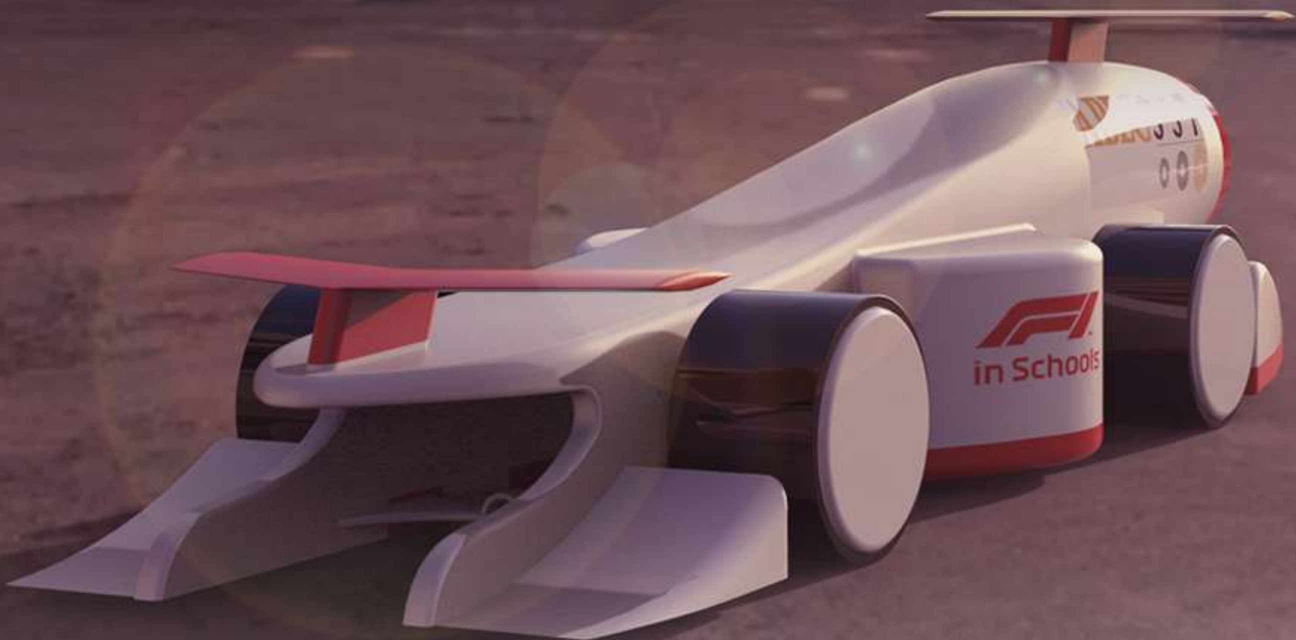
DESIGN AND ENGINEERING PORTFOLIO

F1 IN SCHOOLS™

WORLD FINALS'19

MATADORS



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BACK IN THE ARENA : MATADORS 2019

Team Matadors' engineering is based on experience gained during the 2018 Indian Nationals and World Finals at Singapore, as well as the recent 2019 Indian Nationals. After elevating our design methodology during by networking with our competitors and interacting with our judges at the World Finals, we built upon this new base by crafting a design took flight in the 2019 Nationals and has flourished with our developments in the following months.

AIM : SHOOTING FOR THE BULLSEYE

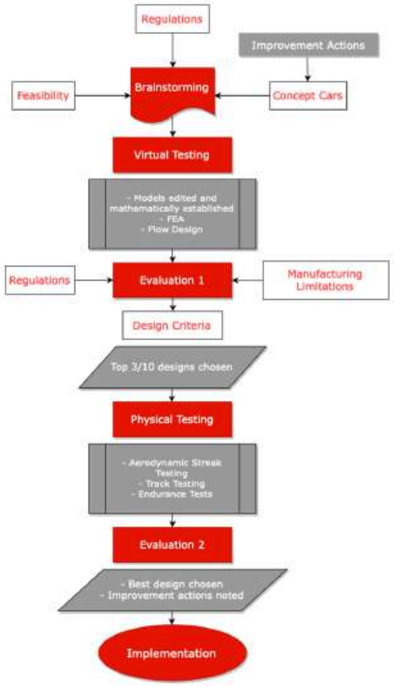
The Matadors' aim for the 2019 Nationals was to reconsider our previous designs from the ground up, and rebuild a car that is legal, fast, and properly engineered. We aimed to approach our design process by looking at individual components, using proper physical and virtual testing, and evaluating the results from testing by our own unique set of criteria.
We believe a process with virtual testing preceding physical testing leading into CAD is optimal for professional-grade car development.

DESIGN THESIS : THE MATADORS CAPE

To create a general set of evaluation criteria, we considered the following factors paramount in our design process:
Compliance - with all competition regulations and manufacturing tolerances.
Feasibility - in the context of available materials and production methods.
Durability - in design, including structural and material integrity ensuring a minimum lifespan of 100 races
Aerodynamic Integrity - to reach desired speeds and stability in accordance with all experimentation and testing

DESIGN PROCESS

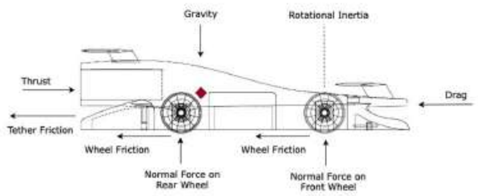
In preparation of establishing a general design process, the team attended a seminar on product design and marketing to help consolidate ideas individual members picked up on their own or during management or design sessions. The process can be summarised as follows:
Design changes pertaining merely to individual components were tested virtually with emphasis on FEA and CFD, while their effects on the overall drag were monitored simultaneously. All the aforementioned analysis, particularly in the evaluation stages, was carried out in the context of the overall design and the design standards defined by the team, as from our research, we concluded that interpreting several dependent variables separately, independent of each other, would leave us quite vulnerable to false conclusions.



MATHEMATICAL MODELING

In accordance with the ground-up approach we quoted in our design thesis, we broke down the fundamental analysis of the car's behaviour and design into how we'd approach a b asic physics problem- by listing and marking all forces on a rough car design. The modelling process involved the following steps :

- Entering all physical formulae pertaining to translational and rotational forces and motion into the spreadsheet, keeping them saved as references for further use.
- Entering all observed forces after virtual and/or physical testing into the spreadsheet's variables.
- Calculating approximations for drag based on exposed surface area and atmospheric conditions.
- Summing up all relevant moments to give rotational and linear kinetic forces.
- Calculation of these parameters across time intervals of 0.001 seconds. An array of time points was generated and calculations were carried out for each element in this array.
- Listing observations from this model and verifying these points of interest out on the actual model by virtual and physical testing.
- Analyzing data across multiple runs with different values of environmental variables in order to obtain a veritable sample set of observations.



From these tests we obtained the following points of interest:

- Given the size of the car and the pressure involved in its launch, the most integral factor in determining its speed was its mass, as a 2-gram increase in mass increased track time by 0.03-0.05 seconds. Therefore, in designing the car, we prioritized minimizing the car's mass within the limits of the regulations over other aerodynamic factors to a reasonable limit.
- The number of sharp edges joined directly to the body correlated with a decrease in speed. The longer the line of contact with the body was, the greater was the decrease in speed observed.

DESIGN STANDARDS

- **Wheel and Axle Engineering :**
  Minimizing weight
  Increasing durability and stability of attachment to car body
  Minimizing surface area in contact with moving parts
  Ensuring enough capping on wheels to minimize drag
  Minimizing energy dissipated due to friction
- **Front Wing and Nose cone :**
  Minimum drag due to turbulence
  Prevention of air flow through only the front and the side of the wheels
- **Mechanical Engineering :**
  Maximizing structural integrity of design
  Minimizing frontal surface area
  Minimizing cost and weight

INTERPRETATION VARIABLES

- **Skin Friction -** Greater skin friction was seen as an immediate detriment, but it the tradeoff between skin friction and turbulence due to the presence of edges was considered at each step. Therefore, it was interpreted in the context of the overall CFD view of the car. Protrusions such as appropriate gaps and hinges could be seen as fixes to improve this value.
- **Lift -** It acts through the centre of pressure of the object and is directed perpendicular to the flow direction. Downforce is to be generated by setting the wings at correct angles to mitigate the lifting. The balance between lift and downforce is considered at all times.
- **Turbulence -** Turbulent flow causes the air to swirl, creating vortices, which further created a low air pressure zone, thus pulling the car backwards. High turbulence was considered undesirable, necessitating support structures for diverting airflow.

EFFECTS CONSIDERED

Throughout our design evaluation process, we utilised the following results to physically explain our test results:
Bernoulli's Principle : The conservation law for fluid dynamics was the result most integral to our analyses. As evidenced by our discussions on front-wing design and inward airflow engineering paradigm, among others, the correlation this principle provided between air velocity and pressure, allowing us to hypothesize reasons for variation in lift and downforce. Moreover, it dictated how we built orifices and hollow spaces within the car.
Coanda Effect : Describing the tendency of rapidly flowing air to follow adjacent surfaces and develop low-pressure regions controlled how we approached designing our main body and side-support structures. Small angles of variation built up to create curvature were thus more effective in directing the air along and over the car body.
Marangoni Effect : The Marangoni Effect factored into our analyses due to the use of CO_2, with its implications being most evident in our concept cars.

COMPONENTARY ANALYSIS

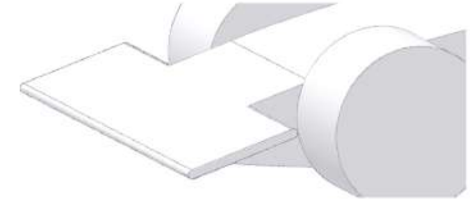
FRONT WING

IDEA 1: MONO-WING NOSE

The base of the front wing, in this design, would act as a medium for directing air over the top of the car's body. By doing so, the form drag, due to the difference in pressure between the front and rear ends of the front wheels, would be vastly reduced. Given the importance we assigned to drag, we decided this idea was worth exploring.

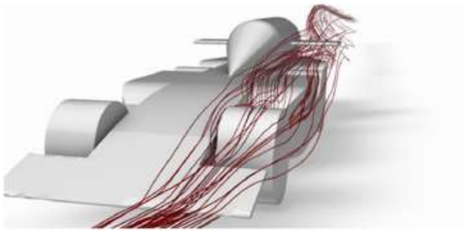
Development

A mono-wing nose, protruding at 20o from the front spoiler was considered. The mentioned angle was chosen in order to minimize form drag. Since the generation of turbulent flow at this point was a major concern, the angle wasn't further increased, which would lead to more unsteady airflow around the nose.



Testing

A CFD view showed that the flow, as previously feared, entered turbulence very early on. It would separate abruptly over the sharp nose surface and become turbulent before even reaching the front wheel surfaces. Upon modifying the angle within the model, we found a correlation between the steepness of the angle of attack and the steadiness of flow beyond this mono-wing nose, and established that its design exceeded the critical angle of attack, making it ineffectual. Moreover, stress-testing also revealed excessive stress on the upper part of this wing, which had little support.



Evaluation

Stress Limit = 23.1 N
Mass = 6.4 g
Aerodynamic Drag = 0.259 N

By testing this design, we were able to establish the necessity of a non-critical angle of attack, and reinforcement to the wing, as any design we would later consider would have a slope of some kind. On further designs, we decided to :

- » Introduce a curve in the front-wing design to smoothen airflow over its surface.
- » Ensure the front-wing would be backed up by some kind of support.

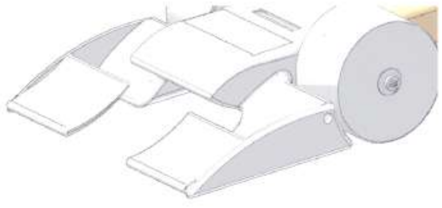
FRONT WING

IDEA 2: SPLIT BI-WING

The smooth arcs we considered going forward from the previous idea's evaluation were incorporated into a split bi-wing design, which, by splitting the front wheel, would theoretically reduce drag made at the centre of the car. The two segments would be placed directly in front of the wheels from the frontal view.

Development

We initially modelled a single curved front-wing unit, which we then proceeded to split and join to the central support. The bi-wing was connected via a plate located on the outermost edge of the car's wing. As for the curve itself, we chose a radius of 60mm on the arc of the front wing to increase the volume of air flowing over the wheels.



Testing

The results we obtained from testing were better in terms of drag and aerodynamicity, but they were unsatisfactory in terms of stress. FEA revealed a large amount of stress acting on the components connected each half of the wing to the nose cone. The design was, therefore, inherently weak, due to these thin connecting sections. While we did observe reduced flow separation in comparison to the mono-wing nose, the sheer volume of air flowing around and inside the wheel's edges created slow-moving vortices of air behind the front wheels.

Evaluation

Stress Limit = 23.1 N
Mass = 6.4 g
Aerodynamic Drag = 0.259 N

In spite of the observed issues with stress, we deemed this design a step in the correct direction from the earlier idea of having a mono-wing nose. The reduction in drag and avoidance of immediate turbulence were definite plus points, but in future designs, we would need to devise better means of connecting the wing's halves to the nose cone. Another major concern was the airflow around the wheels, and the subsequent creation of vortices. Our improvement actions would thus need to involve:

- » Means of reducing airflow past inside and outside edges of the front wheels.
- » Better connections from the wing to the nose cone.

FRONT WING

IDEA 3: JOINED WING HALVES

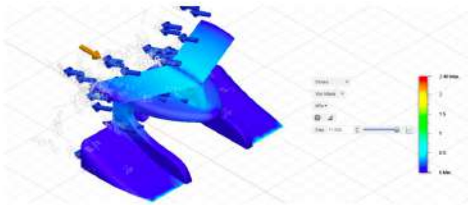
This idea stemmed from the former's issue of increased airflow around the front wheels. In order to reduce this effect, we introduced greater curvature and length into the split bi-wing design, and in an attempt to minimize thin components exposed to excess stress, the halves of the front-wing were joined with the tether placeholder in the middle, creating a direct connection going forward.

Development

We added wing halves that had single units, were more gradually curving, more supported, and connected the halves directly to the car's body, hollowing out the middle to achieve the same effect of reduced turbulence over the central part of the car. The new connection was more compact and less reliant on feeble connecting components than the previous design. The hollowing process also served to reduce the excess mass concentration at the front of the car.

Testing

Upon conducting FEA, virtual stress-testing showed a 45% improvement in impact tolerance in this portion of the car, particularly in the front. Moreover, analysis in Flow Design showed a 10% reduction in drag, the root of which we observed to be the improved airflow over the wheel.



Evaluation

Stress Limit = 19.9
Mass = 12.4 g
Aerodynamic Drag = 0.218 N

This design showed significant improvements over the ones previously considered, even after small modifications in these concepts. The idea of joining the halves of the front wing with a splitter for flow separation drastically upgraded structural integrity while capitalizing upon the airflow benefits of the previous design. The endplates helped mitigate, to a large extent, the problems arising from excess flow density near the edges of the wheel too. We honed in on this design for the final car, for its base design met our needs well.

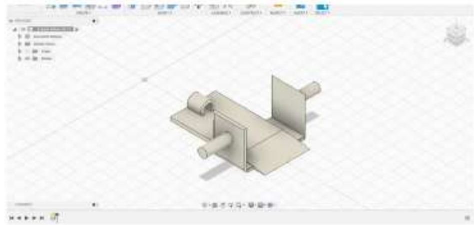
WHEEL SUPPORT SYSTEM

IDEA 1: PROTRUSIONS FROM RECTANGULAR CONNECTION

We initially had a non-rotating axle with the inner race of the bearing in contact with it. It was the motion of the outer race that facilitated in the wheel rotation.

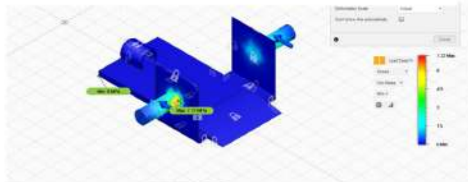
Development

This was a simplistic design, and served as the springboard for idea development pertaining to axle fabrication. We covered the lower part of the car by rectangular sections with protruding cylindrical axles. These sections weren't curved, and rather served as a means to prevent excess airflow below the car.



Testing

VWT testing on Flow Design showed a crowding of streamlines near the wheel joints, making them more prone to eddy and vortex generation. Moreover, FEA revealed increased stress on the car's sides and the axles' connections, while track testing revealed weaknesses in the wheel joints, as they tended to come off several times while testing this model.



Evaluation

This axle model failed in most respects, and apart from its ease in manufacturing, it led to increased mass, and decreased durability, with undesirable aerodynamic behaviour. This did, however, lead to the following improvement actions to consider for further development:

- » Removing external independent connections to wheels, and preferably integrating axles into the car body.
- » Choosing axle and axle integration shapes more in-tune with other aerodynamic considerations of the car.

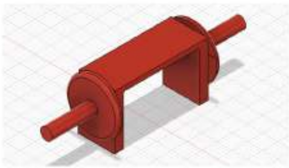
WHEEL SUPPORT SYSTEM

IDEA 2: INTEGRATED AXLE AND WHEEL SUPPORT

Our second idea eliminated the concept of having separate axles and wheel support systems entirely. The axle was, instead, incorporated into the wheel support system, which was made hollow, instead of keeping a massive, yet unnecessary rectangular block attached to the car's body. We predicted this increased structural continuity would lower the wheel detachment rate, increase smoothness, and reduce friction.

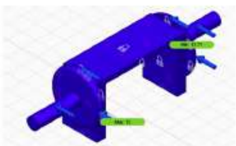
Development

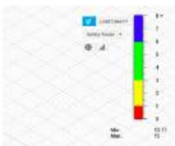
This design combined a U-shaped metallic plate with circular discs attached to its arms with axles protruding from these very discs. These formed a much smaller, lighter alternative to the previous model. Moreover, this was one 3D-printed unit instead of two attached ones, creating continuity in the design.



Testing

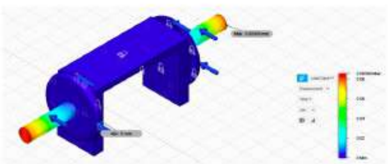
VWT testing revealed less crowding towards the front end of the car, and led to a lower risk of turbulence early in the wind's path across the car's body. This also opened up the possibility of utilizing the lower portion of the car's body to increase ground effects. FEA showed less immediate strain on these support structures, particularly because of the supporting discs, which, we predict, helped distribute pressure and reduced the risk of breakage. This also led to a significantly lower number of instances of wheel detachment during physical testing. There was also significantly less observed internal friction.





Evaluation

This design showed significant improvement over the other, and its low weight and friction, and increased continuity and structural integrity led to us adopting it in our final design.



WHEELS

For the initial wheel support structure the team had concept choices Wheels Wheels with bearings Wheels with bearings and suspensions.

Axle

We chose to use bearings without using suspensions. The structure had non-rotating axle with the inner race of the bearing in contact with it. It was the motion of the outer race that facilitated in the wheel rotation. Such a system was chosen to minimize the energy dissipated in frictional activity.

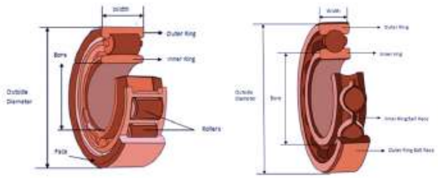
Suspensions

Suspension fitted to the front wheels must be so arranged that its response results only from changes in load applied to the front wheels, and likewise for the rear wheels. Since, the main purpose of suspensions is to absorb the imperfections causing bouncing, we decided to find a substitute instead-in form of material.

Material Composition

The wheel rim is manufactured of ABS plastic. Due to higher flexural modulus and high machinability, the material served the purpose. Furthermore, the shock-absorbing properties of the material performed the function of suspensions, as mentioned above. As a result , the requirement of a complex suspension- based structure was eliminated, reducing the mass.

Bearings



1. Structure

Ball bearings make use of hard spherical balls that can handle both radial as well as thrust loads. The load is transmitted from the outer race to balls and further to the inner race. Because the bearings are spherical, very less surface area is in contact. Since thrust is inversely proportional to area, the bearings get deformed when the load is high.

In roller bearings, the roller is, as the name suggests, cylindrical. As a result, the contact between the load and inner race is a straight line. Therefore there is a larger surface that is in contact with the load. Applying the same relation between thrust and area, we infer that roller bearings can withhold greater load.

Since our car had a very small mass, ball bearings were suitable for the purpose. Further, ball bearings can handle some misalignment of the inner and outer races. Besides reducing rotational friction, they also support radial and axial load.

2. Material Composition

We could either use fully-ceramic or hybrid ceramic (contains stainless steel) bearings. For obtaining less mass we chose upon the former.

- **Balls:** The hardened spherical balls of our ball bearings are made of silicon nitride. Since silicon nitride ball bearings are harder than metal, this reduces contact with the bearing track. This results in 80% less friction, 3 to 10 times longer lifetime, 80% higher speed, 60% less weight, the ability to operate with lubrication starvation, higher corrosion resistance and higher operating temperature, as compared to traditional metal bearings.
- **Outer surface:** This surface is made of ZrO (Zirconium Dioxide). The compound is easily polished to finer surface finishes. Further its frictional behavior is such that it provides rolling friction while minimizing the energy lost against friction

CONCEPT CARS

P1

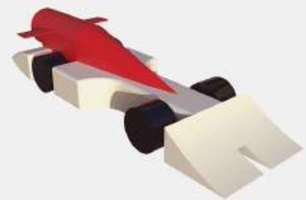
The protruding structure between the wings increased the surface area in the front. The rear end caused the air to swirl around, creating vortices which further created a low air pressure zone, thus pulling the car backwards. Therefore, the increased drag and creation of vortices hampered the speed of the car, thus slowing it down.

Inspiration: Red Bull Racing-Tag Heuer RB12

P2

Concept P2, developed as a separate experimental prototype after P1, was our first attempt at incorporating inward airflow. The design, while rudimentary, provided low drag over its main body, but the sharp edges leading into its body as well as the large surface area exposed in the side-support structures created a large increase in turbulence and skin friction. The former was more prominent given the lack of air diversion leading into the front wheels, making this design inefficient.

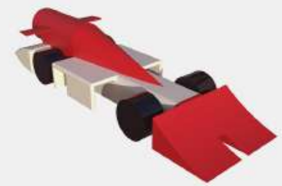
Inspiration: Red Bull Racing-Tag Heuer RB12



P3

Leading off from Concept P1, this design provided a considerable reduction in turbulence due to the proper diversion of wind over the from wheels, due to which this nosecone design was adopted for the next few prototypes. The curvature and large exposed area of the side-support structures proved problematic, as this increased drag significantly and they did not deflect the air, rather struck through it, having a great impact on the car. The height of the rear wing further increased the turbulence.

Inspiration: McLaren Mercedes MP4-29



P4

Concept P4 attempted to improve the side-support structures of P3 by diverting air more gradually through a smaller exposed curved area and reduced mass by hollowing out the actual side-supports. While the reduction of mass was certainly desirable, and hollow side-supports were adopted in later designs, this only lead to instability in P4, as the bulky nosecone led to an erratic distribution of mass and poor predicted performance. Moreover, the sharp slope from the front of the car to the CO2 canister remained a source of turbulence.

Inspiration: NACA Duct, Haack series, Maragoni effect

P5

Concept P5 introduced drastic changes in both the nosecone and the side-support structures, given the problems their combination caused in P4. We realised air diversion could work with less elevation given appropriate curvature. The side-supports were filled in and worked similarly to the previous nosecone. Moreover, the front wing was a pressure amplifier. Since the car had an inward airflow, a direct pressure was to be exerted on the wings. Reducing the area led to an inverse increase in pressure. This design led to an overall reduction in skin friction and turbulence, even though the tether guide's placement did lead to airflow concerns..

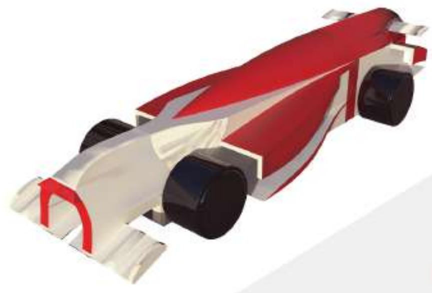
Inspiration: Red Bull Racing- Tag Heuer RB12

P6

In order to prevent the airflow issues of P5, the tether guide was placed directly underneath the car's body and the middle part of the nosecone was removed, leading to a split bi-wing structure that still provided appropriate airflow diversion. This new design, while efficient, wasn't as structurally stable as evident via FEA. Moreover, the side-support structures didn't provide ample prevention of turbulence, since the direction of curvature didn't match where air exactly passed from.

Inspiration: Red Bull Racing- Tag Heuer RB12, Maragoni Effect

CONCEPT P7
PROTOTYPE 1



Drag Coefficient: 0.316
Lift: 0.0835

REQUIRED IMPROVEMENT ACTIONS

» Investigate hollow side-supports with different orientation and curvature
» Revert to original rear-supports
» Investigate new canister-body transitions

Concept P7, though another experimental design, could also be considered the first of our four main prototypes. This is because we separated our analyses of the experimental and regular portions of our design. The hollow, inward curving side-support structures attempted not to divert the air around the rear wheels, but rather chose to direct the air into and out of the main body, playing into the inward airflow principle. The rear-support structures were kept short and compact in order to boost the mass reduction principle of this design, but the main body, with its leading edges from the CO2 chamber, remained the same.

In adjusting for errors caused by the exaggerated side-support design, we observed that while the mass-reduction due to their hollowness was advantageous, the majority of air passing along the sides of the car didn't enter the side-supports and rather flowed along its exterior, it caused massive turbulence at the rear wheels. Moreover, our separate analyses showed that there was scope for improvement in the main body, due to the skin friction at these edges and the vulnerability of the nosecone to high, potentially-damaging levels of stress. Moreover, the shortening of the rear-supports had no considerable effects, in turn decreasing stability,

CONCEPT P8
PROTOTYPE 2

Drag Coefficient: 0.2094
Lift: 0.0897 N

REQUIRED IMPROVEMENT ACTIONS

» Investigate longer front-wing design
» Increase strength of or support to connections between car body and bi-wing halves
» Investigate spoiler-like structures to place on upper front-wing to increase downforce
» Implement the above solution for the rear wing

This design provided a greater pathway for air under the car's body, entering from the front, based on the positive effects observed in the previous prototype. Experimentation with the bi-wing was attempted by first keeping similar-sized halves with a greater upward curvature, backed up by side-support structures with curved outer surfaces without the gradual slope transition of the previous design. The posterior portion of the car was integrated mechanically into the front to form a continuous unit.
While the increased continuity led to lower skin-friction and the reduction in mass due to the more hollow frontal body and the more compact side-support structures were recorded as definite positives, the compromise ideated for the split bi-wing didn't pan out, as this just logged greater stress (revealed by FEA) on each of the wings' components, and lower effectivity of the same. Furthermore, it was observed that the hollowed front may require extra downforce.

CONCEPT P9
PROTOTYPE 3

Drag Coefficient: 0.2128
Lift: 0.0921 N

REQUIRED IMPROVEMENT ACTIONS

» Reduce lift force by using raised, arrow-style front-wing spoilers (devised later)
» Modify lateral curvature of front wing halves.
» Make improvements for manufacturing considerations

Going by our improvement actions, we first focused on the bi-wing design. Concept P9 thus had more curvature and support to its bi-wing structures. A step in the opposite direction from that taken in P8, this focused on lengthening these for better structural integrity. Moreover, they were curved inwards in an attempt to reduce mass. The front of the nose cone was sleekened, and its extruding front-wing portions had a greater surface area to apply downforce. The side support structures were curved differently from the previous design to encourage streamlined flow and reduce drag near the upper part and the latter to reduce mass and keep the compactness of P9.
Testing showed that this design marked improvements in drag and airflow, barring the issue of downforce. This time, the front-wing halves worked well, but the inward curvature made them less effective in directing air away from the sides of wheels. Their effect was opposite to those of endplates, and required a change. However, the greater length and curvature lent greater mechanical support to the design, and FEA also revealed less pressure on the component. The side support structures adequately maintained streamlined flow while not adversely increasing the mass. Hollowing them out reduced mass too.

CONCEPT P10
PROTOTYPE 4

Drag Coefficient: 0.2054
Lift: 0.0792 N

FUTURE IMPROVEMENT ACTIONS

» Investigate new component designs made possible via novel manufacturing techniques
» Investigate structural stability and behaviour under different environmental conditions at World Finals.

With P10, we attempted to redesign our side-support structures to ensure they were compliant with the regulations for the World Finals. Since the change was towards the rear side of the side-supports, it didn't have a large effect on how it behaved aerodynamically, and by slightly increasing the curvature, it was possible to divert air adequately within the new regulations. The validity of this design was also observed in P8. Moreover, the lateral curvature of the split front-wing was eliminated, keeping them straight enough to ensure all air encountered linearly was passed over the front wheels. Finally, by adding an upper component to the front wing, it was possible to remain compliant to the regulations and balance the excess lift with appropriate downforce.

Through testing, we observed a much better balance between lift and downforce, especially due to the greater downforce near the front. The modified side-support structures worked as hypothesized, with their performance almost identical to the previous design, preventing the creation of vortices near the rear wheels, while maintaining low skin friction.

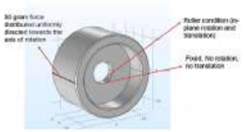
FINITE ELEMENT ANALYSIS

AIM

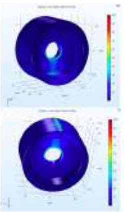
An F1 in schoolsTM car is required to survive about 50 test runs. After entering material and tensile strength of the objects along the points of application of force , the FEA had to reflect how the car would react in the worst case scenarios of deceleration to gauge the strength of car components.

WHEEL TESTING

For testing boundary conditions, tetrahedral mesh was used with quadratic shape function.

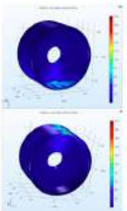


Analysis 1 - Prototype 1



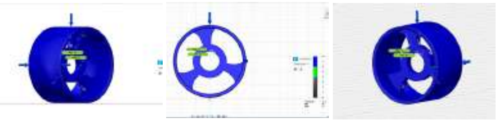
The initial wheel was thick and bulky. The stresses were too low (max ~100 kPa) and were concentrated around the area of applied force. The initial mass was 4.126g and the maximum stress was around 100KPa, that is 0.25% of Yield Stress.

Analysis 2 - Prototype 2



Decreasing the thickness of the wheel outer walls to 1.2mm reduced the mass without allowing the material to yield. The new mass was 2.508g, that is around 40% improvement. Maximum Stress was around 200KPa, about 0.5% Stress Yield.

Analysis 3 - Prototype 3



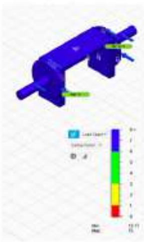
By creating wheel spokes, Maximum stress was moved from outside surface of the wheel to the inner body. It distributed force more evenly throughout the wheel. The mass obtained was 2.0296g, that is approximately 50% improvement. The increase in Stress was about 600%.

PROTOTYPE	MASS	MAXIMUM STRESS
PROTOTYPE 1	4.126g	100KPa
PROTOTYPE 2	2.508g	200KPa
PROTOTYPE 3	2.0296g	1400KPa

Prototype 3, provided the least mass, while the maximum stress was still considerably lower than the yield strength of nylon, that is, 82.75MPa. Wheels with spokes (Prototype 3) transferred the

stress to the inner side of the wheel, since the maximum stress was experieznced at the base of the spokes. Thus, possibility of deformations was reduced. As a result, Prototype 3 was chosen as the design, due to its stability and reduced mass.

WHEEL SUPPPORT STRUCTURE

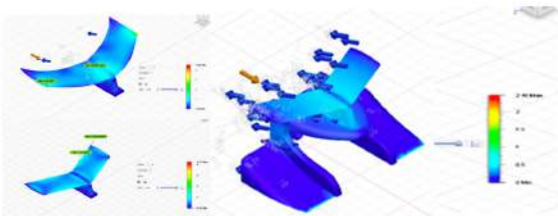


Initially, the results manifested the maximum stress at the joining of the axles and the wheel support structures, posing the threat of deformation and subsequent breaking of axle.

Improvement Action

The structure was re-modelled to transfer the stress to the area which was to be encapsulated by the wheel caps, since they would not come in direct contact with the physical surroundings. As a result, the minimum safety factor turned out to be 15, that is, much higher than the required 3.

NOSE CONE



We began by analyzing the upper wing and split bi-wing structures separately, later analyzing their composite structure. We considered two options for the upper part, one curved upwards and the other more flat. Both designs had their merits. The former led to more air flowing faster below the wing structure, which was aerodynamically favourable given consequent increase in downforce. However, this design was structurally less stable, as the extremes of the wing, due to its curvature, incurred more stress, and were prone to breakage.
The latter design, while not possessing the same aerodynamic edge, provided much more structural stability due to its even distribution of stress, and was more reliable in the long-run. The tradeoff in aerodynamicity was a relatively small one, and was negligible when the maximum possible losses– in time and in points due to potential breakage– were weighed together. Therefore, we went with the flatter design.

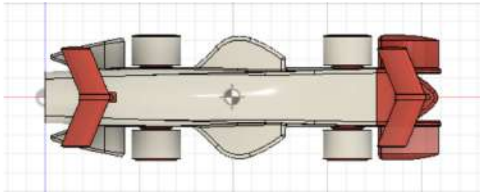
Improvement Action

More material was added to the edges making it stronger which increased our safety factor from 1.5 to 15 (determined by Fusion 360) and preventing improper airflow.

WALL THICKNESS ANALYSIS

To ensure that our car conforms the given 3mm limit for CNC, Inventor was used to map polyurethane component thickness. This analysis was particularly useful in complex areas such as connection between the car body and wheel support structures.Our wheel supports were re-designed to ensure conformance with the rule.

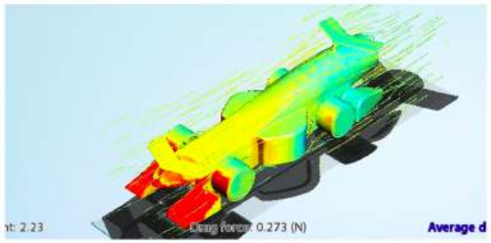
CENTRE OF GRAVITY



To reduce the effect of torque at launch, the CoG was optimised accordingly. All the different materials were appointed to the different components in the design whose density was already defined in Fusion 360. By using Fusion 360, we refined the CoG to reduce the torque at launch.

VIRTUAL WIND TUNNEL

We used Autodesk's Flow Design in order to simulate the effects of a wind tunnel in a virtual space, thereby providing a cheaper, quicker, and more efficient precursor to regular wind tunnel testing. While results obtained on a Virtual Wind Tunnel (VWT) may not accurately reflect the physical car model and the errors that arise from manufacturing intricacies, it gave an adequate idea of the car's aerodynamic behaviour. Since we considered improvements in such behaviour a large contributor to improvements in track time, VWT testing was in integral part of the design process.



Visualization

In order to get a better picture of the aerodynamic behaviour of the car at the expected speeds, we used different visualization methods to focus on different aspects of this behaviour. We used 3 methods sequentially to filter out relevant information :

- **Tufts :** Tufts were efficient visualizations for quick overviews, and helped us interpret macro-scale behaviour before going into the specifics.
- **Colour Maps :** Colour maps across different regions provided a more detailed picture of how streamline density varies along different regions of the car, thereby painting a better portrait of not only the distribution, but the intensity of flow in different designs.
- **Numerical Displays :** We referred to numerical displays when both the density and distribution in two concept designs seemed similar based on the aforementioned visual aids, comparing the the designs parameter by parameter, based on the numbers displayed.

Evaluation

In order to evaluate the results from VWT testing, we analysed the following:

Streamlines:

Density - The density of streamlines around a component was indicative of the speed of wind flowing past that area. High density regions of streamlines above the car would signify lower pressure, which we interpreted in the context of the lift generated, as potentially lower drag was counteracted by greater lift due to lower pressure.
Paths - Streamline paths could highlight the components most exposed to increased air flow before actual stress-testing. They were also used to highlight unusual patterns of airflow and find aerodynamic defects in car components.

Vortices and Turbulence : The turbulent flow obtained was considered in the context of drag generated. While vortex generators themselves tend to cause drag, they also reduce drag by preventing flow separation downstream. Therefore, any turbulence was investigated by further testing.

PRE-TESTING

CENTRE OF GRAVITY

In order to locate the correct range for positioning the centre of mass of the car, we created a custom testing rig, wherein a polyurethane block with hollowed-out slots was used in order to test the effects of different vertical and horizontal centers of mass on the overall speed of the car. By placing and shifting 1-gram lead weights within these slots, we obtained different centers and noted the time for each test run.

Hypotheses

» We theorised that in bringing the horizontal centre of mass closer to the centre of force by gradually decreasing the concentration of car mass towards the front, we affect the tipping motion of the car. This would decrease the track time by improving the canister efficiency.

» Initially, we theoretically hypothesised that by raising the vertical centre of mass, we could prevent the tripping of the car at the time of launching and reduce the race time by increasing canister efficiency.

Process

» To test the variating speed with horizontal centre of mass, we used our testing rig by appropriately placing leads in the 6 slots cut into the sides of the car body.

Test results were noted down for each position of horizontal centre of mass. A relation was drawn between the horizontal centre of mass and the track time.

» To attain the test results of effects of the vertical centre of mass, we utilised our testing rig. This had cargo containers to allow the re-positioning of the lead weights.

Test results were noted down after shifting the lead weights up and down and drawing up a relation between the positioning of the vertical centre of mass and track time that we obtained.

Results

» The testing indicated that the closer the centre of mass was to the rear axle, along the horizontal axis, the better track time we obtained. There were some incoherencies in developing a direct relation from the data obtained, however, we developed a design along the lines of the results of the test.

» The result that we attained did not confirm our initial theory. Much to our surprise, the time obtained for different positions of the vertical CoG were not tangibly different from each other. As a result, we started development on a model that did not focus as much on the vertical as on the horizontal positioning of the centre of mass.

COMPONENT PRE-TESTING

As further explained under Manufacturing, physical pre-testing, particularly manufacturing density tests, were conducted prior to the actual processes, finding the optimal density for the construction of 3D-printed components.

POST-TESTING

FLUID STREAK TESTING SETUP

We wanted to physically visualise the airflow pattern modelled around our car, to investigate the effects of turbulent airflow and check if vortices were being created. Visualization techniques could include free stream smoke, laser sheet, or surface oil flow. The assumption can made that the flow visualization medium moves exactly with the flow. Shadowgraphs or schlerin systems are used to visualize the shape and location of shock waves in compressible flows.

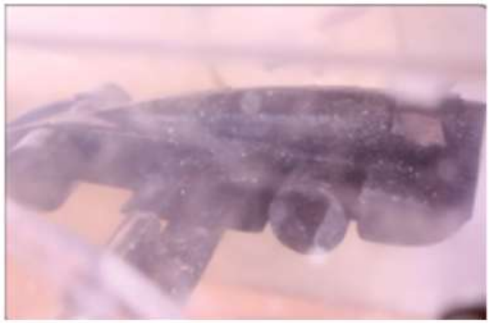
In our case, we choose low speed flows, for which tufts or surface oil were seen as the most suitable way to indicate the flow direction along the surface of a model.

Process

After painting the car black, a layer of lubrication of kerosene was applied. This was followed by the sprinkling of naphthalene powder on the oil layer. Air was passed over the set up at the speed of 10 metres per second.

Further, in order to obtain more accurate results we developed a theoretical hypothesis. While preparing the setup, we theorised that according to the venturi effect (which states that there is a reduction in fluid pressure that results when a fluid flows through a constricted section of a pipe) , if we narrowed the apparatus at certain areas, the air has to speed up to get through. So, instead of keeping the apparatus uniformly shaped all the way round, we kept the pipe wider in some places and much narrower in others. The narrower the pipe, the faster it has to go.

The path of high speed windflow would be traced by the powder spread on the black-coloured, lubricated body. In such a set up, surface oil flows will indicate the boundary of a flow separation since the oil cannot penetrate the separation boundary.



Because of the variation in skin friction caused by a laminar and a turbulent boundary layer, surface oil treated with naphthalene can be used to determine the transition point, where the boundary layer changes from laminar to turbulent, on a model. Oil downstream of the transition point will be swept away.

Results

In this experimental testing, the visualization of oil flow over the main ogive was laminar and the smooth curves created minimal turbulence.

Some eddies were formed, creating vortices as the oil flowed over the rear wing, the angle of which was chosen to achieve a favourable balance between lift and downforce.

The front wing directed the flow towards the center, increasing the pressure.

Improvement Actions

The height of the rear wing was raised, without changing the angle of placement.

The front wing was made replicating the height and angle of the rear wing to prevent the car from lifting and manipulating the direction flow.

MANUFACTURING

CNC ROUTING

The main car body, made of polyurethane foam, was manufactured using the Denford MRC 40 CNC machine which is a 3 axis machine. A common 3 axis machine can only model the block from the sides but MRC 40 CNC allows us to model the block from underneath allowing us to incorporate inward airflow in our design.

The spindle speed of the CNC router is the speed with which the spindle, also called the router, moves. A faster spindle speed reduces the time drastically but also reduces the efficiency of the cut while a slower spindle speed increases the time but ensures an accurate cut. To ensure efficiency and less time consumption, the spindle speed was set at 20. It finished our car in approximately 3 hours and any errors, if any, were removed using the sanding paper.

VR MILLING AND QUICK CAM PRO

For the CNC routing of our car, VR Milling and QuickCAM Pro was used. VR Milling is a CNC machine control software incorporating Denford PCB Manufacturing Software and 2D DXF import facilities. QuickCAM Pro is an advanced, yet simple to use, wizard based CAM package, which is used to create cutter paths for machining 3D parts on a milling machine or router.

- We used the CAD software fusion 360 for making the 3d model of our car. Fusion 360 exports a low quality STL file which ruins the quality of the car parts manufactured. We exported a custom quality STL file, modifying the refinement options such as surface deviation and maximum edge length, to make sure that we get a high quality finish of our car.
- Earlier, we used the software VR milling for the manufacturing of our car but our design was too complex to be uploaded to this software as it first had to make a mesh of the design which was difficult for it. Further, We changed the stepover in the software from 12 to 10 which ensured a better quality of the car.
- Quick CAM Pro manufactures the car by dividing it into two parts, the left half and the right half of the car. Our CNC router first cuts the right half and then the left half. This creates a ridge problem as the Left half is not always identical to the right half of the car. To overcome this problem, we used Slic3r software to codes of the main body and edited them accordingly to ensure that the above problem was removed making manufacturing the car much easier.

G AND M CODES

G-Code, standing for "geometric code", is a programming language for CNC that allows thorough control of both the machine and its attached tools. While elements starting with X, Y, and Z in each line specify position, the main functionality of G-Code is derived from its G and M codes, which enable control of the tool's motion and function, and the overall machine respectively. M codes were used for functionality pertaining to turning tools on (M03/M04) and off (M05), stopping programs (M00), enabling or disabling the flood coolant (M08/M09), etc. The usage of well known canned cycles, i.e. modal conditions incorporating all motions involved in common tasks, resembled that of programmatic functions defined in common languages, and vastly simplified processes like drilling (done by G81) and boring (commonly done by G85).

```
M109 S200 ; set temperature and wait for it to be reached
G21 ; set units to millimeters
G90 ; use absolute coordinates
M82 ; use absolute distances for extrusion
G92 E0
G1 Z0.350 F7800.000
G1 E-2.00000 F2400.00000
G92 E0
G1 X84.499 Y81.706 F7800.000
G1 E2.00000 F2400.00000
G1 F1736.99
G1 X85.879 Y80.258 E2.06187
G1 X86.130 Y80.073 E2.07154
G1 X86.967 Y79.575 E2.10166
G1 X87.793 Y79.229 E2.12938
G1 X88.371 Y79.061 E2.14800
G1 X88.923 Y78.952 E2.16540
G1 X89.310 Y78.904 E2.17748
G1 X89.926 Y78.875 E2.19654
G1 X105.731 Y78.875 E2.68558
G1 X106.214 Y78.893 E2.70053
G1 X107.183 Y79.038 E2.73086
G1 X109.321 Y79.936 E2.80261
G1 X111.003 Y81.496 E2.87357
G1 X111.956 Y83.250 E2.93536
G1 X112.243 Y84.315 E2.96949
```

3D PRINTING

ACETAL (Polyoxymethylene)

Advantages

Acetal was considered because due to higher flexural modulus and high machinability, the material served the purpose.

Why Did We Not Choose It?

Acetal has low adhesive properties. Since, the 3D printing involves layer by layer formation, the structural strength of aerofoil parts was extremely unstable. The very process of manufacturing couldn't be completed as the layer didn't stick together properly.

ABS PLASTIC

Advantages

The clear advantage ABS plastic had was its comparatively low density with respect to Acetal which significantly reduced our weight.

Why did we not choose it?

With a coefficient of friction of 0.5 and yield strength of 52.81 Mpa, ABS is one of the most highly used materials. However, it did not prove to be suitable for our use. Compared to Nylon, it has a higher coefficient of friction and lower yield strength.

ALUMINIUM

Advantages

Aluminium being malleable could be printed by moulding process, as opposed to layering in other materials, thus providing a smoother surface.

Why did we not choose it?

Aluminium posses high coefficient of friction, as compared to other materials. This frictional behaviour dissipated the pneumatic potential energy in form of less usable forms of energy, affecting the car speed.

NYLON

- Nylon has low coefficient of friction which ensured less power loss factor, allowing more conversion into kinetic energy.
- High tensile yield strength was imperative to prevent deformations.
- Even in worst case scenarios, deformations would not lead to breakage.
- Shock absorbing properties of nylon

Material	Alumunium	Polycarbonate	Nylon
Coefficient of Friction	0.4	0.31	0.15 - 0.25
Young's modulus	68.9 GPa	2.27 Gpa	2.93 Gpa
Tensile yield Strength	276 MPa	62.01 Mpa	82.73 Mpa
Poisson ratio	0.33	0.38	0.35
Density	2.7 g/cm^3	1.19 g/cm^3	1.13 g/cm^3

OTHER MANUFACTURING

COMPONENT OUTSOURCING

All our 3D parts were outsourced as the 3D printer in our possession was not able to produce parts with the accuracy we wanted. We got our parts made out of Nylon for reasons stated above, which were printed using Selective Laser Sintering(SLS). This yielded very accurate parts and no supports were required to be placed while in Fusion Deposition Modelling (FDM) printing, they are.

Further, SLS printing also has excellent layer adhesion compared to FDM. SLS printed parts have an average tensile strength of 46 MPa while FDM has 35MPa, Thus making SLS a better choice, considering we have at least twenty races to go through.

QUALITY ASSURANCE

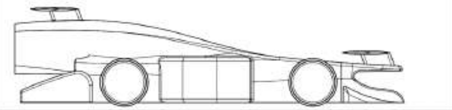
Mass Calculations

Part	Quantity	Material	Density (g/mm^3)	Volume	Expected Weight	Expected Weight	Real weight
Wheels	4	Nylon 66	0.00114	1875.651	2.13824214	12.55296856	13.5
Car Body	1	Polyurethane Foa	0.000159	1.10E+05	17.4423	17.4423	17.4
Nosecone	1	Nylon 66	0.00114	9162.995	10.4458143	10.4458143	10.4
Rear Wing	1	Nylon 66	0.00114	1363.041	1.55386674	1.55386674	1.025
Back Tether	1	Nylon 66	0.00114	194.608	0.22185312	0.22185312	0.22
Front Wheel Support	1	Nylon 66	0.00114	2891.661	3.29649354	3.29649354	2.79
Back Wheel Support	1	Nylon 66	0.00114	2738.733	3.12215562	3.12215562	3.122
						48.63545188	48.455

A major factor to keep in mind while designing the car was the mass. We took various precautions while designing the car to ensure that our mass was as low as possible, therefore we designed a spreadsheet to calculate the mass of each part. The density and volume was taken from Fusion 360. This helped us see how much margin for paint.

Progress Reports

DATE	TASK	DETAIL	TOTAL WEIGHT



To track the car's progress during the manufacturing and finishing process, we created a job card booklet for our race cars, noting down all the changes that were made. It allowed us to track the changes made to the car and to monitor how much weight each part gained.

WOODTECH POLYESTER

The block used to manufacture the car is of the material Polyurethane.

After the finishing of the car we decided to use woodtech polyester which basically helped us in three specific areas of the car:

Glass Finishing - This reduced the skin friction of the car, which would enable a smooth run on the track and also less impact on the car.

High Heat Resistance - Polyurethane adversely gets affected from sunlight giving its direct relation to the heat provided by it. Also, during the race the heat provided by the kinetic energy is also compensated by this material.

High Scratch Resistance - The scratch resistance property enabled the durability of the car for a number of races. This turned out to be highly useful during the transportation of the car and causing unnecessary scratches further increasing the friction during the car.

RUST OLEUM

We decided to use Rust Oleum at the end for two reasons -

- It gives a film thickness of 75- 100 microns in a single coat.
- It gave higher resistance to chemical solvents. This was highly useful after the manufacturing of the car. After the manufacturing of the car, its storing in various places at our school and houses and also during transportation did not hamper its quality.
- This material is highly useful in hot, humid environments. Such environments present a very humid surrounding and the presence of humidity may bring a variation in the foam hardness. Thus, use of this specific material, protects our car from humidity and moisture present in New Delhi during the Summer.

AQUADUR DENT FILTER

One of the most important aspects of the race is deceleration of the car. This further presents us with the problem, which is the impact with which the car stops, creating a possibility of dents on the car. This possibility also arises in the process of transportation. It can be applied on the interior as well as exterior of the surface. This provided extra protection to the car. It provides extraordinary toughness to the block. Both of these aspects made the car more durable. It made sure that the car runs many races and is able to withstand the impact of deceleration without much damage.

ADHESIVES

The adhesive used had to be chosen keeping in mind the various properties of this block. For polyurethane we researched that cyanoacrylates were the best adhesive to be used.

Provided that we were using thermoset polyurethane it was advised to use 'Fevikwik' which is a type of cyanoacrylate. Fevikwik provides a strong and fast adhesive nature and dries within seconds.

SANDING

The grit size of sandpaper is usually stated as a number that is inversely related to the particle size. A small number such as 20 or 40 indicates a coarse grit, while a large number such as 1500 indicates a fine grit. The lowest grit sizes range from 40 to 60. This workhorse paper, used by us, is perfect for shaping or removing a lot of material at a quick pace.

SAFETY CONSIDERATIONS

To ensure the safety of all the team members while manufacturing, latex gloves, masks and manufacturing suits were worn during the CNC routing of the car. Further, we also made sure to clean the CNC machine with a vacuum after car body to ensure that none of the foam dust was left in the machine.

MANUFACTURING PROCESS

The final manufacturing process, from assembly to decal application and wheel assembly was carried out by the process mentioned below, with each step being marked and cross-checking the results with our quality control procedures. The process can be outlined as follows:

- **Main Body Assembly:** Before going into the more detailed procedures involved in manufacturing, there was the need for a foundation upon which further additions could be made. To CNC route this foundation, i.e. the car's body, we set the spindle speed up a few notches, as the overall body itself had a lower concentration of minute bends and errors a higher spindle speed could not handle. Components, during manufacturing, were set aside on a solid platform with adhesive to keep them in place.

- **Primer Application:** Before painting, two layers of primer were added to the car's sealed and assembled body. This served as a proper base for the paint to stick on. The application of the primer was done alternately with sanding, i.e. primer application was followed by sanding to maintain shape and uniformity. The primer is the first coat to be applied. The main functions of the primer are to act as a leveler And protector, and to make the base coat easier to apply to the car. The primer serves several purposes. It serves as leveler, which is important since the car often has marks and other forms of surface defects and therefore a better final product.

- **Painting:** An initial two layer gloss was applied before the car was masked. Thereafter, a layer of Vermilion hue of rust oleum was applied in the required regions. While painting, we periodically measured the car mass to ensure we did not exceed the allocated limit.

- **Waterslide Decals:** Due to the complex printed on the decal paper, these intricate shapes could not be manually cut. We decided to use transparent decals, but due to the material, it quickly wrinkled around. We used waterslide decals which did not increase the car weight, and maintained the gloss of the car. They generally depend on dextrose corn sugar residue from the decal paper to bond the decal to the surface.

- **Wheel Assembly:** Our wheel system consists of an axle running through the center of the wheel and then connected to the wheel cover. The wheel cover keeps the wheel in a fixed position and to prevent the bearing from coming out of the wheel. A bearing cover is attached which comes around spokes and has 3 extrusions that come in front around the disk in front of the bearings

3D MODELING

» Compliance

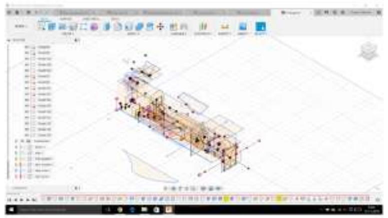
To ensure the extremely crucial compliance with the F1 in Schools technical regulations, throughout the design process, we found that merely referring to the regulations in retrospect and comparing dimensions proves inefficient; even slight errors made early in the design and modeling process render further changes useless and impossible to competently correct. The entire CAD design of the car was created in Autodesk Fusion 360. Autodesk maya was used to perceive, play around and test the model in a more fluid environment with its easy and quick to use tools.

» Attribute Sketch

All the technical regulations were translated into a dimensioned Attribute Sketch, acting as a reference as well as a check throughout the modeling process. This Attribute Sketch contained all of the different components like the virtual cargo, wheels and model block along with their dimensional ranges or limits i.e. attributes, instead of a list of bulleted points. A periodic and frequent comparison of the model being worked upon with our Attribute Sketch, it was easy to identify violations of the Technical and more importantly, the critical regulations. This whole process made it possible to model prototypes, and ultimately the final car, highly efficiently following the various guide matrices.

» Geometric Set

Prior to the actual model assembly and consolidation, we prepared a set of geometrical figures defined in accordance to the dimensions dictated by the Technical Regulations. These figures could then, during the assembly process, be efficiently duplicated and further manipulated to form different car components when not completely magnified.

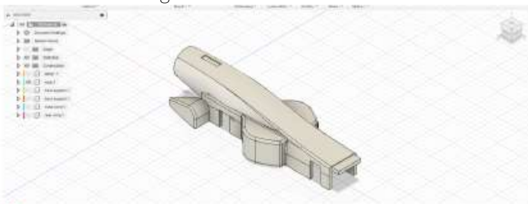


» Main Body

The main body was the most complex part of the car modelling. It is a continuous morph between a cylindrical back profile - which is to hold the CO_2 canister and a hollow cubical structure up front, which is to flow into the front wing. The method for creating this body was firstly was prototyped in Autodesk Maya using NURBS geometry - Non Uniform Rational B-Splines. Here, the main focus was shape and dynamics rather than dimensions. Extrudes, Edge-Bridges, Type-2 Smooth-Curves and Merges were the important techniques used in this stage of the model.

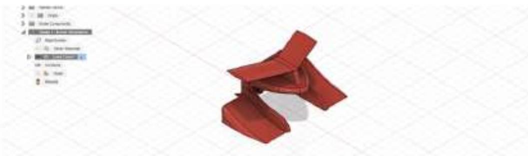
Techniques and testing done in Maya were later used to recreate the main body in Fusion 360 according to the regulations. 5 individual sketches were created on different planes, mirrored along the X-axis for symmetry. These were then connected using the lofts from one plane to another. A version of the Attribute Sketch was created where tangential bezier-curves and 3-point curves were created to formulate the mesh into the required dynamic shape following the testing results. Another mesh was created in order to hollow out the body for the inward airflow, modelled along the same lines. A difference boolean gave the final shape to the main body.

More dynamic sketches for the side support structures were created using Point Arc and Spline Curves and either extruded outwards or lofted to create more complicated structures. After a Join or Combine body, the final mesh for the car. After matching every regulation with this mesh, it was exported as a fbx file to Maya to identify bad geometry. This followed more testing and editing afterwards each sharp edge was filleted in order to remove enclosures of air traps and give the mesh a smooth look and form. It was now a single body, that could be manufactured in one go.



» Nose Cone

Creating the nose cone was tricky and had to be visualised in hand drafted 2 dimensions first. These images were used as references in Maya where once again, NURBS were used to create the test mesh. A more complex body was created with Edge Loops and Curve Geometry. This new digital mesh was used as a reference in Fusion 360 to create the final mesh. Sketches were created in the sketch environment by the simultaneous use of the 3-point arc tool, the line tool and the spline tool. These were then extruded or cut from the body. Afterwards, the edges were rounded using the fillet tool. The bottom wing was created in the sculpt environment to ensure smoothness and consistency. This was then combined with the nose cone body. The front wing on top of the body was created using extrusions of sketches. Using the angle and arc tools, this wing was also rounded and then attached to the rest of the nose cone. A plane was constructed the the nose cone was split from the main body using the split body tool. And attachment mechanism was created, by extruding out a rectangular sketch and a combination of splitting and combining.



» Back Wing

The back wing was created in a similar manner to the front wing, the wing was first sketched and using the arc and rotation tools on different construction planes where the profiles were angled to extreme detail, modelled and then rounded using the fillet tool. A curved rectangular body was created and used to split a part of the main body which would be used to attach the wing. This was done in order to maintain the curvature of the body and allow room around the CO_2 canister.

FINAL CAR DESIGN

The previously mentioned concept P10, a result of months of designing, manufacturing, and documentation, is the car we have chosen to represent Team Matadors at the 2019 World Finals. The design itself incorporates key ideas and elements we had gradually tightened our grasp on during the design development process. This includes hollow interior elements like side-support structures, the incorporation of inward airflow, and an incessant consideration for the principles and goals initially established, keeping in mind the scientific effects that would help us achieve them.

In accordance with the 2019 F1 in SchoolsTM World Finals Technical Regulations, ensuring a minimum gap of 0.1mm to ensure any minor manufacturing errors do not lead to violations in critical regulations. Testing via FEA, and cross-checking with the calculations on our own spreadsheets, we ensured top-grade structural integrity and stress-tolerance beyond that required.

The formerly mentioned salient features of our design, paired with the axle-support system integration unique to our vision, ensured a high degree of continuity, integrity, and smoothness. This consequently resulted in immense ease of assembly and durability during transportation, as well as adaptability to moderately different weather conditions. The design provided 22% less drag and 38% less lift than our 2018 World Finals car, with far easier manufacturing.

Beyond providing a sleek, effective car for our actual scrutineering and races, the final design further demonstrated several of our hypotheses and observations from R&D towards the earlier stages. In particular, this meant successfully focusing the horizontal center of mass backwards and the vertical center of mass upwards correlating with higher speeds, among others. With observations like these, the car shall also serve as a point of learning and research for Team Matadors beyond the World Finals.

	Drag (N)	Lift (N)
World Finals 2018	0.2334	0.1277
Indian Nationals 2019	0.2054	0.0792

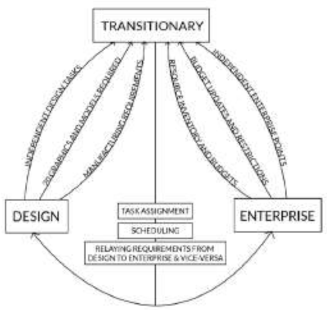
DESIGN PROCESS EVALUATION

DESIGN PROCESS DEVELOPMENT

Initially, our design process was far less structured than what we would've liked it to be. It involved more experimentation in terms of working groups and observation of how teamwork dynamics worked out with the three new members and the new role of Systems and Design Analyst. This meant that initial delays in testing and differences in opinion pertaining to evaluation disturbed the design process in the first two weeks of the competition.

Once the members' roles in the team were fully realized and the design engineers were in tune with each others' workflows, the team observed an improvement in terms of both rate and quality in the design process.

After the initial snag in the design process, the our evaluation became more methodical. At the end of each weekly progress check, the Team Manager and Systems and Design Analyst would recap the mechanics of the design process, and based on the Systems and Design Analyst's observations and notes, they would potentially schedule special design meets to modify the design evaluation process.



Criteria (Preference)	Interpretation (If preference not met)	Action
Number of missed deadlines over 5-day periods (Low)	- Decrease in efficiency of design methods - Workflow incongruities among design engineers	- Review of design methods; contacting mentors or using collaborators - Discussion among design team; reallocation of labour or compromise
Frequency of regulation violations in models (Low)	- Inconsistencies in modelling restraints and reference sketches - Imprecise / hurried / inefficient modelling techniques	- Reference sketch reviewed and corrected according to regulations - Restraints modified programmatically - Graphic and Design Engineer given more time per task temporarily; asked to use alternate modelling tools and techniques
Manufacturing Efficiency (High)	- Incorrect constraints or programming for CNC routing - Inappropriate materials used for the processes employed - Designs not conducive to efficient manufacturing	- G and M codes reevaluated and numbers changed sequentially when small changes required - Spindle speed increased when unwanted details found in the physical models and decreased when low precision observed - Used material compared with other researched (and available) materials - Design features like slots incorporated to simplify manufacturing and assembly
Used Design Criteria (Discussed, Agreed Upon)	- Inadequacy of our own design criteria - Negligence towards discussed criteria and practices	- Discussion on and evaluation of external design criteria. If found to be relevant and useful, incorporated into our list of criteria - Design team meeting, reinforcement of used criteria, and conversation between Team Manager and violator.
Physical Testing Frequency (High, regular)	- Non-availability of required testing materials and locations - Lack of prepared testing methods	- Alternate materials / equipment investigated and used; possibility of creating setups to eliminate special location requirements considered - New testing methods researched and implemented

COMPLIANCE PRECAUTIONS

To ensure compliance with F1 in Schools Technical Regulations throughout the design process, we found that merely referring to the regulations in retrospect and comparing dimensions proves inefficient and errors made early in the design process render further changes useless. Therefore, we devised a set of measures to ensure the maintenance of compliance prior to and during the design process :

» **Reference Sketch:** The technical regulations were translated into a dimensioned reference sketch containing the different components and the ranges for their dimensions instead of a list of bulleted notes. By periodically comparing the model being worked on to said reference sketch, it was easy to see where there were violations in dimensions, among other things. The sketch also highlighted rule requirements like virtual cargo.

» **Geometrical Set:** Prior to the actual process of model assembly and consolidation, we prepared a set of geometrical figures defined in accordance with the dimensions dictated by the Technical Regulations. These figures could then, during the process, be efficiently duplicated and further manipulated to form different car components when not completely magnified.

TIMELINE

Listed below is a timeline of major design process evaluation points and subsequent improvement actions for our World Finals:

Week 2
Establishment of roles in testing and documentation as well as workflow integration effectively complete.

Week 5
Integration of spreadsheet-based mathematical model into the working process complete, and use in conjunction with virtual testing initiated.

Week 10
Independent research on the effects of turbulence revealing its interaction with drag, along with pressure, led to a change in design criteria and process– drag would now be interpreted in the context of turbulence instead of independently, and the role of turbulence in stress would now be evaluated on a case-by-case basis.

Week 16
In-kind sponsorships and increased access to resources due to led to more frequent and more effective physical testing, allowing us to begin finalizing on certain design components

Week 22
The emphasis on brainstorming and experimentation reduced, and was redirected towards honing the design we chose as the basis for our final car. Design Engineers focused on testing and manufacturing accommodations.