Alternative Fuels for IC Engines

Dipl.-Ing. Andreas Kolbeck, Manager Diesel Engines, FEV GmbH

Noordwijk aan Zee, 19.03.2012
Agenda

- Introduction

- Biofuel trends
  - Legislation requirements and distribution
  - Production trends

- Potential and challenges for alternative diesel fuel combustion
  - Fuel properties: Impact on the diesel combustion
  - Utilization of alternative diesel fuels

- Potential and challenges for alternative gasoline fuel combustion
  - Benefit of Ethanol

- Conclusions
Agenda

- **Introduction**

- **Biofuel trends**
  - Legislation requirements and distribution
  - Production trends

- **Potential and challenges for alternative diesel fuel combustion**
  - Fuel properties: Impact on the diesel combustion
  - Utilization of alternative diesel fuels

- **Potential and challenges for alternative gasoline fuel combustion**
  - Benefit of Ethanol

- **Conclusions**
Drivers for Future Mobility

- Emissions
- Climate Change
- Energy Security
- Ressources

- Emission Reduction
- CO₂-Reduction
- Less Imports
- Availability
Greenhouse Gas Reduction Challenge for Road Transport

Crude Production 1–4%

Refining 8–10%

Distribution & retail 1%

Fuel Combustion 85%

Well-to-Tank (WTT) ~15% (production side)

Tank-to-Wheels (TTW) ~85% (consumption side)

Source: For conventional vehicles and fuels: JRC/EUCAR/CONCAWE Well to Wheels Study (2007)
EU Legislation:
2012: 65% of fleet 130 g\(\text{CO}_2/\text{km}\)
2013: 75% of fleet 130 g\(\text{CO}_2/\text{km}\)
2014: 80% of fleet 130 g\(\text{CO}_2/\text{km}\)
2015: 100% of fleet 130 g\(\text{CO}_2/\text{km}\)

Introduction
NEDC Cycle

Fleet target 130 g/\text{km} - up to -7 g/\text{km} by improved A/C systems allowed

Fleet target 95 g/\text{km} in 2019 - to be confirmed in 2013

Source: European Commission
Agenda

- Introduction

- Biofuel trends
  - Legislation requirements and distribution
  - Production trends

- Potential and challenges for alternative diesel fuel combustion
  - Fuel properties: Impact on the diesel combustion
  - Utilization of alternative diesel fuels

- Potential and challenges for alternative gasoline fuel combustion
  - Benefit of Ethanol

- Conclusions
Overview of Biodiesel Blending Targets

10% renewable energy in transport in Europe

B10*

B2

48 billion litres renewable fuel

B20

B10

B3

500 Ml/y oil equivalent renewable fuel

B5

B5

B20 (2015)

B5

B5

B7

B5

B3

B20 (2025)

B5

B20 (2017)

No biodiesel mandate yet

Source: Technology Roadmap Biofuels for Transport, IEA 2011
EU Directive for GHG reduction

- Sustainability
  - Minimum GHG Emission
  - Production chain
  - Environmental protection
- GHG reduction in EU fuel market of minimum 6% from 2010 to 2020

Quelle: Standardwerte aus Erneuerbaren Energien Direktive 2009/28/EG, ohne Netto-CO₂-Emissionen infolge von Landnutzungsänderungen
What is Biomass?

* Mass fraction of cell wall

- **Grain / Fruit**
  - Starch
  - Oil
  - Tuber

- **Cell wall**
  - Hemicellulose: approx. 15 - 30% * breakup: easy
  - Cellulose: up to approx. 50% * breakup: difficult
  - Lignin: approx. 10 - 25% * breakup: very difficult

* * by FEV – all rights reserved. Confidential – no passing on to third parties
Biofuel Production Pathways
1st Generation Biofuels

Grains, Tuber (Sugar Cane, corn, etc.)

<table>
<thead>
<tr>
<th>Enzymatic Depolymerization of the Fruit</th>
<th>Glucose</th>
<th>Fermentation</th>
<th>Bioethanol</th>
</tr>
</thead>
</table>

Rape, Sunflowers, Soybeans, etc.

| Oil Mill | Vegetable Oil | Transesterification | Biodiesel Fatty acid methyl ester (FAME) |
Yield per unit for first generation

1. generation biofuels

- **Grain**
  - Ethanol
  - 1440 l Diesel equivalent

- **Rapeseed oil**
  - Biodiesel
  - 1450 l Diesel equivalent
  - Vegetable oil
  - 1480 l Diesel equivalent

Quelle: FNR 2009
Biofuel Production Pathways
2nd Generation Biofuels

Biomass (entire plant or residue)

- Fermentation → Water/Alcohol Mixture
- Gasification → Synthesis Gas (CO, H₂)
- Fermentation → Biogas (CH₄, CO₂)

Separation

- Fischer-Tropsch Synthesis → Mixture of different Hydrocarbons (BTL)
- Cleaning → Bio-Methane (CH₄)

Alcohols
Yield per unit for first and second generation

1. generation biofuels
- Grain
  - Ethanol: 1440 l Diesel equivalent

2. generation biofuels
- Rapeseed oil
  - Biodiesel: 1450 l Diesel equivalent
  - Vegetable oil: 1480 l Diesel equivalent
- Whole plants
  - BTL-fuel: 3.910 l Diesel equivalent
  - Ethanol (BRA): 3.600 l Diesel equivalent

Quelle: FNR 2009
Biofuel Production Pathways
Next Generation Diesel – Tailor-made fuels from Biomass (TMFB)

Preserving the Synthesis of Nature

Source: Cluster of Excellence, „Tailor-Made Fuels from Biomass“, RWTH Aachen University
Biofuel Production Pathways
Next Generation Diesel – Tailor-made fuels from Biomass (TMFB)

Biomass

<table>
<thead>
<tr>
<th>Cellulose</th>
<th>Glucose</th>
<th>Platform chemicals</th>
<th>Possible fuel components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decomposition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cellulose</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hemicellulose</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lignin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depolymerisation</td>
<td>Fermentation</td>
<td>Dehydratisation</td>
<td>Hydrogenation/Dehydratisation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hydroxymethylfurfural</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>e.g. Esterification</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Butyl levulinate</td>
</tr>
</tbody>
</table>

Source: Cluster of Excellence, „Tailor-Made Fuels from Biomass“, RWTH Aachen University
Biofuel Production Pathways
Next Generation Diesel – Tailor-made fuels from Biomass (TMFB)

<table>
<thead>
<tr>
<th>Platform chemicals</th>
<th>Possible fuel components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Itaconic acid</td>
<td>3-MTHF</td>
</tr>
<tr>
<td>Hydroxymethylfurfural</td>
<td>2-MTHF</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Challenges for engine operation with neat butyl levulinate:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• low cetane number</td>
</tr>
<tr>
<td>• high oxygen content</td>
</tr>
<tr>
<td>• reduced heating value</td>
</tr>
</tbody>
</table>
By 2050, biofuels could provide **27% of total transport fuel** and contribute in particular to the replacement of diesel, kerosene and jet fuel.

The projected use of biofuels could avoid around **2.1 gigatonnes (Gt)** of CO$_2$-emissions per year when produced sustainably.

Source: IEA: Technology Roadmap – Biofuels for Transport, Blue Map Scenario, 2011
Agenda

- Introduction

- Biofuel trends
  - Legislation requirements and distribution
  - Production trends

- Potential and challenges for alternative diesel fuel combustion
  - Fuel properties: Impact on the diesel combustion
  - Utilization of alternative diesel fuels

- Potential and challenges for alternative gasoline fuel combustion
  - Benefit of Ethanol

- Conclusions
Reference Fuels for Parametric Study

- **n-heptane**
- **1-decanol**
- **iso-octane**
- **n-decane**
- **n-dodecane**

**Boiling Temperature**

- 20°C, 30°C, 40°C, 50°C, 60°C, 70°C, 80°C, 90°C

**Cetane Number [-]**

- 20, 30, 40, 50, 60, 70, 80, 90

- **1-decanol** with 10 w-% oxygen content
- **n-dodecane** without oxygen content
- **n-decane** without oxygen content

**Reference Fuels for Parametric Study**

- **n-heptane**
- **1-decanol**
- **iso-octane**
- **n-decane**
- **n-dodecane**
Research Diesel engine

Single-cylinder **HECS**

- Bore x Stroke: 75 x 88.3 mm
- Cylinder displacement: 390 cm³
- Max. BMEP: 30.0 bar
- Spec. Power: 105 kW/l
- Compression Ratio: 15 (var.)
- Peak Pressure: 250 bar
- FIE System: CRIP 3, 2000 bar

**High Efficiency Combustion System**
Parametric Study
Influence of Cetane Number on Engine Performance

→ PM emissions decrease with **decreasing** cetane number
→ Increased effect at medium loads

Euro 6 NOx-Level
- $n_{mot} = 2400 \text{ min}^{-1}, \text{IMEP} = 14.8 \text{ bar}$
- $n_{mot} = 2280 \text{ min}^{-1}, \text{IMEP} = 9.4 \text{ bar}$
- $n_{mot} = 1500 \text{ min}^{-1}, \text{IMEP} = 6.8 \text{ bar}$
- $n_{mot} = 1500 \text{ min}^{-1}, \text{IMEP} = 4.3 \text{ bar}$
Parametric Study
Influence of Cetane Number on Engine Performance

Reduced HC and CO emissions with increasing cetane number
Increased effect at lower loads
High CO / HC critical for emission compliance in certification test cycle
Emissions Potential with Future Biofuels ➔ TMFB

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Diesel EN590</th>
<th>1-Decanol</th>
<th>BLT*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (15 °C)</td>
<td>kg/m³</td>
<td>833</td>
<td>833</td>
<td>914</td>
</tr>
<tr>
<td>Cetane number</td>
<td>-</td>
<td>56.5</td>
<td>~ 50</td>
<td>~ 33</td>
</tr>
<tr>
<td>Oxygen content</td>
<td>w-%</td>
<td>0.14</td>
<td>10.3</td>
<td>20.6</td>
</tr>
<tr>
<td>Lower heating value</td>
<td>MJ/kg</td>
<td>42.9</td>
<td>38.9</td>
<td>32.8</td>
</tr>
<tr>
<td>Boiling behaviour</td>
<td>°C</td>
<td>180-350</td>
<td>221.5</td>
<td>231-253</td>
</tr>
</tbody>
</table>

1-Decanol

Butyl levulinate

n-Tetradecane

* Blend of 70 % butyl levulinate + 30 % n-tetradecane
Future Diesel fuels

- Sustainable fuel production
- Fuel should contain oxygen
- Reduced cetane number, still meeting cold-starting requirements
- Fuel free of aromatics
- Reduced boiling temperature
- High heating value
- Material compatibility with conventional components supplying fuel
- Sufficient lubricity

➔ How to achieve market introduction?
FEV HECS Diesel Demonstrator Vehicle

Specification
- Downsized 1.6l 4-Cyl. Diesel Engine
- 80 kW/l spec. Power
- 2-stage boosting system
- High and Low Pressure EGR
- Advanced Charge Cooling Concept
- 2000 bar Piezo FIE
- DOC + DPF
- Advanced Control Strategies
- Optimized Bowl with CR 15:1

High Efficiency Combustion System

Benefits
- 17% Fuel Consumption Reduction (vs 2.2l with 125 kW, EU4)
- EU 6 emissions w/o NOx Aftertreatment in 1590 kg Vehicle
- High Specific Torque and Power
- Robust Combustion System with Advanced Control Strategies
Multi-Fuel Diesel Engine Concept

1. Robust Combustion System
2. Closed-Loop Combustion Control
3. Closed-Loop Air-Path Control

Graph showing Total Aromatics (% m/m) vs. Derived Cetane Number (DCN) with various fuel types indicated:
- Diesel Fuels
- Kerosene Fuels
- Gasoline-like Fuels
- Other Fuels

Legend:
- Gasoline/Diesel
- US Diesel
- India
- EN 590 Diesel
- Low Aromatic Kerosine
- PRF 25
- GTL
Fuel Compensation by Closed-Loop Combustion Control

1500 rpm 3 bar BMEP

Without CLCC

Pressure Trace

With CLCC

Pressure Trace
Fuel Compensation by Closed-Loop Combustion Control

1500 rpm 3 bar BMEP
$\text{ISNO}_x = \text{const.}$

- Baseline EN590
- Fuel 1
- Fuel 2

- ISPM [g/kWh]
- ISCO [g/kWh]
- Indicated Efficiency [%]
- Centre of Combustion [°CA ABDC]
- ISHC [g/kWh]
- Engine Noise [dB]

- Without CLCC
- With CLCC

© by FEV – all rights reserved. Confidential – no passing on to third parties
Emission Potential of Multi-Fuel Diesel Engine Concept

- Standard EN 590 Diesel
- Gasoline/Diesel Blend (CN 44)
- Low Aromatic Kerosene
- Primary Reference Fuel (PRF 25)

PM raw [g/km]

CO [g/km]

HC [g/km]

CO2 [g/100 km]

NOx [g/km]
Agenda

- Introduction

- Biofuel trends
  - Legislation requirements and distribution
  - Production trends

- Potential and challenges for alternative diesel fuel combustion
  - Fuel properties: Impact on the diesel combustion
  - Utilization of alternative diesel fuels

- Potential and challenges for alternative gasoline fuel combustion
  - Benefit of Ethanol

- Conclusions
Research gasoline engine

**Multi-cylinder I4 SGT**

- Bore x Stroke: 81 x 87 mm
- Cylinder displacement: 448 cm³
- Max. BMEP: 22.4 bar
- Spec. Power: 90 kW/l
- Compression Ratio: 9.3 – 11.5

**Single-cylinder**

- Bore x Stroke: 75 x 82.5 mm
- Cylinder displacement: 364 cm³
- Max. BMEP: > 40 bar ($\varepsilon = 10$)
- Spec. Power: ~ 120 kW/l
- Compression Ratio: 7 – 13.5
Full load results with different Ethanol blends

- ROZ 95, $\varepsilon = 9.3$
- E20 Splash Blend, $\varepsilon = 11.5$
- E85, $\varepsilon = 11.5$

Engine Speed vs. $p_{\text{mi}}$ / bar

- Engine Speed / 1/min
- $\varepsilon$ - Air-Fuel Ratio

Verbrennungs- luftverhältnis
„Tank to Wheel“ CO2 Reduction with Ethanol fuels

ROZ 95:
- 151 – 201 g CO₂/km
- 3.9 – 4.9 %

E20 Splash Blend:
- 145 – 191 g CO₂/km
- 3.9 – 4.9 %

E85:
- 143 – 189 g CO₂/km
- 5.3 – 6.3 %
Agenda

- Introduction
- Biofuel trends
  - Legislation requirements and distribution
  - Production trends
- Potential and challenges for alternative diesel fuel combustion
  - Fuel properties: Impact on the diesel combustion
  - Utilization of alternative diesel fuels
- Potential and challenges for alternative gasoline fuel combustion
  - Benefit of Ethanol
- Conclusions
Conclusions

- Future legislation will require CO$_2$-emission reduction.
- Biofuels have substantial potential for emission reduction, however, in view of CO$_2$-emissions, also the fuel production efficiency has to be taken into account.
- Due to big variety of raw materials and also stakeholders, increasing diversification of fuels in the future to be expected.
- Diesel:
  - New fuel compositions like 70 % butyl levulinate and 30 % n-tetradecane (BLT-blend) have great potential to reduce well to wheel emission balance.
  - soot-free Diesel combustion achievable
- Gasoline:
  - Alternative will mainly be Ethanol, which is already widely established
  - Improved knocking resistance and thus increased engine efficiency