



Designing a race car rear wing: Fluid Flow Assessment

STRUCTURAL AND FLUID ANALYSIS

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Section 1: Abstract

In this Project, I discover that the fluid flow on a formula one car rear wing has an extremely high Reynolds number, giving it a great deal of turbulent flow. This is required in order to provide the necessary downwards forces to keep the vehicle grounded whilst reaching high speeds. The wing is given a curved shape to help achieve the levels of downwards forces to keep the vehicle firmly planted.

The carbon fibre material is the optimum choice for the wing as it provides the strength necessary to withstand the forces acting upon it whilst also minimising the impact of the additional weight created by the wing.

The CFD modelling techniques are the most reliable method to trial designs before manufacturing the final product. This method gave the most accurate findings with the fewest potential discrepancies. However, working alongside physical testing would help to yield the best overall results.

Section 2: Introduction

In this project, I will be looking at a race car rear wing and discuss how the fluid flow surrounding the wing can be affected by different factors and methods in which it can be predicted. The project will cover topics including Reynolds number and discuss how it is used to help identify types of flow. Exploration into Boundary flow and its effect on the shape of the wing. I will Investigate the current material selected to fabricate the wing and see how this would affect the fluid flow. Modelling techniques used to replicate the fluid flow that would affect the wing. Discussing methods that can be used to test a prototype model and then evaluate how the results correlate with the simulations conducted with the modelling techniques.

Section 3: Reynolds Number

Reynolds number is a numerical quantity that allows for the estimation of what type of pattern a fluid flow is experiencing. The number takes in the characteristics of a fluid including the density, viscosity and flow speed as well as uses the pipe/material dimensions to calculate the resulting Reynolds number value.

The Reynolds number essentially is a ratio of the inertial forces over the viscous forces. The density and velocity of the fluid, as well as the diameter/length of the pipe/area represent the inertial forces. Whilst the dynamic viscosity is the representation of the viscous forces. This can be shown using the equation: $RE = \frac{\text{Inertial}}{\text{Viscous}} = \frac{\rho u d}{\mu}$

The resulting number that comes from the equation will determine if the flow should be deemed to be laminar or turbulent. The threshold number is typically agreed upon to be 2000, however some sources disagree with this. If the number is below 2000, it is regarded to be that of a laminar flow. Conversely, if the number is higher than 2000 the flow is deemed to be in a turbulent state. As stated before, some sources would say that the value of 3500 should be considered turbulent and anything between the values of 2000 and 3500 should be considered as transitional flow (Thermal-engineering.org, 2023).

Laminar flow is when the viscous forces dominate over the inertial forces giving a smooth and generally more predictable pattern. As shown on the first example in Fig 1, the fluid particles will travel in parallel layers with minimal mixing of said layers. This usually occurs when the velocity is on the lower end and there are minimal obstructions or disturbances in the fluid flow route.

Turbulent flow is when the inertial forces dominate over the viscous forces. When the velocity of the fluid exceeds a certain value, the fluid particles that would normally travel parallel to each other will now begin to move more erratically and start to form spiral patterns and cause the otherwise separate layers of fluid to mix. This can cause irregular fluctuations in the velocity and fluid flow. A side effect of turbulent flow is the increased resistance it can create. This resistance can lead to the increase in aerial friction and thus leading to energy/pressure losses. This particular feature is what is usually sought after when designing equipment/vehicles in sectors such as the aerospace and formula one industries.

In the example of the race car rear wing, I can work out what the Reynolds number of the air flow that would travel off the rear wing of a formula one car and thus can work out what the nature of the flow is.

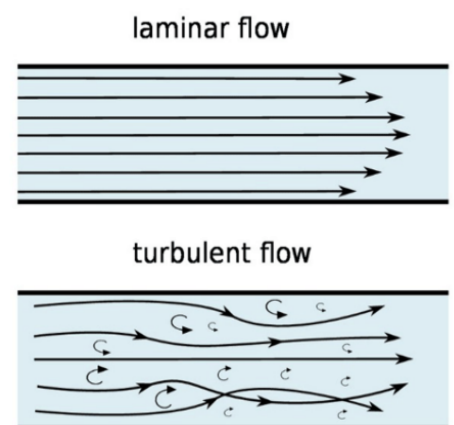


Fig 1. Laminar flow and Turbulent Flows

I will need to obtain the following data:

- Density of air - ρ
- Velocity of the vehicle - u
- Dynamic velocity of the air - μ
- The length of the rear wing that the flow will travel along. – d

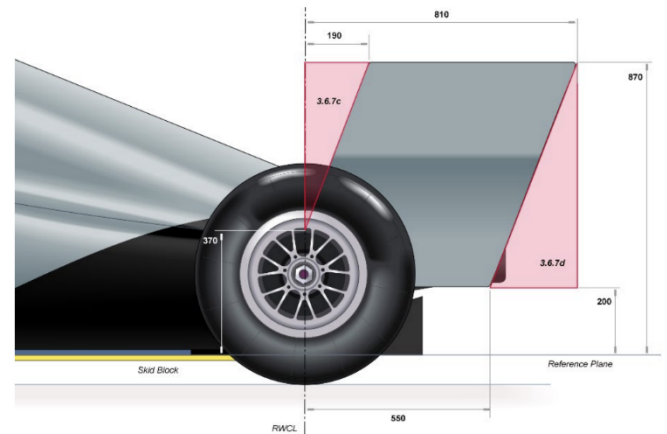


Fig 2. Diagram of Rear Wing Dimensions

The density of air at sea level is **1.225kg/m³** (Engineersedge.com, 2023)

Dynamic velocity of air is **1.803x10⁻⁶kg/ms** (Engineeringtoolbox.com, 2023)

Length of the wing is **550mm** (Fia.com, 2023) which can be converted to **0.55m**

The average velocity of formula one vehicle is around **138MPH/223KPH** (Professionalshq.com, 2023).

This can be converted into m/s as to work within the formula. Therefore, 223,000/3600 = **6.194m/s**

The Reynolds number can now be worked out as below:

$$RE = \frac{\rho u d}{\mu}$$

$$RE = \frac{1.225 \times 6.194 \times 0.55}{1.803 \times 10^{-6}}$$

$$RE = 2314590 \text{ or } 2.3146 \times 10^6$$

Therefore, with the resultant Reynolds number far exceeding the value of 2000, the fluid flow acting on the rear wing of the formula one car is certainly of a turbulent flow nature. As stated before, some sources would consider anything above the value of 3500 as turbulent rather than 2000. However, on this occasion, the value far exceeds even this value. So there would be no need to debate this time.

Section 4: Boundary Flow

Boundary flow, also referred to as the boundary layer, is a layer of fluid or air that is connected to the object as fluid passes around it. As mentioned previously, there are two main types of boundary flow; Laminar Boundary and Turbulent Boundary.

Boundary flow affects flat and curved objects differently. Flat objects, as shown on diagram Fig3, the fluid flow will make contact with the leading edge of the plate and begin to produce a laminar boundary layer. This will initially develop in a predictable manner and gradually thicken; this is until it reaches a transitional stage in which the boundary flow will inevitably become unstable. At this point, the flow will become turbulent. Compared to a curved surface, the transitional period will occur faster on a flat surface.

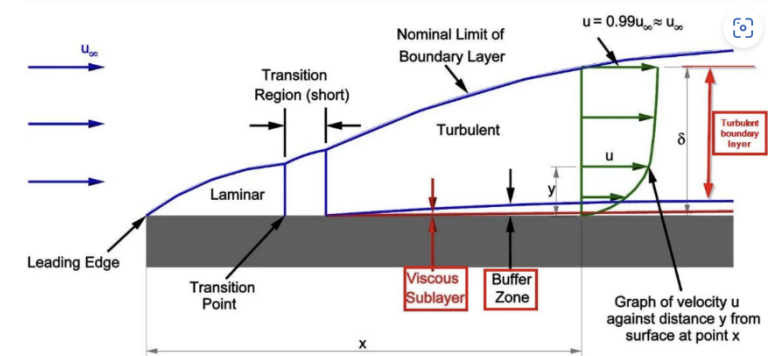


Fig 3. Boundary layer on a flat surface

On a curved surface, some of the fluid will make contact with the stagnation point on the front of the wing. Where the fluid hits this point, the velocity becomes zero as the fluid has been stopped or stagnated. As Bernoulli's principle would suggest, due to the velocity here being zero, this would also be where the object will feel the most static pressure. Fluid flow will from this point be pushed to either the top or bottom layer of the wing. Initially the flow will experience a laminar boundary as the flow becomes attached to the object. Due to this laminar flow on this section of the top of the wing. The wing will now experience lift because of the reduction of pressure on the top layer.

As this layer continues to travel along the face of the object, it will continue to build until it reaches a transitional stage caused by the shape of the wing. When this occurs, the fluid particles will start to detach from the surface of the wing, thus beginning to spiral/mix and become turbulent. This turbulent flow creates a loss in energy in the fluid particles and thus leads to drag and producing a downwards force.

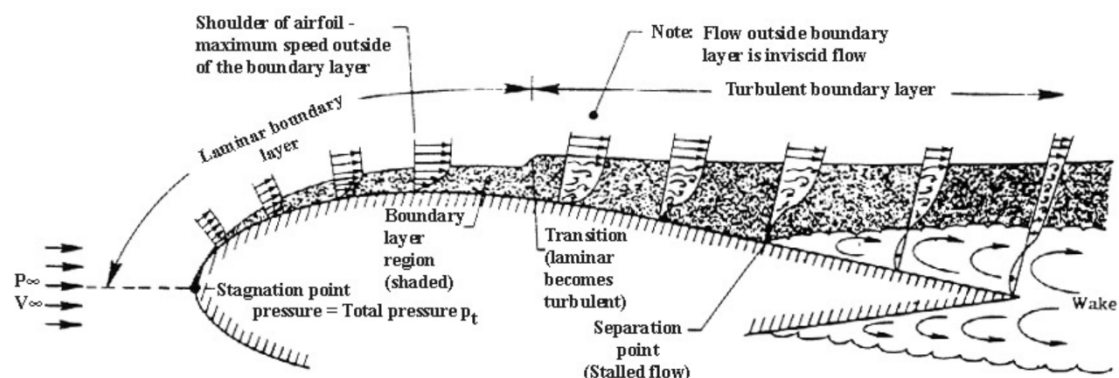


Fig 4. Boundary layers on a wing

When it comes to vehicles such as cars, if the vehicle does not have a tail wing (otherwise known as a spoiler) it can be susceptible to lift if it reaches a high enough velocity. For most cars used on everyday commutes, the velocity of the vehicle would never reach the high values required for the lifting force to become an issue. In Fig 5, the diagram shows the forces that would impact a car if it did not have a rear wing. The diagram shows that the only downwards forces that would keep the vehicle grounded would be those from the front end and some minor downward forces created from the shape of the main body of the car. Similar to how the wing functions, there would be some drag due to the curved shape of the vehicle as this creates a separation point for the flow to become turbulent. However, at higher speeds the vehicle would be susceptible to high amounts of lift force from the underside of the vehicle which would overpower this downwards force.

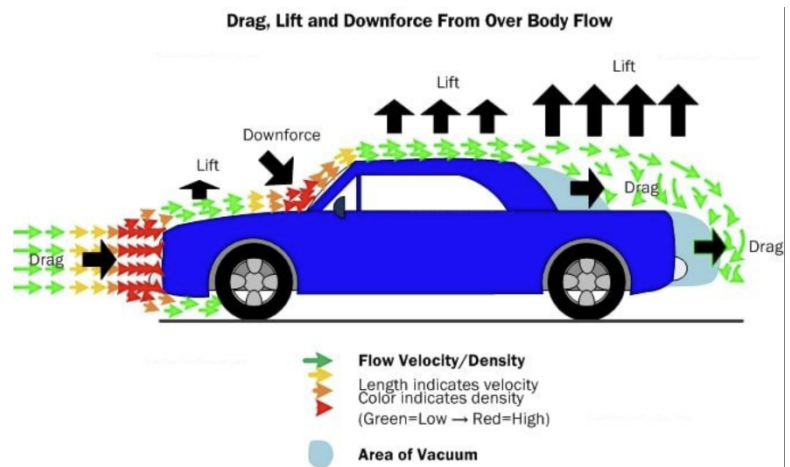


Fig 5. Forces acting on a vehicle with no rear wing.

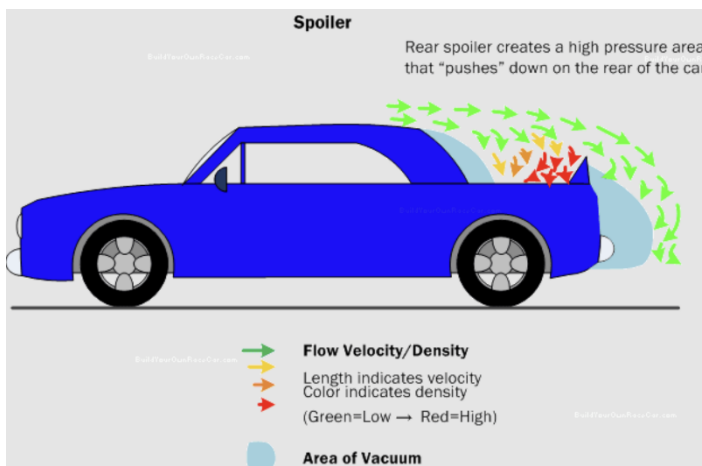


Fig 6. Forces acting on a vehicle with rear wing.

When utilizing a spoiler on the tail end of a car, the shape of the wing creates a new location for the fluid flow to become more dense and further turbulent than what it would have without it. This turbulence then generates high pressure levels that in turn produces greater downwards forces, as shown in Fig 6.

In terms of sports cars that go at much faster velocities than the everyday car, this downwards force is essential to ensuring that the vehicle remains grounded during a race. If the spoiler was not attached to the

vehicle, the sports car would certainly begin to experience lift and cause the cars traction to the racetrack to diminish. This would make it far more susceptible to losing control and causing a major accident.

Section 5: Wing Material

History of rear wing design in motorsport

1950s and 1960s – Motorsport cars back in this time did not reach the high velocities that the cars of the modern age can reach. So, the need for huge spoilers were not as critical. However, small wings were designed and used to add some stability and downforce to the sports cars.

1970s and 1980s – This was the start of the ground effect era. This concept involved using the airflow that travelled underneath the vehicle to create a low-pressure area. The theory was that this would help to pull down the car towards the racetrack. The wings would have a more prominent role by working along side this ground effect. The wings would become much larger with a greater surface area than its predecessors. (Motorsport.com, 2017)

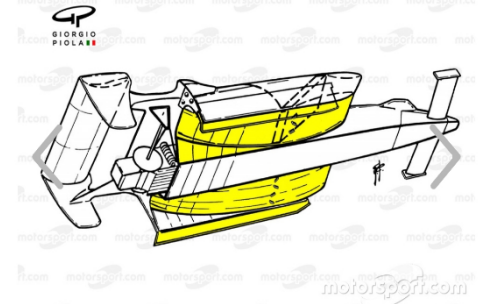


Fig 7. Ground effect tunnels

1990s – As time went on and the technology improved, motorsport cars would also have greater velocity potential. With that, the importance of the functionality of the wings also did. During this time period, adjustable rear wings were designed in a way so that the driver could manually alter the angle of the spoiler. This gave greater flexibility and potential performance even when under different conditions.

Modern day – Over the years the wing designs have continue to evolve to become more sophisticated. Using new technologies to help design and test in non-destructive formats. F1 have since introduced the Drag reduction systems (DRS) to aid in overtaking. Drivers can manually adjust the rear wing flap, reducing the angle of attack and creating a lower drag configuration.

Materials used for rear wings

Materials used in F1 cars must meet to the regulations set by FIA (Fédération Internationale de l'Automobile) in their Formula 1 Technical Regulations document. These regulations are updated yearly and can be located on their website. For a vehicle to be race legal, it must adhere to the standards set within this document. The three main materials I am looking at are Aluminium, Titanium and Carbon Fibre

Aluminium

The main benefits that aluminium has over the other materials is that out of the three, it is the most cost efficient and is the easiest to repair. The material is far cheaper than the others going for rates of around £0.77/Kg (Dailymetalprice.com, 2023). Aluminium is also a material than manipulates and can be worked on with relative ease. However, despite how the manufacturing process for this material is more affordable, it is limited in design complexity. This means that the wing shapes produced with this material will struggle to produce the maximum downforce forces that other materials can perform. Aluminium's strength to weight ratio ranges between 25kNm/kg to 75kNm/kg, this is depending on the specific alloy, grade, or composite of the material. This set of values is the lowest of the three materials. This would mean that if you wanted to benefit the same level as strength as you would with the other materials, you will need to add more material. Thus, adding more weight to the vehicle and affecting the potential velocity of the vehicle. Adding this material could also affect the way in which a rear wing would react to the fluid flow as it travels, possibly hindering the effectiveness

of the downwards forces required. Alternatively, you can use the same amount of material, but you would be sacrificing some of that strength.

Titanium

The specific strength of titanium fares better than aluminium with a range of 50kNm/kg to 150kNm/kg. The specific value depends on the specific alloy and grade of the material. A benefit that highly favours titanium is its resistance to corrosion. F1 cars will often face different types of harsh environments when racing, so having the ability to minimise the effect of corrosion will be a huge benefit when it comes to maintaining the parts made from this material. However, the biggest drawback for titanium is its cost to produce and manufacture. The raw material itself costs around £7.50-£8/kg (Foundrytradejournal.com, 2023) which is far cheaper than carbon fibre, however it is a tough material which is difficult to work with. The time and resources that it takes to be able to manipulate titanium into a working shape boosts the overall cost to use. As the material is so difficult to work with, it stands to reason that the flexibility in design possibilities will also be hindered. This would mean at best you could create more simpler shapes; this would then lead to a lower efficiency in generating the downward forces required for the vehicle to remain grounded.

Carbon Fibre

This is the material that is most used in the F1 industries of modern days. Like the other materials, it provides a lightweight option for the vehicle. However, in comparison to the other materials, its weight to strength ratio ranging between 150 kNm/kg to 500 kNm/kg means that for its low weight it can also provide the strength required to withstand the continuous high vibrations and other forces that can come from such an intensive sport. The biggest benefit that makes this material so attractive is its flexibility in design potential. Carbon fibre can be moulded, which means that it can produce more complex designs in comparison to the other materials. Using modern manufacturing processes, smaller and more intricate shapes can be produced to assist in providing a wing shape that can produce the greatest potential for downwards forces but also to minimise drag. Similar to Titanium, carbon fibre is also a corrosion resistant material; meaning that the material will benefit from fewer maintenance issues. However, carbon fibre is by far one of the most expensive materials to use. This is evident from the material costing roughly £16.92/kg (Infosys.com, 2018) and then for the complex manufacturing process to manufacture the parts. Although this is the case, as technology advances and the manufacturing techniques become more efficient, carbon fibre is becoming the most sought after material for creating such complex pieces. The sporting advantage it provides in the F1 races far exceeds the costs for many racing teams.

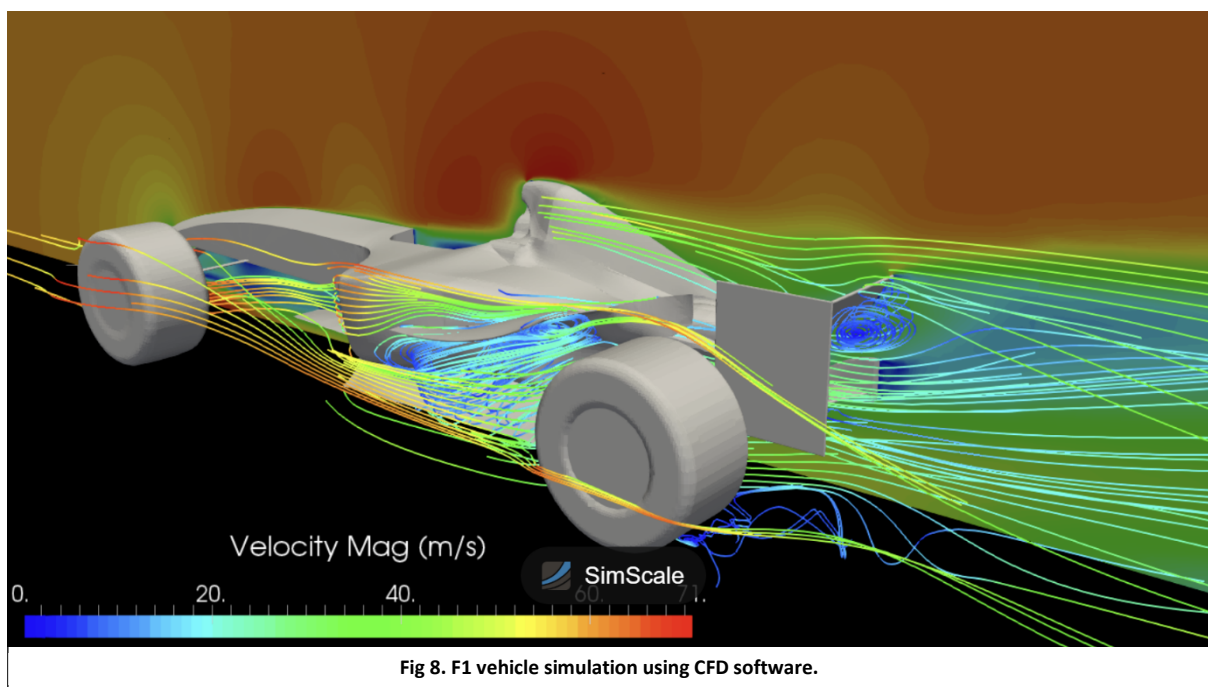
Material	Aluminium	Titanium	Carbon Fibre
Pros	-Lightweight -Cost effective -Repairability -Durability	-Strength and durability -Lightweight -Corrosion resistance	-Lightweight -High strength to weight ratio -Design flexibility -Superior aerodynamics -Corrosion Resistance
Cons	-Low strength to weight ratio -Limited design flexibility -Increased drag in comparison	-Cost -Limited availability -Design flexibility -Manufacturing difficulties	-Cost -Repair complexity -Impact resistance

Section 6: Modelling Techniques

CFD (Computational Fluid Dynamics) modelling software is used in the F1 industry to help in the development stages of the vehicle design. The software uses an algorithm to simulate fluid flow over an object. The model is first designed using a 3D CAD software and then is imported into the CFD software. From here the model is then converted into a mesh. Depending on the scaling of the mesh, the CAD model will be broken up into smaller simpler shapes. This will help the software to complete its calculations. The smaller you make the mesh segments you break the model into, the greater the level the accuracy the software can produce. However, with as the number of segments increase, the greater the amount of processing power it would take the computer to run the simulation. A technique to help with this limitation is to cut the vehicle in half from front to back. This will work for as long as the vehicle is symmetrical.

Once the mesh has been created, the boundary areas in which you want the model to be tested in will now need to be created; this area would act as your 'Wind tunnel'. Once the vehicle has been placed in the testing zone the software can now be used to run its equations and solve to work out the fluid flow.

The software will now work out a set of simultaneous equations and every segment from the mesh at the same time. These complex equations would take a person a drastically long time to solve. Fortunately, as time has progressed, the software we now have in modern times has enough processing power to conduct all these equations for us. The results are shown using colour codes to highlight sections where fluid flow and increased levels of pressure are being applied to the model. From these results we can better predict the outcomes of what would happen if the vehicle was to run on a real-life track.



Advantages of CFD

Cost Effective: With the tests all being run through a digital simulation, there is very little need for physical models to be produced for every test. These cost savings also come from not requiring using any fuel or having multiple people around to run a single test.

Faster development time: If multiple members of the team working on the design have access to the software, multiple tests with different designs can be run simultaneously. Also, the benefit of not needing to wait for the parts to be fabricated to run the tests can greatly speed up the process.

Risk Reduction: Through not requiring a physical prototype to test the design of the vehicle, it means that the risks of any injuries caused by any unforeseen problems are minimised. The results from the tests can highlight any glaring issues during the early development stages before getting to the prototype stage.

Environmental impact: By not using extra materials to create and run prototypes, savings through the lack energy consumption and waste production means the team can be more environmentally friendly.

Highly detailed results: The CFD software can produce results for not only fluid flow but also data on the pressure, temperature and other factors that may not be obtainable from a physical test. The results from these digital tests can also highlight small details that otherwise could be missed if only a physical test was conducted.

Enhance collaboration: When working as part of a larger team, having all this detailed test data digitised means that it can be easily shared and readily available for anyone else who wishes to analyse the results. This data can also be stored for reference for future projects where it may become useful.

Disadvantages of CFD

Complexity: For a person to be able to use the CFD software, they will need to be properly trained in how to operate it. The software requires specialised knowledge to understand be able to use the software efficiently. This can be a steep learning curve as the software is complex and also requires knowledge in other software such as CAD. As with most software, the person who is inputting the data will need to be accurate. The software will work through the equations based off the user. Unfortunately, this means that if the incorrect data has been inputted, the resulting output will also be incorrect.

Hardware Requirements: As mentioned before, the hardware that runs the CFD program will need to be able to handle the vast number of simultaneous equations. The more detailed/accurate the results need to be, the greater the amount of processing power will be necessary from the hardware. If the hardware is lacking, the CFD software will be limited in what results it can produce. Greater hardware will also incur greater costs to purchase and also run.

Initial set up timings: Whilst it can certainly be faster than building a prototype, the initial model can be time consuming to produce. It also takes time to then import the model and create the mesh and boundary layers for the test. However, once you have created this initial base model, making adjustments in future tests will be much quicker.

Assumptions: For the software to function it will need to make a few assumptions. The software cannot account for every possibility in the real world. Assumptions such as the ground being

completely level and at dry conditions, as the software cannot simulate wet or windy conditions, means that it can only predict what would happen in the optimal environments. Other assumptions such as material conditions and using simplified boundary layers means that they are still unaccounted factors that can affect the vehicle in real life.

Validation: The simulation is still at the end of the day, an experiment. Real world testing would still need to be conducted to validate that the results from the CFD software are accurate. However, working in conjunction with such techniques can better help to get the results as accurate as possible.

Section 7: Testing Method

One of the main tools used by the formula 1 team is to use a wind tunnel to simulate the effect of the vehicle travelling at high speeds. The model is placed firmly on the ground and a huge fan is used to produce the air flow. Originally developed for the aircraft industry to test the effectiveness of aerofoils, the F1 team has adopted this technique to safely test prototypes in a controlled environment rather than to take risks by having a person pilot the vehicle in real world conditions. However, the biggest difference with the wind tunnels used in the aerospace industry is that the wind tunnels for F1 cars have a moving ground. This conveyor belt can help to replicate the affects the fluid flows would have in terms of the relationship between the vehicle and the road. Utilizing new 3D modelling and printing techniques, the prototypes can have many parts produced in a timely manner. However, the wings on these tests are made of metal as it is important to keep these parts as close to the desired complete design as possible.

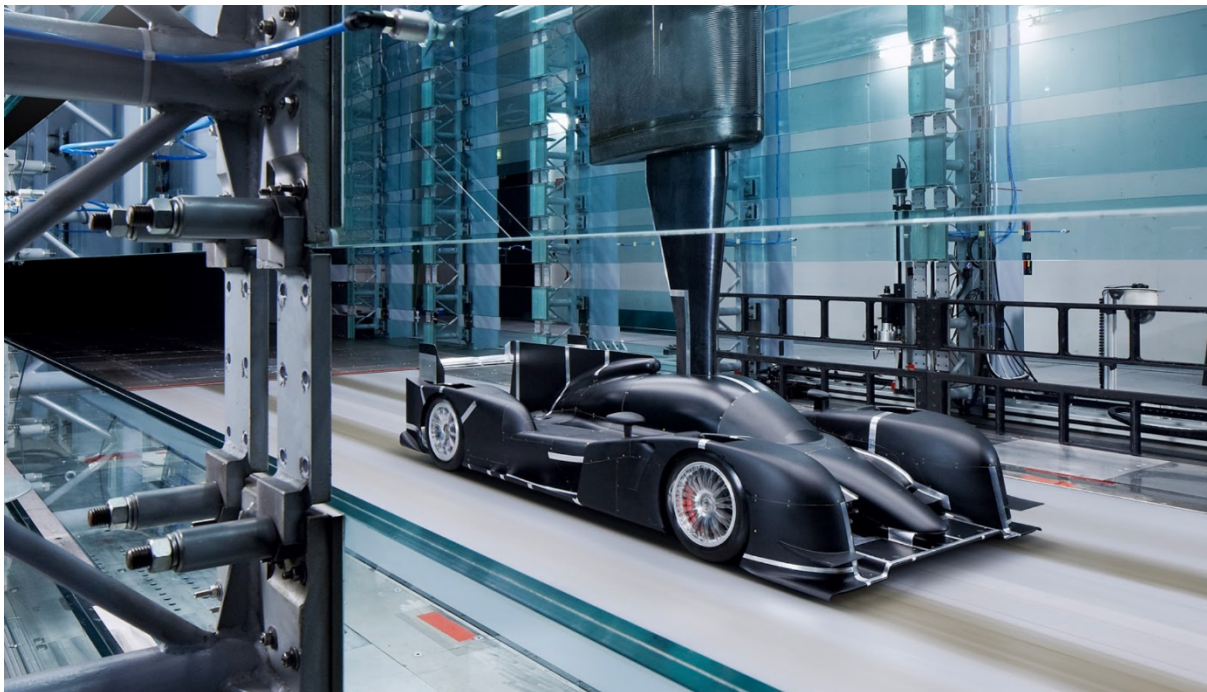


Fig 9. Wind tunnel used to test the Toyota TS030 early prototype version.

The models produced, due to budgeting constraints, are typically produced at a 60% scale Model (MercedesAMGF1, 2021). Other restrictions that are put into place include the tunnel only being ran at a velocity no faster than 110MPH/180KPH. Unfortunately, the average car speed in the F1 is 138MPH/223KPH (Professionalshq.com, 2023); meaning that the wind tunnel does not quite reach the velocity required to match the real world conditions. Furthermore, results from the physical test will need to be put through an equation to work out what the resultant forces would mean for a full scale vehicle. If we are to understand Bernoulli's principle; by applying the 40% reduction to the size of the test model, we would then need to proportionally increase the velocity produced by the fan in order to get a fair equivalence. As the regulations set by the F1 does not allow for this, adjustments to the end results would need to be made to get a more accurate outcome.

Surmising from explanations from Mercedes, teams in the F1 also are only allowed to run a limited number of tests in the wind tunnels; meaning that the teams need to make sure they conduct tests on only builds they are especially happy with. This would suggest the greater importance in using alternative methods, including CFD modelling.

Taking the collected data via the use of software such as CFD modelling techniques, you can compare and look for any correlations against the results of the physically trial run. The CFD modeling can help to produce a level of expectations with the designs created. After completing numerous virtual tests using the CFD software, only the designs that yielded the best results can then be prototyped and used in the wind tunnel. This would help to reduce the costs in manufacturing these prototypes and running the physical simulations.

Section 8: Evaluation

From this project I have learnt that the rear wing of a vehicle is important for high velocities. The shape is designed to produce the extra downforces required to keep the vehicle from losing control from the resultant lift forces created in high velocity environments.

Carbon fibre, although an expensive material to purchase and produce, provides the necessary strength and design flexibility to allow F1 car designers to produce the most efficient methods of generating downward forces.

The digital method used to model and test prototypes has certainly got the most benefits when it comes to obtaining raw data. However, working alongside physical testing like wind tunnels can help to validate this data and provide overall more accurate findings.

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