Potential of the Mild HCCI Combustion for Worldwide Applications
Future Fuels for IC Engines
The Diesel engine: a customer oriented product within the planetary challenge for reducing CO2

- Potentials and threatens
- The Mild HCCI as a promising Low Temperature Combustion system.
- Mild HCCI and available fuels
- Future combustion systems for future fuels or future fuels for future combustion systems?
The Diesel engine: a customer oriented product within the planetary challenge for reducing CO2
Satisfying customers is the main task for automotive manufacturers.
The Diesel Engine: a large success in Europe linked to upgraded technologies

Technological advances deeply linked to customer requirements

European Diesel market share (data from ACEA)

- Fuel Economy Performances
- Noise
- Emissions

Turbo
Variable Turbo
Common rail 1st gen.
Common rail 2nd gen.
By its high fuel efficiency, the Diesel engine is up to now the best contributor for reducing the CO2 rejections due to road transport.
Improvement of averaged CO2 emissions (Western Europe – ACEA data)

Contribution of both

Higher market share

Stronger reduction of the fuel consumption

gasoline

Diesel

total

Diesel market share

Improvement of averaged CO2 emissions

Contribution of both

Higher market share

Stronger reduction of the fuel consumption

gasoline

Diesel

total

Diesel market share
Part2: Potentials... and threatens

- CO2
- Driving pleasure
- And threatens
- Cost
- Noise
A challenge for the future: protecting the environment at an acceptable cost…

25% of the engine cost is due to the after-treatment

Two different strategies for the future

Strategies for Euro 5/6/US

Advanced after-treatment

NOx-trap, SCR

Reduction of Engine out Emissions

New combustion
... on worldwide markets

The combustion system must be compatible with worldwide applications to reduce costs.

- Low CO2
- High performances
- High fuel quality
- High torque
- SUV
- Very low emissions
- Difficult conditions
- Low cost
- Low fuel quality
The Mild HCCI as a promising Low Temperature Combustion system
A low temperature combustion: the key for the future?

Only solution #3 seems to be feasible in the near future.
The split injection as a way of realising a low temperature combustion

Fuel vaporised during the second injection is cooling the first combustion

Combustion due to the first injection

Combustion due to the second injection

BTC

Heat release

Fuel quantities and respective phasing of the two injections are governing the noise/soot trade off

The combustion is actively controlled by the injection
Mechanism of the split injection

- **SOI after TDC (CA)**
  - 3
  - 5
  - 7

- **Mass burnt rate**

- **3**
  - "almost" independent combustions
  - 2nd one late in burnt gases
  - Cool flame
  - 2nd diffusive combustion
  - High cooling due to 2nd injection

- **5**
  - late "fully" premixed combustion

- **7**
  - 2 "almost" independent combustions
  - 2nd one late in burnt gases
Mild HCCI definition

- HCCI because a noticeable part of the fuel is injected early in the compression cycle to get a homogeneous mixture and to secure a quasi fully premixed combustion

- mild because the second part of the fuel is injected later on in the cycle and can burn as a diffusive flame

- associated to a quite conventional Euro4 chamber design and therefore allowing competitive full load performances
Mild HCCI results: simulation on a NMVEG cycle (hot)
Renault Laguna, 6 gear manual transmission

Calculated engine out emissions
noise level equivalent to Euro4 version
(rough estimation of transitions between combustion modes)

<table>
<thead>
<tr>
<th></th>
<th>NOx</th>
<th>IOF</th>
<th>HC</th>
<th>CH4</th>
<th>CO</th>
<th>CO2</th>
<th>f.c. (l/100km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>conventional</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Mild HCCI</td>
<td>22</td>
<td>50</td>
<td>350</td>
<td>400</td>
<td>480</td>
<td>104</td>
<td>106</td>
</tr>
</tbody>
</table>

HCCI strategy is successfully reducing both NOx and soot Engine Out Emission

High penalty on hydrocarbons and especially methane

Fuel consumption must be reduced

Euro4 / 10 ppm S
Mild HCCI and available fuels
**Test engine:**
4 cylinder 2.0 liter 84x90 mm CR 16 engine with HP and LP EGR

**Fuels**

<table>
<thead>
<tr>
<th></th>
<th>Euro 4</th>
<th>US</th>
<th>Euro 3</th>
<th>B30 (30% Diester)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heating value</strong> (MJ/kg)</td>
<td>42.9</td>
<td>42.9</td>
<td>42.5</td>
<td>41.4</td>
</tr>
<tr>
<td><strong>Cetane</strong></td>
<td>54</td>
<td>44</td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td><strong>Sulfur level</strong> (ppm)</td>
<td>10</td>
<td>10</td>
<td>300</td>
<td>10</td>
</tr>
<tr>
<td><strong>O/C</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.007</td>
</tr>
<tr>
<td><strong>50% vaporized</strong> (°C)</td>
<td>280</td>
<td>257</td>
<td>280</td>
<td>290</td>
</tr>
</tbody>
</table>
No noticeable difference between Euro4, Euro3 and US fuels even with the same tuning

For B30, low reduction of performance ( ~3%) due to a lower heating Value but lower smoke level at 4000 rpm ( ~0.5 FSN)
The longer delay due to the low CN is compensated by the higher combustion velocity in pre-mixed mode.

Same injection timing

Same smoke vs equiv.ratio
Part load results US versus Euro4 analysis at 2000 rpm 6 bars BMEP same engine tuning same moderate EGR rate

With Euro4 fuel, the first combustion is effectively slowed down by the second injection.

With US fuel, the low cetane leads to a high delay => there’s only one retarded combustion.

US versus Euro4:
- 25% NOx
- 10 dBA
+ 100 % HC
+ 15% BSFC

Too late combustion leading to unacceptable BSFC
This late combustion leads to a poor acceptance of EGR rates compatible with a fuel neutral target > necessity to move to earlier injection timing for the 2 injections.
Part load results Euro3 versus Euro4 analysis at 1750 rpm 7 bars BMEP same engine tuning same moderate EGR rate

Very close combustion behavior:
- No difference for emissions and BSFC
- Soot +30% due to sulfur level
For Euro3 fuel, high EGR rates are forbidden due to important soot emissions
⇒ NOx reduction and compliance with Fuel Neutral is impossible
⇒ Engine tuning has to be modified
Part load results B30 versus Euro4 analysis at 2000 rpm 6 bars BMEP same engine tuning same moderate EGR rate

Reduced ignition delay for the first combustion
- Slightly higher noise level (+ 2 dBA)
- Lower smoke level due to Oxygen in the fuel
- BSFC higher with B30 but efficiency is the same

Engine tuning could be common for both Euro4 and B30 fuels
B30 fuel results: simulation on a NMVEG cycle (hot)
Renault Laguna, 6 gear manual transmission

NOx level compatible with “fuel neutral” hypothesis
Noise level equivalent to Euro4

But lower spec. heating value > same efficiency

Only one penalty on CH4 > oxycat light off to be secured
Part load optimisation with Euro4 and US fuels analysis at 2000 rpm 6 bars BMEP constant very low NOx level

Retarded combustion for Euro4 fuel
➢ Slightly higher BSFC

Roughly one advanced combustion allowed by the low soot level for US

Low cetane and high volatility compensates the earlier injection
Part load optimisation with Euro4 and US fuels analysis at 2000 rpm 6 bars BMEP constant very low NOx level

Linear correction on injection timing easily achievable in the ECU

Slightly delayed inj1 timing for US

\[ y = 0.8092x + 4.9938 \quad R^2 = 0.9917 \]

\[ y = 0.6667x + 3.6667 \quad R^2 = 0.9383 \]
US fuel results: simulation on a NMVEG cycle (hot)
Renault Laguna, 6 gear manual transmission

NOx level compatible with “fuel neutral” hypothesis
Noise level equivalent to Euro4

HC and CO penalties on cycle (overmixing effect due to a high volatility ?)
Part load optimisation with Euro4 and Euro3 fuels analysis at 2000 rpm 6 bars BMEP constant very low NOx level

NOx level compatible with “fuel neutral” hypothesis
Noise level equivalent to Euro4

Linear corrections for Euro3 versus Euro4 tuning
Conclusion

- The mild HCCI combustion system is compatible with fuels representative of worldwide availability as with 1st generation bio. ones
  - *At full load eg for down-sizing strategies*
  - *within a “fuel neutral” hypothesis (simulation result – transitions to be optimised)*

- HC, CH4 and CO have nevertheless to be secured, especially for cold start

- Fuel consumption has still to be reduced for all the fuels *(Euro4 vehicles still the target)*
The Well to Wheel approach is the key parameter to quantify the actual interest on new fuels… as for the currently existing B30 (tests achieved on a Renault Megane on New European Driving Cycle)
Part 5: New combustion systems and new fuels…

…are like tango couples

They could be the best if they remain together
But they still have to be performant if they change partner and orchestra

Thank you for your attention
Fun to drive and economic

Improved technologies and down-sizing

Vehicle Performance index

Fuel Consumption

G8T 2.2l IDI NA 87ch
F9Q 1.9l DI TC 100ch
K9K 1.5l DI TC 106ch

Euro2 (1996)
Euro3 (2002)
Euro4 (2007)
Euro5? (???)

Improved technologies and down-sizing