The Effect of Diesel fuel properties on Emissions-Restrained Fuel Economy at Mid-Load Conditions

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Research and Technology
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High Efficiency Clean Combustion Program (HECC)
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HECC Objectives

1. Improve brake thermal efficiency by 10% and reduced engine out emissions (2010 compliance)

2. Design and develop enabling components and subsystems (air handling, fuel injection, base engine, controls, etc.)

3. Specify fuel properties conducive to improvements in emissions and fuel efficiency ➔ Focus of this talk

4. System integration for fuel economy optimization (engine and vehicle)
Fuel properties

• Eleven diesel fuels were specially blended according to the experimental design with variation in cetane number, distillation characteristics & aromatic content

• Three target Cetane levels (35, 45 and 55)

• Distillation characteristics involved perturbations around the baseline ULSD #2 properties; three levels for T10 and two levels for T90

• Two levels for aromatics
HECC vs. FACE fuels

- High Aromatic and high cetane for the HECC could not be achieved with commercial refinery blends.
- Distillation variation is achieved by blending light- or heavy-cut blending streams; cetane number affected by mono- aromatic content.
- Heating value, density allowed to float.
Modeling Strategy

Engine emissions and performance parameters

\[ \text{NOx, Smoke, Gross indicated fuel consumption (gisfc), Combustion phasing, ...} \]

\[ = f_1 \text{(Engine controls)} + f_2 \text{(Fuel properties)} \]

- 2nd order with square & interaction terms
- 1st order with least correlated fuel terms
### Fuel property correlations

<table>
<thead>
<tr>
<th></th>
<th>T10</th>
<th>T50</th>
<th>T90</th>
<th>Slope</th>
<th>Cetane</th>
<th>Mono-aromatic content</th>
<th>Poly-aromatic content</th>
<th>Total Aromatic content</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>T50</td>
<td></td>
<td>0.90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T90</td>
<td>0.74</td>
<td></td>
<td>0.94</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>-0.12</td>
<td>-0.30</td>
<td>0.58</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cetane</td>
<td>0.02</td>
<td>0.14</td>
<td>0.12</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mono-aromatic content</td>
<td>-0.32</td>
<td>-0.48</td>
<td>-0.36</td>
<td>-0.15</td>
<td>-0.67</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poly-aromatic content</td>
<td>0.77</td>
<td>0.78</td>
<td>0.76</td>
<td>0.19</td>
<td>-0.32</td>
<td>-0.17</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Total Aromatic content</td>
<td>0.53</td>
<td>0.45</td>
<td>0.49</td>
<td>0.09</td>
<td>-0.67</td>
<td>0.41</td>
<td>0.83</td>
<td></td>
<td></td>
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<tr>
<td>Density</td>
<td>0.80</td>
<td>0.74</td>
<td>0.69</td>
<td>0.03</td>
<td>-0.41</td>
<td>0.00</td>
<td>0.97</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>Heating value</td>
<td>-0.67</td>
<td>-0.56</td>
<td>-0.54</td>
<td>0.02</td>
<td>0.59</td>
<td>-0.25</td>
<td>-0.90</td>
<td>-0.97</td>
<td>-0.96</td>
</tr>
</tbody>
</table>

Cells indicate R-value or degree of linear relationship → +1 or -1 (strong correlation)

Limiting to physical properties and the least correlated ones,

Cetane → Ignition quality

T50 → Volatility

Slope → Rate of change of volatility (T90 – T10)
Test condition

FTP75 coverage
1700 rpm, 372 Nm
Highway operation of a pickup truck

Diffusion Combustion
Partially Premixed

Test condition (Cruise point)

Engine speed (rpm)
Engine torque (Nm)
Experimental method

• Single cylinder ISB engine (displacement 1.1 L/ cyl) used for the experiments
• Emissions meet 2010 US-EPA targets
• Full-factorial test design involving independent manipulation of
  o EGR
  o AF ratio
  o Rail pressure
  o Three pulse fuel injection sequence (pilot, main and post)
  o Main injection (close-to-TDC)
Correlation vs. data for NOx

Generally good correlations for other parameters as well:

- Smoke
- Gross indicated fuel consumption (gisfc)
- Combustion phasing, etc.
Model Results: First-order terms for NOx

T-statistic = \frac{\text{estimated model coeff.}}{\text{standard error}}

Sign indicates the directional effect with everything else fixed.

- Higher T50 and lower cetane increase NOx.
Model Results:
First-order terms for Smoke

- Higher T50 increases Smoke

Abs (t-statistic)

Parameter

Fresh air-fuel ratio
Intake O2 conc.
Rail pressure
Pilot quantity
Pilot to main sep.
Main timing
T50
Cetane
Slope
Model Results:
First-order terms for gisfc

AF ratio and EGR also impact gisfc

Gisfc dominated by main timing:
Improves with adv. timing

Relatively small effect of fuel properties
Model Results:

First-order terms for Combustion Phasing

Crank Angle for 50% Cumulative Heat Release (Normalized)

Little-to-no impact on combustion phasing; confirmed from heat-release data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Abs (t-statistic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh air-fuel ratio</td>
<td>10</td>
</tr>
<tr>
<td>Intake O2 conc.</td>
<td>10</td>
</tr>
<tr>
<td>Rail pressure</td>
<td>10</td>
</tr>
<tr>
<td>Pilot quantity</td>
<td>30</td>
</tr>
<tr>
<td>Pilot to main sep.</td>
<td>10</td>
</tr>
<tr>
<td>Main timing</td>
<td>90</td>
</tr>
<tr>
<td>T50</td>
<td>20</td>
</tr>
<tr>
<td>Cetane</td>
<td>10</td>
</tr>
<tr>
<td>Slope</td>
<td>0</td>
</tr>
</tbody>
</table>
Summary

• Functional relationships determined between fuel properties and engine emissions (SAE paper will be presented for the 2009 World Congress)

• Direct effect of fuel properties on gisfc is small, but fuel effects on NOx and smoke may result in changes on emissions restrained gisfc

• Lower T50 fuel provides simultaneous NOx and smoke benefit; higher cetane provides a small NOx reduction (cetane and T50 are both correlated with mono- and poly- aromatics respectively).
  
  o Literature indicates higher Aromatic $\rightarrow$ higher flame temp.

• Effect of cetane and T50 on heat release characteristics appears too subtle to be detected by in-cylinder pressure based virtual sensing
Future work

1. Optimize for lowest gisfc to determine the “ideal” fuel; assess possible improvements over the baseline one.

2. Characterize emissions fluctuations due to market fuel property variations.

   Engine responses = \( f_1 \) (Engine controls) + \( f_2 \) (Fuel properties)


4. Fuels induced effect vs. those of: EGR, Airflow, Swirl, etc.
   - Compensate for the variable with the largest effect first.