# Gas-Only Internal Combustion Engines

**Project number 652816**

***H2020 GV-3-2014 Future natural gas powertrains and components for cars and vans***

# Work Package - WP2
# Stoichiometric & high structural integrity small TC VVA DI engine

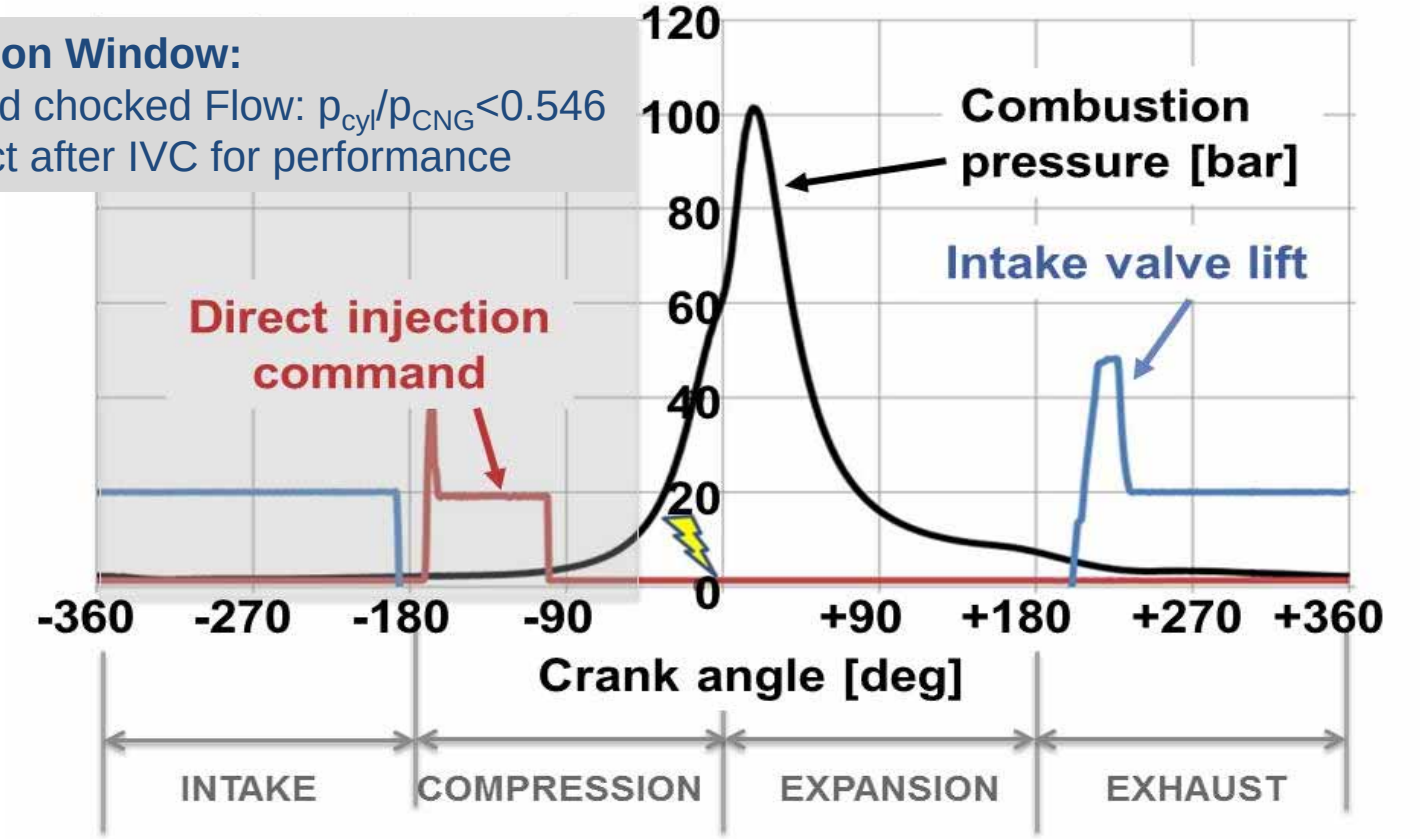
# *WP2 Objectives*

- *Exploit side direct gaseous injection benefits for CO2 reduction potential and performance improvement*
- *Match in the best way direct gaseous injection, boosting & fully flexible variable valve technologies*
- *Guarantee high structural integrity to manage high peak of combustion pressure*
- *Demonstrate vehicle range improvement*

## CNG Direct Injection - Strategy

CNG direct injection strategy coupled with Early Intake Valve Closure (EIVC) removes the volumetric efficiency issue of gaseous fuels

**Injection Window:**
- Avoid chocked Flow: $p_{cyl}/p_{CNG}<0.546$
- Inject after IVC for performance



# Main tasks

CNG DI injection system development and prototyping
(AVL, CRF, DELPHI Technologies)

Mixing process investigation via optical engine
(AVL, CRF, DELPHI Technologies, POLITO)

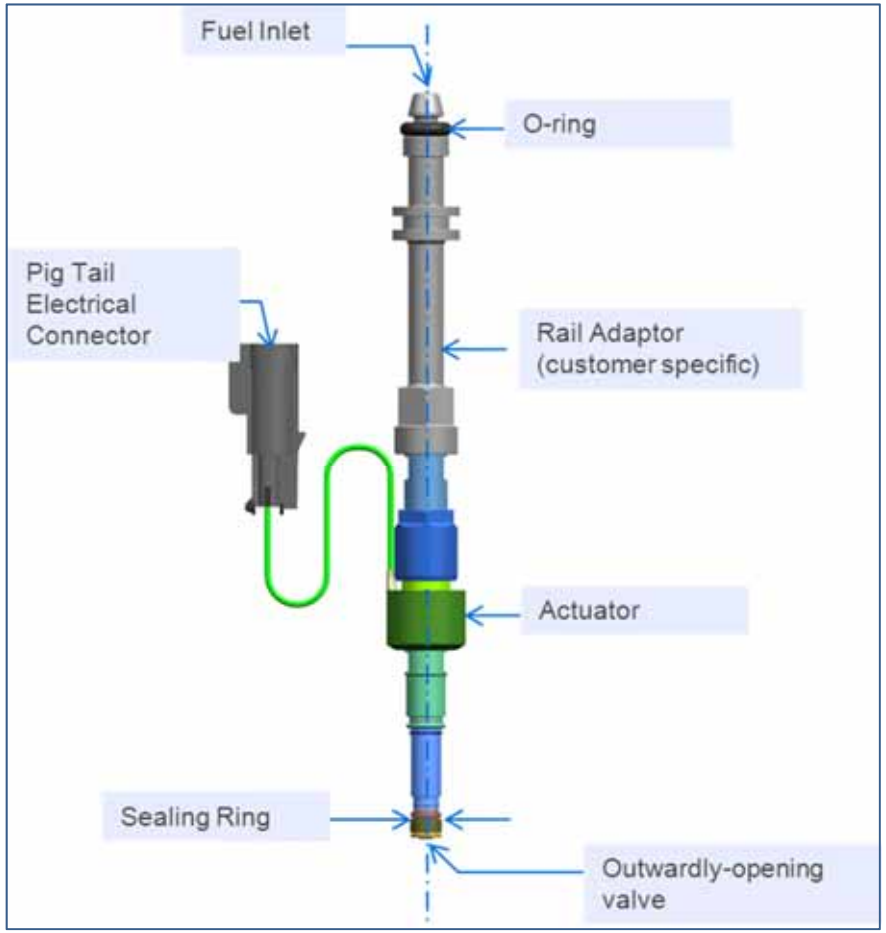
Combustion system development via multi cylinder engine
(AVL, CRF, POLITO)

Design, prototyping, development of multi cylinder engine matching DI injection, boosting and VVA
(CRF)

Multi cylinder engine tuning at dyno optimizing performance and fuel economy
(CRF)

Design storage system, engine & subsystems installation on demo vehicle, refinement & full assessment
(AVL, CRF, DELPHI Technologies)

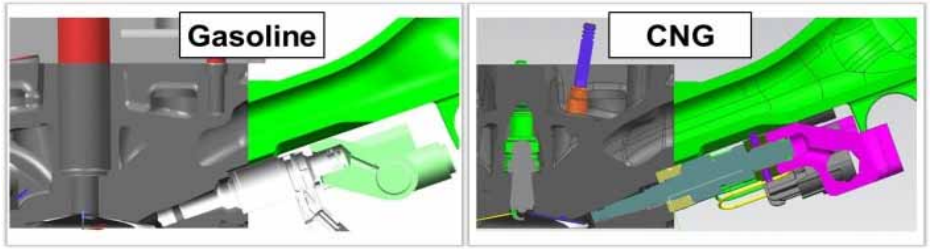
## CNG Direct Injection system development – Delphi Technologies




| Feature | Delphi prototype | Metric |
|---|---|---|
| Operating pressure | 8÷16 | bar |
| Static flow rate | 6.7 (*) @ 16bar | g/s |
| Electric command | peak & hold | - |

(*) Reference fuel: 100% $CH_4$

To execute the injection after IVC a high flow rate / low pressure CNG direct injector was selected based an outward opening valve concept controlled by a peak & hold command

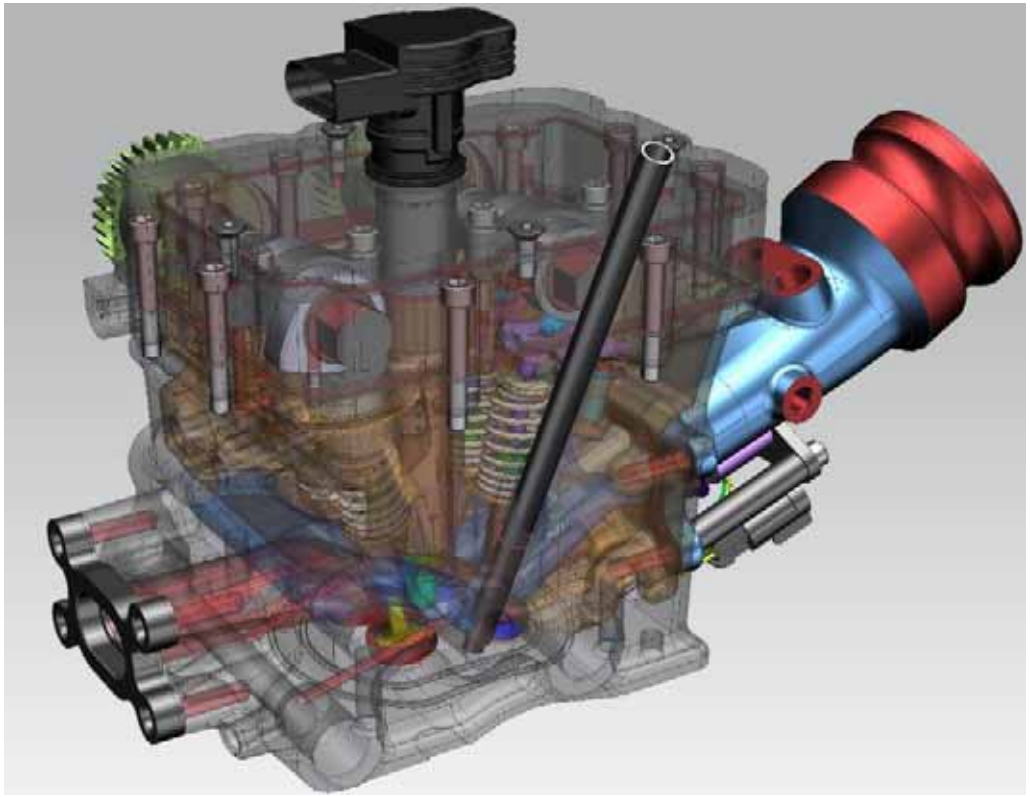



Modern spark ignited engines are equipped with direct fuel injection rather than port fuel.
Exploiting the existing gasoline layout a CNG direct injection system can be easily implemented.

## Mixing process investigation with transparent engine – AVL

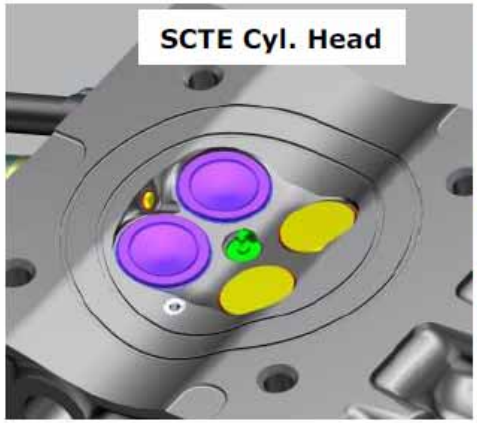
- Single cylinder head design for transparent engine (TE) investigation

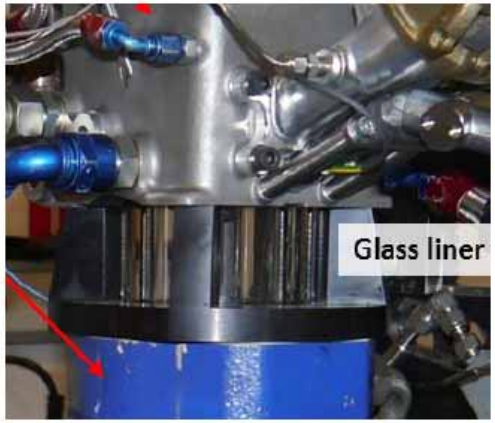
- Ports, combustion chamber design, piston surface, valves and valve angle are carry over from Multi Cylinder Engine
- Design of head with cooling system and oil supply, valvetrain, cam-carrier, intake and exhaust system are specially designed for TE
- Design of glass components for optical access to combustion chamber



## Mixing process investigation with transparent engine – AVL

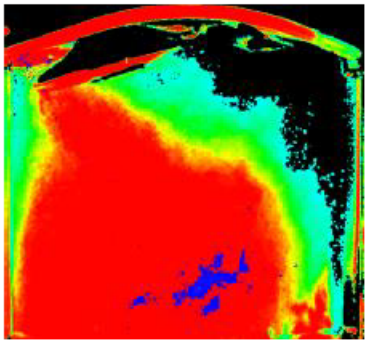
- Single Cylinder Transparent Engine (SCTE) – Specific Parts





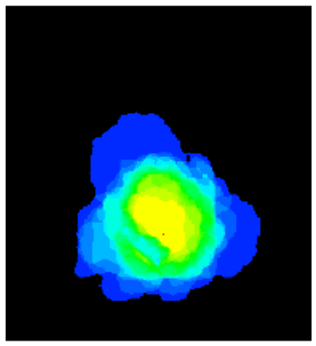

- Single Cylinder Transparent Engine (SCTE) – Measurement Methods



Fuel LIF (Mixture Formation)

Fuel probability [%]

100
High fuel density
1
100
Low fuel density
0



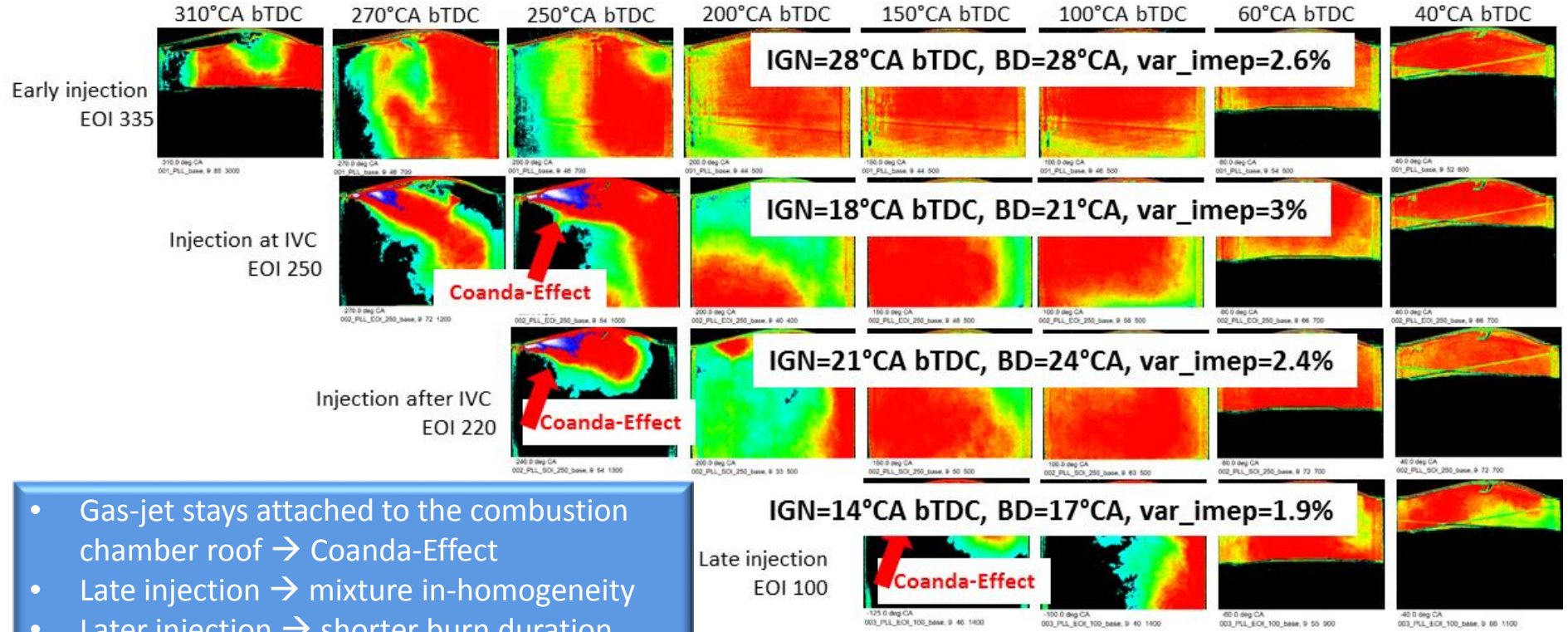
HSP (Combustion)

Flame probability [%]

100
High light intensity
1
100
Low light intensity
0

## Mixing process investigation with transparent engine – AVL

- TE Measurement Result – Summary Low Part Load (2000/4bar)

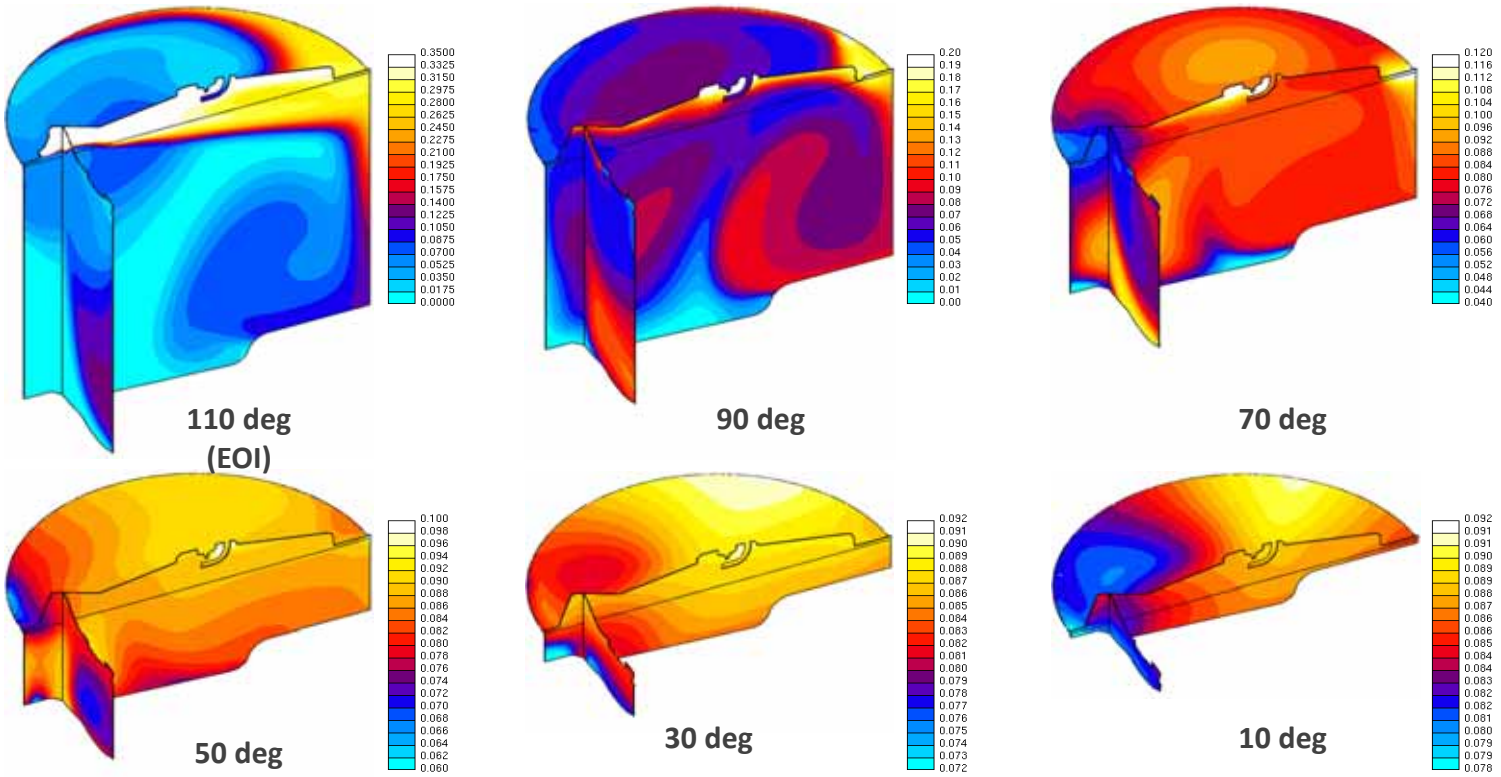



- Gas-jet stays attached to the combustion chamber roof → Coanda-Effect
- Late injection → mixture in-homogeneity
- Later injection → shorter burn duration (turbulence from gas jet)

## Mixing process investigation with transparent engine – Polito

**Examples of simulation results** (CH4 concentration)

**crank angle before combustion TDC**



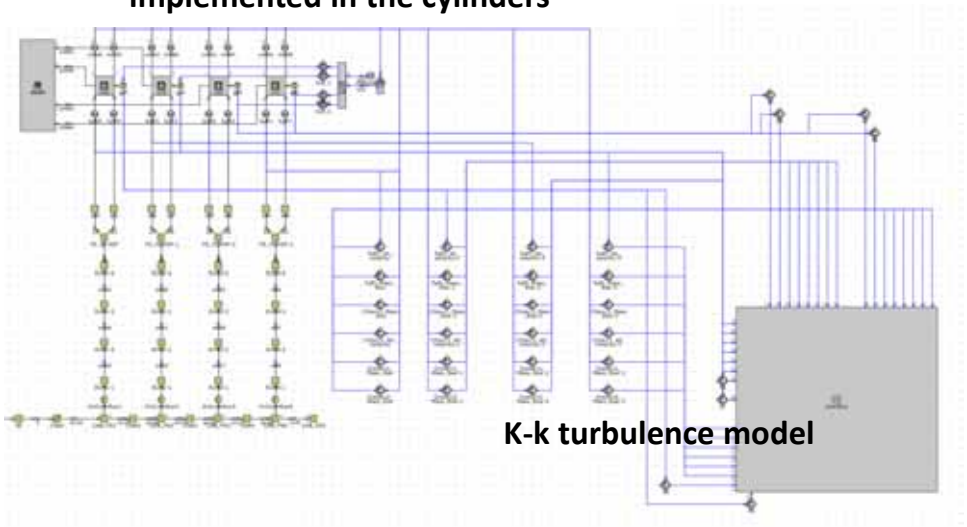

Optical engine analysis & CFD model prediction are confirmed by engine testing:

- air gas mixing improving (early EOI) is mandatory for BSFC reduction.
- turbulence increase (late EOI) is non sufficient to change this tendency

## Combustion system development via multi cylinder engine - Polito

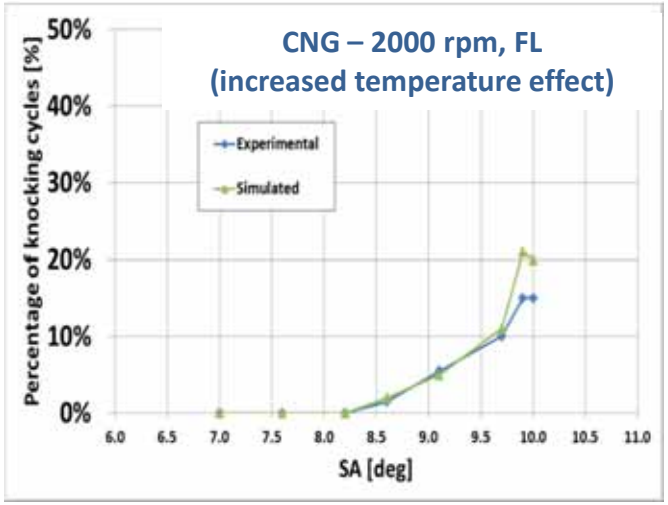
**Knock model development, calibration and final extended validation**

**Fractal predictive combustion model implemented in the cylinders**



**K-k turbulence model**

**Knock model results**



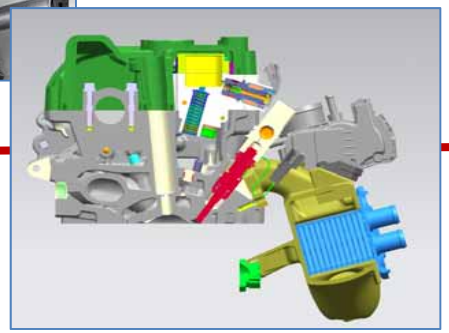
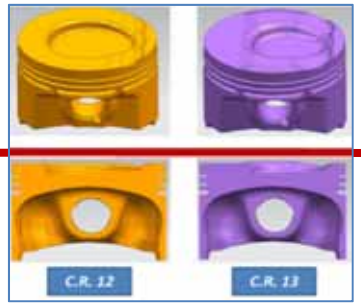
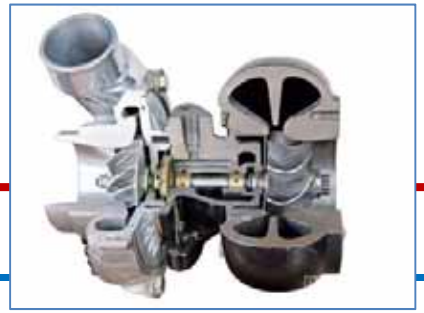

Knocking model prediction is confirmed by engine testing

## CNG Direct Injection demo engine - CRF

The engine selected for the investigation was a 1.0 liter turbocharged always fueled with a 100% CH4 (Low Heat Value 50 MJ/kg)

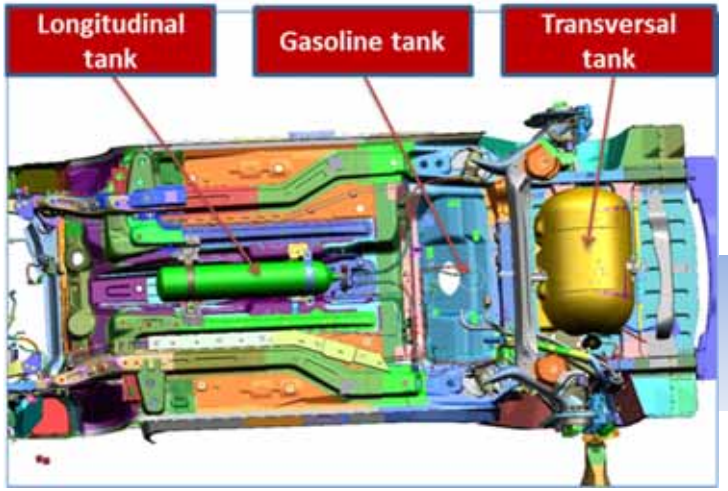
| Feature | | Metric |
|---|---|---|
| **Displacement** | 999 | $cm^3$ |
| **Cylinders** | 3 | - |
| **Bore** | 72 | mm |
| **Stroke** | 84 | mm |
| **Compression Ratio** | 13:1 | - |
| **Rated power** | 88 | kW |
| **at engine speed** | 5500 | rpm |
| **Rated torque** | 190 | Nm |
| **at engine speed** | 1750 - 3500 | rpm |
| **Air management** | Variable valve actuation | |
| **Boosting** | Turbocharger w/ waste gate | |

## Design, prototyping, development of multi cylinder engine matching DI injection, boosting and VVA – CRF/Delphi Technologies

| Device | | Benefit |
|---|---|---|
| *Variable Valve Actuator* |  | *Reduced pumping losses* |
| *NG direct injection* |  | *Removed volumetric efficiency gap due to gaseous fuel* |
| *High CR + robust structure* |   | *Enhanced engine efficiency w/o drawback* |
| *TC NG dedicated* |  | *Enhanced expansion ratio* |

## Design storage system, engine and subsystems installation on demo vehicle - CRF

***Current lay-out – Fiat 500L***




***N. 2 CNG bottles:***

***Transversal tank: 68 liters***
***Longitudinal tank : 18 liters***

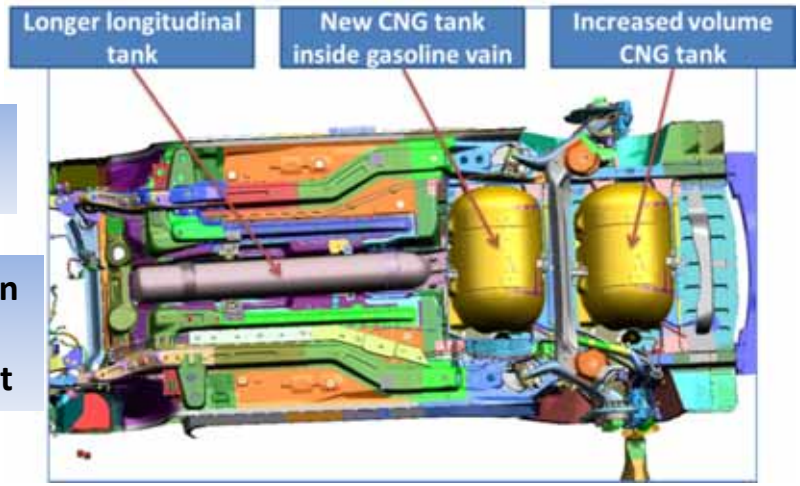
***Current driving (NEDC) range = 295 km***

**Target driving range 600 km (NEDC)**

**17.5% fuel consumption reduction**
**60 kg additional weight**

**Additional tank equal to 84 liters**

***Upgraded lay-out on GasOn demo car***




***N. 3 CNG bottles:***

***An enhanced transversal tank: 77 liters***
***A longer longitudinal tank: 25 liters***
***A new tank instead of gasoline tank: 68 liters***

# *WP2 Final results:*

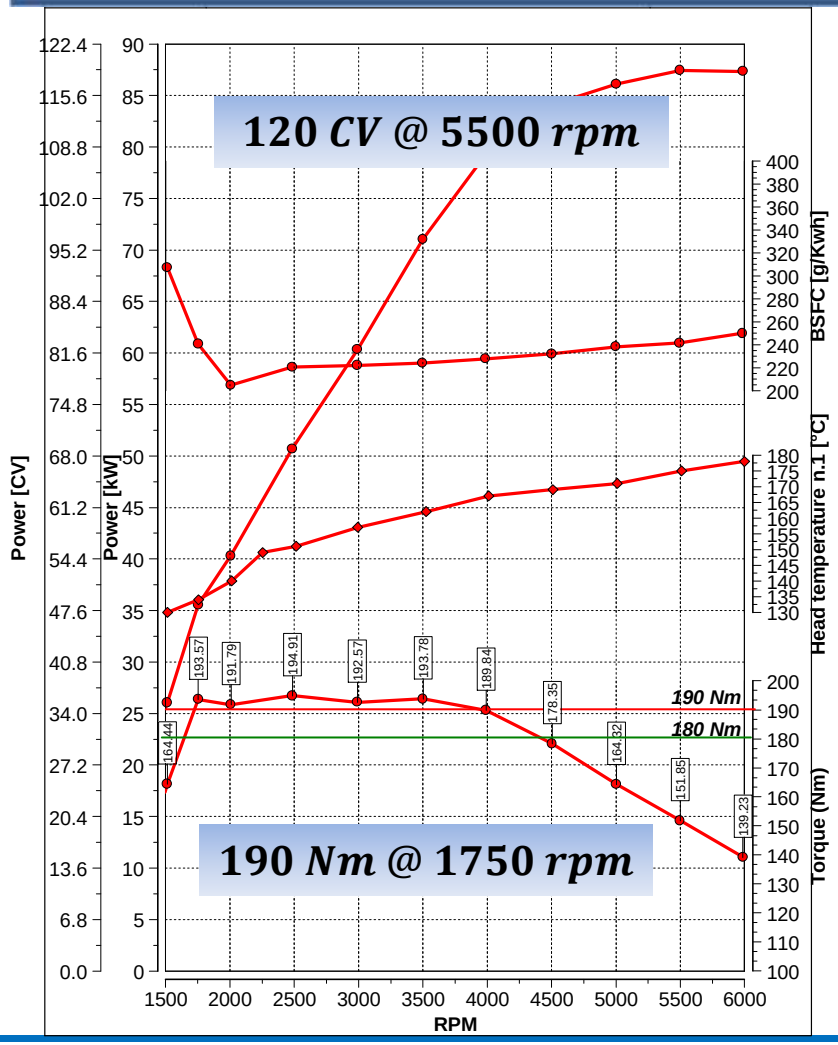
- *Performance gap removal vs PFI technology*
- *Engine efficiency enhancement due synergic effects of innovative technologies*
- *Vehicle driving range improvement*
- *CO2 reduction*
- *PN mitigation on real driving missions*

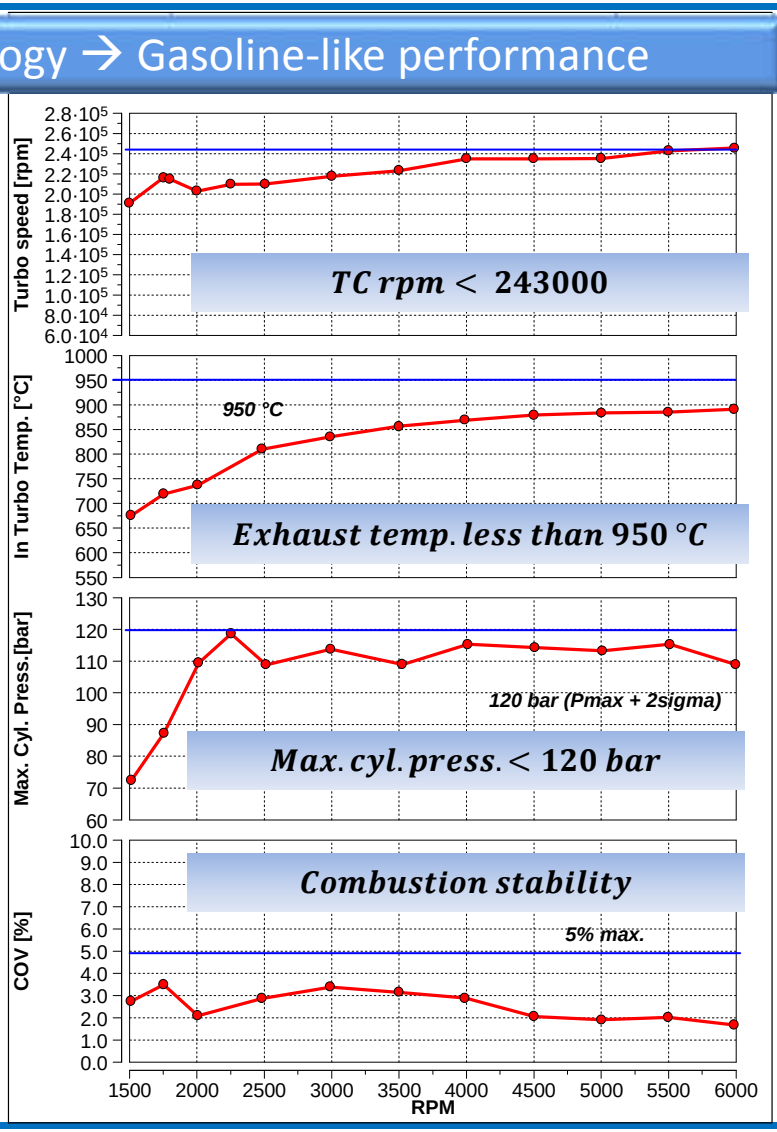
# Gas-Only Internal Combustion Engines

Work Package A2, Stoichiometric & high structural integrity small TC VVA DI engine,

**CRF, AVL, Delphi Technologies, Politecnico Torino**

## Removed performance gap due to PFI technology → Gasoline-like performance



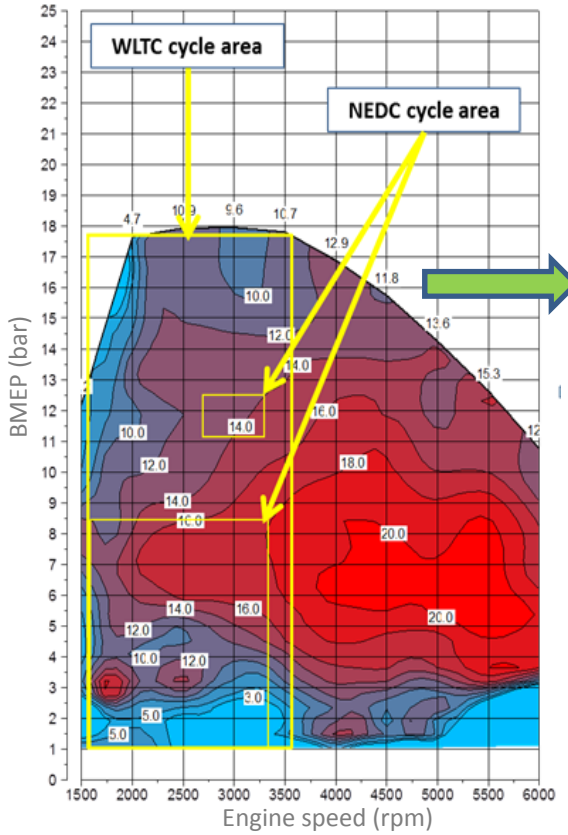



# Gas-Only Internal Combustion Engines

Work Package A2, Stoichiometric & high structural integrity small TC VVA DI engine,
**CRF, AVL, Delphi Technologies, Politecnico Torino**

## Engine efficiency enhancement due to synergic effects of innovative technologies

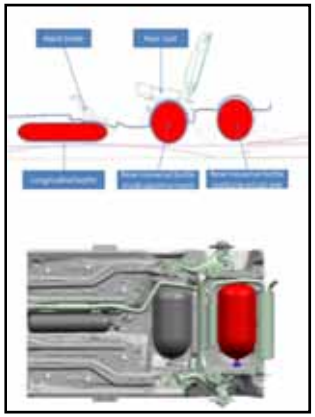
BSFC reduction (%) with GasOn WP2 engine vs CNG PFI version (CR 10.5)




GHG reduction with GasOn WP2 demo car vs Fiat 500L CNG PFI version (CR 10.5)

| GHG Reduction Technology | Enabling Technology | Measured |
|---|---|---|
| Downsizing and combustion benefits | Advanced Boosting | 4% |
| | CNG Direct Injection (CNG DI) | |
| Compression Ratio Increase | High Peak Pressure Capable Engine Architecture | 3% |
| | High compression ratio (13:1) | |
| Dethrottling and/or advanced air management | Advanced Variable Valve Actuation | 6,5% |
| | Charge Dilution | |
| CNG system weight reduction with downspeeding and further vehicle measures | Light Weight CNG Tank System | 4% |
| | Downspeeding with longer final drive to trade performance (gained by weight reduction) against fuel economy | |
| **TOTAL - Measured on demo vehicle (NEDC)** | | 17,5% |
| **TARGET on NEDC** | | 16 ... 22 % |

Upgraded CNG storage to achieve 600km driving range



New gearbox for downspeeding

- CNG direct injection improves the combustion speed allowing increasing spark advance → +3% Brake Thermal Efficiency (BTE)
- Compression ratio 13:1 versus 10:1 improves engine efficiency of 4% without any knocking phenomena due to high octane number (130)
- High expansion ratio by means of early intake valve closure and related boosting is realized by variable valve actuation. The over expanded air through intake valves is cooled into combustion chamber allowing to increase spark advance → +3% Brake Thermal Efficiency (BTE)

# Gas-Only Internal Combustion Engines

Work Package A2, Stoichiometric & high structural integrity small TC VVA DI engine,
**CRF, AVL, Delphi Technologies, Politecnico Torino**

## Demo car equipped with PEMS

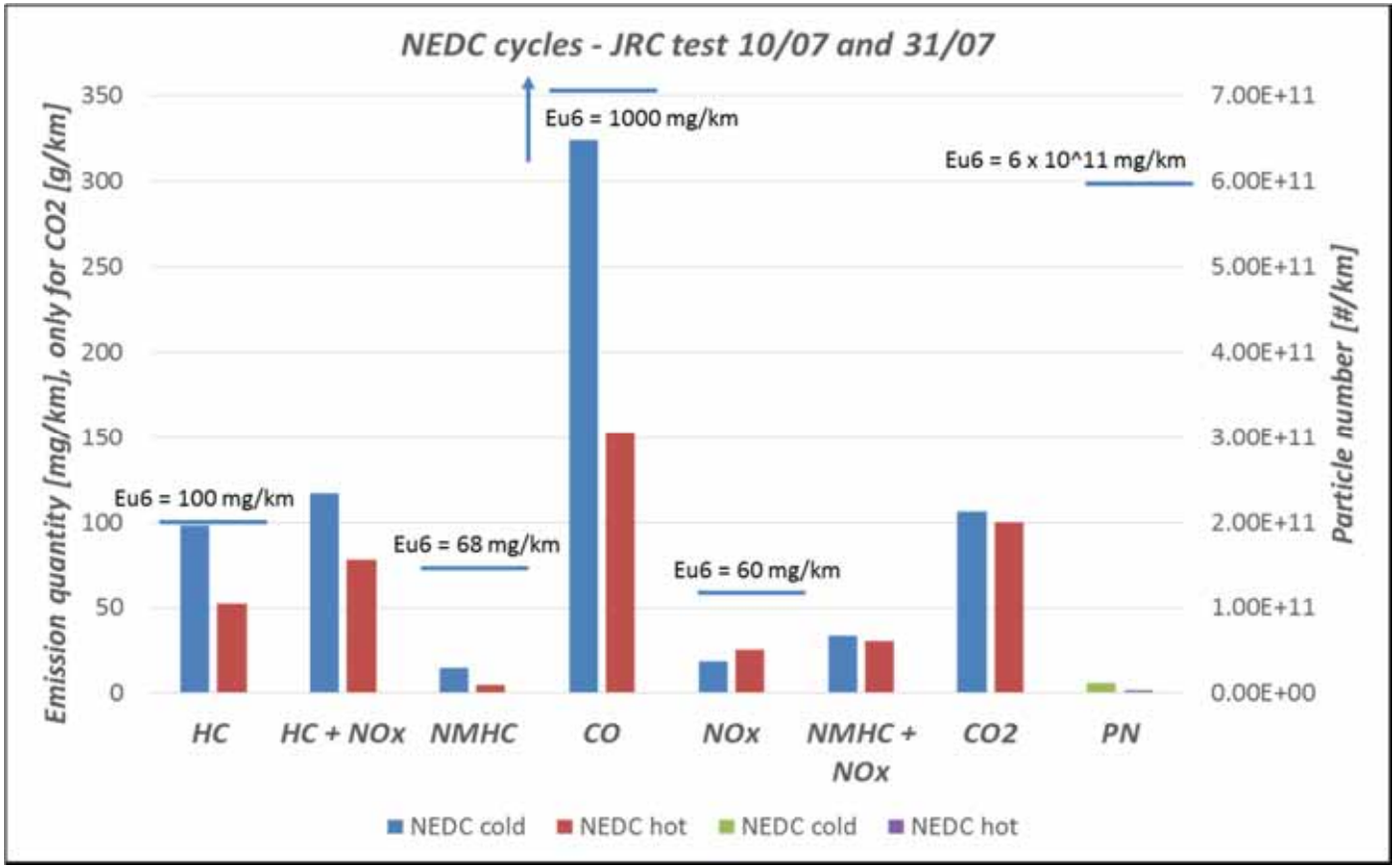
Measured driving (NEDC) range = 590 km
Measured driving (WLTC) range = 550 km

# Gas-Only Internal Combustion Engines

Work Package A2, Stoichiometric & high structural integrity small TC VVA DI engine,

**CRF, AVL, Delphi Technologies, Politecnico Torino**

## JRC certification tests on GasOn WP2 demo car - Emission results (1/3)



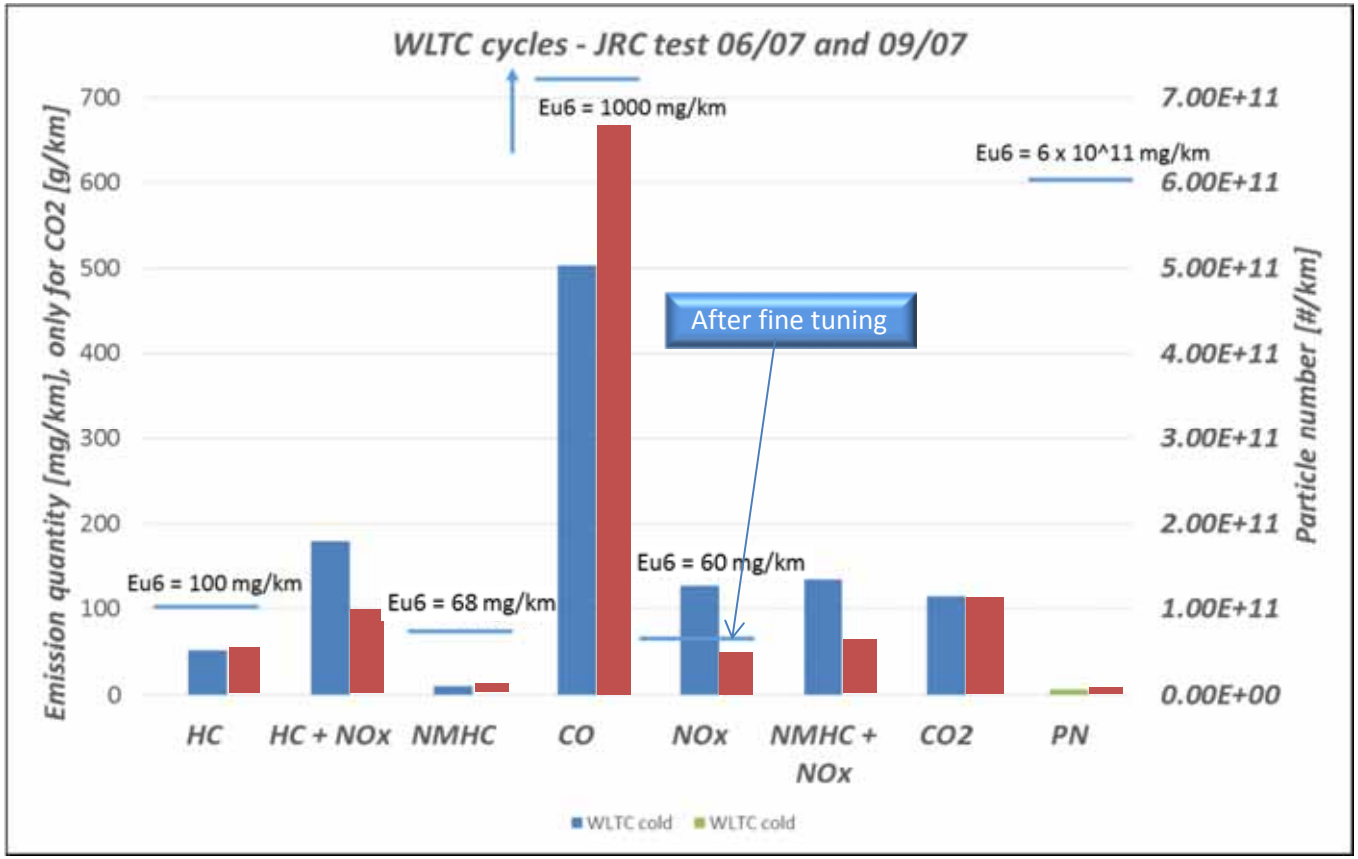

| Ref. Fiat 500L Bifuel CNG PFI | |
|---|---|
| CO2 reduction | -20,0% |
| PN | 1.2E+10 |

All noxious emissions under Euro6d limits

# Gas-Only Internal Combustion Engines

Work Package A2, Stoichiometric & high structural integrity small TC VVA DI engine,
**CRF, AVL, Delphi Technologies, Politecnico Torino**

## JRC certification tests on GasOn WP2 demo car - Emission results (2/3)

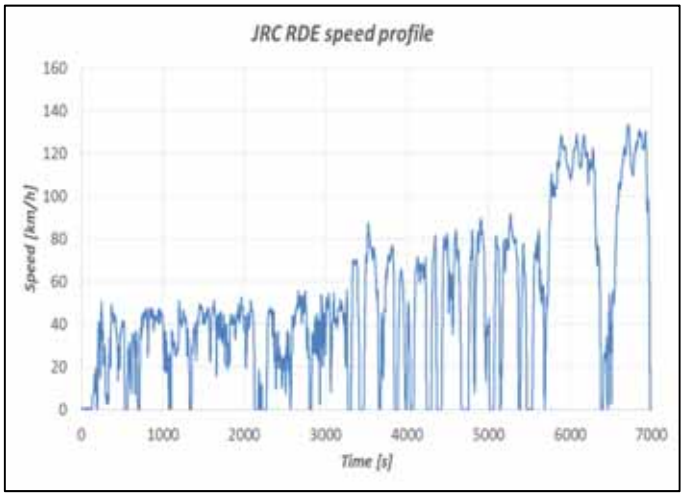



| Ref. Fiat 500L Bifuel CNG PFI | |
|---|---|
| CO2 reduction | -21,8% |
| PN | 7.1E+09 |

All noxious emissions under Euro6d limits after fine tuning

## JRC certification tests on GasOn WP2 demo car - Emission results (3/3)

### Real driving mission




| RDE at JRC | CO (mg/km) | NOx (mg/km) | PN (#/km) | CO2 reduction** |
|---|---|---|---|---|
| Results with PEMS* | 227 | 43 | $2*10^{10}$ | 20% |
| Euro6d limit on WLTC | 1000 | 60 | $6*10^{11}$ | - |

* Mean values of 3 tests

** vs Fiat 500L Bifuel CNG PFI

## First results from PN device developed on EU DownToTen project

| WLTC cold – Jan. 2019 Metric #/km | | |
|---|---|---|
| 23nm | 10nm | 4nm |
| $2.3*10^{10}$ | $3.4*10^{10}$ | $3.7*10^{10}$ |
| $2.5*10^{10}$ | $3.9*10^{10}$ | $4.4*10^{10}$ |

Current PN devices for homologation detect particle diameter > 23 nm

Slight increase of PN with particle diameter down to 10 nm & 4 nm is measured but **absolute PN values are extremely low thanks to extreme clean fuel → CNG**

## Conclusion

| | |
|---|---|
| **At engine level, the synergic adoption of CNG direct injection with tailored boosting system, variable valve actuation and high compression ratio allow to obtain the same rated torque and power as high output gasoline engine** | √ |
| **Fuel saving is consolidated at 17.5% on various cycles and on real driving missions** | √ |
| **Upgraded CNG storage system ensures a full driving range close to 600 km without trunk penalty** | √ |
| **PM and PN are extremely low without any filtration device** | √ |
| **Direct injection of CNG shows a certain impact on THC/NOx emissions that requires a fine tuning especially during cold phase. Anyway RDE emission results carried out by JRC demonstrated the effectiveness of the adopted technologies** | √ |

# Thanks for your attention