An Experimental Investigation of Low Octane Gasoline in Diesel Engines

Stephen Ciatti and Swaminathan Subramanian
Center for Transportation Research
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Objectives

- The concept of using low-octane gasoline fuel to achieve a dictated premixed combustion in a diesel engine
  - Simultaneous reduction soot and NOx
  - Fuel/(Air+EGR) will be premixed, but not well mixed
- Maintain relatively high power densities (10 to 12 bar BMEP) while retaining high efficiency and low emissions
- To study the mixture formation effects through early pilot or early pilot and pre injections followed by a main injection schemes in gasoline LTC.
- Control combustion phasing by utilizing in-cylinder controls and study the influence of EGR, boost pressure and injection pressure on gasoline operated diesel engine in LTC mode
Conventional Combustion Process

SI – Homogeneous Mixture, No soot; HC, CO, (NO) – Emissions; Throttling losses

CI – Diffusion combustion, Fuel Efficient; High Smoke and NOx

Suction stroke

Compression stroke

Ignition

CR 9:1

Spark Ignited Combustion

CR 17:1

Compression Ignited Combustion
HCCI Vs LTC

Homogeneous Mixture

Well premixed fuel-air mixture

CR 17:1

Compression

HCCI

Compression Ignited Combustion

LTC

CR 17:1

Compression

Compression Ignited Combustion

Mixture

Partially premixed but not well mixed fuel-air mixture
Why is LTC an attractive solution to efficiency and emissions challenges?

Ref. SAE 2003-01-1789, Takaaki Kitamura et.al
LTC Approach

+ 
• Lean Mixtures
• Fuel Flexibility
• Low NOx and Soot

? 
• Mixture formation difficulties
• High HC and CO levels
• Combustion control Problems

- This study explored the use of low octane/high volatility fuel
  - Increase ignition delay
  - Limit/eliminate wall and piston fuel wetting

- Gasoline-like fuels with low cetane/high volatility

- Lubricity additive to insure operation of diesel injection equipment

- Use fluid mechanics to control combustion phasing and engine load
Key Factors

Auto-ignition

Pressure & Temperature (air preheating, Turbo charging, EGR & compression ratio)

Physical Properties

Mixture Preparation

Low Temperature Combustion

Chemical Properties

Octane rating, cetane rating (Fuels & Additives)

Inj. Timing, pressure & no of injections
Engine Specifications and Tested Fuels properties

**Engine Specifications**

<table>
<thead>
<tr>
<th>Property</th>
<th>#2 diesel</th>
<th>Low-octane gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression ratio</td>
<td>17.8:1</td>
<td></td>
</tr>
<tr>
<td>Bore (mm)</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>Stroke (mm)</td>
<td>90.4</td>
<td></td>
</tr>
<tr>
<td>Connecting rod length (mm)</td>
<td>145.4</td>
<td></td>
</tr>
<tr>
<td>Number of valves</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Injector</td>
<td>7 holes, 0.15-mm diameter</td>
<td></td>
</tr>
</tbody>
</table>

**Properties of the Two Tested Fuels**

<table>
<thead>
<tr>
<th>Property</th>
<th>#2 diesel</th>
<th>Low-octane gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>0.8452</td>
<td>0.7512</td>
</tr>
<tr>
<td>Low heating value (MJ/kg)</td>
<td>42.9</td>
<td>42.5</td>
</tr>
<tr>
<td>Initial boiling point (°C)</td>
<td>180</td>
<td>86.8</td>
</tr>
<tr>
<td>T10 (°C)</td>
<td>204</td>
<td>137.8</td>
</tr>
<tr>
<td>T50 (°C)</td>
<td>255</td>
<td>197.8</td>
</tr>
<tr>
<td>T90 (°C)</td>
<td>316</td>
<td>225.1</td>
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<tr>
<td>Cetane Index</td>
<td>46.2</td>
<td>25.0</td>
</tr>
</tbody>
</table>

G.M 1.9 L; 110 kW @ 4500 rpm - designed to run #2 diesel; Bosch II nd generation common rail injection system

Experimental Setup
Effect on BSFC and BSNOx emissions

Standard gasoline operation in SI mode was referred from

Emissions behavior (NOx and HC)

- **NOx emissions (g/kW-hr)**
  - Gasoline (LTC)
  - Diesel
  - Gasoline (SI)

- **HC emissions (g/kW-hr)**
  - Gasoline (LTC)
  - Diesel
  - Gasoline (SI)
Split Injection Strategies in LTC gasoline operation

**FIRST STRATEGY (GAS-I):**
First Injection - (-40°CA to -140°CA) (Partially premixed charge was prepared through this first injection)

Second injection - (0°CA) around TDC (heat release rate was maintained through this second injection)
Injection pressure - 600 bar to 900 bar (high injection pressures at higher load conditions)

**SECOND STRATEGY (GAS-II):**
An equal split of two early injections were employed.

First injection - (-70°CA); Second injection - (-25°CA).
Injection pressure - 600 bar.

This strategy had issues of severe knocking and hunting at 5, 8 and 12 bar BMEP conditions.

**THIRD STRATEGY (GAS-III):**
This strategy was nothing but a refinement of the first strategy.

Very early single injection scheme (- 95°CA) – 2 bar BMEP

Equal split of an early injection and a main injection scheme – 5 bar and 8 bar BMEP conditions
Early injection - (- 60°CA to -80°CA); Main injection – Closely after TDC.
Injection pressure - 600 bar
LTC Split Injection Strategies - Emissions

**NOx**

- Diesel
- GAS-I
- GAS-II
- GAS-III

**HC**

- Diesel
- GAS-I
- GAS-II
- GAS-III
Gasoline in LTC mode 1500 RPM and 2 bar BMEP

Emissions (g/kW/hr):
Diesel: 47% EGR : NOx = 0.24, HC = 0.41, CO = 0.172

1500 RPM Around 2 bar BMEP

HRR (J/°CA)

Crank Angle (CA)

260 280 300 320 340 360 380 400 420
Gasoline in LTC mode 1500 RPM and 2 bar BMEP

Emissions (g/kW/hr):
Diesel: 47% EGR : NOx = 0.24, HC = 0.41, CO = 0.172
Gas - I: No EGR : NOx = 2.81, HC = 9.42, CO = 68.8

1500 RPM
Arrround 2 bar BMEP

84 RON Gasoline
CA 50 = 8°C
EGR = 0

Inj. Pre – 600 bar
~Equal split
Gasoline in LTC mode 1500 RPM and 2 bar BMEP

Emissions (g/kW/hr):
- Diesel: 47% EGR : NOx = 0.24, HC = 0.41, CO = 0.172
- Gas - I: No EGR : NOx = 2.81, HC = 9.42, CO = 68.8
- Gas - II: No EGR : NOx = 1.27, HC = 16.4, CO = 78.3

1500 RPM
Around 2 bar BMEP

Injection Pressure - 600 bar
~Equal split

84 RON Gasoline
CA 50 = 8°C
EGR = 0
Gasoline in LTC mode 1500 RPM and 2 bar BMEP

Emissions (g/kW/hr):
- Diesel: 47% EGR: NOx = 0.24, HC = 0.41, CO = 0.172
- Gas - I: No EGR: NOx = 2.81, HC = 9.42, CO = 68.8
- Gas - II: No EGR: NOx = 1.27, HC = 16.4, CO = 78.3
- Gas - III: No EGR: NOx = 0.14, HC = 19.9, CO = 102.14

1500 RPM Around 2 bar BMEP

84 RON Gasoline
CA 50 = 8°CA
EGR = 0

Inj. Pre – 600 bar
Highest EGR level achieved with stable combustion (COV<5%) @ 2000 RPM and 5 bar BMEP
Highest EGR level achieved with stable combustion (COV<5%) @ 2000 RPM and 5 bar BMEP
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Higher speed/load conditions - 2500 RPM and 8 bar BMEP

Emissions (g/kW/hr):
Diesel (6.5% EGR): NOx = 2.48, HC = 0.08, CO = 0.26

2500 RPM
8 bar BMEP

HRR (J/°CA)

Crank Angle (CA)
Higher speed/load conditions – 2500 RPM and 8 bar BMEP

Emissions (g/kW/hr):
- Diesel (6.5% EGR): NOx = 2.48, HC = 0.08, CO = 0.26
- Gas - I (16% EGR): NOx = 0.89, HC = 0.39, CO = 1.43

2500 RPM
8 bar BMEP

Gas - 84 RON Gasoline

Inj. Pre – 900 bar
~ 32 % split
Higher speed/load conditions - 2500 RPM and 8 bar BMEP

Emissions (g/kW/hr):
- Diesel (6.5% EGR): NOx = 2.48, HC = 0.08, CO = 0.26
- Gas - I (16% EGR): NOx = 0.89, HC = 0.39, CO = 1.43
- Gas - III (18% EGR): NOx = 0.53, HC = 0.66, CO = 5.51

HRR (J/°CA)

Crank Angle (CA)

Inj. Pre – 600 bar
Equal split

2500 RPM
8 bar BMEP

Gas - 84 RON Gasoline
2750 RPM and 12 bar BMEP - significant reductions in NOx with very low HC penalty

Emissions (g/kW/hr):
- Diesel (2% EGR): NOx = 4.6, HC = 0.076, CO = 0.15
- 84 RON Gas (14% EGR): NOx = 1, HC = 0.13, CO = 0.89
2750 RPM and 12 bar BMEP - significant reductions in NOx with very low HC penalty

Emissions (g/kW/hr):
- Diesel (2% EGR): NOx = 4.6, HC = 0.076, CO = 0.15
- 84 RON Gas (14% EGR): NOx = 1, HC = 0.13, CO = 0.89

Inj. Pressure – 900 bar

37% of the total fuel

2750 RPM 12 bar BMEP

84 RON Gasoline
CA 50 = 10°CA
EGR = 14%
Design of Experiments Study

Design of experiment (D.O.E) matrix

<table>
<thead>
<tr>
<th>Exp No</th>
<th>EGR</th>
<th>Boost</th>
<th>Injection Pressure</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
</tr>
<tr>
<td>2</td>
<td>(+)</td>
<td>(-)</td>
<td>(-)</td>
</tr>
<tr>
<td>3</td>
<td>(-)</td>
<td>(+)</td>
<td>(-)</td>
</tr>
<tr>
<td>4</td>
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<td>(-)</td>
<td>(+)</td>
</tr>
<tr>
<td>6</td>
<td>(+)</td>
<td>(-)</td>
<td>(+)</td>
</tr>
<tr>
<td>7</td>
<td>(-)</td>
<td>(+)</td>
<td>(+)</td>
</tr>
<tr>
<td>8</td>
<td>(+)</td>
<td>(+)</td>
<td>(+)</td>
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</tbody>
</table>

*Yates Algorithm was used*

George E.P Box, William G Hunter and J. Stuart Hunter, Statistics For Experimeners- An Introduction to Design, Data Analysis and Model Building, John Wiley & Sons, Inc, USA.

D.O.E matrix parameter values at 8 bar BMEP

<table>
<thead>
<tr>
<th></th>
<th>EGR (%)</th>
<th>Boost (bar)</th>
<th>Injection Pressure (bar)</th>
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<tbody>
<tr>
<td>(+)</td>
<td>21</td>
<td>0.7</td>
<td>1000</td>
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<tr>
<td>(-)</td>
<td>13</td>
<td>0.5</td>
<td>500</td>
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Average values from DOE analysis at a BMEP of 8 bar

<table>
<thead>
<tr>
<th>NOx g/kW-hr</th>
<th>HC g/kW-hr</th>
<th>CO g/kW-hr</th>
<th>SFC g/kW/hr</th>
<th>Noise db</th>
<th>COV of IMEP</th>
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</thead>
<tbody>
<tr>
<td>1.51</td>
<td>1.26</td>
<td>5.36</td>
<td>238.7</td>
<td>93.5</td>
<td>1.3</td>
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</table>
Design of Experiments Study done @ 2500 RPM - 8 bar BMEP with EGR, P_inj and Boost as controls

NOx

% difference from the average

1 - EGR
2 - Boost
3 - EGR & Boost
4 - Inj. Pressure
5 - EGR & Inj. Pressure
6 - Boost & Inj. Pressure
7 - EGR, Boost & Inj. Pre

HC

% difference from the average

SFC

% difference from the average

COV of IMEP

% difference from the average
Conclusions

- Power density needs are addressed in gasoline LTC operation - SOC is controlled by means of proper split injection strategy.
- Higher HC emissions than conventional diesel mode, but lower than well-premixed (HCCI) conditions.
- Combination of low-octane fuel with proper fuel distribution and EGR is required to dictate this partially premixed LTC combustion.
- NOx Emissions were reduced through the following injection schemes at different loads.
  - 2 bar BMEP – Single early injection (95°CA bTDC).
  - 5 bar BMEP – Early (60°CA bTDC) and main at 2°CA aTDC.
  - 8 bar BMEP – Early (75°CA bTDC) and main at 2°CA aTDC.
  - 12 bar BMEP - Early (135°CA bTDC) and main at 2°CA bTDC.
- The operating window is limited by the self-ignition quality of the fuel as well as compression ratio of the engine, so low-octane fuels with lower compression ratios could provide a reasonable solution.
- High EGR and high injection pressure with low boost pressure would be the optimum for emissions, fuel efficiency and COV of IMEP.
Thank you
<table>
<thead>
<tr>
<th>BMEP (bar)</th>
<th>LTC Gasoline EGR rates (%)</th>
<th>Conventional Diesel EGR rates (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0</td>
<td>47</td>
</tr>
<tr>
<td>5</td>
<td>32</td>
<td>18</td>
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<td>8</td>
<td>18</td>
<td>6.5</td>
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<td>12</td>
<td>14</td>
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## Combustion parameters

<table>
<thead>
<tr>
<th>BMEP (bar)</th>
<th>Peak Pressure (bar)</th>
<th>Peak Pressure location (CA)</th>
<th>Max. Rate of Pressure Rise (MRPR) bar</th>
<th>MRPR Location (CA)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Diesel</td>
<td>Gas</td>
<td>Diesel</td>
<td>Gas</td>
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<td>31.1</td>
<td>49.3</td>
<td>365</td>
<td>364</td>
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<tr>
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<td></td>
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<td>367</td>
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<tr>
<td>2 **</td>
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<td>363</td>
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<tr>
<td>8 **</td>
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<tr>
<td>12</td>
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<td>362</td>
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# Combustion parameters

<table>
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<th>Peak Pressure (bar)</th>
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<tbody>
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<td>Gas</td>
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<td>5**</td>
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<td>8**</td>
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