Challenges and Opportunities in Future Powertrain Development

Vincenzo Bevilacqua | PEG

16.03.2017
Challenges and Opportunities in Future Powertrain Development

V. Bevilacqua, M. Boeger, M. Penzel, K. Fuoss | PEG-MG

2018 CONVERGE User Conference Europe
Bologna, 19-23 March 2018
Challenges and Opportunities in Future Powertrain Development
Agenda

> Introduction

> Global Warming

> E-Mobility
  - Well-to-Wheel Analysis
  - Cost Analysis
  - Market Share

> Engine Development
  - Engine Efficiency (Knock)
  - Alternative Fuel

> Conclusions
Introduction

E-Mobility…

> “In 2015, about one in every 150 cars sold in the U.S. had a plug and a battery. But mass adoption of electric vehicles is coming, and much sooner than most people realize” C. Mims, Aug. 28, 2016

> “Even in 2040, according to forecasting agencies such as the U.S. Energy Information Administration, cars with gas- and diesel-powered engines will still represent some 95% of the international car market.” S. Levine Jan. 30, 2015
Global Warming
Course of Global Atmospheric CO₂-Concentration

> Atmospheric CO₂-Concentration alternates since more than 400,000 years

> Correlation between Temperature Variation and CO₂-Concentration

> Until 1950 value below 300 ppm

> Starting in the 20st century strong increase of CO₂-Concentration noticeable (up to more than 400 ppm)

> Relationship between Global Warming and CO₂-Concentration increase widely accepted

Source: Petit et al; Nature Vol 399, 3 June 1999

Source: NASA, 2017
Global Warming

Anthropogenic Greenhouse Gas Emissions

> CO₂-Concentration increase is widely considered to be Anthropogenic caused, even if the results of some research may contrast with this statement

> Anthropogenic Share in worldwide CO₂-Emissions: 3,5 %
  - Share of Traffic Segment (PC, LDT and others): approx. 13 %

> Share of Traffic Segment in CO₂-Emissions: approx. 0,46 %

Global CO₂-Emissions p.a. – Total

Source: Prognose zu Rohstoffen, Verbrauch und Emissionen für die strategische Planung der Porsche Engineering Services GmbH, Francesco Antonio Fiore, Hochschule Furtwangen, 2009
E-Mobility

Well-to-Wheel Analysis: BEV

> Assumptions for Midsize Car:
  - Manufacturing CO\textsubscript{2} Footprint of BEV (at 150.000 km Lifetime)
    > 70 gCO\textsubscript{2}e/km
  - Real Life Consumption BEV (Midsize Car):
    > 21,1 kWh/100 km
    (including charging losses)

> Potential of BEV to reduce Greenhouse Gases is strongly depending on electric grid footprint

Source: Statista, Shrink That Footprint
Assumptions:

- CO₂-Grid Footprint
  - DE: 544 gCO₂/kWh
  - China: 750 gCO₂/kWh
- NEDC Cons. VW e-Golf: 12,7 kWh/100 km
- NEDC Cons. Tesla Model S 75D: 14,7 kWh/100 km
- NEDC Cons. VW Golf 1,2 TSI: 4,9 l/100 km
- NEDC Cons. VW Golf 1,6 TDI: 3,2 l/100 km
- NEDC Cons. Audi A7 3.0 TFSI: 7,6 l/100 km
- NEDC Cons. Audi A7 3.0 TDI: 6,1 l/100 km

Significant benefit for luxury cars, limited for compact class.
E-Mobility

Cost Analysis: Cost Forecast for Li-Ion Batteries

> Battery Cost is **key driver** for future development of BEV Share

> Current Battery Cost at Tesla, Renault and BMW:
  - Ca. **200 Euro/kWh**
  - For **100 kWh** Battery Capacity this would sum up to approx. **20,000 Euro**

> Cost for electric motor, converter, charger and cooling system will only gradually decrease, mainly driven by volume effects
E-Mobility

Cost Analysis: Luxury Car

Cost for ICE Top Model
- 7000 Euro V8 Engine
- 3000 Euro Transmission
- Fleet target 2020: < 95 gCO$_2$/km
  - Penalty: 95 Euro/gCO$_2$
- Approx. Energy Consumption
  Topmodel in 2020: 175 gCO$_2$/km
  - + 7600 Euro Penalty per vehicle

BEV Topmodel
- 100 kWh Battery Capacity

PHEV Topmodel
- 15 kWh Battery Capacity
- ICE V6 instead of V8

Production cost of BEV comparable to ICE starting from 2030

Course of total Powertrain Cost (in Percent) – Luxury Car
E-Mobility

Cost Analysis: High Volume Car

> Cost for **ICE High Volume Model**
  > 4000 Euro Engine + Transmission
  > Fleet target 2020: < 95 gCO₂/km
  > Penalty: 95 Euro/gCO₂
  > Approx. Energy Consumption in 2020: **100 gCO₂/km**

> **BEV** High Volume Model
  > 40 kWh Battery Capacity

> **PHEV** High Volume Model
  > 5 kWh Battery Capacity
  > ICE simplified

> **Production cost of BEV** comparable to **ICE** starting from **2035**

Course of total Powertrain Cost (in percent) – **High Volume**

![Course of total Powertrain Cost (in percent)](chart.png)
E-Mobility

Market Share Forecast: Schlegel und Partner

PLDV – Personal Light Duty Vehicle (PKW)

2050 still more than 70% of manufactured Passenger Cars with ICE

Percentage of Worldwide PLDV annual sales

Source: SuP Light Vehicle Prognose 2050, April 2016
E-Mobility

Market Share Forecast: International Energy Agency

Scenario sale IEA (optimistic scenario)

Source: Energy Technology Perspectives 2012, Pathways to a clean energy system, International Energy Agency, IEA

2050 still more than 62% of manufactured Passenger Cars with ICE

Source: SAP Light vehicle Register 2050, April 2015
**E-Mobility**

**Market Share Forecast: Deloitte**

Scenario sale Bosch for Europe

Source: Roadmap to a de-fossilized powertrain, Ulrich Schulmeister, Steffen Eppler, Ansgar Christ, Robert Bosch GmbH, 2017
E-Mobility
Market Share Forecast: Deutsches Zentrum für Luft- und Raumfahrt

Vehicle stock worldwide (4°C/6°C-Scenario with 2°C-Scenario MIX) in Mio.

Deutsches Luft- und Raumfahrtzentrum (max. Total PC Share)
Source: STROMbegleitung, Begleitforschung zu Technologien, Perspektiven und Ökobilanzen der Elektromobilität, DLR, W, März 2015

2050 still more than 70 % of all Passenger Cars with ICE

2050 still more than 62 % of manufactured Passenger Cars with ICE
Within the next 15-20 years minimum, more effort required in **Optimization of ICEs** to achieve legal emission requirements, to avoid/reduce penalties and to ensure the economic production of future vehicles **(Peak-ICE still ahead !!)**

Deutsches Luft- und Raumfahrtzentrum (max. Total PC Share)

**Market Share Forecast: Deutsches Zentrum für Luft- und Raumfahrt**

Vehicle stock worldwide (4°C/6°C-Scenario with 2°C-Scenario MIX) in Mio.

**2050 still more than 70% of manufactured Passenger Cars with ICE**

Source: STROMbegleitung, Begleitforschung zu Technologien, Perspektiven und Ökobilanzen der Elektromobilität, DLR, W, März 2015
Engine Development

Introduction

> According to recent statement of the **Volkswagen Board**, the Electrification of the Powertrain has to be coupled to additional measures to achieve Decarbonisation of Transportation:

- **Optimization** of the Internal Combustion Engines
- Use of **alternative fuel**

> Both of this Strategies requires the efficient use of **CFD simulation**

> **Quote:**

> Die Dekarbonisierung des Fahrzeugantriebs ist daher eine der dringlichsten Aufgaben für einen Fahrzeughersteller, um die Grundfesten des Geschäftsmodells zu sichern und die eigene Zukunftsfähigkeit zu stärken. Dazu bestehen grundsätzlich unterschiedliche Möglichkeiten. Für Volkswagen sind folgende Handlungsfelder relevant:

- Optimierung der verbrennungsmotorischen Antriebe,
- Nutzung alternativer Kraftstoffe,
- Elektrifizierung des Antriebs.

Eichler et al. (Volkswagen)
Volkswagen elektrifiziert den neuen Golf
Engine Development
Motorsport Experience

> “A Formula One car is massively more efficient than any electric car being charged from a power plant which is burning hydrocarbons. It is incredible that we’ve done that, but nobody is really talking about it that much.“ (cit. Paddy Lowe – Technical Director Mercedes Formula One Team 2013-2017)

> Mercedes' Formula 1 engine has hit a landmark achievement on the dyno [...] after breaking the 50% thermal efficiency barrier for the first time. (cit. J. Noble, Autosport)
The high efficiency of Formula 1 powertrains is achieved by the use of different technologies among other Exhaust Energy Recuperation and Ultra Lean Combustion and a high Compression Ratio. CR is the most effective way to increase thermodynamic efficiency.

Formula 1 Technical Regulations (5.3.6) limits the Geometrical Compression Ratio to 18:1. This indicates that current engine design are close to this value. Advantages are expected increasing the CR above this limit (for highly charged SI engines!)

Main Limit for Compression Ratio increase is Spark Ignition Engine is Knock.

A tool is required to allow knock prediction in the early development stage.
Engine Development

Knock: Autoignition Delay

- The **Autoignition** delay time can be evaluated with a rapid compression machine.

- **Pressure** and **temperature** are considered to be constant.

- The **Autoignition Delay** of the **fuel** depends mainly on three factors:
  - Pressure
  - Temperature
  - Air-fuel ratio

- Different **Analytical Correlation** have been proposed to approximate the experimental results.
Engine Development

Knock: Time Ignition Delay in Engine

> How to use the results of the rapid compression machine for the prediction of Knock in Engines?

Idea (Livingood-Wu Integral)
In each time step, a portion of Pre-Reaction equals to $dt/\tau$ occurs

> $\tau$ is the autoignition time corresponding to the temperature and pressure in the combustion chamber
> $dt$ is the timestep duration
> The contribution at every timestep is evaluated
> The contributions are summed up
> When Pre-Reactions reach 100% Knock occurs!

Knock: Time Ignition Delay in Engine

- $T$ Unburned [K]
- $T$ Burned [K]
- Temperature [K]
- Pressure [bar]

- Tau [ms]
- PreReaction TimeStep [%]
- PreReaction Cumulative [%]

Crank Angle [CADeg]
Knock: Modelling in Converge

In order to model the Knock a passive variable \( KI \) (Knock Index) is introduced.

From the physical point of view, this variable represents the Amount of Pre-reaction which already occurred in a cell.

The temporal evolution of the Knock Index depends on:
- A Source term: the Pre-Reaction which occurs in the cell and are defined by the local \( \tau \)
- The Transport from/to adjacent cells due to Convection
- The Diffusion from/to adjacent cells due to the Difference of Concentration

For the Autoignition time \( \tau \) two approaches have been used:
- Douaud & Eyzat
- Kinetics-fit
Engine Development

Knock: Spark Advance Variation

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>705</td>
<td>0.89</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td>Right</td>
</tr>
</tbody>
</table>

> Two different Spark Advance are here compared
Engine Development
Knock: Spark Advance Variation

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>705</td>
<td>0.89</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td>Right</td>
</tr>
</tbody>
</table>

Early Spark Timing

Late Spark Timing

Temperature [K]

Knock Index [-]
Engine Development

Knock: Spark Advance Variation

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>705</td>
<td>0.89</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td>Right</td>
</tr>
</tbody>
</table>

> In the Early Spark Timing case, combustion already started
Engine Development

Knock: Spark Advance Variation

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>705</td>
<td>0.89</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td>Right</td>
</tr>
</tbody>
</table>

Early Spark Timing

Late Spark Timing

Temperature [K]

Knock Index [-]
Engine Development

Knock: Spark Advance Variation

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>705</td>
<td>0.89</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td>Right</td>
</tr>
</tbody>
</table>

> Knock Index begin to rise for Early Spark Timing case

Temperature [K] for Early Spark Timing

Temperature [K] for Late Spark Timing
Engine Development
Knock: Spark Advance Variation

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>705</td>
<td>0.89</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td>Right</td>
</tr>
</tbody>
</table>

Early Spark Timing

Late Spark Timing

Temperature [K]

Knock Index [-]
### Engine Development

**Knock: Spark Advance Variation**

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>705</td>
<td>0.89</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td>Right</td>
</tr>
</tbody>
</table>
Engine Development

Knock: Spark Advance Variation

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>705</td>
<td>0.89</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td>Right</td>
</tr>
</tbody>
</table>

A big portion in the volume (in particular, under Intake Valves) has already completed more than 70% of Pre-Reactions.
## Engine Development

### Knock: Spark Advance Variation

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>705</td>
<td>0.89</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td>Right</td>
</tr>
</tbody>
</table>

**Early Spark Timing**

- Temperature [K]
- Knock Index [-]

**Late Spark Timing**

- Temperature [K]
- Knock Index [-]
Engine Development

Knock: Spark Advance Variation

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>705</td>
<td>0.89</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td>Right</td>
</tr>
</tbody>
</table>

Early Spark Timing

Late Spark Timing

Temperature [K]

Knock Index [-]
Engine Development

Knock: Spark Advance Variation

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>705</td>
<td>0.89</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td>Right</td>
</tr>
</tbody>
</table>

> As expected, at the end of combustion a certain region of the Combustion Chamber shows an high level of Knock Index

> Higher Spark Advance, higher Knock Tendency
# Engine Development

## Knock: Spark Advance Variation

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>705</td>
<td>0.89</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td>Right</td>
</tr>
</tbody>
</table>

### Early Spark Timing

- **Temperature [K]**

![](image1)

- **Knock Index [-]**

![](image2)

### Late Spark Timing

- **Temperature [K]**

![](image3)

- **Knock Index [-]**

![](image4)
Engine Development

Knock: Spark Advance Variation

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>705</td>
<td>0.89</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td>Right</td>
</tr>
</tbody>
</table>

Early Spark Timing

Late Spark Timing

Temperature [K]

Knock Index [-]
Engine Development

Knock: Spark Advance Variation

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Line style</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>708</td>
<td>0.89</td>
<td></td>
</tr>
</tbody>
</table>

> The **cumulated volume fraction** of different Knock Indexes are here represented
**Engine Development**

**Knock: Spark Advance Variation**

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Line style</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>705</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td></td>
<td>708</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td></td>
</tr>
</tbody>
</table>

> The **cumulated volume fraction** of different Knock Indexes are here represented

> At the end of the combustion a clear **difference of Knock Tendency** is detected

> Higher **Spark Advance**, higher **Knock Tendency**
Engine Development

Knock: Spark Advance Variation

<table>
<thead>
<tr>
<th>Engine speed [rpm]</th>
<th>Spark Time [CADeg]</th>
<th>Lambda</th>
<th>Line style</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200</td>
<td>705</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td></td>
<td>708</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td></td>
<td>711</td>
<td>0.89</td>
<td></td>
</tr>
</tbody>
</table>
### Engine Development

#### Knock: Comparison with measurements

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Source</th>
<th>Line style</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200 rpm</td>
<td>708</td>
<td>Simulat.</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>715</td>
<td>Measur.</td>
<td>--</td>
</tr>
<tr>
<td>4800 rpm</td>
<td>705</td>
<td>Simulat.</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>705</td>
<td>Measur.</td>
<td>--</td>
</tr>
</tbody>
</table>

> Two different operating points have been measured at their Knock limit

> The same operating points have been simulated in order to match the performances
Engine Development

Knock: Comparison Low-end torque and Peak power

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Source</th>
<th>Line style</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200</td>
<td>708</td>
<td>Simulat.</td>
<td></td>
</tr>
<tr>
<td>4800</td>
<td>705</td>
<td>Simulat.</td>
<td></td>
</tr>
</tbody>
</table>

> The Knock Tendency of two different operating points at the Knock limit have been compared.

> The tool is able to reproduce the same behaviour, identifying a clear Knock limit.

> A volume fraction of 0.20 for the Knock Index 90% can be considered as the critical condition (Knock onset).
Engine Development

Knock: Comparison Low-end torque and Peak power

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>Spark Time [CADeg]</th>
<th>Source</th>
<th>Line style</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200</td>
<td>708</td>
<td>Simulat.</td>
<td></td>
</tr>
<tr>
<td>4800</td>
<td>705</td>
<td>Simulat.</td>
<td></td>
</tr>
</tbody>
</table>

> The Knock Tendency of two different operating points at the Knock limit have been compared.

Methodology for the **Knock Tendency** evaluation has been developed and, after comparison with measurements data, a general criteria for the detection of the **Knock Onset** has been defined.

> The tool is able to reproduce the same behaviour, identifying a clear Knock limit.

> A volume fraction of 0.20 for the **Knock Index 90%** can be considered as the critical condition (Knock onset).
Engine Development

CNG: Alternative Fuel

- CNG is a promising alternative fuel for ICEs.

- Reduced oil dilution
- Improved knock resistance
- Less expensive than gasoline
- Available distribution net
- CNG is a practical option for ICEs

<table>
<thead>
<tr>
<th></th>
<th>Gasoline</th>
<th>CNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/H</td>
<td>~ 0.44</td>
<td>~0.25</td>
</tr>
<tr>
<td>Octane number</td>
<td>95 - 98</td>
<td>120 - 130</td>
</tr>
<tr>
<td>CO</td>
<td>100%</td>
<td>25%</td>
</tr>
<tr>
<td>HC</td>
<td>100%</td>
<td>40%</td>
</tr>
<tr>
<td>CO₂</td>
<td>100%</td>
<td>75% - 80%</td>
</tr>
<tr>
<td>PM</td>
<td>100%</td>
<td>Potentially free</td>
</tr>
</tbody>
</table>

Source: Bernd Kircher, Christof Schernus, "Integrated Simulation and Tuning of CNG Engine Fuel Rail and Intake Air Manifold", FEV Motorentechnik GmbH, 2004

- Poor Image
- Storage System Expansive and Difficult to Package
- Slight penalty in Volumetric Efficiency
- Reduced charge cooling effect
- CNG is a challenge for emotional vehicles
Engine Development

CNG:P2G

Battery Electrical Vehicle

Current

Motion

Power to Gas

Current

H₂

CH₄

Motion

Current

Electrolysis

H₂O

O₂

CO₂
Engine Development

CNG: P2G

> Research
- **Project:** European Project *Helmeth* (Integrated High-Temperature Electrolysis and METHanation for Effective Power to Gas Conversion)
- **Coordination:** Karlsruher Institut für Technologie (KIT)
- **Targets:**
  - Elaboration of the conditions for an *economic feasibility* of the P2G process
  - Demonstration of the technical feasibility of a *conversion efficiency* > 85%

> Industrial Scale Application
- **Company:** ETOGAS GmbH
- **Costumer:** Audi e-Gas-Anlage Werlte
- **Installed Power:** 6,3 MW Beta Anlage
- **Location:** Werlte, Niedersachsen
- **Efficiency:** 54%
- **Construction:** 2012 – 2013,
- **In Use:** Since Dec 2013
In order to promote CNG penetration, in particular in high performance vehicle, following challenges has to be faced:

**Fuel Storage System**
- Vehicle/Platform Integration
- Advanced Material
- Alternative Structures

**Reduced Cooling Effect**
- Exhaust System Material
- Integrated Exhaust Manifold
- Water Injection

**Vol. Efficiency Penalty**
- Direct Injection
  - Mixture Preparation
  - CFD Analysis
Engine Development
CNG: Mixture Preparation and Combustion

> Backflow in the Intake Ports
> Rich Mixture under the Intake Port and between the Exhaust Port. Lean under the Spark Plug
CNG: Mixture Preparation

> Good Correlation between Simulation Result and Injector Test Bench (literature reference)
Challenges and Opportunities in Future Powertrain Development

Vincenzo Bevilacqua | PEG

CNG: Mixture Preparation

Lambda

> Good Correlation at Start of Injection

SAE Paper:
Stationary CNG injection (110bar)

SAE 2016-01-0801: Numerical and Experimental Studies on Mixture Formation with an Outward-Opening Nozzle in a SI Engine with CNG-DI (Dimitri Seboldt, David Lejsek (Robert Bosch GmbH); Marlene Wentsch, Marco Chiodi (FKFS); Michael Bargende (Universität Stuttgart)), 04/05/2016
Engine Development
CNG: Mixture Preparation

Lambda

> Good Correlation at 408° CADeg
> Significant Influence of the Intake Air Flow on the CNG Injection

SAE Paper:
Stationary CNG injection (110bar)

SAE 2016-01-0801:
Numerical and Experimental Studies on Mixture Formation with an Outward-Opening Nozzle in a SI Engine with CNG-DI (Dimitri Seboldt, David Lejsek (Robert Bosch GmbH); Marlene Wentsch, Marco Chiodi (FKFS); Michael Bargende (Universitat Stuttgart)), 04/05/2016
**Engine Development**

**CNG: Mixture Preparation**

> Good Correlation at **Intake Valve Closing**

**SAE Paper:**
Stationary CNG injection (110bar)

SAE 2016-01-0801: Numerical and Experimental Studies on Mixture Formation with an Outward-Opening Nozzle in a SI Engine with CNG-DI (Dimitri Seboldt, David Lejsek (Robert Bosch GmbH); Marlene Wentisch, Marco Chiotti (FKFS); Michael Bargende (Universität Stuttgart)), 04/05/2016
Engine Development
CNG: Mixture Preparation and Combustion

Lambda

> Very good correlation at BDC

SAE Paper:
Stationary CNG injection (110bar)

SAE 2016-01-0801: Numerical and Experimental Studies on Mixture Formation with an Outward-Opening Nozzle in a SI Engine with CNG-DI (Dimitri Seboldt, David Lejsek (Robert Bosch GmbH); Marlene Wentsch, Marco Chiodi (FKFS); Michael Bargende (Universität Stuttgart)), 04/05/2016
Methodology for the simulation of the CNG Direct Injection and Mixture Preparation has been developed and assessed on the basis of stationary experimental data.

- Very good correlation at BDC
Conclusion

> **Global Warming**
  - Anthropogenic CO₂ Emissions widely considered responsible of **Global Warming**.
  - **Automotive Industry** is requested to **decarbonise** transportation:
    > Electrification
    > Optimization of Internal Combustion Engine
    > Use of Alternative Fuels

> **Battery Electrical Vehicles**
  - Potential for CO₂ Reduction depending of **Grid Footprint**, and higher for **Luxury cars**
  - **Production cost** competitive starting from 2030-2035

> **ICE Optimization**
  - Necessary to reduce **CO₂ Penalty**
  - High Potential in Knock Control: **CFD Methodology**

> **Alternative Fuel**
  - CNG offer Potential for CO₂ Reduction as **fossil fuel** and even more as **synthetic fuel**
  - Challenges at **vehicle** and **engine level**
  - **CFD Methodology** necessary to optimize mixture preparation
Thanks for your attention!