Team VITESSE

Design & Engineering Portfolio

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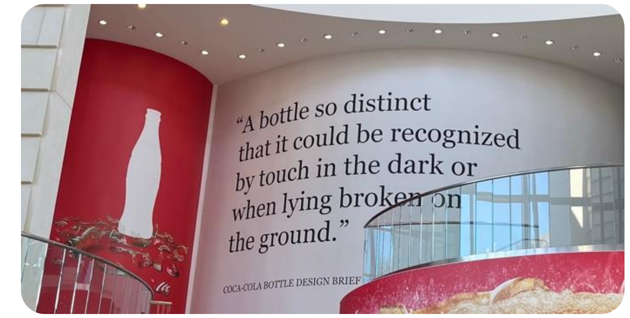
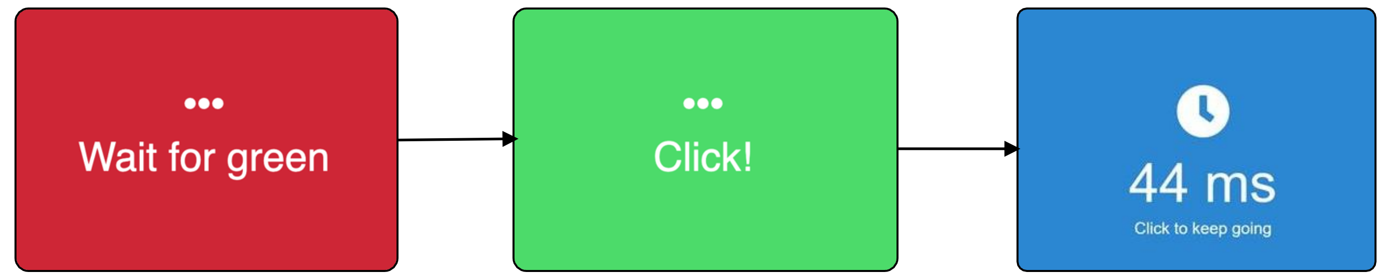
Introduction



"A bottle so distinct that it could be recognized by touch in the dark or when lying broken on the ground." This was kept in mind when designing the Coca-Cola bottle. When we were creating our team's identity, we wanted it to be extremely unique. The shape of the hammerhead inspired our car, thus the name. Our team name, 'Vitesse' which is French for speed, represents our goal, which is to be the fastest in the competition. Our color theme, which is matte black and a glossy dark purple shows power, confidence and elegance. We believe that our team identity is distinct enough, but we'll let you be the judge of that (pun intended). This competition has been a rollercoaster, with many highs and even more lows and I feel like it's taught us a valuable lesson about life- 'Nothing ever goes the way you expected it to, and sometimes, that's a good thing. '

Our Team Members

Lakshya Agarwal: *Design Engineer, CFD Analyst*
Ayan Sur: *Research & Development Manager, Design Consultant*
Aarav Sareen: *Enterprise Portfolio Manager, Co-Sponsorship Manager*
Ryaan Verma: *Project Management Portfolio Manager, Sponsorship Manager*
Suraj Gupta: *Design & Engineering Portfolio Manager , Co-Research & Development Manager*



Reaction Time

To determine who had the fastest reaction time for the race launch, we conducted a reaction time test among our team members. The highest score was achieved by Ryaan, with an impressive reaction time of 44 milliseconds. The test was carried out using the website https://humanbenchmark.com/tests/reactiontime, and the team's average reaction time was approximately 230 milliseconds.

We conducted a test using different drinks to determine which one would yield the best reaction time. The drinks tested included plain water, Gatorade, cold coffee, and Red Bull. We also included a control condition with no drink at all. The test was carried out using the Human Benchmark reaction time test, and results were plotted in Excel to visualise the outcomes. To ensure consistency, we waited around one minute after each drink before starting the test to allow for absorption, and we made sure to consume roughly the same quantity of each beverage. Interestingly, water resulted in the best average reaction time across the group, while drinks containing caffeine, particularly cold coffee and Red Bull, tended to cause more false starts, possibly due to overstimulation. These findings were surprising, as we initially expected caffeine to enhance performance. This experiment highlighted how overconsumption of stimulants can negatively affect fine motor control and timing, which are both crucial during a race launch. It also emphasised the importance of testing assumptions with real data.

Fig 1.1; All drinks used in the experiment, 1) Water 2) Nescafé Coffee 3) Gatorade 4) Redbull

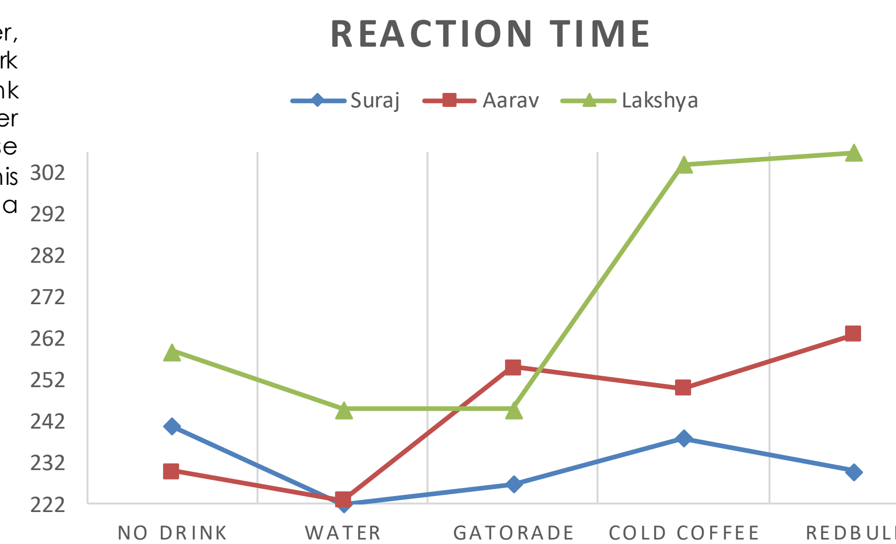
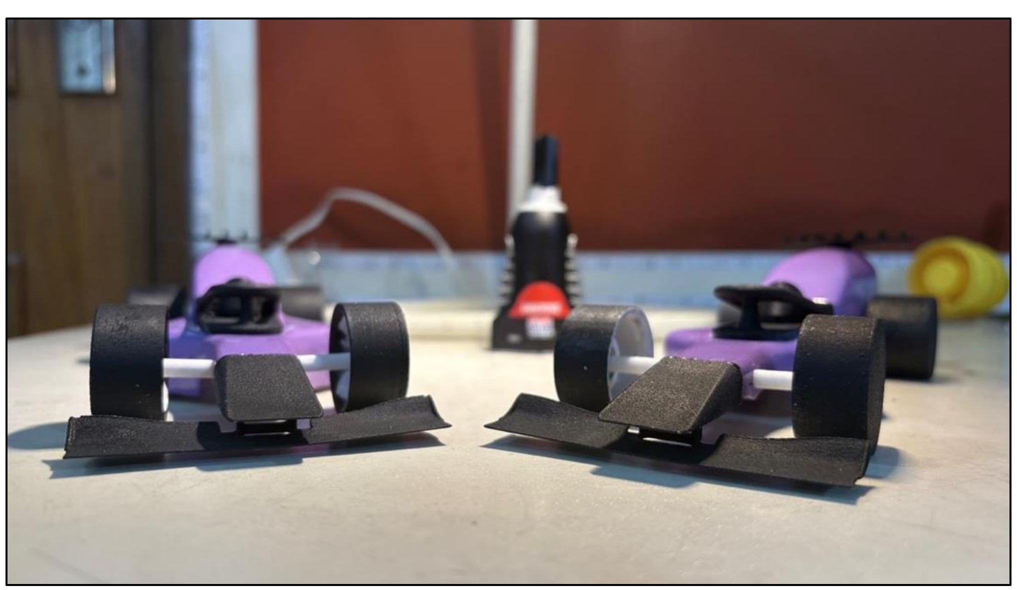
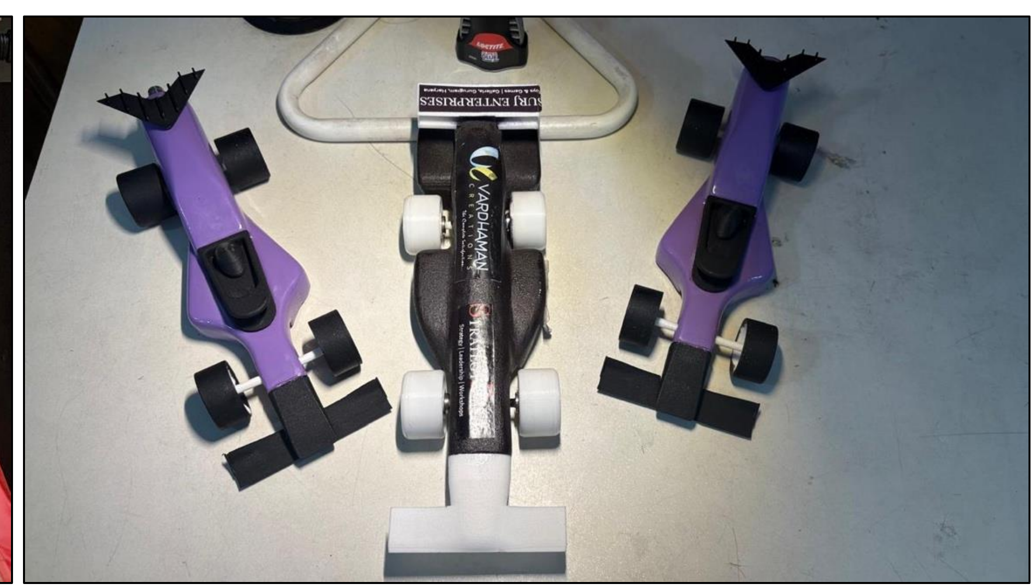


Fig 1.2; Results of the experiment





Forces Acting On Our Moving Car

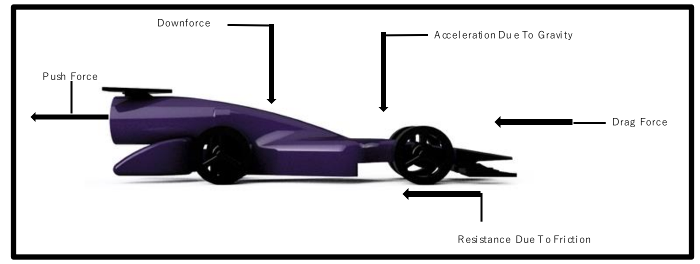


Fig. 2.1 Forces Acting On The Car

Assisting Forces and Opposing Forces

The 5 main forces acting on the car, as shown in Fig. 2.1, are as follows: Downforce, which is the force with which the car is pushed down, the Drag Force, which is the force of resistance acting on the car while it moves across the 20m track, Frictional Force, or Resistance Due To Friction which is the force of resistance acting on the wheels of the car when it's moving at high speeds, Push Force, which is the force exerted by the canister with which the car is pushed forward, and finally, Gravitational Force, or Acceleration Due To Gravity which is the force acting on the car by the Earth as it is pulled towards the center of the Earth. ***The Opposing Forces that are slowing down the car are the Drag Force, and the Resistance Due To Friction. The Assisting Forces are the Push Force, the Downforce, and the Gravitational Force. These help the car push forward and stay on the ground.***

Acceleration Due To Gravity or Gravitational Force

Gravity is a fundamental force of nature that causes mutual attraction between objects with mass leading to acceleration, which is why it's represented in m/s^2. Force of gravity or F_g is given by $G\frac{m_1m_2}{r^2}$ where G is the gravitational constant which is approximately $6.7 \times 10^{-11}\,\mathrm{N} \cdot m^2 \cdot kg^2$, where m_1, m_2 are the masses of the 2 objects and r is the distance between them. Acceleration due to gravity on the Earth's surface is approximately $9.8\,m\,s^{-2}$. This means that the velocity of any object that's falling from a certain height on to the Earth's surface will increase by $9.8\,m\,s^{-1}$ every second until it reaches its terminal velocity. Terminal velocity is the maximum speed an object can reach when falling through a fluid.

$v_t = \sqrt{\frac{2mg}{AC_d\rho}}$, where v_t is terminal velocity, m is the mass of the object, g is acceleration due to gravity, C_d is the drag coefficient of the object, A is the cross-sectional area of the object and ρ is the density of the fluid.

To find the force of attraction between the car and the Earth, we need to use the formula $G\frac{m_1m_2}{r^2}$.

The distance between the Earth's center and the car on the track would be the radius of the Earth.

Since the magnitude the car's elevation is negligible, we can use the Earth's radius which is $6378km = 6.378 \times 10^6\,m$.

The mass of the Earth is $5.92 \times 10^{24}\,kg$ and the mass of the car is $70g = 0.07kg = 7 \times 10^{-2}\,kg$, and the gravitational constant = approximately $6.7 \times 10^{-11}\,\mathrm{N} \cdot m^2 \cdot kg^2$

$$\rightarrow F_G = \frac{(6.7 \times 10^{-11})(5.92 \times 10^{24})(7 \times 10^{-2})}{(6.378 \times 10^6)^2} = \frac{(6.7 \times 5.92 \times 7)(10^{-11} \times 10^{24} \times 10^{-2})}{6.378^2 \times 10^{12}} \approx \frac{277 \times 10^{11-12}}{40} = 6.925 \div 10$$
$$\approx 0.7N \approx 0.07\,kgf$$

An object of mass 70 grams will have a weight of 70 gram force or 0.07 kilogram force. Since that's what we calculated, we can conclude that the force with which the car attracted to the earth is 0.7N

Velocity of the Car

The velocity of the car changes drastically throughout the race. Initially, many factors affect the velocity of the car. Every millisecond, the canister filled with carbon dioxide applies a different magnitude of force on the car which causes the car's velocity to vary.

The force exerted by the canister on the car depends on many parameters, like pressure inside the canister (reaching 60 bar), exit velocity and mass flow rate; since,
$\boldsymbol{F \propto \dot{m}, F \propto v_e \because F = \dot{m}v_e}$ (Force exerted by the canister = mass flow rate multiplied by the exit velocity). This formula doesn't account for various inaccuracies, though.

The pressure inside the canister stays constant until the liquid carbon dioxide runs out. The level of liquid in the canister constantly reduces and the empty space is filled with vapor carbon dioxide. The vapor keeps the pressure constant. Once the liquid runs out, the vapor exits from the canister, this whole process constantly changing the velocity of the car.

To find average velocity of the car, we need to know the velocity of the car throughout the race. Note that each of these datapoints has to be recorded in equal intervals of time. Let's say that n observations were recorded during the race and the magnitude of the velocity at each of these intervals of time would be x_1, x_2, x_3 all the way up to x_n, we could calculate the average velocity ($\bar{v}$ or v_{avg}) by adding the magnitudes of the velocities of the car at each of those points, then dividing the sum by the number of observations.

$$\bar{v} = \frac{x_1 + x_2 + x_3 + \ldots + x_n}{n} = \sum_{i=1}^{n} x_i \times \frac{1}{n}$$

Each of these datapoints have to have the same, extremely short interval of time. Finding the velocity of an object at a given instant in time, extremely close to 0 is known as instantaneous velocity. Instantaneous velocity can be approximated using a limit.

$$v_{instantaneous} = \lim_{\Delta t \to 0} \frac{\Delta s}{\Delta t}$$

This means that the instantaneous velocity of the car (velocity of a car at a giver point in time) is change in distance over change in time. The reason that limit is used here is that we want time to approach 0.

Fig. 2.2; Carbon Dioxide Cartridge

Push Force

The car has a slot behind it for a canister filled with carbon dioxide. This canister usually has carbon dioxide stored at high pressure inside. During the start of the race, the canister's nozzle is punctured and the gas rushes out, pushing the car with an equivalent force. The assumed mass of the car is the minimum, based on the 50g regulation and the mass of the canister which is 22g, 70g is an approximation taken for simplicity.

Concepts used in calculating the force with which the car is pushed in the start

The pressure inside the canister is extremely high, around 58 bar at 21 degrees centigrade. The total mass of carbon dioxide inside the canister at the start of the race is 8 grams. The diameter of the nozzle is around 1mm, therefore the radius of the nozzle through which the gas escapes is around 0.5mm. The estimated exit velocity of the canister over 0.3 seconds is around 150 meters per second. Let's, for the sake of this calculation, assume that the carbon dioxide has the same exit velocity throughout the estimated 0.3 seconds span of it releasing the gas. This does not take into account pressure difference or choked flow, or gas expansion.

$F = \dot{m}v_e \quad \ldots(\mathrm{I})$

where F is the force with which the car is pushed, $\dot{m}$ is the mass flow rate and v_e is the exit velocity of the gas.

$\dot{m} = \frac{m\,(kg)}{t\,(s)} = \frac{0.008kg}{0.3s} \approx 0.03\,kg/s$

For these calculations, the average exit velocity will be used to
Substituting the values in eq. I:
$F = 0.03 \times 150 \approx 4.5N$ which means that the car is initially pushed with a force of 4.5 newton.

$Impulse = Ft = mat = m(v-u) = m\Delta v$
$\rightarrow m\Delta v = Ft \rightarrow \Delta v = \frac{Ft}{m}$
$F = 4.5N, t = 0.3s, m \approx 70g = 0.07kg$
$\rightarrow \Delta v = \frac{4.5 \times 0.3}{0.07} \approx 20\,m/s$

This means that the velocity of the car after 0.3 seconds is around 20 meters per second, assuming that the weight of the car with the canister attached in the start of the race is 70 grams (0.07 kilograms)

The canister runs out of gas after 0.3 seconds, this means that the maximum velocity of the car is 20 meters per second, which the car reaches after 0.3 seconds. To find the point on the 20m track at which the car reaches its maximum velocity, we use the 3rd equation of motion:

$v^2 = u^2 + 2as$
To use this equation, we need to find acceleration
$a = \frac{\Delta v}{\Delta t} = \frac{v-u}{t}$
The initial velocity is 0 meters per second, and the final velocity is approximately 20 meters per second
$\rightarrow a = \frac{20-0}{0.3} \approx 66\,m\,s^{-2}$
The car is accelerating at 66 meters per second per second.
We can then re-arrange the 3rd equation of motion to find displacement (distance)

$$s = \frac{v^2 - u^2}{2a} \rightarrow s = \frac{20^2 - 0^2}{2 \times 66} = \frac{400}{132} \approx 3m$$

This means that the car reaches its maximum velocity (20 meters per second) after 3 meters (because the canister runs out of gas in 3 meters) and then slowly decelerates. Assuming that the car completes the race in 1s (our goal), we can find the final speed of the car and its retardation.

Using the 1st equation of motion; $v = u + at$, we can find the final velocity of the car after it completes the 20m track. So, we have to first find retardation, which is essentially negative acceleration. Using the 2nd equation of motion; $s = ut + \frac{1}{2}at^2$, we can find the acceleration. One thing to keep in mind is, if we're finding deceleration, then the equation becomes ; $s = ut - \frac{1}{2}at^2$
Re-arranging the equation:

$$s - ut = -\frac{1}{2}at^2 \rightarrow 2s - 2ut = -at^2 \rightarrow \frac{2(s-ut)}{t^2} = -a$$

Let $t = 1$, since that's our goal for the competition this time. Since we're taking initial velocity as 20 meters per second, we'll take the length of the track as 17m, since the value of 20 meters per second only applies if we take 3m from the starting point as the actual starting point of the car. With that logic, time also becomes 0.7 seconds. Substituting the values in the equation, we get:

$-a = \frac{2(17 - 20 \times 0.7)}{0.7^2} = \frac{2(3)}{0.49} \approx 12m\,s^{-2}$ which means that deceleration in this case would be 12 meters per second per second.

Substituting these values:
$v = 20 + (-12)(0.7) \rightarrow v = 20 - 8.4 = 11.6\,m/s$ and this means that the velocity of the car at the end of the race would be 11.6 m/s

***Note that most of these calculations do not account for many factors that may speed up or slow down the car. Most of these values are used for the sake of simplicity and purely for conceptual understanding. Do not consider these values as accurate.**

Forces Acting On Our Moving Car

Drag Force

After the initial acceleration of the car, certain forces come into play that slowly decelerate the car. As in our calculations, we can see that the car will have decelerated by a considerable amount after the race is completed. According to newton's 1st law of motion, an object continues to stay in motion until a net external force is applied to it. In this case, the net external force that's acting on the car is drag force, along with frictional force.

Inertia

The tendency of an object to stay at rest or in motion until a net external force is applied to it is called inertia (I). Numerically, $I = m$ of the car. This means, the lesser the mass, the lesser the inertia. We can therefore say that inertia is directly proportional to the mass of an object. Lesser inertia is better, since lesser force is required to push an object to a certain speed, and thus lesser force is required to stop the object or decelerate the object to a certain speed. This means that if mass of an object is lesser, lesser force will be required to accelerate the object. This also means that an object will accelerate more with the same amount of force.

$F_D = \frac{1}{2}C_d A v^2 \rho$ where F_D is drag force, C_d is drag coefficient, A is the frontal area of the car, and v is the velocity at a given point in time.

The deceleration calculated before would be very off, since there are many factors based on drag itself that would slow the car down. Firstly, since velocity is a part of the drag force formula, every millisecond the velocity decreases, drag force also decreases, which means that the amount by which velocity decreases also decreases. To solve for final velocity numerically, one would have to calculate rate of change of deceleration i.e. *jerk* and use calculus. I won't be getting into that, so I'll use a python script to calculate the final velocity of the car. Since $a = \frac{F_D}{m}$ where a is deceleration, the script will find deceleration for every 1/100th of a second and calculate the velocity in each of those times. It will also plot a graph of the car's velocity. The acceleration due to the canister was also inaccurately calculated, but to calculate it with precision, we'd have to dive deeper into the kinetic theory of gases, which is a huge concept. Therefore, we will stick with linear increase in velocity for the start. These values will still not be particularly accurate, since the calculations for initial velocity of the car and the canister propulsion aren't accurate. By putting the drag coefficient as 0.508, the code predicted that our racetime would be 1.1731 seconds, having a final velocity of 16.9 meters per second.

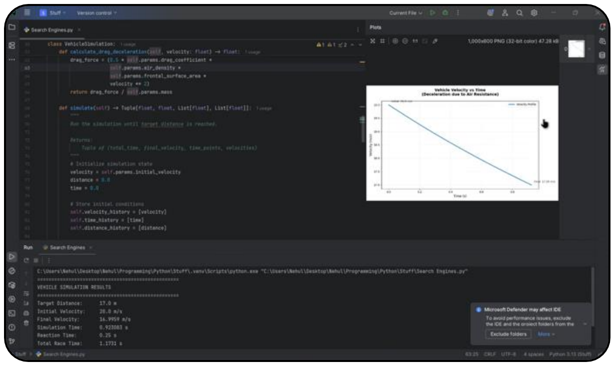


Fig. 3.1; Screenshot of the code

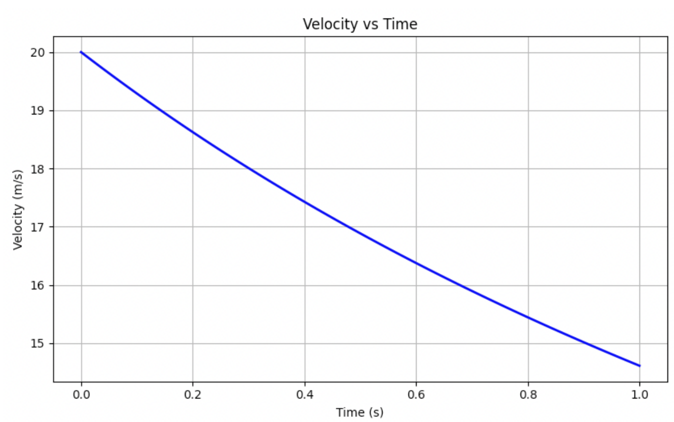


Fig. 3.2; Velocity-time graph showing the deceleration of the car

Flow Separation and Wake

Flow separation is one of the primary causes of aerodynamic drag in a car, particularly in vehicles designed for drag racing, where high speeds exacerbate its effects. It happens when the airflow can no longer stay attached to the surface of the car due to sharp edges, sudden ridges, or abrupt changes in shape. When this occurs, the smooth flow of air becomes turbulent, leading to increased pressure drag. To address this, we ensured our car body was as smooth and streamlined as possible. We carefully avoided any sharp transitions or unnecessary bumps that could disturb the airflow. Smooth curves and gradual slopes were used to encourage the air to stay attached to the surface for longer. Flow separation can be clearly observed in CFD simulations, where the airflow detaches from the surface, creating turbulent regions. One prominent form of separation is the wake that forms at the back of the car. This occurs when the car's rear end ends too suddenly, causing the airflow to break off rather than follow the body smoothly. By refining the rear shape and avoiding abrupt slopes, we reduced the size of the wake and the associated drag. This design choice contributes significantly to improving the aerodynamic performance and speed of the car.

***Note that most of these calculations do not account for many factors that may speed up or slow down the car. Most of these values are used for the sake of simplicity and purely for conceptual understanding. Do not consider these values as accurate.**

Downforce

This is the force that actually keeps the car on the ground. Certain physics concepts lead to downforce in a car. The main one is Bernoulli's principle. It states that the amount of pressure in an area is inversely proportional to the speed of the fluid in that same area, i.e. *the pressure decreases as the speed of the fluid increases and vice versa*. To apply that to our car, we need to observe the speed of the fluid in different parts of the car. Taking a look at the chassis, the speed of fluid is higher there than over the car. This means there should be less pressure under the car. Fluids tend to move from higher-pressure areas to lower-pressure areas. This means that the air over the top of the car will try to get under the car, and therefore push down on the car, creating downforce. The Venturi Effect is the phenomenon where a fluid's speed increases as it flows through a constricted section of a pipe, causing a corresponding pressure drop. This occurs due to the conservation of mass and energy in a streamline flow.

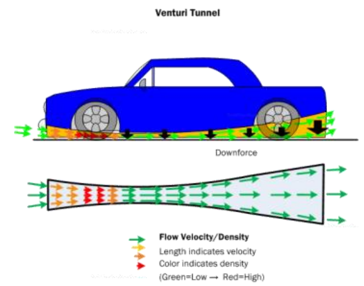


Fig. 3.3; Venturi Effect applied to cars

Downforce has a very similar formula to drag force. But, lift coefficient replaces drag coefficient.

$F_L = \frac{1}{2}C_L A v^2 \rho$ where F_L is lift force, C_L is lift coefficient, A is the frontal area of the car, and v is the velocity at a given point in time.

The lift on the car at 20m/s velocity is approximately -0.032 newton (because the force is in the downward direction). To find downforce coefficient, we need to rearrange the equation and substitute the values.

$$F_L = \frac{1}{2}C_L A v^2 \rho, \rightarrow \frac{2F_L}{Av^2\rho} = C_L$$

$$F_L = -0.032N, A = 15\ cm^2 = 0.0015\ m^2, v = 20\ ms^{-1}, \rho = 1.225\ kg\ m^{-3}$$

$$\rightarrow C_L = \frac{2 \times -0.032}{0.0015 \times 20^2 \times 1.225} = -\frac{0.064}{0.735} \approx -0.09$$

This means that the approximate downforce coefficient for our car is around 0.09 which is really good. It's negative because downforce acts downwards, and upwards is considered positive but downwards is considered negative.

Now, the risk of the car lifting off the ground is quite low but still eminent. To clear doubts, the speed at which the car lifts off the ground can be calculated using the previously defined values.

$$F_L = \frac{1}{2}C_L A v^2 \rho, \rightarrow \frac{2F_L}{C_L A\rho} = v^2 \rightarrow v = \sqrt{\frac{2F_L}{|C_L|A\rho}}$$

Now, for the car to lift off the ground, even by a millimeter, it has to overcome the force the car has on the ground.

$$F = ma, m = 0.07\ kg, a = g \approx 9.8\ m\ s^{-2} \rightarrow F = 0.07 * 9.8 = 0.686N$$

$$\rightarrow F_L = 0.686N, A = 15\ cm^2 = 0.0015\ m^2, C_L = -0.09, \rho = 1.225\ kg\ m^{-3}$$

$$\rightarrow v = \sqrt{\frac{2 \times 0.686}{0.0015 \times 1.225 \times |-0.09|}} = \sqrt{\frac{1.372}{0.0015 \times 1.225 \times |-0.09|}} \approx \sqrt{8.588} \approx 93\ m/s$$

This means that the car will have to acquire a speed of 93 meters per second before it even remotely lifts off the ground.

The need for downforce and its adverse impacts on the car's speed

Even though downforce is one of the most important forces for a race car, having too much of it isn't always a good thing, especially in a straight-line drag race like F1 in Schools. Let's take a simple example: imagine our F1 in Schools car is a small toy car. If we push it down with our finger and then try to push it forward, it becomes harder to move. That's because the extra force pressing it down increasesthe friction between the wheels and the ground, which slows it down. In real F1 racing, downforce is essential during high-speed cornering, it helps the car grip the track and stay stable while turning. But in F1 in Schools, the race is a straight sprint, with no corners at all. So we don'tneed much downforce—just enough to keep the car stable and prevent it from lifting off due to air pressure or uneven weight distribution. Too much downforce in this context only adds unnecessary drag and can slow the car down. The key is finding the right balance: just enough downforce for stability, without compromising speed.

Drag to Downforce ratio

Drag force and downforce are 2 of the most important forces that affect a car. There is usually a golden ratio for drag to downforce which allows for the most efficient drag race. Aerodynamic efficiency is the ratio of the drag force to the downforce of a car. Let η_a be defined as aerodynamic efficiency.

$$\eta_a = \frac{F_D}{F_L} = \frac{\frac{1}{2}C_d A v^2 \rho}{\frac{1}{2}C_l A v^2 \rho} = \frac{C_d}{C_l}$$

Frictional Force

Even though downforce is one of the most important forces that a car needs to have, too much downforce isn't a good thing either.

Let's assume that our car is a small toy car. If we push the car down with our finger, then it'll be harder for the car to speed up, since the force of the car on the ground increases with more downforce. Primarily, in F1 cars, downforce is required to maintain stability during turns. But, this is a drag race, which means that the track is completely straight. The car won't need much downforce, just enough to stay on the ground. The friction coefficient is denoted by μ.

To avoid sliding in the start of the race:

$\mu > \frac{a}{g}$,

where a is the acceleration of the car in the given timestamp we need to check.

Main Scientific Principles that apply to the Car

The concept of air being a fluid

A fluid comprises molecules of matter which are free to move about. The 3 states of matter *i.e. Solid, Liquid and Gas* have different ranges of the possible motion of the molecules in them. Fluidity is a term used to define the ability of a substance to flow. Molecules in a solid are tightly packed together and hence cannot move freely. The molecules in a liquid are less tightly packed together, but enough to keep the liquid as a body which does not disperse into the environment, whereas the molecules in air are extremely loosely packed together and the *intermolecular force* isn't strong enough to hold them together. Fluid refers to any form of matter with free-moving molecules, including both liquids and gases. Since air has these properties, it is also considered a fluid. The study of how objects move through a fluid is called fluid dynamics. To analyse motion within a fluid, principles like Bernoulli's theorem and conservation laws are used. The process of computing values such as air velocity, pressure distribution, and turbulence using numerical methods is called Computational Fluid Dynamics (CFD).

Newton's Second Law

The second law states that force is proportional to the rate of change of momentum of a body. Momentum *i.e.* $p = mv$ is the product of the mass and velocity of a body. It is the quantity of the amount of motion a body has. Momentum is a vector quantity, that means it has direction. For that reason, momentum is given as $\vec{p}$ since that is the symbol that defines a vector quantity.

It is also known as the fundamental law of motion since it cannot be derived. The equation of force *i.e.* $\vec{F} = m\vec{a}$ can be derived using this law. The law states that $\vec{F} \propto \frac{\Delta \vec{p}}{\Delta t} = \frac{p_2 - p_1}{t_2 - t_1}$

Now, t_1 is 0, since the start is considered as 0s and Δp can be written as $mv - mu$ since $p = mv$ and u is initial velocity and v is final velocity. Also, if $a \propto b$, then $a = kb$ where k is the constant of proportionality.

∴ This equation can be re-written as $k\left(\frac{mv-mu}{t}\right)$ and m can be substituted out; $km\left(\frac{v-u}{t}\right)$

Now, $\vec{a} = \frac{v-u}{t}$, therefore that can also be substituted. k is also normally taken as 1

$\rightarrow \vec{F} = m\vec{a}$

This equation is undoubtedly used everywhere when calculating force. Especially when calculating drag force and lift force to find the drag and lift coefficient.

Newton's Action-Reaction Law

Newton famously stated that every action has an equal and opposite reaction in his 3rd law of motion. The canister exerts a force in the opposite direction of the car, and the car is pushed forward at (almost) the same force. Almost, since some of the energy is lost in real-life scenarios. But, in physics, most calculations for things like this don't account for energy loss. Rather, they use formulae which would work in an ideal world with no energy loss.

$$F_A = -F_B \rightarrow m_1 a_1 = -(m_2 a_2)$$

The car exerts a force on the ground based on the Venturi Principle and the ground exerts an equal force on the car. This way, the car does not sink into the ground.

Application of Newton's Laws to the car

1st LAW OF MOTION

The first law of motion defines inertia. Inertia is the tendency of an object to stay in motion/at rest unless a net external force is applied to it. The car will remain in a state of rest until the force of the canister pushes the car and causes it to move. The car is now in motion. Now, the car will remain in motion until a net external force is applied to it. In this case, those forces would be air resistance and rolling friction. The car's wheels rotate at a whopping 10,000 RPM which causes an immense amount of rolling friction.

2nd LAW OF MOTION

Newton's second law of motion defines the formula $F = ma$, which means that the force applied on an object is the product of the mass of the body that's applying the force and the acceleration with which that body is applying it. The second law is basically what lets us calculate the force which the canister applies on the car, along with the force which causes the car to come to a stop, which, again, is a combination of the frictional force caused by the wheels, and the frictional force caused by the aerodynamic shape of the car.

3rd LAW OF MOTION

'Every action has an equal an opposite reaction'. This is the fundamental concept of the 3rd law of motion. The force with which the canister pushes the car is in the opposite direction to where the car needs to go. This allows the car to move forward. The car applies a force on the ground equal to the product of its mass and the acceleration due to gravity. The ground exerts an equal and opposite force on the car and allows the car to not sink into the ground.

Propulsion Physics

The concepts of Canister Propulsion in F1 in Schools are key to understanding the movement of the car across the 20m long track.

Many parameters go into calculating the force exerted by the canister at given timesteps, and the most accurate way to measure the car's movement would be to calculate the force exerted every millisecond. Each parameter of the equations required changes over time due to the complex nature of gas propulsion through an extremely small nozzle (around 1mm in diameter).

Choked Flow

Choked flow occurs when the speed of the gas at the tip of the nozzle is at or exceeding the speed of sound (sonic or supersonic).

This likely happens since the diameter of the nozzle is extremely small and the carbon dioxide is stored inside at an extremely high pressure, ~57 bar (57 times atmospheric pressure). To know whether the current flow is choked, we use the following inequality:

$$\frac{P_O}{P_e} > \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}$$

where P_O/P_e is the ratio of the pressure inside the canister to pressure outside the canister (usually atmospheric pressure) and γ is the specific heat ratio of carbon dioxide, usually 1.3 (no units since it's a ratio).

Now, if this inequality is true, then that means the choked flow equations apply.

The equation for finding the force exerted by the canister is $F = \dot{m}v_e$ which is the product of the mass flow rate and exit velocity. The reason it's important to know whether choked flow is true or not is because the formulae for mass flow rate change based on that.

Choked flow equation for mass flow rate:

$$\dot{m} = C_D A P_O \times \sqrt{\frac{\gamma}{RT_0} \cdot \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

where $\dot{m}$ is mass flow rate, C_D is the discharge coefficient, A is the area of the nozzle, P_O is the pressure inside the canister, γ is the specific heat ratio of carbon dioxide, R is the specific gas constant for carbon dioxide and T_O is the temperature of the gas

Subsonic flow equation for mass flow rate:

$$\dot{m} = C_D A P_O \times \sqrt{\frac{2\gamma}{RT_0(\gamma-1)}\left[\left(\frac{P_e}{P_O}\right)^{2/\gamma} - \left(\frac{P_e}{P_O}\right)^{\frac{\gamma+1}{\gamma}}\right]}$$

where $\dot{m}$ is mass flow rate, C_D is the discharge coefficient, A is the area of the nozzle, P_O is the pressure inside the canister, P_e is the atmospheric pressure, γ is the specific heat ratio of carbon dioxide, R is the specific gas constant for carbon dioxide and T_O is the temperature of the gas

Equation for exit velocity (holds true for sonic, supersonic and subsonic flow)

$$v_e = \sqrt{\frac{2\gamma}{\gamma-1} RT_0 \left(1 - \left(\frac{P_e}{P_O}\right)^{\frac{\gamma-1}{\gamma}}\right)}$$

where v_e is the exit velocity, P_O is the pressure inside the canister, P_e is the atmospheric pressure, γ is the specific heat ratio of carbon dioxide, R is the specific gas constant for carbon dioxide and T_O is the temperature of the gas

Now, in the start, when the canister is full, it's filled with liquid carbon dioxide, which gets converted into vapour, causing pressure to be exerted on all sides of the canister.

Even after the canister is fully filled with vapour, the liquid still remains. That means, until the liquid fully runs out, the pressure inside the canister stays constant, making our equations much easier.

However, once the liquid in the canister runs out, the pressure starts dropping in the canister, and the new pressure is calculated using:

$$P = \frac{RTm_c}{V}$$

Wheel Dynamics

Torque

Torque is the measure of how effectively a force causes something (in our case, a wheel) to rotate. It's extremely important since a car would accelerate faster with less torque. It is given by τ.
$\tau = I\alpha$ where I is the Rotational Inertia of the wheel and α is the angular acceleration of the wheel.

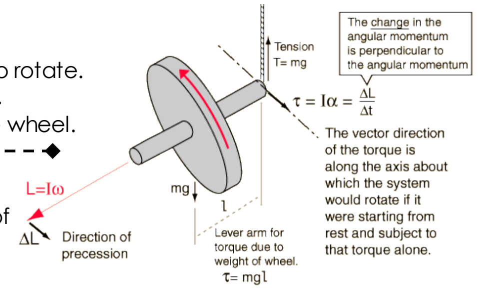


Fig. 5.1; Torque

Rotational Inertia (Moment of Inertia)

Rotational Inertia is the resistance faced by a wheel to turn. It depends on the distribution of mass across the wheel. The formula is quite straightforward.

$$I = \sum_{i=0}^{n} m_i r_i^2 = \sum m_i r_i^2$$

where m_i is the mass of each particle and r_i is the distance of that particle from the centre of the wheel. It essentially adds up the product of the mass and the square of the distance of a particle from the centre of the wheel.

Angular Acceleration

Angular acceleration is the rate at which an object's angular velocity changes with time. It tells you how quickly something is speeding up or slowing down in rotation. It is given by α.

$$\alpha = \frac{\Delta\omega}{\Delta t}$$

where ω is the Angular Velocity of the wheel, (just like how $a = \Delta v/\Delta t$)

Angular Velocity

Angular Velocity is the number of radians a wheel rotates through per second. It is given by ω.

$$\omega = \frac{\theta}{t}$$

where θ is the measure of the rotations in radians (π radians = $180°$, hence a full rotation which is 360° would be $= 2\pi$ radians).

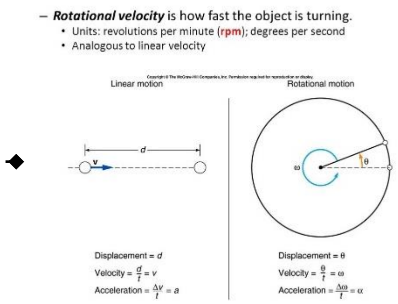


Fig. 5.2; Angular Velocity & Acceleration

RPM (Revolutions Per Minute)

RPM stands for Revolutions Per Minute. It measures how many full rotations an object makes every minute around a fixed axis.

$$RPM = \frac{60\omega}{2\pi} = \frac{60\theta}{2\pi t}, \rightarrow \omega = \frac{2\pi \times RPM}{60}$$

There's another way to calculate average RPM. If you find the number of revolutions the wheel makes in the full 20m race and divide it by race time, you get Revolutions Per Second. Multiply it by 60 and you get Revolutions Per Minute (RPM).

Let s be the total distance of the race $= 20m$
Let r be the radius of the wheel
Let t be the total race time of the car

$$RPS = \frac{s}{2\pi r} \times \frac{1}{t} = \frac{s}{2\pi r t}, RPM = RPS \times 60 = \frac{s}{2\pi r t} \times 60 = \frac{60s}{2\pi r t}$$

Now,

$$\omega = \frac{2\pi \times RPM}{60}, RPM = \frac{60s}{2\pi r t} \rightarrow \omega = \frac{2\pi}{60} \times \frac{60s}{2\pi r t} = \frac{s}{rt} \rightarrow \omega = \frac{s}{rt}$$

Hence, we have arrived at another formula for Angular Velocity.

$$\omega = \frac{\theta}{t} = \frac{s}{rt} = \frac{2\pi \times RPM}{60} \rightarrow \theta = \frac{s}{r}\ radians$$

Fig. 5.3; Tachometer

Horsepower

James Watt observed that a horse was able to lift 550 pounds 1 foot in one second. Now, 1 watt = 1 Joule per second. Joules is the SI unit of work. Watt is the SI unit of power.
Work done by the horse = $550\, lB\ (F) \times 1\, foot\ (d) \approx 2446.5\, N \times 0.3048\, m \approx 745.7\, J$.
$Power = \frac{Work}{Time} = \frac{Fd}{t} = \frac{745.7\, J\ (Work)}{1\, s\ (Time)} = 745.7\, Watts$, Hence, we can conclude that 1 horsepower = 745.7 Watts

Applying this to our car, let force be = 2N, and displacement = 20m. This assumes that a constant force of 2N was applied to the car throughout the 20m track. Let us assume that our car completed the race in 1 second (which is our goal).

$$P = \frac{W}{t} = \frac{Fd}{t} = \frac{2N \times 20m}{1s} = 40\, W$$

40 watts in horsepower = 40/745.7 $\approx 0.05\, hp$, hence, the horsepower of an F1 in schools car with the given parameters would be 0.05 hp.

Bearing Dynamics

Friction

The reason why ball bearings are so useful is that if there were a freely rotating axle, it would rub against the walls of the axle holes, causing friction. That slows down the car, and it also generates heat. The amount of heat generated is equivalent to the amount of work done by the frictional force.

$Q = W = \tau\theta$ where τ is the torque generated by the rotation of the axles and θ is rotational displacement. Q is the heat generated by rotation which is equivalent to W, which is work done.

In this case, the torque being used is frictional torque.
$\tau = \mu F r$ where μ is the friction coefficient, F is radial force, and r is the radius of the axles.

In our case, radial force would basically be the force acting n the axle perpendicular to the ground. It's calculated using the following formula

$F = mg/n$
where m is the mass of the car, g is acceleration due to gravity and n is the number of wheels.

Rotational Displacement, given by θ is essentially the product of angular velocity and time, since the formula for angular velocity is the ratio of rotational displacement to time.

Now, if the torque isn't constant, the curve on the graph wouldn't be constant either, and realistically, in an F1 in Schools race, torque is never constant, since the radial force would vary across the race. S

Since work done is the product of the torque and rotational displacement, the area under the graph. For a graph with a curved slope, the area under the curve has to be integrated.

$$W = \int \tau(\theta)\, d\theta$$

The reason it's like this is because the integral finds the area under the slope, whose formula is given by $\tau(\theta)$. It's a function that gives the formula of the slope. Calculating the area under the slope in the graph gives work.

It essentially integrates under the curve given by $\tau(\theta)$ to find the area.

It's also possible to calculate the friction coefficient of different ball bearings, since rolling friction of each ball reduces the amount of friction. On lubrication, the friction coefficient of the surface of the balls also reduces, making the ball bearings more efficient as well.

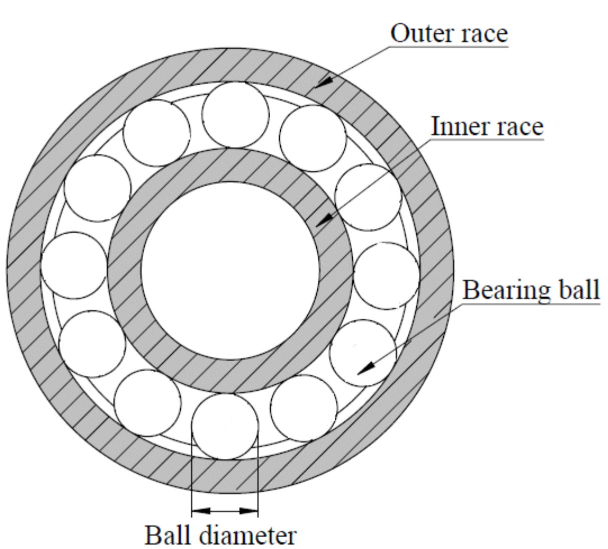


Fig. 5.4; Basic Structure of a ball bearing


Fig. 5.5; 4x9x4mm ball bearings (used in the car)

CAM

Computer-Aided Manufacturing (CAM) is all about using software and computer-controlled machines to make the manufacturing process smoother and more efficient. Typically, CAM systems include:

- Software: This part creates toolpaths and instructions (usually in G-code) that guide the machinery.
- Machinery: This is where the magic happens, as it follows the instructions to produce parts.
- Post-processing: This step takes those toolpaths and turns them into code that machines can understand.

By bringing together design and manufacturing, CAM really boosts production, making it more precise and efficient.

3-D Printing

3D Printing forms an integral part of Design & Technology. Materials commonly used for 3D printing are ABS, PLA, ABS Processed, Carbon Fibre, Nylon, PETG etc.

The term 3D printing encompasses a range of processes and technologies that provide a comprehensive spectrum of capabilities for producing parts and products in various materials. Essentially, what all of the processes and technologies have in common is how production is carried out layer by layer in an additive process which is in contrast to traditional methods of production involving subtractive methods or moulding/casting processes. Applications of 3D printing are emerging almost by the day, and, as this technology continues to penetrate more widely and deeply across industrial, maker and consumer sectors, this is only set to increase.

Types of 3D Printing Technologies

1. Fused Deposition Modelling (FDM)

- Process: This method melts and extrudes thermoplastic filament, building up layers one at a time.
- Materials: Typically uses PLA, ABS, and PETG.
- Advantages: It's budget-friendly, easy to use, and great for making functional prototypes.

2. Stereolithography (SLA)

- Process: This technique employs a laser to solidify liquid resin into distinct layers.
- Materials: Utilises photopolymer resins.
- Advantages: It delivers high-resolution prints with beautifully smooth surfaces.

3. Selective Laser Sintering (SLS)

- Process: This approach uses **a** laser to fuse powdered material into solid forms.
- Materials: Works with nylon, TPU, and various other thermoplastics.
- Advantages: It creates strong, intricate parts without needing support structures.

CNC

Computer Numerical Control (CNC) machines are automated tools that run on computer programs. They read G-code to carry out precise tasks like cutting, drilling, and milling on a variety of materials. CNC machining brings several benefits:

- 1. High Precision: It ensures that parts are produced consistently and accurately.
- 2. Automation: It minimises the need for manual work, boosting efficiency.
- 3. Versatility: It can be used across a broad spectrum of materials and industries.

CNC in F1 in Schools

In F1 in Schools, the manufacturing process includes:
Software: QuickCAM Pro is utilized to create CNC toolpaths from the designs.
Machinery: Denford Compact 1000 or 2600 CNC routers are commonly used, often featuring a 4th Axis Fixture for more complex machining tasks.
Tooling: Typically, a ¼ inch (6.35mm) diameter ball nose cutter is employed to shape the car bodies.

CAD

Computer-Aided Design (CAD) and simulation tools, especially Computational Fluid Dynamics (CFD), play a crucial role in F1 in Schools. These technologies allow us to design, analyse, and fine-tune miniature CO_2-powered race cars, closely reflecting the methods used in professional motorsports engineering.

Computer-Aided Design (CAD) is at the heart of our car development process. It gives us the ability to turn ideas into precise 3D models, letting us visualise every component before anything is physically made.

We use CAD to carefully shape the car's body, wings, wheels, and even the tiniest details like tether line guides, ensuring everything fits within the regulations while still being aerodynamic and lightweight.

With CAD, we can experiment with different design iterations quickly, make adjustments based on test results, and collaborate more easily as a team. Once the model is ready, we move on to simulation, especially CFD. These simulations show us how air flows around the car, helping us understand where drag is being created and how we can reduce it.

By identifying zones of turbulence or flow separation, we're able to tweak the design for smoother airflow, better acceleration, and improved overall performance.

Computer-Aided Design (CAD):

- Used as the foundation for designing every part of our CO_2-powered car, from the main body to the wings, wheels, and smaller components like tether line guides.
- Helps us visualise the car in 3D before manufacturing, allowing us to spot and fix any design flaws early.
- Allows for precise control over dimensions, ensuring we stay within strict competition regulations while optimising performance.
- Makes it easy to test multiple design iterations quickly without wasting physical materials or time.
- Enables team collaboration, as models can be shared, reviewed, and edited by different team members efficiently.
- Integrates seamlessly with CAM (Computer-Aided Manufacturing) tools, making the transition from design to production smoother.

Beyond just shaping the car, CAD helps us think like engineers. Every curve, edge, and cut we make in the model has a purpose—whether it's to reduce drag, lower the centre of mass, or stay compliant with size constraints.

This process has taught us how design and function go hand in hand, and how important it is to make decisions based on both creativity and logic. We also use CAD to build supporting structures like wheel systems or internal chambers, all while maintaining the correct balance and weight distribution.

Moreover, CAD plays a key role in documentation. We generate detailed orthographic drawings, exploded isometric views, and technical diagrams straight from our CAD files, which are not only required for the Engineering Portfolio but also help during manufacturing and team discussions. In short, CAD isn't just a tool—it's a digital workspace where our ideas take shape and evolve into something race-ready.

Application of CAA

Computer-Aided Analysis (CAA) is a crucial part in the design process of the car. It allows the team to test the car and improve its design using multiple tools, such as CFD. Many CFD softwares can be used, such as Ansys, OpenFOAM, etc.

CFD

Computational Fluid Dynamics (CFD) is a fascinating area of fluid mechanics that leverages numerical analysis and algorithms to tackle and understand fluid flow challenges. At the heart of CFD simulations are the Navier-Stokes equations, which detail how fluids move. These equations take into account the conservation of mass, momentum, and energy within a fluid system. In practical terms, CFD involves crafting a digital model of an object—like an F1 in Schools car—and the fluid environment around it. This environment is then broken down into a mesh of individual cells. By solving the governing equations numerically within each of these cells, we can predict how the fluid behaves, including airflow patterns, pressure distribution, and aerodynamic forces.

Examples of CFD

F1 in Schools teams utilize a variety of CFD software tools to take their car designs to the next level:
1. Ansys Fluent: As the official global CFD simulation partner for F1 in Schools, Ansys generously offers free access to its software suite. Teams leverage Ansys Fluent for in-depth aerodynamic analyses, helping them fine-tune their designs to minimize drag and enhance stability.
2. OpenFOAM: This open-source CFD toolbox, crafted in C++, provides the flexibility to customise solvers and utilities for a range of fluid dynamics challenges.
3. SimScale: A cloud-based simulation platform that encompasses CFD, finite element analysis, and thermal simulations. Its user-friendly nature makes it a great fit for educational settings.
4. FEATool Multiphysics: An integrated simulation environment that connects with solvers like OpenFOAM and SU2, making Multiphysics simulations easier through an intuitive graphical user interface.
5. Simcenter STAR-CCM+: Developed by Siemens, this commercial CFD software is designed for modeling and analysing fluid flow, heat transfer, and other related phenomena.

Application of CFD in F1 in Schools

CFD is essential in the iterative design process for F1 in Schools cars:

- **Design Optimization:** Teams kick off by crafting their initial car designs with CAD software. They then run CFD simulations to evaluate the car's aerodynamic performance, with a keen eye on reducing drag and ensuring stability.
- **Iterative Testing:** After analyzing the simulation results, teams tweak their designs to tackle issues like airflow separation and pressure distribution. This back-and-forth continues until they reach peak performance.
- **Validation:** Some teams take it a step further by validating their CFD findings through real-world testing, like wind tunnel experiments, to confirm their simulations are spot on. For example, one study showed that design tweaks based on CFD analysis resulted in a 9.89% drop in drag force.
- **Performance Analysis:** With advanced CFD tools, teams can visualize intricate flow patterns, helping them grasp how design changes affect performance. This thorough analysis empowers them to make informed choices throughout the design journey.

Car Design Evaluation

Many design principles were applied in the design of our car, most prominently in our rear wing. Multiple challenges were faced while designing, mainly issues regarding regulations. The general weight of our current car (Hyperion) is much less than that of our Regional Finals car (HammerHead).

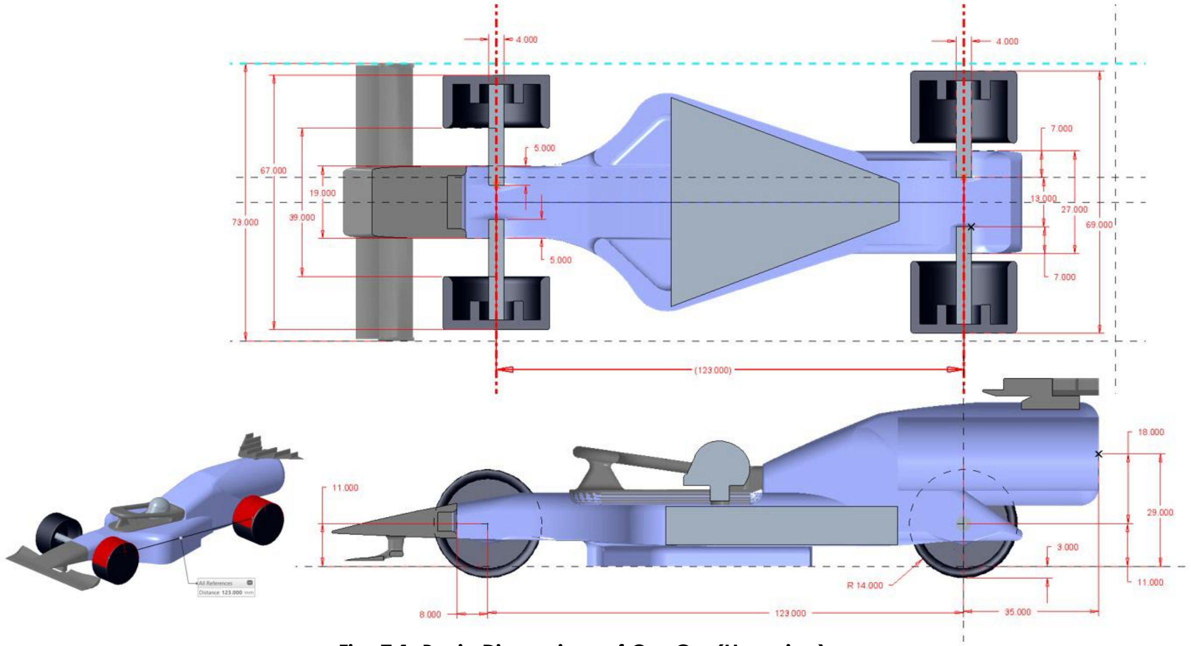


Fig. 7.1; Basic Dimensions of Our Car (Hyperion)

Nosecone Design

The nosecone (Refer to Fig. 7.3) is designed specifically for downforce. Since the car design has much more weight in the back (as mentioned in the rear wing section) in comparison to the front of the car. It was designed while taking inspiration from the nosecones of real Formula One cars, keeping in mind the immense downforce that's needed to equalise the force in the front and back of the car.

The nosecone was intentionally made thinner to reduce the frontal surface area of the car. The reason why the frontal surface area of a car affects drag comes from the drag force formula (as mentioned in previous slides):

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

A is the variable of frontal surface area, and thus affects the drag force acting on the car. For lesser drag force, the frontal surface area has to be lesser, but to account for the thinner nosecone, support structures have been made to make sure that the rear wing doesn't snap easily. It's also been made using Nylon and since that's a more rigid and sturdy material,

Fig. 7.4; Nosecone Front View

Fig. 7.5; Full Car Body View

Rear Wing Design

The rear wing of our car (refer to Fig. 7.2 and Fig. 7.3 incorporates multiple design concepts, causing it to be one of the most technical parts in the car. As seen in the side view of the rear, its function isn't to cause downforce, but the exact opposite. The rear wing of our car introduces lift. The weight of the canister (around 30 grams before the race and around 22 grams after the race) weighs down on the back, and since our nosecone (heavier than the rear wing) is still around 8 grams, and the mass of the car in the back is generally more than in the front (due to more volume), there's immense weight in the back. During the race, if the rear wing introduces lift, the force exerted by the back of the car would be (hopefully) equal to or close to the force exerted by the front, since the nosecone is made specifically for downforce. The edges of the rear wing are designed in a way that makes sure the car adjusts itself and points straight when released (since if the direction of the car isn't completely straight, drag increases since the frontal surface area increases. This is further reinforced by the bars on top of the rear wing, which act somewhat like venturi tunnels to increase airspeed behind the car, reducing race time by a negligible but effective amount. The weight of the rear wing is ~2.5-3 grams. It aims to equalise the force that each portion of the car exerts on the ground.

Fig. 7.2; Rear Wing Front View

Fig. 7.3; Rear Wing Side View

Object	Material Used	Weight (grams)
Car Body	Polyurethane	2.814
Rear Wing	Nylon	1.6
Nosecone	Nylon	3.612
Front Axles	Nylon	0.676
Rear Axles	Nylon	0.650
Front Wheels	PETG	12.996
Rear Wheels	PETEG	16.022
Halo	Nylon	6.236
Helmet	Carbon Fiber	2.130
Ball Bearings	Steel Alloy	4

Fig. 7.7; Material & Weight table

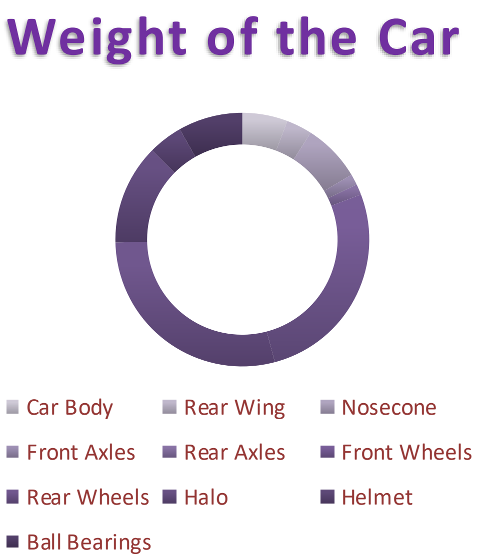
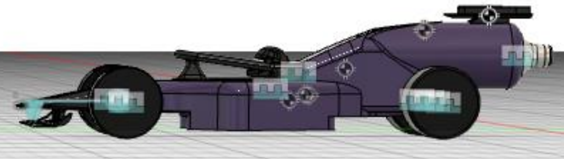


Fig. 7.6; Weight chart



3D Modelling

Design Comparison

Modelling Approach and Design Philosophy
Another significant change was in the design approach. The regional finals car was created using basic solid modelling tools, primarily extrude and fillet. For the national finals, particularly the nosecone, we shifted to form-based modelling in Fusion 360. This allowed us to fine-tune the surface geometry and optimise airflow interactions, particularly around the front of the car, the most aerodynamically sensitive region.

Side View Comparison and Overview
Fig. 8.1 presents the side view of our regional finals car, highlighting several design elements that influenced its aerodynamic performance. In comparison, Fig. 8.2 shows the updated side profile of our national finals car, which incorporates multiple improvements and refinements aimed at increasing aerodynamic efficiency and overall race stability.

Nosecone Aerodynamics: Lift to Downforce
The most impactful aerodynamic change was the nosecone. In the regional car, the nosecone's geometry inadvertently produced aerodynamic lift, especially at high speeds. This occurred due to a slightly upward-curving profile and a low angle of attack, which caused airflow to separate beneath the chassis, ultimately reducing front-end stability.

To counter this, the nosecone in the national finals car was completely redesigned using form modelling rather than only standard solid tools. This allowed for precise control over curvature and surface transitions, enabling the creation of aerodynamic downforce at the front of the car. The updated nose profile features a steeper slope and smoother transitions, effectively directing airflow over and around the car rather than underneath it.

Major Design Upgrades
Two of the most significant upgrades in the national car are the introduction of a halo structure and a completely reengineered nosecone. The halo not only adds to the aesthetic and realism of the design but also contributes structurally by reinforcing the front of the car.

Rear Wing Adjustments: From Downforce to Lift
Interestingly, the rear wing design underwent the opposite transformation. In the regional finals car, the rear wing was optimised to produce downforce, which initially appeared beneficial for increasing grip. However, further testing and analysis revealed that the rear end of the car is naturally heavier due to the placement of the CO_2 canister. The added downforce only worsened the imbalance, increased drag, and destabilised the car's centre of pressure.

To address this, the rear wing of the national finals car was modified to generate a small amount of lift. While this may seem counterintuitive, it was a deliberate strategy. By combining front-end downforce with rear-end lift, we aimed to equalise the vertical forces acting on the car. This resulted in improved aerodynamic balance, reduced pitching moments, and better launch stability.

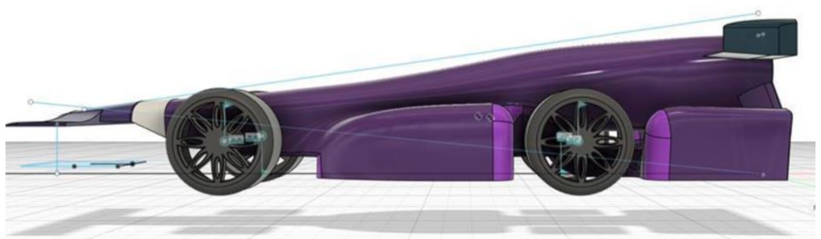


Fig. 8.1; Regional Finals Car


Fig. 8.2; National Finals Car

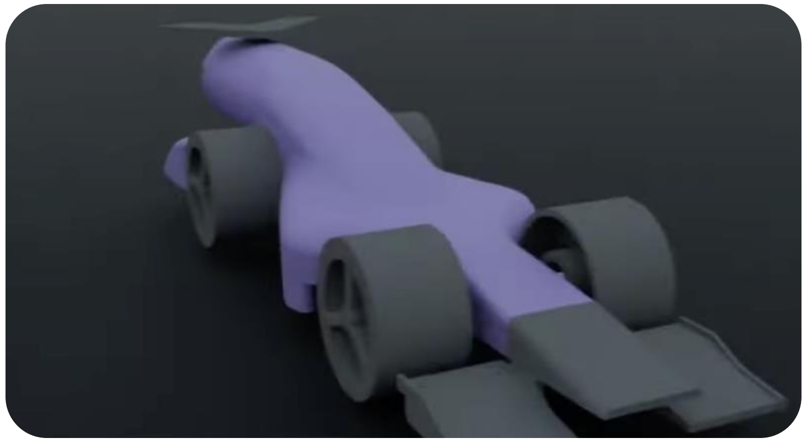


Fig. 8.3; National Finals Car without Halo

Design Comparison.. Continued..

Fig. 8.3 represents the original concept of our national finals car, developed before a detailed regulatory review and aerodynamic optimisation. Compared to the final version, this earlier model differs in several key areas: the absence of the halo, the presence of rear sidepods, open wheel structures, and a nosecone made using only solid modelling tools.

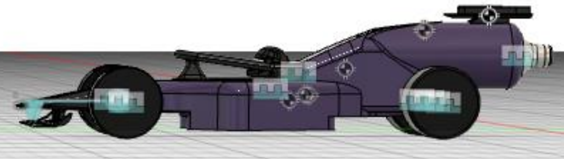
Halo Addition: Function and Realism
The most visually striking change is the addition of the halo in the final version. Initially excluded to simplify the design, the halo was later integrated to improve structural rigidity, add realistic detailing, and influence airflow around the cockpit. Although small in size, its placement contributes to subtle improvements in flow redirection, especially above the front chassis.

Rear Sidepods: Aerodynamic Benefit vs. Regulation Risk
In the original design, we included rear sidepods to control wake and reduce turbulence behind the car. These were designed to guide airflow around the rear wheels more cleanly. However, during regulation cross-checking, we realised the sidepods risked violating body dimension constraints and placement zones. To avoid potential penalties, we chose to remove the sidepods entirely in the final version. While this meant sacrificing a minor aerodynamic benefit, it ensured full regulatory compliance, which was crucial at the national level.

Wheel Design: From Open to Closed for Drag Reduction
Another significant improvement was the transition from open to closed wheels. The early model used open wheels that exposed the internal spokes, leading to increased aerodynamic drag due to vortex shedding and airflow disturbance. In contrast, the final design adopted closed wheel covers, which helped to streamline the wheel region, reduce drag, and create a more cohesive and high-performance look.

Nosecone Evolution: From Solid to Form Modelling
The nosecone in the early version was created using basic extrude and fillet tools. This limited our ability to fine-tune surface continuity and shape flow-friendly transitions. In the final model, we shifted to form modelling in Fusion 360, which allowed for precise control over curvature and surface flow. The new nosecone design generated aerodynamic downforce, reduced flow separation, and improved the car's launch stability and front-end grip.

Conclusion: Iteration Toward Compliance and Performance
This comparison between the original and final national finals designs demonstrates our iterative approach to development, refining the car not only for aesthetics and airflow but also in response to technical regulations and race performance data. Each modification was carefully considered to strike a balance between design intent, aerodynamic efficiency, and rule adherence, leading to a car that was both visually refined and engineered for speed.



Assembly

Car Body Sanding

The car body we received initially from the CNC cutting process exhibited several surface inconsistencies, which included minor scratches, ridges, and uneven patches resulting from the limitations of the cutting tool's precision. To ensure a smooth and aerodynamic surface, we carried out an extensive sanding procedure in multiple stages using progressively finer sandpaper. We began with 1000 grit sandpaper, which was used for the initial dry sanding phase. This level of grit was effective in eliminating the visible and tactile imperfections on the car's surface, such as small bumps, rough edges, and tool marks left by the CNC process. This step was crucial not only for aesthetic purposes but also for performance reasons, as it helped in smoothing out the overall surface to reduce form drag caused by turbulent airflow. Following this, we used 2000 grit sandpaper for wet sanding. Wet sanding involves the use of water to lubricate the surface during the sanding process, which prevents clogging of the paper and allows for a much finer, smoother finish. This second phase of sanding was aimed at refining the surface even further, enhancing the gloss and reducing micro-scratches. It significantly improved the texture of the car body and prepared it for the next critical step, gloss painting. One of the benefits of our sanding process was the reduction in the effective exposed surface area of the car body. A smoother surface contributes to better aerodynamic performance by minimising drag, which can have a measurable impact on the car's speed and stability on the track. After completing the sanding process, we proceeded to apply a high-quality layer of gloss paint, generously provided free of charge by House of Polish. The gloss coat not only enhanced the car's visual appeal by giving it a sleek, professional finish but also contributed to reducing surface friction. The paint layer created a uniformly smooth coating that closely matched the renders we had developed during the design phase, ensuring that our final physical model stayed true to our original concept. Figures 9.1 through 9.3 illustrate this progression. Fig 9.1 displays the raw car body as received from CNC machining, with visible surface imperfections. Fig 9.2 shows the car after the sanding process but before any paint application, highlighting the smooth, matte texture achieved. Finally, Fig 9.3 presents the fully painted and finished car body, showcasing the glossy, refined look that not only improved the aesthetics but also helped enhance aerodynamic efficiency.

Fig. 9.1; Car Body Before Sanding

Fig. 9.3; Car Body After Painting

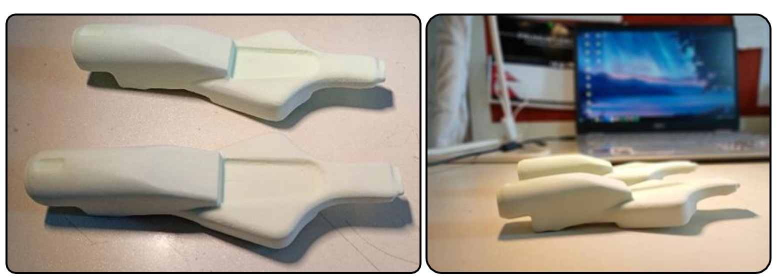


Fig. 9.2; Car Body After Sanding, Before Painting

Fig. 9.4; Ball Bearings Used

Manufacturing Defects

When we received the car body from manufacturing, we immediately noticed a few major defects that raised concerns about the structural integrity and aerodynamic performance of the final model. One of the main issues was with the canister slot, specifically, the portion below the CO_2 canister was much thinner than what we had designed in our CAD model. We were worried that during the high-speed launch, this thin section might snap or deform due to the strong thrust from the CO_2 cartridge. However, during physical testing, we were relieved to see that no failure occurred. The structure held up well under load, giving us confidence in the material's strength. Once the car was painted, the thick gloss coat added reinforcement to the thinner areas and also improved the surface finish, which likely contributed to slightly lower drag and better aesthetics. The paint also made the body feel more rigid overall, adding to our confidence in its durability.
Another issue we faced was at the rear of the car, where we had designed a Z-shaped structure intended to reduce wake and improve airflow. This feature wasn't manufactured correctly, and the final car did not include it. While this was disappointing, especially since it was a key aerodynamic element based on our CFD analysis, we had to quickly adapt and shift focus to other areas of the design. We put extra effort into optimising the front wing, side pods and wheels to help reduce drag and maintain stability. Referring to Fig. 9.5, one can see that the manufactured lower canister segment was different from the one in the CAD model, and the same goes for Fig. 9.6.

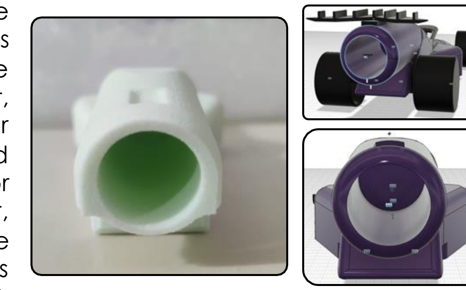


Fig. 9.5; Manufacturing Defect #1

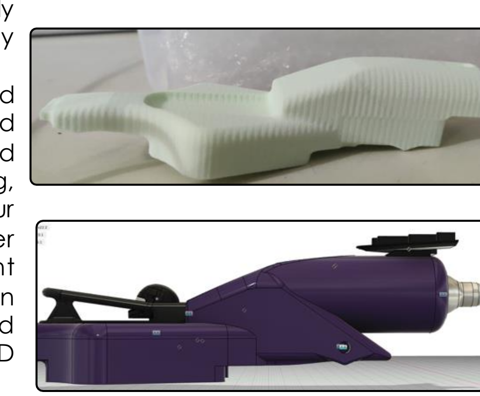


Fig. 9.6; Manufacturing Defect #2

Fig. 9.7; Finished Car

Finished Assembly

Fig. 9.7 shows the finished car, fully painted, assembled and lubricated. We decided not to paint the interior of the wheels, since that would've possibly 1) increased the weight, 2) made the ball bearing hole smaller, making it harder to attach the ball bearings. The car body was painted in a purple gloss while the other components were painted in matte black. The general finish of the car was much better

Conclusion

The finish of the car for this competition was significantly improved compared to our regional finals' model. The quality of the paint, ball bearings, and lubrication was notably better, ensuring smoother motion and reduced mechanical resistance, all contributing to enhanced on-track performance. However, one issue we encountered was the instability of the front wing. The material used was extremely thin, which made the wing wobble under certain conditions—something we believe could lead to performance variations between runs. At this level of competition, consistency becomes critical, and even minor structural instabilities can influence the outcome. With such high sensitivity, the race outcome not only relies on reaction time but also on the precise alignment of the wheels, nosecone, and aerodynamic components to avoid any unnecessary drag. Moving forward, we aim to reinforce such components or use more suitable materials to improve both reliability and aerodynamic stability.

Virtual Testing

Evaluation Parameters

We ran the CFD for 2 main parameters- Velocity magnitude and shear stress.

Fig. 10.1 shows the Shear Stress results across Hyperion. Shear Stress is the frictional force per unit area caused by the air's contact with the body. In the figure, it can be concluded that most of the surface of the car is blue, which means there's low shear stress. From this, it becomes apparent that most areas in the car have low air friction, which is good for performance. There are, however, a few greenish areas where there's a bit of increased air friction due to exposed uneven or sharper surfaces.

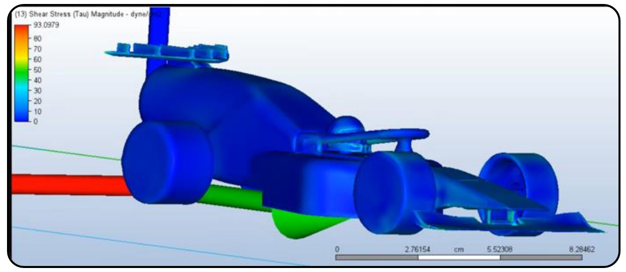


Fig. 10.1; Shear Stress Across the Car

Figures 10.2 and 10.3 show velocity magnitude simulations for Hyperion, our F1 in Schools car. In the first and second images of Figure 10.2, we can see how the air moves around the car. The air travels slightly faster underneath the car than over the top. This small difference is important; it means there is just enough downforce to help the car stay firmly on the track, giving it stability. However, it's not so much downforce that it increases drag, which could slow the car down. This balance is crucial in making the car both fast and steady. In Figure 10.3, we see two more views that help us understand the airflow. The second image highlights an issue behind the halo, due to its shape, air does not flow smoothly past it, creating a small wake or drag zone. This added drag may have reduced the car's speed slightly, possibly affecting our overall time by around 0.05 to 0.1 seconds. The first image of the same figure displays a mesh pattern that shows the direction and path of airflow across the car's surface. Looking closely, it becomes clear that part of the front wheels are exposed to oncoming air. This exposure is not ideal, as it creates extra drag, which also slightly slows the car down. These small aerodynamic challenges give us areas to improve in future versions of the design.

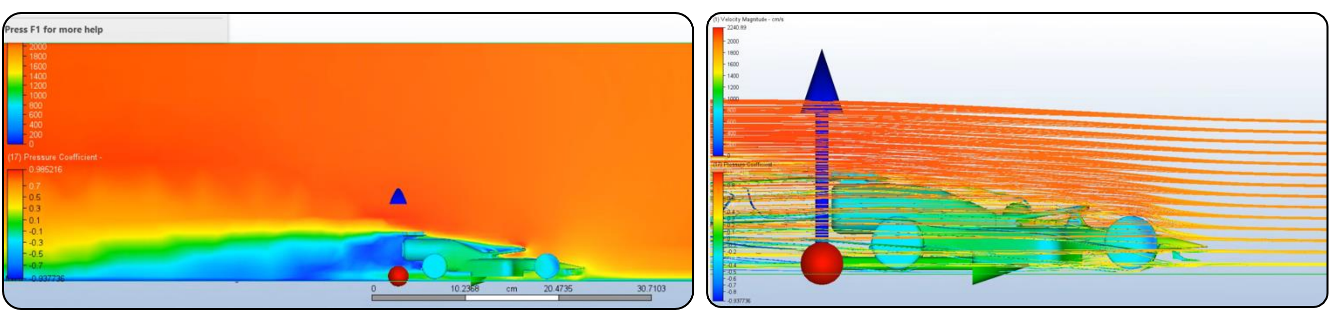


Fig. 10.2; Velocity Magnitude

There was an issue with the meshing of the halo's file, which we received. When we exported the car's file and tried to import it into the CFD software, there was an issue with the mesh of the halo, which we couldn't figure out how to fix for about 2 weeks. We then came up with an innovative solution. We merged the halo's mesh with the body, and we were then able to run the simulation. We ended up with a drag coefficient of 0.506, which is a lot better than our drag coefficient last time.

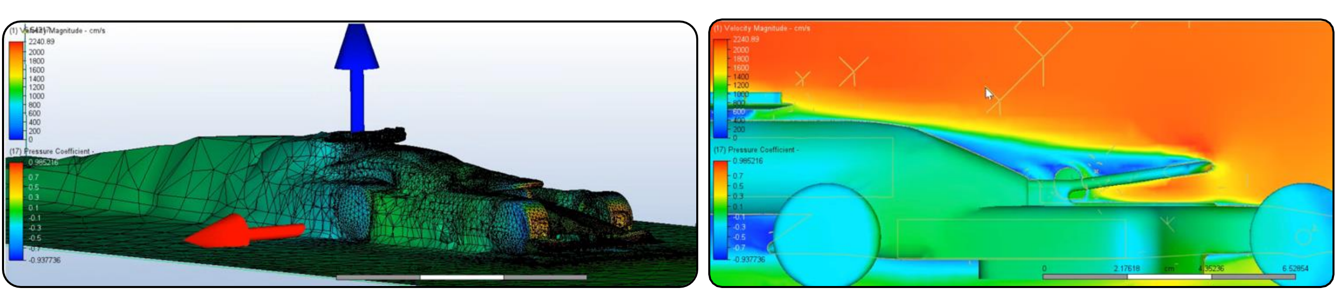


Fig. 10.3; Velocity Magnitude

Fig. 10.4; Assembled Car on the Track

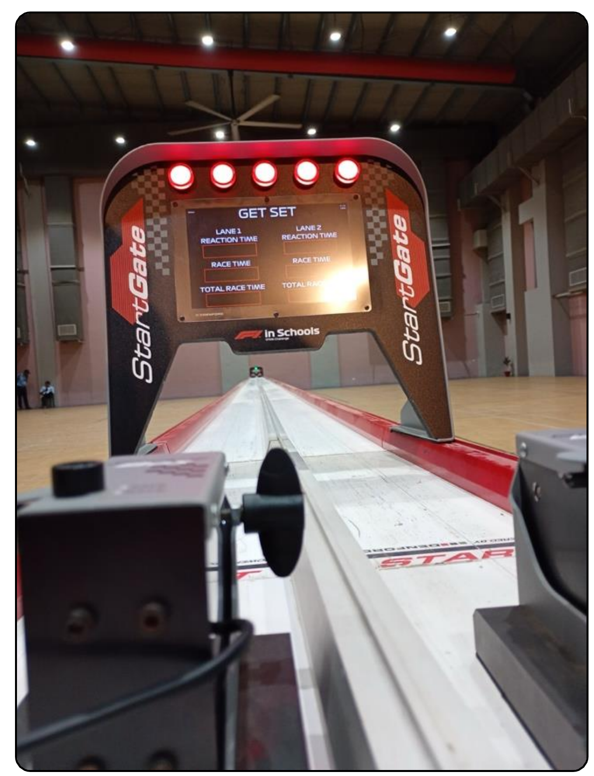


Fig. 10.5; The Track

Racetrack Properties

- It is 25m long, but only 20m is used for racing.
- It is manufactured by a company called Denford
- It has a tether line in the middle made of Teflon.
- Two lanes race 2 separate cars.
- The reaction time tester uses infrared sensors and start gate mechanisms to operate.

Physical Testing

We carried out our physical testing at Suncity School, Sector 37D, which was also the venue for our Regional Finals. This gave us a great chance to test the car in an actual race setup, just like in a real competition.

At the time of testing, the tether line guides weren't built into the body of our car.

Since they weren't part of the original design, we had to attach them separately by hand. These guides are small but important parts that help keep the car aligned with the track and prevent it from wobbling or going off course.

However, adding them manually increased the total weight of the car by 1 gram. While this might not sound like much, in F1 in Schools racing, even a single gram can slightly slow the car down by affecting its acceleration and top speed.

This experience taught us how important it is to include all race parts, like the tether guides, directly into the car's design right from the beginning. Doing so will make future testing more accurate and help avoid performance surprises in competitions.

During testing, both cars performed close to what we had predicted. Car A clocked a time of 1.18 seconds, and Car B finished in 1.21 seconds. We wanted to improve this performance, so we tried lubricating the ball bearings, thinking it would reduce friction and make the wheels spin more smoothly.

But instead of getting better results, both cars became slower by about 0.06 seconds. We believe this happened because over-lubricating can have the opposite effect; it made the wheels slip more at the starting point, which delayed the actual movement of the car.

Another issue we discovered was with the assembly of the ball bearings. The depth of the ball bearings was too shallow, which meant the ends of the axles were under too much pressure.

This caused the axles to wobble during the race, which also affected the car's speed. Because of all these factors, our original time of 1.18 seconds increased to 1.28 seconds.