Velocity Vortex

Engineering Folio
State Finals 2025

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Requirements Analysis

Engineering Philosophy

This is our first time competing in F1 in schools. We have gone into this competition with only one semester of F1 in schools under our belts. Many of use have only used the design and analysis software this year for the competition. Our main objective in this competition is to have crafted a straight and true race car that will compete well and make us proud. Our objectives are stated below and these will help us achieve a satisfactory result.

1. Having accurate wheel and axle systems
2. To have a mass of 50.5g total mass on our final car.
3. In the software CFD to have a drag coefficient lower than .2
4. To have met all race regulations and specifications
5. To have a reliable and working tether guiding system
6. To have a reward centre of mass on the car
7. To have on track reliability and safety when the car goes down the track.

Engineering Cycle

Our engineering cycle was at the centre of our creative car design process. We used the model below on all aspects of the engineering process including individual components and concepts on materials and manufacturing processes.

This allowed us to produce the most efficient aerodynamic car we possibly could whilst adhering to the mass requirements and compliance regulation of the competition.

Wheel Alignment

Wheel alignment plays a critical role in keeping a car tracking straight, which is essential for both speed and stability. In our F1 car, ensuring the wheels are correctly aligned helps reduce body yaw—the unwanted rotation of the car around its vertical axis—improving directional stability and overall performance. Proper alignment not only contributes to faster lap times but also ensures compliance with competition regulations.

Figure 2: Car render showing yaw from Blender

Target Mass

Velocity Vortex takes a systematic approach to achieving the target mass in our car design, aiming for 50.5 g (± 0.2 g) to optimise acceleration. Using the equation $a = F/m$ (where a = acceleration, F = force from the canister, and m = car mass), we understand the direct impact of mass on performance. Our school track testing shows that each additional gram adds roughly 0.003 seconds to lap time, so minimising mass is key to improving speed. Even small differences can have a significant effect, as force is determined by the change in momentum ($F = m \times \Delta v$), with mass and acceleration being critical factors.

Computational Fluid Dynamics

We employed Computational Fluid Dynamics (CFD) to design and analyse the aerodynamics of our car. Using software such as Ansys, Autodesk CFD, and Virtual Wind Tunnel, we obtained detailed and rigorous data that guided and informed the evolution of our design concepts.

Figure 3: Image from VWT of the final car

Principles of Aerodynamics

Newton's first law states "that every object will remain at rest or in uniform motion in a straight line unless compelled to change its state by the actions of an external force". By understanding the basic laws of motion we can create and design a highly efficient racing car which should not only pass our expectations but also create a car to pass the finish line first! Using other laws such as the Newton's Second law which considers the relation between the weight and force applied to the car and how they result in the speed of the car.

Regulations

From examining the rules and regulations and taking advice from other, more experienced teams from our school, we have understood the importance of staying within the regulations for our car to avoid points loss and racing time penalties. Upon each change in the car we continuously checked whether or not the car met the rules and regulations provided, using a combination of digital and physical measuring methods, in particular a digital vernier.

Tether Guides

In the creation of the car, we took into account that the tether guides should be as far apart as possible. For the best stability while also not in contact with the track. We also looked into various different materials to test their dynamic friction coefficients.

Centre of Mass

The CAD model gives a digital centre of mass (CoM) position along all axes, but the physical car must be carefully measured and tested. The centre of mass is the point where the car balances, and we aim to position it rearward along the X-axis on the actual car to help reduce the tipping moment. (New World Encyclopedia, 2024)

Figure 4: Image from Fusion 360 showing the CoM dimensions front he origin

Rotational Inertia

The moment of inertia or more widely known as rotational inertia is the ratio between the torque and the resultant acceleration around the axis of in our case, our wheels. All bodies in motion are subjected to the properties of rotational inertia, consequently we have strived to keep the mass of the whole wheel and axle system to a minimum.

Finite Element Analysis

Finite Element Analysis (FEA) is a computer-based simulation used to predict how a product will respond to real-world forces, vibrations, heat, fluid flow, and other physical effects. We applied FEA to the halo, front and rear wing assemblies, wheel and axle system, and tether guides. (Autodesk, 2024). These tests were mainly conducted to confirm what our track testing indicated, but also provided evidence of digital analysis, using Fusion CAD software.

Figure 5 & 6: Images of the FEA's done on the rear wing and the halo

Start Alignment Jigs

Accurate and true alignment of the car on launch is critical. Having the thrust driving through the car when positioned on the track will minimise tether and other losses and will maximise the acceleration phase. We have created jigs to assist us with this known loss.

Newton's Laws of Motion

Inertia - First Law

"An object at rest or in motion remains so unless acted upon by an external force" our F1 in schools car is initially at rest. The C02 canister then launches the car, acting as an unbalanced external force, overcoming the car and producing inertia. (, Glenn Research Center, 2024) NASA

Force - Second Law

"Acceleration is directly proportional to force and inversely proportional to mass (a=F/m)." the car's acceleration is depend on the force it experiences and its mass. The cars force is the C02 canister which we cannot control, although the mass of the car we can control. Therefore by having the lightest possible STEM Racing car we increase our car's acceleration. (, Glenn Research Center, 2024) NASA

Action and Reaction - Third Law

"For every action, there is an equal and opposite reaction." When the CO2 is released, it propels the car forward with an equal and opposite force pushing it down the track. This reinforces the importance of harnessing the available energy from the canister (, Glenn Research Center, 2024) NASA

Profile Drag

Profile, or pressure drag, is primarily influenced by an object's shape and size, and is proportional to the pressure difference between the front and rear surfaces, including the frontal area. It occurs when airflow separates abruptly from the body, creating pressure imbalances and resulting in induced drag. Understanding this phenomenon helps us design for smooth, laminar flow and minimise disturbances in the airflow. (Nuclear-Power, 2023)

Skin Friction Drag

Skin friction drag is the resistance caused by friction between a fluid and the surface of a moving object. It is directly related to the surface area in contact with the fluid and increases with the square of the object's velocity. Our finishing system is designed to reduce this effect as much as possible. (SKYbrary, 2024)

Figures 7 & 8: Showing skin friction drag and the Coanda Effect.

Coanda Effect

The Coanda Effect occurs when a jet of fluid attaches itself to a nearby surface and continues to follow it, even as the surface curves away. This phenomenon is important to understand when designing our car, as we aim to promote laminar flow around the body and minimise areas that could generate turbulence. Being aware of the Coandă Effect is especially crucial when shaping the rear of the car, to prevent unwanted or unpredictable airflow behaviour. (S & C Thermofluids, 2023)

Bernoulli's Principle

When fluid flows through a restricted space, such as around a wing or wheel assembly, it accelerates, creating a pressure difference that increases drag. Since the total energy of the fluid remains constant, we aim to minimise these pressure differentials to reduce drag. (Byjus, 2024)

Figures 9 & 10: Demonstrating Bernoulli's Principle

Reynolds Number

Reynolds number represents the ratio of internal to viscous forces within a fluid and is used to indicate the laminar or turbulent nature of a flow. It is represented by: **Re=(v*I)nu.**

We found that in isolation, Reynolds number was not that meaningful when studying flow around an object, mainly because STEM cars don't reach meaningful speeds for this analysis.

Laminar Flow

Laminar flow occurs when a fluid moves smoothly around an object in parallel layers with minimal disruption. In contrast, disturbed flow causes turbulence, pressure differences, and increased drag. Our car designs take these flow types into account, and we have worked to minimise aerodynamic losses wherever possible.

Figure 11: Showing Laminar Flow

Tipping Moment

The tipping moment occurs at launch when the canister force acts above the front axle, causing the car to pivot forward since the thrust line and centre of mass are misaligned. This can reduce stability, increase friction and drag, overload the front wheels, and momentarily disrupt aerodynamics. To minimise tipping, we aim to position the centre of mass rearward and align it closely with the canister's thrust line.

Acceleration

Through extensive track testing, we calculated that our car remains in the acceleration phase for the first 5-7 metres using standard 28.5g canisters. Maximising this phase is crucial, as the car must reach peak acceleration before the pressure in the canister reaches equilibrium with the atmosphere.

A-B (S1) Car under power
B-C (S2) Car rolling unpowered
S = S1+S2 = 20m

Figures 12: Showing race summary. Credit Peter Brown

The Canister

$F_G = mG\ aG$

Figure 13: Shows the summation of the race and launch event. Credit ACRUX

When the rear of the cylinder is punctured, the pressured body of gas, (the mass of gas) accelerating out of the hole creates a rearward force F_G. The pressurised gas release creates a reaction back on itself resulting in the encapsulated canister producing a forward force on the car body. Newton's 3rd Law. Average mass for a world cylinder contains 8 grams charge of compressed air and weighs between 28.9g and 29.4g T1.20 (Ref: Peter Brown)

Wheel Wake

Wheels on a car develop initially high, then low pressure areas as the fluid passes them. The fluid passes both underneath and over the wheel, and separates from the wheel causing disturbed flow. It becomes an area of low pressure, sometimes known as a separation bubble immediately behind the wheel. The fluid then wants to rejoin, and eventually does. The side view below illustrates the 'separation bubble'

Figure 14: Highlighting the wheel wake from CFD.

Body Yaw

Misaligned or improperly assembled axles can cause the car to wander on the track, making it difficult to launch straight. This also interferes with the tether system, reducing stability and slowing the car.

Forces Acting on the Car

Figure 15: Showing the forces that act on a car during a race.

While designing our car we went through multiple different design for our front wings, back wings, core body of the car and side pods, as seen below about the different designs which were used as the car's design changed.

Front Wings

Concept 1

The first concept for our front wing originated from Noah's and Liam's cars from their F1 in schools class. This was used as a basic template to expand off to a more effective and intricate wing design. Our main problem with this wing was that it had a lot of weight and we felt that designing a newer one will be more aerodynamic as well as reducing the overall car mass. The wing is compliant with STEM Racing Technical Regulations.

Figure 16: Showing a front wing prototype from fusion 360

Concept 2

This front wing incorporated a multi vein design. Overall we liked this design but it was still too heavy and to intricate compromising its strength. We wanted to design a wing which incorporated the best parts of these two into one but due to how heavy this wing was, it moved the tipping point to far forward. The wing is compliant.

Figure 17: Showing a front wing prototype from fusion 360

Final Front Wing

This is our final front wing we will use in racing. In combination with our older wing designs we have incorporated an effective design that is lightweight, strong and also able to move through the air along the track. To test the new wing we have also used software such as CFD to prove the final design. The front wing was designed to remain lightweight and strong. The front wing was made out of resin to allow for a stronger, heavier, and reliable body. The wing is compliant.

Figure 18: Showing the final front wing prototype from fusion 360

Rear Wing

Concept 1

The rear wing design started with a loop. There is no particular reason we choose this design except it is aesthetically pleasing. However due to it being bulky and very square and not very aerodynamic, not the smoothest thing we decided to not go with this design. The wing is compliant

Figure 18: Showing a rear wing prototype from fusion 360

Concept 2

The 2nd concept we have gone with was just to refine the first attempt and to make it rounder and and overall to just make it lighter and more aerodynamic. The reason we didn't choose this design was because it was still to bulky and we were looking for something lighter and more aerodynamic. The wing is compliant

Figure 19: Showing a rear wing prototype from fusion 360

Final Back Wing

For our 3rd and final concept we have rounded everything and made it as thin as possible but still meeting the regulations. The reason we have selected this design is because it is aesthetically pleasing, aerodynamic, and very minimalist in section, meaning its light and quite simple to machine. The wing is compliant.

Figure 20: Showing the final rear wing prototype from fusion 360

Side pods

Concept 1

The first concept design for our side stems from Noah's and Liam's class cars. The purpose of the front wing was to guide the airflow around the car and have a space to allow wind to funnel through on the side pods under the car. This design was only a concept and was more of a base design to expand off of for a more effective design.

Figure 21: Showing a side pod prototype from fusion 360

Concept 2

In our second concept design we decided to not go with a wind tunnel but instead go with something different. We went with hollowing out the underside of the side pods to decrease mass but we couldn't get rid of it all due to virtual cargo regulations. We were happy with the key idea of this design but felt it could be improved so we decided to further apply changes to the design.

Figure 22: Showing a side pod prototype from fusion 360

Concept 3

In our third design we applied the same ideology as the second concept yet changed it as concept number 2 did not meet the competition regulations. It didn't meet the regulation concerning the side pods not meeting at the angle creating clear air space needed behind the side pods. So we fixed that and we refined the cut outs and made sure that there was still room for virtual cargo

Figure 23: Showing a side pod prototype from fusion 360

Final Side Pod

Our final side pod design was changed for to two major reasons. It's lightweight and it's aerodynamic capabilities combined with the car to produce a fast lightweight car. Simultaneously, underneath the wing the curvature aligns with that of the car. Hence, choosing this design was a crucial step as it allowed car to reach its potential, and helped with overall mass restrictions.

Figure 24 & 25: Showing the final pod prototype from fusion 360

Design Ideas

Car Bodies

Understanding the link between mass and velocity, we designed our car bodies to stay within the ideal 38–42 g range, allowing the final car to reach our 50g target after adding wings, wheels, paint, and glue. Our early concepts focused on a compact body similar to Liam's class car, providing a smaller front-facing area to encourage laminar flow and naturally guide air around the car. We also chose to remove rear side pods to reduce drag behind the rear wheels and minimise overall mass.

Figure 26

P1

Figure 27

P2

Figure 28

P3

Figure 29

P4

Throughout the main body design process, we focused on making continuous refinements. One key improvement was adding a funnel-shaped section behind the halo to eliminate the flat face of the canister holder and guide airflow smoothly around it. Another was thinning the undercarriage on the final body to further optimise performance.

Figure 30

Final Car

Figures 26 - 30: Showing body prototypes from fusion 360

Bearings

We purchased our bearings from **Boca: SMR73C-2OS #7 LD (3×7×3)**. Hybrid ceramic bearings use steel rings with ceramic balls, offering lower friction and higher hardness than steel bearings, while full ceramic bearings use ceramic for both rings and balls.

We chose hybrid ceramics because they provided excellent performance without the high cost of full ceramic bearings—the price difference was over $40, with minimal expected performance gain. After comparing our class steel bearings with a ceramic bearing in multiple spin-time tests (averaged in the graph below), the ceramics showed significantly better results, making them the clear choice.

Full Ceramic

Steel Class

Hybrid Ceramic

Figures 31: Graph showing bearing spin times

Figures 32 - 34: Showing different bearing types

Wheel Designs

Prototype 1

Our first wheel design focused on simplicity to achieve a lightweight, high-performing wheel. It featured five supports, providing strength and durability, making it both simple and robust—a crucial step for the car's overall performance.

Prototype 2

Our second wheel design aimed to add complexity and potential performance benefits. We reduced the supports from five to three, increasing their thickness to balance strength and weight. However, testing showed the wheel was unbalanced and heavier, leading us to develop a new design for better overall performance.

Figures 35 & 36: Showing wheel prototypes from fusion 360

Final Design

Our final wheel design combined simplicity, complexity, and innovation. It featured six thin, symmetrically placed supports for balance, with curved edges to improve aerodynamics and create a visually appealing design. Despite being thin, the supports' total weight nearly matched our second concept, providing a lightweight, balanced wheel that embodied our team's focus on performance and innovation.

Figures 37 & 38: Showing the final wheel prototypes from fusion 360v

Application of CAD

CAD allows us to turn ideas into accurate, testable designs. Without effective use of CAD, STEM Racing cars would struggle with compliance and efficiency. Using Autodesk Fusion, we can model, refine, and virtually test nearly any component, ensuring reliable manufacturing.

Successful CAD work also relies on good organisation, from managing prototype files to tracking changes in sketches and bodies. We prioritise this to streamline our design process. Fusion was used to create all custom car parts, position components like the tether guide, bearings, halo, and helmet, and produce the drawings for our compliance portfolio.

Figures 37: Showing the use of the combine and cut tool in fusion 360

Figures 38: Showing the use of the loft tool in fusion 360

Modelling Techniques

Autodesk Fusion offered a range of tools that helped us create a clean, compliant, and aesthetically pleasing car design. We primarily used sketches with extrude to form the main body, supported by dimensioning to meet regulations. Fillet and chamfer refined edges, while move and joint positioned and secured components. Loft was valuable for creating smooth transitions between faces, though revolve wasn't needed. Offset planes allowed sketches away from existing surfaces, and inspect ensured all measurements remained compliant. Throughout the process we repeatedly cut the car in half using extrude and then used the mirror tool to maintain symmetry.

Figures 39: Showing zebra analysis from fusion 360

Figures 40: Showing tool access analysis from fusion 360

CAD Organisation

As parts are manufactured at different stages, components were saved in separate files and imported into the main model, allowing them to be edited independently and efficiently. The joint tool positioned components accurately, and hiding parts made it easier to access obscured features. Most components were designed externally, but the front wing was created in the main file, then separated to ensure a clean, aerodynamic, and manufacturable transition.

Figures 41: Showing CAD organisation taken from fusion 360

All components and sketches were clearly named, and folders were used to keep the project organised. Fusion's timeline also helped us track and revisit changes throughout the design process.

Prototype 1

Figures 42: Showing a render of P1

Key Features

Our first car we deemed as a prototype is a former team members class car. This car came third fastest in its class and was a very good pre existing car that we could reflect on and expand. The front wing is designed to divert the air up and over the wheels in a attempt to reduce drag. Which then the air flow is guided under the side pods. The cars back wings consisted of four layers of teardrop shaped wings. This was done due to aerodynamic data feedback.

Key Performance Data

CATEGORY	DATA	CHANGE
COMPLIANCE	FAIL	-
CENTRE OF MASS POSITION (mm) (from the origin x axis)	102.77	-
TOTAL DRAG (Cdx)	0.239	-
BODY (Cdx)	0.195	-
CANISTER (Cdx)	0.079	-
BODY AND WHEEL FORCE (N)	0.146	-
FRONTAL AREA (m^2	0.00315	-
ESTIMATED RACE TIME (s)	1.148	-
PROJECTED MASS (g) - (Before paint, glue, decal)	45.78	-
RELIABILITY SIMULATION (FEA)	PASS	-

Figures 43 (above): Showing data table of p1

Figures 44 (below): Showing P1 in VWT

CFD Analysis

You can note the wide wash of disturbed air behind the car which has resulted in the increased drag of the car compared to P3 and the Final Car.

Prototype 2

Figures 45: Showing a render of P1

Key Features

Our second prototype is our engineer Liam's class car. In class, Liam's car won with the fastest single lap with 1.1 seconds and won the overall race. His car also features a snow plow type front wing with the desire to guide air up and over the wings. Side pods designed to help guide air around the car with naturally curved surfaces. Teardrop inspired back wings were also incorporated into this car for it aerodynamic performance.

Liam 's class car has a special change to it compared to the last. The entire car has been lowered, resulting in a thinner body which is lower to the track and has less frontal area. While this car would not meet the competition regulations, this single feature has been developed and implemented in our final car. This will give us weight to spare, allowing larger / more complicated front and back wings to be used, if needed.

Key Performance Data

Figures 46 (below): Showing data table of p2

CATEGORY	DATA	CHANGE
COMPLIANCE	FAIL	-
CENTRE OF MASS POSITION (mm) (from the origin x axis)	108.91	+6.14
TOTAL DRAG (Cdx)	0.293	+0.054
BODY (Cdx)	0.243	+0.048
CANISTER (Cdx)	0.167	+0.088
BODY AND WHEEL FORCE (N)	0.154	+0.008
FRONTAL AREA (m^2	0.0032	+0.005
ESTIMATED RACE TIME (s)	1.153	+0.005
PROJECTED MASS (g) - (Before paint, glue, decal)	41.35	-4.43
RELIABILITY SIMULATION (FEA)	PASS	-

Figures 47 (below): Showing P2 in VWT

CFD Analysis

You can note a much narrower wash of disturbed air behind the car which strangely has resulted in an increased Cdx. This could be due to the stepper front wing angle.

Prototype 3

Figures 48: Showing a render of P3

Key Features

This was the subsequent official car design formed by Liam which was prominently focused on creating a well performing aerodynamic, compliant car which is able to direct airflow through its front, side and rear wings. To elaborate, through the car's front wing the air was able to be directed upwards, leading to the subsequent entrance into the hollow side pods and final travel through the rear wings, this produced a smooth airflow and subsequent aerodynamic wake.

Simultaneously, the car was able to produce a beneficial projected mass of 44.85gms this allowed for significant modifications to be made. This accompanied by a low drag coefficient and an improved frontal area resulted in quicker racing times by 0.001s. This first official team prototype was crucial for our success and featured improved data results.

Key Performance Data

Figures 49 (below): Showing data table of p3

CATEGORY	DATA	CHANGE
COMPLIANCE	FAIL	-
CENTRE OF MASS POSITION (mm) (from the origin x axis)	106.83	-2.08
TOTAL DRAG (Cdx)	0.233	-0.060
BODY (Cdx)	0.245	+0.002
CANISTER (Cdx)	0.107	+0.060
BODY AND WHEEL FORCE (N)	0.143	-0.011
FRONTAL AREA (m^2	0.00319	-0.001
ESTIMATED RACE TIME (s)	1.152	-0.001
PROJECTED MASS (g) - (Before paint, glue, decal)	44.87	+3.52
RELIABILITY SIMULATION (FEA)	PASS	-

Figures 50 (below): Showing P3 in VWT

CFD Analysis

You can see here that the wash stream of disturbed air is narrower from P1 and the front wing angle is not a step. Resulting in a better Cdx than P1 & P2.

Final Car Design

Final Car

Figures 51: Showing a render of the final car

Key Features

Our final car obtained several major and minimal changes. To initiate, the front and rear wings were redesigned to produce a highly aerodynamic car which guides airflow through the car. Simultaneously, the car's side pods were closed with a hollowed underbelly producing a lightweight car which directly influences the race time. One major change was that the car's main body was lowered and the car's underbelly was curved to allow air to flow quickly under the car, hence producing a fast yet lightweight car.

This was supported by the performance data which displayed how the car performed continuously better in comparison to past car designs, hence proving that the changes made were beneficial for our team's success

Key Performance Data

Figures 52 (below): Showing data table of the final car

CATEGORY	DATA	CHANGE
COMPLIANCE	PASS	-
CENTRE OF MASS POSITION (mm) (from the origin x axis)	99.136	-7.69
DRAG (Cdx)	0.192	-0.041
BODY (Cdx)	0.199	-0.046
CANISTER (Cdx)	0.115	+0.008
BODY AND WHEEL FORCE (N)	0.118	+0.025
FRONTAL AREA (m^2)	0.00315	-0.00004
ESTIMATED RACE TIME (s)	1.145	-0.007
PROJECTED MASS (g) (Before paint, glue, decal)	42.25	-2.65
RELIABILITY SIMULATION (FEA)	PASS	-

Rear Wing

The rear wing that we choose for our final car was the open airspace model, which we positioned on the top of the canister housing. We did this to keep the rear wing from further disturbing the airflow which has already been affected further up the car.

Figure 53: Rear wing from fusion 360

As you can see below the airflow around the side of the canister is less affected by the positioning and design of our final wing.

Figures 54 & 55: Showing rear wing comparison in VWT. P3 (left) and Final (right)

Car Body

The final car body was designed to ensure that we maximised airflow and managed our mass. This was inline with engineering objectives 2 & 3.

1. Lofted canister housing to the back of the halo to ensure a more gradual path for the air to flow over.
2. Lofted progression from the nose of the car to the canister at the back to assist with laminar flow.
3. Arched under carriage to allow air to flow easier and reduce mass.
4. Filleted sidepods to assist with managing the mass target.
5. Tapered rear of the car with no pods to also better manage assist laminar flow.

Side Pods

Our final side pod design balanced mass and aerodynamics to meet engineering objectives 2 & 3. Earlier prototypes used an open-cut design to reduce mass and accommodate virtual cargo, but this created an air tunnel that directed airflow into the rear wheel. In the final car, we enclosed this tunnel to reduce trapped air ahead of the rear wheel. Although this shifted mass rearward—impacting objective 6—we offset it by adding underside fillets to better manage overall mass distribution.

Figures 57 & 58: Showing side pod wake in VWT. P3 (left) and Final (right)

Wheels

The wheel design that we have opted for is a six spoked wheel with supporting structures to assist reliability and performance. This aligns with engineering objective 1 & 7.

Figures 59 & 60: Showing wheels in VWT. P3 (left) and Final (middle). Image 61: Final wheel prototype from fusion (right)

Whilst you can clearly see that the enclosed wheel caps were more aerodynamic we chose the spoked wheels for a few reasons to assist with mass target and to help to maximise the launch phase of the car.

Axle System

We chose a common fixed axle which is held in place by standard grommets. We did this to align with engineering objectives 1 & 7. We chose 3mm diameter carbon fiber fubing for the axles as it's strength to weight ratio is excellent and it's cost effective.

Bearings

We looked at 3 different types of bearings during our engineering process and finally settled on hybrid ceramic bearings from Boca. They were clearly the better set during testing and helped us towards achieving engineering objective 1.

Figure 61: Tether guide taken from fusion 360

Tether Guides

Our tether guide choice was made based on reliability and performance. We wanted a basic and known system so that it was easy to align and still provide good performance addressing engineering objective 5, 6 & 7.

Front Wing

The front wing was designed to match the minimalistic nature of the car whilst also providing some shielding of the wind and reliability. We were wary of not making it to pronounced as our testing showed clearly how this can significantly affect the overall Cdx. This helped us address engineering objectives 3 & 7.

Figures 62 & 63: Showing front wings in VWT. P2 (left) and Final (right)

Overall

All decisions made about the final car design have been done so with engineering objective 4 in mind. This has been the overarching objective in the engineering process.

Evaluation Against Engineering Objectives

1. Having accurate wheel and axle systems ✓
2. To have a mass of 50.5g total mass on our final car ✓
3. In the software CFD to have a drag coefficient lower than .2 ✓
4. To have met all race regulations and specifications ✓
5. To have a reliable and working tether guiding system ✓
6. To have a reward centre of mass on the car ✓
7. To have on track reliability and safety when the car goes down the track ✓

Finite Element Analysis

Finite Element Analysis (FEA) is a method to estimate or predict how products are likely to perform under stresses encountered during their intended use.
We used FEA on our rear wing, as this may encounter stresses during the deceleration process.
We used Fusion to conduct the FEA simulation

Inspect Tool

We used the Inspect tool to get the following analysis data:

- **Centre of Mass** - This is an important feature for car design. To minimise the tipping moment on our car when on launch, we needed to locate the CoM towards the rearward of the car, in all three axis. The closer we can get the CoM to the line of thrust, the more efficient the launch sequence is.
- **Measure** - We Measure to check the accuracy of our geometry during the design process. The checking of these dimensions were also critical for our important compliance checks.
- **Draft** - This helped us look at the manufacturability of our car during the CAM process.
- **Accessibility** - We used this to check that all parts of the car design will be able to be accessed during machining.

Figures 64 & 67: Showing components in FEA results

Compliance Checks

As compliance with the Technical Regulations is a vital part of this competition, we analysed our designs both in Fusion and after we made the prototype cars on the Mill. We used digital verniers, 2mm and 3mm drills, some laser cut jigs and a digital height gauge to help.
Using Fusion, the Drawing option helped us check compliance and accuracy easily. We had trouble with the height of the car, so the Halo and Front wing were both out, and would have caused a massive points loss and time penalty.

Figures 68 - 70: Showing compliance checks both physical and digital

Computational Fluid Dynamics

To conduct our CFD testing we used Virtual Wind Tunnel as we experienced issues with our other platforms. VWT was helpful in producing excellent data and images of the drag a force acting on the car and components. This was heavily relied upon to guide the engineering process. SOme of these are:

Body Surface Velocity

This indicates the wind speed as it approaches the car and then how it interacts as it passes over and through surfaces. The wind speed is set at 18 m/s which is indicated as orange (the same colour before it hits the car). What we want to see is a consistent orange colour over the top surfaces of the car meaning that the wind has minimal disruption as it passes the car.

Figures 71 - 73: Images from VWT

P1 P3 Final Car

This data helped us to shape the front loft of the car and ensure that the front complimented the final design.

Wind Velocity Y Plane

The wind speed on the Y Plane of our model allowed us to look at areas where the wind was getting trapped and therefore aerodynamic losses. We looked at the rear of the car in particular. Here we are looking for the wind to return to the speed it entered the car as quickly as possible. In the images below you can see that there is a significant area of blue (disturbed air flow) behind P2 compared with the final car.

P1 *Figures 74 & 75 : Images from VWT* Final Car

This data helped us in the design of the tapered undercarriage at the rear of the car. This made a significant impact on the over reduction in the drag of the final car.

Wind Velocity Z Plane

Much like the wind speed on the Y Plane we used these images and data to fine tune the air flow around the front wing and sidepods of the car. The theory is the same as on the Y plane, with the aim to return the air to the original speed and direction it was on before it hit the car as soon as possible.

P1 *Figures 76 & 77 : Images from VWT* Final Car

The three areas of focus for us here were behind the front wheels, behind the side pod and at the rear of the car. As you can see there is far less blue 'disturbed air' in our final car compared to P1. Again, significantly helping the overall drag.

Streamline Imaging

When analysing streamline data from a car wind tunnel test (real or virtual), you're essentially looking for how the air *moves around and interacts with* the vehicle. Good streamline analysis helps you understand drag, lift, flow attachment, separation, and turbulence, which all influence performance.

In the images below we can see firstly that both P1 has even flow symmetry meaning there are no geometrical flaws, whereas P2 has a few inconsistencies. The below images also highlight has a smaller wake, with less turbulent airflow (tangled streamline).

Figures 78 & 79 : Images from VWT

P1 P2

Furthermore the streamline images help to highlight the narrower wake of P1 compared with P2. This would be due to multiple factors with a couple of these being the tapered rear of the car on P1 and different rear wings. This is reflected in the overall Cdx in the graph below.

Figures 80 & 81 : Images from VWT

P1 P2

	P1	P2	P3	FINAL CAR
Body	0.243	0.195	0.245	0.199
C02 Canister	0.167	0.079	0.107	0.115
Overall	0.239	0.293	0.233	0.192

Figures 82 & 83: Data from VWT

Manufacturing

Manufacturing Goals & Objectives

1. Producing three identical cars.
2. Each car weight no more than 51 grams.
3. Limiting having to recut or reprint aspects of the car after beginning manufacturing.
4. Gain maximum points for scrutineering.

Machines

When we progressed to manufacturing our car, we used the Denford router 2600 pro. We used this machine to cut the main body of our prototypes and final cars. Other machines we used include the Bambu Lab X-1 carbon and the prusa MK 3s 3D printers. The use of the original prusa SL1S speed resin printer was used for the front wing .We used these machines to print prototype and final parts for the cars which include the front and back wings, grommets and wheels.

CAD based design software

While designing our car we used a software called Autodesk Fusion 360. We chose this software for it's vast tools and accessibility. While in our first year of the class we created our class cars using Fusion and all members of the group were familiar with the software and felt it was a safe reliable choice.

Grommets

We have decided to use the grommets that we used in the class and then to glue the axle into it. We have chosen to use these because they are strong, reliable, reasonably light and are accurate.

Coding the machine

Using an app called QUICKcam Pro to run the 3D design we created and write code for the machine to use. After setting the orientation, depth of cuts and what type of cut, we then post processed to get code to cut the block. Each profile of the car is post processed to be cut, using separate codes. We name these code files, starting at 0001 and ending in 0004. Each individual side of the car's code is then edited to tell the machine to cut axle holes in specific location, mirror sets of code and looks for the next set of code.

```
G00 A0
M98 P0001
G00 A90
M98 P0002
G00 A180
M98 P0003
G00 A270
M98 P0004
G00 A0
M30
```

Figure 84: Sub Call from VR Milling

Paints and primer

Tamiya paint is an acrylic paint, one of the three types of paint that we were choosing from. They were acrylic, enamel and oil based and there isn't a lot of difference between the paint's besides some being stronger than others and some lasting longer than others and different finishes. We are using tamiya paint, which from previous teams experience at school was of high quality in terms of finish and ease of application.

Figures 85 & 86 Showing the paint used and finished painted prototype

3D printing

3D printing is a crucial part of the manufacturing of the final car. Without 3D printing the car would be missing crucial parts including the front wing, back wing, wheels, grommets and halo. For our 3D printing we used a combination of the Prusa MK3S, Bambo Lab X1 carbon, Bambo Lab P1S and the Bambu lab A1 printers for testing our designs. The front wing (middle image) has been printed using the resin printer.

Figures 87 - 89: 3D printed parts and slicing

CAD/CAM Manufacture:

We learnt how to write Computer Numeric Code (CNC) during our school lessons.
We know that the first job is to ensure that the geometry of the car is the correct size, to fit into the Balsa wood blocks. This includes overall length, width and height. Our blocks are 223mm x 65mm x 50mm in size.
We studied feedrate, spindle speed and depth of cut as these terms relate to machining

Feed Rate:	2250mm/m	default
Spindle Speed:	23000rpm	default
Depth of Cut:	5mm Max	
Step Over:	.2mm	defaut is .9mm

Figure 90: Showing the difference in machine a model at .9 stepover (front) compared with .2 (rear)

We use the software program QuickCAM Pro to write our code, and have the use of a Denford 2600 Router. This machine enables us to rotate the block to access, top, bottom and side machining without having to turn the block by hand. We use a series of codes, joined together called a sub program, to rotate the work on the chuck.

We used a 6mm diameter ball mill for all of our machining. The sub program was written for us, as all students use it in our class. This is the image illustrating the tool paths and final appearance of our car, from the QuickCAM software.

Figure 91: Showing machining errors and the Machine plot from Quick Cam

Machine Tolerancing

We used the IT14 internal tolerancing grade to give us an idea where to start. Machine tolerance is the maximum and minimum variation a component can be from the original nominated exact size. This means that as long as the component or part, after manufacture, is within these limits, it will be an acceptable and workable part.
We have applied the following tolerances:

CNC machining:	+/- 0.1mm
3D Printing	+/- 0.1mm

Quality Control

Block Selection: Even though we had a limited number of blocks available, we chose the selected blocks which accurately prepared, the correct mass and free of any knot defects.
Compliance Scrutineering: The geometry was scrutineered in CAD form, then physically after machining and then after assembly. This was done by our engineering team.
Additional scrutineering: Another member of the team was given the job to also scrutineer the cars.
Quality of finishing and assembly were closely looked at.

Car Manufacturing Process

We followed the processes we used with our class cars. However there was a lot more work went into designing and developing our State final car. The most important change was the need for the car to be compliant with the STEM Racing technical rules, so we tried to check these key measurements throughout the process.
Safety was always on our minds.
Our Manufacturing process was:

1. Design the car and check compliance using CAD. Ask our teacher for help.
2. Finish the geometry and write the code
3. Make a prototype car, to check that the machine is working accurately.
4. We have learnt that the manufactured car is sometimes different than the drawings, so it was important we measured the car carefully after machining.
5. The machine was working accurately.
6. We then fitted the Front Wing, and found we had an issue with 3mm clearance/airspace and had to make changes. We changed the position of the axle holes to help. We used PVA adhesive
7. Next we fitted the Halo, and again we needed to adjust the axle position to make the make the Halo the right distance from the track.
8. The Rear wing was fitted next checking rule compliance making it looked straight.

The wheel and axle system required careful fitting of the bearings and the wheels themselves. The tether guides were glued in place. We sanded our car using fine grade abrasive paper, before applying undercoats and top coats. We weighed the car several times to check if we were meeting our mass target.

Finishing Process

As part of the final manufacturing process, after the assembly of the front and rear wings, we began preparing our car for painting. As we used a finishing machining plan (canned cycle), there were few marks to remove from car body. However we needed to make sure that we kept the machined shape and that we didn't remove too much wood and make the car too light. We used 240 grit Aluminium Oxide abrasive paper to begin the process, which is a medium grade abrasive to remove any machining marks remaining. This was followed by 400grit for a final smooth finish. This was followed by sprayed coats of high quality paint, weighing the cars between each coat.

Assembly & Physical Testing

Assembly

We tested our car assemblies using custom-made jigs, along with precise marking and measuring tools such as digital verniers and machine blocks from the Design and Technology department.

We 3D printed our pars and glue the relevant pieces in place to begin the prime a paint process

Figure 92 & 93: 3D printed parts and then assembled on car

Our primer and paint process consisted a methodical process in which we recorded the mass of the car after each action, where that was painting or after sanding. You can see this on the mass calculation spreadsheet to the right. This process allowed us to monitor our progress towards our target mass.

Figure 94 & 95: Car being painted and drying

The next step in the process is to again weigh the cars fully assembled to ensure that not too much mass has been lost due to evaporation and then to apply the stickers. We then apply a couple of coats of clear or clear pearl paint to put a final layer over the stickers to help with skin friction drag and improve the aesthetics

Figure 96 & 97: Wheel and axle system on the car and in isolation

After the painting process is complete and the target mass has been achieved it is time to assemble the wheel and axle system. This is a very important aspect of the process. As we have previously stated in our engineering philosophy, we believe that having an accurate wheel and axle system is the most important part of ensuring we have a fast a reliable car.

Once assembly is complete a final weight check is done and then another in 2 days to ensure that the mass of the cars is relatively stable. This then completes the assembly process. For more information on the process please see page 9. We then were able to track test the car (prototype). Please see the results in the right hand side column.

Figure 98: Car on track during testing

Physical Testing

Mass Calculations

As car mass is one of the most critical performance factors, we used CAD to assign physical materials to every component and adjust their densities where needed. This allowed us to generate an accurate ballpark estimate of the final assembled mass. For instance, this process helped us determine whether using 12g brass rear axle tubes would push the car over the 50 g limit. We also used the predictive section of our mass-calculation spreadsheet (shown below) to select the appropriate block mass. During manufacture, we regularly weighed each component to maintain strict quality control and ensure our predicted mass matched the real car.

VELOCITY VORTEX MASS CALCULATIONS CAR A

PROJECTED FINAL CAR MASS CALCULATIONS		
Original Block Mass	88	g
Front Wing	4.94	g
Axles	2	g
Bearings	2	g
Wheels	8.08	g
Halo & Helmet	5.12	g
Car Body	12.620	g
Rear Wing	4.2	g
Tether Guides	0.8	g
Grommets	1.28	g
Paint/Stickers/Glue (Allowance)	-9.460	g
Car Mass (No paint)	41.040	g
Target Mass	50.5	g
Difference	-9.460	g
Car Body Mass before Final Assembly	43.830	g

PROJECTED CAR BODY MASS CALCULATIONS		
Block Mass (BM)	88	g
Projected Block Mass (AM)	12.885	g
Mass % Machined	85.36	%
Block Volume	7.035	mm^3
Car Volume mm3	1.028	mm^3
Volume % Machined	85.39	%
Block Density	125.341	g/mm^3

MASS PROGRESSION		
Off the machine	12.620	25.000 g
After Sand and Essembly	28.160	9.460 g
After Primer 1	32.34	5.280 g
After Sand	31.95	5.670 g
After Primer 2	35.2	2.420 g
After Sand	34.93	2.690 g
After Pant 1	36.5	1.120 g
After Sand	36.2	1.420 g
After Paint 2	37.55	0.070 g
Target Mass	37.620	g

Figure 99: Mass calculation spreadsheet

Block Accuracy

Before the manufacturing of cars can begin, a crucial checkpoint that needs to be checked is to physically measure the blocks prior to machining. This is done by using a digital caliper to measure the canister hole to the sides of the block, this is done to ensure the block centre was central, allowing for accurately cut cars. The block is then compared to the regulations of 65mm wide and 50 deep, and weighed to check mass.

Figure 100 & 101: Physical block accuracy test

Machining Accuracy

After cutting cars for either prototypes or final car we measure the physical model against the CAD one to ensure that we has the machine offsets correctly set and to ensure that we still had a compliant car.

Figure 102 & 103: Physical machine accuracy test

Canister

Although the canisters appear consistent, their weights can vary by up to 1 g. When examining used canisters, we also found that the puncture holes were not always the same size or perfectly centred. To minimise the impact of these inconsistencies, we used the starting mechanism and launch jigs to ensure a controlled and repeatable setup. We also discovered that the CO_2 inside the canisters is stored under high pressure and exists as a liquid before rapidly turning into gas when released.

Figure 104: Physical canister hole accuracy check

Figure 105: Car misaligned on track

Starting Mech Aligned at Launch

Launching the car perfectly straight is crucial. If the car begins at an angle, it will try to turn, increasing contact with the tether line and creating additional drag, which slows the car down.

Car Aligned at Launch

We used a spacing block to ensure the cars were perfectly parallel to the track for every launch. Consistent, accurate alignment with the starting mechanism firing pin is essential for reliable engagement and fair, repeatable race conditions.

Tether Guide Test

To compare tether guide materials, we slid a brass eyelet and an alconite ceramic ring down a fishing line; the faster-moving one indicated lower friction and therefore less drag during racing. We also inspected each internal surface under magnification to assess smoothness. Although the ceramic ring was faster, we prioritised ease of assembly and went with the brass eyelets.

Track Testing

We were able to test the prototype of our final car on tack and were happy with the performance and the reliability of the car as a whole and individual components. We also know that there is more performance to be found from the improved final bearings.

Figure 106: Time data from track testing

Requirements Analysis

As our lead engineer, Liam led our research and development, along with help from Vivaan they set up systems to check regs and requirements which allow us to research and understand the requirements and create a more sophisticated stem racing car.

Ideas

The Car obtained several parts which were developed through continuous testing and reassuring to create parts which were beneficial leading to a fast and innovative car, representing us. To initiate, the body was aimed to be a thin, lightweight and smooth to allow for an advantageous airflow for the car. Accompanying the body, the journey behind creating the wings was lengthy yet led to well built wings which may have been improved minutely. Overall, while minimum adjustments could have been made to our car and its parts, we are excited to produce a car which features well built components.

Development

The final development of the car and its segments was developed through continuous testing and remanufacturing of the wings and body. While our journey was not the smoothest, due to setbacks which immensely delayed our ability to develop the wings and car to its best. Hence, we chose to utilise the remaining time for development of the remaining parts to their best.

Analysis

Analysis was a key tool in allowing us to develop each major component of the car. Through the applications provided by Fusion combined with several applications such as CFD, we were able to analyse weak points on components such as the wings, allowing us to further develop the component, this analysis was further strengthened by physical testing of the prototypes which occurred on a regular basis. Accompanying the analysis of the wings, major analysis on the car's body was done through applications such as CFD which allowed us to analyse and improve parts of the car which were disadvantageous. Overall, we were able to provide some detailed analysis on major components of the vehicle.

Figures 107 - 109: Show the FEA of rear wing (top), Car in VWT (middle) and Car finished as prototype (bottom)

Body

The final body of the car required several changes to be made continuously to allow for a fast car which suited regulations. Such changes were continuously made, such as changing wheel the wheel's location on the car, changing the size of the wheel's bearing holes to suit our purchased bearings. Overall, these changes were crucial to create a car which suits our requirements and more importantly suits the competition's regulations. Overall, we are happy with the final body of the car.

Physical Testing

We conducted a variety of physical testing on our prototypes and final versions of our car. These tests include:

- **Tether Guide** - tether guide testing to experiment with different materials with different pros and cons.
- **Block Accuracy** - block accuracy testing to investigate how accurate our blocks were before use. This was done to eliminate machining errors of the car and to stop any breaches of compliance.
- **Machining Accuracy** - This was a similar testing to the block accuracy, but to the block after machining rather than before. This again was done to keep compliance with the rules of the competition. We found that the machines was cutting the cars accurately, with 0.1 of a millimeter difference.
- **Track Testing** - track testing was a valuable form of evaluation particularly for tipping point, tracking and reliability of front and rear wings upon deceleration.
- **Checking Compliance** - checking compliance of the car was a challenge as we were preparing to machine final cars. We discovered that the car was 7mm over the limit T3.6, this required change of geometry of the car to allow us to rectify the problem. The re-coding and manufacturing of final cars was then applied.

Manufacturing and Machining Process

Machining of the car- This was a smooth process for the car body. Using a 4 machining operations on each side of the block. Using a 6 mill ball nose for all operations. The 0.2 step over required a light sanding on the body of the car post machining. Early on there was mistakes made during the machingning of the car. This was to do with the axle whole positions and depth of the canister housing. As time passed and we gain a better understanding of the software and machines the accuracy and quality of our cars increased.

Front and rear wings - Made at school using our 3D printing lab in the Stem building. This process went smoothly with some reprinting of parts required after updating to align with regulations standards.

Wheel and axle assembly - Wheels were made smoothly using our schools 3D printers, one hiccup was printing older versions of our final wheel which were made to fit a smaller bearing. Axle's were made effectively, cut from Carbon fiber rods to the required size.

Assembly of cars - this was greatly assisted by a genuine understanding of or target result for our cars. Both cars used for racing passed scrutineering following assembly.

Finishing - this process was closely aligned with our target mass goal. We are happy with the final build and appearance of our cars.

Figures 110 - 111: Show the FEA of rear wing (top), Car in VWT (middle) and Car finished as prototype (bottom)

Tolerance & Quality Control

We ensured the each printed segment of the car obtained a minimum tolerance to allow for minimal error which still allows us to create a functional segment which suits regulations and serves its purpose. This was a technique which was useful for us as it allowed room for error during development and allowed us to still remain within regulations. To elaborate, we applied a +/- 1mm tolerance on components which had been 3D printed or created through the CNC machine, this helped us in our journey because we were able to develop with errors while remaining within with regulations. For example, we added 4mm thickness to our chamber housing which allowed to remain within regulations while also adding on extra supports to the chamber housing.

We ensured that the quality for each component was well managed throughout our journey. Liam, our lead engineer ensured that the wheels and bearings were compatible prior to printing them or adding them onto the wheels. Hence, quality control was a technique which was beneficial for the development of all components

CAD

Liam was able to undergo a process which elevated each aspect of his CAD skills. To elaborate, he was able to extend his skills from those which he gained while undertaking the school subject. This was possible due to the continuous support and advice which he received from key mentors who taught him of the several techniques on how to create a well analysed car. Overall, through the journey, Liam was able to successfully lead the engineering department with a clear understanding of each topic.

Compliance

As the engineer Liam ensured that the car was compliant to the regulations provided by the competition. To ensure the compliance of this car we were able to contact Mr. Stephen Read for reassurance on the car's compliance and ability to remain within regulation. The feedback received from Mr. Read was appreciated as it allowed Liam to gain feedback from a STEM Racing Nationals Judge, hence allowing him to add last minute changes and ensure that the car was compliant with the regulations.

Rendering

Rendering was not a major difficulty however, minute issues were faced during the process. Sebastian initiated the rendering process through fusion, however, due to errors with the decals, he transitioned to Blender which offered higher quality renders with detailed decal position. This allowed us to develop high quality renders with accurate sticker location. However, due to the render being developed in Blender, it was not possible to transfer the file with decals to Fusion and hence the renders in the compliance folio were simply a photo of the final car. Overall, rendering was simple with minimal issues.

Figure 112: Final Car Render developed from the Blender Application.