Emissions and control – SI engines

4A13

Heywood: Chap. 11: Pollutant formation and control
Stone: Chap. 3.8: Engine emissions and HC oxidation

SI engines

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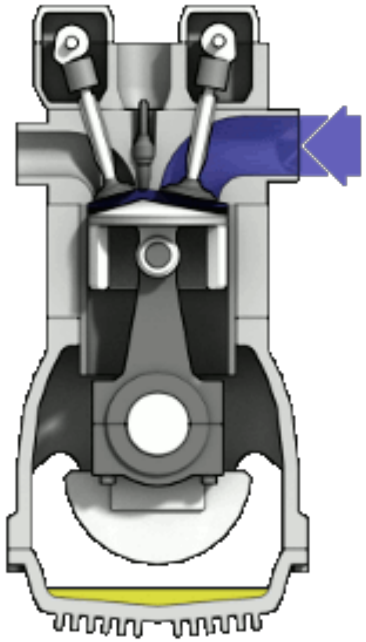


The problem

Pollution

London breaches annual air pollution limit for 2017 in just five days

Brixton Road in Lambeth has already broken legal limits for toxic air for the entire year, with many other sites across the capital set to follow

Damian Carrington

@dpcarrington

Friday 6 January 2017 10.03 GMT

23,305 1,893

Air pollution and traffic on Putney High Street on 3 January 2017, one of London's worst pollution hotspots. Photograph: Elizabeth Dalziel/Greenpeace

German court paves way for diesel driving bans

AFP Andrea HENTSCHEL with Michelle FITZPATRICK in Frankfurt

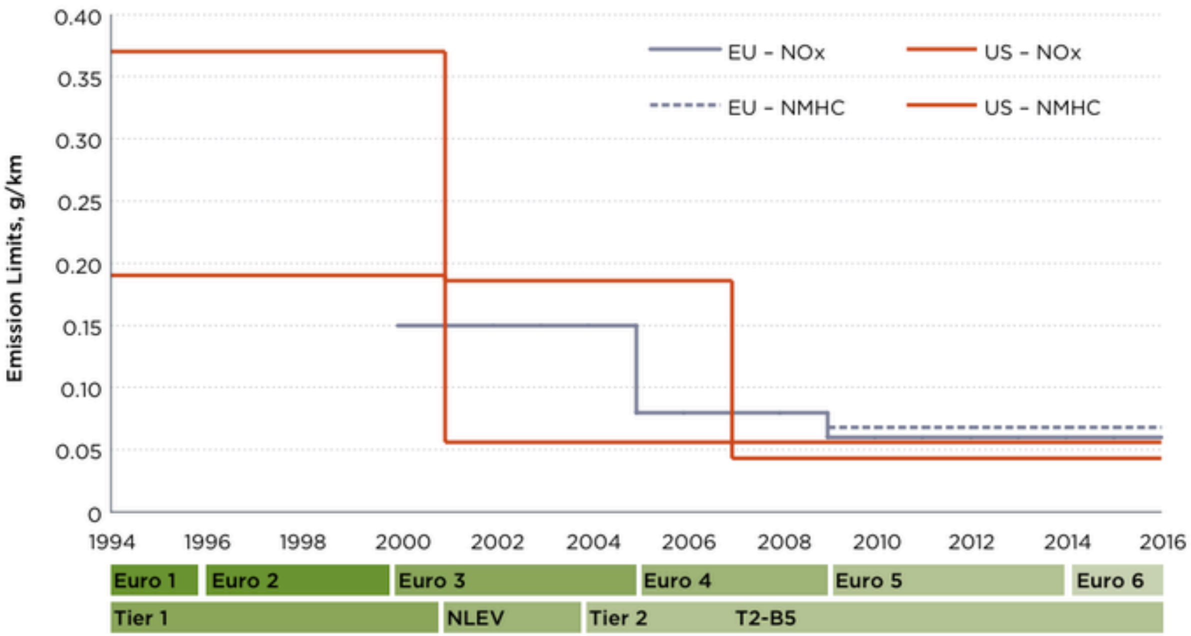
AFP 27 February 2018

Environmental activists, seen here last week in front of Germany's Federal Administrative Court, have won a major ruling that will allow cities to impose bans on older, more polluting diesel vehicles in order to combat air pollution

Photocatalysed reactions of hydrocarbons, nitric oxides, carbon monoxide and soot emitted produce urban ozone (O3) and a variety of peroxynitrates (PAN), leading to poor visibility (smog). Ozone, particulate matter and carbon monoxide all correlate with increased mortality in urban zones.

Criteria (regulated) pollutants

Pollutant	Origin	Effect
Nitric oxides (NOx)	air + high temperatures	direct health effects, production of PAN via photocatalysis and on to smog
Particulate matter (PM)	rich fuel pockets at high temperature	inhaling of nanoparticles leads to respiratory distress
Hydrocarbons (HC)	poorly vaporised fuel, crevices	contributes to PAN formation
Carbon monoxide	partially burned fuel, usually from cold start	toxic, co-morbidities with PM



http://transportpolicy.net/

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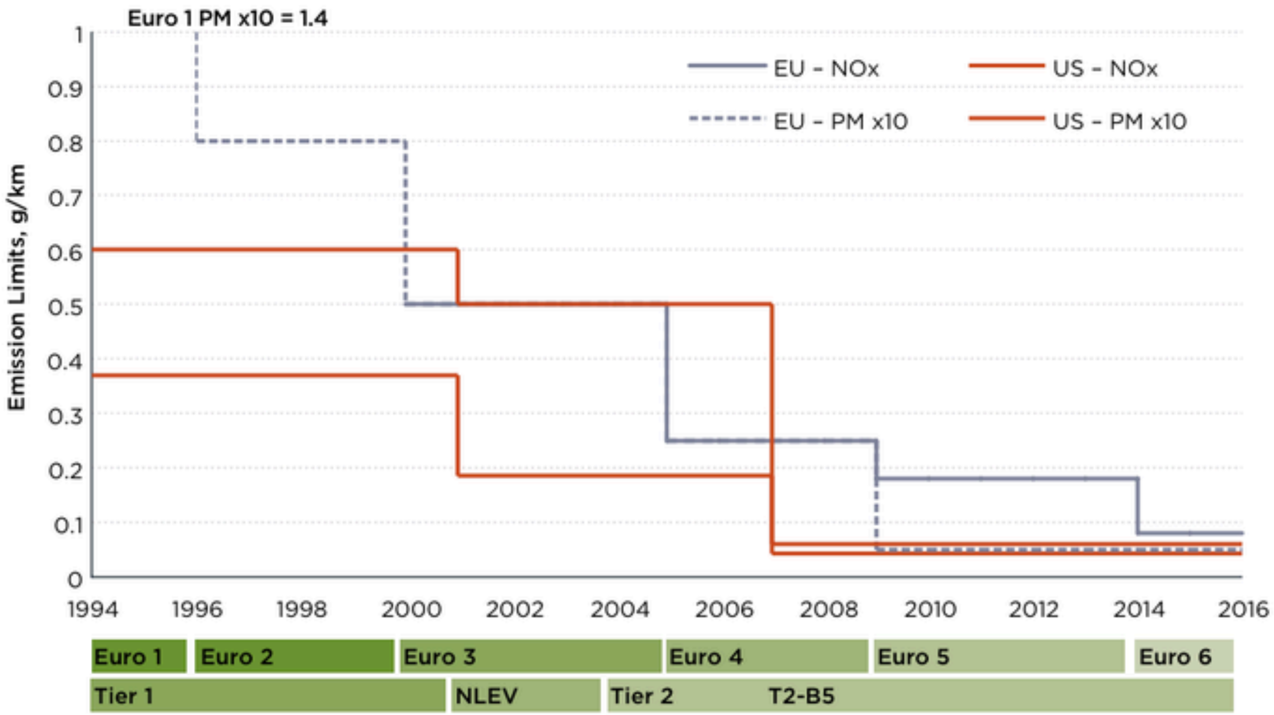
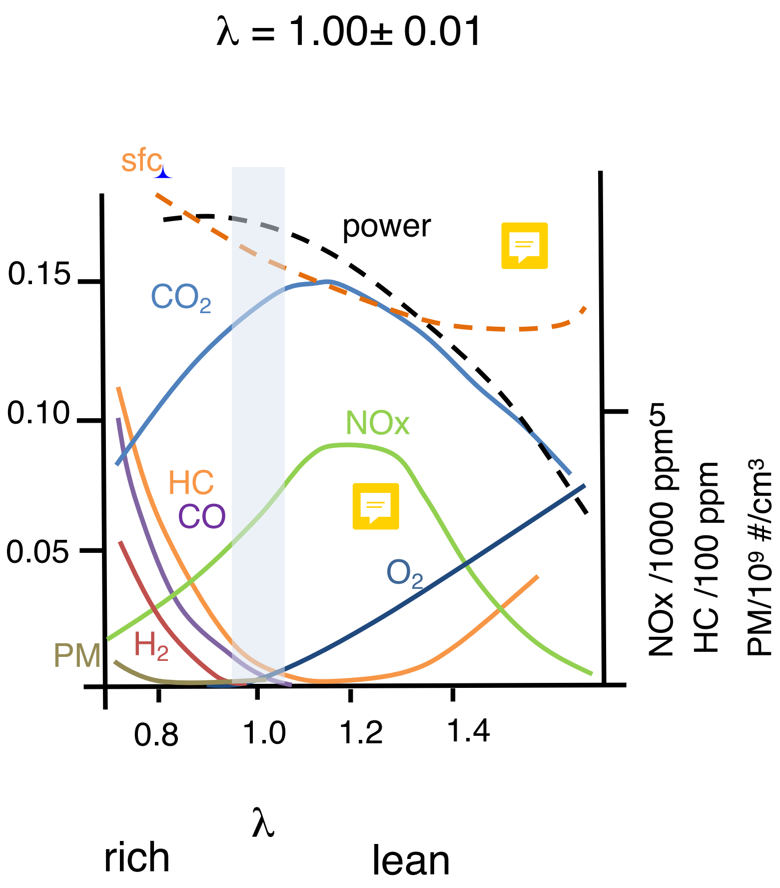


http://transportpolicy.net/

Engine-out emissions vs air-fuel ratio



Engine-out concentrations:

- Major species: approximately at equilibrium (except CO)
- NOx: peaks on lean side
- HC: oxidizes in lean range
- PM: produced by rich pockets at high temperature

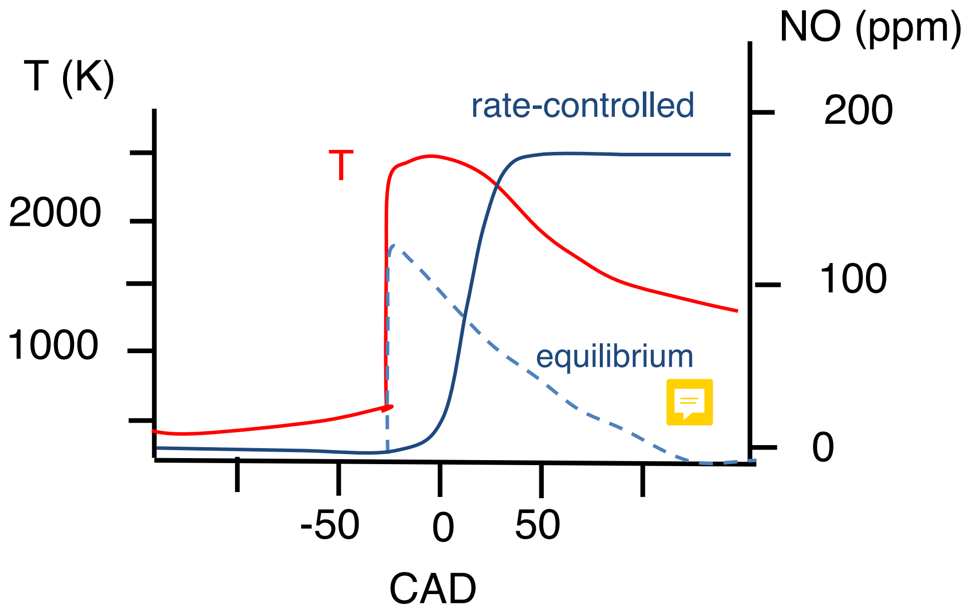
Solution 1: operate very lean

- Very low emissions for λ> 1.4
- sfc can also improve at very lean range (γ effect)
- Problems: 1) poor cycle to cycle stability (too lean), 2) NOx cannot be removed under lean conditions. 3) very high HC

Solution 2: catalytic removal

- 3-way catalyst removes 90-99% HC, CO, 80-90% NOx at stoichiometric conditions (details further on)

NO formation in SI engines



Thermal (Zeldovich) mechanism: main route

$O + N_2 \rightarrow NO + N$
$N + O_2 \rightarrow NO + O$
$N + OH \rightarrow NO + H$

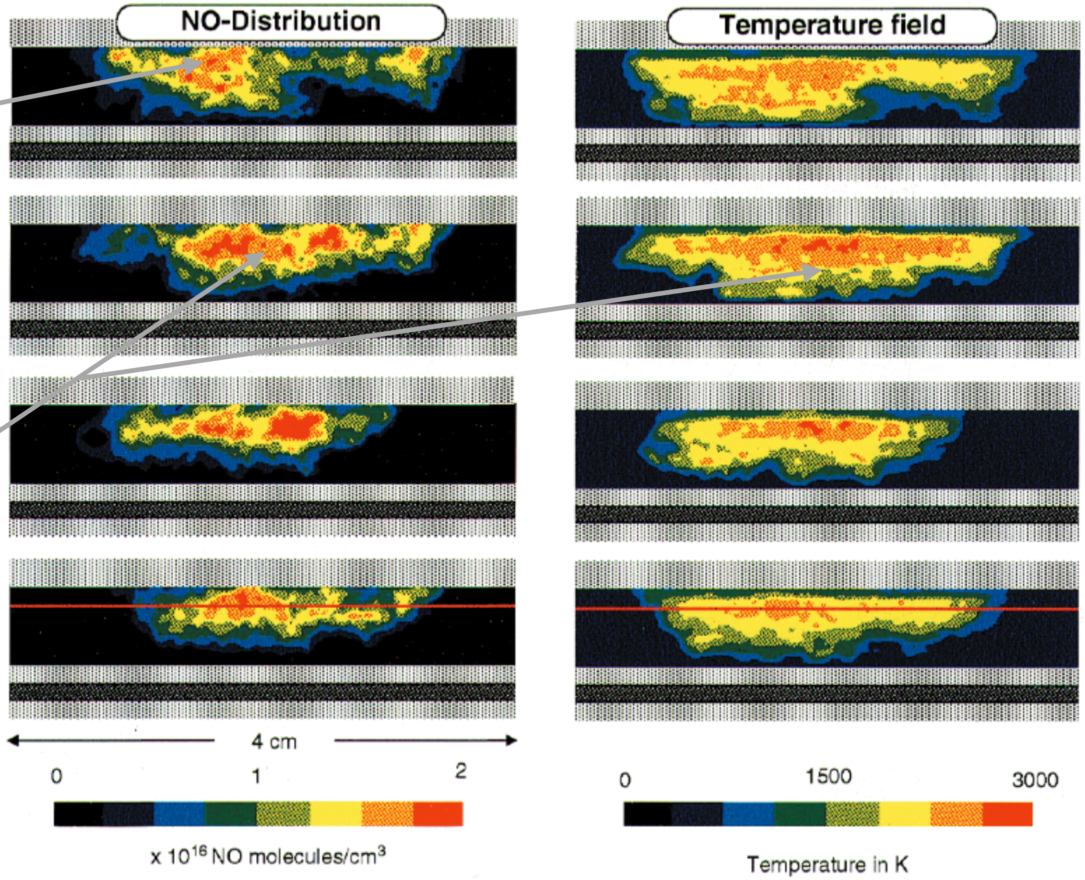
High activation energy process: *very* temperature dependent, slow reaction except at high temperatures

NO concentrations are NOT in equilibrium: kinetic control owing to slow reactions, freezes at high level if taken to high temperatures

NO formation in SI engines

NO concentrations appear in the burned gasses

high temperatures correlate with high NO

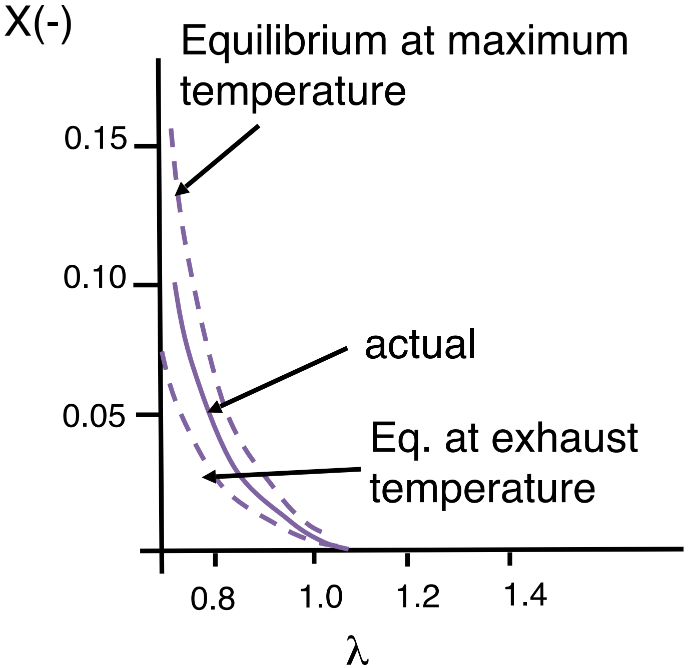


single-shot images
8^o BTC

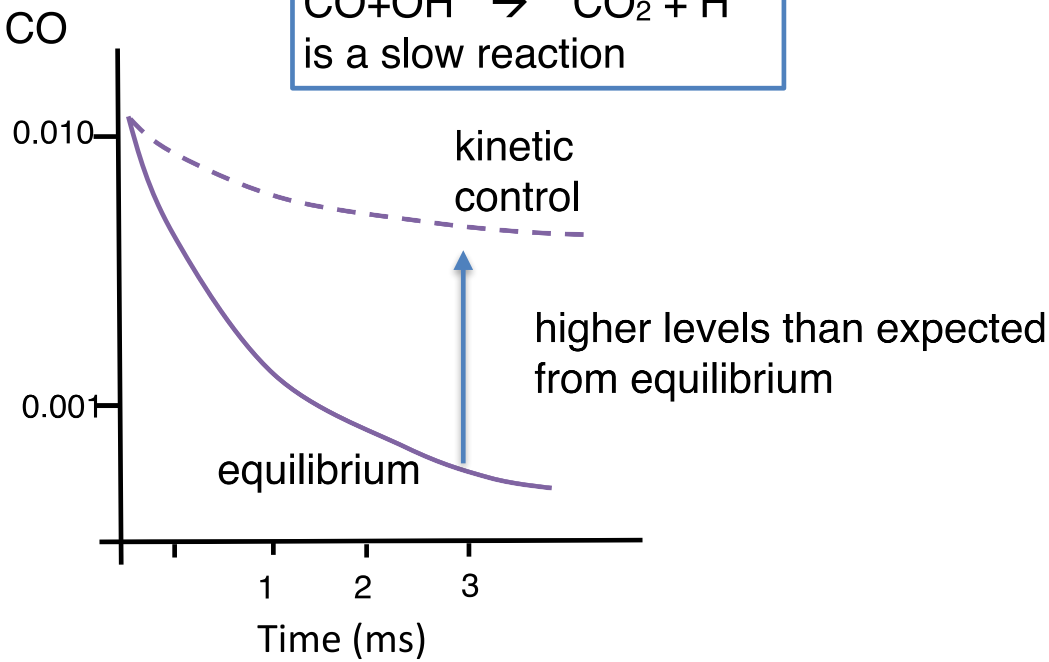
FIG. 4. Simultaneous single-shot absolute NO concentration and temperature fields in the transparent engine fueled with propane/air at λ = 1.0. Ignition at 340 °CA; detection at 352 °CA, 1000 rpm. The horizontal line in the lowest picture indicates the position of the profiles shown in Fig. 5.

C. Schulz et al, Proc. Comb. Inst. 36, 1996/pp. 2597–2604

CO formation in SI engines

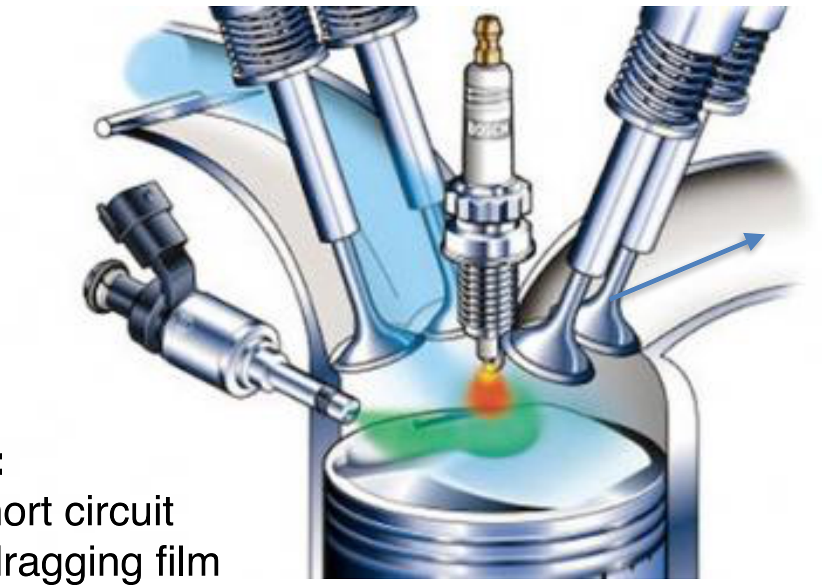


$CO + OH \rightarrow CO_2 + H$
is a slow reaction



Cold start: fuel-rich operation to compensate for poor vaporisation → over-rich operation during first few cycles can also lead to high CO emissions

Unburned hydrocarbons



partial oxidation:
HC oxidised along exhaust, but not sufficiently to eliminate all emissions. Typically 1-2% HC escapes combustion during steady operation.

crevices:
quenched mixture is stored in small gaps (crevices) between piston and cylinder

unvaporized fuel:
- liquid fuel can short circuit by **injection** or dragging film during open valve
- during **cold start** the engine operates fuel rich
- **cold temperatures** lead to higher liquid fuel fraction
- temporary **fuel-rich** operation

HC dissolved in oil:
- small amounts of fuel (<1%) **blow by the rings** into the oil. The gases are brought back into the manifold, but some can find their way back via crevices.

Engine-out particulate matter emissions: DISI (GDI) engines

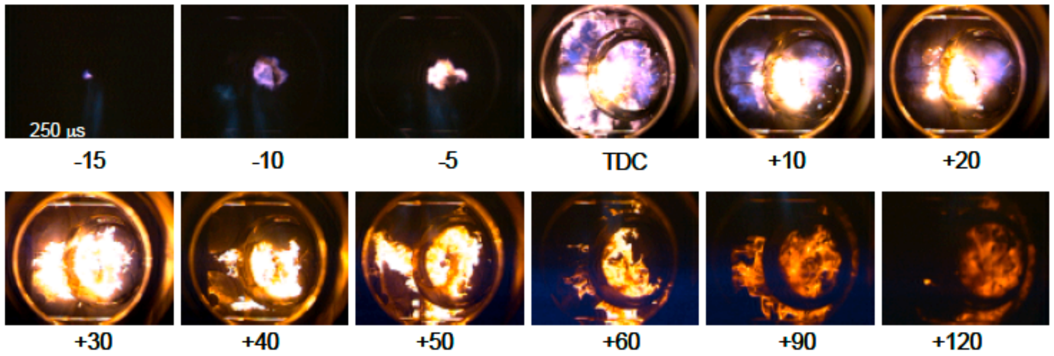
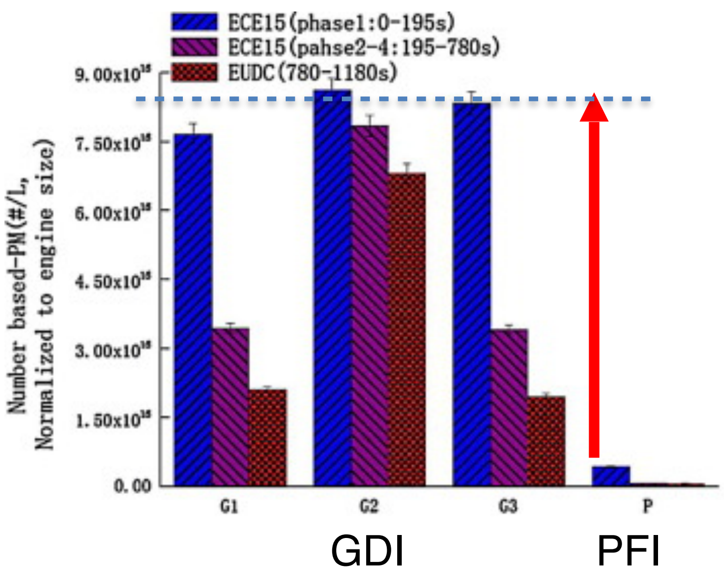


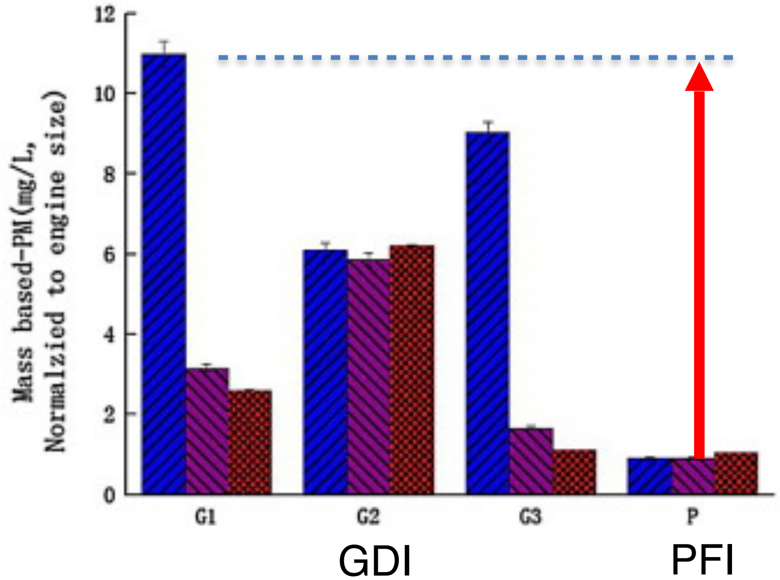
Figure 15. Color images (single frame) of the combustion process, visible through the quartz piston. SOI = -70 °TC. Aperture f#1.8 (max), 100 µs gate, except for –15 and +120° images (250 µs).

Emerging problem: gasoline DI more efficient, but more PM, especially at cold start

SAE SAE2001-01-3645

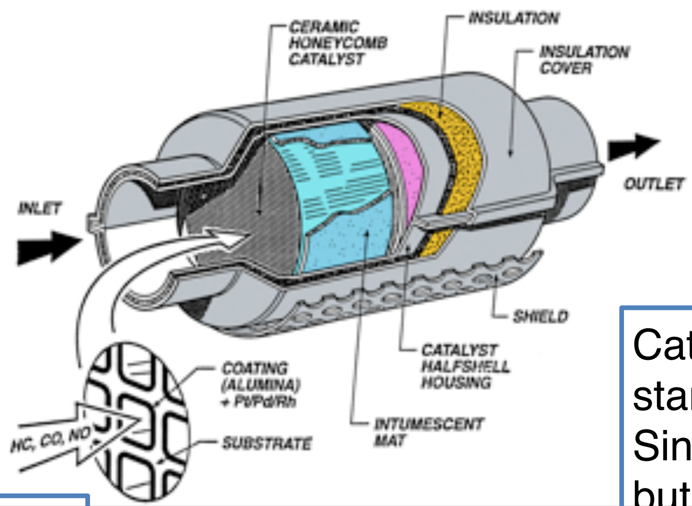


http://dx.doi.org/10.1016/j.fuel.2016.10.055



Three-way catalyst operation

Demands very accurate λ control within 0.001 :
λ– sensor
1 Hz fluctuation: ox/red
typically ceramic O_2 sensor



Pt/Pd/Rh and CeO_2 on structured alumina: stores HC, CO, O2
CeO_2 stores O_2 for part of the cycle; released during oxidation step

Catalyst needs >200 °C to work (problem at start up)
Sintering >900 °C: location near exhaust but not too close. Poisoning by sulphur in fuel or lubricant.

High surface to volume ratio required
~ 1 mm hydraulic diameter channels
(cost: pressure drop)

Rich: store HC for reduction of NO

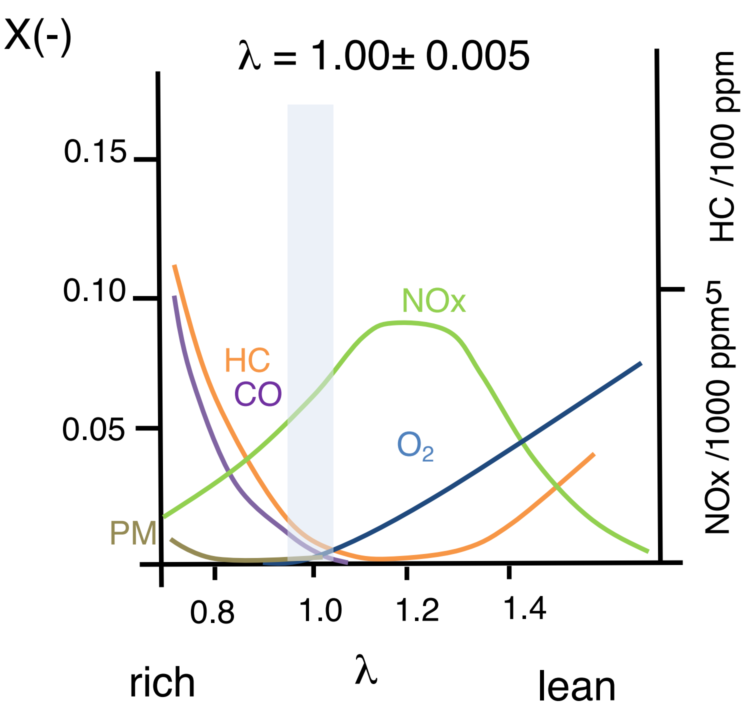
$4HC + 10\,NO \rightarrow 4\,CO_2 + 2H_2O + 5N$
$2CO + 2NO \rightarrow 2CO_2 + N_2$

Lean: store O_2 for oxidation of HC, CO

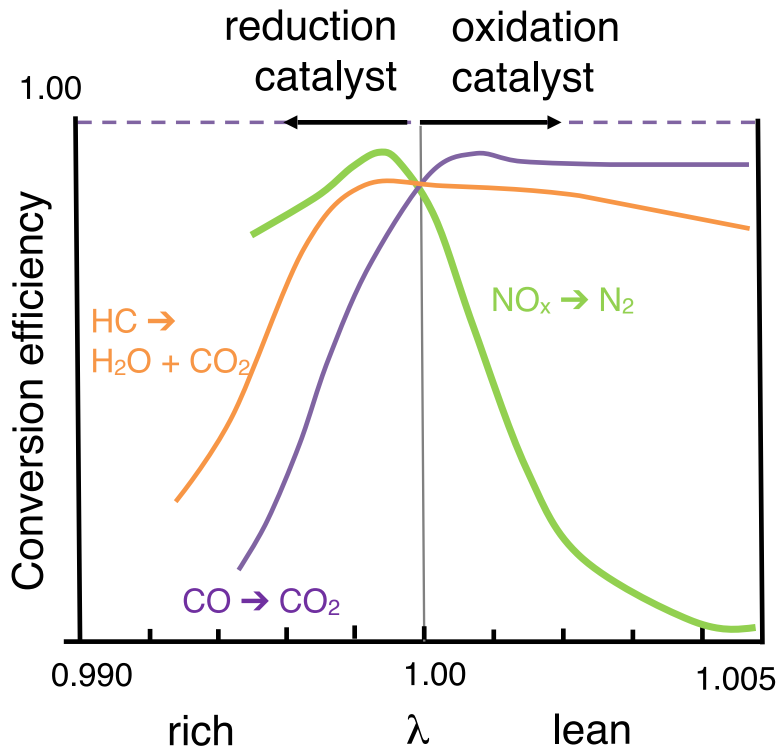
$4HC + 5O_2 \rightarrow 4\,CO_2 + 2H_2O$
$2CO + O_2 \rightarrow 2CO_2$

http://www.meca.org/resources/featured-article

Engine out emissions and catalyst efficiency

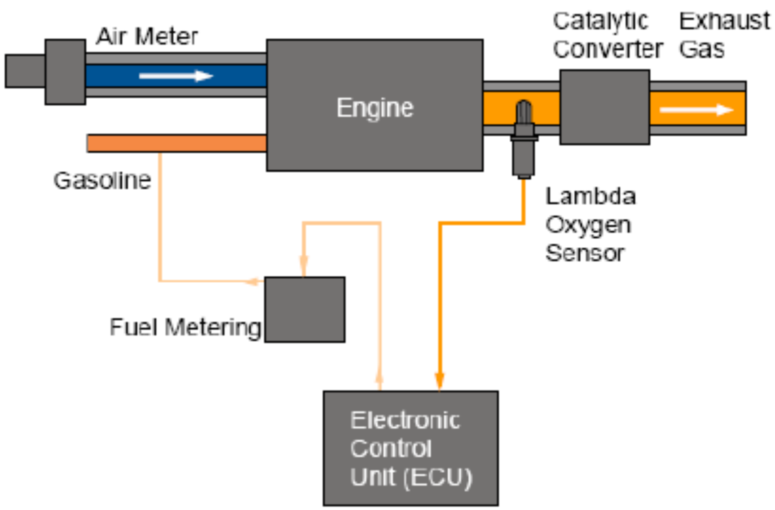


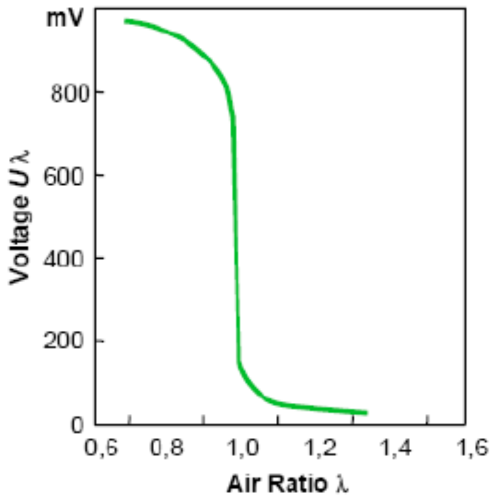
engine out emissions



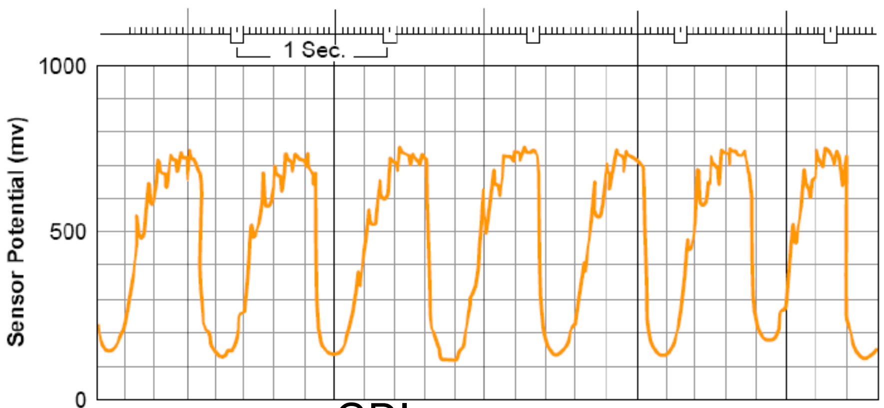
3-way catalytic converter efficiency: stoichiometric operation necessary for peak efficiency for HC, CO and NOx

Lambda fuel control





Lambda sensor: Solid state Electrochemical cell permeable to O_2 ions



GDI

Feedback control to engine based on lambda sensor.
(open loop or different strategies at cold start and hard acceleration conditions)

Three-way catalyst issues

Fast light-off:
- close coupling near engine to reduce cold start emissions.
- lightweight materials
- electrical heater, HC adsorber

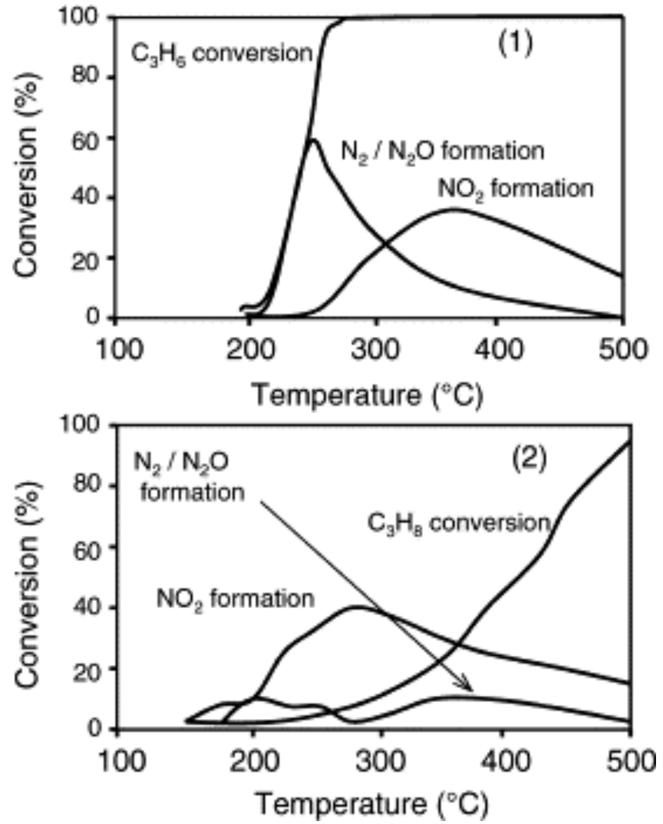
Thermal stability: CeO_2/ZrO_2 oxygen storage prevents sintering and improves aging

Expensive platinum group metals (PGM): fluctuating prices affect use of Pt/Rh/Pd

Poison resistance: sulfur, phosphorus, calcium (in lubricant additives) reduce durability

Pressure drop: manage flow rates and power

Lean catalyst performance



Typical light-off behaviour for **lean catalyst** (1) C3H6–NO–O2 and (2) C3H8–NO–O2 reactions over Pt/Al2O3. Pt: 1 wt.%, reactant feed: 1000 ppm C3Hx, 500 ppm NO, **5% O2**. W/F=4×10−4 g min ml−1 (GHSV 72,000 h−1)

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

Exhaust gas recirculation (EGR)

Zeldovich mechanism of NO formation:

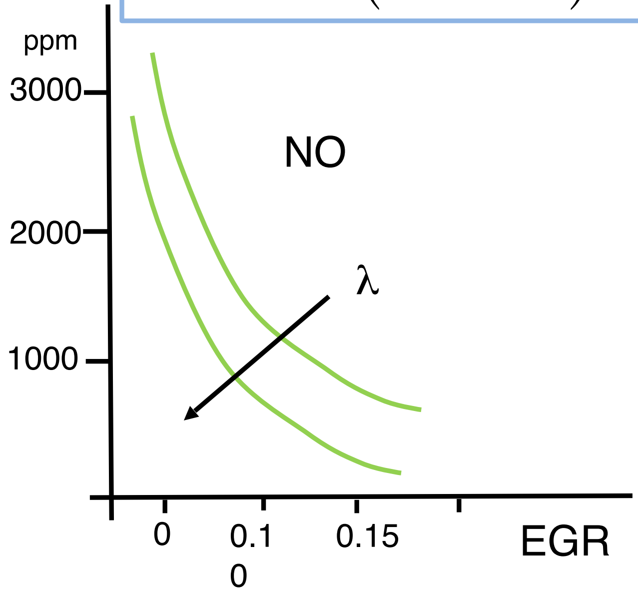
$O + N_2 \rightarrow NO + N$ (1)

$N + O_2 \rightarrow NO + O$ (2)

$[N + OH \rightarrow NO + H]$

assuming [N] is in steady state, and [O] in equilibrium with O_2, and c is total molar concentration

$$w_{NO} = 2k_1 \left(K_p[O_2]/c \right)^{1/2} \qquad k_1 = 1.8 \times 10^{14} \exp(-38730/T) \qquad K_p = \frac{(p_O)^2}{p_{O2}} = \exp(-\frac{\Delta G_O}{\mathscr{R}T})$$



Dilution keeps temperatures low:

$$\Delta T = \frac{Q}{mc_v} = \frac{Q}{(m_a c_{va} + m_f c_{vf} + \boxed{m_r c_{vr} + m_{EGR} c_{vEGR}})}$$

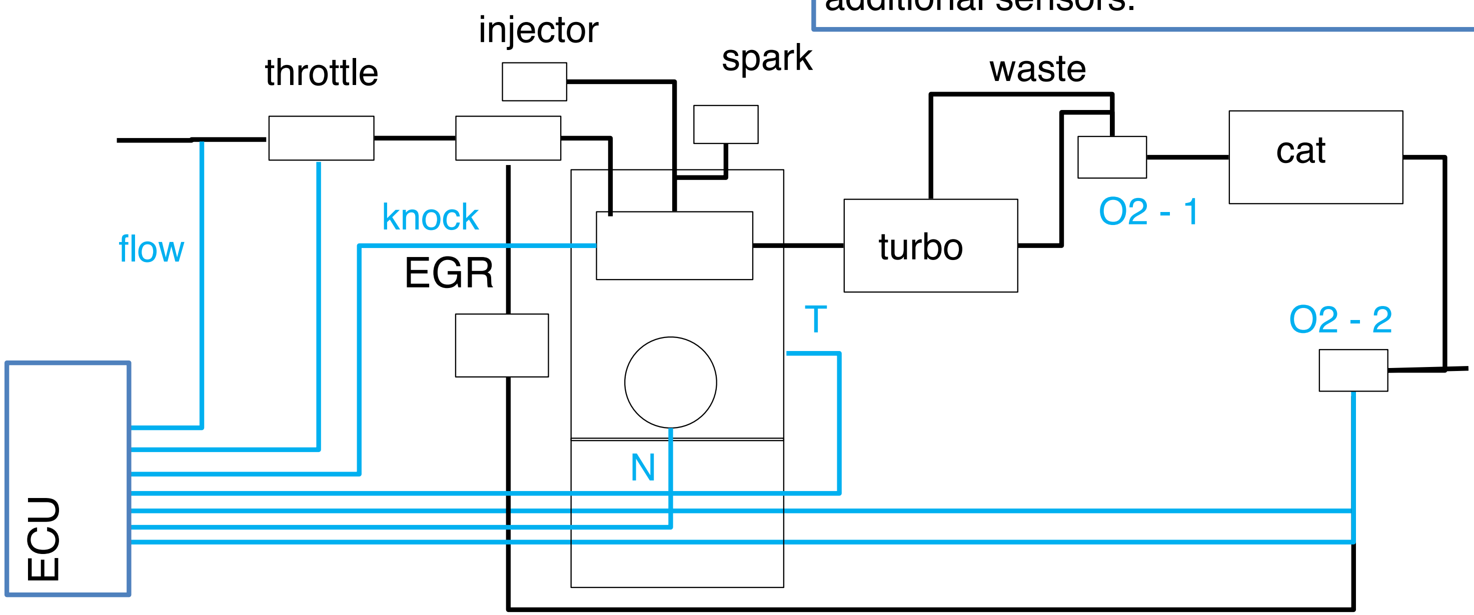
EGR: increases heat capacity of charge, decreases product temperature, and thus NO

Maximum EGR limits: flammability, COV, torque, power.
Max : ~30% for gasoline engines

Engine control systems

Cycle-to-cycle feedback control to each cylinder

ECUs monitor more than 20-30 states of the engine and each cylinder on a cycle to cycle basis. Some of the strategies are open loop, and in more expensive engines, closed loop with additional sensors.



Turbo/variable geometry strategy (closed/open loop)

Quiz time