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Ivan Gonzàlez Casal

AERODYNAMIC ANALYSIS AND IMPROVEMENT OF A ROOF BOX CAR

Supervisor:

Dr hab.eng: **Wladyslaw Mitianiec, Prof CUT**

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Author of work: **Ivan Gonzàlez Casal**

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Glossary

- **CAD:** Computer-Aided Design. Programs used to design and modelling product. In this project we use SolidWorks.
- **CFD:** Computational Fluid Dynamics. Is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyse problems that involve fluid flows. In this project is used Ansys Fluent.
- **P:** Pressure.
- **A or S**: Projected area.
- **C_D:** Drag coefficient.
- **C_L:** Lift coefficient.
- **ρ_a:** Density of air.
- **v:** Speed.
- **D or R_A:** Drag.
- **L:** Lift.
- **R_T:** Resistance due to mechanical friction of transmission.
- **R_R:** Resistance due to the road friction.
- **N:** External resistance that affect to the car.
- **P_n:** Power needed.
- **f:** Tread coefficient.
- **μ_r:** Road friction coefficient.
- **r_r:** Radius of the wheel.
- **B:** Energy consumption per hour.
- **b_e:** Specific energy consumption.

1. Aim and purpose of this project

Nowadays, car has been one of the main vehicles to travel. However, the space offered in the boot is not enough for all the luggage. Consequently of this problem, appeared the idea of putting an extra luggage in the roof of the car. These boxes called roof boxes had an important effect in the whole vehicle modifying the specifications of the car. One of these effects is an increase of fuel consumption. Fuel consumption is one of the most important factors to choose one vehicle than other, consequently installing a roof box has to modify the specifications of the car as little as possible.

The purpose of this project is analysing which effects has in the vehicle specifications when a user install a roof box on the top of the car. As we know, an increase of weight in a car is translated in an increase of fuel consumption. Otherwise the user does not know that depending on the forms of the roof box, the aerodynamic of the car is modified producing an increase the fuel consumption. Therefore, in this project we are going to analyse one of the most popular and commercial roof box (Thule Large Box 634s) and we are going to verify which effect has in his flow, the increase of cD and finally how the motor dynamics of the vehicle is altered.

Another objective of this project is to redesign a new roof box. The idea of this new roof box is to improve the aerodynamic of the car and verify which effect has in the car. However, this new redesign of the roof box has to conserve the effectiveness of this. It means that the volume and the dimensions of the roof box should be very similar with the original model.

To analyse this effects, the programs used in this project are SolidWorks (CAD design) and Ansys Fluent (Engineering simulation software). Consequently of using this program, this project allows us to apply, learn and link technical knowledge of aerodynamics and computer knowledge.

To sum up, we expect with this project to analyse how effective is a commercial roof box and improve the aerodynamics and reduce the fuel consumption when the car is circulating.

2. Problem to solve

As we commented in the aim and purpose of the project, the main problem which is involved in the installation of a roof box in a car is the decrease of aerodynamic efficiency and the increase of the weight. These two consequences affect in the circulation of the car and its fuel consumption. To solve this problem, there are almost two ways to improve it:

- Modify the position and the shapes of the roof box to decrease the distortion of the flow of the air and consequently, reduce de drag coefficient.

- Changing the roof box's material to make it lighter and reduce the total weight of the vehicle.

However, in this project we are going to solve the first problem. The first part is an analysis of a commercial roof box and analyse how is modified the flow of the air, the increase of C_D, the difference between pressures and other aspects in the car. To verify this analysis, the project has a two dimensional analysis (for the first approximation values) and a three dimensional analysis. With the results obtained in the Ansys Fluent, we are going to calculate the increase of fuel consumption.

Finally, in the last part of the project, there are two redesigns of the roof box to improve the vehicle aerodynamics and verify the importance of the accessories design in the circulation of the car.

3. Technical Knowledge

3.1. Theory

3.1.1. Concepts of aerodynamics in cars

3.1.1.1. Introduction of aerodynamic in cars

First of all, we should consider that the aerodynamics of the roof box and cars are very similar. Therefore, we are going to analyse the history and evolution of the aerodynamic of cars.

The start of aerodynamic come from the aerodynamics of planes. However the difference between planes and cars is very different. Planes without aerodynamic cannot exist (their ability to fly is due to their aerodynamic), but in cars it is possible to road without a good aerodynamic design [1]. This idea is due to a bad aerodynamic affects to the need of a more power to move the vehicle, in a plane a bad aerodynamic does not t allow to fly. The primordial objective of both aerodynamics is to reduce drag (air resistance).

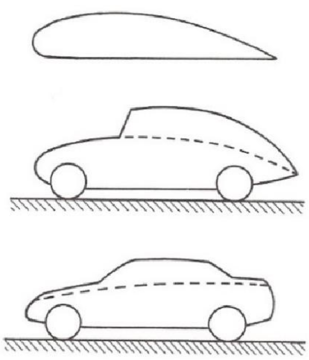


Figure 3.1: *Comparison of a plane wing profile and evolution of cars. [6]*

The main differences of planes and cars aerodynamics are the following:

- Cars work really near from the ground compared with their dimensions. Therefore, the ground effect cannot be ignored.

- In the point of view of cars aerodynamics, cars should be considered as one element. They cannot be separated in components. Planes can be analysed component to component.
- Car aerodynamic has an important experimental development, above all the optimization of forms.

3.1.1.2. History of aerodynamic in cars

3.1.1.2.1. 1900-1920

This is the start of cars, and the first impressions were copying the forms of planes and ships. The first engineers ignored the ground effect and the loss of symmetry of the flow. Therefore, this ignorance in these effects makes an increase of drag. They also ignored that wheels being out of the chassis of the car makes the flow distorted [11]. Consequently, the air resistance increase and all the improvements done in the chassis of the car cannot be denoted in the total of the vehicle.

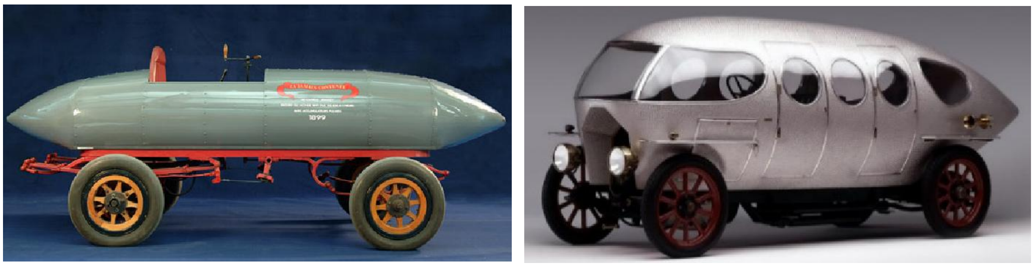


Figure 3.2: *First prototypes of cars based in planes and ships forms (Jamais Contente and Alfa Romeo of 1914) [2]*

3.1.1.2.2. 1920-1970

In this period appeared the first wind tunnel to improve the aerodynamic of vehicles. The aim of the first wind tunnels were not determinate the aerodynamic forces; the objective was determinate the forms of the vehicles to reduce the power needed to move the car in certain values of speed.

We have to remark Paul Jaray's work, who was the first engineer designing a car keeping in mind the aerodynamics. His designs were based in planes and really aerodynamics. However, his design were not accepted by consumers. After some years of his creations, other engineers started to use his ideas in their designs. [2]

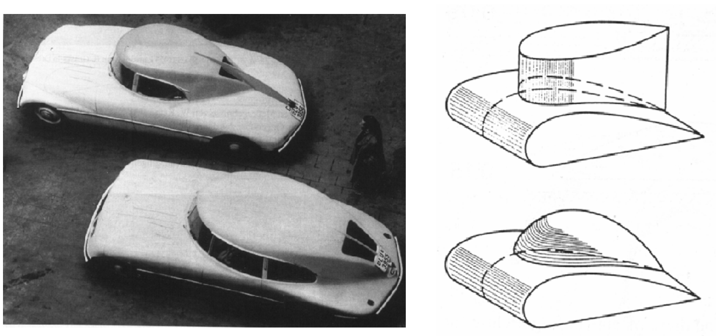


Figure 3.3: *Jaray's design*

3.1.1.2.3. 1970-Nowadays

In this period started to obtain special importance the aerodynamic of the cars. The objective is reduce the drag resistance to reduce the fuel consumption. There are two ways to reduce the drag resistance: [1]

- Reducing frontal area. This consist to reduce the area which the air impact. In this way, the reduction of area reduces the drag resistance.
- Improving the aerodynamics of the car to reduce C_D.

Nowadays, the first option is not possible. All the manufactures have arrived at the same equation of optimization.

$$A = 0.81 \cdot (b \cdot h) \qquad (1)$$

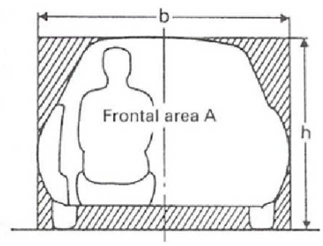


Figure 3.4: *A is frontal area; b is wide; h is height [9]*

In seventies, due to the fuel crisis, engineers started to improve the details and optimize the global aerodynamic of the vehicle. As the result they had decreased the drag coefficient to values of 0.3.

Nowadays with efficiency as the main word in people mind, it is impossible the creation of a new car without thinking in the aerodynamics. For example, in 2013 appears the most aerodynamic production car. This car is Mercedes-Benz CLA which C_D is 0.23 [19]. This value was obtained with the improvement and optimization of details like engine cover, optimized front, mirrors and other elements.

Figure 3.5: *Mercerdes-Benz CLA which C_D is 0.23*

3.1.2. Drag

Drag is the aerodynamic force that opposes a vehicle's motion through the air.[1] Drag is a mechanical force generated by the interaction and contact of a solid body with a fluid. It is specially important in design of vehicles due to the increase of this force will increase the power needed of the vehicle.[12]

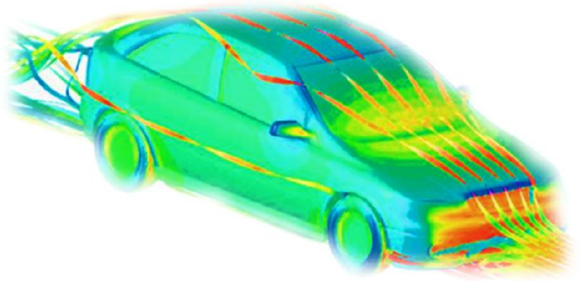


Figure 3.6: *Example of study of aerodynamics of Opel Astra*

To obtain the values of Drag Force, the equations is used is the following:

$$D = c_D \cdot \rho_a \cdot S \cdot \frac{v^2}{2} \quad [N] \tag{2}$$

C_D: drag coefficient

ρ_a: air density (1.225Kg/m3)

v: speed (m/s)

S: projected section

3.1.3. Lift

Lift is a force generated by a body that moves that body perpendicular to the direction of incident flow [1]. It is specially used in airplanes to make them fly. It consists in a differential of pressure between the top and the bottom of the wing. These pressures tend to equal, therefore this force (lift) appears that makes to push up the wing and as the result the plane.[14]

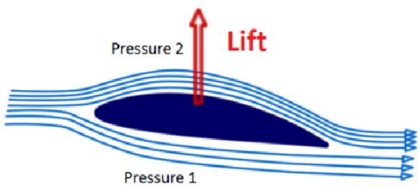


Figure 3.7: *Lift force with differential of pressures Pressure 1 is bigger than Pressure 2, therefore appears a force called Lift that push it up.*

The equation used to obtain the value of Lift is the following:

$$L = c_L \cdot \rho_a \cdot S \cdot \frac{v^2}{2} \quad [N] \tag{3}$$

c_L: Lift coefficient

ρ_a: air density (1.25Kg/m3)

v: speed (m/s)

S: projected section

To sum up, we can see how the forces lift and drag act in a plane. [18]

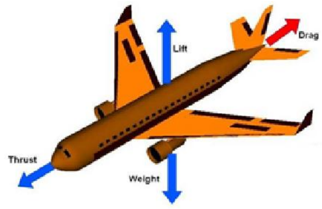


***Figure 3.8**: Summary of forces in a plane*

The sum of forces in direction x and direction y to keep the equilibrium the forces is the following:

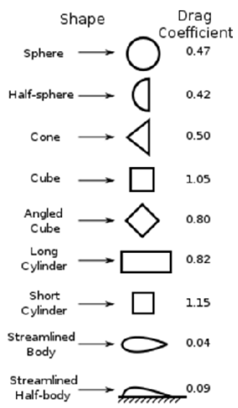
$$\sum F_x: \qquad Thrust - Drag = 0 \tag{4}$$

$$\sum F_y: \qquad Lift - Weight = 0 \tag{5}$$

3.1.4. Drag coefficient

This coefficient is a dimensionless value that allows to quantify the drag resistance of an object. When this value is low indicates that the object has less aerodynamic drag. The drag coefficient depends with the shape and position of the object (projected area) and the properties of fluid (kind of fluid, density, speed…). [1][12]

In the following images there are some examples of the C_D depending on the shape or vehicle shapes. As we see the area of impact and the shapes of impact are very important to reduce de value of drag coefficient.



Vehicle	C_D
Bicycle with cyclist	0.90
F1 Car	0.70-1
Common truck	>0.60
Ford Sierra	0.40
Audi A4	0.33
Citroën C4	0.28
Audi A2	0.25

***Figure 3.9:** C_D of different shapes and cars [10]*

The equation to obtain this value is the next:

$$c_D = \frac{D}{\frac{1}{2} \cdot \rho_a \cdot v^2 \cdot S} \tag{6}$$

D: Drag Resistance

ρ_a: air density (1.225Kg/m3)

v: speed (m/s)

S: projected section

3.1.5. Lift coefficient

Just as the drag coefficient, the lift coefficient is also a dimensionless value. This is used to know the quantity of force in perpendicular direction that the body receives from the incident flow. [1]

The lift coefficient can be expressed as the following equation:

$$c_L = \frac{L}{\frac{1}{2} \cdot \rho_a \cdot v^2 \cdot S} \tag{7}$$

L: Lift resistance

ρ_a: air density (1.225Kg/m3)

v: speed (m/s)

S: projected section

3.1.6. Ground effect

The ground effect is called to the aerodynamic action when a body has a differential pressure between the top and the bottom of the car. The pressure that appears on the top of the car is higher than the pressure of the ground vehicle, therefore this differential makes car to smash the ground. This effect helps to increase the grip and it allows the car to increase its velocity in corners. [1]

This effect is very common in competition cars. Due to the ground effect car can go faster in the turns without losing grip.

Figure 3.10: *Lotus F1 Car*

3.1.7. Motor vehicle dynamics

<u>Force resistance:</u> [8]

In this study, we are going to study that the vehicle is operating in an even road, without slopes and a constant speed of 27.7 m/s (100km/h). Therefore, we should consider that the total movement resistance are the next:

$$F_T = R_T + R_R + R_A \quad [N] \tag{8}$$

F_T: Total resistance force [N]

R_T: Resistance due to mechanical friction of transmission

R_R: Resistance due to the road friction

R_A: Resistance due to the air (Drag resistance)

Resistance due to the mechanical friction of transmission (R_T): [8]

This resistance depends on the efficiency of the transmission (η_{tr}). This value is about 0.85 and 0.9 and it should be considered.

Resistance due to the road friction (R_R): [8]

The resistance R_R is related with the road conditions. Is one of the most important and relevant resistance to the movement of the vehicle. It is possible to simplify in the next equation:

$$R_T = M \cdot g \cdot f \quad [N] \tag{9}$$

M: mass of the vehicle [kg]

g: gravity (9.81 m/s^2)

f: tread coefficient

The f coefficient is a dimensionless coefficient who depends on the road friction coefficient (μ_r) and the radius of the wheel.

$$f = \frac{\mu_r}{r_r} \tag{10}$$

This value for a commercial vehicle in a typical road is about 0.006 to 0.010. [10]

Resistance due to the air (R_A): [8]

The resistance due to the aerodynamics of the most important factors in this project. Therefore we are going to describe this element how acts in the car.

$$R_A = c_D \cdot \rho_a \cdot S \cdot \frac{v^2}{2} \quad [N] \tag{11}$$

C_D: drag coefficient

ρ_a: air density (1.225Kg/m3)

S: projected section

v: speed (m/s)

The C_D coefficient depends on the car, and its accessories and as we can see; if the drag coefficient increase, it will increase the air resistance. Therefore, the total resistance and the fuel consumption will also increase.

Power: [8]

In this part of the project we are going to study which is the power needed to beat the resistance. As we said before, the force to beat is the addition of three resistance forces. Therefore, we can define this power like the manager to beat this forces in one speed.

$$P_N = F_T \cdot v = (R_T + R_R + R_A) \cdot v \quad [W] \tag{12}$$

$$P_N = R_T \cdot v + M \cdot g \cdot f \cdot v + c_D \cdot \rho_a \cdot S \cdot \frac{v^3}{2} \quad [W] \tag{13}$$

$$P_N = R_T \cdot v + N \quad [W] \tag{14}$$

We consider N like the all the external resistance that affect to the car. P_N should be provided by a motor and can be defined with the transmission efficiency. Hence, we can consider the next equation:

$$P_N = \frac{N}{\eta_{tr}} = \left(M \cdot g \cdot f \cdot v + c_D \cdot \rho_a \cdot S \cdot \frac{v^3}{2}\right) \cdot \left(\frac{1}{\eta_{tr}}\right) \quad [W] \qquad (15)$$

With this equation, we can obtain the total power needed for the engine. Now, we have to link it with fuel consumption. Therefore, we should define energy consumption per hour (B) [Kg/h] and specific energy consumption (b_e) [Kg/KWh].

$$P_N = \frac{B}{b_e} \quad [KW] \qquad (16)$$

$$B = P_N \cdot b_e \quad [Kg/h] \qquad (17)$$

The total consumption of energy should be defined:

$$B_T = B \cdot t \quad [Kg] \qquad (18)$$

t: time working

$$t = \frac{d}{v} \qquad (19)$$

d: distance (m)

v: velocity (m/s)

The next equation is the related velocity and energy consumption:

$$B_T = B \cdot \frac{d}{v \cdot 3600} \quad [kg] \qquad (20)$$

To link the consumption with distance it would be better to define the next equation:

$$B_d = \frac{B_T}{d} = \frac{B}{v \cdot 3600} \quad [kg/m] \qquad (21)$$

However, when we talk about consumption, we are used to use the relation with 100 km. Therefore, the equation is the next:

$$B_d = \frac{B}{v \cdot 3600} \cdot 10^5 \quad [kg/100km] \qquad (22)$$

The next step is to relate the equations of power with the energy consumption per 100 km.

$$B_d = \frac{P_N \cdot b_e}{v \cdot 3600} \cdot 10^5 \quad [kg/100km] \qquad (23)$$

$$B_d = \frac{\left(M \cdot g \cdot f \cdot v + c_D \cdot \rho_a \cdot S \cdot \frac{v^3}{2}\right) \cdot b_e}{v \cdot 3600 \cdot \eta_{tr}} \cdot 10^5 \quad [kg/100km] \qquad (24)$$

If we put the density of air and we change the specific consumption taking in care the density of the fuel, the final expression is the following:

$$B_d = \frac{(0.25 \cdot M \cdot f + 0.017 \cdot c_D \cdot S \cdot v^2) \cdot b_e}{\eta_{tr} \cdot \rho_b} \quad [litres/100km] \qquad (25)$$

4. Roof Box analysis

4.1. Ansys & CAD Theory

4.1.1. CAD design

To achieve results in the analysis of the aerodynamics, we have to work in one CAD program to simulate the geometry of the car and the roof box. The program used is SolidWorks. There are two ways to simulate it; the first one is create a 2 dimensional profile with a surface and export it to Ansys Fluent. The other one is create the design in 3 dimensions of the model and also export to Ansys Fluent.

First of all, we have to inform of the dimensions and surfaces of the bodies to reproduce the most similar possible the original model. We ignored the little surfaces on the top of the roof box because they are created to obtain an attractive design and not for the aerodynamics.

After the creation of the roof box, we realized that we had to simulate part of the car due to the flow of the car also affects to the roof box. Consequently, we created an approximation of Audi A4 Avant B7 in 2 dimensions and 3 dimensions to simulate the most realistic way the flow that impacts to the roof box.

4.1.2. Modelling

4.1.2.1. 2 dimensional

When the geometry has been created, we have to import it to Ansys Fluent. Therefore, the solution is to save the geometry like a neutral format file (IGES, STEP…). After that, we can continue working in this project with our geometry. The geometry created represents the air in a wind tunnel. The object to study is an empty space without value. In this part we also rename the parts of the body. The following picture illustrate how the elements are called.

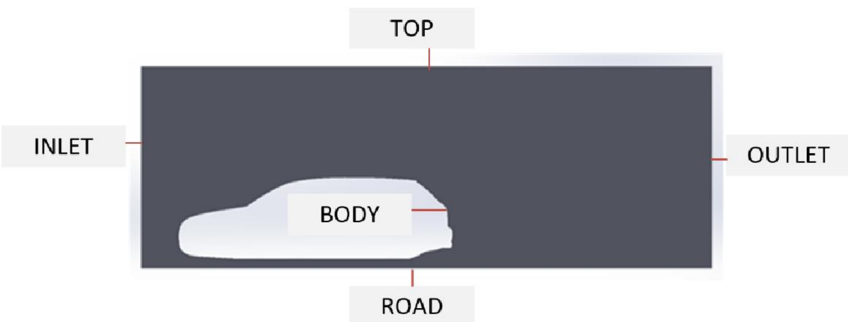


Figure 4.1: *Named selection in 2 dimensional analysis*

4.1.2.2. 3 dimensional

To study the aerodynamics in 3 dimensions is not the same than in 2 dimensions. As in 2 dimensions and 3 dimensions, we have to create our geometry and import. Due to the symmetry, we only need to study the half of the assembly. After that, with the sketch we create a box that represents the air around the geometry. The next step, with a Boolean condition, we have to subtract the original geometry, to obtain the box with the empty assembly inside.

As it happens in the 2 dimensional model, we also rename the walls of the box.

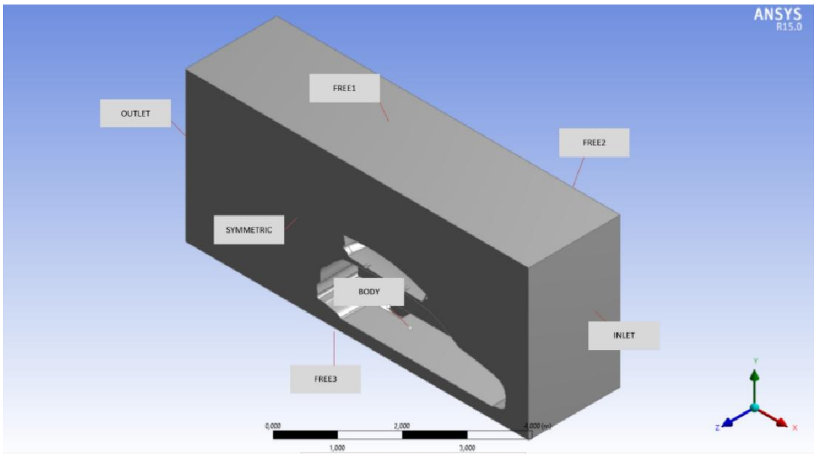


Figure 4.2: *Named selection in 3 dimensional analysis*

4.1.3. Meshing

After the process of modelling, the next step is meshing. Meshing consists in divide the model to little elements. Due to this elements, it is possible to calculate by numerical methods and obtain accurate results. The next parameters are modified to obtain a high density mesh and as a result optimal results:

- Elements

The most important part of the process of meshing is choose which element is the most accurate. To obtain the best results, we selected Quadrilateral elements which give an accurate results of the aerodynamic [3]. However, in the 3 dimensional analysis, we have some problems to get a high density mesh and we have to use another method.

- Sizing

In the first analysis we used a mesh with bigger values of elements to obtain a reference of the results and verify if the method used is the correct. Therefore, the first values are the next:

Table 4.1: Values of sizing used for the first approximation

	Dimension [cm]
Minimum size	1
Maximum face size	8
Maximum size	8

To obtain the correct results, we modified this values. Modifying this values, we obtain a high density mesh and the results are more accurate.

- Inflation

Using a correct inflation mesh for the geometry is strongly tied to the choice of the turbulence model, and the flow field we are interested. We can select to resolve the complete profile of the boundary layer of alternatively we can make use of empirical wall functions to reduce the cell count. If we see the images below, on the left side we observe that the boundary layer profile is modelled with a reduced cell, which is characteristic of a wall function approach. On the right, using the inflation, the boundary layer profile is resolved all the way to the wall. This will provide a more accurate resolution of the boundary layer. [3]

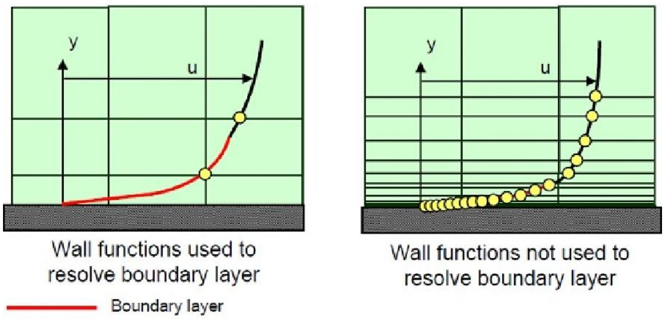


Figure 4.3: *Inflation in boundary layer [3]*

<u>Problems in meshing in 3 dimensional</u>

The main problem in defining the mesh was obtaining a high density mesh. The first approximation, the elements are big and it has low-density mesh. When we reduce to the half the elements of Maximum element size and the minimum size, the mesh failed due to the shapes of the models. Alternatively, we decided to try out other meshing methods. After analysing which would be better, we decided that the best method is Cut Cell Cartesian. [16]

The main ideas of this new meshing method are the next:

- This mesh method generates a high percentage of hexahedral cells in a Cartesian layout in the far field, to deliver accurate fluid flow results.
- Local to the surface, mixed element types are used that allow the mesh to conform to sharp features.
- The surface cells can be inflated to generate hexahedral and prismatic layers to capture near-wall physics effects.
- Rapid mesh generation of hexahedral cells with minimal user setup make this mesh method ideal for complex geometry for computational fluid dynamics (CFD) simulation.

This method consists of creating a mesh of quadrilater elements and then cutting the cells to the nearest node of the surface. Obviusly, a high density mesh gives an accurate result.

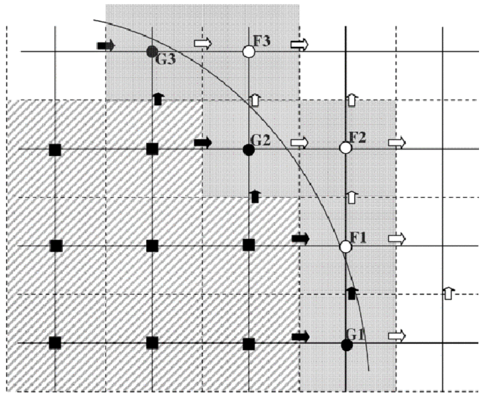


***Figure 4.4:** Cut Cell Cartesian Method*

To apply this method, we reduced the sizing of the elements to obtain a high density mesh. The values introduced in Ansys Fluent are the following:

Table 4.2: Values of sizing used for the Cut Cell Method

	Dimension [cm]
Minimum size	0.5
Maximum size	4

With those values, we obtain an increase of 1000% of elements comparing with the method of Hexa Dominant. Therefore, using a mesh with a density higher the values obtained have to be more accurate than the mesh with the lower density

4.1.4. Analysis [3] [15]

The main items to take in consideration in the analysis of the roof box is which model is used to calculate the values, the fluid, the speed of the fluid and finally the area of impact of the fluid.

- k-epsilon turbulence model

  This model is used in Computational Fluid Dynamics (CFD) to simulate turbulent conditions. It is based in two equations that gives a description of turbulence by means of two transport equations.

  The original impetus for the K-epsilon model was to improve the mixing-length model, as well as to find an alternative to algebraically prescribing turbulent length scales in moderate to high complexity flows. The first transported variable determines the energy in the turbulence and is called turbulent kinetic energy (k). The second transported variable is the turbulent dissipation (ϵ) which determines the rate of dissipation of the turbulent kinetic energy.

- For turbulent kinetic energy k:

$$\frac{\partial}{\partial t}(pk) + \frac{\partial}{\partial x_i}(pku_i) = \frac{\partial}{\partial x_j}\left[\left(\frac{\mu_t}{\sigma_k}\right)\frac{\partial}{\partial x_j}\right] + 2\mu_t E_{ij}E_{ij} - \rho_\epsilon \qquad (26)$$

- For dissipation ϵ:

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x_i}(\rho\epsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\frac{\mu_t}{\sigma_k}\right)\frac{\partial\epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k}\mu_t E_{ij}E_{ij} - C_{2\epsilon}\rho\frac{\epsilon^2}{k} \qquad (27)$$

u_i: velocity component in corresponding direction

E_{ij}: component of rate of deformation

μ_t: eddy viscosity

- Air

In the inputs values of Ansys, it is necessary to determinate the fluid. Obviously, the fluid is air and depending on the temperature the fluid has a different density. The value of temperature is the medium and the most common.

Table 4.3: Properties of air applied in Ansys Fluent

Density	1.225kg/m^3
Temperature	20ºC

- Velocity

To simulate the situation of the car is involved, we suppose that the car is travelling at 100 km/h (27.7m/s) without transversal wind air (the air only appears on direction x). Therefore, when these values have to been entered in Ansys, we have to put that the car is stopped and the only element that is moving is the air.

- Front Area

In this case, we have to put the projected area that impact the car. Depending on the case,, the value changes. Without roof box the projected is about 2.18 square meters. When the car has the roof box, the value changes and it is 2.58 square meters.

4.1.5. Results

After running the calculation the values that really interest in our study to analyse are the drag coefficient, pressure, velocity, turbulence and Reynolds. To obtain these values, the program runs iterations since finding the convergence solution. In some cases the convergence is not possible and the decision taken is running more calculations since finding a stabilized solution. In this way we obtain values of our results with a low oscillation. Depending on the case (if it is 2 dimensional or 3 dimensional) the solution is stabilized faster or lower. In 2 dimensional analysis with less than 100 iterations, we can obtain a converged solution. On the other hand, for 3 dimensional analysis, it is needed near 500 iterations to obtain a stabilized solution.

One of the main results needed to this project is drag coefficient. The drag coefficient is used in this project to compare between the roof boxes which is more aerodynamic efficient and it allows to calculate the motor vehicle dynamic equations to obtain the total force to beat, the power needed and the fuel consumption.

The other results that are interesting in this project are pressure, velocity, turbulence and Reynolds. However, these values are obtained through plots of the model. The pressure allows knowing where the parts are impacted by fluid with more high pressure and where the dynamic pressure amounts zero. This difference of pressure is also useful to know which air resistance has to beat the car. The velocity plots are useful to know where the point of impact of the car is (the speed in this point is 0 m/s). With this plot, we can also compare the speed between the top and the bottom of the car and where the biggest speed is located. Finally, the turbulence and Reynolds plots allow analyse how the fluid is involved depending on the shapes of the cars. The turbulence shows where the fluid has low momentum diffusion, high momentum convection and rapid variation of pressure and velocity in space and time. However, the Reynolds plot allows to know how is changing the fluid during the impact and creation of flow around the model.

4.2. Specifications

4.2.1. Roof box

The roof box analysed is Thule Sonic Large 634s. Thule is a Sweden brand that has specialized in car accessories since 1942. However, it was in 1968 that they created the first roof box. Since that creation, the company has specialized in roof boxes and nowadays is one of the most important in this sector.

Thule Sonic Large 634s is the most typical product of roof box due to its size. Most of the cars which use roof box had the correct dimensions to use this model. This is the motive to analyse this commercial roof box.

Figure 4.5: *Thule Sonic Large 634s*

Table 4.4: Specifications of Thule Sonic Large 634s

Volume	460 litres
Length	185.4 cm
Width	87.6 cm
Height	40.6cm
Weight	18 Kg
Box opening	Dual Side

Consulting the website of Thule, we can obtain the main information and technical specifications of the model to study:

The special features of this roof box comparing with other manufactures are the next:

- Patented AeroNose Design reduces drag and noise making it the most aerodynamic box available.
- Patented Rear-Angled Base and expanded vehicle mounting points help maximize trunk and hatch clearance.
- AcuTight Mounting “clicks” when you reach optimal hold to ensure your box is secured to the rack.
- SecureLock™ ensures that all gear is locked and box is properly closed prior to driving.

4.2.2. Car

The car chosen to this project is an Audi A4 Avant B7. We have chosen that vehicle due its specifications. This is a medium class vehicle, common for using roof box. About the main characteristics of this car is the Avant version is used for families who travel and sometimes the porter is not enough big to carry all the belongings.

The main specifications to take in consideration for our work are the next:

- Weight = 1635 Kg
- Front Area = 2.18m^2
- C_D = 0.33
- Dimensions:

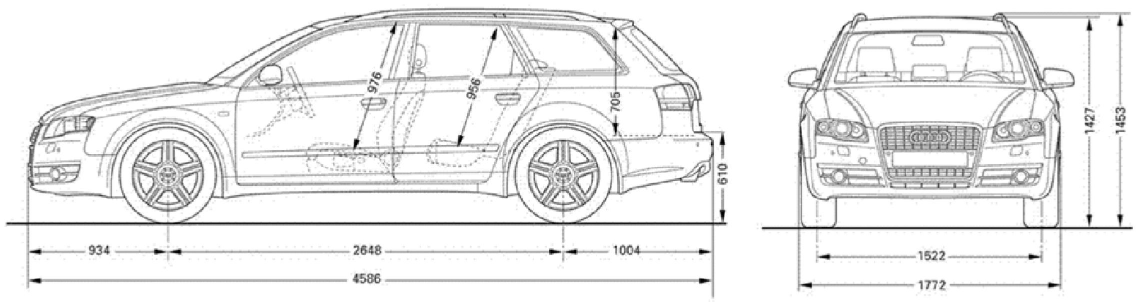


Figure 4.6: *Dimensions of Audi A4 Avant B7*

4.3. CAD

4.3.1. 2 Dimensions

For the first approximation of obtaining results of C_D and how affect in the aerodynamics, we started with a 2D design of the same car and roof box. The next step of this 2D design will be modelled like a surface and study in Ansys Fluent.

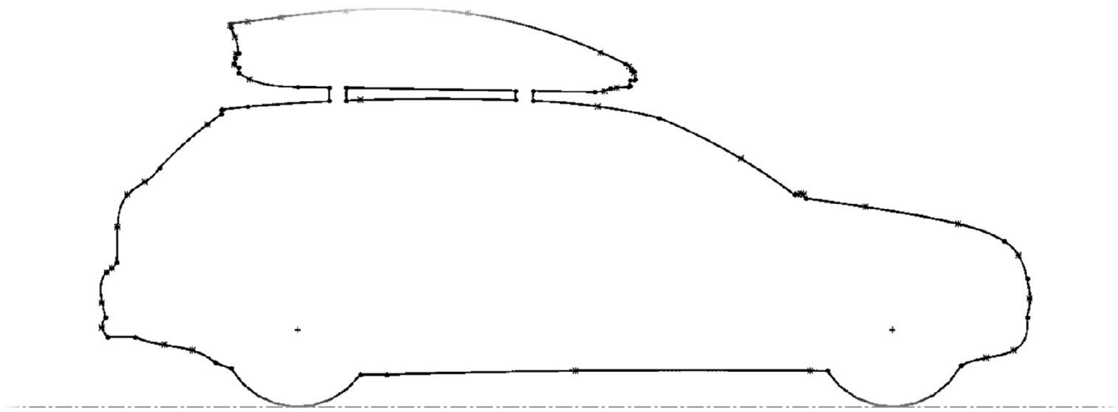


Figure 4.7: *Solidworks profile of Audi A4*

To realize that profile we use SolidWorks with a 2D sketch. After that we created the contour that we want to study. This contour is the fluid and it is a box that includes the profile of the car. After that we use the surface tool to create sheet of the fluid around the car. To simplify our results and have more accurate in the 2D analysis, we decide to not put the wheels of the car. Due the wheels can distort our aerodynamic results.

To sum up, the geometry of the object to study is the next and the next step is exporting this geometry to Ansys.

Figure 4.8: *Surface to export to Ansys*

4.3.2. 3 Dimensions

First of all, for the 3 dimensional analysis, we designed with Solidworks of the roof box Thule. The shapes are the most similar possible to obtain an accurate results. For the car, we extruded the 2 dimensional sketch. The main objective of the car is to obtain a value of C_D without a roof box and then with the roof box comparing the results. Another important reason of the creation of the car is to simulate the most accurate possible the flow modified by the car. Therefore, the exactitude of the car is not as important as the roof box.

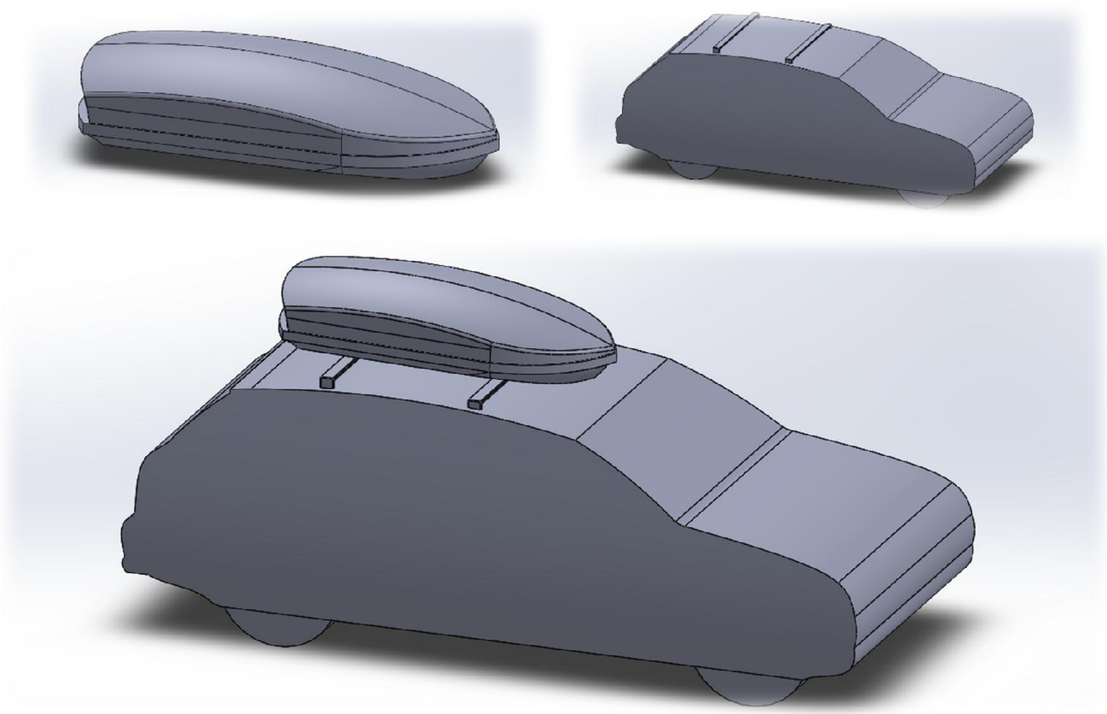


Figure 4.9: *Models of Thule roof box and Audi A4 Avant*

4.4. Renders

To compare the similarity between the real model and the design done with Solidworks, we created some renders of the model. The main shapes and dimensions are completely equal. On the other side, the shapes and little curvatures to make the product more attractive are avoided because their effect in the aerodynamics are practically zero. Therefore, a complex design creates a high density mesh in points not significant and consequently problems in the final solution.

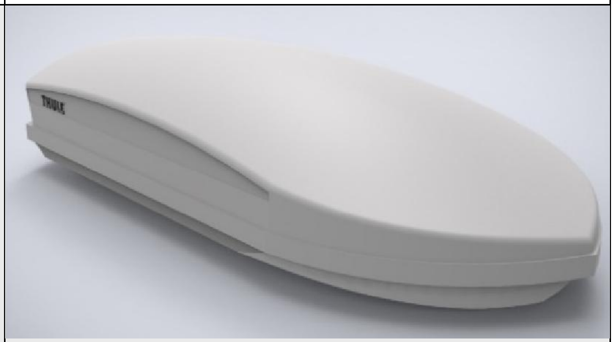
Original roof box Thule Sonic Large 634s	Render
	
	
	
	
	

Figure 4.10: *Comparison between the original roof box and the CAD model*

4.5. Ansys Fluent

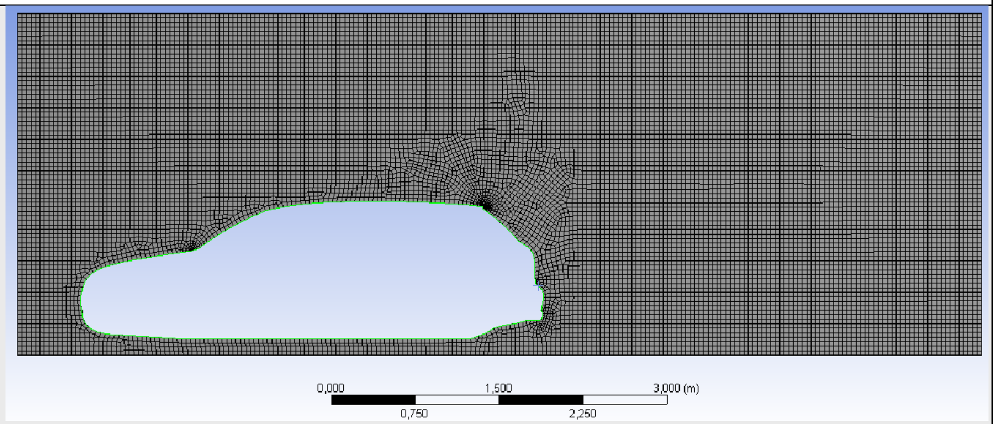
This project is divided in two big parts. One part is analyse a commercial roof box (Thule Sonic Large) and the other one is the redesign of the roof box to reduce the C_D and therefore, all the fuel consumption. To analyse these roof boxes, the first part is to simply in 2 dimensional geometry to obtain an approximation of results. The next step is analyse in 3 dimensional geometry to obtain more accurate results and verify it, if all the suppositions are correct.

4.4.1. 2 dimensional analysis

In the first 2 dimensional analysis, we are going to obtain the results of the car without the roof box, with the roof box in the most common position and finally with a modification of the position of the roof box to improve the total C_D of the total body.

4.4.1.1 Audi A4 Avant without roof box

Table 4.5: Image of the mesh and the number of nodes and elements for the model without roof box

Method	**Quad dominant**
Mesh	
Nodes	14686
Elements	14263

After having the mesh, we proceed to calculate the solution. In the 63th iteration the solution converged to those values:

Table 4.6: Values of C_D and C_L for this model

Model	**Audi A4 Avant**
C_D	0.3573
C_L	-2.24

The real value of C_D of Audi A4 Avant is 0.33. However, this is not the same value, we can calculate the error and check if the difference is notable.

$$\mathcal{E} = \frac{0.35763-0.33}{0.33} \cdot 100 = 8.37\% \qquad (27)$$

As we can see the error obtained is big, but less than 10%. Due to the 2 dimensional analysis is only an approximation, we are going to accept this result as correct. Part of this error is due to the 2D simulation cannot represent all the surfaces, because it is only the profile of the car.

The next step is plotting the results and observe the pressure, velocity, turbulence and Reynolds in the model.

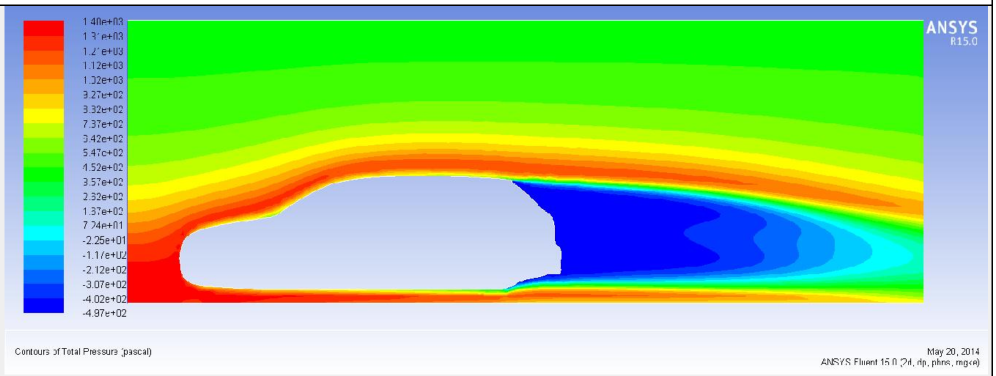
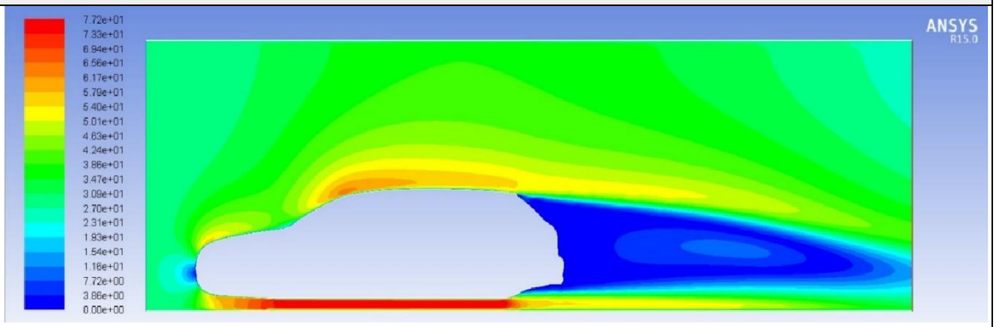
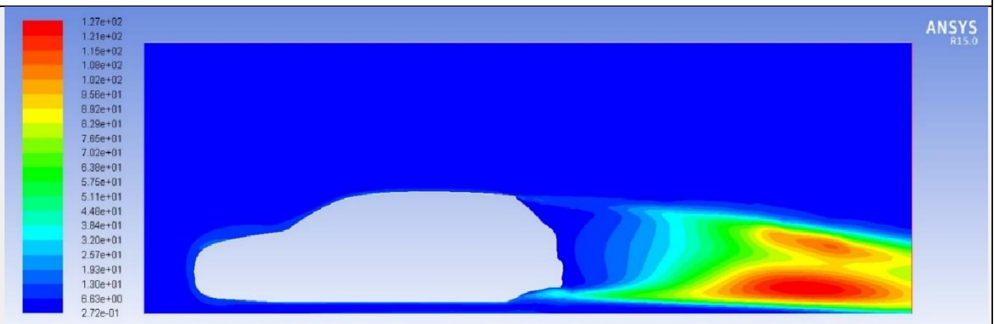
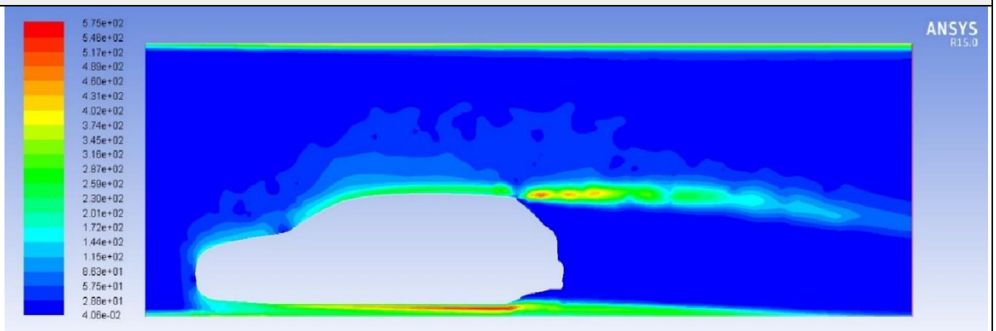
	Model	**Audi A4 Avant**
A	Pressure	
B	Velocity	
C	Turbulence	
D	Reynolds	

Figure 4.10: *a) distribution of pressure b) distribution of velocity c) turbulence d) Reynolds*

The first plots obtained we can observe that the pressure (Fig. 4.10, image A) is higher in the front part of the vehicle with a value near 1400 Pa. If we compare with the value obtained in the rear part we can observe that the pressure is negative and around -450 Pa. This difference of pressure is created by the fluid when it impacts to the model. Comparing the pressure of the top and the bottom of the vehicle we can see that is very similar, therefore there is not a pronounced ground and lift effect to the car.

Comparing the speed (Fig. 4.10, image B), the point of impact is the blue zone on the front of the car. This point the speed of the fluid is 0 m/s and then the air is shared up and down the vehicle. In the rear, there is a wake that the air is 0m/s. This part is called recoil.

Applying the equations of motor dynamics (Chapter 3.1.6.), we can obtain the power needed and the fuel consumption.

Table 4.7: Calculation of motor vehicle dynamics of the car without roof box

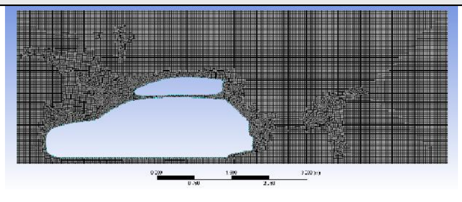
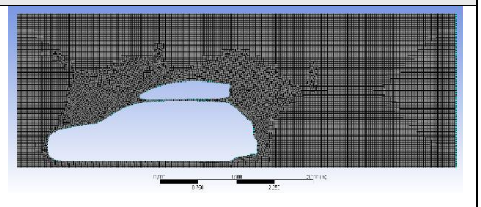
		[2D] Without Roof box
Total force	F_t	502,70
Resistance Mechanical force	R_t	0,85
Resistance Road friction	R_r	128,31
Resistance Air	R_a	373,53
Resistance Mechanical Force	η	0,85
Resistance Road Friction	R_t=m·g·f	128,31
Mass	m	1635,00
Gravity	g	9,81
Tread coefficient	f	0,01
Resistance Air	R_a	373,53
Drag coefficient	c_D	0,3573
Air density	ρ	1,25
Projected section	S	2,18
Speed²	v^2	767,29
POWER	P_n [W]	13924,73
	P_n [KW]	**13,92**
Fuel consumption	B [litres/100km]	**4,3108**
Density fuel	ρ_b	0,832
Specific Energy Consumption	b_e	0,227

The total fuel consumption is 4.31 litres/100km to beat the resistance forces of the car without the roof box. The power needed is near 14KW. This two values are used to compare the difference between the cases.

4.4.1.2 Audi A4 Avant without roof box in different positions.

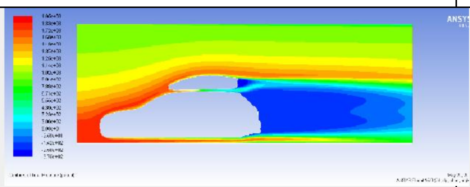
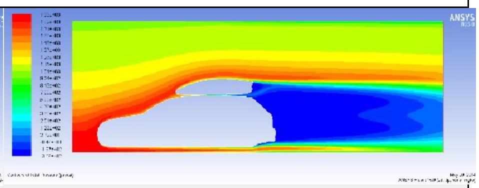
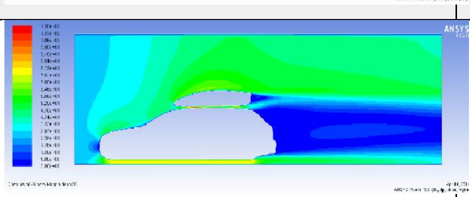
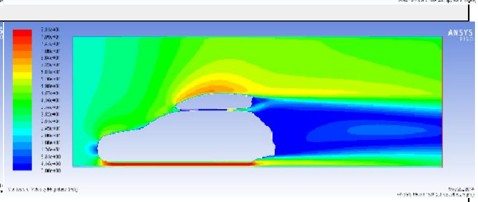
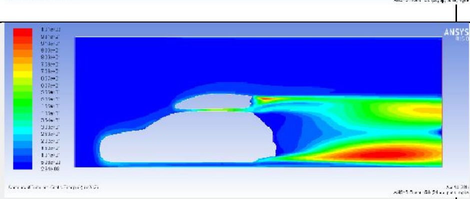
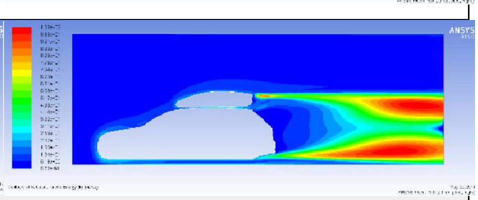
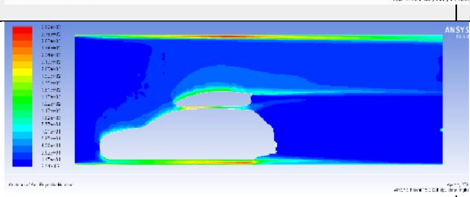
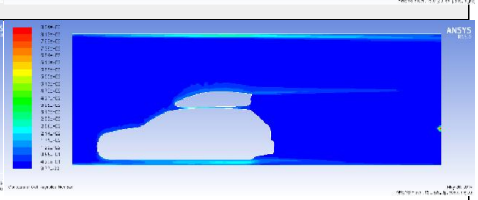
In this case, the study is based with the same profile of roof box (Thule Sonic Large 634s). However the difference between these two profiles is the position. We want to compare if the position of the roof box involves a significant modification of the values of C_D. In the first case is the roof box collocated in the typical place and the second one the position is lower (5 centimetres nearer to the roof of the car) and 15 centimetres displaced to the bottom.

Table 4.8: Comparison between the two models meshed with modification of position

Method	**Quad dominant**	**Quad dominant**
Position	1	2
Mesh		
Nodes	25364	25277
Elements	24764	24681

Running the solution, at the 72th iteration in the first case and the 79th iteration in the second case, the solution converged to the following values:

Table 4.9: Comparison between the two models with modification of position

		Position 1	**Position 2**
	C_D	0.5546	0.56535
	C_L	-3.1753	-3.1887
A	Pressure		
B	Velocity		
C	Turbulence		
D	Reynolds		

Comparing the two positions, we can see there is not a significant difference between two cases. In the second position, the drag coefficient increases 1.93%. If we compare the plots from the table 4.9 are almost similar values and shapes of the flows. Therefore, we can affirm that a modification in the position of the roof box does not take important differences in its flow.

We have to compare the results between the installation of a roof box and the car without the roof box. As we see the increase of C_D is high, the area of impact also increase, the weight of the vehicle increase approximately 70 kilograms. This increases takes effect in the fuel consumption and the power needed to bet the forces.

Table 4.10: Calculation of motor vehicle dynamics of Thule Sonic Large in 2 different positions

		[2D] Thule Large Xl position 1	[2D] Thule Large XL position 2
Total force	F_t	714,06	725,30
Resistance Mechanical force	R_t	0,85	0,85
Resistance Road friction	R_r	133,42	133,42
Resistance Air	R_a	579,80	591,04
Resistance Mechanical Force	η	0,85	0,85
Resistance Road Friction	R_t=m·g·f	133,42	133,42
Mass	m	1700,00	1700,00
Gravity	g	9,81	9,81
Tread coefficient	f	0,01	0,01
Resistance Air	R_a	579,80	591,04
Drag coefficient	c_D	0,5546	0,56535
Air density	ρ	1,25	1,25
Projected section	S	2,18	2,18
Speed²	v^2	767,29	767,29
POWER	P_n [W]	19779,54	20090,85
	P_n [KW]	**19,78**	**20,09**
Fuel consumption	B [litres/100km]	**6,1534**	**6,2515**
Density fuel	ρ_b	0,832	0,832
Specific Energy Consumption	b_e	0,227	0,227

After obtaining the results, we can compare the increases between the two positions of the roof box:

- Increase of power needed between different positions of the roof box:

$$\Delta\ Power\ needed = \frac{Pn_{\ position\ 2} - Pn_{\ position\ 1}}{Pn_{\ position\ 1}} \cdot 100 \tag{29}$$

$$\Delta\ Power\ needed = \frac{20.09 - 19.78}{19.78} \cdot 100 = 1.51\%$$

- Increase of fuel consumption between different positions of the roof box:

$$\Delta\ Fuel\ Consumption = \frac{Fuel\ consumption_{\ position\ 2} - Fuel\ consumption_{\ position\ 1}}{Fuel\ consumption_{\ position\ 1}} \cdot 100 \qquad (30)$$

$$\Delta\ Fuel\ Consumption = \frac{6.2515 - 6.1534}{6.1534} \cdot 100 = 1.59\%$$

After comparing the increases of fuel consumption and the power needed, we can see that there is not a significant improvement of the values. Consequently, the next calculation is related between the best position of Thule and the car without roof box to compare the increases of the values.

- Increase of drag coefficient between Audi A4 Avant without roof box and installing Thule Sonic Large 634s:

$$\Delta C_D = \frac{C_{D_{Thule\ position\ 1}} - C_{D_{Without\ roof\ box}}}{C_{D_{Without\ roof\ box}}} \qquad (31)$$

$$\Delta C_D = \frac{0.5546 - 0.3573}{0.3573} \cdot 100 = 55.21\%$$

- Increase of power needed between Audi A4 Avant without roof box and installing Thule Sonic Large 634s:

$$\Delta\ Power\ needed = \frac{Pn_{\ Thule\ position\ 1} - Pn_{\ Without\ roof\ box}}{Pn_{\ Without\ roof\ box}} \cdot 100 \qquad (32)$$

$$\Delta\ Power\ needed = \frac{19.78 - 13.92}{13.92} \cdot 100 = 42.09\%$$

- Increase of fuel consumption between Audi A4 Avant without roof box and installing Thule Sonic Large 634s:

$$\Delta\ Fuel\ Consumption = \frac{Fuel\ consumption_{\ Thule\ position\ 1} - Fuel\ consumption_{\ Without\ roof\ box}}{Fuel\ consumption_{\ Thule\ position\ 1}} \cdot 100 \qquad (33)$$

$$\Delta\ Fuel\ Consumption = \frac{6.1534 - 4.3108}{4.3108} \cdot 100 = 42.74\%$$

As we see, the increases of C_D is 55.21% and there's also the fact of that the weight of the vehicle has increased 65 Kilograms and the increase of power needed is about 42%. The increase of power needed is also an increase of fuel consumption. In this case the total increase is of 42.74%.

To sum up the first analysis in 2 dimensions, we can obtain the following conclusions:

- The analysis in 2 dimensions gives us an approximation of the values of what happens when the user installs a roof box in the car.
- The value of C_D of the real car and the model can be accepted because the approximation has an error less than 10%.

- Modifying the position of the roof box does not improve the values of the motor dynamics.
- Installing a roof box increases the value of C_D about 55%, fuel consumption and power needed around 42%.

4.4.2. 3 dimensional analysis

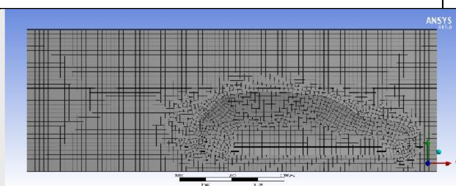
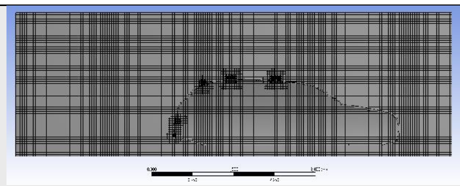
4.4.2.1. Audi A4 Avant B7 without roof box

As it is given in the technical specifications of Audi A4, the real C_D of the car is 0.33. In this project, we designed a car with the dimensions and the main shapes of Audi A4 Avant. The only idea of simulating the car is to take consideration of the flow when impact to the car and go up to the roof box and obtaining the values to check the increases.

Figure 4.11: CAD of Audi A4 Avant B7 and the real vehicle

After obtaining the designed model of the Audi A4 B7, we modelled the car to import to Ansys Fluent and we meshed with Hexa Dominant and Cut Cell Cartesians Method the new geometry obtaining the following results. The Hexa Dominant Method was the first approximation of results. As we commented before, the problem with this method was that we cannot obtain a high density mesh. Therefore, we used the other method.

Table 4.11: Comparison between the same models meshed in different methods

Method	**Hexa Dominant**	**Cut Cell Cartesian**
Mesh		
Nodes	103416	810551
Elements	103147	754346

The next step is running the solution. After near 500th iteration in the first case and 600th iterations the values stabilized.

Table 4.12: Values of C_D and C_L for this model

Method	**Hexa Dominant**	**Cut Cell Cartesian**
C_D	0.35667	0.36308
C_L	-0.22355	-0.37961

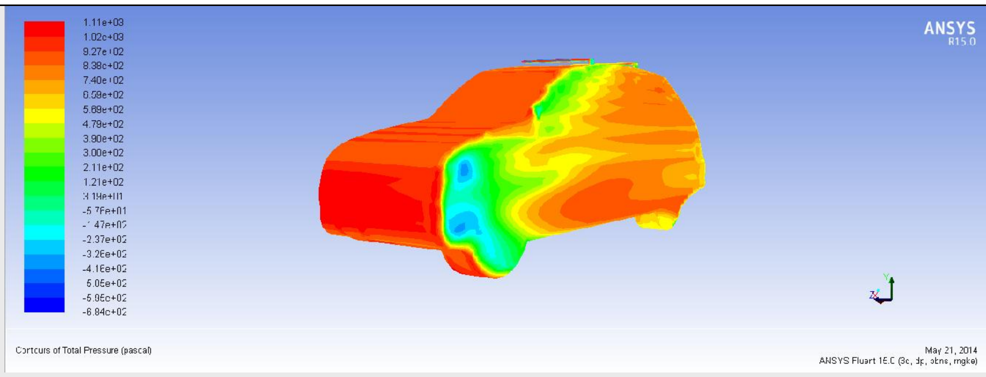
As we can see, the most approximated values of the real roof box car are in the first method. On the other hand, the mesh has not a good density of elements and it involves a non-realistic value of C_D. The value that we accept is with the high density mesh obtained with Cut Cell Cartesian.

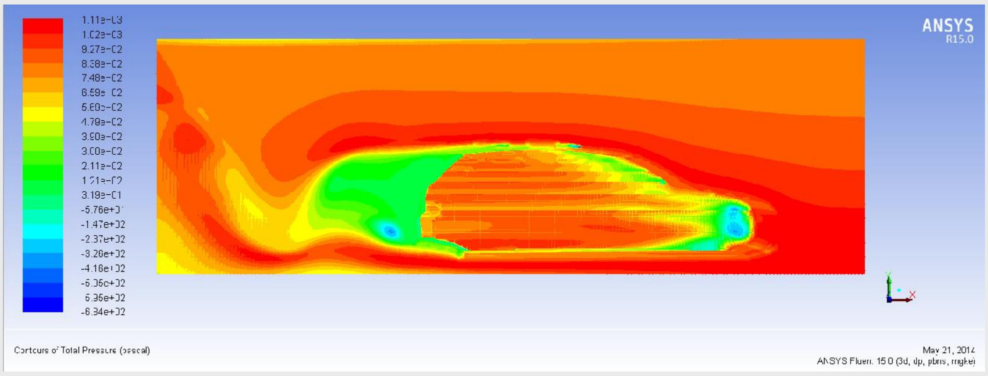
If we calculate the error of the real value and the obtained due to the simulation is the next:

$$\mathcal{E} = \left|\frac{0.36308-0.33}{0.33} \cdot 100\right| = 10.02\% \qquad (34)$$

This error is big, but the main cause is that the shapes are not real. The only objective of the car is creating a simulation of the impact flow to the roof box. In the next chapters, we use this value to compare the increase of C_D with commercial roof box (Thule Sonic Large) and the redesigned roof boxes.

After that we have plotted the pressure, turbulence, velocity and Reynolds results to compare the fluid flow effects.

<table>
<tr><th></th><th>Model</th><th>Audi A4 Avant</th></tr>
<tr><td>A</td><td>Pressure</td><td>




</td></tr>
</table>

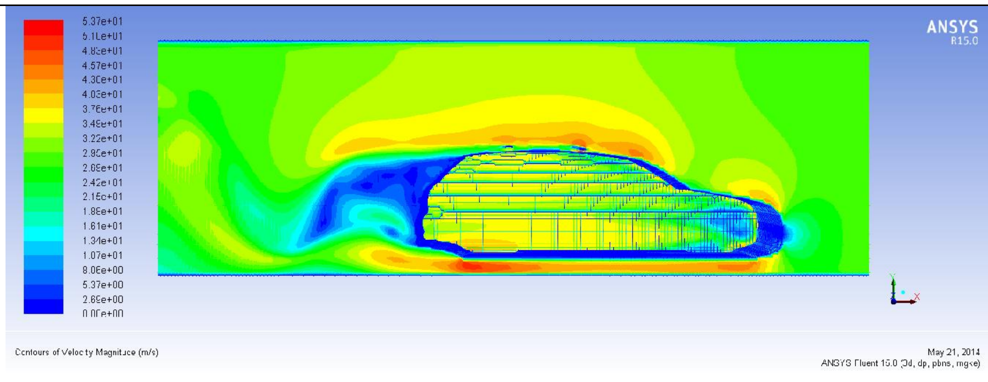
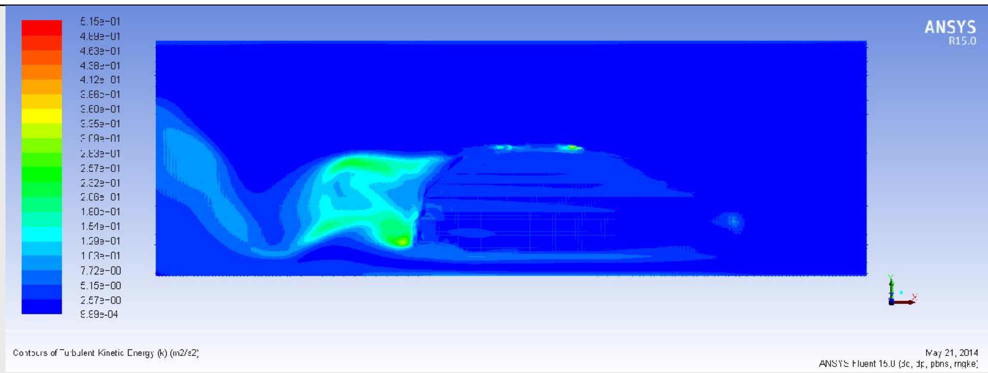
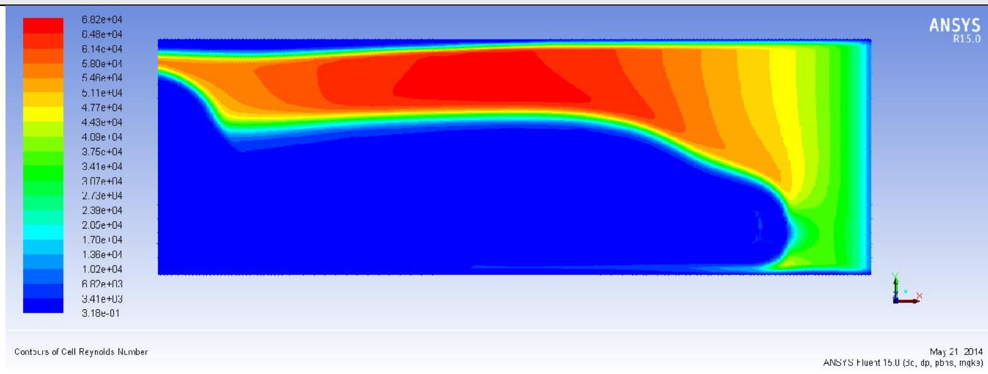
B	Velocity	
C	Turbulence	
D	Reynolds	

***Figure 4.12**: a) distribution of pressure b) distribution of velocity c) turbulence d) Reynolds*

The results obtained in the 3 dimensional are very similar to the 2 dimensional analysis. As we can see in this image (Fig. 4.12, image A) the part of the car with high pressure is in the front of the vehicle and in the supports of the roof box. The maximum pressure in this parts is 1100 Pascals. About the speed (Fig. 4.12, image B) it happens completely the same than in 2 dimensional. There is one point in front of the car which the velocity is 0 (point of impact) and the fluid flows up and down the car with some symmetry of the speed. At the rear part, it also appears a zone without speed as expected.

4.4.2.2. Thule Sonic Large 634s

This case is the commercial roof box analysis. It consists in putting the Thule roof box up in the vehicle and simulates the same conditions than the case without roof box. The difference between the both values gives the increase of C_D, increase of power and fuel consumption.

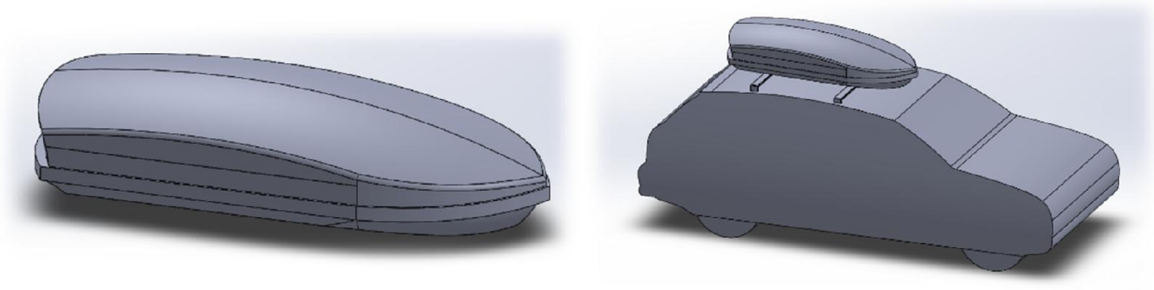
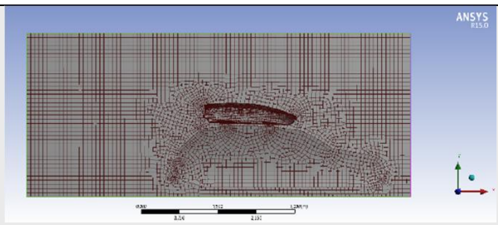
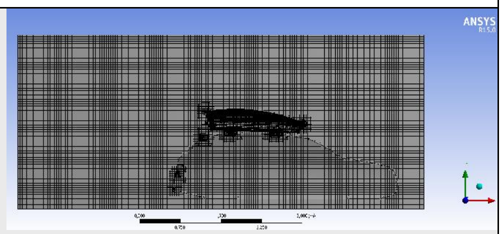


Figure 4.13: *Models of Thule and the car with Thule roof box*

In the same way than the case 4.4.2.1, the first attempt to obtain the results is using a Hexa Dominant mesh. At the moment to increase the density of the mesh, the system does not allow this increase and the method that we finally have used is Cut Cell Cartesians. In this case the increase of the density of the mesh is about 1300% of elements density.

Table 4.13: Comparison between the same models meshed in different methods

Method	**Hexa Dominant**	**Cut Cell Cartesian**
Mesh		
Nodes	68147	1037461
Elements	67974	963702

After the mesh, the next step is calculate the values of drag and lift coefficients.

Table 4.14: Values of C_D and C_L for this model

Method	**Hexa Dominant**	**Cut Cell Cartesian**
C_D	0.46245	0.45232
C_L	-0.41108	-0.46179

We can observe that the increase of C_D is obvious in the two cases. If we compare the both methods of meshing. We can realize that the difference of C_D of both methods is very similar:

$$\Delta C_D = \left|\frac{C_{D_{HEX\ DOMINANT}} - C_{D_{CUT\ CELL\ CARTESIANS}}}{C_{D_{HEX\ DOMINANT}}}\right| \qquad (35)$$

- Case 1: Audi A4 Avant without roof box:

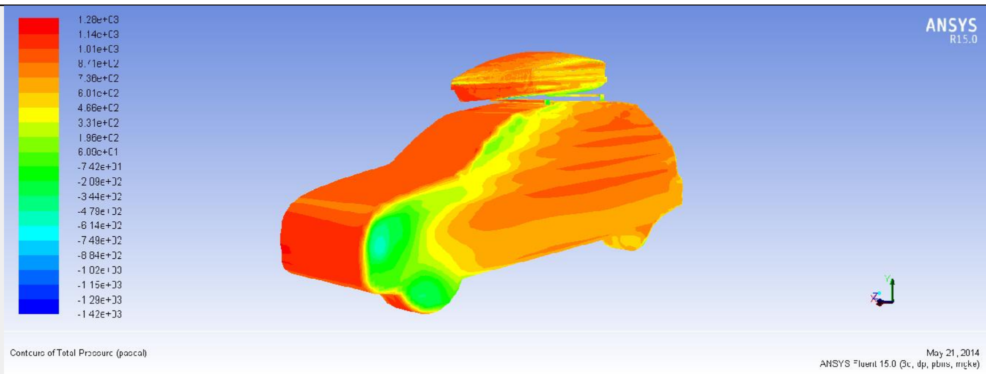
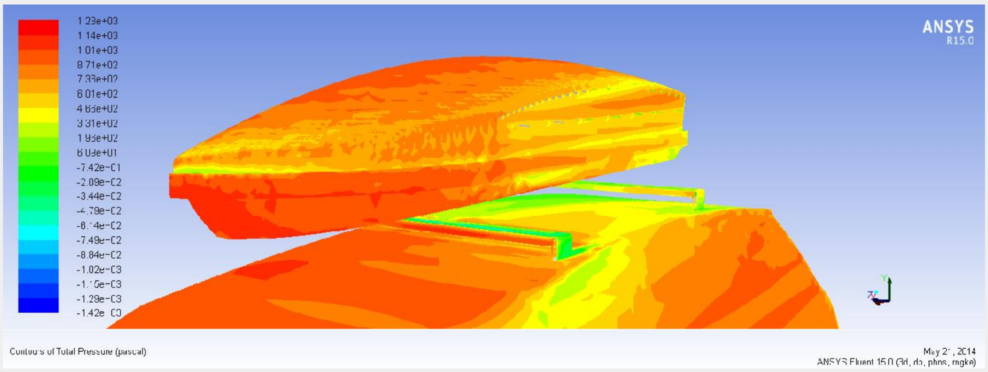
$$\Delta C_D = \left| \frac{0.36308 - 0.35667}{0.35667} \cdot 100 \right| = 1.79\%$$

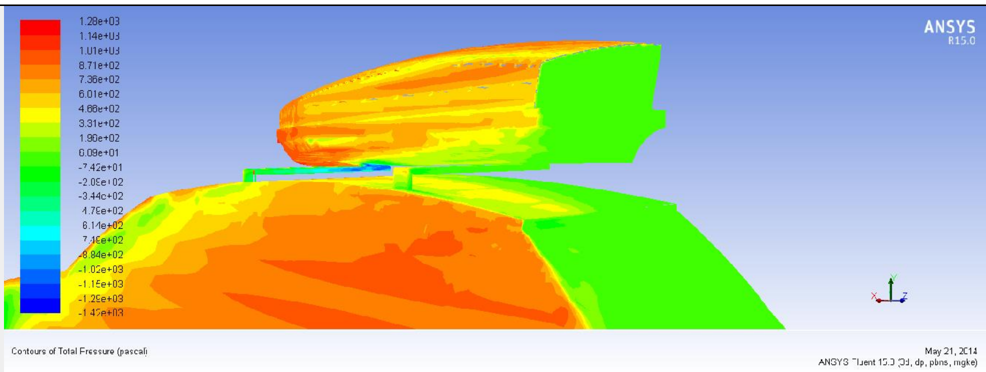
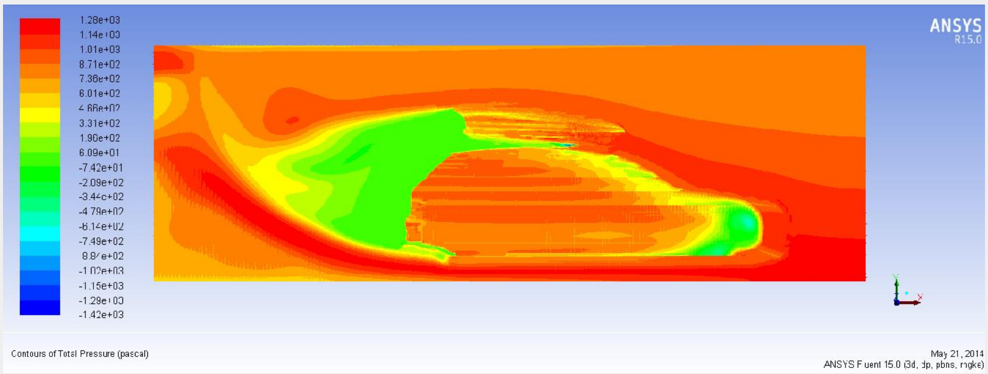
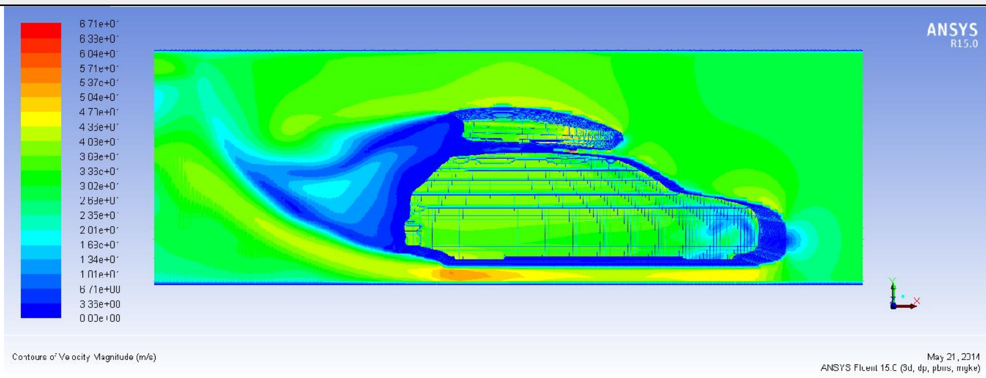
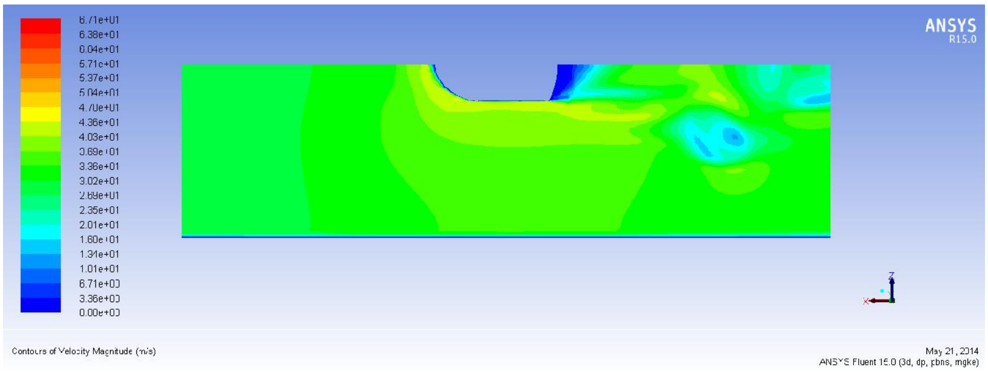
- Case 2: Audi A4 Avant with Thule Sonic Large 634s:

$$\Delta C_D = \left| \frac{0.45232 - 0.46245}{0.46245} \cdot 100 \right| = 2.19\%$$

The difference between meshing with hex dominant and Cut Cell Cartesian is near the same. Otherwise, the value in the first case is positive and in the second one is negative. However, the method that we use is Cut Cell Cartesian because we obtain a high density mesh and more accurate results.

If we plot the results obtained with Cut Cell Cartesian method, the results are the following:

	Model	**Thule Sonic Large 634s**
A	Pressure	 

		ANSYS R15.0 Contours of Total Pressure (pascal) May 21, 2014 ANSYS R15.0 Contours of Total Pressure (pascal) May 21, 2014
B	Velocity	ANSYS R15.0 May 21, 2014 ANSYS R15.0 Contours of Velocity Magnitude (m/s) May 21, 2014 ANSYS Fluent 15.0 (3d, dp, pbns, rngke)

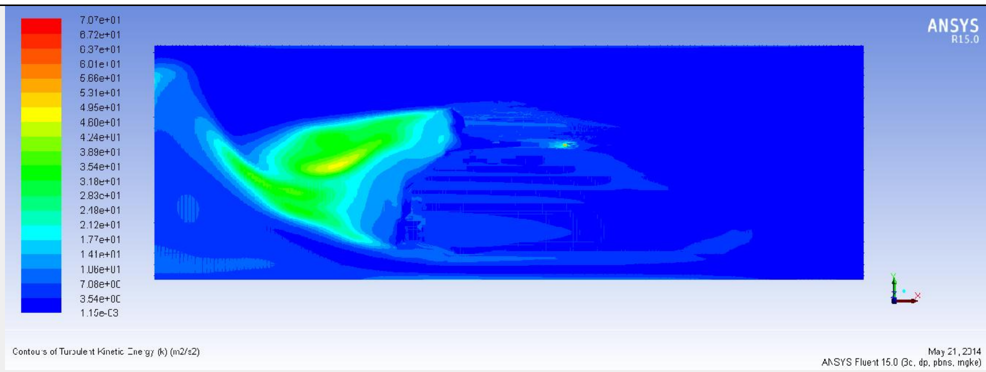
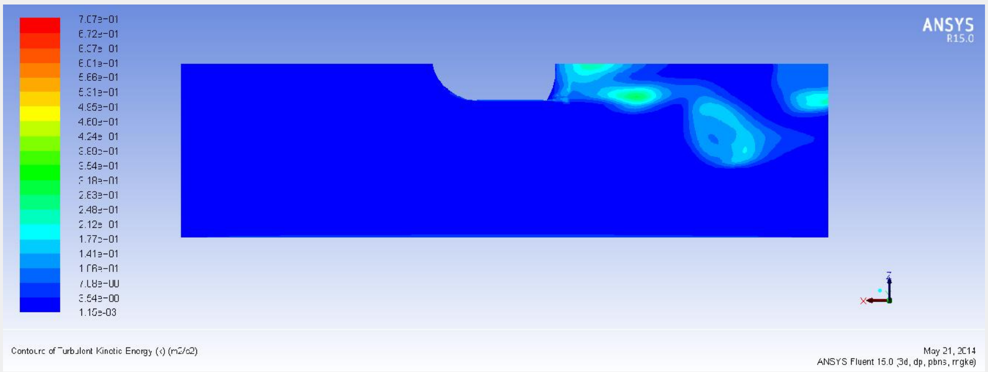
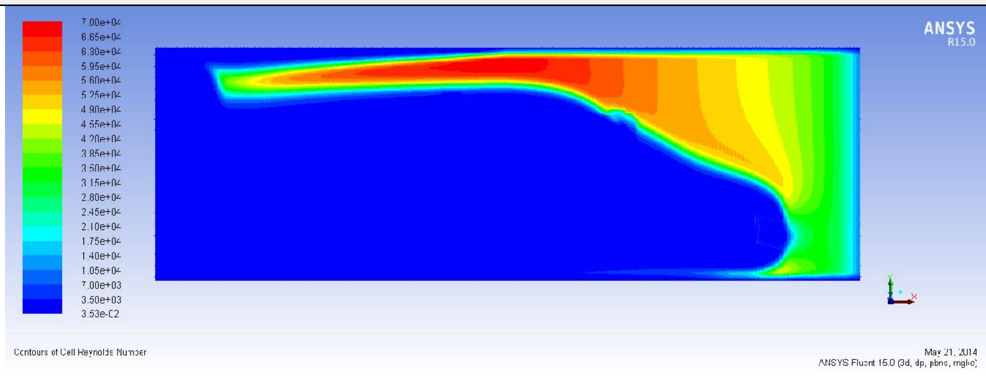
C	Turbulence	 
D	Reynolds	

Figure 4.14: *a) distribution of pressure b) distribution of velocity c) turbulence d) Reynolds*

In this case, we can observe an increase of pressure (Fig. 4.14, image A) compared respect the car without roof box (Fig. 4.12, image A). The places that the pressure is higher is in the front of the car, the supports and the front part of the roof box. The value is near 1280 Pa and it is an increase of 15% of the pressure. We also can observe that the low pressure has increased considerably in the rear part of the vehicle due to the increase of area. It also happens in the speed (Fig. 4.14, image B) of the fluid; now the zone without speed is bigger than the car without roof box. In addition, there are more points of impact of the fluid where the speed is zero. One is in the same part of the case 4.4.2.1 (car without roof box) and the new place is located in the front of the roof box.

After comparing that the value that this value is very similar, we apply the equations written in point 3.1.6 (Motor dynamics) to check and verify the power needed and the increase of fuel consumption.

Table 4.15: Calculation of motor vehicle dynamics of Thule Sonic Large and the car without roof box

		[3D] Without Roof box	[3D] Thule Sonic Large 634s
Total force	F_t	595,80	715,59
Resistance Mechanical force	R_t	0,85	0,85
Resistance Road friction	R_r	128,31	133,42
Resistance Air	R_a	466,63	581,33
Resistance Mechanical Force	η	0,85	0,85
Resistance Road Friction	R_t=m·g·f	128,31	133,42
Mass	m	1635,00	1700,00
Gravity	g	9,81	9,81
Tread coefficient	f	0,01	0,01
Resistance. Air	R_a	466,63	581,33
Drag coefficient	c_D	0,36308	0,45232
Air density	ρ	1,25	1,25
Projected section	S	2,68	2,68
Speed²	v^2	767,29	767,29
POWER	P_n [W]	16503,64	19821,91
	P_n [KW]	**16,50**	**19,82**
Fuel consumption	B [litres/100km]	**5,1237**	**6,1668**
Density fuel	ρ_b	0,832	0,832
Specific Energy Consumption	b_e	0,227	0,227

After calculating the values of total resistance, power needed, and fuel consumption, we can compare the values of using a roof box or not.

- Increase of drag coefficient between Audi A4 Avant without roof box and installing Thule Sonic Large 634s:

$$\Delta C_D = \frac{c_{D_{Thule\ position\ 1}} - c_{D_{Without\ roof\ box}}}{c_{D_{Without\ roof\ box}}} \tag{37}$$

$$\Delta C_D = \frac{0.45232 - 0.36308}{0.36308} \cdot 100 = 24.57\%$$

- Increase of Power needed:

$$\Delta\ Power\ needed = \frac{Pn_{\ Without\ roof\ box} - Pn_{\ Thule}}{Pn_{\ Without\ roof\ box}} \cdot 100 \tag{38}$$

$$\Delta\ Power\ needed = \frac{19.82 - 16.50}{16.50} \cdot 100 = 20.12\%$$

- Increase of fuel consumption:

$$\Delta\, Fuel\ Consumption = \frac{Fuel\ consumption_{\ Without\ roof\ box} - Fuel\ consumption_{\ Thule}}{Fuel\ consumption_{\ Without\ roof\ box}} \cdot 100 \tag{39}$$

$$\Delta\, Fuel\ Consumption = \frac{6.1668 - 5.1237}{5.1237} \cdot 100 = 20.35\%$$

In this case we can see the increase of drag coefficient is less than in 2 dimensional (near 55%). The increase is 24.57% and this increase involves an increase of power needed of 20.12% and an increase of 20.35% of fuel consumption. This values are more logical than in 2 Dimensional because the shapes designed are modelling the correct flow and the correct values of drag coefficient.

5. Redesign of roof box

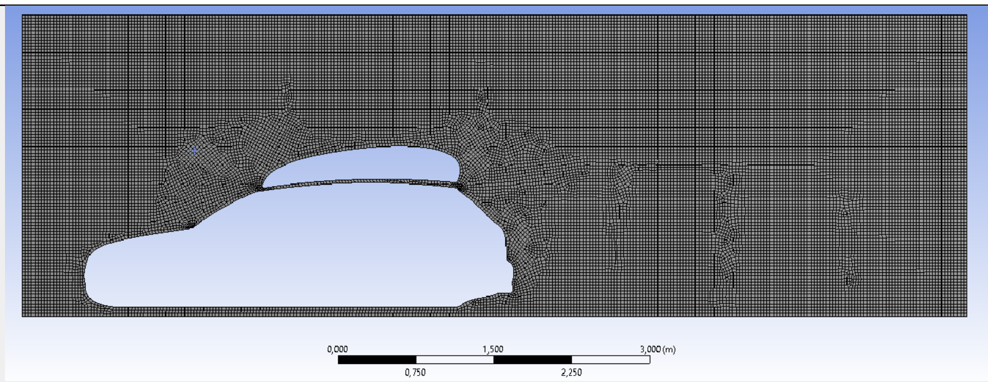
5.1. 2 dimensional idea

5.1.1. Audi A4 Avant with a possible redesign of roof box

The objective of this part is to simulate a 2 dimensional profile of a roof box to import the idea to 3 dimensional modelling. The forms used are the best fitting in the roof shape. Doing that shapes, we can affirm that the drag coefficient is better than the Thule roof box.

The mesh method used is the Quad Dominant with the same sizing done in the 2 dimensional models of the part 4.4.1.2. The result of the mesh and the number of nodes and elements are the next:

Table 5.1: Image of the mesh and the number of nodes and elements for the model without roof box

Method	**Quad dominant**
Mesh	
Nodes	25319
Elements	24692

After the mesh, the next step is running the calculation obtaining the following values of C_D:

Table 5.2: Values of C_D and C_L for this model

Model	**2D redesign**
C_D	0.36882
C_L	-2.0892

The next step is plotting the result and obtaining the drawings of the fluid of pressure, velocity, turbulence and finally Reynolds.

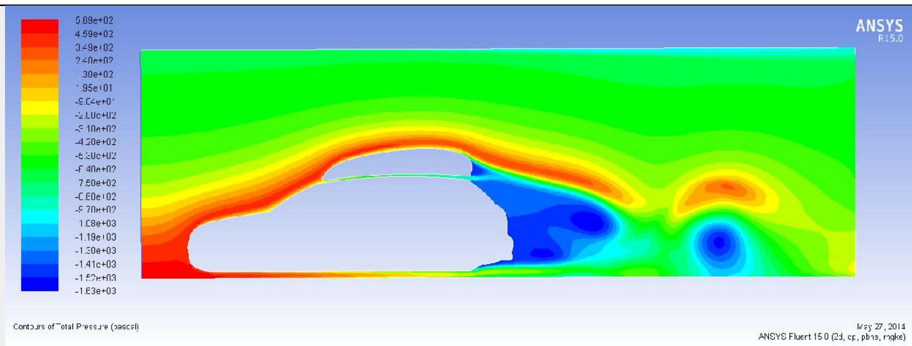
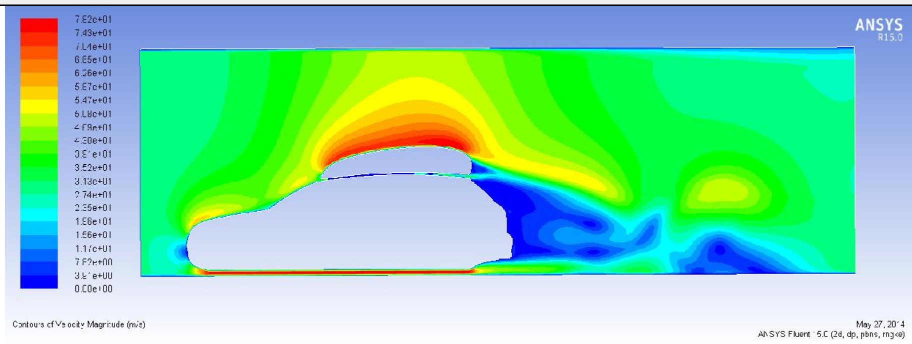
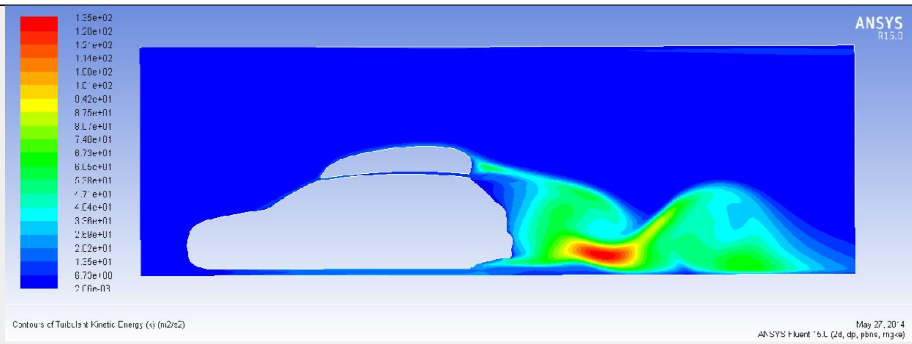
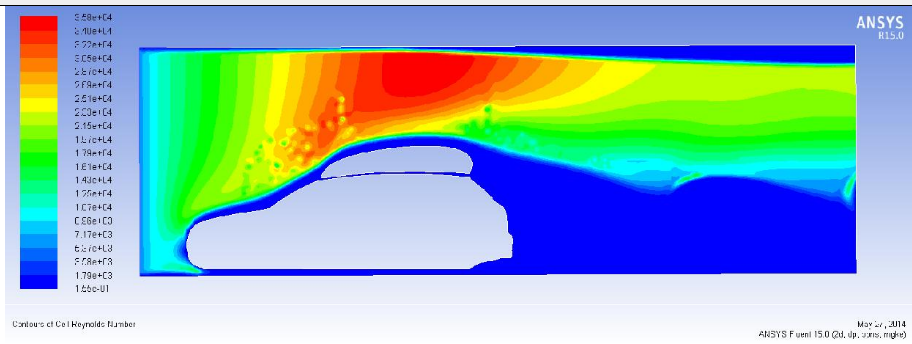
	Model	**Redesign in 2D**
A	Pressure	
B	Velocity	
C	Turbulence	
D	Reynolds	

Figure 5.1: *a) distribution of pressure b) distribution of velocity c) turbulence d) Reynolds*

Applying the formulas of motor dynamics we obtain the following table with the values of force, power and fuel consumption:

Table 5.3: Calculation of motor vehicle dynamics of the idea of redesign

		[2D] Redesign
Total force	F_t	519,84
Resistance Mechanical force	R_t	0,85
Resistance Road friction	R_r	133,42
Resistance Air	R_a	385,58
Resistance Mechanical Force	η	0,85
Resistance Road Friction	$R_t=m \cdot g \cdot f$	133,42
Mass	m	1700,00
Gravity	g	9,81
Tread coefficient	f	0,01
Resistance Air	R_a	385,58
Drag coefficient	c_D	0,36882
Air density	ρ	1,25
Projected section	S	2,18
Speed^2	v^2	767,29
POWER	P_n [W]	14399,64
	P_n [KW]	14,40
Fuel consumption	B [litres/100km]	4,4577
Density fuel	ρ_b	0,832
Specific Energy Consumption	b_e	0,227

Comparing the values obtained with the redesign box and car without roof the results are the next:

- Increase of C_D:

$$\Delta C_D = \frac{c_{D_{Redesign}} - c_{D_{Without\ roof\ box}}}{c_{D_{without\ roof\ box}}} \tag{40}$$

$$\Delta C_D = \frac{0,3682 - 0.3573}{0,3573} \cdot 100 = 3.22\%$$

- Increase of Power needed:

$$\Delta\ Power\ needed = \frac{Pn_{\ Redesign} - Pn_{\ Without\ roof\ box}}{Pn_{\ Without\ roof\ box}} \cdot 100 \tag{41}$$

$$\Delta\ Power\ needed = \frac{14.40 - 13.92}{13.92} \cdot 100 = 3.45\%$$

- Increase of fuel consumption:

$$\Delta\ Fuel\ Consumption = \frac{Fuel\ consumption_{\ Redesign} - Fuel\ consumption_{\ Without\ roof\ box}}{Fuel\ consumption_{\ Without\ roof\ box}} \cdot 100 \tag{42}$$

$$\Delta\ Fuel\ Consumption = \frac{4.4577 - 4.3108}{4.3108} \cdot 100 = 3.41\%$$

If we compare the values obtained with the representation of a possible redesign of a roof box respect Thule Sonic Large roof box:

- Increase of C_D:

$$\Delta C_D = \frac{C_{D_{Redesign}} - C_{D_{Thule\ Sonic\ Large\ Xl\ 6\ 33}}}{C_{D_{Thule\ Sonic\ Large\ Xl\ 6\ 33}}} \tag{43}$$

$$\Delta C_D = \frac{0.3608 - 0.5546}{0.5546} \cdot 100 = -34.94\%$$

- Increase of Power needed:

$$\Delta\ Power\ needed = \frac{Pn_{\ Redesign} - Pn_{\ Thule\ Sonic\ Large}}{Pn_{\ Thule\ Sonic\ Large}} \cdot 100 \tag{44}$$

$$\Delta\ Power\ needed = \frac{14.40 - 19.78}{19.78} \cdot 100 = -27.19\%$$

- Increase of fuel consumption:

$$\Delta\ Fuel\ Consumption = \frac{Fuel\ consumption_{\ Redesign} - Fuel\ consumption_{\ Thule\ Sonic\ Large}}{Fuel\ consumption_{\ Thule\ Sonic\ Large}} \cdot 100 \tag{45}$$

$$\Delta\ Fuel\ Consumption = \frac{4.4577 - 6.1534}{6.1534} \cdot 100 = -27.55\%$$

The increase of fuel consumption and power needed with this roof box is lower with the Thule Sonic Large. Of course, installing a roof box in the car affects in the aerodynamics and motor dynamics of the car and the values obtained are bigger than the car without roof box. Apparently the idea of this redesign of roof box seems good. In the 3 dimensional model, we use this model as the base for the model created to improve the commercial roof box.

5.2. 3 dimensional

5.2.1. Redesign 1 of the roof box

The idea of this redesign is create a roof box specially designed for Audi A4 Avant. The surfaces are totally fitted in the roof of the car. Therefore, the advantage of this roof box is that it would be more aerodynamic, but the universality of putting this roof box in other car disappears.

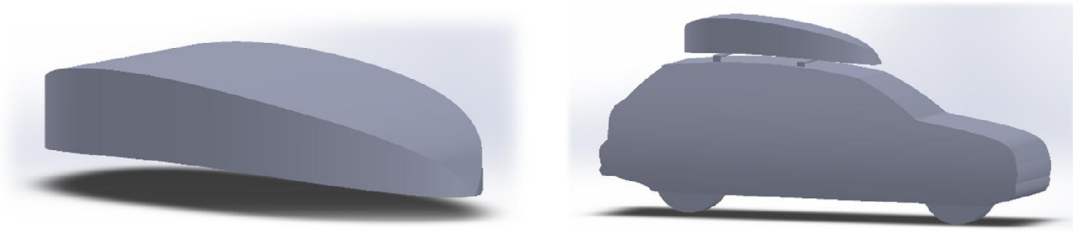
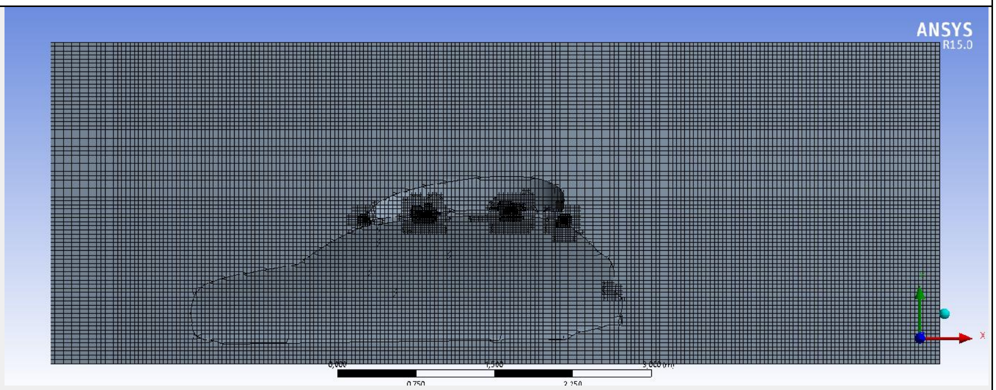


Figure 5.2: *Models of redesign 1 and the car with redesign 1 roof box*

Applying the same method to mesh used in the other cases:

Table 5.4: Image of the mesh and the number of nodes and elements for the model without roof box

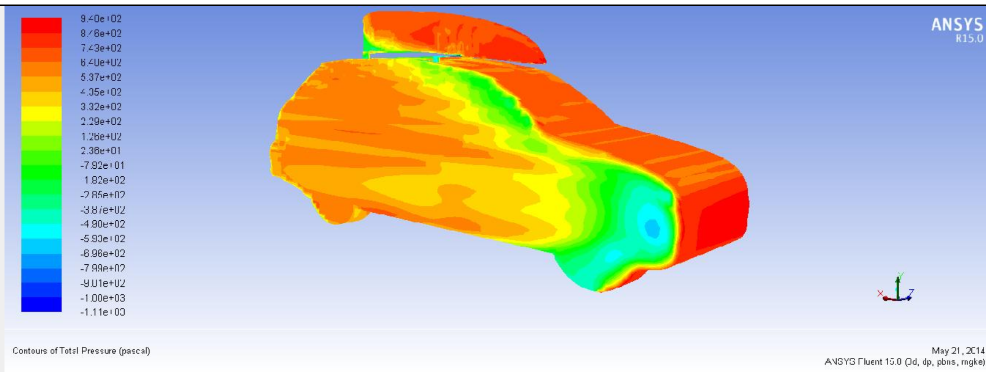
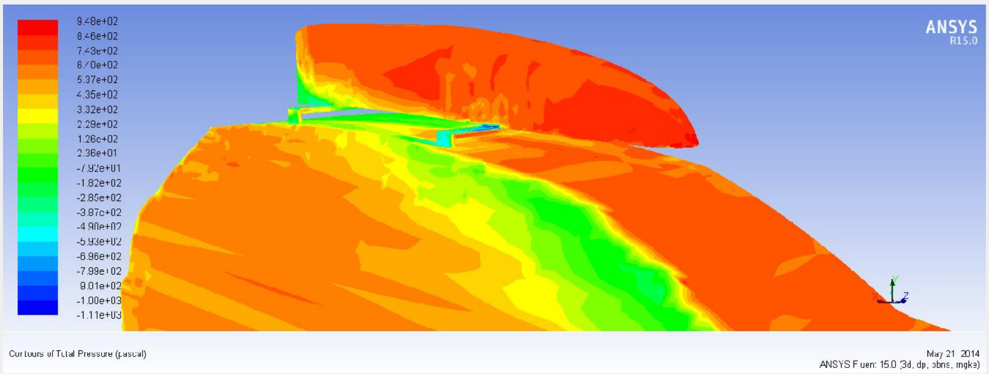
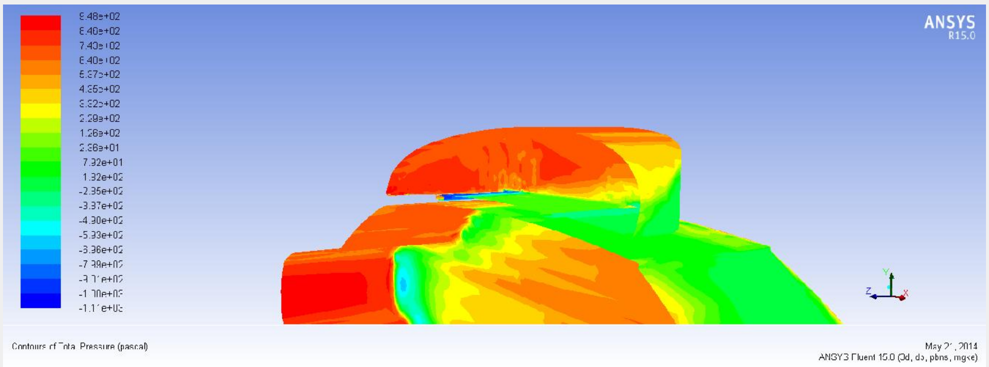
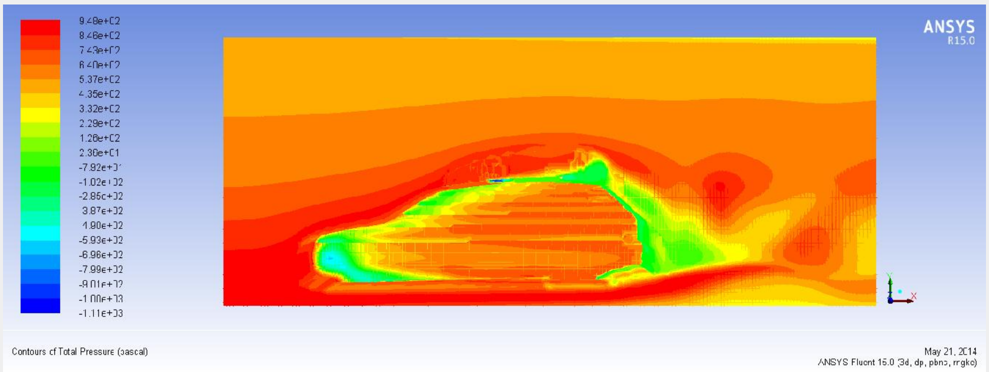
Method	**Cut Cell Cartesian**
Mesh	
Nodes	913955
Elements	859799

After doing the mesh, the next step consists in doing the simulation. The values obtained of drag coefficient and lift coefficient are the next:

Table 5.5: Values of C_D and C_L for this model

Method	**Cut Cell Cartesian**
C_D	0.41314
C_L	-0.33686

The next step is plotting the results to the model and analyse how the flow is affecting to the surfaces:

	Model	Redesign in 2D
A	Pressure	   

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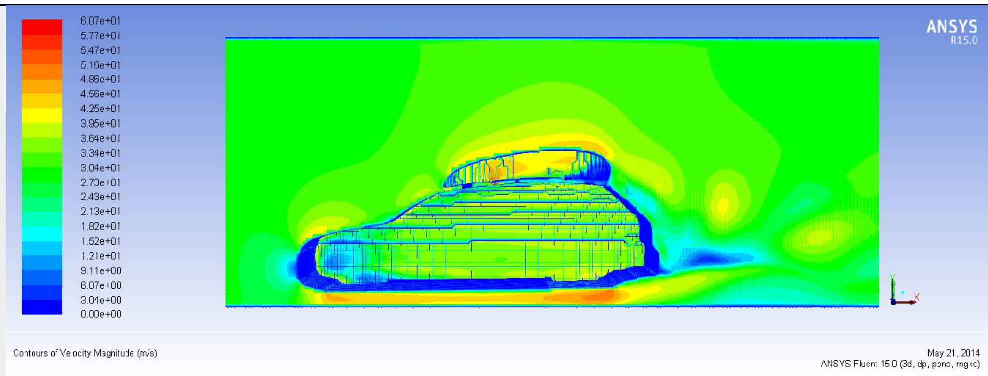
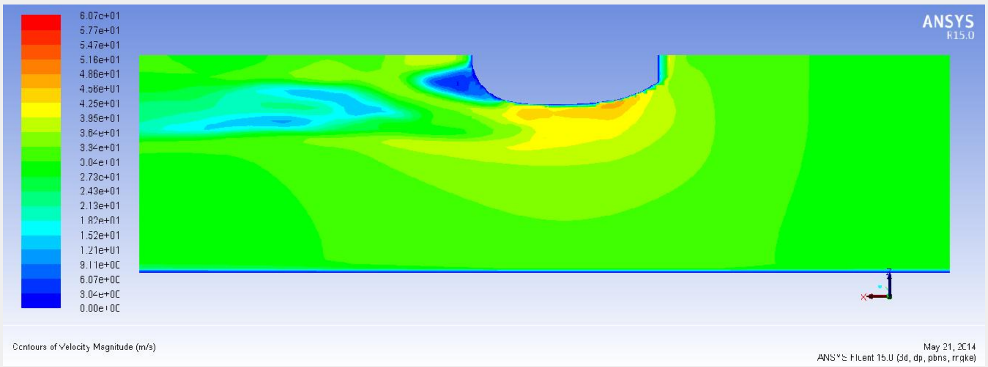
<tr><td>B</td><td>Velocity</td><td>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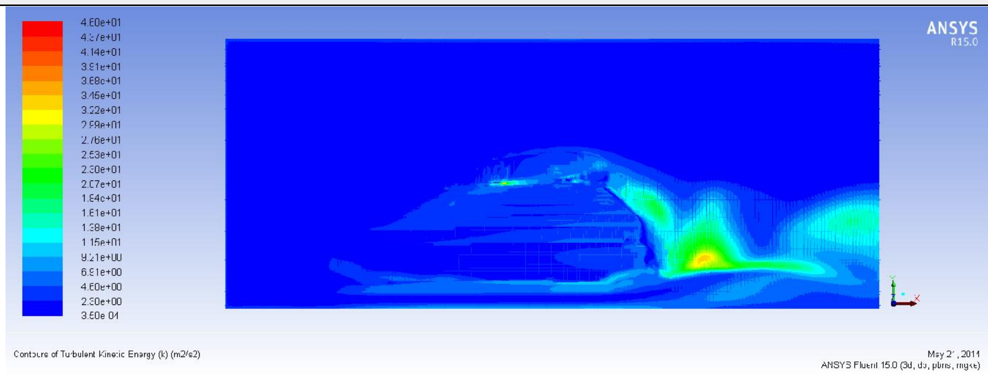
<tr><td>C</td><td>Turbulence</td><td>

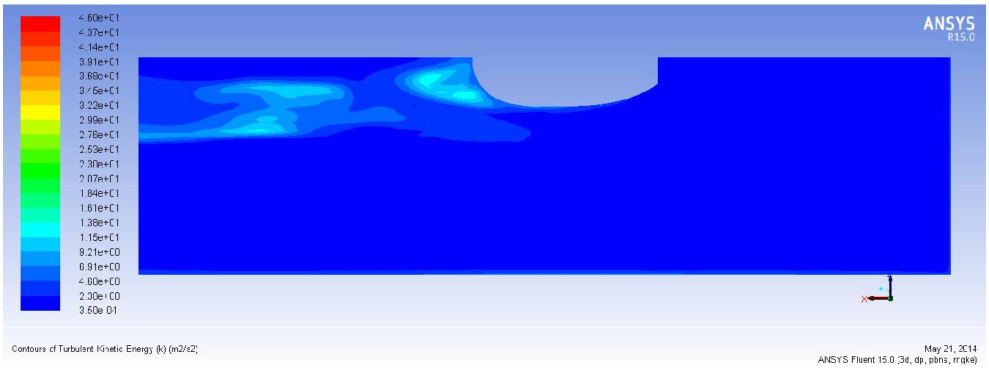
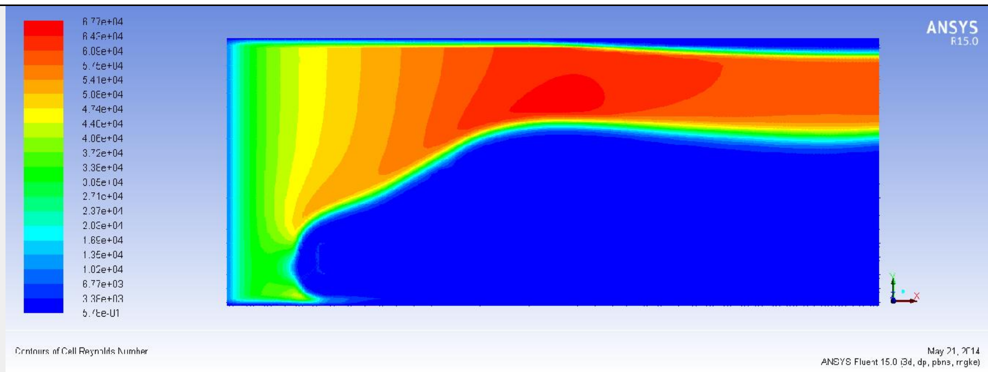

</td></tr>
<tr><td>D</td><td>Reynolds</td><td>
</td></tr>
</table>

Figure 5.3: *a) distribution of pressure b) distribution of velocity c) turbulence d) Reynolds*

In this case, the shapes of the roof box are adapted totally to the roof box car. The supports are covered by the front of the roof box and due to this design, the pressure (Fig. 5.3, image A) is lower than the other cases. Now the pressure is 948 Pa (without roof box (Fig. 4.12, image A) is 1110 Pa and with Thule Sonic Large (Fig. 4.14, image A) 1280 Pa). It involves a decrease of 14% of the highest value of the total pressure. About the points of impact, now only exist one; this point is the front of the car, because the new shape of the roof box is totally fitted on the roof of the car and it involves a disappear of the point of impact in the roof box.

Applying the formulas of motor vehicle dynamics to check the improvement of power needed and fuel consumption, we can obtain these values:

Table 5.6: Calculation of motor vehicle dynamics of Redesign 1

		[3D] Redesign 1
Total force	F_t	602,08
Resistance Mechanical force	R_t	0,85
Resistance Road friction	R_r	133,41
Resistance Air	R_a	467,81
Resistance Mechanical Force	η	0,85
Resistance Road Friction	R_t=m·g·f	133,41
Mass	m	1700
Gravity	g	9,81
Tread coefficient	f	0,008
Resistance Air	R_a	467,81
Drag coefficient	c_D	0,364
Air density	ρ	1,25
Projected section	S	2,68
Speed²	v^2	767,29
POWER	P_n [W]	16677,69
	P_n [KW]	16,67
Fuel consumption	B [litres/100km]	5,175
Density fuel	ρ_b	0,832
Specific Energy Consumption	b_e	0,227

Comparing with the values obtained in the other cases, this roof box allows a decrease of fuel consumption despite increasing the weight of the vehicle. The reduction of C_D is more important than the increase of weight and projected section.

- Increase of C_D:

$$\Delta C_D = \frac{C_{D_{Redesign\ 1}} - C_{D_{Without\ roof\ box}}}{C_{D_{without\ roof\ box}}} \tag{46}$$

$$\Delta C_D = \frac{0{,}41314 - 0.36308}{0{,}36308} \cdot 100 = 13.78\%$$

- Increase of Power needed:

$$\Delta\ Power\ needed = \frac{Pn_{\ Redesign\ 1} - Pn_{\ Without\ roof\ box}}{Pn_{\ Without\ roof\ box}} \cdot 100 \tag{47}$$

$$\Delta\ Power\ needed = \frac{18.43 - 16.50}{16.50} \cdot 100 = \ 11.69\%$$

- Increase of fuel consumption:

$$\Delta\ Fuel\ Consumption = \frac{Fuel\ consumption_{\ Without\ roof\ box} - Fuel\ consumption_{\ Redesign\ 1}}{Fuel\ consumption_{\ Without\ roof\ box}} \cdot 100 \tag{48}$$

$$\Delta\ Fuel\ Consumption = \frac{5.7271 - 5.1237}{5.1237} \cdot 100 = 11.77\%$$

If we compare the values obtained respect Thule roof box:

- Increase of C_D:

$$\Delta C_D = \frac{C_{D_{Redesign\ 1}} - C_{D_{Thule\ Sonic\ Large\ Xl\ 6\ 33}}}{C_{D_{Thule\ Sonic\ Large\ Xl\ 6\ 33}}} \tag{49}$$

$$\Delta C_D = \frac{0.41314 - 0.45232}{0.45232} \cdot 100 = -8.66\%$$

- Increase of Power needed:

$$\Delta\ Power\ needed = \frac{Pn_{\ Redesign\ 1} - Pn_{\ Thule\ Sonic\ Large}}{Pn_{\ Thule\ Sonic\ Large}} \cdot 100 \tag{50}$$

$$\Delta\ Power\ needed = \frac{18.43 - 19.82}{19.82} \cdot 100 = \ -7.01\%$$

- Increase of fuel consumption:

$$\Delta\ Fuel\ Consumption = \frac{Fuel\ consumption_{\ Redesign\ 1} - Fuel\ consumption_{\ Thule\ Sonic\ Large}}{Fuel\ consumption_{\ Thule\ Sonic\ Large}} \cdot 100 \tag{51}$$

$$\Delta\ Fuel\ Consumption = \frac{5.7271 - 6.1668}{5.1237} \cdot 100 = -7.13\%$$

The conclusion obtained after doing the calculation of increases and decreases of motor dynamics is the redesign of the model which has better results than the commercial roof box. Of course, installing a roof box is impossible to equal or improve the values obtained without the roof box.

5.2.2. Redesign 2 of the roof box:

In this project, there are another redesign due to the non-universality of the first roofbox. We designed another one, with a shape that fits in every car.

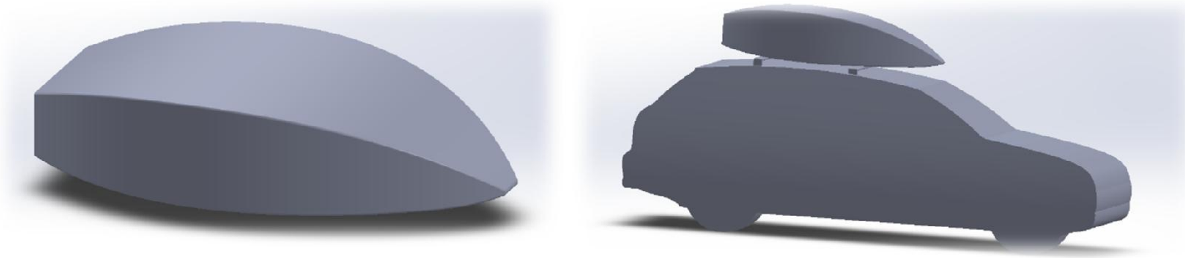
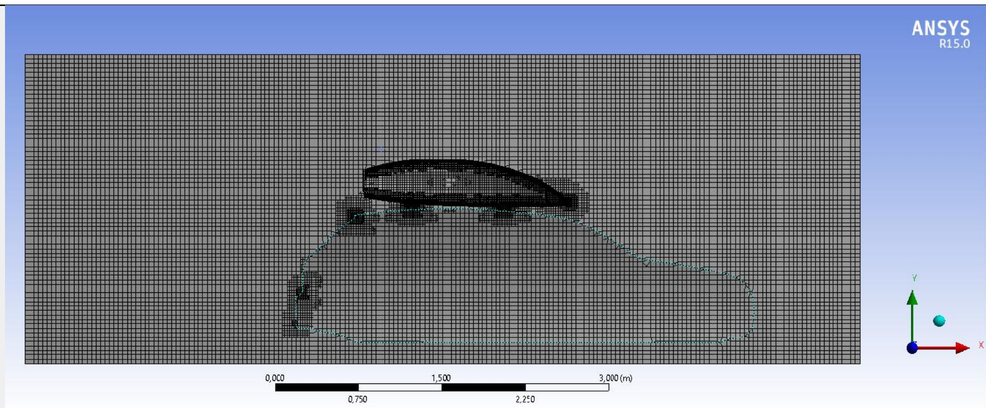


Figure 5.4: *Models of redesign 2 and the car with redesign 2 roof box*

The method to mesh is the same that we use in all 3 dimensional cases. The method of Cut Cell Cartesian allows to obtain a high density mesh with near 1 million of nodes.

Table 5.7: Image of the mesh and the number of nodes and elements for the model without roof box.

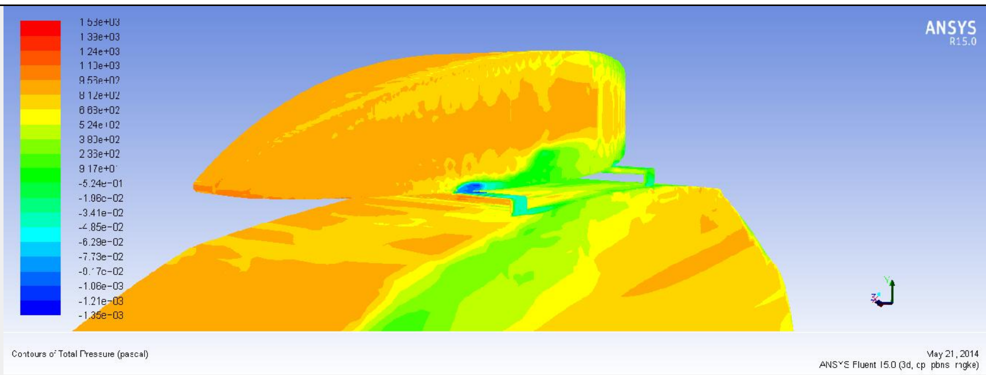
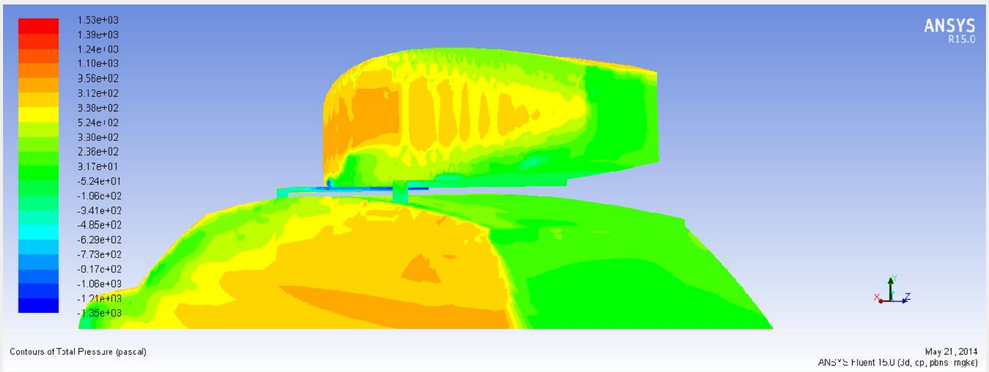
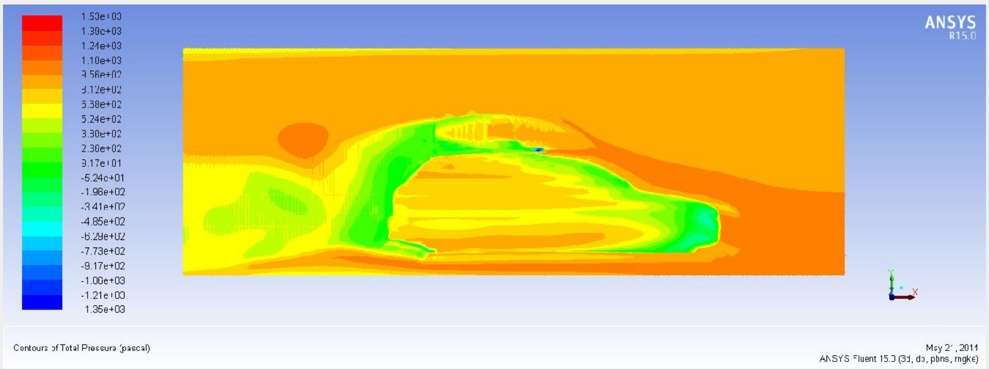
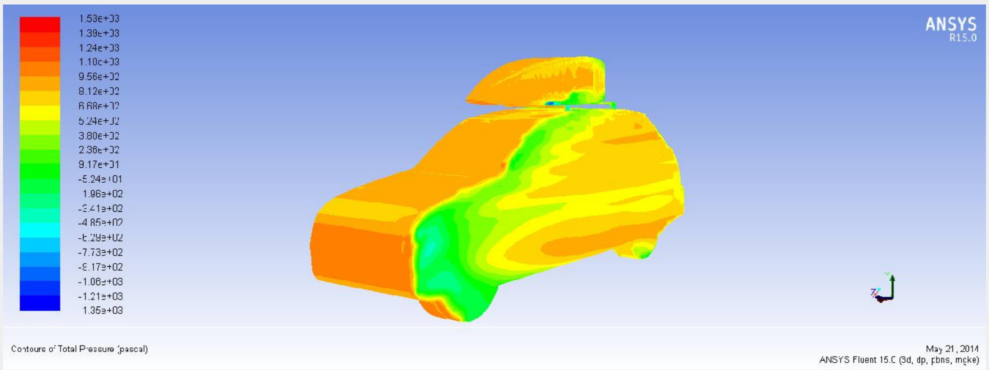
Method	**Cut Cell Cartesian**
Mesh	
Nodes	965644
Elements	887672

After the meshing, the solution run until the 300th iteration given that results.

Table 5.8: Values of C_D and C_L for this model

Method	**Cut Cell Cartesian**
C_D	0.43372
C_L	-0.15044

The plots of the model of redesigned roof box are the following:

	Model	Redesign in 2D
A	Pressure	

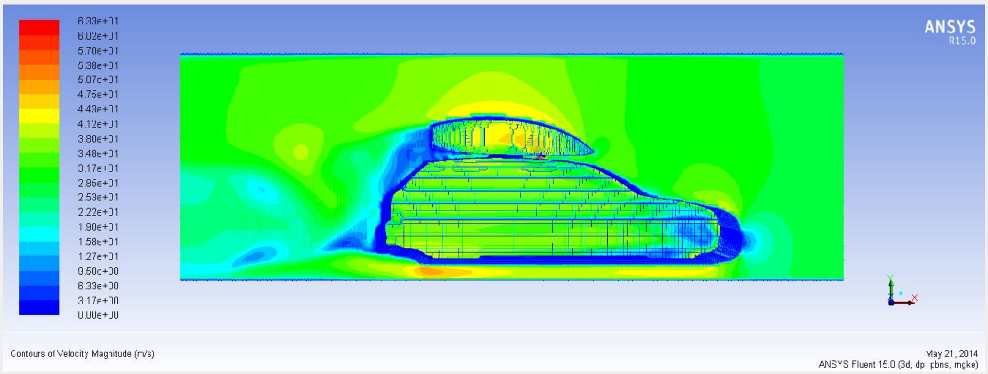
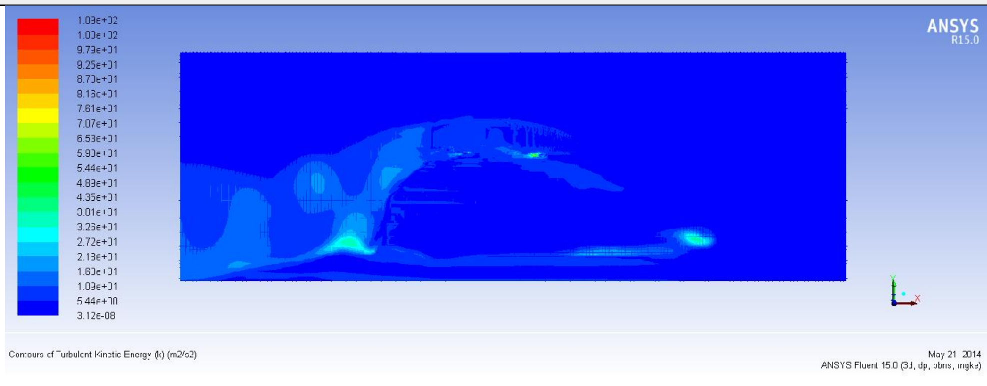
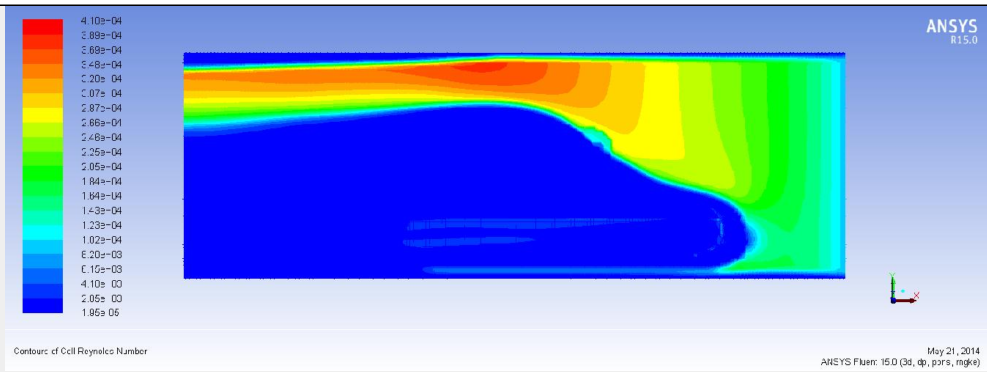
B	Velocity	
C	Turbulence	
D	Reynolds	

Figure 5.5: *a) distribution of pressure b) distribution of velocity c) turbulence d) Reynolds*

In this case we can observe that the high pressure is not showed in the plots because it is located in the support in a little part and it is higher than the other cases. However, in the redesign most of the plot is in orange which means that the highest pressure is 1100 Pa. This is the same result in case 1 (without roof box). About the speed, there is only one point of impact and it is in the front of the vehicle. The shape without speed is lower than the other cases. However the results show that the value of drag coefficient is lower than the other and the pressure has decreased

Applying the formulas of motor vehicle dynamics to check the improvement of power needed and fuel consumption, we can obtain this values:

Table 5.9: Calculation of motor vehicle dynamics of Redesign 2

		[3D] Redesign 2
Total force	F_t	691,69
Resistance Mechanical force	R_t	0,85
Resistance Road friction	R_r	133,42
Resistance Air	R_a	557,42
Resistance Mechanical Force	η	0,85
Resistance Road Friction	R_t=m·g·f	133,42
Mass	m	1700,00
Gravity	g	9,81
Tread coefficient	f	0,01
Resistance Air	R_a	557,42
Drag coefficient	c_D	0,43372
Air density	ρ	1,25
Projected section	S	2,68
Speed²	v²	767,29
POWER	P_n [W]	19159,75
	P_n [KW]	**19,16**
Fuel consumption	B [litres/100km]	**5,9581**
Density fuel	ρ_b	0,832
Specific Energy Consumption	b_e	0,227

Comparing with the values obtained in the other cases, this roof box allows a decrease of fuel consumption despite increasing the weight of the vehicle. The reduction of C_D is more important than the increase of weight and projected section.

- Increase of C_D:

$$\Delta C_D = \frac{c_{D_{Redesign\ 2}} - c_{D_{Without\ roof\ box}}}{c_{D_{without\ roof\ box}}} \tag{52}$$

$$\Delta C_D = \frac{0{,}43372 - 0.36308}{0{,}36308} \cdot 100 = 19.45\%$$

- Increase of Power needed:

$$\Delta\ Power\ needed = \frac{Pn_{\ Redesign\ 2} - Pn_{\ Without\ roof\ box}}{Pn_{\ Without\ roof\ box}} \cdot 100 \tag{53}$$

$$\Delta\ Power\ needed = \frac{19.16 - 16.50}{16.50} \cdot 100 = 16.12\%$$

- Increase of fuel consumption:

$$\Delta\, Fuel\ Consumption = \frac{Fuel\ consumption_{\ Redesign\ 2} - Fuel\ consumption_{\ Without\ roof\ box}}{Fuel\ consumption_{\ Without\ roof\ box}} \cdot 100 \tag{54}$$

$$\Delta\, Fuel\ Consumption = \frac{5.9581 - 5.1237}{5.1237} \cdot 100 = 16.28\%$$

If we compare the values obtained respect Thule roof box, we will be able to compare the efficiency of the redesigned roof box:

- Increase of C_D:

$$\Delta C_D = \frac{C_{D_{Redesign\ 2}} - C_{D_{Thule\ Sonic\ Large\ Xl\ 6\ 33}}}{C_{D_{Thule\ Sonic\ Large\ Xl\ 6\ 33}}} \tag{55}$$

$$\Delta C_D = \frac{0.43372 - 0.45232}{0.45232} \cdot 100 = -4.40\%$$

- Increase of Power needed:

$$\Delta\, Power\ needed = \frac{Pn_{\ Redesign\ 2} - Pn_{\ Thule\ Sonic\ Large}}{Pn_{\ Thule\ Sonic\ Large}} \cdot 100 \tag{56}$$

$$\Delta\, Power\ needed = \frac{19.16 - 19.82}{19.82} \cdot 100 = \ 3.32\%$$

- Increase of fuel consumption:

$$\Delta\, Fuel\ Consumption = \frac{Fuel\ consumption_{\ Redesign\ 2} - Fuel\ consumption_{\ Thule\ Sonic\ Large}}{Fuel\ consumption_{\ Thule\ Sonic\ Large}} \cdot 100 \tag{57}$$

$$\Delta\, Fuel\ Consumption = \frac{5.9581 - 6.1668}{5.1237} \cdot 100 = -2.89\%$$

After calculating the results, we can see that this roof box improves the values obtained with Thule Sonic Large. On the other hand, if we compare with the redesign 1, the values are not very different but higher. The advantage of this roof box is the universality of using it. The first redesign is created fitting with the roof of the car, so the universality of the roof box is impossible.

6. Renders and drawings of the redesigns

6.1. Renders and drawings

Finally, we have decided to create some renders of the redesigned roof box to get an idea about their shapes and how it fits on the roof box of the car.

6.1.1. Renders of Redesign 1

The first images correspond to the redesign 1. This roof box is specially designed for Audi A4 Avant B7 due to the shapes are totally fitted with the roof of this car. We have to add that this renders only represent the main shapes of the roof box. To obtain the real, we would include some details as the locks and other elements to fix on the car.

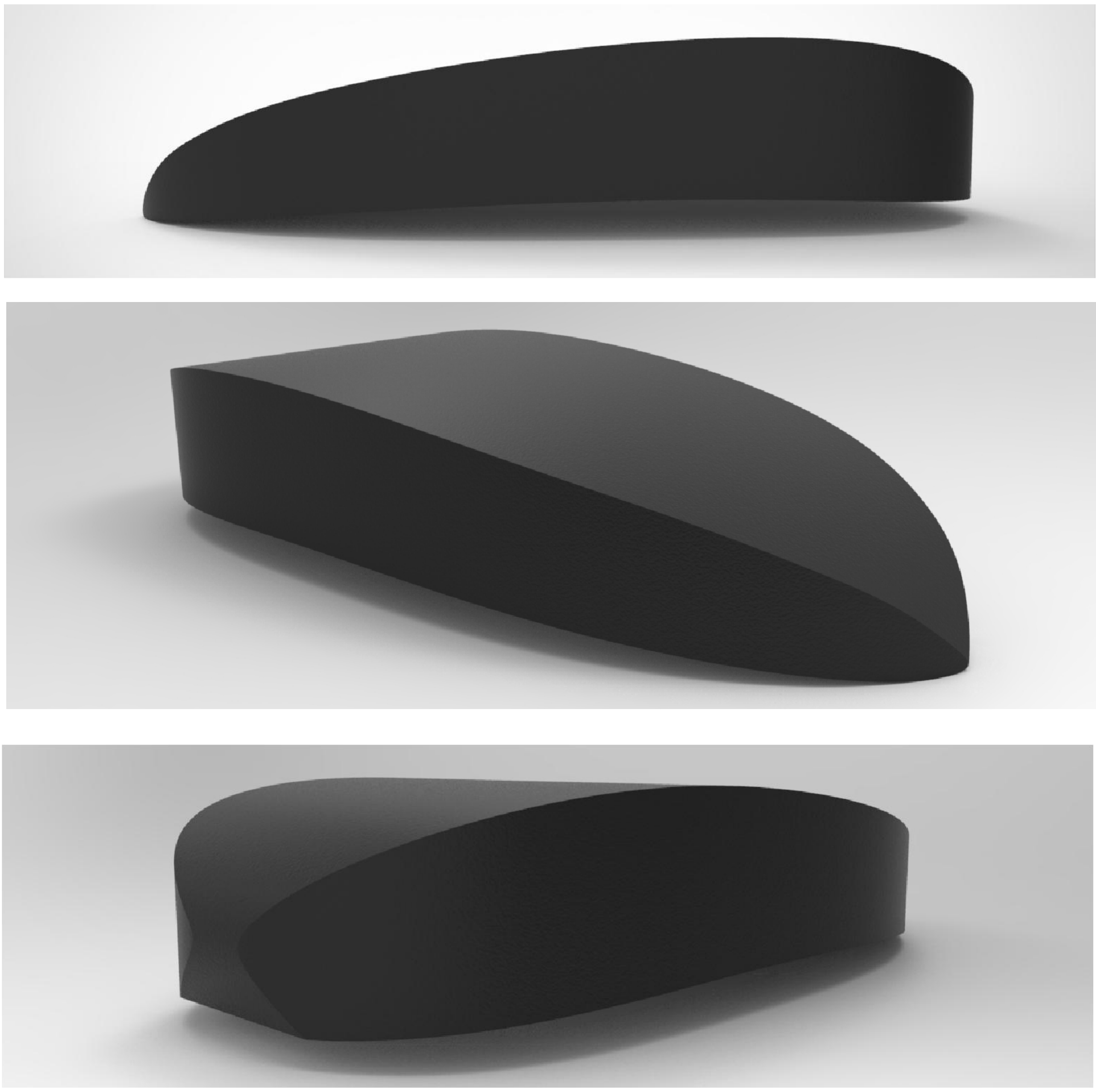
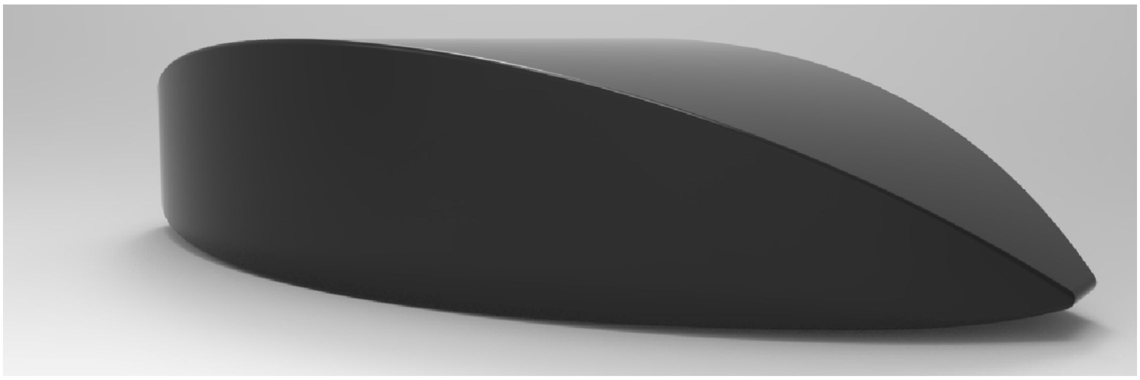


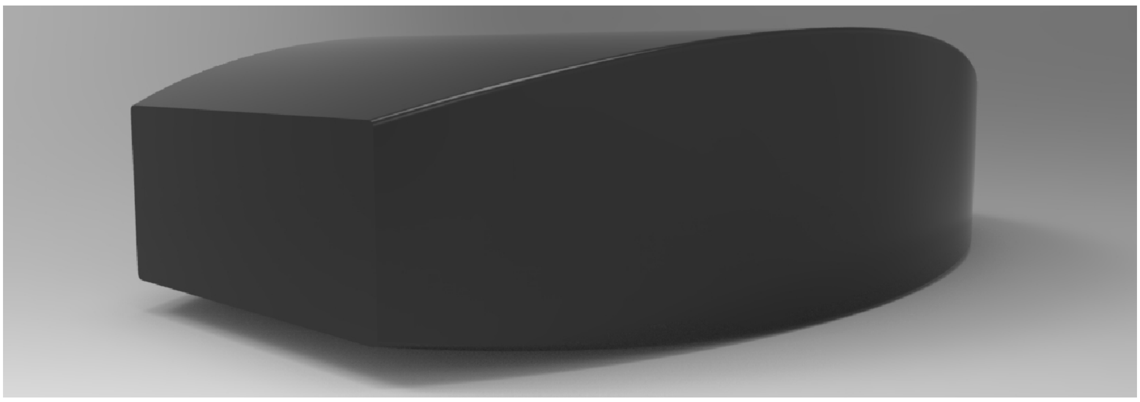
Figure 6.1: *Renders of redesign 1*

Figure 6.2: *Renders of redesign 1 fitted in Audi A4 Avant B7*

6.1.2. Renders of Redesign 2

These images are the second redesign. This roof box is specially designed to improve the actual roof box and fitting with most of the car (it has the property that can fit with almost cars, not as the first redesign). The last image represents how it would be fitted in a common car.





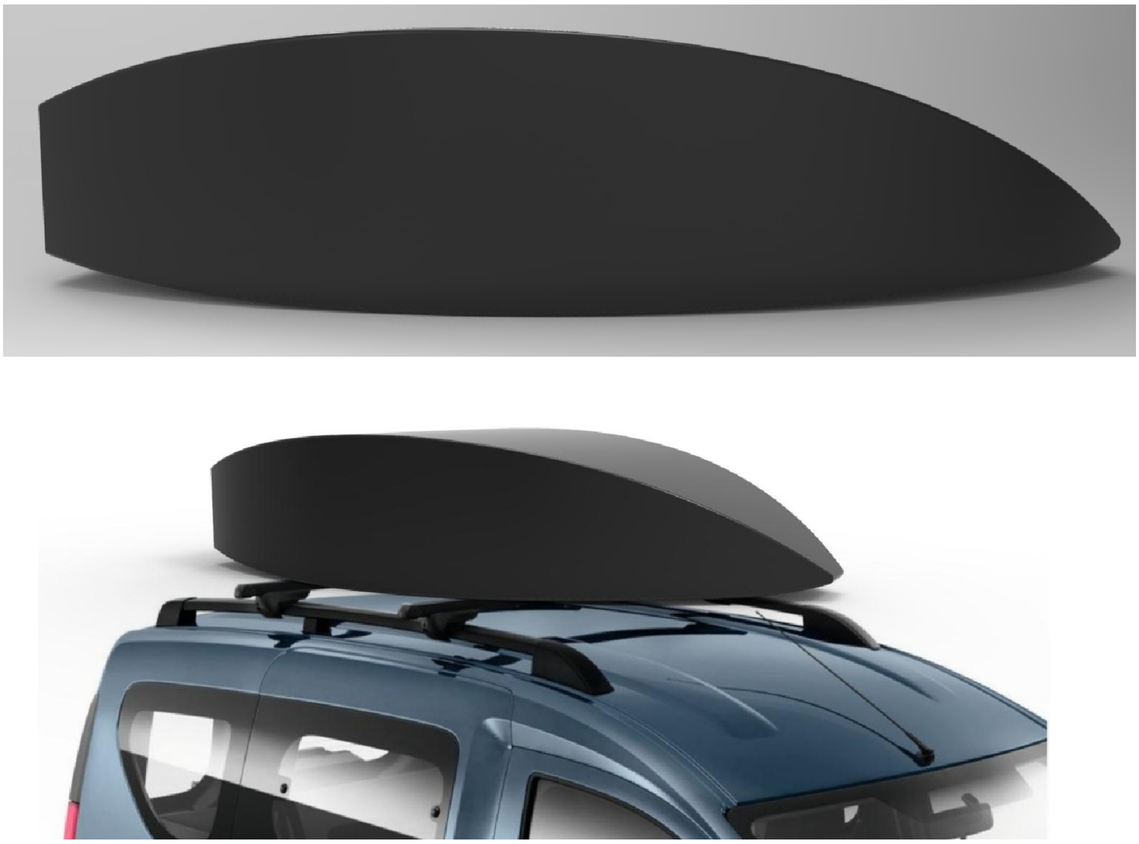
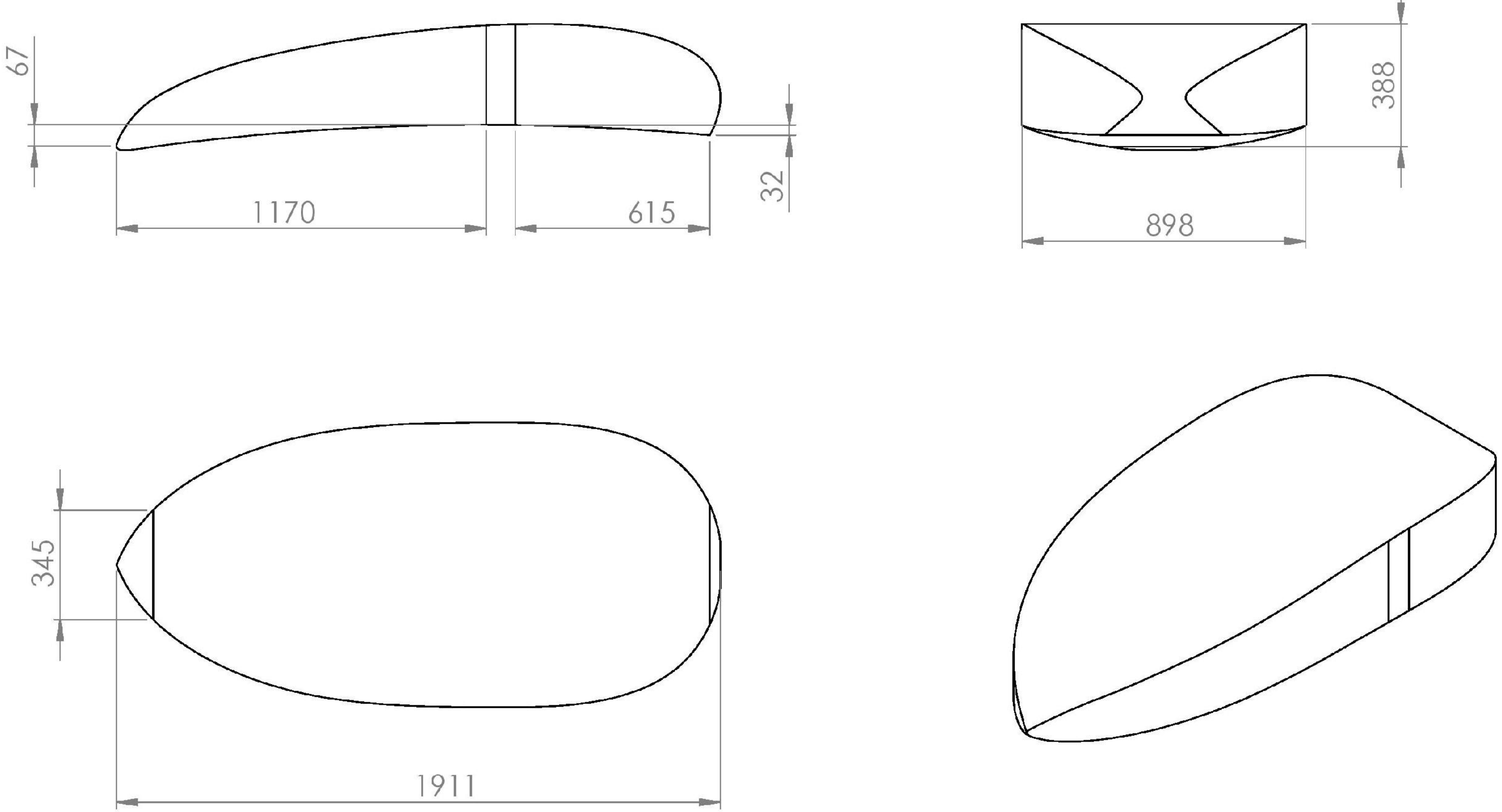


Figure 6.3: *Renders of redesign 2*



Ivan Gonzàlez Casal

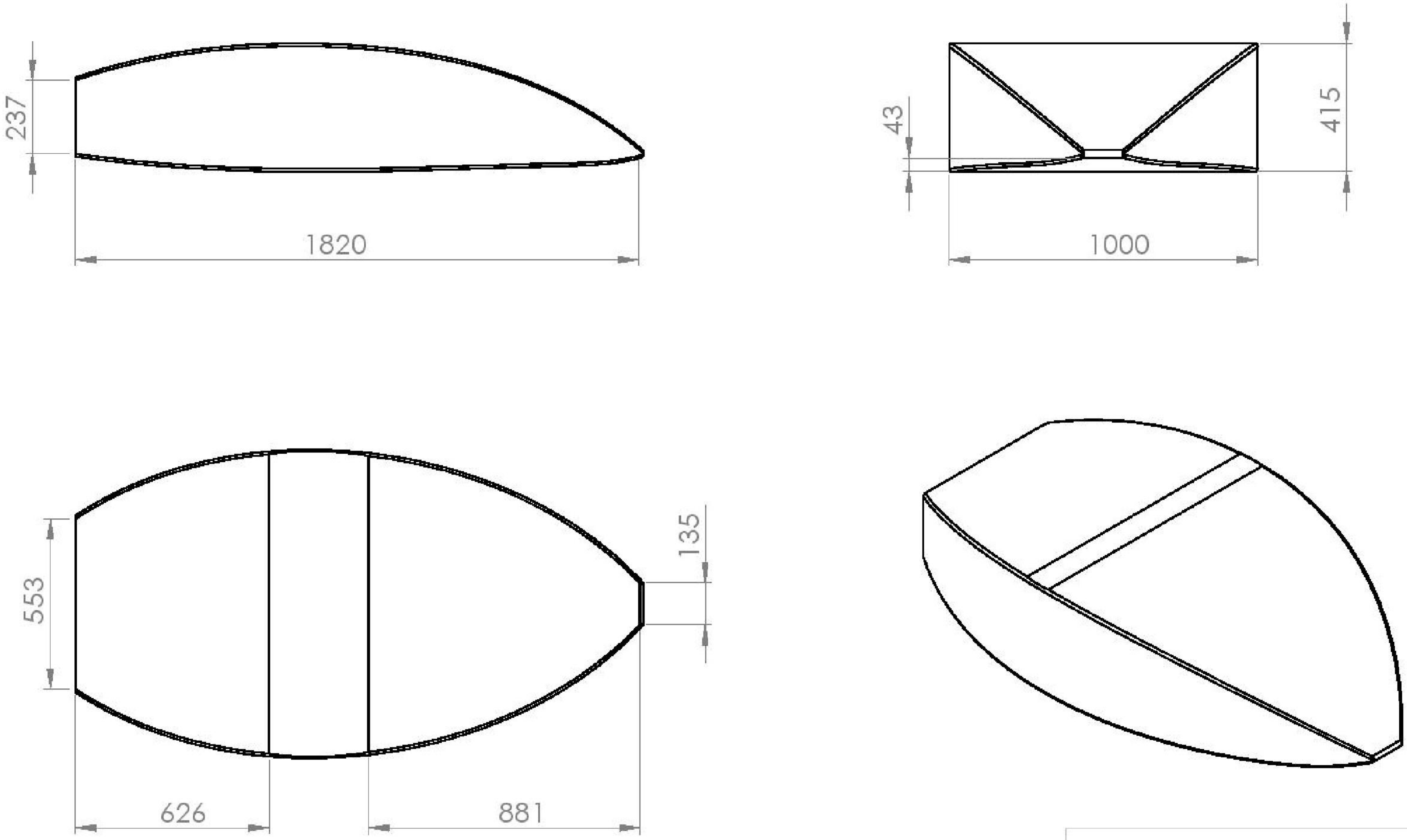
Master Thesis:

AERODYNAMIC ANALYSIS AND IMPROVEMENT OF A ROOF BOX CAR

Redesign 1

A4

1:20



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AERODYNAMIC ANALYSIS AND IMPROVEMENT OF A ROOF BOX CAR

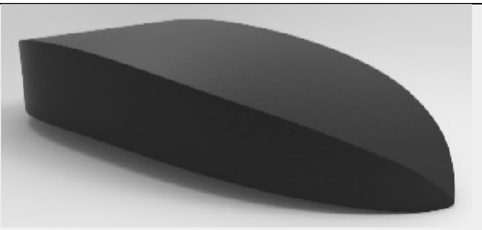
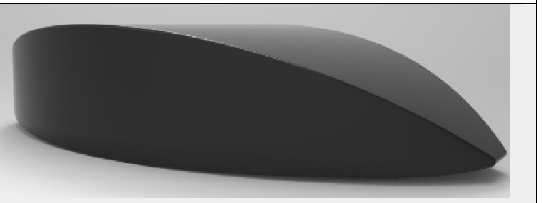
Redesign 2

A4

1:20

6.2. Dimensions and specifications

Table 6.1: Comparison of the specifications of the different roof boxes

	Thule Sonic Large 633s	**Redesign 1**	**Redesign 2**
Image			
Height [mm]	406	388	415
Length [mm]	1854	1911	1820
Width [mm]	876	898	1000
Volume [l]	460	395	520
C_D	0.45232	0.41314	0.43372

7. Conclusions and results

In this project we analyse a commercial roof box and his effects when the user install the roof box. The conclusions obtained in the first part are that the increase of drag coefficient is notable and adding an increase of weight makes an increase of fuel consumption and power needed to beat the resistance forces. To obtain these values, we made to two types of analysis; one in 2 dimensions and the other one in 3 dimensions. The first is only to get an approximation of the values that we can obtain and if we were going in the correct way. The second analyse is a complex calculation and we get an accurate results of the values that we are interested (drag coefficient, pressure, speed, turbulence and Reynolds).

To solve this problem, we decided to create a possible redesign and a modification of the position of the roof box. There are three possibilities:

- Modify the position of the roof box to improve the fluid flow and reduce the air resistance.
- Create a roof box totally fitted with the vehicle that we analyse with the problem of having a non-universal roof box
- The other possibility is redesigning of the roof box and obtaining a universal roof box and try to get a better values comparing with the commercial roof box.

After creating the both solutions we obtained the following tables of results. The first one is the 2 dimensional analysis and the second a 3 dimensional analysis.

Table 7.1: Comparison of the motor dynamics of the different roof boxes in 2 dimensional analysis

2 DIMENSIONAL	Car without roof box	Thule Sonic Large Position 1	Thule Sonic Large Position 2	Redesign
C_D	0.3573	0.5546	0.56535	0.36882
Power needed [KW]	13.92	19.78	20.09	14.40
Fuel consumption [litres/100km]	4.3108	6.1534	6.2515	4.4577
Increase of C_D compared to case 1	-	55.21%	58.22%	3.22%
Increase of power compared to case 1	-	42.09%	44.32%	3.45%
Increase of fuel consumption compared to case 1	-	42.74%	45.01%	3.41%

In the 2 dimensional analysis, we can observe that there is an important increase of the values when we install the Thule Sonic Large. With the proposed redesign, we obtain very good values of increasing C_D, fuel consumption and power needed. However, as we said before, these values are only an approximation due to the 2 dimensional analysis does not reflex the reality.

Table 7.2: Comparison of the motor dynamics of the different roof boxes in 3 dimensional analysis

3 DIMENSIONAL	Car without roof box	Thule Sonic Large	Redesign 1	Redesign 2
C_D	0.36308	0.45232	0.41314	0.43372
Power needed [KW]	16.50	19.82	18.43	19.16
Fuel consumption [litres/100km]	5.1237	6.1668	5.7271	5.9581
Increase of C_D compared to case 1	-	24.57%	13.78%	19.45%
Increase of power compared to case 1	-	20.12%	11.69%	16.12%
Increase of fuel consumption compared to case 1	-	20.35%	11.70%	16.18%
Decrease of C_D compared to case 2	-	-	8.66%	4.40%
Decrease of power compared to case 2	-	-	7.01%	3.32%
Decrease of fuel consumption compared to case 2	-	-	7.13%	2.89%

In the 3 dimensional analysis, the values obtained are more reliable due to the model is more realistic and the mesh has a high density number of elements. As we can see the increase with the Thule Sonic Large is not as big as the two dimensional analysis. Despite that the increase of fuel consumption and power needed is considerable. About the redesigns we obtain a lower increase of fuel consumption and power needed. The best values of the two redesigns were the redesign 1. This redesign is a non-universal roof box fitted to Audi A4 Avant. The second is the universal roof box with the possibility to adapt to any car. In a commercial point of view, it would be more profitable to produce the second roof box due to the market will be bigger than producing the first redesign.

The main problems in this redesigns is that we don't define the totally of the shapes and the details of the roof box. Therefore, when the final product is completely designed the values of drag coefficient, the shapes of the flows and the results will be different. Another thing that it would be interesting to comment is the difficult to manufacture these designs. In spite of the modern techniques of manufacturing, the possibility of creating some shapes maybe will be associated to a difficult of production and an increase of the price of manufacturing this product.

It would be interesting to comment, thanks the CFD programs as Ansys Fluent allows designing a product and analysing their effects without creating a model and doing an experimental analysis. These programs help to the designers, companies and manufactures to reduce their costs and obtain a reduction of time to get the final product.

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