Diesel Emissions and Control

- Diesel emissions
- Regulatory requirements
- Diesel emissions reduction
- Diesel exhaust gas after-treatment systems
- Clean diesel fuels
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
Demonstration of over-mixing effect

Diesel HC emission mechanisms


Effect of nozzle sac vol. on HC emissions
NOx mechanisms

- NO: Extended Zeldovich mechanism
  \[ \text{N}_2 + \text{O} \leftrightarrow \text{NO} + \text{N} \]
  \[ \text{N} + \text{O}_2 \leftrightarrow \text{NO} + \text{O} \]
  \[ \text{N} + \text{OH} \leftrightarrow \text{NO} + \text{H} \]
  - Very temperature sensitive: favored at high temperature
  - Diffusion flame: locally high temperature
  - More severe than SI case because of higher CR

- NO\textsubscript{2} : high temperature equilibrium favors NO, but NO\textsubscript{2} is formed due to quenching of the formation of NO by mixing with the excess air
  \[ \text{NO} + \text{HO}_2 \leftrightarrow \text{NO}_2 + \text{OH} \]
  \[ \text{NO}_2 + \text{O} \leftrightarrow \text{NO} + \text{O}_2 \]
  - Gets 10-20\% of NO\textsubscript{2} in NO\textsubscript{x}
Normalized NO concentration from cylinder dumping experiment. Injection at 27° BTC. Note most of the NO is formed in the diffusion phase of burning.

NOx and NO emissions as a function of overall equivalence ratio $\Phi$. Note that NO$_2$ as a fraction of the NOx decreases with increase of $\Phi$. 

Diesel combustion

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)
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 m²/g
  - Soluble Organic Fraction (SOF) 10-30%
    - (use dichloromethane as solvent)
Elementary soot particle structure

Diesel Particulate Matter
(schematic representation, after dilution with air)

- Semi-Volatile Condensed Aerosol (VOC+sulfate+H2O+ trace metal compounds)
- Adsorbed Semi-Volatile Compounds (VOC+sulfate+H2O + trace metal compounds)
- Elemental Carbon Agglomerate

Source: EPA

PM formation processes

Nucleation → Dehydrogenation, Oxidation

Surface growth → Dehydrogenation, Oxidation

Agglomeration → Dehydrogenation, Oxidation

Adsorption, condensation

Time

In-cylinder

In atmosphere
Diesel NOx/PM regulation

(Note: Other countries regulations are originally in terms of g/KW-hr)
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
1.35 L single cylinder engine, Direct Injection, 4-stroke

Split Injection

PM Control

Post injection filter regeneration


- 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 (CeO₂) to lower light off temperature
- Control engine torque
- Minimized fuel penalty

Peugeot SAE 2000-01-0473
Diesel particulate filters use porous ceramics and catalyst to collect and burn the soot

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

Integrated DPF and NOx trap

Image removed due to copyright restrictions. Please see: Fig. 3 in Nakatani, Koichiro, et al. "Simultaneous PM and NOx Reduction System for Diesel Engines." SAE Journal of Fuels and Lubricants 111 (March 2002): SP-1674.

From Toyota SAE Paper 2002-01-0957
Clean Diesel Fuels

1. Lower sulfur levels
   - 350 ppm → 15 ppm
2. Lower percentage aromatics
3. Oxygenated fuels
4. Higher cetane number
5. Narrower distillation range
Diesel Emission Control

Summary

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