CFD optimization of powertrain components using CAESES®

Giuseppe Cicalese, PhD
Mattia Brenner
Prof. Stefano Fontanesi
Mike Saroch

- ✓ **Introducing R&D CFD**
- ✓ **Case-studies: optimization targets**
- ✓ **Case-study #1: exhaust manifold optimization**
  - ✓ CFD strategy
  - ✓ Geometry parametrization
  - ✓ Results
  - ✓ Geometry re-design
  - ✓ Conclusions
- ✓ **Case-study #2: compressor inlet pipe optimization**
  - ✓ CFD setup
  - ✓ Results
  - ✓ Conclusions

- ✓ **Introducing R&D CFD**
- ✓ **Case-studies: optimization targets**
- ✓ **Case-study #1: exhaust manifold optimization**
  - ✓ CFD strategy
  - ✓ Geometry parametrization
  - ✓ Results
  - ✓ Geometry re-design
  - ✓ Conclusions
- ✓ **Case-study #2: compressor inlet pipe optimization**
  - ✓ CFD setup
  - ✓ Results
  - ✓ Conclusions

R&D CFD by numbers…

- ✓ born in July 2012
- ✓ 7 CFD engineers + 5 high level CFD Specialists
- ✓ 400 core HPC cluster
- ✓ 2 funded PhD positions in 4 years
- ✓ +30% per year increasing revenue since foundation
- ✓ 4 commercial partners to provide a 360° consultancy
- ✓ engineering services for some of the most renowned engine manufacturers
- ✓ R&D CFD is a partner of FRIENDSHIP SYSTEMS

http://www.red-cfd.it
info@red-cfd.it
+39 059 205 6345
Via P. Vivarelli 2
41125 Modena
ITALY

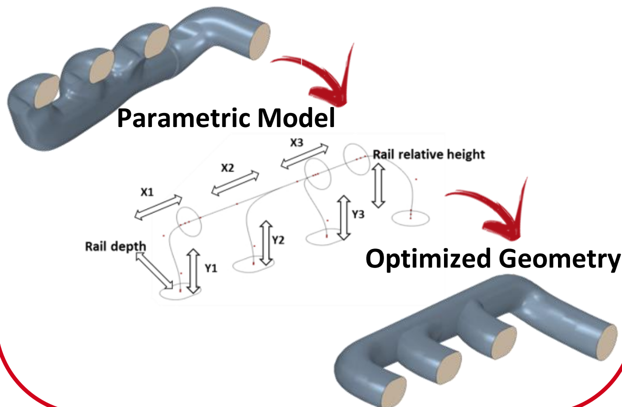
UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

R&D CFD: who we are, what we do

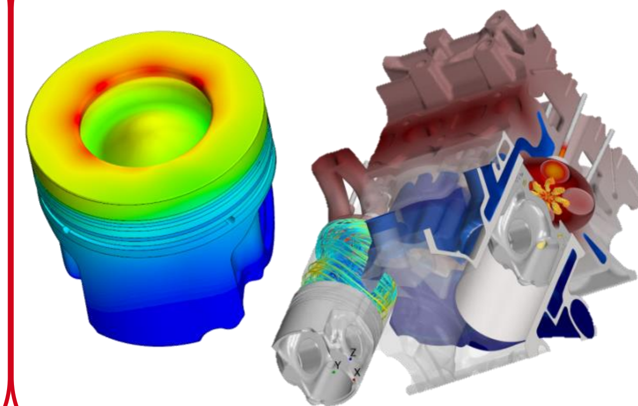
Geometrical Optimizations

Optimization processes driven by CAESES

Original Geometry



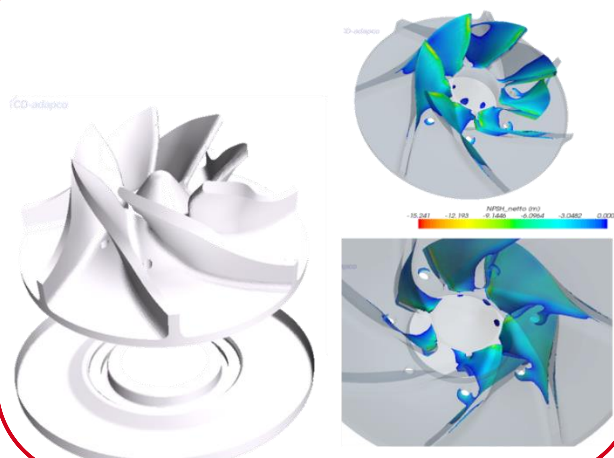
Heat Transfer



Combustion and Knock

Sloshing Simulations

Turbomachinery



Detailed Chemistry Calculations

The most relevant computed properties are:
- ✓ laminar flame speed
- ✓ auto-ignition delay
- ✓ soot precursor formation rate

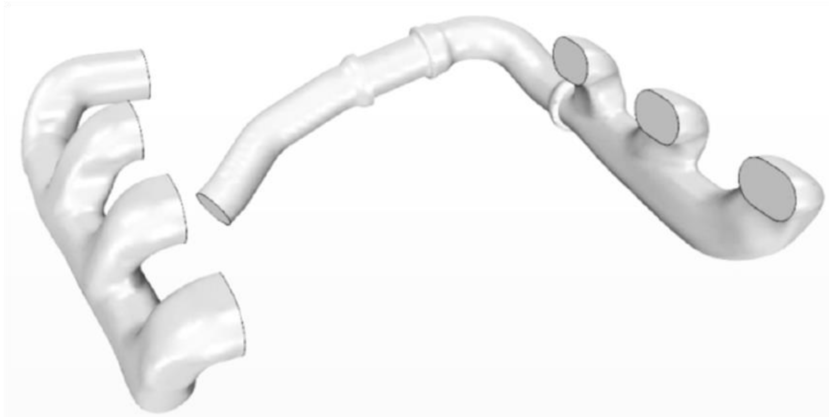
...and much more!

UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

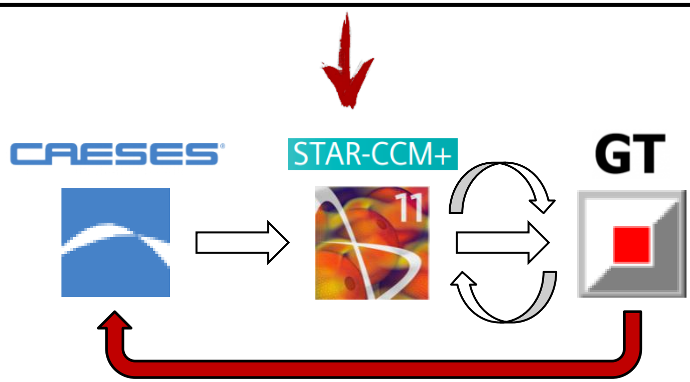
- ✓ Introducing R&D CFD
- ✓ **Case-studies: optimization targets**
- ✓ Case-study #1: exhaust manifold optimization
  - ✓ CFD strategy
  - ✓ Geometry parametrization
  - ✓ Results
  - ✓ Geometry re-design
  - ✓ Conclusions
- ✓ Case-study #2: compressor inlet pipe optimization
  - ✓ CFD setup
  - ✓ Results
  - ✓ Conclusions

Optimization Targets

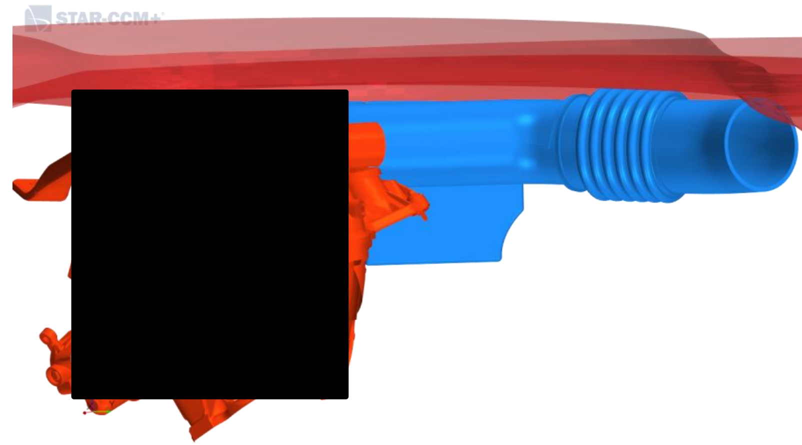
Case-study #1



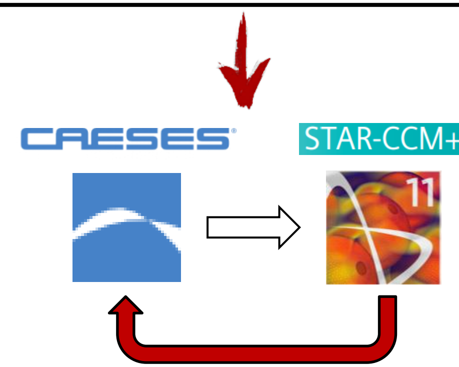
- BSFC reduction
- BMEP increase



Case-study #2



- Pressure drop reduction
- High flow uniformity @ compressor inlet
- High EGR uniformity @ compressor inlet

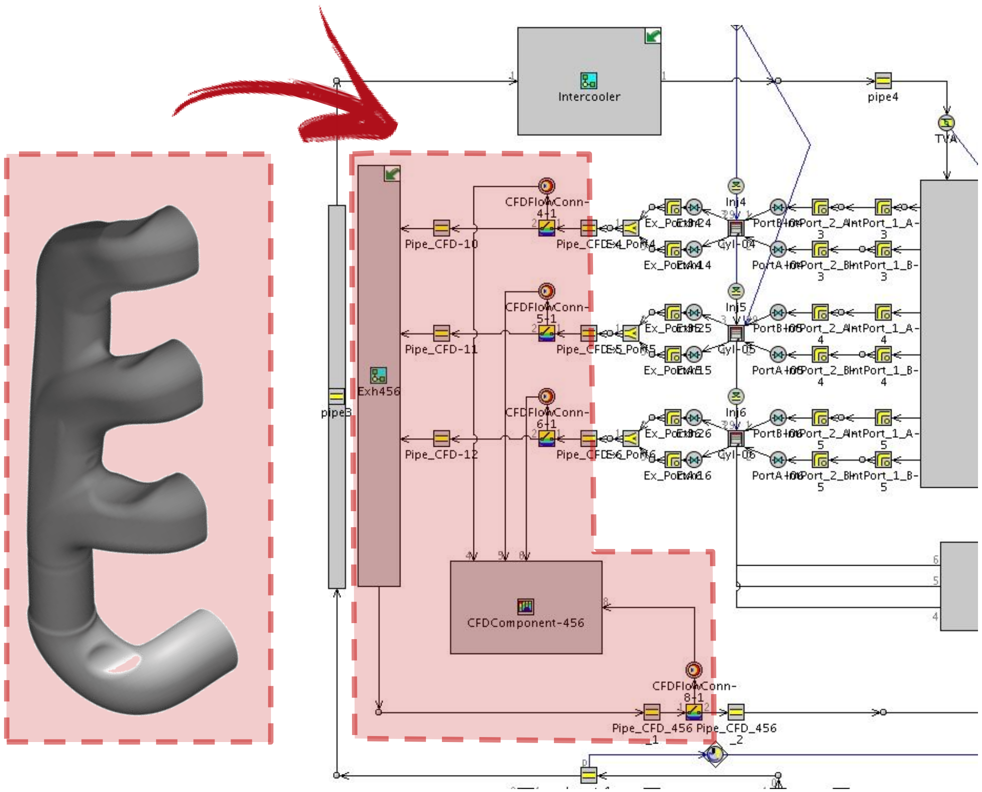


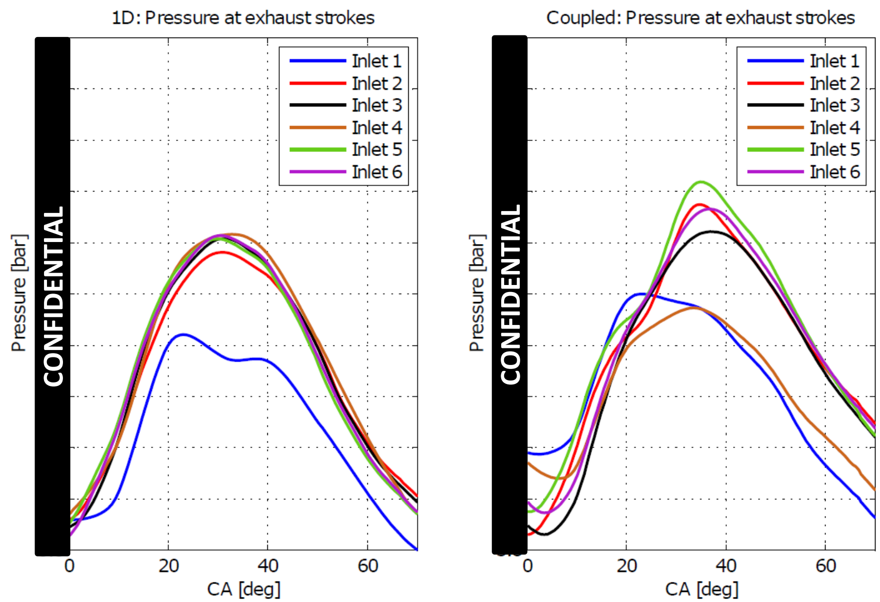
- ✓ Introducing R&D CFD
- ✓ Case-studies: optimization targets
- ✓ **Case-study #1: exhaust manifold optimization**
  - ✓ CFD strategy
  - ✓ Geometry parametrization
  - ✓ Results
  - ✓ Geometry re-design
  - ✓ A look at FE analyses
  - ✓ Conclusions
- ✓ Case-study #2: compressor inlet pipe optimization
  - ✓ CFD setup
  - ✓ Results
  - ✓ Conclusions

The 1D-CFD model is modified for the coupling with Star-CCM+

The manifolds are not symmetric → both of them are simulated

Despite the global engine parameters are not deeply affected by the coupling, all the cylinders show a different behavior during the exhaust stroke → 3D effects are well captured





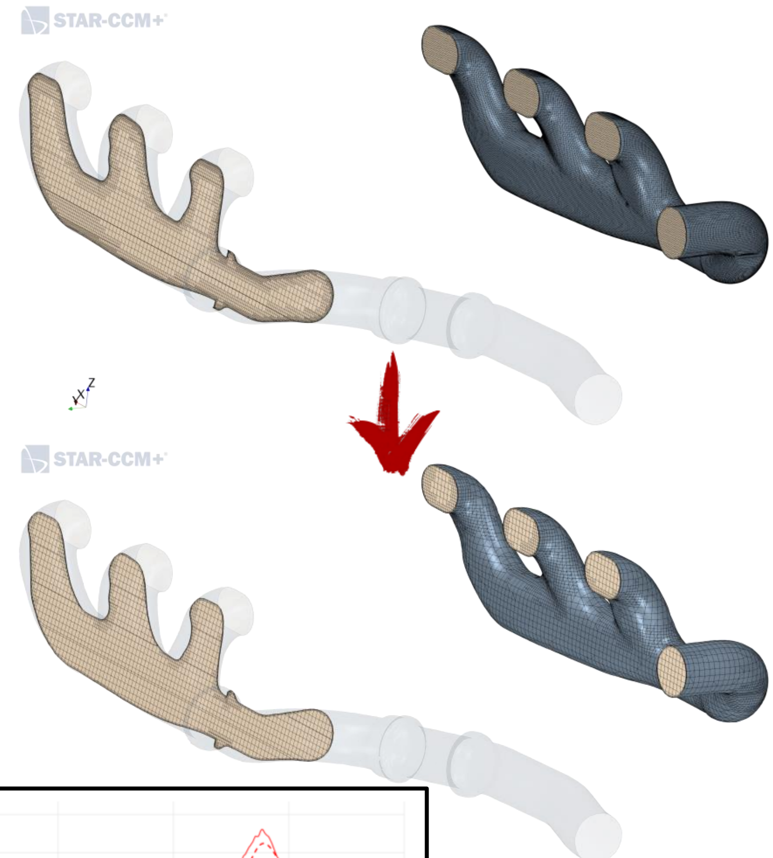
- ✓ Typical 3-D meshes range between 500.000 to 1.000.000 cells
- ✓ «PISO unsteady» solver is used
- ✓ Timestep (according to Courant Number): 0.1 to 0.5 °CA

Pros

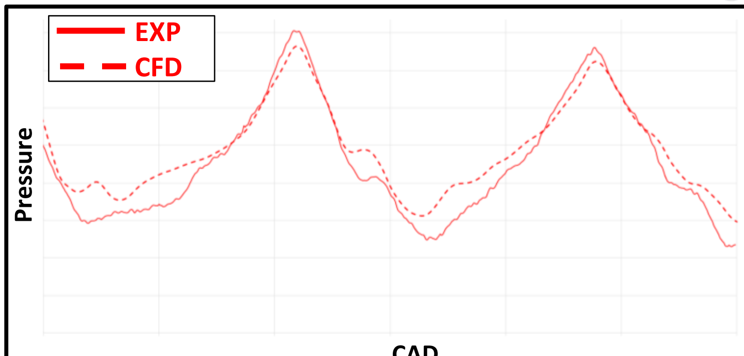
- ✓ Performance are well estimated

Cons

- ✓ CPU time: about 24h/36h for high revving speeds, even more than 50h for low revving speeds



- With coarser mesh a higher time-step is used
- With accurate initial conditions, convergence is met within a reduced number of cycles
- A trade-off has to be searched between calculation time and accuracy
- 3h per design are suitable to proceed to the optimization
- The simplified model keeps a good reliability against the experimental data



- ✓ **Introducing R&D CFD**
- ✓ **Case-studies: optimization targets**
- ✓ **Case-study #1: exhaust manifold optimization**
  - ✓ CFD strategy
  - ✓ Geometry parametrization
  - ✓ Results
  - ✓ Geometry re-design
  - ✓ Conclusions
- ✓ **Case-study #2: compressor inlet pipe optimization**
  - ✓ CFD setup
  - ✓ Results
  - ✓ Conclusions

Case-study #1: Geometry Parametrization

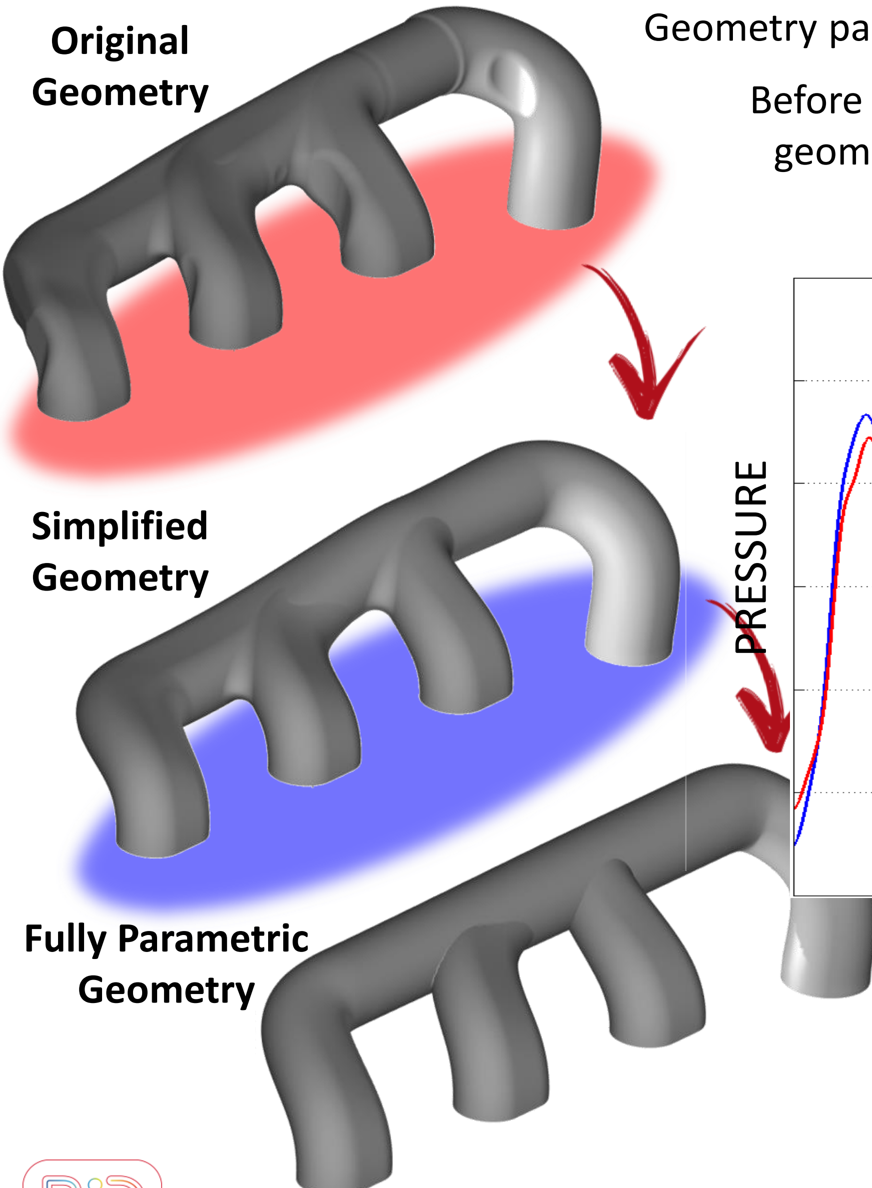
Geometry parametrization is provided by CAESES team

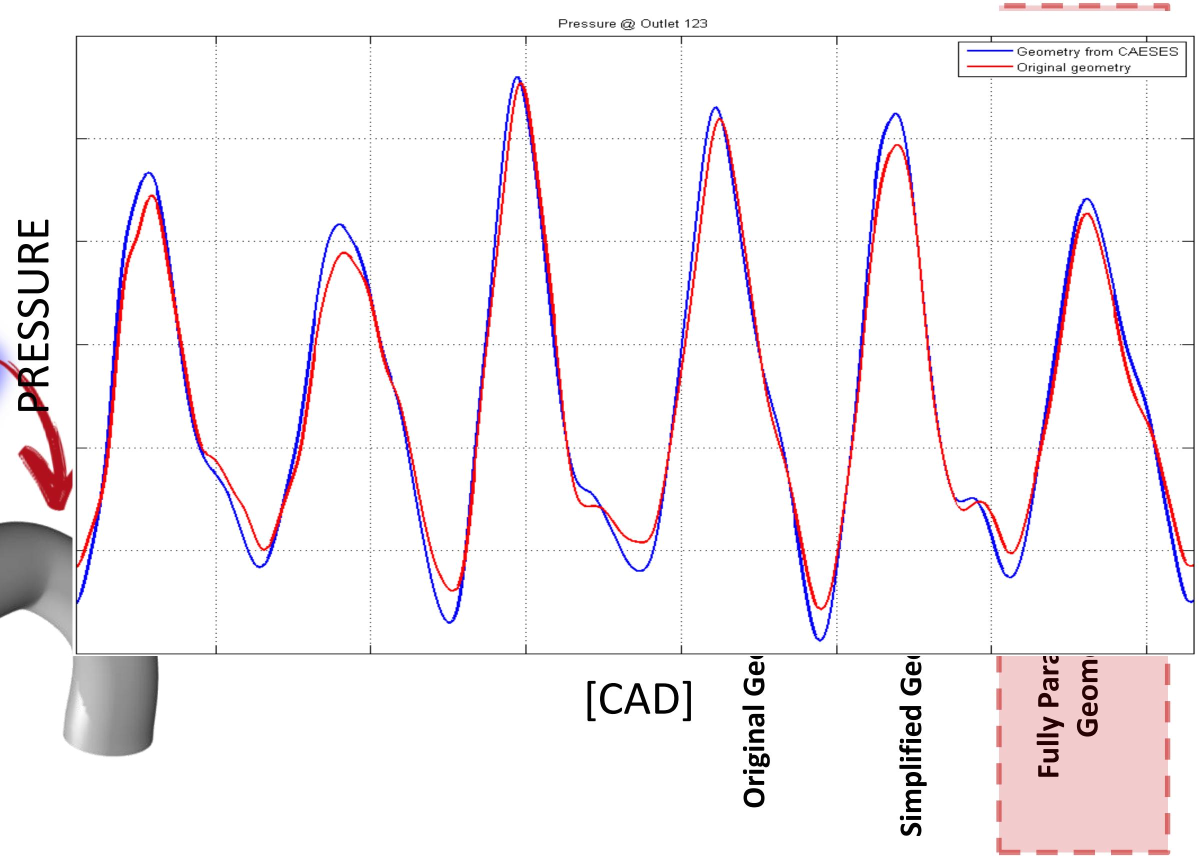
Before performing the optimization, a progressively less complex geometry is generated and some interesting results emerge in comparison with the baseline solution

Original Geometry

Simplified Geometry

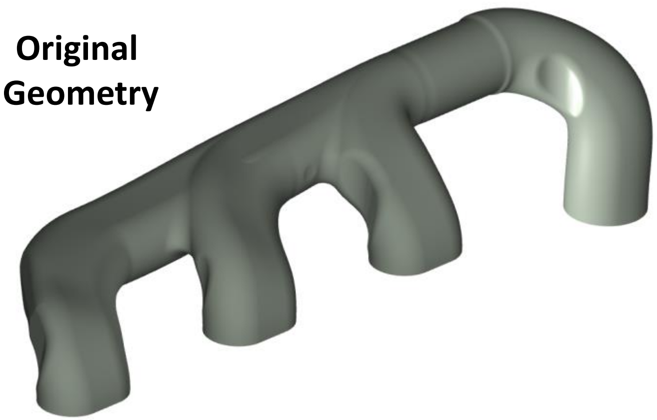
Fully Parametric Geometry

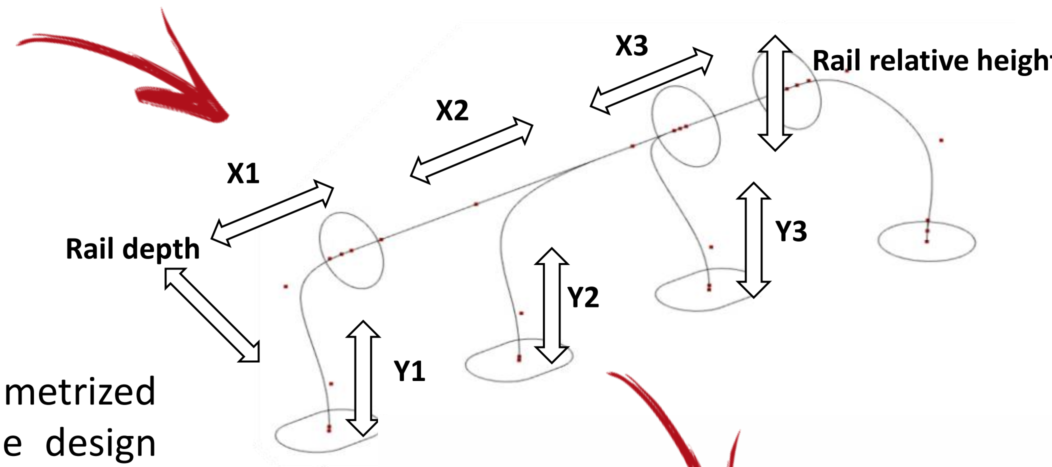


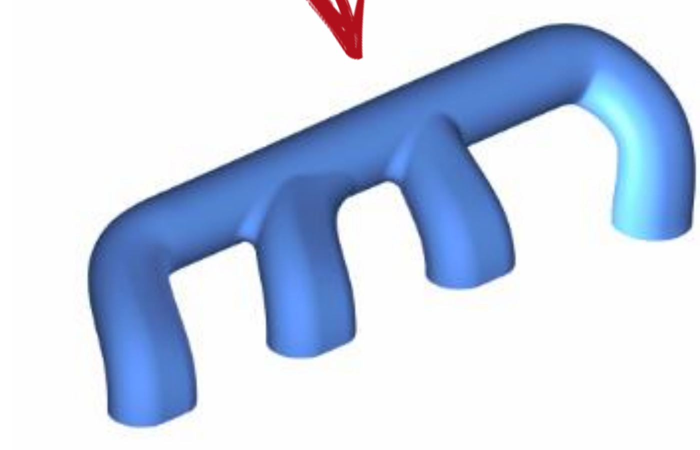


UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

Original Geometry



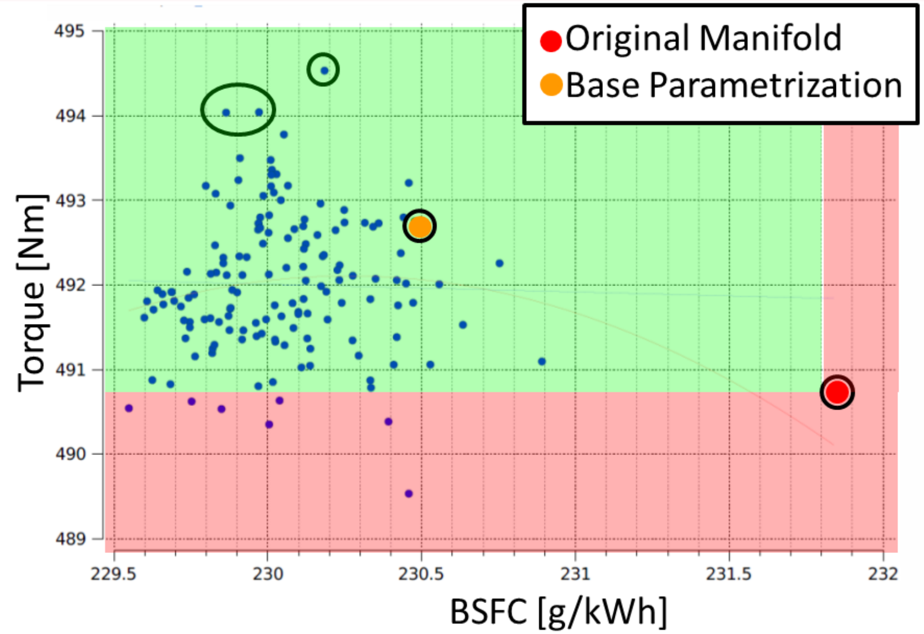


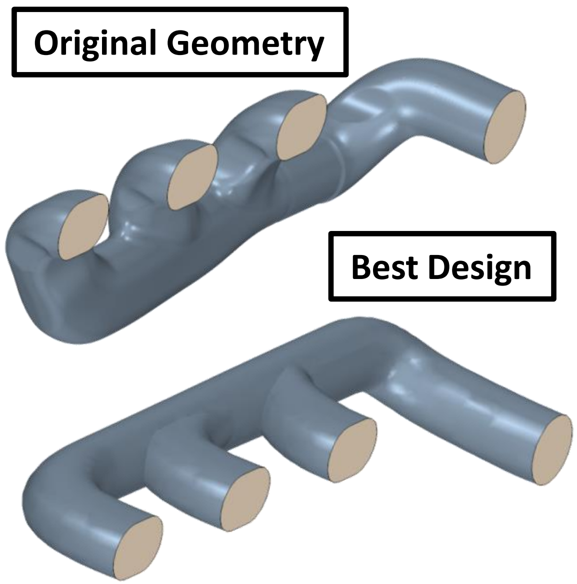


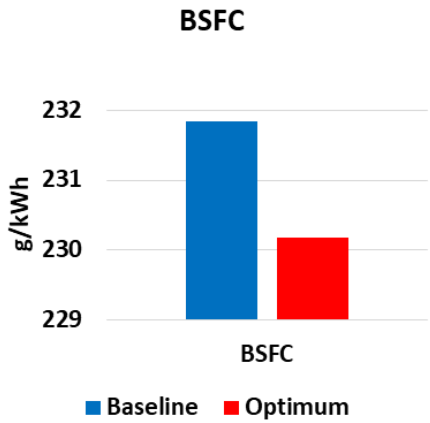
- ✓ The original geometry is parametrized by 8 different parameters to make the design space as wide as possible
- ✓ Less than 100k cells are used for each design
- ✓ The calculation time @3800rpm is ≈180min
- ✓ PISO solver is used
- ✓ Convergence is met after 40 1D-CFD cycles and 20 1D/3D-CFD cycles
- ✓ 150 different solutions are evaluated

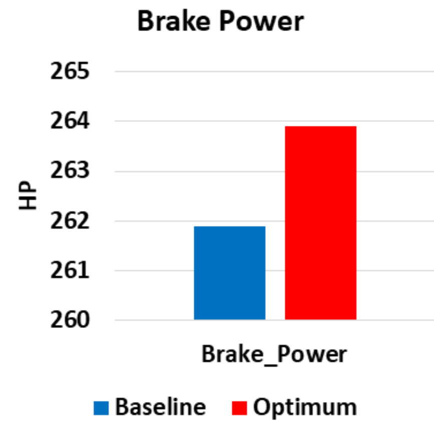
- ✓ **Introducing R&D CFD**
- ✓ **Case-studies: optimization targets**
- ✓ **Case-study #1: exhaust manifold optimization**
  - ✓ CFD strategy
  - ✓ Geometry parametrization
  - ✓ Results
  - ✓ Geometry re-design
  - ✓ Conclusions
- ✓ **Case-study #2: compressor inlet pipe optimization**
  - ✓ CFD setup
  - ✓ Results
  - ✓ Conclusions

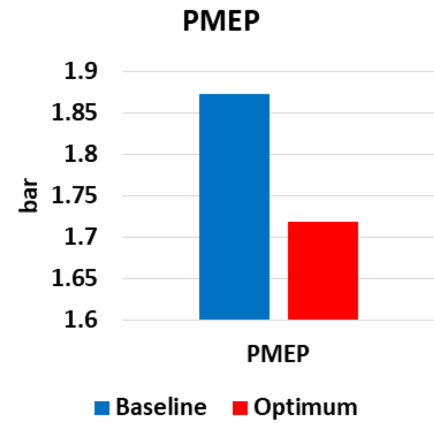
- ✓ Each case ended the calculation (robustness)
- ✓ Best designs show +2HP in power and -2.5 g/kWh in fuel consuption compared to the original geometry (red dot)
- ✓ The base parametrization is an improvement itself
- ✓ Power increasing is due mainly to a reduction of pumping losses
- ✓ Less volume →faster engine response









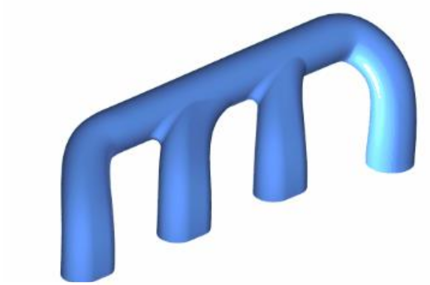


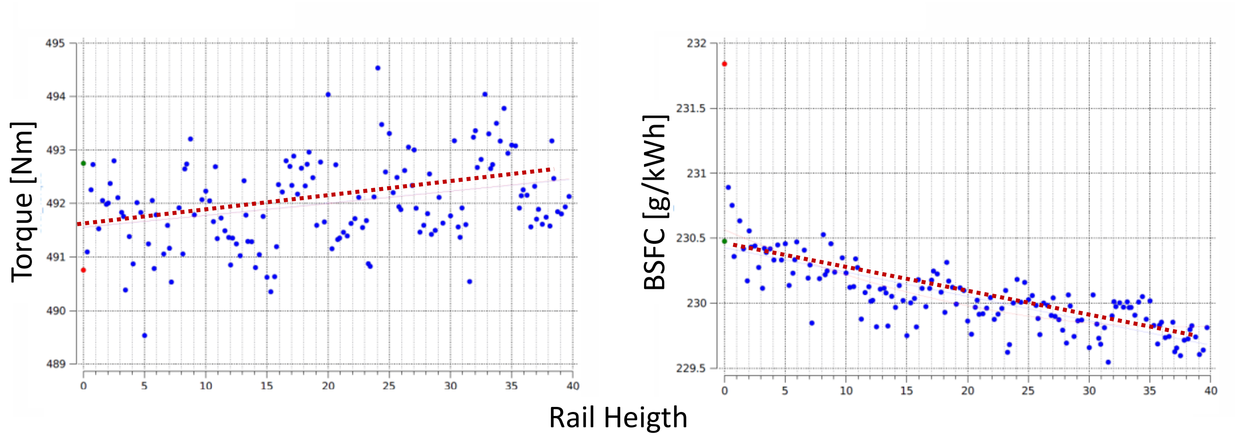
UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

Just some design parameters show a clear trend

Rail Height increase:

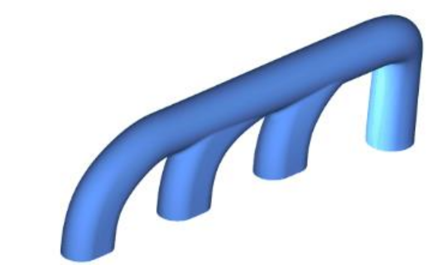
- ✓ increases output power
- ✓ decreases fuel consumption

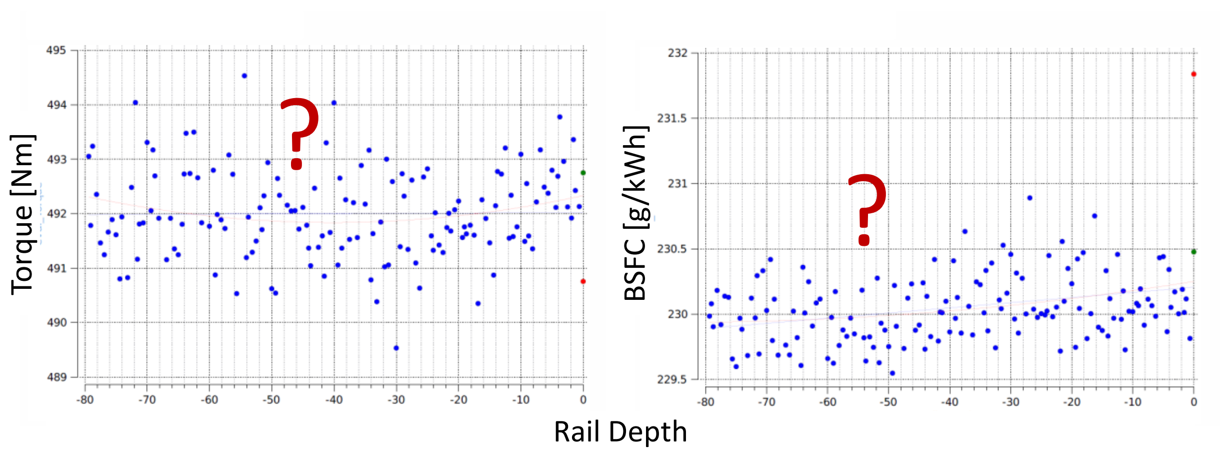




Rail Depth increase:

- ✓ Does not show clear trends



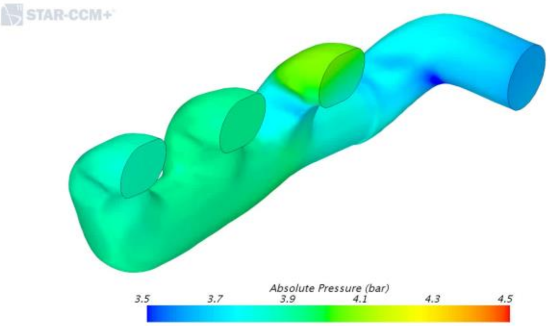


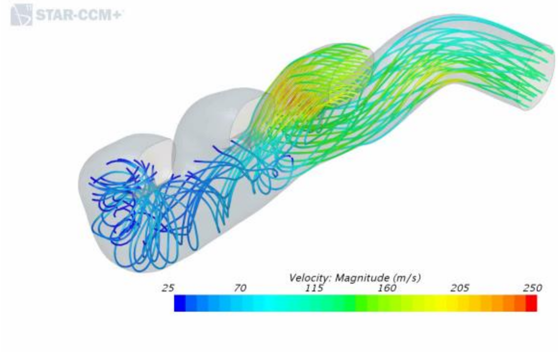
Case-study #1: Results

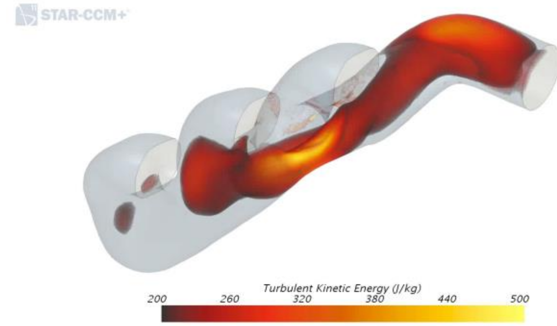
Original Geometry

inhomogeneous swirling flow

high turbulence -> dissipation







Absolute pressure [bar]

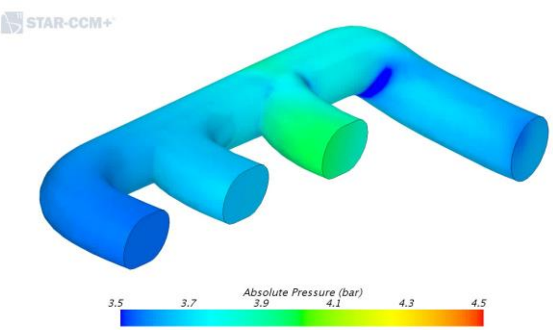
Velocity magnitude [m/s]

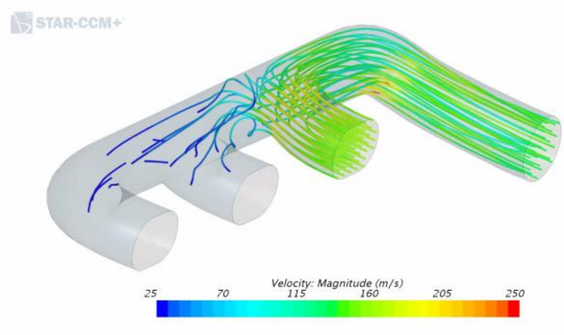
TKE [m²/s²]

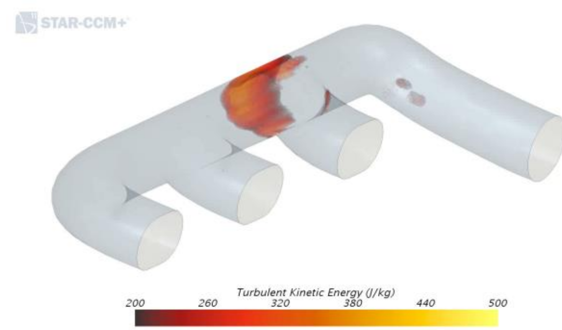
Best Design

well-organized homogeneous flow

low turbulence -> reduced losses



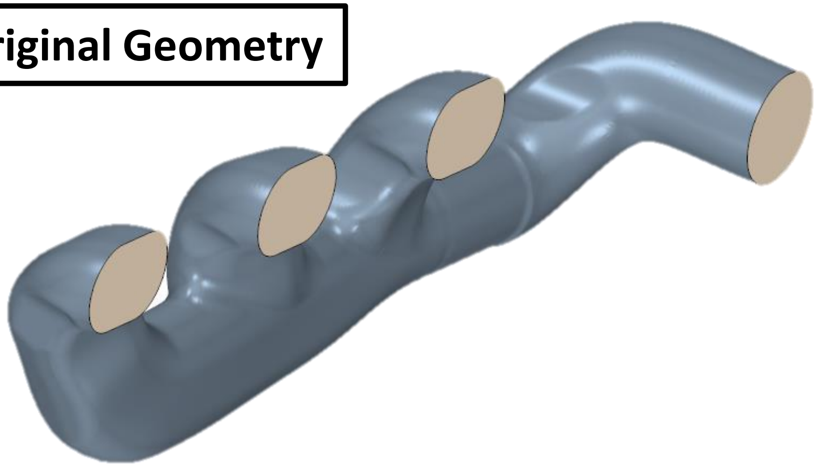




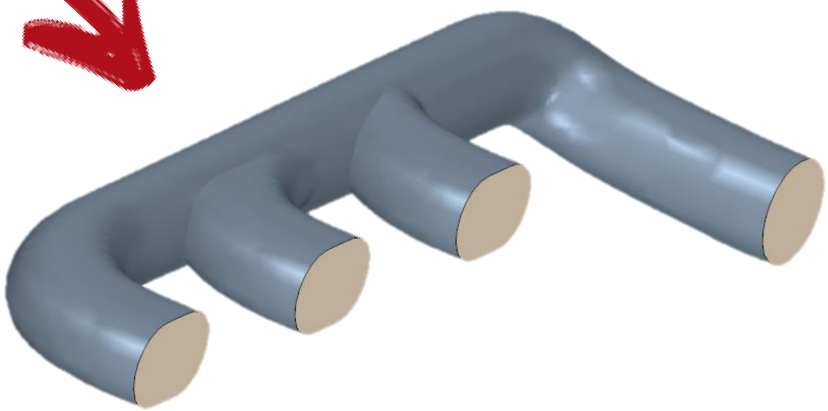
- ✓ Introducing R&D CFD
- ✓ Case-studies: optimization targets
- ✓ **Case-study #1: exhaust manifold optimization**
  - ✓ CFD strategy
  - ✓ Geometry parametrization
  - ✓ Results
  - ✓ **Geometry re-design**
  - ✓ Conclusions
- ✓ Case-study #2: compressor inlet pipe optimization
  - ✓ CFD setup
  - ✓ Results
  - ✓ Conclusions

The driving design factors emerged during the optimization process are taken into account to re-design the exhaust manifold.

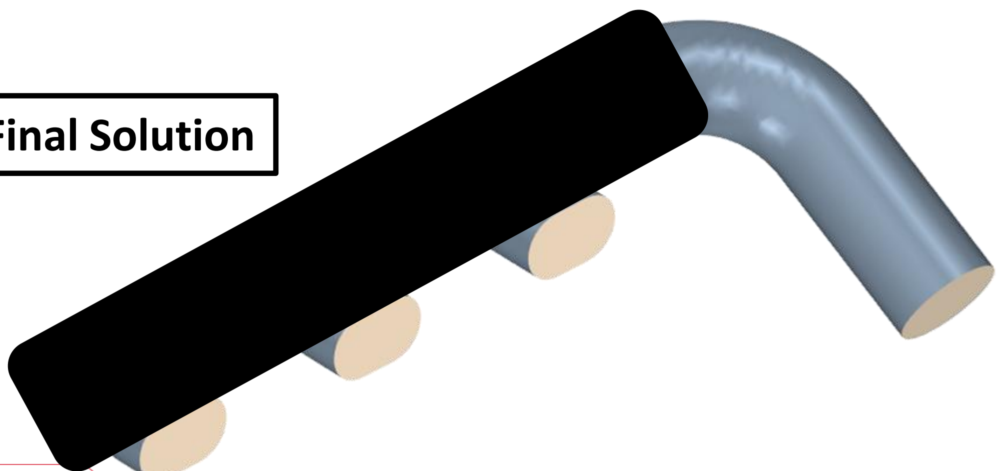
Original Geometry



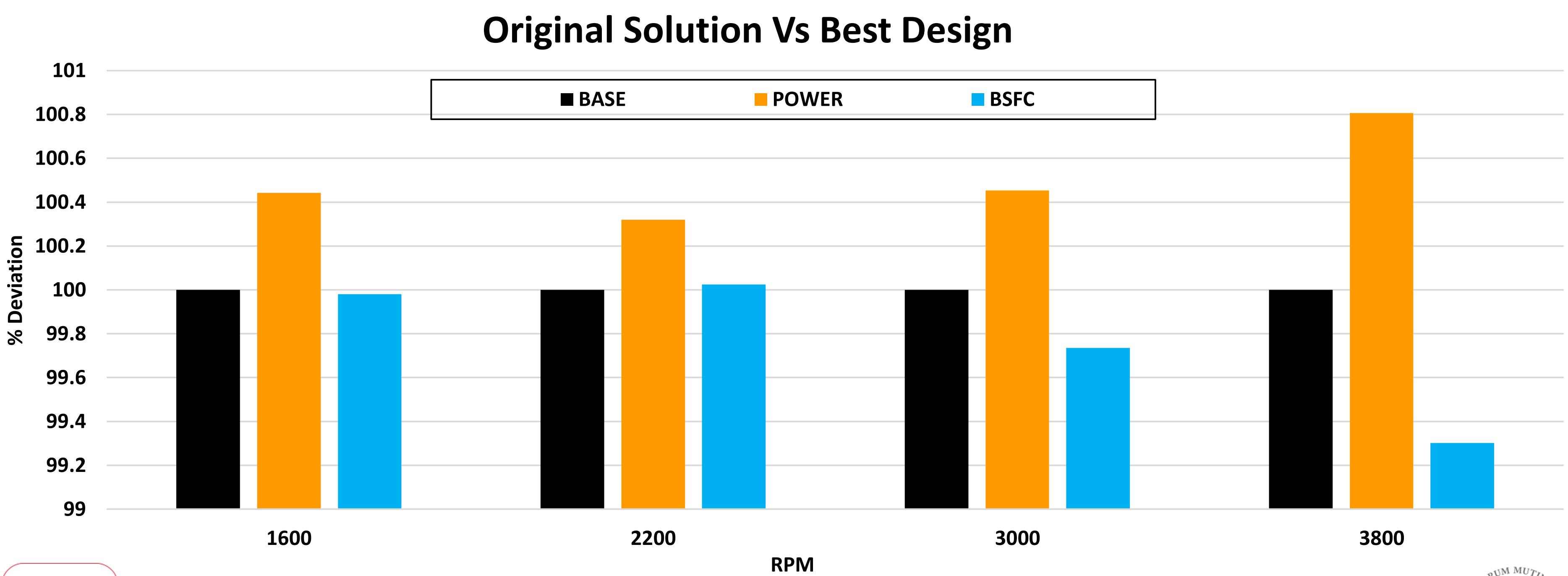
Optimized Design



Final Solution



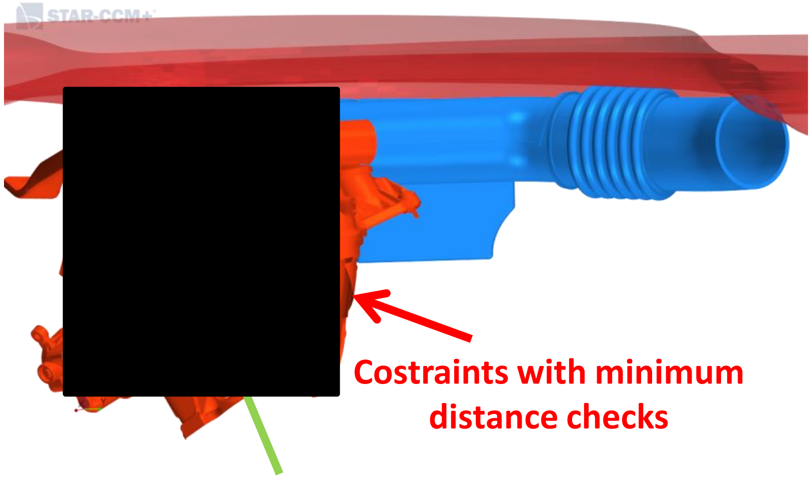
- ✓ The best solution is tested at different operations and it always shows a better behavior than original geometry
- ✓ Optimized design manifolds show higher power under all operating conditions
- ✓ BSFC saving is higher for high engine revving speed
- ✓ turbine Efficiency changes due to changes in P3 and T3
- ✓ Compressor Efficiency remains unaffected, since Airflow and Boost Pressure do not change significantly



- ✓ Introducing R&D CFD
- ✓ Case-studies: optimization targets
- ✓ **Case-study #1: exhaust manifold optimization**
  - ✓ CFD strategy
  - ✓ Geometry parametrization
  - ✓ Results
  - ✓ Geometry re-design
  - ✓ **Conclusions**
- ✓ Case-study #2: compressor inlet pipe optimization
  - ✓ CFD setup
  - ✓ Results
  - ✓ Conclusions

- ✓ Coupled simulations are very suitable for exhaust system simulations and intake as well.
- ✓ Thanks to the reduction of computational costs and times, coupled simulations can be used in a DOE or optimization process.
- ✓ A wide range of geometrical solutions can be investigated and an optimal design can be found according with imposed geometrical constraints.
- ✓ The optimized design improves both BMEP and BSFC, as well as the re-designed component.
- ✓ From a thermo-mechanical viewpoint the new component overcomes the limitations of the previous one.

- ✓ **Introducing R&D CFD**
- ✓ **Case-studies: optimization targets**
- ✓ **Case-study #1: exhaust manifold optimization**
  - ✓ CFD strategy
  - ✓ Geometry parametrization
  - ✓ Results
  - ✓ Geometry re-design
  - ✓ Conclusions
- ✓ **Case-study #2: compressor inlet pipe optimization**
  - ✓ CFD setup
  - ✓ Results
  - ✓ Conclusions



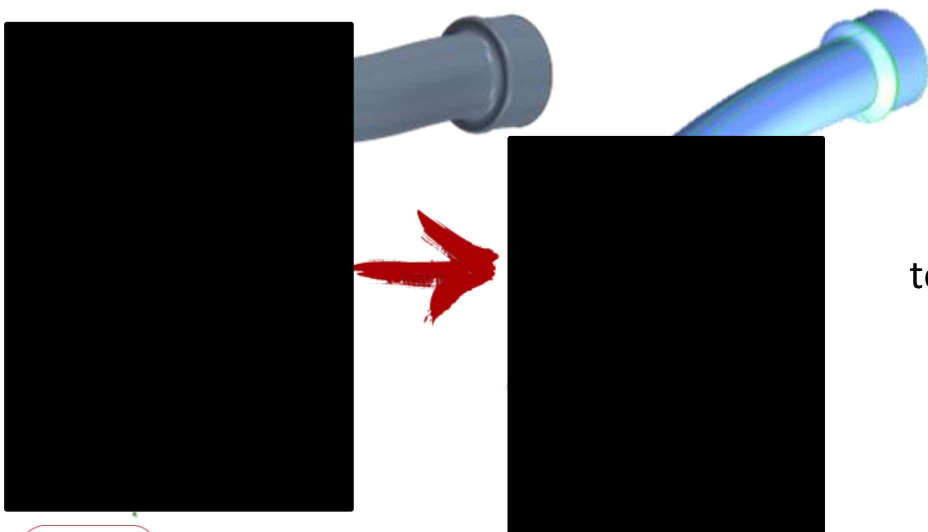
Targets of the optimization:

- Pressure drop reduction
- High flow uniformity @ compressor inlet
- High EGR uniformity @ compressor inlet

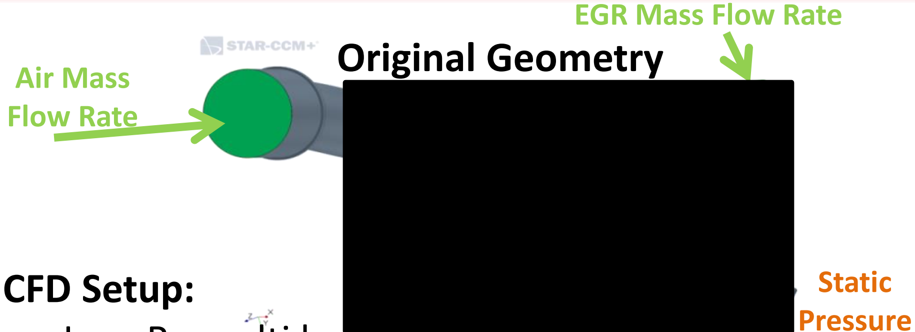
The optimization process is performed over 3 different OPs:

- WOT @ peak power operation
- High EGR @ mid-to-high revving speed
- High EGR @ low revving speed

Multi-objective multi-operation optimization



Original design is reproduced by CAESES team in a parametric fashion and it is tested to evaluate its performance.



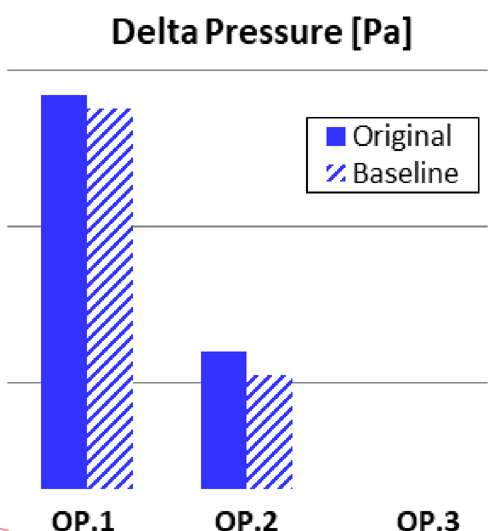
CFD Setup:

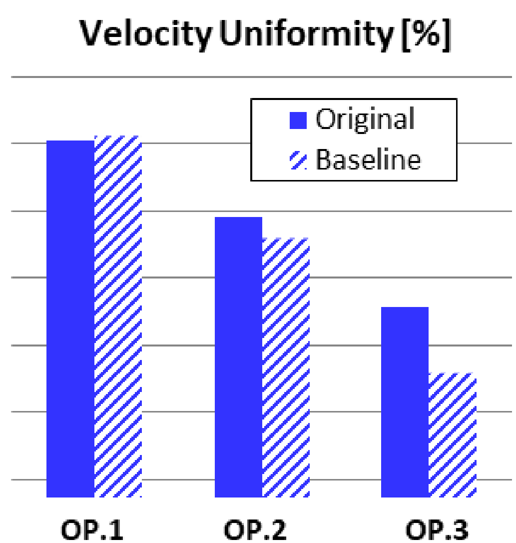
- Low-Re multi layer approach
- Ideal gas
- EGR represented by means of a Passive Scalar
- Extrusion at inlets and outlets
- The convergent compressor inlet is included

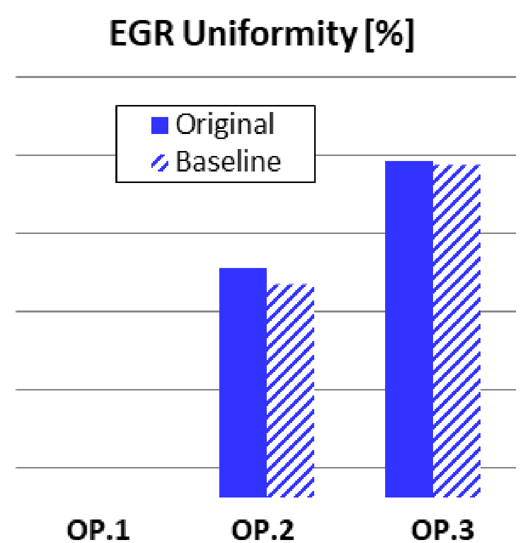
The baseline parametric model is very close to the original design

In order to weight the target for each operation over the mass flow rate, 3 functions are defined for each objective

All targets are evaluated over all the investigated operating conditions and a cumulative function for each target is introduced





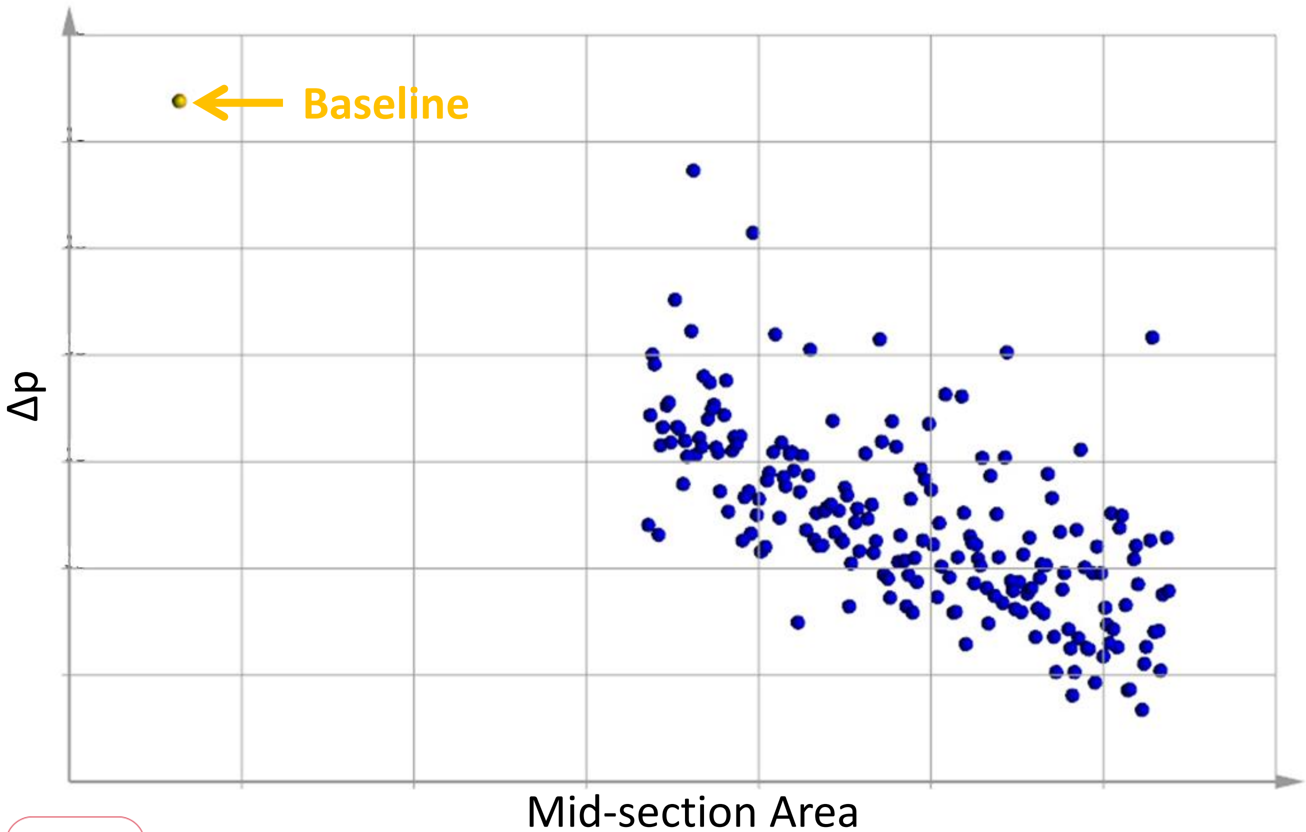


UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

- ✓ **Introducing R&D CFD**
- ✓ **Case-studies: optimization targets**
- ✓ **Case-study #1: exhaust manifold optimization**
  - ✓ CFD strategy
  - ✓ Geometry parametrization
  - ✓ Results
  - ✓ Geometry re-design
  - ✓ Conclusions
- ✓ **Case-study #2: compressor inlet pipe optimization**
  - ✓ CFD setup
  - ✓ Results
  - ✓ Conclusions

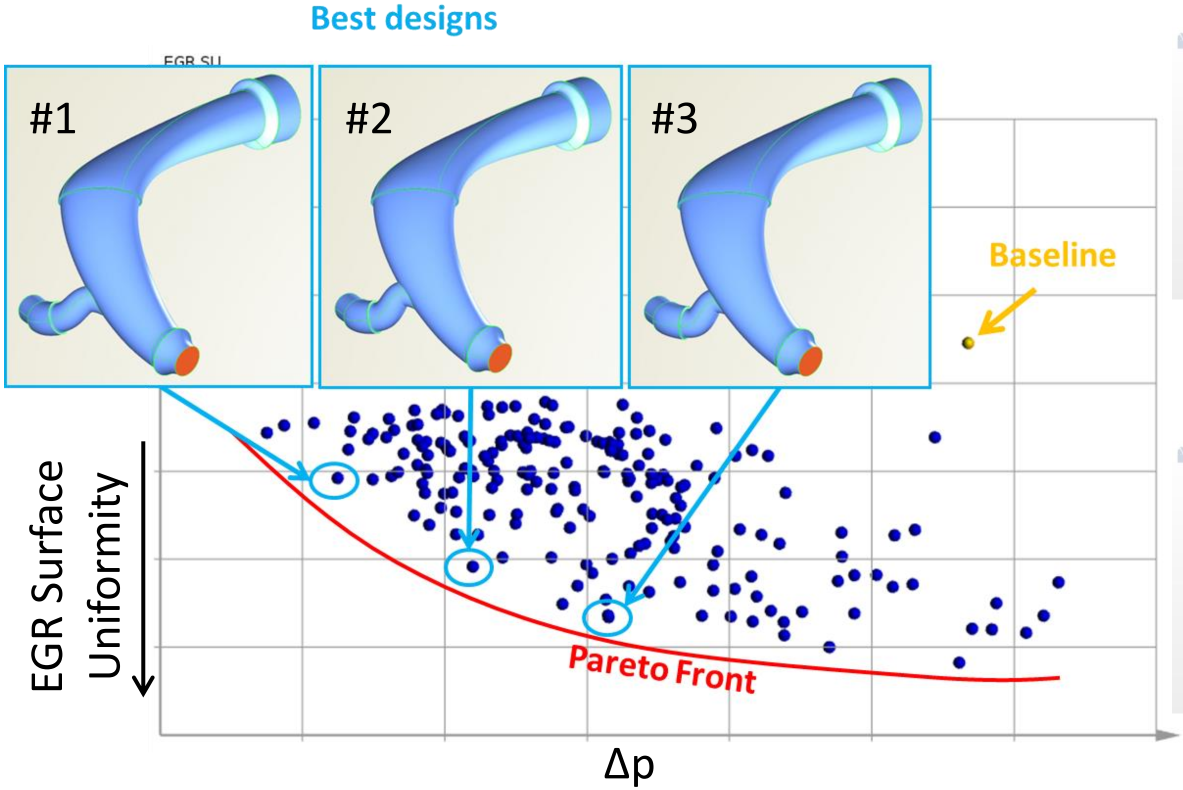
A design exploration of 200 designs is performed in order to identify the optimization driving factors.

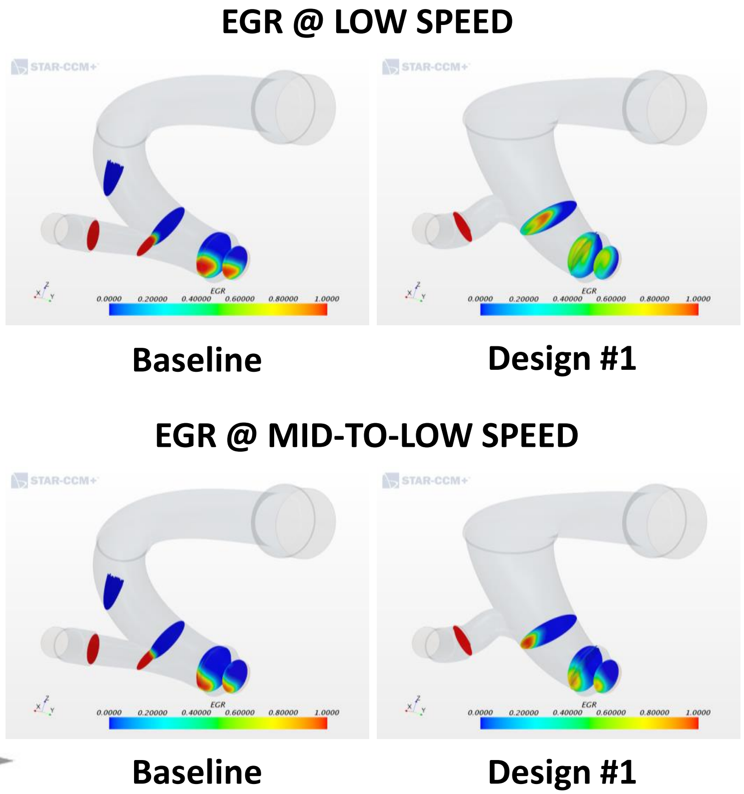
- Pressure drop is very tightly correlated to mid section area → **elliptic shape because of the constraints**
- A correlation emerges between pressure drop and EGR pipe junction position
- EGR Surface Uniformity is dominated by the pipe junction position
- Surface uniformity is pretty unaffected by geometrical modifications.



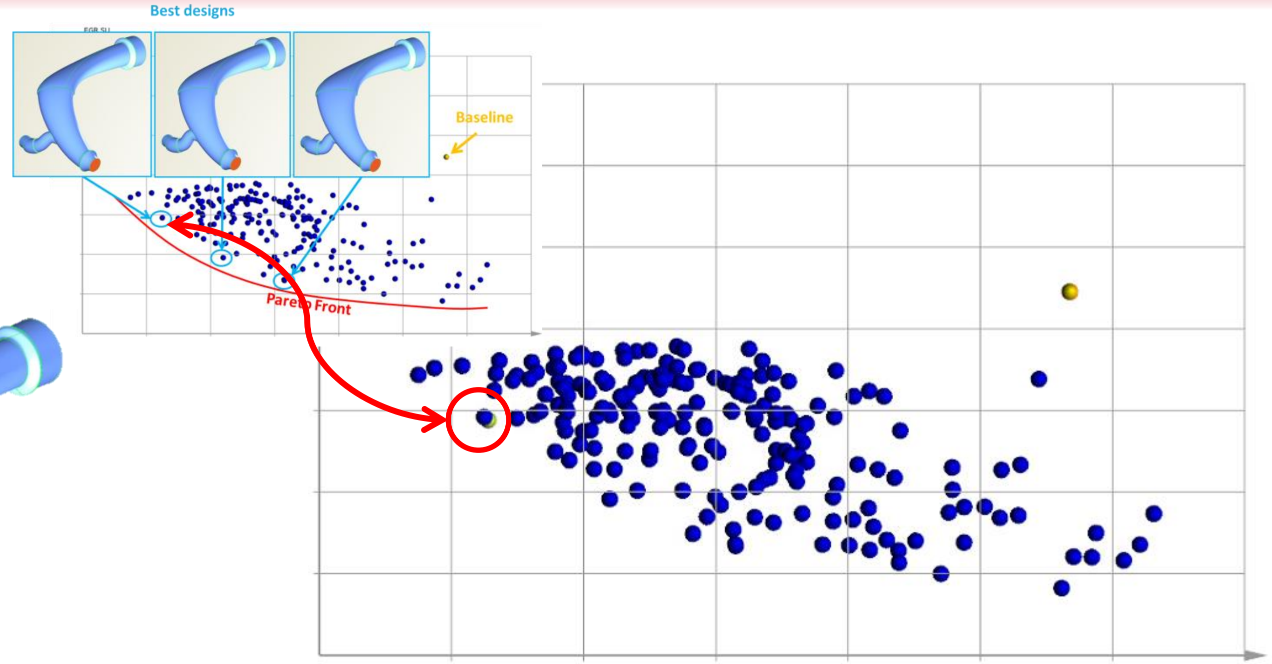
30% of pressure drop reduction thanks to the increased mid section area @ Peak Power operation.

- The **Pareto Front** is identified and the best solutions in terms of trade off between EGR Surface Uniformity and Δp are selected.
- Both targets are evaluated as the weighted average among the three operating conditions.

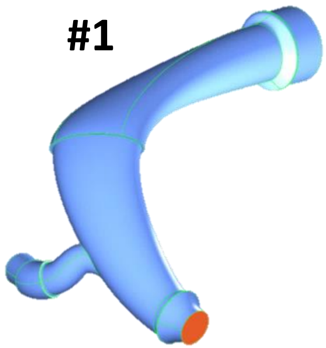




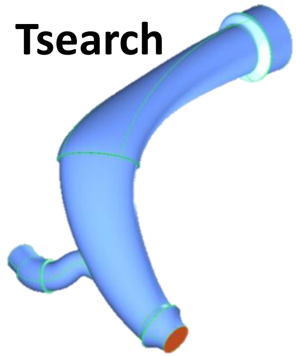
- Starting from **Design #1** a Tsearch optimization is run
- The optimized design is practically equal to **Design #1**
- **DOE** is able to identify a very good solution



#1

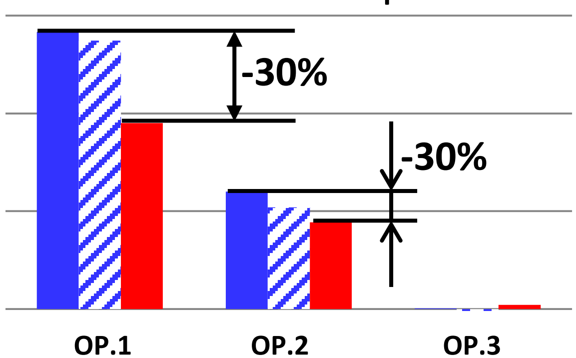


Tsearch

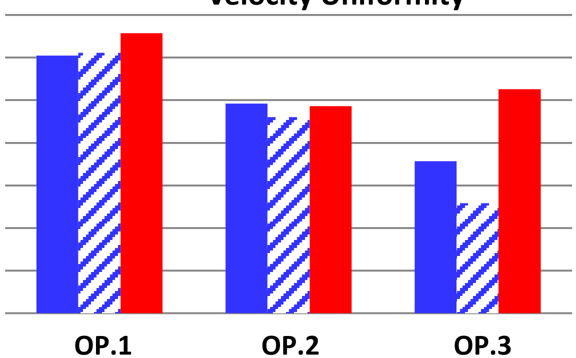


The optimized solution shows relevant improvements at all the investigated conditions.

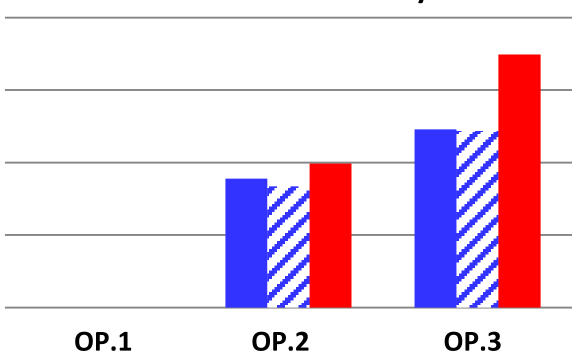
Pressure Drop



Velocity Uniformity



EGR Uniformity



Original Baseline Tsearch

- ✓ **Introducing R&D CFD**
- ✓ **Case-studies: optimization targets**
- ✓ **Case-study #1: exhaust manifold optimization**
  - ✓ CFD strategy
  - ✓ Geometry parametrization
  - ✓ Results
  - ✓ Geometry re-design
  - ✓ Conclusions
- ✓ **Case-study #2: compressor inlet pipe optimization**
  - ✓ CFD setup
  - ✓ Results
  - ✓ Conclusions

- ✓ A multi-objective multi-operation optimization requires the definition of a smart objective function
- ✓ Thanks to the geometry parametrization some beneficial solutions laying close to the Pareto Front can be identified
- ✓ A wide set of design analyses allows to identify geometries that are very close to an optimized one
- ✓ Thanks to the DOE and the subsequent optimization the overall pipe pressure drop can be dramatically reduced and the EGR surface uniformity at the inlet pipe can be increased at the same time

UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA

FRIENDSHIP SYSTEMS

Thank you for your attention!
Any questions?

Giuseppe Cicalese, PhD
Ph.: +39 059 205 6345
Mobile: +39 347 6414938
E-mail: giuseppe.cicalese@red-cfd.it

Prof. Stefano Fontanesi
Ph.: +39 059 205 6242
Mobile: +39 331 6704200
E-mail: stefano.fontanesi@unimore.it