Emissions and control – CI engines

4A13

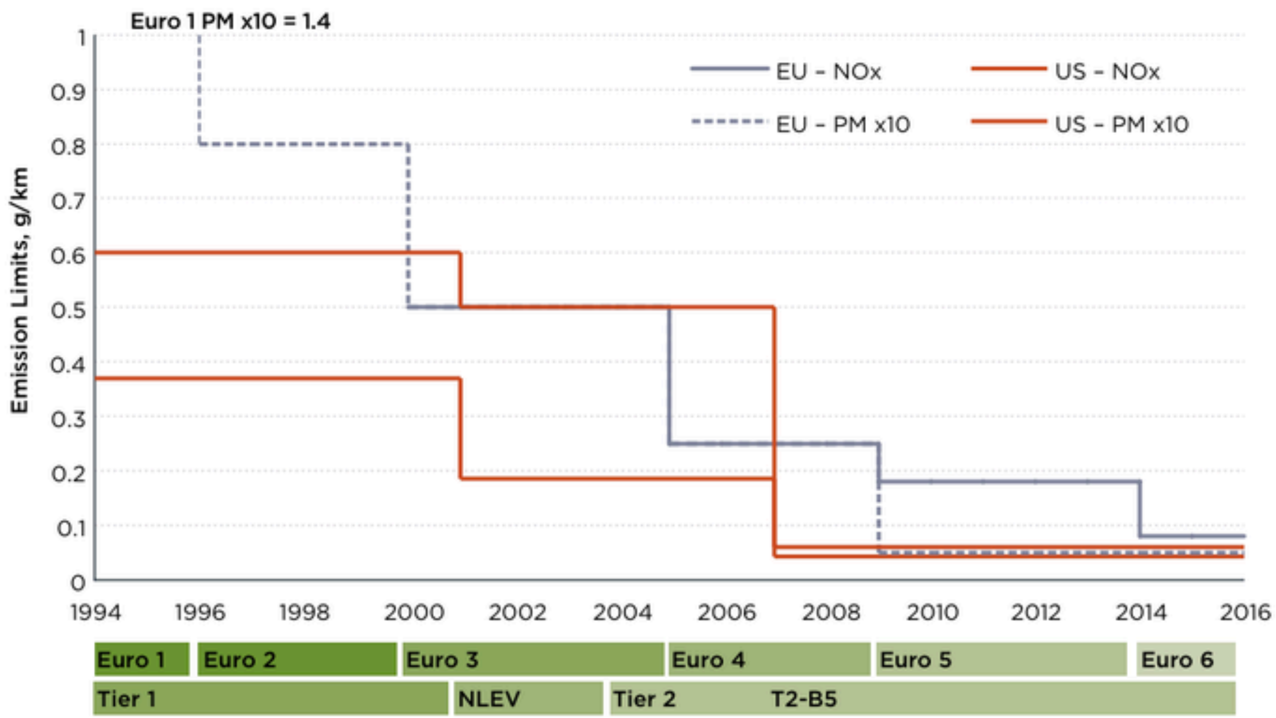
Heywood, Ch. 11: Pollutant formation and control
Stone, Ch. 3.8: Engine emissions

CI engines

http://www.cleanmpg.com/photos/data/500/di.jpg

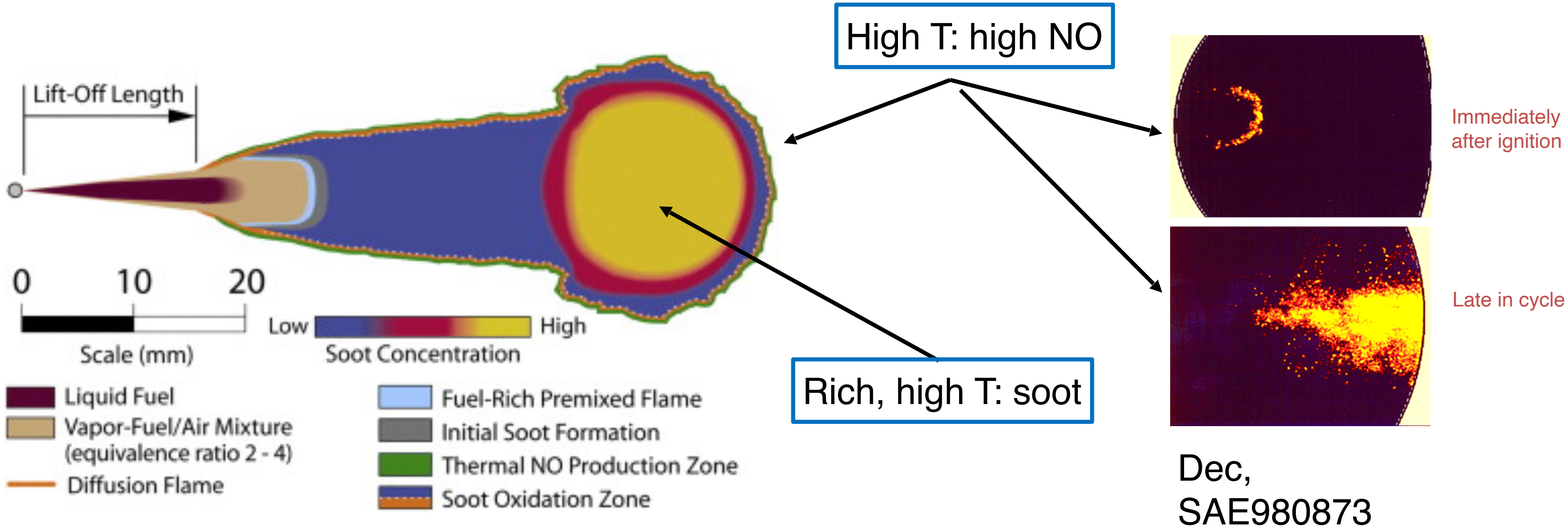
Criteria pollutants for CI: NOx and PM

•Nitric oxides (NOx)	air + high temperatures
•Particulate matter (PM)	rich, high temperature fuel pockets
•Hydrocarbons (NMHC)	not usually a problem, as engines run lean
•Carbon monoxide (CO)	not usually a problem, as engines run lean



http://transportpolicy.net/images/thumb/9/9a/Ldv_emissions_graph_-_diesel.png/700px-Ldv_emissions_graph_-_diesel.png

Review: NO and soot formation in CI engines



Dec,
SAE980873

http://dx.doi.org/10.1016/j.pecs.2012.09.001

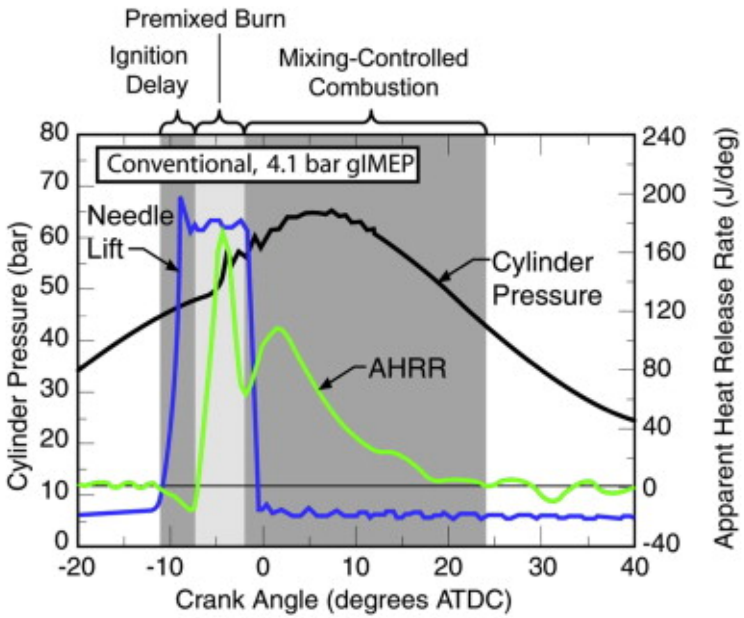
Non-premixed flame : high temperatures → **high NOx**
Soot production at rich conditions, high temperatures → **high PM**

Engine-out control methods:

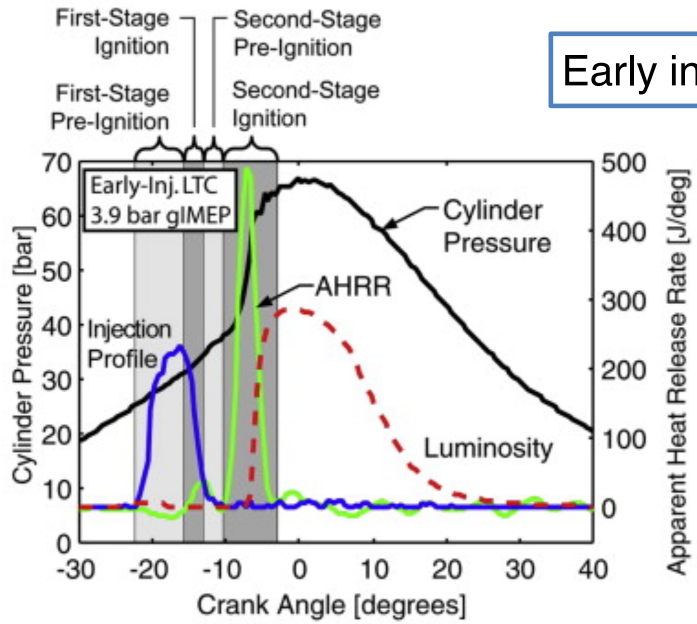
- **more premixing:** small high velocity droplets, multiple injections (lowers NOx and soot, higher noise)
- **dilution:** EGR lowers overall temperatures to lower NO, but make it more difficult to oxidise soot.

Review of combustion modes in CI engines

Normal



Early injection



- **Single injection near TDC operation:** simpler strategy, good noise characteristics with smooth combustion, but produces non-premixed flames for a larger fraction of combustion, leading to **higher soot and NOx.**
- **Early injection:** provides **more premixing**, and thus **lower NOx and PM emissions**, but typically a **sudden higher rate of heat release rate and pressure rise:** more noise limits the total pressures and loads that can be reached.
- **Multiple injection:** The number and mass fraction of injections is varied with operating conditions to optimise the balance between emissions, efficiency and noise and vibration.

http://dx.doi.org/10.1016/j.pecs.2012.09.001

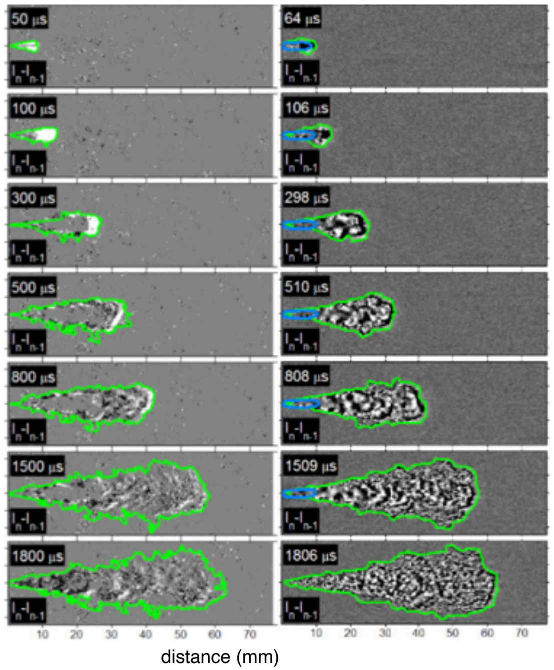
Improving atomisation: high pressure injection

Injection interval:
1500 µs

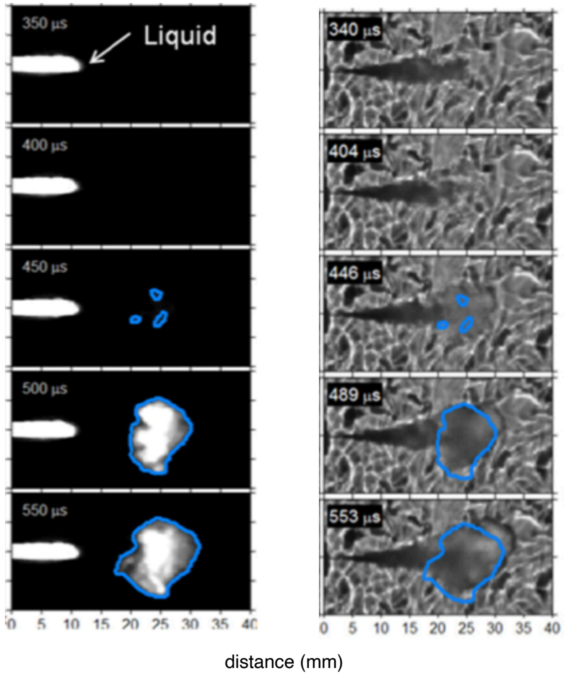
non-reacting single spray (schlieren images: density patterns)

900 K
6 MPa

schlieren over 1500 µs



luminosity schlieren

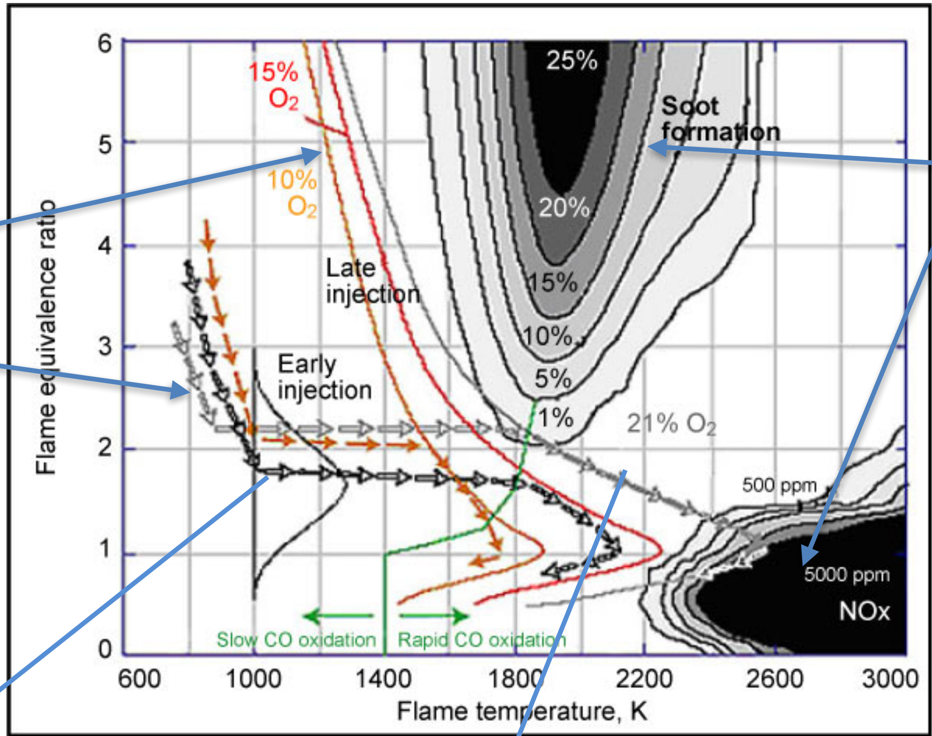


reacting single spray

. 2010, SAE *Int. J. Engines* , Vol. 3, No. 2 (2010), pp. 156-181
jstor.org/stable/10.2307/26275554

High pressure atomisation using high pressure injector: 1000-3000 bar, 100-200 micrometer holes!
Higher momentum and smaller droplets: better combustion with lower emissions

Methods of in-cylinder control of NOx and PM



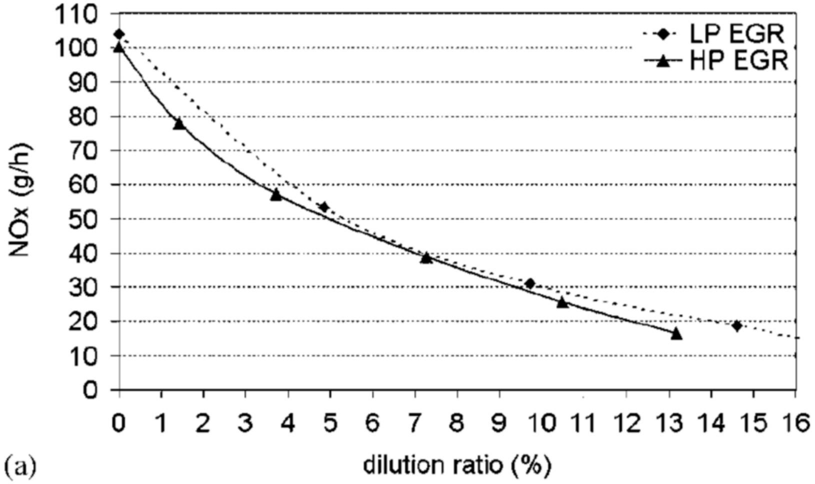
mixture trajectories

computed iso-contours of soot and NOx formation for a given residence time at a given ϕ, T

Better premixing
Low T combustion,
multiple injections

Higher dilution by EGR means lower O_2 than normal air (<21%) leading to lower temperatures, and overall lower NOx, but increase in soot
Limits to EGR: low load (too dilute) and incomplete combustion (high CO, HC)

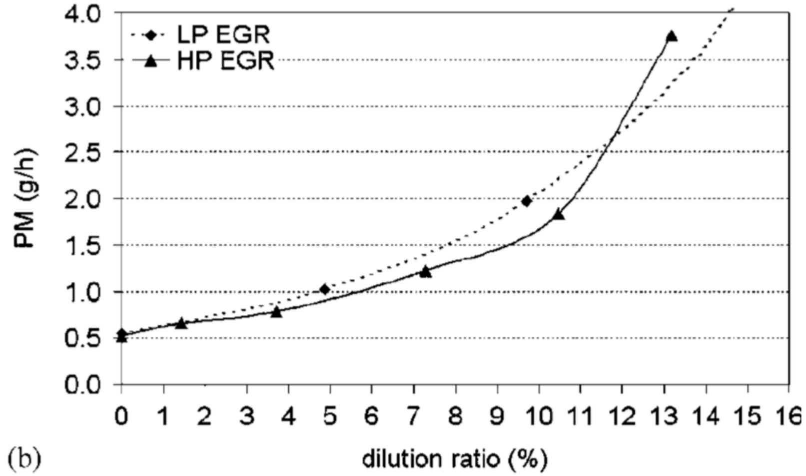
Effect of EGR on PM and NOx



$$DR = 1 - X_{O2}/0.21$$

EGR lowers NOx and increases PM

Int. J. Energy Res. 2008; 32:1383–1398
DOI: 10.1002/er.1455



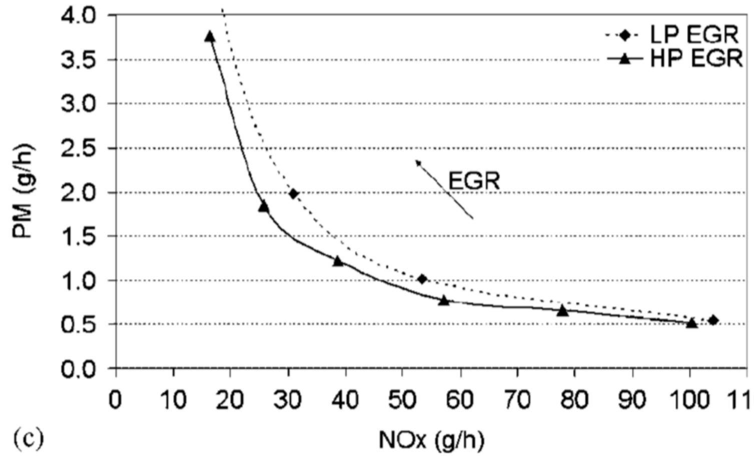
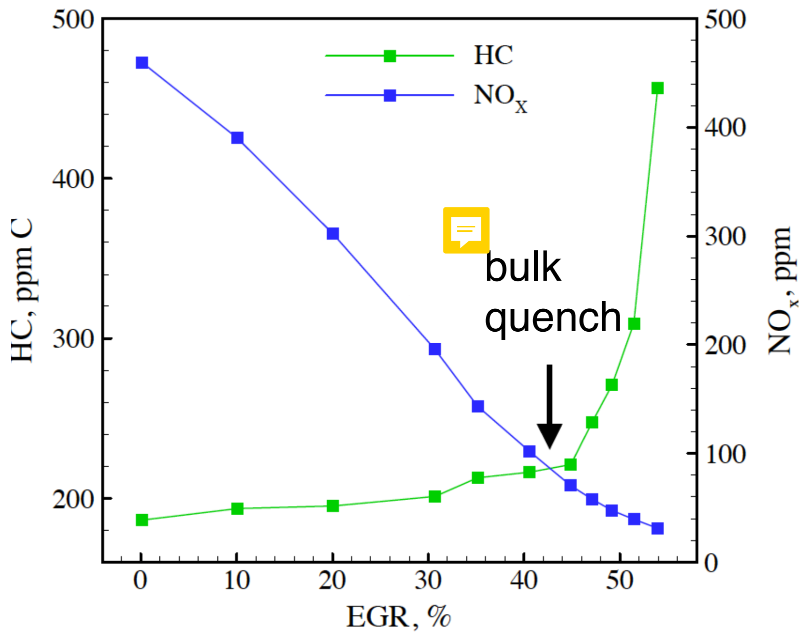
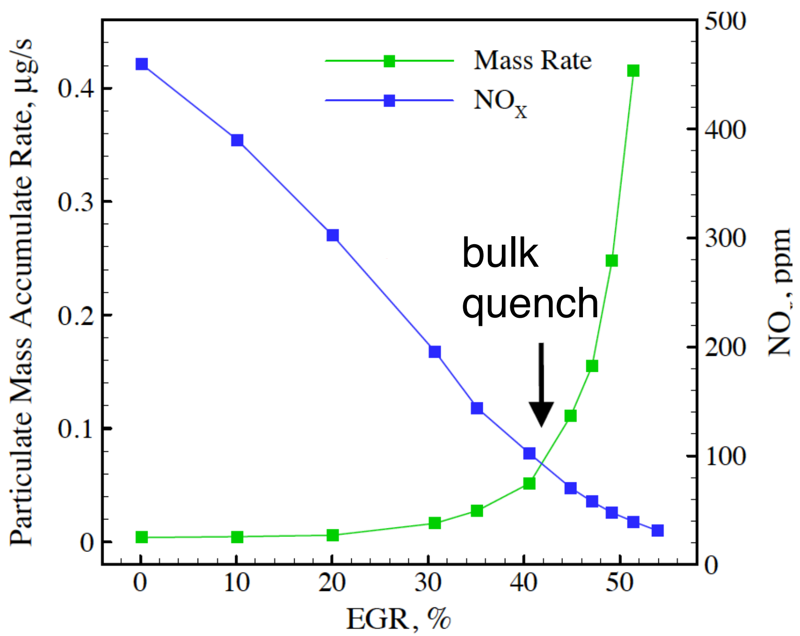


Figure 3. Comparison between HP and LP EGR on NO_x and PM emissions, operating point B.

HC vs NOx in CI engines



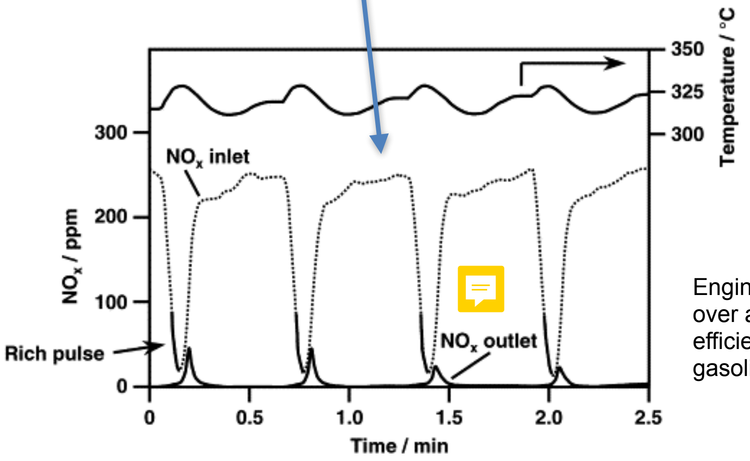


Battelle, OakRidge National Labs,
`http://angst.engr.utk.edu/`

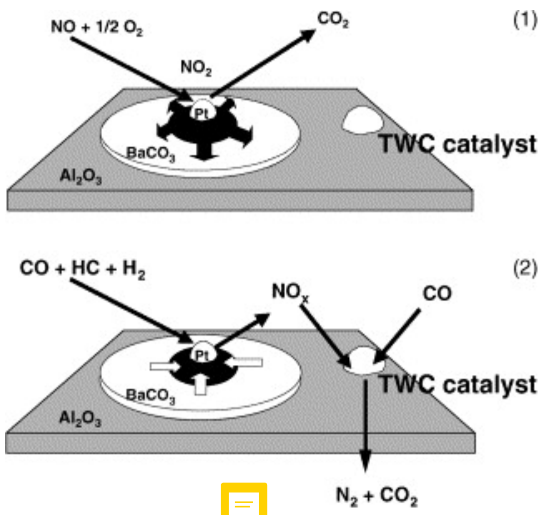
EGR limited by onset of **bulk quench** (post-flame oxidation stops), leading to very high HC, CO, PM

Lean DeNOx catalysts

- Lean operation desirable for efficiency (higher γ , lower HC, PM emissions), but…
- NOx removal a challenge:
  - **NOx trap:** holds NOx during lean operation until it is switched to stoichiometric/rich for regeneration/reduction (barium carbonate, ceria)
  - **SCR: S**elective **C**atalytic **R**eduction: ammonia (NH_3) or urea ($(CO(NH_2)_2$) added
  - **Active DeNOx**: inject fuel periodically to regenerate catalyst



Engine-out and tailpipe-out emissions from a 1.9 L diesel engine over an NSR catalyst deposited on a ceramic filter. Similar efficiencies may be achieved over the NSR catalysts in lean gasoline engines



Principle of operation of an nitrogen storage catalyst: NOx is stored under oxidising conditions (1) and then reduced on a three way catalyst (TWC) when the A/F is temporarily switched to rich conditions (2).

Catalysis Today, Volume 77, Issue 4, 2003, 419–449 http://dx.doi.org/10.1016/S0920-5861(02)00384-X

Selective Catalytic Reduction (SCR)

Urea decomposition

$H_2N\text{-}CO\text{-}NH_2 + H_2O \rightarrow CO_2 + 2NH_3$

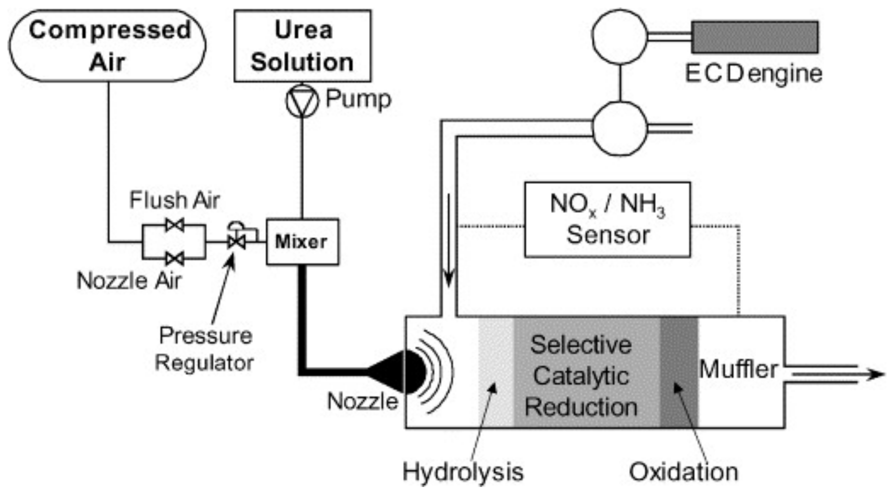
Ammonia reduction

$4\ NO + 4\ NH_3 + O_2 \rightarrow 4\ N_2 + 6\ H_2O$

$6\ NO_2 + 8\ NH_3 \rightarrow 7\ N_2 + 12\ H_2O$

Good removal efficiency, but requires ammonia (from urea)

Ammonia slip across exhaust also a problem



A typical arrangement for abatement of NO_x from a heavy duty diesel engine using urea as reducing agent.

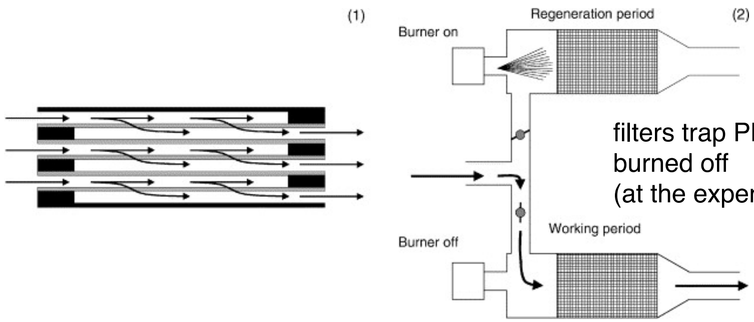
Catalysis Today, Volume 77, Issue 4, 2003, 419–449 http://dx.doi.org/10.1016/S0920-5861(02)00384-X

PM removal

- PM: 40-500 nm diameter
  - Soot
  - Soluble organic fraction (SOF): coats soot
  - Sulphates (from fuel S)

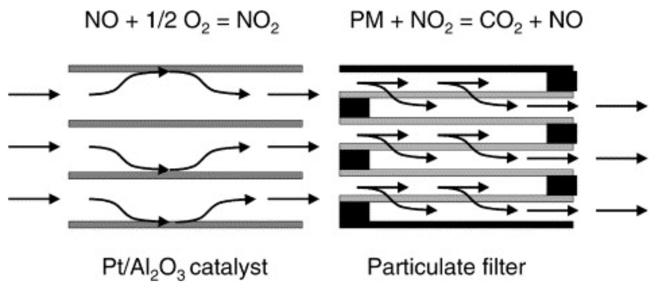
- Solid & organic fraction removal:
  - oxidation catalyst (CeO_2, AlO_2/Pt)
  - low temperatures of exhaust of efficient engines are a problem (120-350 ^oC), as is sulphur poisoning from fuel (controlled in EU to <500 ppm in liquid fuel)

- Soot removal:
  - filtration (DPF: Diesel Particle Filtration)



filters trap PM, which gets periodically burned off
(at the expense of burned fuel)

  - continuously regenerating trap

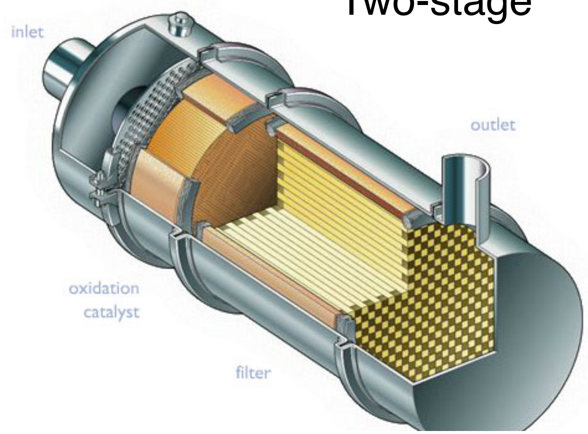


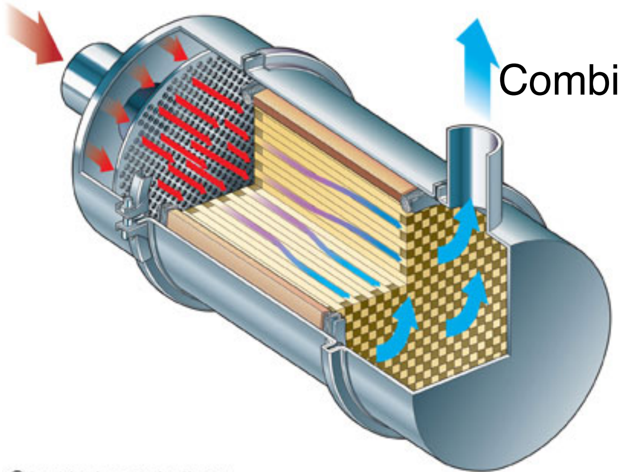
NOx trap followed by PM trap. Periodic flow between one and the other.

Regenerating Oxidation Particle Filter

Oxidation catalysts generate NO_2
Particles are oxidized downstream by both NO_2 and O_2
Careful management of **temperatures** and **stoichiometry** periodically to regenerate particle filter.

Two-stage





Combined

Oxidation

$[C] + O_2 \rightarrow CO_2$	$T > 500$ C
$[C] + NO_2 \rightarrow CO_2 + NO$	$T > 250$ C

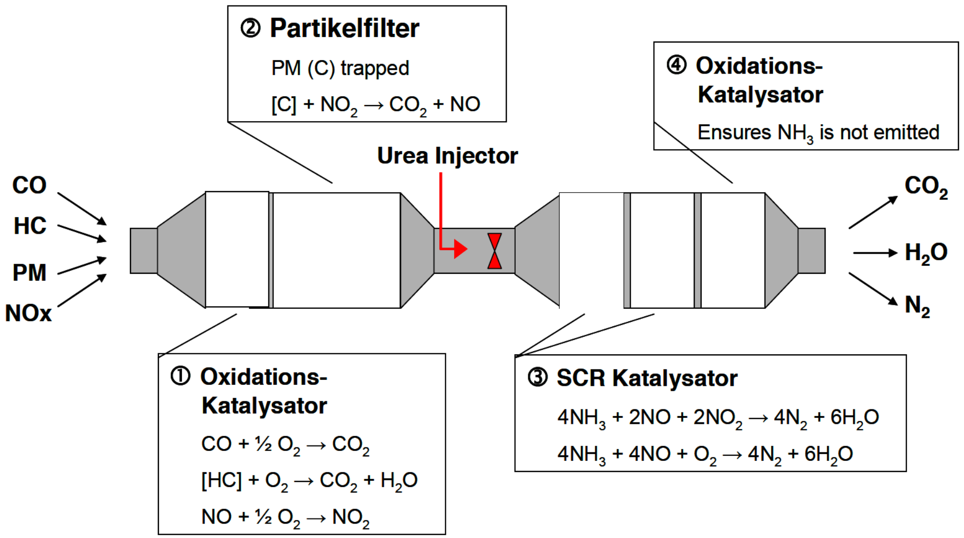
Various other alternatives, using fuel-borne catalysts, electrical heating, etc.

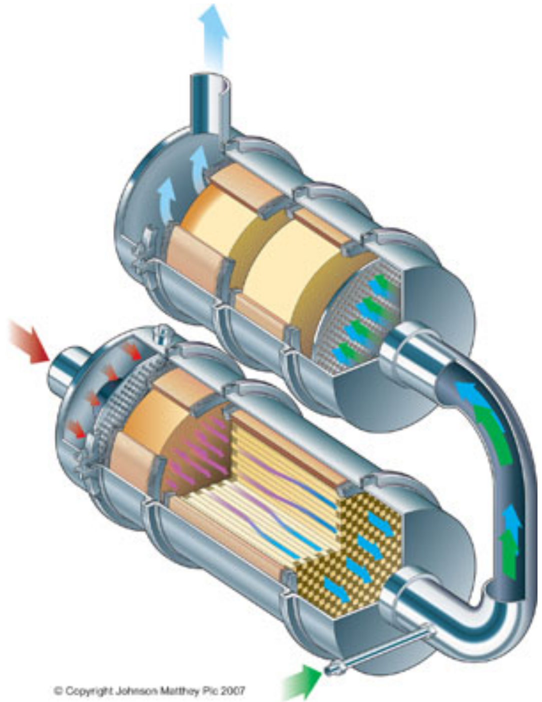
http://www.axces.eu

NOx + PM + CO + UHC removal

Selective catalytic reduction

CRT® System + SCR System = SCRT® System





$4NO + 2(NH_2)_2CO + O_2 \rightarrow$
$4N_2 + 4H_2O + 2CO_2$

Requires urea ($2(NH_2)_2CO$) or ammonia (NH_3) (typ. extra tank)

http://www.jmdpf.com/pdfs-library/

Summary: in-cylinder strategies for low emissions CI

NOx

- **Fuel injection** systems for improved mixing rate
  - High pressure rail: small droplets
  - Early injection: more time for mixing
  - Multiple injections: better spatial mixing
  - Issue: cost, weight, deposits on injector
- **EGR**
  - Lowers flame temperature by mixing with entrained air and products
  - Cooled: lowers charge temperature further
  - Limit: combustion stability and completeness, higher soot (lower temps)
- **Combustion chamber design for improved mixing**
  - Increased swirl
  - Bowl geometry (tumble)
- Charge air **cooling** (additional intercooler needed)

PM

- **Fuel injection systems**
  - High pressure: smaller droplets improved mixing rate, limits excursions into rich, high temperature regions
  - Increased injection rate: higher velocity jets improve mixing rates
  - Injection timing advance: more mixing
  - Multiple injections: more mixing
- Fast in increased in **charge air** (turbo) during acceleration (storage)

Summary: Exhaust control technologies

NOx

- Lean NOx catalysts
- Selective catalytic regeneration
- NOx adsorbers/regenerators
- [Plasma assisted catalysis]

PM

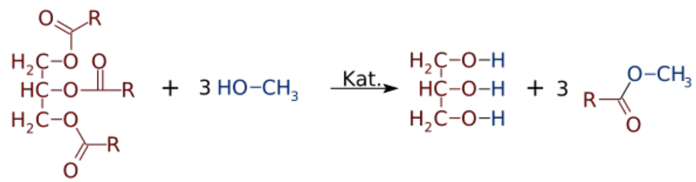
- Diesel oxidation catalysis
- Particulate traps
  - Passive regeneration
    - Fuel additives
    - Catalyst loaded
  - Active regeneration
    - Electric
    - Burner

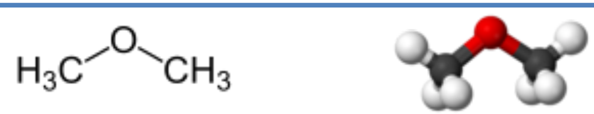
Fuel efficiency penalties of 1-5% for regeneration, all lead to additional marginal penalties

How about using different fuels?

- **Diesel fuel changes**
  - Lower sulphur: lower poisoning
  - Lower aromatics: lower soot
- **Diesel fuel additives**
  - Cerium, sodium, copper, other: inherent catalysts, but expensive and can form deposits
- **Biodiesels and synfuels**
  - Significant lowering of soot (straight long oxygen containing methyl esters), but concerns about life-cycle CO_2 emissions, forest destruction etc.
- **Dimethyl Ether (DME)**
  - Small molecule with high oxygen content, eliminates soot. Produced from natural gas
- **Fischer-Tropsch**
  - Synthetic hydrocarbon paraffin from e.g. biogas: straight-chain produces lower soot

vegetable oil biodiesel (less corrosion)





$$(2n + 1)\, H_2 + n\, CO \rightarrow C_nH_{2n+2} + n\, H_2O$$

Quiz time

https://www.vle.cam.ac.uk/mod/quiz/view.php?id=11945312