Fuel Economy – How Do We Get There?

39th Automotive-Petroleum Industry Forum

Dearborn, MI, April 19th, 2016
Dr. Dean Tomazic, Executive VP & CTO, FEV North America, Inc.
Agenda

- Introduction
- Development Trends
- Potential Game Changing Technologies
- Future Lubricant Requirements
- Summary
The Future of Powertrains
Current Global Situation

<table>
<thead>
<tr>
<th>Global Mega Trends</th>
<th>Resulting Drivers</th>
<th>Powertrain Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Security</td>
<td>Urbanization</td>
<td>Green Themes</td>
</tr>
<tr>
<td>Mass Mobilization</td>
<td></td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Legislation</th>
<th>Government Policies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cost of Ownership</td>
<td></td>
<td>(Taxation, Subsidies etc.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ICE</th>
<th>Natural Gas ICE</th>
<th>HEV</th>
<th>HHV</th>
<th>Fuel Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT</td>
<td>DCT</td>
<td>Hybrid</td>
<td>CVT</td>
<td>AT</td>
</tr>
</tbody>
</table>
# U.S. Emissions, Fuel Economy, and CO₂ Regulation

## Overview

### U.S. - Passenger Cars and Light Trucks (GVW < 6,000lbs)

<table>
<thead>
<tr>
<th>Year</th>
<th>PC</th>
<th>LT</th>
<th>Fuel Economy</th>
<th>NOx</th>
<th>CO</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>33.8</td>
<td>25.7</td>
<td>PC 27.5mpg / LT 22.2 mpg</td>
<td>From 0.2 (Bin 8) - 0.02 (Bin 2)</td>
<td>4.2 (Bin 5-8) - 2.1 (Bin 2-4)</td>
<td>0.02 (Bin 7-8) - 0.01 (Bin 1-6)</td>
</tr>
<tr>
<td>2010</td>
<td>39.5</td>
<td>28.8</td>
<td>FE I</td>
<td>Tier II</td>
<td>Tier III – Phase In</td>
<td>Tier III</td>
</tr>
<tr>
<td>2020</td>
<td></td>
<td></td>
<td>Combined Fleet Average</td>
<td>Combined NMOG&amp;NOx limit ramp down</td>
<td>CO limit ramp down</td>
<td>0.03 NMOG+NOx</td>
</tr>
<tr>
<td>2025</td>
<td></td>
<td></td>
<td>Tier III emission average</td>
<td>Tier III emission average</td>
<td>Tier III emission average</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Source:** Delphi, FEV Research

### California

<table>
<thead>
<tr>
<th>Year</th>
<th>NOx</th>
<th>CO</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>0.07 (LEV, ULEV) - 0.02 (SULEV)</td>
<td>4.2 (LEV), 2.1 (ULEV), 1.0 (SULEV)</td>
<td>0.01</td>
</tr>
<tr>
<td>2010</td>
<td>LEV II</td>
<td>LEV III – Phase In</td>
<td>PM ramp down</td>
</tr>
<tr>
<td>2020</td>
<td>+ 3 new low emission categories</td>
<td>Combined NMOG&amp;NOx limit ramp down</td>
<td>0.03 NMOG+NOx</td>
</tr>
<tr>
<td>2025</td>
<td>SULEV-level emission average</td>
<td>CO limit ramp down</td>
<td>Durability Increase to 150k mi</td>
</tr>
</tbody>
</table>

**Source:** Delphi, FEV Research
Agenda

- Introduction
- Development Trends
- Potential Game Changing Technologies
- Future Lubricant Requirements
- Summary
Worldwide regulations for CO₂ reduction – CO₂ fleet targets (g/km) NEDC based

2006 Target  
2015 Target  
2020 Target  
2025 Target

2006 Target  
2015 Target  
2020 Target  
2025 Target

2006 Target  
2015 Target  
2020 Target

2006 Target  
2015 Target  
2020 Target

* Proposed Target
Development Trends
Gasoline Engines

Specific Power: History and Future

- Extrapolation of trend based on ongoing market survey
- Maximum specific power depends on market position of individual OEM
- Mainstream engine of Premium OEM might have higher BMEP than ‘high performance engine’ from large volume OEM
- Additional features for future considered, e.g. variable compression ratio (VCR)

Source: FEV Consulting
Development Trends  
Gasoline Engines

Development Trends Gasoline Engines

**Gasoline Engines**

- **Trend:**
  - Further downsizing
  - High specific power & LET
- Several high performance engines in development at FEV
- Boosting system is key component
- 1-stage boosting limited
- 2-stage boosting to combine high specific power and low-end-torque (LET):
  - TC + eC
  - TC + TC
  - TC + SC

---

### Development Trends Gasoline Engines

**Scatterband**

- Borderline TC engines MY2015
- Borderline TC engines MY2008

### Specific power / (kW/l)

### Specific low-end-torque / (Nm·min/l)

### Development Trends Gasoline Engines

**Legend:**

- NA engines
- 1-stage boosted engines
- 2-stage boosted engines
- Motorcycle engines FEV under development at FEV

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Technology Trends
Hybridization / Electrification / Transmissions

Conventional Vehicles
- Gear Box
- Fuel Tank

Hybrid Electric Vehicles
- Micro Hybrid
- Mild Hybrid
- Full Hybrid
- Plug-In Hybrid
  - Charging from Grid
  - +Pure Electric Drive
  - +Electric Take-off
  - +Engine Assistance
  - +Kinetic Energy Recovery

Start-Stop & Intelligent Energy Management
- 4kW ...
- 10kW ...
- 30kW ...
- 80kW ...

Increasing electrical power
- 5-10% ...
- 10-20% ...
- 20-30% ...
- depending on battery size

CO₂-emissions

Complexity ICE
- small impact on transmission design (start/stop)

Complexity PT/Gearbox
- big impact on transmission design* (2 inputs)

Battery Electric Vehicles
- Battery

Increasing battery size/cost

new transmission design
Agenda

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### Development Trends
Gasoline Engines

<table>
<thead>
<tr>
<th>Combustion Efficiency Improvements</th>
<th>Reduction of Throttling Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Injection (&amp; Var. Charge Motion)</td>
<td>Downsizing</td>
</tr>
<tr>
<td>Variable Compression Ratio (VCR)</td>
<td>Boosting</td>
</tr>
<tr>
<td>Miller/Atkinson Cycle</td>
<td>Cylinder Deactivation</td>
</tr>
<tr>
<td>Controlled Auto-Ignition (CAI)</td>
<td>Variable Valvetrain</td>
</tr>
<tr>
<td>Cooled EGR</td>
<td>Lean-burn Operation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrification/Hybridization</th>
<th>Reduction of Parasitic &amp; Idle Losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro/Mild/Full Hybrid</td>
<td>Friction Reduction</td>
</tr>
<tr>
<td>PHEV</td>
<td>Stop/Start</td>
</tr>
<tr>
<td>48V Infrastructure</td>
<td>Advanced Thermal Management</td>
</tr>
<tr>
<td>Accessory (FEAD) Electrification</td>
<td>Accessory (FEAD) Electrification</td>
</tr>
</tbody>
</table>
Friction Reduction
Base Engine Design Opportunities

- Friction reduction → Impact on bearing dimensioning → Higher bearing loads
- Discrepancy in bearing load between FE vs. high-power version (LSPI)
- Stop-start (polymer coatings)
- Oil aeration

Friction Energy in %

Base
Optimized
Crank Shaft
Piston Group
Oil & Oil Pump
Valve Train
Alternator
Water Pump
Transmission

Base Vehicle: 1.8 l Turbo, 1500 kg, 150 g/km CO₂, NEDC
Development Trends
Gasoline Engines

Example:
Three-Cylinder GTDI
• Best in class BSFC
• Variable valve lift
• Friction optimized
• State-of-the-art combustion
• Optimized air and exhaust management

Brake Specific Fuel Consumption
norm. to calor. val. = 42.5 MJ/kg
2000 rpm / BMEP = 2 bar
- SI engines
- Production state
- Model year > 1997
Combustion System Challenges
Gasoline Engine Development: Low-Speed Pre-Ignition (LSPI)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil/Cool Temp.</td>
<td>40 deg C</td>
</tr>
<tr>
<td>Intake Temp.</td>
<td>90/90 deg C</td>
</tr>
<tr>
<td>Lambda Spindt</td>
<td>1.100</td>
</tr>
<tr>
<td>Exh. backpres.</td>
<td>50 mbar</td>
</tr>
<tr>
<td>SOI</td>
<td>480 deg CA</td>
</tr>
<tr>
<td>Engine speed</td>
<td>1600 rpm</td>
</tr>
<tr>
<td>Rail pres.</td>
<td>120 bar</td>
</tr>
<tr>
<td>Camph. IV/EV</td>
<td>15/35 deg CA</td>
</tr>
<tr>
<td>Fuel</td>
<td>Type 1</td>
</tr>
<tr>
<td>Spark plugs</td>
<td>No.1</td>
</tr>
<tr>
<td>Pre-conditioning</td>
<td>Dirty Pre-Conditioning</td>
</tr>
</tbody>
</table>

Example:
- Picture taken 3 deg CA before spark event
- LSPI event in the middle of the combustion chamber
- Pressure rise 1 deg CA before spark
2-Step Variable Compression Ratio (VCR) Mechanism

Background & Incentive

Key figures

- Conflict of aims:
  - High compression ratio for excellent part load efficiency
  - Low compression ratio for reduced knocking at high / full load

- This trade-off can be solved by systems allowing a variable compression ratio

Source: FEV
## 2-Step Variable Compression Ratio (VCR) Mechanism

### Background & Incentive

#### Gasoline
- Fuel consumption reduction
- Low End Torque (LET) improvement
- Potential of high knocking resistance for upcoming fuels (E100, CNG) in Bi-fuel applications
- No interference with other thermodynamic measures for fuel consumption
  - Variable valve lift
  - Miller
  - External cooled EGR

#### Diesel
- **Low load:**
  - High CR for increased efficiency and reduced HC emissions
- **Medium & high load:**
  - Low CR for reduction of particulate matter emission with constant NO\(_x\)
- **Full load:**
  - Increased rated power / improved efficiency with same peak firing pressure
  - Same rated power enables reduced peak firing pressure to reduce friction by optimized engine design

Source: FEV
2-Step Variable Compression Ratio (VCR) Mechanism
Design Features

- Connecting rod design
  - lever
  - support rod (gas forces)
  - support piston (gas forces)
  - check valve
  - eccentric
  - support rod (mass forces)
  - support piston (mass forces)
  - shift valve

- Mechanical actuation

Source: FEV
2-Step Variable Compression Ratio (VCR) Mechanism Functionality

Source: FEV
Development Trends
Transmissions

‘Direct’ Transmission Efficiency Improvements
- High Efficiency Oil Pumps
- Minimized Open Clutches
- Low-Loss Bearings/Seals/Gears
- Low-Leakage Hydraulics
- Low-Viscosity Oils

‘Indirect’ Transmission Efficiency Improvements
- Increased Number of Speeds
- Increased Ratio Spread
- Aggressive Torque Converter Lock-Up
- Active Thermal Management

Transmission Types
- Manual/AMT/DCT
- Planetary Automatics
- CVT
- Hybrids

Development Path
# Hybridization

## Architectural Alternatives

## Increasing Degree of Hybridization/Electrification

<table>
<thead>
<tr>
<th>Conventional ICE-Only Vehicle</th>
<th>Hybrid Electric Vehicle (HEV)</th>
<th>Plug-In (PHEV)</th>
<th>Battery EV (EV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gear Box</td>
<td>Parallel-Hybrid</td>
<td>Parallel-Hybrid</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>Fuel Tank</td>
<td>Power Split-Hybrid</td>
<td>Power Split-Hybrid</td>
<td>BEV with REX</td>
</tr>
<tr>
<td></td>
<td>Series-Hybrid</td>
<td>Series-Hybrid</td>
<td></td>
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<tr>
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</tbody>
</table>
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Engine Lubricants
Future Requirements

- Engine
  - Friction reduction → Impact on bearing dimensioning → Higher bearing loads
  - Discrepancy in bearing load between FE vs. high-power version (LSPI)
  - Higher operating temperatures (oil and coolant)
  - Low viscosity desired during start up (rapid warm-up)
  - Piston skirt lubrication ( honing pattern)
  - Piston ring tension reduction (friction, blow-by, oil consumption)
  - HLA’s, VVL, stop-start, etc.
  - Fuel in oil entrainment (dilution) w/ DI engines (E10-100)
  - Oil aeration
  - Variable oil pumps (2-step or continuous)

- Transmission
  - Friction reduction → Impact on bearing dimensioning → Higher bearing loads
  - Separate oil pump (stop-start)
  - Higher operating temperatures (‘fill for life’)
  - Accelerated warm-up (cold start)
  - Optimized gear geometries
  - Etc.
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Summary

- The industry is facing multidimensional challenges from a legislative, economic and societal perspective. Technical solutions must satisfy all of these requirements to succeed in the marketplace.

- Technologies to meet future requirements are either already available or under development. However, different markets have different requirements and hence different technical solutions.

- Due to these requirements, the variability of different powertrain types will continue to increase resulting in the need to also adapt fuels and lubes accordingly.

- A ‘one fits all’ solution becomes more and more unlikely due to the vast differences among the different powertrains and the way they will be used in the market.

- The main challenge remaining is to develop a cost efficient powertrain portfolio that meets legislative requirements and is accepted by the customer despite fluctuating fuel prices.