Intersection of Powertrain Innovation for Improving Future Vehicle Fuel Efficiency and Connected Autonomous Vehicles

Powertrain Control and Optimization for Future Fuel Efficiency

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EVP & CTO  
FEV North America Inc.

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Powertrain Control and Optimization for Future Fuel Efficiency

Agenda

1. Introduction
2. Potential of Powertrain Technologies
3. Potential of Vehicle Connectivity
4. Summary and Outlook
5. Discussion
Powertrain Control and Optimization for Future Fuel Efficiency

Key Drivers

Fuel Economy and CO₂ Emissions
Downsizing, Downspeeding, GTDI, Friction Reduction, Combustion Optimization, etc.

Emissions
SULEV Average w/ Stoichiometric and (Stratified) Lean-Burn Combustion Systems

Fuels
Increased Share of Biofuels (e.g., Ethanol (Corn, Algae, Cellulosic), Biodiesel, CNG, etc.)

Reliability and Affordability
TCO for Consumer
# Powertrain Control and Optimization for Future Fuel Efficiency

## U.S. Emissions, FE and CO₂ Legislation

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

<table>
<thead>
<tr>
<th>Year</th>
<th>2005</th>
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<th>2010</th>
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<td>FE 2</td>
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<td>PC: 33.8 → 39.5</td>
<td>PC: 5% p.a.</td>
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<td>LT: 25.7 → 28.8</td>
<td>LT: 3.5%-5% p.a.</td>
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**U.S. CAFE Standards**
- PC: 27.5 mpg / LT: 22.2 mpg

**California AB 1493**
- PC/LD1: 323 → 205
- LD2/MDPV: 439 → 332
- PC: 5% p.a./LT: 3.5%-5% p.a.

**Minimum ZEV Requirements:**
- MY 15-17: 14%, MY 18+: 16%

**Coordinated Approach**
- Tier II
  - 0.07 g/mi NOx fleet average
  - From 0.2 (Bin 8) - 0.02 (Bin 2)
  - 4.2 (Bin 5-8) - 2.1 (Bin 2-4)
  - 0.02 (Bin 7-8) - 0.01 (Bin 1-6)

**Tier III – Phase In**
- Combined NMOG & NOx limit ramp down
- CO limit ramp down
- PM ramp down
- 0.03 NMOG+NOx

**Tier III**
- 0.07 g/mi NOx fleet average
- From 0.2 (Bin 8) - 0.02 (Bin 2)
- 4.2 (Bin 5-8) - 2.1 (Bin 2-4)
- 0.02 (Bin 7-8) - 0.01 (Bin 1-6)

**California**

**LEV II**
- 0.07 (LEV, ULEV) - 0.02 (SULEV)

**LEV III – Phase In**
- + 3 new low emission categories
- Combined NMOG & NOx limit ramp down
- CO limit ramp down
- Durability Increase to 150k mi

**LEV III**
- 0.03 NMOG+NOx
- 0.07 g/mi NOx fleet average
- From 0.2 (Bin 8) - 0.02 (Bin 2)
- 4.2 (LEV), 2.1 (ULEV), 1.0 (SULEV)
- 0.02 (Bin 7-8) - 0.01 (Bin 1-6)

**PM**
- 0.01

Source: Delphi, FEV Research

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1. Introduction

2. Potential of Powertrain Technologies

3. Potential of Vehicle Connectivity

4. Summary and Outlook

5. Discussion
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

- *SI engines*
- *Production state*
- *Model year > 1997*

*Brake Specific Fuel Consumption*  
norm. to calor. val. = 42.5 MJ/kg

2000 rpm / BMEP = 2 bar

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**Development Trends – Gasoline Engines**

Scatterband includes CDA

BSFC / (g/kWh)

Engine displacement / cm³

Benchmark

Friction optimized

Friction optimized + VVL

Friction optimized + CVVL + Miller

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Powertrain Control and Optimization for Future Fuel Efficiency
Development Trends – Variable Compression Ratio (VCR)

Working Principle:

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

Working Principle:

- Powertrain Control and Optimization for Future Fuel Efficiency
- Development Trends – Variable Compression Ratio (VCR)

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Powertrain Control and Optimization for Future Fuel Efficiency
Development Trends – Variable Compression Ratio (VCR)

<table>
<thead>
<tr>
<th>2.0l, TC, Two-Stage VCR 8/12 (optimized for RON 95)</th>
<th>Remarks</th>
</tr>
</thead>
</table>

- New, additional fuels will enter the market
- Fuels like Ethanol (RON 111) or CNG (RON 130) have a significant higher octane rating
- VCR systems allow an optimized CR depending on the utilized fuel
Powertrain Control and Optimization for Future Fuel Efficiency
Development Trends – VCR and RON Potential

Vehicle CO₂ emissions can be reduced by ~ 3 – 5 % with high octane fuels and adapted engines with increased compression ratio.
Powertrain Control and Optimization for Future Fuel Efficiency Development Trends – Combustion System Development (CMD Process)

- Decreased mass flow over the backside of the valve (better separation of the flow)
- High mass flow over front side following head contour
- Robust tumble structure

Graphs showing Tumble values over crank angle for 6000 WOT conditions, with different port configurations (C1/Port #1, C1/Port #2, C1/Port #3, C2/Port #4) and crank angles.

- Chrysler Voyager
- 6000 rpm, WOT
- Crank angle/

Powertrain Control and Optimization for Future Fuel Efficiency Development Trends – Combustion System Development (CMD Process)
Powertrain Control and Optimization for Future Fuel Efficiency
Development Trends – Closed Loop Combustion Control (CLCC)

Graph showing emissions over time with two lines:
- Blue line: BASE - No combustion control
- Red line: Combustion control ON

Emissions measured in ppm:
- NOx emissions [ppm]
- HC emissions [ppm]
- CO emissions [%]

Time [sec] range from 0 to 500.
Powertrain Control and Optimization for Future Fuel Efficiency Development Trends – Closed Loop Combustion Control (CLCC)

US06 - Combustion control effect on engine out emissions

- **Combustion control ON**
- **BASE - No combustion control**

<table>
<thead>
<tr>
<th>NOx</th>
<th>THC</th>
<th>CO</th>
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<tbody>
<tr>
<td>0.68</td>
<td>0.46</td>
<td>3.16</td>
</tr>
<tr>
<td>0.67</td>
<td>0.53</td>
<td>3.86</td>
</tr>
</tbody>
</table>

**Fuel Economy [miles/gallon]**

- 29.09
- 28.02
FTP75 and US06 are more wide spread compared to NEDC. The WLTP is closer to US cycles.
Powertrain Control and Optimization for Future Fuel Efficiency Development Trends – FTP-75 Exhaust Gas Temperatures (Gasoline)
Powertrain Control and Optimization for Future Fuel Efficiency Development Trends – Cold Start Exhaust Gas Temperatures (Gasoline)

Vehicle Cold Start Testing: FTP 75 C/H, 25° C

Close-Coupled Catalyst Temperatures (Midbed)

- 2007 2.3L PFI, T/C - CCC+UBC
- 2008 3.0L Stratified Lean - CCC+UBC
- 2011 2.4L GDI, N/A - UBC Only
- 2011 2.0L GTDI, T/C - UBC Only
- 2012 1.8L PFI, N/A - UBC Only

- 3.0L Stratified Lean CCC (front bank)
- 2.4L GDI, N/A
- 2.0L GTDI, T/C
- 2.3L PFI, T/C CCC Brick 1
- 1.8L PFI, N/A

Factor 10 !!!
## Lambda Control

<table>
<thead>
<tr>
<th>Speed [km/h]</th>
<th>Integrated lambda diff.</th>
<th>time [s]</th>
<th>actual lambda</th>
<th>target lambda</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.7</td>
<td>0.8</td>
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<tr>
<td>25</td>
<td>0.2</td>
<td>50</td>
<td>0.8</td>
<td>0.9</td>
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<td>50</td>
<td>0.4</td>
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<tr>
<td>150</td>
<td>1.2</td>
<td>300</td>
<td>1.3</td>
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</table>

## Conclusion

- Lambda controller typically consists of a feed forward controller combined with a feedback loop control principle.
- As the closed loop part is driven by deviation, an error has to occur before corrective measures are taken.
- The integrated absolute deviation between target lambda and actual lambda shows performance of the lambda controller, ideal this would be zero.
- Better open loop control could reduce the CO2 emissions.
Powertrain Control and Optimization for Future Fuel Efficiency
Development Trends – Thermal Management Options (Gasoline)
### Powertrain Control and Optimization for Future Fuel Efficiency

#### Development Trends - Hybridization

<table>
<thead>
<tr>
<th>Conventional Vehicles</th>
<th>Hybrid Electric Vehicles</th>
<th>Battery Electric Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gear Box</td>
<td>Micro Hybrid</td>
<td>Mild Hybrid</td>
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<tr>
<td>Fuel Tank</td>
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<td>Start-Stop &amp; Intelligent Energy Management</td>
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</tbody>
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**Increasing electrical power**

**CO₂-Emissions**

**Battery size/price**

**Complexity ICE**

**Gasoline NA**

**Complexity Transmission**

**Downsizing Diesel and Gasoline**

**Gasoline Atkinson**

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Introduction to Waste-Heat Recovery Technologies

Organic Rankine Cycle (ORC)
- The Rankine Cycle is a thermodynamic cycle that converts heat into work.
- The heat is supplied externally to a closed loop, which uses water or another fluid as working fluid.

Thermoelectric Generator (TEG)
- Temperature difference between the hot and cold surfaces of the thermoelectric module(s) generates electricity using the Seebeck Effect.

Turbocompound
- A turbine recovers energy from the exhaust gas.
- Three main forms: Mechanical Turbocompound, Electric turbocharger, Turbogenerator.
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Potential of Vehicle Connectivity

Potential Scenario and Benefits:

- Establish intelligent connection unit/service (iCU/iCS)
- Cloud services for different applications
- Collection of data from various vehicles (swarm intelligence) → predictive behavior
- Intelligent algorithms to combine different data sources incl. potential updates over V2X
- Added value for driver, infrastructure and society

Source: DAF, BMW
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Summary and Outlook

• Significant improvement of fuel economy and emissions based on legislation are impetuous yet mandatory.

• Engine technologies in combination with advanced controls in the field of engines, transmissions, aftertreatment, hybridization, thermal management, etc., offer significant potential for improvement beyond the current state-of-the-art allowing to meet the legislated targets for 2025.

• In addition, vehicle connectivity provides additional potential which, when properly applied, further improves vehicle fuel economy while simultaneously improving driving comfort and vehicle/passenger safety.

• More work in the area of powertrain and vehicle connectivity is required to not only achieve improvement in their corresponding fields but also to connect the two with each other allowing to maximize the gain in overall vehicle fuel economy.