Low Emissions Combustion – One Path Forward?

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Progression Of Heavy-Duty Legislation And Technology In USA

Possible 2014 Standards
- 0.05 gm/hp-hr NOx
- 0.001 gm/hp-hr PM
Areas of Greatest Potential

- **Fuel Management**
  - High Pressure Injection Essential
  - Injection Rate Control Essential
  - Air Utilization Essential
  - Liquid Fuel Wall Interactions must be Avoided

- **Gas Management**
  - High Density Essential
  - High EGR Levels Essential
    - Outcome is High Boost Pressure
  - Uniform EGR Distribution Essential
  - Intake Cooling is Desirable
  - High Efficiency Turbocharger Systems Essential
  - In-Cylinder Flow Management Essential

- **Combustion Chambers**
  - Matched to Nozzle Spray Capabilities
  - Design for Maximum Mixing Rates
  - Premixed Combustion Considerations
    - Surface-to-Volume Ratio Minimized
    - Quench Volume Minimized
Premise

Lowest Possible Emissions and Highest Efficiency in Diesel Engines Achieved Using:

- Ultra High Injection Pressure and Small Holes
- Massive EGR
- Ultra High Boost
- Well Designed Pistons and Intake
High Injection Pressure and Small Holes

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High Pressure Electronic Unit Injector Operating on a Fixed Cam at Constant Speeds

- Single Hole Nozzles 0.086 to 0.18 mm Dia
- Peak Injection Pressures from 254 to 283 MPa
- Higher Mixing Rates and Smaller Drops

<table>
<thead>
<tr>
<th>Injection Hole Diameter (mm)</th>
<th>Peak Injection Pressure (MPa)</th>
<th>½ Peak Injection Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.086</td>
<td>283</td>
<td>142</td>
</tr>
<tr>
<td>0.100</td>
<td>281</td>
<td>141</td>
</tr>
<tr>
<td>0.128</td>
<td>266</td>
<td>133</td>
</tr>
<tr>
<td>0.144</td>
<td>267</td>
<td>134</td>
</tr>
<tr>
<td>0.18</td>
<td>254</td>
<td>127</td>
</tr>
</tbody>
</table>
1. Mixing Rates Quantified in Terms of SwRI Defined Mixing Parameter
2. Mixing Parameter Defines the Mass of Fuel at Phi Greater Than 1.0 for more than 0.6 ms
3. Rich Regions Mean More Soot

- Mixing Parameter and Drop Size both Decrease with Smaller Holes
- $P_{\text{inj}}$ Increases with Smaller Holes

**Conditions for Calculations:**
- $P_{\text{inj}} = P_{\text{max}}$
- $T_{\text{air}} = 515 \, ^\circ\text{C}$
- $P_{\text{ar}} = 5.52 \, \text{MPa (55.2 bar, 800 psig)}$

Assume Smoke ~ Mixing Parameter

![Graph showing mixing parameter vs. hole tip diameter](image)
Fuel Injection - High Pressure

- Small Holes Produce High Pressure, Small SMD, High Mixing Rates and Low Soot Formation Rates

0.144 mm
0.128 mm
0.086 mm
Fuel Injection - High Pressure

- High Pressure does not affect the jet penetration rate in either evaporating or non-evaporating sprays.

- Small holes do affect both the penetration rate and the liquid length in evaporating sprays.

\[ \rho_{\text{air}} = 13.95 \text{ kg/m}^3 \]

2005-01-1239
Fuel Injection - High Pressure

- **Constant Injection Duration Requires Higher Pressure when using Small Holes**

- **Variable Area Nozzle (0.17 to 0.131 mm) Gives a Significant Improvement**
  - 0.131 Used for Light Loads
  - 0.17 Used for High Loads

- **Duration, Liquid Length, and Mixing Rate are Important**

- **12% Cam and 0.17 mm Nozzle Give same Duration as Baseline**

- **12% Cam and 0.131 mm Nozzle Give Higher Rates**
Fuel Injection - Future Requirements

- **Requirements**
  - High Injection Pressure
  - Multiple Injections
  - Rate Shaping for NOx and PM Control
  - Low Parasitic Loss

- **Unit Injectors**
  - Provide High Pressure, Rate Shaping, Multiple Injections, and Low Parasitic Loss

- **Unit Injector Event Timing** Limited by Cam Design

- **Common Rail**
  - Provides Multiple Injections, but Lower Pressure, Typically Square Rates, and Higher Parasitic Loss
Fuel Injection - Advanced Concepts

Common Rail

- **Dual Rail CRS**
  - High and Low Pressure CR for Rate Shaping

- **Intensifier CRS**
  - Rate Shape Accomplished using the Combination of A and B Solenoids

2005-01-0907
Fuel Injection - Advanced Concepts
Common Rail

Piezoelectric Stack Provides:
1. Fast Response
2. Precise Injections
3. Repeatable Injections
4. Short Dwell
5. Rate Shape

- Multiple Injections for Conventional Diesel Combustion System
  - Pre and Post Injections
  - Rate Shaping

- Provides Several Opportunities for Advanced Combustion Systems
  - PCCI, HCCI, LTC

![Diagram of fuel injection system](Image)
Fuel Injection - EUI

- EUI Provide Highest Injection Pressure and Lowest Parasitic Loss
- Dual Valve EUI Combined with Cam Design Provide almost All of the CRS Opportunities
  - Rate Shape
  - Multiple Injection
  - High Pressure
High Boost

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Fuel Injection - High Density

- Liquid Length Affected most Strongly by Hole Size and the Ambient Density
  - Smaller Holes
  - Higher Density
- Gas Jet Always Interacts with Combustion Chamber
  - Wall Jet Mixing Important
  — Air Motion
Boost Systems

**Advantages of High Boost**
- Maintain Power Density with Massive EGR
- Better Mixing Rates
- Exhaust Energy Recovery

**Options**
- High Efficiency, High PR single Stage
- e-Boost
- VGT
- Series
  - Intercooled and Aftercooled
Boost System

- **VGT**
  - **Advantages**
    - Flexible EGR Control
  - **Disadvantages**
    - Efficiency Low
    - Cost

- **E-Boost**
  - **Advantages**
    - Low Load Boost
    - Energy Recovery
    - Response
  - **Disadvantages**
    - Cost
    - Reliability

- **Series**
  - **Advantages**
    - Simple
    - Reliable
    - Flexible Control
  - **Disadvantages**
    - Cost
    - Packaging

- **Two-Wheel Turbo**
  - **Advantages**
    - Simple
    - Reliable
    - Packaging
Combustion Chamber Design

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Combustion Chamber Design

- **Spray Wall Interactions are Unavoidable**
  - Avoid Liquid Impingement
  - Take Advantage of Jet Break-up and Wall Jet Opportunities

- **Pilot and Post Injections Change the Bowl Shape and Spray Angle Requirements**
  - Cat uses Pilot at Almost all Conditions
    - Spray Angle Narrower
Fuel Injection
Wall-Wetting Issues

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Background

Is Liquid Impingement and Oil Dilution a Concern?

- Concerned with both Early Pre-Injection for Emissions and Noise Control and Late Post-Injection Strategies for DPF and LNT Regeneration
  - Fuel Jet Penetration Increases during Late Injection Due to the Lower Density
    - Decreasing Pressure and High Temperature
  - Liquid Fuel can Impinge on the Wall and Some can Adhere and Enter the Lubricant

- Approach
  - Developed an empirical based model for estimation of the relative quantity of injected fuel that becomes associated with, or adheres, to the combustion chamber walls
**DDC Series 60, 1600 rpm, Pilot**

- **Liquid Mass Fractions at Bore**
  - 90°C = 31% Liquid
  - 65°C = 37% Liquid
  - 40°C = 43% Liquid

- **Adhering Mass Fraction on Bore is 71%**
  - 90°C = 22%
  - 65°C = 26% Liquid
  - 40°C = 31%

**DDC Pre-Injection Conditions**
- Time (msec): 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
- Pressure (MPa): 40 50 60 70 80 90
- Bore Radius = 65mm

**Equation**

\[ z = \frac{(a + bx + cx^2 + dy)}{(1 + ex + fy)} \]

- \( r^2 = 0.99994146 \) DF Adj \( r^2 = 0.99921122 \) F(Chi2)=0.0037559038 Fstat=3345.7347
- a=0.1555328 b=0.0064228738 c=0.00012273555
d=0.034622713 e=0.012891396 f=0.022692769
OM 611, 1500 rpm, Pilot

- **Liquid Mass Fractions at Bore**
  - **High Load**
    - 65°C = 22% Liquid
    - 40°C = 34% Liquid
  - **Low Load**
    - 90°C = 50% Liquid
    - 65°C = 64% Liquid
    - 40°C = 76% Liquid

- **Adhering Mass Fraction 71%**
  - **High Load**
    - 65°C = 16%
    - 40°C = 24%
  - **Low Load**
    - 90°C = 36%
    - 65°C = 45%
    - 40°C = 54%

**OM 611 Pre-Injection**

- Bore Radius = 44 mm

**Graphs**

- **OM 611 Pre-Injection 1500 rpm**
- **3D Graph**
  - Adhering Mass Fraction vs. Pressure (MPa) and Distance (mm)
  - **Equation**
    
    \[
    z = \frac{ax + by + cx^2 + dy}{1 + ex + fy}
    \]
    
    - \( r^2 = 0.99964146 \), \( DF = 9 \), \( F = 21.372 \)
    - \( a = 0.18504 \), \( b = 0.008429 \), \( c = 0.00003 \), \( d = 0.00005 \)
    - \( e = 0.02089 \), \( f = 0.00913 \), \( r = 0.02026 \)
Fuel Injection - Pilot and Post

- Split Injection Offers Opportunity to Reduce Liquid Length and Liquid Impingement
- Benefits for both Pre and Post Injection

First Pilot, 0.17 ms
Second Pilot, 0.17 ms
Main, 0.45 ms
First Post, 0.17 ms
Second Post, 0.17 ms
Massive EGR

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Massive EGR
Background    EPA-Ford Data

Brake Specific NOx (g/HP/h)

<table>
<thead>
<tr>
<th>Type</th>
<th>4-cylinder, 2 valve/cyl OHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>1896 cm³</td>
</tr>
<tr>
<td>Bore</td>
<td>79.5 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>95.5 mm</td>
</tr>
<tr>
<td>Comp. Ratio</td>
<td>19.5:1</td>
</tr>
<tr>
<td>EPA Fuel System</td>
<td>Hydraulically intensified</td>
</tr>
<tr>
<td>Injector Location</td>
<td>7mm offset w/ 26° inclin.</td>
</tr>
<tr>
<td>Boost Systems</td>
<td>externally supplemented</td>
</tr>
<tr>
<td></td>
<td>(P_{out} = P_{int} + 0.1Bar )</td>
</tr>
<tr>
<td></td>
<td>partial map TC matched</td>
</tr>
<tr>
<td></td>
<td>(Initial effort)</td>
</tr>
</tbody>
</table>

EPA/Ford MIT Workshop 11/02
Massive EGR
Background - Diffusion Burn Engine
(Alternative to NOx After treatment)
- SwRI Has Extensive Data Base of 8-Mode Data for Cat 3176 2.5 g/hp-hr NOx + HC Engine
- Use Cycle Simulation to Model Different Levels of EGR
- Assumed LP Loop EGR After DPF
- Conditions Examined
  - Baseline - Good Prediction of Existing Data
  - Baseline A/F and Timing + EGR + Boost
  - Baseline Timing + A/F=25:1 + EGR + Boost
  - A/F=15:1 + EGR + Boost + Timing Advance
Massive EGR

- Baseline Engine Around 2 g/hp-hr
- BSFC Penalty with Variable Due to Back Pressure Increases
- 25:1 A/F Produced Lots of Turbine Energy
- 15:1 A/F Lowered the Air Flow and Boost Requirements
Massive EGR Issue

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Cooled EGR

- **S in the Fuel Raises**

  - Concentration of \( \text{H}_2\text{SO}_4 \) in Exhaust
    - \( \Phi = 0.5 \), 0.011 kg/kg Humidity
    - Exh T (K)
    - 260 280 300 320 340 360 380 400 420 440
    - H2SO4 Concentration (ppm)
    - 0.00 0.05 0.10 0.15 0.20 0.25

- **HNO3 in the Exhaust**

  - Concentration of \( \text{H}_2\text{SO}_4 \) in Exhaust
    - \( \Phi = 0.5, \ P = 1 \text{ atm}, 0.011 \text{ kg/kg Humidity} \)
    - Exh Temperature (K)
    - 260 280 300 320 340
    - Fuel Sulfur Concentration (% mass)
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- **Exhaust Dew Point**

  - \( P_{\text{exh}} = 1 \text{ atm}, T_{\text{exh}} = 40^\circ\text{C} \)
  - \( \Phi = 0.5, 0.011 \text{ kg/kg Humidity} \)
  - Exh Dew Point
    - Fuel Sulfur Concentration (% mass)
    - 0.00 0.05 0.10 0.15 0.20 0.25

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Thank You

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