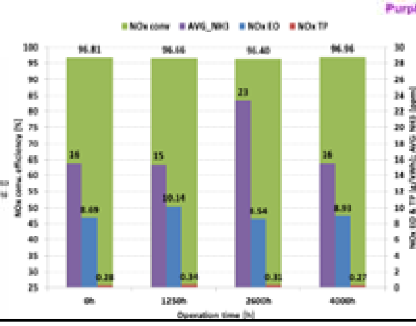
Passive regen of SCRoF measured using variety of application cycles. Only cont. low-load ops caused soot to accumulate (X) past limit.





SCRoF is 20% longer than SCR-only system





deNOx eff. maintained after 4000h on custom durability cycle (torque curve range at max RPM, <400C)

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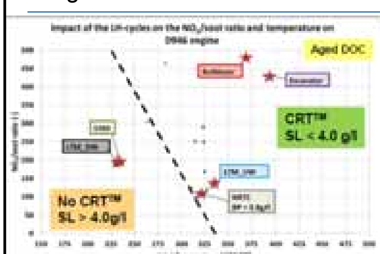
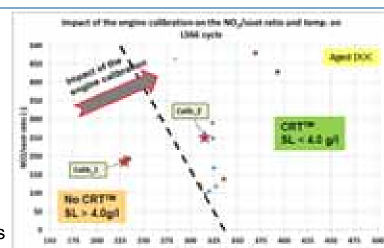
Passive regeneration of SCRoF is characterized.

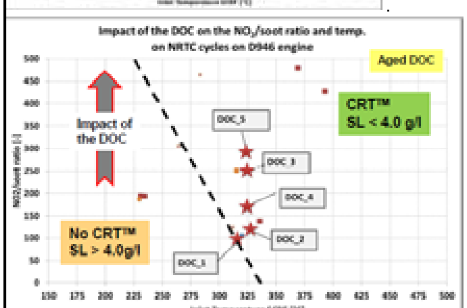
Engine calibration and DOC formulation can impact. Δp more sensitive to ash.

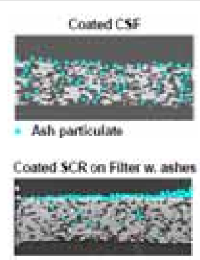


Passive regen regimes identified using various applications



Engine calibration can be used to increase T and NO2/soot to impart passive regen.





SCRoF Δp much more sensitive to ash. For CSF, 1000 g of ash increased Δp 50% (60% captured); SCRoF: 300g gave 100% Δp (80% captured).

Liebherr, CTI SCR 7-14

DOC formulation can increase NO2/soot. deNOx not significantly affected.

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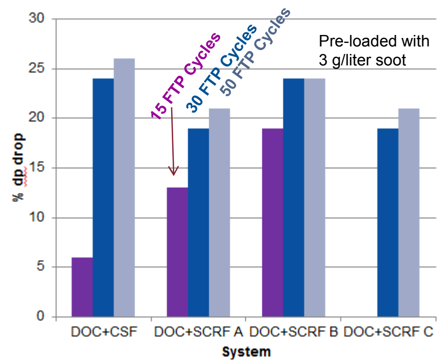
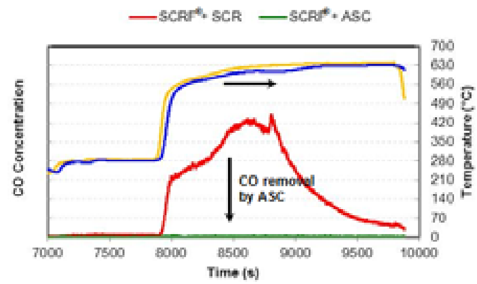
Issues with SCRF DPF management can be managed.

Improved passive regeneration and CO reductions during active regenerations.



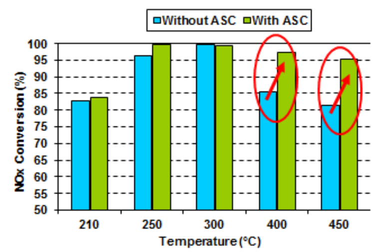
Proper design of the SCRF can improve passive regeneration to DOC+CSF levels



Active regenerations will create high levels of CO, but ASC can manage

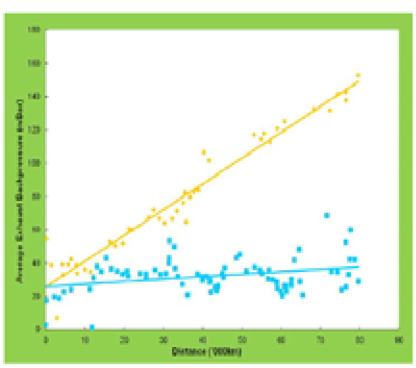
JM, CLEERS 4/13

ASC can allow increased urea injections and improved deNOx efficiency



Lube oil ash can have a big impact on HD fuel consumption

Rate of DPF Pressure Increase was 5x higher for 1.8% SA oil than for 1.0% SA



In 100,000 km operation:

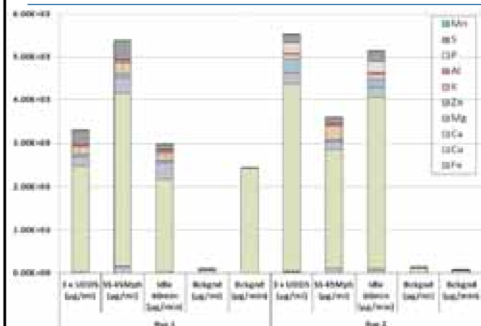
- 1.8% ACEA E4 oil - 2.0% decrease in FE
- 1.0% ACEA E6 oil - 0.4% decrease in FE

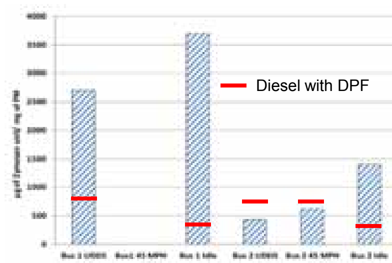
Assuming fuel consumption of 44 litres/100 km and diesel cost is €1 per litre

- Annual operator's savings by using the E6 lubricant is €362

Lubrizol, Emissions 2013 6-13

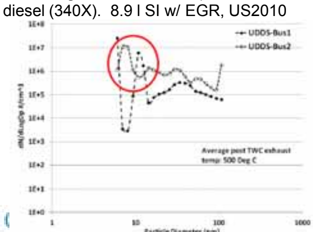
SI CNG has quite high metal oxide emissions. >300X vs. DPF diesel. Toxicity is up to 12X greater per mg of PM.

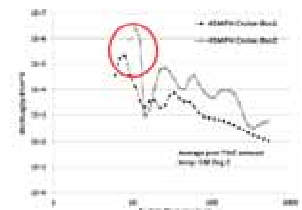




Cell toxicity is -30% to +12X vs. diesel metal oxide emissions. Correlates to Cu, Zn, P.

Metal emissions are quite high for the NG engines: about 4 mg/mile or ~2.5-3 mg/kW-hr. This compares with about 0.008 mg/kW-hr for filtered diesel (340X). 8.9 l SI w/ EGR, US2010





WVU, ETH Conf 6-13

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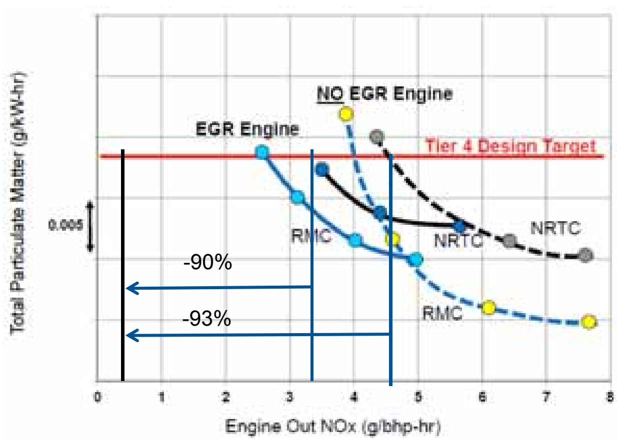
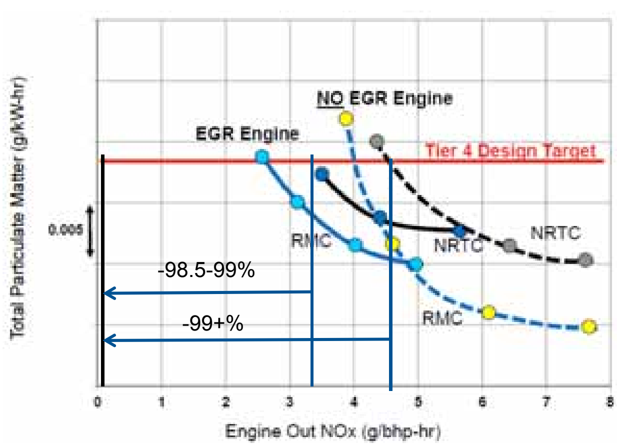
NOx Control

Current non-road engines require 90-95% deNOx efficiency to meet the PM standard without DPFs.



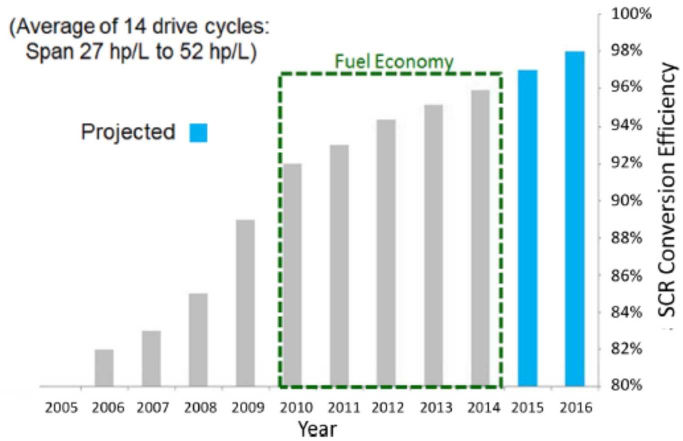
Cummins, CTI NOx Conf 6-12

If CARB has its way (and EPA NAAQS tightens), future non-road engines could require 99% deNOx efficiency to meet the PM standard without DPFs.



Cummins, CTI NOx Conf 6-12

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

CORNING | Environmental Technologies

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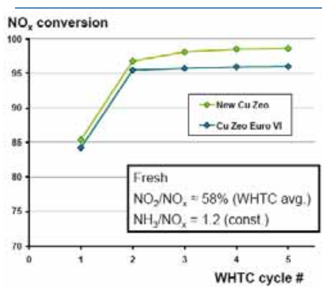
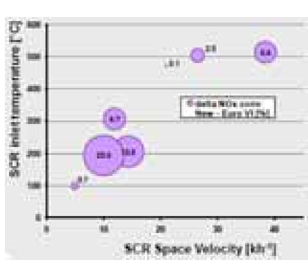
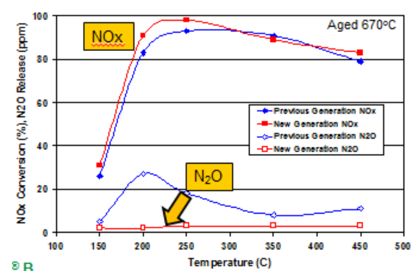
Improved Cu-zeolite is described. Better LT performance and durability.





Umicore FAD Emissions Conf, 11-13



JM, SAE F, L, & E Symp 11-13

New CuZ has better LT – low SV and HT – high SV performance. NO2/NOx = 0.58, ANR=1.2 NTRC

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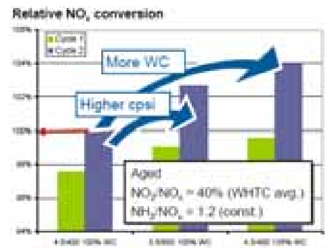
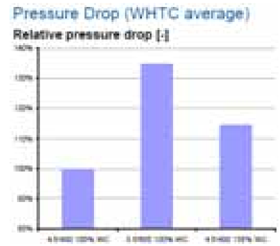
The effect of SCR substrate cell density and washcoat loading is shown for the WHTC and NRSC.

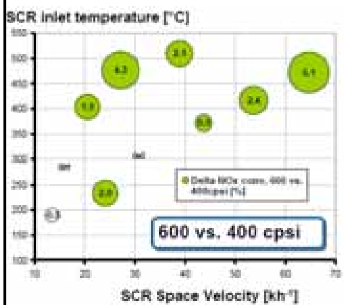
Higher loading strikes good balance between efficiency and Δp.



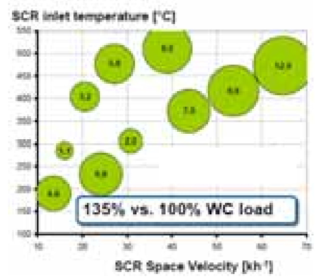


Comment:

- Bang-for-the-buck is in high csi



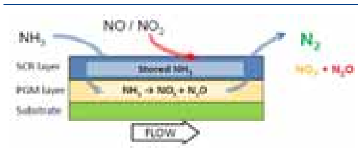
On the NRTC, 600-csi generally performs better at the higher temperatures (>400C) and space velocities.



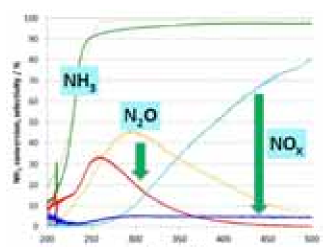
On the NRTC, higher WC loading performs better at the higher temperatures (>400C) and space velocities, but also at the lower temperatures.

Ammonia slip catalysts are improving.

Layered approach reduces NOx, NH_3, and N_2O. Acts as an added SCR catalyst.

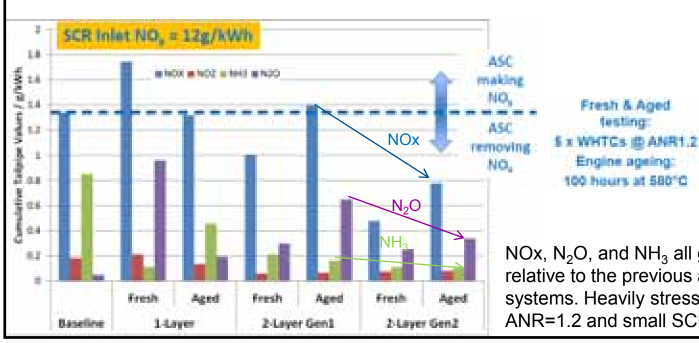


NOx from NH_3 oxidation is converted by on SCR layer with stored NH_3.



NH_3 conversion is similar to previous versions, but N_2O and NOx are greatly reduced.

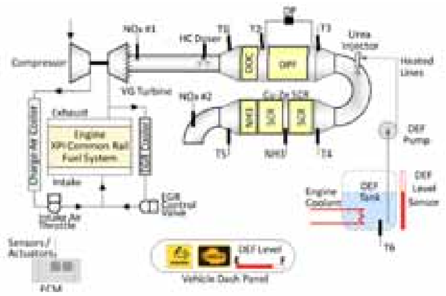
JM, CTI SCR Conf 7/13



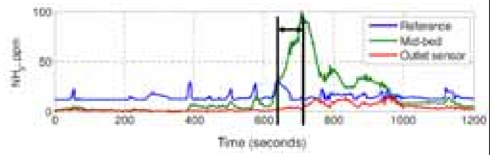
NOx, N_2O, and NH_3 all go down relative to the previous aged systems. Heavily stressed ASC with ANR=1.2 and small SCR catalyst.

A closed-loop NH_3 control system is outlined.

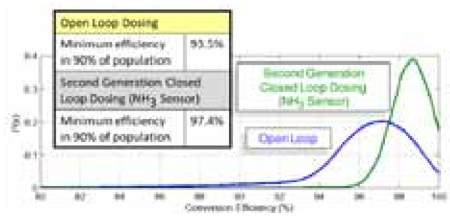
Mid-bed NH3 sensor allows optimal performance in second bed with minimal slip and same catalyst volume.



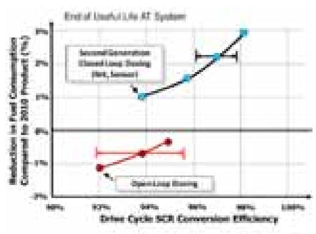
2013 SCR system has a split SCR catalyst with an NH_3 sensor in between for closed loop control of NH_3 injection.



Relative to a tailpipe NH_3 sensor, the mid-bed sensor offers 80-100 sec lead time of NH_3 slip.



Closed loop control of NH_3 injection using mid-bed sensor enables second catalyst to operate at near stoichiometry conditions with minimal NH_3 slip. This increases system efficiency from 93.5 to 97.4% with no increase in catalyst volume.

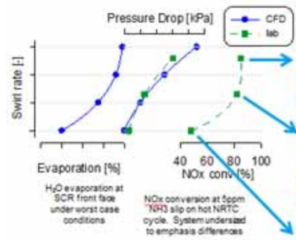


Efficiency is maintained to end of life, improving FC.

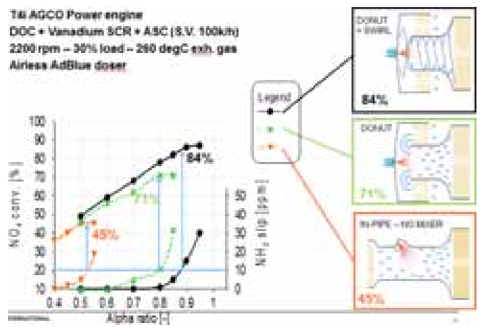
Cummins, SAE 2013-01-2421

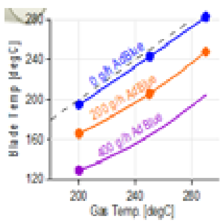
DOCs

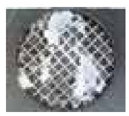
New donut DOC urea mixer-swirl compact NR design improves LT SCR performance.



New donut DOC and exit swirl mixer improves urea mixing.







24 hr at 200C steady state: No deposits

Std. mixer blades can cool on urea contact.

Donaldson, SAE FL&E 11-13

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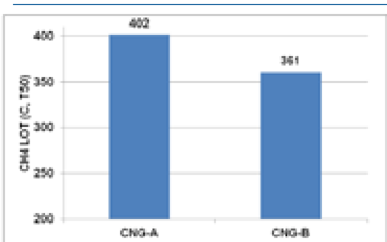
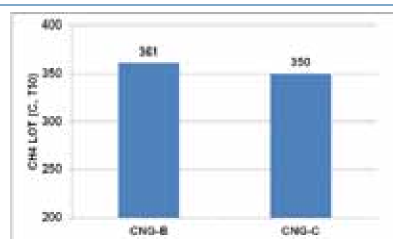
Improvements to a methane oxidation catalyst drop the T50 from 402C down to 317C. Stability improved.

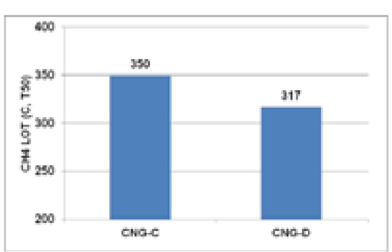
Heesung, SAE 2013-01-2591



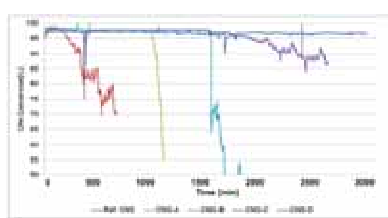
Dispersing and stabilizing the Pd dropped CH4 T50 from 402 to 361C.



Adding an optimized OSC dropped CH4 T50 from 361 to 350C.



Using promoters to improve the electronic properties of the Pd drops T50 from 350 to 317C.



Durability is improved to 38 hrs vs 4 hrs in a steady state test at 450C

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Summary

- Diesel exhaust is a proven carcinogen, requiring maximum control in high-exposure environments.
  - Very fine particles are emerging as the main impact. ~90% of PM2.5 toxicity resides in the <0.1 μm fraction.
- New engine designs and strategies are making impressive gains
  - HD engines are close to 50% BTE with realistic technologies and very low emissions
    - Combustion, pumping, friction, WHR
    - Pathway to 55% BTE outlined
- NOx
  - LT NOx control, better catalysts, system integration
- PM control being optimized for diesel
  - SCRF advancing in LD
  - Fundamental ash behavior
- DOCs: Higher CO+HC a real challenge, and gap for DOCs

Trends to watch

- Regulatory
  - California developments and ultra-low NOx
- Engines
  - High-performance gasoline approaching diesel efficiency. Pathway to LCV and MD?
  - New engine designs – RCCI, 2 stroke- opposed piston
  - High-efficiency HDD and SuperTruck
  - Natural gas
- Emission control
  - SCR durability and variability
  - OBD
  - SCRF
  - LT emissions reduction