Engines, Energy and Environment Group

POLITECNICO DI TORINO

Dipartimento Energia

Tecniche per il controllo della detonazione in motori ad accensione comandata ad alto grado di sovralimentazione

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Giornata di Studio "Giorgio Minelli" sui Motori a Combustione Interna

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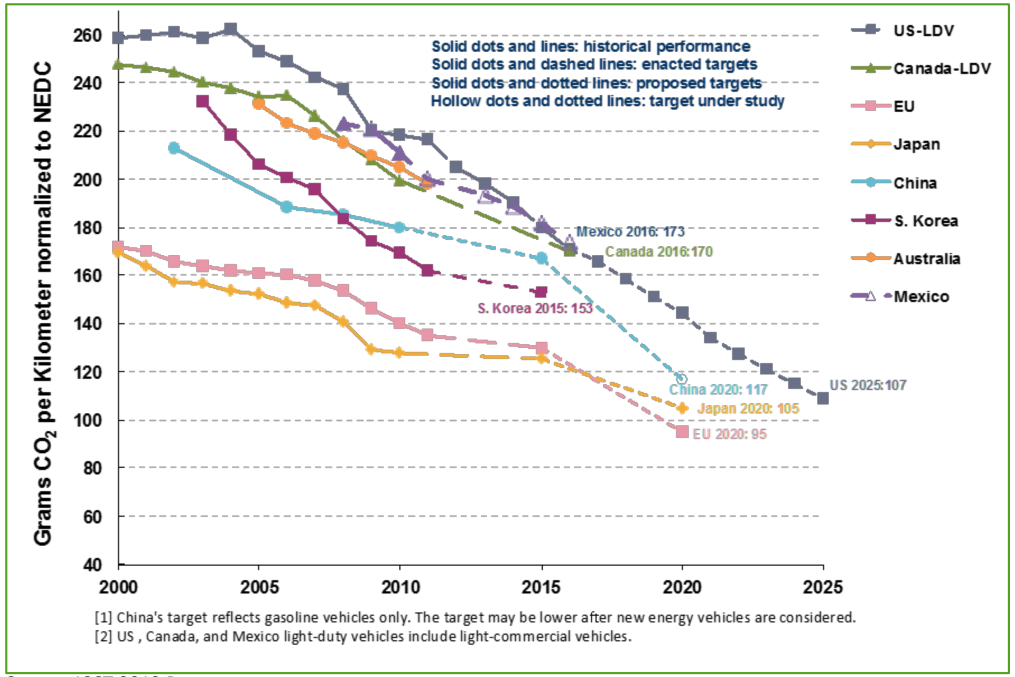
Agenda

- Introduction
- Experimental Setup
  - Engine *A*
  - Engine *B*
- Knock Mitigation Techniques
  - Miller Cycle
  - Water Injection
- 0D/1D combustion simulation and knock prediction
- Conclusions and Future Work

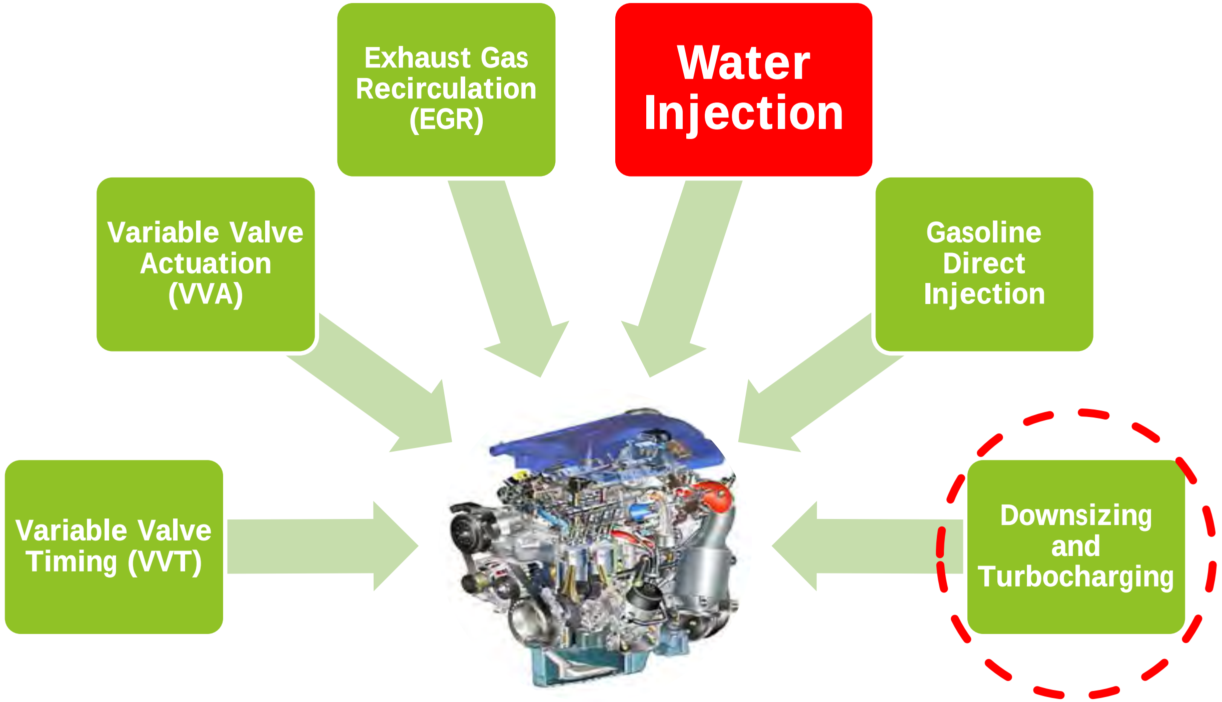
Introduction

Legislations worldwide are converging to long-term fuel economy and CO_2 emissions targets of below 100 g/km, hence invoking the necessity of utilizing advanced technologies in SI engine development with a synergic approach.



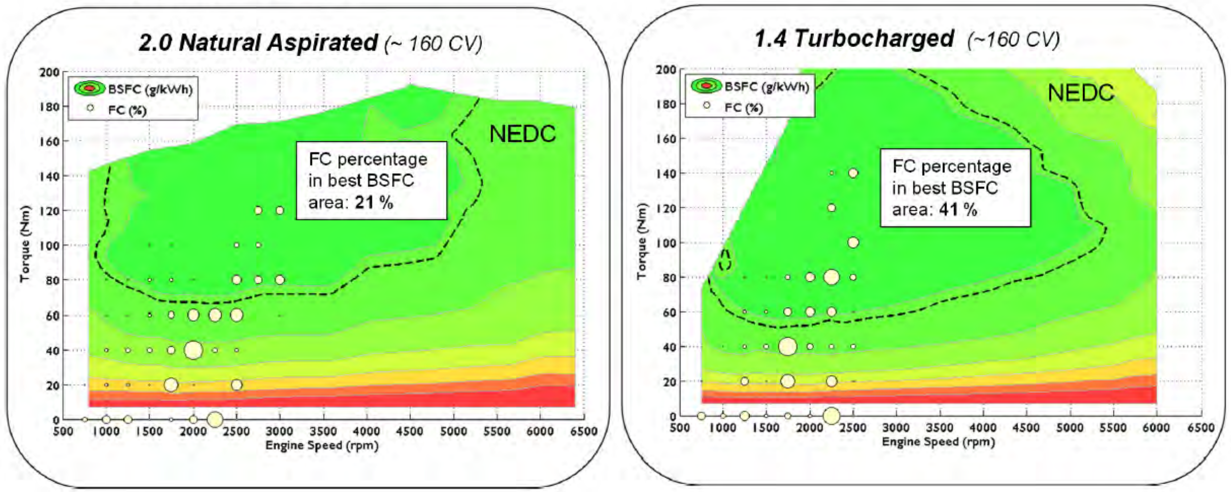
Source: ICCT 2013 Report

Gasoline Engine
TECHNOLOGIES for FUEL ECONOMY IMPROVEMENT



Introduction

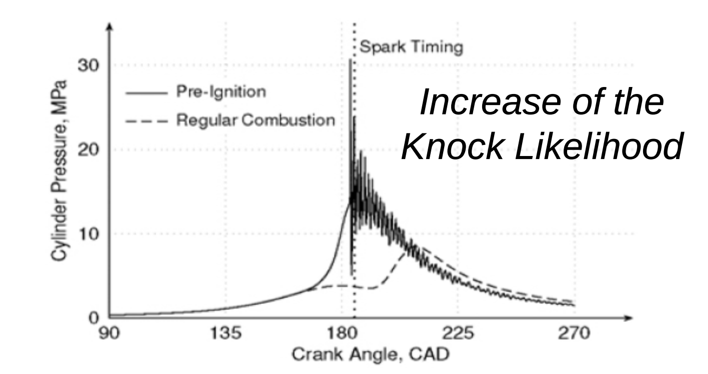
DOWNSIZING example



Source: Luisi S., Doria V., Stroppiana A., “Knock Mitigation Techniques for Highly Boosted Downsized SI Engines”, in Proc. CO2 reduct. transp. Syst. ATA/SAE Int. Conf., Turin, Italy, 2017

KEY ENABLER for DOWNSIZING→ TURBOCHARGING

DRAWBACK: to maintain a favorable torque output an high boost level is required to compensate the lower engine displacement → increase of knock likelihood

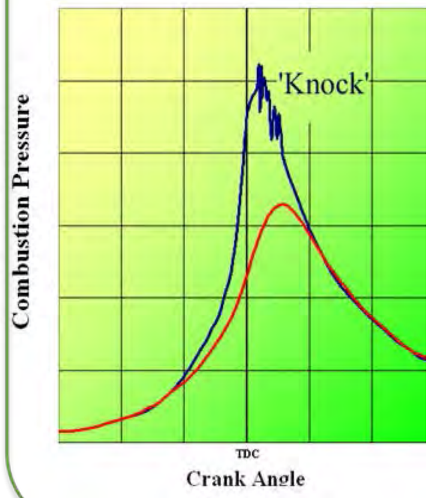


Source: C. Dahnz, at al., “Investigations on Pre-ignition in Highly Supercharged SI Engines”, SAE Int. J.Engines 3(1):214-224, 2010, doi:10.4271/2010-01-0355

Introduction

To maintain a favorable torque output an high boost level is required to compensate the lower engine displacement → increase of knock issue at medium / high engine load

KNOCK ISSUE



CONS

- Fuel Enrichment
- Retarded Spark Timing

Fuel Economy Deterioration

KNOCK MITIGATION APPROACHES

- Cooled EGR
- Variable Compression Ratio:
  - Mechanical systems
  - Miller cycle
- Water Injection

Among the different possible knock mitigation approaches current work will focus on:
Miller Cycle and Water Injection

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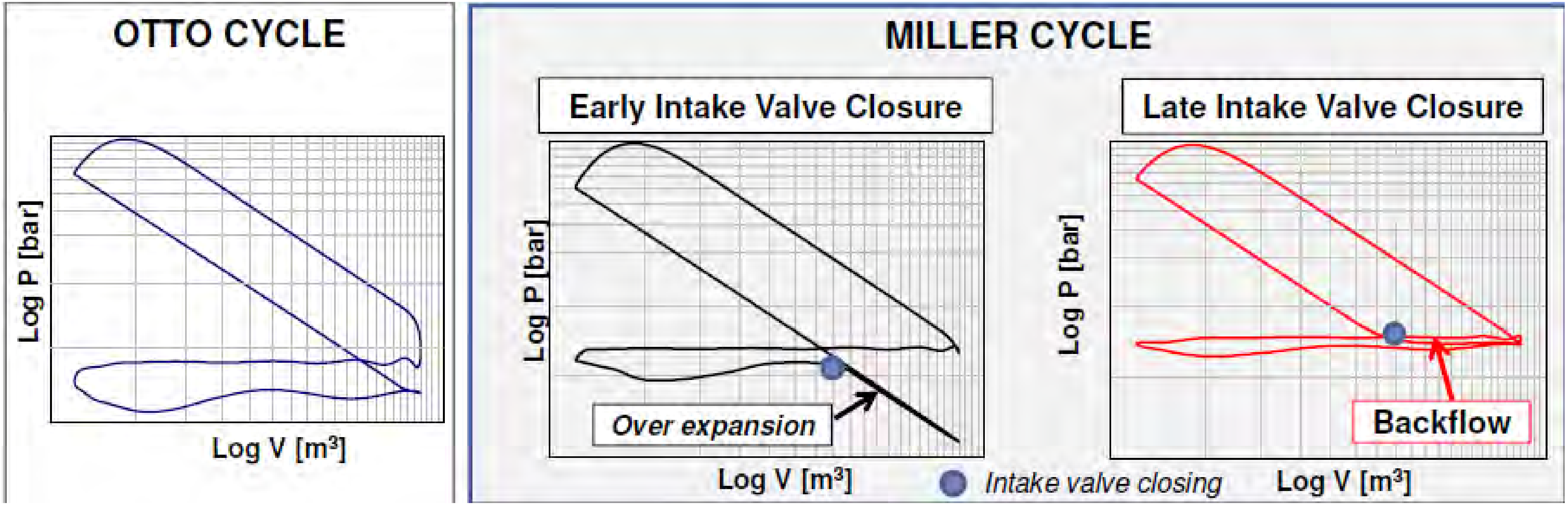
Experimental Setup

Engine *A*

- Two different downsized turbocharged spark ignition engines were investigated, named engine ***A*** and ***B***.
- Regarding engine ***A***, experimental investigations were performed to evaluate Miller cycle for knock mitigation at high load.
  Late Intake Valve Closure (LIVC) and Early Intake Valve Closure (EIVC) strategies were compared.

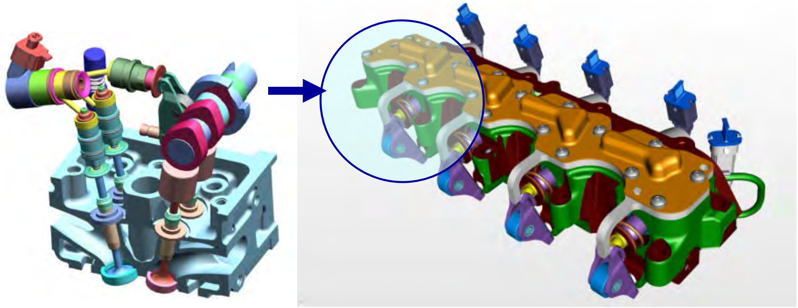


Experimental Setup
Engine *A*

Engine A characteristics

ENGINE SPECIFICATION	FIRE MAIR TC 140CV
Displacement [cc]	1368
Cylinder n°	4
Injection System	PFI
POWER [KW @ rpm]	103 @ 5000
TORQUE [Nm @ rpm]	230 @ 1750
Compression ratio	9,8
Bore [mm]	72
Stroke [mm]	84
FUEL Type	GASOLINE
Cylinder head	SOHC 4V
Timing valve drive	Belt / MULTIAIR

MULTIAIR: **Electro-hydraulic valve lift system**



MAIN FEATURES:

- Throttle-less Load Control
- Optimal Charge Trapping Efficiency
- Fast and direct Intake Valve Control
- Flexible Combustion Management
- Effective compression ratio & Internal EGR Control

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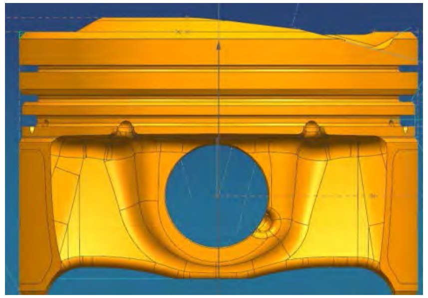
Experimental Setup

Engine *B*

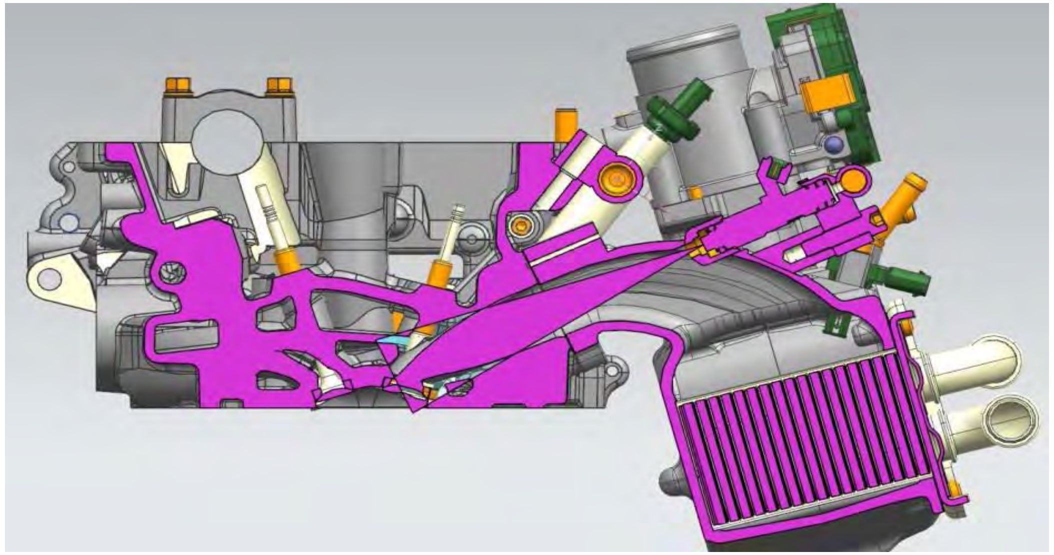
- The second phase of the investigation was carried out on engine ***B***, which is, differently from engine ***A***, equipped with Gasoline Direct Injection, and with a water injection system, a schematic section of which is shown below.

- Water injectors have been installed into intake manifold runners (Port Water Injectors).

- Two different configurations of engine ***B*** were tested, the first featuring a CR of 10, the second with a CR of 13. The water injection technology has been utilized in the CR13 configuration.



Piston CR=13



Layout of engine head, intake manifold, and runner with water injector

*Source: Luisi S., Doria V., Stroppiana A., "Knock Mitigation Techniques for Highly Boosted Downsized SI Engines", in Proc. CO2 reduct. transp. Syst. ATA/SAE Int. Conf., Turin, Italy, 2016

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Knock Mitigation Techniques

Miller Cycle: Knock Mitigation Features

MILLER CYCLE	
EIVC **Early Intake Valve Closure**	**LIVC** **Late Intake Valve Closure**

EFFECTIVE COMPRESSION RATIO REDUCTION

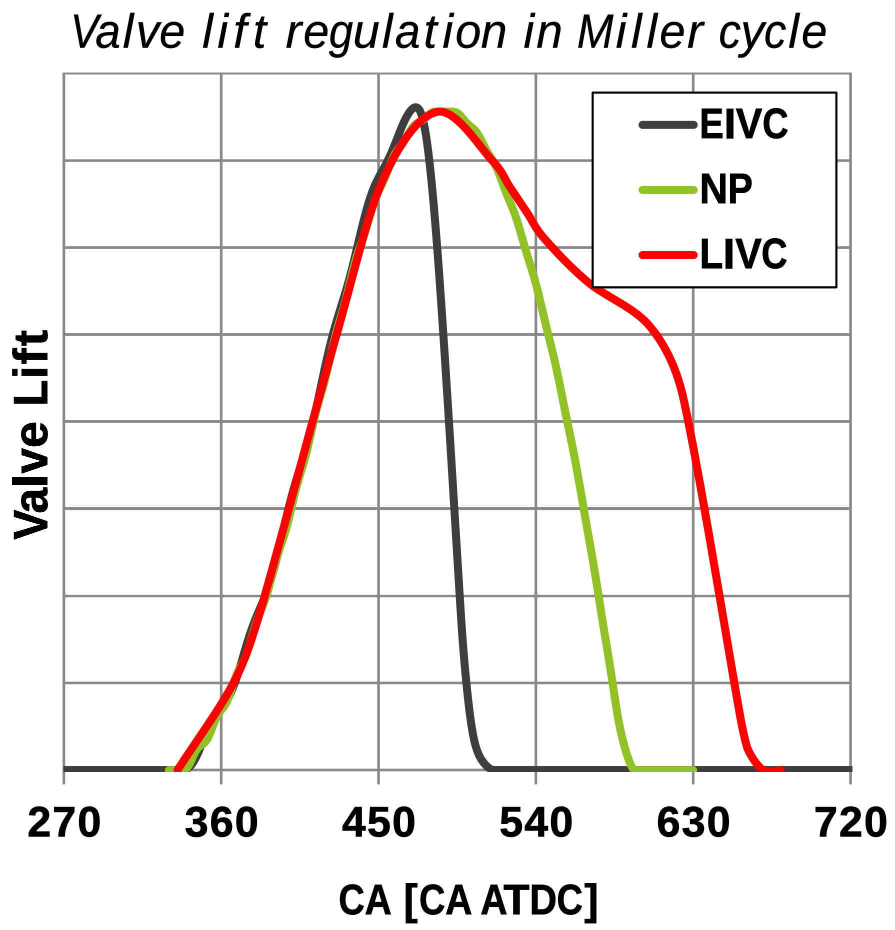
LOWER CHARGE TEMPERATURE

MITIGATION OF KNOCK OCCURENCE

VOLUMETRIC EFFICIENCY REDUCTION

(to be compensated with higher boost)

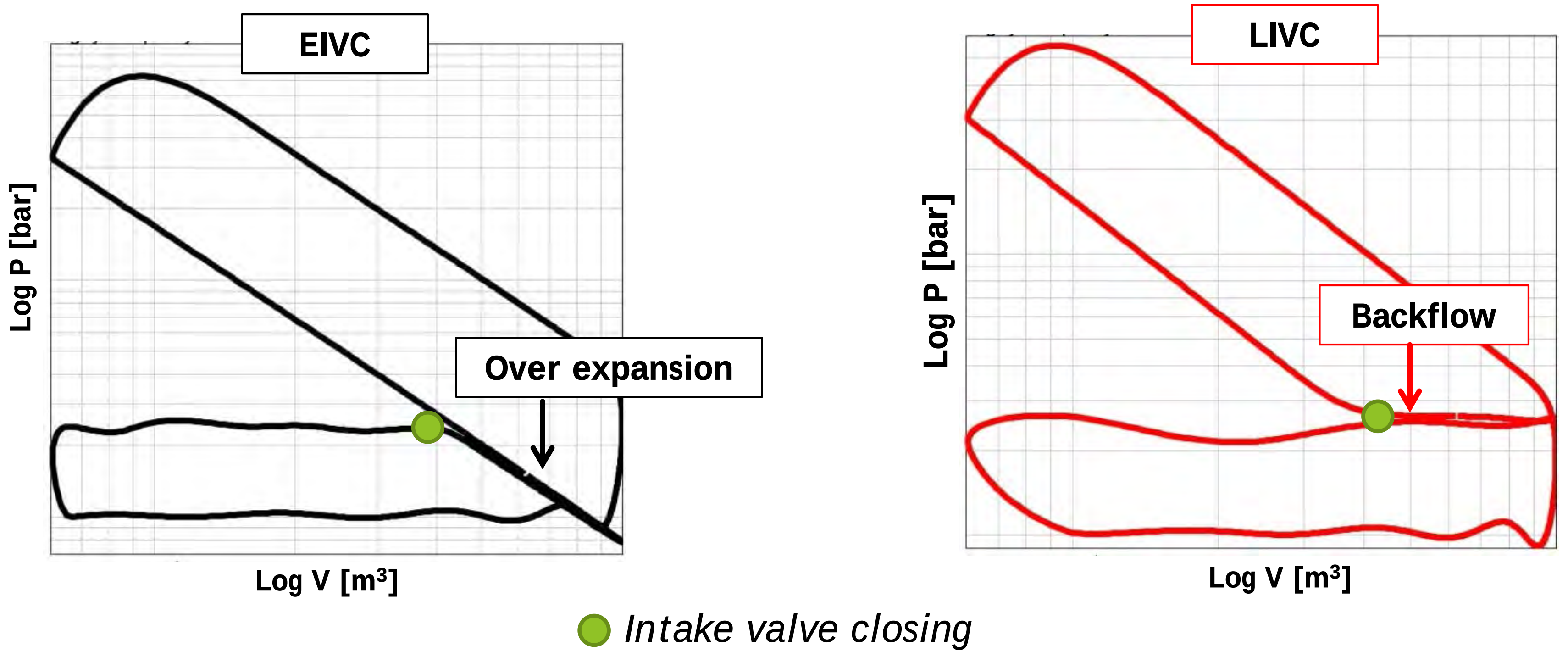
- **LESS RETARDED SPARK ADVANCE**
- **MIXTURE ENRICHMENT REDUCTION**



Knock Mitigation Techniques

Miller Cycle: Knock Mitigation Features

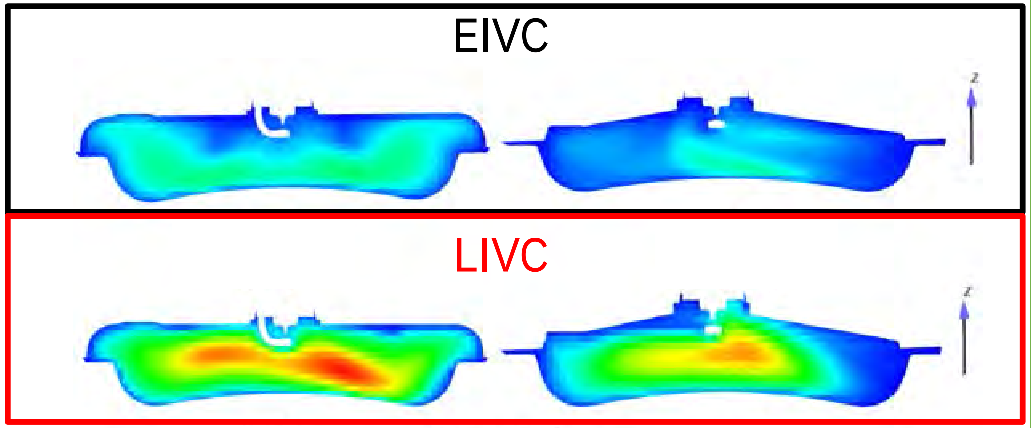
MILLER CYCLE Features	EIVC Early Miller	LIVC Late Miller
Cylinder Turbulence	Reference	HIGHER
Mixture Homogeneity		ENHANCED

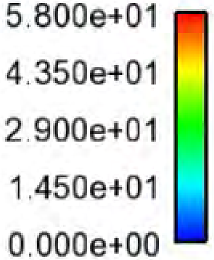


Knock Mitigation Techniques

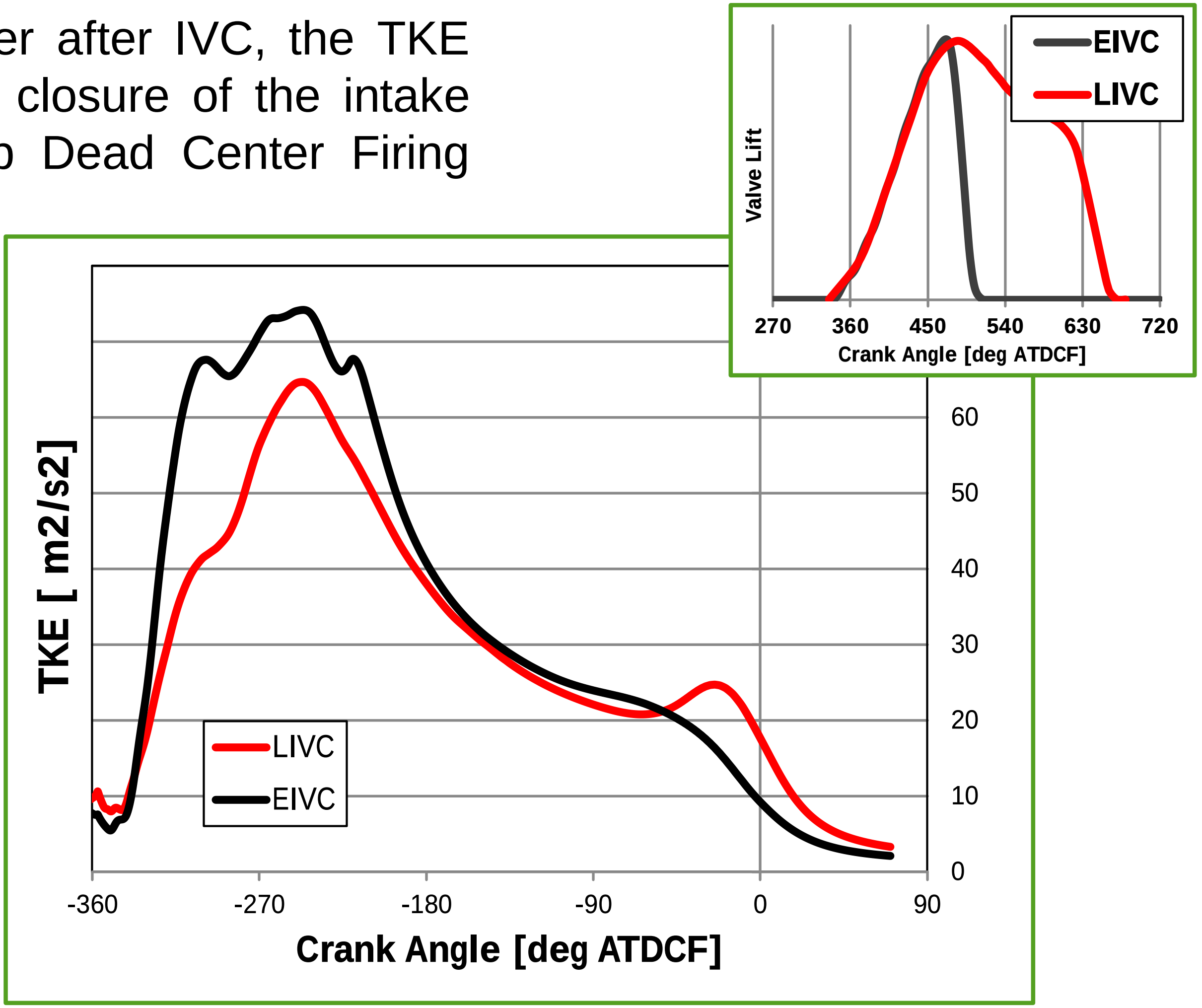
Miller Cycle: Knock Mitigation Features

Since for the EIVC strategy the intake valves are closed earlier and there are no sources to support the turbulence inside the cylinder after IVC, the TKE decreases rapidly, while for the LIVC strategy the late closure of the intake valves leads to a higher level of turbulence near Top Dead Center Firing (TDCF).





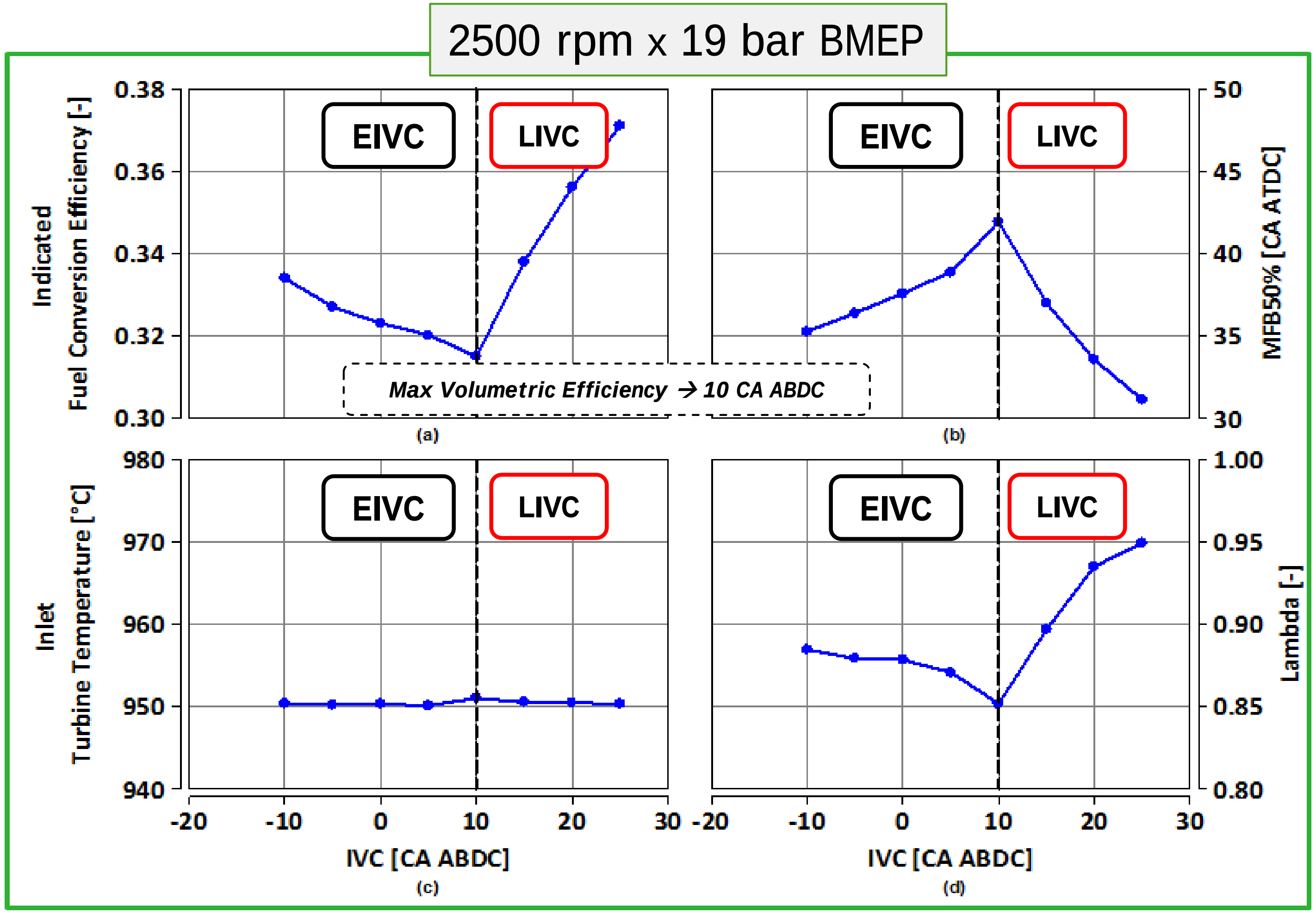
3D visualization of TKE 20 deg before TDCF



*Source: Luisi S., Doria V., Stroppiana A., "Knock Mitigation Techniques for Highly Boosted Downsized SI Engines", in Proc. CO2 reduct. transp. Syst. ATA/SAE Int. Conf., Turin, Italy, 2017

Knock Mitigation Techniques

Miller Cycle: Knock Mitigation Features



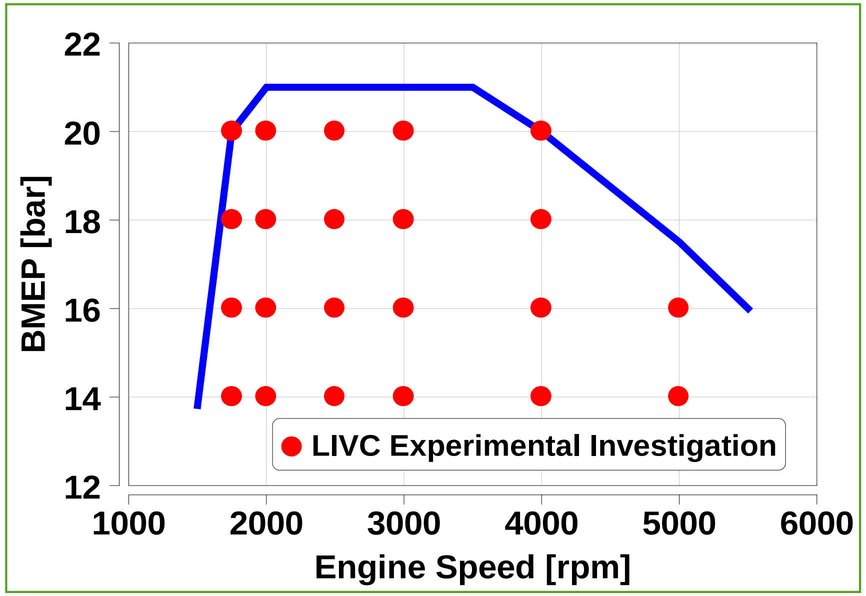
$$Indicated\ fuel\ conversion\ efficiency = \frac{P_{ind}}{\dot{m}_f \cdot LHV}$$

The superior knock mitigation capability of LIVC strategy was also experimentally proved.
It allows more advanced combustion phasing and lower mixture enrichment
→ Better fuel conversion efficiency

*Source: Luisi, S., Doria, V., Stroppiana, A., Millo, F. et al., "Experimental Investigation on Early and Late Intake Valve Closures for Knock Mitigation through Miller Cycle in a Downsized Turbocharged Engine," SAE Technical Paper 2015-01-0760, 2015, doi:10.4271/2015-01-0760.

Knock Mitigation Techniques

Miller Cycle: Operating Points/Limits



Operating LIMITS	Value
Turbocharger MAX speed	240.000 rpm
Absolute boost pressure	2500 mbar
Average peak cyl. pressure	85 bar
Inlet turbine temperature	950 °C
Outlet intercooler Temperature	50°C
Spark Advance	limited at KNOCK trace level

- **ENGINE OPERATING POINTS:**

  - **Engine Speed [rpm]:**

    1750 - 2000 - 2500 - 3000 - 4000 - 5000

  - **Engine Load-BMEP [bar]:**

    14 - 16 - 18 - 20

- **TEST PROCEDURE:**

  Comparison of indicated fuel conversion efficiency (η_i) between **LIVC** cam profile vs **STANDARD NP** one for each engine operating point.

*Source: Luisi, S., Doria, V., Stroppiana, A., Millo, F. et al., "Experimental Investigation on Early and Late Intake Valve Closures for Knock Mitigation through Miller Cycle in a Downsized Turbocharged Engine," SAE Technical Paper 2015-01-0760, 2015, doi:10.4271/2015-01-0760.

Knock Mitigation Techniques

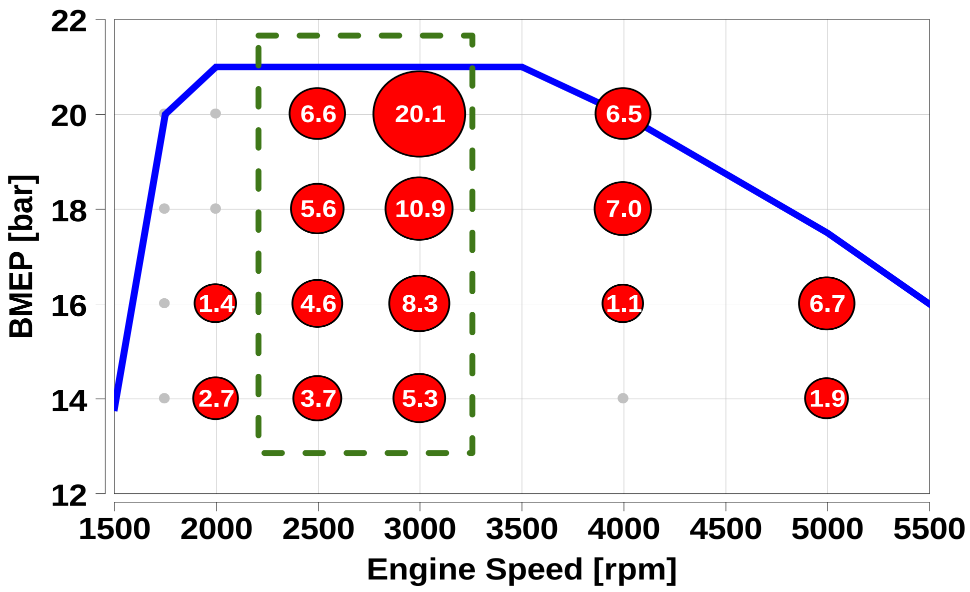
Miller Cycle: Results

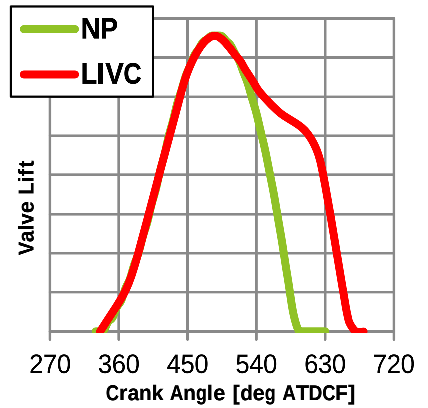
LIVC** vs **NP regulation

*FUEL ECONOMY BENEFIT @ **MEDIUM Engine Speed***

X

LIVC vs NP regulation
% FE improvement





NP CAM PROFILE

MEDIUM ENGINE SPEED

MEDIUM Engine LOAD	Moderate KNOCK tendency	Spark timing RETARD
HIGH Engine LOAD	High KNOCK tendency	Spark timing RETARD & mixture ENRICHMENT

LIVC CAM

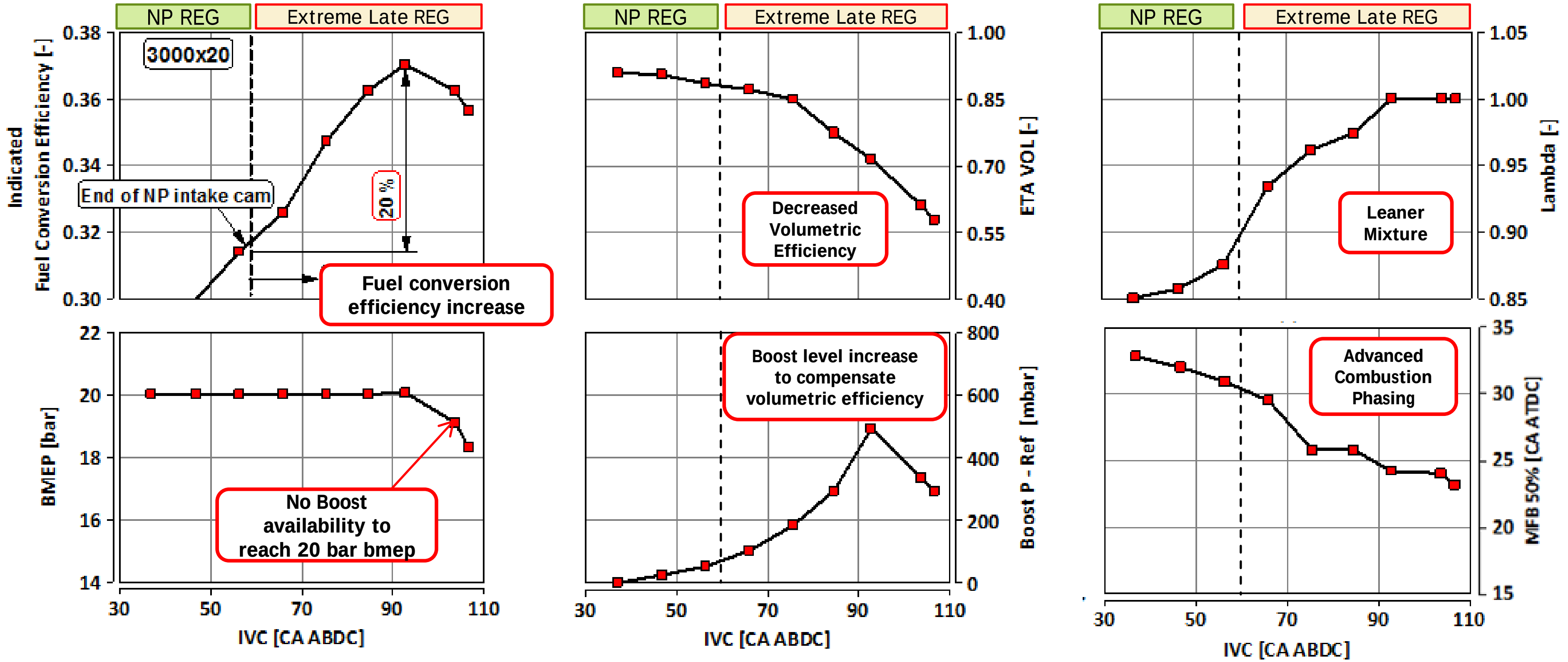
NOTICEABLE FE IMPROVEMENT due to LIVC KNOCKING mitigation

*Source: Luisi, S., Doria, V., Stroppiana, A., Millo, F. et al., "Experimental Investigation on Early and Late Intake Valve Closures for Knock Mitigation through Miller Cycle in a Downsized Turbocharged Engine," SAE Technical Paper 2015-01-0760, 2015, doi:10.4271/2015-01-0760.

Knock Mitigation Techniques

Miller Cycle: Results

Most effective operating point (3000 rpm x 20 bar bmep)



Engine can be operated with a delayed IVC of 90° CA after BDC achieving **20% improvement of indicated fuel conversion efficiency** maintaining same BMEP with respect to NP REGULATION, thanks to high boost pressure availability.

*Source: Luisi, S., Doria, V., Stroppiana, A., Millo, F. et al., "Experimental Investigation on Early and Late Intake Valve Closures for Knock Mitigation through Miller Cycle in a Downsized Turbocharged Engine," SAE Technical Paper 2015-01-0760, 2015, doi:10.4271/2015-01-0760.

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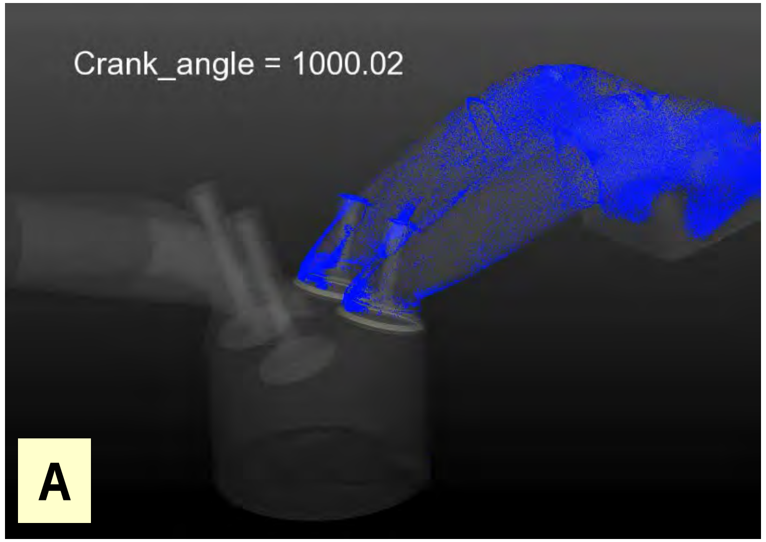
Knock Mitigation Techniques

Water Injection: Knock Mitigation Features

Water Injection is a well known technology that can be adopted to reduce knocking tendency in turbocharged gasoline engines.

Inj. P= **6bar**
EOI= **360°CAdeg**
W/F= **18.5**
Inj = **2**



3D CFD simulation of WI on engine B

WATER INJECTION

FEATURE

HIGH LATENT HEAT of VAPORIZATION

EFFECTS

LOWER INTAKE AIR TEMPERATURE

LOWER CHARGE TEMPERATURE at the END of COMPRESSION STROKE

MITIGATION OF KNOCK OCCURENCE

BENEFITS

PERFORMANCE Increase	FUEL ECONOMY Improvement
LESS RETARDED SPARK ADVANCE	LESS RETARDED SPARK ADVANCE
HIGHER BOOST LEVEL	MIXTURE ENRICHMENT REDUCTION
CR STANDARD	CR INCREASED

*Source: Luisi S., Doria V., Stroppiana A., "Knock Mitigation Techniques for Highly Boosted Downsized SI Engines", in Proc. CO2 reduct. transp. Syst. ATA/SAE Int. Conf., Turin, Italy, 2016

Knock Mitigation Techniques

Water Injection: Experimental Investigation

- Experimental investigations were carried out to fully exploit the synergies between different knock mitigation techniques, such as Miller cycle and water injection.

- To exploit the reduced knock tendency (due to WI) the engine geometric Compression Ratio was increased from 10 to 13.

- Thanks to the augmented CR, significant benefits could be obtained at low and medium load, while the knock risk at high load is significantly increased.

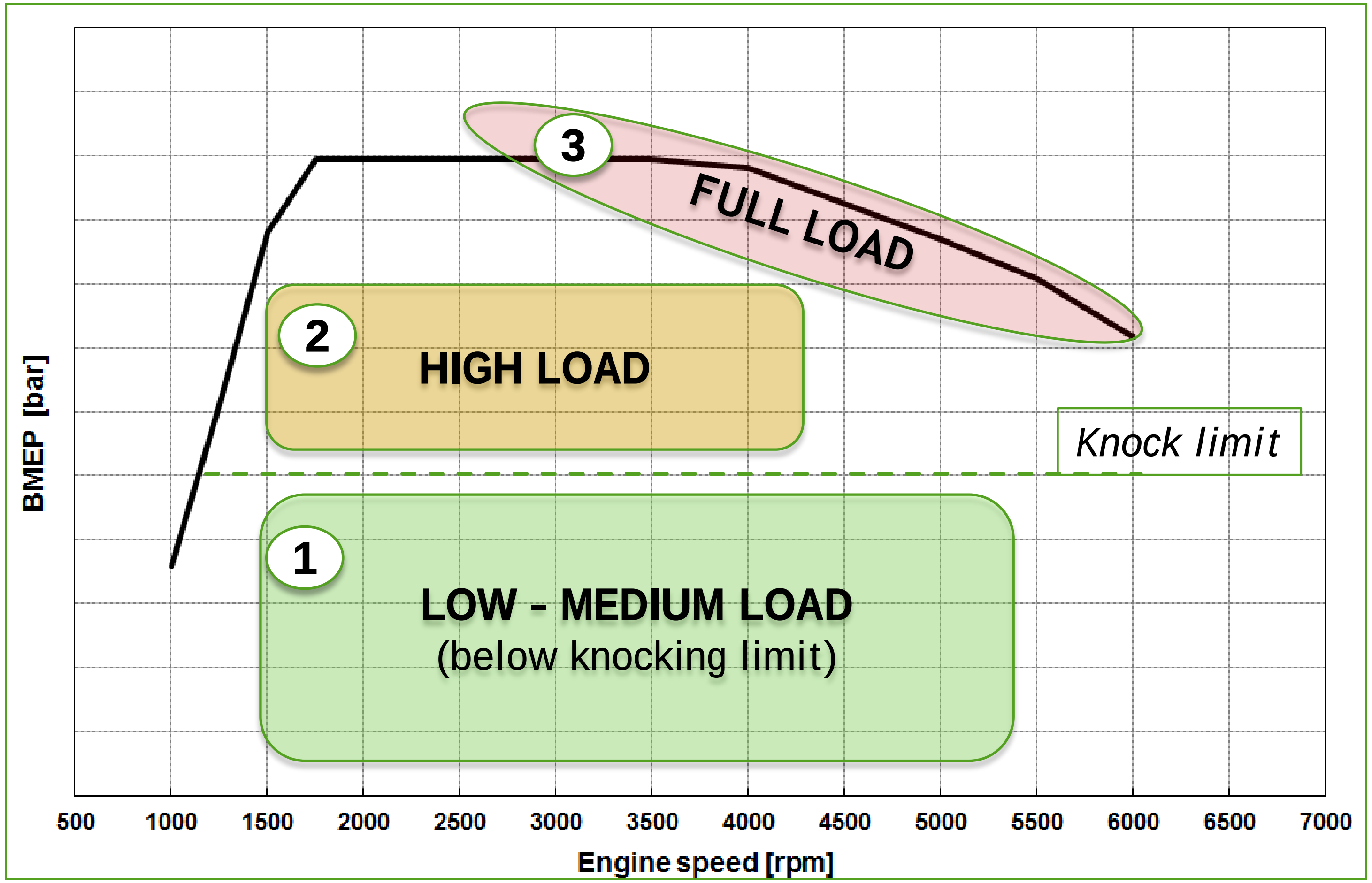
- In order to understand the possible benefits of water injection technology, the BSFC of engine configuration with CR10 without water injection has been compared with CR13 configuration with water injection

- Target: to improve engine efficiency over the whole engine operation map (even below the typical knocking zone) for CO_2 emission reduction maintaining good performance level.

Knock Mitigation Techniques

Water Injection: Experimental Investigation

Investigated points: to quantify the benefits in term of FE improvement and to check the impact on full load performance investigations varying water injection rate were carried-out in 3 different regions:

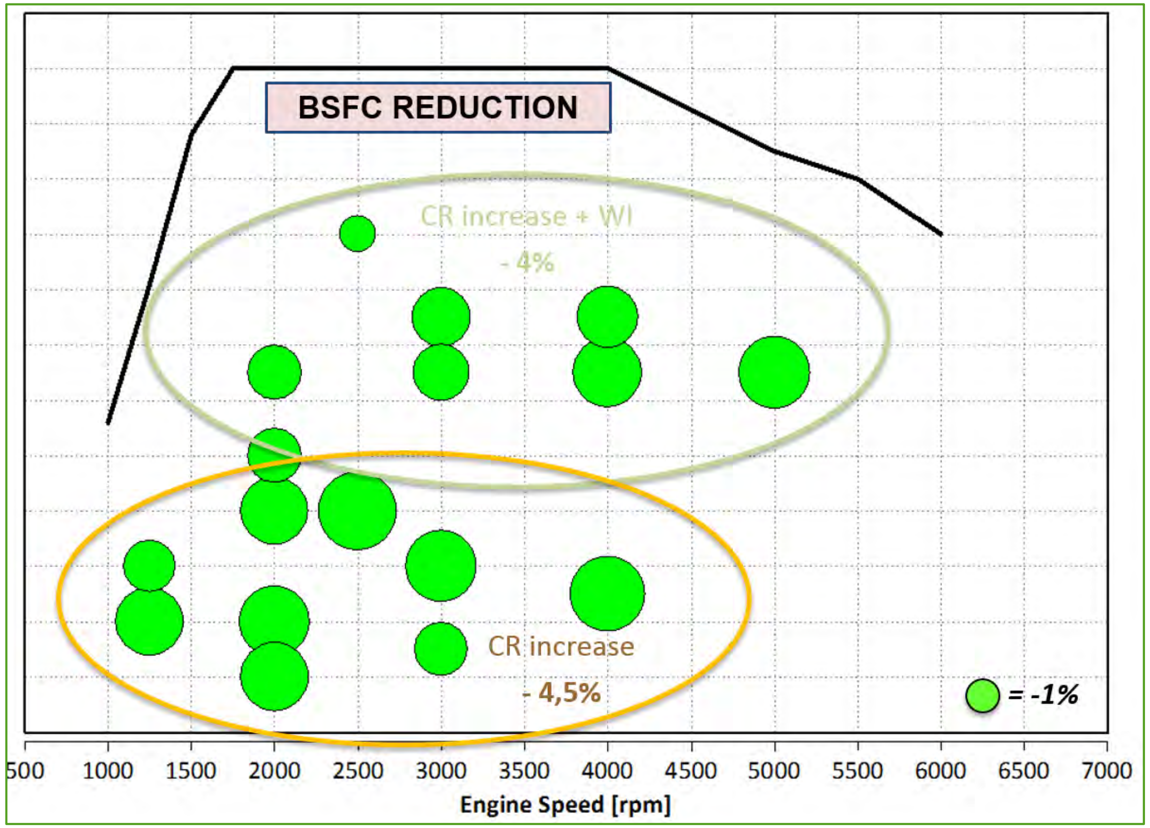


*Source: Luisi S., Doria V., Stroppiana A., “Knock Mitigation Techniques for Highly Boosted Downsized SI Engines”, in Proc. CO2 reduct. transp. Syst. ATA/SAE Int. Conf., Turin, Italy, 2017

Knock Mitigation Techniques

Water Injection: Results

- Thanks to the augmented CR and to the knock mitigation effect provided by the simultaneous exploitation of water injection, the BSFC could be reduced by a maximum value of about 4%.
- On the other hand, at lower loads, where knock is not likely to occur and there is no need to use water injection, the augmented compression ratio still allowed the achievement of BSFC reductions up to 4.5%.



CR 13 + Water Injection vs **CR 10**

*Source: Luisi S., Doria V., Stroppiana A., "Knock Mitigation Techniques for Highly Boosted Downsized SI Engines", in Proc. CO2 reduct. transp. Syst. ATA/SAE Int. Conf., Turin, Italy, 2017

CFD-3D model and validation

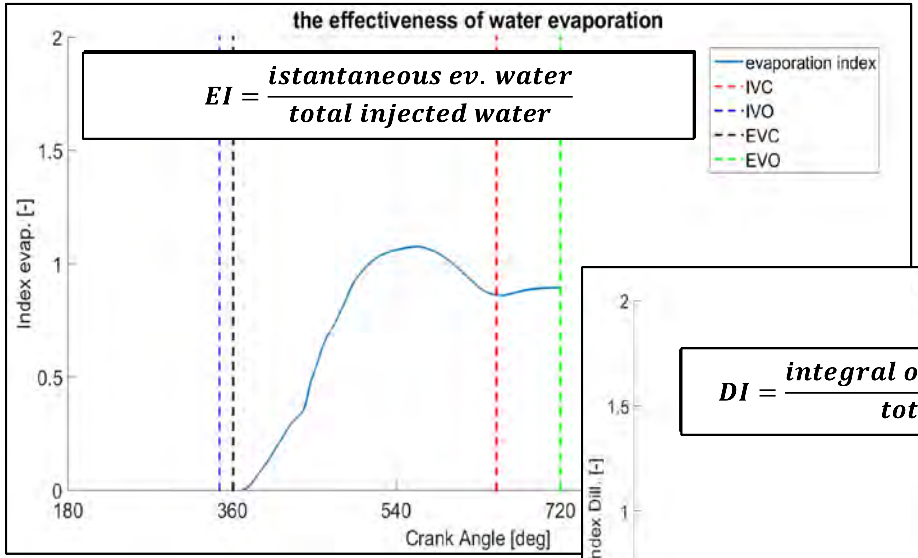
3D-CFD model capabilities in predicting water evaporation and the risk of engine oil dilution were assessed by comparing simulation results with experimental data @ **4000rpmxWOT**.

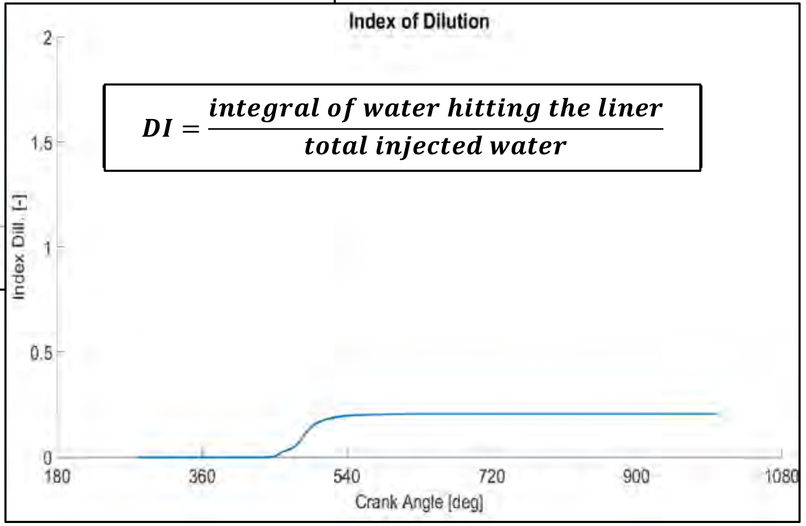
A sensitivity analysis was performed by acting on the following WI calibration parameters:

- Injection pressure (6/9) [bar]
- End of injection (360/450) [CAdeg]
- Water to fuel ratio (18.5/50) [%]
- Number of injectors/cyl. (2/1)

New CFD-3D indexes were specifically defined:

- **Evaporation Index (EI)**
- **Dilution Index (DI)**





They were used to compare the effectiveness of water injection for different layouts and calibration parameters.

CFD-3D model and validation

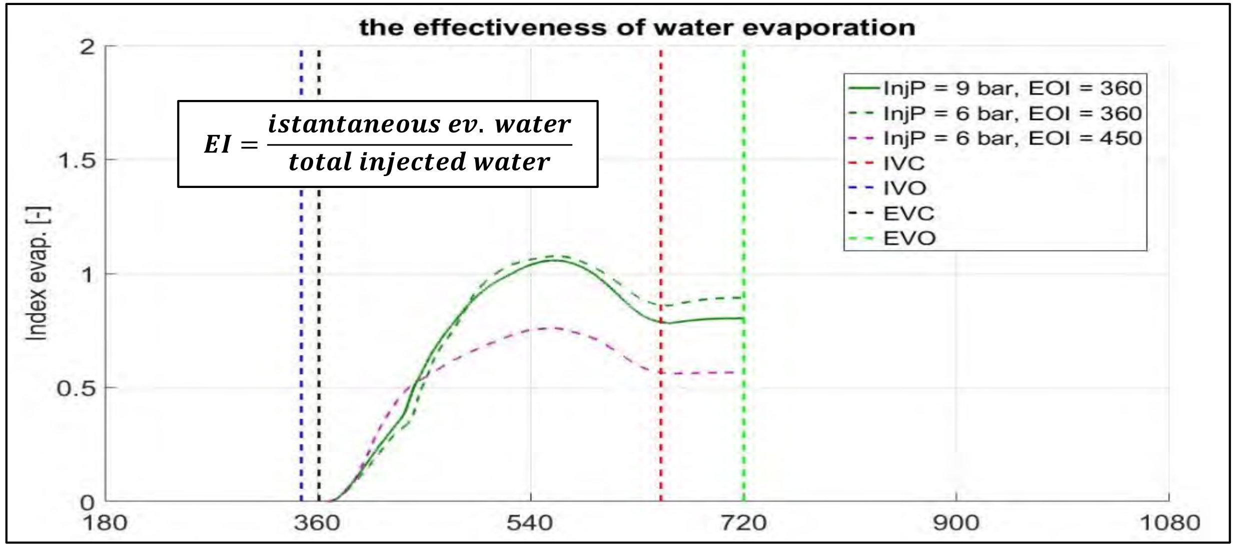
WI calibration parameters:

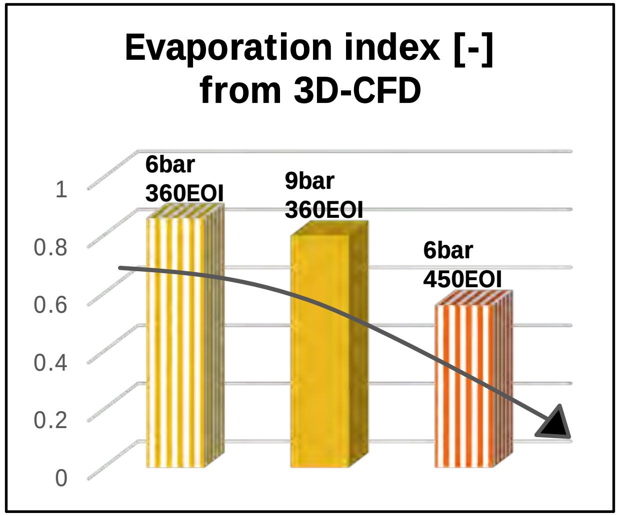
- **Injection pressure (6/9) [bar]**
- **End of injection (360/450) [CAdeg]**
- Water to fuel ratio (**18.5**/50) [%]
- Number of injectors/cyl. (**2**/1)

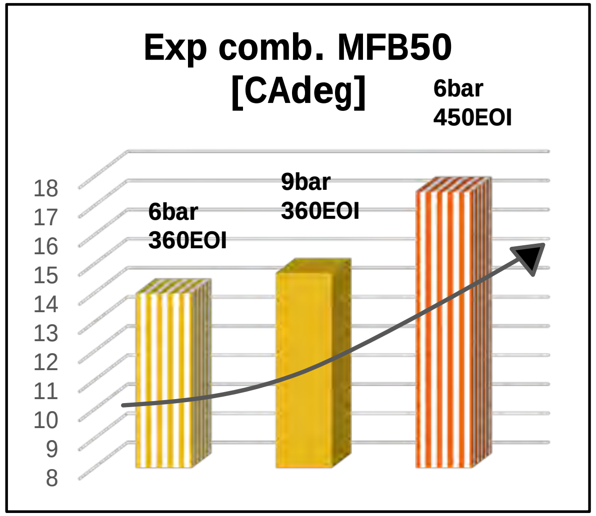
Water evaporation effectiveness is strictly related to combustion phasing, since the higher the percentage of vaporized water during intake, the lower the mixture temperature during compression and thus the less retarded combustion (lower MBF50 AFTDC).

Takeaways from 3D-CFD:

- **Injection Pressure has negligible effects** on water evaporation effectiveness.
- **Injection Phasing is important:** EOI@360CAdeg allows increasing the water dragging into cylinders.







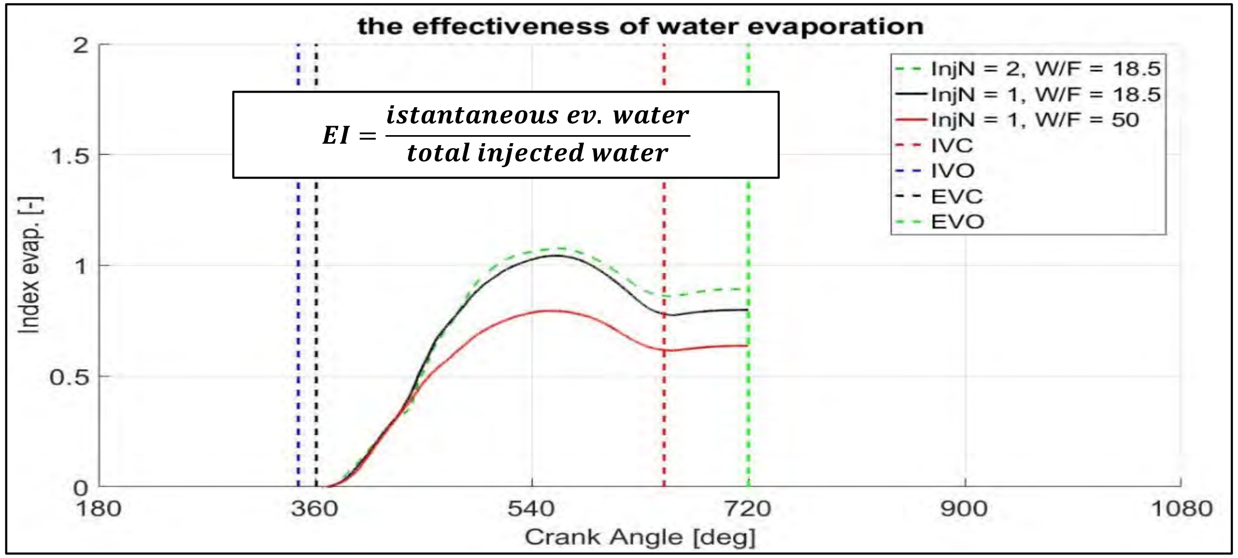
CFD-3D model and validation

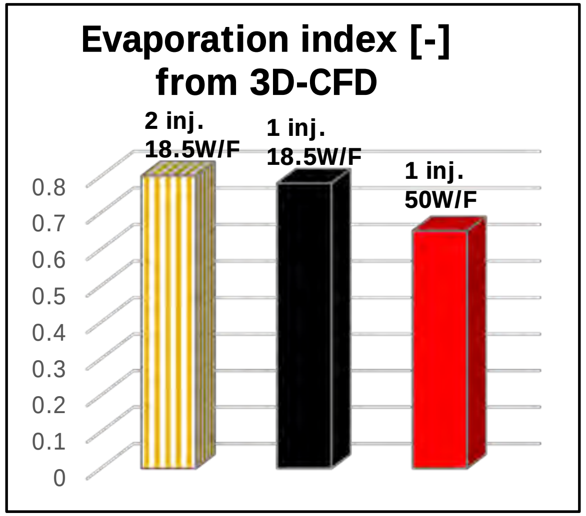
WI calibration parameters:

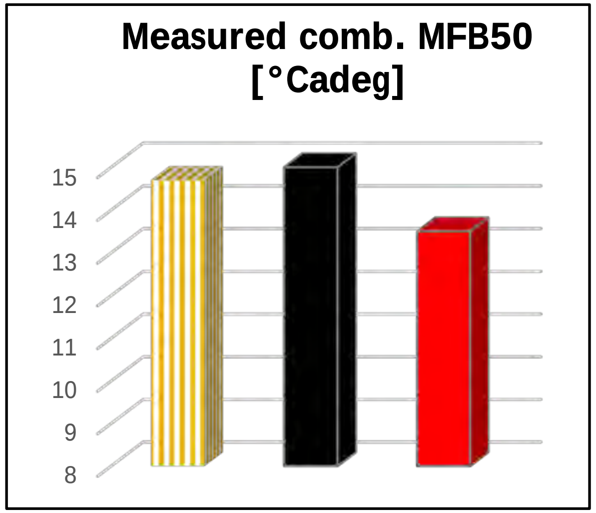
- Injection pressure (**6**/9) [bar]
- End of injection (**360**/450) [CAdeg]
- **Water to fuel ratio (18.5/50) [%]**
- **Number of injectors (2/1)**

Takeaways from 3D-CFD:

- **The number of injectors has negligible effect** on water evaporation effectiveness;
- W/F at 50% results in better combustion phasing. However, the injected water is almost tripled compared to the other two cases, with a lower evaporation effectiveness index ($\sim 0{,}6$) due to high water injection duration.







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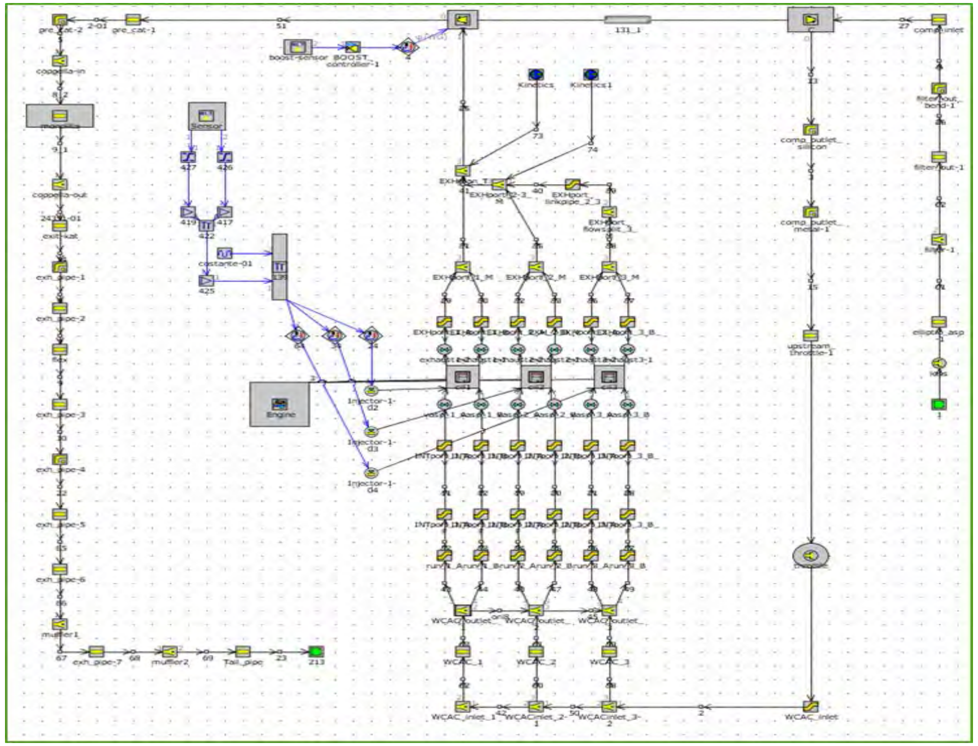
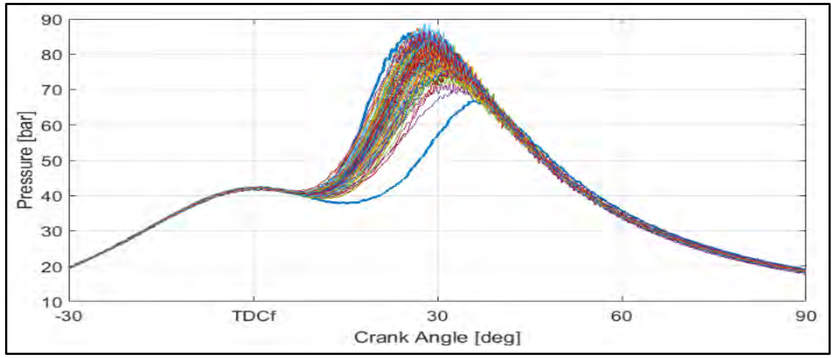
0D/1D combustion simulation and knock prediction

- Results of the experimental investigations and results obtained from 3D-CFD analysis were merged to calibrate a 0D combustion model in GT Power to simulate the effect of water injection on the combustion process and on knock mitigation.

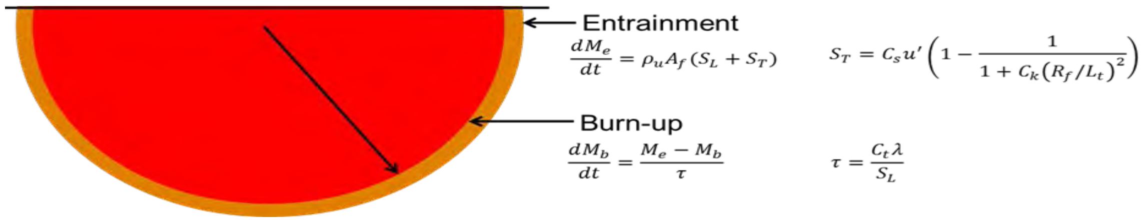
- The model is capable to reproduce Cycle to Cycle Variations (CCV) of the combustion process, and the probability of knock occurrence on a cycle by cycle basis.



GT-Power 1D/0D engine model



CCV of the combustion process



SI Turb 0D model used in GTPower

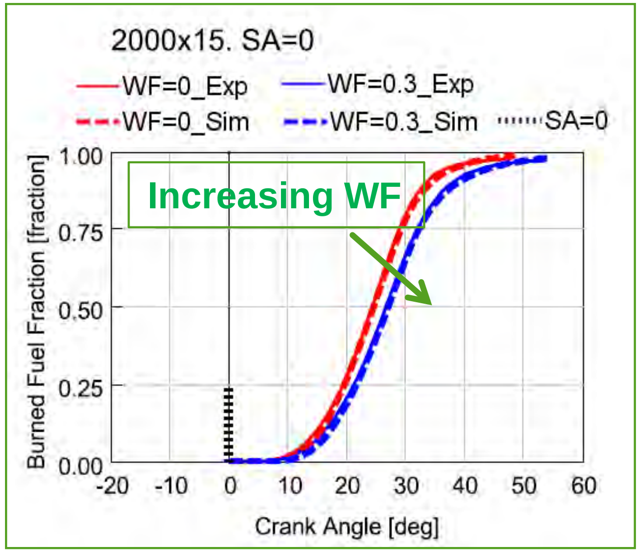
Preliminary 0D Modelling

Results

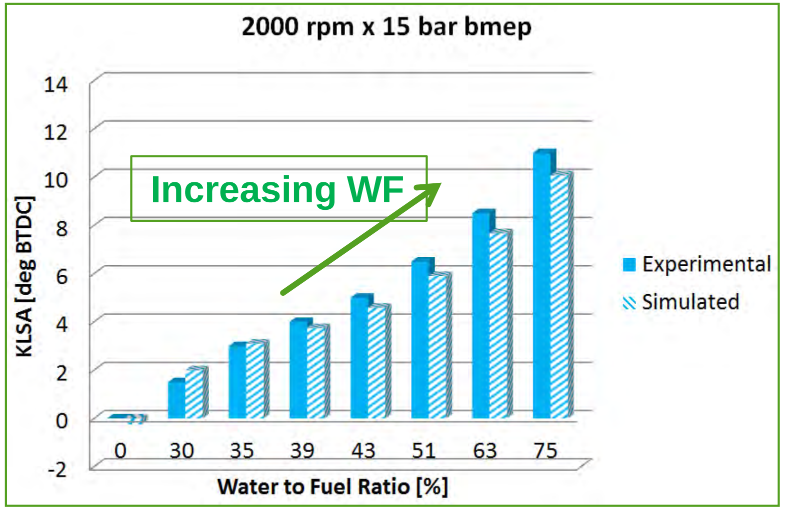
- The SI-Turb combustion model is capable to fully capture the effects of the presence of water in the in-cylinder charge on the combustion process, correctly predicting a noticeable decrease of the burn rate even for a moderate water-to-fuel rate of 30%.

- The SI-Turb combustion model coupled with the DE knock model is capable to predict Knock Limited Spark Advance (KLSA) values as a function of the water-to-fuel ratio.

✓ *Combustion:*
increasing combustion duration



✓ *Knock mitigation:*
increase of knock limited spark advance

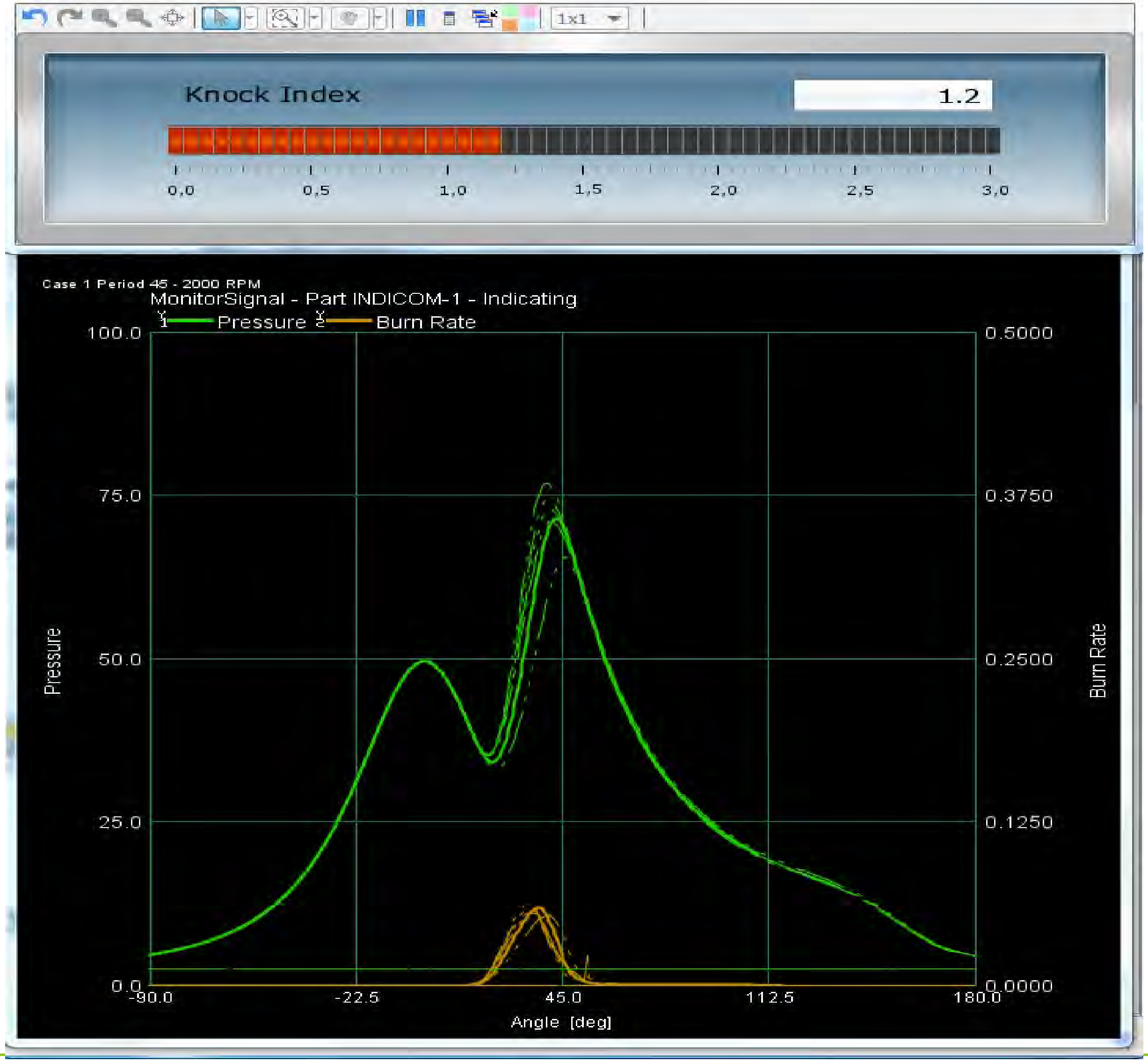


0D/1D combustion simulation and knock prediction

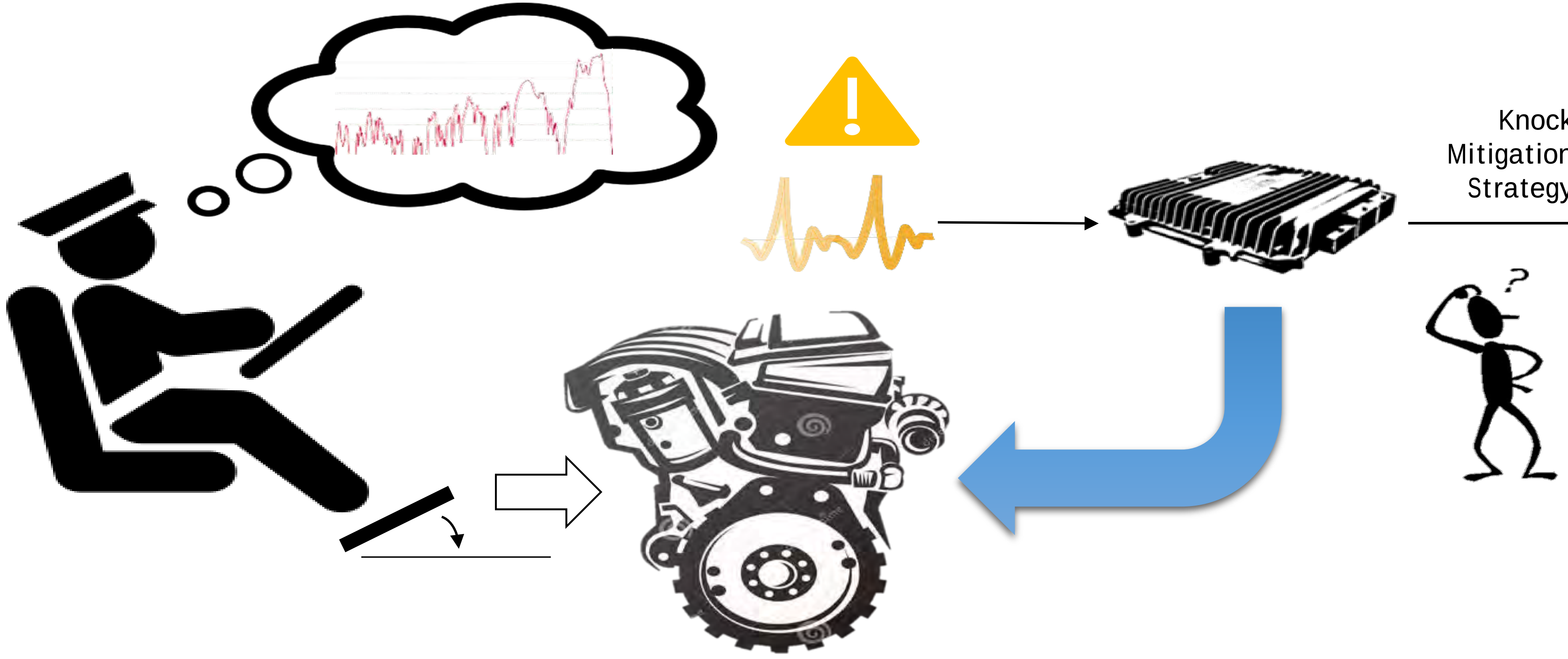
OPERATING POINT

2000 rpm@WOT

(CCV artificially emphatized)



0D/1D combustion simulation and knock prediction



Knock Mitigation Strategy

Water Injection

- Water Consumption

Spark Retard

- Efficiency penalty

SITurb

- **CCV Model**
- **Knock Model**

Evaluate knock occurence probability during transients

Mimic ECU Knock Control Strategy in GT

- Evaluate water consumption
- Evaluate efficiency penalty

Agenda

- Introduction
- Experimental Setup
  - Engine *A*
  - Engine *B*
- Knock Mitigation Techniques
  - Miller Cycle
  - Water Injection
  - 0D/1D combustion simulation and knock prediction
- Conclusions and Future Work

Conclusions and Future Work

- Application of Miller cycle and Water Injection for knock mitigation at medium-high load on a turbocharged downsized spark ignition engine was experimentally investigated.

- Thanks to Miller Cycle impressive efficiency enhancements (up to 20%) have been achieved at medium speeds and high loads. The analysis of the utilization of Miller cycle with EIVC and LIVC strategies showed more substantial improvements in terms of knock mitigation for LIVC.

- Water Injection confirmed an high potential to mitigate knock tendency. Results demonstrates the possibility to improve engine fuel efficiency increasing geometric compression ratio, achieving a decrease of fuel consumption of about 4% on most of engine operating conditions.

- Finally, a knock model was coupled with a predictive 0D combustion model (SI-Turb developed by Gamma Technologies), with the aim to predict the effects on the combustion process on knock tendency of LIVC and water injection, thus obtaining a powerful virtual test rig on which different design and calibration options could be tested and compared.

Engines, Energy and Environment Group

Tecniche per il controllo della detonazione in motori ad accensione comandata ad alto grado di sovralimentazione

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