Spark versus Compression Ignition in a New Energy Environment

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Global Progress Drives Demand

Population
Billion

GDP
Trillion 2010$

Energy Demand
Quadrillion BTUs

Rest of World
Key Growth
India
China
OECD*

Mexico and Turkey included in Key Growth countries

ExxonMobil 2015 Outlook for Energy
The Middle Class Continues to Grow

Middle Class per The Brookings Institution
Billion People

- Rest of World
- Key Growth
- China
- India
- OECD*

- Mexico
- South Africa
- Nigeria
- Saudi Arabia
- Iran
- Turkey
- Indonesia
- Egypt
- Thailand
- Brazil
- Mexico (included in Key Growth countries)
- India
- Brazil
- China
- Turkey
- Iran
- Mexico

ExxonMobil 2015 Outlook for Energy
Electricity Generation Leads Growth

Primary Energy Demand by Sector
Quadrillion BTUs

ExxonMobil 2015 Outlook for Energy
Electricity Generation Leads Growth

Primary Energy Demand by Sector
Quadrillion BTUs

- Electricity Generation
- Industrial
- Transportation
- Res/Comm

- Other Renewables
- Biomass
- Nuclear
- Coal
- Gas
- Oil

ExxonMobil 2015 Outlook for Energy
Spark versus Compression Ignition in a New Energy Environment
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Transportation Demand

Sector Demand
MBDOE

0 25 50 75
2000 2020 2040

Light Duty
Heavy Duty
Aviation
Marine
Rail

ExxonMobil 2015 Outlook for Energy
Light Duty Vehicles

Fleet by Type

Million

- Elec/Plug-In/Fuel Cell
- Full Hybrid
- Natural Gas & LPG
- Diesel
- Gasoline

ExxonMobil 2015 Outlook for Energy
CO₂ Emissions Plateau

Energy-Related CO₂ Emissions by Region
Billion Tonnes

Emissions per Capita
Tonnes / Person

ExxonMobil 2015 Outlook for Energy
Background to Advanced Diesel Studies

- Europe’s diesel/gasoline demand ratio is continuing to increase:
  - Continuing consumer demand for personal mobility
  - More dieselization of the light-duty (LD) fleet
  - More heavy-duty demand for freight transport
  - Europe is importing diesel and jet fuel/kerosene and exporting gasoline

- Euro 6 (2014) emissions limits will lower NOx and PM emissions with new requirements anticipated for ‘real-world driving’ performance
  - Adding cost and complexity to LD diesel vehicles

- EU mandates will require better fuel consumption from LD vehicles
  - 130g CO\textsubscript{2}/km from 2012; 95g CO\textsubscript{2}/km by 2020
  - 43 to 47 MPG\textsubscript{US} from 2012; 58 to 65 MPG\textsubscript{US} by 2020
  - ‘Systems’ approach needed to capture improvements from entire engine/vehicle

- Renewables mandated to achieve 10% energy content in road fuels by 2020
  - Vehicle technology must be robust to a diverse fuel and biofuel mix
Extensive studies previously completed on bench engine and demo vehicle

- Diesel engine optimised for low temperature combustion (LTC)
- Closed Loop Combustion Control (CLCC) important
- Bench engine operated successfully on diesel, diesel/gasoline, naphthas, gasoline
  Primary Reference Fuels having low cetane numbers (DCN 30)
- Demonstrator vehicle achieved CO₂, NOx/PM, and combustion noise targets over the New European Driving Cycle on various fuels
- Advanced diesel engines found to tolerate a wide range of fuels

Concawe publications related to advanced combustion studies:

- Literature review: Advanced combustion for low emissions and high efficiency (Report 4/08)
- Part 2: Impact of fuel properties on HCCI combustion (SAE 2008-01-2404 and Report 10/10)
- Part 3: Advanced combustion in a demonstrator vehicle (SAE 2010-01-0334)
- Exploring a Gasoline Compression Ignition (GCI) Engine Concept (SAE 2013-01-0911)
- Modelling a Gasoline Compression Ignition (GCI) Engine Concept (SAE 2014-01-1305)
- Exploring a Gasoline Compression Ignition (GCI) Engine Concept (Report 13/14)

For CONCAWE reports, see www.concawe.org
## What Fuel for Advanced CI Engines?

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Will work in advanced CI engines?</th>
<th>Already available at retail stations?</th>
<th>Helps rebalance diesel/gasoline demand ratio?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel (EN590)</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>Kerosene</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Blends of diesel and gasoline</td>
<td>✓</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>New lower cetane fuel</td>
<td>✓</td>
<td>✗</td>
<td>?</td>
</tr>
<tr>
<td>Gasoline (EN228)</td>
<td>?</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

- **Evaporative emissions and flashpoint?**
- **New mixing dispensers at retail stations?**
- **Depends on performance and market uptake?**

- **Challenge with pump gasoline is its resistance to ignite**
- **Can Variable Valve Timing and combustion assistance aid low load operation?**
## Advanced Diesel Bench Engine Specifications

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>Units</th>
<th>Bench Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>[cm³]</td>
<td>390</td>
</tr>
<tr>
<td>Stroke</td>
<td>[mm]</td>
<td>88.3</td>
</tr>
<tr>
<td>Bore diameter</td>
<td>[mm]</td>
<td>75</td>
</tr>
<tr>
<td>Compression Ratio (CR)</td>
<td>[-]</td>
<td>19:1</td>
</tr>
<tr>
<td>Valves per cylinder</td>
<td>[-]</td>
<td>4</td>
</tr>
<tr>
<td>Maximum peak pressure</td>
<td>[bar]</td>
<td>220</td>
</tr>
<tr>
<td>Fuel injection system specifications</td>
<td>[-]</td>
<td>Bosch Piezo Common Rail System</td>
</tr>
<tr>
<td>Maximum injection pressure</td>
<td>[bar]</td>
<td>2000</td>
</tr>
<tr>
<td>Hydraulic Flow Rate (HFR)</td>
<td>[cm³/30s at 100bar]</td>
<td>310</td>
</tr>
<tr>
<td>Nozzle hole diameter</td>
<td>[µm]</td>
<td>109</td>
</tr>
<tr>
<td>Number of spray holes</td>
<td>[-]</td>
<td>8</td>
</tr>
<tr>
<td>Spray Cone Angle</td>
<td>[°]</td>
<td>153</td>
</tr>
<tr>
<td>Charging</td>
<td>[-]</td>
<td>Max. 3.8 bar absolute</td>
</tr>
</tbody>
</table>

- **19:1 CR and pilot injection enabled gives better combustion at full load**
- **Success criterial low NOx, lowest posible PM/HC/CO, FC/noise similar to diesel**
Stable Operation Achieved over Wide Range

- Stable operation was achieved over a large part of the operating range with good fuel consumption and acceptable CSL (noise)
- NOx emissions were higher than desired with limits on EGR rate
- Fuel’s ignition resistance (low CN) prevented more improvement
Fuel Consumption Better than Gasoline Engines

Comparison of the measured fuel consumption of the GCI engine and state of the art SI and CI engines (MY 2012 - benchmarked by FEV)
Lower load operation: What else can be done?

- With the objective of using market gasoline as the primary fuel:
  - More complex cam profile allowing a more flexible variable valve timing (VVT) arrangement
  - Use of a supercharger as well as a turbocharger to increase the boost pressure at low load
  - Use of an advanced ignition source (glow plug, spark plug, or laser) to initiate combustion and assist at lower loads
  - Use of Variable Compression Ratio (VCR)
  - Dual-fuelling operation

- All these options add complexity and cost → benchmarking of potential improvements against the cost and efficiency of aggressively downsized and boosted SI engines would be needed

- Additional cost would also be incurred in adding an evaporative emissions control system to a Gasoline CI (GCI) concept
Modelling Methodology

- Gas exchange and turbulent non-reacting flow
  - Modelled using STAR-CD
  - 1x $10^6$ grid mesh containing inlet/outlet ports, piston, cylinder head and walls
  - 1D simulation (GT-Power) provided $T+P$ boundary conditions for CFD model.

- Combustion
  - Modelled using KIVA 3V with Engine Research Center (ERC) model extensions
  - Segment of the $\omega$-shaped piston bowl of approximately 50 000 cells
VVT Strategies Simulated

Base Cam Shifting
48 °CA

Reduced I/E-Event
Cam Shifting 48 °CA

Base Exhaust Extra
Cam

Valve Lift / mm

Crank Angle / °CA

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VVT can increase gas temperature by 100K

\[\text{VVT can increase gas temperature by 100K}\]
In most promising VVT configuration, combustion assistance needed (glow plug)

Lambda ≤ 1 Colored by Temperature @ TDC-F

Reduced I/E-Event Cam Shifting @ 48 °CA

Advanced Boosting

Reduced I/E-Event Cam Shifting @ 48 °CA

Diesel Boundary Conditions

Realistic Boosting

Temperature / K

700  800  1000  1200
Simulating spark plug assist
(1500rpm, 4.3 bar IMEP, Nozzle cone angle = 160°)

- Nozzle Cone Angle of 160° and nozzle protrusion > 1.5 mm found to be optimal to ensure ignitable mixture around spark location.
Summary

- Increasing dieselization of the market due to increased commercial transportation amongst other factors is increasing pressure on the diesel/gasoline demand from refineries
- Running a higher volatility fuel such as gasoline in a diesel engine has been shown to give some emissions and fuel economy benefits
- Previous Concawe work has shown that running market gasoline in a compression ignition engine is achievable over a large part of the speed/load range by applying common optimization techniques
- Modelling work shows that advanced VVT strategies can increase in-cylinder gas temperature, enhancing gasoline’s ignitability at low loads especially in the presence of advanced boosting
- The most promising VVT strategy and nozzle configurations give an ignitable mixture in the vicinity of the glow
  - Spark plug ignition also possible with wider nozzle cone angle and nozzle protrusion > 1.5mm
- Increasing interest in GCI as a viable technology which could help solve future supply issues as well as meet future regulation needs
Acknowledgements

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