PHOTONIC | ENGINEERING PORTFOLIO AUS NATIONAL FINALS

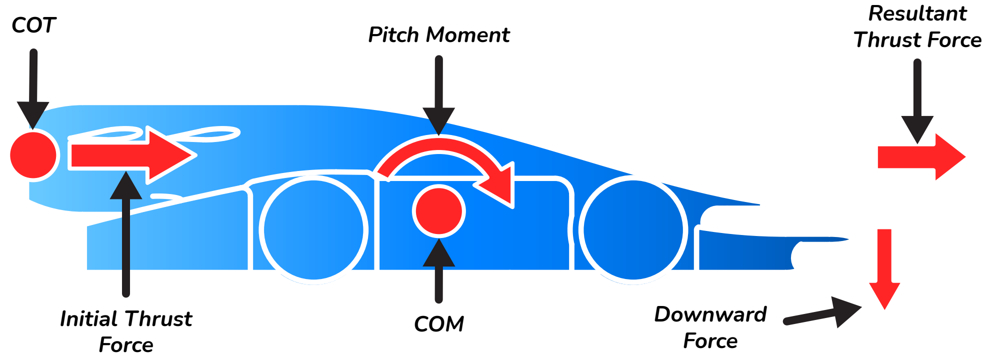
PREPARATION

Research

Before beginning the design ideation phase of the design process, we thoroughly investigated all the major factors, that we can control, that influence our race time. We researched and analysed these factors in detail to determine how we can either use them to our advantage or mitigate any unwanted influences effectively.

Thrust Efficiency & Race Stability

At its peak, the carbon dioxide canister that powers an F1 in Schools car will produce approximately 18 N[1] of thrust. Ideally, all of this thrust would be converted into the forward motion of the car. To make this possible, the car's Centre Of Mass (COM) must be directly in line with the car's Centre Of Thrust (COT).
However, there are several regulations (namely T10.1) that indirectly limit the positioning of the COM relative to the COT, and therefore they cannot be directly in line with each other without violating critical regulations or making the car unstable. Given that the COM will always be positioned lower on the car than the COT, a pitch moment will be induced around the COM that will force the front of the car downwards. Because some of the thrust force is transformed into a moment, the resultant thrust force that contributes to the forward motion of the car will be less, and the overall thrust will be less efficient.



A diagram representing the effects of less than ideal thrust efficiency.

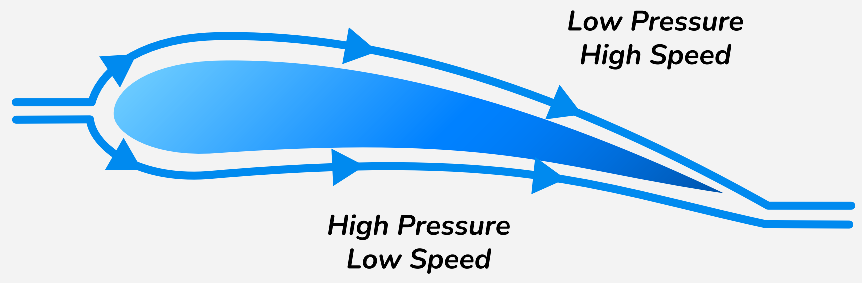
The efficiency of the thrust conversion to forward motion will have a huge effect on the car's speed, given that any drag or rolling resistance forces will likely be no more than 2% of the maximum thrust force produced by the canister. The only way to maximise this efficiency is to raise the COM.

However, another result of this that must be considered is the effect of the pitch moment on the stability of the car. There are many variables, such as launch imperfections or track surface anomalies, that affect the stability of the car throughout its race. These can easily be observed by watching an F1 in Schools car race. If the car is highly unstable throughout its launch due to these variables, the car will not accelerate directly down the track, and further thrust force and forward motion will be lost.
This can be limited by introducing downward forces that press the car onto the track during the launch where any instability is created. This force would increase stress on the wheels which would increase unwanted rolling resistance. This pitching moment and downward force from the thrust can be used to reduce any instability created during the launch, and it only acts during the 0.4-0.5 seconds[1] that the instability is created, and afterwards allows rolling resistance to be reduced for the remainder of the race.

1 - Lake Mills Area School District. (2021). Speed on Land [PDF] (p. 18).

Lift & Downforce

Depending on the shape of an F1 in Schools car, it will produce a net verticle force from the various aerodynamic influences that affect the car. Areas of positive and negative pressure can induce verticle forces. A positive verticle force is often defined as lift, which reduces the car's apparent weight force. A negative verticle force is often defined as downforce, which increases the car's apparent weight force.
Usually, a car with any lift or downforce will have greater drag than a car without these forces, so overall the car's aerodynamic design should be focused on minimising these verticle forces and therefore maximising aerodynamic efficiency.
However, aerodynamic efficiency is not the only factor influencing a car's speed. Other factors such as stability and rolling resistance can influence a car's speed. Verticle forces acting on different places on the car can aid stability if implemented correctly, and a net lift force on the car can reduce the pressure on the wheels, thus reducing rolling resistance.
Lift and downforce are best manipulated by employing wing surfaces, which are designed to create a pressure difference between the upper and lower faces of the wing. Air has to travel further around one side of the wing and therefore faster around the wing to rejoin the air from the other side of the wing. As per Bernoulli's Principle, the difference in speed will ultimately cause a pressure difference.



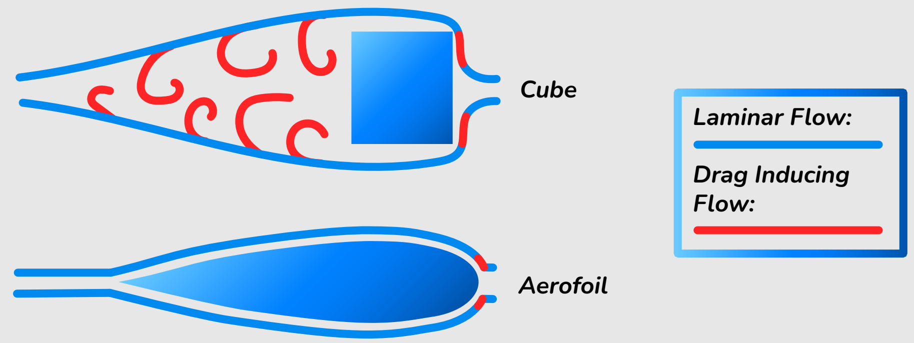
An example diagram of a lift generating wing surface, supported by Bernoulli's Principle.

Drag

As an object moves through a fluid, in this case, a car through air, the car will be presented with resistance from the air that it must overcome. This resistance comes in the form of drag, which is a force that opposes the car's direction of travel. Drag comes in two main forms: Form Drag and Skin Friction Drag.

Form Drag

Form drag is created as the car essentially 'punches a hole' in the oncoming airflow, and as a result, creates a pressure difference between the leading and trailing edges of the car. At the leading edge, the air 'bunches together' creating a high-pressure zone. At the trailing edge, the air must fill that hole in the airflow created by the car but does not do so instantly, and this creates an area where there is less air, lower pressure and also induces unwanted turbulence (a wake). Both of these pressure areas around the object contribute to form drag and reduce the aerodynamic efficiency of the car.
There are two main ways to reduce form drag. The first is to simple reduce the size of the 'hole' it creates in the oncoming airflow, which is to reduce the frontal area of the car. The other is to make the car into a form that effectively fills the low-pressure wake behind the car, and allows the air to return to its original position without decreasing its pressure or inducing turbulence.



A diagram illustrating how the shape of an object can be optimised to reduce form drag.

Skin Friction Drag

Skin friction drag arises due to the interaction between the surface of the car and the boundary layer of the air going past it. As the boundary layer moves past the car, it will naturally transition from laminar flow to unwanted turbulent flow. Turbulent flow is unstable and irregular and therefore causes more friction between the air and the car surface, whilst laminar flow is smooth and regular.
To reduce skin friction drag, the creation of turbulent flow must be minimised, and this can be done by reducing any elements of the car that could create unstable vortices, such as sharp edges or geometry transitions. Creating a paint finish that is smooth with minimal imperfections also significantly reduces skin friction.

Design Requirements

Based on the research we conducted, we drafted a set of design requirements for our car. These are a reflection of what we learnt in our research, and our experience from past competitions. These requirements are what we believe will allow our car to fulfil its purpose: to set the shortest race time.

Minimal Frontal Area

Minimal frontal area ensures that form drag is reduced significantly due to the reduced volume of air required to be deflected around the car during a race.

Minimal Surface Area

Minimal surface area reduces the car's skin friction drag by simply having less area for the surrounding air to interact with.

Laminar Aerodynamics

Aerodynamics that promote laminar flow is crucial to reducing both form drag and skin friction drag, by preventing the boundary layer from separating and becoming turbulent.

High Thrust Efficiency

High thrust efficiency ensures that the car experiences the greatest possible acceleration at the race launch, thus reducing our race time significantly.

High Stability

High stability allows the car to travel down the track smoothly and prevents motion loss due to turbulence inefficient acceleration.

Regulation Compliant

The car must be compliant with all critical regulations such that it is safe and has no time penalties added to its race.

DESIGN IDEAS

Throughout the ideation and testing phases of our design process, we tested a variety of different and innovative design ideas and features, each aimed at improving a certain aspect of our car's performance. Not all of these design ideas were implemented in the designs used in our refinement phase or the final design, but the insight and analysis were still valuable, and positively contributed to our overall design.

Note: Each of the quoted drag and lift values represents the change in force at 20ms^{-1}, relative to the control design in its given major iteration.

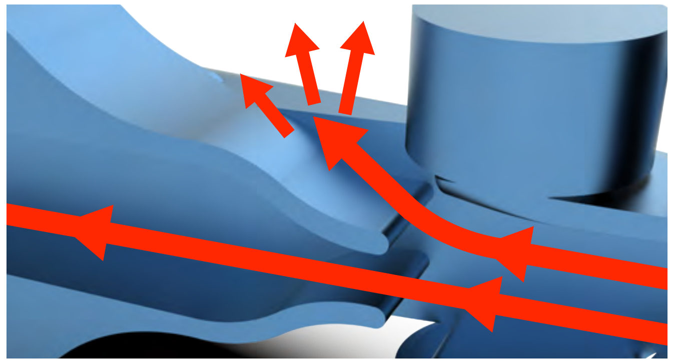
Channel Outlets

PDCR4.1 & PDCR4.2

When analysing our CFD solution fields and some of our previous cars in a wind tunnel, we noticed that behind the front wheels is a pocket of highly turbulent air, which hinders our car's aerodynamic efficiency. This is due to the low-pressure zone created by the oncoming airflow not being able to flow entirely around the wheel fast enough. We decided to combat this by finding ways to deliver air to this area, and one way of doing this is to take air from the underbody airflow channel and direct it into those low-pressure areas behind the front wheels.

Drag: +0.027N

Lift: -0.172N



This design idea was highly effective at delivering air to the low-pressure zones behind the front wheels, however, it prevents the underbody airflow channel from effectively delivering air to an even larger low-pressure area at the rear of the entire car. This increased our overall drag, so we decided to employ a different method to remove turbulent air from behind the front wheels (see PDCN19.1).

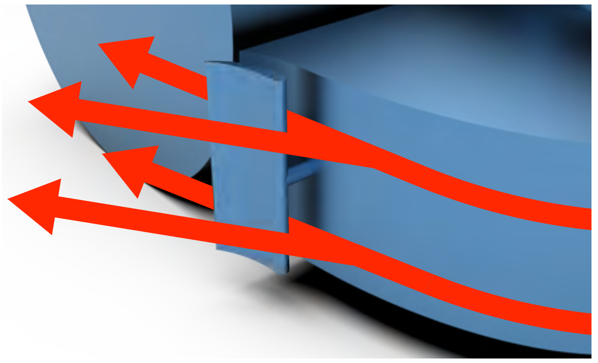
Aerodynamic Manupulators

PDCR11.1 - PDCR11.7

To manipulate the aerodynamics in very specific places around our car, we introduced small winglets or vortex generators into various places around our car. Each of these had varying effects, but the overall aim was to reduce drag.

Drag: All increased

Lift: Varying



None of these aerodynamic manipulators had a positive impact on our car's performance. However, we gained further insight into how the aerodynamics of our car operates and applied this in further design ideas, developments, and refinements.

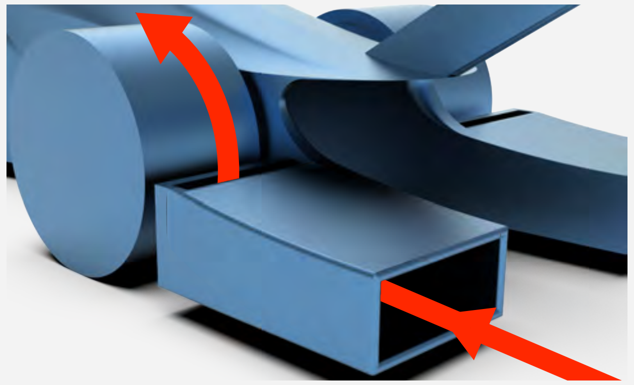
Pressure Reduction Wings

PDCR5.1

During the research phase, we came across the McLaren Elva, a high-performance sports car that utilises an innovative technique, AAMS[2], to create a 'virtual windscreen'. It does this by directing air from the lower front of the car through the nose and directs it out at an upwards angle that slightly opposes the direction of the oncoming air. This creates a pocket of low pressure that shields the occupants of the Mclaren from the oncoming air. We decided to investigate this to reduce the high-pressure area that resides in front of the front wheels, in an attempt to 'virtually' reduce the frontal area of the wheels.

Drag: +0.032N

Lift: +0.028N



This pressure reduction front wings were very effective at reducing the pressure immediately in front of the front wheels, however, in doing so the pressure inside the box that deflects the airflow was so high that it produced more drag overall. As a result, we designed our front wing system to simply deflect air over and around the wheels in a more conventional way.

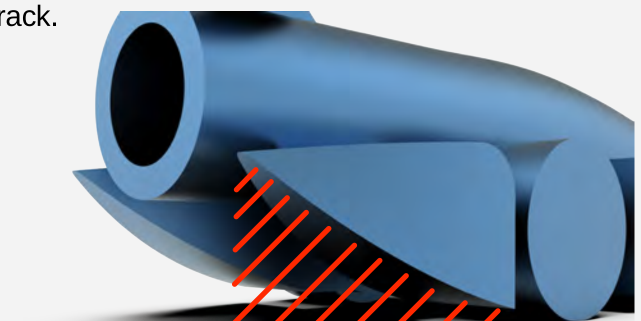
Downforce Inducing Rear Pods

PDCR6.2

To further stabilise the car during launch, we decided to implement a downforce inducing rear pod design. This design created a low-pressure area beneath the rear of the car, which would create downforce and suck the rear of the car to the track.

Drag: +0.025N

Lift: -0.06N



This design idea did produce more downforce, but not nearly enough to justify the increase in drag. Because of this, we decided to further tune our Centre Of Mass relative to the Centre Of Thrust to help stabilise the car.

2 - McLaren Elva. Cars.mclaren.com. Retrieved 9 April 2021, from https://cars.mclaren.com/au-en/ulti-mate-series/mclaren-elva.

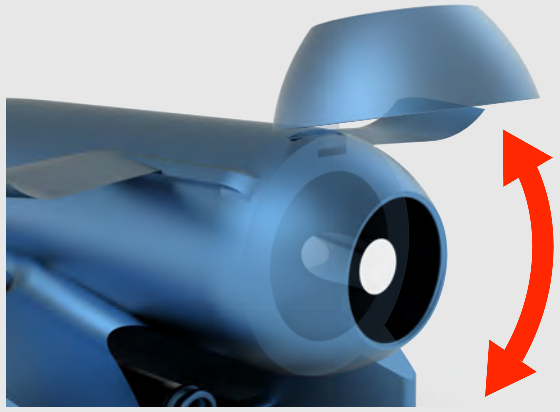
ALES

PDCS16.1 & PDCN22.1

For the NSW State Finals, we began to develop an Aerodynamic and Launch Enhancement System (ALES) that is designed to both reduce form drag, by partially filling the low-pressure wake behind the car, and to also deflect some of the lost energy at the very start of the race launch. For more information on how this works, see its respective section on Page 3.

Drag: -0.023N

Lift: -0.018N



This had a very positive impact on our car's drag, so we decided to further develop this for our State Finals car. However, due to COVID-19's time constraints, we could not develop a reliable hinge mechanism in time. Because of this, we revisited this for the National Finals, and opted for a similar but more simple design.

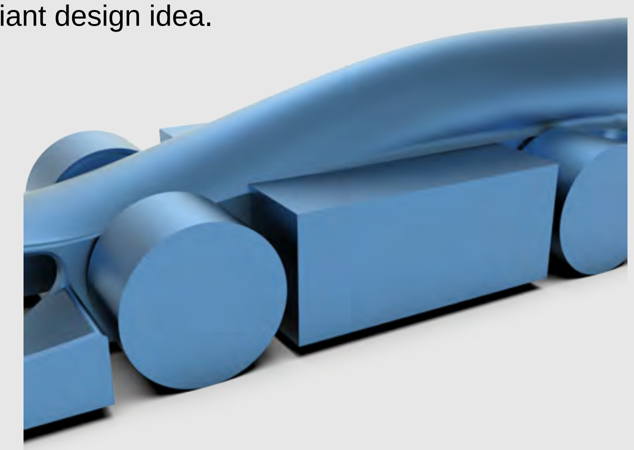
Side Pod Extensions

PDCN19.1

F1 in Schools has now been held in Australia every year for 18 years, and as a result, there is significantly more limited scope for teams to find a competitive edge by exploiting regulations than there used to be. This is why, for the National Finals, we decided to investigate design ideas outside of the regulations to improve our car, whilst assessing the associated risks and penalties for any violations related to those given ideas. This, when weighed against the gain in performance, helped us determine if we should pursue a given non-compliant design idea.

Drag: -0.013N

Lift: +0.004N

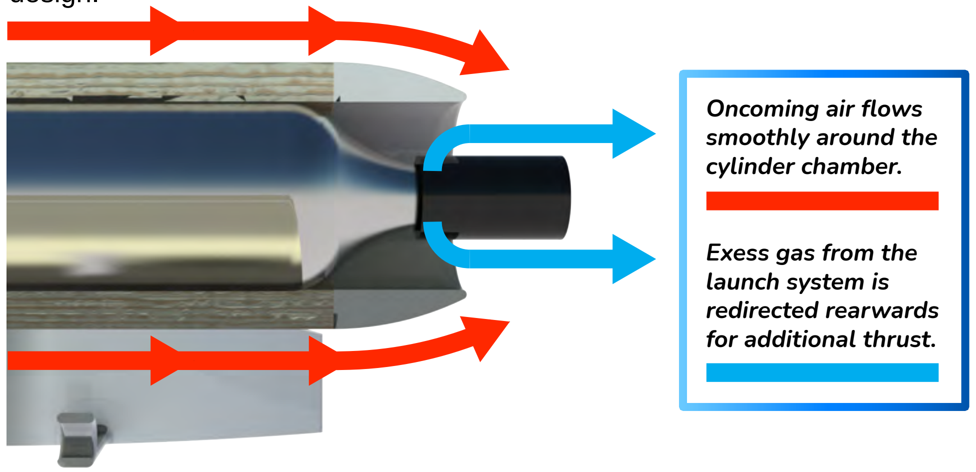


The only non-compliant design idea we decided to develop and implement was our side pod extensions. This only gives us a 2 point penalty, which we believe we can gain back from our car's more effective performance. For more information on this design idea, see its respective section on Page 3.

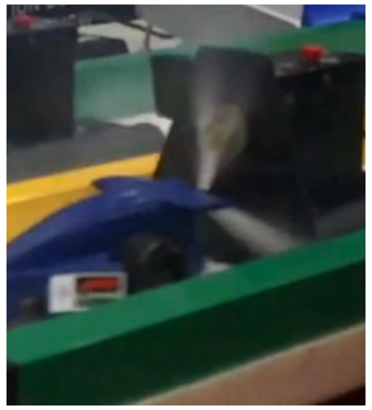
INNOVATION

ALES

Integrated into our Rear Wing Support System is a design feature, an Aerodynamic and Launch Enhancement System (ALES), which enhances the effectiveness of our cars aerodynamics and the thrust of the carbon dioxide cylinder during launch.
ALES reduces our car's form drag by simply filling a significant proportion of the low pressure wake that travels behind the car. Due to our highly optimised rear pod design, nearly all of this low pressure wake resides behind the cylinder chamber. ALES is the only way to directly target this area of drag without increasing overall drag. The cylinder chamber diamater and wall thickness are standard, so their width cannot be reduced, and any aerodynamic manipulators may reduce this part of the low pressure wake but negativly impact the overall design.



Above: A diagram illustrating the effects of ALES.
Right: The excess launch gas being released.

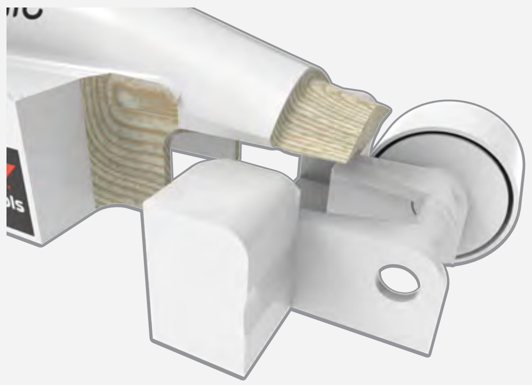


This 3D printed tapered extension of the cylinder chamber walls not only reduces drag, but also captures excess gas not used by the launch system to increase the applied thrust at the moment of the launch. This excess gas is sent outwards from the car perpendicular to the direction of travel. Without ALES this gas would be wasted and not used in the launch system. ALES prevents this gas from escaping outwards, and deflects it back in the opposite direction of the car's motion as additional thrust.
In addition to this, ALES places more mass at the upper rear of the car, which moves the car's COM closer to the COT. This further improves thrust efficiency.

Side Pod Extensions

One of the largest causes of drag on an F1 in Schools car is the body exclusion zone defined in T4.6: "*the car body MUST NOT exist within a dimension of 15mm immediately rear of either front wheel.*" This zone is prone to filling with turbulent air, and this, in turn, impacts the rest of the car directly rearwards of this zone. If this zone could be filled, our car's drag would be reduced significantly.
T4.6, a critical regulation, specifies that only the "*car body*" cannot exist within this zone, but it does not state that this also applies to any component of the car that is not considered part of the car body. However, the regulations still do not allow for other components to exist in this zone through other limitations, though each with less of a penalty.

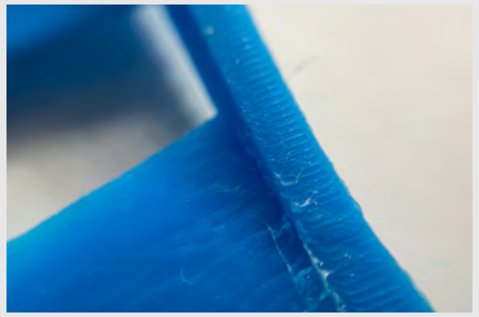
Given the significant drag reduction benefits of filling this zone, we have decided to deliberately infringe regulation T8.1: "*The wheel support system MUST be fully contained within the volume of the cylinder formed by the projection of the wheel circumference.*" We are only deliberately infringing on this regulation, and this incurs a two-point penalty. We feel that this penalty is small enough that the car's performance gains outweigh this penalty. Using these extensions, our drag can be reduced by up to 20%.
This has allowed us to extend the side pods as part of our front wheel support system. Given that this is not balsa and is the same component as the wheel support system, according to T1.9 ("*The body is defined as...a solid, uninterrupted piece of balsa wood*") the part is not considered to be the body and therefore does not infringe on the critical regulation of T4.6. This can still be considered part of the wheel support system because according to T1.19 ("*The wheel support system is defined as the collection of components that connect the wheels to the car body*") this single component consists of the side pod extensions and attaches the wheels to the car.

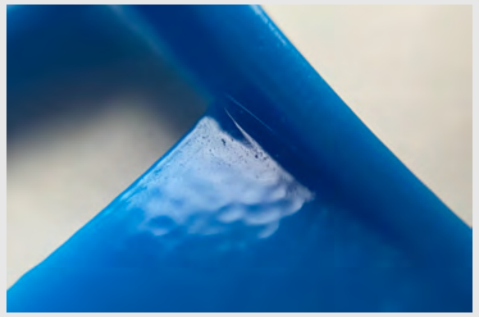


Above Left: A partially exploded view of the side pod extension component as the wheel support system.
Above Right: Our assembled side pod extensions.

PolySmooth

A significant contributor to our car's drag, more specifically skin friction drag, is our surface finish quality. Using fast and efficient manufacturing processes, such as increased layer hight 3D printing, can significantly reduce the surface quality of 3D printed products. This gain in print speed would then be made redundant due to a large amount of sanding required to gain a good surface finish.
However, we have decided to use a unique 3D printing filament called PolySmooth, for some of our plastic components. This is a PLA based filament that is designed to partially dissolve in Isopropyl Alcohol (IPA). After printing as if it were standard PLA, it is placed in a machine, for up to 15 minutes, that vaporises IPA and dissolves the surface of the component. After a short time waiting for the IPA to evaporate, once out of the machine, the end product is a component that has a glossy and smooth finish with no layer lines. Not only does this enhance the surface finish, but it also significantly increases the strength of the component.
This innovation only improves surface finish and strength but also allows us to manufacture much more efficiently, using fast printing processes that can then quickly be processed to an excellent finish.
However, this process is not without its downsides. To use this for wing surfaces we had to slightly oversize the trailing edge of the wing to stop it from easily being warped in the polysmoothing process. This was a minor problem that had little impact on our manufacturing processes.

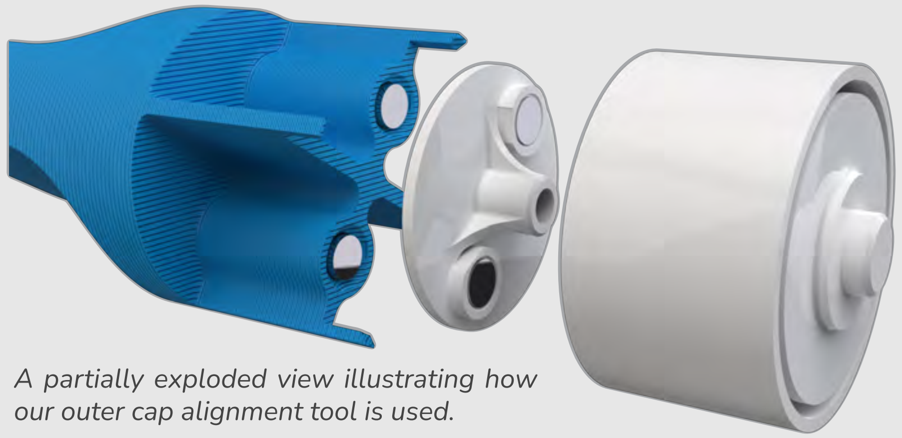




Above Left: A magnified image of a part before the polysmoothing process.
Above Right: A magnified image of a part after the polysmoothing process

Magnetic Wheel Caps

The greatest difficulty we have had so far in our time competing in Professional Class has been accurately assembling our wheel support system. This can be incredibly difficult due to the small size, high accuracy, and rotating nature of the component. We found even designing and using custom jigs to align the wheels does not fully solve this issue.
This is why we have designed our outer wheel caps with integrated rare earth magnets. When used with a custom-built magnetic alignment tool, we simply clip the cap to the tool so that while the glue sets it can be accurately and steadily held in place on the axle without the need for complex tools or jigs. This ensures that our outer cap is perfectly concentric and flush to the wheel, and improves assembly speed, accuracy, and reliability. Once the glue is set, the magnets are weak and small enough that the tool just clips off, and that the magnets have little impact on the car's overall mass.



A partially exploded view illustrating how our outer cap alignment tool is used.

Rear Wing Alignment

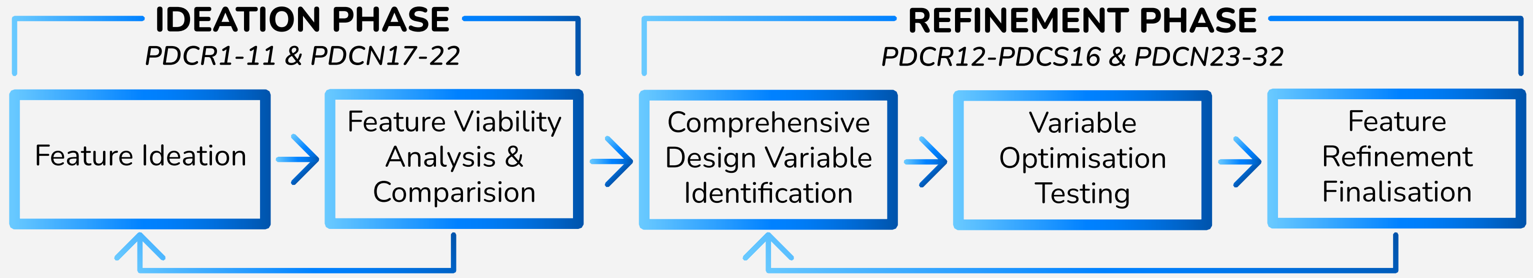
Contrary to traditional F1 in Schools wings, which are solely designed to be the most drag efficient surfaces, we have aligned our rear wings such that they have a slight angle of attack, which means they produce lift and also promote airflow over and down our rear pods. Even though the wings themselves are less aerodynamically efficient, the alignment has reduced our overall drag. The lift being produced at the rear also adds to the pitch moment produced by the COM and COT relative positioning (see page 1, Thrust Efficiency & Race Stability) further increasing our car's stability.

Our angled rear wing alignment.

DESIGN DEVELOPMENT

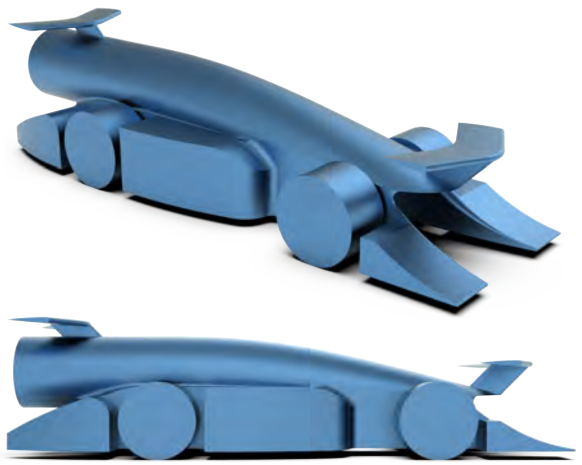
Our Design Process

Before we began designing the car, we devised an iterative and structured dual-phase design development process (see right), to ensure that each development is tested fairly, and ensures any implementations benefit the car's performance.
The first phase, Ideation, focuses on brainstorming and assessing the best design features for each component on the car, working rearwards from the front wing. Major iteration in the Ideation Phase focuses on comparing a set of different design features that could be implemented in a given component. The second phase, Refinement, focuses on fine-tuning the most effective features from the first phase, to create a fully optimised design. None of the overall features of the design was changed in the refinement phase, only specific variables that would alter the geometry, and therefore aerodynamics of that feature. Each major design iteration in the Refinement Phase focuses only on one design variable (e.g. rear pod height).
The main focus of this design process is to reduce our cars drag through quantitative testing, but it also includes qualitative evaluations that include other factors, such as manufacturability.
Below are five designs that we feel represents our design development through its 32 major iterations and all 177 designs.



A flowchart representing our two design phases and their major components.

PDCR1.0



Drag: 0.317 N
Lift: -0.221 N

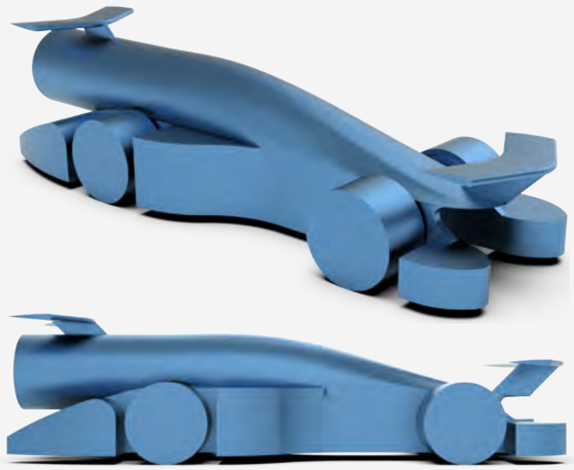
Description

PDCR1.0 is a culmination of successful design features and ideas from our experience in our previous F1 in Schools teams. This car features a long body to minimise frontal area, elevated front and rear wings to allow for more freedom in the design and to aid manufacturability, respectively. This also features a characteristic face-to-face body loft style, an alternative to the equally popular face-to-point body loft style. The front pods are designed to maximise airflow over the wheels. The rear pods are long and tapered to minimise the low-pressure wake. This is a rough design and does not comply with all regulations.

Evaluation

This car design is a good start to our design process, but almost none of the features on the car benefit the car's performance. This is expected from the very first design.

PDCR5.4



Drag: 0.236 N
Lift: 0.04 N

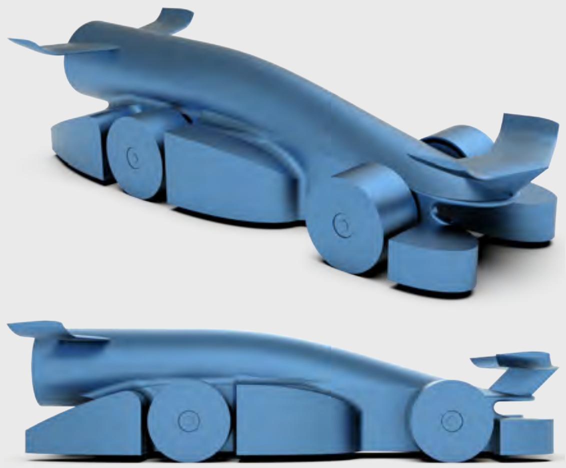
Description

PDCR5.4 was the first implementation of one of our regional and state final car designs' main features. This was the semi-elliptical front pod design. This design also features a number of other changes such as deflective side pods (alternative to the previous design which was created to fill the volume behind the front wheel), and a redesigned body loft curvature profile, which is now tangent to both the cylinder chamber walls and the nosecone. This design is part of the Ideation Phase, so therefore little effort has been put towards attention to detail. The wing surfaces are not aerofoils and our wheel design is not yet implemented.

Evaluation

This car design showed us the unexpected improvement that was our front pod design. Again, this design does have somewhat limited manufacturability.

PDCS16.0



Drag: 0.208 N
Lift: 0.145 N

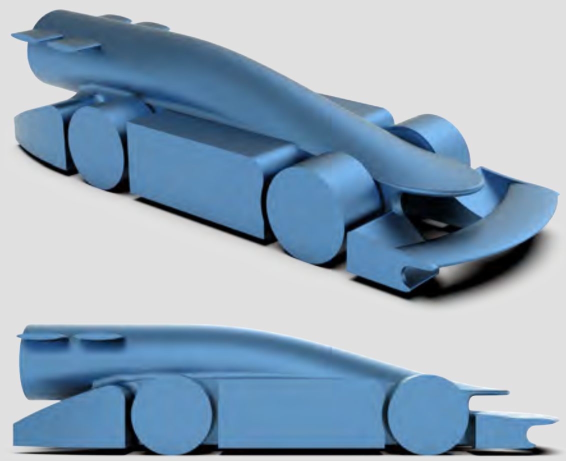
Description

PDCS16.0 was the design we used for the NSW State Finals, which is very similar to the design we used for the Western Sydney Regional Finals. Given this was our final car design, this did include details such as aerofoil profile wings and manufacturing fillets. This also included our dual bearing wheel design, which aided the stability of our wheels, as well as an overall shorter wheelbase.

Evaluation

This design was somewhat successful. We feel that this design maximised our car's performance based on its design features, and had what we thought was exceptionally low drag. Unfortunately, however, we were not able to see this car in action due to last-minute wheel manufacturing issues, relating to the functionality of our 3D printer. In the end, this car did not set a race time.

PDCN20.0.1



Drag: 0.164 N
Lift: 0.171 N

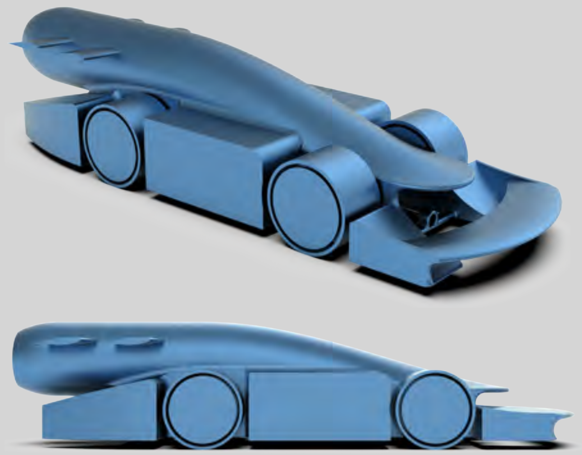
Description

PDCN20.0.1 is situated towards the end of the Ideation Phase for the National Finals, with only the rear pods, rear wings, and ALEC system to be tested. To increase the strength of our nosecone, and to promote laminar airflow of the car body, we decided to move our front wing down in front of the wheels. In order to fit the required wing span, we had to find an alternative to our semi-elliptical front pods. This design also features our innovative side pod extensions, which decreased our car's drag significantly.

Evaluation

This design could have been our final design for the National Finals, with the exception of the wheels and the tether line guides. However, this had not yet passed through the Refinement Phase, so we knew that this design did not maximise our car's performance.

PDCN32.0



Drag: 0.149 N
Lift: 0.118 N

Description

PDCN32.0 is our final car design for the National Finals. This design features longer front pods, a very short wheelbase, increased rear pod trailing edge height, and a new, single bearing wheel design. As the final design, this features greater manufacturing tolerances, greater accuracy, and a full part assembly.

Evaluation

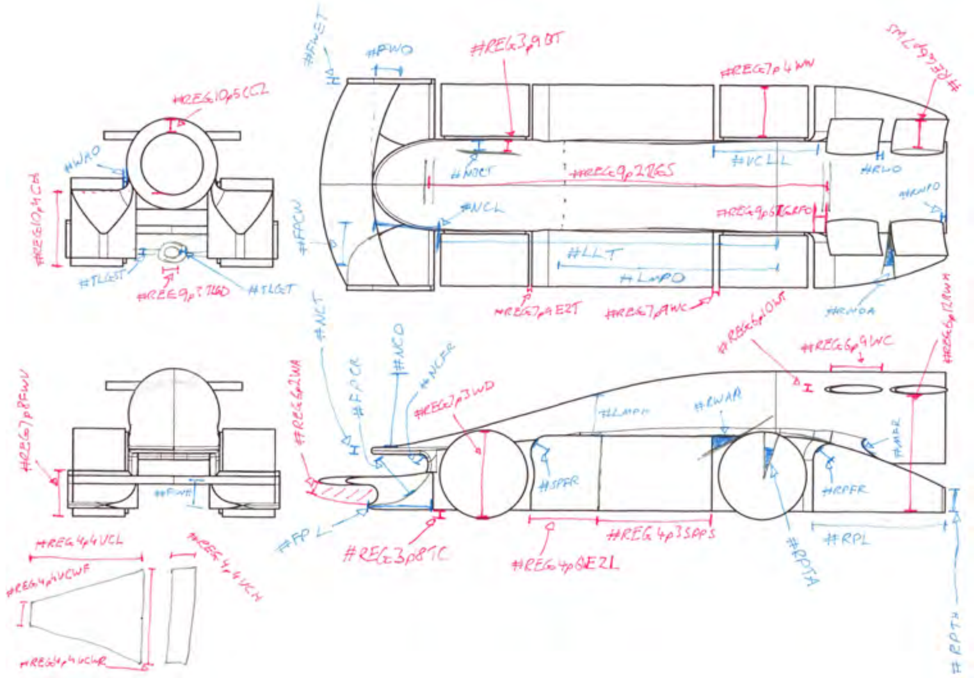
We feel that this design is our best car design we have created in our combined total of 9 competitions, including the 2019 World Finals. This design is not without its disadvantages, but we feel that this design is as close to perfect as we can make it. We just cant wait to see it race.

Note: Each of the quoted drag and lift values are representative of our CFD data on the car travelling at 20 m/s.

TESTING & ANALYSIS

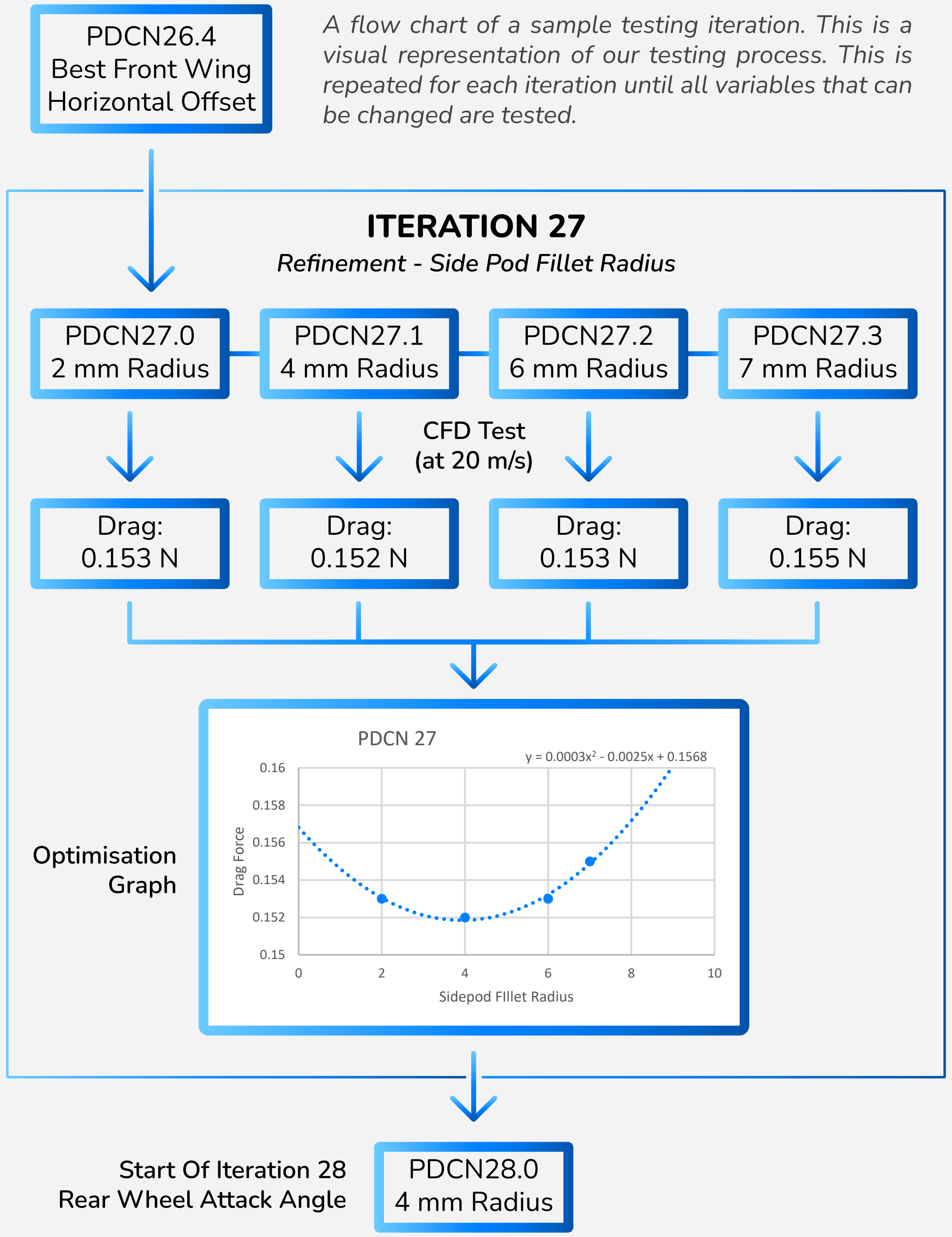
Virtual Testing Process

Our virtual testing process was a fundamental part of our design development process (outlined on page four). Each major design iteration, irrelevant of its design phase, was all placed through the same testing process. The only differences between the two phases were that the Ideation Phase tested overall shapes and forms of different design features (qualitative shape & form descriptions), and the Refinement Phase was testing against specific quantifiable variables in the already predefined geometrical shapes and forms of each design feature.
The testing variables in the Ideation Phase is difficult to represent fully without viewing all the related CAD models, however, the testing in the Refinement Phase can easily be shown in a labelled drawing of our car, which shows all the variables that define the geometry of the car (see below). This was used to create our entire CAD model using variable based CAD. This allowed for quick and easy editing of our car by simply only changing a given dimension, without needing to edit any sketches or geometry operations.



A drawing of our car design, for our Nationals Refinement Phase, that details all the possible variables that define the car geometry. Variables in red are regulation-bound variables that cannot be changed. Variables in blue are variables that we are free to change, and these are the variables we test in the Refinement Phase. For a full resolution image and full variable list, see our testing document.

For each major iteration, we have a very specific testing process that we follow. We start by taking the best design version from the previous iteration. We take that design and use it as a control design for the current iteration. Then, a certain aspect of the design, be it a quantitative variable or a qualitative feature variation, is changed in a number of different ways, ensuring that every other aspect of the design is unchanged. Each of these becomes a different design version. These versions are then run through CFD, and an optimisation graph is created from the drag values of each version. From this, the best design is chosen, and the next iteration begins.



A flow chart of a sample testing iteration. This is a visual representation of our testing process. This is repeated for each iteration until all variables that can be changed are tested.

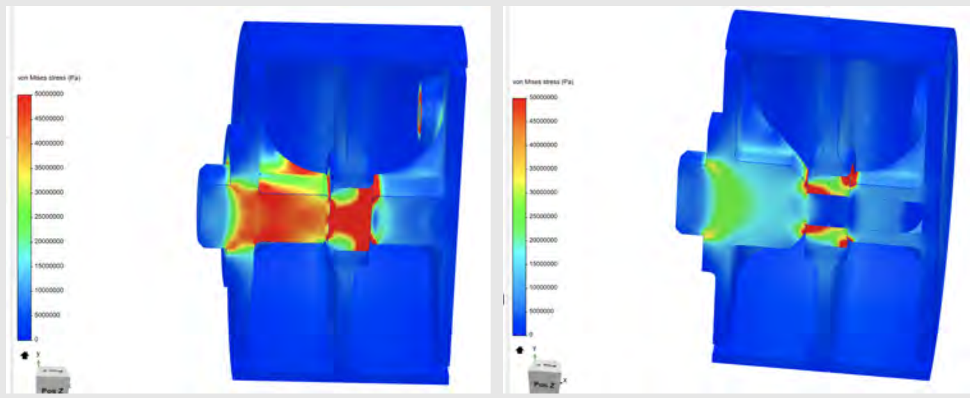
CFD Analysis

Our main design development and testing processes work around improving the aerodynamics of the car. Due to the significant number of designs that require testing, producing these for physical testing is not a viable solution. This is where Computational Fluid Dynamics (CFD) becomes useful. CFD allowed us to analyse every one of our CAD design versions, such that we could develop a comprehensive and efficient aerodynamic optimisation process. This was crucial for us to identify areas of improvement in the Ideation Phase, and to compare each design. We used a variety of different tools in the CFD solution fields, such as particle traces, cutting planes, and isovolumes, to identify and analyse areas of turbulence, high pressure, and low pressure.

CFD however, does have its disadvantages. CFD only provides us with a simulation of reality and is not reality itself. This means that there is some inconsistency in the simulations which must be accounted for, and even the slightest change in the simulation setup parameters can have significant effects on the results. This is why for every simulation, every single setup parameter is checked against previous simulations to ensure complete consistency. For example, CFD data, see our Testing Document.

FEA Analysis

Given that the size and thickness of components of the car, the major variables that determine strength, are limited by manufacturing, material, or regulatory constraints, we concluded that testing every aspect of the car is simply an inefficient use of resources. Most of the plastic components of the car, due to our manufacturing constraints at our school, would have to be 3D printed out of PLA and are at least partially supported by the balsa car body, which also has a minimum thickness regulation. This means that the materials and minimum thickness that we can achieve are limited, and, based on our experience, is by far strong enough to withstand all the forces exerted on the car throughout the race.
However, there are fewer constraints applied to wheel manufacturing, so this was an area where we performed a large number of FEA tests. For our FEA tests, we tested all the components in PLA, given this was our planned material for the wheels at the time. We calculated the force exerted on the wheels during the race using the wheels' greatest angular velocity and mass. This was 377 newtons. Using our FEA software, we tested our initial wheel outer thickness of 1 mm, and this produced only a maximum of 3 MPa of stress in the outer wheel when the yield stress of PLA is 30 MPa. This is why, for manufacturing purposes, we decided to reduce our outer wheel thickness to 0.75 mm, and this produced maximum stress of 6 MPa. Due to manufacturing accuracy, we later decided to manufacture our wheels out of SLS nylon, which should be stronger than 3D printed PLA, and to manufacture these, the outer thickness has to be at least 1 mm. This meant that our finals wheels were going to be strong enough.
However, during our FEA tests, we also tested our wheel support system withstanding the acceleration and braking forces. This was a different situation, with our initial design producing up to 50 MPa of stress, which is significantly greater than the yield stress of PLA. As a result, we significantly thickened the areas where stress built up, and our final wheel system only produced 20 MPa of stress.

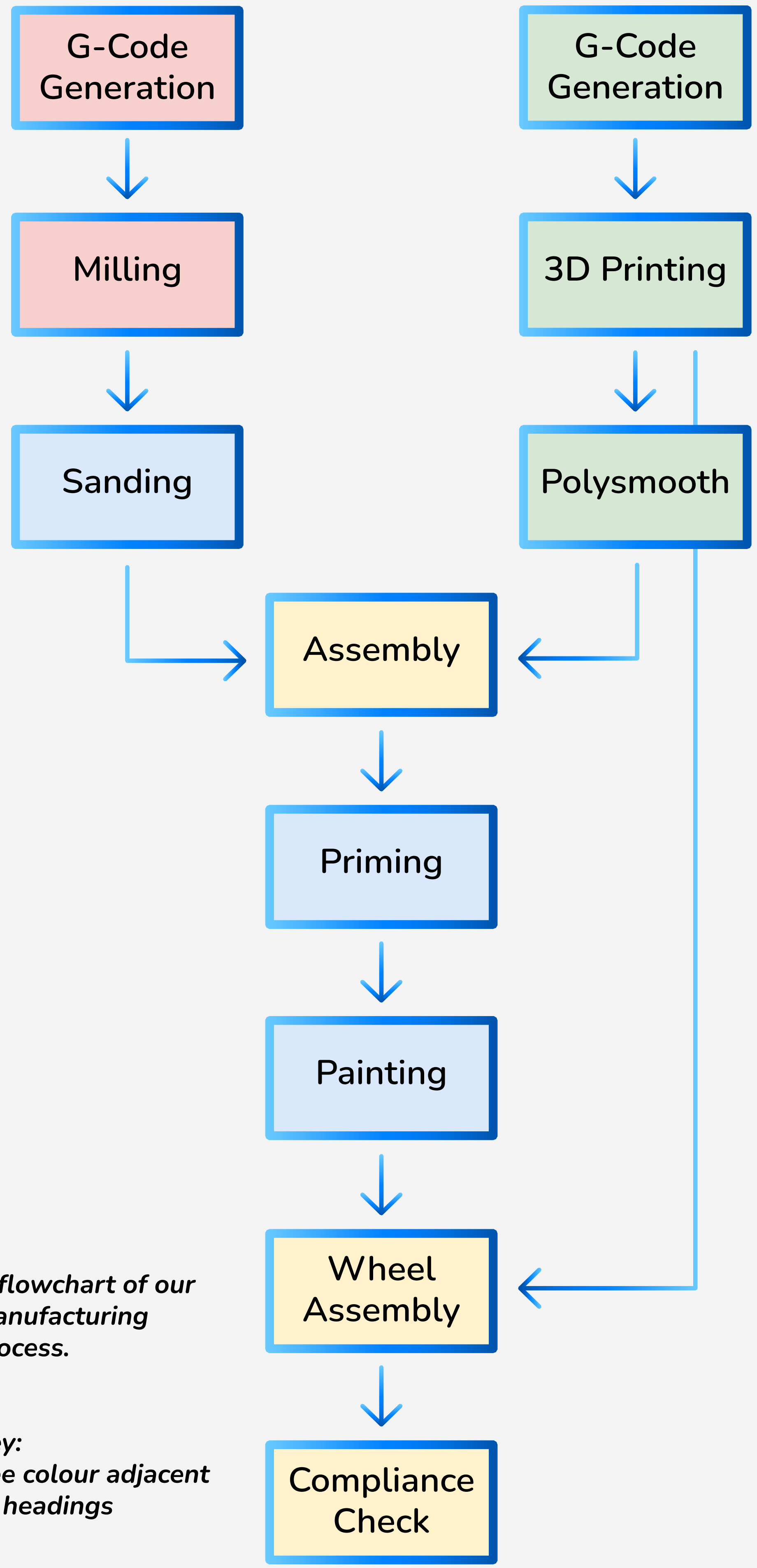


The FEA solution fields of our wheel support system design before and after increasing the thickness of the inner axle. The scale shows Von Mises Stress, and shows 0 Pa at blue, through to 50 MPa at red.

MANUFACTURING

Manufacturing Overview

We have utilised a number of innovative processes and technologies in our manufacturing and assembly process, to achieve our goals of creating a fast car, completely accurate to our CAD model and renders. We began our manufacturing by researching and educating ourselves on various manufacturing techniques, and the requirements for our car, and decided what we would utilise to reduce weight, improve accuracy, and strengthen our car as much as possible. During our preparation, we also talked with our mentors, including Michael Laws from Teaching Tech. Michael has been involved in the manufacturing industry for many years and has immense knowledge and experience with various technologies and machinery, and how we should utilise them. He introduced us to the concept of PolySmoothing, a method of printing using a specific type of PLA, then spraying a thin mist of isopropyl alcohol onto the surface, melting it and allowing it to reform perfectly smooth. Our collaboration video with him helped us to explore the concepts of thermoforming, melting PLA into liquid, then pouring it into moulds, allowing perfectly accurate and repeatable parts, as well as the idea to use recycled plastic offcuts for this process. We have been in regular contact with Advanced Manufacturing Services, and they have helped us refine our wheel concepts to improve the strength and manufacturability, and in choosing the correct manufacturing process and material for our specific needs, settling on using SLS (Selective Laser Sintering) Nylon printing to shape our wheels. To assemble our wheels, we have devised an extremely innovative system, using magnets placed in the wheel hubs to attract to a magnetic device, which we can then easily manoeuvre to assemble our wheels perfectly. To the left is our Work Breakdown Flowchart of the car manufacturing process, allowing us to visualise what work had to be completed, and in what order, streamlining and simplifying our manufacturing process. Our overall manufacturing process has been extensively planned and executed to produce a car of the highest possible quality.



A flowchart of our manufacturing process.

Key:
See colour adjacent to headings

Milling

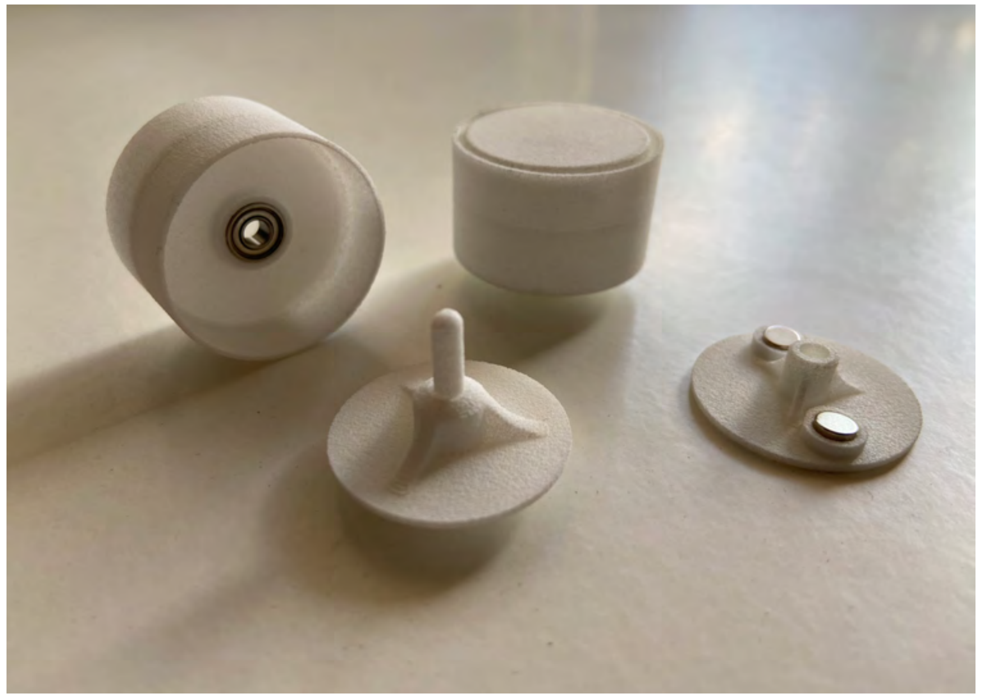
The milling of the car is one of the most important stages of the manufacturing process, as it lays the foundation for the rest of the manufacturing, and the calibration of the equipment must be done to precision, often by eye. We have put extensive research, thought, care and effort into our milling process, to create as accurate and manufacturable a car body as possible. We have researched the most effective methods of milling complex shapes and parts, as well as the best parameters to mill balsa, and decided to use a very small stepover to create as accurate and smooth a finish as possible, while minimising the number of cutting processes. First, we converted our CAD models from Onshape into G-Code for our IMPACT! CNC router to interpret. We chose to use Fusion 360 for our software, as it is free, easy-to-use and compatible with our router, with the correct post-processor. We set a feed rate of 2500 mm per minute, a two-way parallel cutting strategy, a stepover of 0.2 mm for high accuracy, and no roughing, as we believed this extra milling time was not worth the minimally improved accuracy. To mount our cars on the mill bed, we have designed and 3D printed our own custom milling jigs, which hold the block in place while milling, and yet allow the ball mill to access any areas of the block required. To achieve this, we used a system in which two 3D printed parts snap onto each end of the block, one which also fits into the canister chamber, and is then screwed into the block then the bed, fixing it in place. Once mounted, we used a “zeroing jig” which helped snapped onto the end of the block and used a cup to guide the ball mill into the appropriate location for zeroing. We decided to use the standard 6 mm ball nose endmill for Development Class teams, to mill our car because our school has two Development Class teams, as well as us, all needing to cut their cars at the same time, and this made the whole process far more efficient. We repeated this process four times, for top, bottom, left and right cuts, taking around an hour to complete one full cut. Our carefully considered milling process has allowed us confidence in the milling of our car, and in our ability to produce a perfectly accurate form.

Our car being milled on our school’s CNC router.

MANUFACTURING

3D Printing

To produce all our components, besides the car body, we decided to use 3D printing, a form of additive manufacturing. This method of manufacturing is cheap, accurate, and reliable, and can be used with a variety of different materials and configurations. After testing 6 different materials for price, strength, accuracy, reliability and surface finish, we decided that PolySmooth PVB (see page 3) plastic was the most suited to our needs. We printed our parts on a Prusa Mini printer and set the extrusion thickness to ultrafine (0.05 mm), and the infill to 5%. This gave us a light, accurate yet strong enough print, suiting our requirements. The surface finish of our front wings is critical to the performance of our car, as any imperfections can cause pockets of turbulent air that spiral along the car, increasing drag greatly. To achieve an immaculate finish and increased strength, we have utilised Polysmoothing, a process that involves spraying a fine Isopropyl Alcohol mist over our parts, which lightly dissolves the surface layer. This is then left to dry and reforms as a perfectly smooth part. We have also utilised 3D printing to create our assembly jig, allowing us to position parts perfectly accurately before attaching and gluing them to the body. To manufacture our wheels, we collaborated with Advanced Manufacturing Services, who discussed with us the requirements and properties of our wheels. We understood our wheels should be light, very strong, and have a fairly smooth surface finish. To achieve these objectives, we decided to utilise SLS (selective laser sintering) nylon, alternative to our FDM (Fused Deposition Modelling) printers at school, in order to build up an extremely accurate (+-0.01mm) form. This process also leaves a very strong part, which allowed us to create a light wheel design by reducing unnecessary parts in our CAD design. The overall wheels, when assembled are perfectly accurate, minimising excess rolling resistance to perfection.



Our SLS nylon wheel and wheel support system.

Assembly

An accurate car assembly can be the difference between having a competitive car, a slow car, or perhaps not even a car that finishes the race. We designed and created a variety of custom jigs and tools to ensure that our assembly is highly accurate, in addition to that each of our parts is designed to slot together in a very specific way, so there is very little scope for error.
We used a combination of cyanoacrylate and epoxy glue to hold the car together. Cyanoacrylate is perfect for the initial assembly, where the glue needs to set incredibly quickly, but it can be brittle. This is why we also used epoxy glue, which can take up to a day to set but is significantly stronger and less brittle than cyanoacrylate.
Our wheel support system is the most 'sensitive' component of the car to an assembly error, and we have taken a number of steps to ensure that all the components fit together and operate correctly. Our FDM printed wheel support system chassis is designed to be mounted onto the body separately from the rest of the wheel support system, and then painted, with the wheels being attached later. This ensures a cohesive body assembly and gives us the ability to amend any wheel support system alignment issues directly when we attach the wheels themselves. Our SLS wheel support system is incredibly accurate, much more than any FDM component, and this meant the entire system fit together with minimal finishing (sanding filing) and in some cases no glueing either. To make the wheel assembly even more accurate, we employed our custom outer cap magnet system (see page 3), which allows us to perfectly position the wheel outer cap quickly and accurately, and our custom magnetic tool simply detaches once the outer cap is in place.
Another crucial part of the assembly process is checking our car's compliance with the regulations. Before delivering our cars to REA, we systematically made our way through every technical regulation, checking each car's compliance, and rectifying any critical regulations.
Throughout the assembly, we also consistently checked our car's mass. The car's mass is a major indicator of a car's performance. Based on our calculations, with our large and heavy design features (ALES and the side pod extensions, page 3) our car's mass would be between 50.5 and 54 grams. We constantly weighed our car and its components before, during, and after assembly. As a result of this, our cars have a mass of 50.7 and 51.5 grams, which is just above our target of the minimum mass, 50 grams.

Our wheels being weighed before assembling the rest of the car. This way we knew exactly how much mass the car body had to have before assembly and finishing.

Finishing

To achieve a perfect skin finish for our cars, we have implemented a precise finishing process. First, our balsa body was sanded down, then spray wood primer was added. Then we repeated this process 3 times, each with more and more fine sandpaper until a smooth finish is achieved, with little imperfections. We then added wood filler to fill any areas that were not true to the CAD model form and sanded this further. Once our car was assembled, we used wood filler gain to fill any small gaps between any 3D printed components and the car body, to maintain a cohesive car assembly. This made any joins between components seamless. Once the filler was once again sanded down, and then the car was sprayed with a primer. To reduce our mass, we opted for a single gloss white coat of paint, an alternative to our previous method of up to three coats of white paint, a blue livery coat on the rear of the car, and a gloss coat. This was to save a significant amount of mass, up to 5 grams per car. This also made the painting process much faster and efficient.
After the paint dried and the wheels were attached, we used water slide decals to apply our sponsor logos to our car, as well as a couple of livery decals to accentuate our car design and team identity.

Above: John performing a test coat on a blank balsa block. Below: Our final cars.

PHYSICAL TESTING

Physical Testing Overview

Though virtual testing is incredibly valuable, it never fully reflects how a car will perform in real life. This is why we decided to conduct several different physical tests to test certain aspects of our car. Due to the significantly higher logistical difficulty of performing physical tests, these tests lacked the speed and efficiency to be highly integrated into our design development process as virtual testing, but it still had a huge impact on our design and manufacturing decisions.

Physical testing allows us to test a wide variety of variables that is either very difficult or impossible to test using virtual testing methods. These variables include race stability, aerodynamic behaviour visualisation, manufacturing anomalies, and race launch variability.

Our physical testing process is the same as our virtual testing process, only we did not use physical testing for consecutive iterations. This involved creating a design that we would test, producing several different versions of this design, each all the same except for one variable, performing our physical test, and then analysing the results to determine which change in that variable would be most beneficial to our design.

The changes to our design that were prompted by physical tests were simply incorporated into the version of the design that chosen to be the be most effective in the previous design development iteration before any variables were changed.

3D Printing Testing

Before manufacturing any 3D printed parts, we decided to test for the advantages and disadvantages of a variety of different types of 3D printing plastics, to helps us determine the best material for us to use.

To do this, we tested 6 different materials, some common and some with a very niche application, by using each of these materials to print a simplified front wing. The variables we tested were mass, surface finish, warping, accuracy tolerance, and strength. To test the mass we simply weighed each wing. To test the accuracy tolerance we compared the dimensional accuracy of the printed models to the CAD design. For the strength testing, we performed a controlled drop test of the wing using a support structure. The surface finish and warping comparisons were simply observations of the printed wings.

We concluded that the PLA filament was best suited to our application, with a good surface finish, good mass, high accuracy, and no warping at all. It also easily passed our strength tests. These were all printed using FDM printing, except for the tough resin which used SLA technology.

MATERIAL	MASS (g)	SURFACE FINISH (rank)	STRENGTH (P/F)	WARPING	ACCURACY (+/-, mm)
PLA	4.97	3	Pass	None	0.1-0.2
Tough Resin	7.16	1	Pass	Noticable	0.2-0.3
Polycarbonate	4.61	2	Fail	Minimal	0.1-0.4
ASA	4.58	4	Pass	None	0.2-0.4
Nylon	4.41	6	Fail	Excessive	0.1-1
Pegausus PP	2.76	5	Pass	None	0-0.4

A table showing our 3D printing testing results.

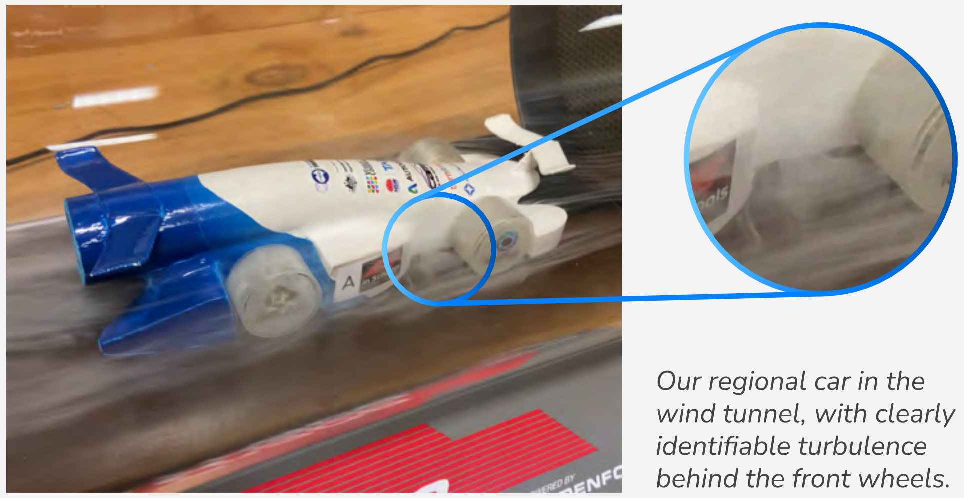
Left: Several of the wings we tested. Right: Part of the strength testing setup.

Wind Tunnel Testing

For us to find another perspective of analysing our car's aerodynamics, we used our school's Denford Air Trace Visualisation System. We placed several design prototypes, including our regional and state final cars, as well as our cars from each of our previous teams. This gave us insight into not just how air behaved around an F1 in Schools car, but also what specific areas of the car need to be optimised, improved, and manipulated. This was useful to observe before designing our car and during our design process.

We used wind tunnel testing mainly as a qualitative measurement of our car's aerodynamics. Our school does not have a wind tunnel equipped with any measuring apparatus, so we mainly used our CFD to analyse our car's aerodynamics quantitatively. We completed our wind tunnel testing in conjunction with analysing the solution fields of the design prototypes that were in the wind tunnel, often side by side. This gave us a much deeper understanding of our car's aerodynamics.

It was in the wind tunnel testing that we highlighted the two major contributors to the car's form drag. These were the low-pressure wake behind the car and the car body exclusion zones behind the front wheels. These were clearly identified by the distinctive swirling, turbulent air, in contrast to the smooth, laminar flow over much of the rest of the car. These observations inspired our two largest design innovations: ALES and our side pod extensions (see page 3).



Our regional car in the wind tunnel, with clearly identifiable turbulence behind the front wheels.

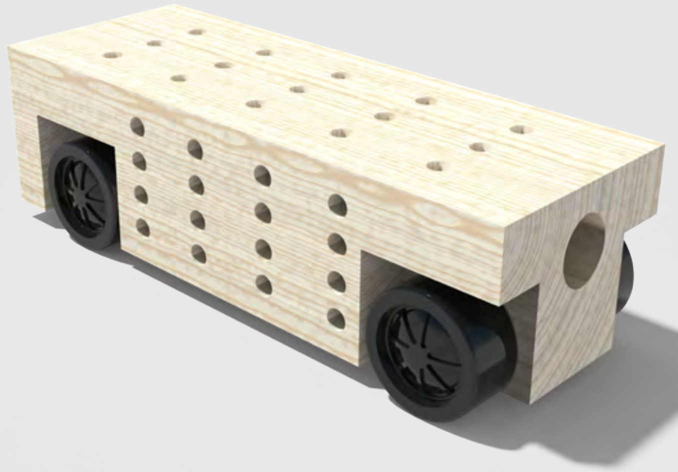
Track Testing

There were a variety of variables that influence an F1 in Schools car's race that can only be tested by performing race tests on a track. These variables include anything that relates to the track system, such as launch power variability, and race stability.

For the Western Sydney Regional Finals and onwards, we have planned to perform several sets of track testing, but our school does not own an F1 in Schools track. This made logistically organising this testing highly difficult, and only for this competition did we get the opportunity to undertake this testing, when our school borrowed the track from Western Sydney TAFE.

The tests we ended up performing involved testing our thrust efficiency versus our stability (COM/COT positioning, see page 1), testing the length of our wheelbase (stability) versus the surface area increase (aerodynamics) larger wheelbases give the car, and testing for variabilities in the launch system.

To test our thrust efficiency versus our stability, we designed and manufactured an F1 in Schools block with an array of drilled holes situated around the body. In these holes, we can place dense objects such as drill bits, and control where the car's centre of mass lies. These holes then had 3D printed caps that were placed in the top of the holes to ensure the car was safe to race (no sharp metallic projectiles). This car was manufactured solely from a balsa block and a Development Class wheel kit. We compared the race times from a variety of centre of mass positions and concluded that the thrust efficiency was significantly more important than the car's stability, and therefore took steps to move the centre of mass of our car as high up and as rearwards as possible.



A render of our thrust efficiency track testing car.

Also to test the car's stability, we created 4 cars, each with the same design, testing a wheelbase of 80 mm, 90 mm, 100 mm, and 110 mm. This wheelbase testing allowed us to gauge how important the surface area of the car is versus the mass and stability of the car. Longer wheelbases will naturally give the car a higher mass and surface area but will be more stable. Shorter wheelbases will give the car less mass and a lower surface area, but could also make the car less stable. We compared the race times between these four cars, and we concluded that the stability gained by having a longer wheelbase is not justified with the gain in mass and surface area.

Our launch system variability testing was simply to determine how reliable the launch system is, and what variables affect how effectively the car is launched. This was done by continually racing the same car down the track, and comparing each of its race times with other variables in the launch system, such as the cylinder puncturing accuracy. This was conducted less to make judgments on design decisions, but more to give us a greater understanding of how the launch system affected our other track tests, so we can draw valid conclusions from the data.

EVALUATION

Research Evaluation

Our research and preparation process, before beginning to design our car was the first stage in our engineering process. We researched all forces that would act upon, and affect our car, including aerodynamic principles, thrust forces, pitch forces, and the impacts of imperfect manufacturing. This research was extensive and ensured that all team members could understand what was required of our car design, allowing all of us to be able to ideate and understand how we can improve it in various ways. Throughout our design process, each team member has contributed innovative ideas and concepts that have influenced our final design. We believe our research process allowed us to create an extremely innovative and unique car design, utilising beneficial features such as our side pod extensions, our raised front wing, magnetic wheel caps, and our ALES system, as well as several innovations that weren't used in our final design. During this period, we also contacted mentors to assist us in our learning, such as Michael Laws and Jousef Murad, who taught us about manufacturing processes and computational data, respectively. We also conducted research into our manufacturing processes, and how we could manufacture our parts, as well as the strength and finish requirements for each part. This allowed us to view a range of material and machinery options for various parts and evaluate the effectiveness of each one in helping us create a lightweight, accurate and strong car. We decided to utilise Polysmoothed PVB for our printed parts, and to use an extensive sanding and priming process, in which we use wood putty, spray primer, various grits of sandpaper, and a glossy finish of paint to allow as smooth a finish as possible. We utilised a magnetic tool assembly system to allow easy and perfectly accurate assembly of our wheels, which is extremely beneficial to our car's race times. Our research phase was extremely valuable to the development of our car, and our learning, and we believe the research we conducted allowed us to design and manufacture a fast F1 in Schools car. In preparation for future competitions, we would have more time to work, allowing us to research more in-depth into these topics and processes, and refine and build on the knowledge we have gained.

Design Evaluation

The design of our car is a critical element in its race performance, and as such, we spent a lot of time and effort in our design process, to perfect our final car. We decided to use a structured testing process, testing individual elements against a control version, then combining these into various versions, from which we refined further. From here, we developed a variable-based system, which worked extremely well, as it allowed ease of adjustment of our CAD, and we could test various measurements for a part or feature, then use these to plot a graph and determine the optimal feature size or shape. We believe that this process has worked extremely well, as we learnt what design elements work, could experiment and adjust extensively, and we have tested every single element of our car's performance, ensuring we are extremely confident in the design of our car. This process was based around our CFD testing, conducted using Simscale, but in the prototype testing and refinement phase, we integrated physical testing analysis from our wind tunnel and track testing data, to improve specific areas of airflow. We also used a similar process for the design of our wheels. We first designed initial prototypes, each utilising a different concept, such as independent wheels, wheels joined by an axle, magnetic technology and integrated hubcaps. We analysed their weight, strength, cost and effectiveness, then selected the best prototype for our needs. We then refined it using FEA data, adjusting the design to minimize weight and maximise strength. In future, we will spend even more time developing our wheel design, as it is a critical component of the car, and look into some more innovative concepts for our wheel design and manufacturing. We would also like to spend more time during our track testing phase, to collect as much data as possible. Unfortunately, this was not available to us for this competition, as we had access to the track for only a day. Overall, we believe our structured design process for both the car design and our wheels was extremely effective and allowed us to conduct in-depth testing into all design elements, and integrate data from both physical and CAD-based testing. If we progress to the World Finals, we will further refine our current design, and test a variety of new design ideas, to create an extremely innovative and highly engineered car.

Manufacturing Evaluation

The manufacturing of our car is the most important stage in ensuring our car is as fast as possible, so we tried to perfect the manufacturing of our cars. We researched many innovative concepts, some of which we have used to manufacture our car, some of which we would love to look into further and work with in the future. We have been introduced to concepts such as Polysmoothing, plastic moulding, recycling parts, thermoforming, magnetic systems, as well as various finishing processes. The milling of our cars worked extremely well, and the custom jigs we designed worked perfectly to keep the block still and accurately positioned. Our 3D printed parts also worked well, and our Polysmoothing process was extremely successful. Our assembly jig also worked extremely well, and reduced assembly times and inaccuracies immensely, though we would have liked to have spent more time on putting our final model to fill in minor gaps between parts. We feel that the least refined section of our manufacturing process has been the finishing of our cars, as they were rushed far more than we would've liked. This resulted in a poor surface finish in the underbody of our car, though we have still managed to make the top of our car smooth to the touch and looking good, our surface inaccuracies will cost race time. We researched materials for wheels, such as nylon, acrylic, Teflon, PTFE or PEEK, and planned to lathe our wheel parts on a high-quality machine. Unfortunately, this plan did not materialise, as companies were busy and did not reply, could not manufacture our wheels, or had too short a timeframe. We finally decided on utilising SLS Nylon manufacturing, as it produces strong enough parts for our needs, and extremely accurate manufacturing, and, though is far cheaper than lathing, produces a slightly rougher finish, but in wheels, we felt this would not affect performance. In future, we would line up the manufacturing process far earlier, to ensure that we can create the best car with the best finish possible. Overall, our manufacturing process has been a success, and in future, we would love to continue to innovate and excel.

PHOTONIC