Diesels – Promises & Issues

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Outline

• Why Diesels – Efficiency
  – Cost
  – CO2
• Emissions Progress And Issues
• NOx
  – Potential And Issues
• Particulate
• Conclusions
Effective Expansion Ratio vs. Efficiency

- Spark Ignition
- Diesel

Indicated To Mechanical Conversion
Is Gasoline An Option
Must Have High Expansion Ratio Power Plants

- Spark Ignition Expansion Ratio Too Low
  – Poor Efficiency
- Gasoline Engine Too Big To Fit Truck
- Diesel Provides High Expansion Ratios
  – Lower Operating Cost
  – Lower CO2 Emissions
  – Must Control Particulates
  – Must Control NOx
Evolution of Engine Emission Control

- 1974 EPA (HC + NOx)
- 1987 Models: Retard Timing, Lower IMT, Shorten HRR, Low Friction
- 2004 (2002): Cooled EGR
Emissions Control

• 90%+ Reduction In Particulate Emissions
• 85%+ Reduction In NOx Emissions
• New Proposals Would Require Additional 90% Reductions In NOx And Particulate Emissions
• Requires 90% Efficient Aftertreatment Systems For Both NOx And Particulates That Last 435,000 Miles
Evolution of Engine Emission Control

Exhaust Aftertreatment Required

Particulate [g/(HP-hr)]

NOx [g/(HP-hr)]

- 1991
- 1994
- 1998
- 2007 Proposal

Exhaust Aftertreatment Required
Summary - Overall Picture

Temperatures

- 350 K
- 950 K
- 825 K
- ~1600 K
- ~2700 K

Chemistry

- Cold Fuel
- Rich Fuel/Air Mix $\phi \sim 4$
- Warm Air
- Products of Rich Combustion CO, UHC & Particulates
- $\text{NO}_X$
- $\text{CO}_2$ & $\text{H}_2\text{O}$
Observations

• Droplets Vaporize in a Short Distance Creating a Reacting Gas Jet
  – Mixture Temperatures Too Low for Chemical Reactions

• Temperature Rise and Start Low Temperature Reactions (825K)

• Fast Reactions at Temperatures Above 1100K Consume All Available Fuel or Oxygen

• Local Temperatures Drive Chemical Reactions
  – 3 Critical Regimes
    • 800 to 850K Weakly Bonded Hydrogen
    • 1050 to 1100K Hydrogen-Peroxide Decomposition
    • 1500 to 1600K Chain Branching, Yielding 19900 to 2000K Flame temperatures
Observations cont.

• Fuel Burning Is a Two Stage Process
  – Rich Premixed Reaction on Entry
    • Forms Carbon Particulate Precursors
    • Particulate Emissions Controlled By Early Completion of Process
  – Peripheral Diffusion Flame to Complete Fuel Burning
    • Steep Concentration Gradients
    • Consumes Particulates
    • Forms NOx Because of Flame Temperatures Above 1900K

• Cooling the Flame Will Cause Incomplete Combustion
Limits of Diesel Engine Combustion

Diesel Flame Cooled With EGR

fsNOx (g/kg fuel)

Complete Combustion

Incomplete Combustion (High CO, UHC, Soot)

Minimum Viable

5.5 g/kg fuel

GISFC (lbm/hp-hr)

Peak Flame Temperature (K)

SAE 2000-01-1177
In-Cylinder NOx Formation Limits

- Heavy-duty Engines Require Majority of Energy Release Through Flame Processes
- Minimum Flame Temperature Limits Minimum NOx Emissions

<table>
<thead>
<tr>
<th></th>
<th>Comb. Chem. Limit (g/kg fuel)</th>
<th>Min. HD Cycle Target (g/hp-hr)</th>
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</thead>
<tbody>
<tr>
<td>SI</td>
<td>2.5</td>
<td>0.75</td>
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<tr>
<td>Diesel</td>
<td>5.5</td>
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SAE 2000-01-1177
The new engine increased number emissions 10 to 30 fold!

The new engine sharply reduced mass emissions, by about a factor of 3.

HOWEVER, 1979 roadway measurements made on behind a truck powered by an engine of the same family showed high nanoparticle emissions! Other roadside and on road measurements made since the late 60’s have shown high nanoparticle emissions.
Nanoparticle Measurements Made under Roadway Chase Conditions.
The Formation of the Nuclei Mode during atmospheric Dilution Depends upon Ambient Conditions.

The open symbols show runs made at 11 C
The closed symbols show runs made at 21 C

Average plume minus background SMPS size distributions normalized to 1 µm/cm³ volume concentration are shown here

Lower Dilution Temperatures Increase Fine Particulates
The Nanoparticle Mode Appears to Consist of Mainly Volatile Materials

+ TD denotes use of thermal denuder at 300 C

Federal Fuel (~400 ppm S)
The Combination of Low Sulfur Fuel and an Oxidizing Catalyst Effectively Prevents Nanoparticle Formation (courtesy C.Barnes, Perkins Engine Company)
Particulates

- Carbon Particulate Formed During Combustion Would Require Removal With Actively Controlled Particulate Traps
- Fine Particulate (Formed At Tailpipe Exit By Condensation) Elimination Requires Removal of Sulfur From Fuel And Oil
Conclusions

• Diesels Still Key To Transportation Economics
• Much Progress On Emission Control To Date
• Active Aftertreatment For Both NOx And Particulates Required In The Future
• Aftertreatment Systems Require Much Research and Development To Reach Tough 90% Effectiveness Target For 435,000 Miles