Direct-injection of CNG: A breakthrough technology for future green vehicles?

Dr. Joachim Kiefer, Jean-Francois Preuhs, Dr. Guy Hoffmann

Research Technologist,
Powertrain Systems
Delphi Automotive Systems Luxembourg

www.delphiau.to/Life
1. Introduction
   • Delphi Automotive Systems
   • Social challenges and global legislations for emissions reduction

2. CNG vehicle technology and competition
   • CNG as sustainable green vehicle fuel option

3. Delphi DI-CNG injector development
   • Life DI-CNG and GasOn research programs
   • DI-CNG injector requirements and design evolution
   • Port fuel injection vs direct injection of CNG
   • Test & validation and engine / vehicle implementation results

4. Summary and Outlook
Delphi’s global team – at the center of technology innovation

19,000 engineers and scientists

$15.2B 2015 revenue

126 manufacturing sites

14 major global technical centers

$1.5 B in Research & Development

more than 173,000 people in 44 countries

Delphi Powertrain Headquarter in Bascharage, Luxembourg

Annual report 2015
Megatrends drive our technology portfolio

Safe
- Active Safety Systems
- Driver State Alerts
- Safety Electronics
- Battery Disconnects
- Human Machine Interface
- Occupant Classification Systems

Green
- Gasoline Direct Injection
- Diesel Fuel Injection Systems
- Fuel Economy & Performance Technologies
- Hybrid & Electric Vehicle Technologies

Connected
- Vehicle Infrastructure Interface (VII) & Vehicle-to-Vehicle Interface
- Telematics
- Digital Receivers
- Connected Vehicle
- Satellite, Audio, Video & Data Systems

Focused on solutions to customers’ problems
Social challenges for decarbonization of transport

**Congestion**

Today

![Congestion image](Cedexis.com)

**Health**

![Health image](Earthfirstjournal.org)

**Global warming**

![Global warming image](disqus.com)

**Mobility on demand**

**Alternative Powertrain Technologies**

- Plug-in Hybrid EV
- Mild hybrid
- BEV, FEV
- Range Extender
- Fuel Cell
- Bio-fuel
- CNG hybrid
- LPG

**NOx & Particulates**

- monovalent DI-CNG
- Dual Fuel
- Bi-fuel

**CO₂ & GHG**

- synthetic fuel
- Bio-methane
- Bio fuel
- LNG
- PtG

**Diversification of powertrains and fuels**
2. CNG vehicle technology and competition

- Natural Gas as alternative fuel for internal combustion engines
- CNG vehicle fleet in Europe
- NGVs vs 2020 CO₂ emissions target in Europe
- Competition of NGVs in Europe
  - End consumer perspective
  - NGVs vs modern direct injection gasoline engines
  - European forecast on development
- Technology and competition gaps of current NGVs
- Promise and objectives of DI-CNG technology
CNG: Key fuel characteristics

- CH$_4$ has highest H:C ratio of any fossil fuel -> minimum CO$_2$ output
- Worldwide availability and existing grid infrastructure
- High quality standards for safe transport, storage and handling
- High gravimetric energy density and interesting volumetric energy density
- High octane number and knock resistance ideal for downsizing
- Complete miscibility with biogas and hydrogen from renewable sources
- No solid contaminations

- Global warming potential 25*CO$_2$
- No EN fuel specification
- Bio-methane content is invisible
- Price declaration [€/kg]

**Physical properties**

Fig. 4.1, p. 53 in R. van Basshuysen, M. Bargende: Erdgas und erneuerbares Methan für den Fahrzeugantrieb
# NGV market: Vehicle fleet in Europe

<table>
<thead>
<tr>
<th></th>
<th>Engine</th>
<th>VW</th>
<th>Skoda</th>
<th>Seat</th>
<th>Audi</th>
<th>Engine</th>
<th>Fiat</th>
<th>Engine</th>
<th>Opel</th>
<th>Engine</th>
<th>Daimler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mini</td>
<td>1.0L/3Zy/50kW</td>
<td>Up</td>
<td>Citigo</td>
<td>Mii</td>
<td></td>
<td></td>
<td>Panda</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.8L/2Zy/50kW</td>
<td></td>
<td>500L</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compact</td>
<td></td>
<td>Golf</td>
<td>Leon</td>
<td>A3</td>
<td></td>
<td>1.4L/4Z/51kW</td>
<td>Punto</td>
<td>Quobo</td>
<td>Combo</td>
<td>2L/4Z/112kW</td>
<td>B-class</td>
</tr>
<tr>
<td>Transport</td>
<td>1.4L/4Z/81kW</td>
<td>Caddy</td>
<td></td>
<td></td>
<td></td>
<td>Doblo</td>
<td></td>
<td></td>
<td>Combo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Van</td>
<td>1.4L/4Z/110kW</td>
<td>Touran</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.6L/4/110kW</td>
<td>Zafira</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle</td>
<td>1.4L/4Z/88kW</td>
<td>Passat</td>
<td>Octavia</td>
<td></td>
<td>A4,</td>
<td>1.4L/4Z/88kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>E-class</td>
</tr>
<tr>
<td>Upper/SUV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A5</td>
<td></td>
<td></td>
<td>2L/4Z/112kW</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**New:** Audi A4 Avant g-tron – 125kW

All vehicles are equipped with port-fuel CNG injection and separate gasoline fuel handling and fuel injection system.
NGV market: End consumer perspective

Customer is very well informed about CNG vehicle environmental benefit

- **Higher NGV price** than for comparable gasoline vehicle
- **Lower power** than for comparable gasoline vehicle
- Not possible to perform test drive and experience driving comfort
- Car dealers do not have CNG cars in house but can offer plenty of alternative deals

**Common concerns**

- Lack of infrastructure
- Safety for fuelling and storage

**Are NGVs competitive?**
Emissions of passenger cars: CNG vs DI-gasoline

Efficiency of GDI vehicles improved and approach NGV emission levels

Source: [www.dat.de](http://www.dat.de)
Leitfaden über den Kraftstoffverbrauch, die CO₂ Emissionen und den Stromverbrauch neuer PKW

Status: Feb 2017
NGVs: Future vehicle market and investor perspective

**Figure 37: Evolution of activity of passenger cars and vans by type and fuel**

Source: EU Reference Scenario 2016: Energy, Transport and GHG emissions Trends to 2050

NGVs need breakthrough technology to increase market share
DI-CNG Technology potential

Source: www.dat.de
Leitfaden über den Kraftstoffverbrauch, die CO₂ Emissionen und den Stromverbrauch neuer PKW

Direct injection of CNG will lead to further CO₂ reduction
Technology gaps of NGVs

1. **System complexity** of CNG hybrid vehicles
   - Limited range on both fuel options due to dual gasoline and CNG storage tanks with restricted size
   - Dual fuel handling and injection systems
   -> **High NGV costs** due to dual systems

**Monovalent NGVs could reduce system complexity and cost + increase range**

2. **Injection and engine technology**
   - Port fuel injection of current NGVs is no longer state-of-the-art
   - GDI vehicles have significantly higher power output and close gap with regards to emissions and fuel consumption
   - Direct injection of CNG is needed to become competitive with regards to performance and driving comfort.
   - Direct injection of CNG can improve engine efficiency and further reduce fuel consumption

**DI-CNG injection technology could render NGVs competitive and increase end consumer acceptance**
3. Development of DI-CNG injectors at Delphi

- History of DI-CNG injector development
  - Life DI-CNG project: Installation of pilot line for injector manufacturing
  - Outlook for Horizon 2020 GasOn project
- DI-CNG injector requirements
- Port fuel injection vs direct injection of CNG
- DI-CNG injector design: Principle and benefits
- DI-CNG injector results
- DI-CNG application experience: Performance results on engines and vehicles
DI-CNG injector development at Delphi

- **2010:** Feasibility Study
- **2012:** Proof of Concept
- **2014:** Industrialization
- **2016:** Monovalent DI-CNG vehicles
- **2018:** Production
- **2020:** Drives

Timeline:
- 2010
- 2012
- 2014
- 2016
- 2018
- 2020
Introduction of LIFE+ program and principles

• The DI-CNG injector industrialization development is supported by LIFE+

• LIFE+
  - Is a Europe’s funding instrument for environment aiming to contribute to nature conservation, climate change and development of EU environmental policy and legislation
  - Finances the testing, prototyping and demonstration phases, meaning the development and validation of a technology at pre-industrial stage
  - The project must be innovative and have a significant impact on environment on European level
European program Life13 ENV/LU/000460: DI-CNG injector development and industrialization

Objectives

• Develop Direct Injection CNG injectors with equal or better torque than comparable direct injection gasoline and Diesel engines leading to improved driving comfort as basis for OEM and end consumer acceptance

• Install semi-automated pre-industrial manufacturing and assembly line suitable for small scale production of DI-CNG injectors

• Achieve significant reduction in emissions on engines
  • 25% reduction in CO₂ emissions; 80% reduction in CO emissions (compared to gasoline)
  • Over 90% reduction in particulate emissions and 35-60% reduction in NOx emissions (compared to Diesel)

Duration: June 2014 – May 2018
Horizon2020 GasOn program: DI-CNG application

Objectives

• Build three different monovalent CNG cars to demonstrate potential of DI-CNG technology for sustainable mobility in compliance with

• Post Euro 6 noxious emissions
• 2020+ CO₂ emission targets; >20% lower CO₂ emissions than best-of-class CNG vehicle
• New homologation cycle and Real Driving conditions
• Improved engine efficiency and vehicle performance also with regard to its CNG range capability

Duration: May 2015 – Oct 2018
CNG Direct Injector high level requirements

• Injector design and development driven by the primary requirements:
  ▪ Applicable to a passenger car engine which is downsized and boosted
  ▪ Match the torque and power of the gasoline version of the engine
  ▪ Injector can be mounted in the existing injector "pocket" in cylinder head
  ▪ Maximum range of the vehicle from the CNG tanks

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CNG Direct Injector Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Range</td>
<td>6-bar to 16-bar absolute</td>
</tr>
<tr>
<td>Flow Rate (Natural Gas at 16bar)</td>
<td>7 g/s</td>
</tr>
<tr>
<td>Injector Body Diameter</td>
<td>21 mm</td>
</tr>
<tr>
<td>Injector Tip Diameter</td>
<td>7.5 mm</td>
</tr>
</tbody>
</table>

Direct Injection of CNG requires development of new injector hardware
Challenges of CNG

• Non technological challenges
  ▪ Limited and non-uniform infrastructure of fuel stations
  ▪ Regional tax regulations, and unknown future situation

• CNG technology challenges
  ▪ Currently low CNG vehicle range
    • Tanks → increase size + pressure
    • Injector → reduce operating pressure
  ▪ Competitive driving comfort: manifold injection → low torque at low rpm compared to current technologies (Diesel and gasoline) due to:
    • Reduced volumetric efficiency
    • Limited possibilities of scavenging since gas would directly flow to exhaust

Port-fuel injection:
Air + CNG premixed before intake valve → amount of air offset by presence of CNG

Stoichiometric volumes

0.65 kg/m³
1.2 kg/m³
10% Vol 90% Vol

Life
DI-CNG solution

• **Direct injection benefits**
  - Solution to recover loss of volumetric efficiency of PFI technology
  - Allows use of scavenging
  - Easy conversion of existing GDi engines

• **Challenges**
  - Reliability in hot environment
  - Flow: low density fuel and limited injection time window
  - Pressure trade-off between flow, leakage and driving range:
    - Pressure $\uparrow \rightarrow$ Flow $\uparrow$, leakage $\uparrow$, range $\downarrow$

Direct injection is a solution to recover the loss of volumetric efficiency of the PFI technology, which comes with own new challenges.
Injector realization

Current generation of DI-CNG Injector Design

- Sealing to Fuel Rail (Customized)
- Solenoid Actuator
- Valve Group

Special materials and interfaces designed for robust durability
High-flow nozzle

Entire flow path optimized for high gas flow rates
Valve selection

**Inward-opening Valve**
- Is susceptible to being opened by cylinder pressure
- Requires high spring forces in injector to counteract

**Outward-opening Valve**
- Is naturally sealed by cylinder pressure
- Higher flow rates possible

16 bar peak gas pressure inside injector

> 100 bar peak firing pressure at high load

Outward-opening valve selected based on pressure relationship across the valve
The performance of the prototype injectors have been assessed in terms of flow delivery, injector tip leakage, reliability and lifetime durability.

Excellent injector performance over full life
DI-CNG application experience: low-end torque demonstration

- Both Daimler and Ford demonstrated the potential of DI-CNG technology in terms of low-end torque improvement compared to PFI
- The achieved level of performance was similar to today’s Gasoline DI applications
- Side & central mount possible

Source: Ford, 23rd Aachen Colloquium, October 6-8, 2014

Low-end torque considerably improved via direct injection!
DI-CNG injection: summary and outlook

• 2020 and 2025 CO₂ targets require dramatic improvements in powertrain efficiency

• CNG is a solution to reduce CO₂ and particulate emissions compared to gasoline engines, with a path to sustainability with bio-methane

• Through direct injection, CNG as a fuel becomes an attractive alternative in terms of fuel consumption, driveability and emissions

• Delphi and partnering OEMs have shown the technology potential at the engine and vehicle level equipped with R&D injectors. Lifetime durability has also been demonstrated on a small quantity of injectors

• Delphi’s progress on the injector development from demonstration to production-intended solutions will enable the technology to be marketable at the project end (Q2/2018).
Direct-injection of CNG:

A breakthrough technology for future green vehicles?

YES