Diesel Emissions and Control

- Diesel emissions
- Regulatory requirements
- Diesel emissions reduction
- Diesel exhaust gas after-treatment systems
- Clean diesel fuels

1

Diesel Emissions

- CO – not significant until smoke-limit is reached
  - Overall fuel lean
  - higher CR favors oxidation
- HC – not significant in terms of mass emission
  - Crevice gas mostly air
  - Significant effects:
    - Odor
    - Toxics (HC absorbed in fine PM)
  - Mechanisms:
    - Over-mixing, especially during light load
    - Sag volume effect
- NOx – very important
  - No attractive lean NOx exhaust treatment yet
- PM – very important
  - submicron particles health effects

2

Diesel HC emission mechanisms

Demonstration of over-mixing effect

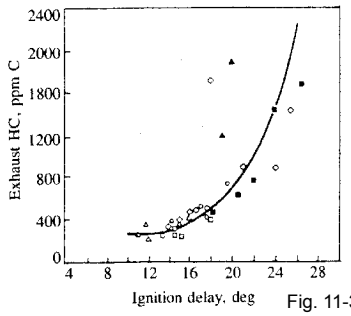


Fig. 11-35

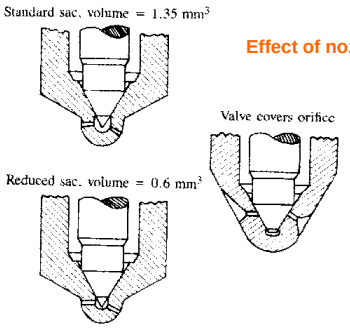
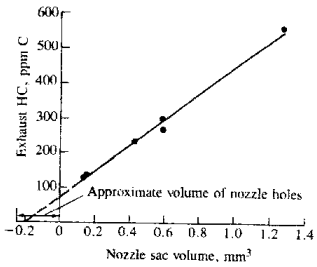


FIGURE 11-36

Effect of nozzle sac vol. on HC emissions



3

NOx mechanisms

- NO: Extended Zeldovich mechanism

  $N_2 + O \leftrightarrow NO + N$

  $N + O_2 \leftrightarrow NO + O$

  $N + OH \leftrightarrow NO + H$

  – Very temperature sensitive: favored at high temperature
  – Diffusion flame: locally high temperature
  – More severe than SI case because of higher CR
- NO_2 : high temperature equilibrium favors NO, but NO2 is formed due to quenching of the formation of NO by mixing with the excess air

  $NO + HO_2 \leftrightarrow NO_2 + OH$

  $NO_2 + O \leftrightarrow NO + O_2$

  – Gets 10-20% of NO_2 in NO_x

4

NOx formation in Diesel engines

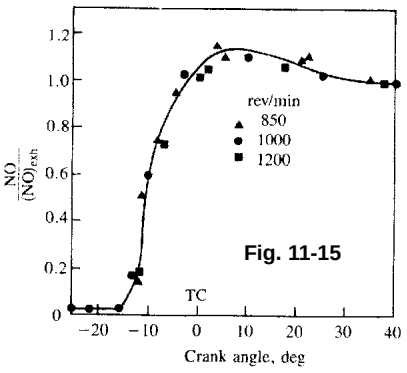


Fig. 11-15

Normalized NO concentration from cylinder dumping experiment. Injection at 27° BTC. Note most of the NO is formed in the diffusion phase of burning

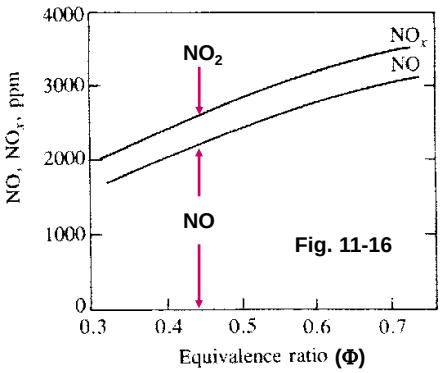


Fig. 11-16

NOx and NO emissions as a function of overall equivalence ratio Φ. Note that NO_2 as a fraction of the NOx decreases with increase of Φ.

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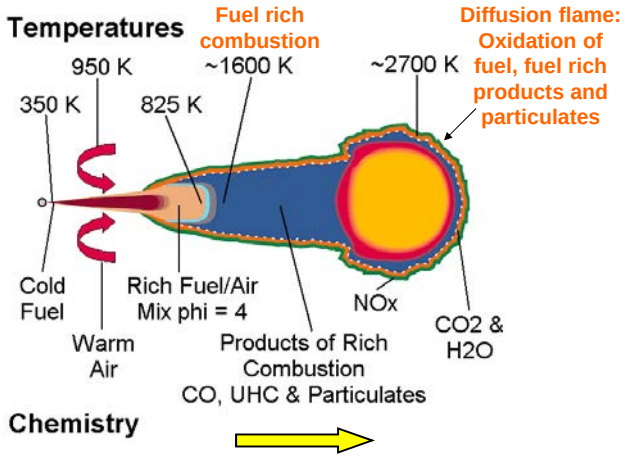
Diesel combustion



Flynn et al, SAE990509

Particles grow and agglomerate into bigger particles

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Particulate Matter (PM)

- As exhaust emission:
  - visible smoke
  - collector of organic and inorganic materials from engine
    - Partially oxidized fuel; e.g. Polycyclic Aromatic Hydrocarbons (PAH)
    - Lubrication oil (has Zn, P, Cu etc. in it)
  - Sulfates (fuel sulfur oxidized to SO2, and then in atmosphere to SO3 which hydrates to sulfuric acid (acid rain)

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Particulate Matter

- In the combustion process, PM formed initially as soot (mostly carbon)
  - partially oxidized fuel and lub oil condense on the particulates in the expansion, exhaust processes and outside the engine
    - PM has effective absorption surface area of 200 m^2/g
  - Soluble Organic Fraction (SOF) 10-30%
    - (use dichloromethane as solvent)

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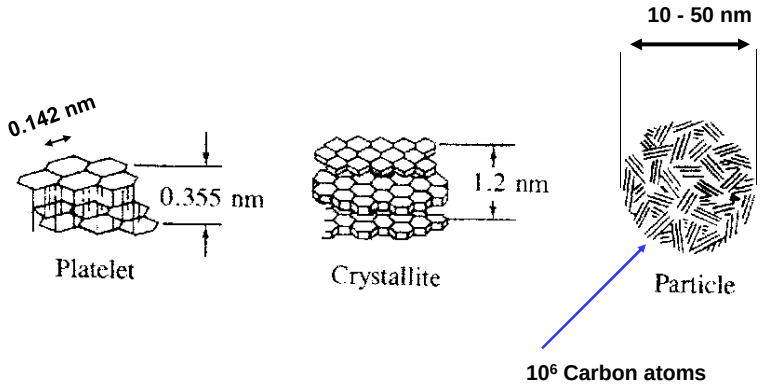
Elementary soot particle structure



(See Fig. 11-38 and 11-40 for micro-image of soot particles)

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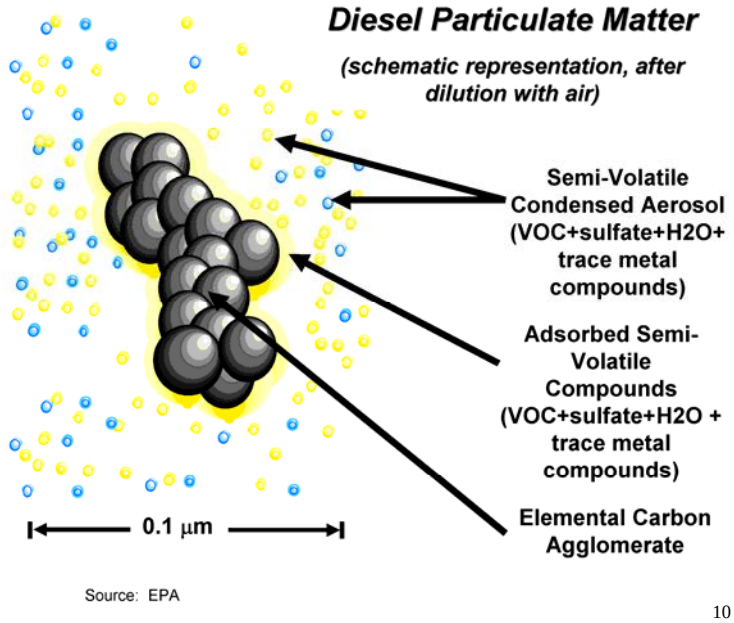

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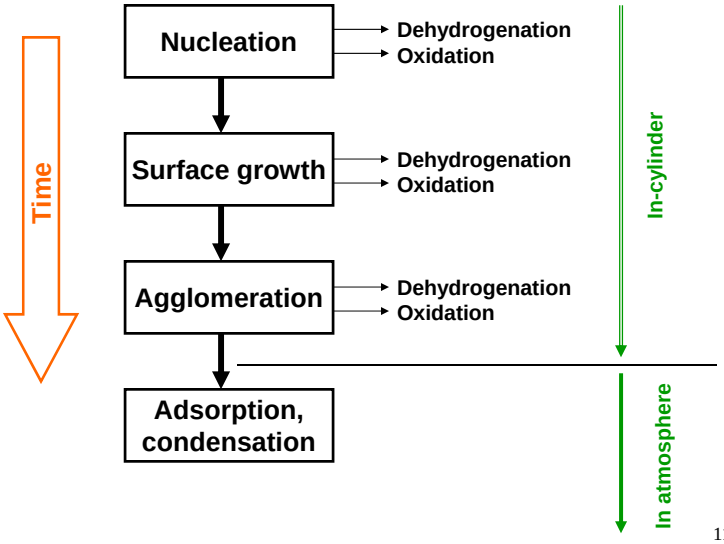
Image courtesy of EPA.

PM formation processes



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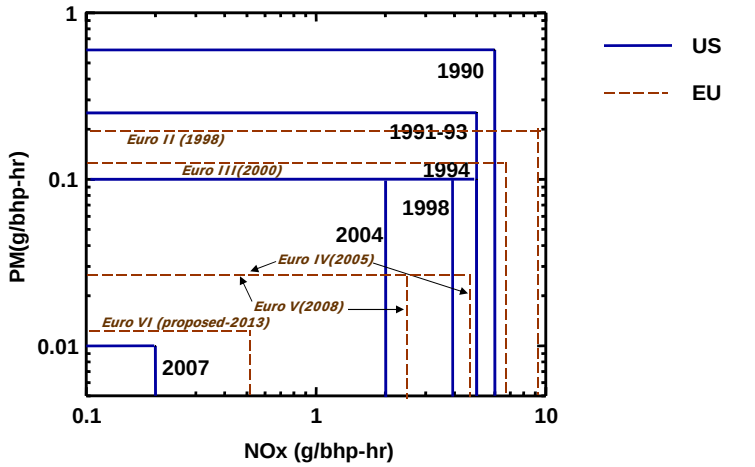
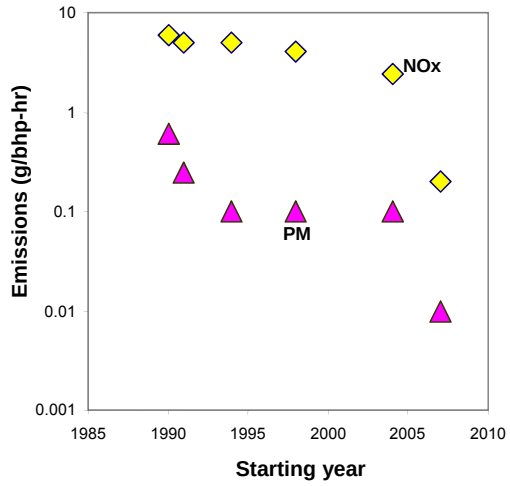
Diesel NOx/PM regulation



12

(Note: Other countries regulations are originally in terms of g/KW-hr)

US HD diesel regulation history



Note: from 2004 on, NOx regulation is on NOx+NMHC

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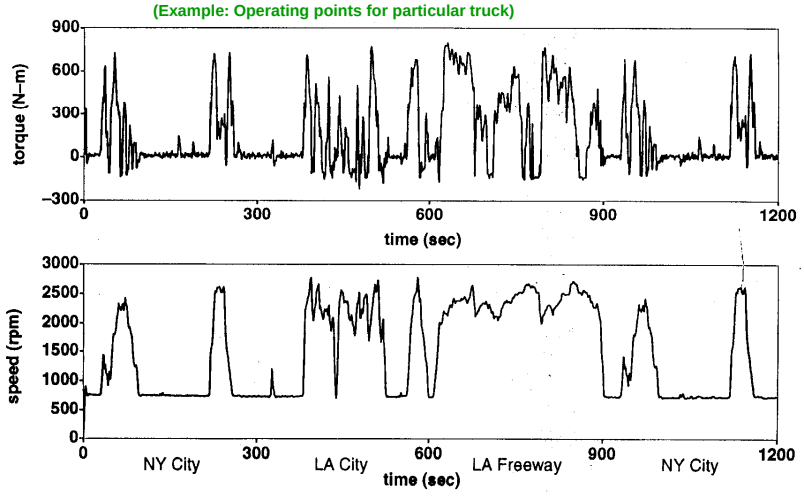
TYPICAL US EPA TRANSIENT CYCLE, HD TRUCKS

(Test based on % (rated-idle speed) and % lug torque)

(Example: Operating points for particular truck)



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European Stationary Cycle (ESC)

EUROPEAN R-49 13-MODE TEST - WEIGHTING FACTORS

MODE	SPEED (rev/min)	LOAD (%)	WEIGHTING
1	Idle	0	0.25/3
2	Peak Torque	10	0.08
3	Peak Torque	25	0.08
4	Peak Torque	50	0.08
5	Peak Torque	75	0.08
6	Peak Torque	100	0.25
7	Idle	0	0.25/3
8	Rated	100	0.10
9	Rated	75	0.02
10	Rated	50	0.02
11	Rated	25	0.02
12	Rated	10	0.02
13	Idle	0	0.25/3

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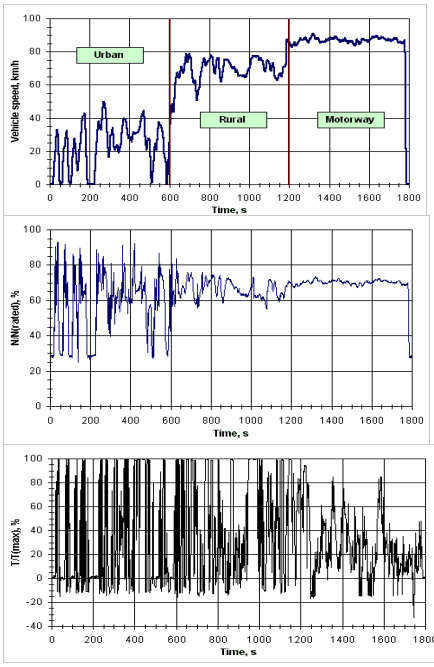

European Transient Cycle (ETC)

EU HD Diesel emissions regulation

HD Diesel (Euro number denoted by roman-numerals)

Standard	Year	PM (g/KW-hr)	NOx (g/KW-hr)	HC (g/KW-hr)	CO(g/KW-hr)
Euro I (>85KW)	1992	0.36	8	1.1	4.5
Euro II (ESC)	1996	0.25	7	1.1	4
Euro II (ESC)	1998	0.15	7	1.1	4
Euro III (ESC)	2000	0.1	5	0.66	2.1
Euro IV (ESC)	2005	0.02	3.5	0.46	1.5
Euro V (ESC)	2008	0.02	2	0.46	1.5
Euro VI (ESC) -proposed	2013	0.01	0.4	0.13	1.5
Euro III (ETC)	2000	0.16	5	0.78	5.45
Euro III (ETC)	2005	0.03	3.5	0.55	4
Euro III (ETC)	2008	0.03	2	0.55	4
Euro VI (ETC) -proposed	2013	0.01	0.4	0.16	4

Change of test cycle from Euro III to include ETC
Values different for steady test (ESC) and transient test (ETC)

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Diesel Emissions Reduction

1. Fuel injection: higher injection pressure; multiple pulses per cycle, injection rate shaping; improved injection timing control
2. Combustion chamber geometry and air motion optimization well matched to fuel injection system
3. Exhaust Gas Recycle (EGR) for NOx control
   - ➢ Cooled for impact
4. Reduced oil consumption to reduce HC contribution to particulates
5. Exhaust treatment technology: NOx, PM
6. Cleaner fuels

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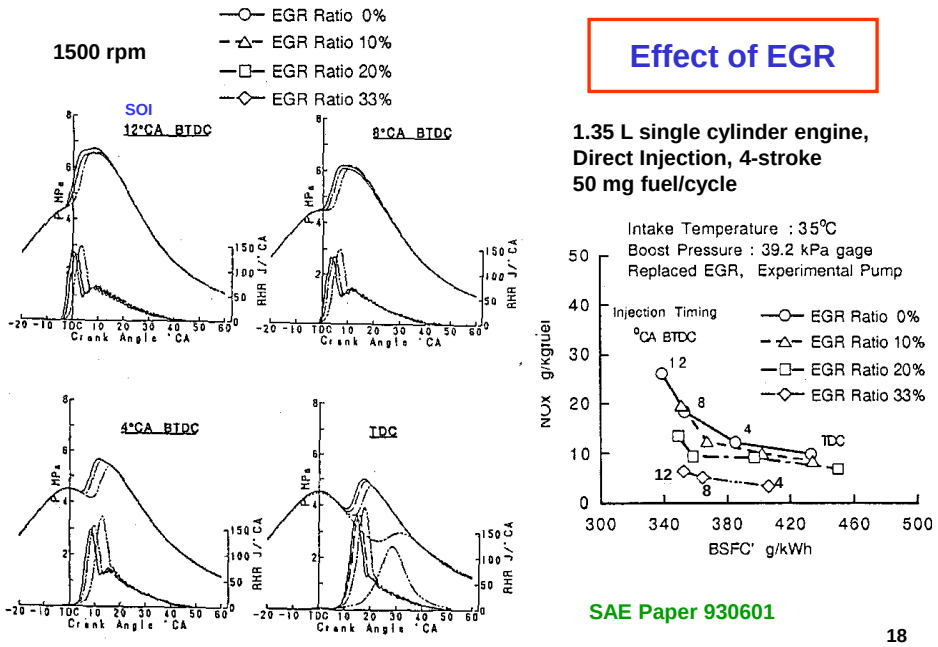

Effect of EGR

1.35 L single cylinder engine, Direct Injection, 4-stroke
50 mg fuel/cycle

SAE Paper 930601

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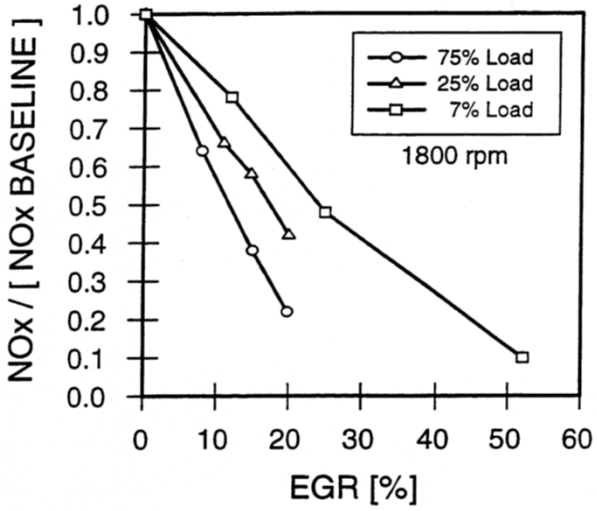

Effect of EGR
at different loads

SAE Paper 980174

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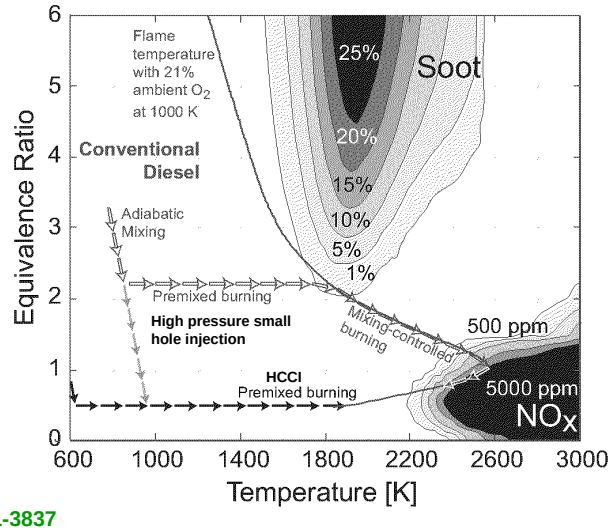
Combustion control of diesel emissions



SAE 2005-01-3837

The contour map is for soot formation for n-heptane at P=6MPa, time=2 ms, EGR=0.

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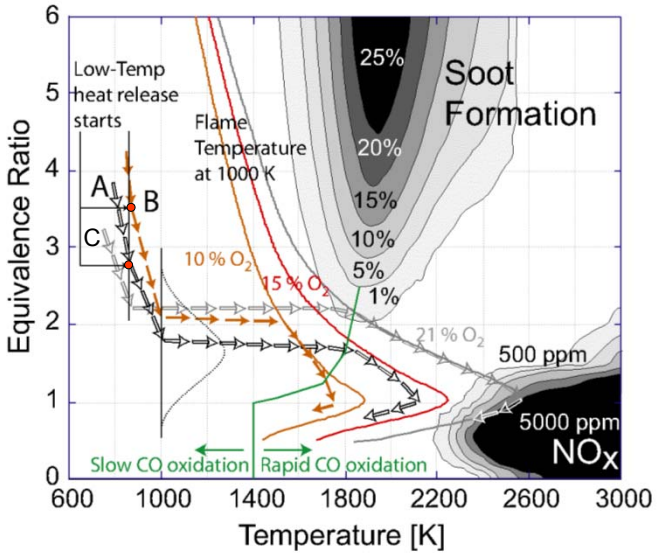
Combustion control of diesel emissions



A Late injection, moderate dilution
B Early injection, high dilution
C Conventional diesel

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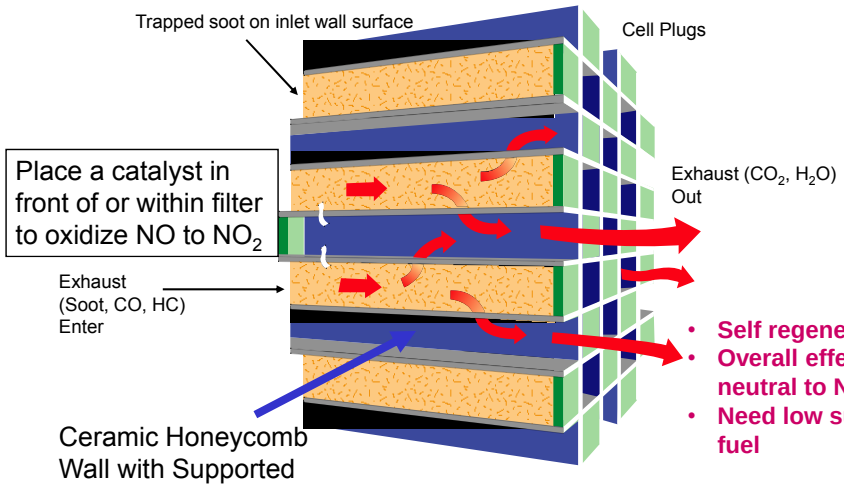
Diesel particulate filters use porous ceramics and catalyst to collect and burn the soot



- **Self regenerating**
- **Overall effect neutral to NOx**
- **Need low sulfur fuel**

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Post injection filter regeneration

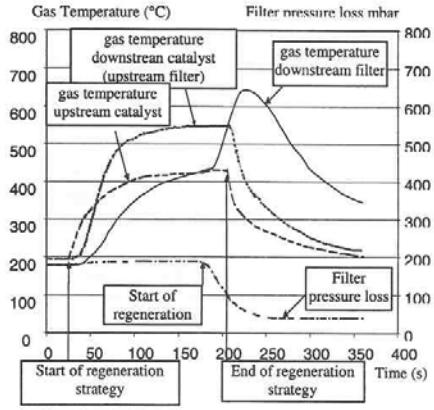

Figure 8. Example of exhaust gas temperature increase and particulate filter regeneration under steady state conditions

Increase exhaust gas temperature by injection of additional fuel pulse late in cycle.

- **Regeneration needs ~550°C**
- **Normal diesel exhaust under city driving ~150-200°C**
- **Need oxidation catalyst (CeO_2) to lower light off temperature**
- **Control engine torque**
- **Minimized fuel penalty**

Peugeot SAE 2000-01-0473

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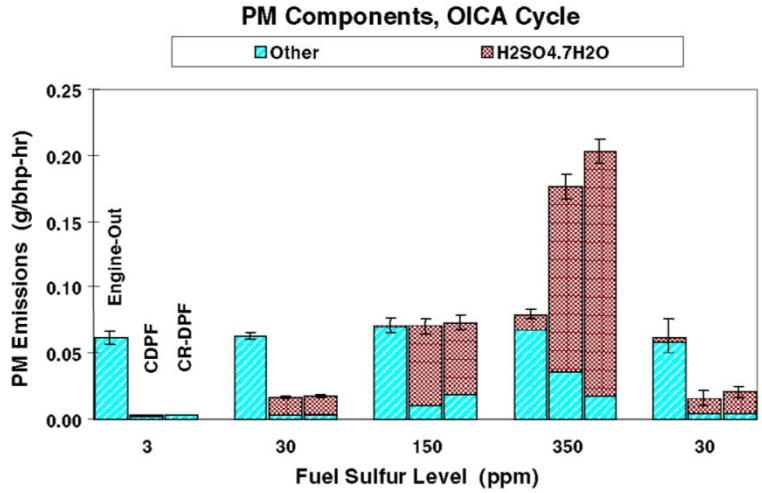
Sulfur effect on PM filter performance



OICA cycle: International Organization of Motor Vehicle Manufacturers cycle
CDPF: Catalyzed diesel particulate filter
CR-DPF: Catalyzed regenerating diesel particulate filter

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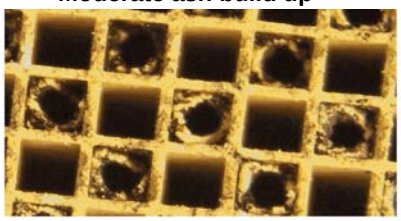
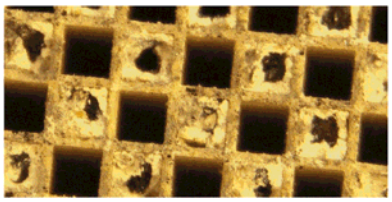
SAE Paper 2000-01-1879

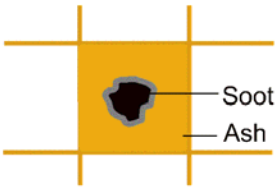
Ash build up

Moderate ash build up



Heavy ash build up





From SAE 2008-01-1549

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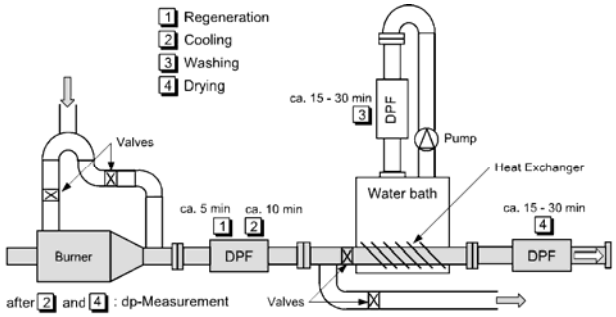
Ash cleaning from DPF

Picture as per ADAC website, Aug.28, 01



Zeuna Stärker, SAE 2001-01-3199

Cleaning process:

1. Burn-off of soot with hot air
2. Cleaning with water and air under “high” pressure.

All fuel delivery trucks in the ARCO (BP) ECD retrofit program went 150K miles before ash build-up became an issue. Some trucks went 250,000 miles.

BP SAE 2002-01-0433

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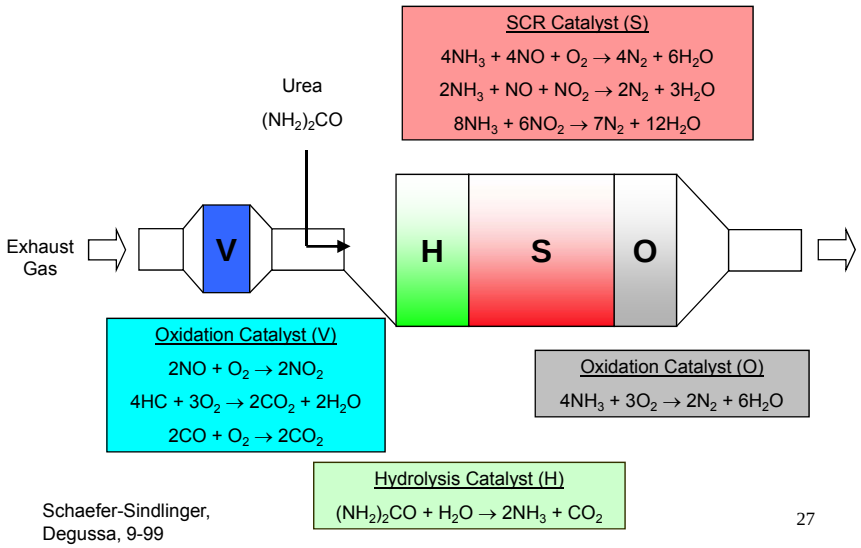
Slide courtesy of Tim Johnson, Corning

State-of-the Art SCR system has NO2 generation and oxidation catalyst to eliminate ammonia slip



Schaefer-Sindlinger, Degussa, 9-99

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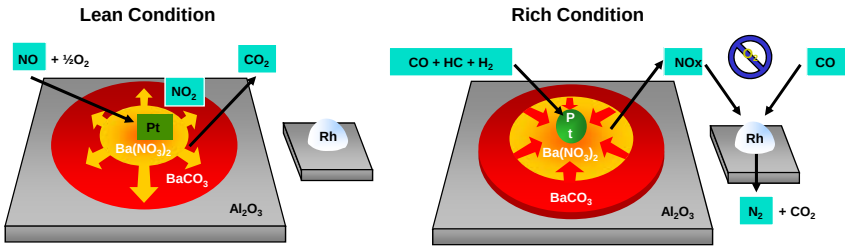
NOx absorber



Lean condition: Store NOx as nitrate

$2NO_2 + BaO + 1/2O_2 = Ba(NO_3)_2$

Rich condition: Store NOx as nitrate

Dissociate nitrate to NO_2, which is converted by the CO and H_2

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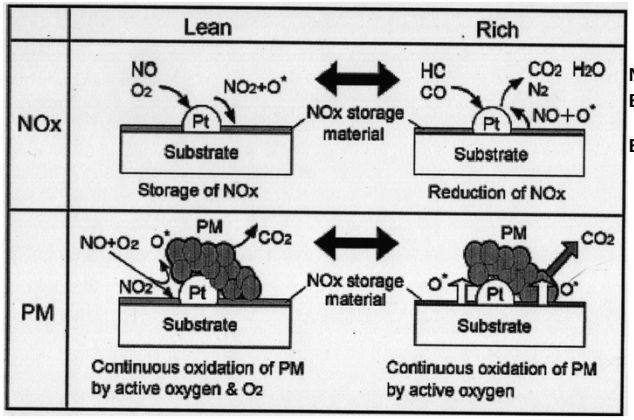
Integrated DPF and NOx trap



$NO+1/2\ O_2 \leftrightarrow NO_2$

$BaO+2NO_2+1/2\ O_2 \leftrightarrow Ba(NO_3)_2$

Better than 80% simultaneous reduction in PM and NOx

From Toyota SAE Paper 2002-01-0957

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Clean Diesel Fuels

1. Lower sulfur levels
   - 350 ppm → 15 ppm (to enable SCR technology; enforced since 2006)
2. Lower percentage aromatics
3. Oxygenated fuels
4. Higher cetane number
5. Narrower distillation range

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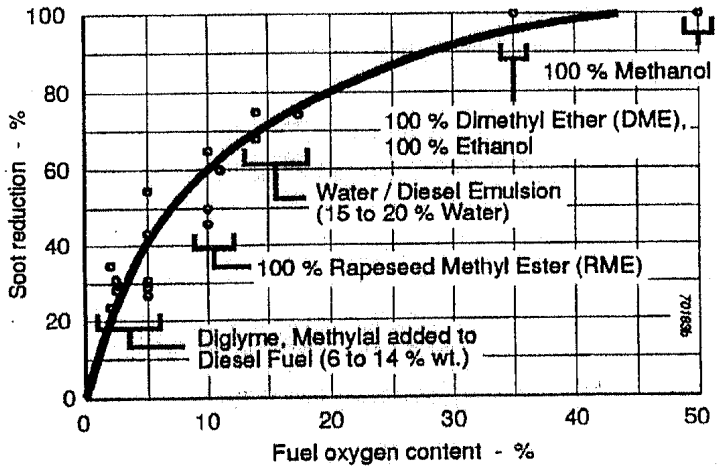
Effects of Oxygenates on PM emission



AVL Publication (by Wofgang Cartellieri in JSME 1998 Conference in Toykyo)

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Diesel Emission Control

Summary

- Emission regulations present substantial challenge to Diesel engine system
- Issues are:
  - performance and sfc penalty
  - cost
  - reliability
  - infra-structure support

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2.61 Internal Combustion Engines
Spring 2017