French Air and Space Force Academy
Bachelor

Internship Report

Airbrake CFD Analysis for Land Speed Record Vehicle

Internship carried out at the
US Air Force Academy

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Previous picture : "Wairua II" (concept) 1999cc Streamliner for the "*kiwi can do challenge*" [CMR official page 2022].

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Résumé

Ce projet s'inscrit dans la continuité de ceux réalisées par les personnels de la promotion LCL Pouliquen en 2021. Elle consiste à imaginer et rechercher des axes d'optimisation aérodynamiques sur les aérofreins d'un véhicule terrestre. « Cook Motor Racing Team » est une équipe néo-zélandaise, elle s'est spécialisée dans la confection de véhicule pouvant battre des records du monde de vitesse sur des lacs salés, plus précisément à Bonneville UTAH. Wairua I (esprit en Maori), fut leur premier prototype pouvant atteindre une vitesse de 380 MPH. Après ce succès , l'équipe CMR a voulu continuer sur cette lancé et lança le projet Wairua II, avec pour objectif d'améliorer les précédentes performances, ils ont notamment fait appel à l'USAFA , qui proposa en 2021 deux études dans le but de réduire la trainée du véhicule, l'une sur l'amélioration du dessous de la voiture et la seconde sur l'optimisation de l'entrée d'air. La présente étude portera donc sur les aérofreins du véhicule Wairua II , avec pour commencer un rapide exposé sur l'histoire de l'équipe et des lieux où se dérouleront les tentatives de records de vitesse. Puis une présentation de l'historique du freinage dans l'automobile. Il sera ensuite présenté les différents outils de travail nécessaires à cette étude, pour ensuite détailler le protocole de simulation numérique. Les résultats de ces simulations seront ensuite analysés et comparés entre eux. La conclusion permettra enfin de proposer le plus performant des aérofreins à l'équipe et ouvrira de nouvelles pistes de réflexion pour les futurs travaux sur Wairua II.

Abstract

This project is a continuation of those carried out by the staff of the LCL POULIQUEN class in 2021. It consists in imagining and researching aerodynamic optimisation axes for the airbrakes of a land vehicle. "Cook Motor Racing Team" is a New Zealand team that specialises in building vehicles that can break world speed records on salt lakes, more specifically at Bonneville UTAH. Wairua I (spirit in Māori), was their first prototype capable of reaching speeds of 380 MPH. After this success, the CMR team wanted to continue this success and launched the Wairua II project, with the aim of improving on the previous performance, they called on USAFA, who proposed two studies in 2021 with the aim of reducing the drag of the vehicle, one on improving the underside of the car and the second on optimising the air intake. This study will therefore focus on the airbrakes of the Wairua II vehicle, starting with a brief presentation on the history of the team and the places where the speed record attempts will take place. Then a presentation of the history of braking in the automobile. The various working tools necessary for this study will then be presented, followed by a detailed description of the digital simulation protocol. The results of these simulations will then be analysed and compared. The conclusion will finally allow the team to propose the best performing airbrake and will open new avenues of reflection for future work on Wairua II.

Acknowledgments

I want to particularly thank Mr FEIER from the mechanics and engineering department for his tips and all the skills he gave me. I would also like to thank the United States of America Air Force Academy for their infrastructure and especially the 17^{th} cadet squadron for their welcome. I want to thank our exchange officer Lieutenant-Colonel RIVAT for his help and all the work he did before and during our project in USAFA. I would also like to acknowledge the work of my predecessors, LTT SCHWABB and LTT PAILLAT, who gave me an excellent basis to start this research work. I would also like to thank the youtubers of the "*Vilebrequin*" channel who, in addition to entertaining me during my breaks, allowed me to organize my first part thanks to their video "*Vultech-LES FREINS : comment ca marche"*. A big thank to the language department of the French Air and Space Force Academy and especially to Mrs BRADLEY who took the time to support me in practising English. And finally, I would like to thank Reg Cook and the entire CMR team for Bonneville and Wairua vehicle data.

list of symbols

Latin letters

a	Propagation speed of pression waves in a gas [$m.s^{-1}$]
Cd	Drag coefficient[-]
Cl	Lift coefficient[-]
D	Drag [N]
h	Height [m]
L	Lift [N]
l	Length [m]
M	Mach Number [-]
m	Mass [kg]
p	Pressure [Pa]
Re	Reynolds Number [-]
r	Specific Gaz Constant [$J.kg^{-1}.K^{-1}$]
S	Frontal area [m^2]
t	Time [s]
T	Temperature [K]
U	Velocity [$m.s^{-1}$]
U_f	Velocity of fluid [$m.s^{-1}$]
V	Volume [m^3]
x	Width [m]
y	Altitude [m]
z	Length [m]

Greek letters

α	Angle of incidence [°]
δ	Boundary layer thickness [m]
ρ	Density [$kg.m^{-3}$]
γ	Ratio specific heat [-]
μ	Dynamic viscosity [$kg.s^{-1}.m^{-1}$]
ν	Kinematics viscosity[m^2/s]
Ω_w	Wheel speed rotation

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Introduction

Going fast is good but going fast and staying safe is better, when we talk about speed records, we often forget that after the maximal speed, we must stop the vehicle. Fortunately, engineers are here to develop brakes systems, and today it becomes mandatory on all homologated vehicles in the world. Brakes are used in a lots of domains like industry or aeronautics, and this is a major part of safety. For this paper, we will be interested in a land vehicle : *Wairua II,* developed by *Cook Motor Racing Team*, with the aim of breaking the world speed record in its category on salt flats. The main question we can ask ourselves will be :

How can the vehicle be slowed down from top speed without deploying the parachute right away ?

This work was focused on the airbrake section of the car. The drag optimization in the airbrake area and how to do it are the main subjects of this report. We will analyse by Computing Fluid Dynamics (CFD) the air flow around the vehicle without airbrakes to have a reference. We will create several types of airbrakes. We will make other CFD to analyse and compare them. Then present those different analyses to the team for them to choose the one that suits them best.

This work will be divided into five parts, to begin, the project support will be presented in order to familiarize the reader with the environment. Secondly, we will see the history about the automotive brakes. Thirdly, the description of the working tools like software or fluid mechanic's equations. Then, the description of the CFD method will be considered. And to finish, the experimentation and results will be present.

I – PROJECT SUPPORT

I-1 CMR Bonneville team presentation

Reg Cook is a former car driver from New Zealand, he was born in 1946 and started his career in 1969 when he was 23 years old, he participated in 94 car races, reached 26 podiums, including 11 victories in several categories [Driver data base 2022], today he follows his dreams with different projects like Wairua 2 .

Reg Cook and the team at CMR (Cook Motor Racing) Bonneville are engaging in a multiyear plan to return to Bonneville and continue re-inventing Land speed records on the salt [CMR official page 2022]. They have already driven two vehicles they built on salt : the *cookie-Nissan coupe synergy V8* (FIA category A, group 1turbo class7) and *Wairua I* (FIA category A, group 1turbo class 7), Wairua means "spirit" in the MAORI language.

Two other projects are in preparation : the *CMR mini* (FIA category A, group 1 turbo class 5) [CMR Bonneville 2022] and *Wairua 2* (cover page)which will be described in another part; indeed, this study will focus on the development of an airbrake on this vehicle.

Figure 1 : a)Cook Motor Racing behind Wairua 1 at the Salt Lake of Bonneville Utah
b) The *cookie-Nissan coupe synergy V8* (FIA category A, group 1turboclass7)
c) The *CMR mini* (FIA category A, group 1 turbo class 5)
[CMR official page 2022]

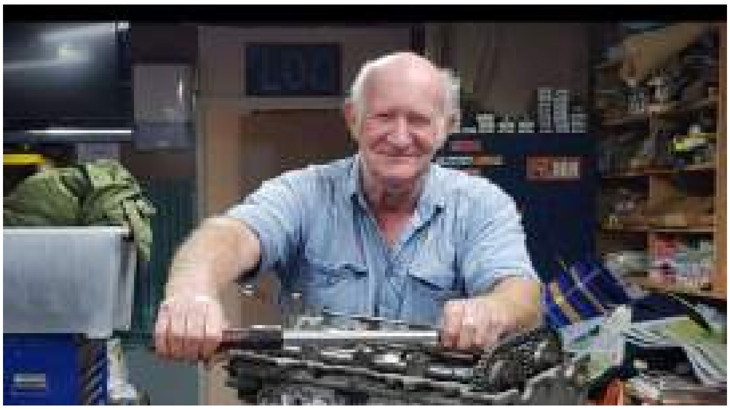


Figure 2 : Reg Cook
[CMR official page 2022]

I-2 Race place presentation

Bolivia's *Salar de Uyuni* is the most appropriate place that the team finds for their car run .Located in south America between Argentina, Chile, and Bolivia in the "*Altiplano*" region, it is the world's largest salt flat area with about 4,050 miles² (10 489km²) surface [Unger E. May 2017]. The altitude is hight because it culminates at 12 000 feet (3 656m), the main advantage of such an altitude is that the air density is lower than at sea level, the air is thinner, so there is less resistance. This parameter is very important when a world speed record wants to be broken. Usually, CMR team tested its vehicle on the Salt Lack of Bonneville, Utah.

Figure 3 : Bolivia's *Salar de Uyuni*
[Unger E. May 2017]

I-3 Wairua II vehicle presentation

I-3-1 Mains characteristics

Wairua II is a land vehicle with a length of 10,33 meters, this is an evolution of Wairua I, and we do not have information on the engine yet. This vehicle including four front wheels tractive power, and on rear wheel. It also bears a vertical fin to limit the yaw moment with a wing stabilizer for the pitch moment on the tip of it with an air foil profile NACA 66-099, all for a weight of 1,700 kg [FEIER I.I. et al. , January 2022]. Today the brake system is made up of 4 disk brakes and drag parachutes.

The last works done on this vehicle was an intake analyses in order to see the mass flow which goes inside the engine. Another study on the underbody shaping was made to improve the air flow and reduce the drag which comes from the perturbation under the vehicle.

I-3-2 Expectation of the project

The CMR team has provided us with the digital model in order to make modifications on airbrakes. It will be used to slow the car speed down and then deployed when deploying parachutes. The main difficult part of this project will be that air perturbation from airbrakes do not interfere with the opening of the parachute, that is why we will try to propose to the CMR team several prototypes in order to make comparisons between different geometry and leave them the choice of the best one. As we can see on the figure 4, CMR team started to build the frame of the car and they include a hole to put the airbrake. During this study, we are only interested in the geometry of the airbrake and not in the hydraulic system allowing it to deploy.

Figure 4 : Wairua II in front of CMR's workshop in New Zealand
[CMR Bonneville 2022]

II-STORY OF BRAKING SYSTEM FOR LAND VEHICLES

II-1 What is a brake system?

A brake is a system which permits to decelerate and immobilize a vehicle. Modern cars weight between 500kg and 2,5 tones so the inertia which is created is huge, it is necessary to develop a relevant braking system. For most braking systems, the principle is to create a contact between two bodies, to change power (here kinetic energy) into heat by means of friction. Friction is the resistance to relative motion between two bodies in contact. The type of material used, the force applied (here the weight), and the contact surface will determine the coefficient of friction (COF) see figure 5. In the other sections we will look at the evolution of braking systems for land vehicles.

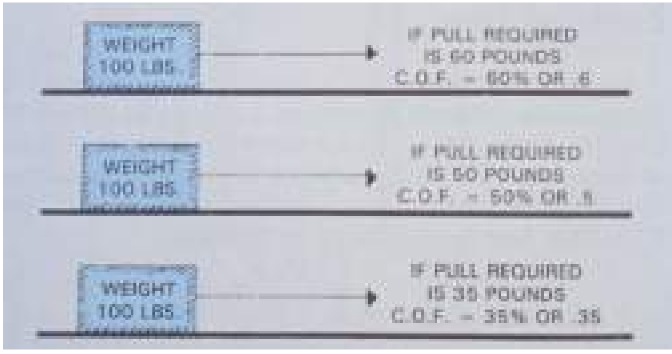


Figure 5 : Coefficient of friction function different material
[TOBOLDT et al. June 2006]

II-2 Hoof brakes

It was used at the beginning of automotive because this system equipped animals-drawn vehicles. It consists in applying a mobile part called hoof against the circumference of the wheel in order to make friction between those two parts. It is not relevant because it was applied with lever or by cable transmission and even if the driver applied a strong force, the engine became too powerful to make this system appropriate. Moreover, climatic conditions affected a lot the breaking, if the path was wet because of the rain or if the road was muddy, the decreasing of COF was significant. However, this system is still used today especially on trains. This system is very noisy and less efficient than the other, but it is cheaper and on a train it is used on each wheel, moreover there are no tires.

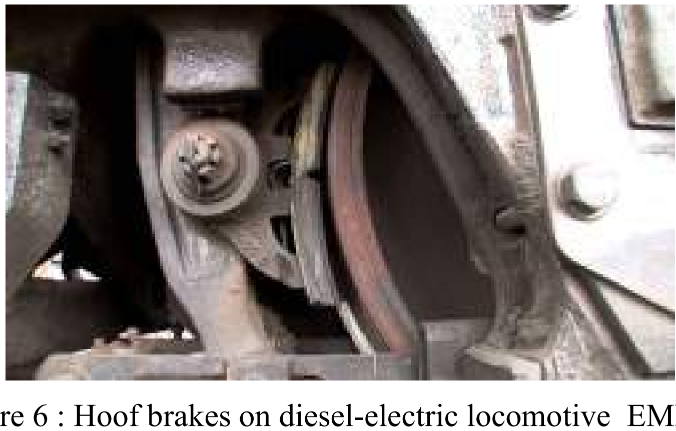


Figure 6 : Hoof brakes on diesel-electric locomotive EMD F7
[EdissonTechCenter 2014]

II-3 Drum brakes

In the early twentieth century, it was the first safety system which was installed on serials cars because it is simple and efficiency. The principle is simple, a sort of bell is fixed on the wheel and rotated as fast as it can be and inside there are two parts called brake shoes. When the driver wants to brake, he pushes the brake pedal and hydraulic energy will spreads the pistons and the shoes will rub against the bell, this friction will generate a brake in order to decelerate or stop the vehicle. The ease of manufacture is the advantage of this system, moreover it resists a lot to overheat. Unfortunately, to be efficient, this system needs to be correctly dimensioned. That is why it is common to see it on big vehicles like buses or trucks. If not, we add unnecessary weight to a current car.

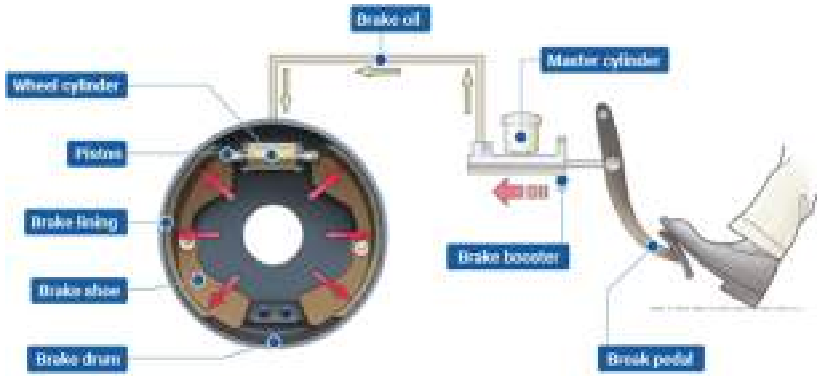


Figure 7 : Principle drawing a of drum brake
[Akebono 2022]

It is important to state that the speed of 400km/h was exceeded on February 24th, 1932, with the Campbell-Napier-Railton *blue bird.* So, it was necessary to develop a new kind of brake system, light and efficient.

II-4-Disc brakes

The type of brake is quite recent because the first one was tested in 1953 in the race "*les 24 heures du Mans"*. It was revolutionary because thanks to this brake, pilots could brake later before turns. This year, brake system was considered as the secret weapons of *Jaguar* and they wone the race. Only two years later that, this system was fitted on front wheels, as standard on the French car "Citroën DS".

Figure 8 : Victory of Jaguar with new C-type disc brakes "les 24 heures du Mans" 1953
[Chargé T. , 2020]

The operation of disc braking looks like drum brakes except that disc (rotor) which rotate with the wheel, and it is located between brake pads, see figure 9. Usually on cars, the driver operates the hydraulic system when he pushes the brake pedal, and the pistons push the brake pads and create a friction which decelerates the car. This system is very efficient because we can adjust with a lot of precision the pressure we apply on the disc, and this ensures that the wheels are not locked. The maintenance is also easier because it is only necessary to remove the wheel to access the brakes. However, disc brakes have different problems, first it is very sensitive to overheating that is why on mountain roads we can see some signs which indicate "using your engine brake" in order to avoid vitrifying the brake pads. Secondary brake forces could be very strong, and the consequence is wheel lock which is a problem when the road is wet because the driver loses the ability to steer the vehicle. To counter this problem, it exists an anti-lock braking system(ABS) exist which is automatic, it releases the brake when wheels are locked to keep the control of vehicle, but the braking distance is longest.

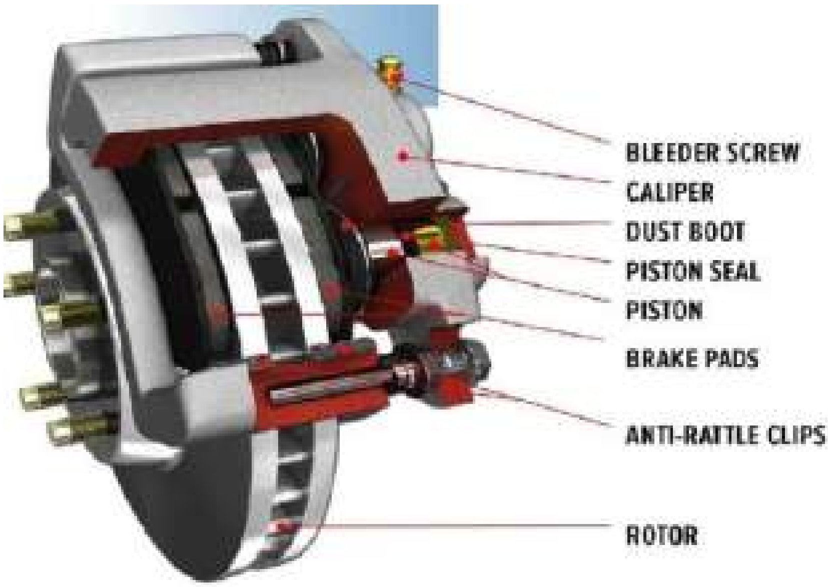


Figure 9 : Cross section of a brake disc
[Mechanical jungle , 2022]

II-5 Aeronautic brakes

Those sorts of brakes are also working thanks to a friction but this time, it will be the air that will oppose the movement, it will increase the drag (see part II-1-4). We saw that brakes on wheels were sensitive to overheating, it was necessary to find a system to add to wheels brakes. We will see that the aeronautical domain influences a lot of automotive domains.

II-5-1 Parachute

Etymologically, parachute comes from French Latin : *"para"* means *"against"*, and *"chute"* means *"fall"*. When parachutes are deployed, the sail surface creates a way in the atmosphere by pushing air molecules. The goal is to preserve wheel brake from overheating. A lot of airplanes use this system in order to reduce the landing distance , for example it is used on the *Lockheed F117,* see figure10. It is important to know that the parachute is only used when the airplane is totally on the ground because this system is irreversible, so if the approach speed is too hight, the aircraft need to use other systems to decrease it.

Figure 10 : Lockheed F-117A stealth attack aircraft having deployed its braking parachute at a US base in Italy [US department of defence 1999]

In the automotive domain, this principle is used for hight speed vehicles but on the horizontal axe, see figure 11. It is very useful to decelerate but you must fold the parachute every time, or replace it with a new one, which in terms of time and money is not profitable. Today this system is mostly used for safety.

Figure 11 : Parachute from DJ-Safety companies used between 180 and 220 mph [MSCN motorsport 2022]

II-5-2 Airbrake

As we saw in the previous part, parachutes are irreversible systems, contrary to airbrakes. Originally airbrakes are used for airplanes, to considerably reduce the speed, it permits to increase the drag, before landing for example. In this case it is used symmetrically so as not to destabilize the airplane’s seat. But it can also be used unsymmetrically in order to create a roll moment to help the aircraft during a turn.

Figure 12 : C160 Transall with airbrake deployed
[airpics.net 2022]

Airbrakes are rare for land vehicles because it is only relevant for hight speed that is why we find those sorts of systems only on fast car and it also increases the prices. For examples “*Mercedes SLR*” , “*Bugatti Veyron*”, or “ *McLaren MP4-12C*” are using airbrakes because they are racing cars. The goal of airbrakes on a speed car is to protect wheel brakes from overheating, it will not immobilise the vehicle, but it can considerably reduce the maximal speed up to an acceptable speed for disc brakes. And of course, it is reversible.

Figure 13 : McLaren MP4-12C airbrake in action
[carmagazine 2022]

III- WORKING TOOLS

III-1 Fluids mechanics reminders

III-1-1 Fluid notion

A Fluid is a liquid or gas which has no form of its own, it takes the form of the container in which it is. In fluid mechanics, we considered that a fluid medium is permanently deformed because of constants forces during the time. To simplify the calculation, a convention exists which says that a fluid is divided in fluid particuli. This particuli is a physics domain which is infinitesimal for the naked eye, small enough to make local measurements and big enough to have a lot of molecules in its volume. The goal of fluid mechanics is to predict the movement of each particuli of the study fluid study.

III-1-2 Mach number

This is a number without dimensions to know if the fluid flow is compressible or uncompressible. It is defined with this formula:

$$M = \frac{U_f}{a} = \frac{U_f}{\sqrt{\gamma r T}}$$

U_f is the fluid speed, γ is the ratio specific heat, r is the specific gas constant , T is the temperature.

III-1-3 Reynold number

This is a number without dimensions which compares the inertial forces to the viscosity's forces of a fluid. This parameter is used in order to know if the fluid is laminar or turbulent. It is defined with this formula:

$$R_e = \frac{U_f.l}{\nu} \qquad \text{with} \quad \nu = \frac{\mu}{\rho}$$

$$R_e = \frac{\rho.U_f.l}{\mu}$$

ρ is the volume mass, l is the vehicle length, ν is the kinetic viscosity and μ is the dynamic viscosity.

III-1-4 Boundary layer thickness

A boundary layer (figure 14) is the region where we can observe the viscosity influence of fluid with hight Reynold number. At the surface of a solid immersed in a flow, the boundary layer is the zone where the characteristics of a viscous fluid can be observed. The velocity of this flow equals zero at the surface until it reaches the flow velocity. The thickness of the boundary layer (δ) increases with the distance along the solid surface, generally it starts as a laminar and becomes turbulent :

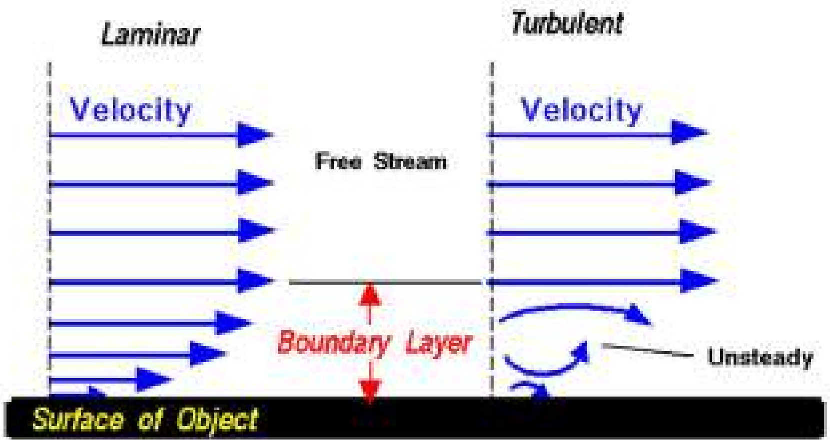


Figure 14 : Drawing of boundary layer

We can estimate the boundary layer thickness thanks to theses formula :

$$\delta = \frac{0.375\,x}{Re^{0,2}} \quad \text{Turbulent formula}$$

$$\delta = \frac{5\,x}{\sqrt{R_e}} \quad \text{Laminar formula}$$

With x, the distance from the nose of the vehicle.

III-2 Aeronautics reminder

III-1-4 Drag

The drag is an aeronautics force which is opposite to the propulsion force, its unit is the newton, and we can distinguish four kinds of drag. As the flow is subsonic, we will not be interested in the wave drag nor to the induced drag because this one is specific for an airplane wing. The drag force is an addition of pressure and shear drag. The formula is definite defined by :

$$D=1/2.\,\rho.S.U^2.C_d$$

As this project is focused on the deceleration of the vehicle, this parameter will be very important. To see a relevant difference, we will compare the drag coefficient (C_d) of the different airbrakes.

III-1-4-1 Pressure drag

This is a normal drag because the closer the fluid is to the wall, the lower is its speed. So, the pressures differences around the body also cause drag.

III-1-4-2 Shear drag

Called skin friction drag, or tangential drag, this is a force due to the friction between the fluid and the wall. It is due to the fluid viscosity

III-1-5 Lift

The lift is a force directly opposed to the weight. It is generated thanks to a pressure differential on a wing profile, there is an under pressure on the extrados and an over pressure under intrados. Usually this is used for aircraft to fly, but for automotive road holding and grip requires the car to be placed on the ground, that is why wing profiles are use upside down. The lift value is obtained with the following formula :

$$L=1/2.\ \rho.S.U^2.C_l$$

As with the drag, we will extract the lift coefficient from this formula to have a best comparison value.

III-2 Software

III-2-1 Fusion 360

III-2-1-1 Presentation

Fusion 360 is a computer aided design software (CAD) developed by Autodesk incorporation, an American multinational specialised in the software engineering, construction, or manufacturing software. Thanks to the numerical model sent by CMR's team, the author was allowed to modify the airbrake design. The creation and modification of the airbrake shape will enable the increase the drag of the car. After the vehicle modification, it was necessary to export it in a .STL(Stereolithography) to analyse it on STAR CCM+ and it was also possible to export it to a 3D printer.

III-2-1-2 Interface

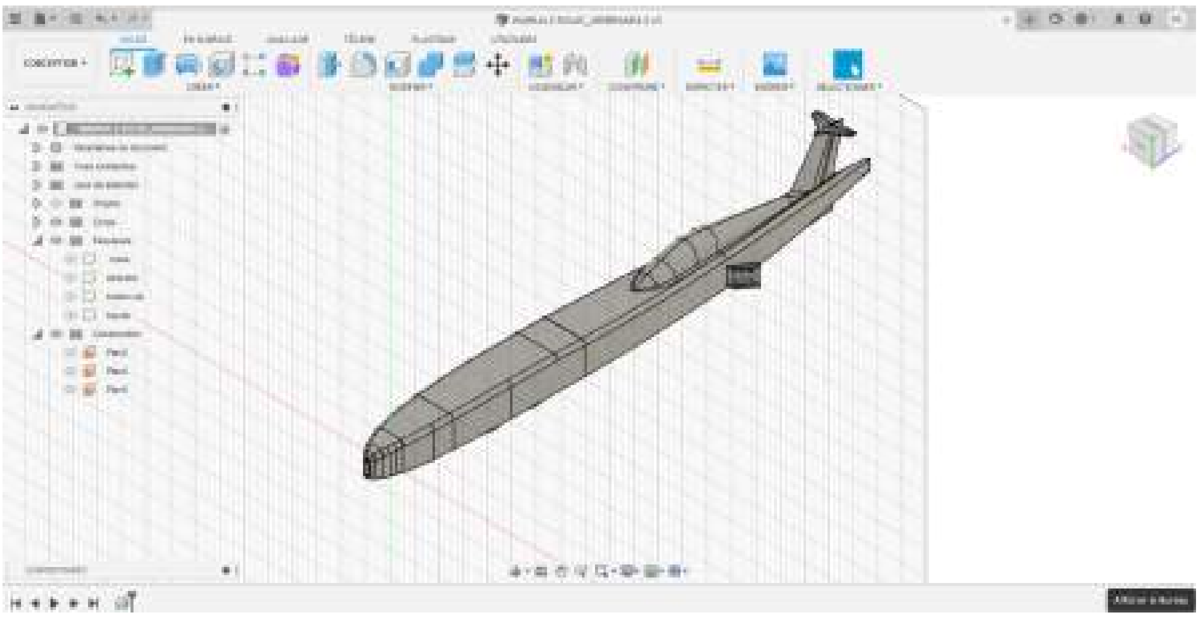


Figure 15 : FUSION 360 software window

III-2-2 STAR-CCM+

III-2-2-1 Presentation

Fluid mechanics is a vast field which includes solving complex equations (*Navier-Stokes*) that is why today the computational Fluid Dynamics (CFD) is used in order to resolve problems faster. This study of fluids flow with a numerical method allows to analyse metaphysical problems like temperature transfer, pressure differential or phase change. As the car is not at our disposal, it is impossible to use a wind tunnel, and thanks to STAR CCM+ software, it is possible to reduce considerably the cost of simulation. Indeed, a wind tunnel is very hight in energy consumption. STAR-CCM+ is a software developed by *Siemens* (an international group that is active in the energy, health, industry, and construction sectors). This software is very complete because it regroups all the steps of numerical simulation which are :

- geometry CAD model import or creation
- the domain creation and the conditions at its border
- definition of the physics of the fluid around the study geometry
- mesh creation
- choice of numerical solver
- launch of calculations
- visualisation of results

We find different windows on the interface; the model tree or operating panel contains the characteristics of the simulation. The nodes of the tree have properties which can be changed in the properties window, for example it is possible to change the physics of the domain. The output text window summarises all tasks performed since the beginning of the simulation; it is also possible to display physical values in this window.

III-2-2-2 Interface

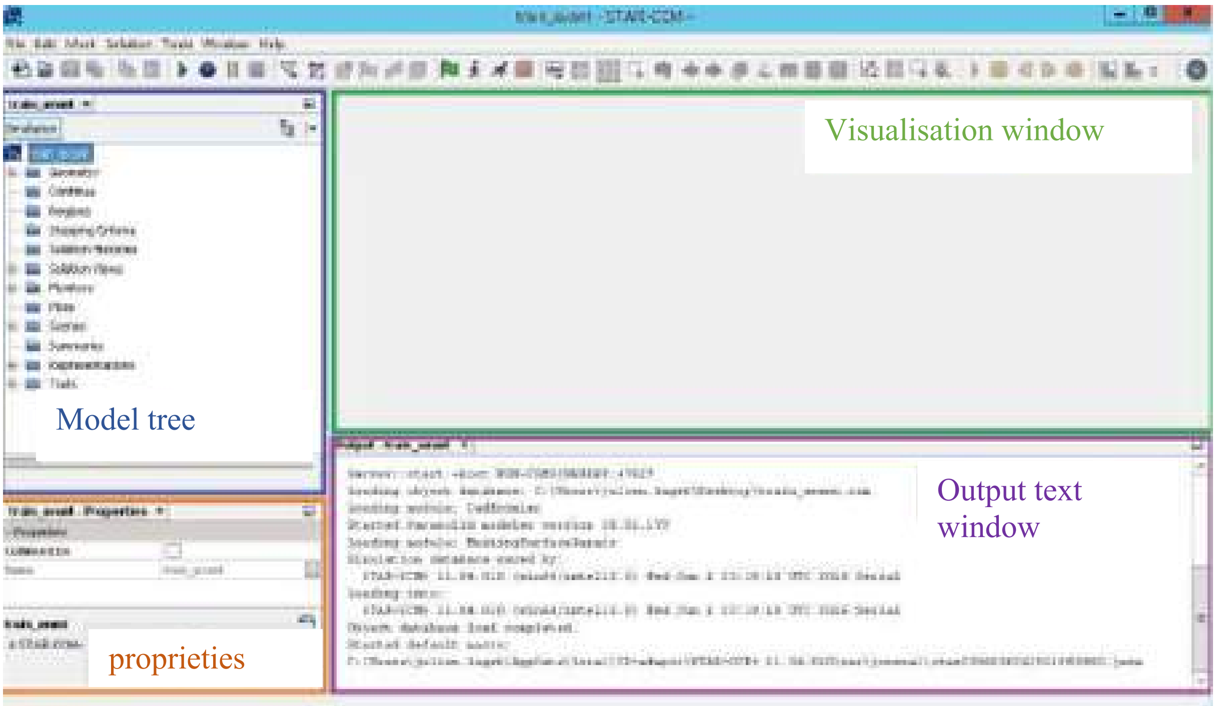


Figure 16 : STAR-CCM+ software window

IV-Computational Fluid Dynamics

IV-1 Software initials parameters

The first step of a CFD analysis is defining the processes option of the software to have the best simulation. It is important to know the number of cores inside the computer. On STAR-CCM+, it is possible to make the simulation locally on the computer or transfer it on another one, the choice is made thanks to the following window. It is possible to create a new simulation with *"ok"* or download one thanks to the "*browse*" option.

Figure 17 : STAR-CCM+ initial window

IV-2 Geometry CAD

IV-2-1 Sketches conception

It was conceived thanks to the software *"Fusion 360"*. The CMR team had given us the numerical sketch of the car with the airbrake they had imagined. It was very helpful to imagine what the team hoped for. To begin, the author started by removing airbrakes from the sketch, to study the flow around the car and see if results were consistent with the previous works. Then 5 designs were created including the one which the team gave us, to compare them thanks to the software STAR CCM+.

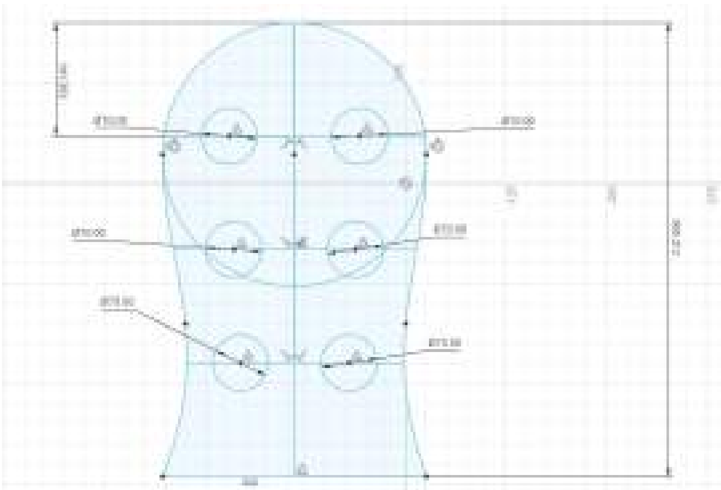


Figure 18 : FUSION 360 Sketches conception.

IV-2-2 Part in STAR-CCM+

IV-2-2-1 Import a figure

First, after creating the sketch we must export from fusion to STAR CCM+, to do that, it is necessary to save the file in “.stp”, this file is also used to print with a 3D printer. It can also be read by the software STAR CCM+, as a part.

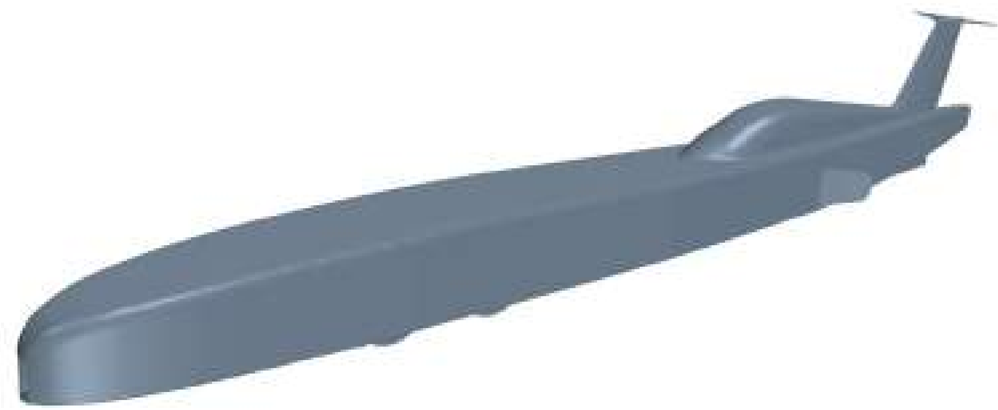


Figure 19 : STAR-CCM+ Wairua II geometry scene

IV-2-2-2 Surface wrapper

This operation consists in generating a surface mesh by wrapping around the input geometry. It is very useful to correct any default due to the importation and the changeset of file. This step is the first refinement of the import part, and some parameters could be changed, it should be adapted between a good result and the computer capacity, the following table shows us the settings that the author has chosen.

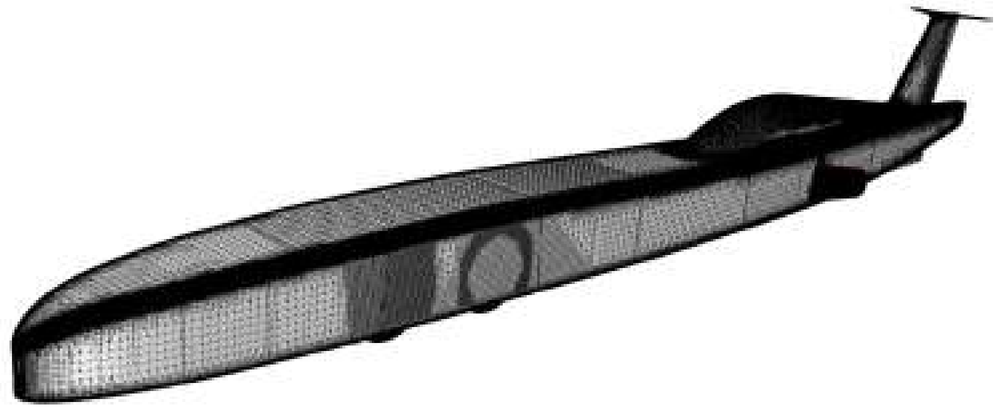


Figure 20 : STAR-CCM+ Wairua II surface wrapper scene

Table 1 : surface wrapper parameters

base size	1	m
target surface size	0.05	m
minimum surface size	0.002	m
surface curvature	120	#pts/circle
volume of interest	external	
smallest disconnected surface	1000	faces

IV-2-2-3 Domain

Thanks to the software STAR-CCM+, it is possible to create different basics forms like block or sphere to assign it to a domain where the study fluid (here air) will evolve according to several parameters applied on the boundary of the domain.

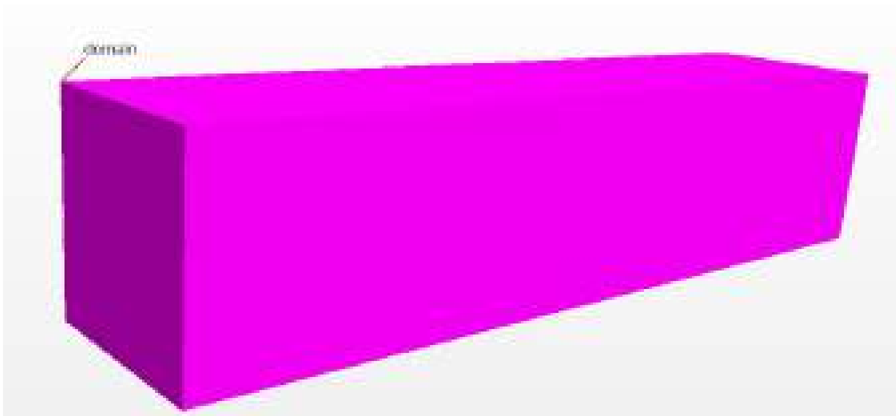


Figure 21 : STAR-CCM+ domain representation in a geometry scene.

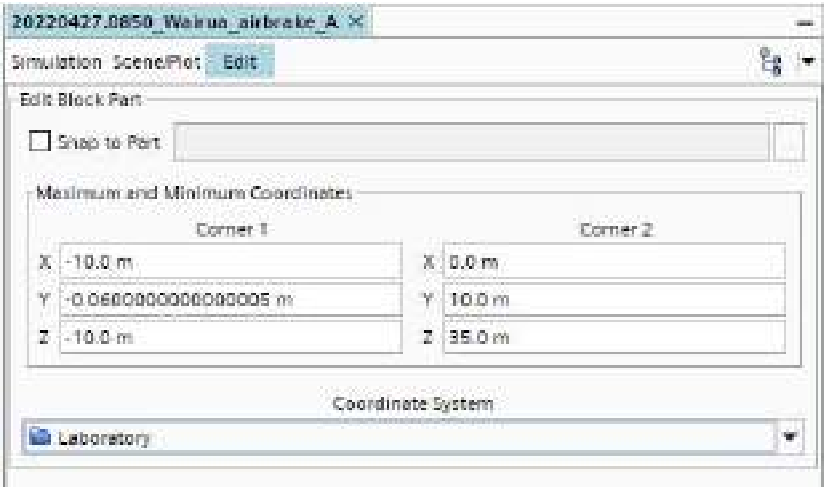


Figure 22 : STAR-CCM+ block coordinate window which defines the domain.

IV-2-2-4 Subtract

When the wrapper and the domain are done, we should carry out a Boolean operation which consists in removing the shape of the car to the study domain for the purpose of studying the air flow inside the block and around the shape of the car.

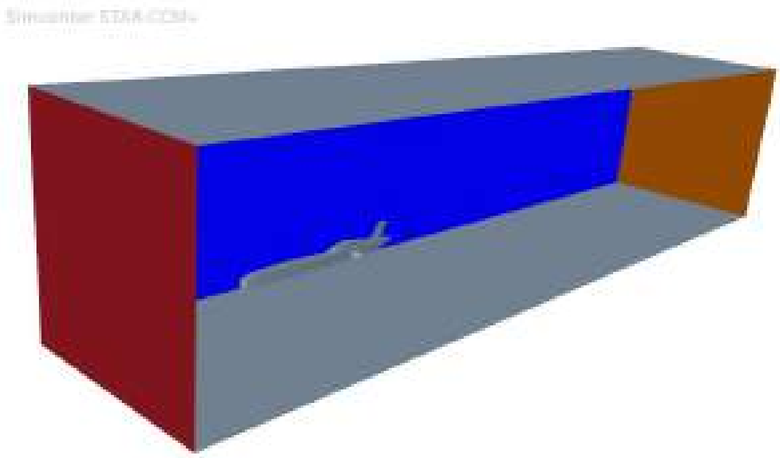


Figure 23 : STAR-CCM+ geometry scene of subtract

IV-3 Regions

IV-3-1 Initial parameters

STAR-CCM+ works with regions, which means that all parts created before have to be assigned to a region. Each region has its own characteristics, on the following picture we can see all the types of regions proposed by the software :

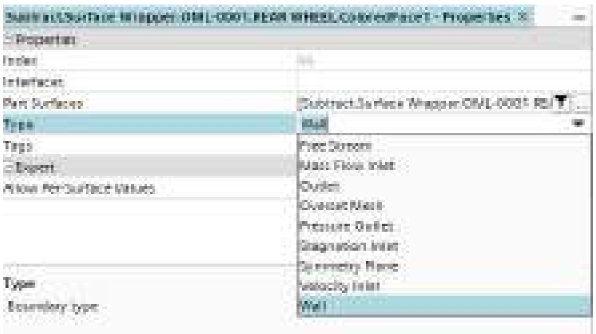


Figure 24 : STAR-CCM+ region configuration window

For this study the author has chosen to assign the following part to the following type of regions :

Table 2 : Part assignation to region

Part	Type of region	Colour
inlet	velocity inlet	
outlet	pressure outlet	
side	slip wall	
top	slip wall	
ground	wall	
symmetry	symmetry plan	
car	wall	

IV-3-2 Parts moving

To make the simulation as close to reality as possible, thanks to STAR-CCM+, it is possible to make some parts move. In this case we will make ground and wheels move.

IV-3-2-1 Ground

As Wairua II must run at a speed of 500 mph over the ground, it is necessary to change the frame of reference, so we will make the ground move in relation to the car with a speed of: **U=223.52 m.s^{-1}**. This function is possible in the in the section *"region"* of the exploitation tree, the *"tangential velocity specification"* function will be *"vector"*. As we can see on the following picture it is just necessary to fill in the value of ground speed and it is done.

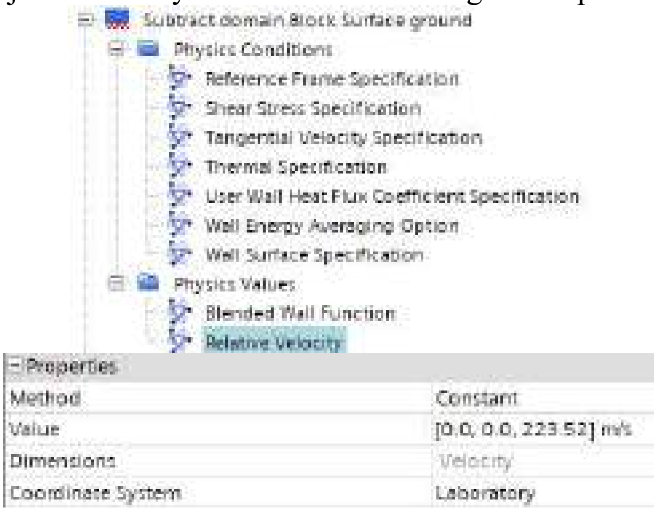


Figure 25 : STAR-CCM+ value of ground speed.

It is also important to know that the "altitude" of the ground in the work referential is **y=-0.06m**, in order to respect tyre crushing due to the weight of the vehicle, and so the surface of each tyre on the ground is approximately 0,015m².

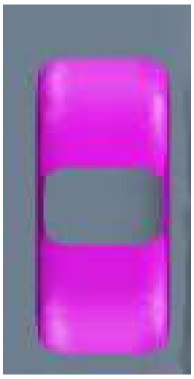


Figure 26 : STAR-CCM+ wheel surface of tyre on the ground (bottom view)

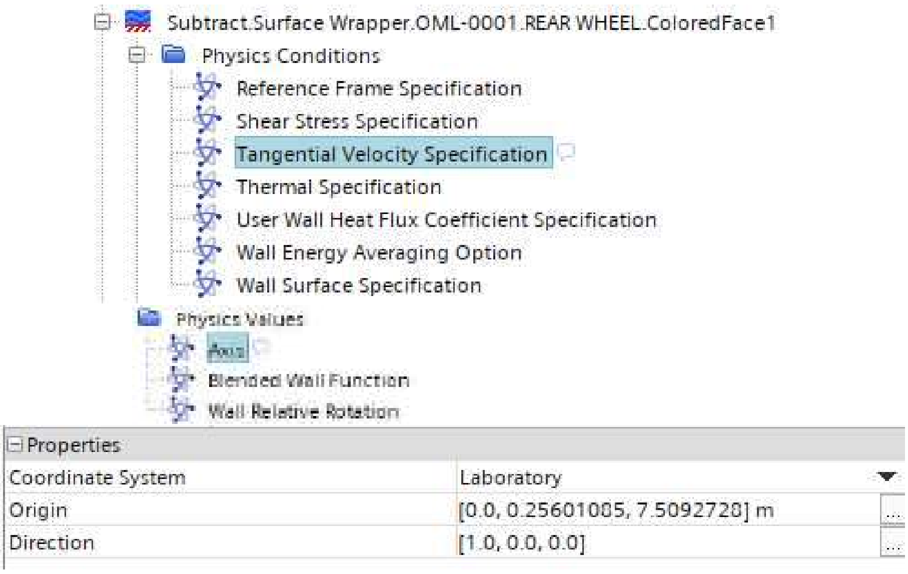
IV-3-2-2 Wheels

The process of the wheel rotation looks similar with those of the ground movement; however, the mode of *"tangential velocity specification"* will be *"local rotation rat"*. We need two things for this function, on the one hand, the wheel centre of rotation which will be found thanks to STAR-CCM+. On the other hand, it is also necessary to calculate the wheel rotation to fill the information in the software:

$$\Omega_w = \frac{U_c}{2\pi r}$$

Ω_w : the wheel speed rotation
U_c : the car speed
r : the wheel radius

With a radius of 0,311m and a car speed of 223,52m.s^{-1}, the rotation speed is **Ω_w=114,33 rps.** However, to respect the wheels direction of rotation, it is necessary to put a negative value to field the parameters.



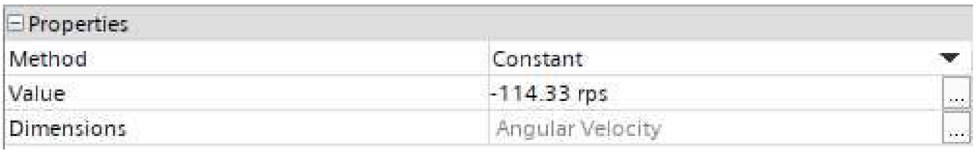


Figure 27 : STAR-CCM+ physics values of the rotating wheels.

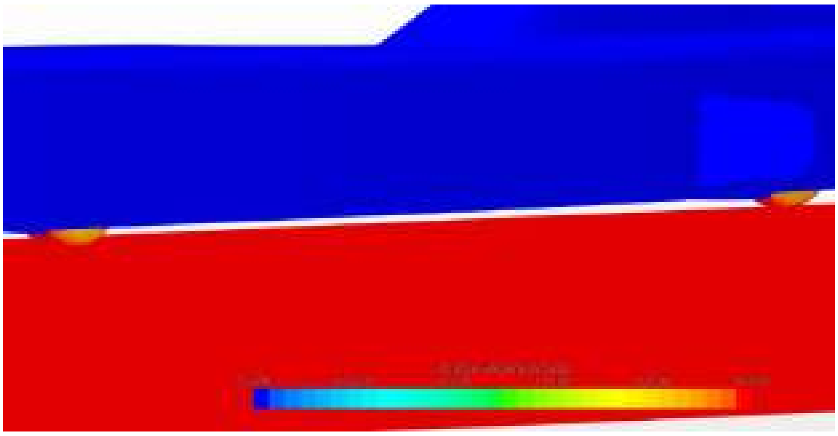


Figure 28 : STAR-CCM+ velocity scalar scene with ground and wheel moving.

IV-4 Derived parts

Derived parts can be used to help the visualisation after the simulation had run. It could be considered like a kind of part. The following items on the picture will be particularly useful to compare our different air flow around airbrakes.

Figure 29 : STAR-CCM+ derived parts used during simulations

IV-5 Physics choices

IV-5-1 Fluid parameters

-Reynold number :

Thanks to website : “aerospaceweb.org” we know that dynamic viscosity is :

$$\mu=1.7456.10^{-5}\ kg.m^{-1}.s^{-1} \text{ and } \rho= 0.80458\ kg.m^{3}$$

If we say that U_f=223.52m.s^{-1} = 500 mph and length is 10.33m, we obtain :

$$\mathbf{R_{e\ Wairua\ II}=106{,}424{,}399.9}$$

As the Reynold number is much higher than 4,000, we considered that the fluid flow is **turbulent.**

-Mach number :

If we suppose that U_f =223.52m.s^{-1} = 500 mph, γ=1,4, r=287 J.kg^{-1}K^{-1} and T=279.15K=6°C, at Bolivia's Salt Lake altitude, we obtain :

$$M_{Wairua\ II} \approx 0.667$$

So, in this case, we can conclude that the flow is **subsonic**, moreover, as M>>0.3 the flow is also **compressible.**

-Boundary layer thickness :

As we previously saw with the Reynold number, the fluid flow is turbulent so, the boundary layer thickness will be defined thanks to the turbulent formula. Here the maximal thickness will be **0,093 m**.

IV-5-2 Externals conditions

As we saw in the first part , at Bolivia's salt flat, externals conditions are ideal for a speed record breaking, indeed, as the altitude is very hight, so less air resistant. The following table shows the most appropriates externals conditions at this place, moreover, it will be our data for the CFD :

Table 3 : Bolivian Salt Flat externals conditions [Aerospaceweb.org]

	Initials conditions	Units
altitude	3656	m
velocity	223.52	m/s
length	10	m
Temp increment	14.7503	°C
static temperature	6	°C
air pressure	64472	Pa
air Kinetic temperature	279.15	K
air density	0.80458	kg/m^3
air dynamic viscosity	1.75E-05	Pa.s
Molecular weight	28.9644	kg/kmol
specific heat	1003.62	J/kg.K
laminar boundary layer thickness	0.005123	m
Turbulent boundary layer thickness	0.093561	m
Total boundary layer thickness	0.098684	m

IV-5-3 Software parameters

The physics choice on STAR-CCM+ consists in selecting all characteristics of the fluid in order to match our expectations. With regards to the turbulence, the author chose a *"k-ω"* model, which is used in fluid mechanic to model instabilities : *k* represents the turbulence, this is the average kinetic energy, and *ω* is the average energy dissipation rate. It proposes a convergence for the Navier-Stokes equations.

Figure 30 : STAR-CCM+ physics selection window.

IV-6 Mesh

The imported shape is divided into prisms to improve the quality of the surface of the object and to allow the software to calculate variations in pressure, speed, etc. It takes a lot of memory resources that is why it is important to know the computer capacity in terms of memory. If the cells are too small it will take a very long time to generate mesh and then the computation will be longer. However, if cells are too big, results will be distorted.

IV-6-3 Automated mesh

IV-6-3-1 Mesh

The principle of meshing is to discretise the space into many cells, this step requires a big part of the computer resources, and so, a lot of time is necessary to execute the volume mesh because all the area will be cut into small mesh. That is why it is recommended to execute a surface mesh before, because it takes less resources, moreover, in case of mistakes, it will be quicker to spot and correct. On the following picture you can see on the right column all the mech option which it is possible to choose, and on the left column the one which has been chosen.

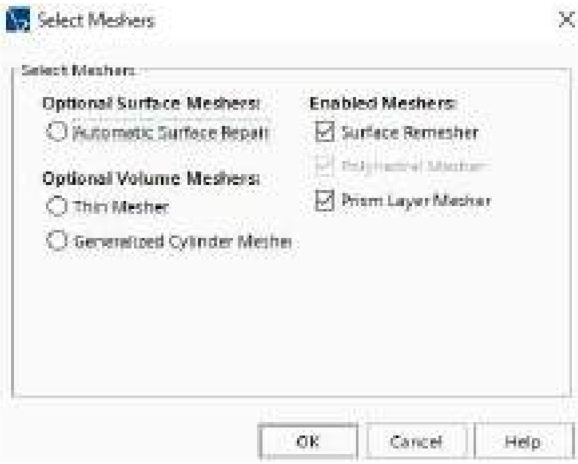


Figure 31 : STAR-CCM+ mesh selection window

IV-6-3-2 Default controls

All mesh is based on a *"base size"* which will be the reference of the most of other mesh parameters. The following data has been chosen to stay in the compromise : not too many cells to be quick and not enough to have relevant results.

Table 4 : Mesh default controls parameters

base size	1	m
target surface size	0.06	m
minimum surface size	0.02	m
surface curvature	96	#pts/circle
number of prism layer	25	
prism layer stretching	1.35	% of previous cell
prism layer total thickness	0.09	m
volume growth rate	1.05	% of previous cell

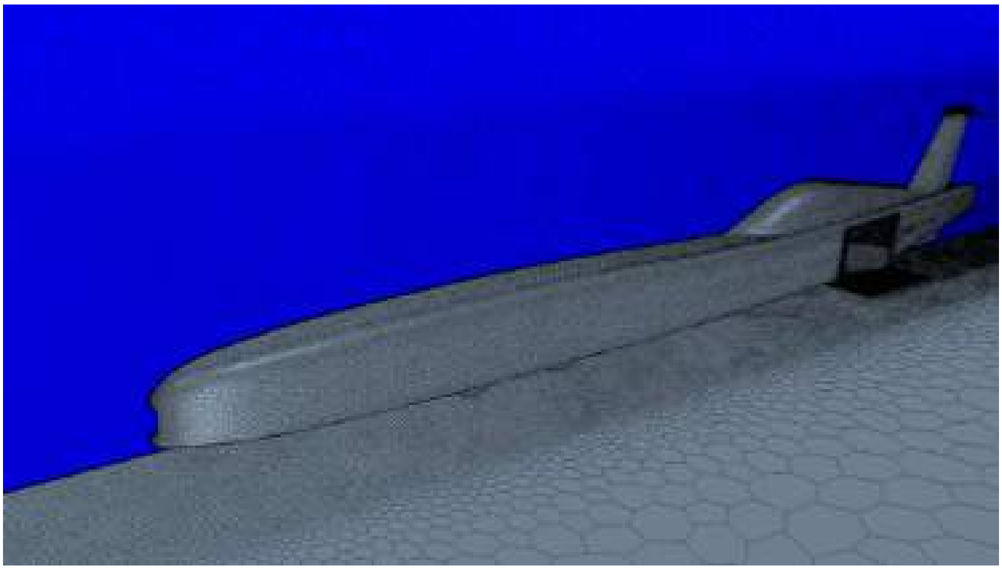


Figure 32 : STAR-CCM+ volume mesh scene

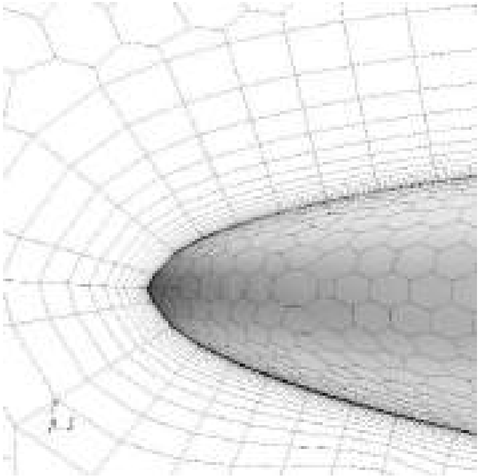


Figure 33 : STAR-CCM+ volume mesh scene, stabiliser leading edge (prism layer).

IV-6-3-3 Custom controls

Customs controls consist in detecting some zones we want to be focused on, here the airbrake, and create a better mesh in a smaller volume. It permits to save resources with a bigger mesh in areas where there is little interest. It takes the same principal as the domain, you create a new part, here a block and you mesh it with a best refinement, just like we saw before. It is also possible to refine surfaces and curves in the same way.

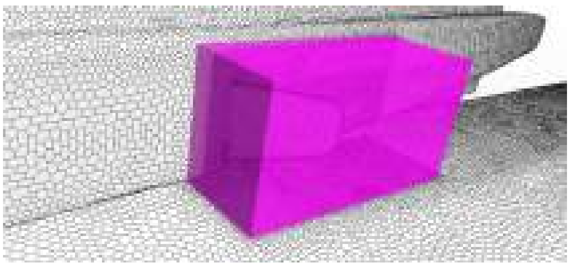


Figure 34 : STAR-CCM+ volume control (airbrake A) around the vehicle air brake.

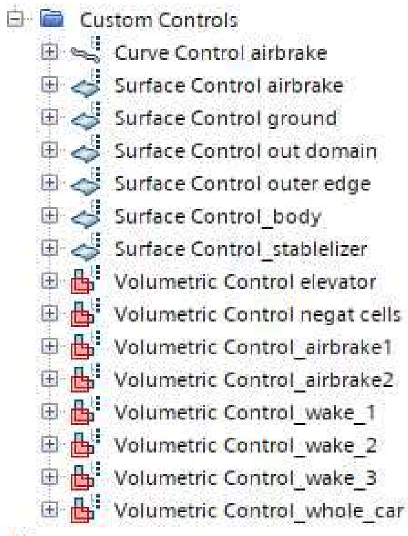


Figure 35 : Custom controls used during simulations

IV-6-3-4 Number of cells

After mesh operation, and before launching the simulation, it is very important to check this parameter because mesh take a lot of resources, but simulation takes much more. During a simulation STAR-CCM+ performs Navier-Stokes equation between each cell, that is why we must be careful with the computer performances. For this work, the author was limited to 8 million cells.

Table 5 : Number of cells for each simulation.

	Cells
No airbrake	3 446 145
Airbrake A	3 112 643
Airbrake B	3 234 289
Airbrake C	3 540 012
Airbrake D	3 508 339
Airbrake E	5 487 203

After that it is possible to launch the simulation. Before it is necessary to initialize all parameters. Thanks to STAR-CCM+ a function called *"expert initialisation"* in the section *"solver"* of the exploitation tree allows to get rid of the first moments of the simulation, and thus, accelerate the simulation.

IV-7 Residuals

When a simulation is running on STAR CCM+ a "residual" graph is created, the residual is the difference between a physical quantity in one spatial iteration and the next or with other words, the physical differences between each mesh. The aim is that these curves converge. Thus, the calculation is finished, and the results are usable.

Figure 36 : STAR-CCM+ residual plot

IV-8 Problems encountered

Several troubles have occurred during this project. The biggest of them was the time of the simulation and the space it took because it was impossible to make two simulations at the same time on the same computer. Another problem was, if parameters are wrong, the residual plot diverge and looks like the figure 37.

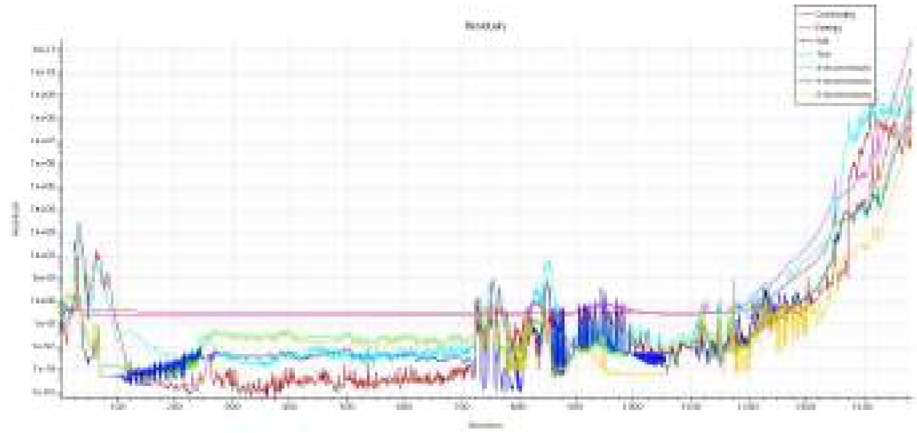


Figure 37 : STAR-CCM+ wrong residual plot

The error message that came up most often was an information of *"negative cell"*, that means it was a mesh problem, and it was possible to detect it with the function *"temperature"* in the a *"scalar scene"*.

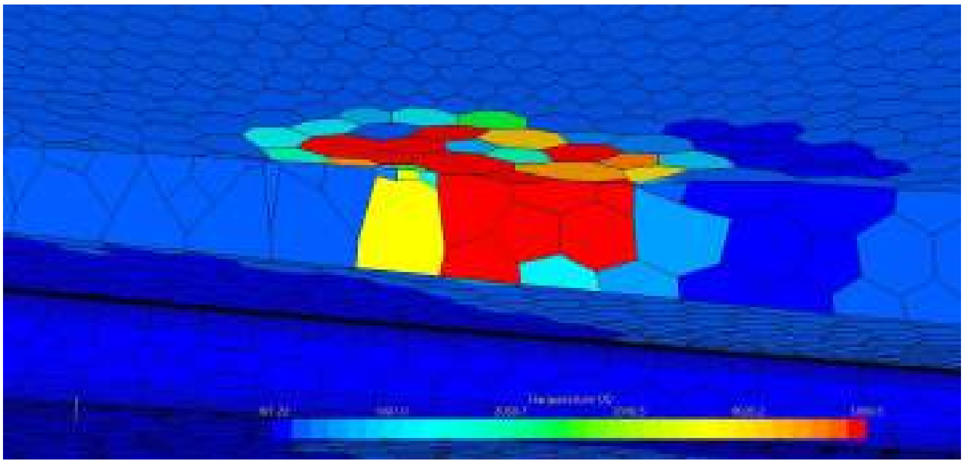


Figure 38 : STAR-CCM+ scalar scene with negative cells detected

To remedy this problem, it was necessary to make a new volume control and remesh.

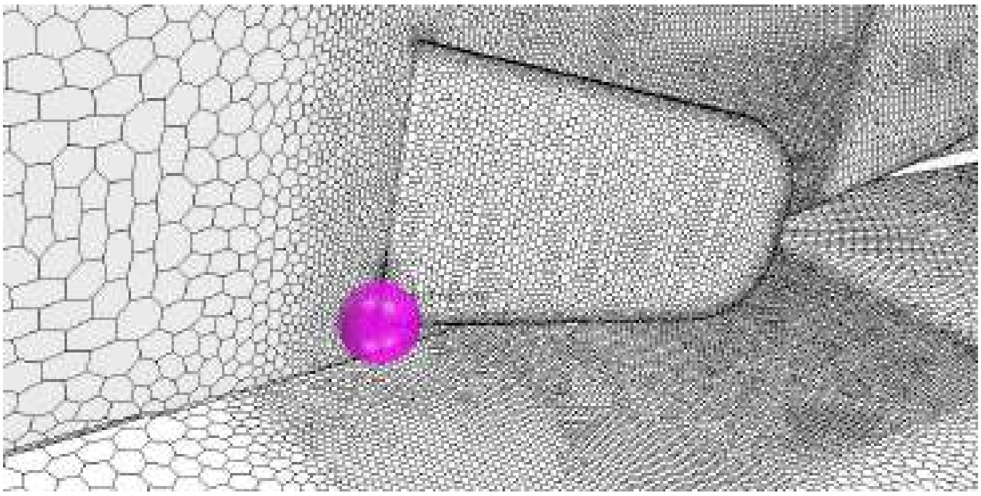


Figure 39 : STAR-CCM+ volume control to correct negative cells.

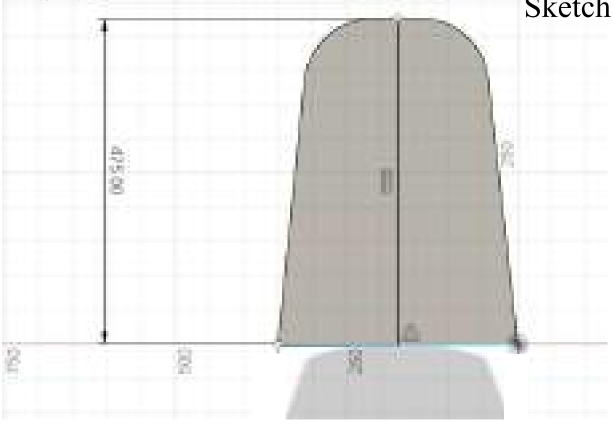
V- Experimentation

V-1 Presentation of the different types of airbrakes

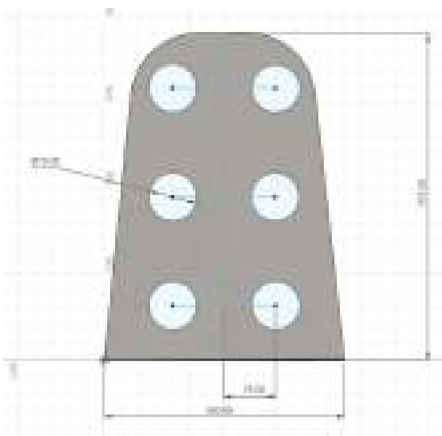
V-1-1 Fusion 360 sketches conceptions

Five airbrake designs for the vehicle are under consideration, they are 10mm wide, and the material is yet to be defined. They are approximately the same size but have variations in shape or outer edges. The model the team gave us (A) is a simple shape with rounded tip corners, after some research, especially in the aeronautical field, we learned that some airbrakes have holes to create an air disturbance, so we added it to the original shape (B). The size of the holes has been defined to allow the structure to remain solid, so this size will not change during this study. The third (C) was designed to provide a larger frontal air surface with smoother curves. As we have seen, the holes created some disturbance. We thought that discontinuous curves could do the same, which was the purpose of the fourth airbrake (D). Finally, for the last airbrake (E), we decided to try a basic rectangular shape but with two partitions on each side, the aim of this modification is to direct the fluid as far away from the body as possible. We took inspiration from a car that has a top speed of 1000mph, the "Aussie invader 5R" this airbrake was used to reduce the speed by 800mph and when deployed, seven tonnes were applied to the surface [Aussie invader 2022].

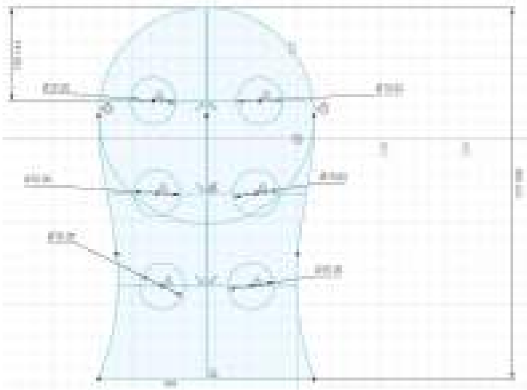
Sketch A



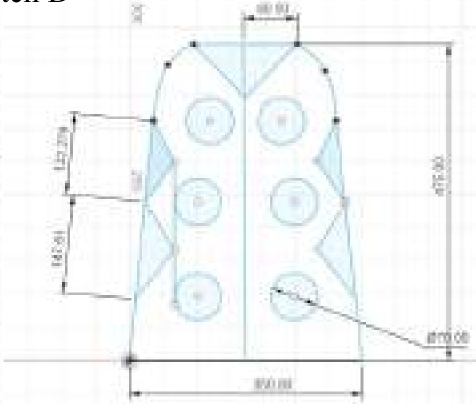
Sketch B



Sketch C



Sketch D



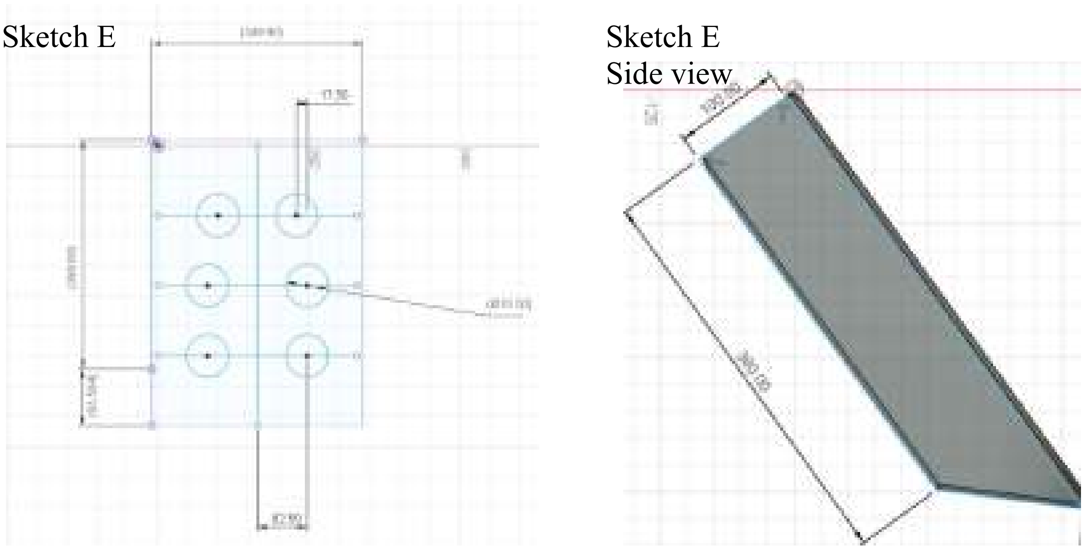


Figure 40 : Sketches of each design on *Fusion 360.*

Figure 41 : Aussie invader 5R computer drawing, airbrake on the vehicle rear.
[Aussie invader 2022]

V-1-2 STAR-CCM+ Parts imported and airbrake mesh

After creating the sketches, we imported the 360 fusion solids into STAR-CCM+. Figure 42 shows the five designs that we will study and compare in the next sub-sections. After analysing the first and second design, we decided to keep the holes on each airbrake design, as we learned that the pressure was better distributed, and the fluid flow was less disturbed, see figure 44.

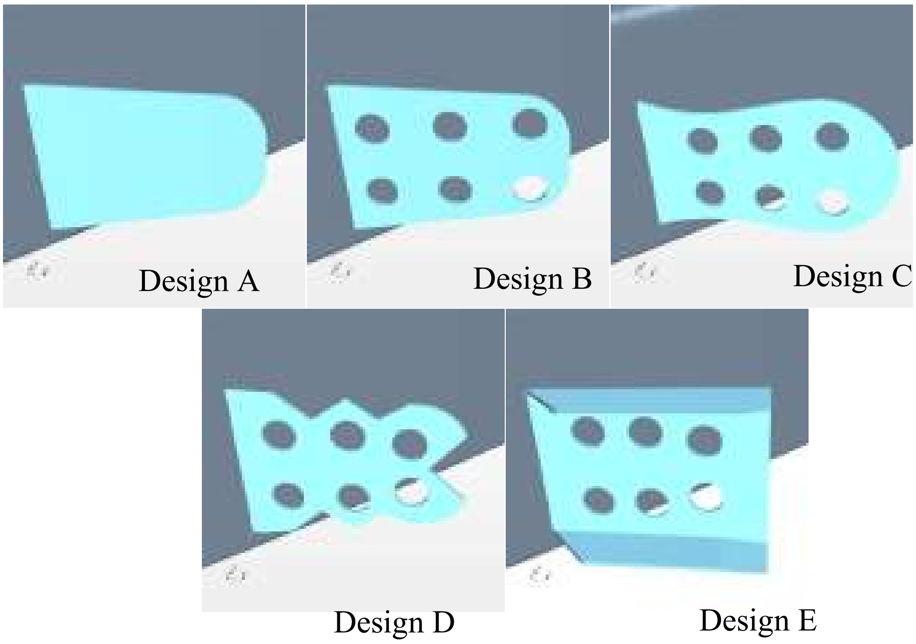


Figure 42 : Airbrake geometry part.

Particular attention was paid to the mesh in the airbrake area. The figure 43 show the high concentration of cells on the holes and curves of each airbrake.

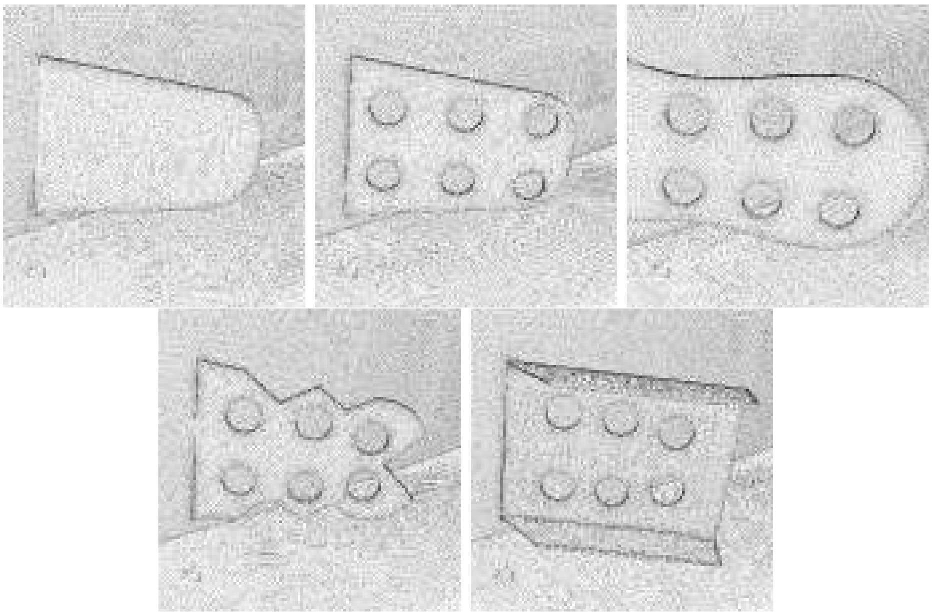


Figure 43 : Airbrake zone mesh.

V-2 Results and analyses

For the experiment, the airbrakes will be deployed symmetrically to the left and right, at an angle of 40° to the body. They are placed as far away from the centre of gravity as possible for stability reasons.

V-2-1 Vehicle and airbrake deployed frontal area.

STAR-CCM+ can give the frontal area along a reference axis, here it is "+Z". These data, presented in Table 6, are very relevant for calculating the drag and lift coefficient, and they also show that not all frontal areas are so different from each other.

Table 6 : Wairua II frontal area for each airbrakes deployed

	Frontal area	
No airbrake	4,05503E-01	m²
Airbrake A	4,36637E-01	m²
Airbrake B	4,33470E-01	m²
Airbrake C	4,63173E-01	m²
Airbrake D	4,34426E-01	m²
Airbrake E	4,54326E-01	m²

V-2-2 Pressure distributions, flow separation and streamlines

In figure 44, the pressure distribution on the surface of each airbrake is visible in the left column. The highest pressure is located at the front of the airbrakes and the holes change the surface pressure. Also visible is the flow separation zone in purple which is located behind the airbrake and at the junction of the hinge with the vehicle. The right-hand column shows the streamlines in black and the vortices in green. Each design generates vortex cores that affect the vehicle downstream.

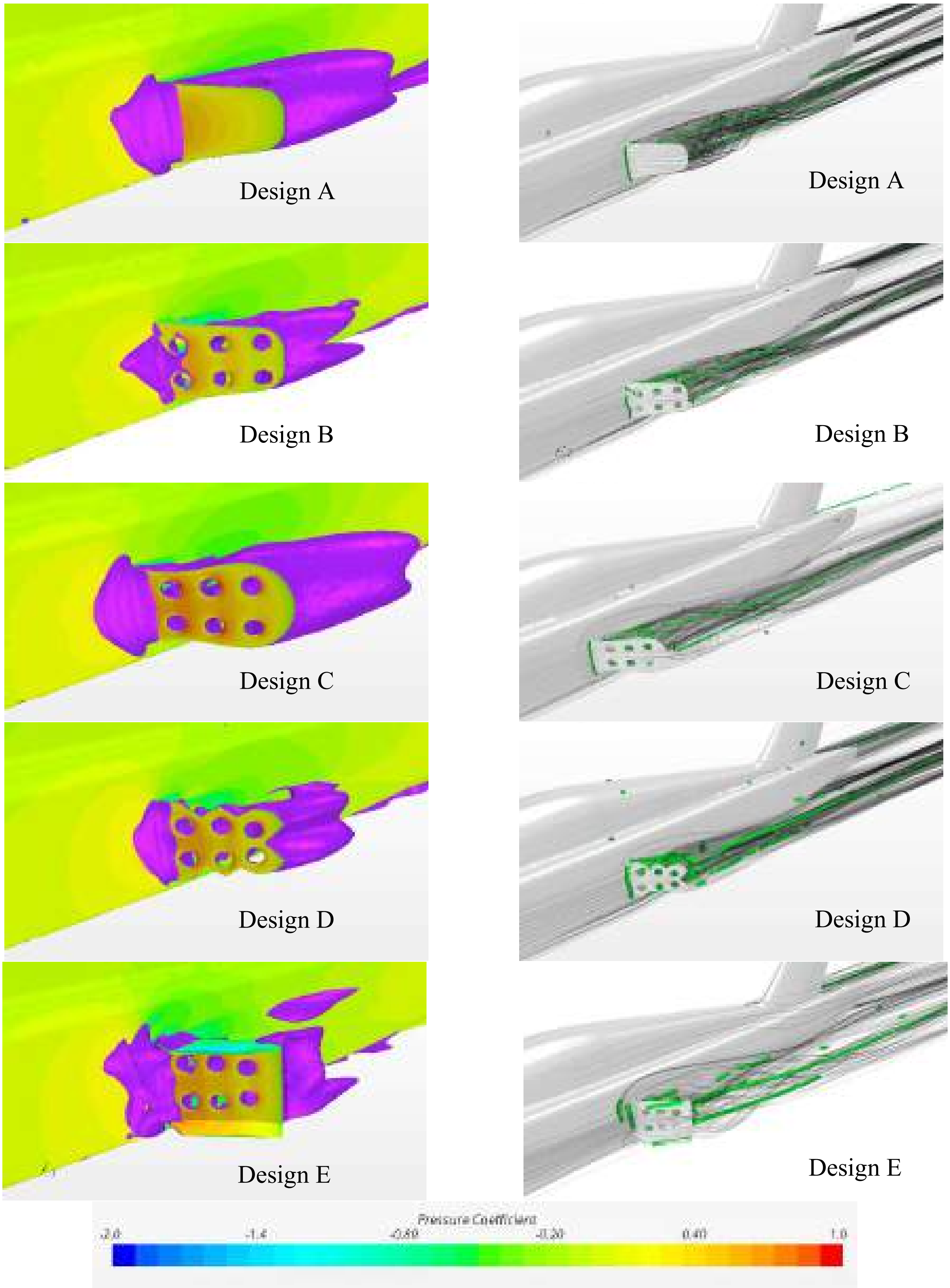


Figure 44 : (left) Coefficient of pressure with separation surface in purple; (right) streamlines and vortices (green) aft of the airbrakes near the vehicle shape. For a speed ok 223.52m.s^{-1}.

V-2-3 Downstream effects

This part of the analysis shows the disturbance behind the vehicle. In the following images we can see in black the streamlines and in green the vortices generated by the air disturbance. Vortices are regions where the fluid rotates around a fixed axis and causes induced drag, which is why we are interested in them. It is important to know that after the airbrakes are deployed, the pilot will use a parachute to help the vehicle stop and it is therefore necessary that it deploys properly, the best thing to do for this is to avoid air disturbances in the parachute deployment area.

Design A generates strong vortices at each end of the airbrakes, as we can see a large concentration of streamlines around it. The vortices are less strong with design B; indeed, we can see the streamline further from the centre of the vortices. Design C shows strong vortices and a large disturbance area behind the car. In drawing D, the flow is not deviated too many outwards and many small vortices are generated around the airbrakes, but the flow downstream of the vehicle seems stable, which is an advantage for the parachute. The last model highlights the flow directions created by the airbrake; it generates strong vortices like model A but further away from the parachute opening area. See Figure 46 for another view of the tangential velocity of the flow.

Figure 45 : Streamlines and vortices downstream of the vehicle for a 223.52 m.s^{-1} speed

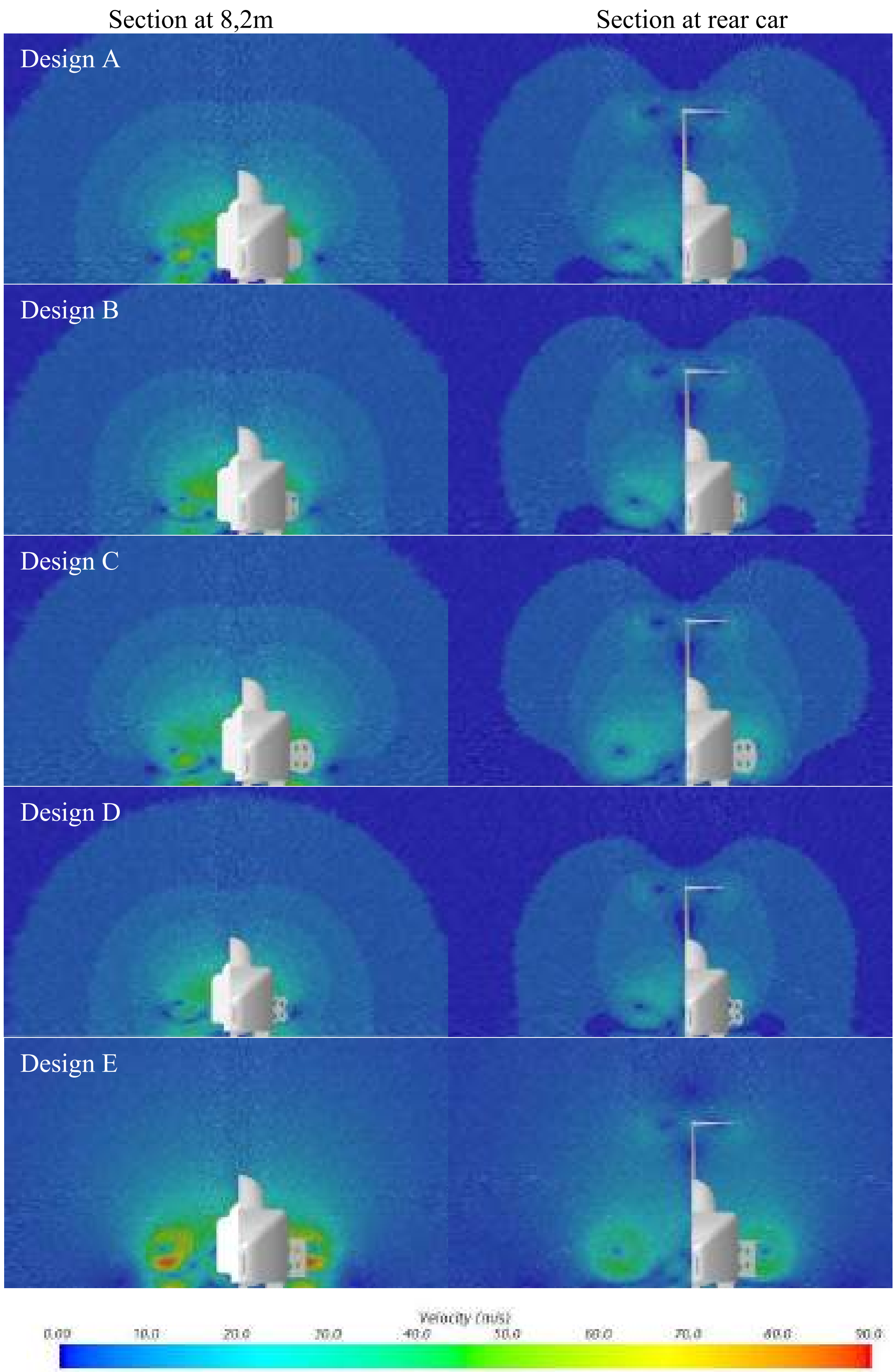


Figure 46 : Front view cutting plans at two locations behind airbrakes. Tangential speed distribution shows the vortices created by airbrakes.

V-2-4 Efforts on airbrake

Thanks to the function *"report"* on STAR-CCM+, it was possible to analyse the effort on only airbrake figure 47 shows the drag coefficient for each design. Note that C and E have the highest coefficient. Thanks to the figure 48 shows the side force (red) the lift (green) the drag (blue) and the hinge moment (mocked) for each airbrake, we can see that the drag and side force are very big in front of the lift. The hinge moment will be useful to elaborate the deployment system (actuator, etc…).

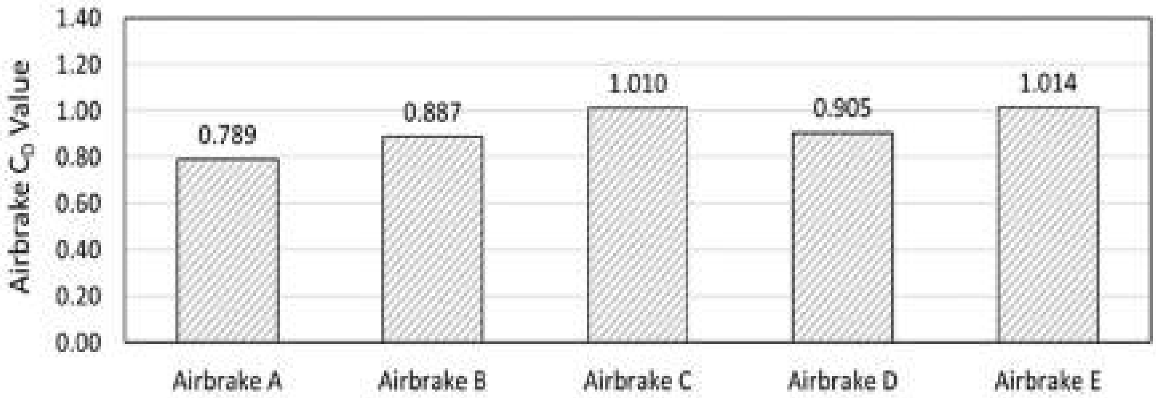


Figure 47 : Drag coefficient for airbrakes

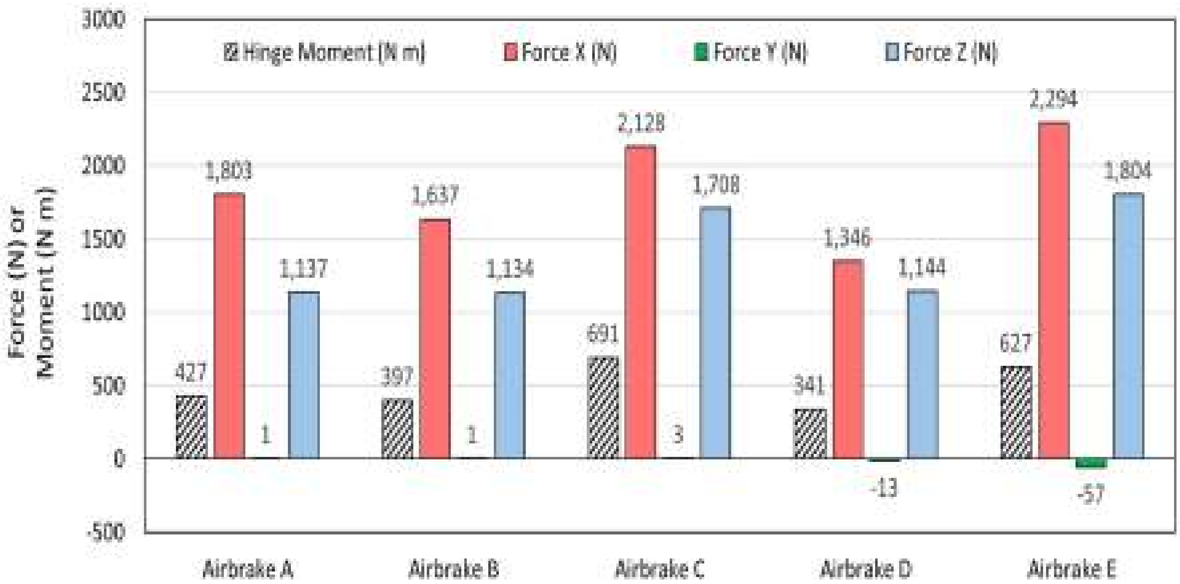


Figure 48 : Moment and forces on the five airbrakes for 223.52 m.s^{-1} speed

Another force which applied on the airbrake is useful to elaborate the deployment system. This is the compound of the drag and the side forces, indeed, on figure 48 we have seen that the lift is not relevant. The column "total force" writes in the table 7 is the summing of F_x and F_z together, which can be obtained thanks to the formula :

$$F = \sqrt{(F_x)^2 + (F_z)^2}$$

Also, the angle of force application (Θ) can be obtained with:

$$\Theta = \tan^{-1}(F_x/F_z)$$

Table 7 : Force components and total force values on each airbrake design, half vehicle.

Airbrake Design	F_x, Side Force (N) [% of Total]	F_z, Drag Force (N) [% of Total]	F,Total Force (N)
Design A	1,803 [85%]	1,137 [53%]	2,131
Design B	1,637 [82%]	1,134 [57%]	1,991
Design C	2,128 [78%]	1,708 [63%]	2,729
Design D	1,346 [76%]	1,144 [65%]	1,767
Design E	2,294 [79%]	1,804 [62%]	2,918

Table 8 : Angle of direction of airbrake total force in XZ plan.

	Angle Θ (°)
Design A	57,8°
Design B	55,3°
Design C	51,2°
Design D	49,6°
Design E	51,8°

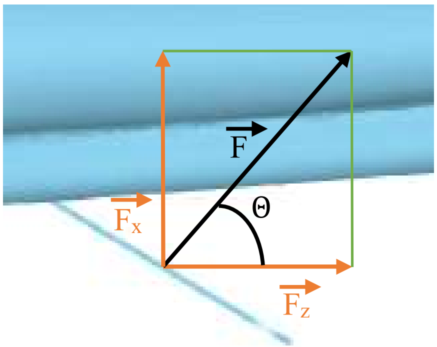


Figure 49 : Illustration of forces on airbrake in the plan XZ.

V-2-5 Effort on whole car

Compared to the vehicle without airbrake, the figure 49 shows the relevance of airbrakes because the drag coefficient with airbrake deployed are more doubled, we can highlight that design C and E have the higher drag coefficient.

The lift of Wairua II is visible on the figure 50, it shows that all vehicle design maintains a downforce which that allows the car to be placed on the ground, except the design A which cause a lift force, however due to the 1,700 kg of Wairua II, this parameter don't affect a lot the vehicle brake performance.

A nose up pitch moment is created by all the design which is not an asset of the car brake performance, that of drawing C is particularly high compared to the others.

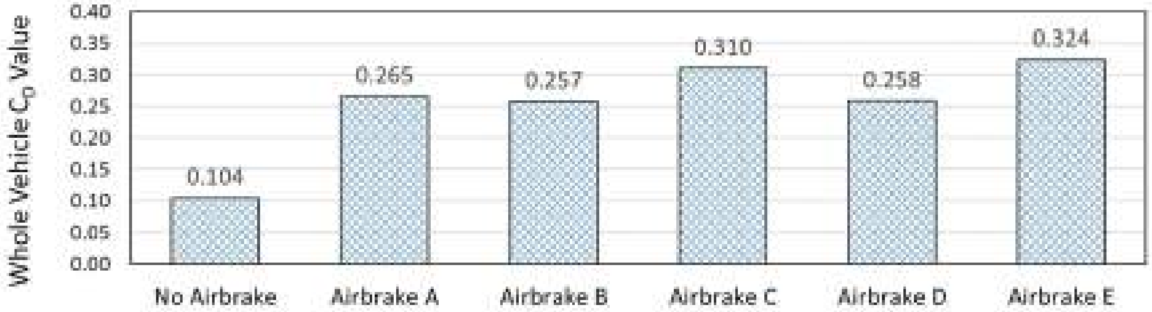


Figure 50 : whole car drag coefficient

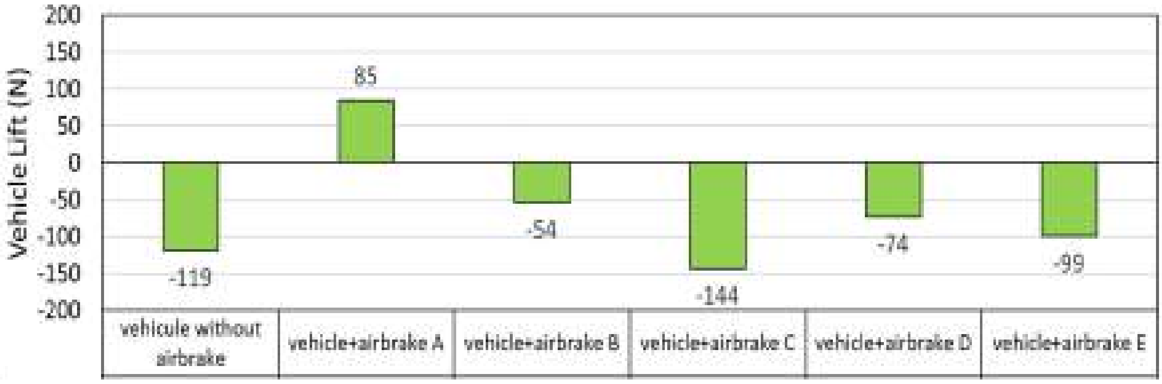


Figure 51 : Half vehicle lift for each airbrake

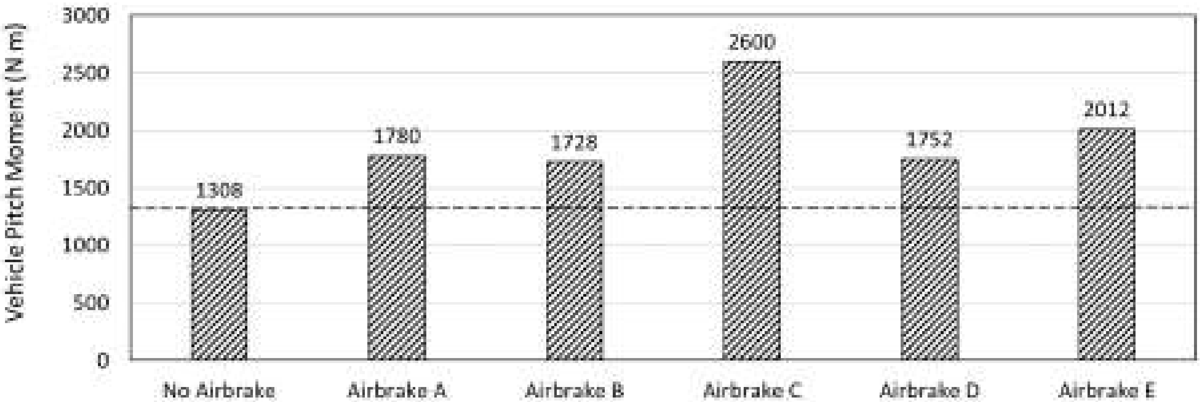


Figure 52 : Half vehicle pitch moment from the centre of gravity for each airbrake

See appendix 1 to see a comparison between each vehicle about the drag and lift distribution on the length of the vehicle.

V-3 Summary of results

Based on figures 47 to 51, we draw up a table according to five relative criteria in relation to the absence of airbrake, we decided to assign the symbol "+" for a positive point and the symbol "-" for a negative point. This table gives a visual summary of this study. Those five criteria are :

- the difficulty of manufacture
- the drag force of the whole vehicle with airbrakes deployed
- the lift force of the whole vehicle with the airbrakes deployed
- the moment of inclination of the whole vehicle relative to the vehicle's centre of gravity.
- The hinge moment is applied to the airbrake with respect to the hinge between the body and the airbrake.

Table 9 : Summary table of the different parameters studied during this project.

	Airbrake A	Airbrake B	Airbrake C	Airbrake D	Airbrake E
Manufacturing	++	+	-	-	- -
Drag (vehicle)	+	++	+++	++	+++
Lift (vehicle)	- -	-	++	-	+
Pitch moment (vehicle)	+	+	- -	+	-
Hinge moment (airbrake)	+	+	- -	++	-

Conclusion

This project proposes a first approach for the airbrake system of the Wairua II land vehicle. The study of this system was a great opportunity but also a challenge. We had to adapt our project to the expectations of the CMR team, we chose to modify the shape of the airbrake even if other directions could be taken. We decided to carry out a study on the vehicle without airbrakes in order to have a basis for further simulations; in addition, this allowed us to become familiar with the STAR-CCM+ software. Finally, five potential air brakes were designed. We submit the relevance of holes in the shape that generate more drag. The overall CD and CDA values were compared, with the perforated plate with edge fences having the highest CD value. Various other parameters were investigated such as lift, drag, pitching moment or hinge moment of the airbrake. All airbrakes slightly reduce the downforce of the vehicle when deployed and result in an increase in the nose down pitching moment. All this has enabled us to produce a table that will help the team to make a choice and equip their vehicle with the best airbrake.

As a continuation of this project, the development of the deployment system could be an interesting study, indeed, a material strength study could be carried out to determine the type of material in which the air brake should be constructed. In addition, a kinematic study will help to find the point of application of the actuator on the airbrake and may help to dimension the airbrake actuator.

In order to further develop this project, other CFD studies should be carried out, among others, the impact of the airbrakes on the vehicle when retracted, the study with different deployment angles or the size of the holes in the airbrakes.

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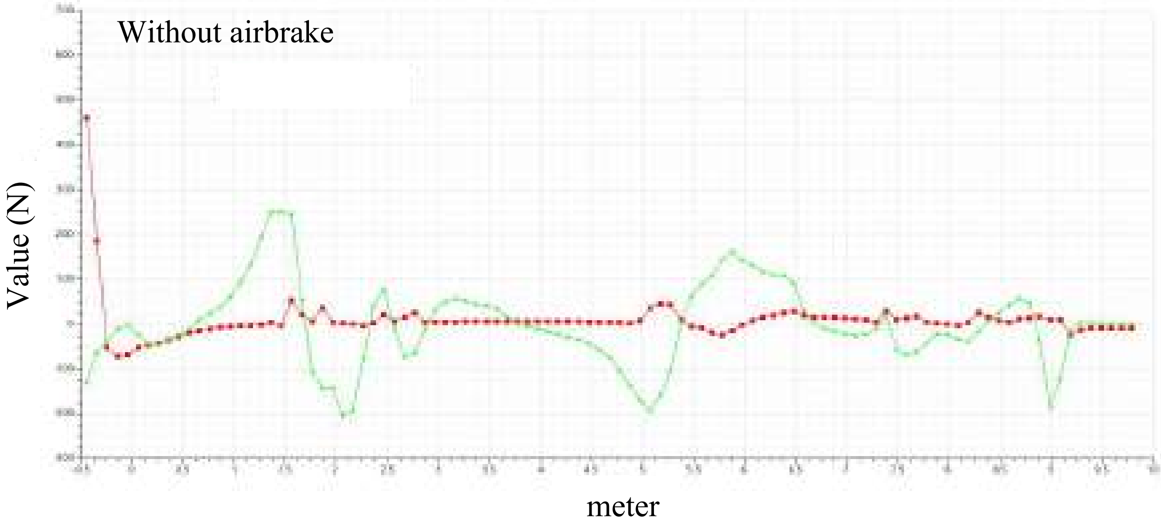
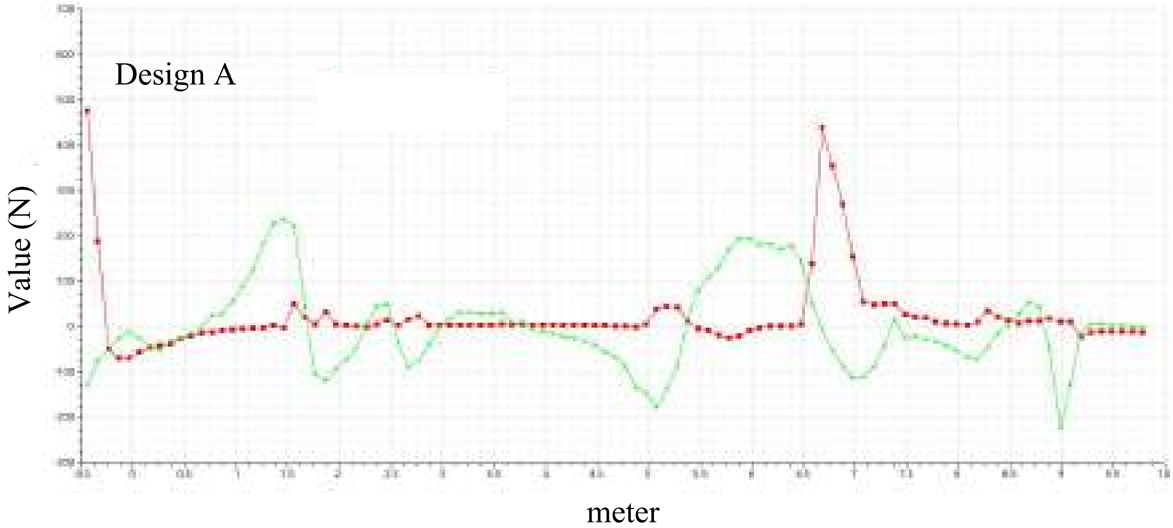
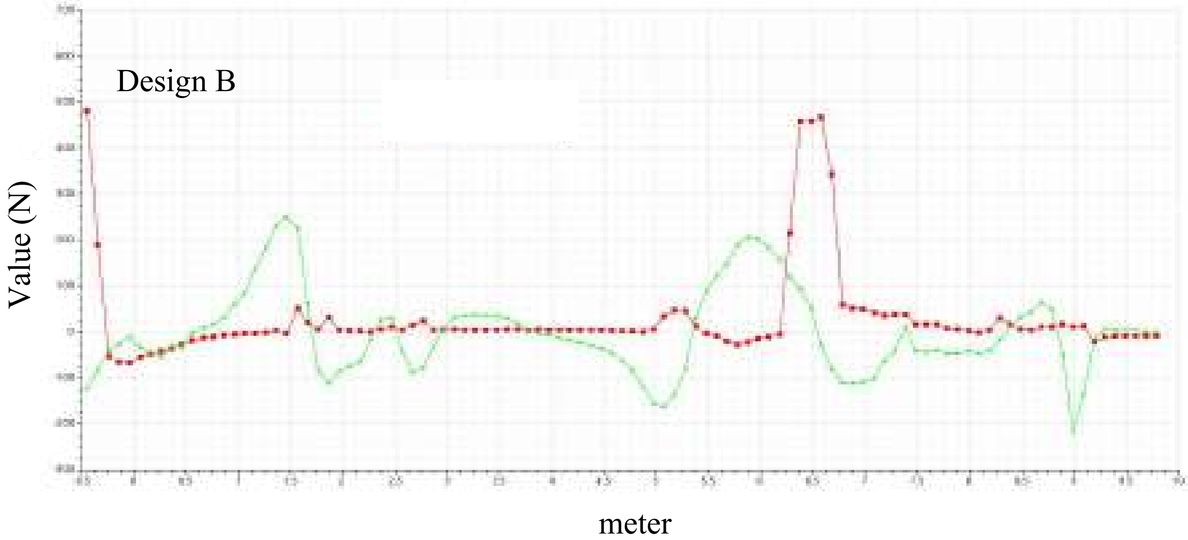
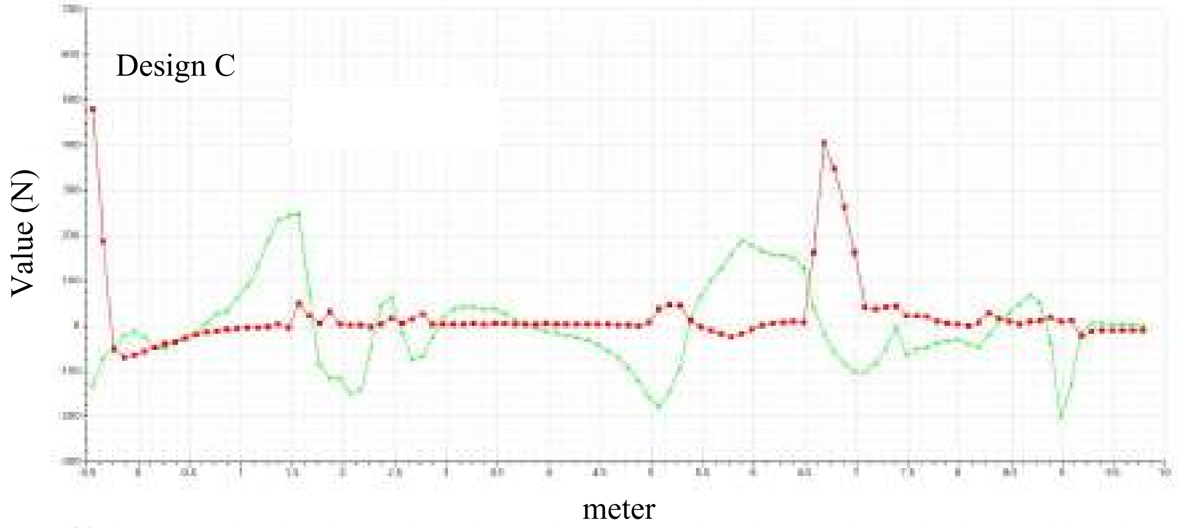
Appendix

Appendix 1: Lift (green) and drag (red) distribution on the length of the vehicle





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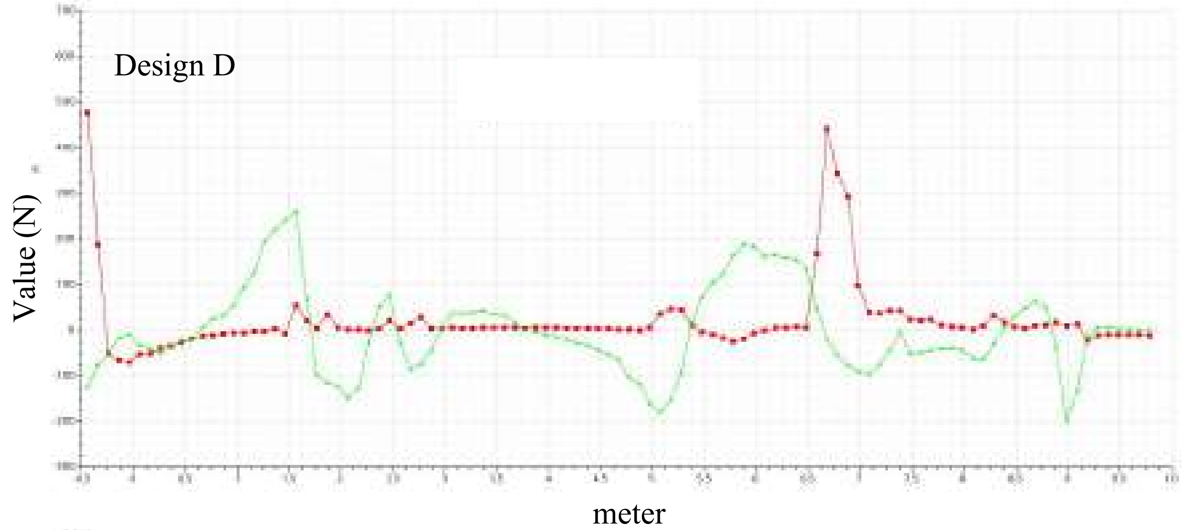
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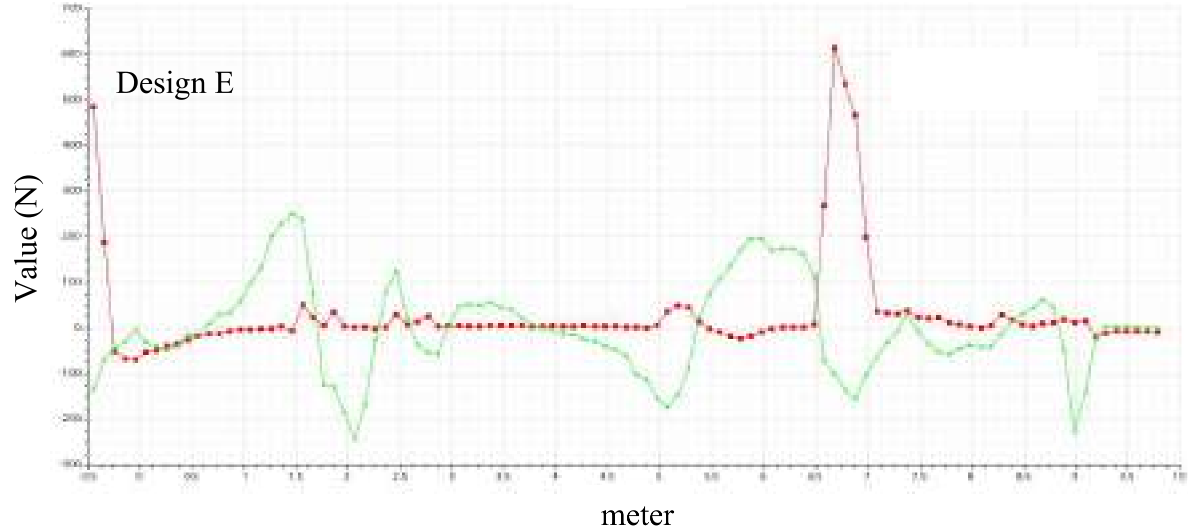
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