GHG Reducing Advancements and Technologies

CARB ACC Symposium

Diamond Bar, CA, September 28th, 2016
Dr. Dean Tomazic, Executive VP & CTO, FEV North America, Inc.
Agenda

■ Introduction
■ Development Trends
■ Potential Game Changing Technologies
■ 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></td>
<td></td>
<td>Mass Mobilization</td>
</tr>
<tr>
<td>Total Cost of Ownership</td>
<td>Legislation</td>
<td>Government Policies (Taxation, Subsidies etc.)</td>
</tr>
<tr>
<td>ICE</td>
<td>Natural Gas ICE</td>
<td>HEV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HHV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fuel Cell</td>
</tr>
<tr>
<td>MT</td>
<td>DCT</td>
<td>Hybrid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CVT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AT</td>
</tr>
</tbody>
</table>

Source: FEV
# U.S. Emissions, Fuel Economy, and CO\textsubscript{2} 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>FE I</th>
<th>FE 2</th>
<th>Combined Fleet Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2019</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2021</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2022</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2023</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2024</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fuel Economy**

- **PC**: 33.8 → 39.5
- **LT**: 25.7 → 28.8
- **Combined Fleet Average**: 35.5
- **California AB 1493**: Minimum ZEV Requirements:
  - MY 15-17: 14%, MY 18+: 16%
- **PC/LD1**: 323 → 205
- **LD2/MDPV**: 439 → 332
- **PC**: 5% p.a./LT: 3.5%-5% p.a.
- **Coordinated Approach**: 163

**U.S. Federal**

- **NOx**: From 0.2 (Bin 8) - 0.02 (Bin 2)
- **CO**: 4.2 (Bin 5-8) - 2.1 (Bin 2-4)
- **PM**: 0.02 (Bin 7-8) - 0.01 (Bin 1-6)

**California**

- **NOx**: 0.07 (LEV, ULEV) - 0.02 (SULEV)
- **CO**: 4.2 (LEV), 2.1 (ULEV), 1.0 (SULEV)
- **PM**: 0.01

**Phase-In**

- **Tier II**: 0.07 g/mi NOx fleet average
- **Tier III – Phase In**: Combined NMOG&NOx limit ramp down
- **Tier III**: 0.03 NMOG+NOx

**Durability Increase to 150k mi**

- **California Phase IV**: + 3 new low emission categories

Source: Delphi, FEV Research
Agenda

- Introduction
- Development Trends
- Potential Game Changing Technologies
- Summary
Development Trends
Global CO₂ Emission Targets

Worldwide regulations for CO₂ reduction – CO₂ fleet targets (g/km) NEDC based

<table>
<thead>
<tr>
<th>Year</th>
<th>Target 2006</th>
<th>Target 2015</th>
<th>Target 2020</th>
<th>Target 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU</td>
<td>160</td>
<td>130</td>
<td>95</td>
<td>68-78*</td>
</tr>
<tr>
<td>US</td>
<td>249</td>
<td>182</td>
<td>140</td>
<td>101*</td>
</tr>
<tr>
<td>Japan</td>
<td>149</td>
<td>125</td>
<td>105*</td>
<td>-57%</td>
</tr>
<tr>
<td>China</td>
<td>188</td>
<td>167</td>
<td>120*</td>
<td>-38%</td>
</tr>
</tbody>
</table>

* Proposed Target
### Development Trends
#### Consumer Expectations

<table>
<thead>
<tr>
<th>Low Total Cost of Ownership (TCO)</th>
<th>Vehicle Appearance/Styling</th>
</tr>
</thead>
<tbody>
<tr>
<td>-(Vehicle purchase price / taxes)</td>
<td>-(Application driven)</td>
</tr>
<tr>
<td>-(Fuel economy (consumption))</td>
<td>-(Ergonomic design)</td>
</tr>
<tr>
<td>-(Maintenance/repair cost)</td>
<td>-(Sporty / Color)</td>
</tr>
<tr>
<td>-(Residual value)</td>
<td>-(Infotainment)</td>
</tr>
<tr>
<td>-(Etc.)</td>
<td>-(Etc.)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Environmentally Friendly</th>
<th>Performance &amp; NVH</th>
</tr>
</thead>
<tbody>
<tr>
<td>-(High FE (low CO2 emissions))</td>
<td>-(High power)</td>
</tr>
<tr>
<td>-(Low harmful emissions)</td>
<td>-(High low-end torque)</td>
</tr>
<tr>
<td>-(Recycle)</td>
<td>-(Quiet yet sporty)</td>
</tr>
<tr>
<td>-(Etc.)</td>
<td>-(Active &amp; passive NVH measures)</td>
</tr>
</tbody>
</table>

Source: FEV
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)
Development Trends
Gasoline Engines

**Development Trends**

**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

Source: FEV

© by FEV – all rights reserved. Confidential – no passing on to third parties
Technology Trends
Hybridization / Electrification / Transmissions

Conventional Vehicles
- Gear Box
- Fuel Tank

Hybrid Electric Vehicles
- Micro Hybrid
- Mild Hybrid
- Full Hybrid
  - Charging from Grid
  - Pure Electric Drive
  - Electric Take-off
  - Engine Assistance
  - Kinetic Energy Recovery
- Start-Stop & Intelligent Energy Management
- Increasing electrical power
- CO₂-emissions

Battery Electric Vehicles
- Battery

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

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

Battery size/cost
- New transmission design

Source: FEV
Technology Trends
Vehicle Landscape: Automation, Shared Mobility and Connectivity

Source: FEV
Agenda

- Introduction
- Development Trends
- Potential Game Changing Technologies
- Summary
# Development Trends: Gasoline Engines

## Combustion Efficiency Improvements
- Direct Injection (& Var. Charge Motion)
- Variable Compression Ratio (VCR)
- Miller/Atkinson Cycle
- Cooled EGR
- Controlled Auto-Ignition (CAI)

## Reduction of Throttling Losses
- Downsizing
- Boosting
- Cylinder Deactivation
- Variable Valvetrain
- Lean-burn Operation

## Electrification/Hybridization
- Micro/Mild/Full Hybrid
- PHEV
- 48V Infrastructure
- Accessory (FEAD) Electrification

## Reduction of Parasitic & Idle Losses
- Friction Reduction
- Stop/Start
- Advanced Thermal Management
- Accessory (FEAD) Electrification

Source: FEV
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

Source: FEV
2-Step Variable Compression Ratio (VCR) Mechanism
Background & Incentive

- **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
Design Features

<table>
<thead>
<tr>
<th>Connecting rod design</th>
<th>Mechanical actuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>lever</td>
<td>eccentric</td>
</tr>
<tr>
<td>support rod (gas forces)</td>
<td>support rod (mass forces)</td>
</tr>
<tr>
<td>support piston (gas forces)</td>
<td>support piston (mass forces)</td>
</tr>
<tr>
<td>check valve</td>
<td>shift valve</td>
</tr>
</tbody>
</table>

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

Source: FEV
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>
</tr>
</tbody>
</table>

Source: FEV
## Development Trends
### Fuels and Lubricants

#### Spark Ignition Engine Fuels
- Low octane fuels
- 10% Ethanol content
- LPG
- CNG
- Etc.

#### Diesel Engine Fuels
- Low cetane fuels
- Nationwide quality fluctuations
- Availability
- Cost disadvantage
- Etc.

#### Lubricants
- Low viscosity
- High temperature stability
- Additive packages
- ‘Fill for life’ (transmission & axles)
- Etc.

#### Other Potential Fuels
- Alcohols (Methanol, Ethanol, etc.)
- 2nd gen. biofuels
- Tailor-made fuels
- Biodiesel
- Etc.

Source: FEV
Agenda

- Introduction
- Development Trends
- Potential Game Changing Technologies
- Summary
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.