Numerical simulations on passenger vehicles equipped with a cover under transportation

Master's thesis in Applied Mechanics

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Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The concern of the car companies to offer an image of quality to their clients has led to take care of every single detail. An example of this, is that newly produced cars are now being covered during their transportation on trucks. The design of the covers involve several wind tunnel tests for each new car model. This has high cost in time and resources. The aim of this work is trying to develop the first step on a procedure to conduct numerical simulations to extract the information needed to optimise the design process and reduce the number of tests in the wind tunnel. The cover is a deformable material and its behaviour can be compared to sails. The behaviour of sails under up-wind conditions has been studied over the last years and some parts of its method can be applied to the current work. The study is performed on the generic model DrivAer, which is an open source model especifically created for aerodynamic studies. The process consists in simulating three different cases on which a variation on the cover geometry is applied, starting from the car model itself and applying successive modifications to generate a more realistic model. The first simulation is thus the model itself and the results obtained are used for the next case, in which a wrapping is applied to the car, to resemble the uneven surface of the cover. The third case consists on generating a geometry that resembles the cover alone, by means of morphing the original model. The last case allows to simulate two geometries at the same time (cover and vehicle) and the flow in between. On the first two cases only the pressure on the outer surface is obtained, whereas on the third case the pressure is obtained on the outer and inner surfaces of the cover. The results obtained from the wall shear stress made clear that the next step should be a structural analysis to find the actual stress on the cover. Finding the pressure difference on the surfaces of the cover (in the third case) is essential to perform the structural analysis and with that, predict the deformation and stress.

Key words: DrivAer, CFD, ANSA, Star-CCM+, aeroelastic analysis, car covers.

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I do not finish without mentioning the support of the department Vehicle Engineering and Autonomous Systems at Chalmers, especially to the PhD students that have helped me throughout my work all these months.
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1 Introduction

The interest of the car brands to focus on the customers and offer them a product of quality that fulfills all the expectations, has led to pay attention to every detail. The image of quality of the brand is as important as the quality itself. For these reasons, premium car brands are now setting a cover over the newly produced vehicles. This way, the vehicles are protected in their transportation from the factory to the dealers, preventing damage or dirt on the materials and paint.

The covers are unique for each car model type since they have to fit perfectly the shape of the vehicle. In the design of every new cover, several tests on the wind tunnel are carried out, trying to simulate the conditions that the car will experience when is being transported on a truck. After each test, modifications are implemented on the cover design and the fixations until a successful test is accomplished (the cover has not been ripped nor got loose). The wind tunnel tests have a high cost of time and resources (i.e. energy), so that any measure that can lead to a reduction in the number of tests that need to be performed, would result in a visible increase of the efficiency of the process, affecting to the whole chain of production. In this point, the aim of this project comes up: try to reduce the number of tests needed, by predicting some of the issues found during the tests by means of numerical simulations.

1.1 Objective

The numerical simulations performed in this work tried to emulate the conditions and configuration of the wind tunnel tests. Thus, the first step taken, was to establish an efficient but robust CFD procedure that resembled the actual tests. For this purpose, the DrivAer model [1] and different modifications of it were used.

The results obtained from the numerical simulations were compared to those experienced in the wind tunnel tests in order to establish a correlation between them. Special attention was paid to the areas that are usually the source of failure.

1.2 Limitations

Since this problem is relatively new for the car industry, no previous publications on this matter could be found. The complexity of the question makes the scope of this work to be a first step in a longer line of investigation. The main limitation is the impossibility of simulating a material that is being deformed during the simulation by the action of a fluid (fluid-structure interaction). Another complexity, is the effect of the clips and fixations used in the actual vehicles, since the software cannot differentiate between a rigid and a deformable material (all materials are considered rigids).

1.3 Method

The method followed consisted in a pre-treatment of the model in ANSA. The model was then imported into the CFD solver Star-CCM+ to proceed with the mesh generation, the numerical simulations and the post-processing.

2 Background

The study of the covers on passenger vehicles is relatively new, but some research has been developed on numerical simulations with sails. Since there is a similarity between the covers and the sails (deformable material) it is therefore a good idea to look on the methods used in that field to get a deeper understanding of the problem, the line of development followed and its limitations.

The sails are considered a membrane structure, meaning that they cannot hold moments and perpendicular forces. When one of those are applied to the material, it deforms until it reaches an equilibrium.

It is stated that "The sail shape determines the pressure distribution and, at the same time, the pressure distribution on the sail stretches and flexes the sail material determining its shape." [2]

For that reason, an aeroelastic analysis needs to be carried out. This analysis consists on a series of steps following an iterative process:

1. Generation of the model with an initial shape of the sail.
2. Aerodynamic analysis: a simulation is run with the previous configuration to calculate the loads (pressure).
3. Structural analysis: the deformation (new sail-shape) and stress distribution of the sail is obtained by applying the calculated loads.

The process is repeated until an equilibrium is reached (slight difference in deformation and stress between one step and another).

This process implements a variation of the Vortex Lattice Method (VLM) [3]. The Vortex Lattice Method consist on a panel method of CFD study rather than a volume method.

The aim of this work was to develop the first part of this process, the aerodynamic analysis. Future work should get a closer look to the methods to perform the structural analysis.

It is important to remark that the tendency is that more and more premium car brands are adding to the practice of covering the vehicles during the transportation. All of these companies will have to deal with the problem presented so it is expected that more research will be published on this matter.

3 Methodology

As it was mentioned before, the main purpose of this work is to develop a procedure to carry out numerical simulations of passenger vehicles equipped with a cover. For that reason, no special attention was paid to the CFD simulations methodology, therefore the steps followed were the usual: geometry preparation, volume meshing, simulation and post-processing. To achieve a resemblance between the simulations and the actual tests the focus was on the geometry preparation and the mesh generation.

In comparison with the sails numerical simulations approach, it should be noted that while the sails are directly exposed to the wind on both sides of them, the cover of a car is exposed to the wind just on one of the surfaces having the other surface facing the vehicle. Even though it is known from experience that there exists an air flow between the cover and the car, this is not a free flow (atmospheric pressure on both sides). Another big difference between the sails and the covers are the fixations and shape of them. The sails have less restrictions (fixations) allowing that to have a more uniform pressure distribution and a gradual deformation. This is not the case of the covers on which the pressure distribution depends on the part of the vehicle considered, and the deformation depends on the fixations implemented. For all these reasons, the method employed for the aerodynamic analysis varies from the one used for sails.

On the process followed, first, it was needed to know the object of study, the cover and its layout on the vehicle, and the model on which the work was going to be based on, the DrivAer model. The model will be discussed in more detail in section 3.2.

Once all the information needed was collected, the work on the model began. Different cases were analysed, starting from a basic shape of the model and progressing to more realistic ones. In the beginning a baseline of the DrivAer model was selected and the following geometries were based on it. In the second case, a wrapping was applied to the baseline in order to make a rough surface imitating the surface of the cover. The final case consisted of the creation of the cover as a geometry apart by morphing the baseline model. The software used to carry out the geometry preparation is ANSA.

Following the geometry definition, the volume meshing, simulation and post-processing were executed with the commercial software Star-CCM+. The simulation conditions were the same for the different cases although some different operations were needed when generating the volume mesh.

3.1 Description of the cover

The cover consists of two pieces, one for the hood and one for the rest of the vehicle. The windshield, the underbody and the wheels are not covered. The fixations include ropes below the body and clips on the wheelhouse's arches. The cover is taped on the windshield to keep it attached to the car, preventing a big mass of air from coming in under the cover. On the driver's door, there is a zip to allow a driver come in and drive the vehicle to the pick-up point and onto the transporting trucks.

The cover is tight to the body of the vehicle in order not to increase the drag and keep it attached to the vehicle. To cope with the projecting geometry of the mirrors, the current design includes a fabric reinforcement on them which is stitched to the cover of the body. Those stitches are usually the origin of a rip. As it can be seen on the pictures (see Figure 3.1), the area around the mirrors presents wrinkles that will also affect the behaviour of the material. It is also observed that on the front of the car the covers present a set of holes to refrigerate the engine compartment. The material of the cover presents orthotropic characteristics (see material specifications on Appendix C).

All the information referred above was provided by Volvo Cars Corporation (VCC).

Figure 3.1: Example of two vehicles equipped with a cover – courtesy of VCC.

3.2 The model: DrivAer

The DrivAer model was conceived as a generic model that would allow to perform aerodynamic analysis on passenger vehicles with more detail than the oversimplified generic models that already existed. This way, a deep understanding of the aerodynamic phenomena could be reached without the necessity of having to appeal to the specific vehicle models. The model was developed in the Technology University of Munich.

The model is combination of the Audi A4 and the BMW 3 Series. It includes different configurations for the rear end, the underbody and the wheelhouses. The three different configurations of the rear end are: Fastback, Notchback and Estate Back. The underbody present two options: a detailed underbody and a smooth underbody for simplified and symmetric simulations. Finally, the wheelhouses can be closed. [1]

On Figure 3.2 the DrivAer model can be seen on the isometric view. Figure 3.3 shows the different rear and underbody configurations.

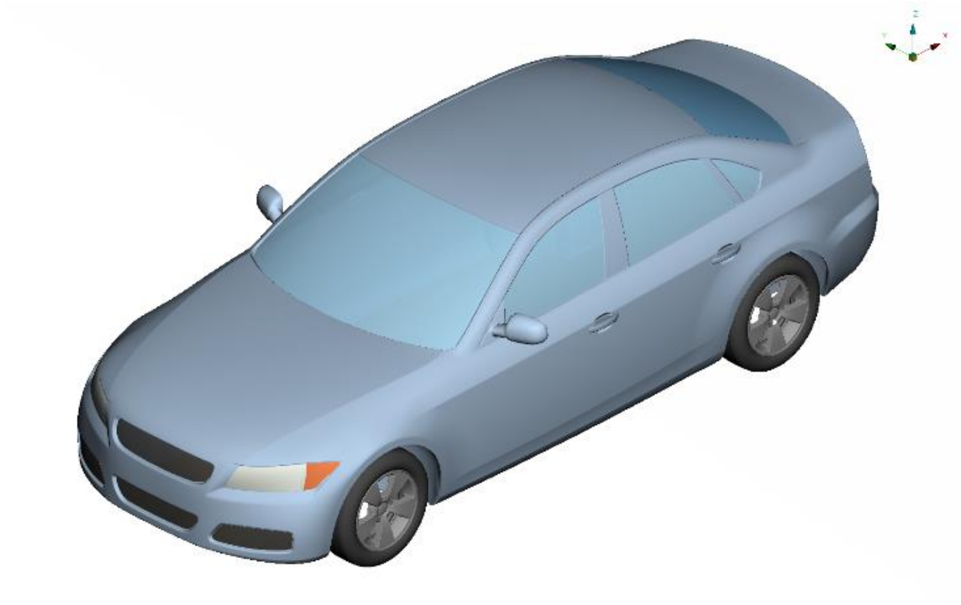
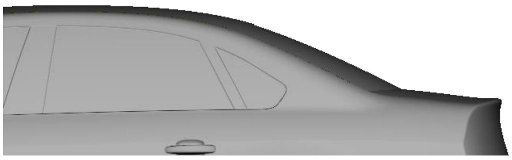
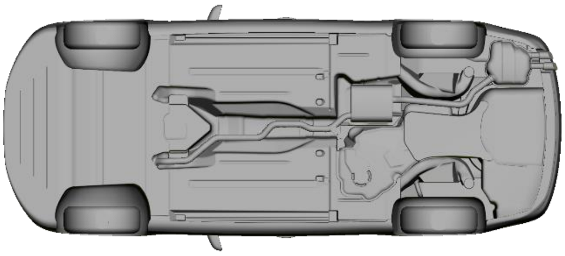


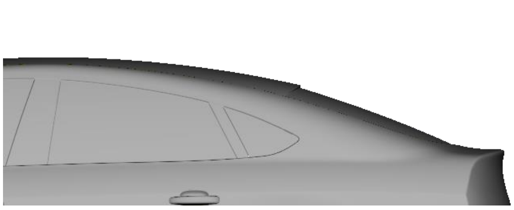
Figure 3.2: *DrivAer model | Notchback.*



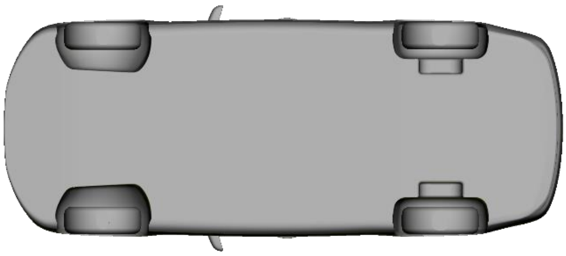
(a) *Notchback*



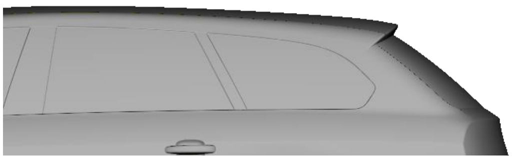
(d) *Detailed underbody*



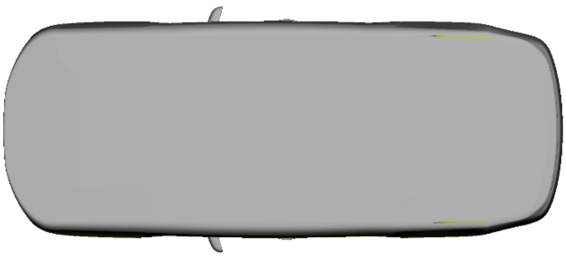
(b) *Fastback*



(e) *Smooth underbody*



(c) *Estate back*



(f) *Closed underbody*

Figure 3.3: *Configurations of the DrivAer Model*.

3.3 Case 1: Baseline

3.3.1 Geometry preparation

The first case studied, consisted on the car model itself without any modifications. Due to aerodynamic behaviour and the wake of the vehicle are not of interest in this work, a simplified configuration (which is going to be called baseline) was chosen: notchback, smooth underbody and open wheelhouses. Figure 3.4 shows the baseline configuration. The rest of the back configurations were not considered because it is not the purpose of this work to study the behaviour of the cover on different models of a car.

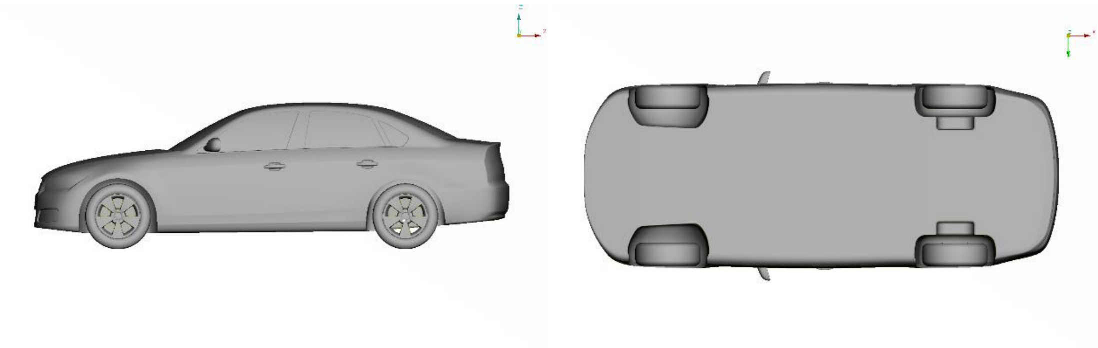


Figure 3.4: *Baseline model: DrivAer | Notchback | Smooth underbody*.

3.3.2 Volume mesh

When the geometry was ready, it was imported to Star-CMM+ where the volume mesh was generated. The simulation tried to imitate the conditions of the wind tunnel tests, so that the model was placed into a box (tunnel) of the following dimensions: 10 m x 10 m x 50 m (Width x Height x Length)

- X min (inlet) = 15 m ahead of the car nose.
- X max (outlet) = approximately 35 m from the car rear end.
- Y min (infinity) = -5 m.
- Y max (infinity) = 5 m.
- Z min (ground) = z ground contact of the front wheel.
- Z max (infinity) = 10 m above z ground contact of the front wheel.

On Figure 3.6, the tunnel and a density box are showed. The function of the density box is to generate a volume mesh with more density of cells around the car to capture the aerodynamic effects. The dimensions of the density box are specified in Figure 3.5. These dimensions are standard in aero CFD simulations at VCC. [4]

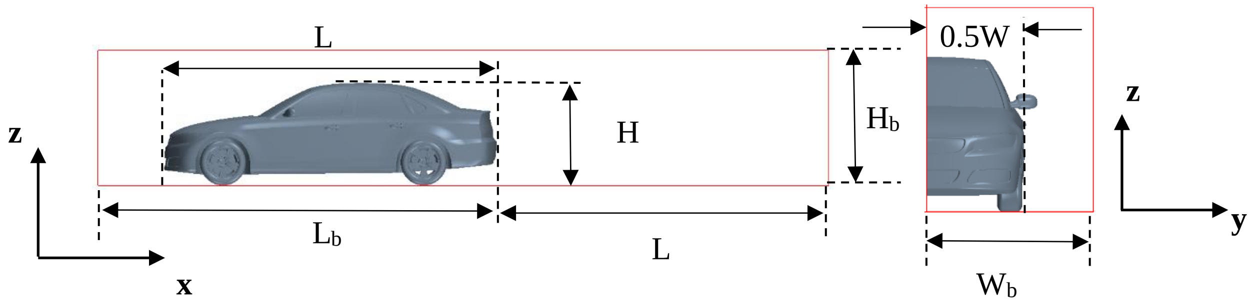


Figure 3.5: Standard d*imensions of the density box in CFD simulations on Star-CCM+.*

$$W_b = 0.31D$$

$$H_b = 0.38D$$

$$L_b = 1.2L$$

$$D = \sqrt{H^2 + L^2 + (0.5W)^2}$$

Figure 3.6: *Tunnel and density box in Star-CCM+.*

The reason of having just one refinement box is that the wake is not of importance for the purpose of this work, allowing this also to reduce the number of cells.

Another measure to reduce the number of cells (and thus the simulation time) was to simulate only half of the car, considering the plane y=0 as a symmetry plane. This was done by applying a subtract operation. The subtract operation was applied to the baseline and the half tunnel, being the latter the objective part. The subtract operation has also the purpose of generating the intersection between the wheels and the ground, to reproduce the tread of the tyre.

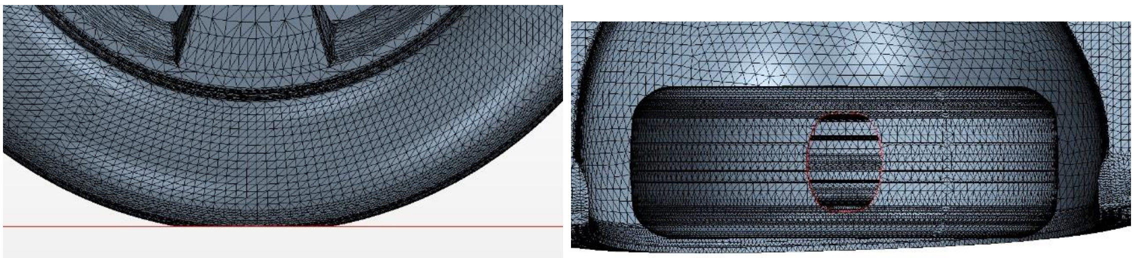


Figure 3.7: *Tyre tread generated with a subtract operation in Star-CCM+.*

Following the subtract operation, the mesh was generated. The characteristics of the mesh are defined in the Appendix A.

The main interest was on the phenomena occurring on the surface of the model (the cover), for that reason 8 prism layers were generated.

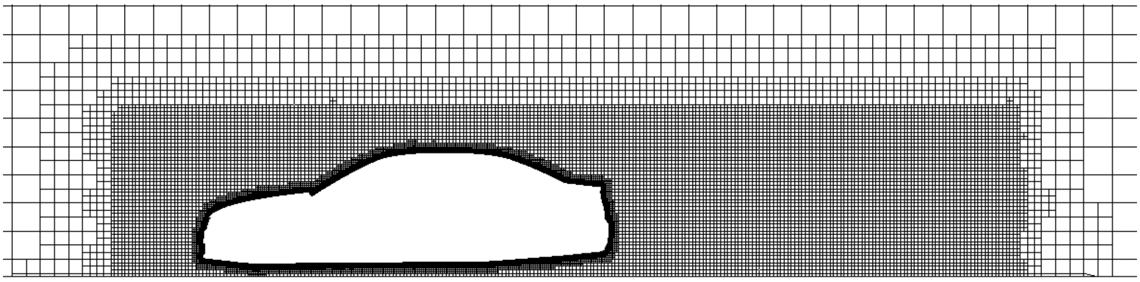


Figure 3.8: *Volume mesh of the baseline model on y=0 plane.*

3.3.3 Simulation

With the baseline, three different simulations were carried out. The first one was run with a speed of 100 km/h, the second one at 140 km/h and the latest was run with the car on reverse position and a speed of 100 km/h.

The speed of 100 km/h was taken as a reference velocity for trucks on highway (it may be lower or higher depending on the country). The simulation at 140 km/h was carried out to simulate the highest velocity to which the vehicle can be exposed when being transported. Finally, the cars are sometimes placed in a reversed position on the trucks, so that this setup needs to be studied as well.

The conditions applied were the following:

- Inlet velocity: 100 km/h and 140 km/h.
- Fluid: air
    - Density: 1.205 kg/m^3.
    - Viscosity: 1.805 e-05 kg/ms.
- Pressure: atmospheric.
- Turbulence model: k-omega SST.
- Turbulence intensity = 0.1%.
- Ground: slip.
- Tunnel walls: symmetry wall.

These conditions are based on the flow conditions at Volvo Cars wind tunnel (PVT) where the tests with the cover are performed.

Only the configuration with the vehicle placed on frontal position and a speed of 100 km/h was simulated in the following cases. The same solvers and conditions were used in all cases. (No further comments will be mentioned on the other cases about the simulation).

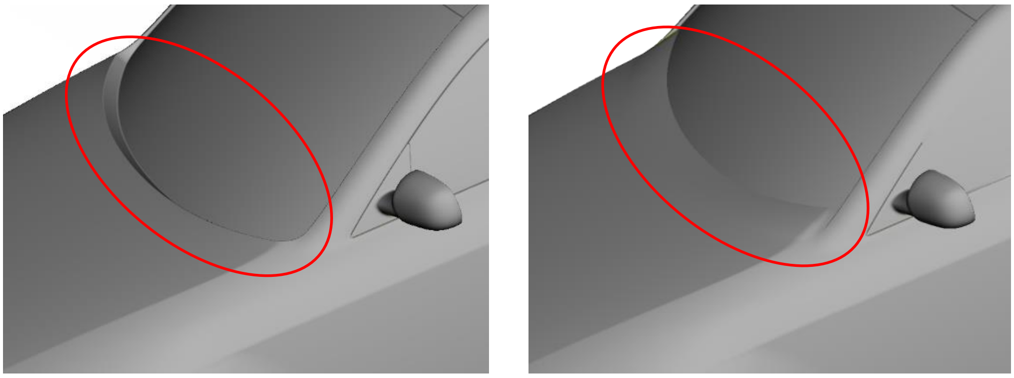
3.4 Case 2: Wrapped model

3.4.1 Geometry preparation

This case was meant to be a step on the process to reproduce a geometry similar to the car with a cover on it.

The purpose of the wrapping is giving a coarser aspect to the surface of the model to imitate the irregular shape and the wrinkles of the cover. To get a proper approximation to the actual appearance of the cover, different wrapping parameters were applied to some parts.

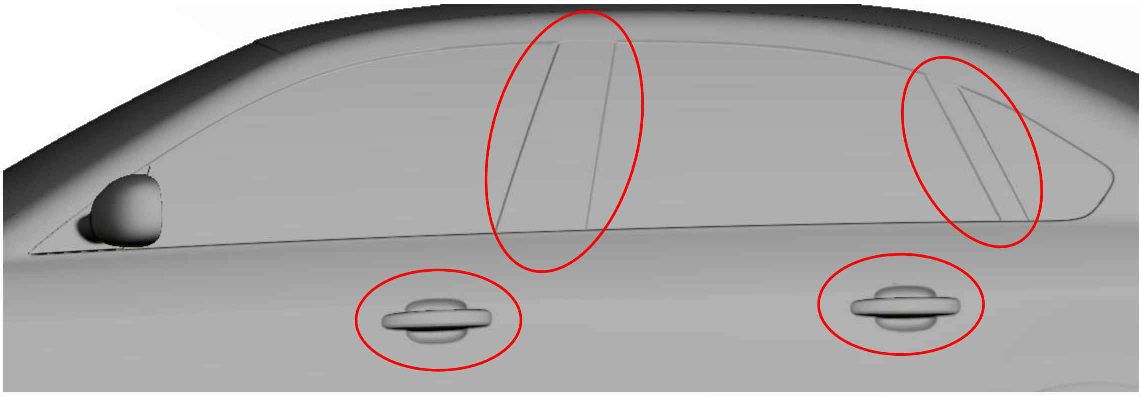
Before the wrap, some gaps were closed and some details eliminated (see Figures 3.9 and 3.10).



(b) *Baseline*

(b) *Wrapped model*

Figure 3.9: *Detail eliminated on the hood before the wrap.*



(a) *Baseline*

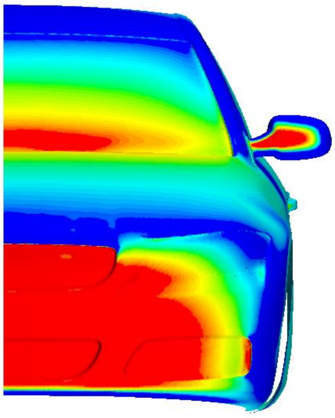
(b) Wrapped model

Figure 3.10: *Details eliminated on the side of the car before the wrap.*

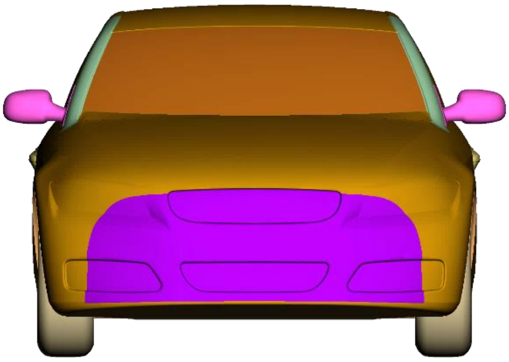
The base wrapping had the following parameters: 50 – 70 mm of element length, feature angle of 20º and curvature refinement of 20º. Local controls to set different element length on different regions were used on some parts of the model.

Local control was applied on the windshield. On the actual vehicles, this part is not covered, thus a tight and smooth wrapping was applied on it, 4 – 8 mm of element length.

The front of the car required special treatment as well. This is the stagnation point, meaning that high pressures are found on this area, leading to a compressed and tighter shape of the cover on this part of the vehicle. The dimensions of this area were obtained as an input from the pressure results obtained in the simulation of the baseline model (see Figure 3.11). The local control applied is 25 – 50 mm of element length.



(c) C_p on Case 1 simulation | Star-CCM+

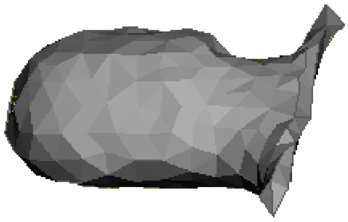


(b) *Region for local control | ANSA*

Figure 3.11: *Stagnation area with smoother wrapping parameters.*

When the wrapping was applied to the whole model, a problem was detected due to the rough wrapping (50 – 70 mm) applied. The mirrors, that are projecting out of the body, suffer a deformation as it can be seen on Figure 3.12 (a). The solution found, is to wrap the mirrors individually. A constant length wrapping of 25 mm target length and shells out structure ensure that the volume of the mirrors is not reduced and the link to the body is thickened (see Figure 3.12 (b)).

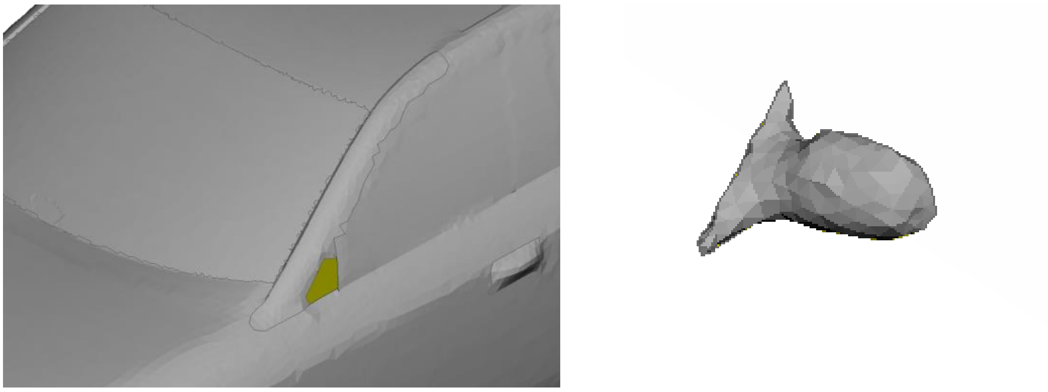
(a) *Wrapped with the body*



(b) *Wrapped apart*

Figure 3.12: *Different wrap applied on mirrors.*

The last step was to get the two wrappings (body and mirrors) together as a closed geometry ready to be meshed. This was done with a final wrap applied on the two previous wrapped parts (see Figure 3.13). The parameters applied were a variable element length of 4 – 8 mm. The reason of using a smooth wrapping is that the coarse surface and the suppression of details on the surface was already achieved by the previous wrappings and high values of element length would lead to an exceedingly coarse surface on the body and the same issue on the mirrors mentioned before.



(a) *Body wrap* (b) *Mirror wrap*

Figure 3.13: *Two previous wrappings before final wrap.*

The final wrap is shown in Figure 3.14. This model together with the wheels (unwrapped) was exported to Star-CCM+ to proceed with the next steps. It must be noted that on this step there is no differentiation between the cover and the vehicle itself, the wrapped model would represent a case on which the cover is so tight to the car surface that there is no flow in between.

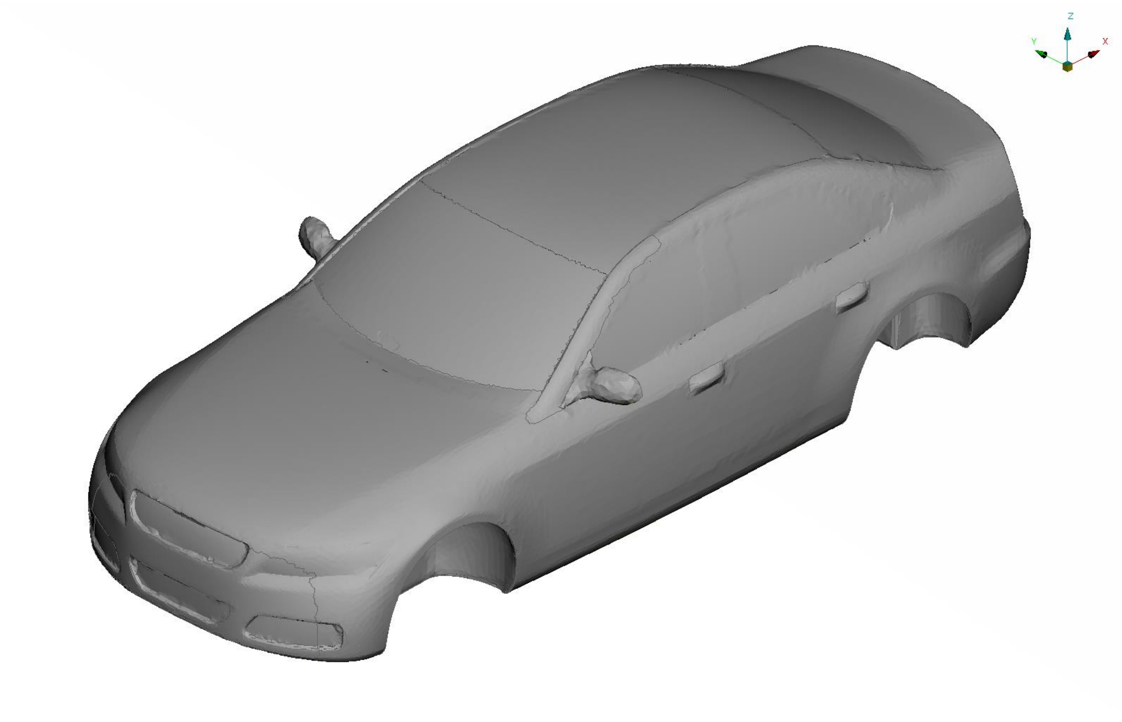


Figure 3.14: Case 2: *Wrapped model.*

3.4.2 Volume mesh

The same parameters and operations for the mesh generation were used in this case as those used for the baseline model.

3.5 Case 3: Morphed model

3.5.1 Geometry preparation

The aim of this stage was to generate an independent geometry that imitates the cover of the car. The consequent simulation included two geometries: the baseline model and the cover over it, with the purpose of simulating air flow between them. To achieve this, a gap long enough to generate cells and prism layers between the inner surface of the cover and the outer surface of the baseline needed to be created. This was done by means of the morphing tool in ANSA.

Two different shapes were implemented in this stage. The first one corresponded to the shape of the cover when the vehicle is standing still (or initial shape) and the other one corresponded to the shape of the cover when it is exposed to an air flow during transportation.

Case 3.1: Initial shape

The initial shape of the cover consisted only on moving (morphing) outwards all the surfaces of the car a distance of 1 cm. Note that outwards in this case means a perpendicular direction to the surface. Due to the difficulty of morphing every single surface of the vehicle along its perpendicular direction, the solution adopted was to create groups of surfaces that were displaced in the three coordinate directions (i.e. the front-bump, the hood, the lateral side, the roof, the back, the underbody…). Since there is no cover on the windshield, this part was not morphed, furthermore the edges were not displaced because the actual cover is taped there, meaning that the edge of the cover should be in contact with the windshield of the baseline.

Morphing boxes (Figure 3.15) were used instead of direct morphing to avoid having a stepped final surface. The use of morphing boxes results in a gradually deformed surface. This gradual deformation leads to a shorter displacement on the areas near to the edge of the box (see Figure 3.16), for that reason, additional morphing steps had to be taken on these areas (blue) to equalize the displacement to those areas in the middle of the box (red and yellow).

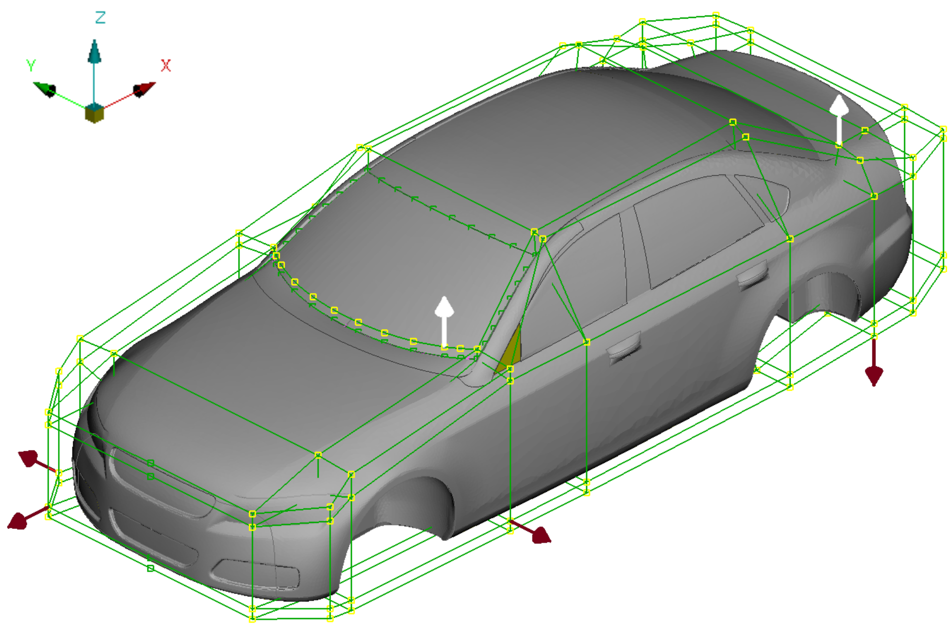


Figure 3.15: *Morphing boxes and direction of morphing.*

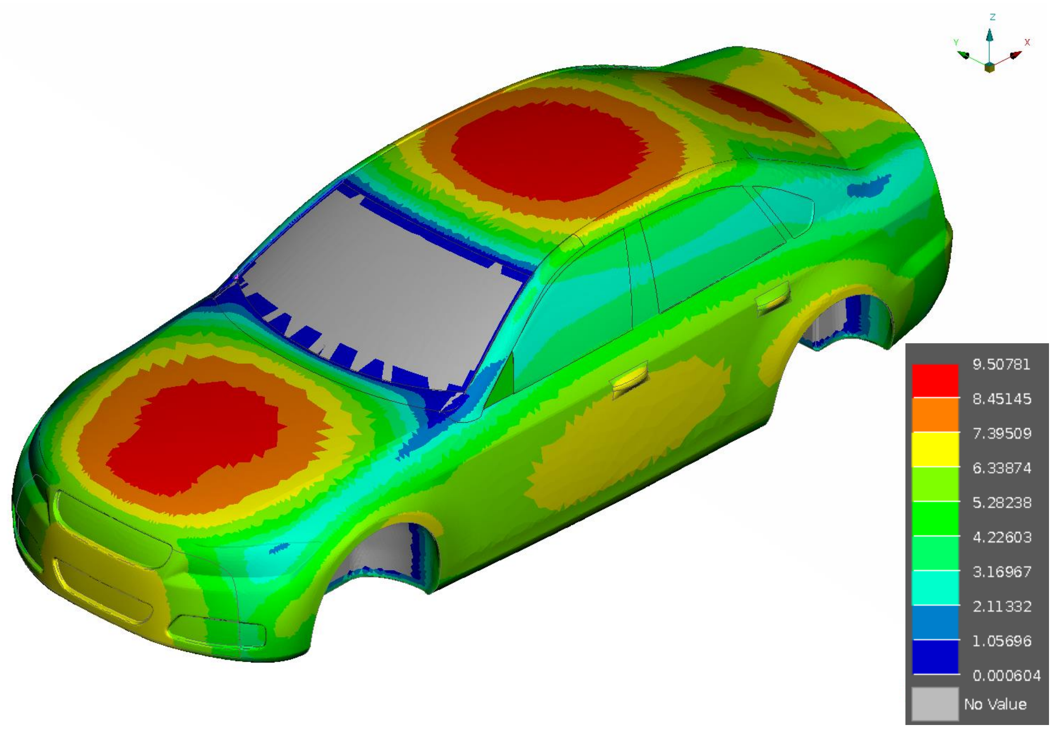


Figure 3.16: *Deformation range – 1st morphing.*

The areas painted in blue (light blue included) were those areas that needed another morphing operation (see Figure 3.18). To do that, the original morphing boxes were split into new smaller ones (see Figure 3.17) to apply a more precise morphing only on those areas mentioned. This step was of great importance to ensure that there is a gap wide enough between the car and the cover to generate prism layers on those parts of the surface, allowing this to simulate air flow under the cover.

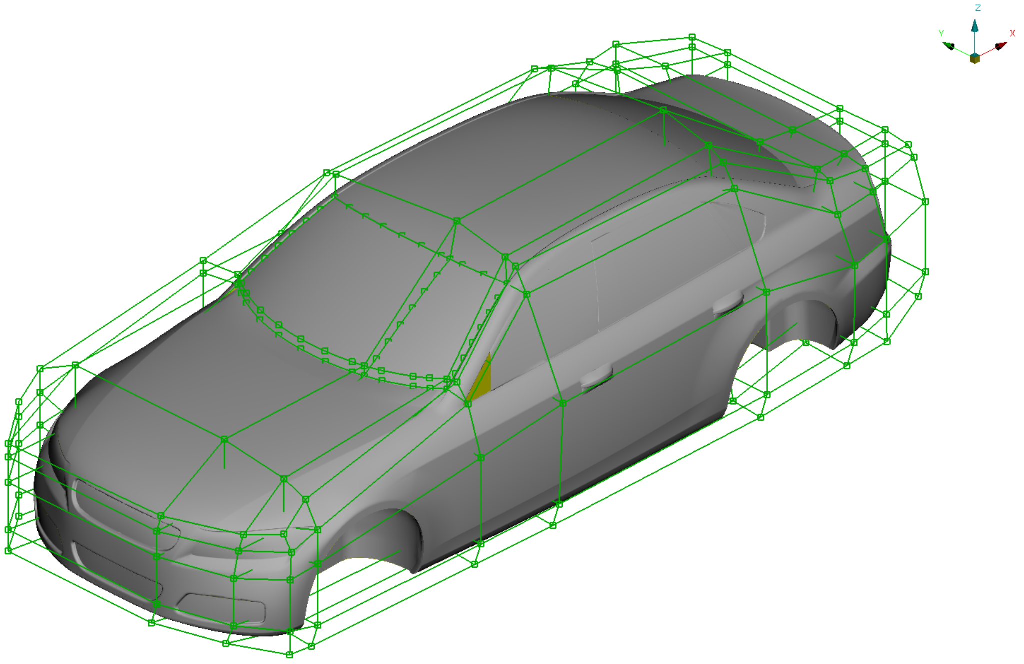


Figure 3.17: *Split morphing boxes for second morphing.*

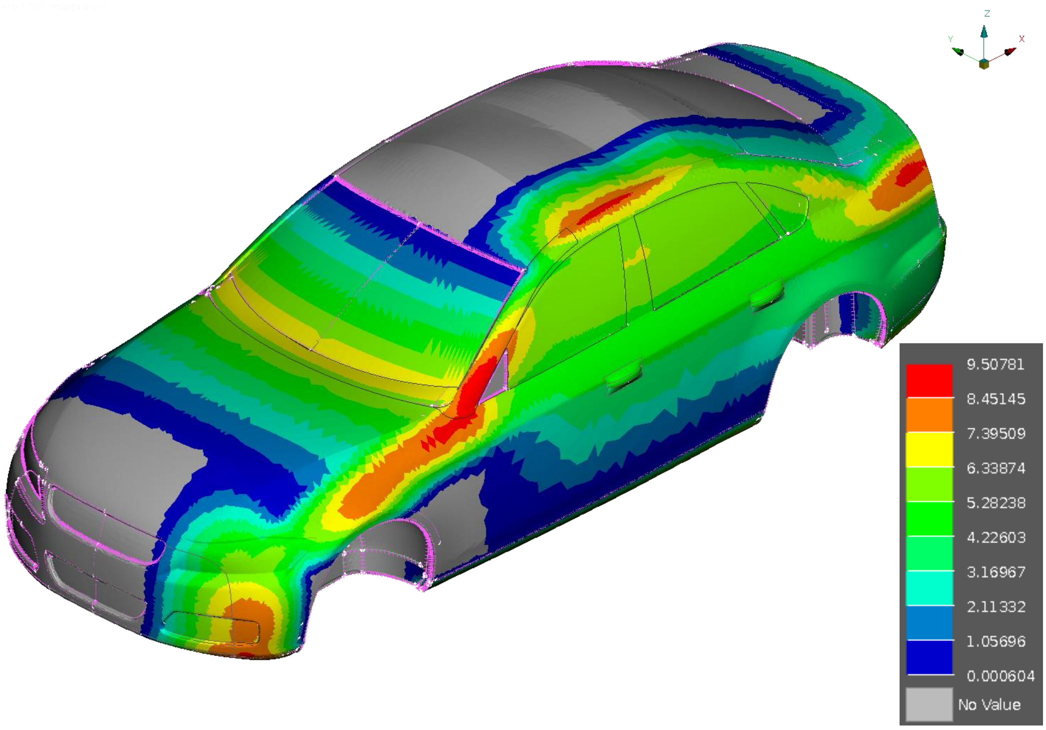


Figure 3.18: *Deformation range – 2nd morphing.*

The morphing was applied to the car body except to the mirrors. Due to their complex geometry, the mirrors were treated apart again. In this case, the operation applied to the mirror was a successive wrapping operation on them. Doing this, a gap was generated between the final wrap and the initial mirrors shape (see Figure 3.19). Note that it is essential to specify the nodes out structure wrap option to ensure that the new wrapping is completely covering the previous one.

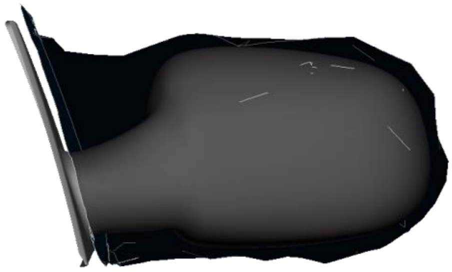


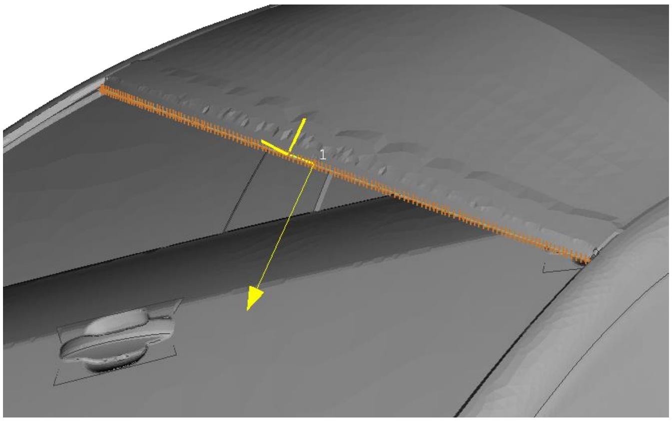
Figure 3.19: *Final wrap (transparent black) over original mirror (grey).*

A final wrap was needed again to get a linked and closed geometry between the body and the mirrors (the wheels are again excluded from the wrap).

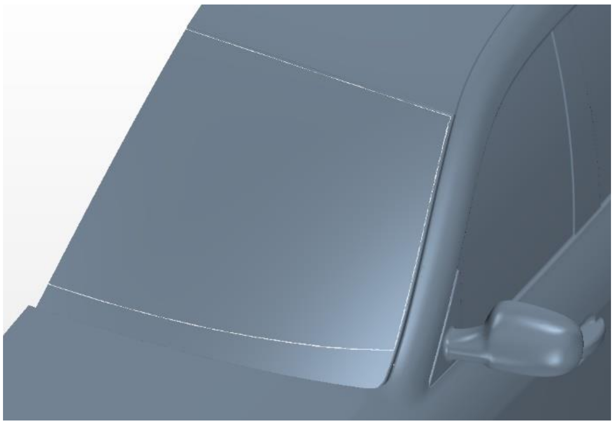
Once the wrap was generated, another operation had to be done, opening a set of holes in the front of the car to imitate the actual covers (see Figure 3.1). This operation was simply done by projecting curves (circles) on the shell mesh.

On applying that last step, it could be considered that the geometry preparation was finished, nevertheless an error obtained during the mesh generation in Star-CMM+, made necessary one last morphing operation on the model of the cover. The error reported, was a contact between the cover and the baseline. The specific source of contact was the edge of the windshield (remember that it was not displaced during the morphing). One solution could have been to separate the edges of the cover from the windshield a short distance to avoid the contact, but this solution would not be correlated to the actual layout of the cover on the vehicle and would allow flow coming in. In order to get a closed transition between the windshield and the cover, thus preventing the air flow to come in, the solution adopted was to generate an intersection between the cover and the windshield of the baseline. Then the subtract operation on Star-CCM+ would perform a cut on the intersection leaving the two different geometries perfectly connected on it.

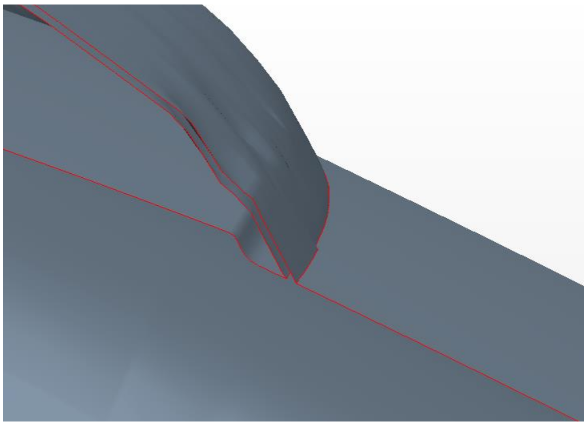
The operation carried out on ANSA was a direct morphing of the edge of the cover on the windshield in a direction inwards the vehicle (see Figure 3.20 (a)) and a distance long enough to ensure that there is a complete intersection between the cover and the baseline on the windshield.



(a) *Morphing on the edge of the roof*



(b) *Intersection on the baseline*



(c) *Detail on the upper edge of the windshield with cover*

Figure 3.20: *Intersection on the windshield after the subtract operation in Star-CCM+.*

It can be seen on Figure 3.20 the result after performing the subtract operation, on 3.20 (c) it can be appreciated that the cover and the windshield are in contact and closed preventing air flow coming in under the roof.

The surface shown in Figure 3.21 is the geometry imported to Star-CCM+. Note that it is an open geometry. The model was morphed with all its parts from the baseline but only those that are part of the cover were imported for the simulation.

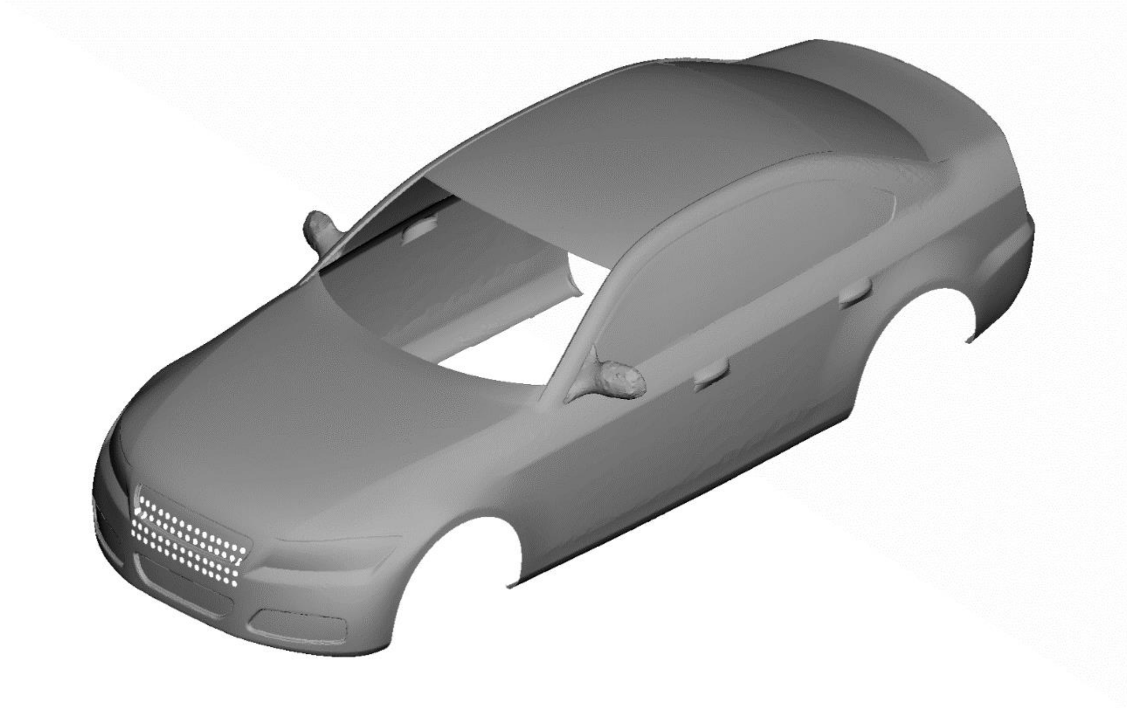
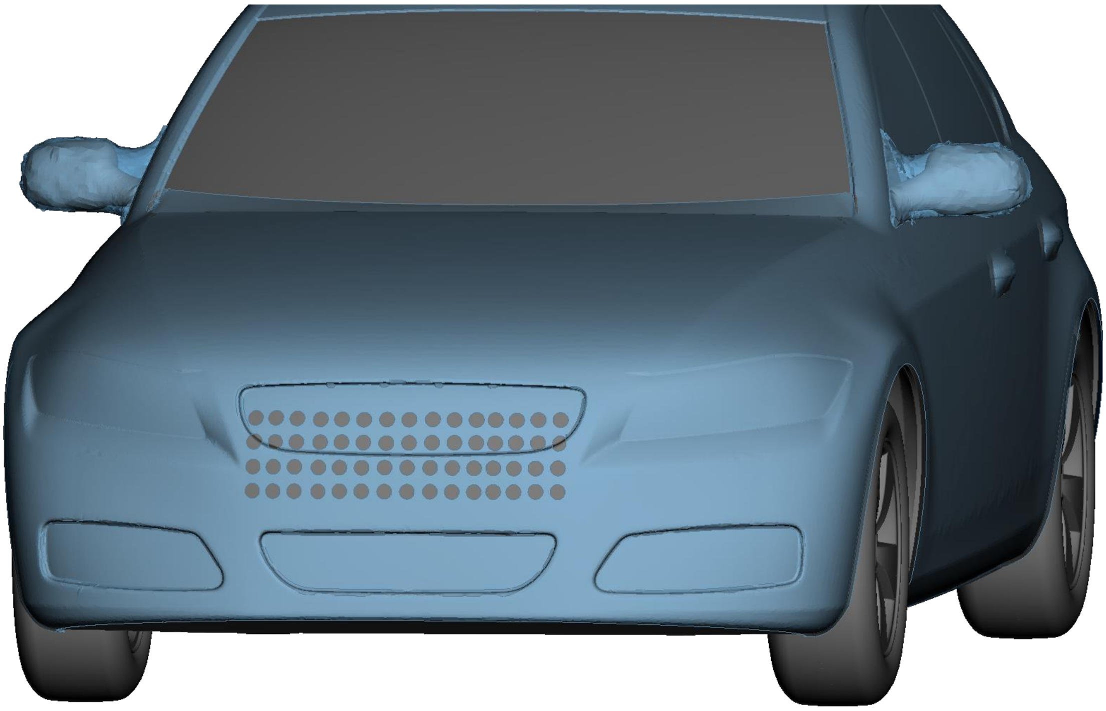


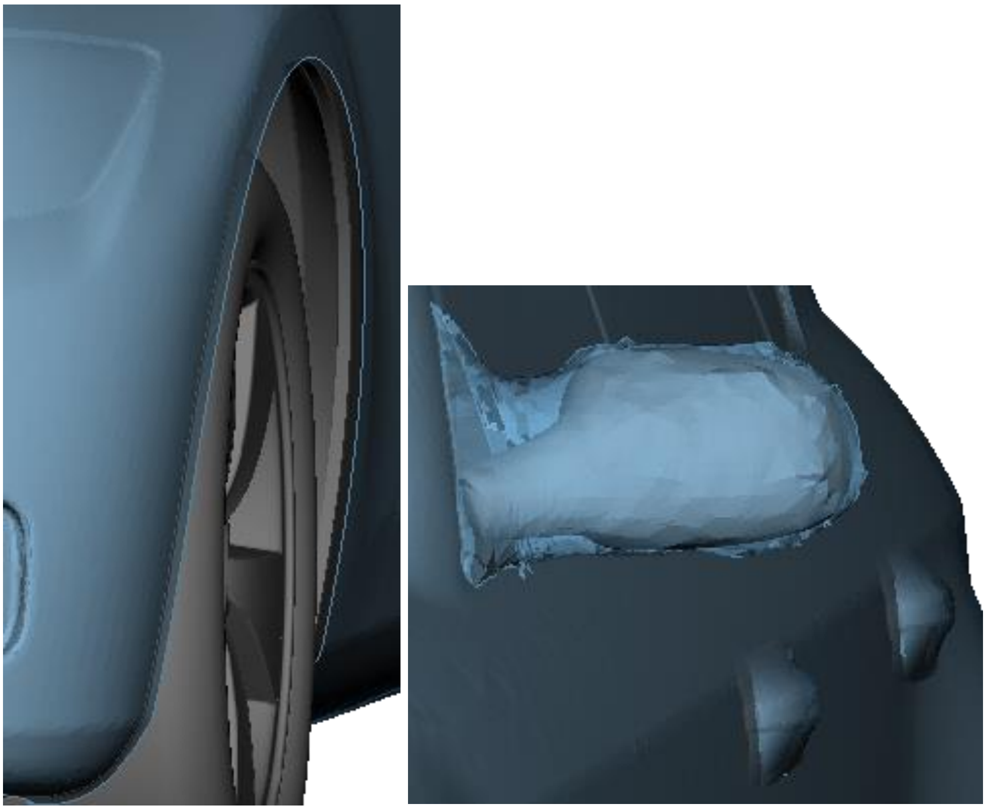
Figure 3.21: *Model of the cover in its initial position.*

The cover was simulated together with the baseline. On Figure 3.22, both geometries are showed in the position they were simulated.

The process to generate the cover is quite time consuming but in the future the process could be automatized.



(a) *Baseline with the cover on it*



(b) *Details of the gap between the cover and the baseline*

Figure 3.22: *Cover (transparent blue) and baseline (grey).*

On the details of the Figure 3.22 the gap between the cover and the baseline can be appreciated.

Case 3.2: In motion shape

It is known from experience that when the covered vehicles are subjected to a flow, the cover is deformed creating bubbles of air between the cover and the car. These bubbles of air show a wave-like motion. Due to the fact that it is not possible to simulate this motion, the adopted solution is to reproduce the shape of the cover at an instant. Further simulations could be done by changing the shape of the cover to a different instant.

This case consisted on giving to the cover a similar shape as the one it has in the wind tunnel, with the bubbles of air under the cover. The process followed is the same as in the previous case, using morphing boxes. The initial shape of the cover morphed in the former case is used as starting point. In a deeper approach, the pressure and stress results obtained on the simulation of case 3.1 should be used as an input to morph the cover. For this case, the values used for the morph are based on the information from the tests at VCC.

On the hood, the lift applied was 10 cm whereas on the roof a lift was applied on three different points, 10 cm, 3 cm and 8 cm from the front to the rear (see Figure 3.23).

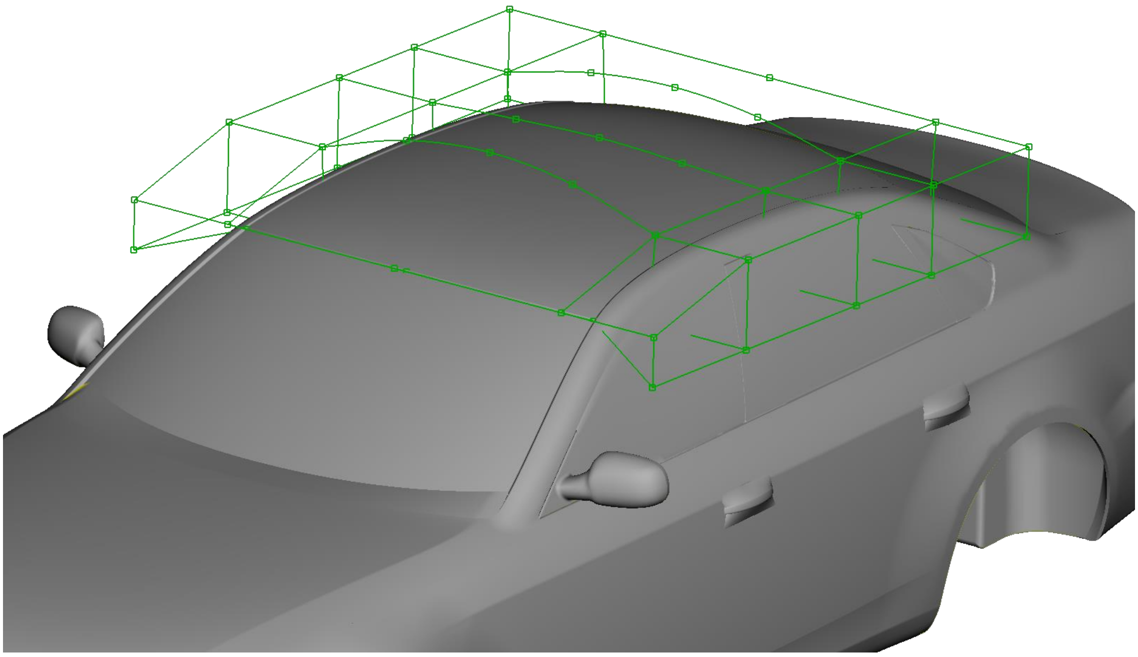


Figure 3.23: *Morphing boxes to generate bubble shape on the roof.*

The final surface can be seen in Figure 3.24 below, being this the geometry imported to Star-CCM+. All the additional steps (the direct morphing on the edges of the windshield) taken for the first morphed model were implemented on this case.

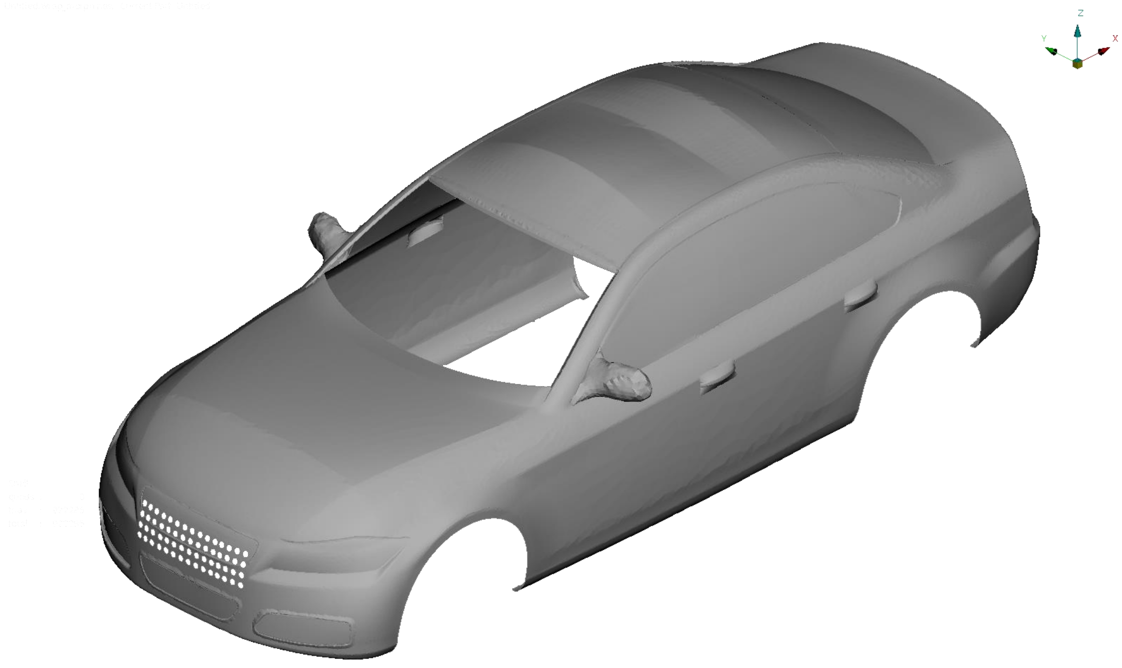


Figure 3.24: *Model of the cover when subjected to a flow.*

3.5.2 Volume Mesh

In this case, there is a modification in the process to generate the volume mesh with respect to the case 1. First of all, in this case, two geometries were imported to the simulation file as it was shown in Figure 3.22. One of these geometries is the baseline imported in the case 1 and the other one is the cover as it has been shown before. The cover is an open geometry therefore a volume mesh cannot be generated from it. To solve this issue a wrap operation was done, yielding a closed volume with the same shape of the cover (The wrap operation was not performed on ANSA because the wrapping operation was not well performed as it can be seen in the Figure 3.25 below).

Figure 3.25: *Wrap on the model of the cover in ANSA.*

Once this problem was solved, the process was the same. At first, the subtract operation was performed helping to solve in this case the problem found on the windshield edges and creating an intersection as it was showed before. The subtract operation was applied to the cover, the baseline and the half tunnel, being the latter the objective part again.

Proceeding to the mesh generation (see Figure 3.26), again, due to the fact that there were two geometries, two different surface controls had to be applied (See details on appendix B).

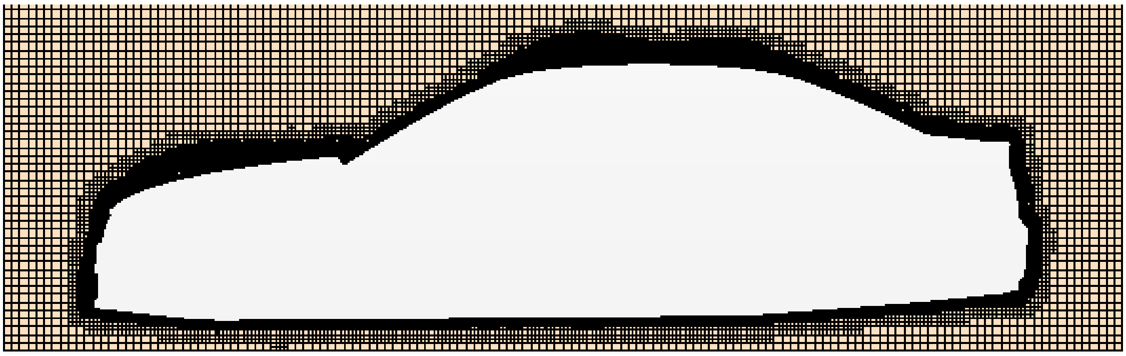
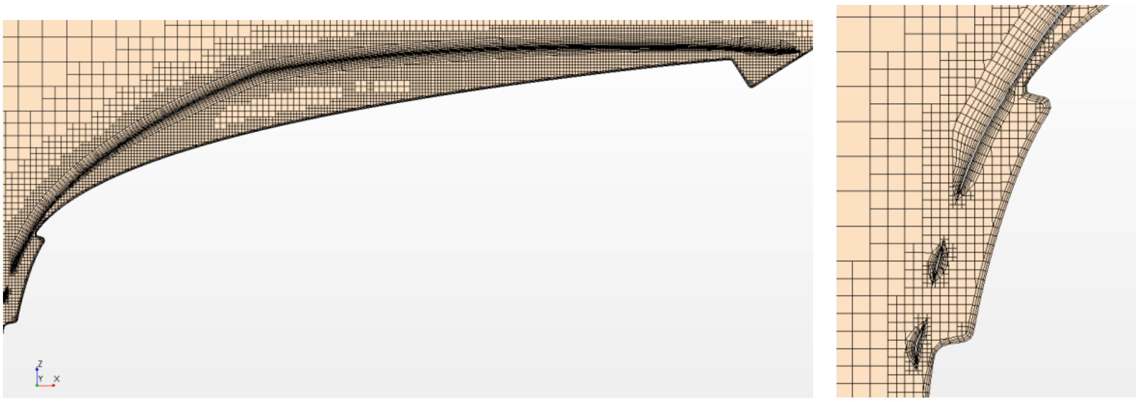


Figure 3.26: *Mesh of the case 3.2 (cover with bubbles of air).*

The cells between the hood and the cover simulating the bubble of air can be observed in Figure 3.27 (a). In Figure 3.27 (b) a detail of the prism layers is showed, there are prism layers on the cover (in both surfaces inner and outer) and on the baseline.



(a) *Hood* (b) *Radiator of the car*

Figure 3.27: *Detail of the mesh of the case 3.2 (cover with bubbles of air).*

4 Results

The results of the different parameters of interest are presented comparing the different cases simulated. The interest of this paper is on what happens on the cover, trying to find a correlation between the failures observed in the wind tunnel tests and the source of it. For that reason, the results are focused on the forces and stress to which the cover is subjected.

The simulation of the vehicle in a frontal position with a speed of 100 km/h is going to be analysed together for the three different cases. The simulation of the case 1 in its three different configurations will be analysed apart.

4.1 Pressure

The pressure is the higher source of stress on the cover and the origin of the deformation on it. For that reason, special attention was paid to it.

The pressure field on the cover is determined by its shape and the pressure itself will determine the shape of the cover and the stress distribution on it. As it was mentioned before, only an instant of deformation was simulated, so that the deformation of the cover due to the effect of the pressure was not calculated.

To compare the different cases, the pressure coefficient (C_p) was used.

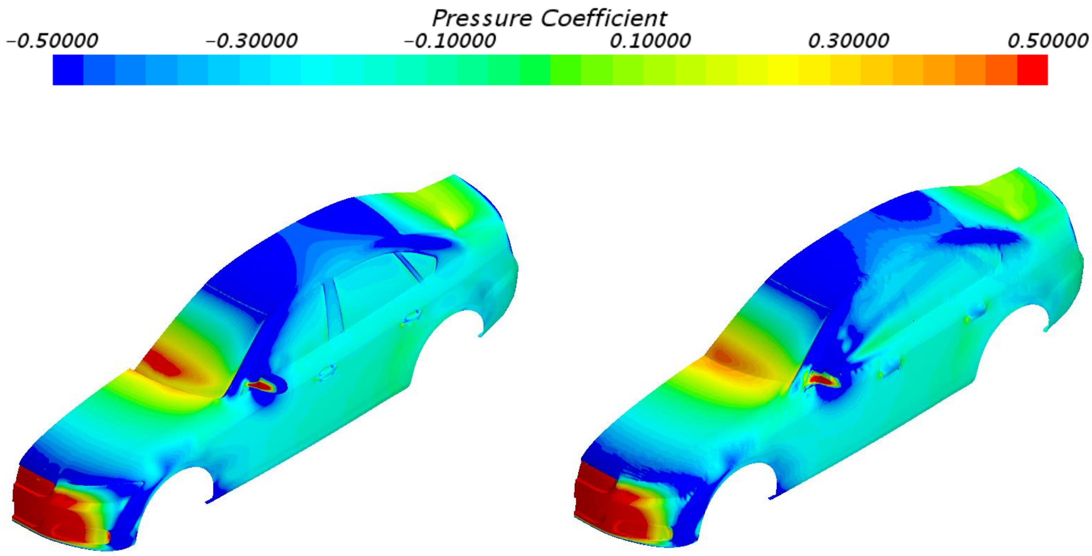


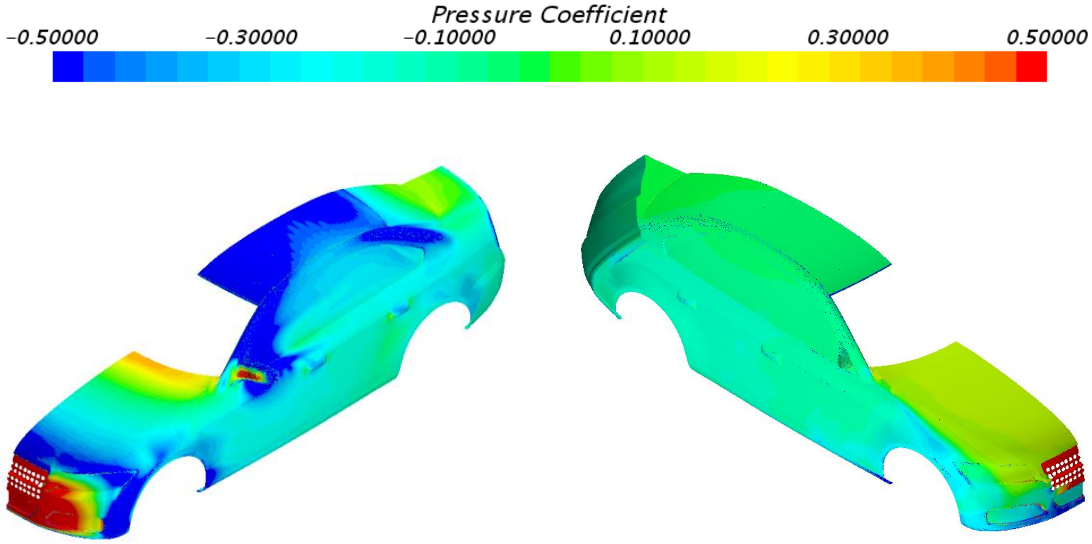
Figure 4.1: *C_p on case 1: Baseline (left) and case 2: Wrapped model (right).*

The main difference that can be observed between the case 1 and 2 (Figure 4.1) is that the pressure distribution is less uniform in the second case due to its rough surface. This is of importance because this could lead to areas of stress concentration.

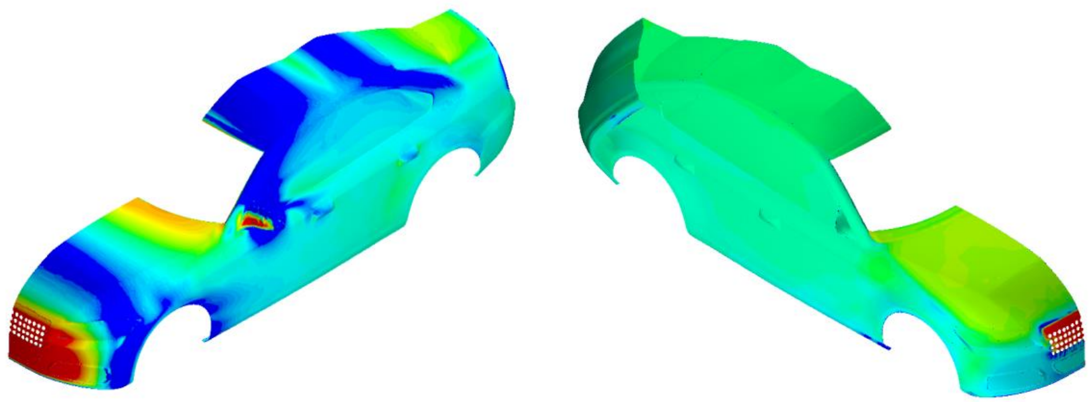
It is basic to remark that the deformation on the cover is not determined by the pressure on its outer surface but by the pressure difference on both surfaces. On these first two cases, only the external pressure could be obtained because the model simulated was a closed body. In a simplified analysis, it could be considered that the pressure under the cover is the atmospheric.

The areas with lower pressure on the external surface than the internal surface of the cover, will experience a deformation or suction outwards, generating those bubbles of air that appear under the cover as it is known from the wind tunnel tests. Assuming atmospheric pressure under the cover, all the regions with negative pressure (blue) will suffer the suction effect.

This result confirms that there is a correlation between the simulation and the actual tests because the bubbles of air can be predicted with the results shown on Figure 4.1.



(a) *Case 3.1: initial shape – external surface* (b) *Case 3.1: initial shape – internal surface*



(c) *Case 3.2: bubbles shape – external surface* (d) *Case 3.2: bubbles shape – internal surface*

Figure 4.2: C_p *on case 3: Baseline + morphed cover.*

On the case 3 (morphed cover over the baseline model), in its two configurations, the pressure was analysed only on the cover even though the simulation was carried out with the two geometries and therefore there is a pressure distribution on the baseline as well.

In this case, having an open geometry for the cover and air flow circulating between the cover and the vehicle, the pressure distribution was obtained on the outer and inner surfaces of the cover, so that the pressure difference (Δp) was known as it can be seen on Figure 4.2.

As it was mentioned in the methodology section, the pressure result on the initial shape (case 3.1), is to be used in the morphing of the bubbles shape for the case 3.2. The case 3.1 can be seen as the instant when the vehicle changes from a standing still position to a moving position in which it is exposed to the air resistance (or the instant when the wind tunnel is started). This way, the evolution of the cover from the initial state to the other can be predicted. It is a simplified way of calculating it because the vehicle does not change from 0 to 100 km/h instantly. A more precise calculation would need an iterative process in which the velocity was increased step by step.

Interestingly, it is observed in the case 3.2 that the negative pressure is concentrated on the bubbles, which due to the pressure difference would lead to an increase in their height (deformation). Another remarkable fact observed is that the pressure under the cover is not the atmospheric, especially on the hood, where the proximity of the openings on the front create a flow under the cover. So, the assumption on the first two cases can be accepted as a first approach to the problem but not when a more precise solution is aimed. It must be pointed that refrigeration flow into the vehicle is not simulated, that would also change the results.

From the experience in the wind tunnel it is known that the areas where the cover usually come off are the lower front and the wheelhouses. For that reason, they were analysed with more detail.

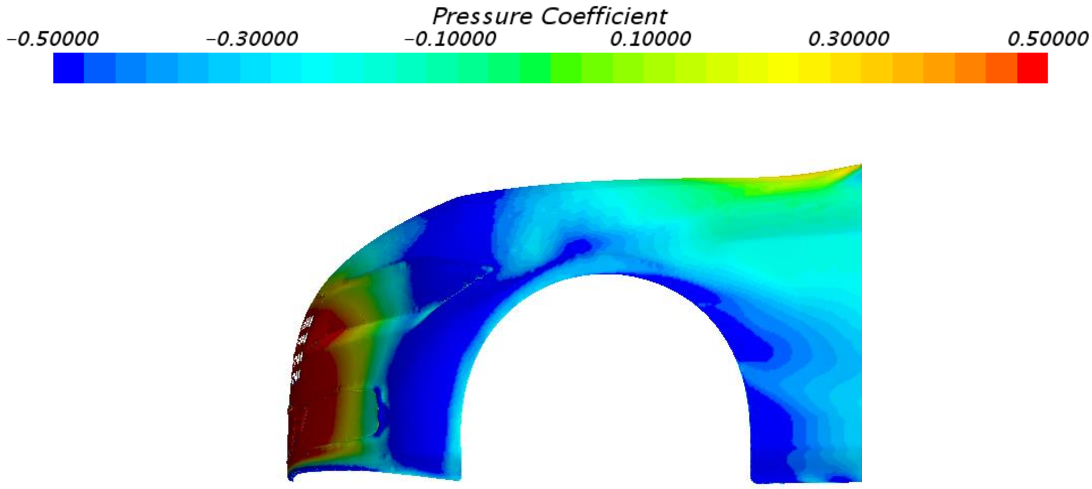
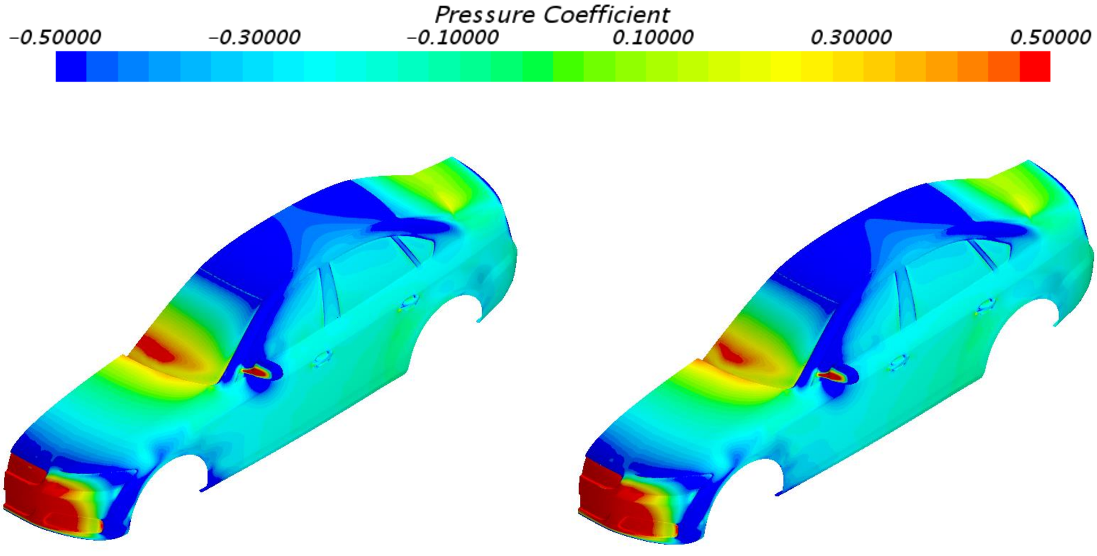


Figure 4.3: *C_p on case 3.2 (cover with bubbles) – detail of the wheelhouse.*

It is observed on Figure 4.3 that negative pressure appeared on the low border in the front, meaning that in those areas the cover will tend to loosen (because of the suction effect). In this model, the fixations were not simulated, but it is clear that fixations will be needed. On the right corner of the wheelhouse arch the same problem can be found.

Variation on the conditions of the simulation (position of the vehicle and velocity) were only analysed on the baseline model (case 1). The Figures 4.4 and 4.5 show the results obtained on its different configurations.



(a) *100 km/h* (b) *140 km/h*

Figure 4.4: C_p *on Case 1: Baseline – frontal configuration.*

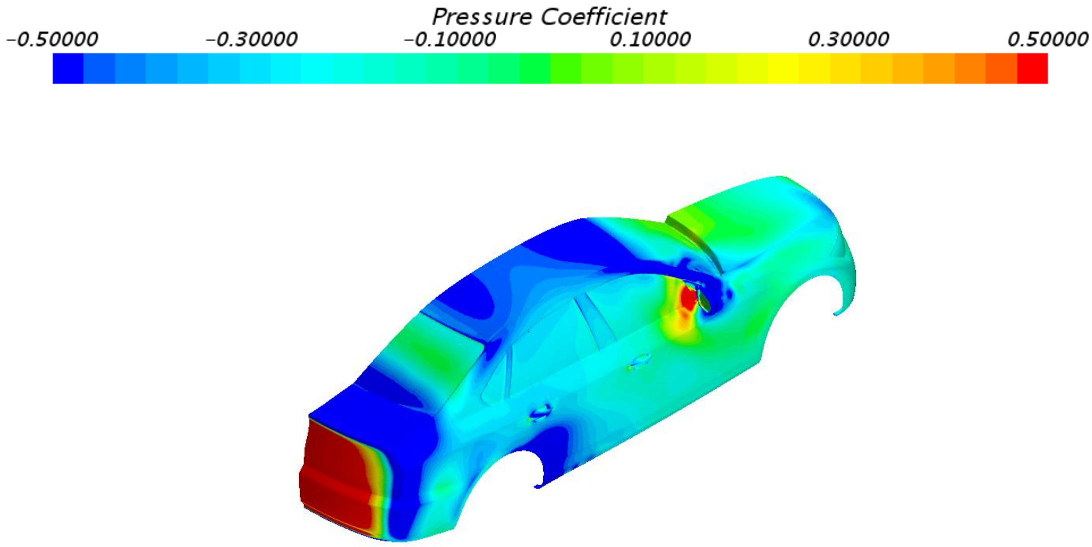


Figure 4.5: C_p *on Case 1: Baseline – reverse configuration (100 km/h).*

The only difference found between the simulation at 100 km/h and the one at 140 km/h is the higher pressure and a bigger area of negative pressure on the roof in the second case, which would result on a bigger bubble of air.

On the reverse configuration, the bubbles on the roof would probably be smaller by looking at the result. A negative pressure area can be seen on the trunk, this would induce to think that there will be another bubble there, however from the experience in the wind tunnel we know that the cover has not a big deformation on that part. This proves that even though most of the phenomena could be predicted by means of numerical simulations, experimental information is always needed to compare and validate a model.

4.2 Wall shear stress

The wall shear stress has a negligible magnitude when compared to the pressure, however it is still of importance because it will be the cause of the wave-like motion on the cover. It will cause the strain of the cover in those areas where there is a change of direction in the fibers of the material, generating stresses in different directions too that could lead to a rip in the material.

The non-dimensional skin friction coefficient is used to compare the different cases.

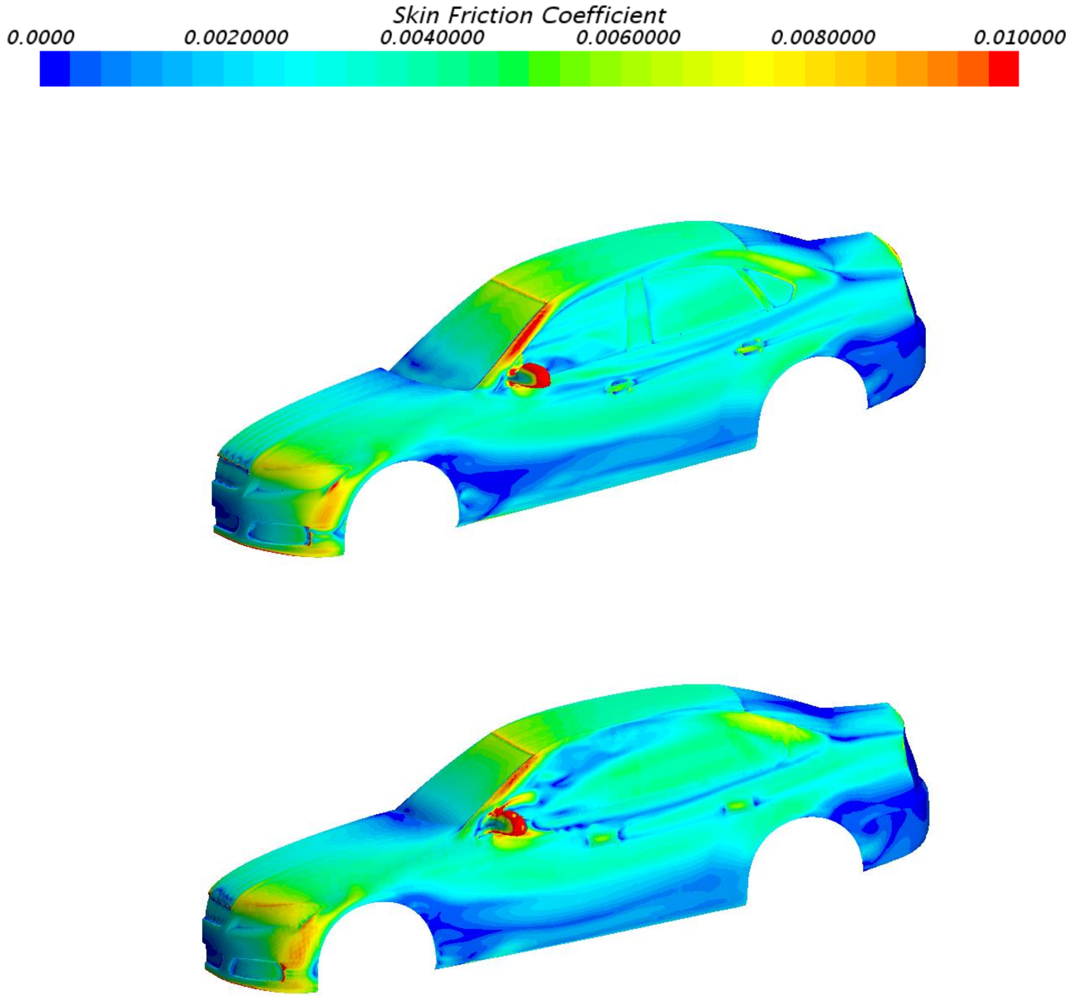
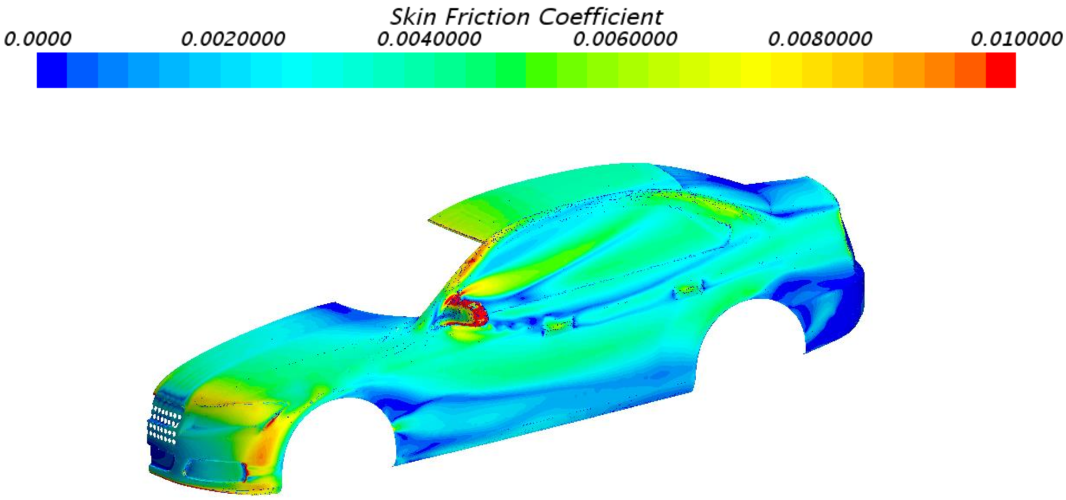
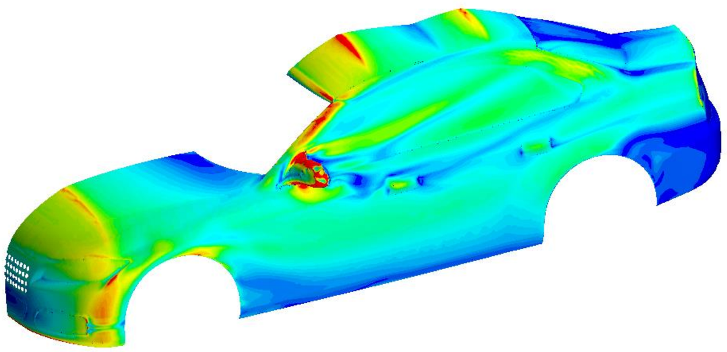


Figure 4.6: *Skin friction coefficient – Case 1: Baseline (up), Case 2: Wrapped model (down).*



(a) *Case 3.1*



(b) *Case 3.2*

Figure 4.7: *Skin friction coefficient – Case 3: Baseline + morphed cover.*

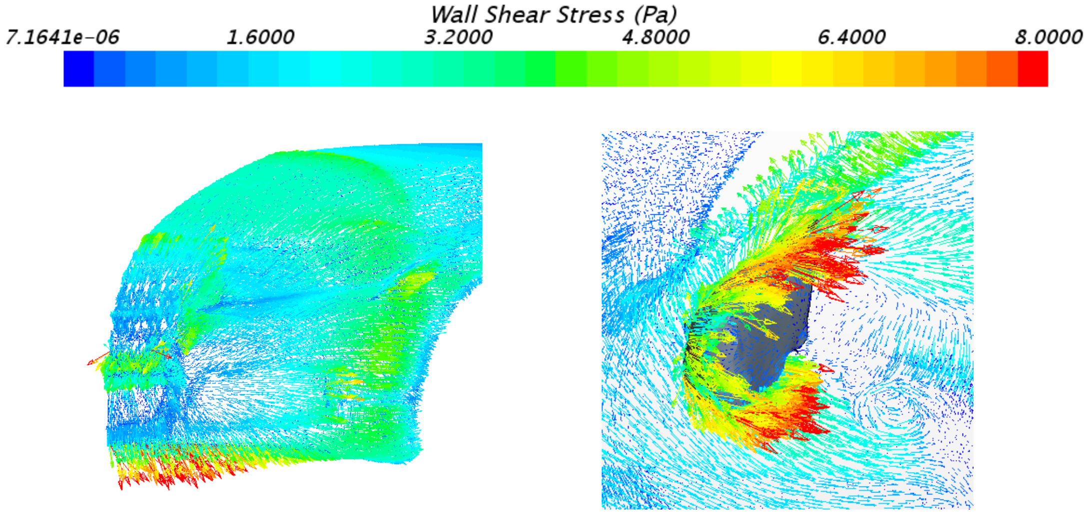
The first thing observed on these results is that the friction is concentrated mainly on the mirrors and the A-pillar which is the expected because of their protruded position.

In the first two cases (Figure 4.6), again no significant differences were found, just a less regular distribution of the stresses, especially on the wake of the mirror, whereas when simulating the case 3.1 (Figure 4.7 (a)) some differences could be overserved. These differences are located on the side part of the vehicle, on the windows and on the rear part of the front wheelhouse. Basically, it was an increase on the friction, which is comprehensible because the cover was placed in a more exposed position than the surface of the car.

The most remarkable phenomenon observed from the skin friction coefficient appears on the last case (3.2). High friction on the peak of the bubbles can be seen on Figure 4.7 (b). Due to the deformable nature of the cover this friction would produce a backwards displacement of the bubbles, generating the wave-like motion mentioned before. To calculate the new shape of the cover, it would be needed an iterative process combining this result with the one obtained from the pressure.

Another critical point on the cover, besides the front and the wheelhouses, are the mirrors. The wind tunnel tests result often in a rip on the part of the cover where the mirror and the A-pillar join. For that reason, the friction was analysed not only on the front of the car but also on the mirrors.

It must be reminded that the wall shear stress is defined by a vector so that the direction of it, is of importance. For that reason, only looking to the skin friction coefficient is not enough, it only represents the magnitude of the vector as a non-dimensional number. The vector representation was analysed on the areas that its effect might be critical either causing a rip or the cover to loosen.

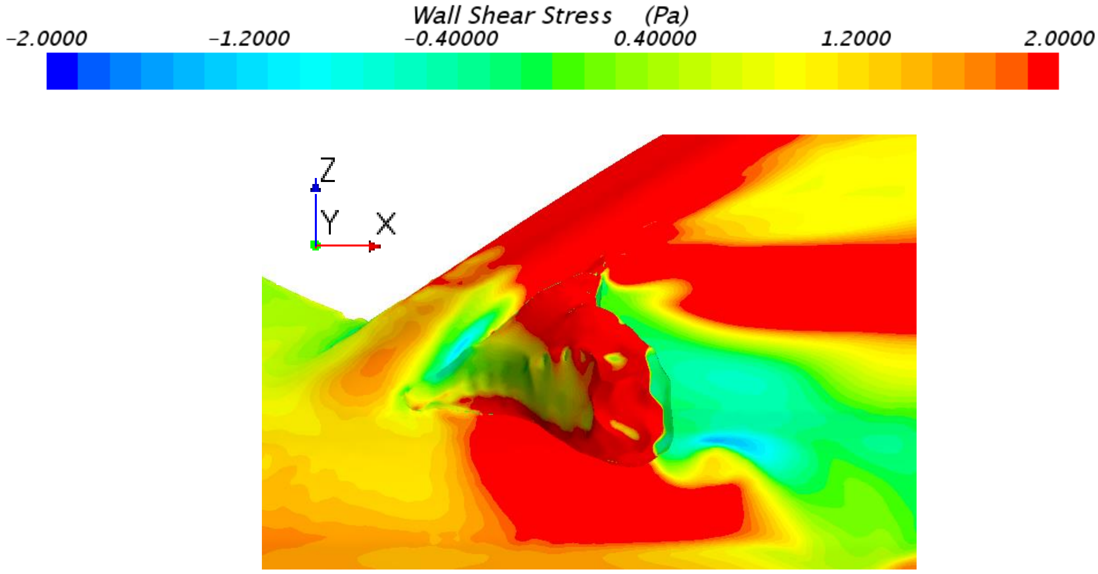


(a) *Case 3.2: cover with bubbles – Front of the car* (b) *Case 3.2: cover with bubbles – mirror*

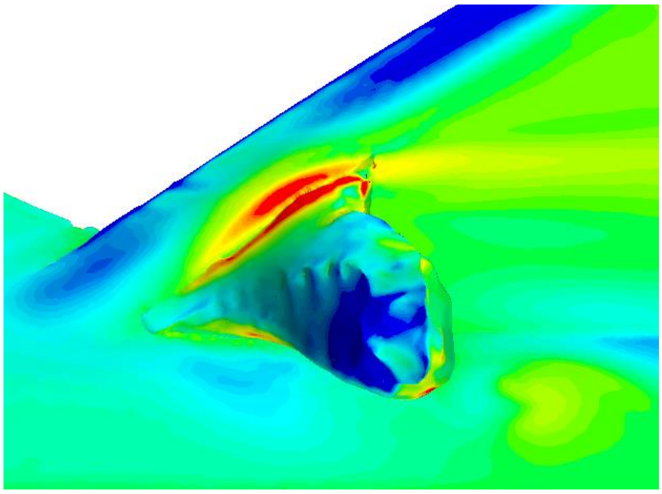
Figure 4.8: *Wall shear stress – vector representation.*

On the front of the car (Figure 4.8 (a)), the vectors point downwards meaning that the cover may loosen on that part, being the origin of it coming off, specially combined with the suction effect observed in the pressure results. On the mirror (Figure 4.8 (b)), high friction occurs and a big variation on the direction of the stresses is also observed. These different directions of the stresses may be the origin of a rip and it is important to consider them due to the fact that the material is orthotropic.

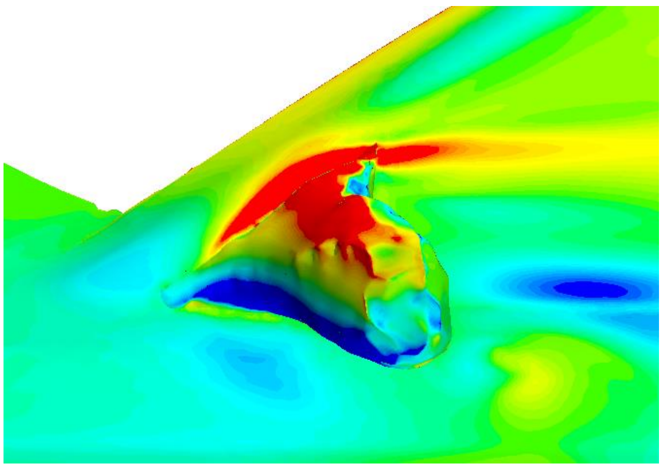
To see with more detail the different directions of the stress on the mirror, a surface representation of the magnitude on the three different vector components was analysed on Figure 4.9.



(a) *x direction*



(b) *y direction*



(c) *z direction*

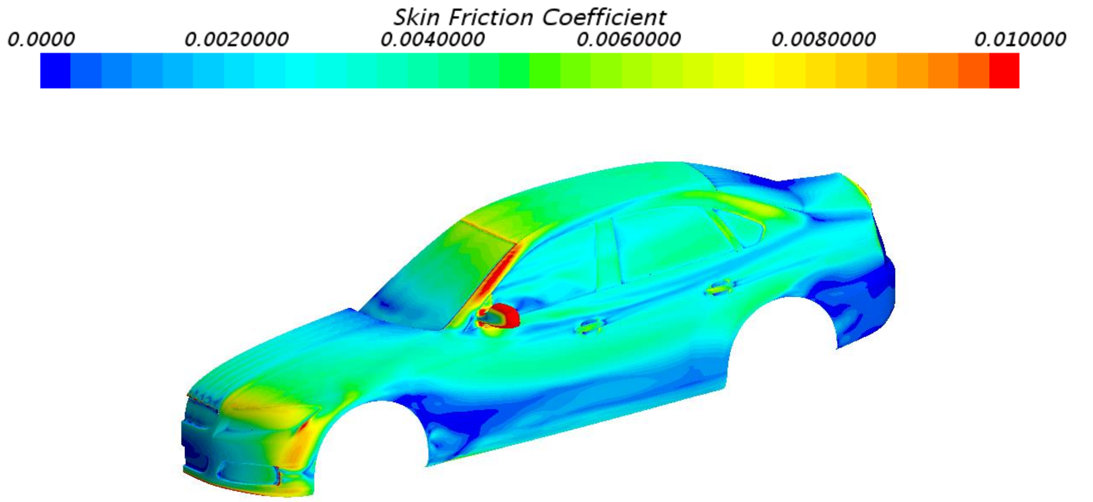
Figure 4.9: *Components of the wall shear stress on the mirror.*

As it was expected, the highest shear stress was found on the x direction, being that the direction of the air flow. But the most interesting fact is that stress was not only found to be high on the x direction but also on y and z direction. The y direction is on some parts of the cover the perpendicular direction, the same as the pressure, for that reason it is the least important of the three components of the shear stress. However, taking a look at the z direction, we can see high stress on the upper and lower sides of the mirror as well as on the joint between the mirror and the A-pillar.

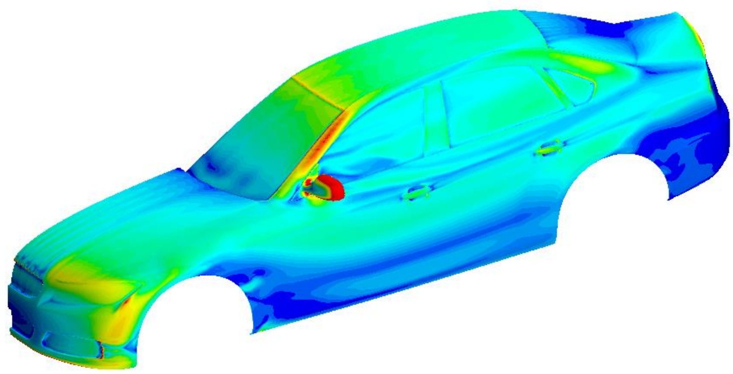
Focusing on that joint, it was made clear by the results that the cover will be subjected to high stresses on two perpendicular directions (x and z) being this a potential source of failure or rip on the cover.

Nevertheless, the magnitude of the shear stress is lower than the ultimate tensile strength of the material ($10\ N/m^2 << 26\ x10^4\ N/m^2$). That lead to a question, from experience it is known that there are rips on the cover in this part but from the results it cannot be asserted that. The reason is that in this simulation, the cover was considered as a rigid body (while in reality it would suffer a deformation caused by the pressure) so the final shape and stresses are not known from the results obtained. An iterative process, in which a structural analysis is performed, similar to the one mentioned for sails could give the final solution and the real stress on the cover.

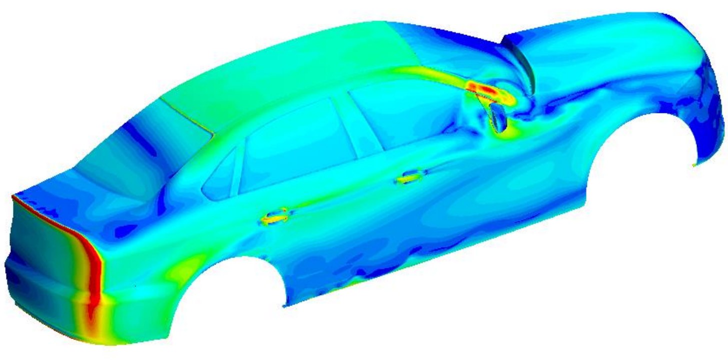
On Figure 4.10 the skin friction coefficient on the three different configurations of the case 1 is shown.



(a) *100 km/h frontal configuration*



(b) *140 km/h frontal configuration*



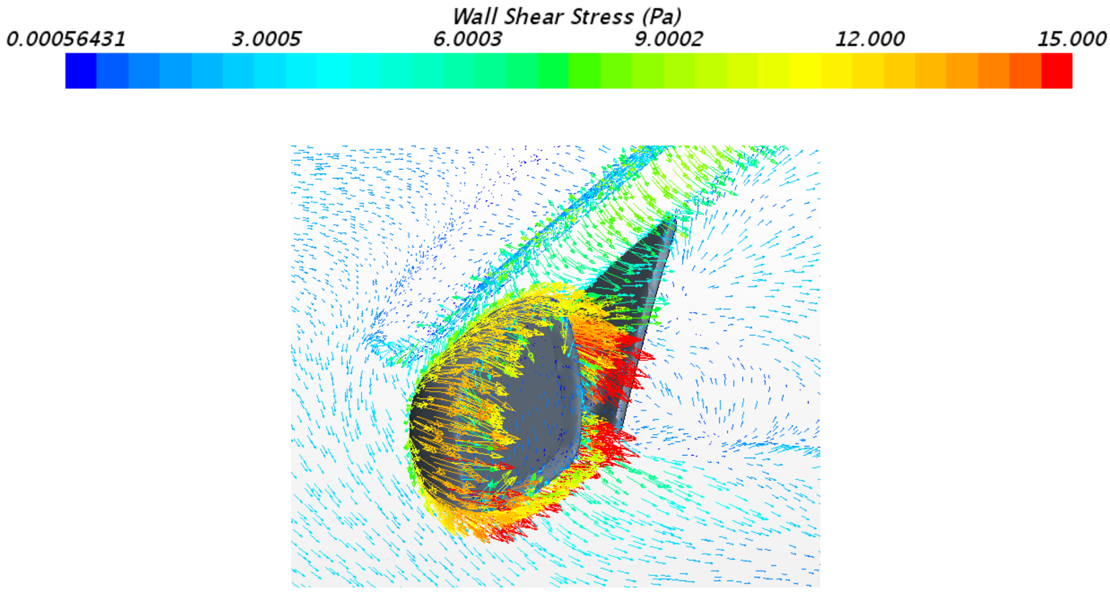
(c) *100 km/h reverse configuration*

Figure 4.10: *Skin friction coefficient – Case 1: Baseline | different configurations.*

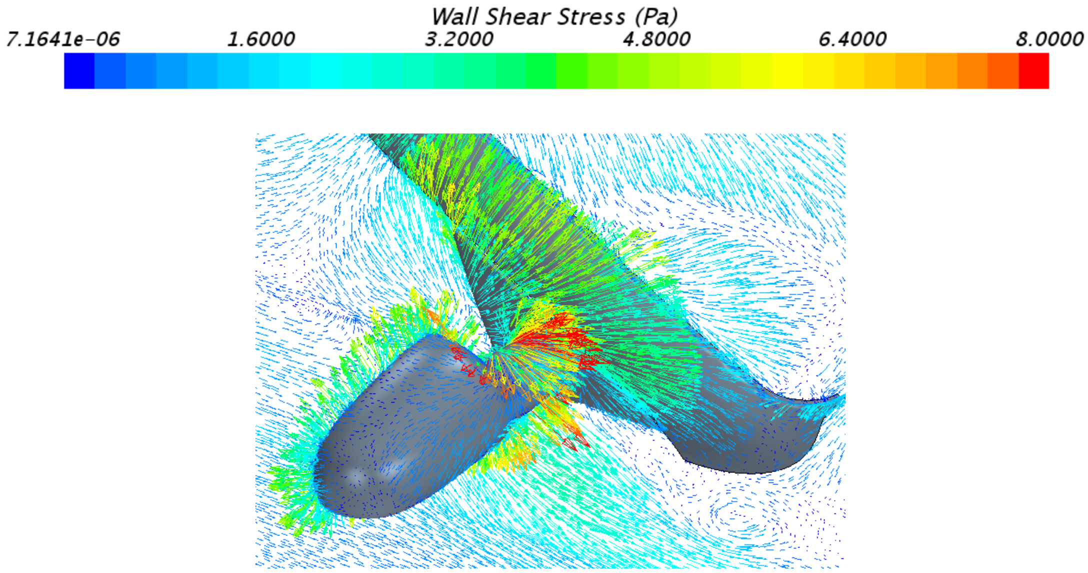
As it can be seen in Figure 4.10 above, there is not a remarkable difference between the simulation at 100 km/h and the one at 140 km/h. That is one of the reasons why not further simulations were carried out at this higher speed.

On the reverse configuration, however new and interesting results can be observed. High friction appears on the edges of the trunk and again on the joint between the A-pillar and the mirror.

To analyse the wall shear stress with more detail in those areas of high friction, again the vector representation was obtained (Figures 4.11 and 4.12).



(a) *140 km/h frontal configuration*

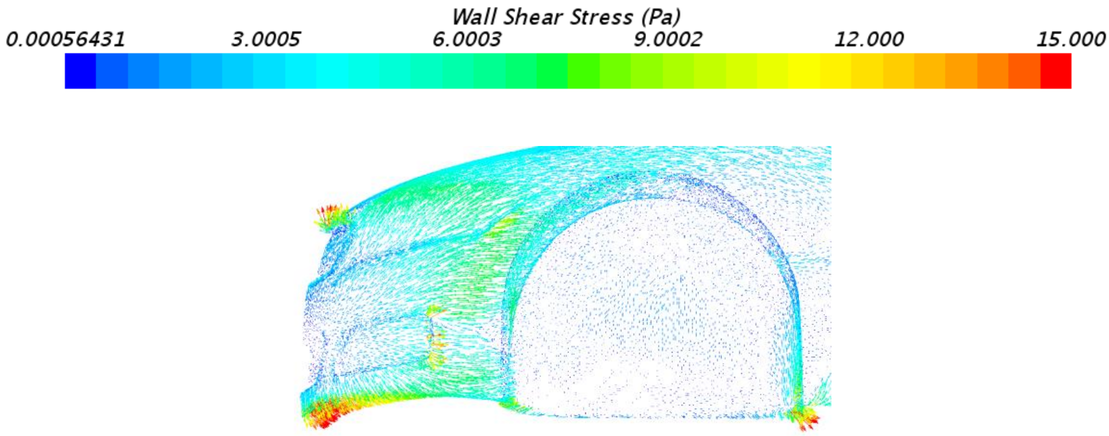


(b) *100 km/h reverse configuration*

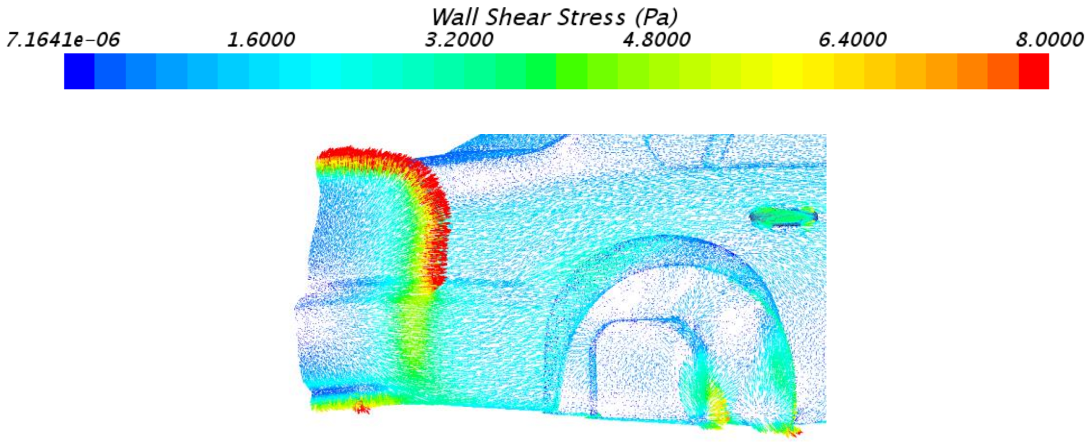
Figure 4.11: *Wall shear stress vector on mirror – Case 1: Baseline.*

It can be seen on Figure 4.11 (a) that the magnitude of the shear stress is increased with respect to the simulations at 100 km/h. It must be noted that the most extreme situation could happen when two trucks driving in opposite direction pass by near each other. In that situation, the turbulence would generate higher pressure and thus higher stress on the cover.

On the Figure 4.11 (b) the reverse configuration shows the same problem on the mirror as in frontal position, the stress is directed in different directions subjecting the material of the cover to a strain that may cause a failure. Furthermore, it has to be considered that in the design of the cover, both the frontal and the reverse configuration have to be taken into account because there is only one unique design that has to stand both configurations.



(a) *140 km/h frontal configuration*



(b) 100 km/h reverse configuration

Figure 4.12: *Wall shear stress vector on the body – Case 1: Baseline.*

On Figure 4.12 the parts of the body with higher stress are shown. On the frontal configuration at 140 km/h it can be seen again a high stress on the lower front part of the vehicle pointing downwards but with a bigger magnitude that the one obtained on the simulations at 100 km/h, so the problems associated to it are increased.

On the reverse configuration, the high stress is found as we noted before on the edges of the trunk pointing with approximate 45º on the XZ plane. This, linked to the negative pressure observed on the trunk before, reinforce the idea of having a lift on the cover over the trunk. There is no correlation between the model and the actual behaviour of the cover because no fixations are considered in the model. The cover is very tight on this part of the car and that is why it does not lift creating a bubble of air.

Finally, it can be pointed out that on both configurations there is a small region on the corner of the wheelhouse where the vectors point downwards. This could be the cause of the cover getting loose on that part, meaning that fixations will be needed there as we know from the experience in the wind tunnel.

5 Conclusions

The scope of this work was to establish a first step on a longer process to develop a procedure to predict where potential problems may be found on the cover used to protect vehicles under transportation. The objective is to reduce the number of wind tunnel tests needed and optimize the design process of the cover using a numerical procedure. In this way, the first step has been taken, developing a procedure to carry out a simple aerodynamic analysis of a model of the vehicle equipped with a cover.

The first conclusions about this procedure can be extracted. There is a correlation between the numerical results obtained and the phenomena experienced on the wind tunnel tests. This correlation is an assessment of being set on a good direction. Examples of that are the prediction of the bubbles on the hood and on the roof. When simulating the case 3.2 (the baseline with the cover morphed with bubbles) the wave-like motion of the cover as experienced in the actual tests was also predicted by looking at the shear stress. It was also clear that the union between the mirrors and the A-pillar is a conflict area, although the origin of a rip could not be asserted yet.

From the different three cases studied it is clear that the case 3 (the baseline with the morphed cover) gives more accurate results. The main difference is found in the result of the pressure, obtained on both sides of the cover, which would be essential for further study about the deformation of the cover.

The conclusions extracted from the study of the case 1 (baseline) at 140 km/h are that the forces and stresses are higher but not significant difference can be appreciated on the effects occurring on the cover. For that reason, it would be interesting to study this situation once the complete procedure that includes a fluid-structure interaction analysis is established. However, during the development of this work, the simulation of further cases at this speed would not add any extra information.

Finally, from the study of the case 1 (baseline) in a reversed position it was concluded that the results obtained from this configuration to predict the different stresses that the cover will stand, are necessary to find an optimum design of the cover. It also made clear that validation of the model is always needed for a further development of the process.

In spite of the match between some results and the experience from the wind tunnel, not everything could be predicted. Limitations on the work are found on the impossibility to calculate the real stresses on the cover. The reasons are that the action of the fixations was not included in this first approach to the problem and the deformation of the cover due to the effect of the pressure was neither computed (only the aerodynamic analysis was performed).

Most of the work that has been carried out was directed to find correlations between the model and the real experience with the aim of validating and establishing a robust procedure that can be used in a further development of the method to predict the possible source of failure on the wind tunnel tests. As a first attempt of studying this kind of problem, the work has given a good insight and set a good basis for future investigations.

5.1 Further development

With the results and the limitations found on doing this prediction, it should be considered that the next step is a structural analysis, as it has been done on the sails analysis, to obtain the actual stresses on the cover (remember that the cover was simulated as rigid material). This would be an iterative process on which the first step (aerodynamic analysis) has already been taken.

Another further step would be to include the effect of the fixations on the model and the simulations, as well as a more detailed geometry including wrinkles.

With the mentioned improvements and further steps, it would be possible to predict those areas where the fixations or the cover itself will be subjected to a stress higher than its rupture limit and thus the design of the cover could be optimised including just the necessary reinforcement (no waste of material) and shortening the process followed for the design (lower number of tests). In conclusion, costs from the material and the wind tunnel would be reduced as well as time, yielding a measurable profit for the company.

6 References

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A Mesh generation: Baseline

Automated mesh:

- Meshers:
  - Surface remesher
  - Trimmed Cell mesher
  - Prism layer mesher
- Default controls
  - Base size: 320 mm
  - Target surface size: 320 mm
  - Minimum surface size: 40 mm
  - Surface curvature: basic curvature – 36
  - Surface proximity: 2 points in gap
  - Surface growth rate: 1.3
  - Number of prism layers: 8
  - Prism layer stretching: 1.2
  - Prism layer total thickness: 16.4990848 mm (First prism layer thickness: 1 mm)
  - Maximum size/thickness ratio: 5
  - Maximum cell size: 320 mm
- Custom controls:
  - Vehicle surface
    - Target surface size: 4 mm
    - Minimum surface size: 4 mm
    - Surface growth rate: 1.2
  - Tunnel surface
    - Target surface size: 320 mm
    - Minimum surface size: 320 mm
  - Control volume (density box):
    - Surface remesher custom size: 40 mm
    - Trimmer: customize isotropic size

B Mesh generation: Morphed model

Surface wrapper: applied to the cover

- Default controls
  - Base size: 8 mm
  - Target Surface size: 8 mm
  - Minimum surface size: 2 mm
  - Surface curvature: basic curvature – 36
  - Surface proximity: 2 points in gap
  - Volume of interest: external
  - Smallest disconnected surface*:* number of faces – 1000
  - Feature angle*:* 30
- Contact prevention: no contact prevention.

Automated mesh: the same parameters as those used for the baseline (see A) except those mentioned below.

- Custom controls
  - Vehicle surface: baseline except wheels, underbody and wheelhouses
    - Target surface size: 4 mm
    - Number of prism layers: 3
    - Prism layer total thickness: 3.64
    - Minimum surface size: 4 mm
  - Cover surface: cover, wheels, underbody and wheelhouses.
    - Target surface size: 4 mm
    - Minimum surface size: 4 mm
    - Surface growth rate: 1.2

C Material specifications

Material of the hood: CarTect® 115 F/40

- Surface density (g/m^2) → 115
- Thickness (mm) → 0,45
- Ultimate tensile strength (longitudinal) (N/5cm) → 170
- Ultimate tensile strength (transversal) (N/5cm) → 130
- Elongation at break (longitudinal) (%) → 70
- Elongation at break (transversal) (%) → 85

Material of the body: CarTect® 115 H/40

- Surface density (g/m^2) → 115
- Thickness (mm) → 0,65
- Ultimate tensile strength (longitudinal) (N/5cm) → 200
- Ultimate tensile strength (transversal) (N/5cm) → 140
- Elongation at break (longitudinal) (%) → 90
- Elongation at break (transversal) (%) → 140

Information obtained from:

http://www.caplast.de/html/automobile_schutzbeschichtungen.html