Gasoline Direct Injection – SIA / CNAM 2012

- Gasoline direct injection: A long history
- Electronic direct injection
- Main components of the gasoline direct injection
- New challenges with Euro 6 legislation
Gasoline direct injection: Historic

- Gasoline direct injection introduced by Bosch in 1937 on engines for aviation.

- Advantages:
  - No impact of the negative G on the fuel supply in contrast with carburetor
  - No explosion risk of the intake manifold in case of « back-fire »
  - No risk of ice formation (venturi of carburetor)
Direct injection in aviation: historic

In-line fuel injection pump with 12 pistons for aviation engine (V12 Daimler, L=70 ccr)
Direct injection in aviation: historic

- Daimler engine DB603 with «inversed» V12 architecture (Mercedes Museum in Stuttgart)

- The fuel injection pump is placed inside the V
Direct injection in aviation: historic

Radial engine with 9 cyl. (BMW)

Fuel injection pump (Boxer form)
Direct injection in car: historic

- After 2\textsuperscript{nd} world war, development of several economical cars with 2 stroke engine.
- The direct injection allowed a reduction of consumption by removing the fuel losses through scavenging.

**Gutbrod Superior 600 Cabrio (1950-1954 ; direct injection from 1952)**

**Goliath GP700E (1951-1957 ; direct injection from 1954)**
Direct injection in car: historic

Direct injection system for 2 stroke engine

Injection pump for 2 cyl. Engine (L=15cm)
Direct injection: Sport car

- In 1955, launch of Mercedes 300 SL with direct injection.
- First serial application with 4 stroke engine.
- Target: Increase of the maximum engine performance.
Direct injection: Sport car

300 SL engine
- Gasoline direct injection: A long history
- **Electronic direct injection**
- Main components of the gasoline direct injection
- New challenges with Euro 6 legislation
Electronic injection: historic

- In 1967, first serial application of the indirect injection controlled by electronics (VW 1600).
- First legislation for the emission in USA.
Evolution of the European legislation

Introduction ratio of catalytic converter on passenger cars in Germany
Evolution of the European legislation

New test cycle:
Start of sampling with engine start introduction with EU 3 from 2000
Electronic Direct Injection

- **1996:** First stratified gasoline direct injection on Mitsubishi Galant
- **1998:** Toyota D4
- **1999:** Renault IDE (Lambda 1 with high EGR rate)
- **2000:** First Bosch gasoline direct injection VW « FSI » engine
- **2000:** PSA HPI engine
- **2005:** PSA Prince engine THP

- **Target:** Consumption reduction by removing the suction losses at partial engine load (stratified mode).

- **Difficulty:** Global air-fuel mixture lower than ignition readiness limit
  - Necessity to create a stratified mixture with the condition to have enough fuel near to the spark plug.

- **Issue:** Large NOx generation without any reduction possibility by three way catalytic converter due to Lambda > 1.
  - Necessity to have a NOx-Trap, but expensive and tricky (fuel without sulfur).
NOx after-treatment equipment

VW – Lupo FSI 1.4
Electronic Direct Injection

- Due to the technical issue and the costs associated to the stratified direct injection, the concept « direct injection, homogeneous, Lambda=1 » has emerged on the market in recent years.

- Advantages:
  - Effective cooling of the combustion chamber (fuel evaporation) with the possibility to push the knock limit
  - Increase of the compression ratio of 1 point with consumption gain
  - Associated to supercharging controlled by electronics, new turbochargers (twin-scroll), possibility to enlarge the use of « down-sized » engines → Consumption reduction, torque increase
Electronic Direct Injection: The come back!

- The Audi R8 4.2l FSI gained the victory in 2001 of the famous race “24 heures du Mans” with the gasoline direct injection technology!
Gasoline Direct Injection – SIA / CNAM 2012

- Gasoline direct injection: A long history
- Electronic direct injection
- Main components of the gasoline direct injection
- New challenges with Euro 6 legislation
Main components of the gasoline direct injection
High Pressure Gasoline Injector (solenoid)
High Pressure Gasoline Injector (piezo)
HDP: High Pressure Pump

- **HDP1**: 3-cylinder pump, Max. pressure 12MPa, Year 2000
- **HDP2**: Single cylinder, Max. pressure 12MPa, Year 2002
- **HDP5**: Single cylinder, Max. pressure 20MPa, Year 2006
High Pressure Pump HDP5: Working
Pressure regulation by dosing fuel quantity
Gasoline Direct Injection – SIA / CNAM 2012

- Gasoline direct injection: A long history
- Electronic direct injection
- Main components of the gasoline direct injection
- New challenges with Euro 6 legislation
- Major Drivers and Requirements
- Advanced Spray Technologies for DI
Major Drivers for Powertrain Systems

Fuel Economy / CO2
- CO2 fleet targets
  W-EU: 130/95g CO2/km 2012/20,
  US CAFE: 34.1 mpg in 2016
- Fuel availability ("Peak Oil")

Variants
- Globalization
- Powertrain & vehicle diversification
- Fuel differences

Fun to Drive
- Power and low end torque
- Response time (dynamics)

Quality and Safety
- Reliability, Robustness
- ISO26262

City Restrictions
- Ban on driving
- Specific traffic lane, parking

Emissions & Diagnosis
- EU6 (PM/PN, ext. EOBD)
- LEV III (SULEV20, PM)
- Worldwide Driving Cycle
- Real Driving Emissions

Image & Emotions
- Fuel Economy Labeling
- Willingness-to-pay for green image and emotions

Costs
- Affordable mobility (price, TCO)
- OEM entry efforts (invest, E&A)
- Incentives and taxation

Driving comfort
- Noise, vibration, harshness
- Shift- & launch quality
- Easy driving

Variants
- Globalization
- Powertrain & vehicle diversification
- Fuel differences

Main market drivers are still emission legislations incl. CO₂ which impacts fuel economy. Costs remain very important.
Gasoline Direct Injection – SIA / CNAM 2012

EU6 Emissions Legislation Roadmap

|------|------|------|------|------|------|------|------|------|------|------|

**Emissions Test:** NEDC

- **PFI**
  - no PN limit
  - PN: $6 \times 10^{11}$ 1/km
  - upon choice of manufacturer

- **GDI**
  - no PN limit
  - PN: $6 \times 10^{11}$ 1/km

- **Diesel**
  - no PN limit
  - PN: $6 \times 10^{11}$ 1/km

**CO2 Test:** NEDC

- NEDC
- NEDC WLTC (CO₂-targets to be adapted)

**WLTC**

- RDE: monitoring only
- RDE mandatory: compliance factors open

**PN standards and RDE PN testing only for DI. RDE limits to be defined for 2017.**

**Challenge Gasoline:** Robust solution to fulfill PN-limits.

- Major Drivers and Requirements
- Advanced Spray Technologies for DI
**Sources of Particulate Emissions at DI Engines**

<table>
<thead>
<tr>
<th>sources at DI</th>
<th>formation / conditions</th>
<th>real engine conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>➔ Diffusion combustion</td>
<td>➔ Fuel:</td>
<td>°CA [BTDC]</td>
</tr>
<tr>
<td>1. Wall wetting piston</td>
<td>Cracking</td>
<td>-12</td>
</tr>
<tr>
<td>2. Wall wetting roof/valves</td>
<td>Pyrolysis</td>
<td>0</td>
</tr>
<tr>
<td>3. Fuel deposits injector tip</td>
<td>➔ Soot:</td>
<td>-20</td>
</tr>
<tr>
<td>➔ Inhomogeneous gas phase</td>
<td>Precursors</td>
<td>&gt;20</td>
</tr>
<tr>
<td>4. Local rich areas (stratified/HSP)</td>
<td>Generation</td>
<td></td>
</tr>
<tr>
<td>5. Fire land stored fuel</td>
<td>Soot formation region</td>
<td></td>
</tr>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- Fuel:
  - Cracking
  - Pyrolysis

- Soot:
  - Precursors
  - Generation

- **Temperature [K]**
  - Soot formation region
  - Low O₂
  - > 1500 K

- **Time**

- **Combustion Ignition**
  - °CA [BTDC]: -12
  - O₂ [%]: 21
  - T [K]: 400

- **Combustion**
  - °CA [BTDC]: 0
  - O₂ [%]: 21
  - T [K]: 500

- **Fuel film @ piston**
  - °CA [BTDC]: >20
  - O₂ [%]: <1
  - T [K]: ~2000

---

**Gasoline Systems**

Confidential | GS/EPC-EM | 21/03/2012 | P_12_0089 | © Robert Bosch GmbH 2012. All rights reserved, also regarding any disposal, exploitation, reproduction, editing, distribution, as well as in the event of applications for industrial property rights.
Gasoline Direct Injection – SIA / CNAM 2012

Soot origin from wall film

Homogeneous 2000 1/min 5 bar pmi early injection

Combustion finished oxygen content < 1%

Very small amounts of fuel film under:
- high temperature
- low oxygen conditions responsible for soot-emissions
Adv. Combustion Concepts: Challenge and Solution
(Fuel Metering)

Downsizing / Displacement Reduction
- wetting (piston, valve)
- oil dilution
- mixture preparation (homogenization)
- spread (idling, catalyst heating, boosted full load)

Lean Burn Concepts (SGDI, HCCI)
- multiple injection >=3
- combustion concept robustness

Solution
Spray-Targeting
- variable hole design
- innovative manufacturing technologies

Mixture Preparation
- multiple injection

Adv. Injection Spread
- using ballistic range towards smallest quantities @ 200 bar

Gasoline Systems
Confidential | GS/EPC-EM | 21/03/2012 | P_12_0089 | © Robert Bosch GmbH 2012. All rights reserved, also regarding any disposal, exploitation, reproduction, editing, distribution, as well as in the event of applications for industrial property rights.
Gasoline Direct Injection – SIA / CNAM 2012

Contribution of innovative manufacturing technologies

**Reduced penetration:**
- Better spray break-up and increased entrainment of air due to enhanced turbulence generation at sharp edged nozzle inlet

**Optimization/adaptation of individual spray pattern:**
- Flexible hole design of single beams to avoid critical zones
- Improvement of homogenization due to improved capture of air
Spray examples: Eroded / inno. man. tech.

- Reduction of PN-emission, especially at higher loads
- Due to reduced penetration reduced oil dilution
- Widening of application area

Comparison Particle Emission

Oil dilution

bmepr: brake mean effective pressure
IMT: innovative manufacturing technologies
Controlled Valve - HDEV5 Operation

CVO gains benchmark on small quantities with solenoid injector

Gasoline Direct Injection – SIA / CNAM 2012

Gasoline Systems

Confidential | GS/EPC-EM | 21/03/2012 | P_12_0089 | © Robert Bosch GmbH 2012. All rights reserved, also regarding any disposal, exploitation, reproduction, editing, distribution, as well as in the event of applications for industrial property rights.
Optimized PN combining DI Advanced Spray and Calibration

Start Calibration
- Quick fuel pressure rise up
- Multi injection in suction stroke to avoid wall wetting

Catalyst Heating
- Minimize wall wetting by minimized fuel quantity for turbulence injection

Homogeneous Mode
- Minimize piston wetting by optimized start of injection
- Multi injection (depending on combustion system)

Overall Result in PN - Reduction

Gasoline Systems
Summary

➔ Drivers:
  • Main market drivers remain CO2/fuel economy and emissions
  • At least ‘til 2020 the ICE plays a major role for CO2 reduction

➔ Advanced Fuel Metering as key feature for DI to fulfill the legislation requirements and gain the ultimate gasoline engine

➔ DI solutions:
  • Innovative manufacturing technologies for optimized spray targeting and mixture preparation
  • Controlled Valve Operation for smallest quantities accurate @ 200 bar in combination of multiple injections

BOSCH offers DI Advanced Spray Technologies to meet the worldwide market requirements
Conclusion
Conclusion

- CO2/fuel economy and emissions are the main market drivers
- The gasoline direct injection plays a major role in this technical context
- The market share of the diesel engine is decreasing worldwide
- The gasoline indirect injection remains at a high level worldwide

The gasoline injection will be the strong winner in 2020
Thank you