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Tim Johnson
May 2007

Overview of Diesel Emission Control Retrofit Options

Diesel emission control retrofit programs are spreading throughout the world

- California and Switzerland are mandating retrofits of all diesel vehicles by end of decade, including construction equipment.
  - NYC: city operated construction equipment and trucks
  - NJ, MA, CT passed or are drafting legislation
- Sweden,Tokyo, and Hong Kong require retrofits for city vehicles
- US EPA has voluntary retrofit program
  - Formal school bus program
  - Spreading into other applications
  - CMAQ funding for federal highway construction equipment
- Korea
- Dozens of city programs

Retrofit Technology Options

PM Control

- Particulate Filters
- Oxidation Catalysts
- Fuel Emulsions
- Reduce Fuel Sulfur

Current Focus

NOx Control

- Fuel Emulsions
- Lean NOx catalysts
- Selective Catalytic Reduction Systems (SCR)
- Exhaust Gas Recirculation (EGR)

Early commercial stages

A variety of on- and off-road applications have been successfully retrofit










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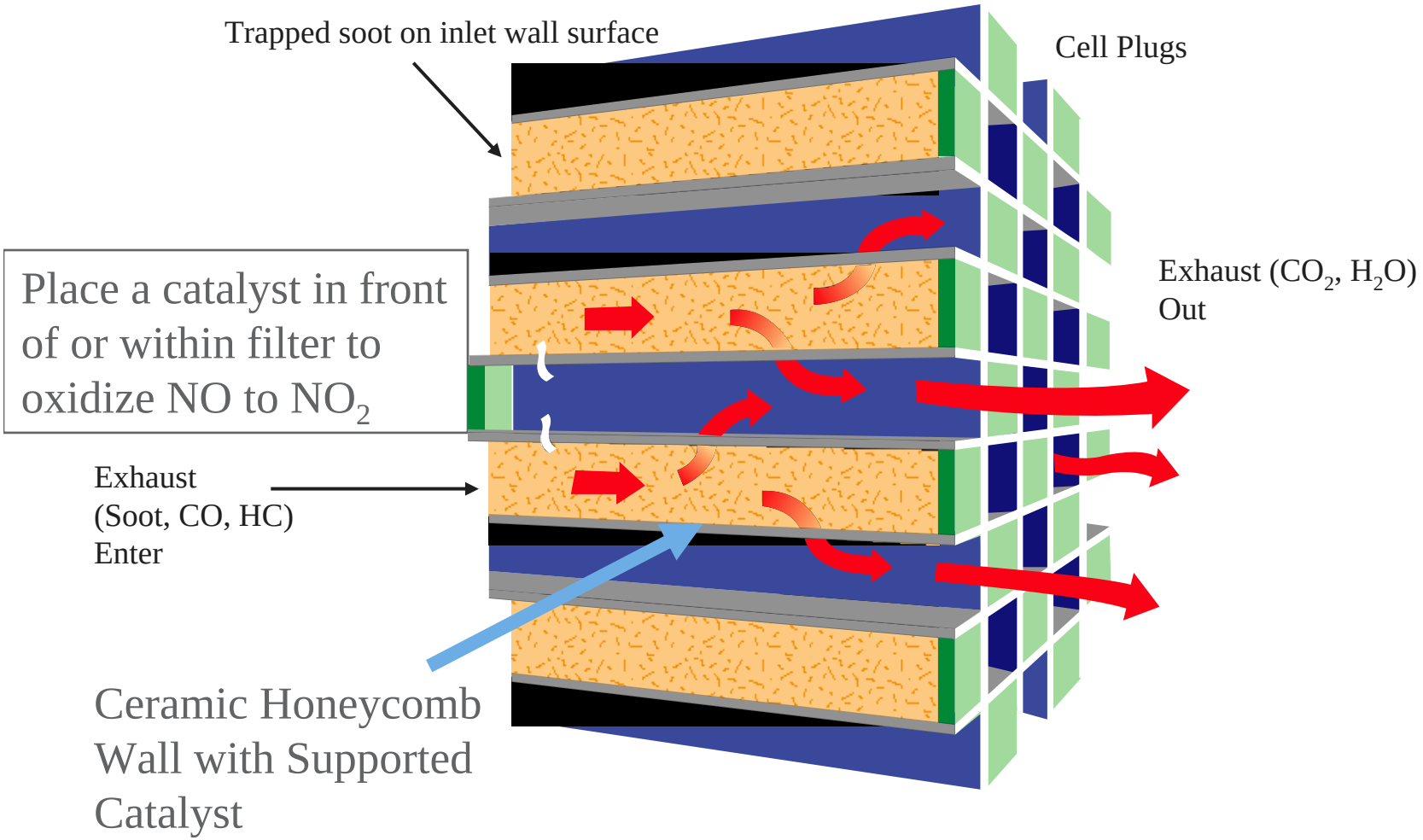
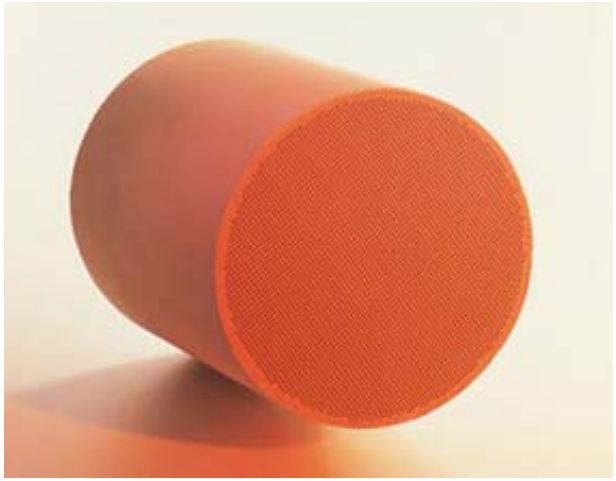
Diesel Particulate Filters (DPF)

- 200,000+ retrofits worldwide
- Many regions are mandating
- Variety of technologies for a variety of applications
- Still not universally applied, but coming

Diesel particulate filters use porous ceramics and catalyst to collect and burn the soot

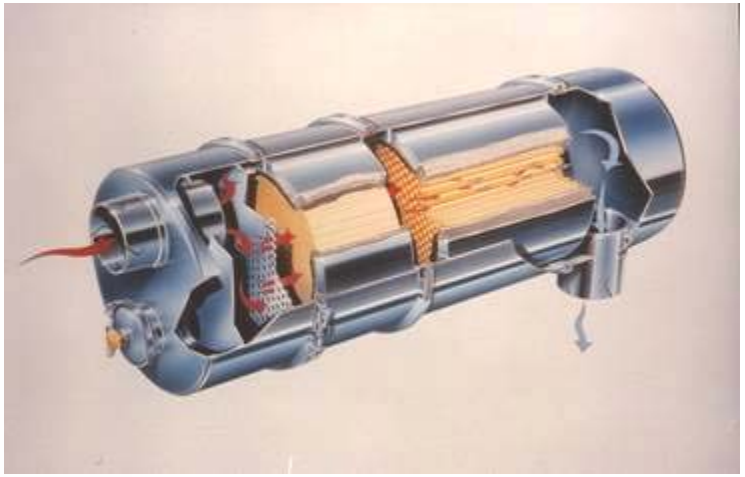


DPF systems are comprised of several components -
ceramic, catalyst (depending), mat, can



Bare diesel particulate filter substrate. Depending on the technology, it is used as is, or with catalyst. Corning

Filter is placed in a can with retaining rings to facilitate removal for ash cleaning. Lubrizol - Canada



Canned systems can have DOCs (here), or NOx catalysts in the same can as the filter. Courtesy Johnson Matthey

Filters Are Very Effective in Reducing Ultra-Fine Particles

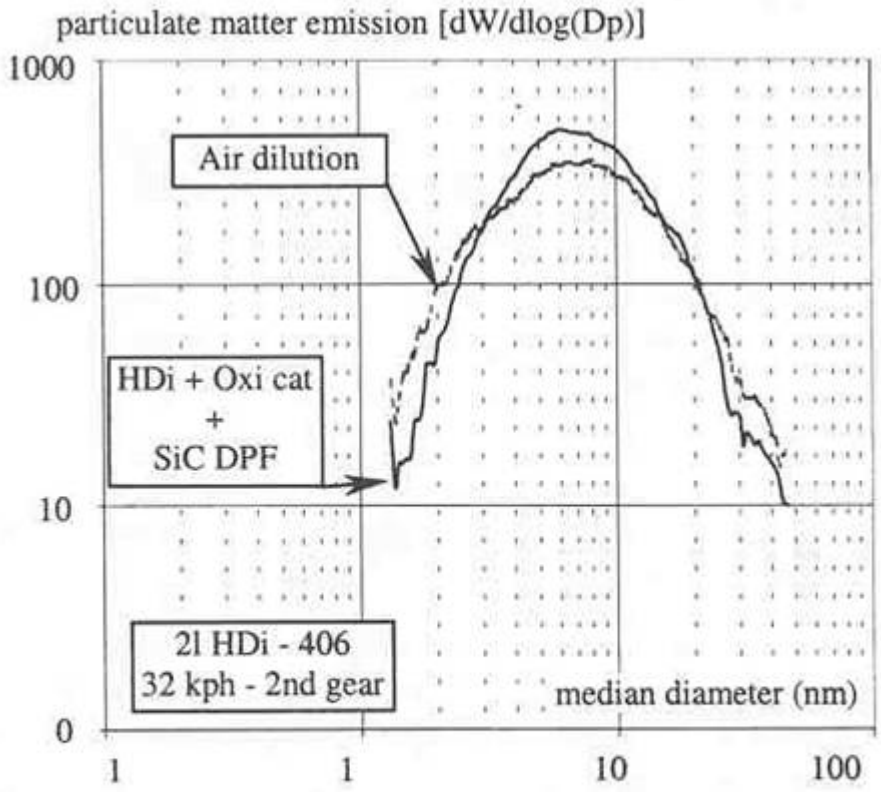
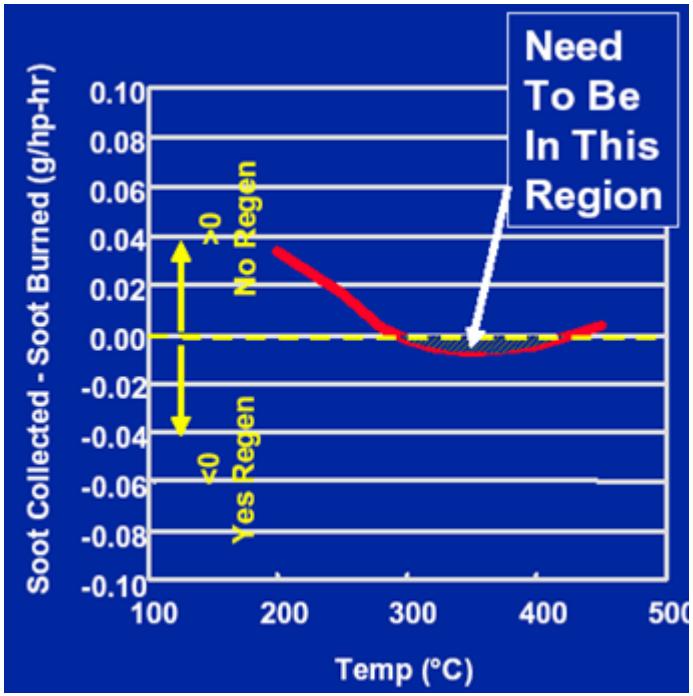


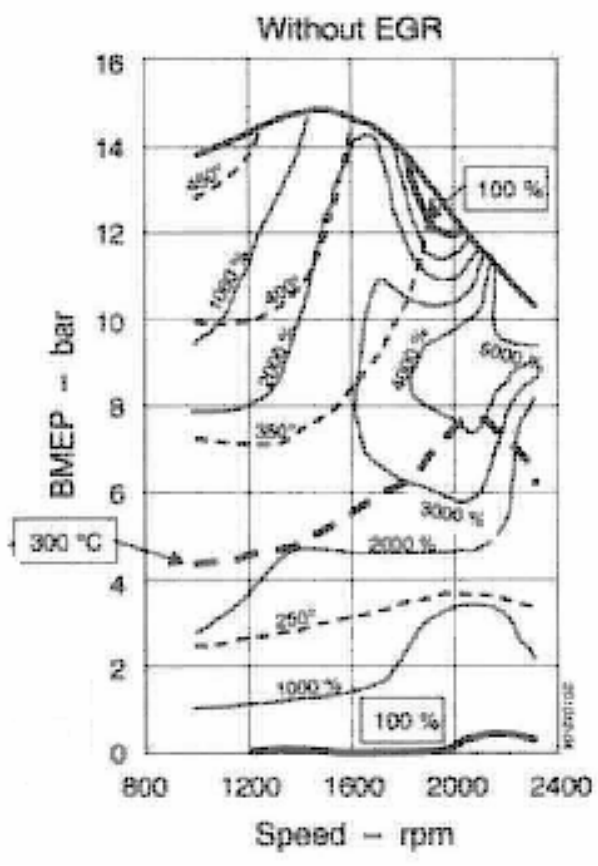
Figure 17. Comparison of SiC filter particulate matter emission with air dilution on a 406 - 2l HDi (32kph)

- Post filtered gas has the same particulate concentrations as the dilution air
- Carbon-Based Ultra-Fine Particles Reduced by in Excess of 99.99 %

Passive regeneration uses NO_2 as the oxidant, formed by the oxidation of NO



Passive regeneration requires appropriate temperature. Too hot, and NO2 can not be formed. Too cold and kinetics of oxidation are too slow. Caterpillar ATA TMC 6/03



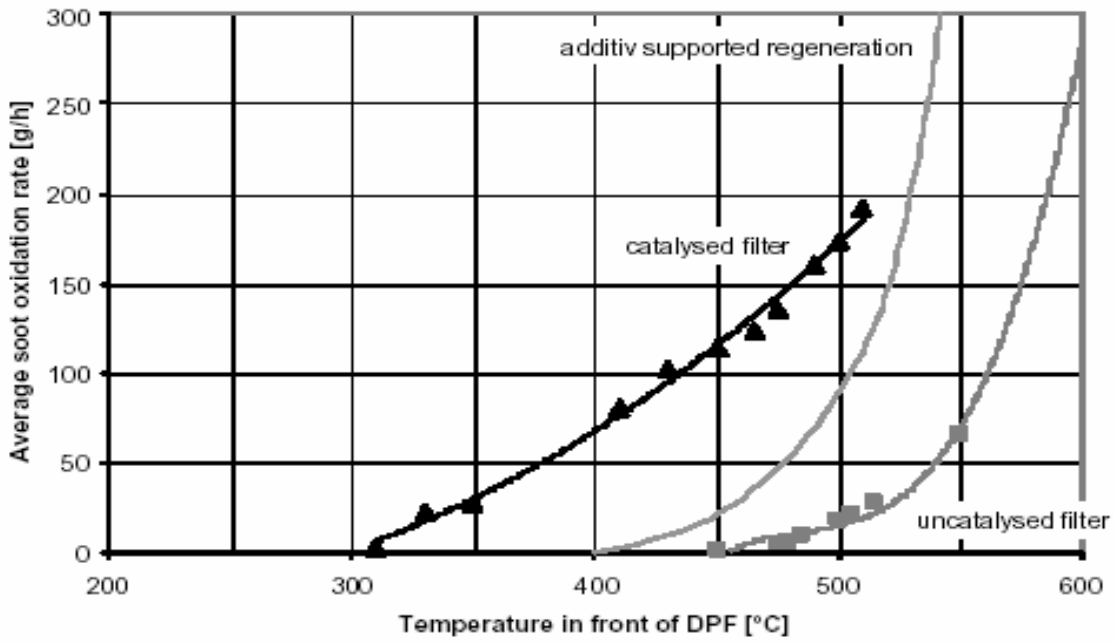
NO + 1/2O2 = NO2

NO2 + C = NO + CO

Passive regeneration also requires NO2:C>16:1. Percentages indicate level of required NOx.

6 cyl DI/TCI, 9 liter, 200kW engine with unit injections. AVL JSAE 20015347

Active regeneration is needed if passive regeneration is not acceptable

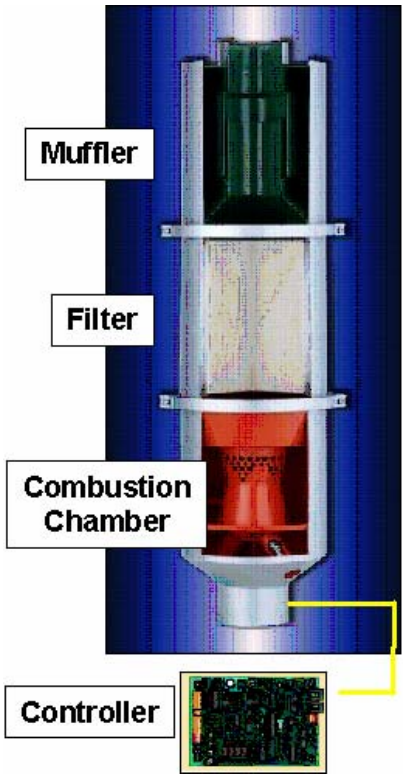


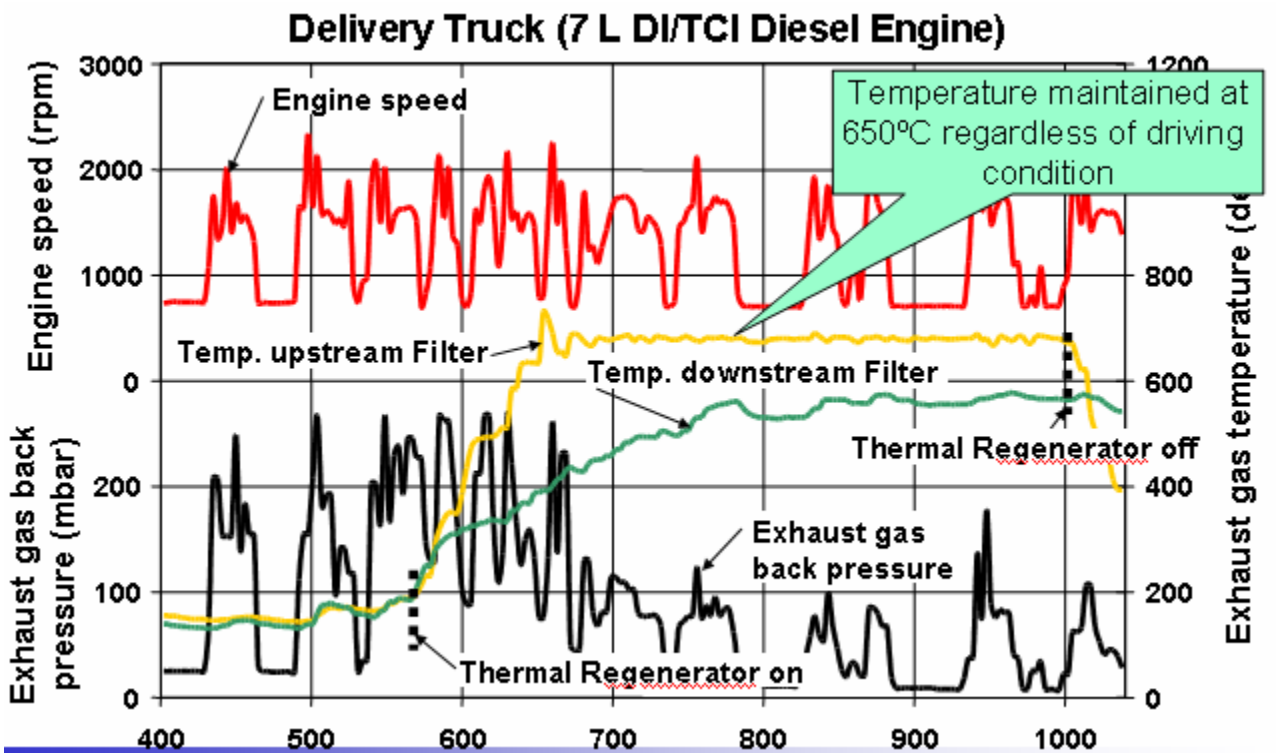
CSF oxidize soot at 50 - 100C less than FBC and 150C less than uncatalyzed systems; 75 g/ft^3 pt. Umicore, SAE 2003-01-3177

$C + O2 = CO2$

- Heat needs to be actively added to increase temperature to get fast oxidation.
- Uncatalyzed filters need T>600C
- Fuel borne catalyst systems need T>300–500C depending on formulation.
- Catalyzed soot filters need T>300-450C depending on formulation.

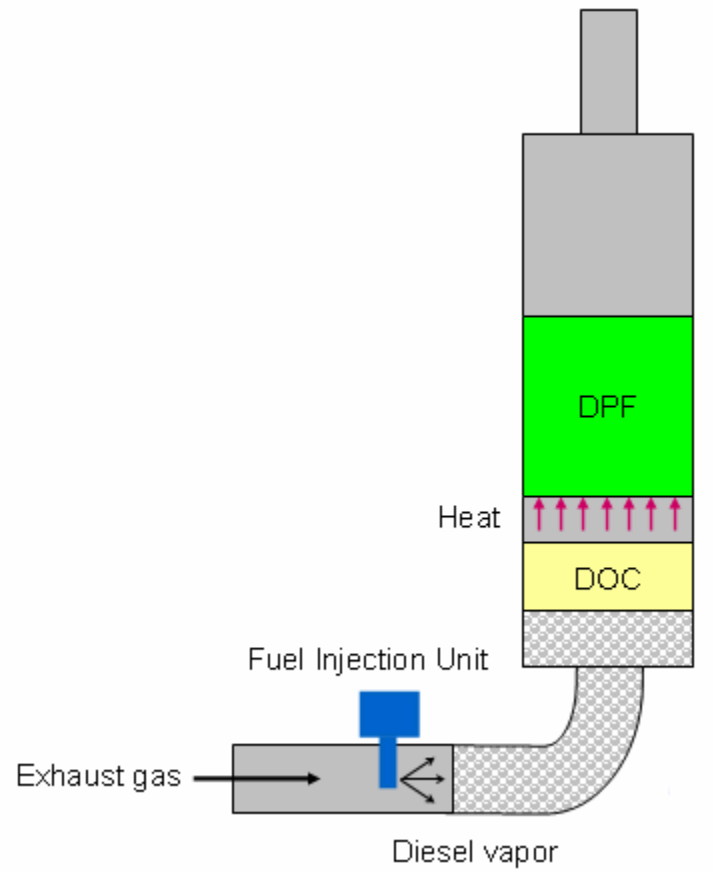
Burner system is described for regenerating filters

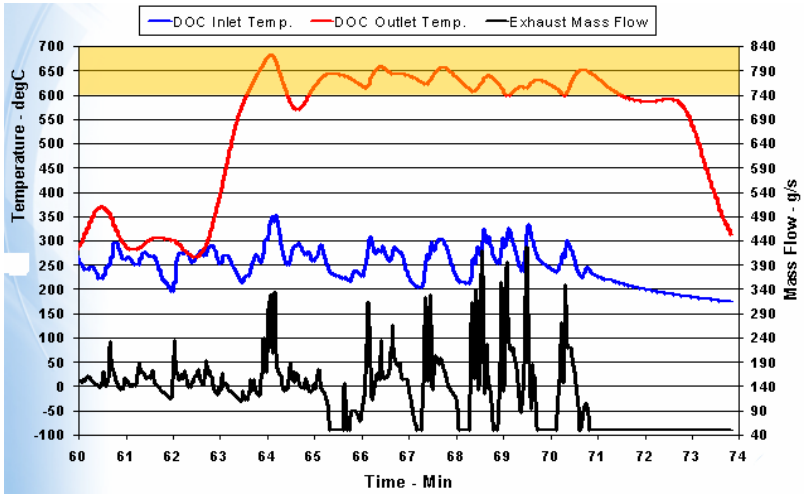




HDD is moving toward auxiliary heating of DPFs in the exhaust system. Also good for retrofit.

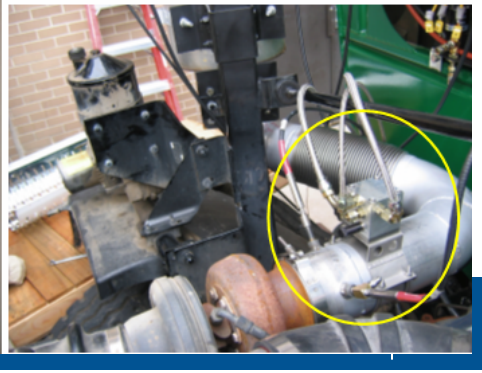
Donaldson, DEER 8-04





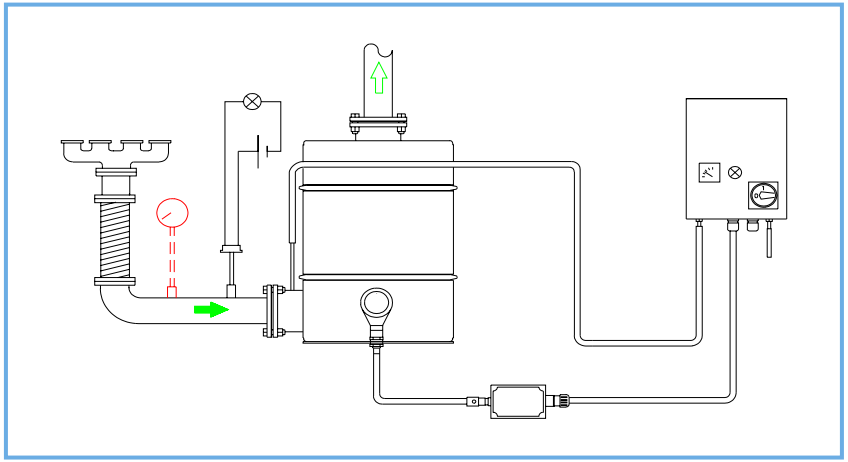
Fully Installed Active System

Fuel Delivery System



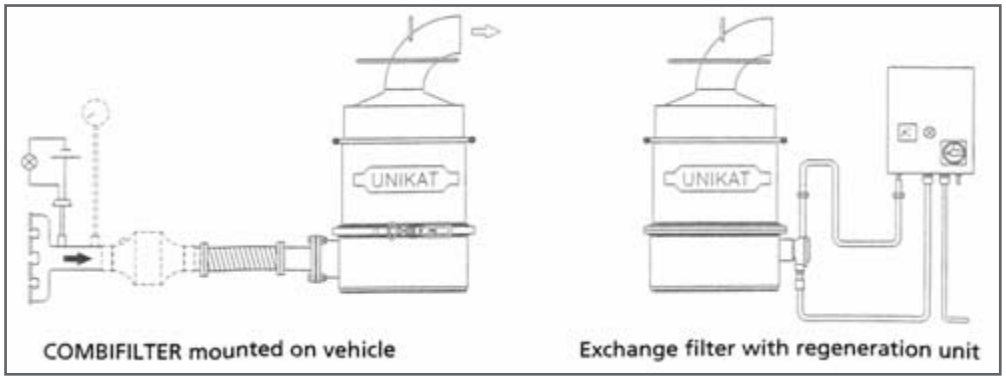
On-board electrical heating or off-line cleaning can be used to regenerate filters

On-board auxiliary electrical regeneration



V-Type: Cordierite filter, 8 hours regeneration
K-Type: SiC filter, 8 hours regeneration
S-Type: SiC filter, 60 minutes regeneration

Off-line regeneration



V-Type: Cordierite filter, 8 hours regeneration
K-Type: SiC filter, 8 hours regeneration
S-Type: SiC filter, 60 minutes regeneration

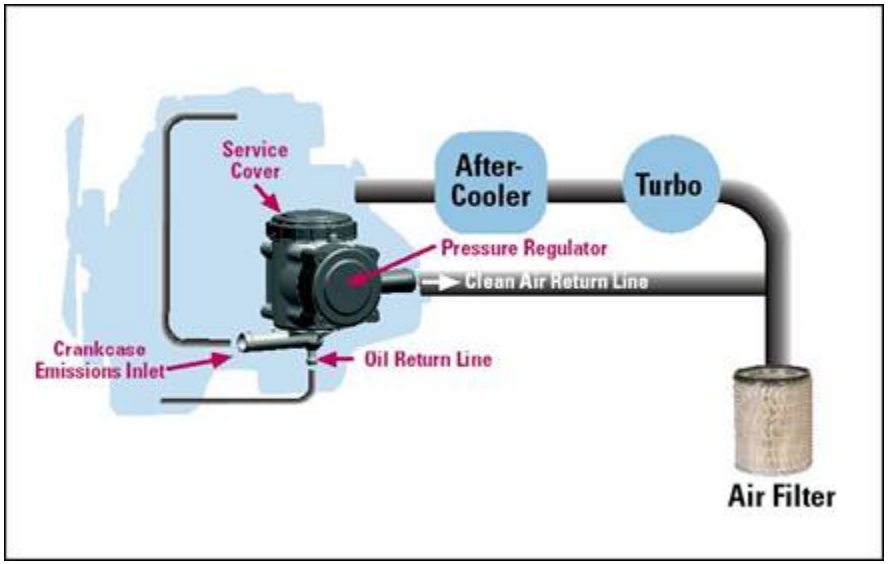
Engine Control Systems

Devices are developed to clean ash from filters, either with water or hot gas

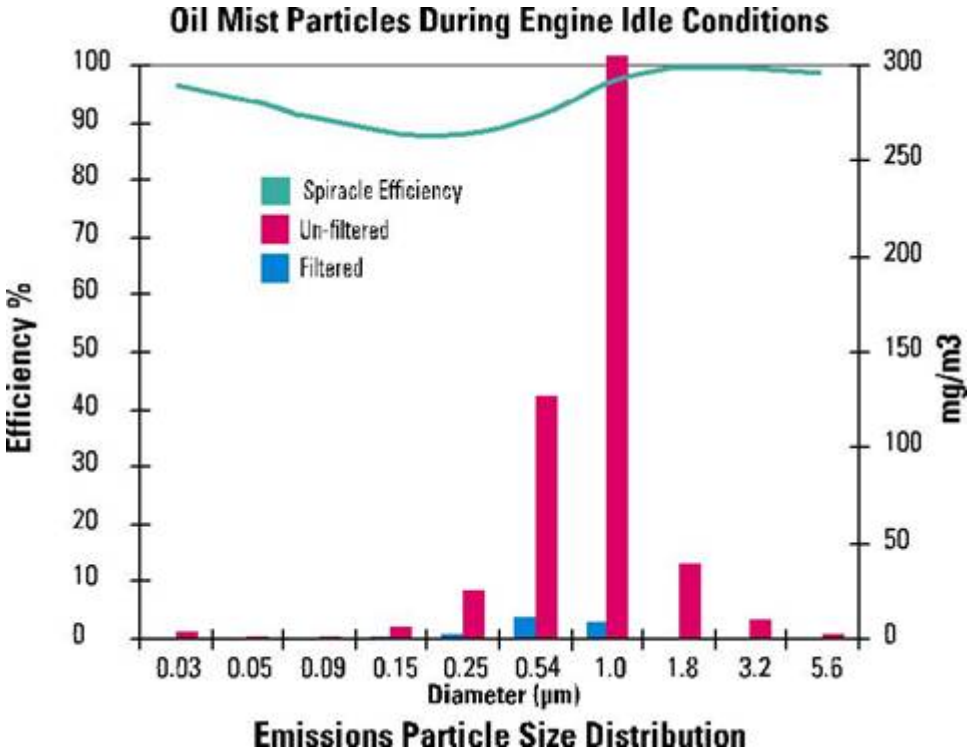
- Quick release DPF
- Burn out soot and SOF
- Blow in hot gas in reverse direction
- Collect ash in bag
- Reinstall filter
- Faurecia reported on assembly line method to handle 10's of filters (DEER 8-03)

Engine Control Systems

Crankcase ventilation ports can be a large toxin and PM emitter; solutions available



Filter cleans crankcase ventilation port and returns clean gas to air intake.



Spiracle crankcase filtration system is efficient over a broad range of oil mist sizes and that the oil mist form engine blow-by range from 30 nanometers to 6 microns in size

Figures courtesy of Donaldson

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NOx Control

- Most difficult and expensive of the retrofit options
- 1000's have been successfully fit
- Much progress on modest (20-50% removal) systems
  - Emerging success on higher-efficiency systems (SCR)

NOx control is difficult in lean conditions

- In stoichiometric conditions (like typical gasoline engines), the three way catalysts takes our 98%+ of the NOx:

$$CO + NOx = CO_2 + N_2$$

- In lean conditions, the CO prefers to react with oxygen:

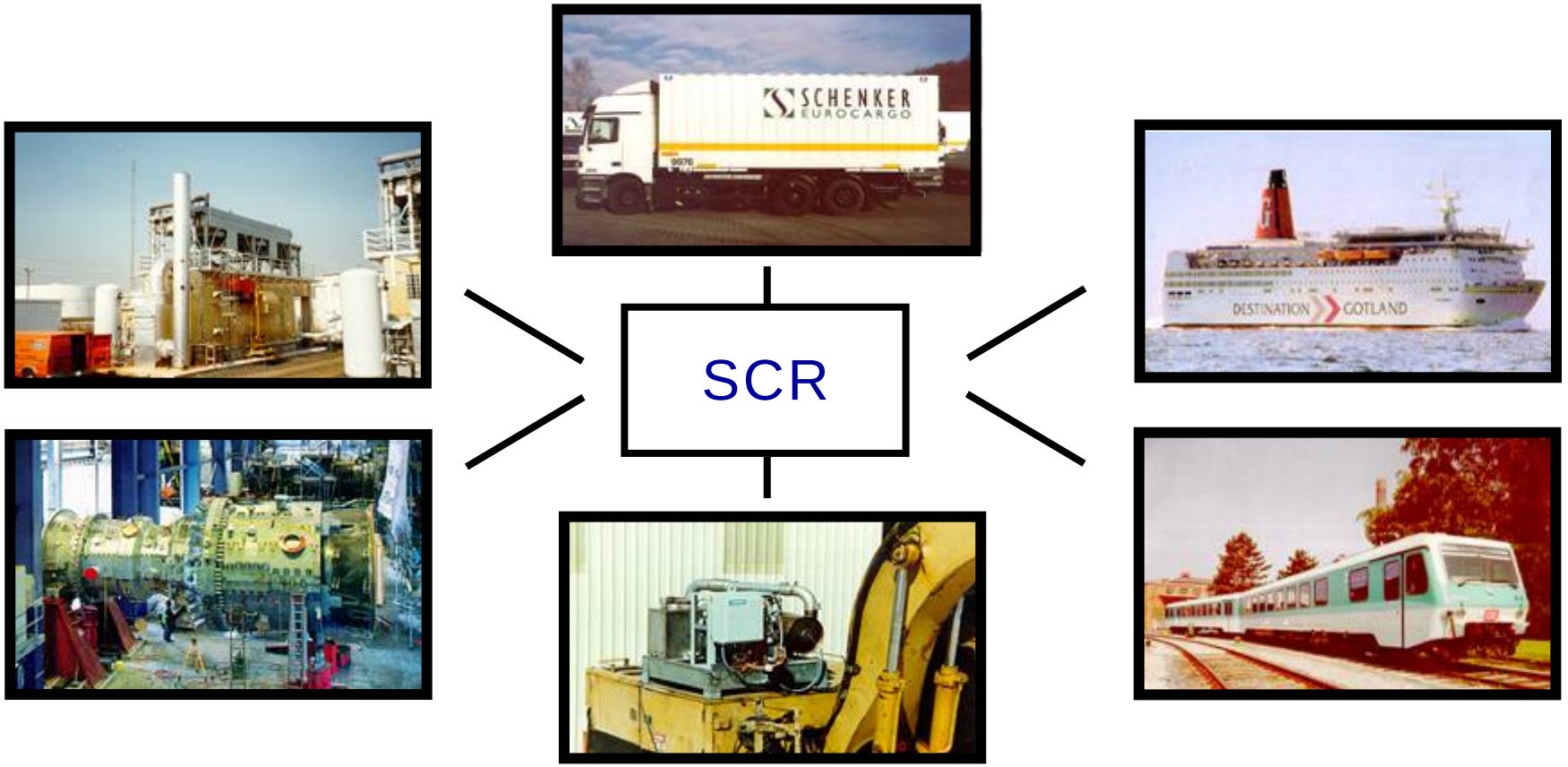
$$CO + 1/2O_2 = CO_2$$

- Emission control systems need to accommodate

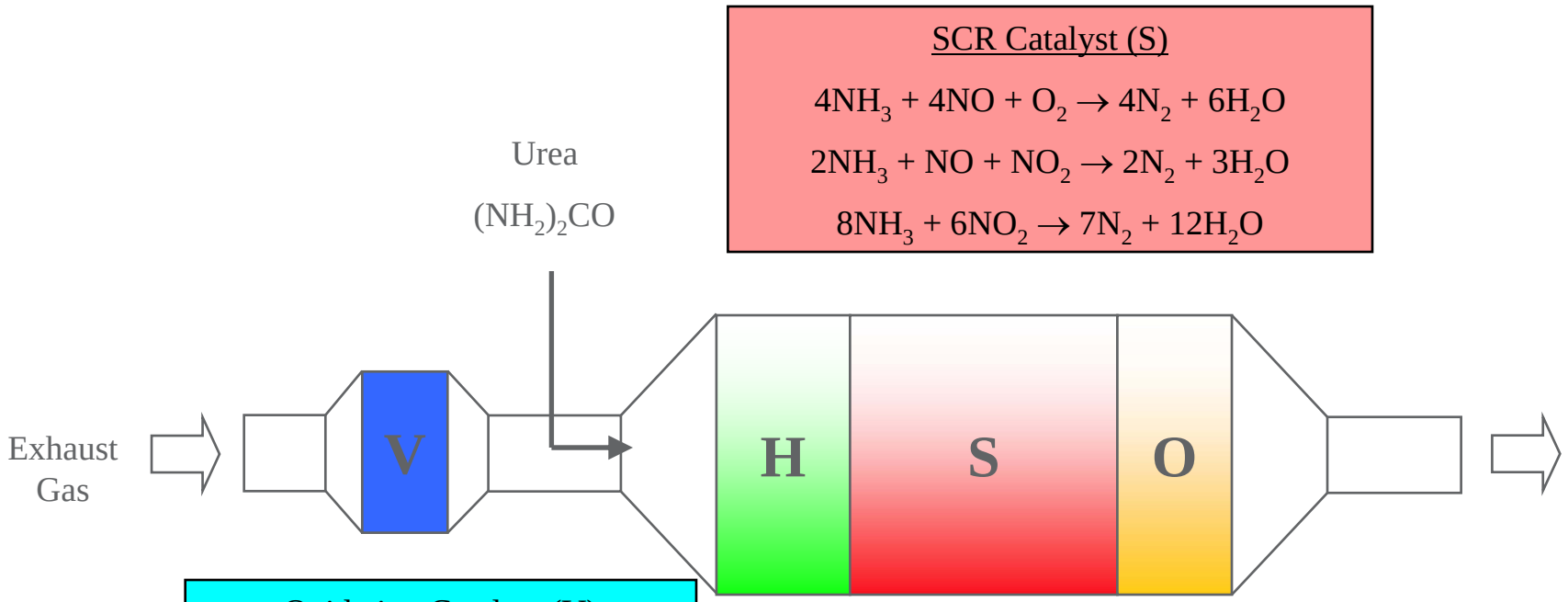
NOx Control Technology

Technology	Performance Range			
	NOx	CO	HC	PM
Active Lean NOx	25-50	>70	>70	~ 30
SCR Urea	>80	>50	>70	≥ 30
Exhaust gas recirculation	10-50%	-	-	-

SCR Applications are quite varied



State-of-the Art SCR system has NO_2 generation and oxidation catalyst to eliminate ammonia slip



Umicore, 9-99

Basics of a US urea infrastructure are described. Lube oil shop interval for LD and MD. One on-road fill for long haul. Nominal $0.50 to $0.65/liter retail cost.

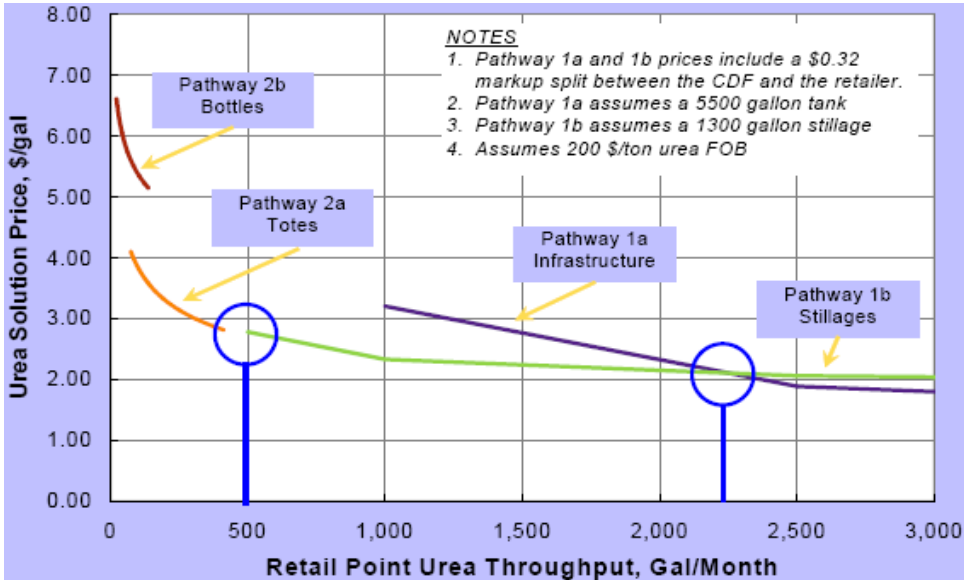
Stillages[a]

Totes[a]

Bottles[a]

AdBlue Retail Containers	Container Volume	Price of AdBlue ($/gal)[c]
Stillages[b]	15,000-L (3,963-gal) 3,000-L (793-gal)	2.12 2.52
Totes	1,000-L (264-gal)	2.78
Bottles	18-L (4.8-gal) 10-L (2.6-gal) 5-L (1.3-gal)	4.30 4.63 5.30

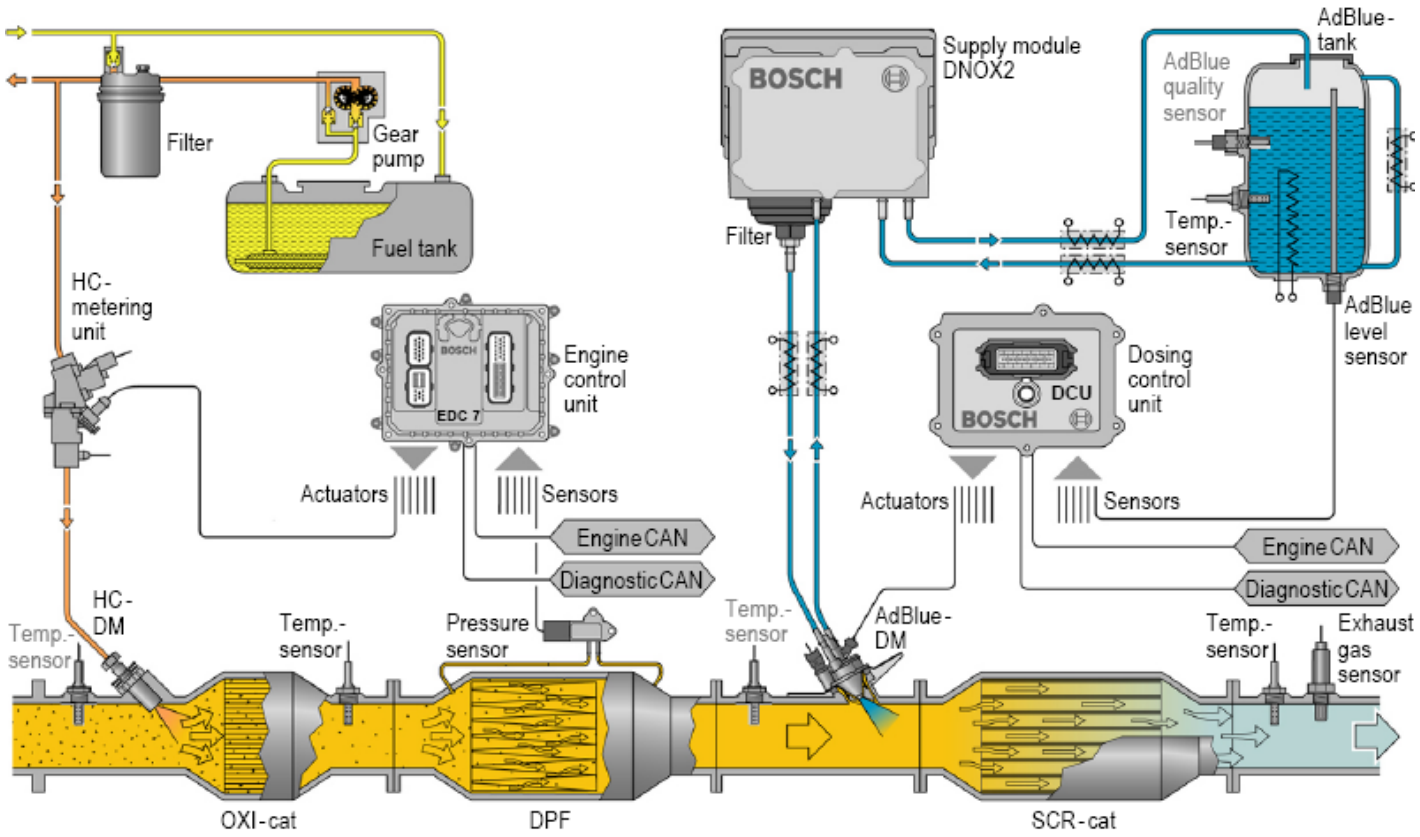
Examples of Europe urea systems and pre-tax pricing. 1 gal = 3.8 liter.



Projected US urea retail prices for various distribution methods. Examples of retail costs are about $0.74/liter at 3800 liter/mo and $0.40/liter at 9500 liter/mo.

TIAX, DEER 2006, 8/06

Layout of a PM/NOx urea-based system



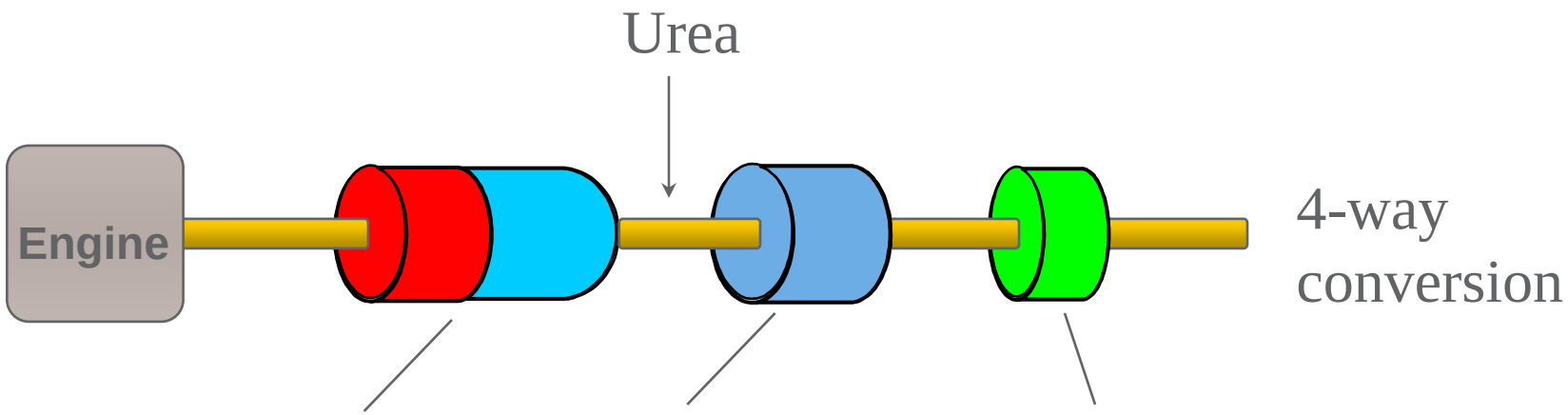
Key features:

- airless urea injection
- urea temperature control
- closed-loop aftertreatment control

Bosch, Euro V/VI conference 6-06

Examples of Integrated Systems

Integrated System Using a DOC, DPF, and SCR



Catalyst/Filter

Removal of
HC, CO, PM

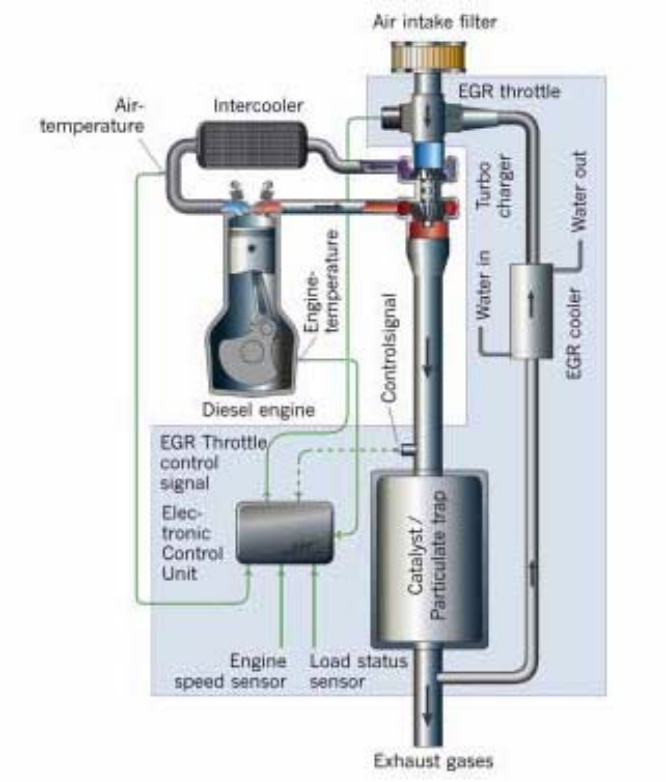
SCR

Removal of
NOx

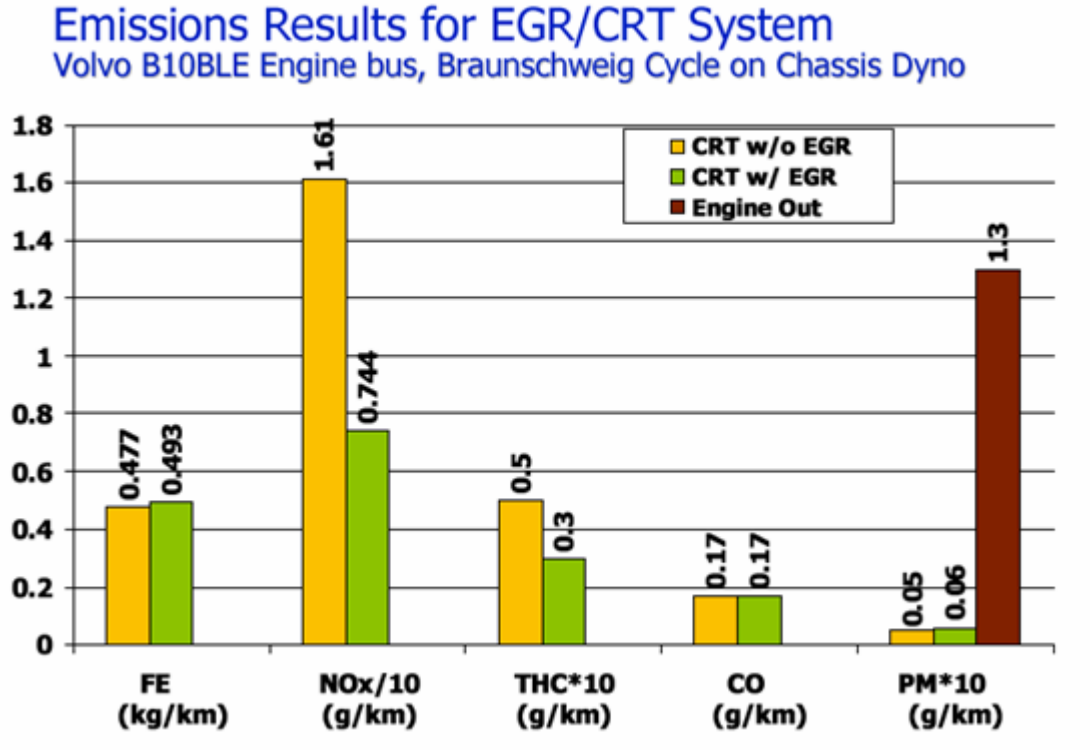
Oxidation Cat

Removal of
NH_3 slip if required

Integrated NOx and PM solutions are emerging for retrofit applications

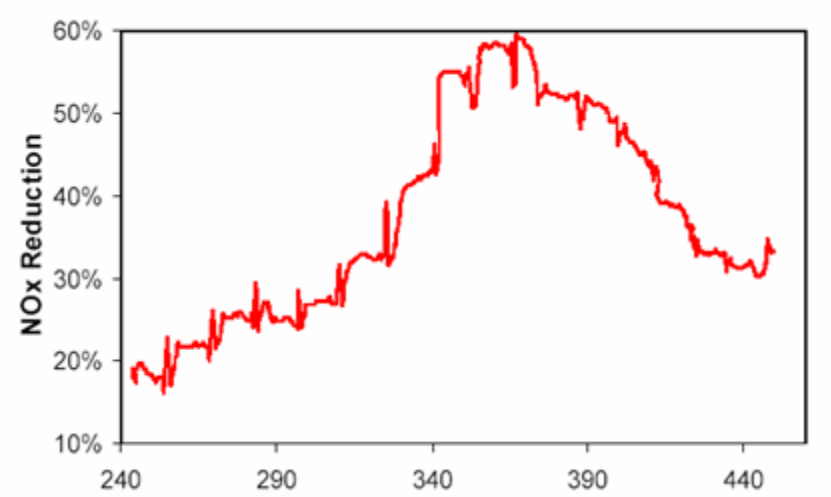


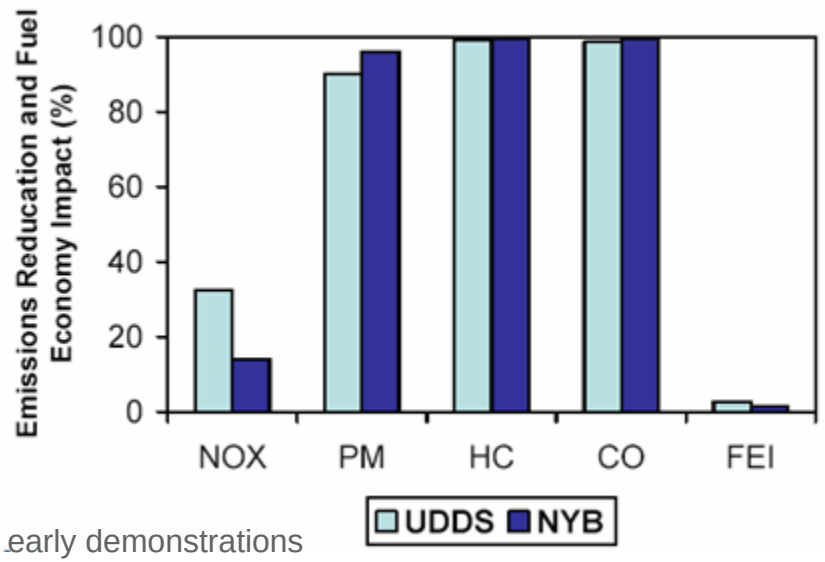
Low pressure (long route) EGR is best suited for retrofit applications. Inputs to EGR control are load, back pressure, and RPM.



54% NOx reduction and 96% PM reductions were experienced on a chassis dyno running on the Braunschweig test cycle. 5% fuel penalty

LNC+DPF systems are available for retrofit





The upstream NOx catalysts (HC-SCR) do not contain precious metals, but above 300 C they ask like oxidation catalysts. In addition to significant NOx reductions (up to 40%), this heats the filter and soot layer.

- Field test and early demonstrations
  - ~90 systems operating in the field
  - Used in transit, refuse, line haul vocational, and nonroad applications.
- Product success
  - Over 1,800 installations committed over the next 18 months.
- CARB verified in April, 2003
- Some Cummins and ITEC engines, others to follow
- 25% NOx reduction
- >85% PM reduction
- Verified for use with ULSD fuel

A Variety of Demonstrated Technologies Are Available to Significantly Reduce Emissions from HDDEs

- Filters applications are growing - significant PM, toxins, HC reductions
- Some NOx solutions are available - SCR for big time hit, NOx catalysts for easier, more modest reductions
- Fleet fuel offers solutions - emulsions, fuel-borne catalysts for PM, HC, NOx reductions