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Challenges and Opportunities in Future Powertrain Development

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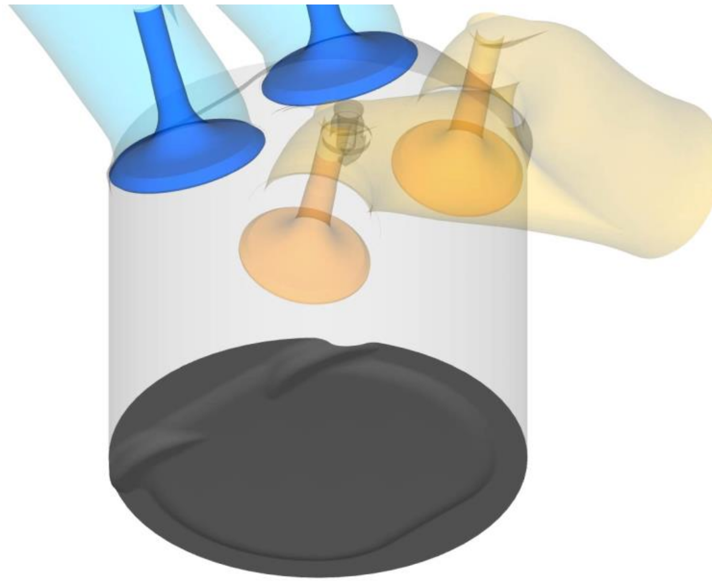
Porsche Engineering
driving technologies

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…


THE WALL STREET JOURNAL.

Why Electric Cars Will Be Here Sooner Than You Think

Adoption of electric vehicles will not be gradual, because the factors required to unlock demand for them are in place

… or not


THE WALL STREET JOURNAL.

The Car of the Future May Run on Gasoline

For all the talk of electric cars, the old-fashioned internal combustion engine is proving to be hard to beat

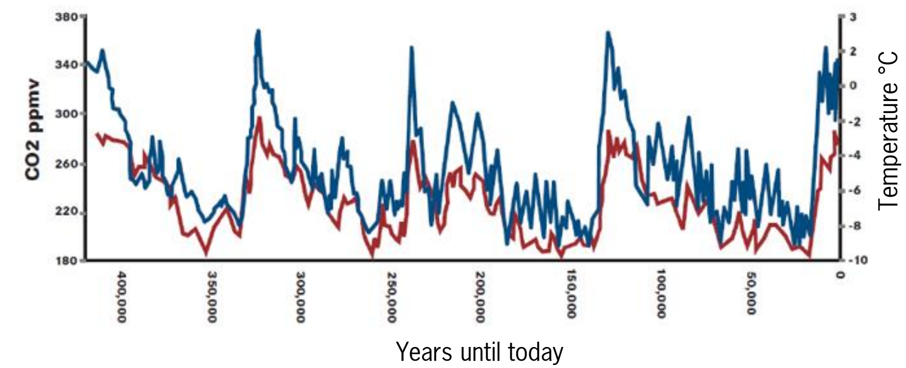
> *"In 2015, about* ***one in every 150 cars*** *sold in the U.S. had a plug and a battery. But mass adoption of electric vehicles is coming, and* ***much sooner*** *than most people realize"* C. Mims, Aug. 28, 2016

> *"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

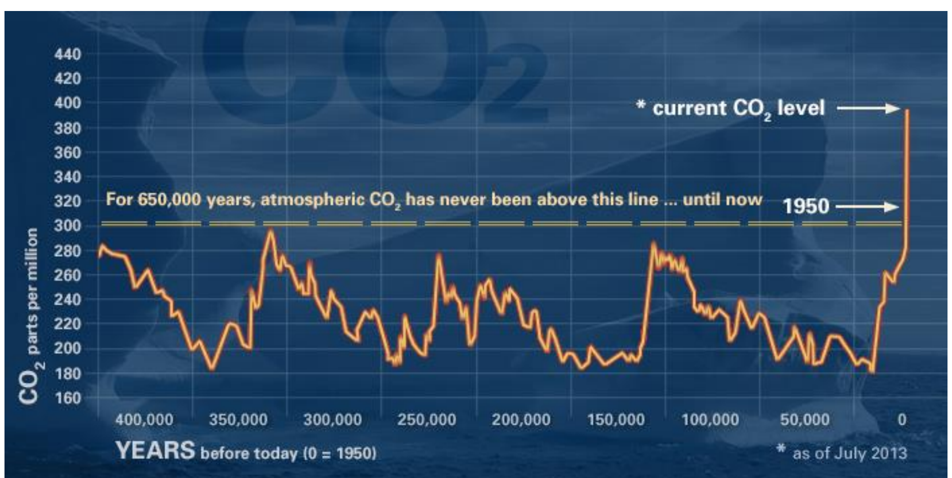
Global Warming

Course of Global Atmospheric CO_2-Concentration

- Atmospheric CO_2-Concentration alternates since more than 400.000 years
- Correlation between **Temperature Variation** and **CO_2-Concentration**
- Until 1950 value **below 300 ppm**



Source: Petit et al; Nature Vol 399, 3 June1999



Source: NASA, 2017

- Starting in the **20st century** strong increase of CO_2-Concentration noticeable (up to more than **400 ppm**)
- Relationship between Global Warming and CO_2-Concentration increase **widely accepted**

Global Warming

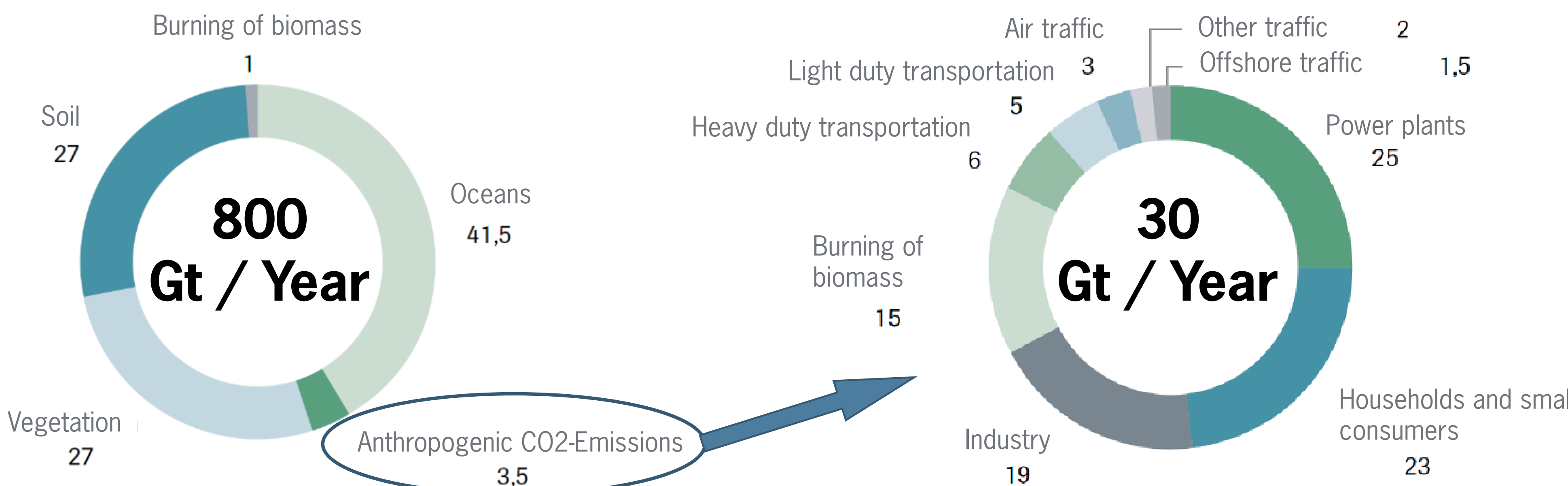
Anthropogenic Greenhouse Gas Emissions

> CO_2-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 CO_2-Emissions: **3,5 %**

– Share of Traffic Segment (PC, LDT and others): approx. 13 %

> **Share of Traffic Segment** in CO_2-Emissions: approx. **0,46 %**



Global CO_2-Emissions p.a. – **Total**

Global CO_2-Emissions p.a. – **Anthropogenic**

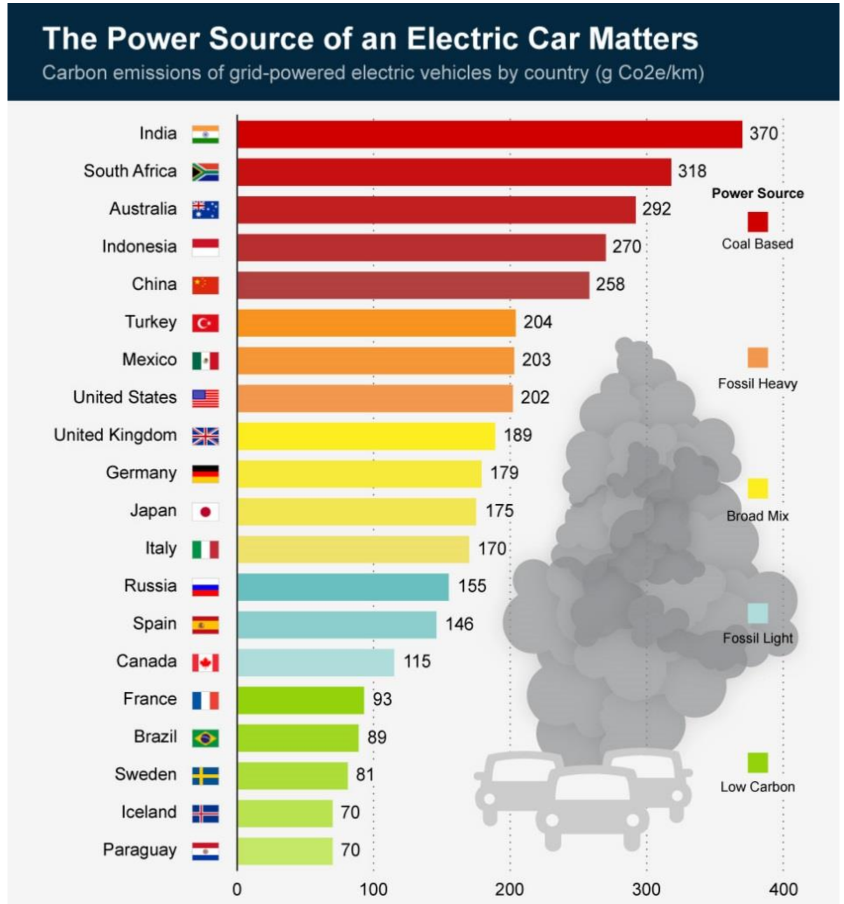
Source: Prognose zu Rohstoffen, Verbrauch und Emissionen für die strategische Planung der Porsche Engineering Services GmbH, Francesco Antonio Fiore, Hochschule Furtwangen, 2009

E-Mobility

Well-to-Wheel Analysis: BEV

- Assumptions for Midsize Car:
  - Manufacturing CO_2 – Footprint of BEV (at 150.000 km Lifetime)
    - *70 gCO_2e/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

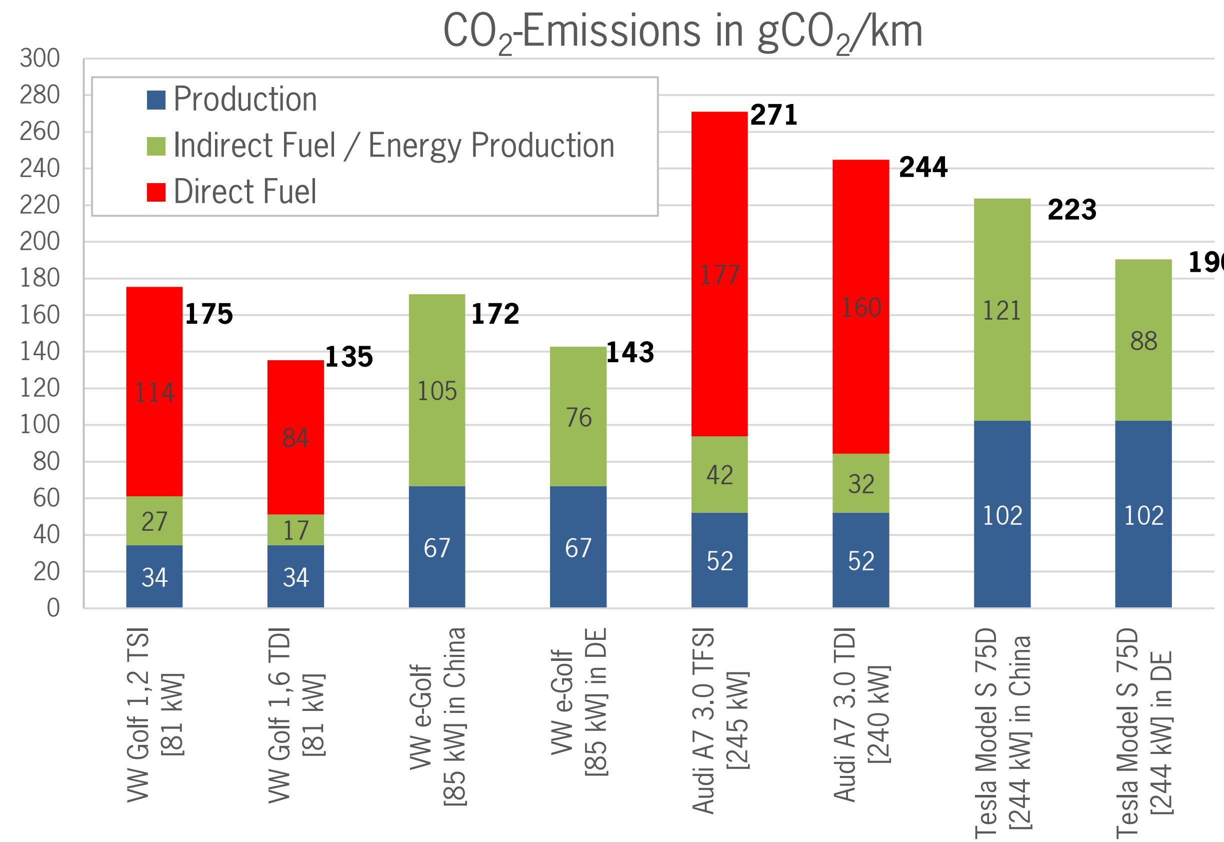
E-Mobility

Well-to-Wheel Analysis: Technology Comparison

- Assumptions:
  - CO_2-Grid Footprint
    - DE: *544 gCO_2/kWh*
    - China: *750 gCO_2/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*

Including 10% Charging Losses (applies to the e-Golf and Tesla Model S 75D)

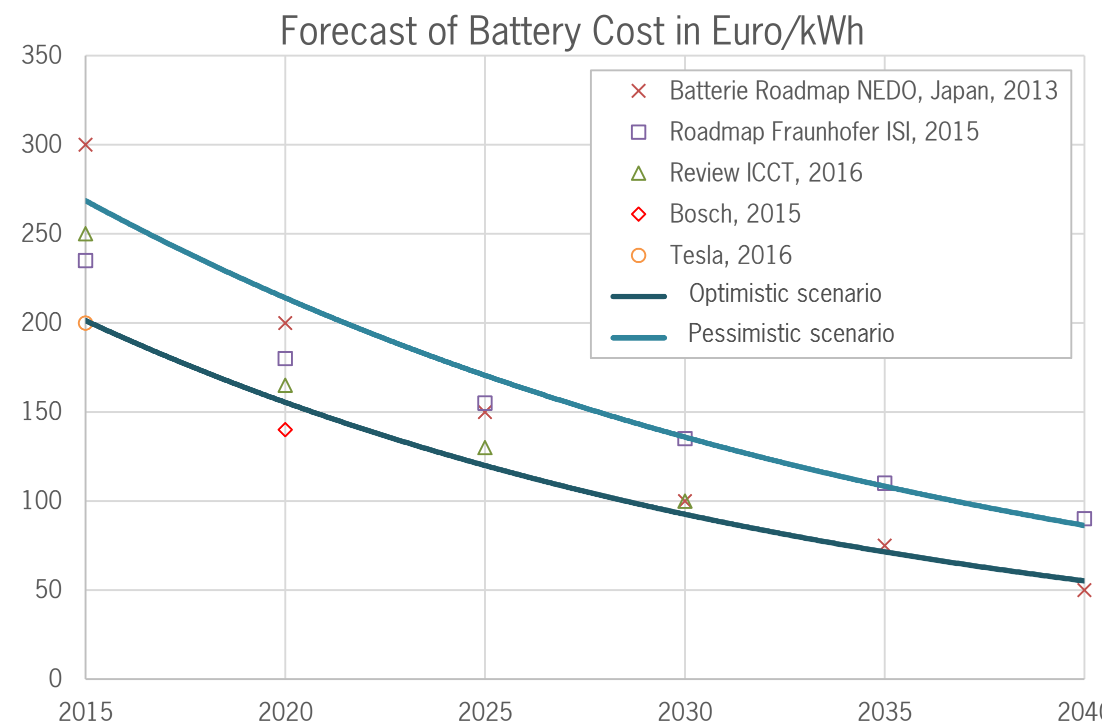
- **Significant** benefit for **luxury cars**, limited for compact class



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

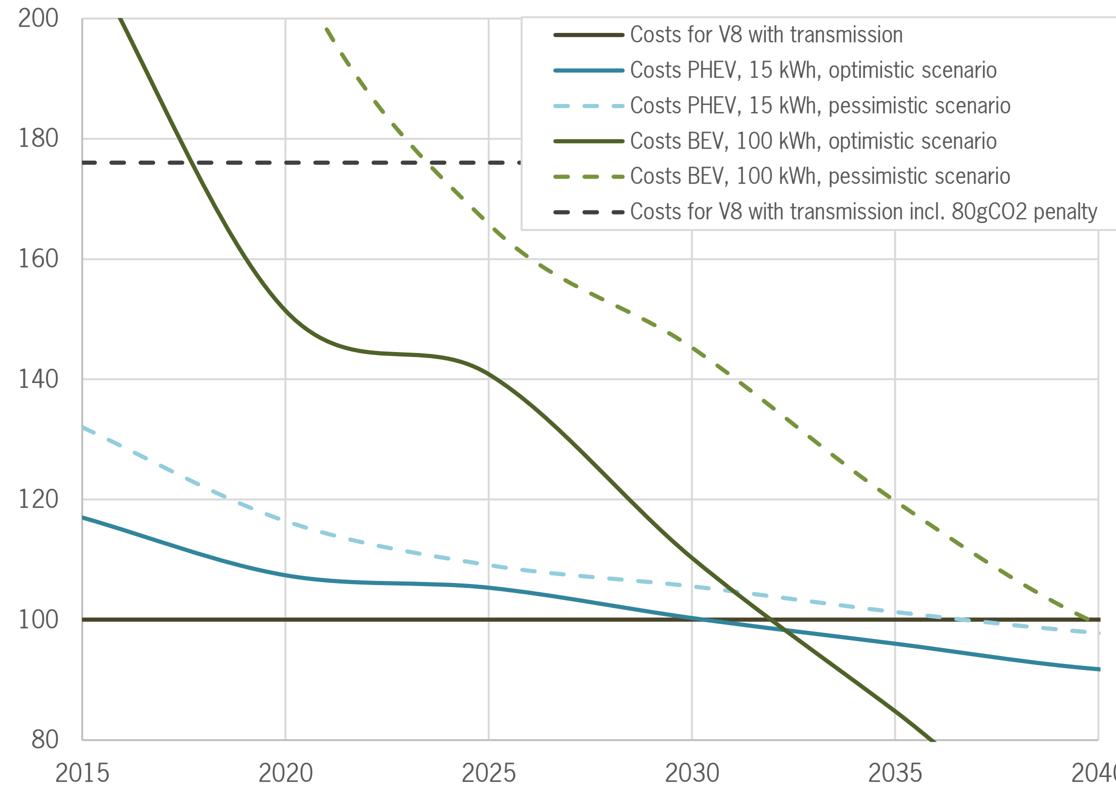


E-Mobility

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**

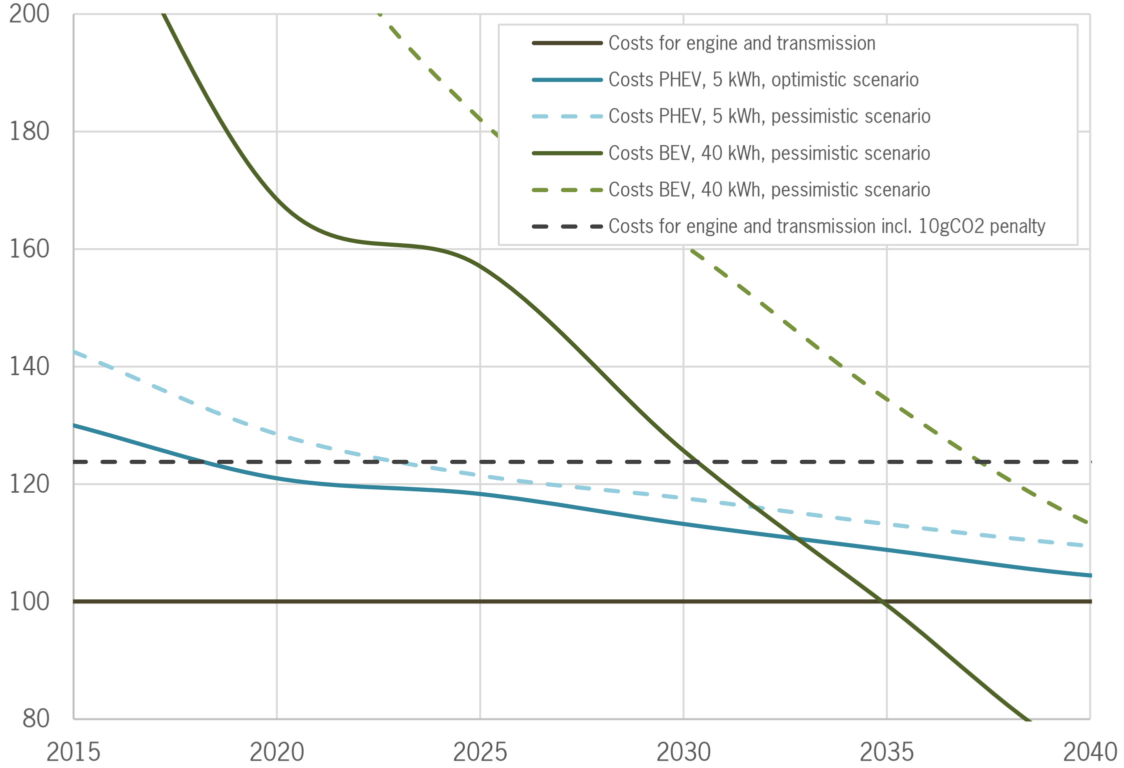


E-Mobility

Cost Analysis: High Volume Car

- Cost for **ICE High Volume Model**
  - **4000 Euro** Engine + Transmisson
  - Fleet target 2020: < 95 gCO_2/km
    - Penalty: 95 Euro/gCO_2
  - Approx. Energy Consumption in 2020: **100 gCO_2/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**

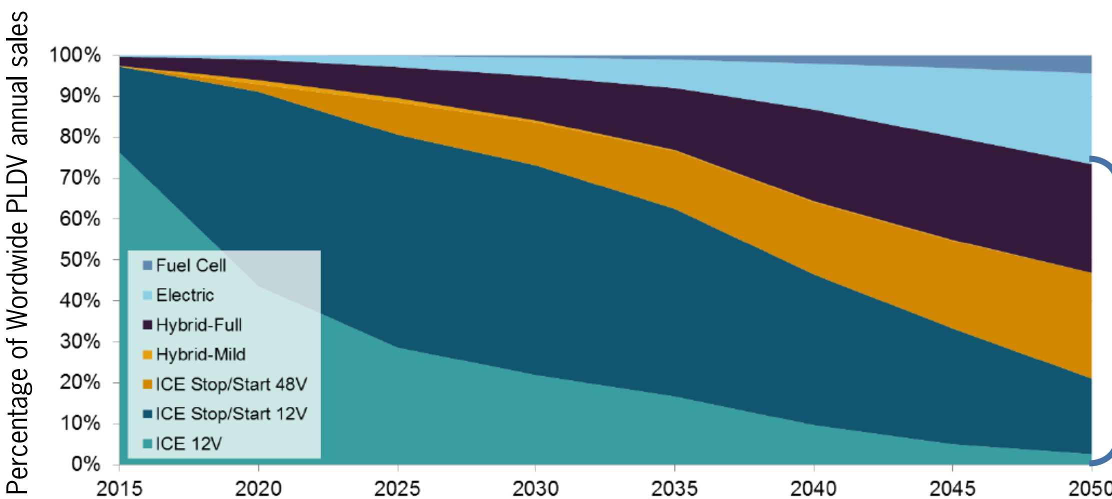
Course of total Powertrain Cost (in percent) – **High Volume**



E-Mobility

Market Share Forecast: Schlegel und Partner

PLDV – Personal Light Duty Vehicle (PKW)



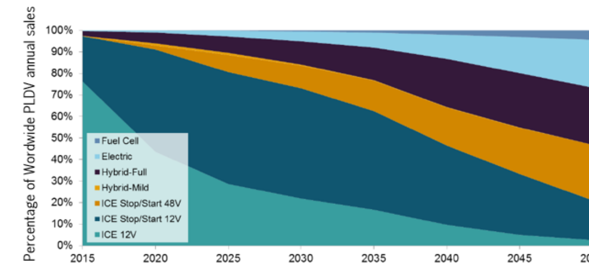
2050 still more than 70 % of manufactured Passenger Cars with ICE

Scenario sale Schlegel und Partner

Source: SuP Light Vehicle Prognose 2050, April 2016

E-Mobility

Market Share Forecast: International Energy Agency



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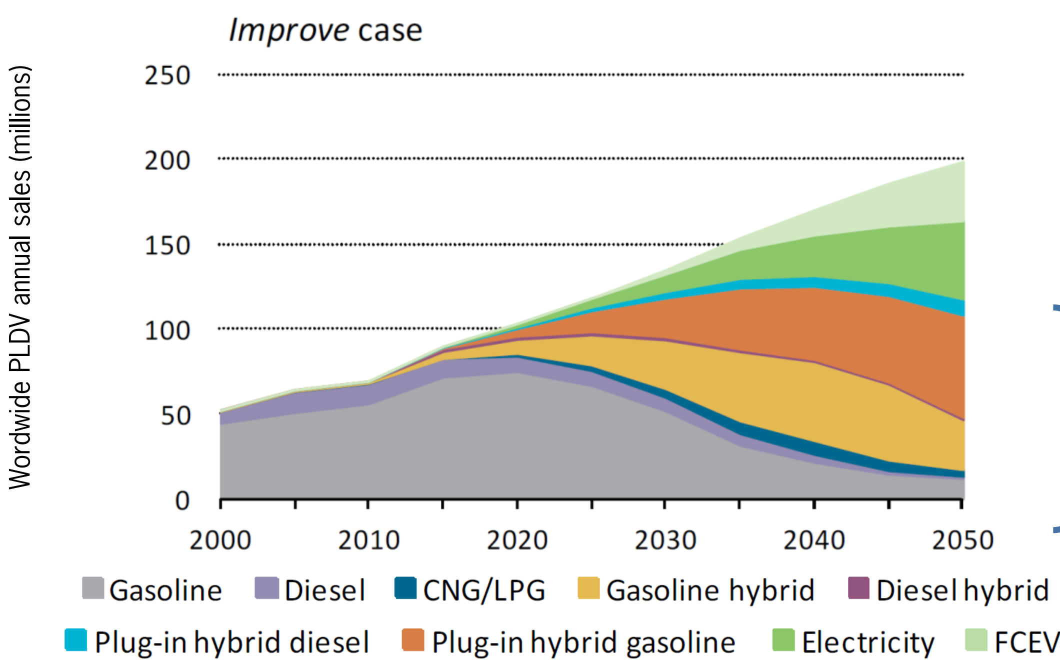


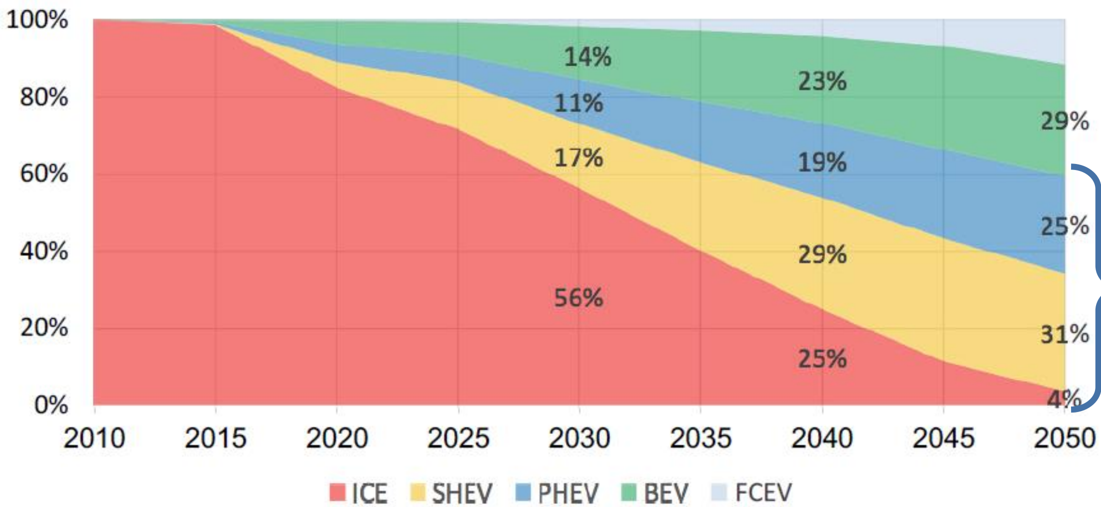
2050 still more than 62 % of manufactured Passenger Cars with ICE

Scenario sale IEA (optimistic scenario)

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

E-Mobility

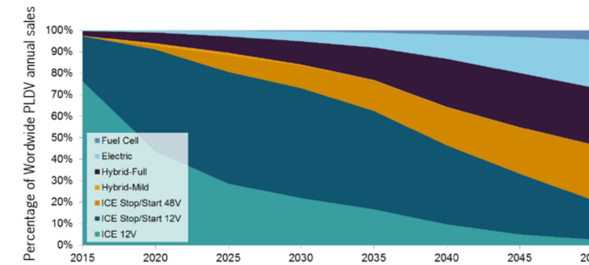
Market Share Forecast: Deloitte



2050 still 60 % of manufactured Passenger Cars with ICE

Scenario sale Bosch for Europe

Source: Roadmap to a de-fossilized powertrain, Ulrich Schulmeister, Steffen Eppler, Ansgar Christ, Robert Bosch GmbH, 2017



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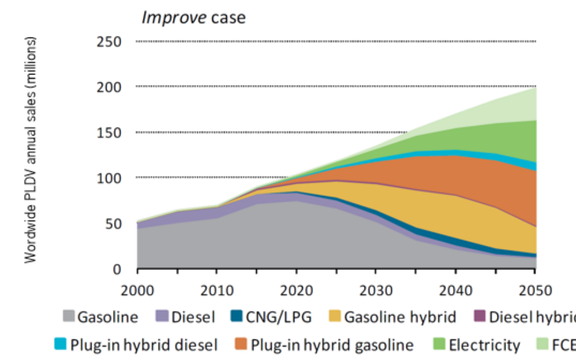

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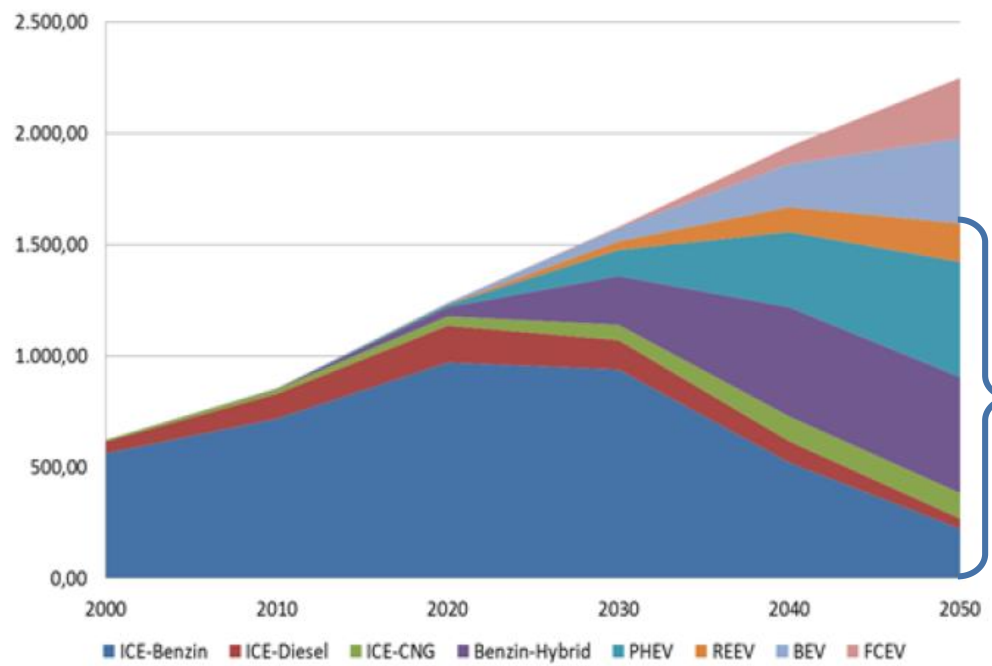
E-Mobility

Market Share Forecast: Deutsches Zentrum für Luft- und Raumfahrt

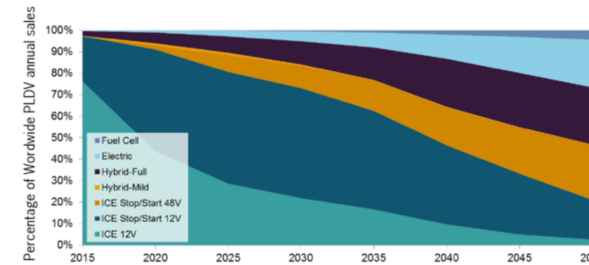
Vehicle stock worldwide (4°C/6°C-Scenario with 2°C-Scenario MIX) in Mio.



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

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

Source: STROMbegleitung, Begleitforschung zu Technologien, Perspektiven und Ökobilanzen der Elektromobilität, DLR, WI, März 2015

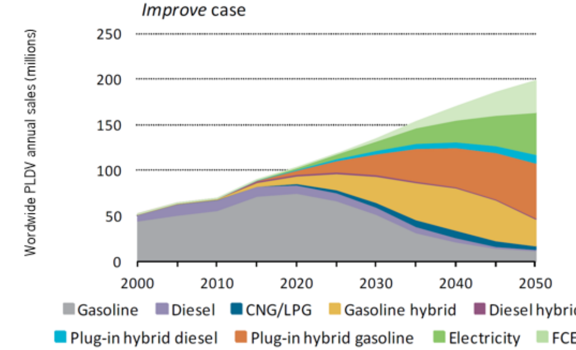


2050 still more than 70 % of manufactured Passenger Cars with ICE

Scenario sale Schlegel und Partner

Source: SuP Light Vehicle Prognose 2050, April 2016

Improve case



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

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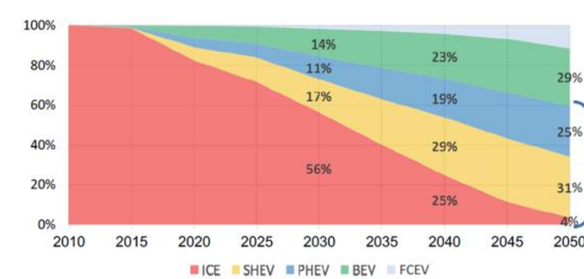

2050 still 60 % of manufactured Passenger Cars with ICE

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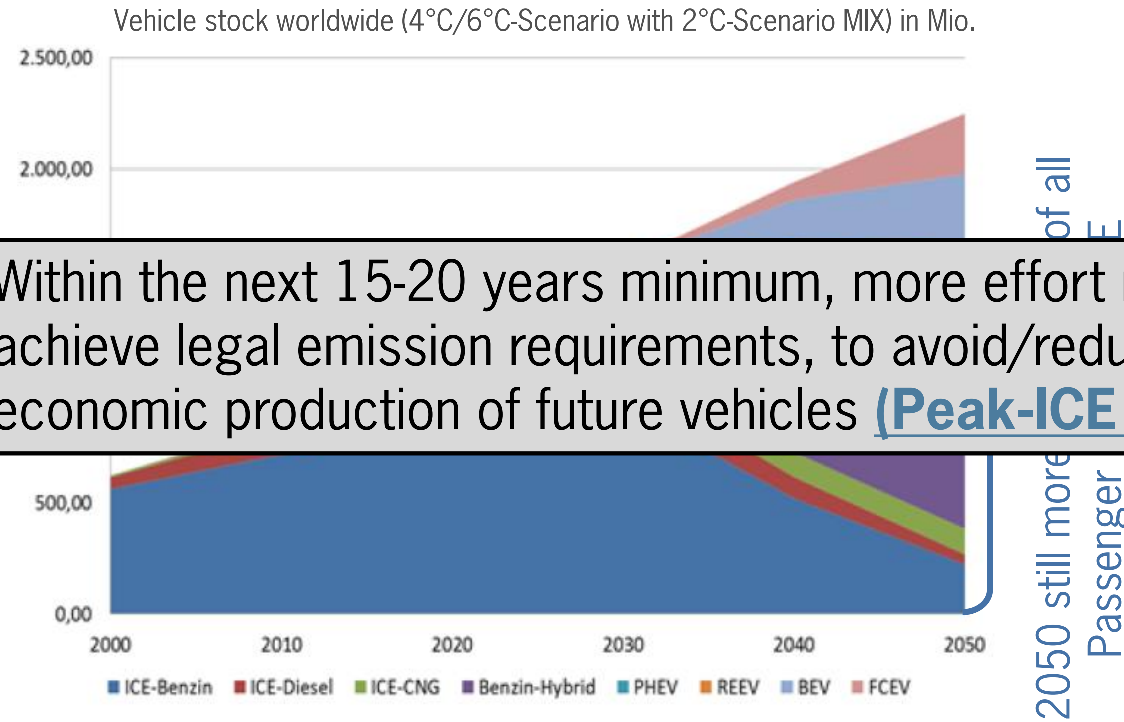
Source: Roadmap to a de-fossilized powertrain, Ulrich Schulmeister, Steffen Eppler, Ansgar Christ, Robert Bosch GmbH, 2017

E-Mobility

Market Share Forecast: Deutsches Zentrum für Luft- und Raumfahrt



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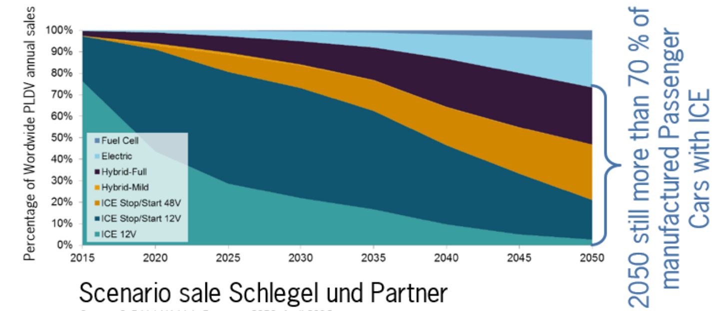

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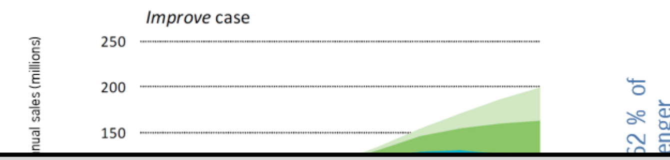
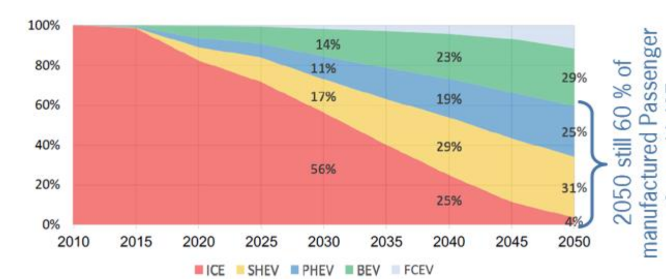


Within the next 15-20 years minimum, more effort required in **Optimization of ICEs** to achieve legal emission requirements, to avoid/reduce penalties and to ensure the economic production of future vehicles **(Peak-ICE still ahead !!)**

Scenario sale IEA (optimistic scenario)

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



Scenario sale Bosch for Europe

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Engine Development

Introduction

> According to recent statement of the **Volkswagen Board**, the Electrification of the Powertrain has to be couple 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:

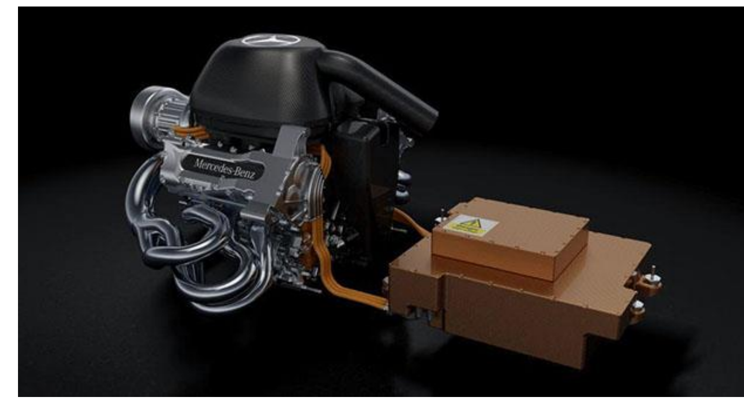
- Optimierung der verbrennungsmotorischen Antriebe,
- Nutzung alternativer Kraftstoffe,
- Elektrifizierung des Antriebs.

Eichler et al. (Volkswagen)
Volkswagen elektrifiziert den neuen Golf

Engine Development

Motorsport Experience

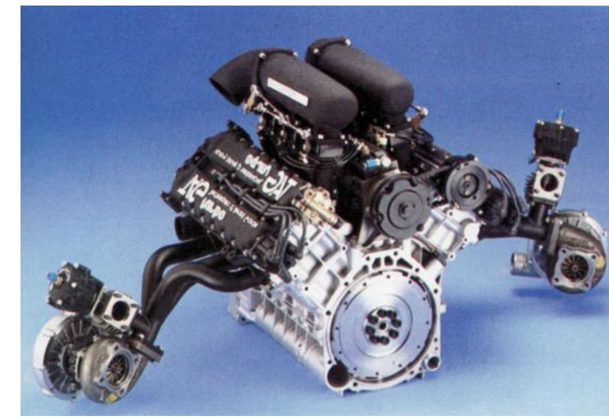
> "**A Formula One car is massively more efficient than any electric car being charged from a power plant which is burning hydrocarbons**. It is incredible that we've done that, but nobody is really talking about it that much." (cit. **Paddy Lowe** – Technical Director Mercedes Formula One Team 2013-2017)



> 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)

Engine Development

Motorsport Experience



> 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

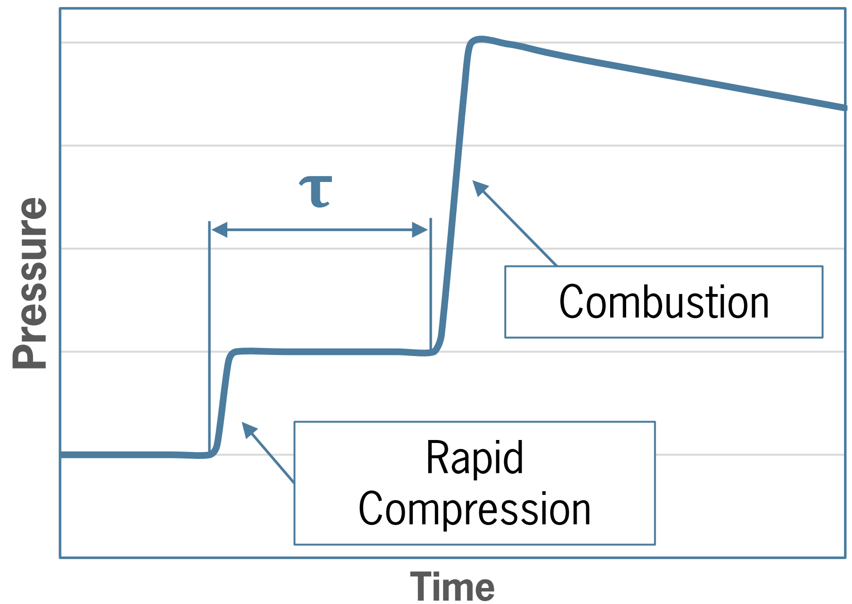
Engine Development

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

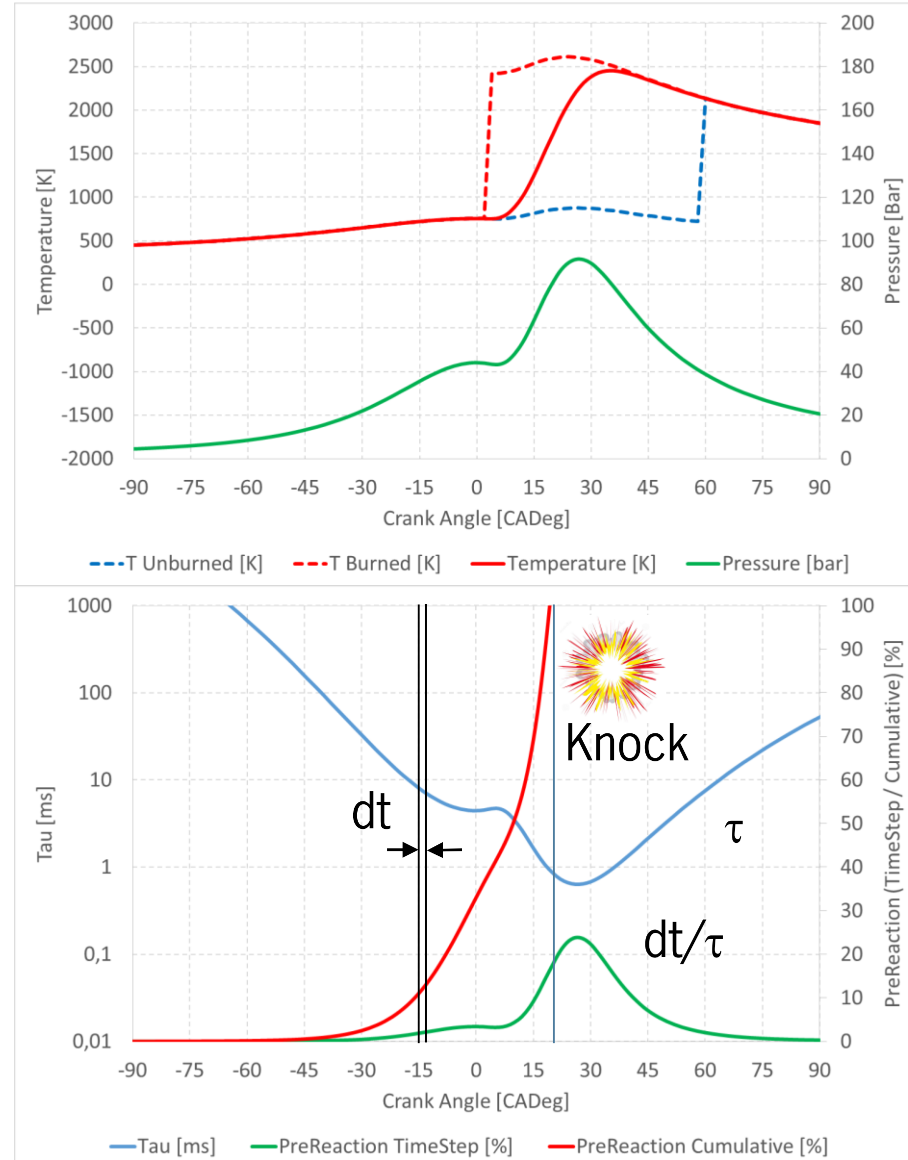
Engine Development

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/τ occurs

- τ 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!



Engine Development

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

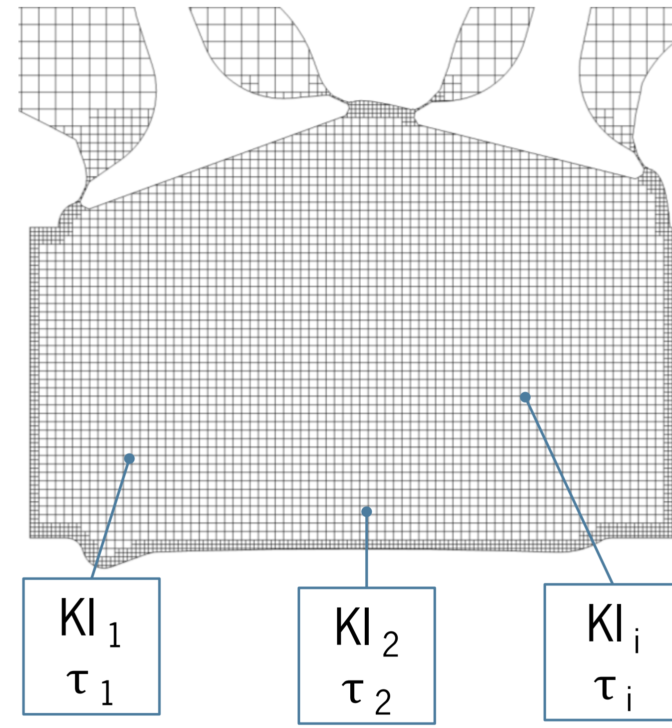
SOURCE | DIFFUSION

TEMPORAL EVOLUTION

$$\frac{\partial \rho KI}{\partial t} = S - \frac{\partial \rho u KI}{\partial x} + \frac{\partial}{\partial t}\left(\rho D \frac{\partial KI}{\partial x}\right)$$

CONVECTION

- 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** τ
  - 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** τ two approaches have been used
  - **Douaud & Eyzat**
  - **Kinetics-fit**



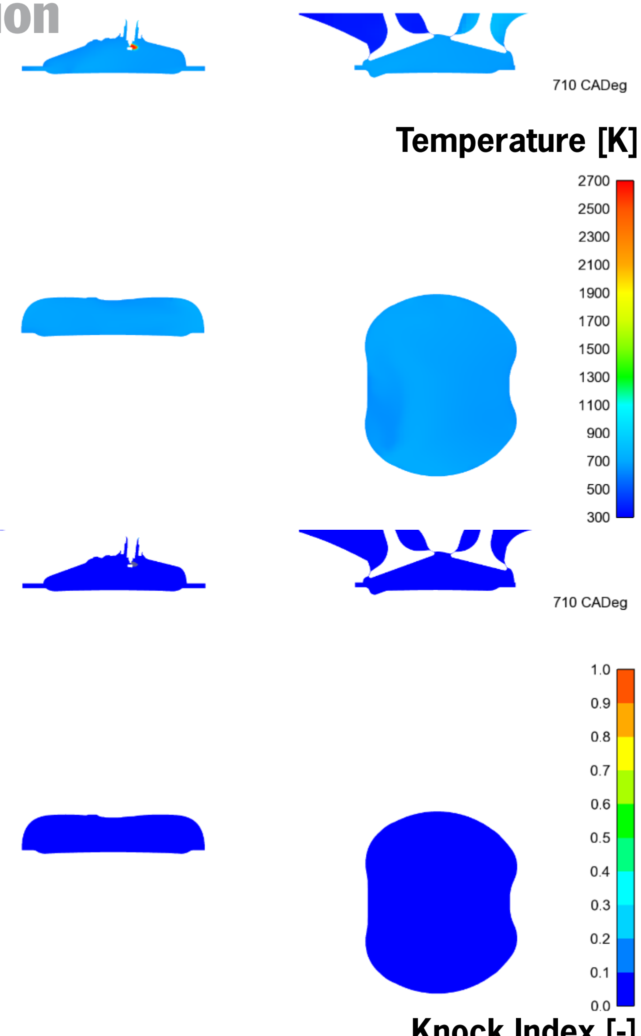
Engine Development

Knock: Spark Advance Variation

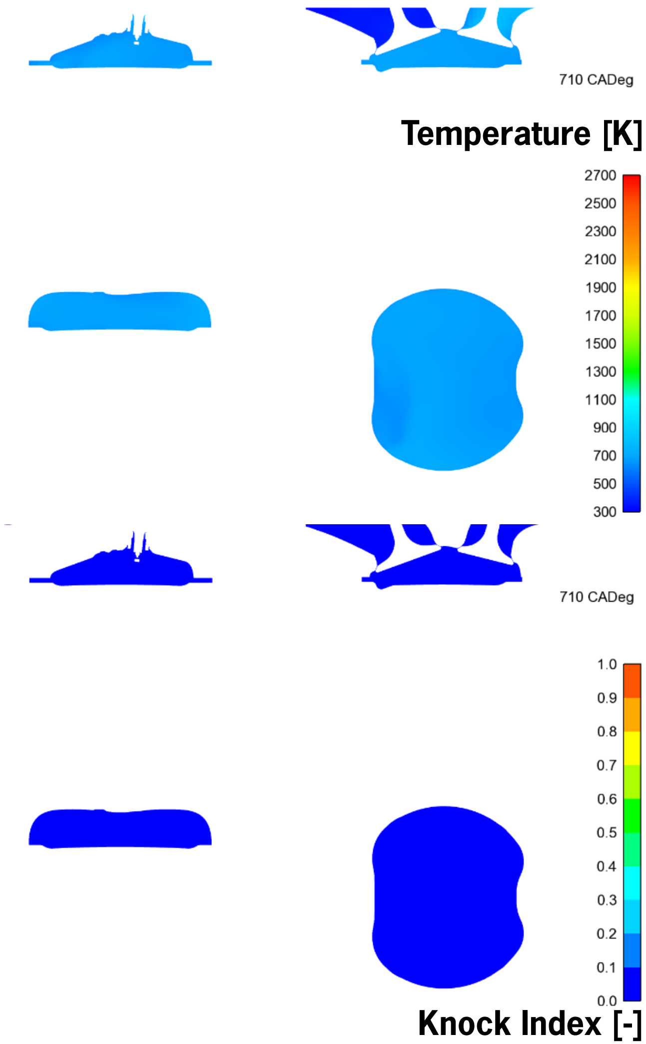
Engine speed	Spark Time [CADeg]	Lambda	Position
2200 rpm	705	0.89	Left
	711	0.89	Right

> Two different **Spark Advance** are here compared

Early Spark Timing



Late Spark Timing



Engine Development

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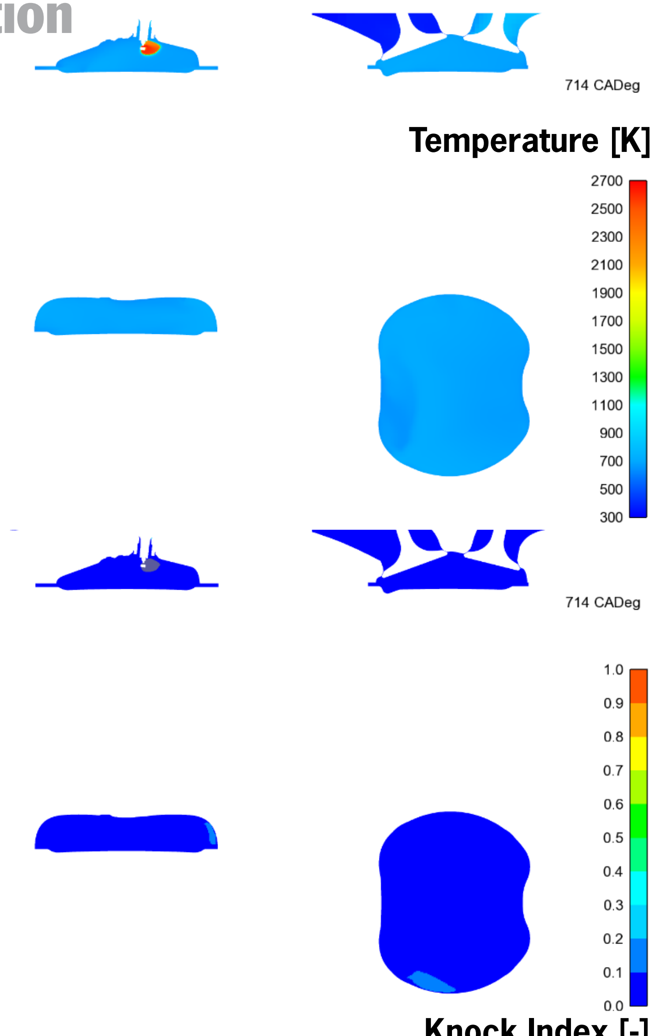
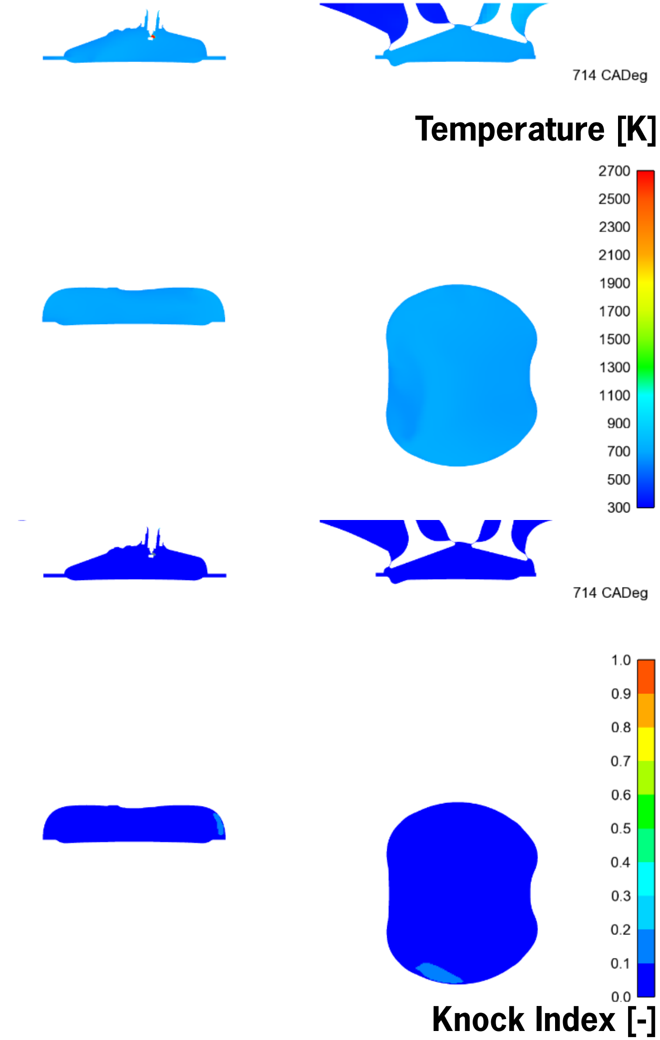


Late Spark Timing



Engine Development

Knock: Spark Advance Variation

Engine speed	Spark Time [CADeg]	Lambda	Position
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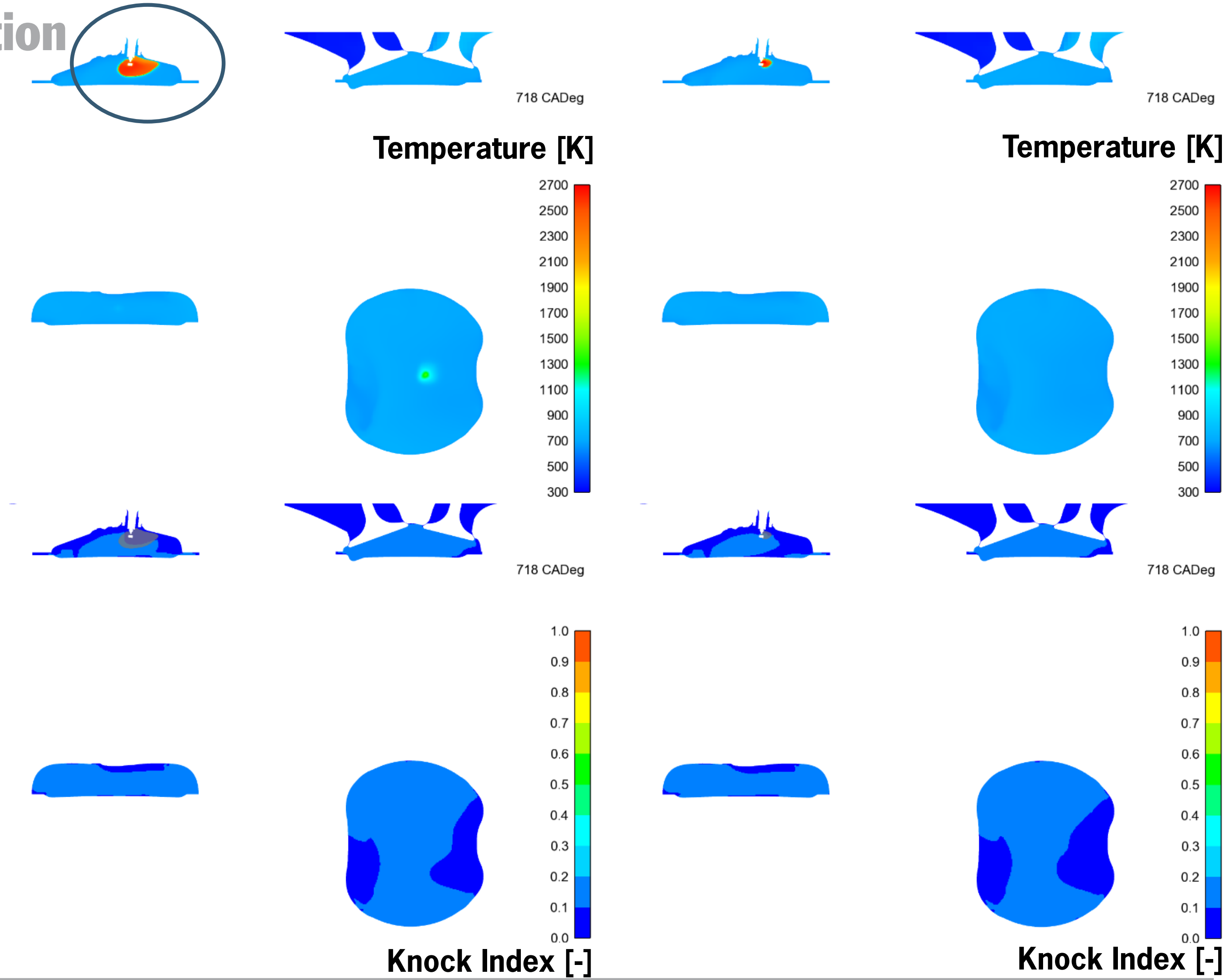
> In the **Early Spark Timing** case, combustion already started

Early Spark Timing

Late Spark Timing



Engine Development

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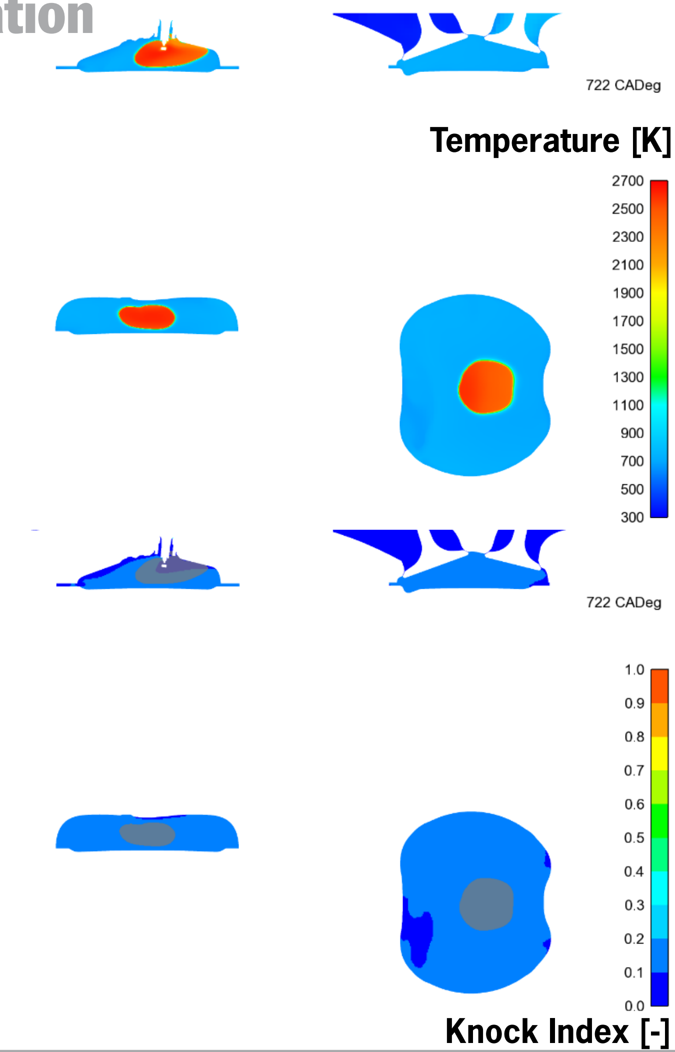
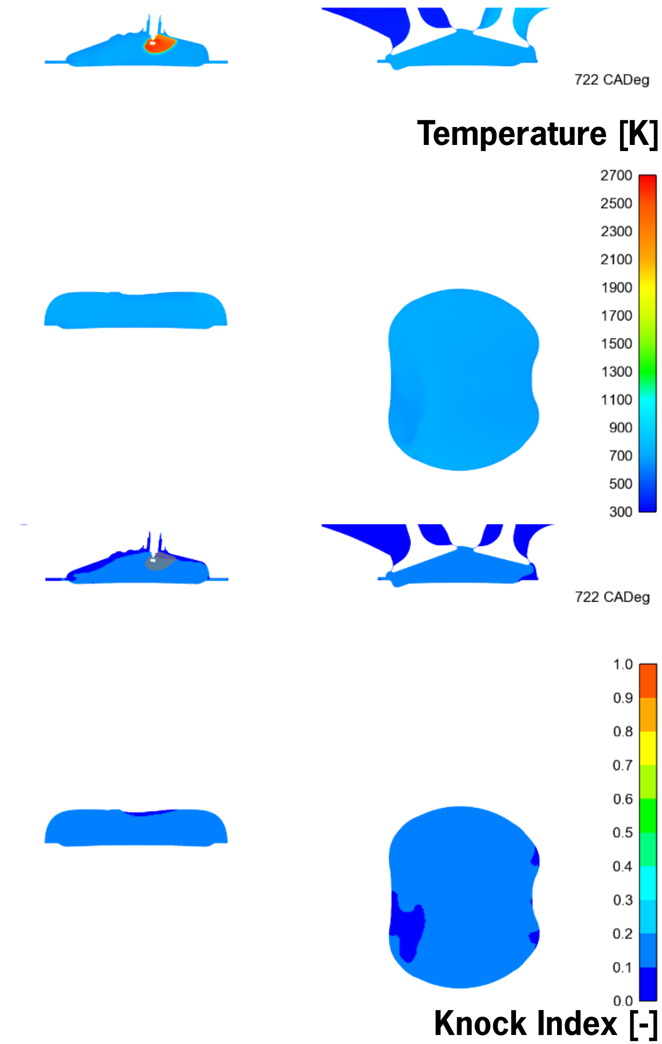


Late Spark Timing



Engine Development

Knock: Spark Advance Variation

Engine speed	Spark Time [CADeg]	Lambda	Position
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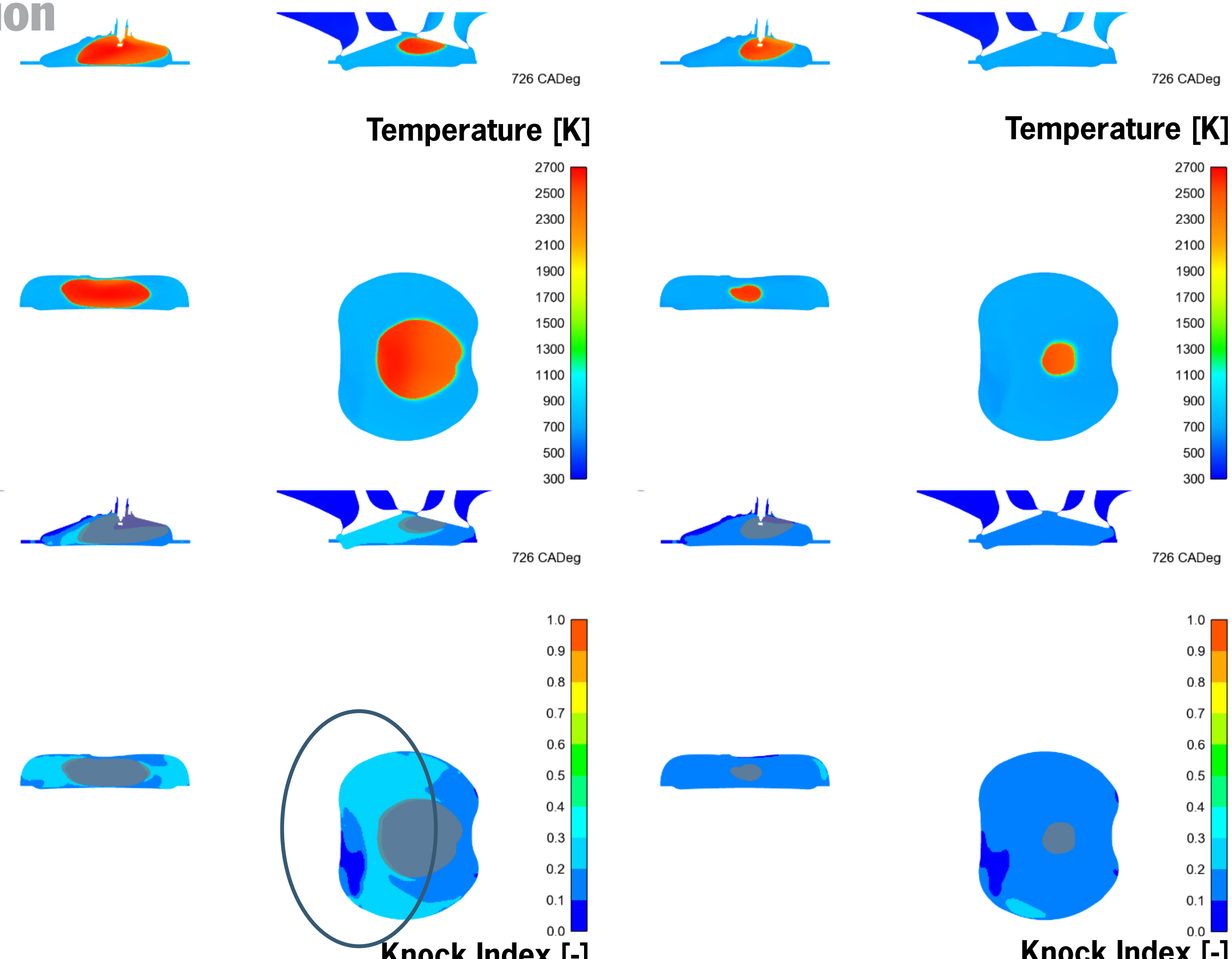
> Knock Index begin to rise for **Early Spark Timing** case

Early Spark Timing

Late Spark Timing



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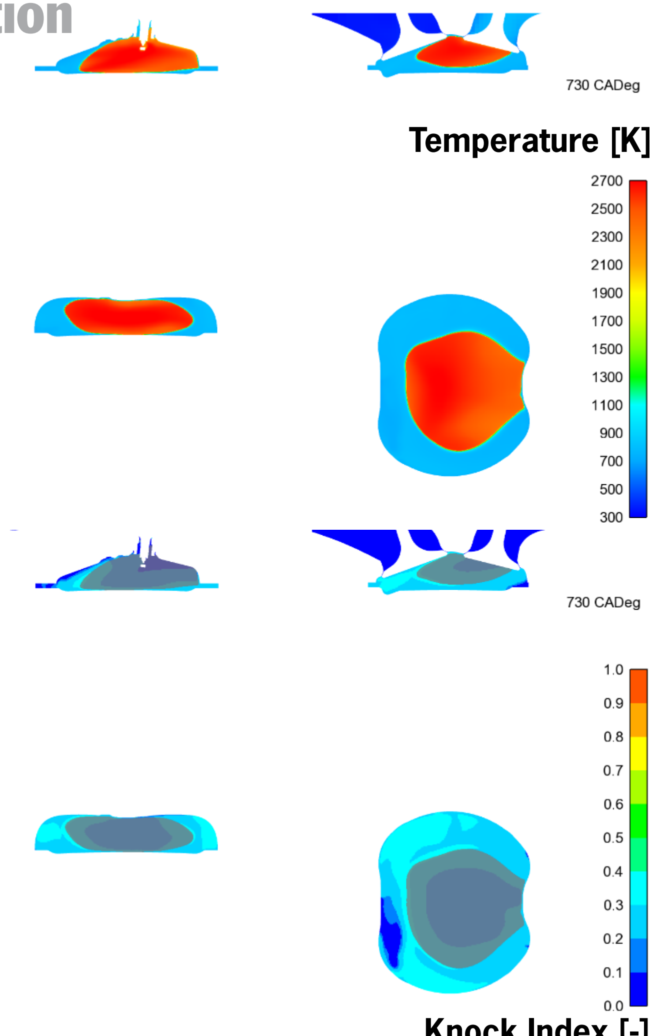
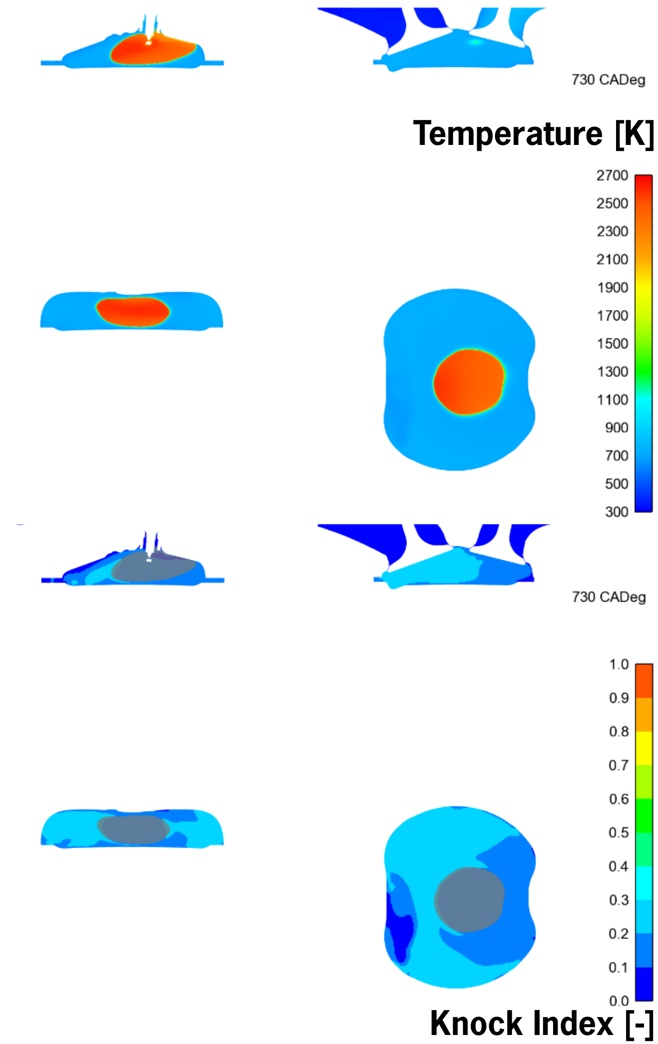


Late Spark Timing



Engine Development

Knock: Spark Advance Variation

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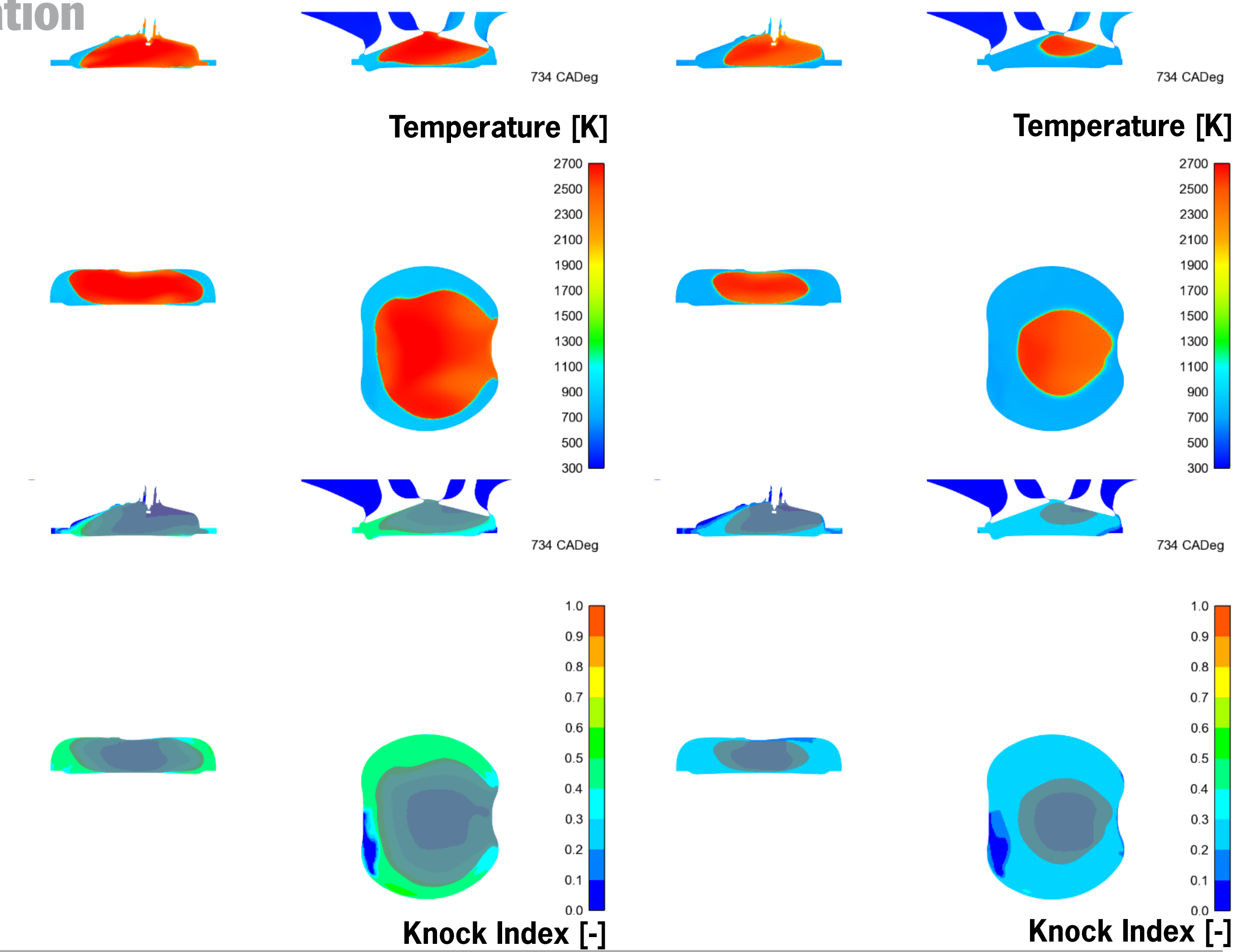
	711	0.89	Right

Early Spark Timing | Late Spark Timing

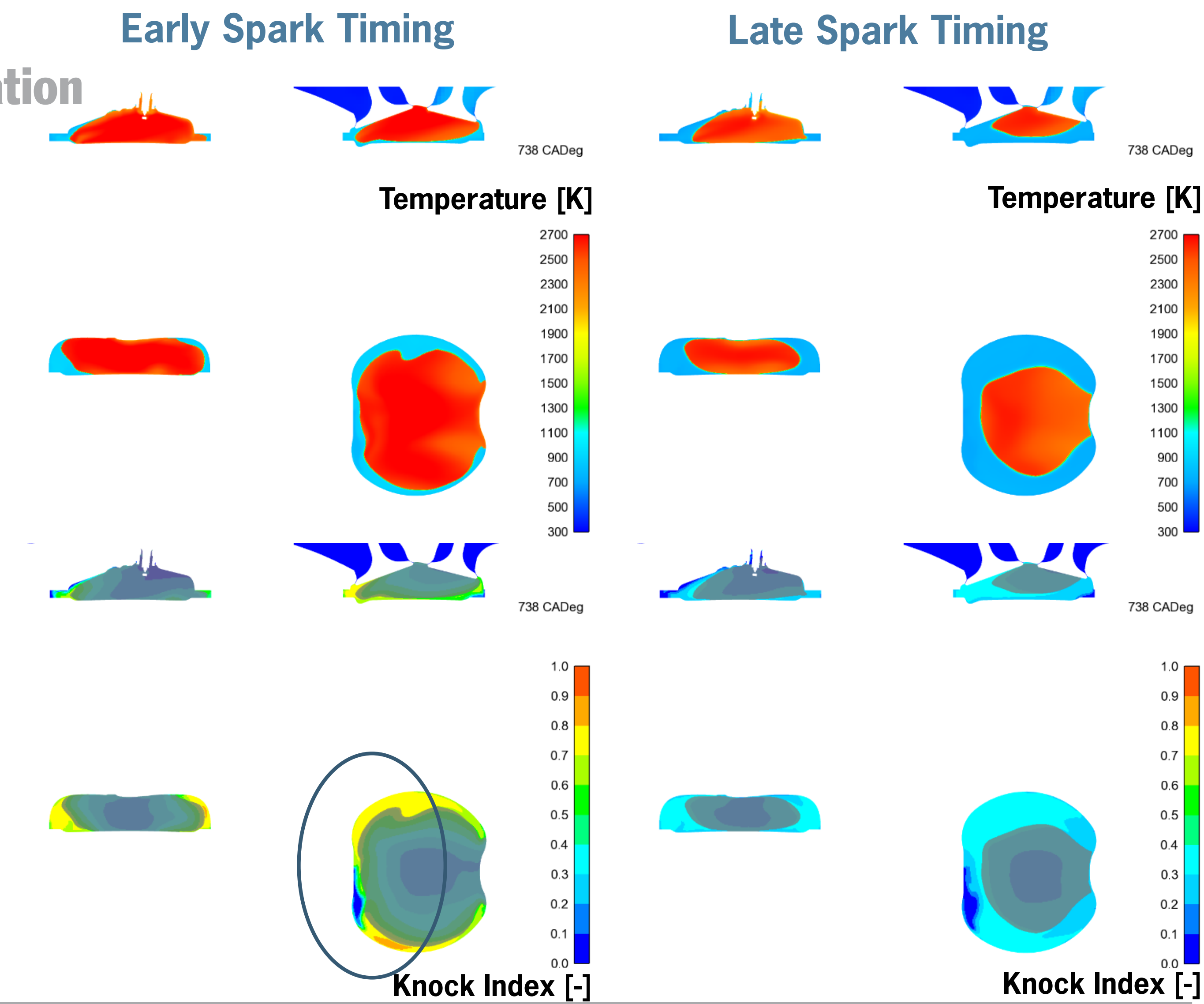


Engine Development

Knock: Spark Advance Variation

Engine speed	Spark Time [CADeg]	Lambda	Position
2200 rpm	705	0.89	Left
	711	0.89	Right

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

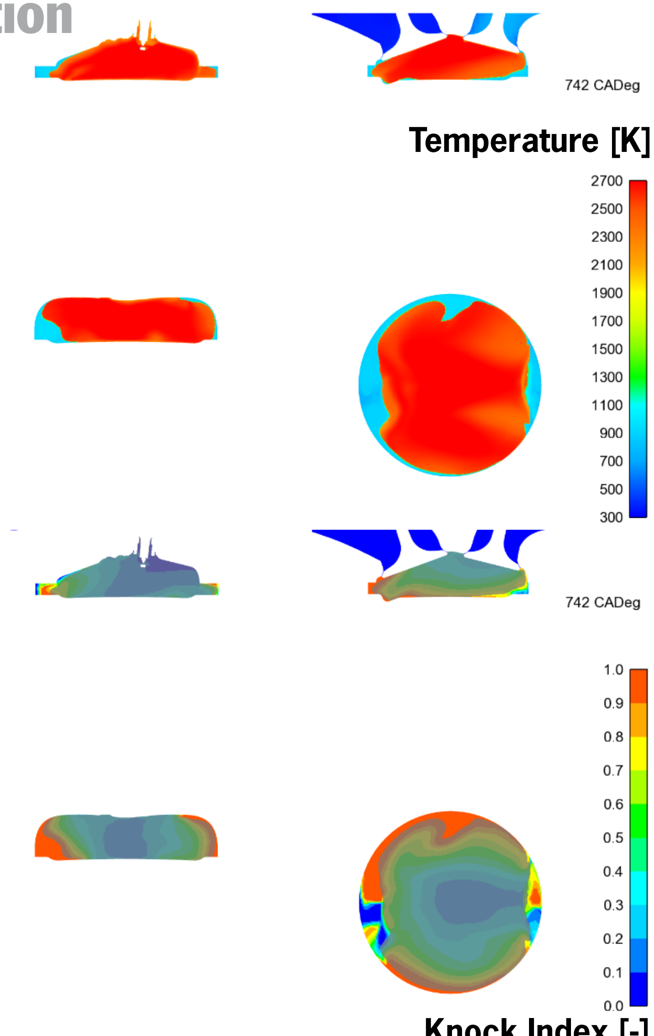


Engine Development

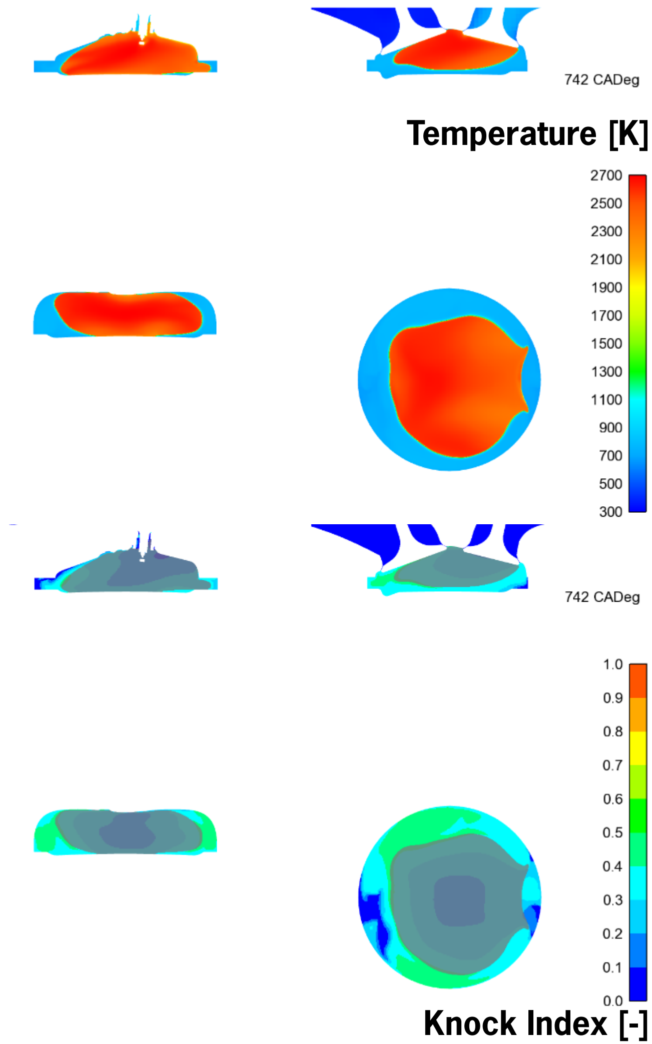
Knock: Spark Advance Variation

Engine speed	Spark Time [CADeg]	Lambda	Position
2200 rpm	705	0.89	Left
	711	0.89	Right

Early Spark Timing



Late Spark Timing

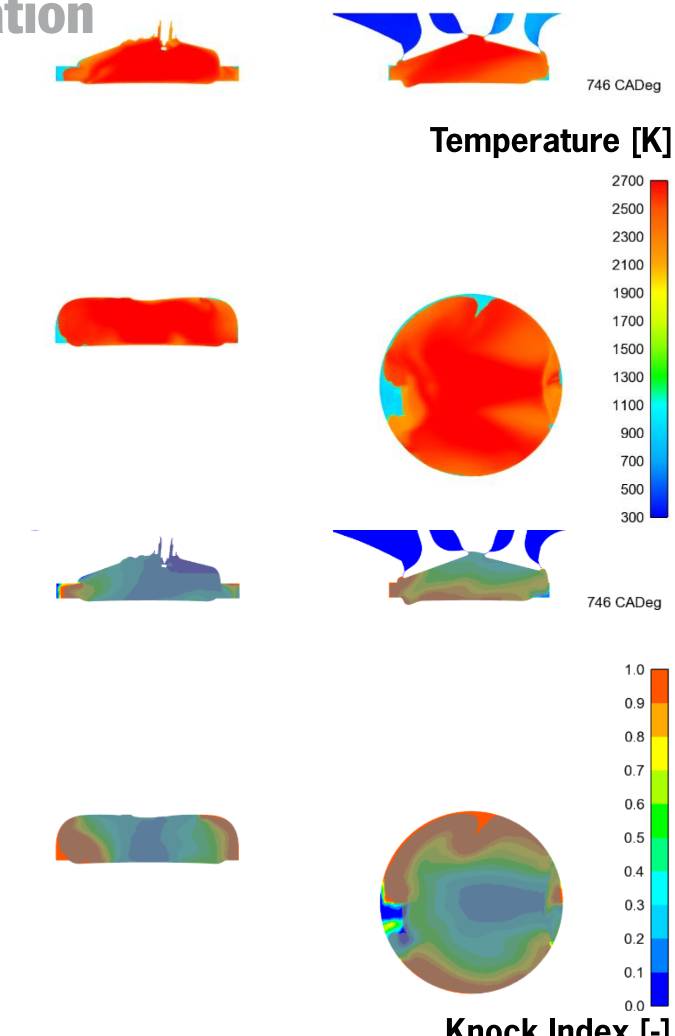


Engine Development

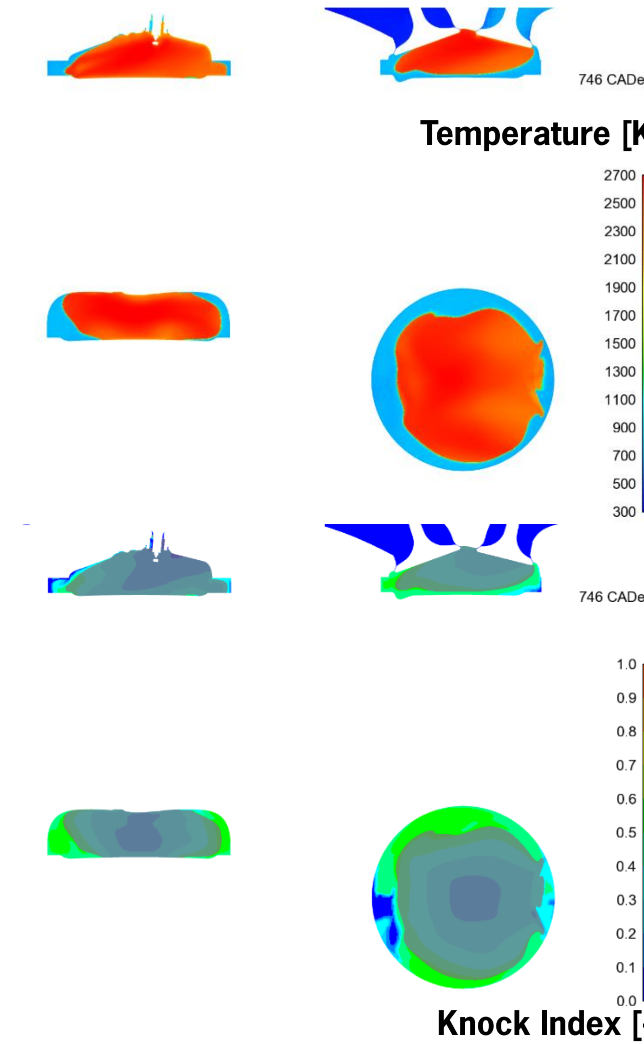
Knock: Spark Advance Variation

Engine speed	Spark Time [CADeg]	Lambda	Position
2200 rpm	705	0.89	Left
	711	0.89	Right

Early Spark Timing



Late Spark Timing



Engine Development

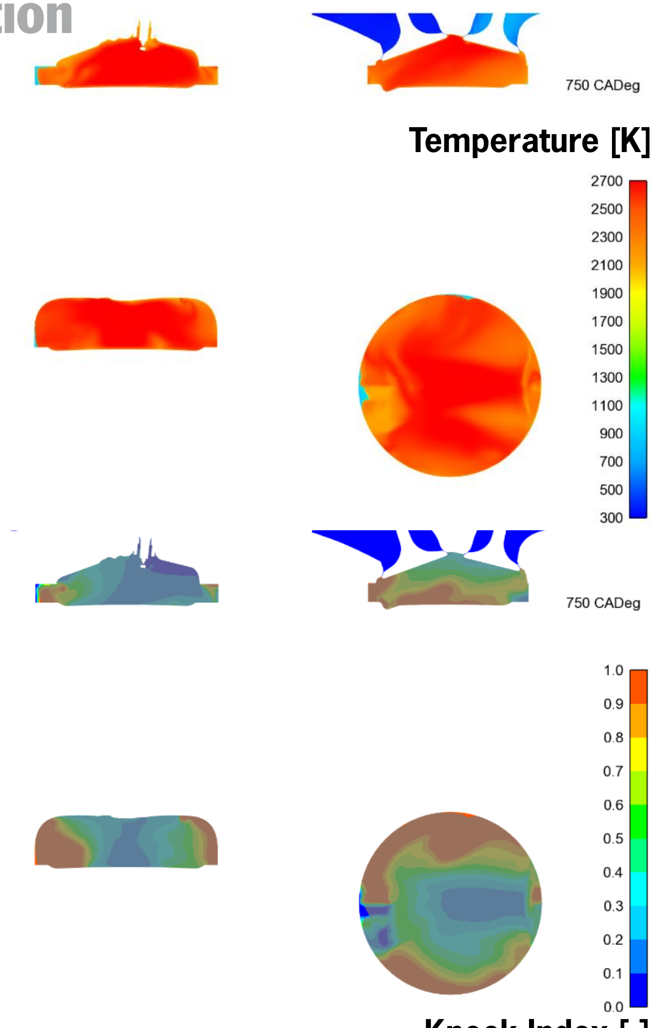
Knock: Spark Advance Variation

Engine speed	Spark Time [CADeg]	Lambda	Position
2200 rpm	705	0.89	Left
	711	0.89	Right

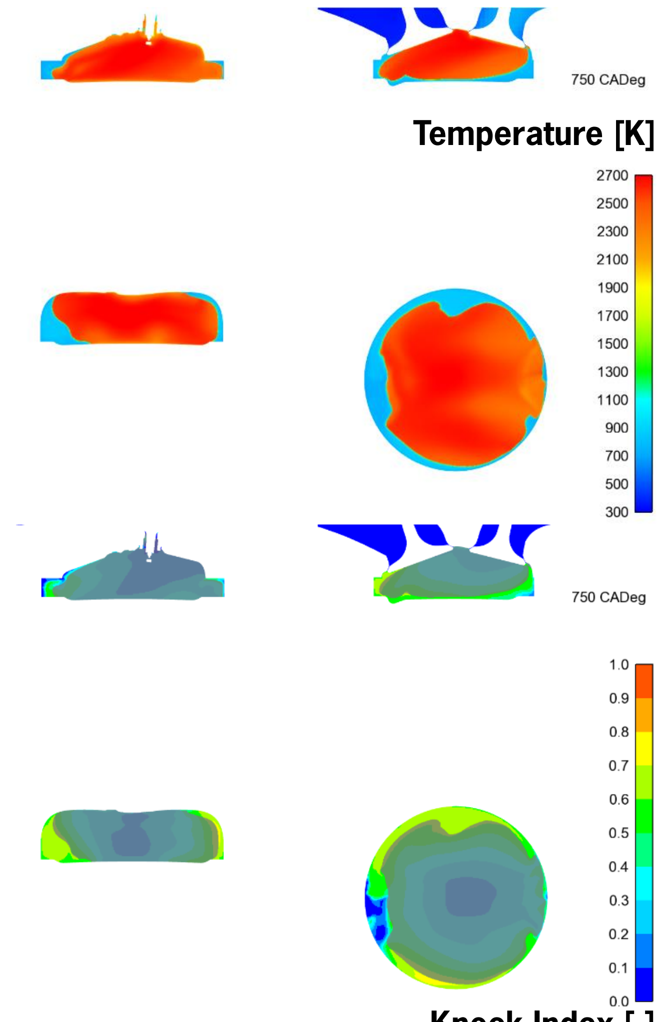
> As expected, at the end of combustion a certain region of the **Combustion Chamber** shows an high level of **Knock Index**

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

Early Spark Timing



Late Spark Timing

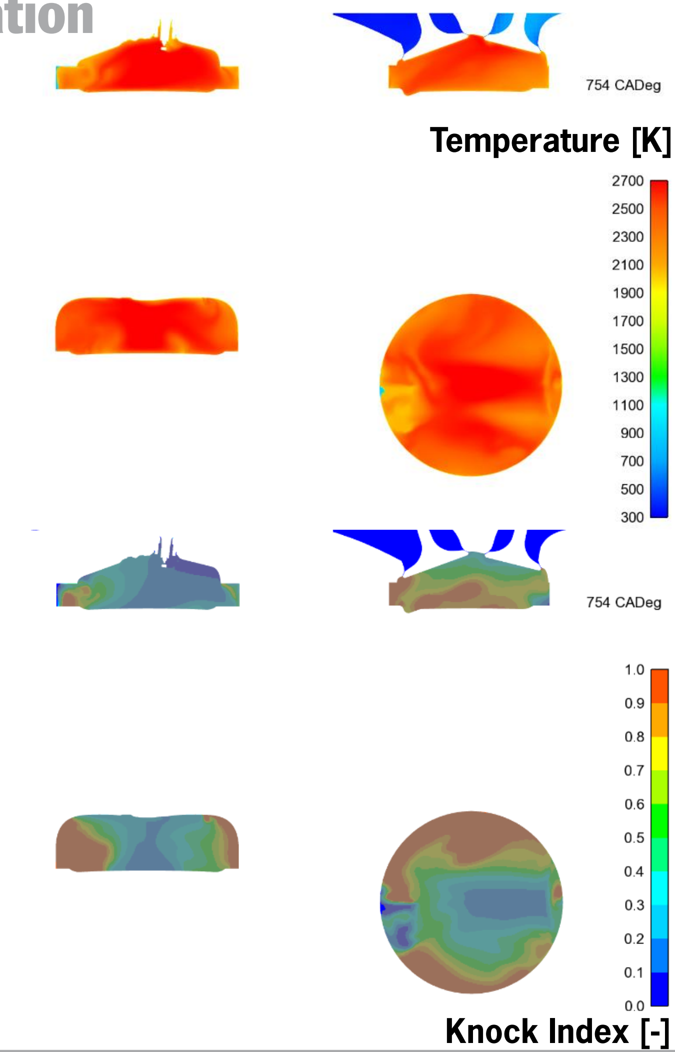


Engine Development

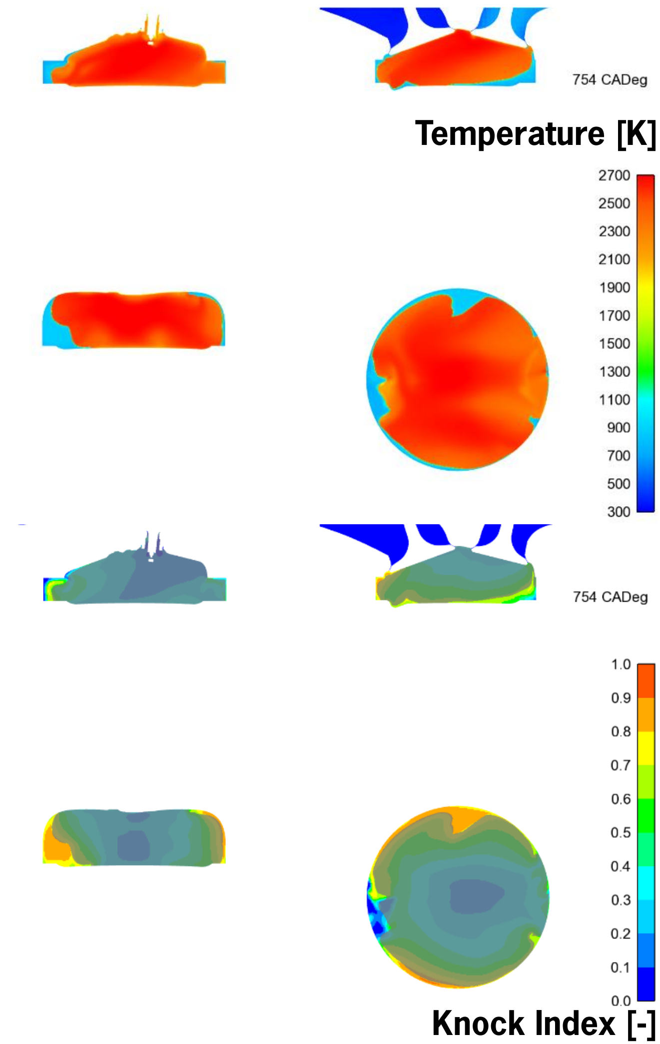
Knock: Spark Advance Variation

Engine speed	Spark Time [CADeg]	Lambda	Position
2200 rpm	705	0.89	Left
	711	0.89	Right

Early Spark Timing



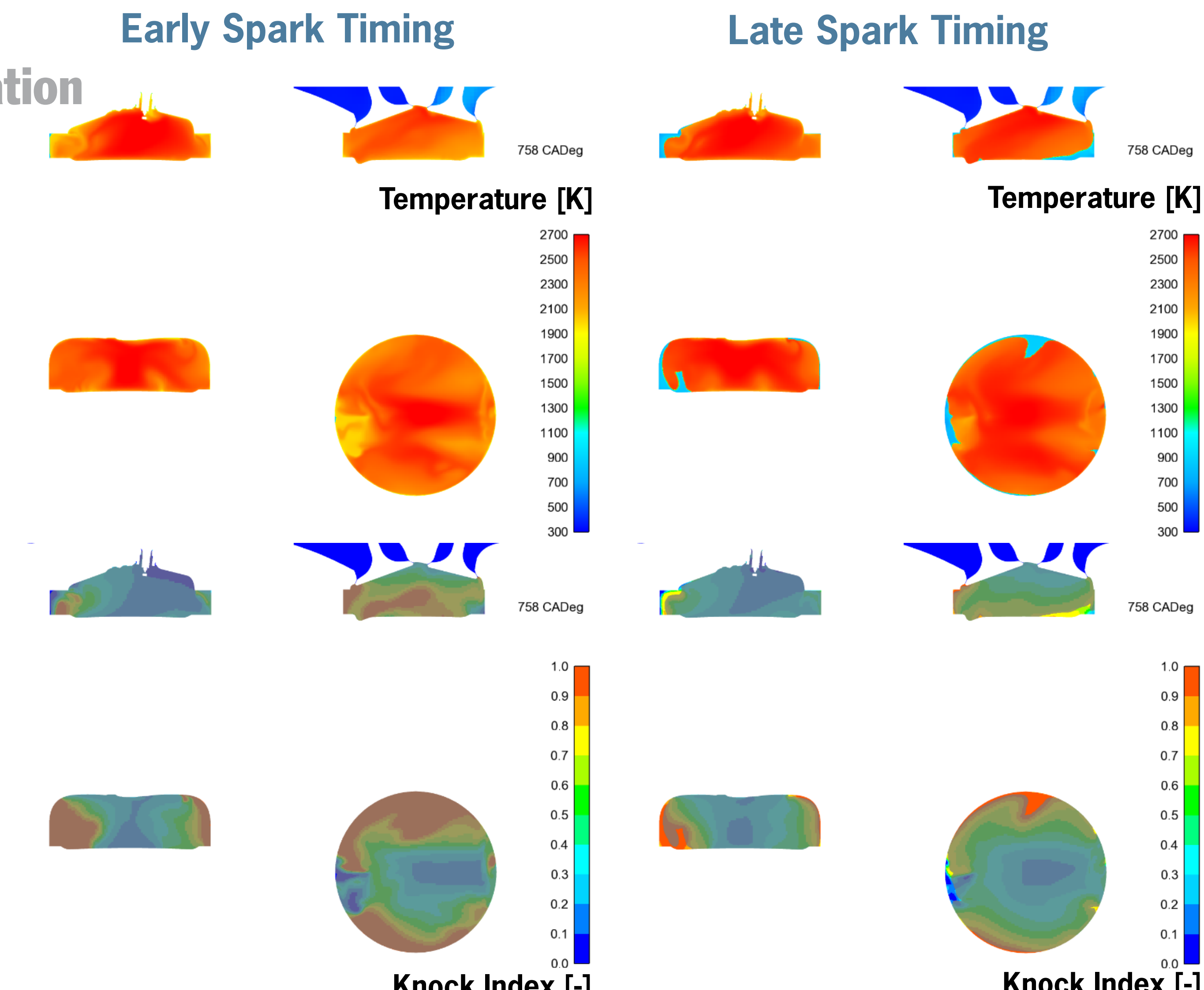
Late Spark Timing



Engine Development

Knock: Spark Advance Variation

Engine speed	Spark Time [CADeg]	Lambda	Position
2200 rpm	705	0.89	Left
	711	0.89	Right

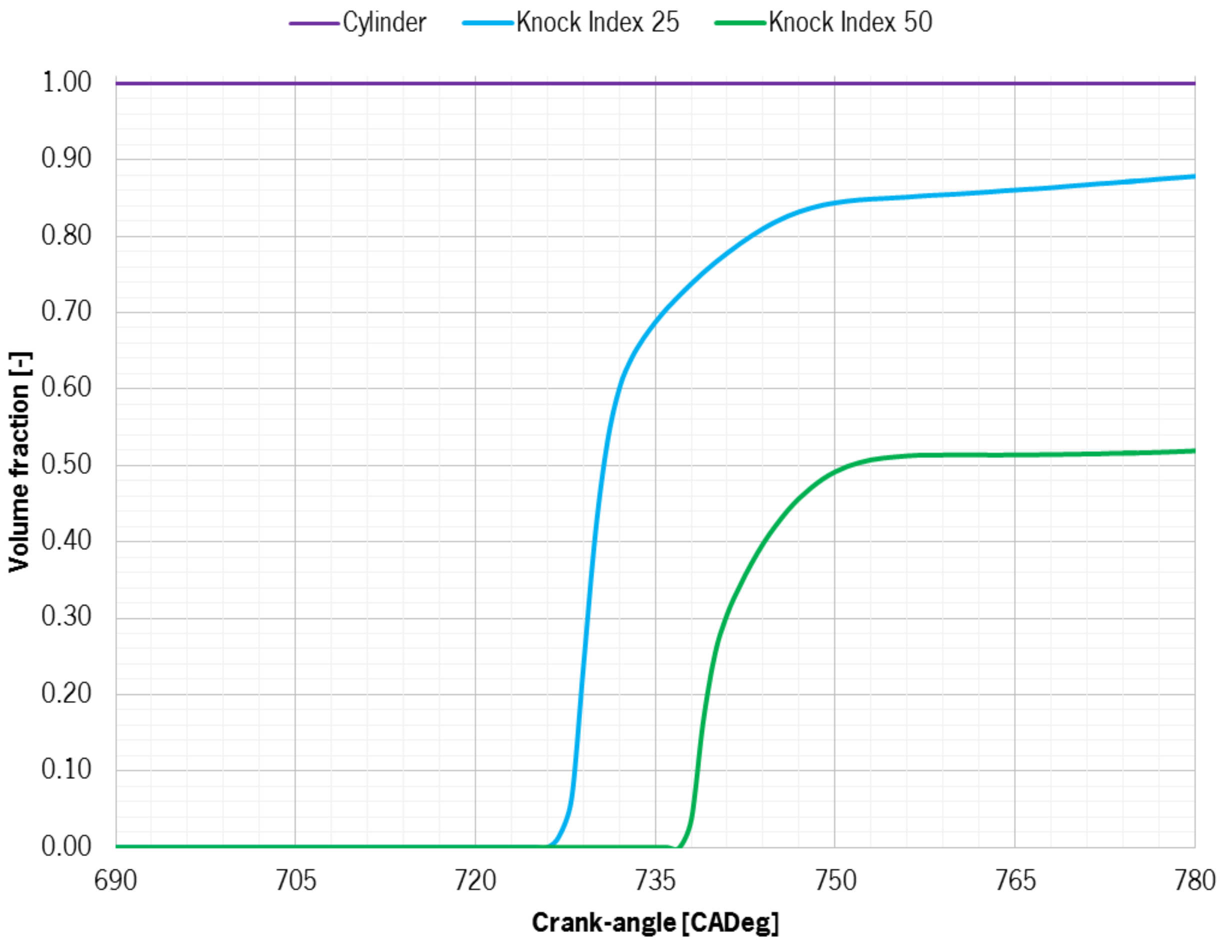


Engine Development

Knock: Spark Advance Variation

Engine speed	Spark Time [CADeg]	Lambda	Line style
2200 rpm			
	708	0.89	

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



Engine Development

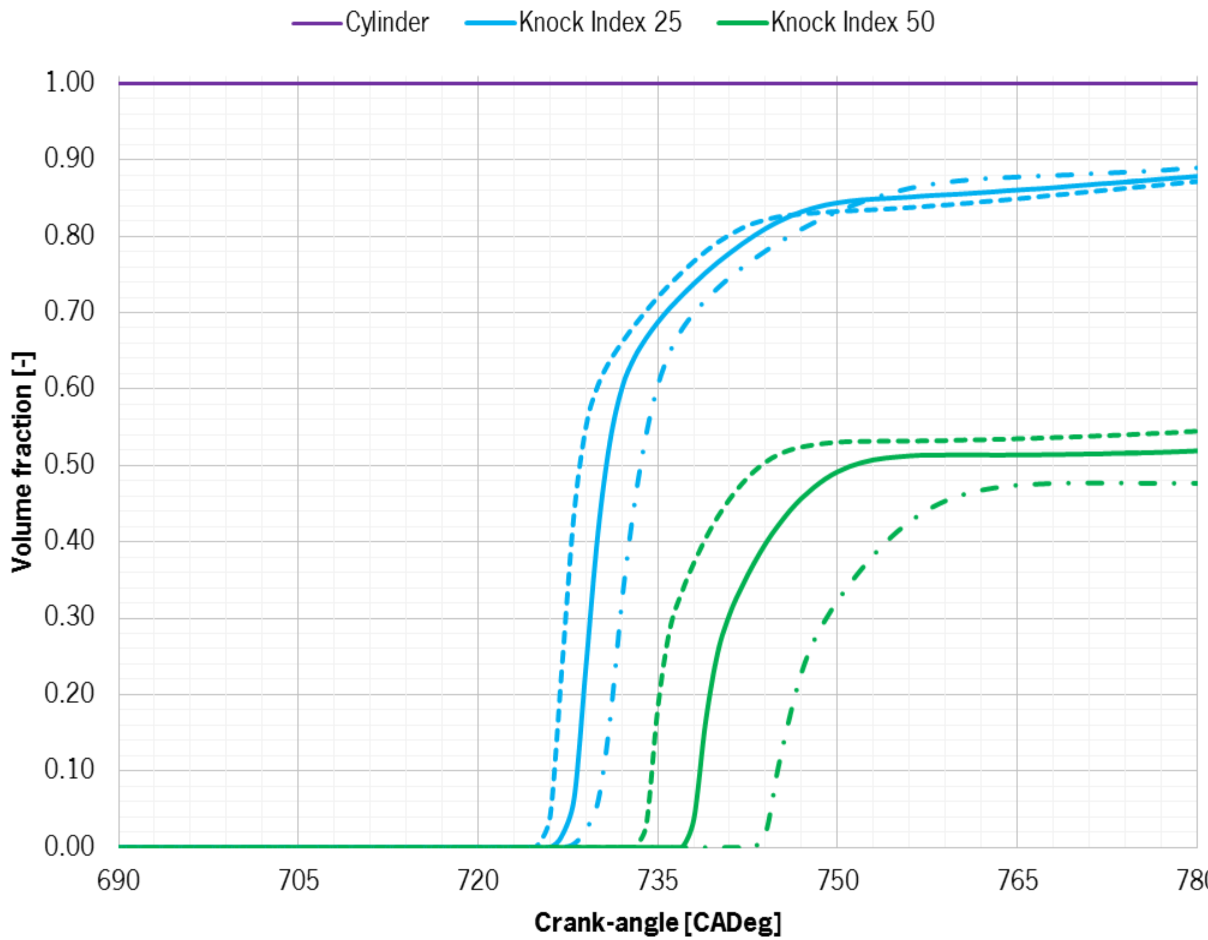
Knock: Spark Advance Variation

Engine speed	Spark Time [CADeg]	Lambda	Line style
2200 rpm	705	0.89	- - - - ·
	708	0.89	——
	711	0.89	– · –

> 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

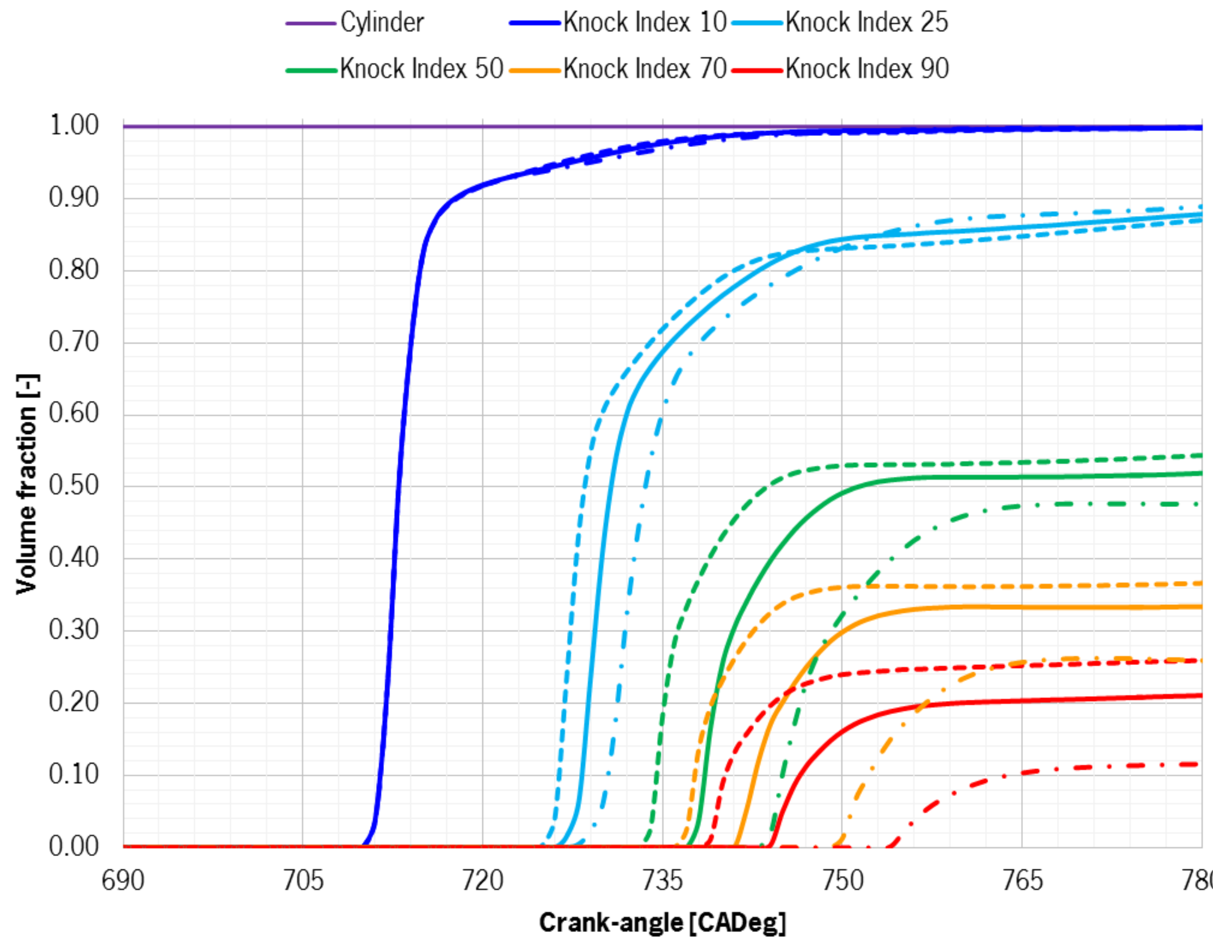
> Higher **Spark Advance**, higher **Knock Tendency**



Engine Development

Knock: Spark Advance Variation

Engine speed	Spark Time [CADeg]	Lambda	Line style
2200 rpm	705	0.89	dashed
	708	0.89	solid
	711	0.89	dash-dot



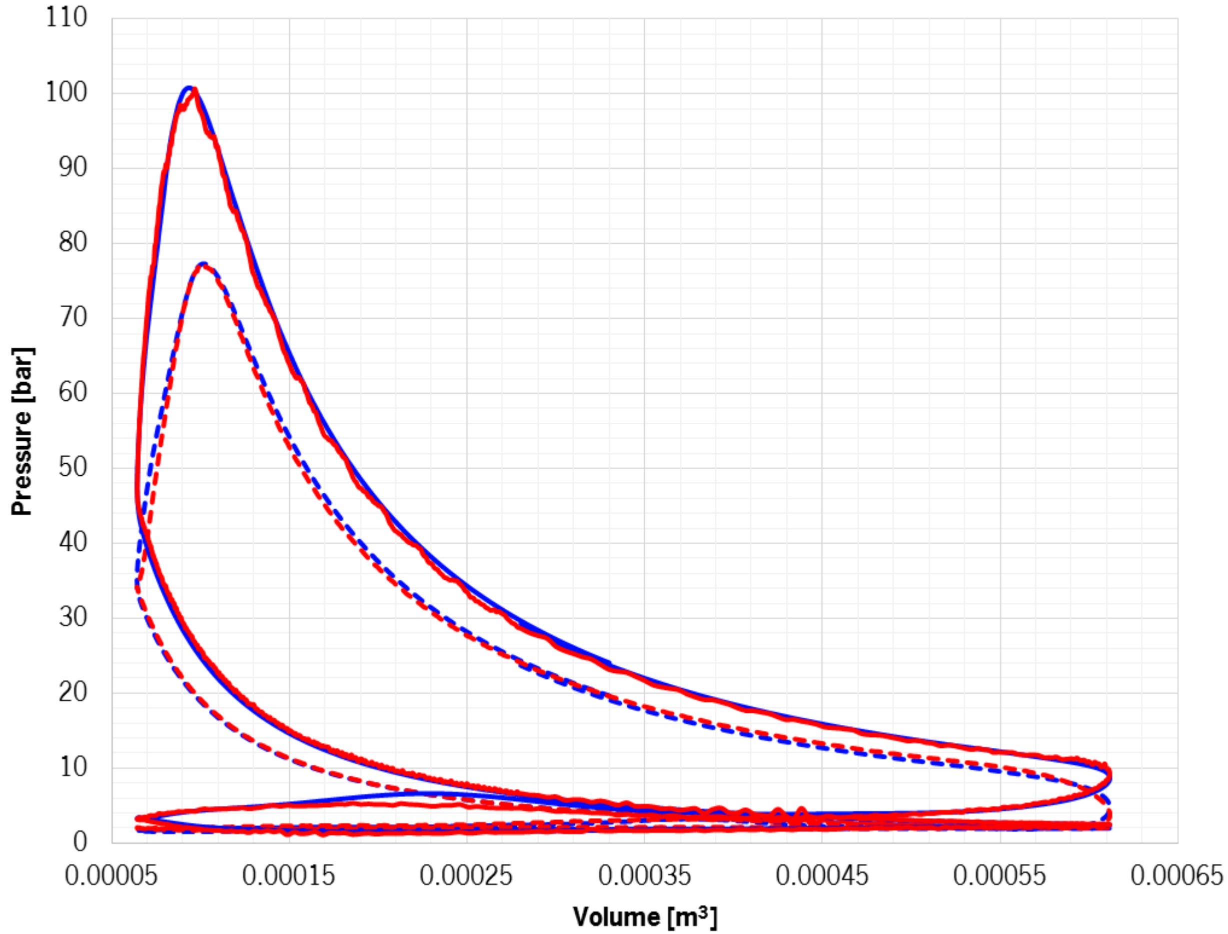
Engine Development

Knock: Comparison with measurements

Engine speed	Spark Time [CADeg]	Source	Line style
2200 rpm	708	Simulat.	blue dashed
	715	Measur.	red dashed
4800 rpm	705	Simulat.	blue solid
	705	Measur.	red solid

> **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

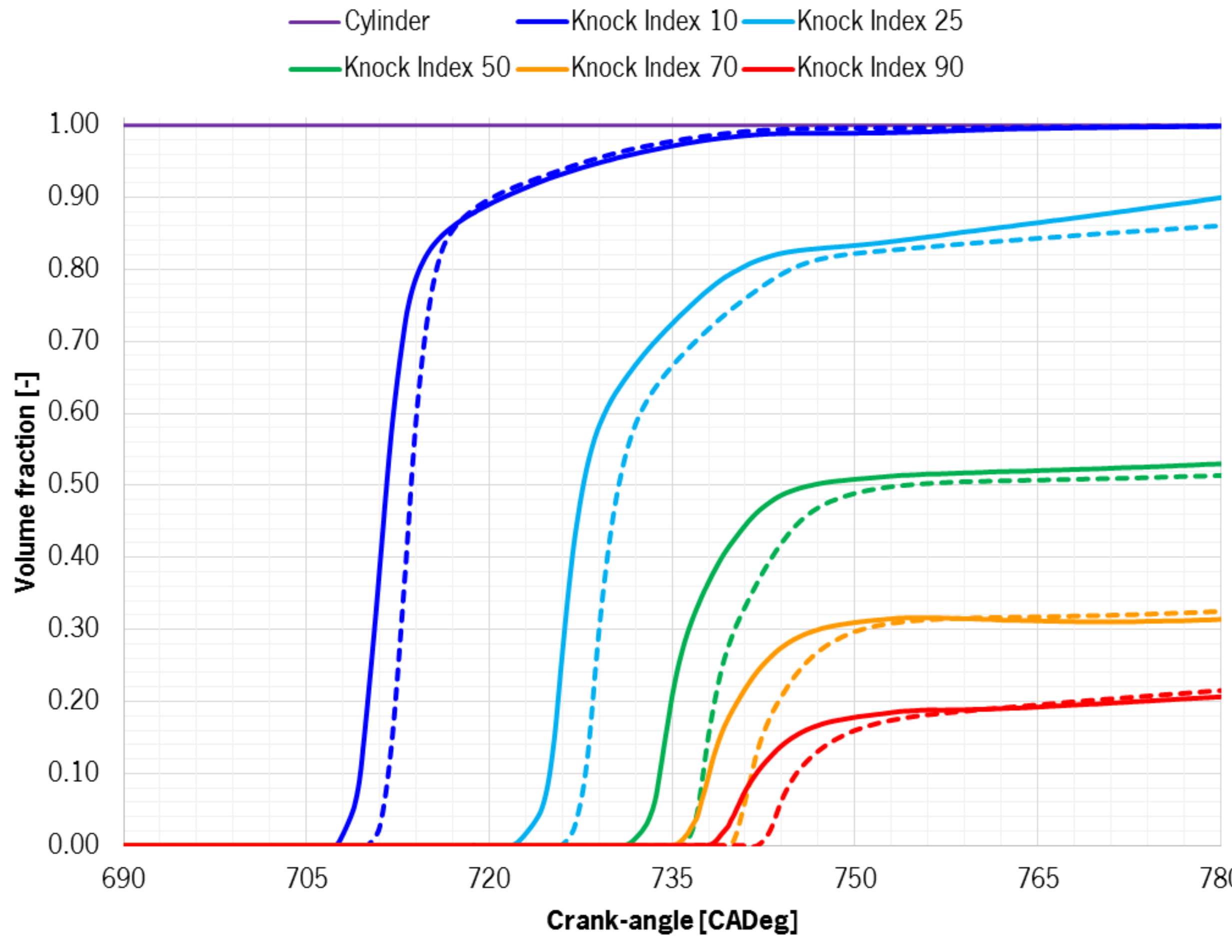
Knock: Comparison Low-end torque and Peak power

Engine speed	Spark Time [CADeg]	Source	Line style
2200	708	Simulat.	———
4800	705	Simulat.	·········

> 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)

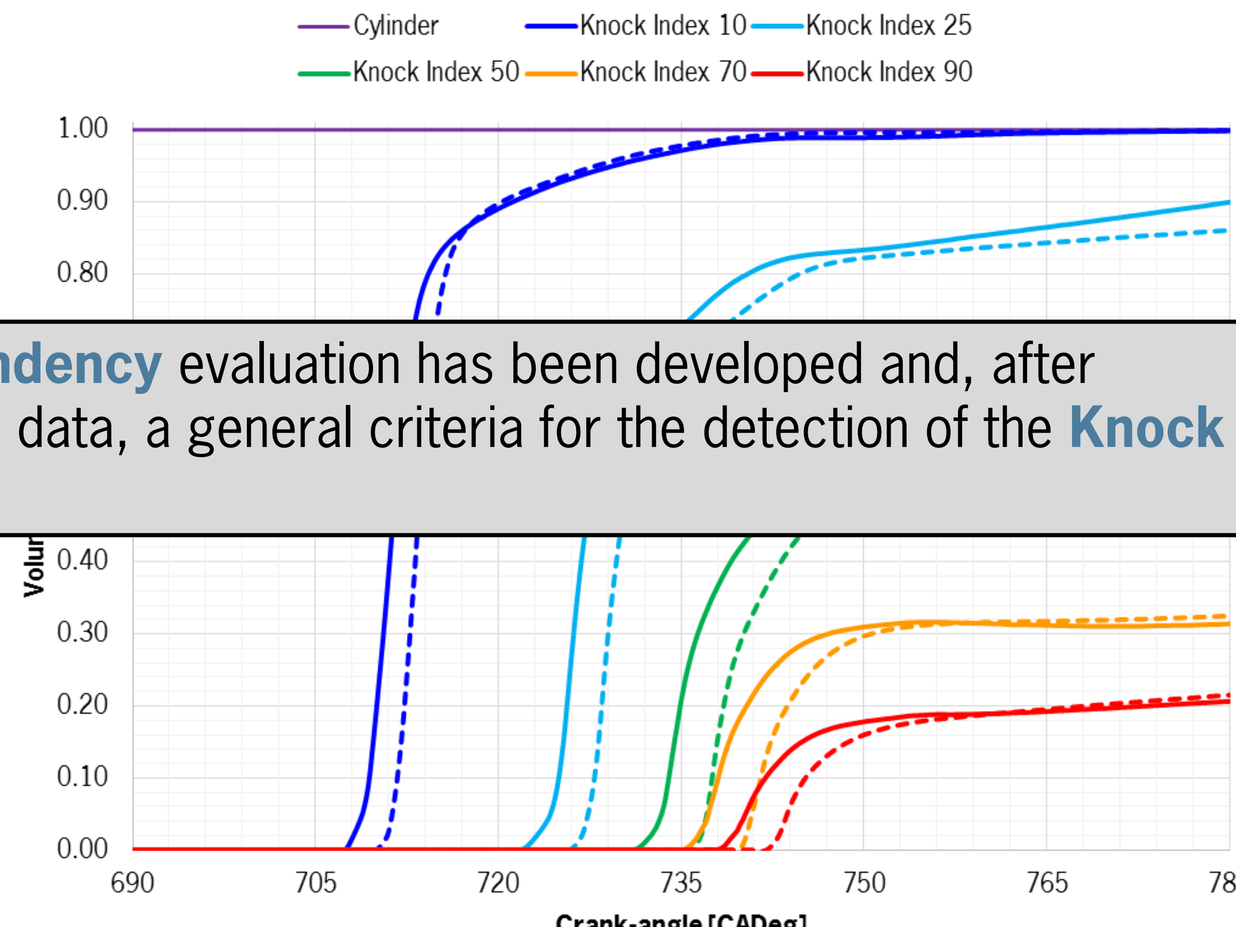


Engine Development

Knock: Comparison Low-end torque and Peak power

Engine speed	Spark Time [CADeg]	Source	Line style
2200	708	Simulat.	———
4800	705	Simulat.	·········

> The Knock Tendency of **two**



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.

	Gasoline	CNG
C/H	~ 0.44	~0.25
Octane number	95 - 98	120 - 130
CO	100%	25%
HC	100%	40%
CO_2	100%	75% - 80%
PM	100%	Potentially free

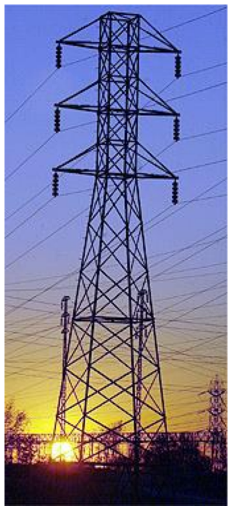
Source:Bernd Kircher, Christof Schernus,"Integrated simulation and Tuning of CNG Engine Fuel Rail and Intake Air Manifold", FEV Motorentechnik GmbH, 2004

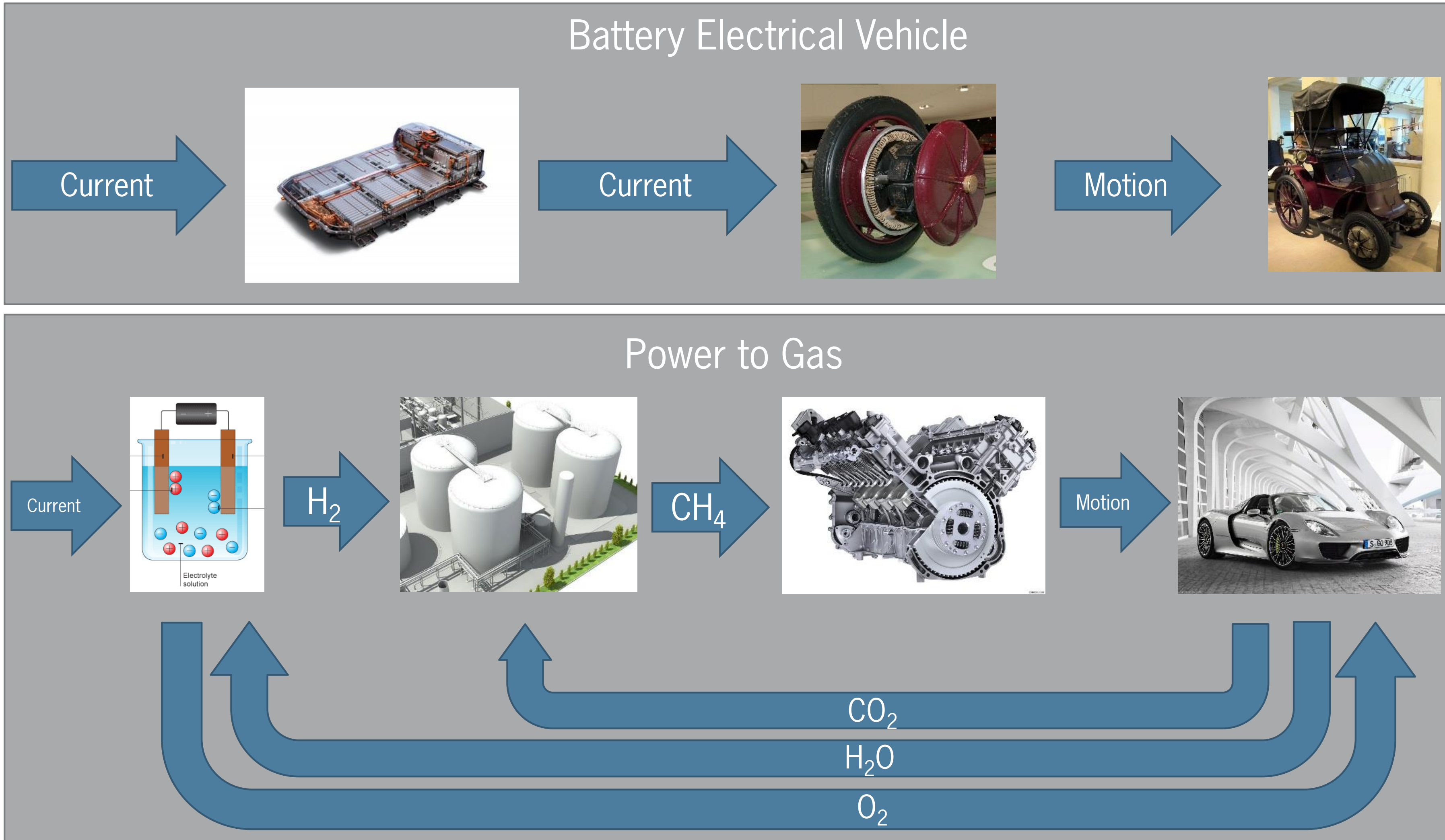
- Reduced oil dilution
- Improved knock resistance
- Less expensive than gasoline
- Available distribution net
- **CNG is a practical option for ICEs**

- 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





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

Engine Development

CNG: Development Challenges

> 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

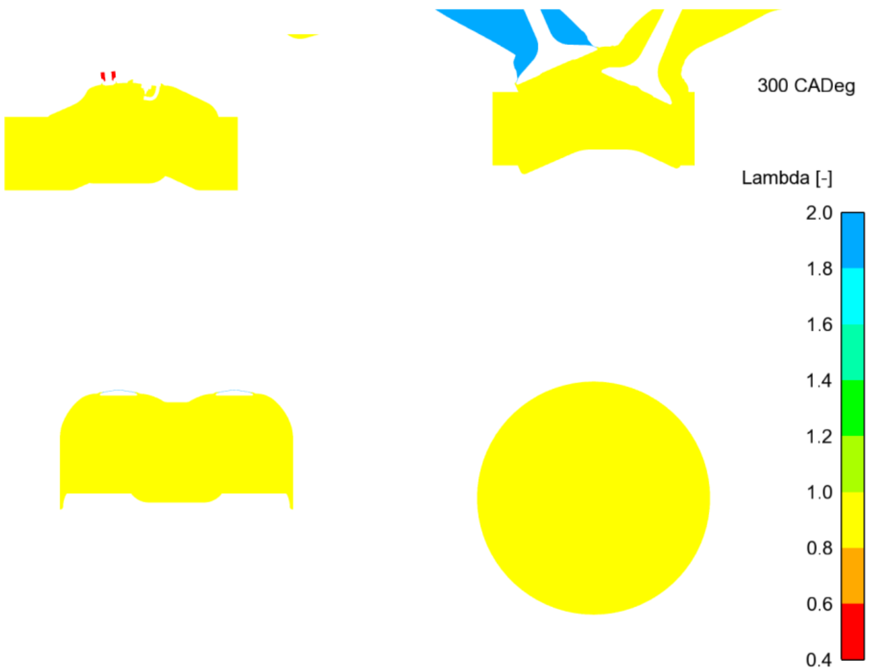
> **Reduced Cooling Effect**
- Exhaust System Material
- Integrated Exhaust Manifold
- Water Injection

> **Vol. Efficiency Penalty**
- Direct Injection
  - > Mixture Preparation
  - > **CFD Analysis**

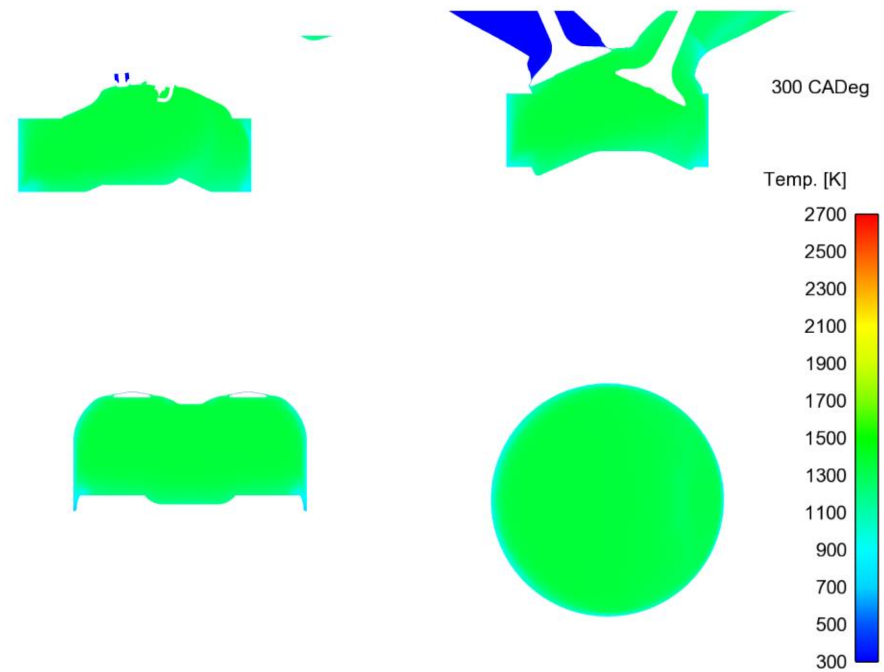
Engine Development

CNG: Mixture Preparation and Combustion

Lambda



Temperature



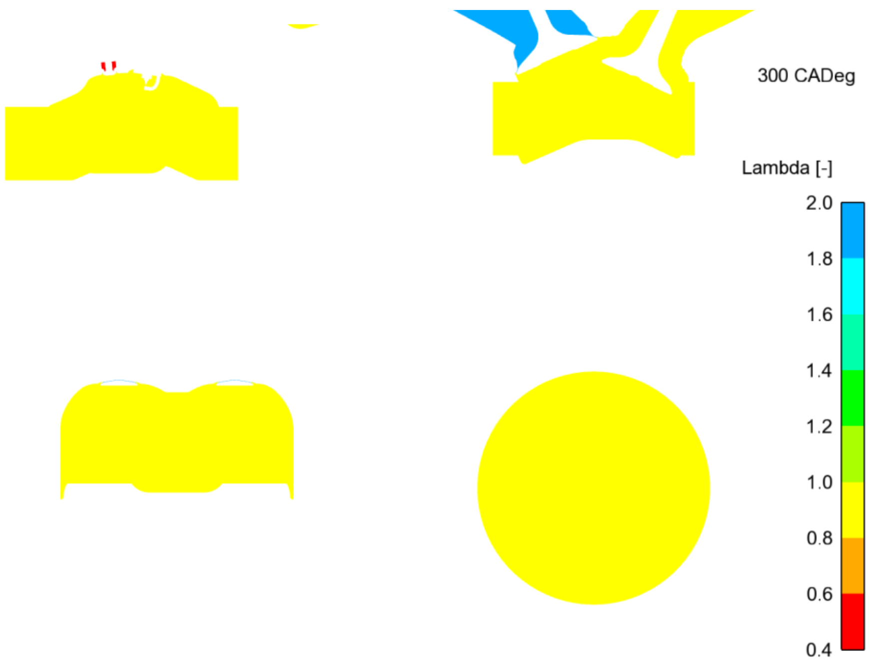
> **Backflow** in den Intake Ports

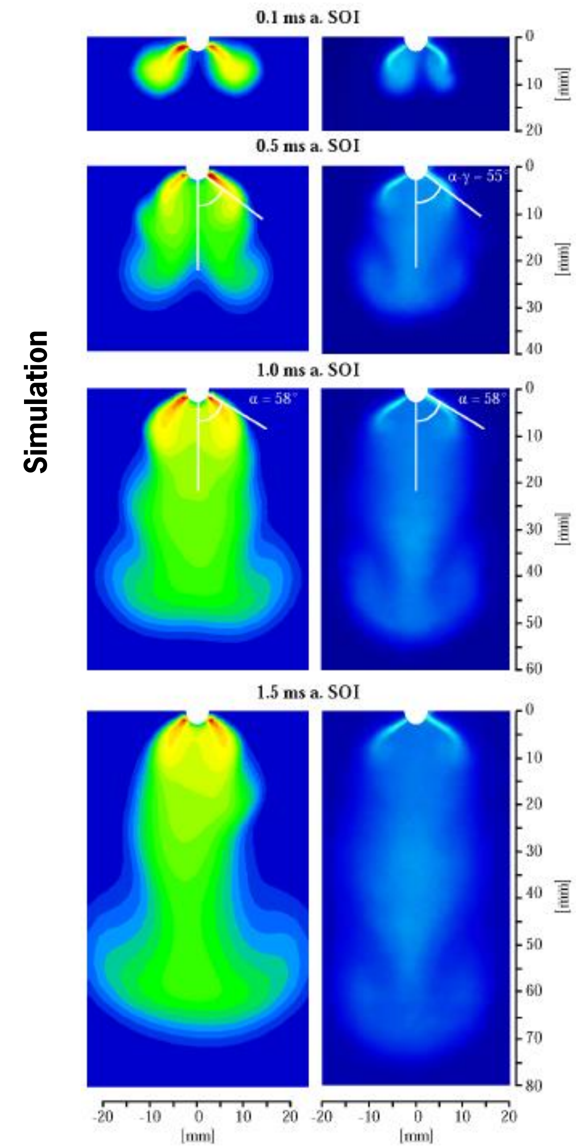
> **Rich Mixture** under the **Intake Port** and between the **Exhaust Port. Lean** under **Spark Plug**

Engine Development

CNG: Mixture Preparation

Lambda





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

- Good Correlation between **Simulation Result** and **Injector Test Bench** (literature reference)

Engine Development

CNG: Mixture Preparation

Lambda

SAE Paper:

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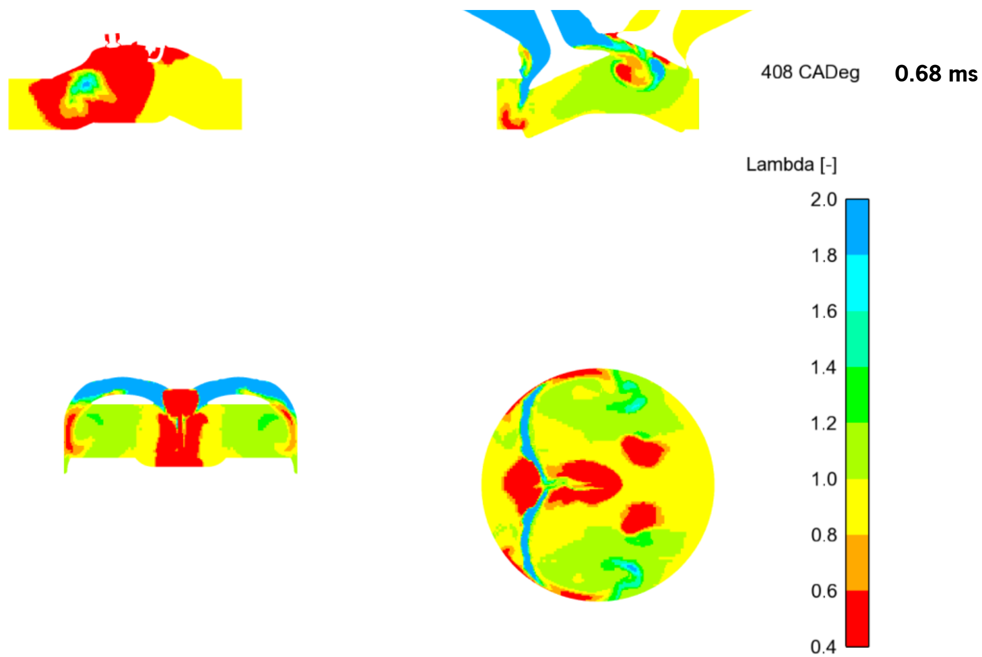
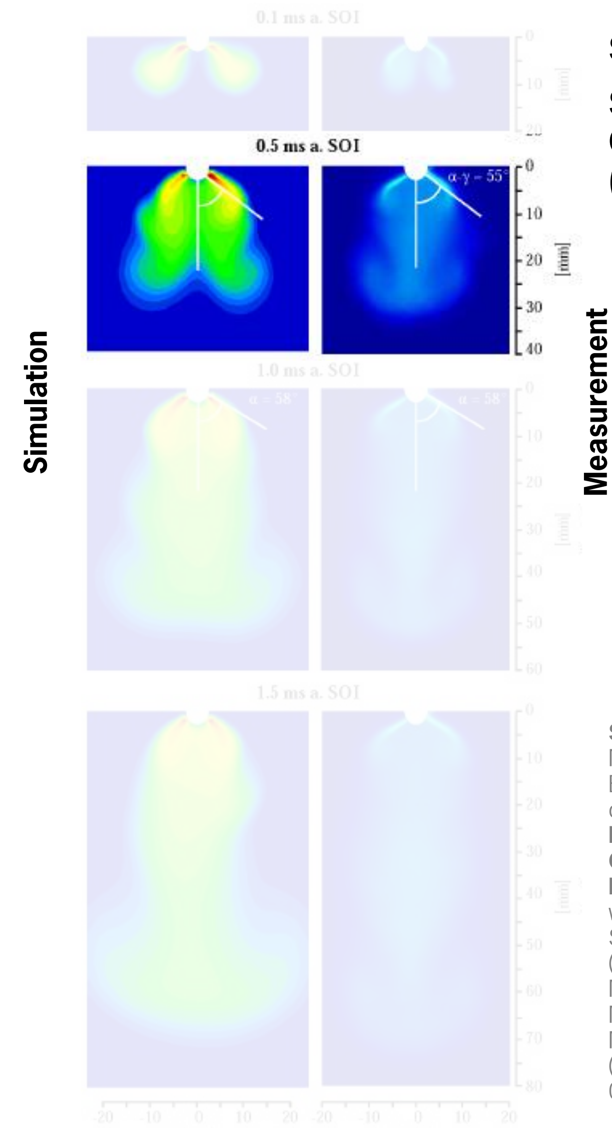
> Good Correlation at **Start of Injection**

Engine Development

CNG: Mixture Preparation

Lambda





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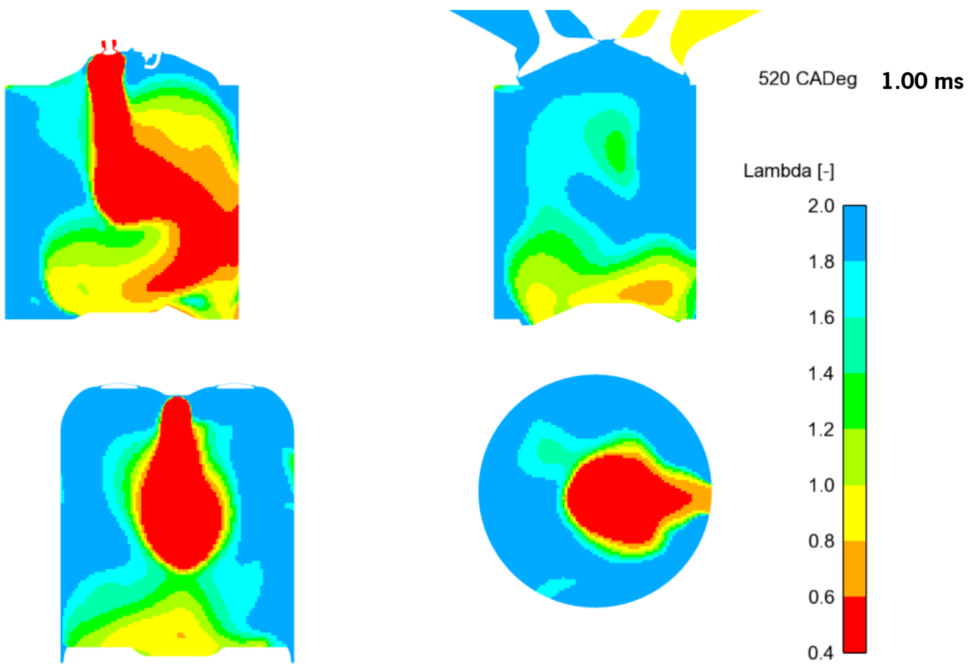
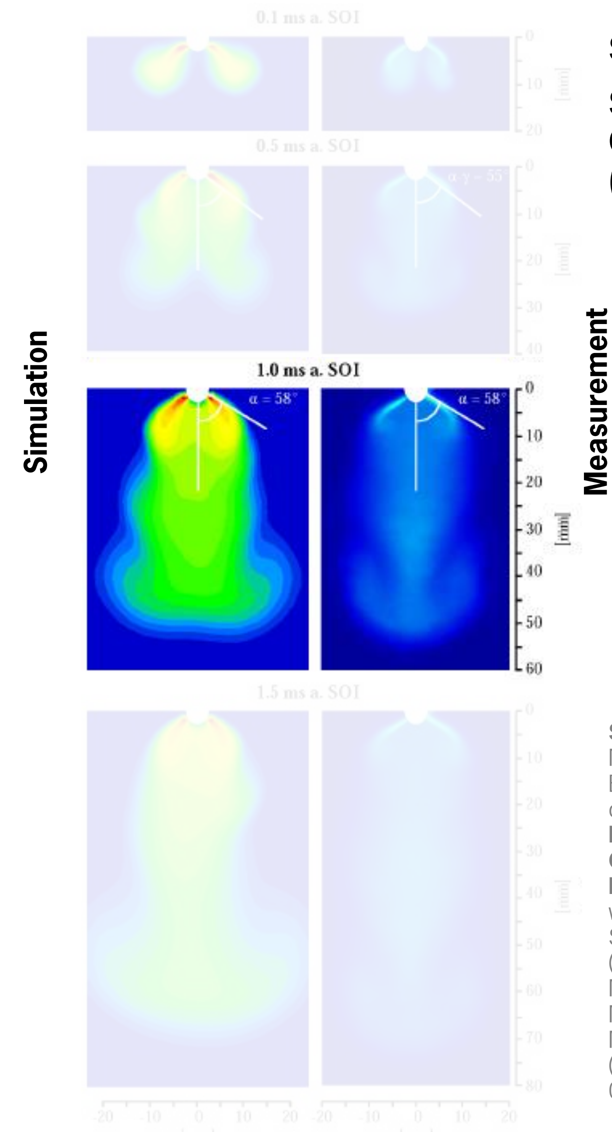
- Good Correlation at **408° CADeg**
- Significant Influence of the **Intake Air Flow** on the CNG Injection

Engine Development

CNG: Mixture Preparation

Lambda





SAE Paper:

Stationary CNG injection (110bar)

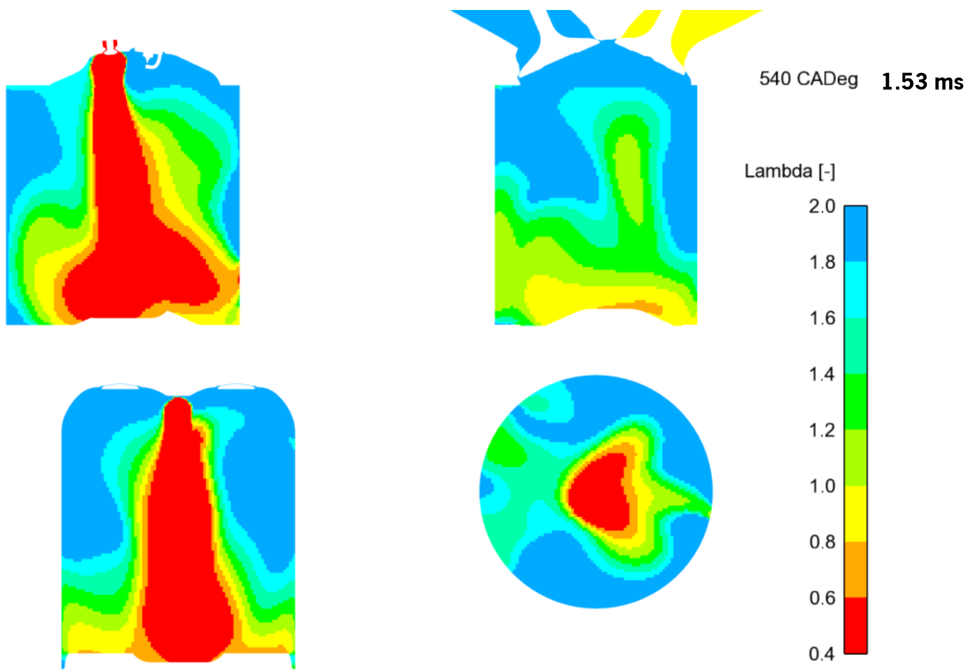
SAE 2016-01-0801: Numerical and Experimental Studies on **Mixture Formation** with an **Outward-Opening Nozzle** in a SI Engine with **CNG-DI** (Dimitri Seboldt, David Lejsek (Robert Bosch GmbH); Marlene Wentsch, Marco Chiodi (**FKFS**); Michael **Bargende** (Universitat Stuttgart)), 04/05/2016

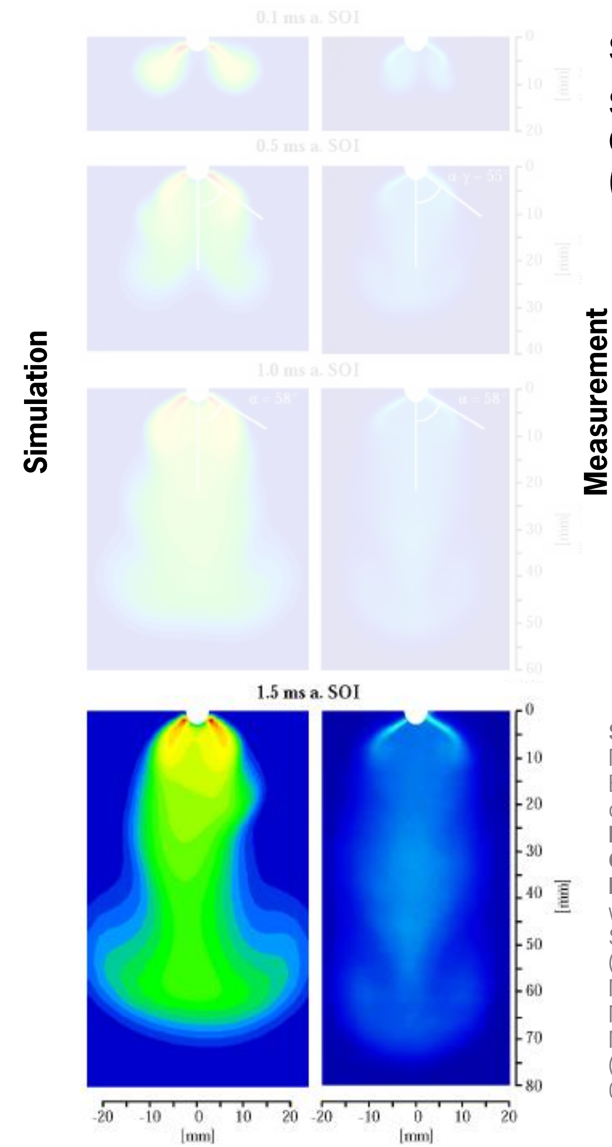
> Good Correlation at **Intake Valve Closing**

Engine Development

CNG: Mixture Preparation and Combustion

Lambda





SAE Paper:

Stationary CNG injection (110bar)

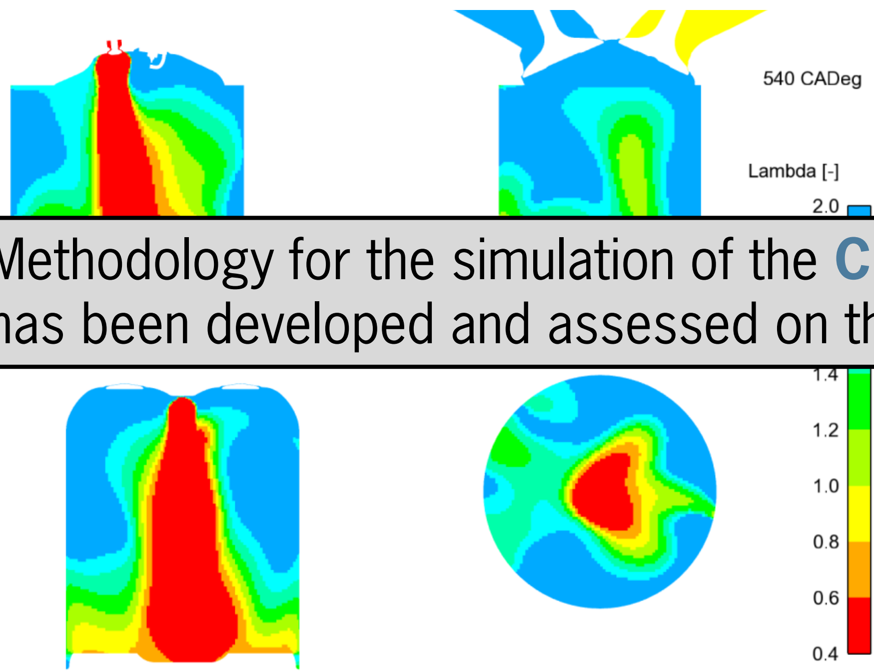
> Very good correlation at **BDC**

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

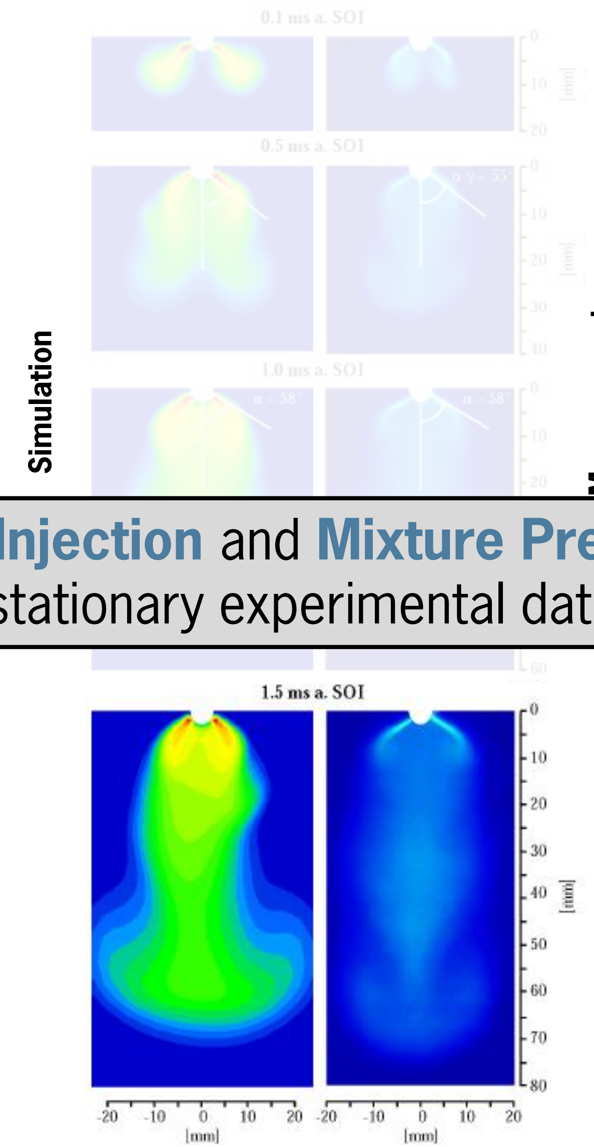
CNG: Mixture Preparation and Combustion

Lambda



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**



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

Conclusion

> ## Global Warming

– **Anthropogenic** CO_2 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 CO_2 Reduction depending of **Grid Footprint**, and higher for **Luxury cars**

– **Production cost** competitive starting from 2030-2035

> ## ICE Optimization

– Necessary to reduce **CO_2 Penalty**

– High Potential in Knock Control: **CFD Methodology**

> ## Alternative Fuel

– **CNG** offer Potential for CO_2 Reduction as **fossil fuel** and even more as **synthetic fuel**

– Challenges at **vehicle** and **engine level**

– **CFD Methodology** necessary to optimize **mixture preparation**

PORSCHE

Thanks for your attention!

Porsche Engineering
driving technologies