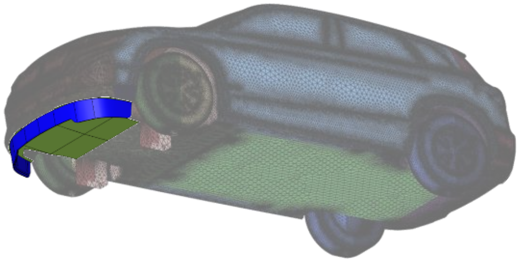
(1)

Aerodynamic Optimization of a Reduced Scale Ground Vehicle with Shape Morphing Technique



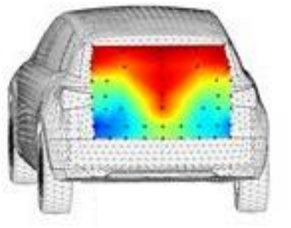
C. Erdem(2), P. Gilotte(1), S. Harries(2), C. N. Nayeri(3)

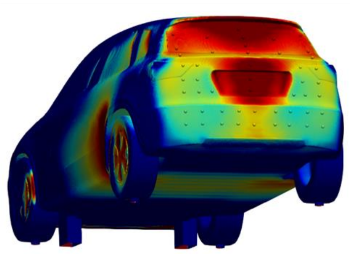
CAESES USER MEETING - SEPTEMBER 22TH. 2022

(2)

(3)

Aerodynamic optimization with morphing technique – outline

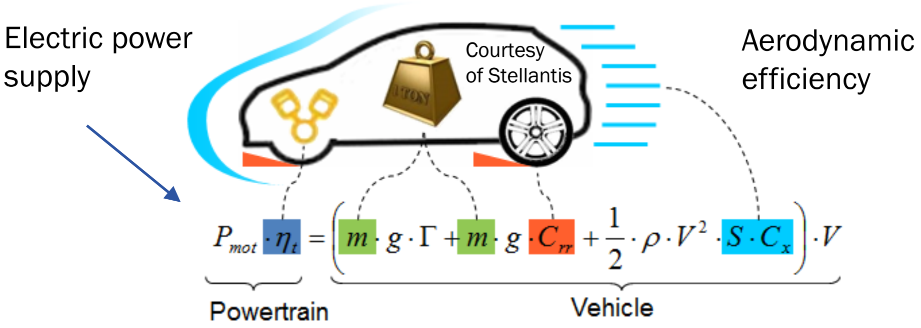


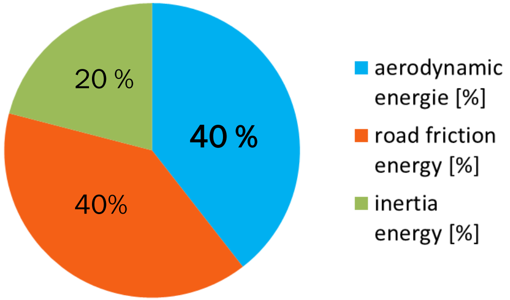


- **Context :** aerodynamic losses
- **Reference case study**
  - Available experimental data
  - Geometry selection : baseline and optimized
  - Aerodynamic performances
- **Numerical optimization**
  - CFD performance with standard and coarse meshes
  - geometrical parameters and optimization process
  - Analysis of the optimization results
- **Conclusion**

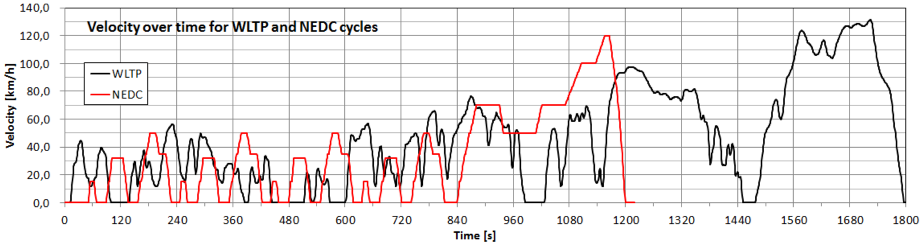
Aerodynamic optimization with morphing technique : context

- Aerodynamic losses contribution on total energy losses





Energy repartition on WLTC



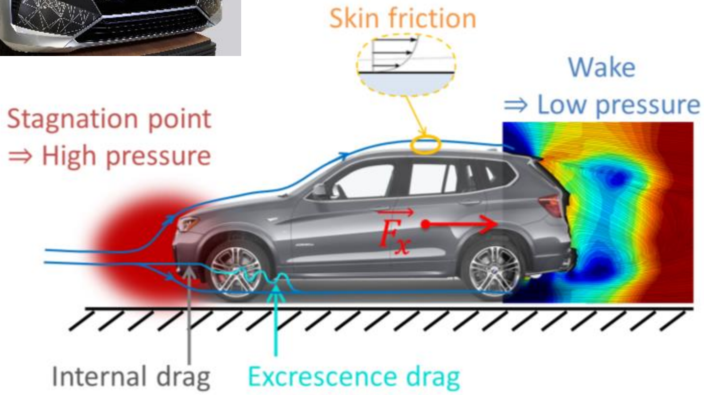
20 kg weight reduction <=> Drag ΔCx= -3 % reduction

Battery weight | Aerodynamic improvement

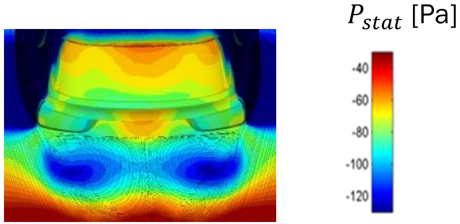
➢ Target in 2021 of 95 g/km of $C0_2$ emission for NEDC (21 g/km of reduction for average OEM vehicles)

Aerodynamic optimization with morphing technique : context

- Aerodynamic losses on a full scale realistic car



Representation of aerodynamic forces responsible for aerodynamic losses



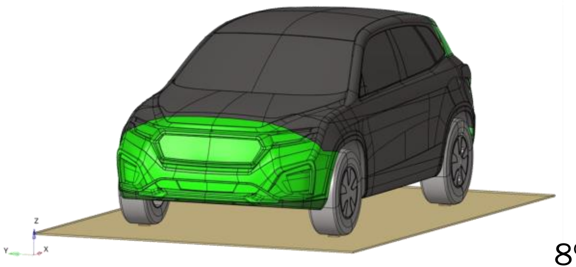
Static pressure in the wake of SUV tailgate contributes to 35% of aerodynamic losses

➢ How to increase rear static pressure ?

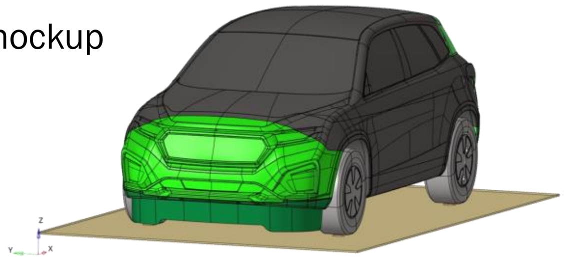
Aerodynamic optimization with morphing technique : context

- **Aerodynamic status for a reduced scaled mock up**
  - Drag reduction found with an optimized airdam thanks to a design of experiments in a wind tunnel
  - Numerical optimization process used to decrease furthermore the drag value

Generic modular mockup



Cd = 0,36

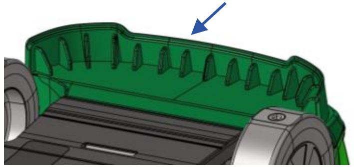


Cd = 0,32

8% of Cd reduction

$$Cd = \frac{F_x}{1/2 \rho A V_{Pitot}^2}$$

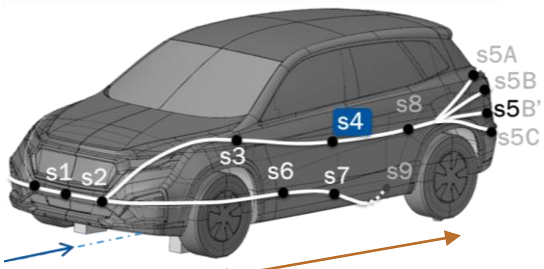
Height reduction ?



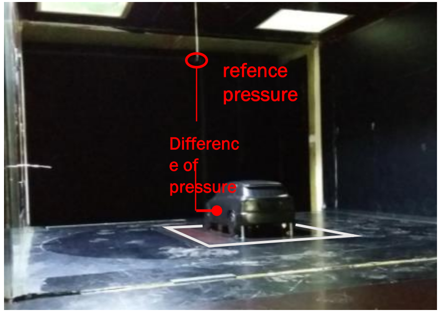
➢ Potential for additional Cd reduction with a smaller airdam section ?

Aerodynamic optimization with morphing technique : measurements

- Wind tunnel tests : pressure and drag coefficient measurements



side pressure measurements



Pressure measurement in the TU-Belin wind tunnel

rear pressure measurements

Cd measurements with aerodynamic balance

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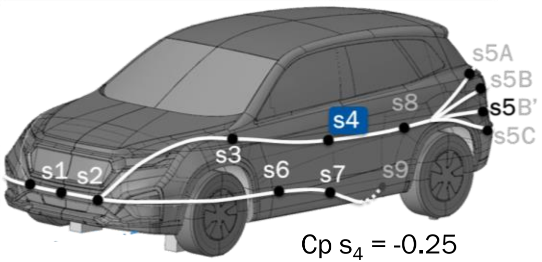
➢ Different tested configurations : selection of the best result for drag reduction (-> objective)

Aerodynamic optimization with morphing technique : measurements

- Side and rear pressure measurements related to Cd reduction

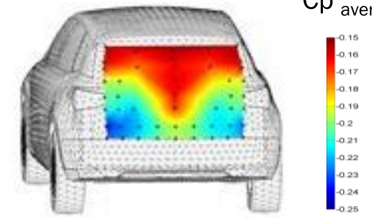
$$Cp_{rear} = \sum_{1}^{N} \frac{1}{N}\left(\frac{P_n - P_{Pitot}}{1/2 \rho V_{Pitot}^2}\right)$$

$$Cd = \frac{F_x}{1/2 \rho A V_{Pitot}^2}$$



Cp s_4 = -0.25

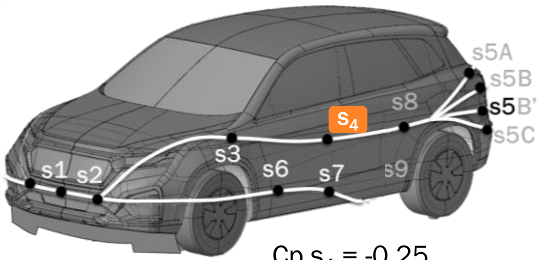
Without air dam



Cp rear = -0,195
Pressure probes

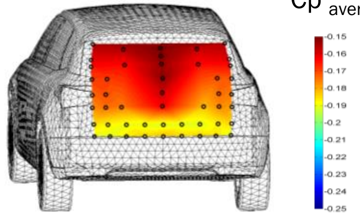
Cd = 0,36

Cp_{rear} /Cd = 55 %



Cp s_4 = -0.25

With air dam



Cp rear = -0,175
Pressure probes

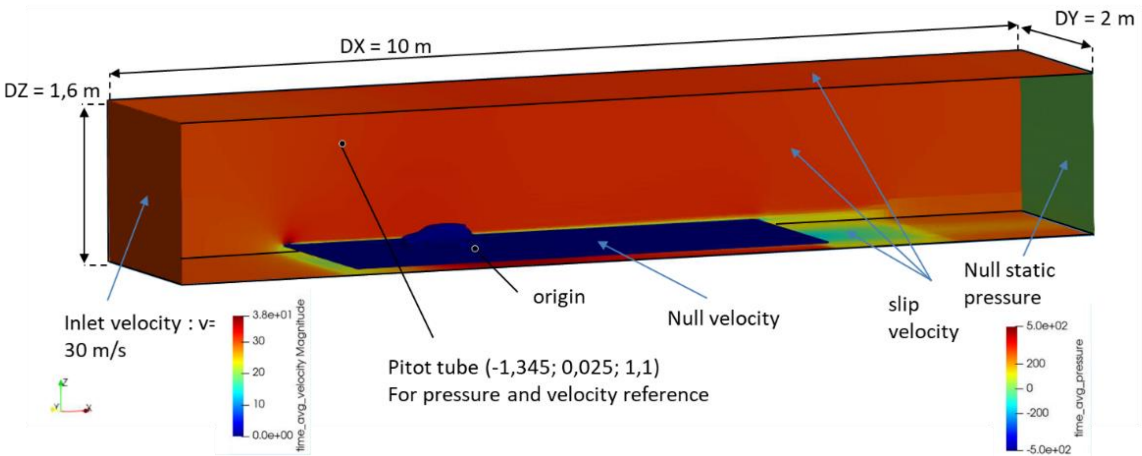
Cd = 0,32

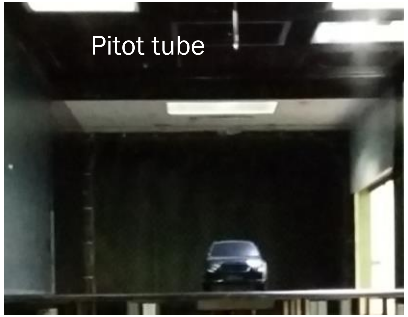
Cp_{rear} /Cd = 53 %

➢ Constant rear pressure / drag ratio and constant side pressure (-> constraints)

Aerodynamic optimization with morphing technique : aero simulation

- Numerical domain and boundary conditions for aerodynamic simulations





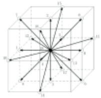
POSUV mockup in the main section of the TU-Berlin wind tunnel geometry

Aerodynamic optimization with morphing technique : aero simulation

PLASTIC OMNIUM

- **Mesh size and computation time**

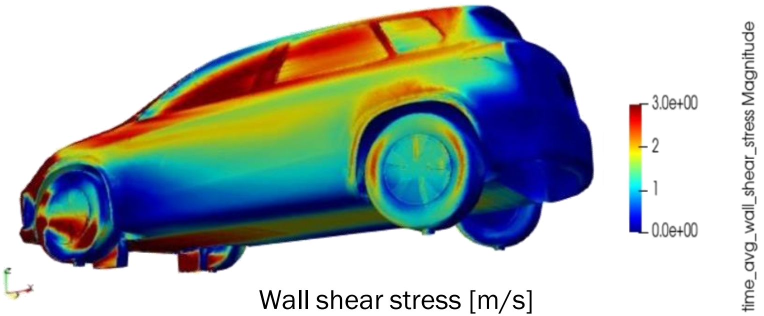
- Lattice Boltzmann solver (ultraFluidX)



  - LES turbulence model of Smagorinsky
  - friction velocity computed with a wall model to match LES computation in the third wall layers

- Mesh optimization for CFD computation :
  - 50 millions cells, time step = 0,673 ms (4 000 iterations) => 3 hours
  - ➢ 60 design space + 155 optimization iterations : 645 hours = 27 days

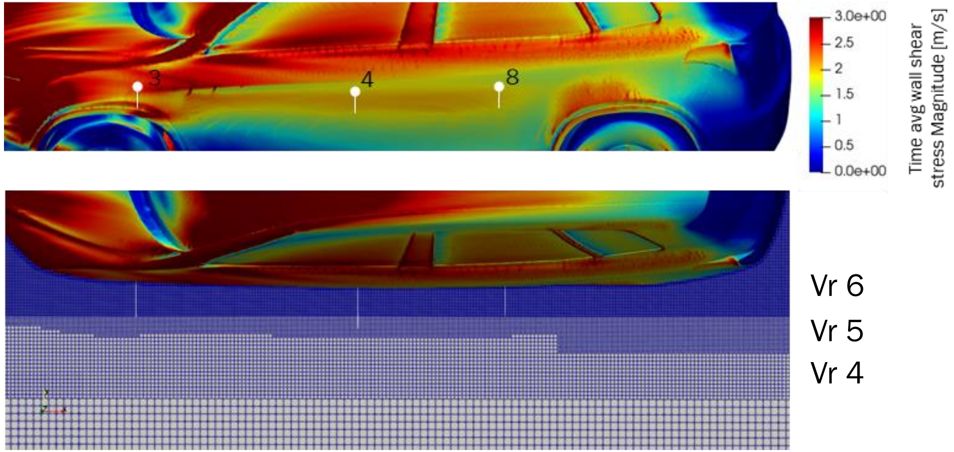
DGX server on
8 GPU Tesla cards



Wall shear stress [m/s]

Aerodynamic optimization with morphing technique : aero simulation

- mesh definition : coarse and refine meshes



Vr number	cell size per Vr [mm]	nb of layer per Vr	thickness [mm]
7	0,390625	5	1,95
6	0,78125	27	21,09
5	1,5625	11	17,19
4	3,125	16	50

Refined mesh : 400 millions cell mesh

Vr number	cell size per Vr [mm]	nb of layer per Vr	thickness [mm]
7	0,78125	6	4,69
6	1,5625	12	18,75
5	3,125	6	18,75
4	6,25	8	50

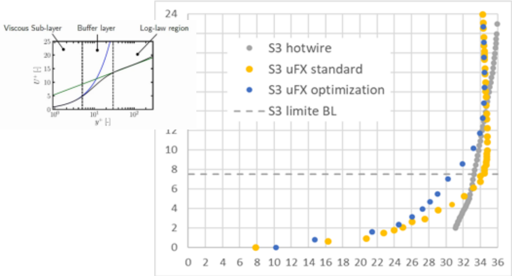
Coarse mesh 50 millions cell mesh

➢ Wall shear stress of the refine mesh -> mesh reduction ?

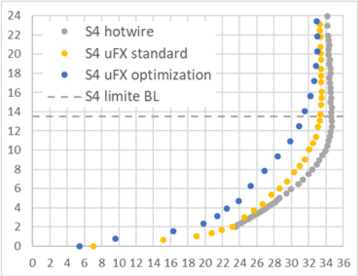
Aerodynamic optimization with morphing technique : aero simulation

PLASTIC OMNIUM

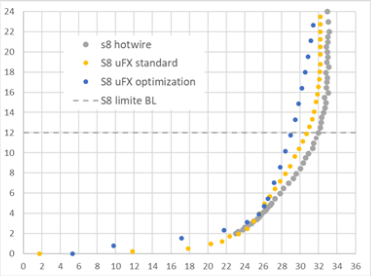
- Boundary layer thickness (compute at the end of the log law)



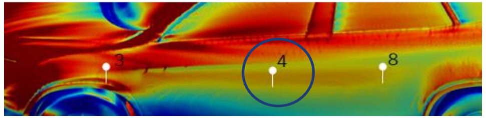
U [m/s]



U [m/s]

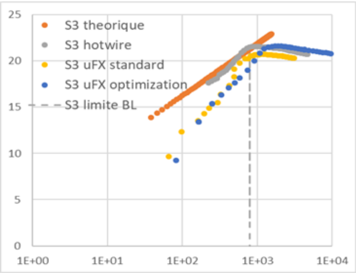


U [m/s]



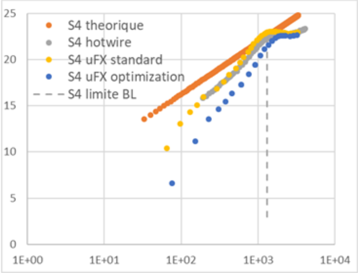
➢ Velocity profiles with a refine mesh (in yellow) is closer to the experimental data (in grey)

U^+



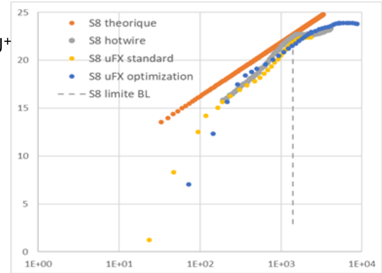
y^+

U^+



y^+

U^+



y^+

$$U^+ = f(y^+) \ with \ U^+ = \frac{U}{U^*} \ , y^+ = \frac{U^* y}{\nu}$$

$$U^+ = \frac{1}{K}\ln(y^+) + C \ with \ K = 0{,}41 \ and \ C = 5$$

Log law region

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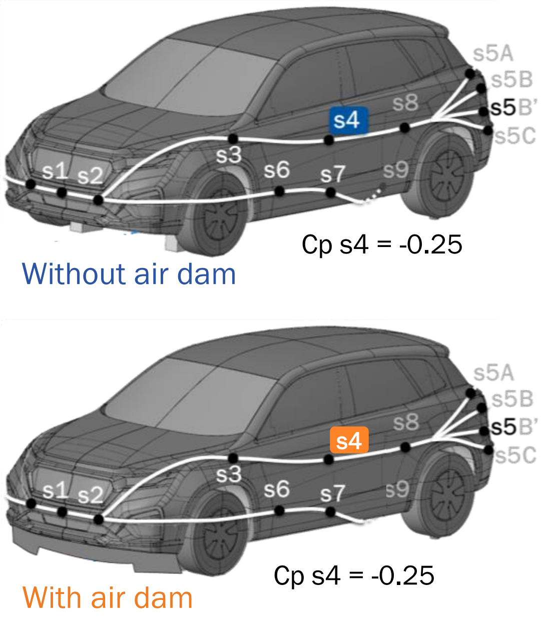
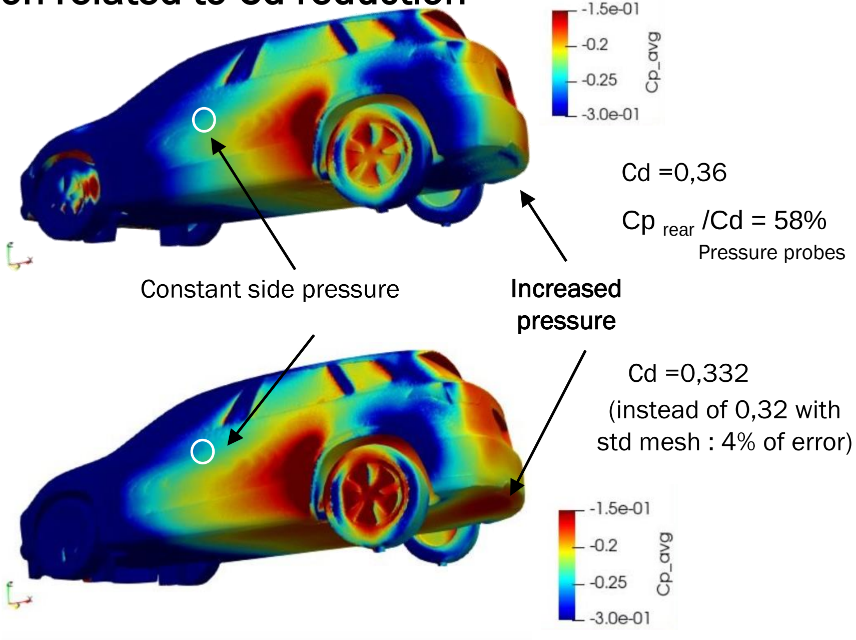
➢ But coarse and refine mesh lead to the same boundary layer thickness and same wall friction (=> pressure)

Aerodynamic optimization with morphing technique : aero simulation

- Side and underfloor pressure computation related to Cd reduction

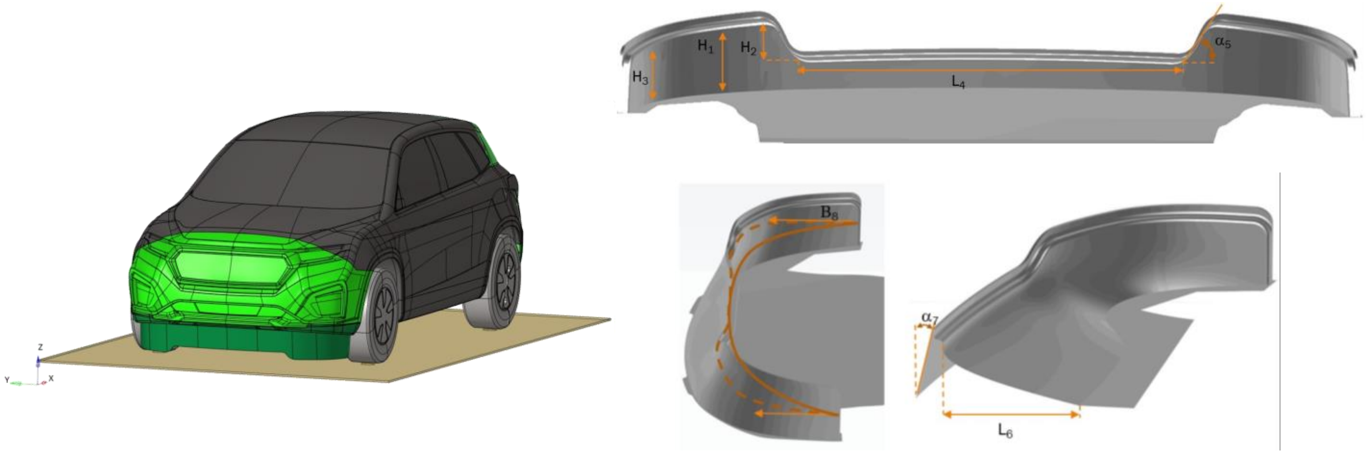




➢ Airdam geometry increases the underflow and rear pressure

Aerodynamic optimization with morphing technique : optimisation objective

- Airdam shape optimization process :



H_1 : delta total height

H_2 : delta mid height

H_3 : delta end height

L_4 : mid width

α_5 : transition

L_6 : thickness

α_7 : delta inclination angle

B_8 : deviation factor

Starting from the experimental airdam, defining parameter variation ....

Aerodynamic optimization with morphing technique : optimisation objective

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- Airdam shape optimization process :

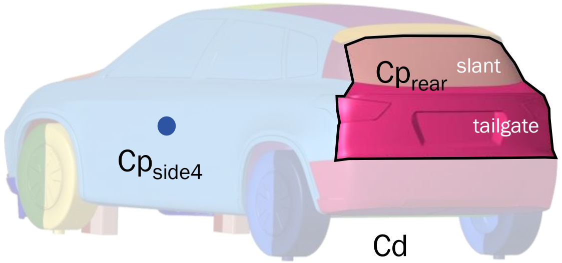
$$Cd = \frac{F}{1/2\, S . V_{Pitot}^2}$$

Drag coefficient Objective **Cd < 0,32**

$$Cp = \frac{P - P_{Pitot}}{1/2\, V_{Pitot}^2}$$

Pressure coefficient constraints

$$\begin{cases} Cp_{side4} > -0,25 \\ Cp_{rear} / Cd > 0,35 \end{cases}$$



... for drag coefficient reduction, respecting pressure constraints

CAESES

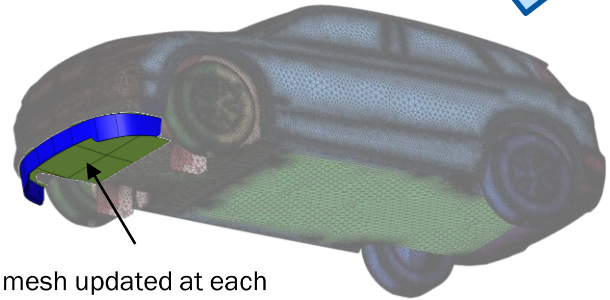
Aerodynamic optimization with morphing technique : optimisation objective

- Airdam shape optimization process :

CAESES 1 - Design space exploration (SOBOL) – 80 iterations

Objective **Cd < 0,32**

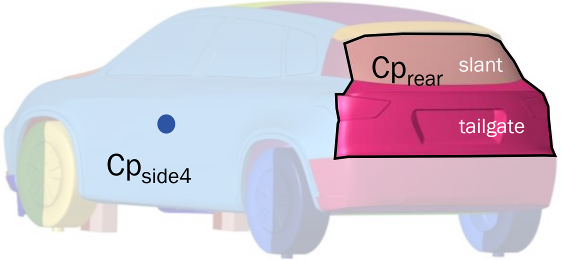
constraints
$$\begin{cases} Cp_{side4} > -0{,}25 \\ Cp_{rear} / Cd > 0{,}35 \end{cases}$$



Surface mesh updated at each computation step (CAESES)

Frozen surface mesh

Airdam morphing



(ultraFluidX CFD solver)

Lattice Boltzmann computation

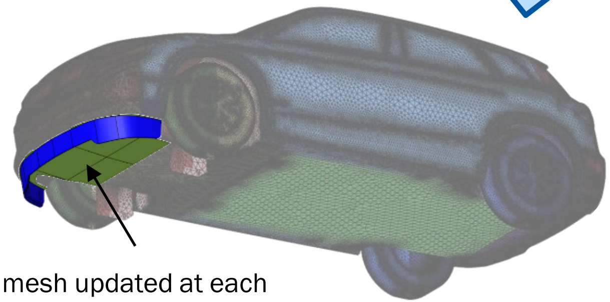
Aerodynamic optimization with morphing technique : optimisation objective

- Airdam shape optimization process :

CAESES 2 – Genetic algorithm (Dakota) – 155 iterations

Objective **Cd < 0,32**

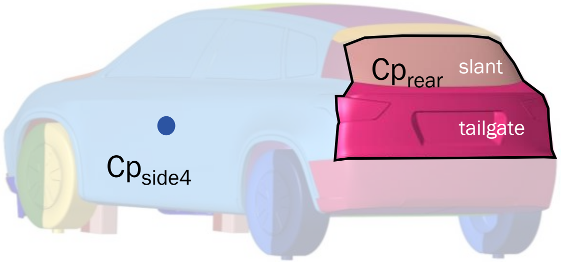
constraints
$Cp_{side4} > -0{,}25$
$Cp_{rear} / Cd > 0{,}35$



Surface mesh updated at each computation step (CAESES)

Frozen surface mesh

Airdam morphing

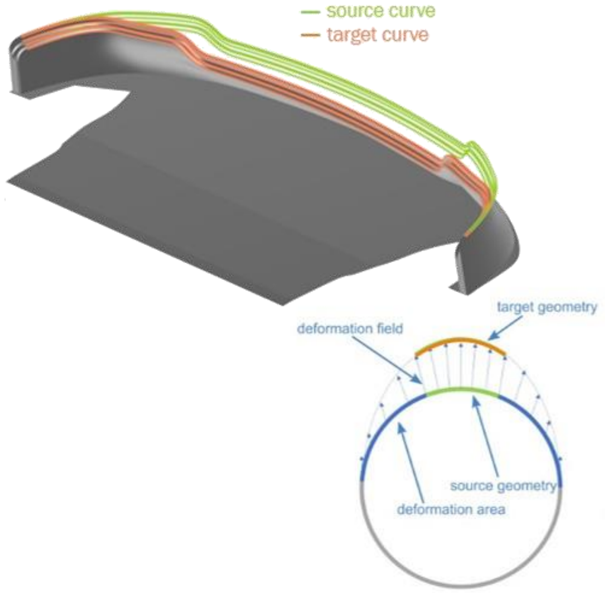


(ultraFluidX CFD solver)

Lattice Boltzmann computation

Aerodynamic optimization with morphing technique : optimisation objective

- Airdam shape optimization process :



H_1 : delta total height

H_2 : delta mid height

H_3 : delta end height

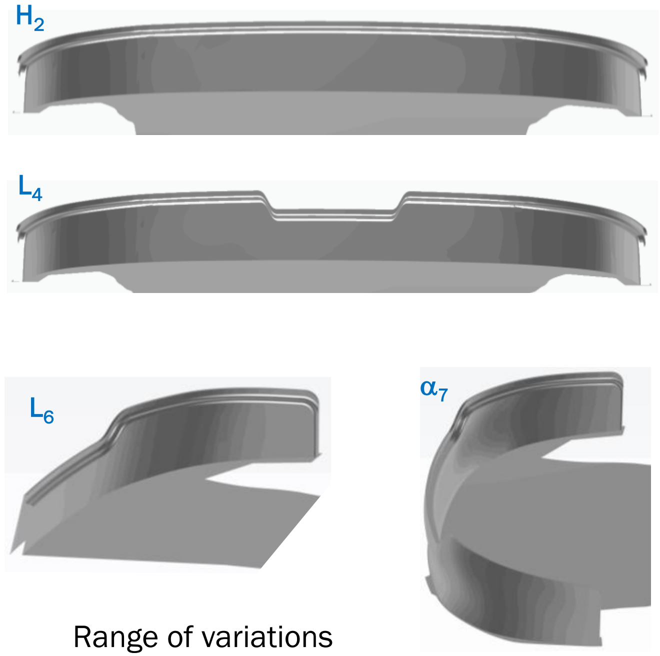
L_4 : mid width

α_5 : transition

L_6 : thickness

α_7 : delta inclination angle

B_8 : deviation factor



Range of variations

Morphing with Radius Basis Functions defined with 8 geometrical parameters

Aerodynamic optimization with morphing technique : optimisation objective

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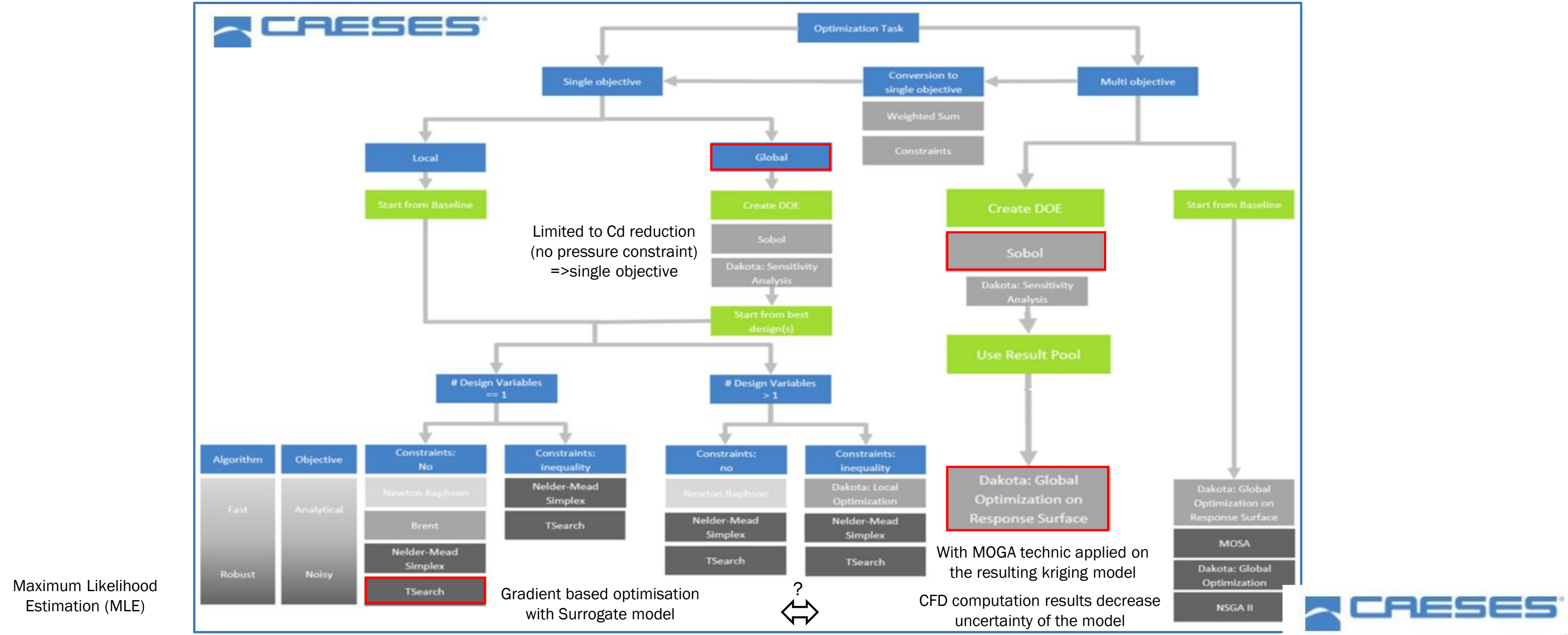
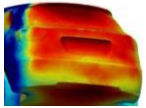
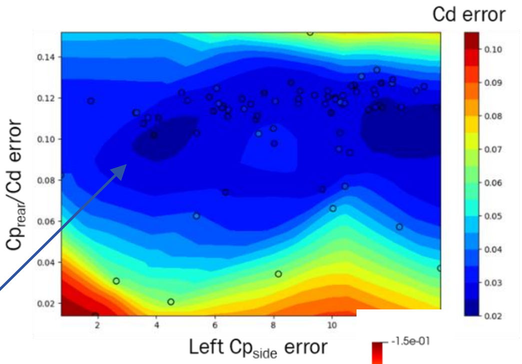
- Airdam shape optimization process : Sobol and Dakota algorithm

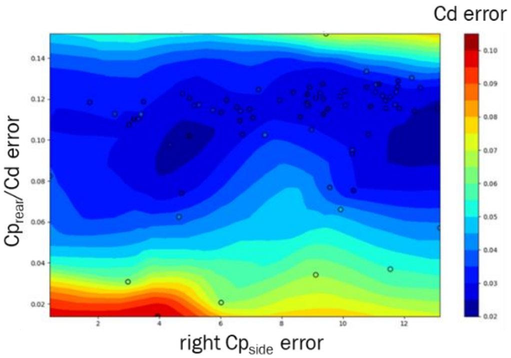


Aerodynamic optimization with morphing technique : results

- Airdam shape optimization : Sobol response surface



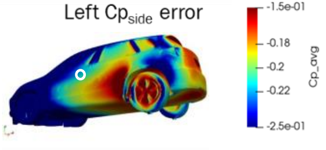




$Cp_{side} = -0.21$

Cd = 0.34

Cp_{rear}/Cd = 0.25

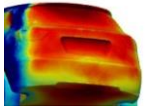


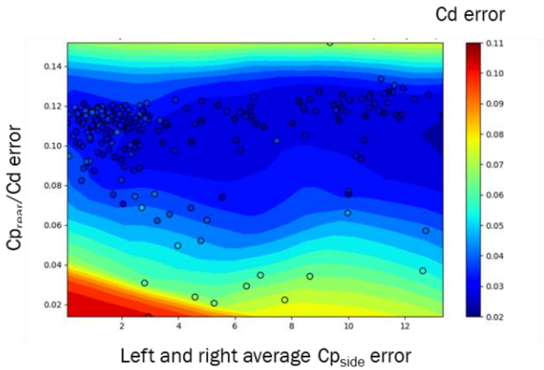
Symmetric behavior of side pressure

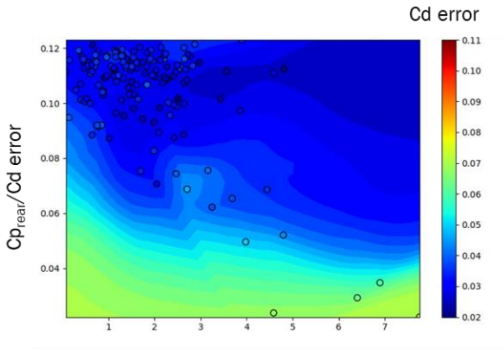
➢ Improvement with optimization algorithm ?

Aerodynamic optimization with morphing technique : results

- Airdam shape optimization : Dakota genetic algorithm (MOGA)







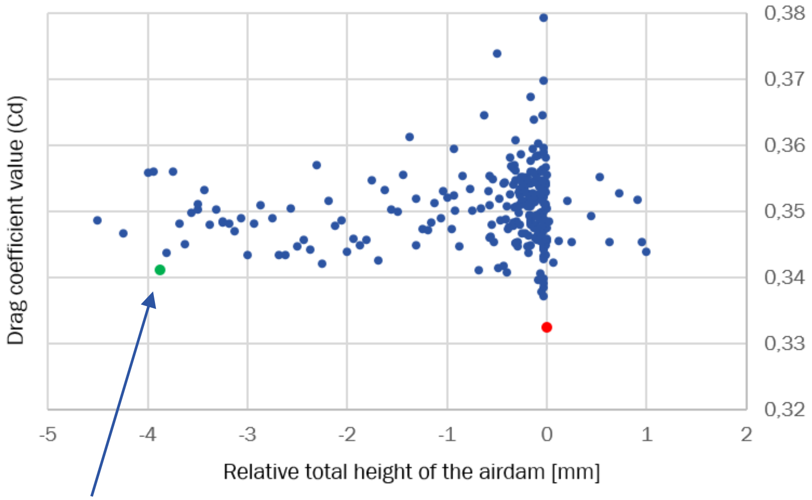
Kriging surrogate model suggests to increase side pressure

Results include in the Sobol sequence response surface

➢ Analysis of airdam height, according to the Cd reduction ?

Aerodynamic optimization with morphing technique : results

- Airdam shape optimization : Dakota genetic algorithm (MOGA)



Geometry selection for design phase ?

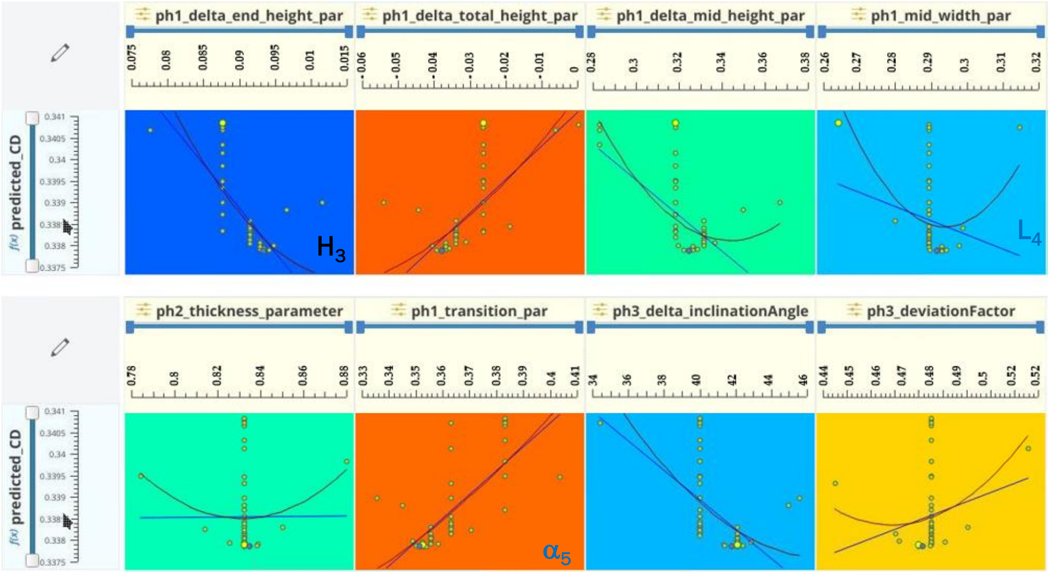
5 % of Cd gain

8 % of Cd gain

➢ Influence of other parameters

Aerodynamic optimization with morphing technique : results

- Airdam shape optimization : Dakota genetic algorithm (MOGA)



Parameter ranges large enough to explore minimum of the parameters

Effect of parameters apart from the total height ?

H_1 : delta total height

H_2 : delta mid height

H_3 : delta end height

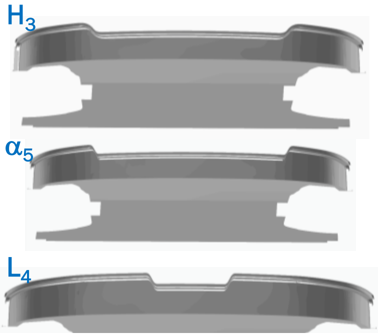
L_4 : mid width

α_5 : transition

L_6 : thickness

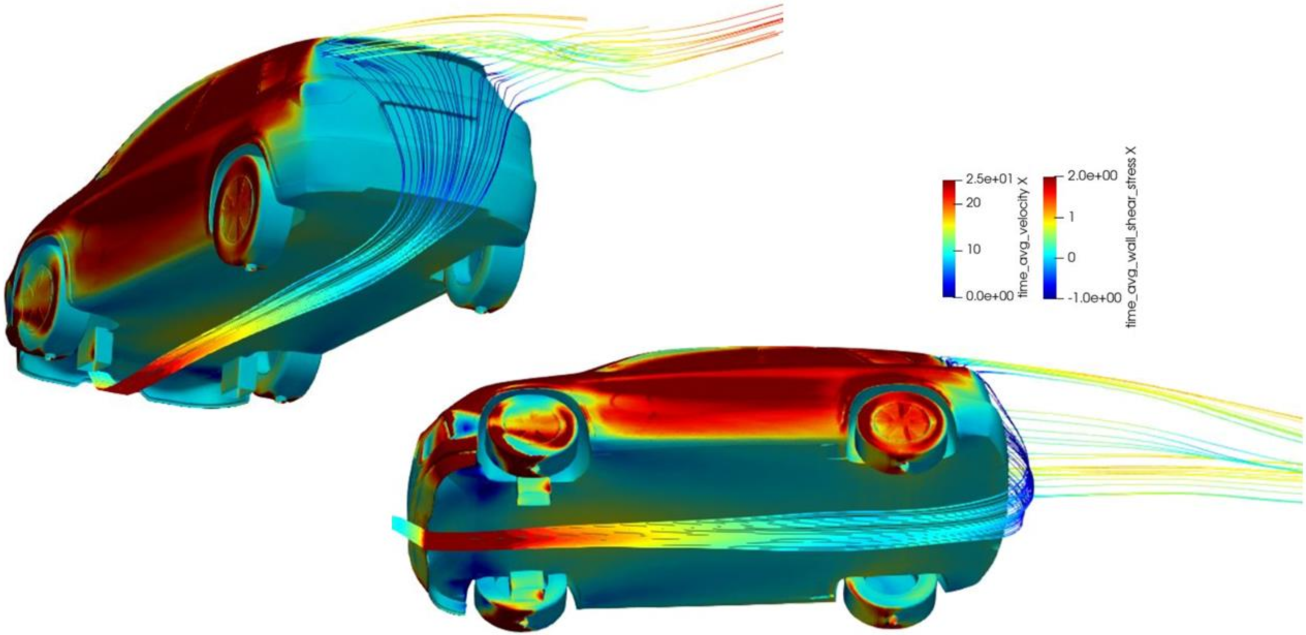
α_7 : delta inclination angle

B_8 : deviation factor



Aerodynamic optimization with morphing technique : flow analysis

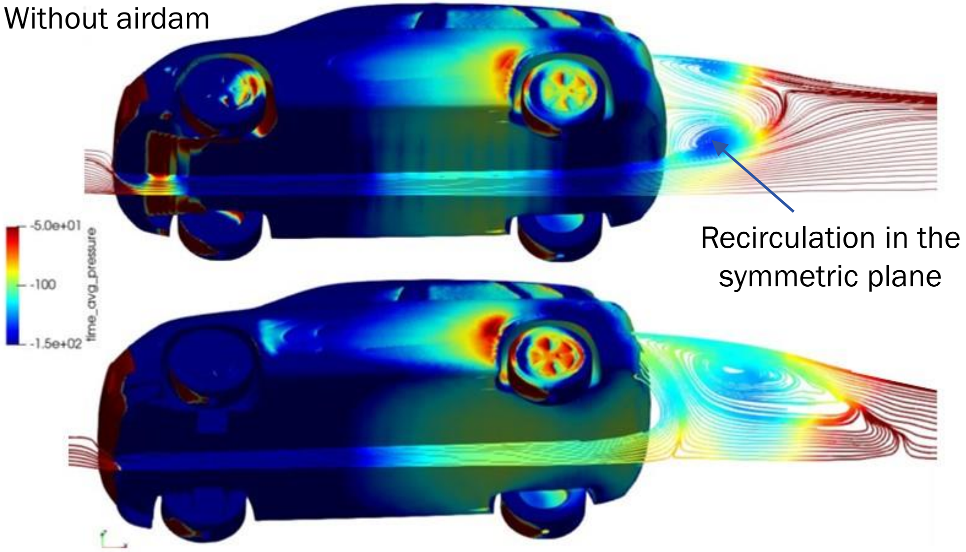
- Airdam shape optimization : streamlines through the airdam indentation



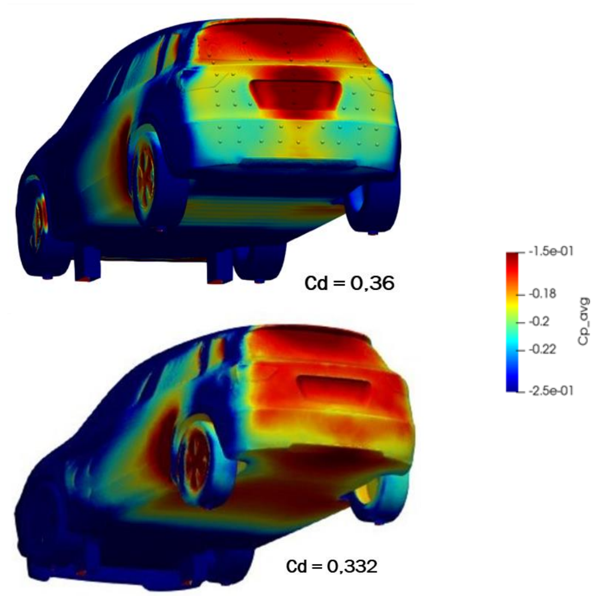
Aerodynamic optimization with morphing technique : flow analysis

- Streamlines and pressure results with a coarse mesh

Without airdam



With airdam

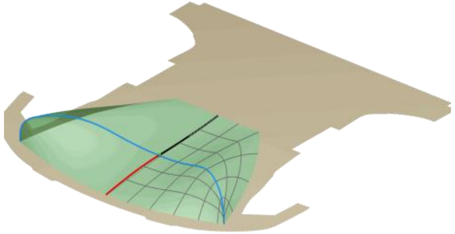


With pressure probe Cp rear /Cd = 58%

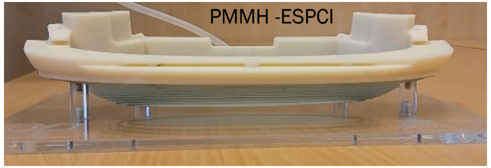
➢ Rear recirculation disappears with optimized airdam

Aerodynamic optimization with morphing technique : design phase

- Actuation with surface deformation



Shape optimisation



Fluid structure interaction

Wind tunnel test

➢ Optimization for full scale prototype mounted on a vehicle

Aerodynamic optimization with morphing technique : conclusion

- Optimization with coarse meshes enables to find the same airdam shape than in experiments leading to the maximum Cd gain
- remaining significant gains with smaller airdam height

➢ Gradient based optimization with ANN instead of kriging for flow topology discontinuity ?

➢ Optimization at full scale

Thank you