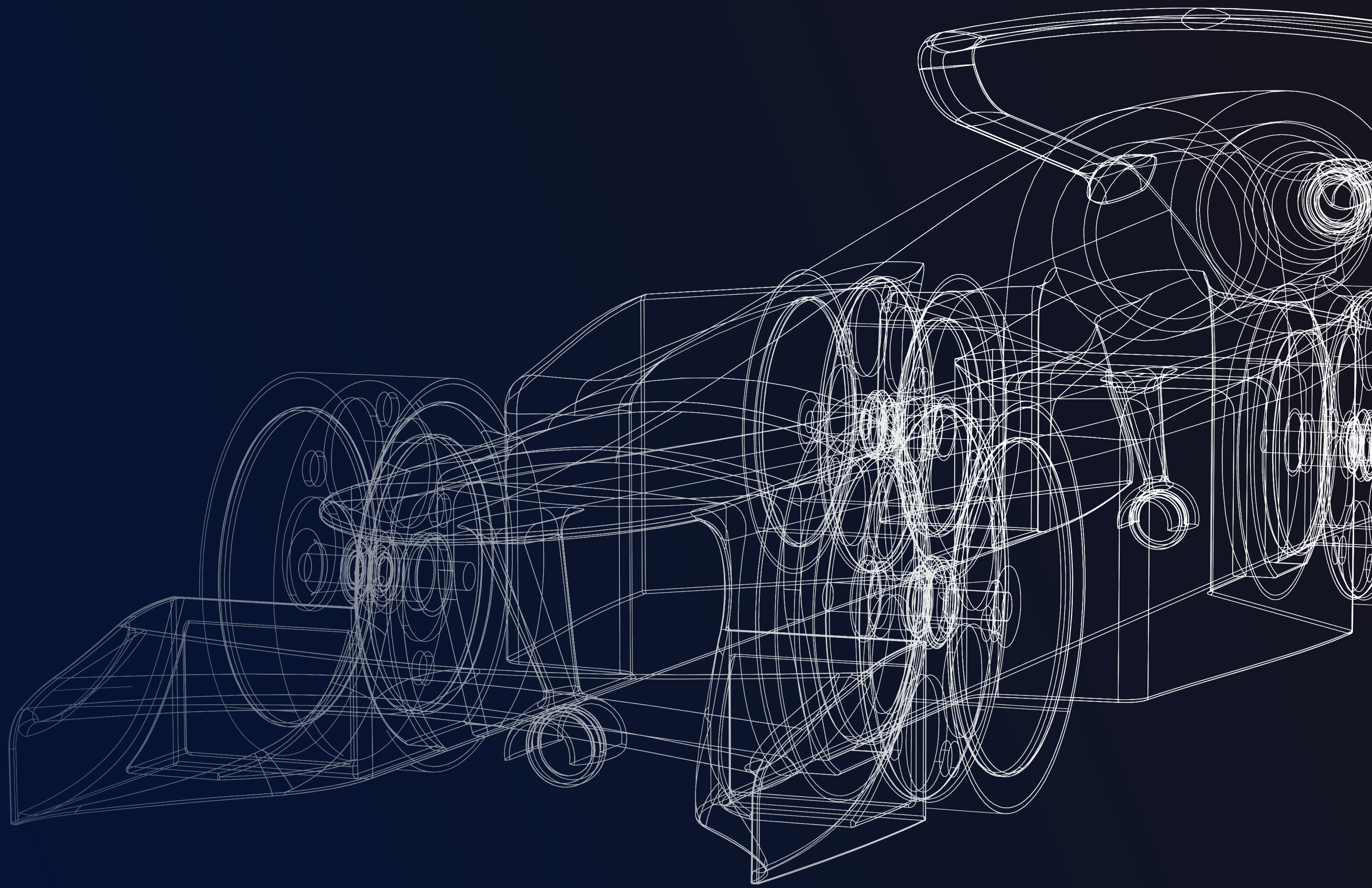
**World Finals 2021/22**
Team Sonic Boom

# Engineering Portfolio

Silverstone, UK

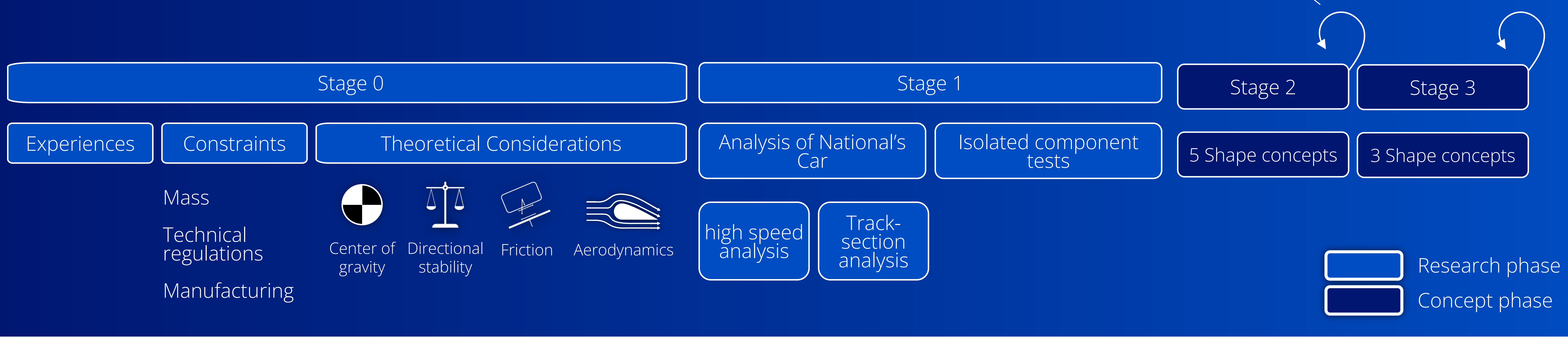
09th July - 15th July



## Contents

# DEVELOPMENT CONCEPT

We aimed for the fastest race time of this year's world finals. That's why we created an efficient development process that allowed us to test a variety of different concepts and optimize every area of the car.




## Concept

The general concept behind our development plan was to test variety of radically different concepts and to filter these concepts along our schedule until we end up with the final car. We started our process by taking our old experiences into account as well as carrying out research on the factors that influence the race time. These theoretical considerations where then used as guidelines for the further stages.

## Status reports and Quality Management

After every development stage, we set a quality gate in our schedule. We reflected on the challenges that occurred in the stage and reassessed details in our development plan. With that came also a detailed status report in which we summarized all the results that we would carry into the next development stage.

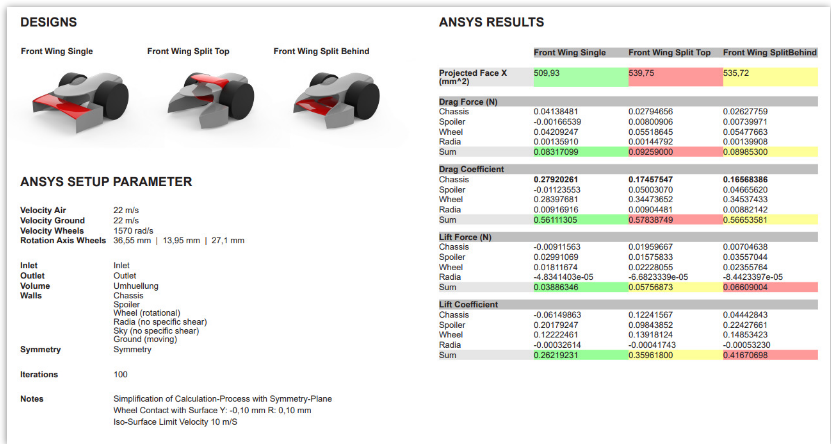



*Fig. 1: Extract from our status report for the front wing study*

## Research phase

### Stage 0

In this initiating phase of our development process, we summarized the experiences we made in past competitions. We analyzed the mistakes we did and highlighted areas of improvement. In this stage, we also made ourselves aware of the constraints we had in our engineering. These were the technical regulations as well as limitations with respect to manufacturing. Another limiting factor was mass. It was clear from our experience that the car had to be as close as possible to the minimum weight. We set a target value of 50.15g for the weight of the final cars. We came to this conclusion as we assessed the risk of deviations between our scale and the scales used for scrutineering, as well as the threat of evaporating glue between our final assembly and the racing of our cars. Stage 0 was also the phase of the project where we analyzed the influencing factors on the race time. An example is the tipping moment that occurs at the start of the car (Read more on the page 4 and 5).

### Stage 1

In this stage, we analyzed our national's car. We did a track section and high speed analysis to further understand areas of improvement.

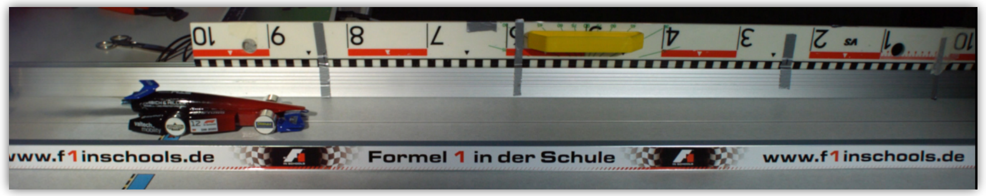



*Fig. 2: high speed analysis of our national's car*

After that, we started doing isolated component tests (e.g wheel systems, tether line guides...). The idea behind that was to ensure that we would use the best possible components in further testing stages.

## Concept phase

This phase consisted out of two development stages. In the first stage, we created five prototypes, all with their own design philosophy and strengths with respect to different influence factors. To ensure an efficient process, the prototypes were manufactured using rapid prototyping. The three best concepts where then optimized iteratively in CFD. In case of any breakages, we optimized the stability of the respective prototype.

In the next stage we took the optimized concepts and ran track tests again. This time with CNC-milled chassis. We found that differences between two of the three prototypes were minimal but that the faster prototype had a higher risk of breakage. We decided to optimize the two fastest prototypes again in an iterative process and to then decide which prototype would become our final car.

## Definition of final cars

The two optimized candidates for our final had to be tested under competition-like conditions. Apart from using CNC-milled chassis, we also decided to paint both cars and bring them to the target weight for the competition.

This method proved to be the right decision, as the prototypes which seemed to have only minor differences in performance, had quite a difference at the race time for the final definition.

# TESTING METHODS OVERVIEW

We used several methods for testing, both virtual and physical. All of our prototypes were virtually analyzed using CFD and FEM analysis prior to manufacturing. Additionally, the injection moulding process used for our wheels had to be visualized by our partner, Werner Breitschädel. Our physical testing revolved around race track tests as they offered us competition-like conditions.

## Physical testing

**Race track tests**
We put a lot of effort into our race track tests to verify our expectations, theoretical assumptions and observations from for example CFD Analysis. The biggest advantage of track tests are the real race conditions and reliable results. That's why we did seven race track testing days in preparation for the world finals. More about our test planning and the different stages can be found on the following pages.

**Reliable Results**
In order to get reliable results, our first priority in physical testing was to keep the standard deviation as low as possible. To achieve that we focused on the following aspects:

- Cleaning the race track before each run
- Keeping the cartridges at a constant temperature
- Using the same race track and launch pod for all testings
- Correcting the error of different amounts of gas in the cartridges with our gas formula
- Increasing the number of runs in case of high standard deviations or close results within the standard deviation

Overall the further we were in our development process the more runs we did with our prototypes in the different stages. We started with 6 runs per prototype and ended up with 16 runs.

We carefully documented all of our results in an Excel sheet that allowed us to visualize the results quickly and accurately.

## Physical wind tunnel

To validate our CFD results, we did real wind tunnel tests. Of course, small deviations can't be avoided. But overall, the behavior and relation between the analyzed cars seemed to be correct and didn't differ significantly from the simulations. So we were able to focus on optimizing the cars in the virtual wind tunnel before doing track tests.

*Fig. 3: Real wind tunnel testing (measuring the drag force)*

## Virtual testing

CFD Simulations were one of the most crucial parts in our development process. As we managed to produce high quality analysis of our car with Ansys Fluent we were able to focus a lot on optimizing the car virtually.

Besides the CFD Simulations we used virtual analysis methods to simulate the process of injection moulding for our wheels. In order to keep the deformations in mind these analysis helped us in finding the right amount of material, the right sizing constraints and the stability as the material cools down at different rates.

Lastly, for stability analysis of single car components we simulated different stresses by using the FEM Analysis from Solid Edge 2022.

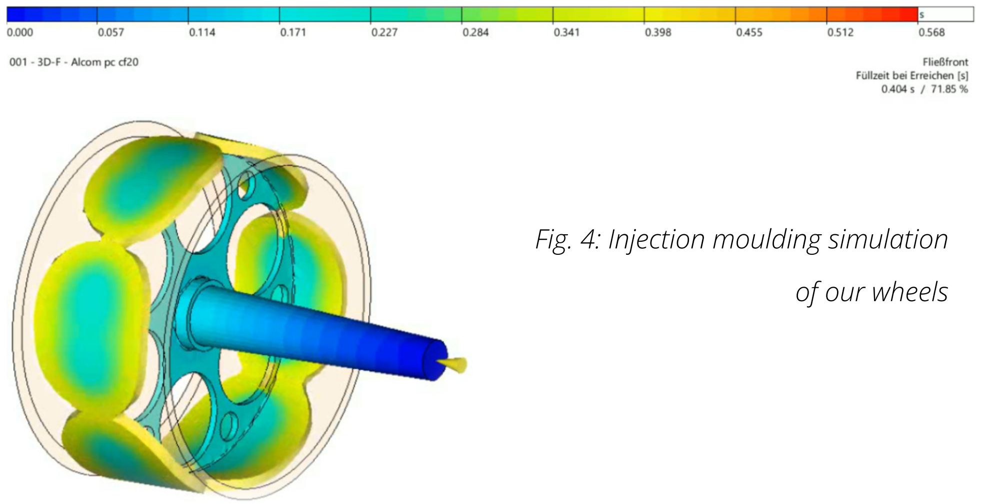



*Fig. 4: Injection moulding simulation of our wheels*

## Gas Deviation Correction Formula (GDCF)

One of the biggest factors of error in physical testing has always been the different amounts of gas within the cartridges. Even the official race cartridges with an error of +-0.5 grams were unsatisfying to us. That's why we developed the Gas Deviation Correction Formula (GDCF) to reduce that deviation to a minimum.

$$adjusted\ race\ time = race\ time * \left(\frac{weight\ CO_2}{average\ weight\ CO_2}\right)^{exponent}$$

We presupposed a negative correlation between race times and the amounts of gas. Therefore, we corrected the gas amounts of the single runs to the average amount of gas of the set of runs. Now, a lower standard deviation can be expected in comparison with the original race times.

The formula for the corrected race time uses a correction factor (a number close to 1) which is calculated by dividing the current run's amount of gas by the average amount of gas from the set of races.

That way, the runs with more than the average amount of gas have a higher correction than 1, thus increasing the corrected race time once multiplied with the original race time.

To vary the influence of that correction factor, we used an exponent above it and determined its value experimentally. Results showed that the standard deviation of the corrected race times was the lowest when using an exponent of 0.5.

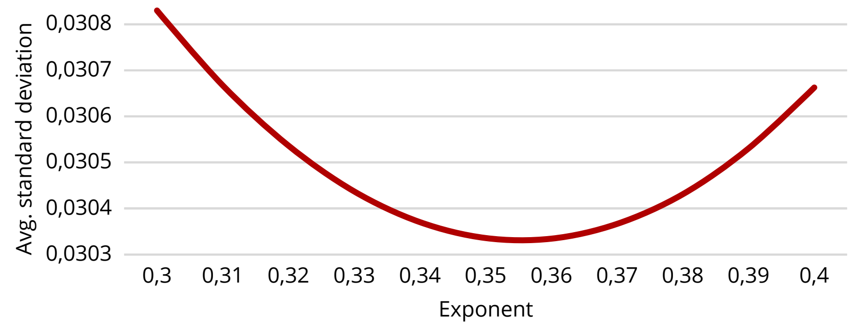



*Fig. 5: Exponent determination from testing day 4*

We were confident that the decrease of the standard deviation was indeed because of the gas amount as the exponent of 0.35 (+-0.02) consistently decreased the race time standard deviation by the maximum amount across all testing days and all prototypes. Using our formula has decreased our average standard deviation by 15% down to 0.02 s.

# RESEARCH OVERVIEW

To develop the fastest car, there are several aspects to reflect on. To use the energy produced by the CO2 cartridge as efficiently as possible, all aspects slowing down the car need to be minimized.

In stage 1 of our development process, we analyzed our car from the national championship and gathered theoretical information about car design. In the same stage, we also looked at the components of the car such as the wheel system and the tether line guides.

## Directional Stability

We observed flaws in the aerodynamic stability during the run. Our car moved towards the sides a lot without being able to stabilize itself.

After gaining knowledge from aerospace literature, we found out that a center of gravity towards the front of the car helps achieving aerodynamic stability. Just like with an arrow, vertical faces behind the center of gravity further stabilize the car against side movements. This way, once the car is turned to the side a bit, the airflow coming from the front pushes sideways against the vertical faces at the rear of the car, creating a torque to counteract the displacement. If the center of gravity is towards the front, it creates a longer lever and thus a higher counter-torque.

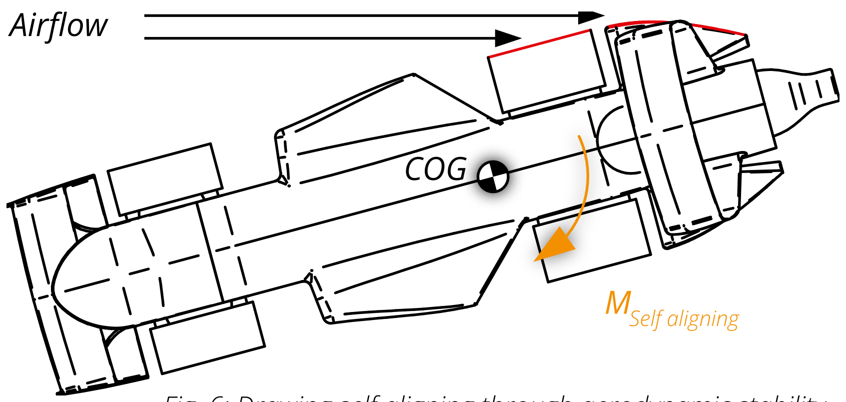



Fig. 6: Drawing self aligning through aerodynamic stability

Besides the COG an instability can be reduced by a perfect assembly quality with all wheels being perfectly parallel and aligned.

→ Larger nose construction for a forward center of gravity, flat nose for less vertical faces in front of the center of gravity.

## High speed analysis of the national's car

Taking advantage of having a completely assembled car in the best quality, we chose to evaluate our National Final's car with regards to launch behavior and aerodynamic stability. In cooperation with our high speed partner, we were able to see the smallest movement of the car, both at the start and towards the middle of the track.

Fig. 8: High speed national's car

To understand the acceleration of the car for the national finals, we marked the race track at regular distances and tracked the times in the high speed recordings using Tracker. We identified the different phases of a run. The acceleration phase lasts about 0.4 s with a maximum acceleration of 74 m/s². Important for the deceleration is the car's speed at the finish line with about 20 m/s.

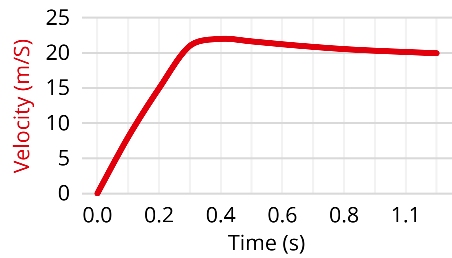
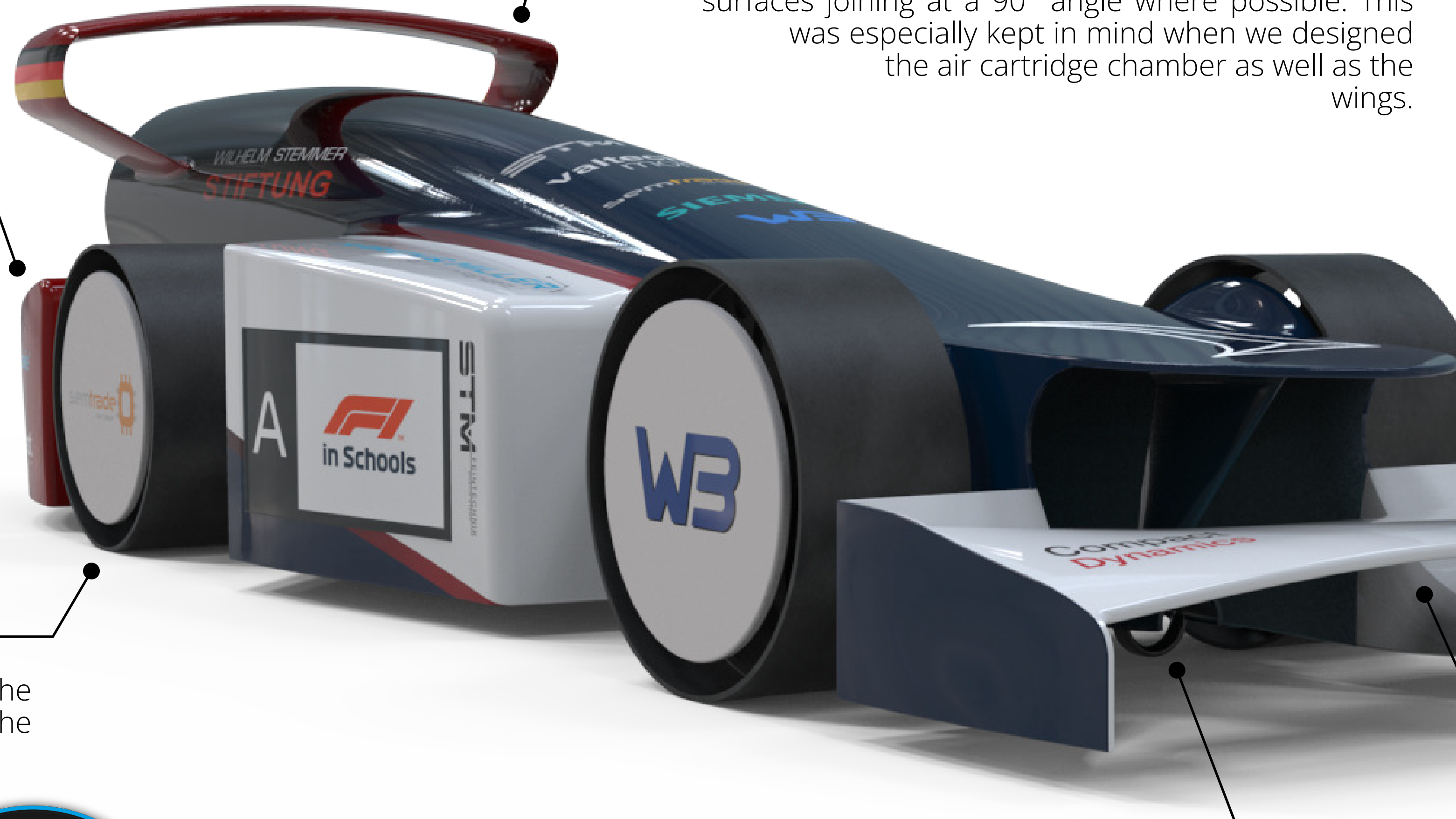



Fig. 7: Results from high speed analysis

## Avoiding Turbulence, low pressure areas and radical angles

A big part of the energy loss due to aerodynamics is related to turbulence and low pressure areas. The main idea is to reduce them to a minimum. To achieve that, we focused on reducing airflow stalls due to big changes in the surface. Another aerodynamic phenomenon is the drag arising in radical angles. Therefore, we tried to avoid surfaces joining at a 90° angle where possible. This was especially kept in mind when we designed the air cartridge chamber as well as the wings.



## Wheel System

The wheel system was one of our most researched parts because it has one of the largest impacts on the car's performance, as we know from experience. A big factor to improve on is the wheel itself. Because the wheel starts in a standstill, it absorbs energy in order to start spinning. This energy needs to be minimized and is proportional to the moment of inertia I.

$$I = \sum_{i}^{N} m_i r_i^2$$

In this simplified formula, a sum of theoretical points of mass is used to describe the turning object. Because of the squared radius, mass far away from the axis increases the moment of inertia by a lot. Concerning the wheel, the overall mass should be as light as possible. But especially the outside wall needs to be as thin as possible because of its high impact on the moment of inertia.

Another factor in a wheel system's performance is the mounting, especially regarding the bearings. We knew that the bearings should have a good fit both inside the wheel and on the axle while not being under too much pressure. Additionally, the axles should be perfectly parallel and aligned. Because of our bad experiences with plastic axles from the national championship, we decided right away to use steel axles for all prototypes and the final car.

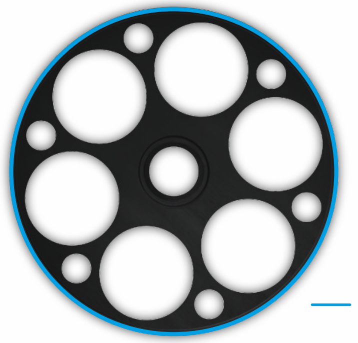



Fig. 9: side view wheel

## Friction by the tether line guides

The cars are secured by two tether line guides attached to the nylon cord along the track. As there is constant friction during the race, the best position and material possible needed to be found trough track testing in order to minimize this loss in energy.

## Center of Gravity (COG)

High speed analysis showed that f1 in schools cars tend to lift when launching. This can be explained by looking at the thrust vector of the $CO_2$ cartridge. Inserted in the air cartridge chamber, the height and angle determines the vector of force. By changing the angle of the chamber other than parallel to the track surface, a small amount of energy is lost as shown in the graphic below. Therefore, we stuck to an unangled chamber.

But with the COG located below the thrust vector, a tipping moment can be seen. As this is a loss in energy, we decided to design the car in a way the COG is as close to the vector of force as possible (high position) and verified the behavior through track testing. This helped to reduce the lift of the rear end.

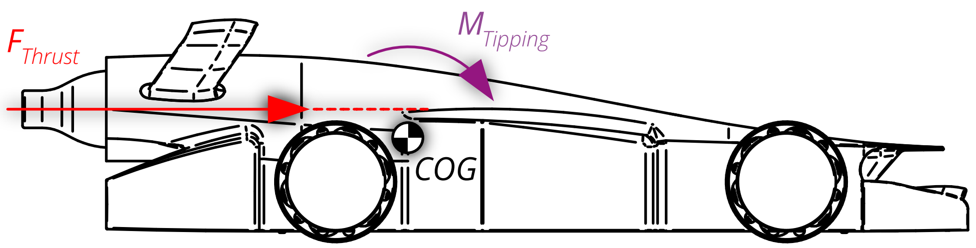



*Fig. 10: schematic drawing tipping around COG*

*Tipping Moment as the COG is located below the thrust vector*

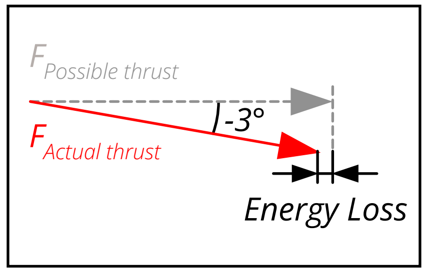
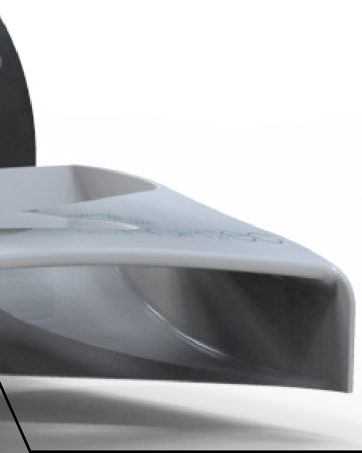



*Fig. 11: Energy loss in case of an angled air cartridge chamber*



## Keeping the projected area as low as possible

Keeping the projected face as low as possible means designing the smallest wheel diameter possible, keeping the center of the air cartridge chamber as low as possible over the race track surface having a minimum wing support structure and wing thickness. Parts which are not necessary for the general aerodynamics like the rear wing were designed at the very end of the design process with the most neutral shape possible.

# COMPONENT TESTINGS OVERVIEW

In order to be more sustainable and more cost-effective, we designed two modular prototypes to analyze the car's components. This also eliminated the error of having slightly different car bodies, which would lead to differences not caused by the components we're trying to observe. On top of that, we built a third modular prototype to evaluate different centers of gravity.

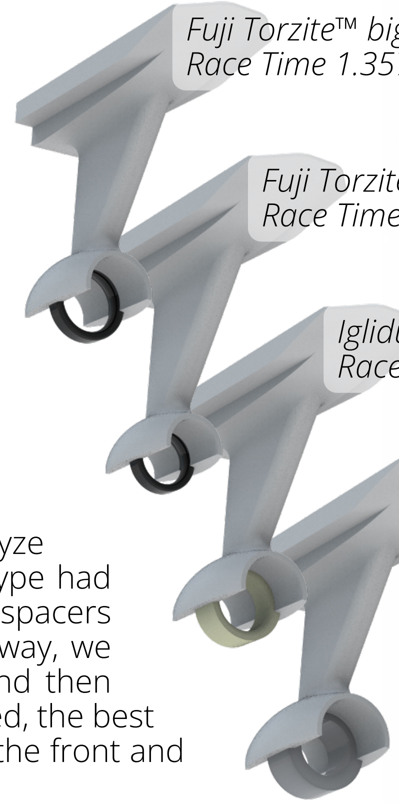
## Stage 1

### Wheel system prototype

For this prototype, we designed six different interchangeable wheel systems. They were fit onto the car using cross-shaped connectors on the wheel systems and dedicated holes in the car body. Using a single car body for all wheel systems enabled us to have a maximum weight deviation of 0.1 g across all configurations. After extensive testing using our GDCF, we found out that the single axles with the smaller bearings produced the best results.


### Tether line guide prototype

This prototype used two slots in the car's floor to fit different tether line guides (TLG). We tested six different configurations. Three different materials, two different sizes and three different heights over the track with one of the TLGs. After testing and correcting the race times using the GDCF, the bigger Fuji Torzite™ TLGs in the lowest position proved to be the best option.




### COG prototype

We used our last modular prototype to analyze different placements of the COG. The prototype had five holes on the bottom and we used plastic spacers to vary the height of the metal weight. That way, we first tested extreme positions of the COG and then tried to find the best configuration. As expected, the best placement of the center of gravity is towards the front and as close to the height of the cartridge center axis as possible.

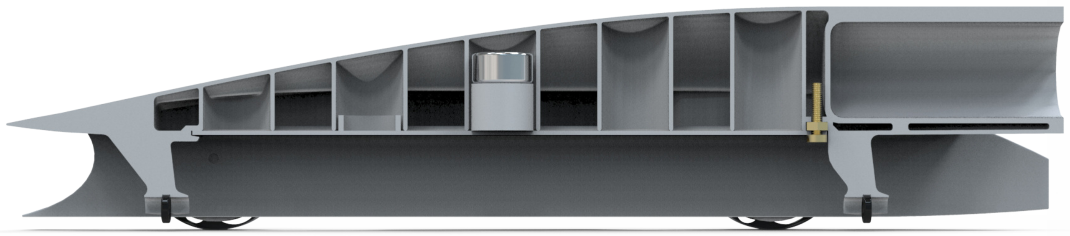


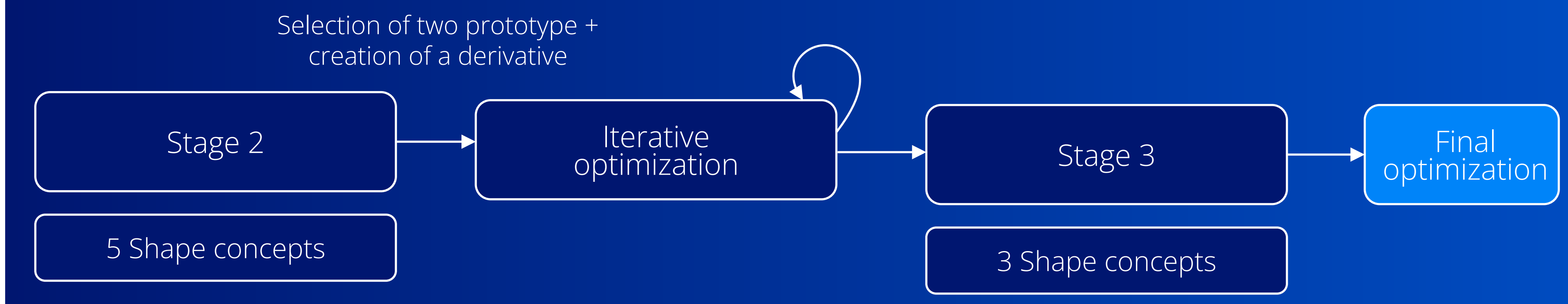
*Fig. 12: COG prototype with different COG positions possible*

### Fixed components for future car designs

Because we figured out which components will be on our final car, we were able to ensure a lower environmental impact and a better cost-efficiency as we could order TLGs, bearings and axles for all future prototypes and the final cars in one go. We also knew how our wheel mounting system had to look like, so we could build our future car body prototypes around those fixed components.

# CONCEPT PHASE OVERVIEW

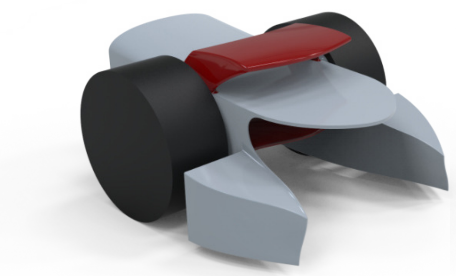
Our concept phase consisted out of two stages (Stage two and 3 of our development process). In the first stage we tested five radically different prototypes. The two best prototypes were selected for the further testing stage. Out of one of the prototypes we created a derivative which implentented a new concept for the front spoiler.



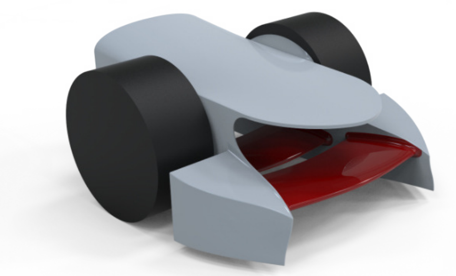

## Stage 2

This was one of the most crucial stages in our development plan. We designed five radically different prototypes, all with their own compromise between the influencing factors determined in the research phase.

**Split-Wing**
In our development process, we came up with the idea of using split front wings which a loophole in the rules would allow. This is the only way to be able to place a high wing at the nose to ensure the wheels are visible at all times. This raises the COG. We developed two different concepts of this idea and analyzed them in CFD.



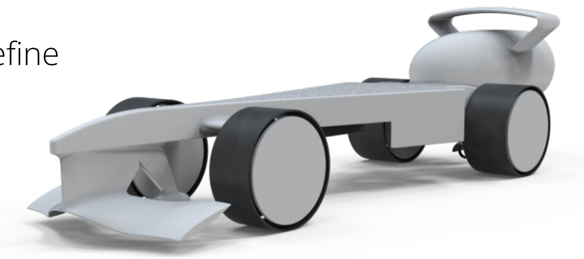
*Concept 1 - Drag Force 0.0926 N*



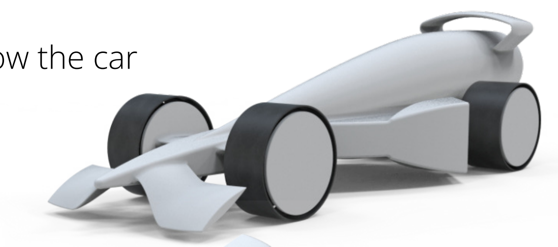
*Concept 2 - Drag Force 0.0899 N*

We found that both split-wing concepts didn't have a great performance in CFD. But we still wanted to verify this result on track. We decided to use concept 1, which had a marginally worse performance in CFD than concept 2, but came with a higher center of mass, which would be better for the launch behavior of our car.

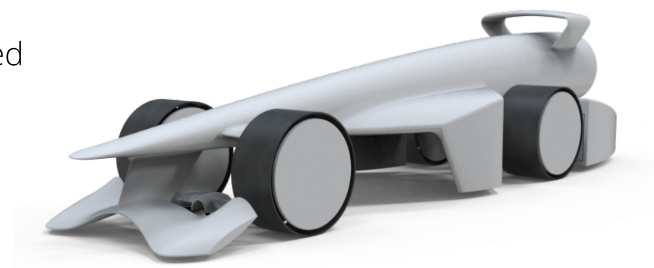
**Prototype 1 - 1.307 s**
- Compact car design
- Only what the rules define
- Higher COG



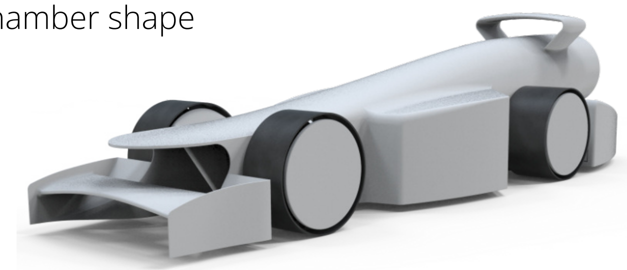
**Prototype 2 - 1.310 s**
- Compact car design
- Reduced air tunnel below the car
- Rocket shape short



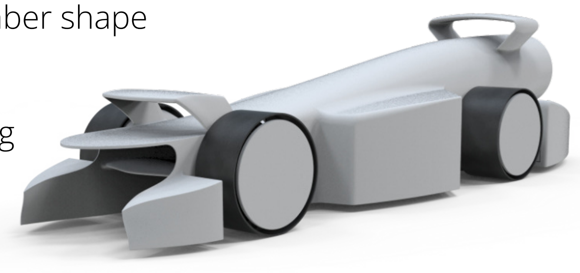
**Prototype 3 - 1.296 s**
- Higher COG
- Air tunnel but not closed
- Rocket shape long



**Prototype 4 - 1.282s**
- No 90° angles of the chamber shape
- Air tunnel closed
- Simple shape



**Prototype 5 - 1.300 s**
- No 90° angles of the chamber shape
- Air tunnel closed
- Simple shape
- Loophole of split front wing
- Higher COG



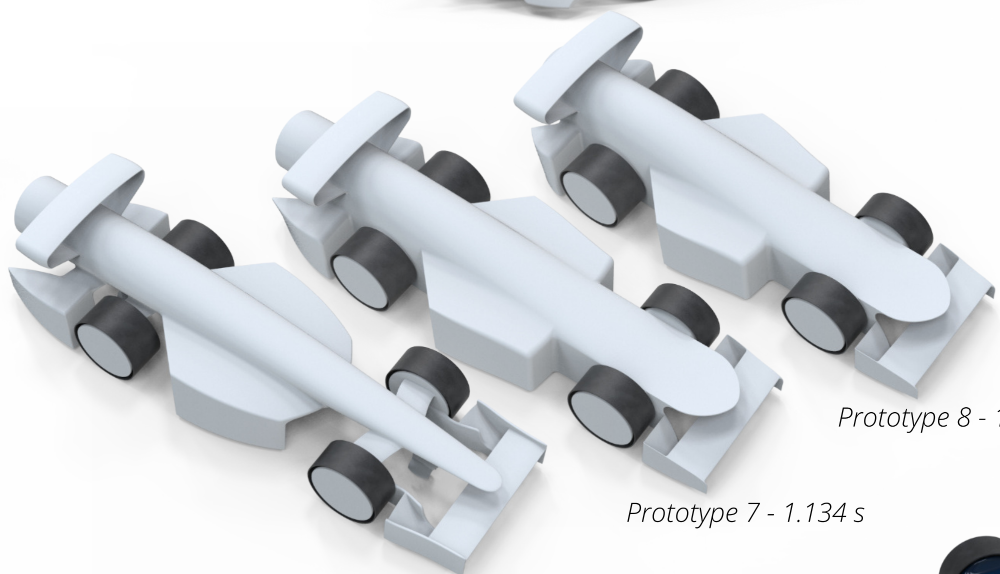
## Results

We came to the conclusion that we would take prototype 3 and prototype 4 into the next testing stage, as they outperformed the other cars by a great margin.

## Stage 3

In addition to testing the two best prototypes, we derived a third car from Prototype 4. This prototype was a shorter version of the best prototype in order to check the assumption that longer cars are faster. In this testing stage, we stopped using rapid prototyping to have competition-like race conditions.

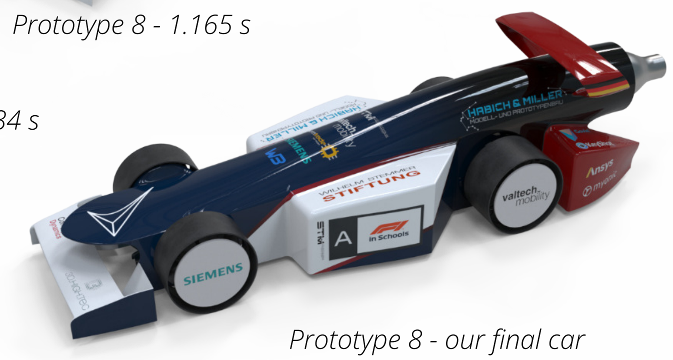
We found out that the differences between prototype 6 and 7 were marginal. We decided to optimize both concepts in CFD and carry out a final testing day which would determine our race cars for the world finals. We wanted this test day to be as close as possible to competition conditions. That's why both cars were painted and were manufactured to the target value of 50.15 g. With a race time of 1.060s in comparison to 1.093 s Prototype 8 became our final car.



*Prototype 8 - 1.165 s*

*Prototype 7 - 1.134 s*

*Prototype 6 - 1.133 s*



*Prototype 8 - our final car*

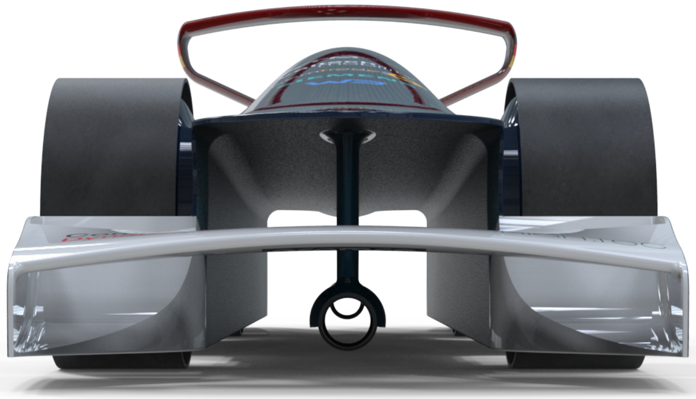
# DESIGN CONCEPTS

Before and during the development process there were different design concepts we looked at and evaluated.



## Catamaran Concept

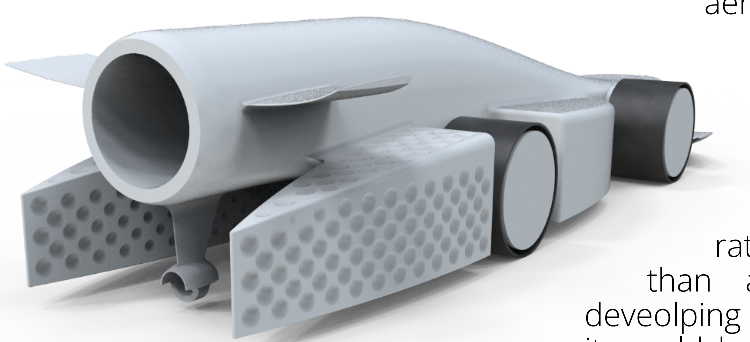
This concept significantly reduces the projected area resulting in a lower overall drag force. Secondly, unnecessary turbulence is avoided which is useful for an efficient design process as different components and areas can be looked at separately in terms of aerodynamics. Furthermore the big air channel inlet allows the air to pass under the car almost unrestricted.



*Catamaran concept*

## Low pressure areas act as solid bodies

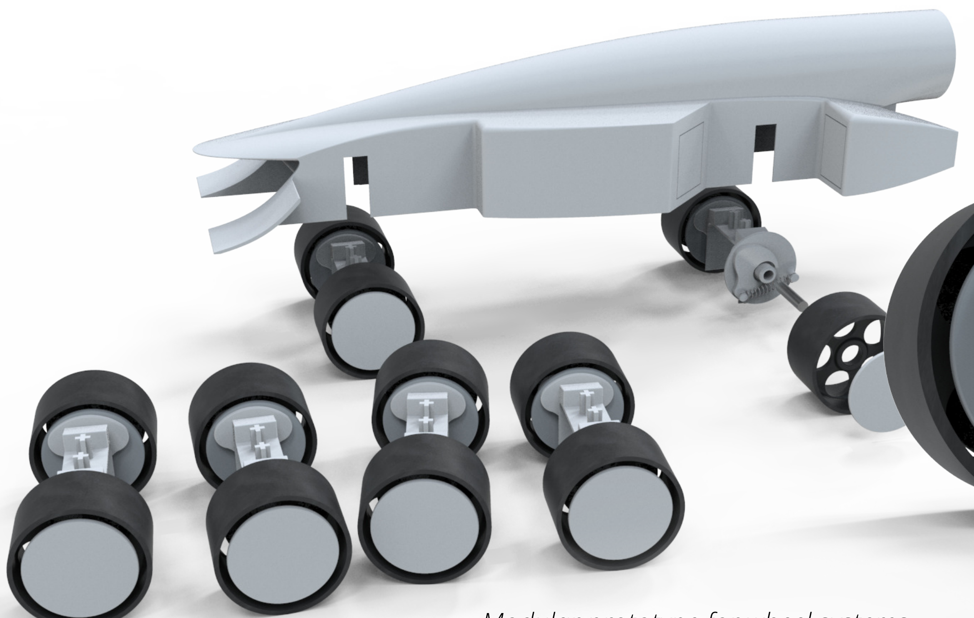
When analyzing the CFD results, our engineers focused especially on the low pressure areas and came up with a special idea. After the low pressure areas have formed, they seem to act like a solid body. As a result, we now focused on implementing these “bodies” in our design without trying to reduce them by guiding air in those areas. This proved to be a significant improvement in our aerodynamic design (see Iteration 8 on page 11).



*Dimples at the rear side pod*

## Modular Prototypes

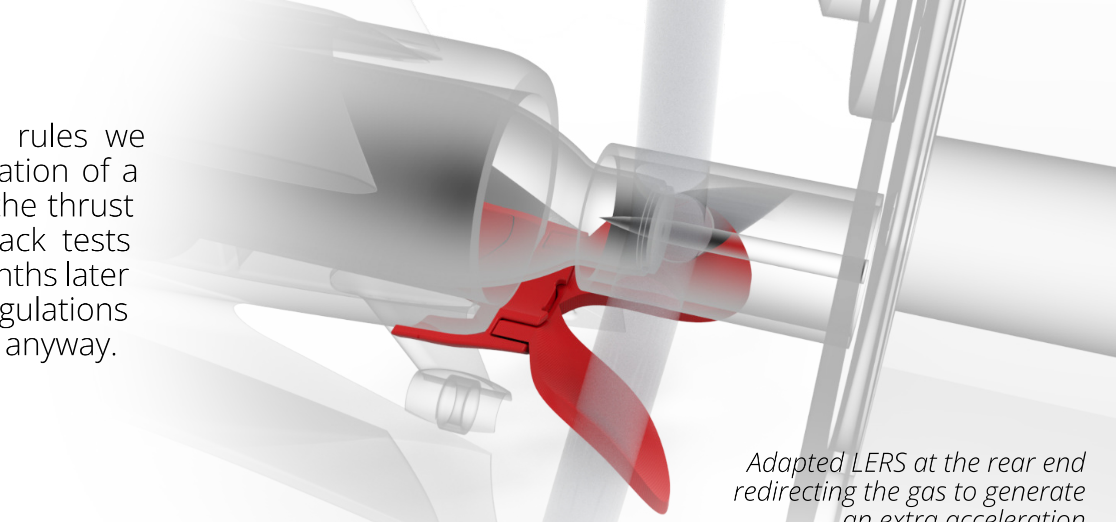
For an efficient and more sustainable development process we designed modular prototypes for the different tests in stage 0. This means the different wheel support systems and tether line guides could be easily changed. To ensure the parts can be compared as best as possible without changing the COG we designed all parts having the same mass.



*Modular prototype for wheel systems*

## Adapted LERS

Before knowing the new technical rules we experimented with a new interpretation of a LERS. This would recover a part of the thrust reflected from the launch pod. Track tests revealed the concept to be a fail. Months later with the release of the technical regulations the concept would have been illegal anyway.



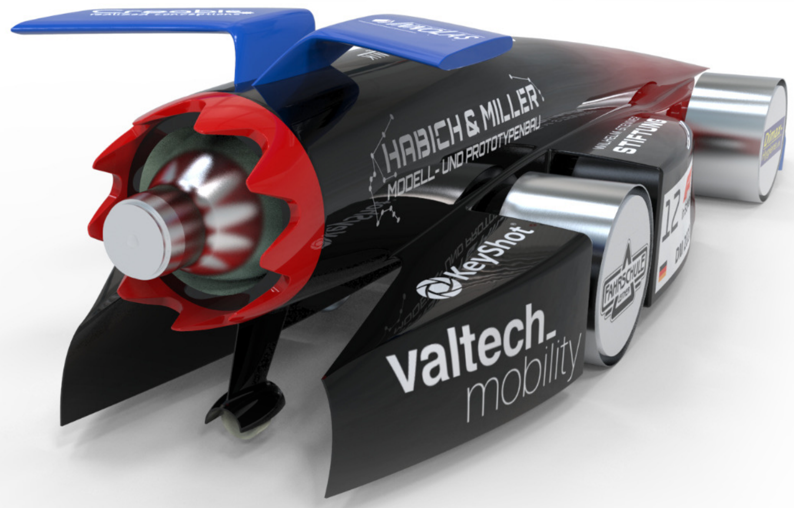
*Adapted LERS at the rear end redirecting the gas to generate an extra acceleration*

## Chevrons

Our initial idea of this concept was to generate small vorticies to create a turbulent area to reduce the low pressure area behind the car. As this is a unnecessery high loss in energy we discarded the concept.

## Dimples

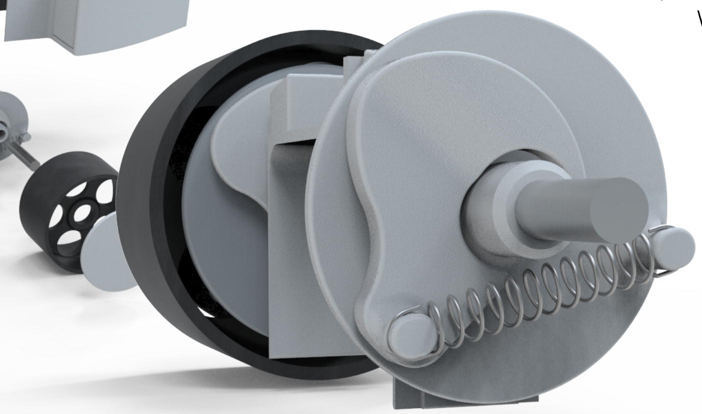
Inspired by golf balls we testet the aerodynamic effect of dimples on track. In theory by intentionally causing a turbulent baundary layer the airflow would stick longer to the surface and reduces the low pressure area. As the results showed there is rather a small performance loss than a gain we decided to stop deveolping this concept further. Furthermore it would have been difficult to manufacture with CNC milling and paint.




*Chevrons at the rear end*

## Wheel suspension system

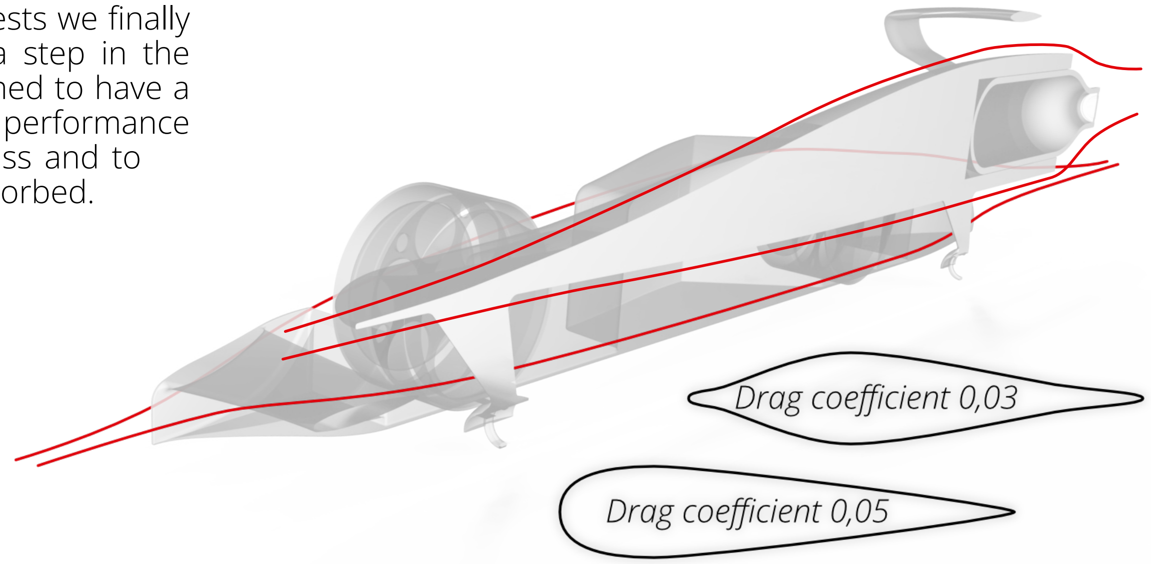
By analyzing our car from the national finals we noticed a significant bouncing when it passed the transitions between the single parts of the race track. To minimze these hits we developed a wheel suspension system. The first problem was the manufacturing process. As there are small tolerances and filigran parts needed it was a big effort to assemble the system. After track tests we finally proved the concept to be a step in the wrong direction as it seemed to have a bad impact on the cars performance with a rather heavy mass and to much energy being absorbed.



*Wheel suspension system*

## Penguin and Drop Shape

Before starting the design process we found out that the most aerodynamic shape is not the drop shape. Instead, we focused and analyzed the penguin shape as the drag coefficient is significantly lower.



## Data Management: Cloud based storage

To ensure both engineers have access to the latest files at all times we decided to work with a cloud based file storage. With hundreds of files stored in our cloud a standardized naming strategy was needed. We named the files by assigning a part identification number, using the Initials of the design engineer and the version.

**SB22-PAR-03_Rear-Wing_FW_v.4.1**

## Software

Our engineers agreed on a common standard to make the team work as efficient as possible. A lot of effort went into designing parametrically with all sketches fully defined and named properly.

Solid Edge 2022 comes with various tools and controls ensuring an efficient and overall unrestricted design process of the car.

**Thin Wall**
Designing a Car for 3D Printing is more complex as the inside must be hollow to only print thin walls. Using the thin wall feature from solid edge automatically creates an offset from the outer surface forming a wall with a certain thickness.

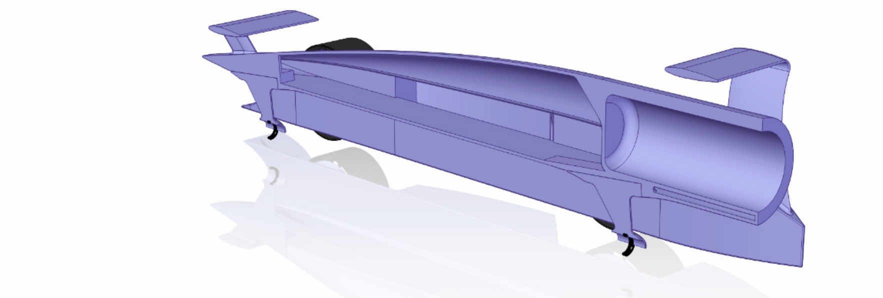


*Fig. 13: thin wall half chassis*

**Loft**
Lofts are solid body operations which define a solid body by at least 2 profile sketches at both ends

**Cross Curve**
Crossing 2 fully defined sketches from different orientations result in a combined and parametric 3D curve.

**Surface Modelling**
Using 3D curves and sketches a parametric frame can be designed which then forms the edges of a surface. The boundary conditions can be either set as normal, perpendicular or tangential if another surface is following. This gives the designers a lot more control over the resulting body created. This was especially used for the rear spoiler.

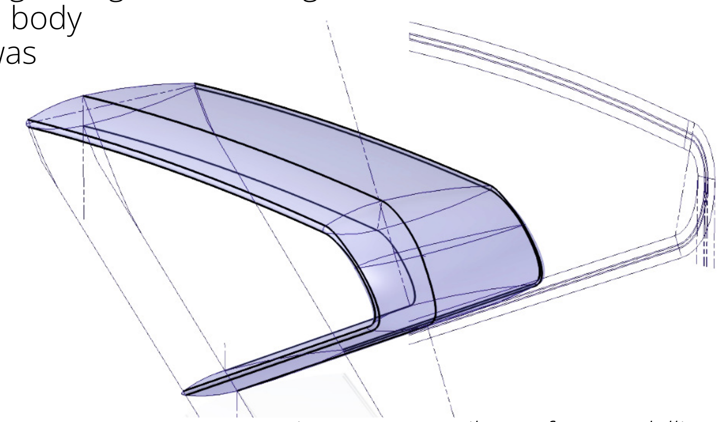
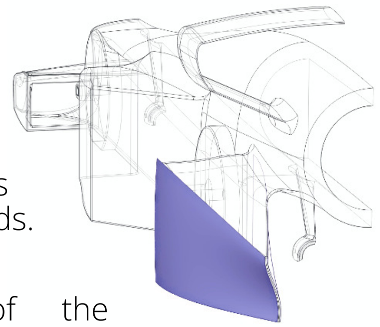
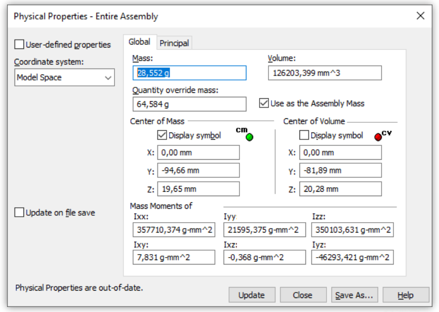


*Fig. 14: rear spoiler surface modelling*

**Hybrid Design**
A more efficient way shaping single free form surfaces is the combination of ruled bodies and surfaces defined by sketches. The original surface is then replaced by the free form surface. This method was mainly used for the side pods.



**Mass Calculation**




One of the most important things to look at during the design process (especially for 3d printed cars or parts) is the mass.

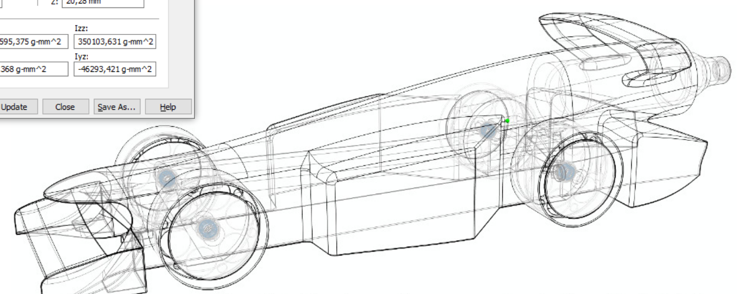


*Fig. 15: Centre of mass calculation Solid Edge*

By assigning materials to all parts of the assembly solid edge provides a mass calculation tool. From our experience from the seasons before we could estimate the mass of the paint job so that we fixed the weight of the car aiming for about 30g. In addition, the center of gravity can be calculated and displayed. This was part of our design process as we determined the optimal center of gravity early in our research and testing.

**Inspection Tools**

To check the model for small irregularities in the surface we used the zebra stripes in solid edge. In case of an error in the surface there would have been a significant change in the parallel zebra stripes.

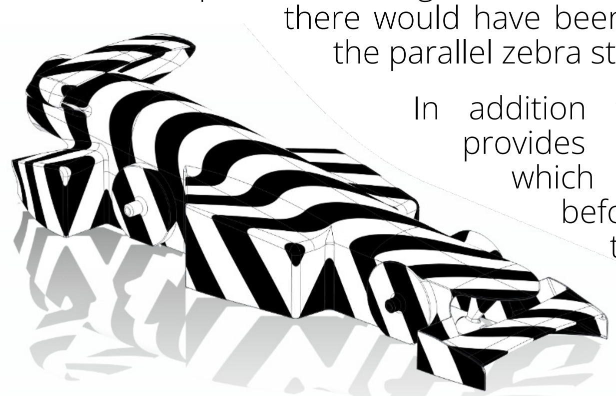


*Fig. 16: Zebra stripes chassis*

In addition to that, the software provides a geometry inspector which we used for all files before the final export for the manufacturing process. Solid Edge checks the model for errors, especially small faces and edges.

**Parametric modeling, .par, .asm**

Designing parametrically was one of the most important agreements between both design engineers. Parametric design describes the modeling in a way that changes in variables result in a self-adjusting design with minimizing errors in the model. This makes rapid prototyping for design changes and simulations possible.

First the sketches need to be fully defined by using variables, reference points and relations between the different lines and points. Just by changing the reference points of the side pod splines via variables for example we could easily create dozens of iterations without having any troubles with the model.

Furthermore, we designed the whole car except the standard parts

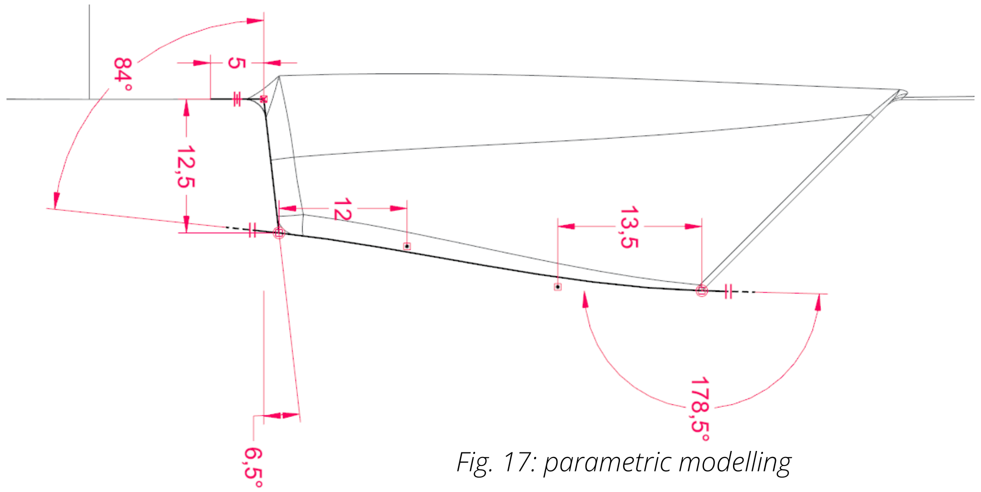



*Fig. 17: parametric modelling*

in a single part file parametrically. Once finished we used the function of splits which means the model is split at parametrically defined surfaces. Linking the created different part files to the main parametric file results in a perfect parametric model.

To check the fittings of all parts we created an assembly. All parts are connected by assigned relations. Changed single parts are then automatically updated in the assembly file. Here we inserted the exclusion zone volumes, the virtual volume and placed dimensions to check different rules like the total car length.

**Dimension constraints / Modeling for an optimized manufacturing process**

Having construction bodies as constant reminders for rule limitations helped us significantly as hundreds of iterations are designed during the design process. Therefore, sorting out rule violations in the beginning of a car design is elementary in order to avoid any big changes after finishing the design. The official model block was also implemented as helper as the car must be manufactured from it.

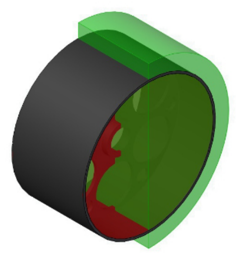


*Fig. 18: rule body*

Besides that, the design engineers must agree and follow certain design restrictions for the development process. As our partner is capable of 5 axis CNC Milling the engineers were almost unrestricted in the design. Nevertheless, there are different milling tools available. For example, agreeing on the use of certain radii (2mm) with our partner significantly reduced the complexity and time for milling the cars. Furthermore, care was taken to ensure there is no need for the milling head to rotate in a horizontal 70-90° position so that all cars could have been manufactured next to each other.

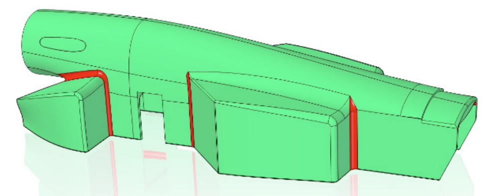


*Fig. 19: design restrictions certain radii*

The only restrictions for 3D printed parts was the minimum thickness of 0.2mm.

# CAM AND CNC PROCESS

To mill our cars, the first step is to set up a CAM code. The machine then processes the CAM code step by step. Motion vectors define the tool paths where the material is to be removed. Furthermore, the code contains informations such as spindle speed and feed.

## Basic Approach

We decided not to clamp the model block in a special rig for milling as it would have had to be manufactured first. Furthermore, the capabilities of 5 axis CNC shouldn't be limited and there is no post processing for remaining support structures needed. Instead, the chassis were glued on a foam block. In order to reduce the workload, we milled all chassis at once. To ensure that the program works properly and no mistakes will occur, we first simulated the milling process with all toolpaths.

## CNC Process for each side

**Roughing / Carbide end mill cutter (Ø 10 mm)**

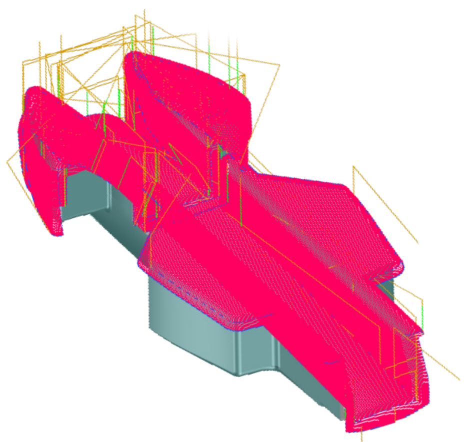
| Infeed | Cutting depth | Spindle speed | Feed |
|---|---|---|---|
| 8.00 mm | 4.00 mm | 22.000 r/min | 20.000 mm/min |

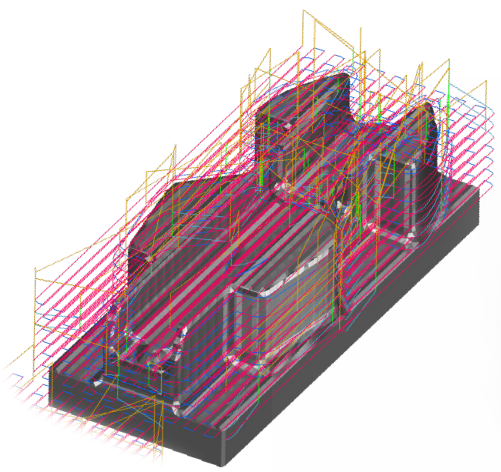
**Finishing 1 / Spherical cutter (Ø 10 mm)**

| Infeed | Cutting depth | Spindle speed | Feed |
|---|---|---|---|
| 0.35 mm | 0.35 mm | 22.000 r/min | 15.000 mm/min |

**Finishing 2 / Spherical cutter (Ø 2 mm)**

| Infeed | Cutting depth | Spindle speed | Feed |
|---|---|---|---|
| 0.20 mm | 0.20 mm | 22.000 r/min | 15.000 mm/min |



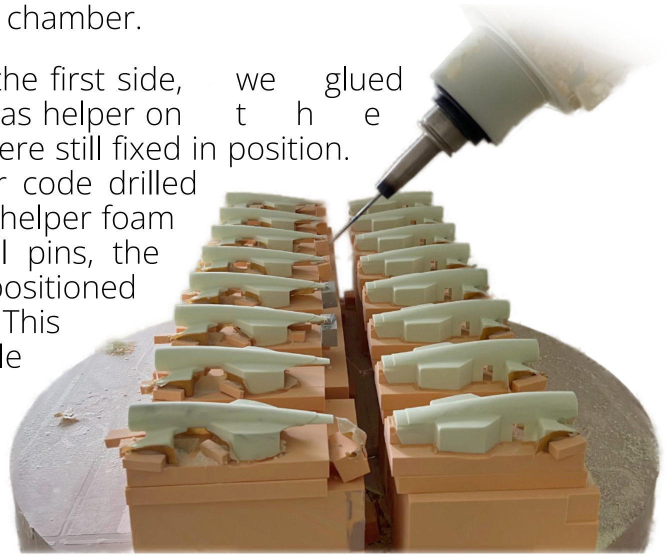


## Improvements after milling the prototypes

While milling our prototypes, we noticed the thin walls of the air channel beneath the car began vibrating and bending towards the inside of the air channel. We optimized the milling parameters and placed another foam block in the air channel below the car to stabilize it properly which solved the problem.

### Devided in two steps

We started milling the bottom side, as it is the only flat surface. Next, we measured the exact model block positions by using an edge finder touching the three different outer surfaces and the air cartridge chamber.

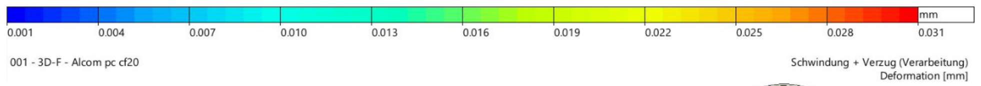


Once finished with the first side, we glued another foam block as helper on the chassis while they were still fixed in position. Another step in our code drilled precise holes in the helper foam blocks. Using dowel pins, the cars were then positioned withoud measuring. This made the whole process very efficient as no chassis position had to be determined again.

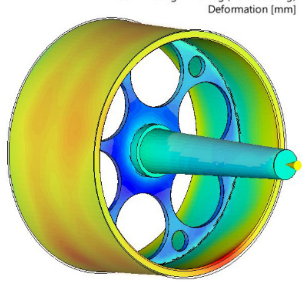
## Other Manufacturing

### Injection moulding and CNC-Turning wheels

Another big innovation are our wheels. Together with our partner WB we came up with an outstanding manufacturing process. To reduce the moment of inertia, the smallest wall thickness possible is needed. As there is a high risk of deformation when using metal, we decided to use a composite material consisting of polycarbonate and 30% carbon fibers. This allowed us to reduce the wall thickness to a minimum of 0.40 mm.




We recycled and adapted an injection mold for the process. For the wheels surface and track contact width an offset was designed that was later trimmed of by CNC turning the wheels. This ensured we only need one injection mold for both wheels with different track contact widths. Furthermore this guaranteed a perfect roundness.



We noticed the problem of a concave thread after the CNC process. We figured out that due to the small wall thickness, the wheels outer surface bent towards the inside while cutting. To solve this issue, a mounting rig was designed to support the wall during turning. These wheels proved to be a major factor in our cars performance.

### Workplace Safety

Before each use of machines, we have had a briefing to ensure excellent safety. When needed we worked with earmuffs. Through the whole manufacturing process we strictly followed the safety requirements. Before starting a maschining process for example we ensured that all doors were closed and locked.

### 3D-Printing SLS process

All spoilers, TLG suspensions and wheel support systems were 3D printind using selective laser sintering. The printer produces layer by layer from a polyamid 2200 powder using laser. This process gives us the needed freedom when designing complex shapes.

## Preassembly

### FDM 3D-printed preassembly mounting

Besides the fittings of each single part, a mounting rig was designed and 3D printed using FDM. This ensured the oversized holes for the wheel system assembly are in the correct position. We used a 2 component glue to guarantee a perfect connection between the parts. In order to avoid any deformations we used a glue which remains tension-free during the curing process.

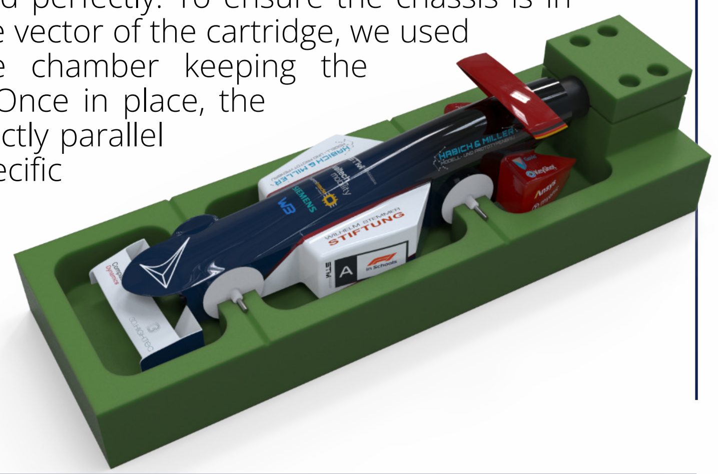
## Paint finish

To avoid any unnecessary drag force and stalls, the smoothest surface possible is elementary. To ensure a perfect finish quality within the exact weight specifications, we decided to outsource the painting process to a professional car painter. First, the rough surface was sealed by a thick primer. We used as little primer as possible on the bottom side of the car to maintain a high center of gravity. After smoothing the surface and measuring all critical dimensions, the paint layers, extra thin decals and al last layer of clear coat were applied. To guarantee we won't exceed the weight limit, we weighed the cars after every layer of paint and checked how much paint can still be applied.

## Assembly

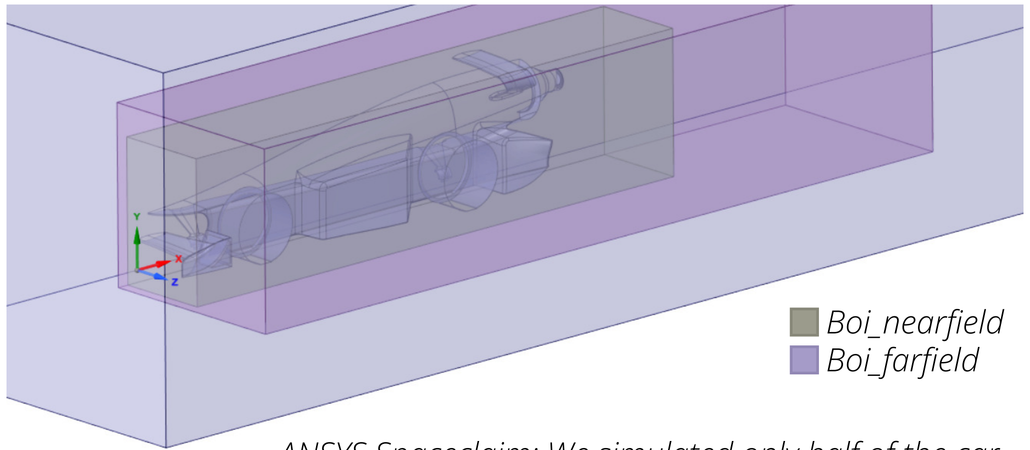
### Complex mounting rig for final cars

As every aspect of the car assembly plays an important role for the performance, we designed a mounting rig for the final axle assembly. This was made from PW920 - a hard plastic. We made the holes in the wheel support structure oversized in order to allow the axles to be moved freely into position for the perfect alignment. Before inserting the axles, the 2 component glue was applied. Using the grooves in the mounting rig, the axles were aligned perfectly. To ensure the chassis is in line with the force vector of the cartridge, we used an inlet for the chamber keeping the chassis straight. Once in place, the axles cured perfectly parallel and with the specific height over the racetrack.



# CFD SIMULATIONS

Using CFD was a crucial part of our car development procss as track tests were not always possible. By gaining a better understanding of the cars aero-dynamics, we were able to identify areas to improve more quickly.




*ANSYS Spaceclaim: We simulated only half of the car*

## Working with Ansys CFD

After launching Ansys Spaceclaim, the model was imported using a plug-in which is able to read the native files from Solid Edge 2022. Then we created an external volume around the car forming the fluid region. The next important step before the meshing and simulation process was the creation of bodies of influence (boi) which were later used for mesh sizing and quality controls. To optimize the simulation performance we only increased the number of cells in regions with lots of fluid dynamics by using the boi.

## Meshing

Meshing is probably one of the most important steps during the simulation setup as the quality of the mesh determines the accuracy and performance of the simulation. Therefore, we put a lot of work in the creation of a good mesh.

In theory with an infinite amount of cells the exact solution can be calculated. But The number of cells is limited. The following factors were considered.

**Project Schedule**
The time in the development process is limited for each iteration.

**Hardware**
With calculating on our workstations at home the hardware limits the number of simulations possible during the development process.

**Accuracy**
Keeping this time to accuracy relations in mind we want to calculate the exact solution for the number of cells possible for our project schedule.

## Reducing the numerical error

**Number of cells**
This is limited by our time constraints of our development process.

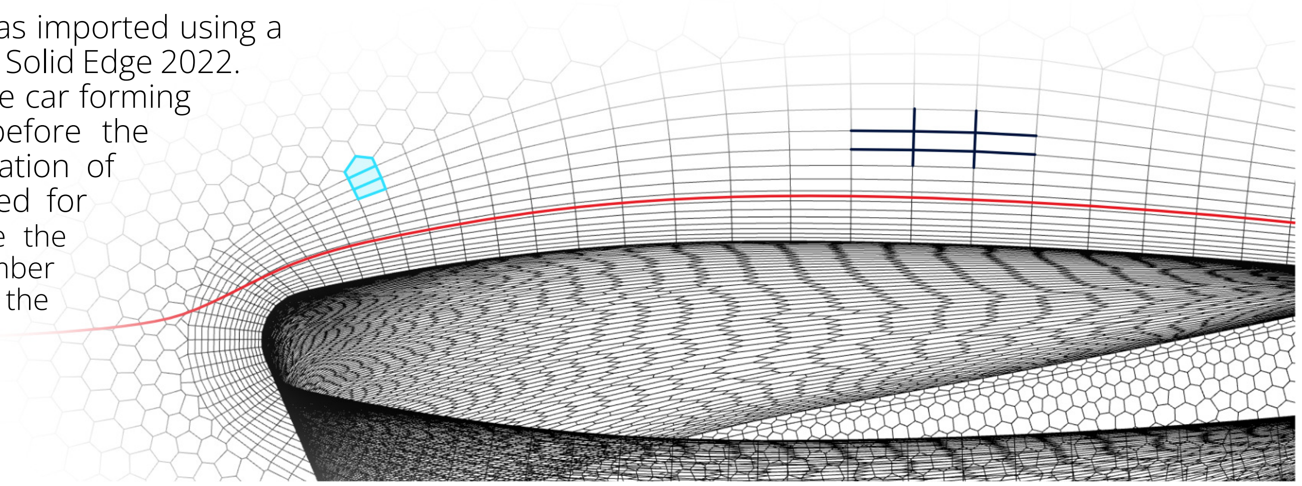
**Orthogonality of the cells**
The aim is to get as close as possible to a number of 1 which means the angles of the mesh lines are at 90°.

**Volume Ratio**
The maximum size change between neighboring cells should be 20%.

**Orientation of cells**
The cells should be orientated in a way that the airflow hits them at a 90° angle. As a result, we decided to use a polyhedral mesh as it handles complex geometries easily and needs less cells while having a perfect orientation in comparison with a tetrahedral or polyhexcore mesh.

**Double Precision**

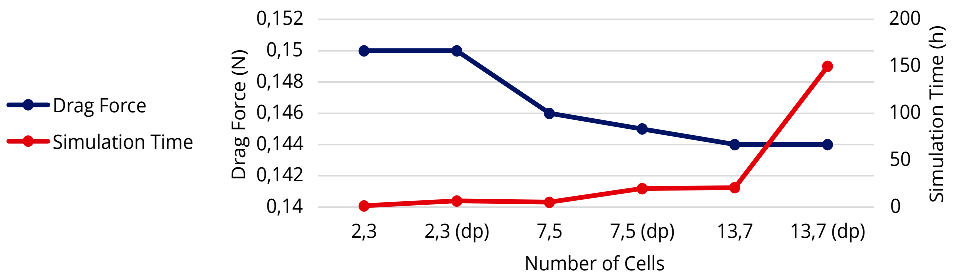
As the mesh contains large aspect ratios (long but thin cells) there is a possible risk of rounding errors during calculation. Therefore, we ran our simulation in double precision mode with longer simulation times, but less iterations needed for an accurate result.



*Mesh cells around the front wing*

## Mesh Independence Study

In order to find the best comprise between simulation time and accuracy in dependence of the number of cells we did a study. Monitoring the drag and lift force results show, that 8 Mio. Cells in double precision (dp) work best for our setup and time constraints.




## Solver Setup

Then a steady state pressure-based simulation was set up. The different boundary conditions were then defined.

- Inlet flow velocity of 22m/s
- Moving ground with the same velocity
- Rotating wheels
- Symmetry plane
- Sky with no specific shear

The turbulence model k-omega sst was chosen because of its best compromise between computing effort and accuracy for standard scenarios.

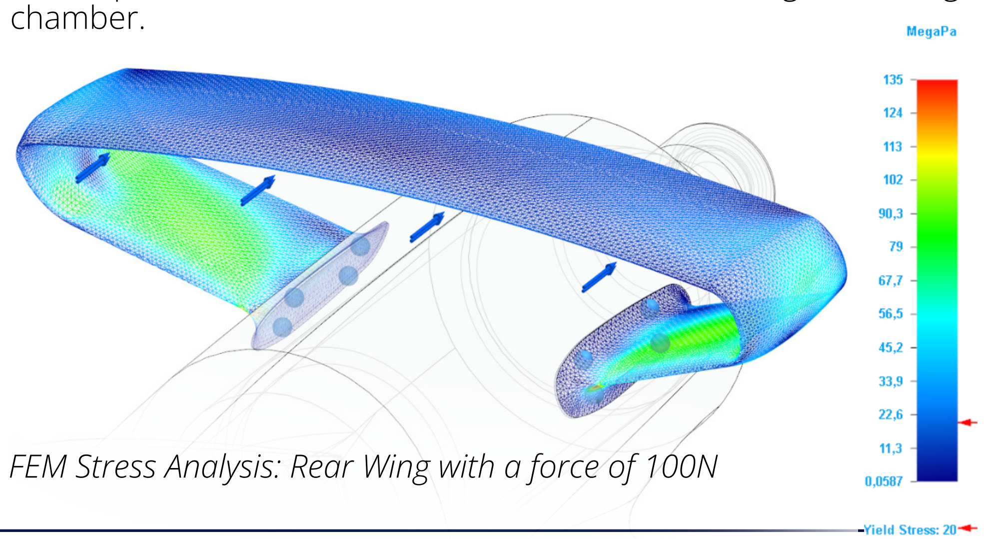
Finally the converging criteria were defined. We agreed on accepting a 2% numerical error for the simulation results. Therefore, the iteration error needs to be 0.2% or less. As the residuals show the deviation between the expected and the actual value of the variable the criteria was set 0.002. Our target values were the lift and drag force. As a result, we plotted them during the simulation process and monitored them in order to ensure they didn't change significantly for the last 50 of the 150 iterations.

## Analyzing results

Ansys Fluent provides different options to analyze the results. First of all, we looked at our drag and lift force to see if the overall performance improved. The next step is to go into detail. Fluent gave us the opportunity to create planes to be able to visualize different flow velocities and other parameters at any given cross section. Other methods like ISO-Surfaces or flow lines were a huge help in deciding between Design Directions.

## FEM Stress Analysis

Based on our experience we focused our stress analysis to the nose cone and rear wing of the car. After assigning a material to the part and defining boundary conditions like fixed faces and the impact force of decelleration applied a simple FEM Analysis can be calculated. In our case we decided to angle the rear wing to derive the impact force into the rear end of the strength cartridge chamber.

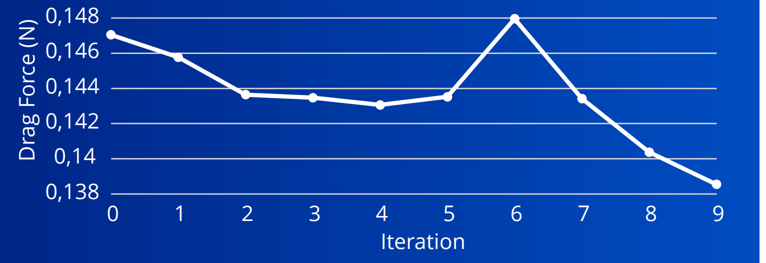


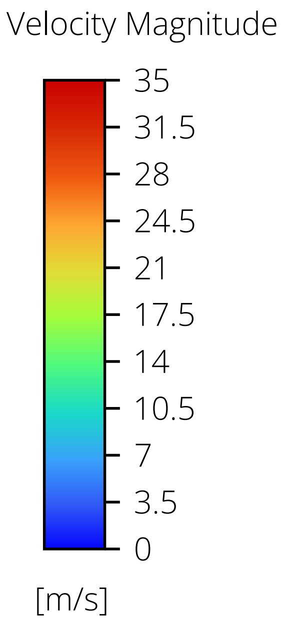

*FEM Stress Analysis: Rear Wing with a force of 100N*

# CFD OPTIMIZATION

When optimizing the car in CFD, we followed the general principle of working from the front to the rear end, as the airflow in the front influences the aerodynamics at the rear end.

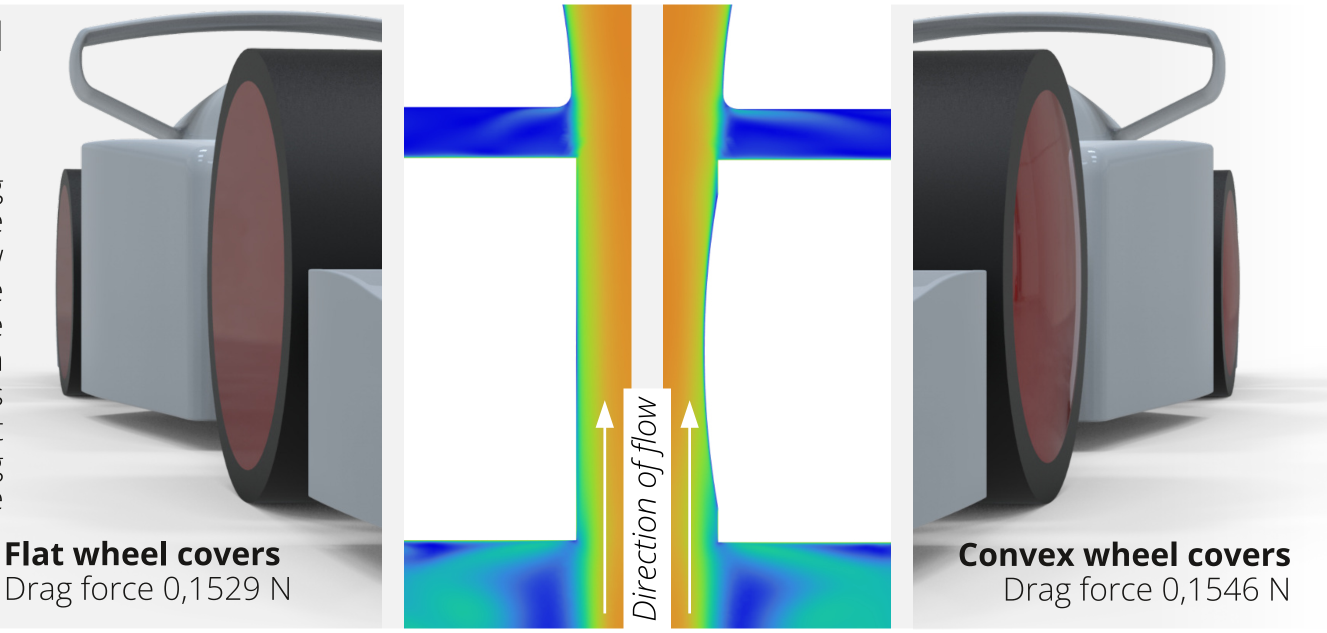
We started optimizing the car after track tests in stage 3. We were able to reduce the initial drag force of 0.1470 N by almost 6% down to 0.1385 N in 9 iterations. The improvement in % is compared with the original drag force (velocity 22 m/s).




## Convex wheel covers

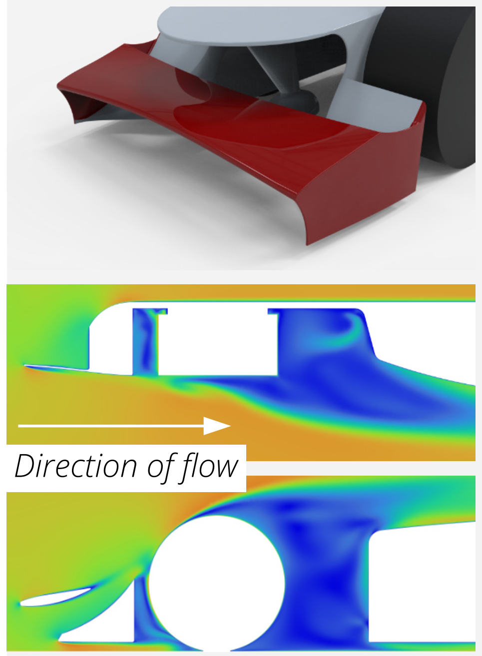
When analyzing simulation results we noticed a small flow detachment at the wheel covers. We came up with rounded wheel covers but sadly this didn't work out as the drag force increased a liitle bit.




**Flat wheel covers**
Drag force 0,1529 N

**Convex wheel covers**
Drag force 0,1546 N

### Iteration 2




**Drag force 0,1436 N**
(-2,32%)

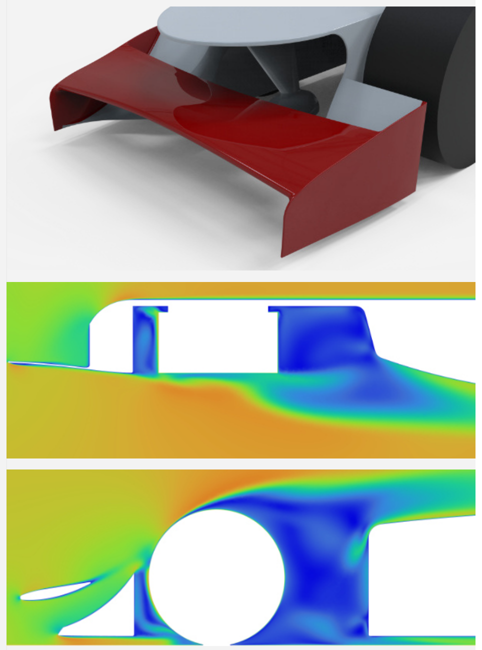
+ Splitting the air efficiently for passing the wheel sideways and above

+ Wing integrated in the airflow

- Wide low pressure area behind the wheel as the airflow detatches at the wheel early

- Turbulent flow seperation at the leading edge of the endplate

### Iteration 4



**Drag force 0,1431 N**
(-2,71%)

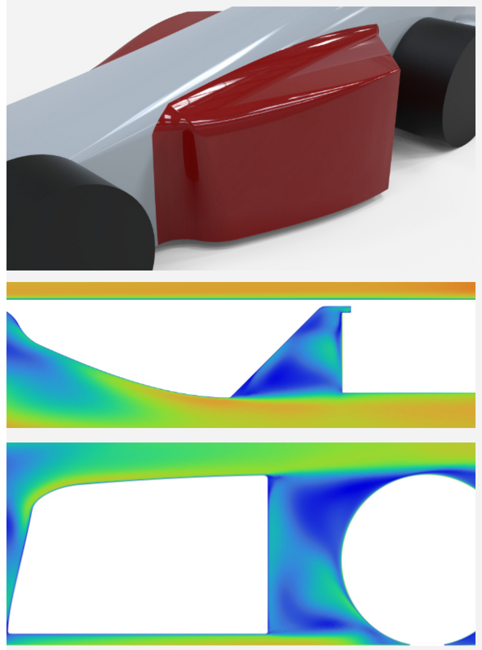
+ Splitting the air efficiently for passing the wheel sideways and above

+ Wing perfectly integrated in the airflow

+ Reduced low pressure area behind the wheel as the airflow detatches at the wheel late

+ Minimized turbulent flow seperation at the leading edge of the endplate

### Iteration 6



**Drag force 0,1480 N**
(+0,62%)

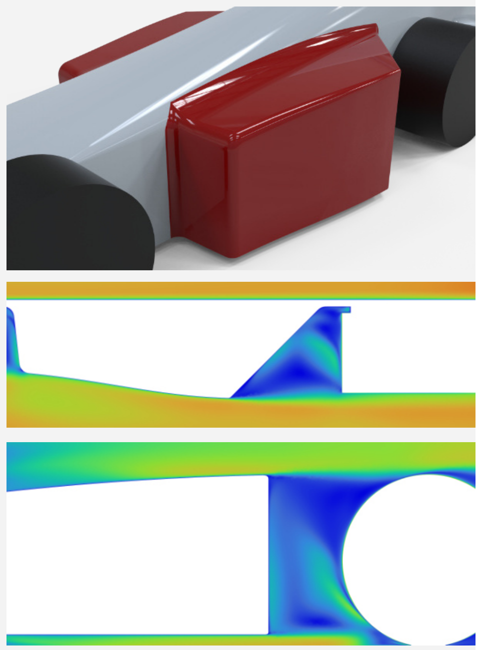
+ Wider side pod results in a pefectly attached airflow at the wheel

+ Higher side pod helps the airflow to pass the wheel above perfectly

- Very large low pressure area behind the front wheel

- High flow acceleration at the leading edge of the side pod

### Iteration 8



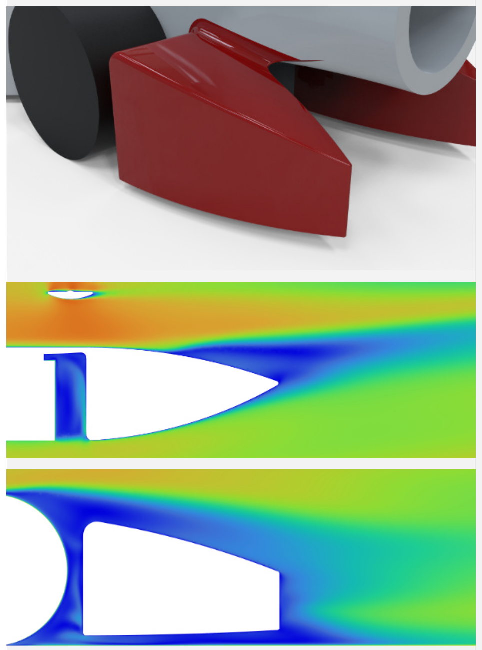
**Drag force 0,1404 N**
(-4,54%)

+ Wider side pod results in a pefectly attached airflow at the wheel

+ Higher side pod helps the airflow to pass the wheel above

+ Low pressure area behind the front wheel is concentrated and acts as a streamline body

### Iteration 8



**Drag force 0,1404 N**
(-4,54%)

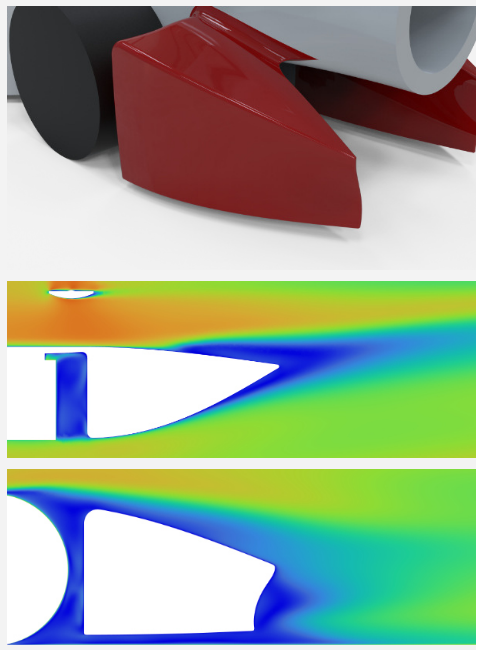
+ Aerodynsmic shape

+ Outer airflow detaches late

- Inner airflow detaches early

- Large low pressure area above the side pod

### Iteration 9



**Drag force 0,1385 N**
(-5,79%)

+ Aerodynsmic shape

+ Reduced low pressure area above the side pod

+ Inner airflow detaches later and reduced low pressure area behind

- Outer airflow detaches early