spark racing

Ever to Excel

Engineering Portfolio

F1 in Schools 2023
Hong Kong Finals

16 th December 2023

Section A - Research on Aerodynamics

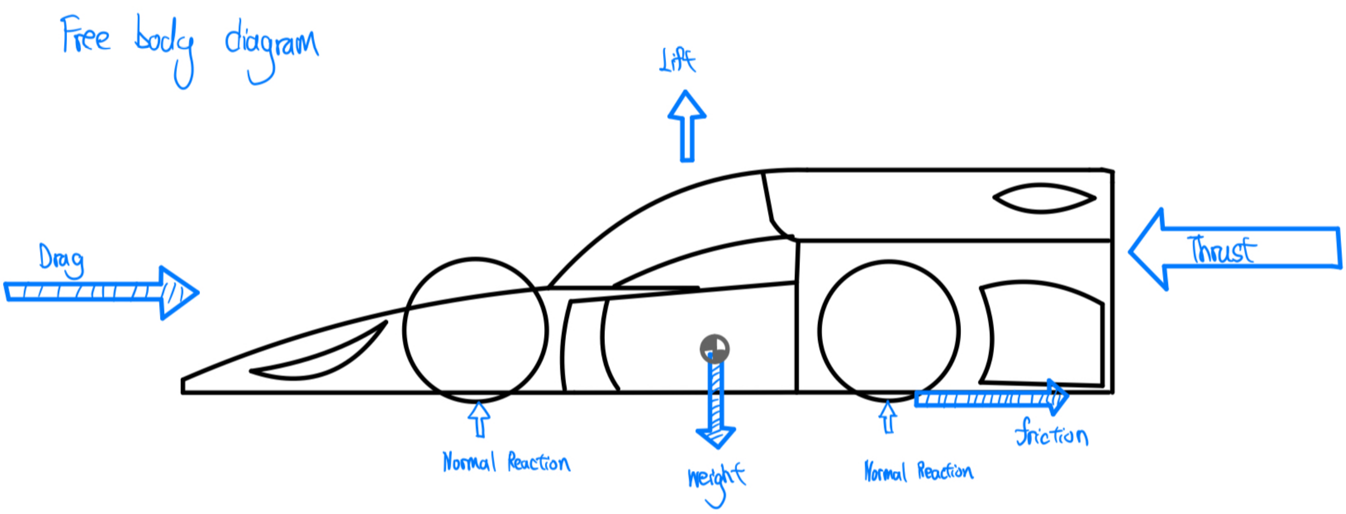
The drag equation

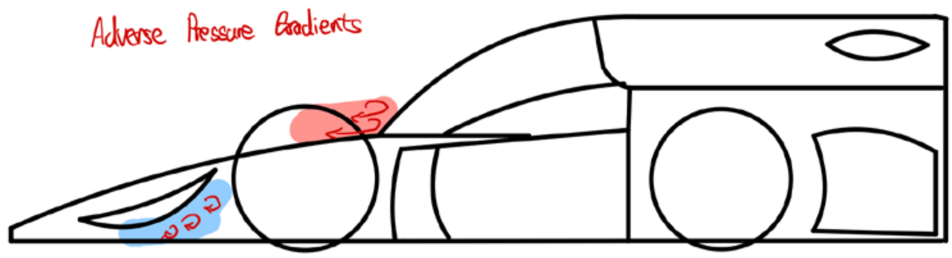
$$F_D = \frac{1}{2}\rho v^2 C_D A$$

Where:

- **Drag Force** (***F**$_D$*) is the force exerted by the fluid on the object, acting in the opposite direction of its motion.
- **Drag Coefficient** (***C**$_D$*) represents the object's shape and how streamlined it is. It is a dimensionless quantity that varies depending on the object's geometry and the fluid flow conditions.
- **Fluid Density** (***ρ***) is the mass per unit volume of the fluid the object is moving through.
- **Velocity** (***v***) is the relative velocity between the object and the fluid.
- **Reference Area** (***A***) is the area of the object that is perpendicular to the direction of motion.

Referring to the equation, there are certain aspects that we cannot change when trying to lower the drag force of the car, which includes the density and the drag coefficient. A higher velocity is beneficial to the overall finishing time of the car. We concluded that we should reduce the cross sectional area of our car as much as we could.

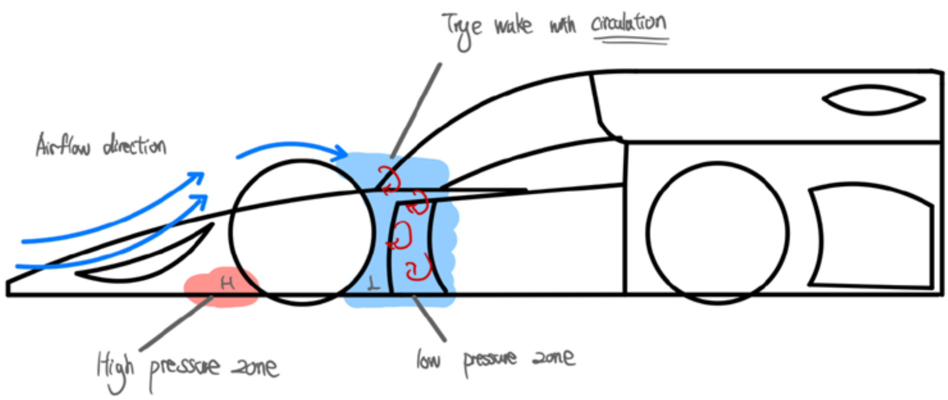




Adverse pressure gradients

Adverse pressure gradients are regions of airflow recirculation, where air flows against the direction of the surrounding airflow. These are the primary causes of airflow separation on the car. Adverse pressure gradients behind a surface create a pocket of low pressure, resulting in increased drag.

Alternatively, this type of airflow is formed when a high-pressure region exists on a surface, possessing a flow direction opposite to its conventional surroundings. As stated in the name, adverse pressure gradients move in a direction 'adverse' to their surroundings, making them undesirable on an F1 in Schools car due to the inherent recirculation of airflow in the form of turbulent eddies, inducing pressure drag. Based on this information, eliminating or reducing adverse pressure gradients became a key aerodynamic objective to reduce drag.



Wheel Wake

Wheel wake is the result of the rotating surfaces of the wheel pulling airflow into a high-pressure region before being forced sidewards, creating a large airflow separation region rearwards of the wheels. This has the overall effect of increasing drag and turbulence of the airflow rearwards of the wheel, reducing the aerodynamic efficiency of components rear of the front wheel.

Magnus effect

The Magnus effect is a phenomenon caused by the deflection of air from the counter-directional spin of the wheels on the top half of the front wheel, and the directional spin of the wheels on the bottom half of the front wheel in relation to the direction of airflow. This creates a large low-pressure zone above the center of mass, as well as a high-pressure region at the bottom of the wheel, resulting in an overall increase in drag and lift.

Due to both the wheel wake and Magnus effect, the drag produced by the front wheel faces was found to severely impact overall drag values. As a result, we identified one of our primary aerodynamic objectives to be reducing airflow collision with the rotating surfaces of the wheels.

Newton's Second Law of Motion

According to Newton's second law of motion, the acceleration of an object is directly proportional to the force applied to it and inversely proportional to its mass. The formula for this relationship is

$$F = ma$$

Where:

- **Acceleration** (***a***) is the acceleration of the object.
- **Force** (***F***) is the net force on the object.
- **Mass** (***m***) is the mass of the object.

It is typically the frontal area of the object. In simpler terms, if the force acting on an object remains constant, an increase in mass will result in a decrease in acceleration. Conversely, a decrease in mass will lead to an increase in acceleration, assuming the force remains constant.

Key design objectives

Car mass

- The car should be as close to the 50g limit as possible.

Durability

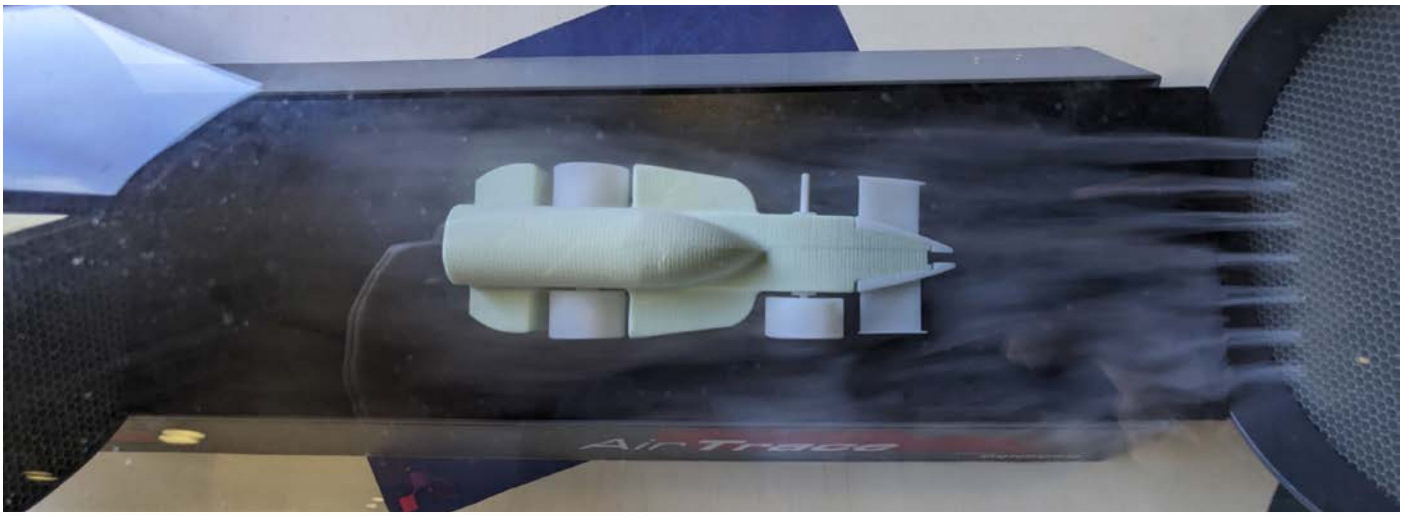
- The car must be able to withstand 10 races without breakage.

Compliance

- The car should comply with all regulations.

Aerodynamics

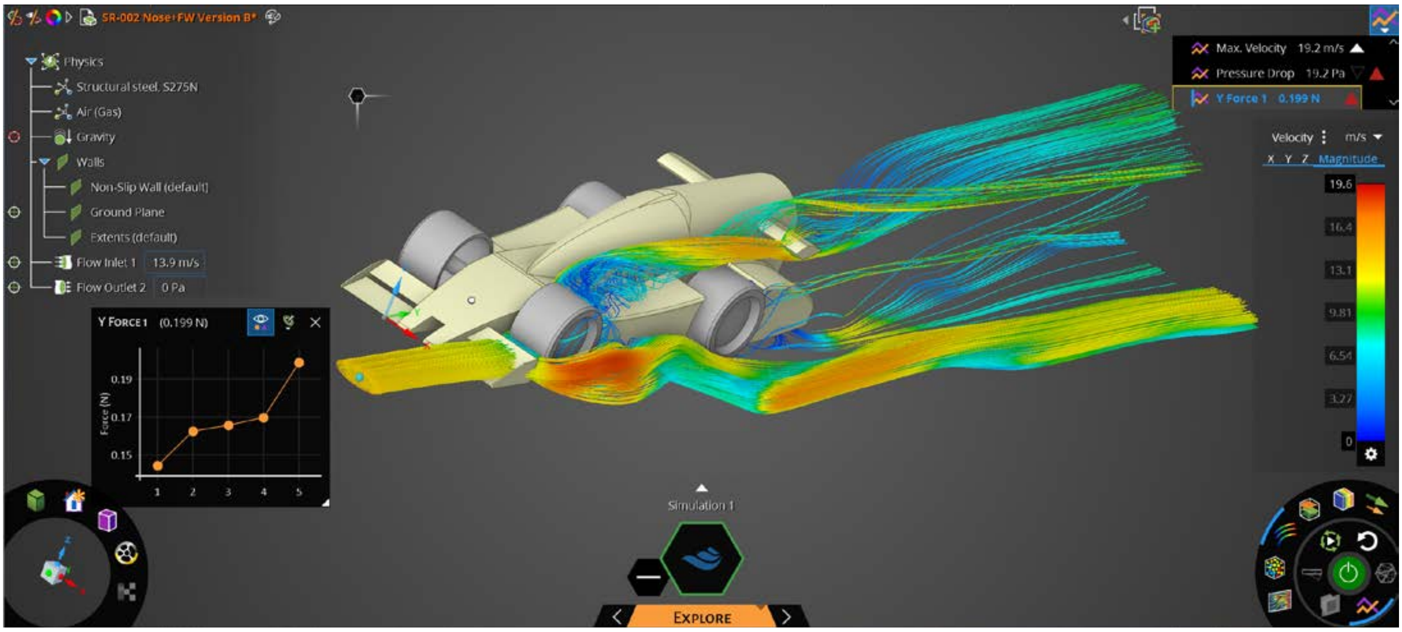
- Reduce or eliminate adverse pressure gradients. Redirect airflow away from rotating wheel surfaces.
- Achieve a drag value as low as possible given technical restrictions.



Software used

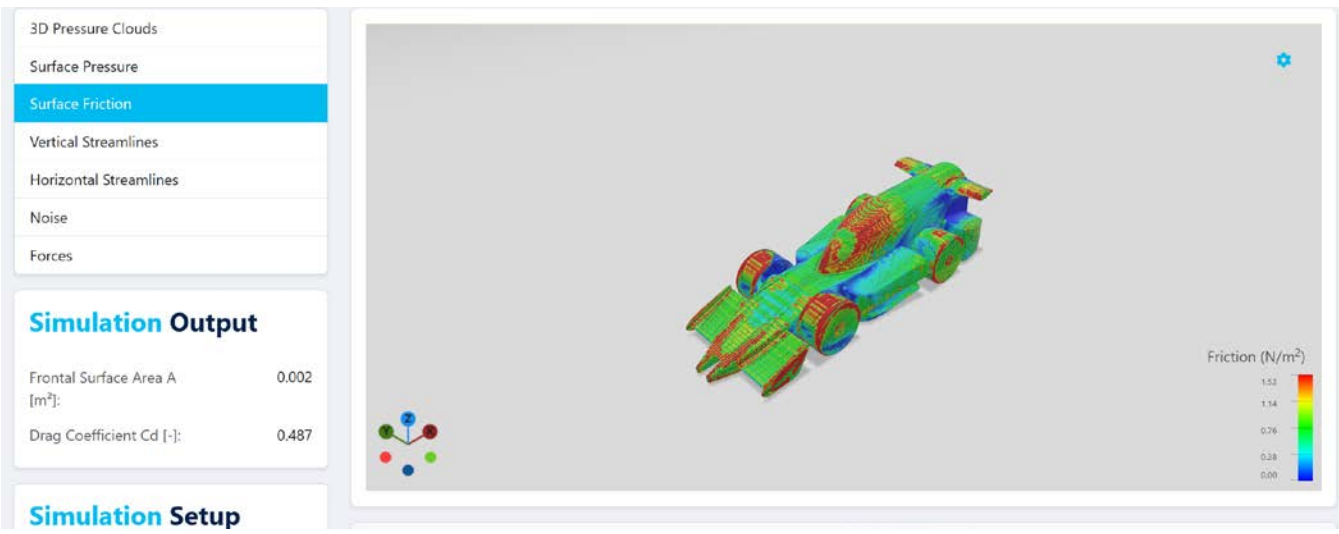
Ansys Discovery

Ansys is the world's leading provider of high-fidelity CFD software. Most noticeably, it is the software provider of ORACLE Red Bull Racing and is trusted by many organizations including NASA. As we are not aerospace engineers or F1 aerodynamicists, we decided to use their entry-level software, Ansys Discovery. Ansys Discovery vastly increases the accuracy of our simulations and provides us with powerful tools to visualize airflow patterns, pressure gradients, and flow structures around the car. This was previously not achievable when we used Autodesk CFD.



Airshaper

Airshaper is used to double-check our simulation results. As there might be mistakes made when setting up simulations in Ansys Discovery, running it in a separate CFD software allows us to validate the results. Moreover, as Airshaper runs its simulations through cloud servers, we can get results quicker due to the higher computational power.



Section B - Evaluation of Dev. Class Car

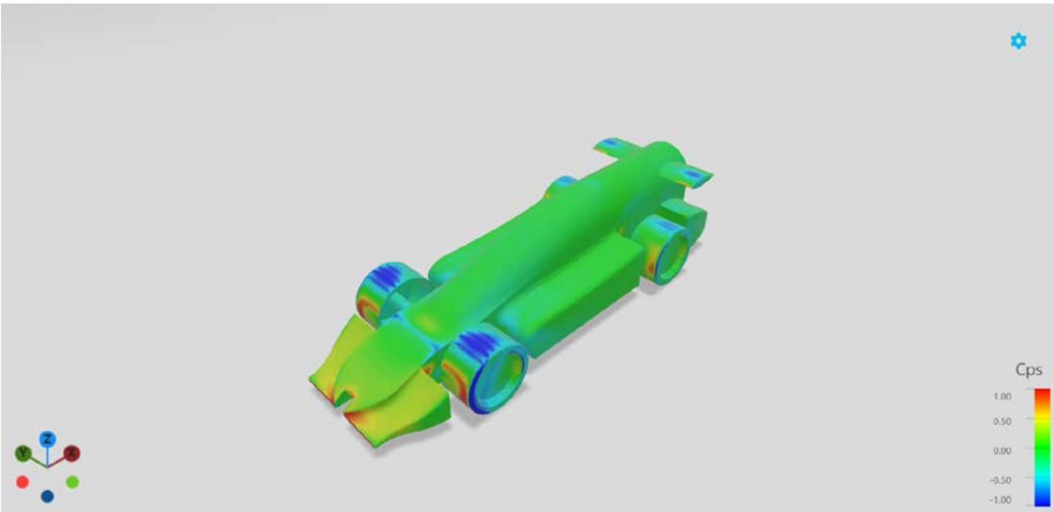
We always believe that in a development process, the most important thing is to carry out evaluations consistently, critically pointing out areas of improvement. This mindset has been the cornerstone of our development process.

With a limited understanding of aerodynamics, the confrontations of the car we raced in development class were rudimentary. The front wing resembled a wedge, with sidepods having uniform curvature along its length and simple, rounded leading edges. There was a clear lack of detail and methodologies regarding the way we managed airflow around the car.

Major faults and improvements

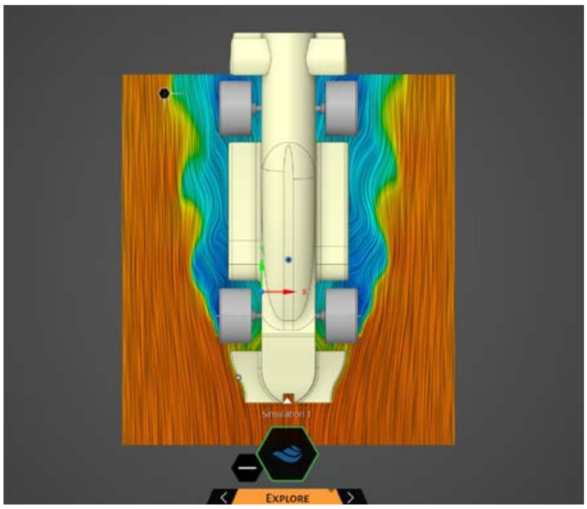
1. Massive high-pressure area in the front of the car

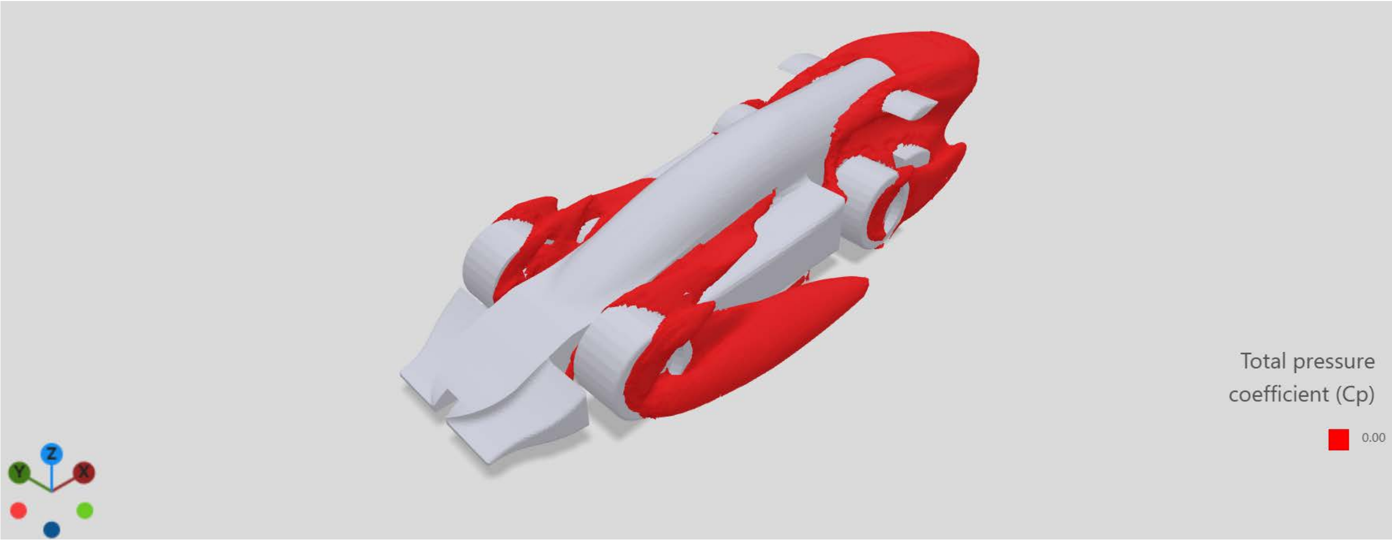
The regulated spec. axles and wheels used in development class meant that the sidepods and front wing could not be covered sufficiently. To make matters worse, the front wing was placed too high, and a substantial surface area of the tire was exposed directly to the freestream air. In addition, the leading edge of the front wing was deemed too thick, causing some serious stagnation and flow separation locally.



2. Blunt surfaces causing uncontrollable flow separations

Although the front wing directed airflow amply over the front wheels, reducing the size of the tire wake, there was a low-velocity flow field behind it as the shape of the front wheel ended abruptly . A similar situation is also apparent on the rear of the car, where the blocky shape resulted in an enormous separation region.



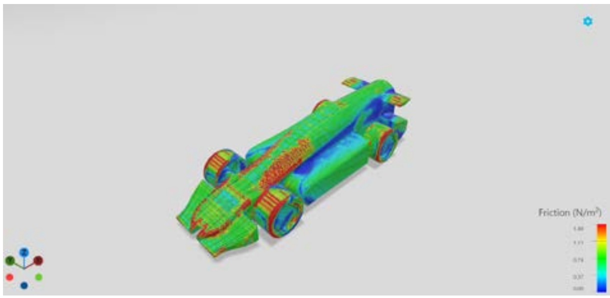


3. Tyre wake control

Front tyre wake: The outwashing profile of the front wing led to adverse effects. The air pushed aside collided head-on with the front face of the tire, leading to a messy flow regime. As nothing was conditioning the flow towards the lower part of the front tyre, airflow there displayed unpredictable and uncontrollable characteristics. The outer surface of the wheel which is curved inwards leads to further flow separations with large circulations observed. The width of the wake was particularly expensive. At the same time, as there was no surface for the flow to reattach behind the front tires, the flow was dragged towards the center parts of the car with higher pressure, hindering the flow to the rear wing of the car. The large low-pressure region adhered to the sides of the car and there was little control of the wake.

4. Large frontal area, high ride height and all kinds of other losses

In the pursuit of a smoother curvature on the top of the car, the width and height of the central proportion of the car were deemed to be too thick. Not only did this add mass to the car, but the larger frontal area also caused higher overall drag. We also believed that the high ride height, which was 5mm, could be lowered to reduce the frontal area.



Vortex shedding along sharp edges was also acknowledged as the cause of drag. These were particularly apparent on the front wing.

Drag number:	**0.184 N**
Weight:	**33.3 g**

Improvement actions

- Redesigning the front end of the car, including the front wing and the nose cone
- Weight reduction
- Reducing the frontal area
- Using more advanced geometries to contain the tyre wake and tyre squirt

Section C -
Car Development

The sidepod dilemma:
Large or small?

Given that the tyre wake contributes heavily to the overall drag of the car, adequate measures (design features) have to be in place to better control the turbulent air. We believe that the sidepods, which are located directly behind the front tyres, are a powerful tool to mitigate and manage the losses generated by the front tyre wake. Our various development prototypes mostly focused on sidepod geometry, hoping to find the best solution to the problem.

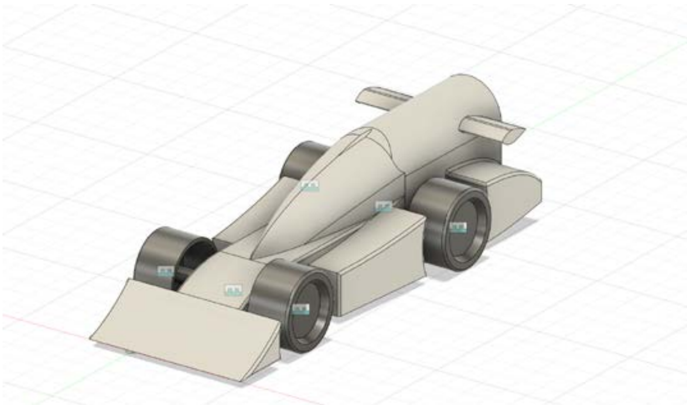
The geometry of our car has been inspired by multiple real-world motorsport applications, as such designs have been refined over decades of development and have largely converged and modified into very effective solutions.

Version A and B

The baseline model: finding opportunities for development

Concept aim:

In our research process, we noticed that many cars at the 2022 F1 in Schools World Finals featured blocky and outwashing sidepod designs, with a flat surface facing the front tyre. CFD runs proved that such sidepod design was better at narrowing the size of the tyre wake, hence it was incorporated into our car. At the rear of the car, we once again drew inspiration from cars at the 2022 F1 in Schools World Finals, with an elongated rear pod aiming to close to attach the rear tyre wake, pulling it downwards and inwards, thus reducing the size of the wake and the drag produced.



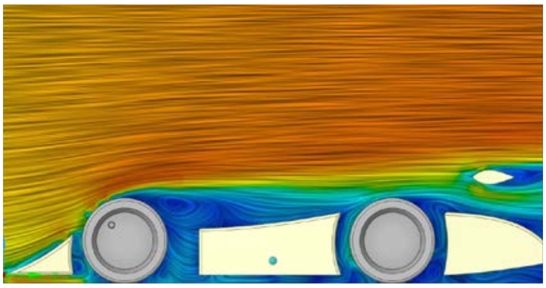
Version A

With a concentrated focus on the sidepod geometry, the front wing was kept simple and retained a wedge-like shape, albeit with smoother curvature and improved covering of the front tyres. The rear wing profile was kept simple as the previous iteration used in the development class car was deemed to be of high performance. In addition, a cone-like structure in front of the C02 canister was adopted, aiming to streamline our car.

Drag number:	**0.173 N**
Weight:	**31.612 g**

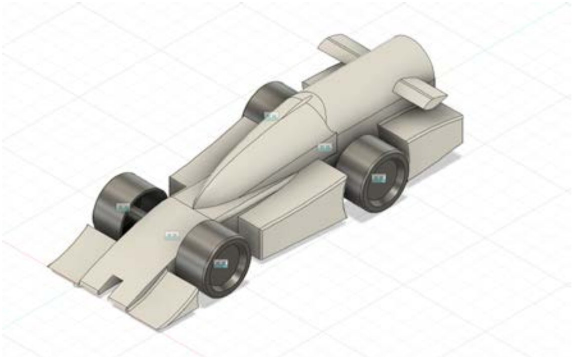
Improvement actions:

- Front wing development: The current iteration does not mitigate the problems mentioned in the evaluation of the Development Class car
- Exploring other sidepod geometries

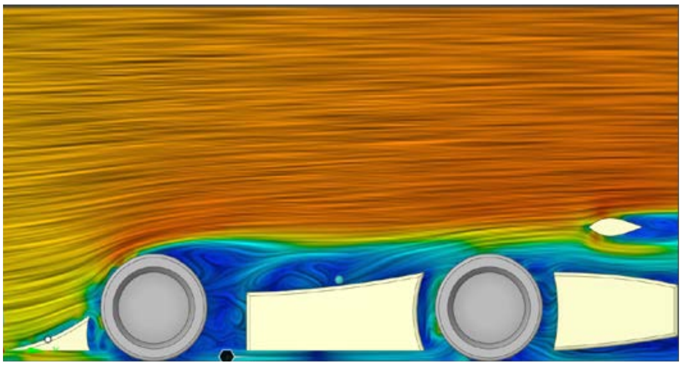


Further development:

Version B of our car was largely similar to the previous model, with its development solely focusing on the aerodynamics of the front wing. The front wing was separated into two and now attaches to a nose cone, which has rounded leading edges. Improved onset flow from the new front wing not only reduced drag locally, but also benefited the flow structures downstream, bringing compounded gains.



Version B



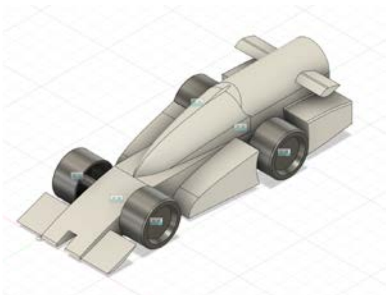
Side velocity profile showing reduced stagnation

Drag number:	**0.169 N**
Weight:	**31.316 g**

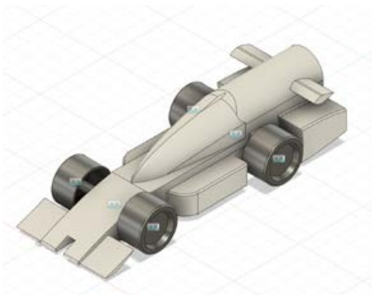
Version C, D and E

Looking into other possible concepts

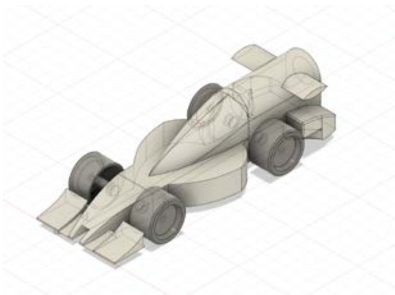
The front wing design further matured, it is now much thinner in width, cranked higher and resembles much more to a front wing profile found in single seaters in real life. We achieved remarkable gains with this design, hence it served as the basis for our future front wing designs.



Version C



Version D

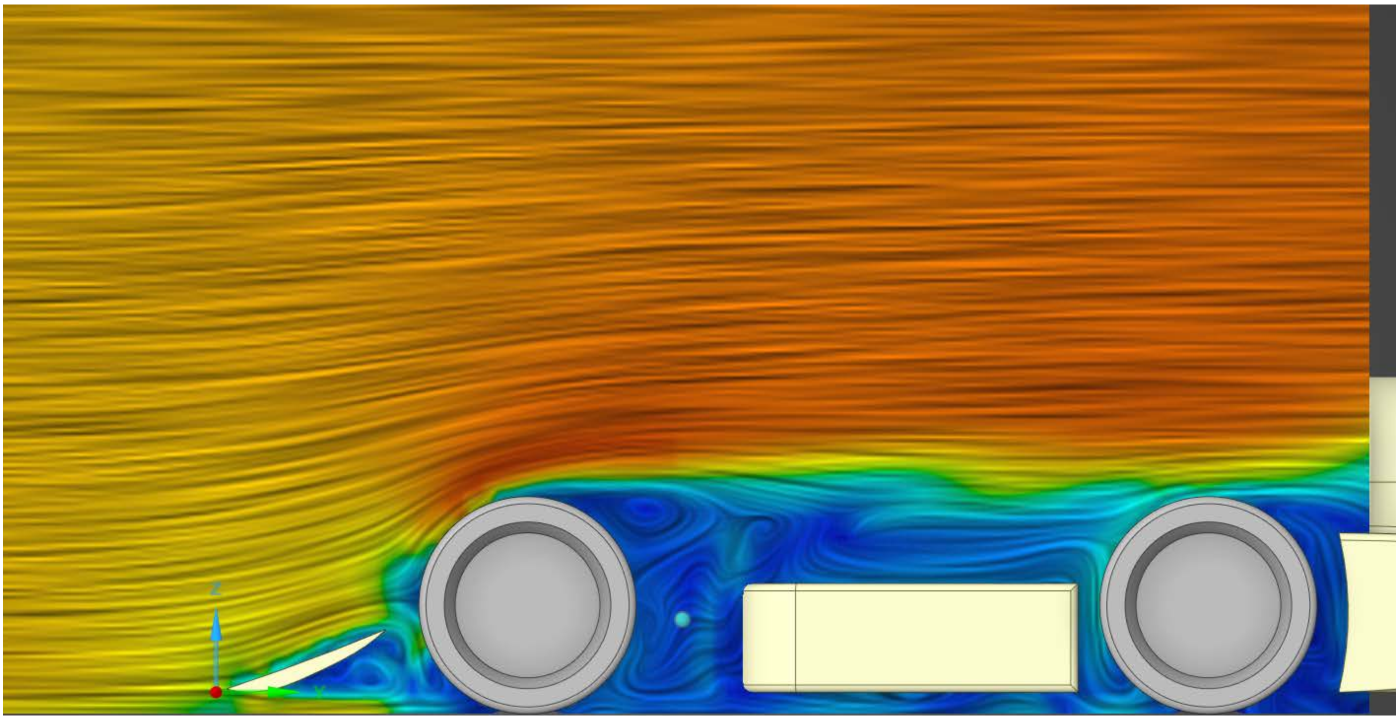


Version E

Drag number:	**0.165 N**
Weight:	**30.322 g**

Drag number:	**0.175 N**
Weight:	**29.904 g**

Drag number:	**0.181 N**
Weight:	**26.665 g**



Improved onset flow in front and rearwards of the front wing

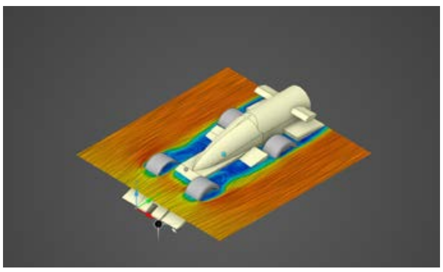
The front wing design further matured, it is now much thinner in width, cranked higher and resembles much more to a front wing profile found in single seaters in real life. We achieved remarkable gains with this design, hence it served as the basis for our future front wing designs.

Version C and D have some wildly differing sidepods, as we did our very best to evaluate all kinds of concepts. Regrettably, none of them were as promising as the design used in Version A and B.

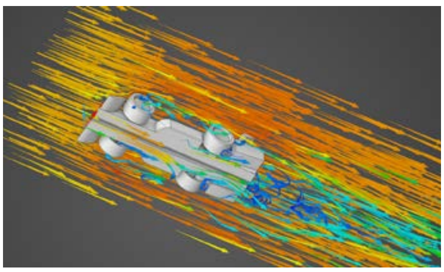
The sidepods on Version E were slightly inspired by the bathtubs of the Ferrari F1 75. Conceptually, this should allow better tyre wake attachment along the sides of the car. The front wing was also changed, where we experimented on adding more “through-flow” to the leading edges of the sidepods by lowering the height of the portion that connects to the nose cone.

Evaluation:

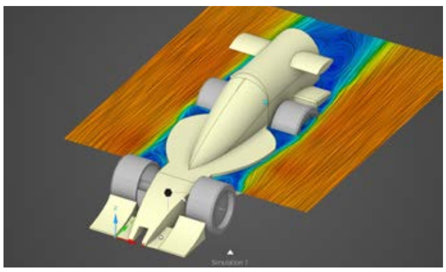
- Tyre wake management was still very poor, with turbulent regimes everywhere
- Overall drag of the car has not decreased by much, need to consider other development paths



Version C



Version D

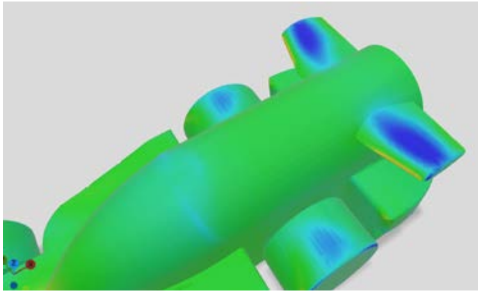


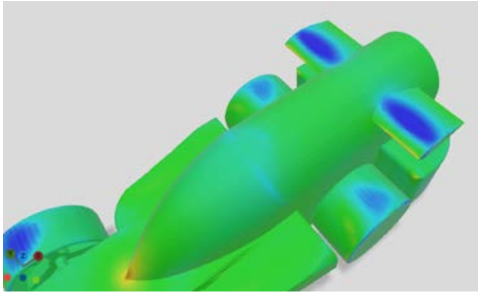
Version E

Section D -
Iterative Design Process
Continuous experimentation

Wings

Swept wings

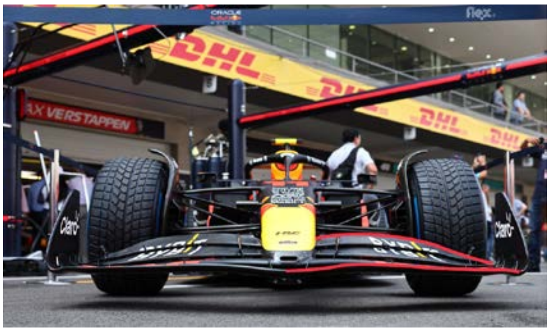

Swept profile


Uniform profile

Inspired by fighter jets, swept wings were added to the rear of the car to reduce drag, though the magnitude brought by such change may be quite negligible referring to the CFD results. Yet, there were subtle improvements in the pressure gradient on the upper and lower surfaces of the rear wing, so we added this to our car at the end.

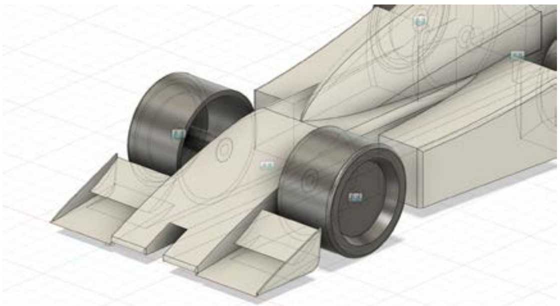
Multi-profile wings

This means that the cross-section of the wing does not remain consistent throughout its span. Such designs are found on every front wing on the whole F1 grid. These wings are a great choice as it has the ability to direct airflow in multiple directions, for instance, an outboard curving wing could lead to more outwash in front of the front tyres. We trailed this on our car, but sadly due to the “5 mm thickness rule” mandated in the technical regulations, the idea was not as effective. We believe this design is much more suitable for multi-element wings.



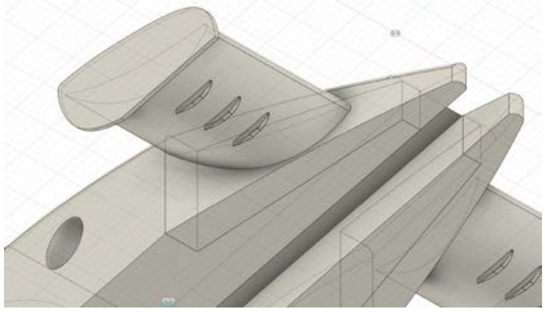
Multi-element front wing

Multi-element wings are used heavily in motorsports, especially in series that are very downforce-dependent, such as Formula 1. As the angle of attack of our front wing is large, significant flow separation occurs at the leading edges. By using multi-element wings, in which slot gaps are present between the various elements of the front wing, flow separation could be delayed, lowering drag. Yet the regulations do not allow such designs so it was not implemented in our car. We hope that the knowledge gained from this could benefit us in the future as we develop more sophisticated front wings.



Aerodynamic trickery

Vortex Generators



Given that the front wing has such a high angle of attack, we predicted that airflow separation on the underside of the wing was inevitable. Vortex generators, which can re-energize flow on the boundary layer, were trailed. Yet due to the flowfield's complexity, we could not align the vortex generators to the incoming flow, so their effect was limited.

Strakes

A view of the mind blowing complexity of a 2018 F1 car front wing

Instead of mounting them on the top of the wing, we attached strakes to the underside of the front wings, which had an effect similar to an outboard curving front wing endplate, encouraging outwash, allowing airflow to wrap around the front tyres, leading to better management of the front tyre wake. This was a very effective solution so it made its way onto our final car design.

Front wing diveplane and endplate foot

Alas, the effect of these components was not quite significant so we wasted no more time researching and experimenting on them.

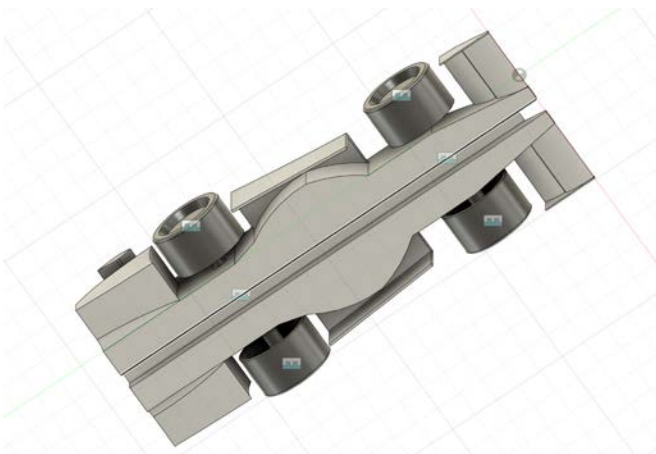
Diveplane

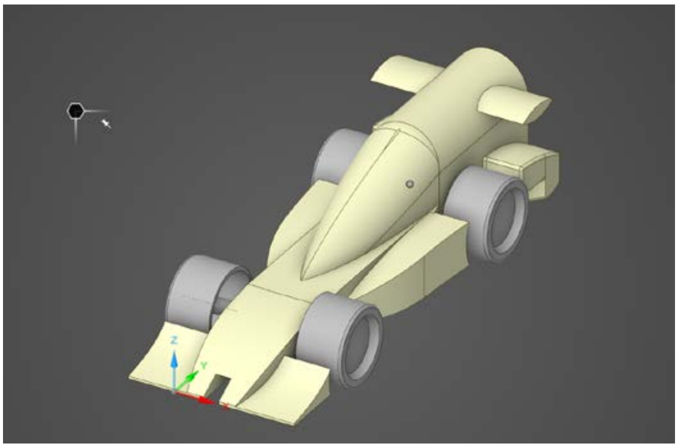
Enplate foot plate

Others

Sidepod opening with inner channels

This type of design was prevalent in the World Finals, so naturally we were intrigued by it. Yet due to the "No-go" Zone restrictions, the channel created was extremely narrow. Added to this, we are not allowed to drill from the underside of the car using the CNC router, so such a design was dropped swiftly soon after early experimentations.



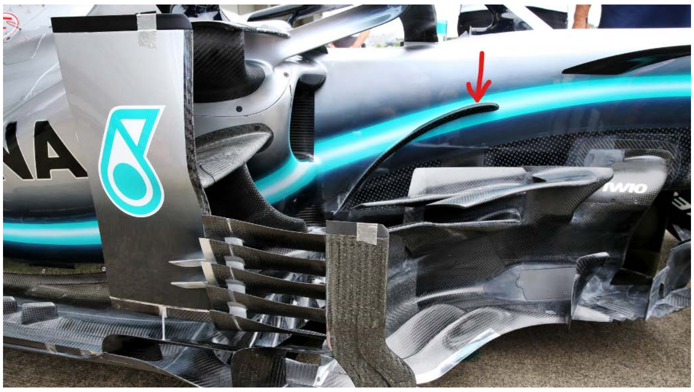


The feature shown on the Acura ARX-06

Cutout on the bottom of the rear pod

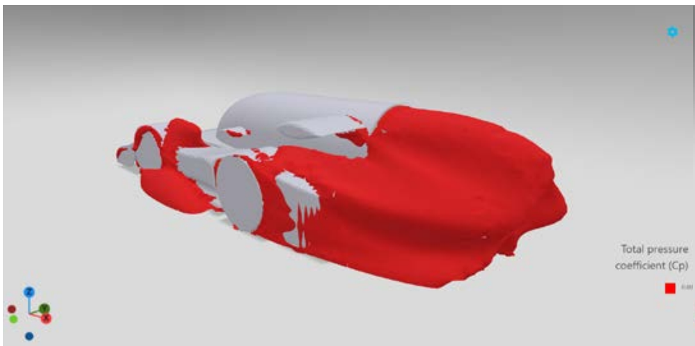
Previous iterations of the rear pods aimed to contain the rear tyre wake by creating a smooth surface for it to attach on. From our research, we found that the Acura ARX-06, a hypercar competing in IMSA, had a small cutout behind the rear tyres, which pushed the lower part of the tyre wake outboard. While the design was promising, changes we made upstream (new sidepods, front wings) caused us to be uncertain about the actual performance of this component so it was not implemented in the final iteration of our car design.

Chassis canards



Chassis canard shown on Mercedes W10, on top of the bargeboard area

When we were observing the wake of the rear tyre, we descried that the wake closer to the body of the car was pulled up to the rear wing, which led to a bulbous wake forming very high up on the car. To mitigate this, a canard was placed in the central portion of the car in hope that the rear tyre wake could be kept closer to the downward-sloping rear pods. CFD results were extremely positive, both versions tested showed promising results, a much cleaner flow was achieved at the rear end of the car. These versions had a simpler geometry with a downwashing wing profile and a relatively longer chord, while Version 2 was reminiscent of the chassis canards found on the Mercedes F1 W10, with double fins on top of the floor entrance. However, due to manufacturing difficulties, this idea could not be implemented on our car.



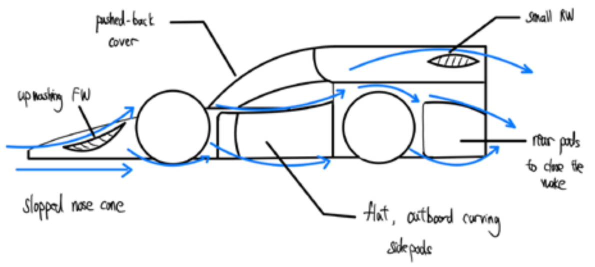
The addition of the canard shows cleaner flow

Without the canard, flow is much messier

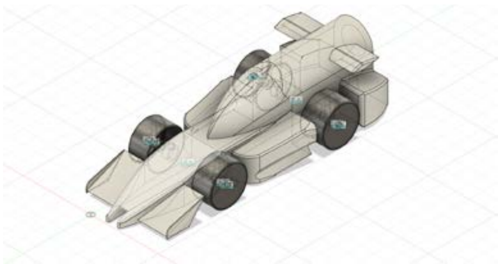
Section E -

Our Final Design

The final version of our car was created with all the knowledge we attained throughout the 3-month development journey.



Initial sketches on the overall layout of our car, with clear annotations



Overall mass

As mentioned beforehand, the mass of the car is the most critical factor in determining the overall speed of the car. Even though the drag coefficient of the previous iterations was lower than the development class car, their mass was indifferent, with some versions even heavier than the development class car. Hence drastic action was taken to cut down the weight of the car

Size matters

Through experiments in CFD, we realized that the length of the rear pods could be greatly reduced as adjustments to the curvature showed similar abilities in closing the rear wake of the car. Moreover, we realized that there was room to cut down the length and width of the sidepods without compromising the aerodynamics of the car. The overall length of the car was thus reduced to 178 mm, with a longer, the lower and smoother nose further reducing the mass.

Aerodynamics

Side profile

We noticed that land speed record cars have cockpits placed further back on the car. We wondered if implementing this could aid in reducing drag. Experimental results in CFD were positive indeed, airflow stagnation was reduced and cleaner flow could be achieved on the upper surface of the car. The nose was also smoothened as much as we could so that sudden, abrupt changes in geometry could be avoided, lowering drag.

Sidepods

The sidepods were further developed, with complex shapes. The confrontation varies throughout the height of the sidepod, with the upper surfaces focused on pushing the tyre wake outwards and the lower parts containing the turbulent air created by the front tyre by dragging them closer to the car.

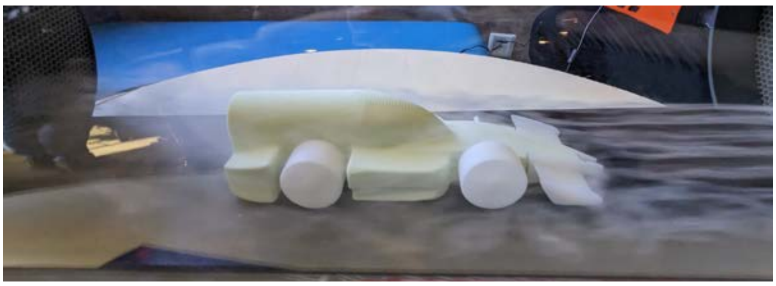
Most noticeably, we have added an undercut to the sidepod. Inspired by the hypercars in the World Endurance Championship, including the Toyota GR010 hybrid, we pondered on the idea of whether an undercut could pull the front tyre wake closer to the car. Compared to previous designs, the tyre wake size was largely reduced, it was effectively pulled downwards along the curvature on the side.

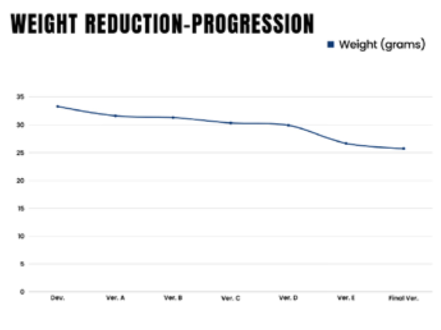
Front end

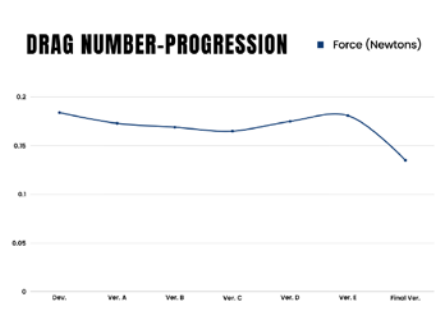
Focusing on the front end of the car, we designed a new front wing with a higher angle of attack which allowed us to route more air over the top of the wheels which delayed flow separation. The increased coverage also decreased the size of the high pressure region on the front of the car which also aided us in reducing the overall drag. The endplates on the front wing, which is a novelty, allow us to decrease flow circulation behind the front wing. Typically, there is a high pressure area on top of an inverted wing (our FW) and a lower pressure area underneath it. As high pressure air tends to flow to a region of lower pressure, the airflow curves downwards and creates a large vortex, which brings a lot of drag. By having endplates, a physical barrier is formed to prevent circulation, lowering drag and also boosting downforce. The tips of the nose structure were also minimized to the max.

Drag number:	**0.135 N**
Weight:	**25.5 g**

Air visualization testing using the Airtrace system







Recording of key performance indicators of our car

Wheel design

Evaluation

- The steel axle used was particularly heavy
- There was a far too large distance between the two wheels
- A sudden concave confrontation on the wheel leads to unfavorable aerodynamic characteristics

Main area of focus

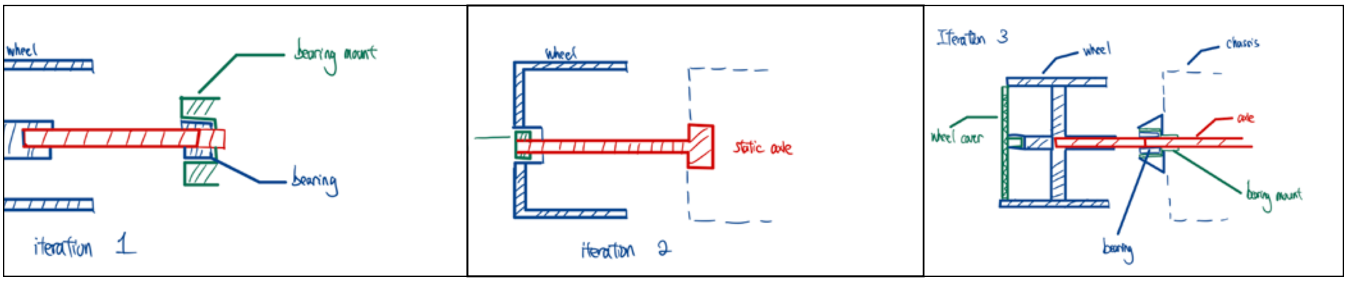
- Reducing mass
- lowering the drag
- investigating on potential materials that could be utilized in 3D printing

Type of 3D-printing used and the reason

Stereolithography was used. SLA (Stereolithography) 3D printing is a type of additive manufacturing technology that uses a liquid resin cured by a UV laser to create three-dimensional objects layer by layer. We choose it due to its high accuracy and resolution. SLA printers can achieve very fine details and high precision, allowing for the creation of intricate and complex geometries with smooth surfaces. This makes SLA suitable for applications that require high levels of detail and precision, such as our front wing.

Design features: Bearings

Bearings reduce friction by providing a smooth interface between two moving parts. They are designed to allow controlled motion with minimal resistance. Most bearings consist of rolling elements, such as balls or rollers, that are located between the inner and outer raceways. These rolling elements help distribute the load evenly and reduce the contact area between the moving parts. As a result, the friction between the rolling elements and the raceways is significantly lower than the friction between two surfaces sliding directly against each other.



Various conceptual iterations of our wheels and the support system

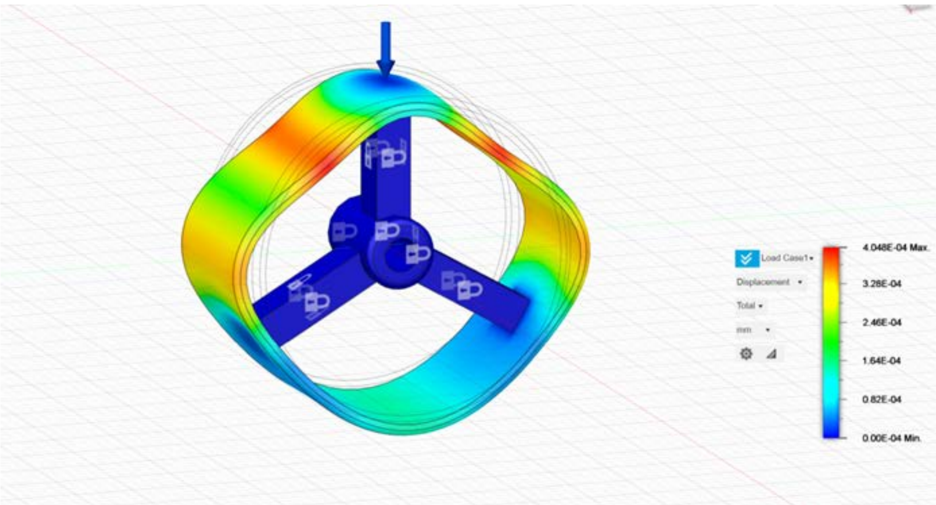
Iteration 3 was chosen to be the iteration that will make its way to the physical testing phase. A wheel cover was added to ensure a smooth surface for the air to flow along the sides. Structurally, spokes were used to reduce the mass. To reduce the mass to the maximum, we brought carbon fiber axles.

Coping with failures: Preserving and engineering better solutions

Our lack of expertise in wheel design led us to a multitude of problems, though we still managed to test various components and gained valuable experience on how to better produce such parts.

Problem	Details	Solution	Result
Bendy axles	The resin used in SLA printing was very sensitive to its surrounding temperature and issues may have arisen in the setting process of the liquid resin. Yield strength of the axle produced was very low.	Experimenting with PLA printing	New axles worked
Not fitting bearing mounts	The margins were too small and the axle became stuck on the mount	Enlargement of the hole	It leads to a new problem. As the axle produced was prone to bending, it brushed along the sides of the bearing mounts and created a lot of friction
Loose axles	The axle did not join to the bearing tightly, making the use of a bearing limited	Dilated axle diameter	New axles worked
Deformation of wheels	Wheels rotate in a non-uniform manner	Critical problem- no imminent solution	

To better understand the deformation, an FEA (finite element analysis) was carried out. Assuming that the central strokes are structurally sound, when a load of 20 N is applied serious deformation can be observed. We did hope to try experimenting with other types of 3d printing or even trying out milling aluminum blocks with CNC machines yet the limited time we had meant that none of this was achievable. Regrettably, we had to continue to use the standardized wheels supplied. Still, a weight reduction of around 5 grams was achieved as we created our own axles instead.



Section F - Manufacturing

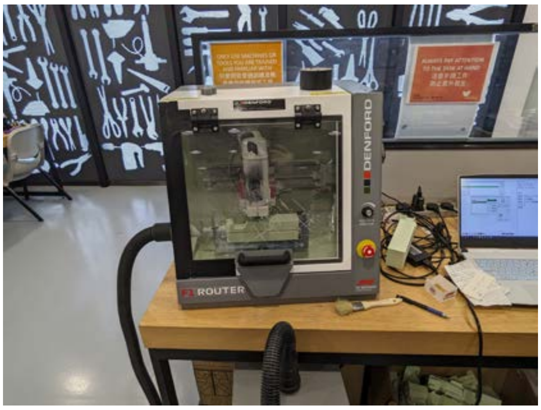
Manufacturing Considerations

We first identified the limitations of the CNC router available

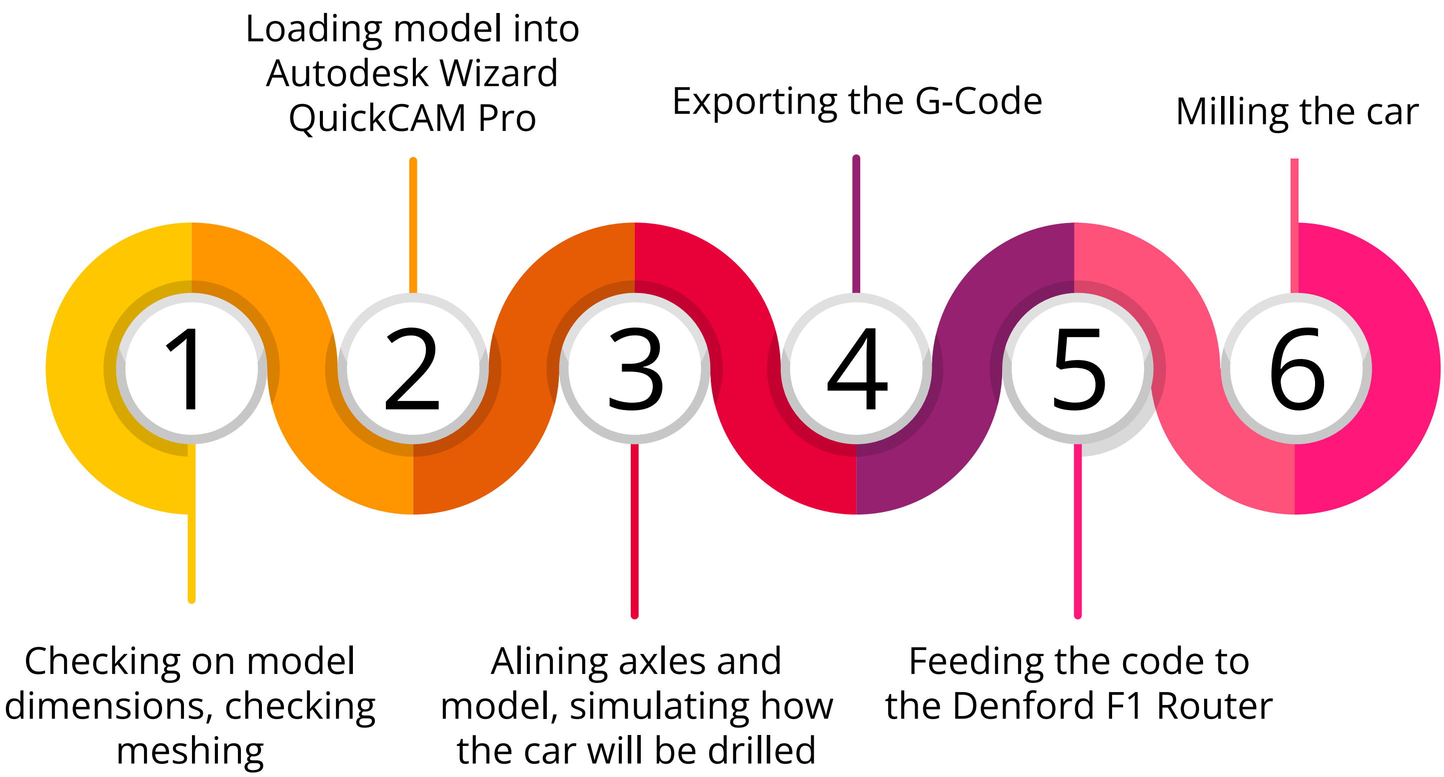
- The drill is 6.35mm and has a ball-shaped head, which means that sharp edges will mostly be smoothened, and delicate details might not be manufacturable
- No drilling is allowed on the top and bottom of the car
- The accuracy, especially at axle holes may not be optimal (concerns about calibration)

Following actions

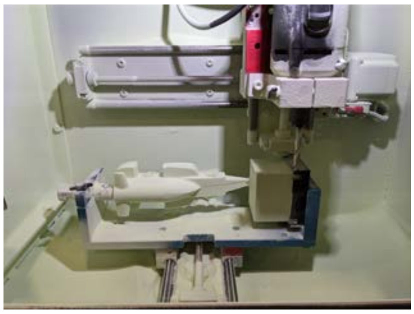
- Adding filets along the edges so we could accurately manufacture the curvature
- Checking the width of any tunnels (such as the sidepod undercut) constantly so the car could be manufactured
- Avoiding any gullies or underbody channels in the design
- Adding margins to the tip of the nose cone as it might break off
- Adding curves to all the connecting faces to the 3D-printed components
- Subtle rear wing design



Manufacturing process



Surface finish by hand



After the car was milled out of the CNC machine, we used sandpaper to smoothen the surface. Starting with rougher ones (400), we gradually moved on to finer ones (maxed at 2500). The car is then painted with a primer, which fills any gaps or small dents on the surface while also allowing better adhesion of the paintwork. The basecoat paint was a mix of gray and pearl white which allowed us to achieve a silverish colour without using heavy chrome paint. The blue colors were painted on afterward. Finally, the decals are stuck to the car. The front wings and the bearings are then attached to the car by using superglue.

Outsourcing

The white components are outsourced 3D printing parts from Addify 3D

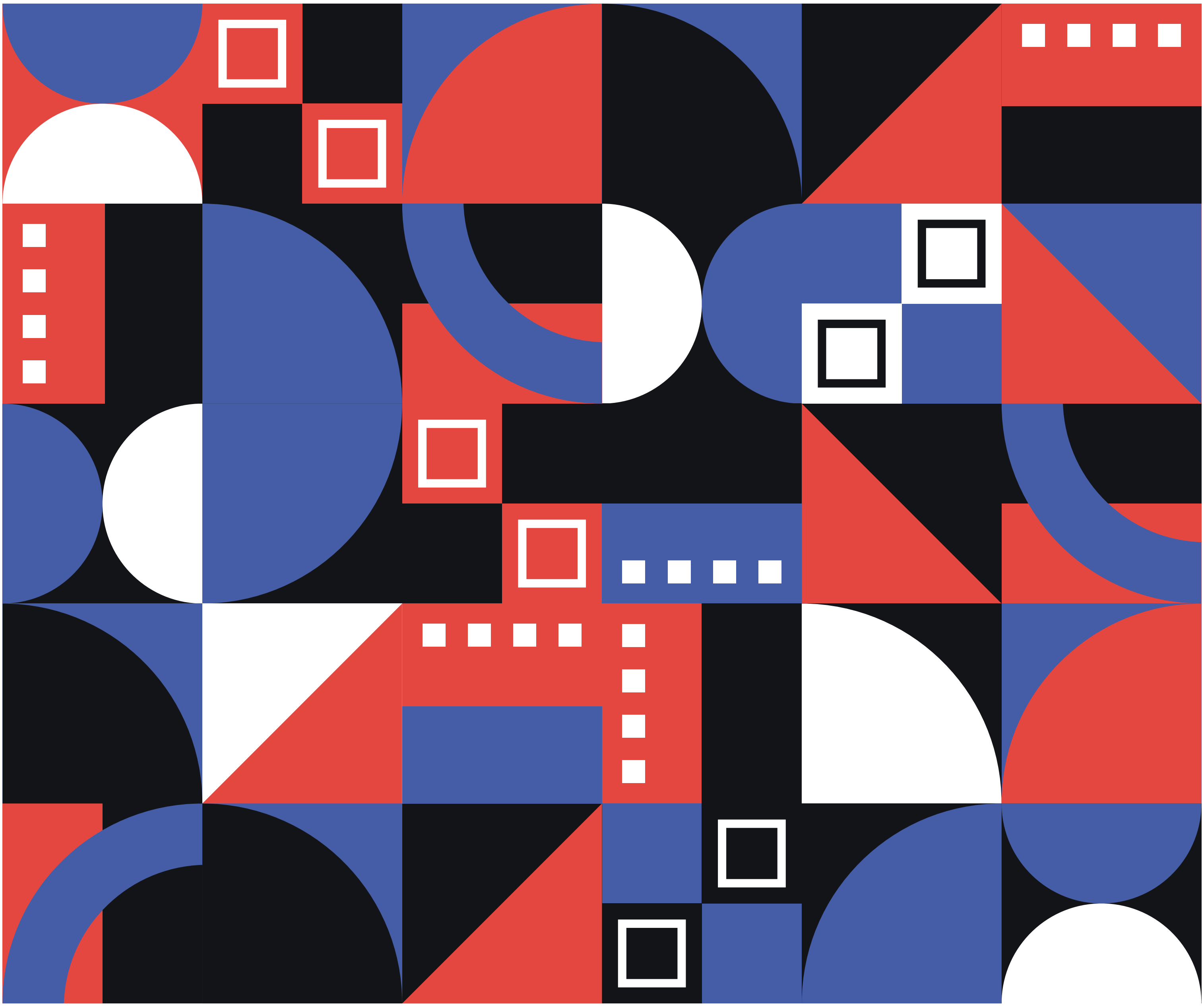
To ensure the smoothness of the wheels produced, the PLA 3D printers at our school were deemed inadequate.

Our team decided to use an SLA 3D printer for the production of the front wings and parts for the wheels. Production of the front wing and the experimental versions of the wheels and bearing was appropriately outsourced to Addify3D. The parts produced had extremely high yield strength and lower mass than their PLA counterparts. The axle was printed using PLA 3D printers at our school.

Workplace safety

We created a risk assessment chart in order to ensure a safe manufacturing process. We treat this very seriously as safety is paramount.

Risk description	Causes of risk	Probability (P)	Impact (I)	Risk Score (P×I)	Risk Control
Skin, Eye, and Lung Irritation	Foam dust exposure and inhalation	0.6	0.4	0.24	A dust collection system was used in the CNC router, minimizing loose dust after CNC machining was complete. Hand sanding of cars was conducted in a well-ventilated area.
Drowsiness or dizziness	Prolonged aerosol spray paint inhalation	0.4	0.6	0.24	All spray painting was conducted outdoors with good ventilation. PPE in the form of a dust mask was worn during painting.
Entanglement or impact	Operator entanglement in CNC router, or CNC router ejecting workpiece	0.1	0.8	0.08	All CNC milling operations were conducted under the supervision of an experienced supervisor. The workpiece was checked to be firmly secured and the safety door was closed before all cuts.



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