Kantonsschule Im Lee Winterthur

Matura Thesis Fall Semester 2023/24

Front Wing Aerodynamics of a Formula One Model Car

Theoretical Study and Wind Tunnel Testing

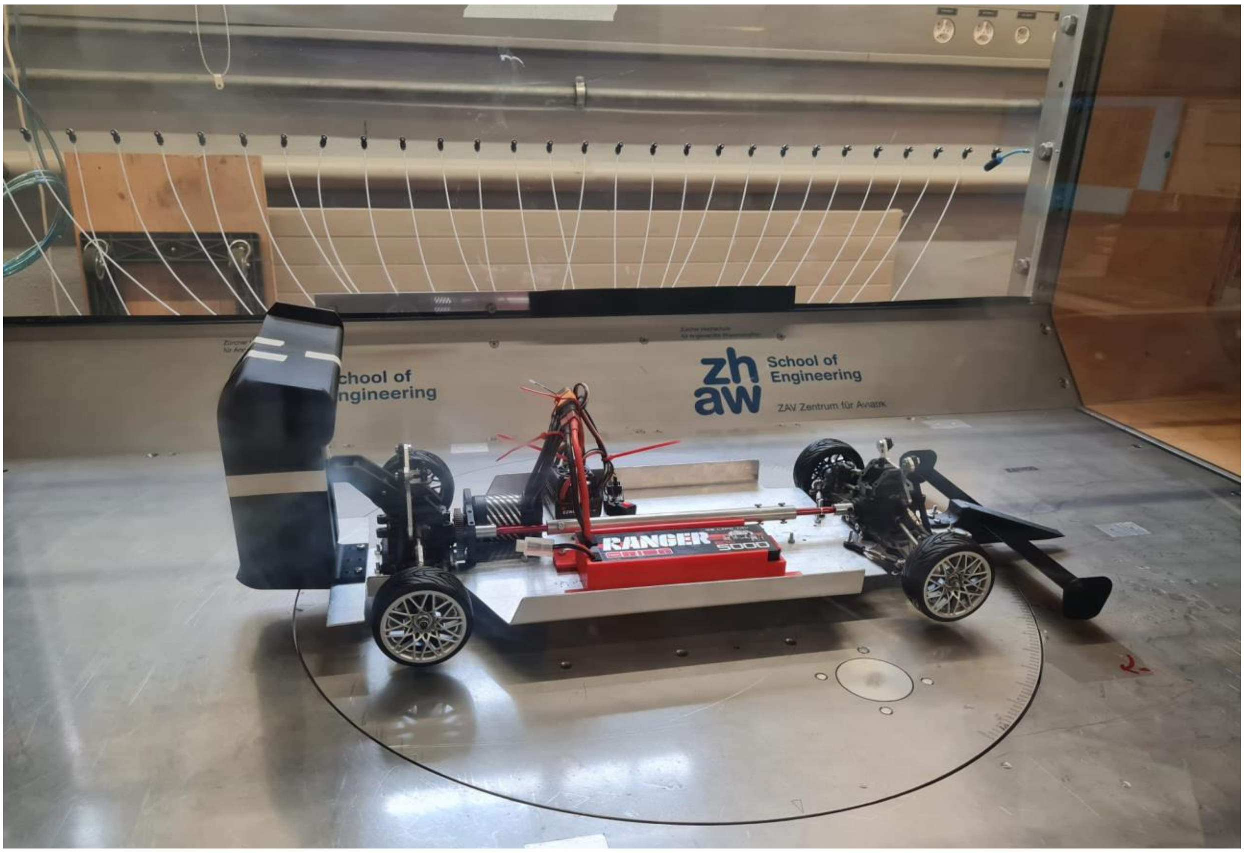

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Table of Contents

1 Preface

In 2017, I stumbled upon a very popular sport, called Formula One. I hadn`t been exposed to Formula One before since nobody in my family used to watch the prestigious sport. I was hooked instantly. The drama, speed, danger, and high stakes pulled me into the world of Formula One and I have been a massive Formula One fan since then. As I grew older, I started becoming increasingly interested in the cutting-edge technology the different teams must create to become world champions. For this project, I decided to look at the aerodynamics of the car, since the aerodynamic components are relatively easy to understand and therefore replicate. Formula One teams change their aerodynamic components every race, depending on the track, to maximize performance. This concept, of changing something small about the bodywork of the car which then makes such a big difference on its overall performance, fascinates me and that was my main motivation to pursue this as my Matura thesis. I wanted to understand how the aerodynamics of a real Formula One car work by using a small model replica.

At this point, I would like to thank all the people who have helped me during my project. My friends and family who always supported me and helped me not only emotionally but also gave their useful insights into many of the problems I encountered. I also want to give a huge thanks to the ZHAW for not only allowing me to use their wind tunnel but also helping me during the whole process of preparing the car for the wind tunnel test and giving other helpful tips. A special thank you in that regard goes to Professor Leonardo Manfriani and Mr. Marco Caglioti, whose expertise were essential for my ideas to come to light. I would like to thank our physics mechanic, Mr. Tobias Werner, who spent countless hours helping me with my plethora of challenges, and of course, I would like to thank Ms. Margherita Fierz, my supervisor during this project. I could not have done my project without the help of all these amazing people.

2 Abstract

In this project, I immersed myself into the world of Formula One aerodynamics. The goal of this project was to design different front wings, in the style of Formula One front wings, and then find out what effect different aspects have on the amount of downforce produced by them in a small model car.

To accomplish this, I built a model car, which had an easily exchangeable front wing. 5 different kinds of front wings, each with a different idea behind them, were designed using CAD and 3D printed. These different front wings were then attached to the model and these different configurations were tested in a wind tunnel. The ZHAW offered me time in their wind tunnel to test the model. A basic theoretical knowledge about fluid dynamics had to be built up to design the wings and understand the data.

It turned out that even at such a small scale, a slight difference in the design of the front wings made a considerable difference to the amount of downforce created. These differences were able to be analyzed and mostly explained on a theoretical level.

3 Introduction

3.1 What are the goals?

I want to learn about what effect the front wing of a model Formula One car has on its performance. More precisely, the effect it has on the downforce produced by the car when trying out different configurations. What the different configurations are shall be specified later. To answer this question, a model built by myself shall be looked at. The model car, which shall be remote-controlled, must have an easily exchangeable front wing, like a real-life-sized Formula One car.

3.2 What is downforce?

Downforce is a force which pushes the car towards the surface it is driving on. It is created by the aerodynamic features of the vehicle [1]. It can also be called a negative lift force. How downforce is created by the aerodynamic components of the car shall be described in chapter 4.

3.3 Why is downforce needed in a Formula One car?

Downforce is needed in a Formula One car, especially around high-speed corners, to increase grip. If the car did not produce any downforce, then it would lose grip and slide off the track. This can be explained by the concept of inertia since when the car is going in a straight line, it wants to keep going straight. If the force making the car turn is higher than the friction force between the tires and the ground, which is often the case around corners in a Formula One track, then the car would lose traction and slide off the corner. One could think increasing the car’s weight would be a simpler way to solve this problem, but this approach does not work, since increasing the weight would affect the car`s lateral acceleration (the side force) at the same rate [2]. This would therefore make no difference in the car`s ability to turn and would even make the car heavier and therefore slower. Aerodynamic downforce increases the force the tires exert on the ground, essentially making the car “stick” to the ground, without increasing the weight of the car therefore allowing them to go faster around corners, reducing lap times significantly [2].

3.4 Hypothesis

The following hypotheses were made based on the theoretical part of the book “Race Car Aerodynamics – Designing for Speed” by Joseph Katz [2]. Furthermore, the model was completed built by this stage. These hypotheses shall be tested in a wind tunnel.

The model has no body panels and therefore it can be assumed that the airflow over the car shall become incredibly turbulent. That`s why the first hypothesis is that the front wing shall be much more effective than the rear wing. The speed of the car is about 50 km/h, and the model is not that big, meaning that the wings shall not have a big surface area either. That`s why the assumption is made that the forces measured shall be very small. The final hypothesis is a vague one but still important. All the assumptions about the front wings, which shall be specified while designing them, shall be confirmed by the wind tunnel test. This is because the difference in the amount of downforce produced between the front wings should still be measurable with the highly sensitive measuring tools the ZHAW has in its inventory.

4 Theory

4.1 Bernoulli Equation

This equation is by far the most important equation in my project. It belongs to the most important equations in the whole field of fluid dynamics, an enormous field in physics. Aerodynamics is a specialized form of fluid dynamics. Once we understand this essential equation, we gain a much better understanding of how downforce is created in a Formula One car.

$$\mathbf{P_1 + \frac{\rho}{2}v_1^2 + \rho g h_1 = P_2 + \frac{\rho}{2}v_2^2 + \rho g h_2}$$

$P_1 = Static\ Pressure\ at\ Point\ 1$
$\rho = Density\ of\ Fluid$
$v_1 = Velocity\ at\ Point\ 1$
$g = Gravitational\ const.$
$h_1 = Height\ at\ Point\ 1$
$P_2 = Static\ Pressure\ at\ Point\ 2$
$v_2 = Velocity\ at\ Point\ 2$
$h_2 = Height\ at\ Point\ 2$

The equation above might look scary, but it’s actually really simple to understand. Each side describes the pressure of a fluid (air is also a fluid) in a specific point. What must be said is that these relations only work in a streamlined flow as seen in figure 1.

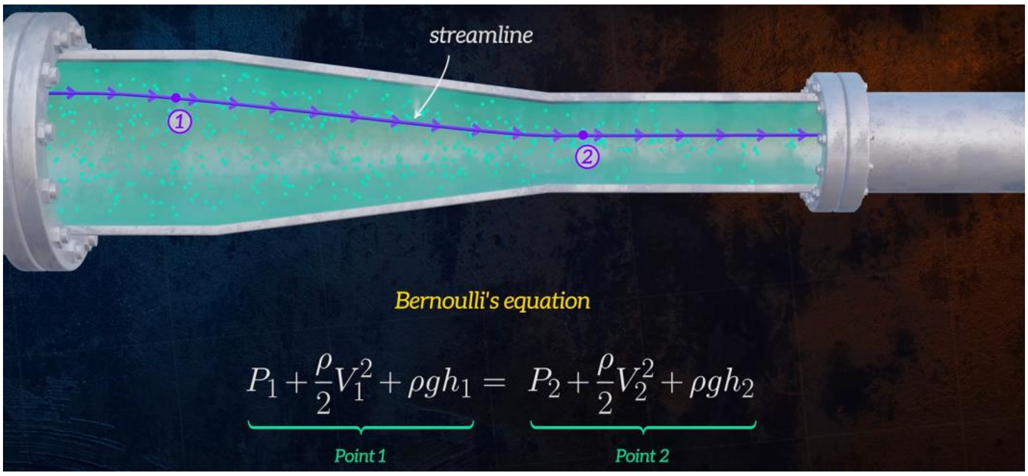
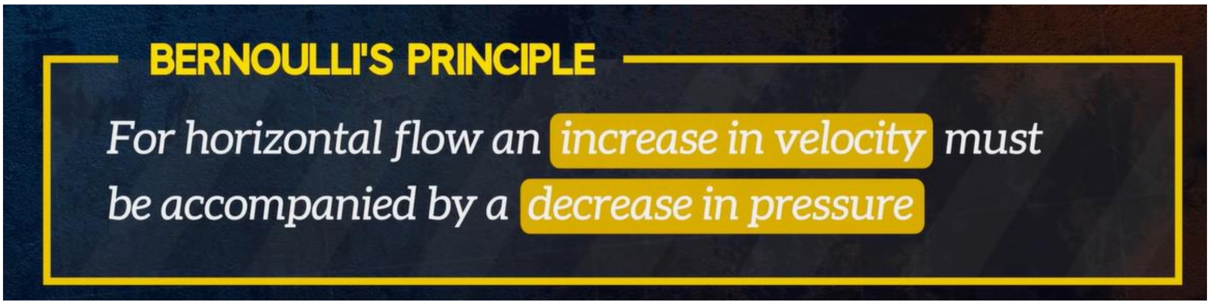


Figure 1: Water in a pipe, which is a closed, streamlined flow with 2 points marked [3]

The first term is static pressure, the second one the dynamic pressure and the third one is the hydrostatic pressure. The Bernoulli equation says that the sum of these three terms, these three pressures, stays the same in a streamlined flow. This can be seen as a continuation of the law of energy conservation [3].

The only thing which is relevant for us from this equation is a simple observation. Namely, that if the velocity is higher in point 2, and the height is the same, then the pressure of the fluid in point 2 has to be lower. This is because, otherwise the equation would not be fulfilled since the right side would increase while the left side stays the same. This principle is called Bernoulli`s principle (see figure 2) and is essential for the aerodynamics of racing cars.



BERNOULLI'S PRINCIPLE

For horizontal flow an increase in velocity must be accompanied by a decrease in pressure

Figure 2: Bernoulli`s Principle [3]

4.2 Newton`s Third Law

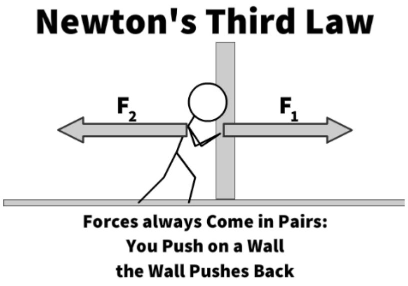


Figure 3: Visualization of Newtons third law [4]

“For every action, there is an equal and opposite reaction.” This is Newton`s third law of classical mechanics and is very relevant when looking at how an airfoil creates lift, or in the case of a race car, how it creates downforce. What the law says is that for every force there is also a force present, which is equal in magnitude, but faces in the opposite direction [4] (see figure 3).

4.3 Laminar vs Turbulent Flow

Laminar and turbulent flow are two properties which describe the motion of a fluid (see figure 4). If we look at the motion of a fluid and it looks “organized”, then it is laminar. Organized means the fluid particles move in parallel lines to each other with minimal disruption and at a constant velocity. If the flow looks chaotic, then the flow is considered turbulent. Reynolds number is a dimensionless property of a

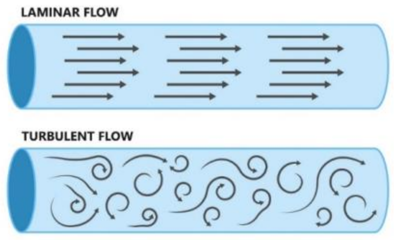


Figure 4: Laminar vs Turbulent Flow [5]

fluid which describes how turbulent or laminar a flow is. High Reynolds numbers means the motion of the fluid is turbulent. Knowing whether or not the flow of air around the car is laminar or turbulent is particularly important for race car engineers, since this property has a massive effect on aerodynamic factors such as airflow separation [2].

4.4 Flow Separation

It is easiest to explain this concept by looking at the following figure.

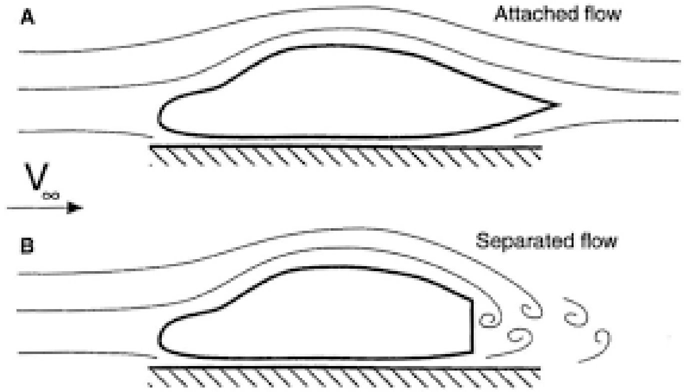


Figure 5: Attached vs Separated flow [2]

From the left there is a flow of air coming at the constant velocity V_∞. If we look at the highly aerodynamic shape of car A, then we can observe that the air flow always follows the surface of the car closely. This is an attached airflow. In contrast, car B, with a more realistic car shape, experiences flow separation at the end, meaning that the air no longer follows the surface of the car closely. An attached flow is essential to produce downforce [2].

4.5 Drag and Lift Coefficients

Drag and lift coefficients are both dimensionless properties of an object used to describe its behavior in a fluid such as air. The drag coefficient describes how much drag (in our case drag can be thought of as air resistance) an object will create; on the other hand, the lift coefficient tells us how much lift an object will produce. They both depend on a multitude of things, including the shape of the object [2]. A negative lift force is what we call downforce. That means, if the lift coefficient of a certain object is negative, then that object is going to produce downforce. The drag coefficient works very similarly. If the drag coefficient is low, then the drag force produced is low. This means that the car is not going to experience a lot of drag, meaning they will not experience much air resistance. It is challenging to figure out these values theoretically and they are therefore mostly found by wind tunnel testing and simulations. These coefficients are very important when calculating the downforce produced by an airfoil, as shall be seen later [2].

4.6 Applications of Theory

4.6.1 How is Downforce Created in a Formula One Car?

Downforce is created in many ways in a Formula One car. The 4 main ones are the front wing, the rear wing, the diffuser, and the general bodywork of the car. The diffuser creates by far the most downforce, followed by the front and rear wings. The bodywork only has a very slight effect on the downforce produced by the whole car [6]. Exactly how much downforce is created by each component differs from car to car, but as a general rule of thumb, it is as seen in the following figure. For our purposes we shall only focus on how the front and rear wings produce downforce.

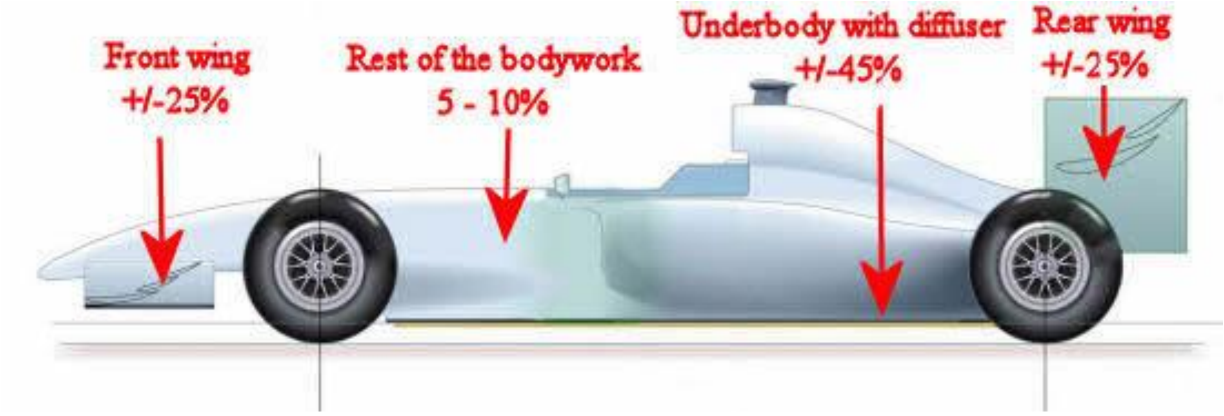


Figure 6: Downforce distribution in a Formula One car [6]

4.6.2 Airfoils

The front wing works using multiple wings attached to a nose. To see how these wings create downforce, it is simpler to look at airfoils. An airfoil is a two-dimensional cross section of a three-dimensional wing, as seen in figure 7 [2]. Picture A shows a three-dimensional wing with the span b, B shows the corresponding airfoil. Following standard aerodynamic practices, the airfoils in this chapter shall be depicted as generating lift, for a race car these airfoils must be turned upside down. An airfoil generates lift mainly using two theories which we have already seen, Bernoulli`s principle and Newton`s 3rd law.

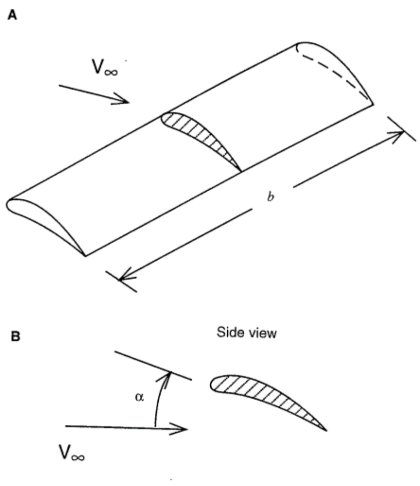


Figure 7: Wing vs Airfoil Definition [2]

A very common misconception of how Bernoulli`s principle is used in an airfoil is the “equal transit time” explanation [7]. This explanation argues that the path the air has to go is longer on the top of the wing, and therefore the speed of the air on the top of the wing must be faster. An increase in velocity must be accompanied by a decrease in pressure according to Bernoulli under certain conditions, which are fulfilled here. This decrease in pressure than leads to an upwards acting force, known as lift. This misconception is depicted visually in figure 8.

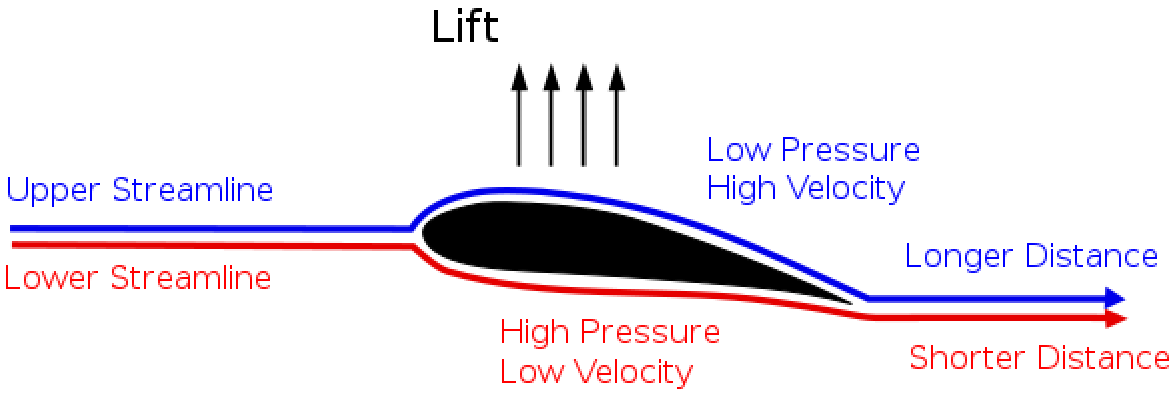


Figure 8: False misconception of lift generation [7]

The fact that the air on top of the wing moves faster than the air on the bottom is not wrong. The error in this explanation of lift generation is that the air has to take the same time to cover the longer distance. This is simply not the case [7].

What is true though, is that Bernoulli`s principle is valid and that there is a pressure differential between the top and bottom of the airfoil resulting in a force which we know as lift. This explanation can still be used, just with a more complicated explanation of lift generation, which we shall not look at. When measuring the airflow speed on top of the airfoil using simulations, the actual speed of the air on top of the airfoil is much higher than would be expected with the “equal transit time” idea [7].

Providing the flow stays attached, meaning it follows the surface of the airfoil closely, then the airflow shall be flowing away from the airfoil at slightly downwards angle. This means the air is being pushed downwards by the underside of the wing. Following Newton`s 3rd law this can be seen as the "action" force (see figure 9). The logical "reaction" force must be a force pushing the wing up, which we know as lift [8].

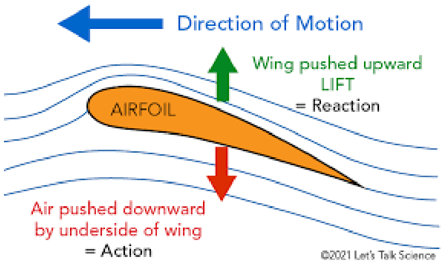


Figure 9: Newtons 3rd Law on an airfoil [8]

In a Formula One car the goal is not to generate lift, but to produce a negative lift force, downforce. This is done very intuitively by simply flipping the airfoil upside down. The air is then pushed up by the upper side of the wing resulting in a reaction force which pushes the wing down. The same concept applies to the pressure differential, if the airfoil is the other way around, an area of low pressure arises under the wing, pushing it towards the ground. How changing different things, such as the angle of attack or surface area of the wing, affects the amount of downforce produced on a theoretical level shall be discussed later on, while designing the wings. The rear wing works in the same way.

4.7 Downforce Equation

Now that we know how downforce is created and what it is, we can calculate it using following equation [9]:

$$\boldsymbol{Downforce = \frac{1}{2}\rho \cdot v^2 \cdot A \cdot C_L}$$

$\rho = Density\ of\ Fluid$

$v = Velocity$

$A = Surface\ Area\ of\ Wing$

$C_L = Coefficient\ of\ Lift$

What is very important from this equation for us is that the validity of this equation does not have to be tested in this project. So, most of these things shall be constant in the wings which shall be designed later. The coefficient of lift shall be changed a few times, since it depends on a multitude of other interesting factors, but otherwise the goal of this project is to figure out what role other factors, such as airflow separation and turbulent flow, play in the amount of downforce generated. Air resistance is calculated identically, the only difference being that the drag coefficient is used instead of the lift coefficient.

5 Designing and Building the Car

5.1 Basic Idea

The base of the car is an aluminum plate and everything else is attached to the plate. For some things such as the battery, a bracket was designed using CAD software and then 3D printed. For other things such as the ESC or receiver, strong tape has been used to attach the components to the plate. The model works like a commercial RC car using a receiver and transmitter. Since the building of the car is not the focus of this project, all parts which were harvested from other cars or could be bought were utilized.

5.2 What is needed to build an RC car?

The things needed to build an RC car can be split into two main classes of components. The mechanical ones and the electronic ones. The heart of the car is the battery [10]. A so-called LiPo battery was used in the model, like in almost all commercial RC cars sold nowadays. This was decided since they are high power batteries, which are easily rechargeable. A motor and an ESC are also needed. The ESC (Electronic Speed Controller) is the brain of the car [10]. It receives signals from the receiver, another part which one needs, and sends it to the motor which powers the wheels, and also the servo motor. The servo motor is a different kind of motor needed for the steering mechanism [10]. To control the car, the final component needed is a transmitter. The big advantage of all the electrical elements which were used for the car is none of them had to be soldered. This not only simplifies things a lot but also makes the car even more easily modifiable in the future. The mechanical components needed shall be specified in chapter 5.4. All the electronic elements connected together can be seen in figure 10.

Figure 10: Electrical Components

5.3 Electrical Components

The following list of electrical components was created after doing some research on the internet [11] and talking with RC car hobbyists. All the components were ordered from digitec.ch. The servo motor was provided by the school. The fact that the motor and ESC cost exactly the same is not a mistake. The cost of these components are extremely volatile, this is what was paid for them.

Component	Model Name	Cost
Brushless Motor	3652SD 5400KV Hobbywing Brushless Motor	82.80 CHF
ESC (Electronic Speed Controller)	Hobbywing Ezrun Max 10 G2 80A ESC	82.80 CHF
Battery	Team Orion 2S 60C Ranger LiPo Battery	44.00 CHF
Receiver and Transmitter	Absima 4-Kanal Fernsteuerung CR4S 2.4GHz inkl. Empfänger R4WP-Micro	56.41 CHF

Figure 11: Table with Electrical Components

5.4 Mechanical Components

For most of the mechanical components needed, the credit goes to Dominic Fässler. He is an RC car hobbyist and the wheels, whole steering mechanism, suspension and rear part of the car were taken from one of his RC cars. Specific things such as gears were ordered from conrad.ch, while other things needed to build an RC car such as screws, bolts, and the aluminum plate itself were bought from Hasler. The base of the car, the plate, must be self-built since the electrical components ordered were slightly bigger than his original ones. Furthermore, the front and rear wings would have to be attached to the plate somehow, and the car as a whole has to be able to be mounted in the wind tunnel. Therefore, it would be very beneficial to control the dimensions of the base. The big advantage of taking the rear and front of the car from another car was that the whole steering mechanism and motor mechanism were included with them, meaning that no time and money would have to be invested into making these complicated elements.

5.5 Planning the Aluminum Plate

The planning was finished after having a final idea about how the car would be mounted in the wind tunnel, this process shall be described later in chapter 7. The front and rear wings had also already been designed at this point. Therefore, it was already known how the wings would be attached to the car. The shape of the plate is heavily based on the original shape in Dominic's car (see figure 12). The holes needed to attach the front part of the car and rear could therefore simply be copied onto the plate. The rest of the holes were carefully drawn onto the plate manually, as well as the outline of the entire car. More than enough space was left on purpose, since one can always cut away more material but adding additional material is very difficult. At the end all the outlines were marked using a scriber and the holes were prepared to be drilled using a center punch.

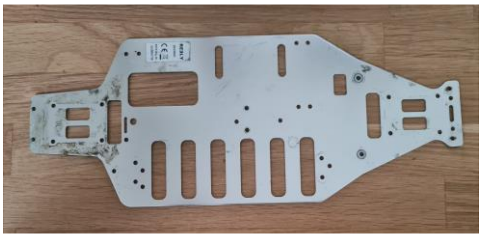


Figure 12: Original Plate

5.6 Building the Car

Preparing the Plate

The plate was cut and all the relevant holes were drilled using the machines available at our school. The outline was cut using a bandsaw and the holes were drilled using a pillar drilling machine as seen in figure 13. Some of the larger holes, for example the hole for the gear, had to be cut out using a fretsaw. All the sharp edges were filed to keep the car safe for transportation. The two big holes in the middle of the finished plate as seen in figure 14, are for the mounting of the vehicle in the wind tunnel. At the end, to add stability to the whole plate since aluminum is a very soft metal, the edges were folded up at a 90 degrees angle.

Figure 13: Drilling machine

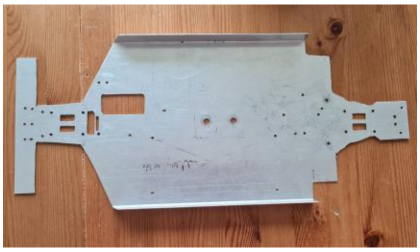


Figure 14: Finished Plate

Assembling the Car

Assembling the car after the plate was finished was not a very difficult process. M3 screws and nuts were used to attach everything to the plate, strong mounting tape was used to attach the ESC and receiver to the plate. The battery and servo were also screwed onto the plate using brackets, which were designed by me, and 3D printed. The front and rear part of the car already had thread holes in them, so those parts could be screwed on to the plate without any problem. The finished model, without any aerodynamic components can be seen in figure 15. The suspension has been replaced here through 3D printed rods, which shall be elaborated on in chapter 7.

Figure 15: Finished Model with no Aerodynamic Components

6 Designing and Printing the Wings

6.1 Basic Idea Behind Front Wings

The front wings were all designed by me using CAD software (Onshape) and then 3D printed. To save time and simplify the analysis, it was decided to make 5 front wings all with the same kind of nose, so that the only changing factor would be the wings. Therefore, each front wing was made up of 3 parts: the nose, a connecting element with which it would be screwed on to the plate and the wings themselves. The elements were all printed separately and then glued together using a simple mechanism involving metal rods to stabilize the wings. This mechanism shall be described in more detail using the example of the first front wing which was designed, printed, and assembled.

6.2 Front Wing 1

This would become the basic front wing. All the following ones would be compared using this as a basis value and this would be kept in mind while designing this front wing.

Nose

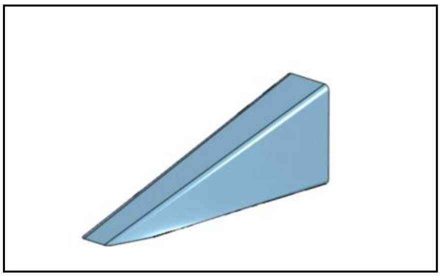


Figure 16: Front Wing Basic Nose

First of all, the nose had to be designed. This was done after taking some inspiration from a real Formula One front wing. This can be seen in figure 16. After this basic form, I had to figure out a way to attach the wings to this nose. For this a slotting mechanism was thought of. That way the wings would go neatly into the nose itself and therefore be more stable than if only just stuck on to the nose. When designing this slotting mechanism, the wing shape and size was already known. Furthermore, since the stability of the whole front wing was very important for the testing in the wind tunnel later onwards, the idea of putting a metal rod through the wings and nose came to mind. This way the wings could not just fall of if the glue failed but would still be attached because of the metal rod. This idea can be seen in figure 17. Another advantage of sticking a 4mm aluminum rod through the whole wing was that the filament the 3D printer prints, PLA, is not very strong. Although very unlikely

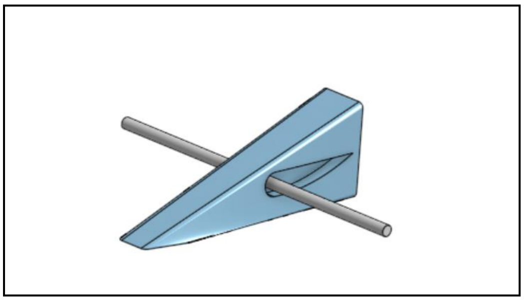


Figure 17: Nose with assembling mechanism

anyways, the metal rod would eliminate any chance of the wings bending. The rods do not even have to be very long to achieve this effect.

Wings

The airfoil shape for this wing would be the same for all the following wings as well. A typical but still simple airfoil shape [2] was chosen as described in chapter 4.6.2(see figure 18). The front wing would ideally be as wide as the car, like a typical Formula One car, therefore the length of the wing was decided to be 12 cm. The wing connected to the nose can be seen in figure 19. In this figure the wings have been set to be slightly translucent to visualize the effect of the metal rod which is inserted through both the wings connecting them.

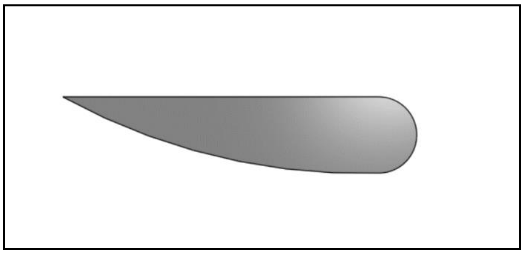


Figure 18: Airfoil Shape for All Wings

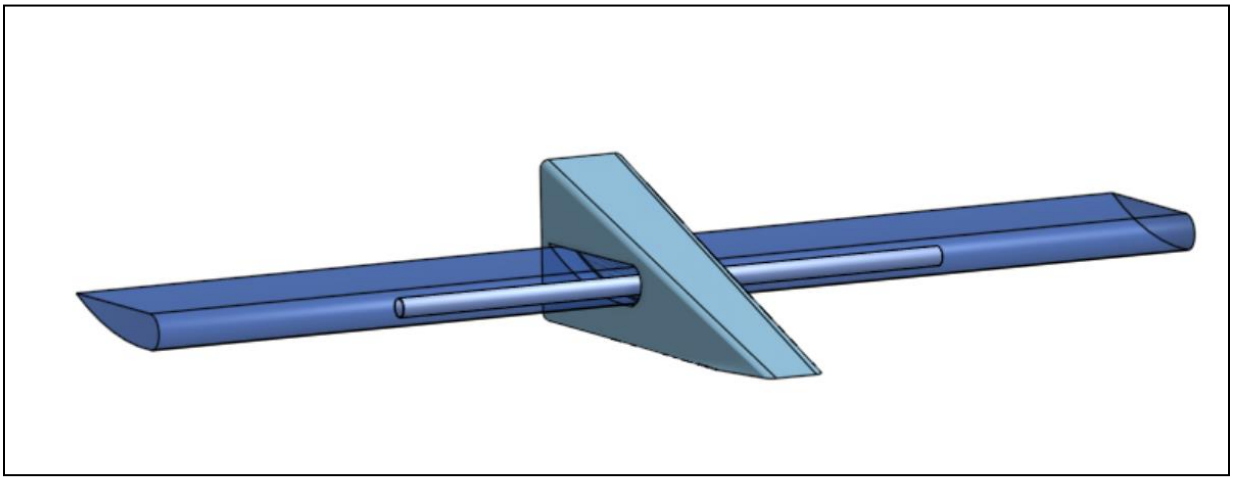


Figure 19: Front wing 1

Connecting Element

The final element needed to complete the front wing was something to connect it to the car with. A slotting mechanism further supported by 2 screws was thought of for this process. The connecting element would be attached to the nose and would then be able to be slid on to the plate and fastened using 2 M3 screws and bolts. The connecting element can be seen in figure 20.

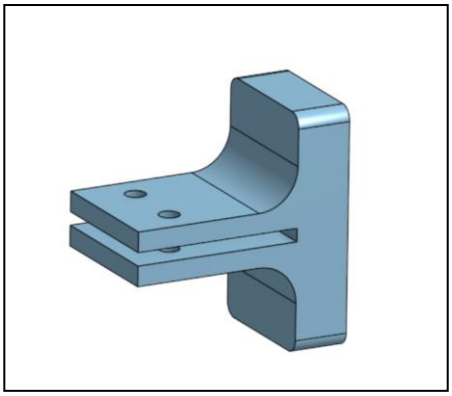


Figure 20: Connecting Element

It would be attached to the nose using 2 small aluminum rods and glue. The reason for the rods in this case wasn't the stability though, it was to make sure the nose would be glued straight. Without the rods to guide the connecting element onto the nose, the chances of me gluing the nose slightly sideways was very high. This was confirmed by multiple failed attempts before reaching this solution.

Assembling Front Wing 1

After printing everything and making the rods using a metal saw, one could say there was something like an assembly set for the whole front wing (see figure 21). Gluing everything together with strong glue worked very well and the final result can be seen in figure 22.

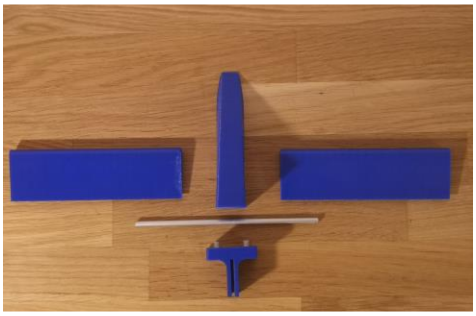


Figure 21: Assembly Set for Front Wing

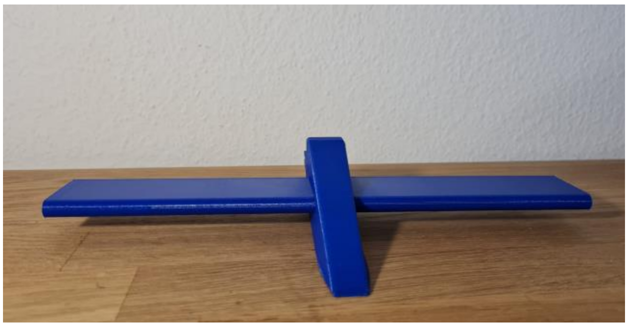


Figure 22: Final Front Wing 1

6.3 Front Wing 2/Angle of Attack

All the following front wings were designed and assembled exactly like front wing 1, therefore the focus from now on shall be the defining aspect about each front wing and its expectations. The slot in the nose was adjusted from nose to nose to fit the newly designed wings, but the overall shape of the nose stayed the same.

Front wing 1 had a completely straight wing, but looking at real Formula One cars one notices very quickly that they are set with a certain angle. This is called the angle of attack of the airfoil and can be seen in figure 23.

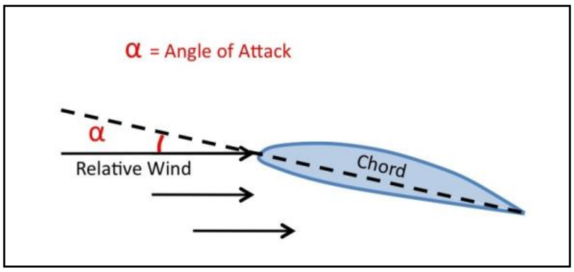


Figure 23: Angle of Attack [12]

The defining aspect of front wing 2 is that it has an angle of attack of minus 20.5 degrees, which is what my hypothesis was for the critical angle of attack. The lift coefficient of an airfoil gets higher with increasing angle of attacks, until the point where the airflow separation caused by the angle is larger than the benefits gained. This turning point is the critical angle of attack [13] and can be seen in figure 24 as the peak of the graph. This value was estimated using my gained theoretical knowledge for this project, talking with multiple experts, and the known critical value for similar airfoils, since this angle differs from airfoil to airfoil [13]. A very high angle of attack has been chosen since it would be more interesting to see a decrease in downforce because of a too high angle of attack, than not reaching the critical value at all. The final 3D model can be seen in figure 25. The 3D models have been decided to be shown here, not the printed and assembled front wings, since it is easier to see the differences between them using the 3D models.

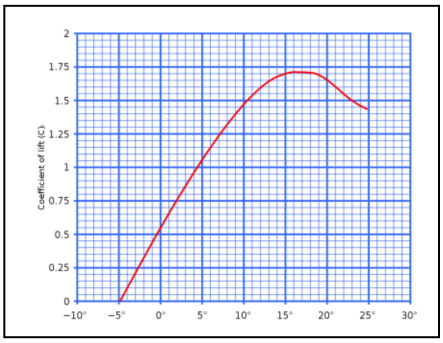


Figure 24: Lift Coefficient Graph [13]

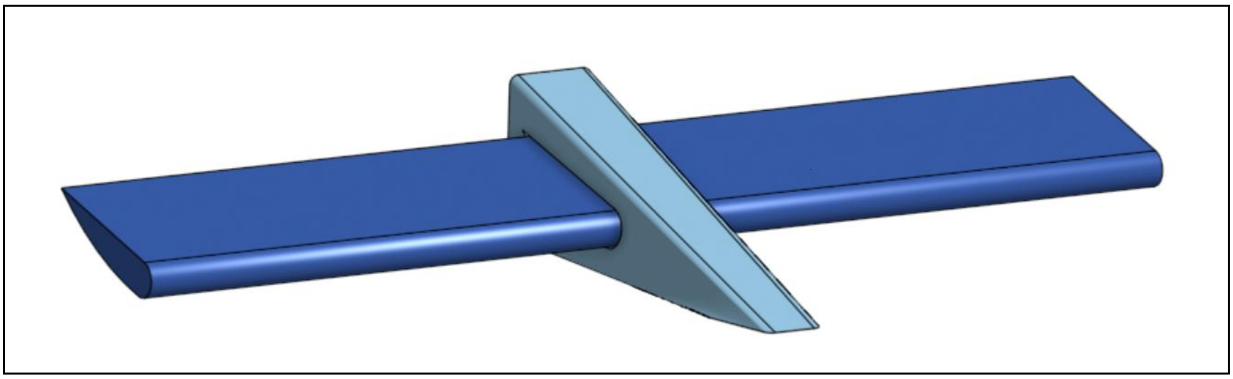


Figure 25: Front wing 2

6.4 Front Wing 3/Wing Tips

The defining factor of this front wing are wing tips, which are elements attached to the end of the wings. One goal of wing tips in a Formula One front wing besides creating downforce is to divert the air around the car. The important difference in the design between those kinds of wing tips and the one in this front wing is where they are situated. In Formula One they are mostly on the top of the wing, whereas in these wings, the wing tips shall reach as close to the ground as possible. In technical Formula One terminology these are then not called wing tips, but endplates. The goal of these wing tips is to protect the low-pressure area under the wing by disconnecting it from the high-pressure area on top of the wing. Another phenomenon known as ground effect should be increased drastically through these wing tips. Ground effect is the phenomenon mostly used in diffusers [2], but it may also play a role here and therefore the hypothesis was made that this front wing would create more downforce than the basic one. It can be seen in figure 26.

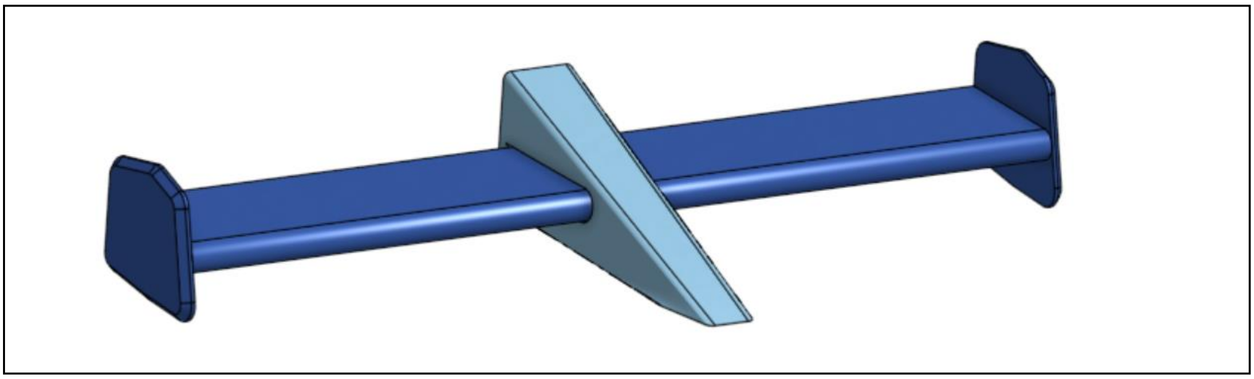


Figure 26: Front Wing 3

6.5 Front Wing 4/Multiple Wings

This is the most different front wing from the basic one. There are multiple wings, 2 per side instead of one, but the wings are much smaller in size. Still, as the only one of the 5 front wings, the total surface area of these 4 wings together is slightly bigger than the basic wing. 17 percent higher to be precise. This was the case since while designing the wings and fitting them onto the nose, this size seemed to work the best. The wings are set up on the nose close together but still completely above each other. The hypothesis for this front wing was that it would be significantly worse than the rest of them. This conclusion was reached, thinking about what happens to the air when it flows under the wing. Flow separation results in a turbulent wake of air behind it and turbulent air is very much not ideal to create downforce [2]. The front two wings would probably experience flow separation at some point, even if they are straight, leaving a turbulent wake behind them. That’s why it was hypothesized that the 2 wings behind wouldn’t work and therefore this front wing wouldn’t be very effective. The fact that the wings are above each other was also taken into consideration, but the conclusion was reached, that the airflow would still disturb the latter two wings. The final front wing can be seen in figure 27.

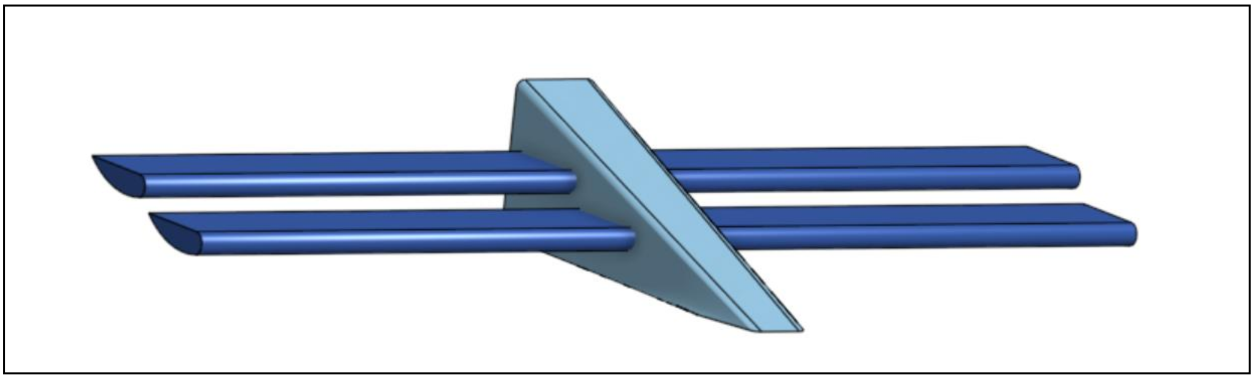


Figure 27: Front Wing 4

6.6 Front Wing 5/Angle of Attack + Wing Tips

The thought process behind the final front wing was the simplest one of them all. It was hypothesized that front wings 2 and 3 would both improve the amount of downforce created in comparison to the basic front wing. Therefore, it was concluded that both of them together would improve the downforce creation the most, meaning that this front wing would produce the most downforce. The final product can be seen in figure 28.

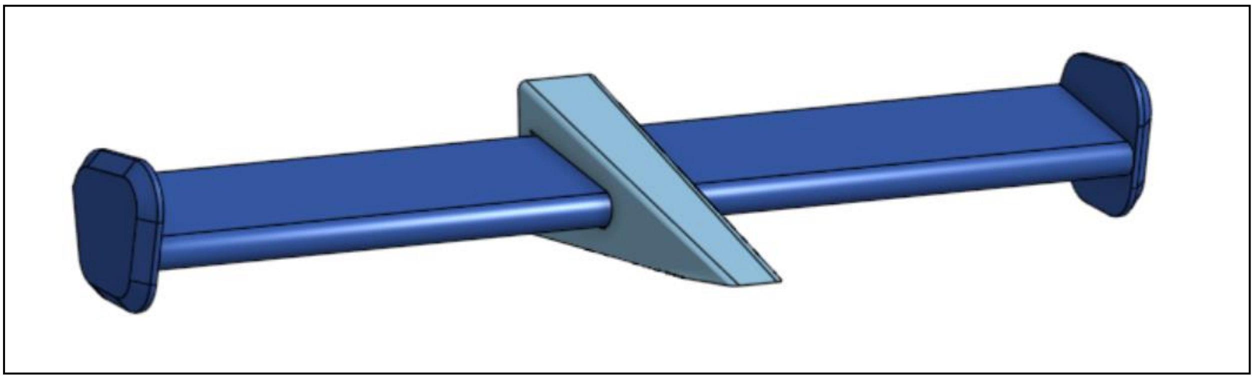


Figure 28: Front Wing 5

6.7 Rear Wing

The rear wing was made using the same concepts as the front wing. It is a lot more complicated since it has to be higher, as rear wings always are. The rear wing of this model car is extremely high up, this was done on purpose to try to avoid the turbulent air created by the rest of the car seeing as the car does not have any body panels. Still, to try to see any effect from the rear wing, it has a 20 percent larger surface area than front wing 1. The rear wing can be seen in figure 29. Some elements have been set to be slightly translucent to show the connecting mechanism between the separate parts.

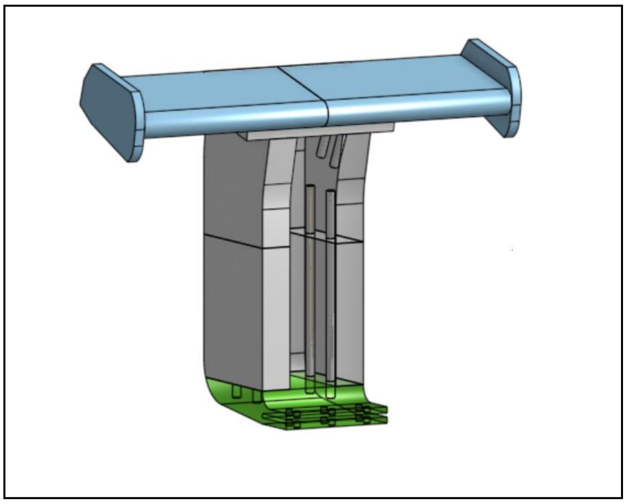


Figure 29: Rear Wing

6.8 Overview

All in all, there are five front wings which have to be tested, as well as one rear wing. Front wing 1 should give a base value from which all the other ones will be compared too. The wings shall be attached to the car using a mechanism involving screws and therefore be easily replaceable. All the front wings printed and assembled can be seen in figure 30. The colors do not have any specific purpose, they are just what was available in the 3D printer at the time.

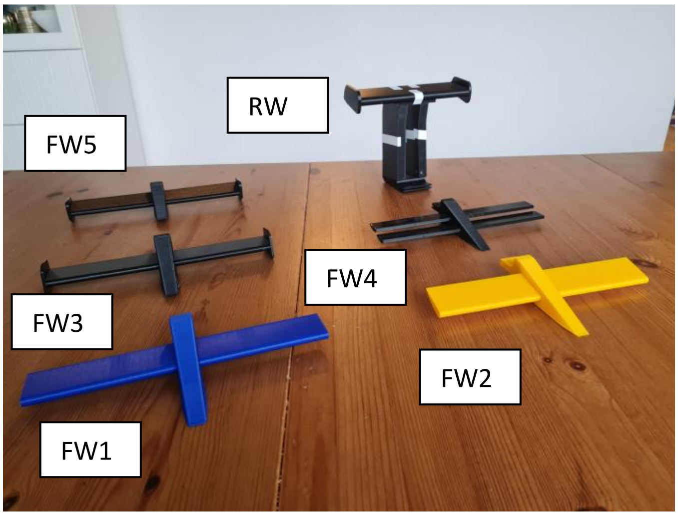


Figure 30: All the Wings

7 Wind Tunnel Testing

7.1 What is Wind Tunnel Testing?

Wind tunnel testing is a method for testing the aerodynamics of many things, one of these things is for testing the aerodynamics of a Formula One car. The applications go much further than this though, this method of testing has extensive uses not only in obvious industries such as the aviation industry, but they are also used to test, among other things, the aerodynamics of buildings [14].
Wind tunnels usually work using large fans to create a laminar airflow in some kind of tube, where the object is held stationary. The forces experienced by the object can then be measured, as well as a multitude of other things as shall be seen later in chapter 8. Wind tunnels can be less than a foot wide but can also been 30 m wide, with wind speeds reaching from walking speed to faster than the speed of sound [14].

7.2 ZHAW`s Wind Tunnel

The wind tunnel, which was used for this project, is operated by the ZHAW, the Zürich University of Applied Sciences. The wind tunnel is part of the aviation department at this university. More information about the wind tunnel used for this project, such as the technical data, is available on their website (https://www.zhaw.ch/de/engineering/institute-zentren/zav/air-vehicle-design-and-technology/aerodynamik/labor-alfa/) [15]. The maximum size of an object which can be measured in the tunnel is 1.2m x 0.9m x 0.6m(x, y, z), which is more than big enough for the model in this project. The maximum wind speed is 50m/s, which is 180 km/h [15]. This is much higher than the speeds which would need to be tested on for this model car. The wind tunnel can be seen in figure 31.

Fig 31: ZHAW Wind Tunnel [15]

7.3 Measuring the Forces

The goal of this project was to see what effect the different front wings have on the downforce produced. To accomplish this, the downforce produced by each configuration would have to be measured and then compared. The forces would be measured using a scale which is part of the wind tunnel ground. The scale measures the forces experienced in the x, y, and z directions. The technical data about the exact scale which was used can be found in the appendix.

7.4 Preparing the Car for the Wind Tunnel

The following list of things to think about was created after multiple meetings with Professor Leonardo Manfriani, the former head of aviation at the ZHAW, and the wind tunnel assistant, Mr. Marco Caglioti:
All wheels have to be turning at the same speed. This is necessary to simulate the conditions the car experiences while driving on the road. The speed of the wheels have to be known to regulate the wind speed, since the wind speed should be as close as possible to the wheel rotation speed. This is to simulate the real-life situation of a car driving on the road as closely as possible. They also requested technical sketches of the whole car as well as the expected forces to be exerted on the scale, to ensure that no limits of the scale would be crossed. The suspension has to be non-elastic, because otherwise the forces change depending if the car is on the ground or if the car is suspended. The car has to be stable, meaning that vibrations should be kept to a minimum to ensure good measurements. Finally, the car would have to be attached to the scale using an adapter, which I would have to provide.

Wheel Rotation

The problem that the car was a rear wheel drive and had to be converted into a 4-wheel drive for the wind tunnel was easily solved, since the original model car from which the front and rear of the model were harvested from, was a 4-wheel drive. Therefore, a driving shaft could be easily inserted from the front to the rear of the car. The driving shaft from the original had to be slightly lengthened since the model is longer than the original RC car. This was done by the physics mechanic at our school, Mr. Tobias Werner. The extended driving shaft can be seen in figure 32.

Figure 32: Extended Driving Shaft

The maximum speed of the wheels was calculated using the maximal rpm of the wheels, which was measured using a tachometer. The maximum rpm of the wheels was measured to be about 4940 rpm and the maximum speed of the wheels was calculated to be 15.51 m/s by using these formulas:

$$v = w \cdot r$$
$$w = 2\pi f$$

$v = velocity\ in \frac{m}{s}$

$w = angular\ speed\ in \frac{rad}{s}$

$r = radius\ in\ m$

$f = frequency\ in\ Hz$

The radius of the wheels is 0.03m and the frequency, which is calculated by dividing the rpm through 60, is 82.3¯Hz. 15.51m/s is about 56 km/h.

Providing specifications for ZHAW

The ZHAW required only a very broad estimation of the forces to be expected. That`s why it was decided to choose extreme cases to calculate a minimal and maximal air resistance and downforce, which are the 2 forces they requested an approximation for. An estimation for the torque was also required since the scale is very sensitive towards such forces. What is meant by extreme cases, is for example for air resistance the upper bound was calculated by calculating the air resistance of a cube with the same cross-sectional area as the car. The actual air resistance experienced by the car then has to be lower than this value. Using the formulas for downforce and air resistance as described in chapter 4.7, the following estimation of forces was calculated and sent to the ZHAW:

Expected forces from air resistance	0.406N - 6.827N
Expected forces from downforce	-0.217N - -1.965N
Expected torque	0 - 0.458Nm towards front of car

Figure 33: Estimation of Forces

The effects of ground effect were also calculated, but were deemed to be too little to include, since the upper bound for downforce was already much higher than realistically to be expected.
The top, side, front, and rear views of the car were sketched. All the relevant dimensions such as maximum length or distance between the wheels could be found in those sketches. These technical drawings as well as my calculations for the expected forces can be found in the appendix. They are no longer completely accurate though since some things were changed later. The following summary was sent to the ZHAW as they wished:

Maximum height	140mm
Maximum length	662mm
Maximum width	255mm
Weight	1700g

Figure 34: Dimensions of Model

The length and width are still accurate, the weight and height of the car are not completely correct anymore, after completely preparing the model for the wind tunnel.

Replacing Suspension

To replace the suspension, connecting rods were 3D printed, which could be attached to the car exactly the same way as the suspension. Many rods were printed so that the height of the wheels could be adjusted so that the wheels would be as close to the ground as possible in the wind tunnel, to further improve the accuracy of the experiment. The 3D model can be seen in figure 35.

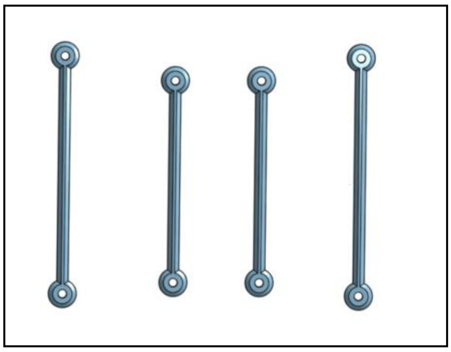


Figure 35: Suspension replacement

Adding Stability

To add additional stability Mr. Caglioti recommended adding metal profiles to the bottom of the car, going from the front of the car all the way to the rear of it. This turned out to be the perfect solution to the problem that the car was vibrating too much. These metal profiles under the car can be seen in figure 36. The vibrations did not fully go away as we shall see while looking at the data, but they were drastically less than before adding them.

Figure 36: Profiles

Adapter for Wind Tunnel

The adapter for the scale was created completely by our physics mechanic, Mr. Werner. It is attached to the car using 2 M8 screws with a distance of 35 mm between them, and it is attached to the wind tunnel ground using 6 M8 screws. The 3D model can be seen in figure 37. The dark blue part was 3D printed; the light blue part on the bottom was made out of metal. The grey plate is a sample part of the aluminum plate of the model. The raindrop shaped part would be above the wind tunnel ground, therefore affecting the measurements, and that's why an aerodynamic shape such as a raindrop was chosen for this part.

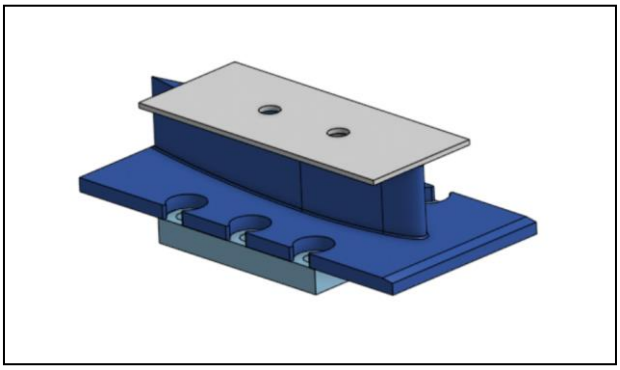


Fig 37 – Adapter for Wind Tunnel

7.5 Wind Tunnel Tests

In total, 16 runs were done. At first, the runs lasted 10 seconds, measuring with a frequency of 10 Hz, resulting in 100 measurement points. Later to save battery, it was decided to only measure for 5s with a frequency of still 10 Hz. All 5 front wings and the rear wing were tested separately. Then to see the effect the wings were having at all; one test was conducted with no aerodynamic components. To see how the two would combine, front wing 5 and rear wing were tested together. Additionally, to see the effect of wheel rotation each run was repeated without the wheels spinning. The car in the wind tunnel can be seen in figure 38. For each run, an Excel file was created. All the tests were conducted at 15.5 m/s so that the maximal wheel speed would equal the wind speed. The tests went flawlessly with the help of the wind tunnel assistant Mr. Caglioti, who accompanied me the whole time during the experiments. Each Excel file contains an extraordinary amount of information, including air pressure at different points, temperature, and airspeed. The most relevant data from the files for our purposes though, are the forces along the F_z axis, which is the downforce, and also the forces measured along the F_x axis, which is the air resistance. What was also done for front wing 5 was a visualization with smoke, to see how the air flows. This can be seen in figure 39.

Figure 38: Model in Wind Tunnel

Figure 39: Smoke Visualization

8 Results and Analysis

8.1 Comparison of Front Wings

In the following table, one can see the different amounts of downforce each front wing produced, as well as how much downforce was produced without any aerodynamic components at all. The wheels were not spinning in these values. Why the values without wheel spin have been chosen will be explained during the analysis. These values were calculated using the average of all measurements during the duration of the run in each category.

Test #	Description of Test	Downforce Produced in Newtons
1	No Aerodynamic Components	-0.22±0.050
2	Front Wing 1/Basic Wing	0.29±0.039
3	Front Wing 2/Angle of Attack	0.31±0.066
4	Front Wing 3/Wing Tips	0.44±0.050
5	Front Wing 4/Multiple Wings	0.58±0.048
6	Front Wing 5/Angle of Attack + Wing Tips	0.20±0.046

Figure 40: Table comparing Front Wings

What is already obvious to be seen at first glance, is the fact that with no aerodynamic components we have a negative downforce, meaning a lift force was created by only the chassis. All the other wings created downforce. The same data displayed as a graph to show the differences visually can be seen in figure 41.

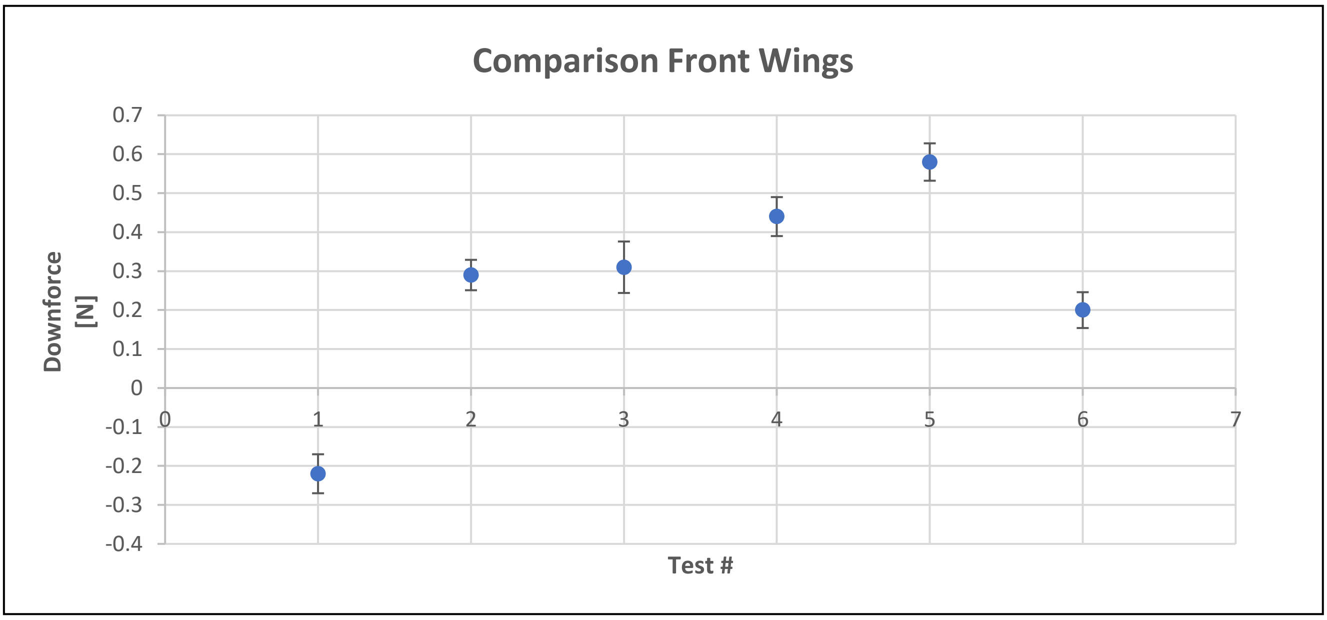


Figure 41: Graph comparing different Front Wings. The capped lines vertically going through each data point is standard deviation. Test #1 is with no wings, Tests 2 till 6 are front wing 1 through 5.

8.2 Analysis of Front Wings

As already mentioned before, the chassis alone creates a slight lift force. This makes sense seeing as since the car had no body panels, the air above the main part of the car was probably very turbulent and turbulent airflow is often the reason for lift generation [2]. This combined with the fact that there were no components meant to create downforce, explains why the chassis wasn`t at exactly zero (no lift or downforce). In contrast to this, all the front wings worked since they all produced a certain amount of downforce. To see the true amount of downforce produced by them therefore, one has to take the difference between the value for only the chassis, -0.22, and the value for the specific front wing.

8.2.1 Analysis of Front Wing 1

Front wing 1 produced 0.51N of downforce, providing a good base value for all the other ones to be compared to. In this regard front wing 1 fulfilled its goal and this base value shall be mentioned multiple times while talking about the other wings. All my calculations for the wind tunnel for the downforce approximation were based on this front wing, so it is interesting to see that the calculation of a maximum of 0.65N of downforce to be generated was almost reached.

8.2.2 Analysis of Front Wing 2

Front wing 2 produced 0.53N of downforce, only 0.02 more than front wing 1, and seeing as the standard deviation of front wing 2 is also larger, one can say that these two wings had the same effect on the downforce produced. This is not what was expected, the hypothesis was that increasing the angle of attack would increase the downforce produced. Since this is clearly not the case, a mistake must have been made while deciding the angle of attack for the wings. This must be the case, since increasing the angle of attack does increase downforce production up to a certain critical moment, which was described in detail in chapter 6.3 [13]. The assumption that 20.5 degrees would be the critical angle of attack where the lift coefficient would be maximum though, has been proven to be wrong through the results of front wing 2. This means the critical angle of attack for this wing is lower than 20.5 degrees. This must be the case, since such a large increase in angle of attack would never make such a small difference in the amount of downforce produced, if the critical value were not to be reached yet. On a theoretical level this means the amount of flow separation experienced by the airfoil at this angle of attack was higher than the benefits gained from it [13]. This is an interesting conclusion to see since all the people I asked, who have no knowledge of Formula One aerodynamics, said that front wing 2 would be much better than front wing 1 and that an even higher angle of attack should be chosen. The results prove this approach to be incorrect to maximize downforce.

8.2.3 Analysis of Front Wing 3

Front wing 3 produced 0.66N of downforce, slightly more than the previous 2. This was expected to be seen. The only thing different about front wing 3 are the wing tips, with the goal of protecting the low-pressure area under the wing, and this 29 percent increase in downforce produced compared to front wing 1 can be explained through this phenomenon. The increase in downforce produced by ground effect leads to a 29 percent more efficient front wing with wing tips than without them.

8.2.4 Analysis of Front Wing 4

Front wing 4 produced 0.8N of downforce and was therefore by far the best wing, producing about 60 percent more downforce than the basic wing. This is in stark contrast to the hypothesis that this would be the worst wing. It has a 17 percent higher surface area than the basic wing, and if looking at the equation to calculate downforce, this could also be expected as the increase in downforce. But the actual measurement has an increase which is approximately 3 times bigger than the expected 17 percent increase, which would only be possible if all 4 wings worked perfectly and weren't influenced by each other. This means these smaller wings have a different coefficient of lift somehow. This might be explained by the fact that the wings are smaller, meaning that airflow separation happens later during the airflow, or ideally, not at all. Why airflow separation might be happening later can be explained when thinking about what happens in the gap between the first and second wing. This gap allows air to flow from the top to the bottom of the wing, therefore eliminating the pressure differential. This is not ideal if one thinks about it superficially, since don't we want a large pressure differential resulting in a larger downforce? This is true but a large pressure differential comes at the cost of airflow separation [16]. Allowing the pressure to bleed out between the wings nullifies the pressure differential and could therefore delay airflow separation significantly. The fact that while watching this front wing it was noted that it vibrated the least of all the front wings, supports this idea. Flow separation causes turbulent air [2] which than could cause vibrations, less vibration could mean less flow separation.

A further factor which might have contributed to this front wing being the best one was discovered while investigating the CAD model. An error was made by me while designing the wings for this front wing and the airfoil shape is not exactly the same (see figures 42 and 43)

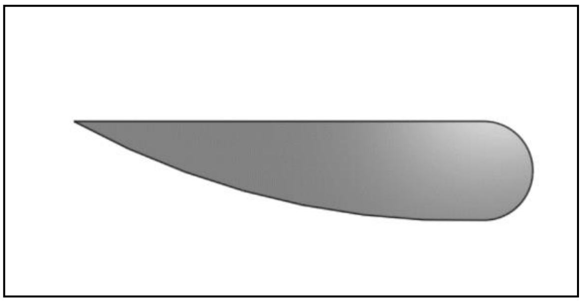


Figure 42: Airfoil Shape for all big Wings

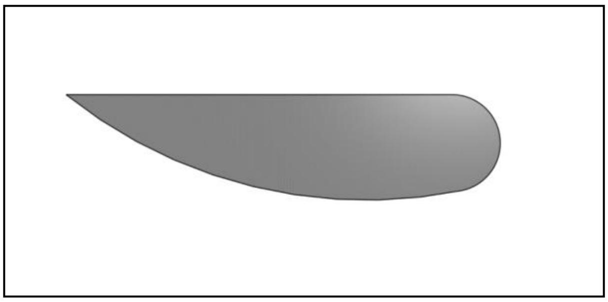


Figure 43: Airfoil Shape for smaller Wings

This difference in airfoil shape probably also had a difference in the amount of downforce produced. This rounder kind of airfoil might have worked well with the smaller wings since the pressure differential was less, more curvature could be allowed without airflow separation happening. But it is also possible that this kind of airfoil is not as efficient as the normal airfoil, this can unfortunately not be found out by the data gained, since the difference in this front wing in comparison to the other ones can be explained by multiple factors. I believe that the increase in surface area, airflow separation happening later or not at all, and the different airfoil shape all contribute positively to this being the most effective front wing. This is because I believe the different factors alone are not enough to make these wings so efficient. This can unfortunately not be said with certainty.

8.2.5 Analysis of Front Wing 5

If one only looks at the data provided before, front wing 5 seems to have the most surprising result. It was predicted that this would be the most efficient front wing, but this hypothesis was obviously going to be proven incorrect after seeing front wing 2 not improving the amount of downforce produced. Nevertheless, it should not be the case that this front wing is less than half as efficient as the rest of the front wings. This is also not the case in reality. In reality front wing 5 is slightly better than the basic front wing, but slightly worse than front wing 3 with wing tips. How this conclusion is reached will become clear once we see some other results, such as when front wing 5 and the rear wing were tested together. Why there was a problem with the measurements in this exact measurement could not be figured out. This front wing being slightly more efficient than front wings 1 and 2 can be explained since these wings also have wing tips, and as seen in front wing 3, these have been proven to improve downforce production. Why it does not completely reach front wing 3`s values is not as clear. It might be because wing tips are less efficient on wings with a higher angle of attack, which could be caused by the fact that airflow separation occurs earlier in airfoils with a high angle of attack. Front wing 5 was also the only front wing for which the airflow was visualized by injecting smoke. In the visualization seen in figure 44 one can see the airflow separation happening very early, which is the decisive factor in front wing 5 and 2 not being much more efficient than front wing 1. If airflow separation were not to happen, the smoke would follow the bottom edge closely and there would be no gap between the wing and the smoke.

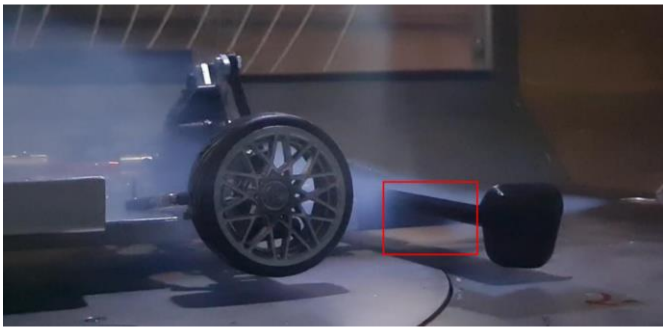


Figure 44: Airflow Separation visible through Smoke Visualization

8.2.6 Standard Deviation

The standard deviation in the data provided is quite high, ranging from 8% to 23%. This large and also varying standard deviation can be easily explained when looking at the reason behind it. The main 2 factors behind this standard deviation are vibrations and measurement errors. The vibrations are caused by the aerodynamics of the model, one of the factors most likely being airflow separation occurring along the wings. Airflow separation leads to turbulent air [2] which could then lead to vibrations. This would be supported by the data, since front wing 4 has a very low standard deviation and it was noted during the wind tunnel test that front wing 4 experienced exceptionally less vibrations in comparison to the other front wings. In contrast to this, front wing 2, which experienced early flow separation, vibrated strongly. This difference could be seen visually very well and can be confirmed by the standard deviation in the data. Another factor is just measurement errors. If one plots the data as a function of time, the corresponding graph does not look like a perfect sine wave (see figure 45). If it looked like a perfect sine wave, than one could say that the standard deviation was caused only by the vibrations and nothing else.

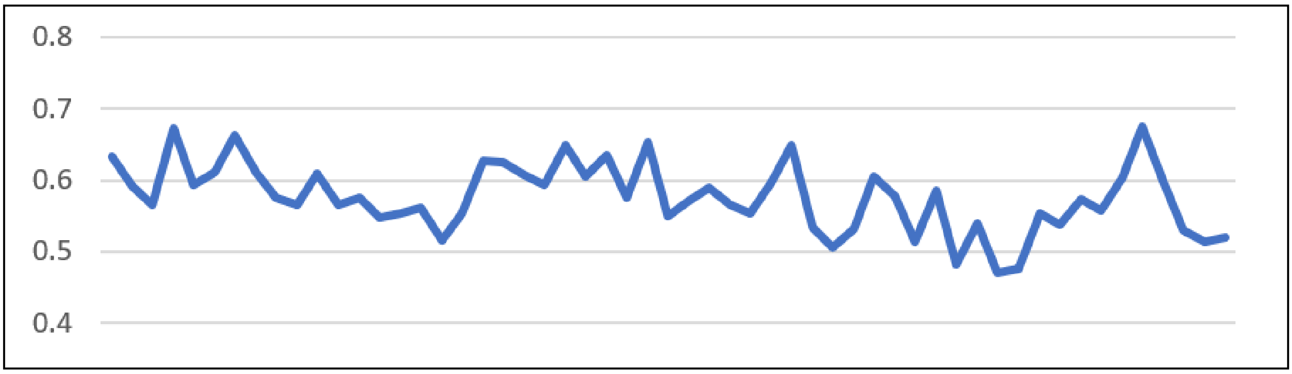


Figure 45: Measurements as a function of time over 5s. Left one can see the amount of downforce measured. Data taken from front wing 4 without wheel spin, where the least vibrations were visible.

8.3 Effect of Wheel Spin

The wheels of a Formula One car have a massive influence on the car. However, what influence do the wheels spinning have on the model? The difference in measured values between the runs with and without wheel spin can be seen in the following table:

Test #	Description of Test	Downforce Produced in Newtons without Wheel Spin	Downforce Produced in Newtons with Wheel Spin
1	No Aerodynamic Components	-0.22±0.050	-0.20±0.15
2	Front Wing 1/Basic Wing	0.29±0.039	0.44±0.12
3	Front Wing 2/Angle of Attack	0.31±0.066	0.44±0.14
4	Front Wing 3/Wing Tips	0.44±0.050	0.55±0.18
5	Front Wing 4/Multiple Wings	0.58±0.048	0.64±0.11
6	Front Wing 5/Angle of Attack + Wing Tips	0.20±0.046	0.50±0.13

Figure 46: Table showing Effect of Wheel Spin

For all the measurements with wheel spin, the wheels were spinning at the same velocity, namely 15.5 m/s. This data has been visualized in figure 47.

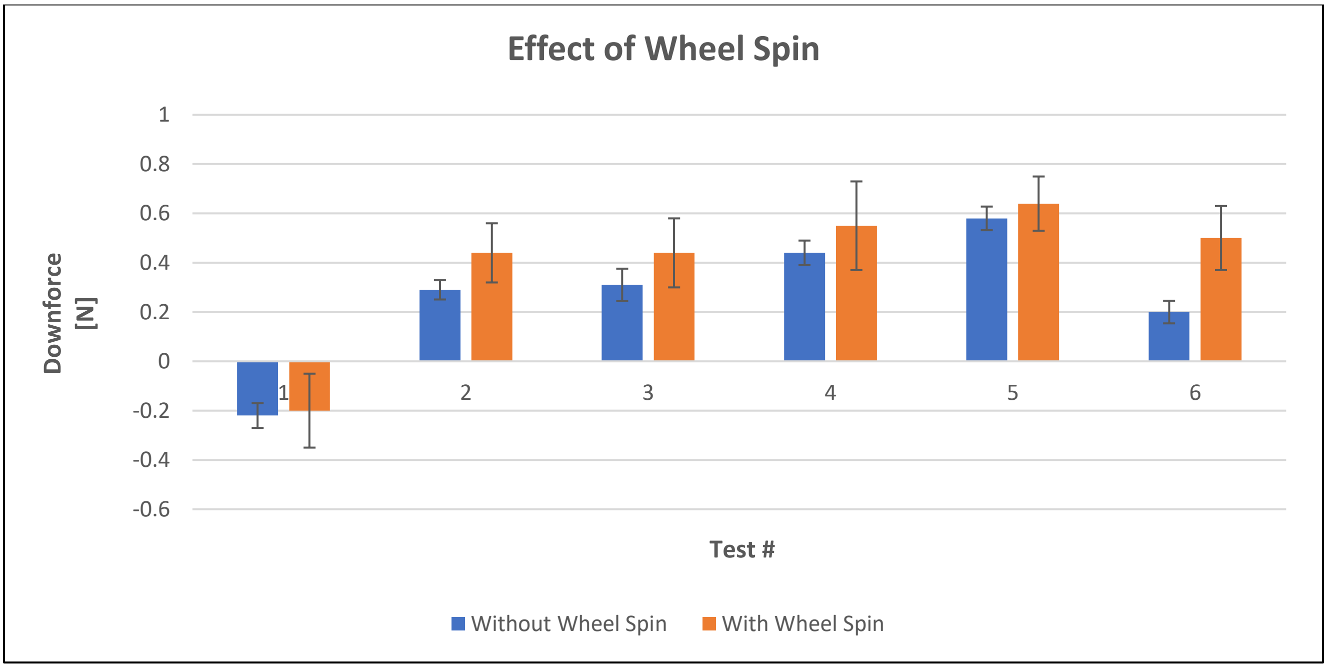


Figure 47: Graph showing effect of Wheel Spin. The capped line vertically going through each data point is standard deviation. Test #1 is without wings, Tests 2 till 6 are front wing 1 through 5.

8.4 Analysis of Wheel Spin

“Open wheels are aerodynamically the worst thing for Formula One cars”. This is something which I heard again and again from multiple experts. But if one looks at the data generated, it is obvious from a first glance that in all cases, the downforce produced by the wheels spinning in my model was higher than without the wheels spinning.

This fact, which is consistent along all the measurements, is very confusing to see but might be explainable if one compares my model to a real Formula One car, as well as when one considers the testing environment. A real Formula One car obviously has an extremely aerodynamic body, meaning that the air flow around the car itself stays laminar. My car does not have any body panels and is not optimized at all to keep the airflow around the car laminar. That might be the reason why the additional effect of the wheels making the air above the car turbulent does not make a difference, since the body of the car already created so much turbulent air.

The car was tested in a wind tunnel, meaning it was raised above the ground slightly. This is a big alteration from reality, and these kinds of errors will be discussed in more detail in chapter 9. This slight amount of space beneath the wheels could enable an effect which can be seen in multiple areas of life, most famously in sports. This is namely the fact that if something is spinning, the air gets accelerated along the direction the object is rotating [17]. This air will be faster than the air above the wheels than, and therefore according to Bernoulli`s principle an area of lower pressure would result under the wheels and therefore the car. This is known as the “Magnus Effect” and is visualized in figure 48. Here it is visualized using the effect of top spin on a tennis ball. This effect does not take place if the car is on the ground, and since it is believed that this is the sole cause for the results with wheel spin always producing more downforce, the values for the analysis of the front wings were taken without wheel spin. Those values are most likely closer to the actual amount of downforce produced by the car.

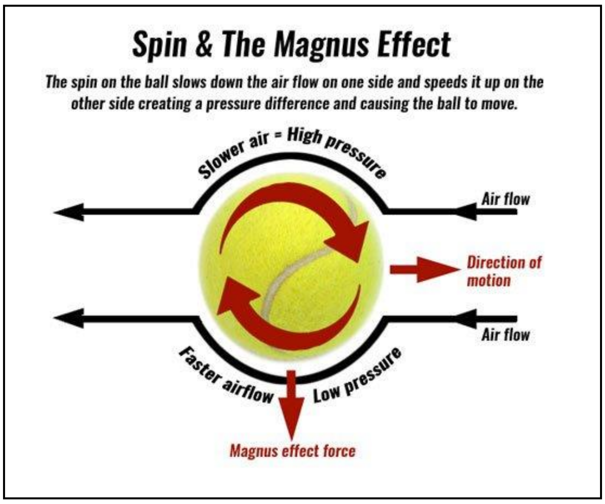


Figure 48: Magnus Effect [17]

The standard deviation of the data with the wheels spinning is much higher, which makes sense with the wheels spinning the car vibrated quite aggressively, while without the wheels spinning, the vibrations were much less.

8.5 Effect of Rear Wing

The most interesting part about the rear wing for me was how it interacts with the front wing. Since front wing 5 and rear wing was the only combination tested, in figure 52 one can see the data for front wing 5 and the rear wing separately as well as the effect of both of them together. The data for this table was chosen to be with the wheels spinning, since as mentioned before there seems to be an issue with the measurement for front wing 5 without wheel spin.

Test#	Description of Test	Downforce produced in Newtons
1	Front Wing 5	0.50 ± 0.13
2	Rear Wing	0.53 ± 0.17
3	Front Wing 5 + Rear Wing	1.21 ± 0.16

Figure 49: Rear Wing Effect

The corresponding graph to visualize the situation can be seen in figure 50.

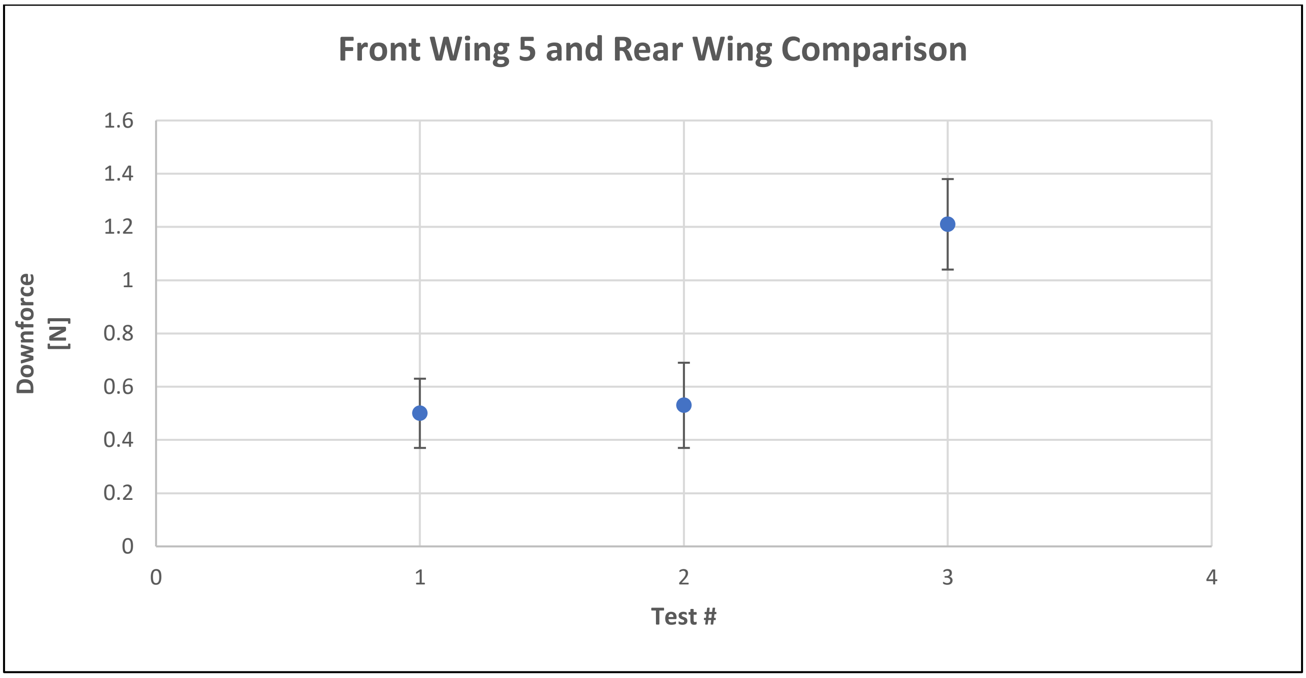


Figure 50: Graph about effect of Rear Wing. The capped line vertically going through each data point is standard deviation. Test #1 is front wing 5, test #2 is rear wing, test #3 is front wing 5 + rear wing.

8.6 Analysis of Rear Wing

The rear wing produced 0.73 N of downforce with the wheels spinning which is about 16 percent more than front wing 2. Front wing 2 has been chosen to compare with since it had the same angle of attack as the rear wing. Since the rear wing had a 22 percent higher surface area than front wing 2, this is slightly less than one would expect. But according to the hypothesis made, that the rear wing would be drastically less efficient than the front wings, this has been proven incorrect by this result. This is most likely because the rear wing is so high up, that the turbulent air created by the wheels and body of the car basically did not reach the rear wing. Why it is still slightly worse might be due to one or both of the following two factors. The first one is that the rear wing being larger than the front wing, might have experienced flow separation earlier than the front wing, the opposite reaction of what could have happened in front wing 4. The second decisive factor could be the design of the wing, the wing was held above the car using a supporting mechanism. This supporting mechanism is attached to the wing and may have reduced its efficiency.

One would expect the values of front wing 5 and the rear wing separately to give the value for front wing 5 and rear wing together when summed up. This is almost the case and is possible if one looks at the standard deviations of all 3 measurements. The only reason which could be thought of for these values not summing up is that one or multiple of the 3 measurements were not completely accurate and this would mean that it should be able to be seen in the standard deviation, which it can be, as mentioned before. The rear wing being so high up eliminated the idea of front wing 5 somehow affecting the airflow around the rear wing.

8.7 Effect of Aerodynamic Components and Wheel Spin on Air Resistance

Air resistance is not the focus of this project, but since the data was also measured and something interesting was noticed, it has been decided to still mention it. This data is taken as the average of the forces measured along the F_x axis. All the values before were averages of forces measured by the scale along the F_z axis. In the following graph one can see the air resistance forces for front wing one through five, as well as the rear wing and the situation when there are no aerodynamic components. Furthermore, one can see the effect of wheel spin on the air resistance of the model. In the following graph one can see the values of air resistance with wheel spin compared to the ones without wheel spin.

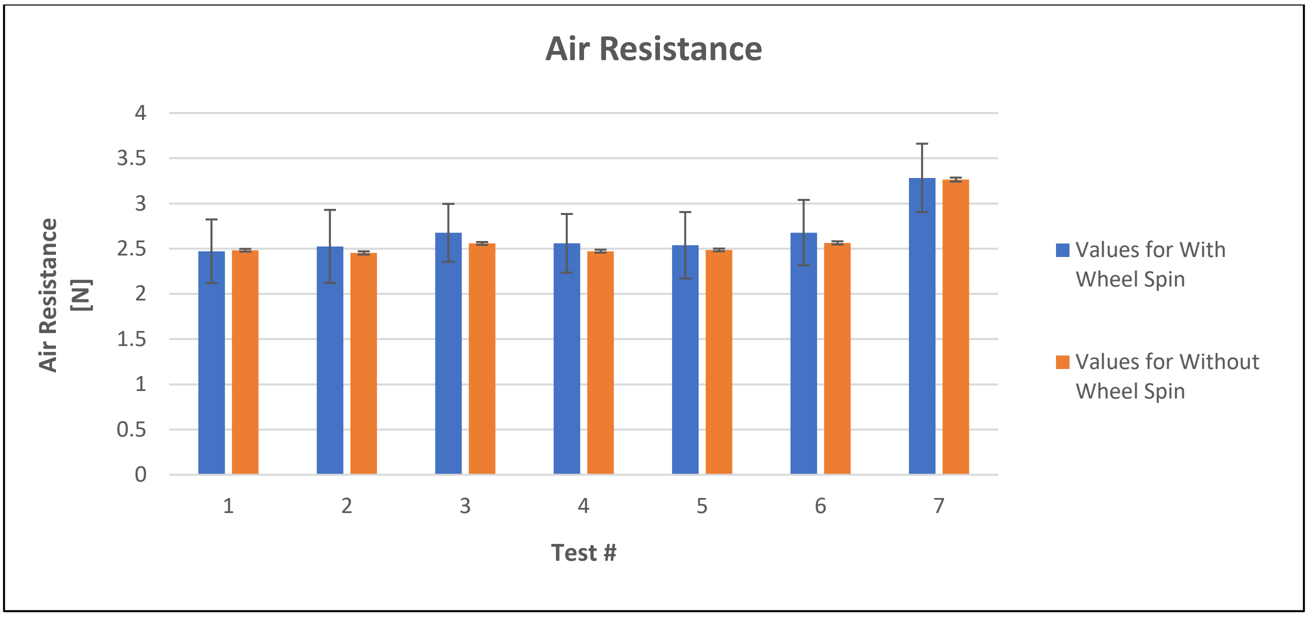


Figure 51: Air Resistance Graph. The vertical line going through each data point is standard deviation. Test 1 is without wings, test 2 to 6 are front wings 1 through 5 and the rear wing data can be seen in test 7.

8.8 Analysis of Air Resistance

What one notices straight away is that the rear wing, produced by far the most air resistance, which makes sense seeing as it was the largest wing. The supporting mechanism to hold the wing up was also a massive part producing a lot of drag. Tests 3 and 6 were the wings with an angle of attack, so it also makes sense that they produced slightly more drag than the rest of the wings, which were straight. Important to notice though is that even if there are differences between the different front wings, the majority of the air resistance is caused by the chassis, with the exception of the rear wing. This is because the difference between the different front wings is so small, that it is irrelevant compared to the total amount of air resistance experienced by the model.

What is very interesting to see is that the values with wheel spin are always higher than the values where the wheels were not spinning. This is most likely because the wheels turning cause turbulent air and turbulent air increases drag [2]. How the wheels spinning influences the air can be seen with the smoke visualization done for front wing 5 (see figure 52).

The standard deviation is higher with the wheels spinning for the same reason as downforce, the vibration caused by the wheels spinning were significantly more than the vibrations caused only by the aerodynamics of the model.

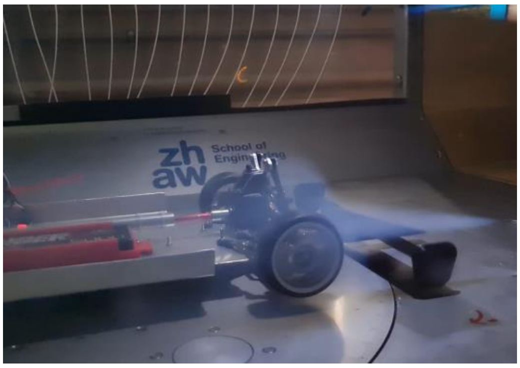


Figure 52: Wheel Spin Influence on Air

9 Conclusion

9.1 Were the Hypotheses correct?

If one looks at the three hypotheses which were formulated at the start of this thesis, one is correct, one is more or less correct and one is incorrect. The fact that the front wings only produced a very small but measurable amount of downforce is correct. Front wing 5 and the rear wing together producing 1.21 N of downforce with the wheels spinning is still a very small amount. If one looks at the total weight of the car, this is much less than even 10 percent of the total weight of the car being produced as downforce.

The rear wing was proven to be basically as efficient as the front wings. This is only because of the high position of the wing itself. The wheels produce a turbulent wake behind them has been proven to be true in other measurements as well as that turbulent air is not ideal to produce downforce is an undebatable fact [2].

A lot of the things I predicted were wrong, but most of these things are incorrect because of me not thinking far enough while formulating my predictions or designing the wings in a slightly incorrect manner. All of the theoretical things which are true for real Formula One cars, such as where flow separation occurs along the wing, have been proven to be applicable on a smaller scale, using aerodynamic components designed and made by myself. This is why this hypothesis was referred to as more or less correct, since the basic idea was correct, the execution was not perfect.

9.2 Validity of Results and Analysis

There is a limitation to what wind tunnel testing can do and what I as a person can do in this relatively short period of time. My results cannot be directly applied to a Formula One car first of all since the model is far from being an accurate replica. For this to be the case, there would have to be plenty more aerodynamic components and the model would have to be built considering Formula One technical regulations. Even then, a small-scale model would never perfectly simulate the situation as it is in a real Formula One car. The concepts which have been proven in this project though, are the same which are also important in the real sport. These concepts might not all be equally applicable to a Formula One car since the testing method used is not 100 percent accurate.

Wind tunnel testing is a very powerful method for testing the aerodynamics of a vehicle. It definitely has its own limitations as well, especially the one which I had the pleasure of using. The wind tunnel which the ZHAW has in their inventory is meant for testing a wide variety of things, not only cars. The wind tunnels which Formula One teams use are slightly different in that regard since they are only used to test the aerodynamics of Formula One cars.

The wheels slightly hovering above the ground in the testing environment has many consequences which make the data more unreliable than if the wheels were turning on the ground. Additionally, when a car is driving, the ground is also moving at the same speed as the car, relative to the car. The effect of this moving ground has some important consequences towards the aerodynamics of the vehicle. These 2 errors in how realistic my testing environment was are eliminated in real Formula One wind tunnels, such as the one in Hinwil, run by the Sauber Formula One team. Even those wind tunnels have their limitations too when it comes to replicating the highly complex situation of a Formula One car driving around a circuit at 300 km/h.

9.3 Were the Goals achieved?

The goal of this project was to learn about what effect the front wing of a self-built model car has on the downforce produced while testing different configurations. This goal was completely fulfilled by the satisfactory data achieved by the wind tunnel testing. The differences in downforce production between the different front wings were able to be measured. The tests showed that even at a relatively tiny scale, even small differences in the design of a Formula One style front wing, have a considerable effect on the amount of downforce produced.

All in all, this project showed me how the field of fluid dynamics and more specifically Formula One aerodynamics is a complex but incredibly interesting field of physics and engineering. In this fascinating field tiny differences can make the difference between creating a Formula One car which wins championships or finishes in last place.

10 References

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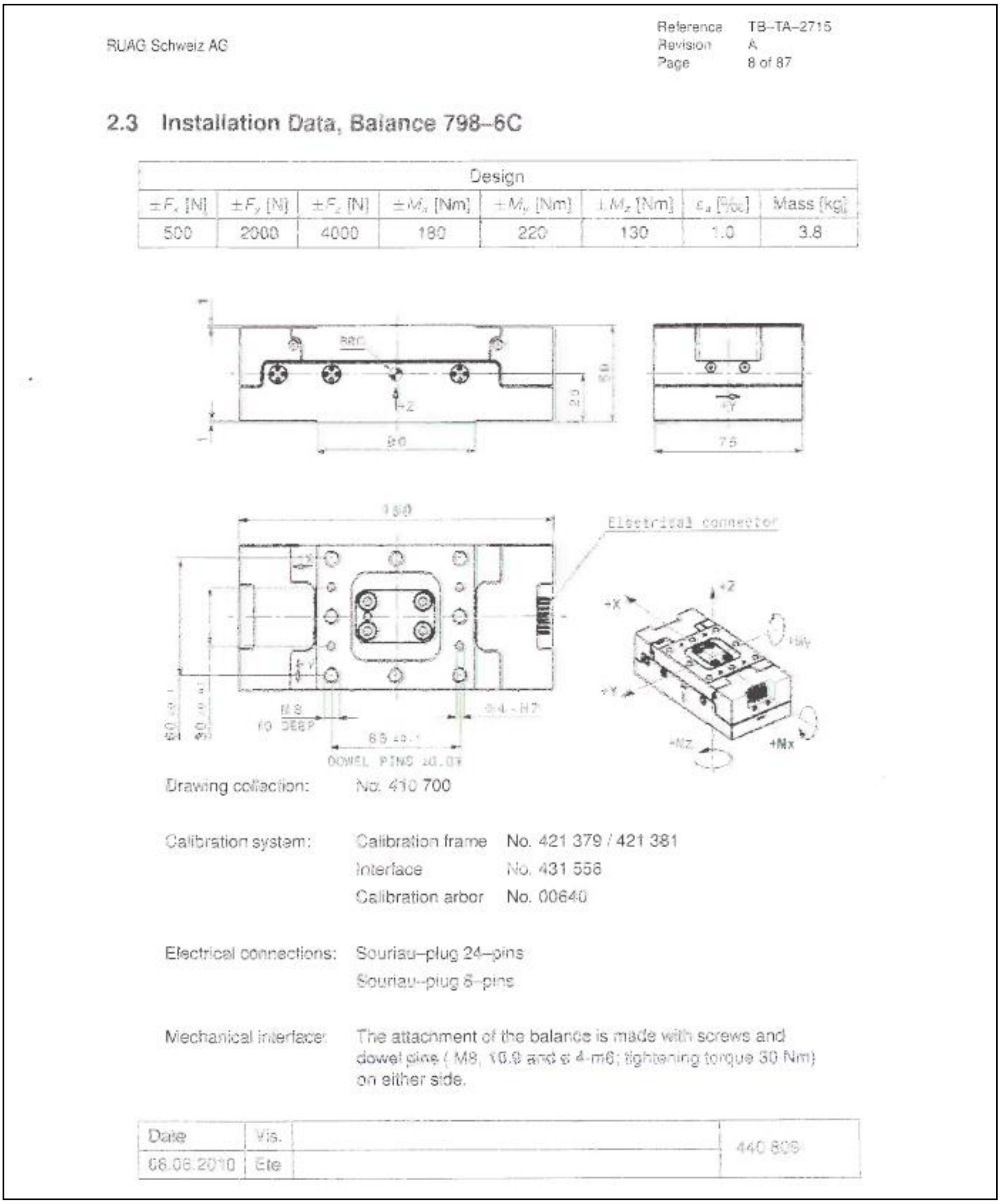
11 Appendix

Wind Tunnel Scale Specifications:



RUAG Schweiz AG

Reference TB–TA–2715
Revision A
Page 8 of 87

2.3 Installation Data, Balance 798–6C

Design							
$\pm F_x$ [N]	$\pm F_y$ [N]	$\pm F_z$ [N]	$\pm M_x$ [Nm]	$\pm M_y$ [Nm]	$\pm M_z$ [Nm]	ε_a [‰]	Mass [kg]
500	2000	4000	180	220	130	1.0	3.8

Drawing collection: No. 410 700

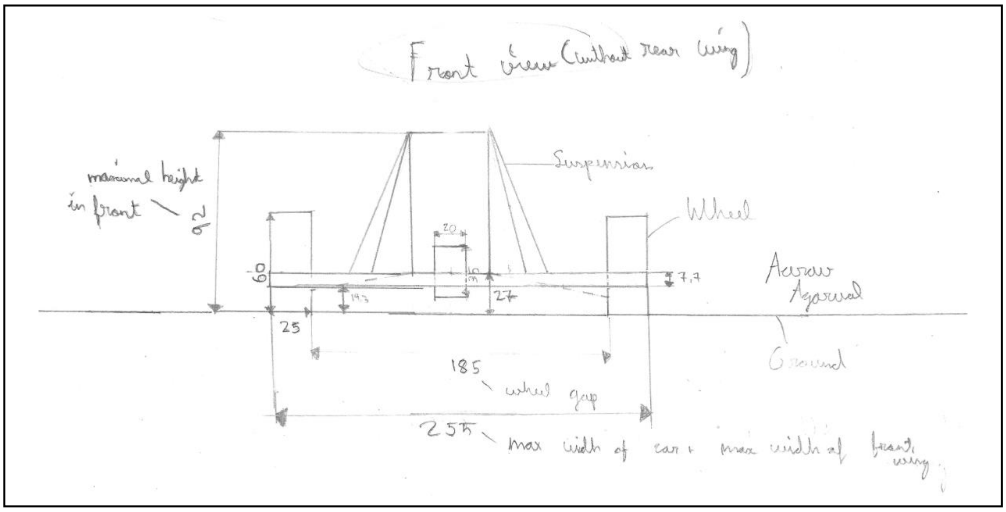
Calibration system: Calibration frame No. 421 379 / 421 381
Interface No. 431 556
Calibration arbor No. 00640

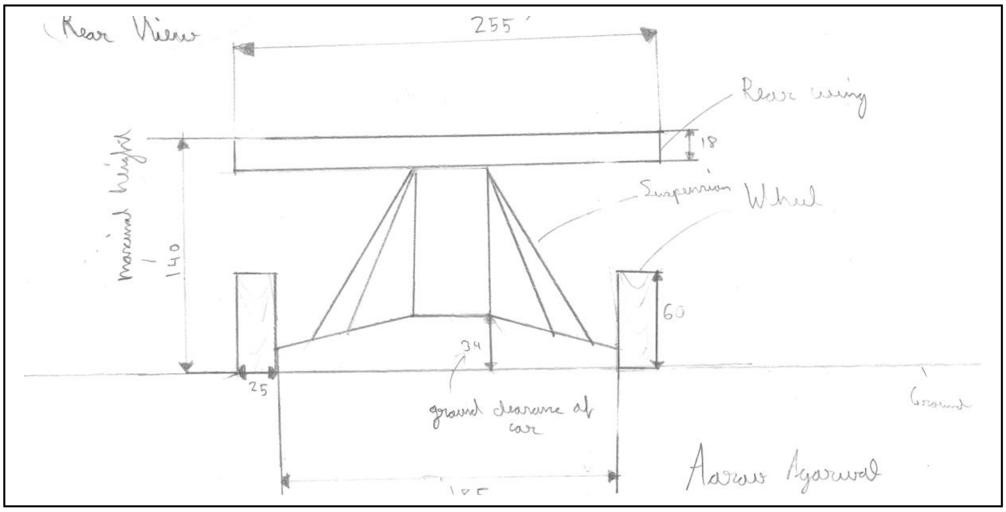
Electrical connections: Souriau–plug 24–pins
Souriau–plug 8–pins

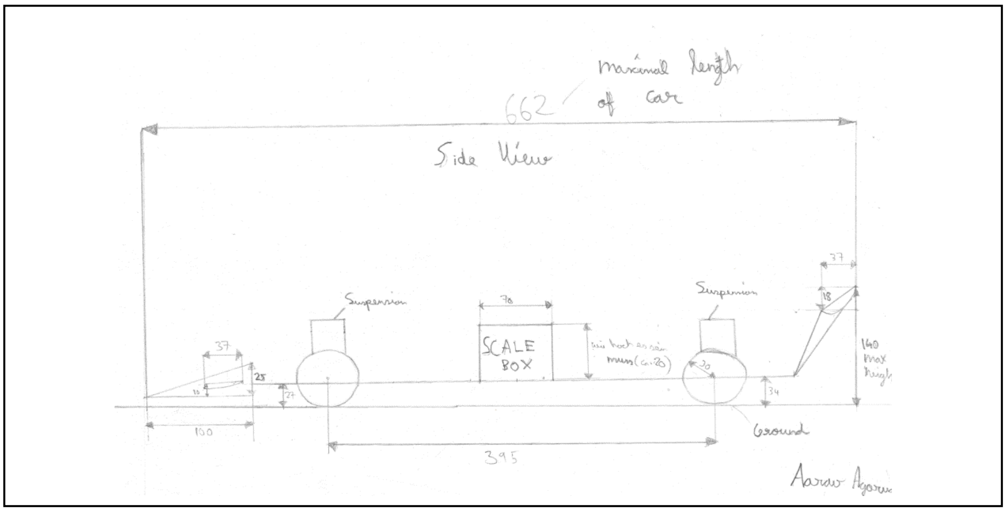
Mechanical interface: The attachment of the balance is made with screws and dowel pins (M8, 10.9 and ⌀ 4-m6; tightening torque 30 Nm) on either side.

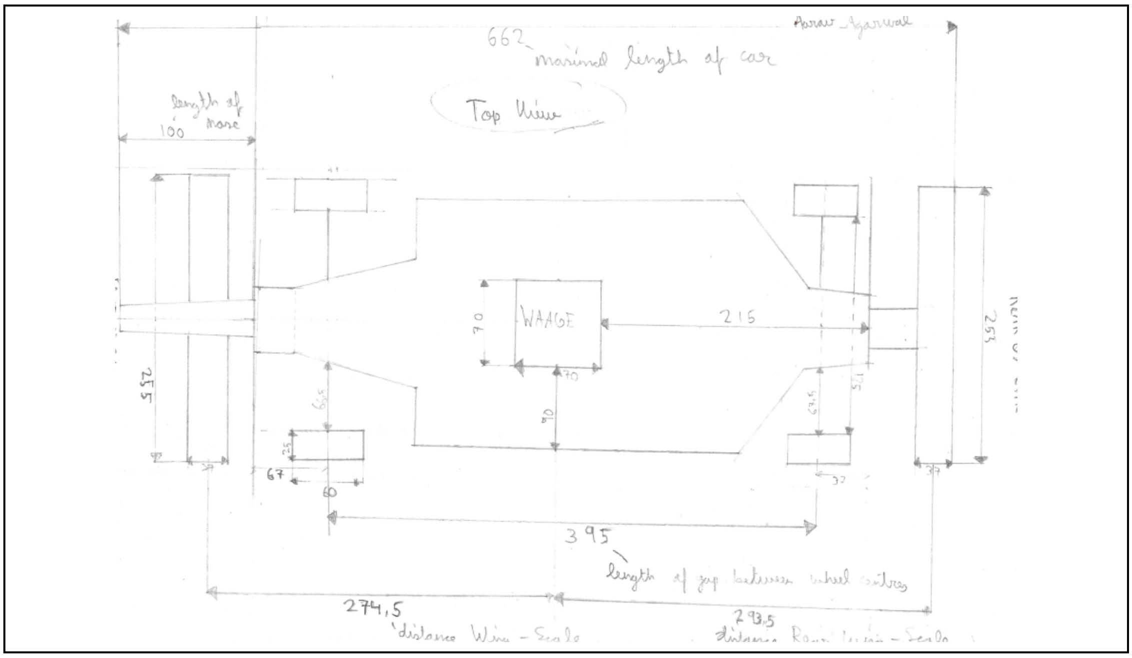
Date	Vis.		440 809
08.06.2010	Ete		

Technical Sketches of Car:



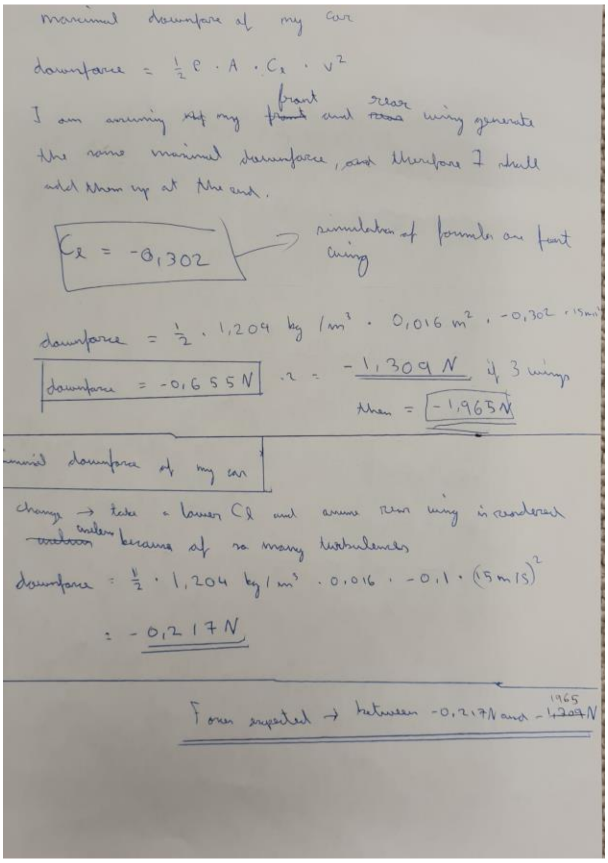






Calculations for Expected Forces:

Expected Downforce:



maximal downforce of my car

$$\text{downforce} = \frac{1}{2}\rho \cdot A \cdot C_l \cdot v^2$$

I am assuming that my ~~front~~ front and ~~rear~~ rear wing generate the same maximal downforce, and therefore I shall add them up at the end.

$$\boxed{C_l = -0{,}302}$$

simulation of formula on front wing

$$\text{downforce} = \frac{1}{2} \cdot 1{,}204\ \text{kg}/\text{m}^3 \cdot 0{,}016\ \text{m}^2 \cdot -0{,}302 \cdot (15\ \text{m/s})^2$$

$$\boxed{\text{downforce} = -0{,}655\ \text{N}} \cdot 2 = \underline{\underline{-1{,}309\ \text{N}}}$$

if 3 wings then $= \boxed{-1{,}965\ \text{N}}$

inimal downforce of my car

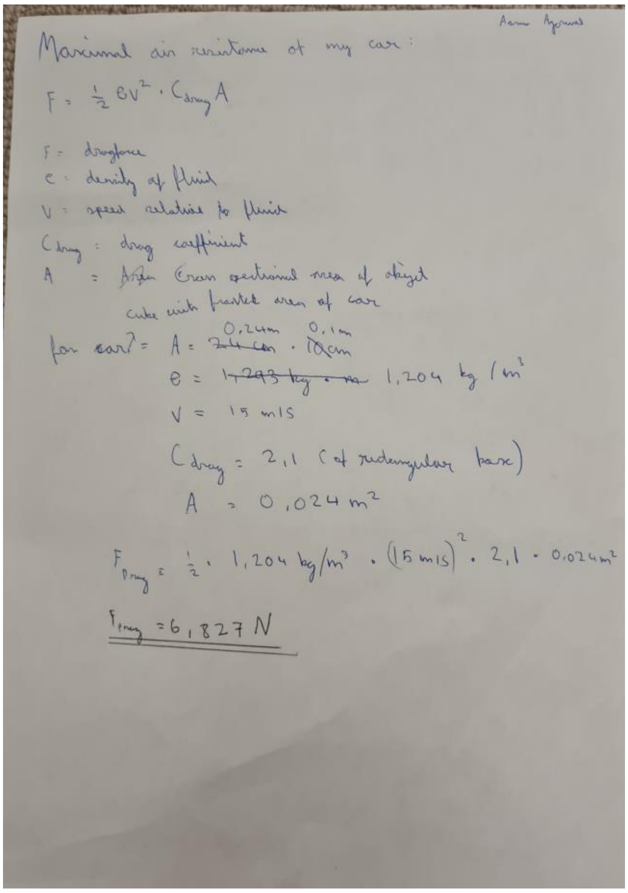
change → take a lower Cl and assume rear wing is rendered ~~useless~~ useless because of so many turbulences

$$\text{downforce} = \frac{1}{2} \cdot 1{,}204\ \text{kg}/\text{m}^3 \cdot 0{,}016 \cdot -0{,}1 \cdot (15\ \text{m/s})^2$$

$$= \underline{\underline{-0{,}217\ \text{N}}}$$

Forces expected → between -0,217N and -~~1,309~~ 1965 N

Expected Air Resistance:



Maximal air resistance of my car:

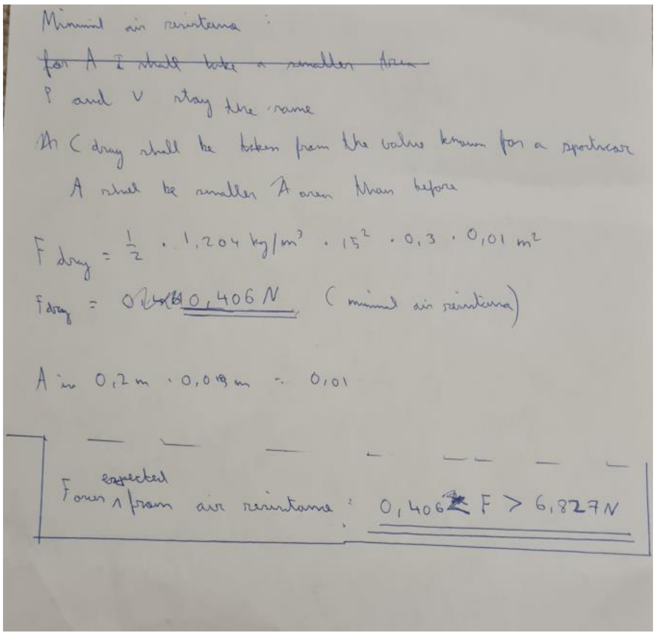
$F = \frac{1}{2} \rho v^2 \cdot C_{drag} A$

F = dragforce
ρ = density of fluid
v = speed relative to fluid
C_{drag} = drag coefficient
A = ~~Area~~ Cross sectional area of object
cube with frontal area of car

for car? = $A = \overset{0{,}24\,m}{\cancel{24\,cm}} \cdot \overset{0{,}1\,m}{\cancel{10\,cm}}$
ρ = ~~1,293 kg · m~~ 1,204 kg / m³
v = 15 m/s
C_{drag} = 2,1 (of rectangular box)
$A = 0{,}024\,m^2$

$F_{Drag} = \frac{1}{2} \cdot 1{,}204\,kg/m^3 \cdot (15\,m/s)^2 \cdot 2{,}1 \cdot 0{,}024\,m^2$

$\underline{\underline{F_{Drag} = 6{,}827\,N}}$



Minimal air resistance:
~~for A I shall take a smaller Area~~
ρ and v stay the same
~~At~~ C drag shall be taken from the value known for a sportscar
A shall be smaller A area than before

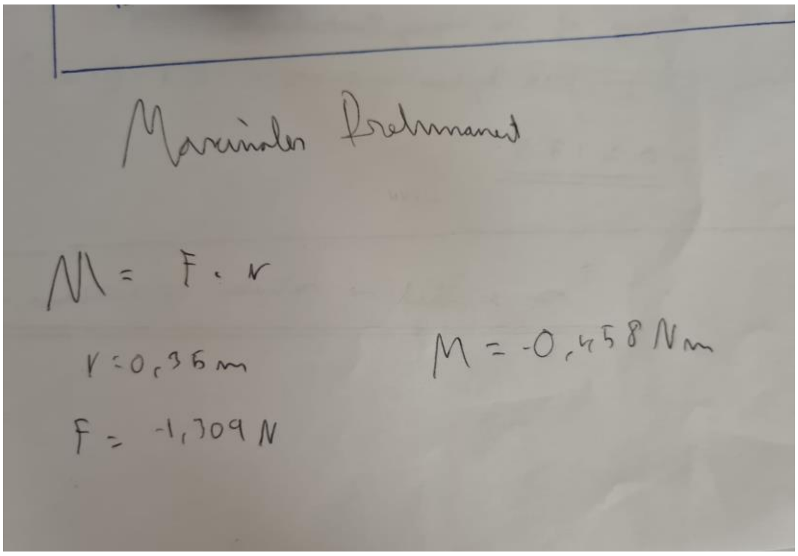
$F_{drag} = \frac{1}{2} \cdot 1{,}204\,kg/m^3 \cdot 15^2 \cdot 0{,}3 \cdot 0{,}01\,m^2$

F_{drag} = ~~0,[illegible]~~ $\underline{\underline{0{,}406\,N}}$ (minimal air resistance)

A is 0,2 m · 0,049 m ≈ 0,01

$F_{expected}$ Force from air resistance: $\underline{\underline{0{,}406 \leq F > 6{,}827\,N}}$

Expected Torque:



Maximales Drehmoment

$M = F \cdot r$

$r = 0{,}35\,m$

$F = -1{,}309\,N$

$M = -0{,}458\,Nm$