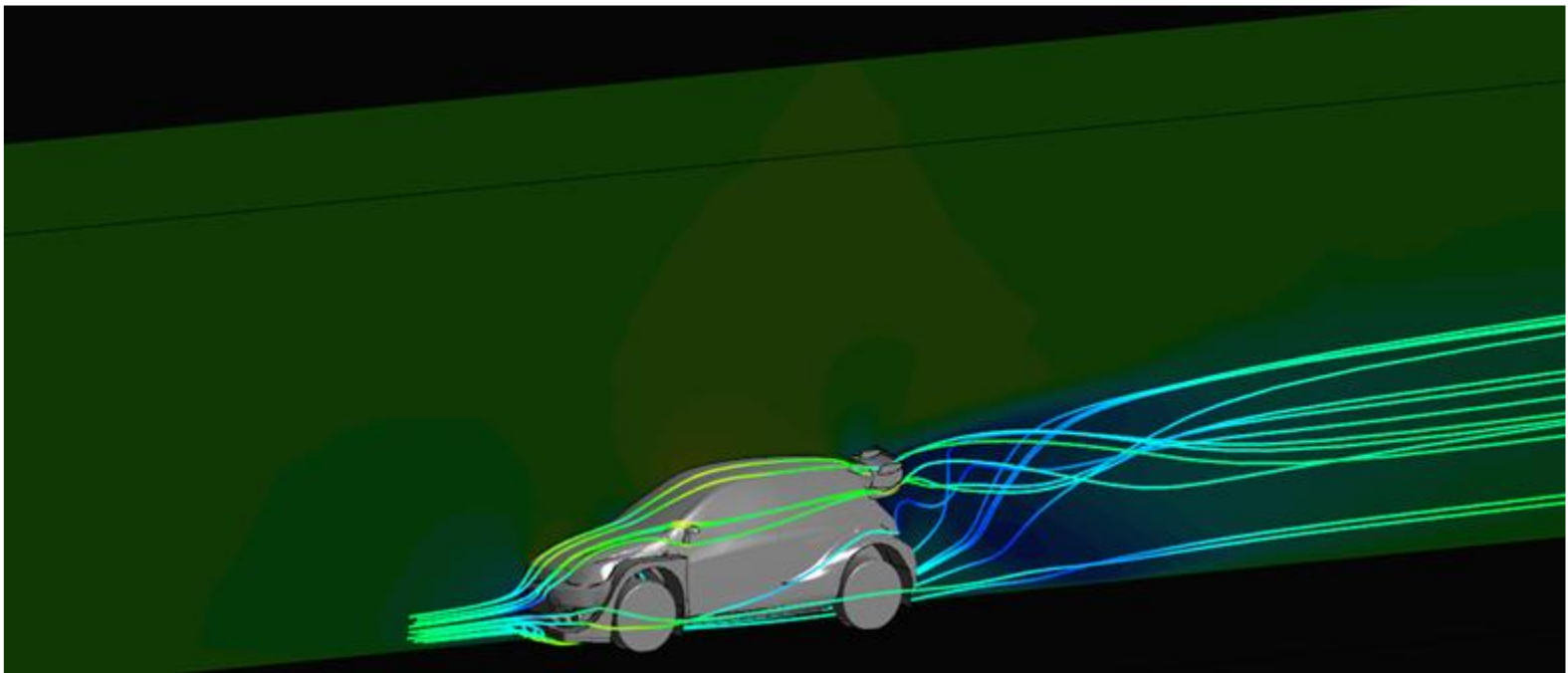




Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

School of Engineering

INVESTIGATION AND DEVELOPMENT INTO AERODYNAMICS OF MIRAGE RX SUPERCAR



Anthony Yin Wai Hau

P146898

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Supervisor: Tim Tudor

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ABSTRACT

This case study project was proposed due to the request of Rally Car Manufacturer Spencer Sport, to see whether their rallycross race car can further improve its aerodynamic efficiency through enhancement of airflow control around the vehicle, by improved design of existing aerodynamic assisting systems.

The geometry of the given rally car model needed to be clean up to create a workable model, this initial model became the baseline model for further development. CFD was used on various development models to find out the aerodynamic behaviour of these models in the post processing state, the most efficient model was then selected for further development, or to find closure to the project.

Initially the project plan was to keep the centre of pressure of the vehicle the same as the original given design, during the project study, from the feedback of rally car driver (Julian Godfrey), it was found that the desired responsiveness of the steering control was lacking, which suggested that there was a lack of grip in the front wheels. To enhance the responsiveness of the steering, it was decided to move the Centre of Pressure further forward towards the front of the race car.

In general, the aim of the project had been achieved. The study has shown that the rally car's body-work can be further improved, especially toward the front of the vehicle.

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LIST OF SYMBOLS AND ABBREVIATIONS

AWD	-	All Wheel Drive
A	-	Car Frontal Area
AOA	-	Angle of Attack
Ap	-	Plan Area
Bhp	-	Break Horsepower
CD	-	Coefficient of DRAG
CFD	-	Computational Fluid Dynamics
CL	-	Coefficient of LIFT
COP	-	Centre of Pressure
D	-	DRAG Force
F1	-	Formular 1
FIA	-	Fédération Internationale de l'Automobile
G	-	Gravitational Force
Kgf	-	Kilogram per square foot
L	-	LIFT Force
Mph	-	Miles Per Hour
SAE	-	Society of Automotive Engineers
WRC	-	World Rally Championship
DOE	-	design of experiment

1 Introduction

1.1 A Brief History of Aerodynamic Application to Cars

The concept of applying aerodynamic to vehicles was initially slow and reluctant, reasons being the first automobiles had been very slow, and that there was only the need to protect the drivers from the natural elements such as rain and wind, vehicles were only designed with horse-drawn carriages in mind. Designs of ships and aeroplanes were much more successful, since they followed the natural shapes of fish and bird.

Automobile design had improved only when road conditions and vehicle speed had much improved. Initially automobile designers borrowed the shapes of aeroplanes and ships, such an approach turned out to be wrong. Only when automobile designers broke away from these improper examples, did the exciting breakthroughs into automobile aerodynamics came about (Schuetz, 2016).

1.2 Road Grip at Speed (the need for Downforce)

On 28th January 1938, Rudolf Caracciola and the Mercedes-Benz team had managed to achieve a new speed record with their Mercedes-Benz W125 Rekord Wagen, at a speed of 268.9 miles per hour on a public road. Afterwards Caracciola the driver reported that he had experienced a complete loss of steering, and roadside observers also reported that they saw the front wheels of the vehicle losing contact with ground (Karl, 1971).

The vehicle was in fact very carefully shaped to meet the head-on wind, nevertheless the instability of the vehicle had become a major concern for the team.



Figure 1-1 Mercedes-Benz W125 Rekord Wagen (Snap LAP, 2020)

1.3 Use of Wings for Downforce

Wings to create additional downforce had caught on in 1966, to increase the vehicle's cornering ability, Jim Hall mounting a large wing over the rear wheels of the Chaparral 2E race car which managed to win the 1966 Nurburgring 1000 Kilometres race (Paul, 1972). From then on the use of wings grew, and they were mounted high over the rear end so that it can operate in the undisturbed air flow region, pivot control was used so that the angle of attack of airfoil can be controlled by the driver during cornering.

By 1968 wings were on high strut mounted at the back, as well as smaller wings on the car nose, unfortunately the designs had not been thought through carefully resulting in structural failures of these contraption during the race, causing injuries in some cases (TheJudge13, 2014). The FIA had officially banned these “high-mounted wing” for safety reasons in 1969.



Figure 1-2 Double-Wing Matra Cosworth MS10 (TheJudge13, 2014)



Figure 1-3 Jim Hall Chaparral 2G (Pinterest, 2020)

1.4 Vacuum Traction

In 1970 Chevrolet/Chaparral introduced a scheme consisted of reducing the air pressure under the car (the so-called Vacuum Traction) to gain downforce, by channelling air with fans to where they are wanted (the LEXAN side skirts were integrated to the suspension to maintain a fixed ground clearance at all times), resulting in the creation of the so called “Sucker Car”.

After running in a few races, this car design was banned due to fellow competitors complained about dirt and pebbles being ejected from this car is causing hazard to other drivers.



Figure 1-4 Chaparral 2J Sucker Car (Paul A Eisenstein, 2014)

1.5 The Discovery of Ground Effect

In 1977, while testing at the Imperial College of London on the idea of putting water radiators in the leading edge of the side-pods to cleaning up the turbulent airflow between the front and rear wheels of their unsuccessful Lotus 77, head engineer Peter Wright of the Lotus Research Team had accidentally discovered the “Ground Effect”, which lead to the development of the Lotus Type 78 F1 machine. The shaping of the car bottom together with the deployment of airfoil sidepods resulted in allowing the vehicle to gain a very high downforce but with only marginal increase in drag (Wright, 1982).



Figure 1-5 Lotus 78 on Sidepod (Addict, 2013)

1.6 Rallycross History and Rules

The Rallycross sport had started as a TV show for the ITV's World of Sport programme in 1967. Then the first FIA World Rallycross Championship (WRX) was held on 4th May 2014, which consisted of 12 events globally in the Supercar Category, attracting audiences all over the world.

Rallycross is a combination of Rallying and Circuit Racing performed on mixed road surface such as on dirt track and on race circuit tarmac. The rallycross race cars used in the 2,000 Turbo category are AWD and can produce around 600Bhp, capable of reaching speed of 60Mph from a standstill position in just two seconds, that is in fact faster than a F1 race car from standstill to 60Mph, under such an acceleration force the driver can experience 1.5G on their body.

According to the Speed Machine Festival held in Silverstone Circuit in May 2018, the competition race rules were:

- Open Practice Sessions
- Four Timed Qualifying Heats – The lap-time (not the positioning of the race car) were used, the best 16 cars can gain championship points (Max achievable is 16 points), but only the best (Lap-time) 12 race car can progress to the next level.
- There were Two Knock Out Semi Finals – 6 cars in each session (Max achievable 6 points), the top 3 from each session can enter the final competition.
- One Final – The championship points allocated at the final was "8", "5", "4", "3", "2", "1" points respectively to the positioning. Which in turn means the maximum championship points for a winner race car is 30 points.

During the race, all competing race cars must do a "Joker Lap" some point in the race, the "Joker Lap" is in fact an extended Lap of the circuit.

2 Literature Review

Aerodynamics is a word used since the 1830s, it is a combined word from the words “Aero” meaning “air” and the word “dynamics” meaning relating to “energy” or to “object in motion”, it is originated from the branch of Physics of mechanics that deals with the motion and equilibrium of systems under the action of forces.

2.1 The Four Forces

Consider an aeroplane while it hangs in the sky, there are four forces acting on the plane, these are thrust produced by the aeroplane engines pushing the plane forward, the resistance as the aeroplane punches through the air known as drag, which is directed in the opposite direction to thrust, with the mass of the aeroplane, weight results due to gravitational pull which is also recognised as downforce, and finally the force working against the downforce in the opposite direction keeping the aeroplane in the sky, the wings of the aeroplane helps to generate lift against its weight.

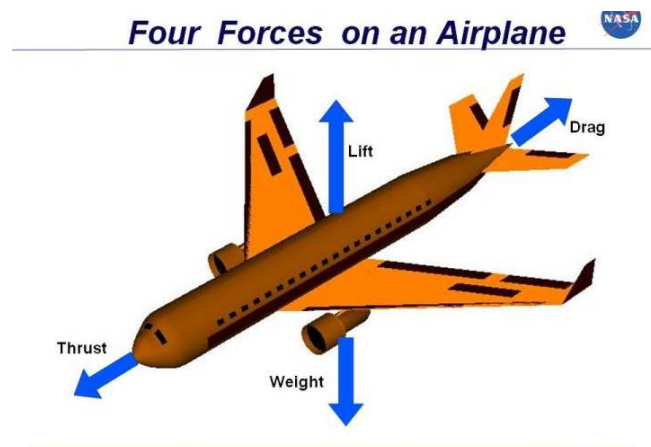


Figure 2-1 Four Forces on an Aeroplane (NASA, 2020)

This four forces idea can also apply to race car because high speed vehicle tended to show similar behaviour as an aeroplane in many respects. It can easily be appreciated that for race car to move very quickly forward, it must produce enough thrust to overcome its drag, but it can be less intuitive as to why race car engineers will pay so much attention to wing generated lift force by race car, when there is no intention to allow the race car to fly into the sky.

From observation, the performance of race car in terms of acceleration and breaking can improve when its tyres are able to stick firmer to the ground, that means the heavier (larger downforce)

the vehicle has, the firmer the vehicle can stick to the ground. Though the weight of the race car can not be changed during the race, by installing an upside down aeroplane wing to the race car and take advantage of its aerodynamic properties, negative lift or downforce can be generated for the race car, which in turn translate to enhancing the grip of the race car tyres to the ground.



Figure 2-2 Lift and Downforce (Oxyzoglou, 2017)

2.2 Drag and Lift Forces

Of the two basic aerodynamic forces acting on the race car, the first is the pressure acting on the race car as it travel in speed, which translate to vehicle lift and some of this translate to vehicle drag. Then there is the shear force (or friction) as air flow travel around the race car body that contributes to the vehicle's total drag.

Drag Force is represented by equation:

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

Where F_D is drag force, ρ is air density, A is frontal area of car, V is speed and C_D is the drag coefficient.

And Lift Force is represented by equation:

$$L = C_L q S \quad \text{where} \quad q = \frac{1}{2} \rho U^2$$

$$L = \frac{1}{2} C_L \rho U^2 S$$

Where L is lift force, C_L is the lift coefficient, ρ is air density, U is velocity of flow, S is surface area and q is the dynamic pressure.

These equations shows that the faster the vehicle is travelling (or the airflow is passing), the greater the forces generated.

Tests have also shown that good and effective Drag Reduction Systems can reduce 20% to 25% of drag to a race Car. Below diagrams show how a typical 2009 F1 race car's downforce and drag is distributed amongst its major componets.

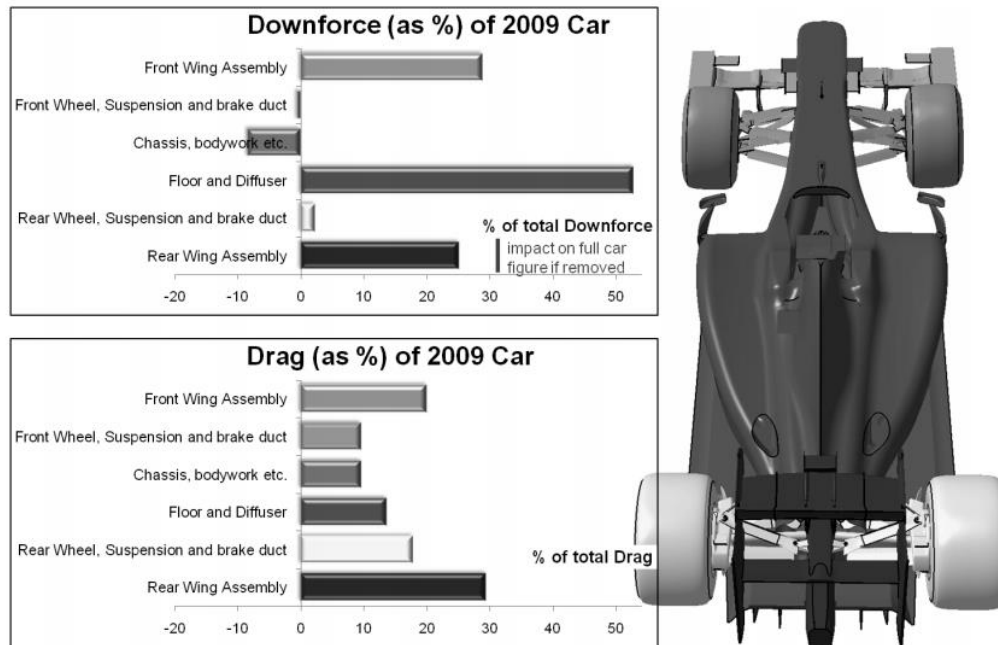


Figure 2-3 F1 Downforce and Drag by Major Components (Toet, 2013)

2.3 The Role of Wings

In today's motorsport, the downforce from the weight of race car alone is no longer enough to allow the vehicle to generate the necessary acceleration and deceleration it wants, especially when considering how engine power has gained efficiency over time. The first known attempt to harness the downforce from an airfoil on to a race car believe to have been made by the swiss engineer Michael May, in 1956, Michael mounted an airfoil on the Porsche Spyder just above the cockpit, in an attempt to direct the down force generated from the airfoil to the centre of the vehicle, unfortunately the scrutineers at the time in both the Nurburgring and Monza Races would not permit its use.

The function of an aeroplane wing can easily be explained by the theory of the airfoil. First there are misconceptions that airflow over and under the wing should be treated like a hail of bullets firing towards the wing in a horizontal straight line, air steams from both top and bottom of the aifoil to be meet up at the end of the wing at the same time " the Equal Transit theory". Then there

is the thinking that the air flowing over the top of the wing has a greater distance to cover before reaching the end to meet the air flowing from beneath the wing, the airflow on top must therefore be travelling faster with greater velocity, so its pressure must be lower according to Bernoulli's Principle, this pressure differential is said to result in the generation of lift to the aeroplane "the long path theory".

Not a hail of bullets



Fluid deforms, flows around obstacle

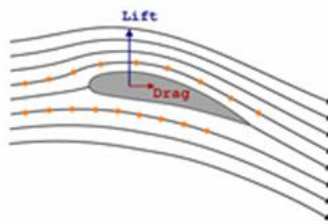


Figure 2-4 Airfoil Air Flow and Forces (Holley, 2013)

Though both thinking are partially correct, it must be very clear that air behave as a liquid, when it flows in speed around the aeroplane wing it will bend as you can see in the diagram above. The wing is in fact turning the incoming airflow downwards to generate lift, the deformation of fluid is generating enough lift to off-set the aeroplane's weight.

2.4 Endplates

Since the wings on race car are inverted, the top of the wing must experience a higher pressure than the bottom of the wing, this results in a pressure gradient which will cause air to flow over the side of the wing from the top, creating a sizable turbulence as is shown in the figure below.

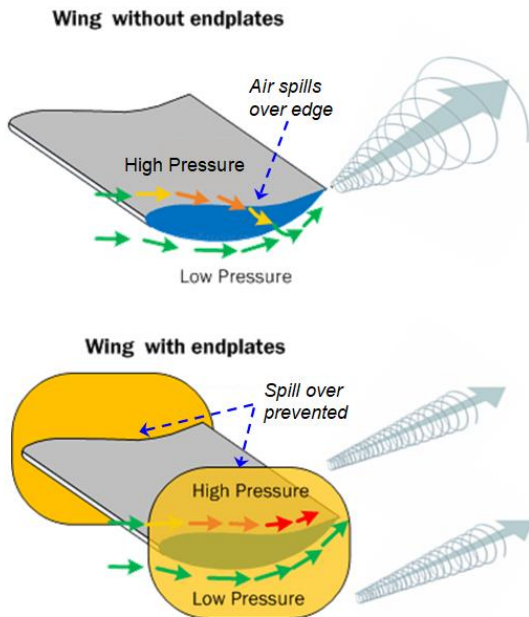


Figure 2-5 Air Flow difference with Endplates (Build Your Own, 2020)

With endplates added, airflow is contained between the endplates, though the endplates themselves will have some air spill over creating turbulences of its own, but these turbulences are much smaller in magnitude and much more manageable, which will translate to lower drag and smoother airflow for the wing.

2.4.1 Diffuser and Vertical Fins in Wings

In the perfect world, the air will flow over the race car in the boundary layer, this flow would follow the curvature of the car roof, car body, and will continue to flow to the back of the car, so that the air can be smoothly discharged at the end of the race car as an attached flow, unfortunately in the real world the airflow after passing over the roof of the car tend to separate, result in creating a sizable turbulence at the back of the car, creating separation bubbles, gaining drag and losing downforce.

The solution to this problem is to keep airflow close to the race car body all the way through, one of the ways is to create vortices so that the vortices can direct fast moving airflow back to the boundary layer, keeping the air flow in line and attached for longer and delay the separation as much as possible.

To direct air flow, diffusers on race car are used, this is why different diffusers are found in the form of wing, louvers, air-dams and canards to help airflow to travel smoothly and quickly under

the car floor, over and around the car body in a controlled manner, helping to generate that vitally needed downforce.



Figure 2-6 Rally Car underbody Diffuser (Nissan, 2017)

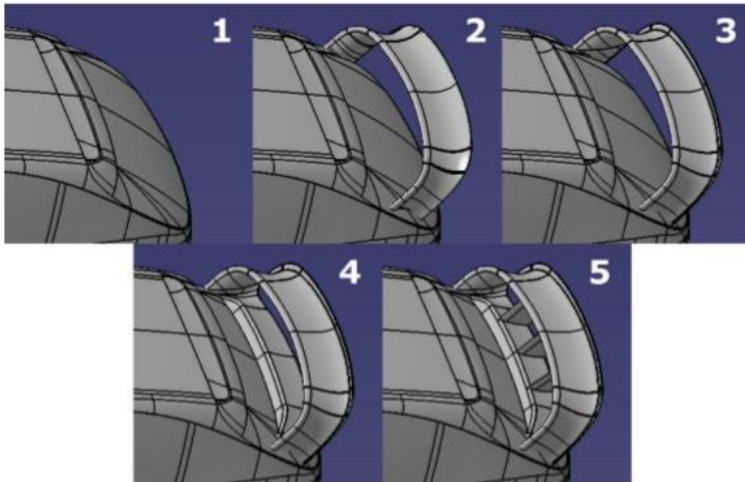


Figure 2-7 Variation of Rally Car Wings (Canada, 2012)

The above diagram shows the variation of wings used in an experiment to find how effective the wings are in generating drag and downforce for rally car, represented by:

1. Rally car without any rear wing.
2. Simple rear wing.
3. Wing with gurney flap.
4. Wing with additional air dam.
5. Wing with air dam and vertical fins.

Below table shows the results of the finding which shows wing with air dam perform best in generating extra downforce, but at a penalty of creating additional drag at the same time. The table also shows the different wing variation's efficiency which is calculated by lift generated over the drag created.

Table 1 Wing Variation results

Variation	1	2	3	4	5
Drag (-Y) [N]	766	874	948	1242	1206
Downforce (-Z) [N]	36	822	882	1518	1466
Efficiency (L/D)	0.046	0.941	0.929	1.222	1.215
Aero balance [% rear]	24.7	39.9	42.42	61.9	60.5

2.4.2 Yaw and Side-Force

The Yaw-Angle is the angle between the air flow velocity vector relative to the vehicle direction of travel, as is depicted in the diagram below.

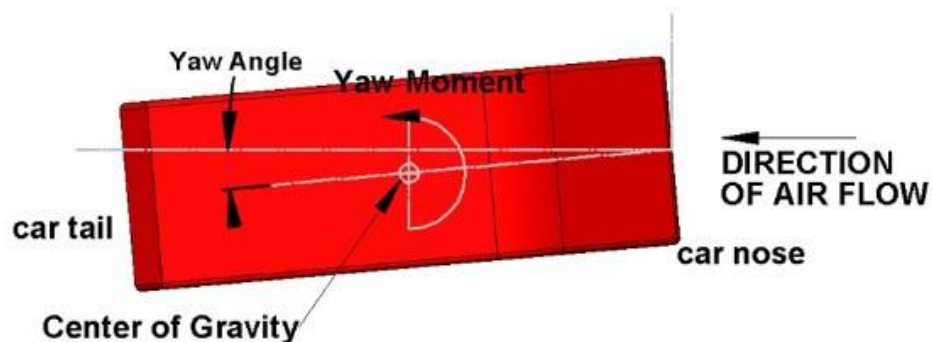


Figure 2-8 Yaw Illustrated (Cipolloni, 2020)

Even when a race car is travelling slightly sideways as would happen round a corner, the aerodynamic forces will tend to straighten the race car if it is yaw stable. Front heavy race cars are more stable in yaw.

SideForce is a counter-intuitive aerodynamic principle, think of a race car about to turn into a left hand corner, as the rear of the race car moves towards the outside of a corner, the air stream going through the rear diffuser will try to rotate the race car back in line and tighten the race car.

Looking at the below figure, as the race car is turning into a left corner, both the front left hand side and the rear right hand side of the race car are in fact experiencing a pressure change during the turn, these pressure changes are different to each other in scale depending on the design of the race car, they will result in a net gain in sideforce towards the inside of the turning corner and will push the race car to the left as it moves through that corner.

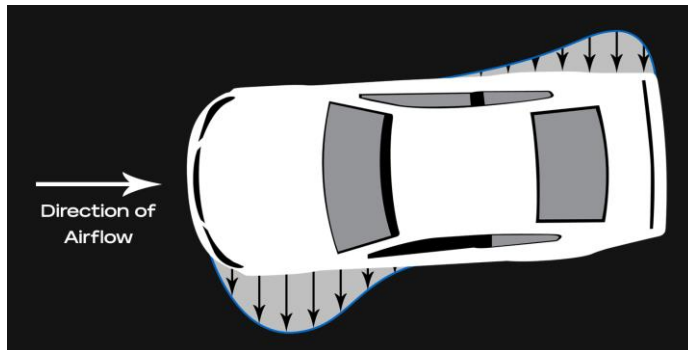


Figure 2-9 Pressure Diagram in a Yaw Situation (Commodore's Garage, 2020)

The forces experience by the front left and the rear right of the race car when plotted on a chart of Yaw-Angle against the resultant force, the graph lines of the two forces will eventually reach a Crossover point (at about 3° for the above vehicle) where beyond this point the race car will change from being relatively stable to being aerodynamically unstable.



Figure 2-10 WRC Wings with Fins (Luis, 2019)

Rally race cars often installed variation of rear wings to help gain aerodynamic assistance, of these the wing design with air dam are the most effective in capturing downforce. Though the wing design with air dam and vertical fins are less efficient than the wing design with just air dam, but when rally race car are turning corners, the Yaw effect will also alter the direction of airflow to the wing. Each fin under the wing will experience its own adverse pressure gradient caused by this “off course” airflow, resulting in air separation at each fin. This disruption of smooth airflow through the wing will result in the loss of downforce and the gain in drag, but on the other hand because of the fins, the gain in additional sideforce often makes it worthwhile for rally cars to have wings with fins. Below plan view diagram demonstrates how sideforce is gained from the fins.

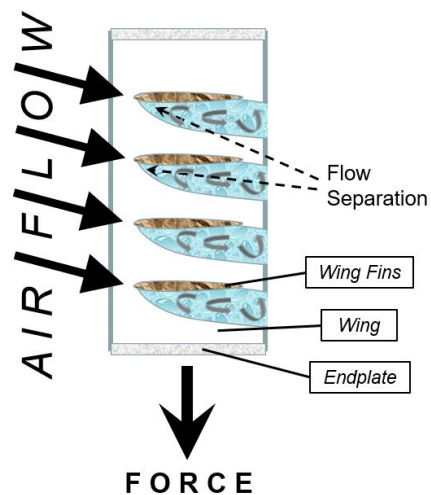


Figure 2-11 Sideforce Gain from Yaw Airflow

This sideforce gain is especially important for rally car racing on dirt roads as the dirt road condition means road friction is poor, and yet in RallyCross motorsport the circuit is half and half on dirt and tarmac road surfaces. The trade off in losing downforce for gaining sideforce may well be a good strategy depending on what kind of trade-off the RallyCross engineers wish to make. It is also understood that a 200Kgf of overall sideforce gain by the rally race car can directly translate to a one second gain in lap-time!

2.5 Bernoulli's Principle

Daniel Bernoulli was a Swiss mathematician, who expanded on Newton's ideas and discovered the motion of fluids, described in the 1738 publication the "Hydrodynamica" that an increase in the speed of a fluid occurs simultaneously with a decrease in static pressure (or a decrease in the fluid Potential Energy).

The relationship between air speed and pressure, represented by a streamline relationship between the local static pressure P , density ρ and velocity V forms the Bernoulli's Equation:

$$\frac{P}{\rho} + \frac{V^2}{2} = \text{Constant} = P + \frac{\rho}{2} V^2$$

Where the constant is unimportant here, need only to compare the velocity and pressure between two points in an inviscid steady flow.

Now thinking of a typical aerodynamic application under a constant flow condition with U_∞ , P_∞ is typically present at a very far distance away from the body to which the flow is applied.

So the Bernoulli's Equation will then become:

$$P + \frac{\rho}{2} V^2 = P_\infty + \frac{\rho}{2} U_\infty^2$$

Then introduce the dimensionless pressure coefficient C_p as:

$$C_p := \frac{P - P_\infty}{\frac{\rho}{2} U_\infty^2} = 1 - \frac{V^2}{U_\infty^2}$$

Bernoulli's equation can also be simplified to energy terms, where the conservation of energy of Bernoulli's equation is represented by 3 major energy components, pressure energy, potential energy (gravity) and kinetic energy (velocity), forming the equation:

$$P + \rho gh + \frac{1}{2} \rho V^2 = P_x + \rho gh_x + \frac{1}{2} \rho V_x^2$$

Where P is pressure, ρ is density, g is gravity, h is height and V is velocity forming the Bernoulli's Equation in energy terms.

By applying the principles, if air flowing on top of the airfoil is with greater velocity, that is there is a gain in kinetic energy, and assuming the weight characteristic of the fluid has not changed, the potential energy will be constant, then to balance the equation there must be a drop in pressure energy, thus there must be the lowering of pressure on the top of the airfoil as a result.

The diagram below shows how air as a fluid deforms and flows around the airfoil and results in the pressure difference created.

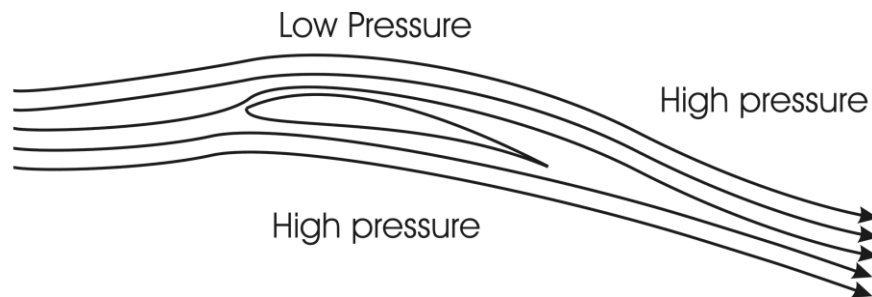


Figure 2-12 Airfoil Pressure Regions (Glownia, 2007)

The above principles are only applicable for isentropic flows, when the effects of turbulence and heat radiation are still very small and can be neglected.

2.6 Boundary Layer

Boundary Layer was discovered by a German physicist Ludwig Prandtl in 1904. Boundary Layer can be defined as a thin layer of a flowing gas or liquid in contact with a surface such that the fluid in the boundary layer is subjected to shearing forces. A range of velocities exists across the boundary layer from maximum to zero, provided the fluid is in contact with or sticking to the surface.

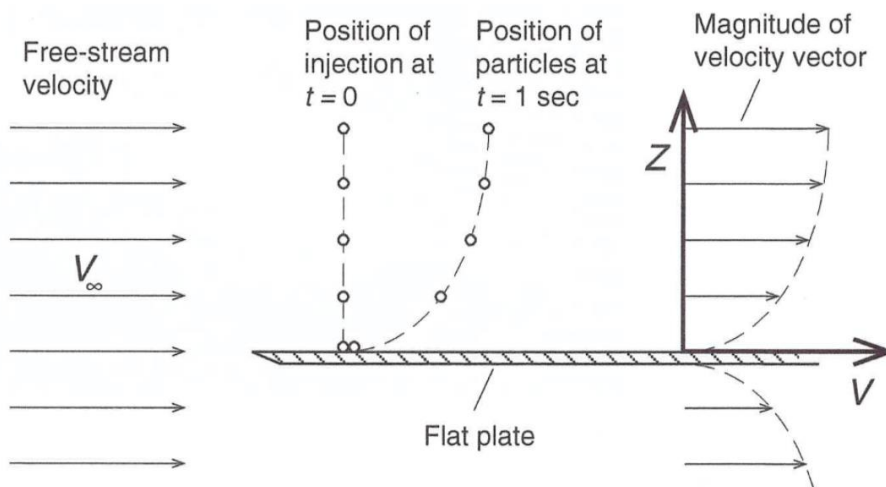


Figure 2-13 Air particle behaviour in Boundary Layer (Katz, 2006)

Air is a fluid, and as such it possesses the property of viscosity, imagine air particles sticking to the surface of the race car or to its wing, this is called the “no-slip condition” where velocity of the air particle at the surface is zero, moving away from the surface, the velocity of air particles increases until it reach the edge of the boundary layer, where the velocity of air particles at the edge are the same as the air particles outside of the boundary layer.

Boundary layers are thinner at the leading edge of a surface or wing and gradually become thicker towards the trailing edge. The flow in a boundary layers is generally laminar at the upstream portion and turbulent in the downstream portion.

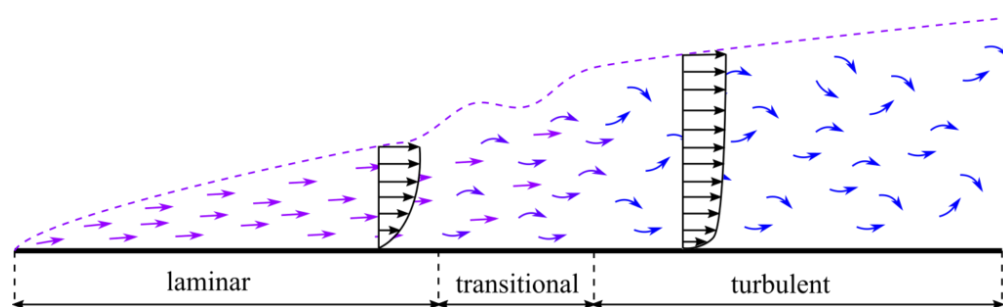


Figure 2-14 Laminar and Turbulent Flow in Boundary Layer (Apetrei, 2018)

Air flow is turbulent when air particles are moving erratic on non-parallel paths, the air particles are said to be momentarily moving in other directions, even though the average velocity of the air flow itself is of the same magnitude and direction as in the laminar case. Vehicle drag or lift and flow separation can change dramatically when air flow changes from laminar to turbulent, that is why the understanding of the different air flow is so important for race cars.

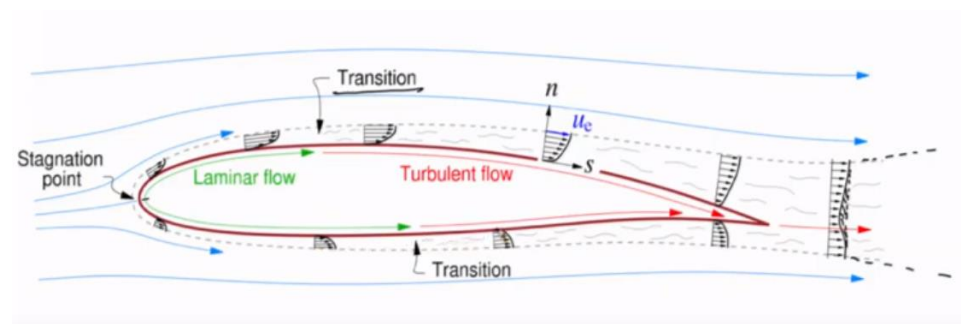


Figure 2-15 Boundary Layer flow features on a wing

A thicker boundary layer of a wing creates more viscous friction drag, further increase in boundary layer thickness can lead to flow separation, resulting in additional drag and a loss in lift.

$$C_f = \frac{\tau}{\frac{1}{2}\rho V_\infty^2}$$

The skin-friction coefficient C_f is a dimensionless number, it helps to indicate the level of friction between the race car surface and the air surrounding it, τ is surface shear force per unit surface, ρ is density and V_∞ is velocity.

2.7 Air Flow Separation and Turbulence

There are two ways of increasing lift on an aircraft wing:

1. Increasing the speed so that more air is flowing over the surfaces of the wing.
2. Increase the angle of attack of the wing, but there is a limit to this angle, there comes a point when the airflow comes away from the wing, at this point the airflow is separated from the wing, and a large proportion of lift is then lost as a result of separation.

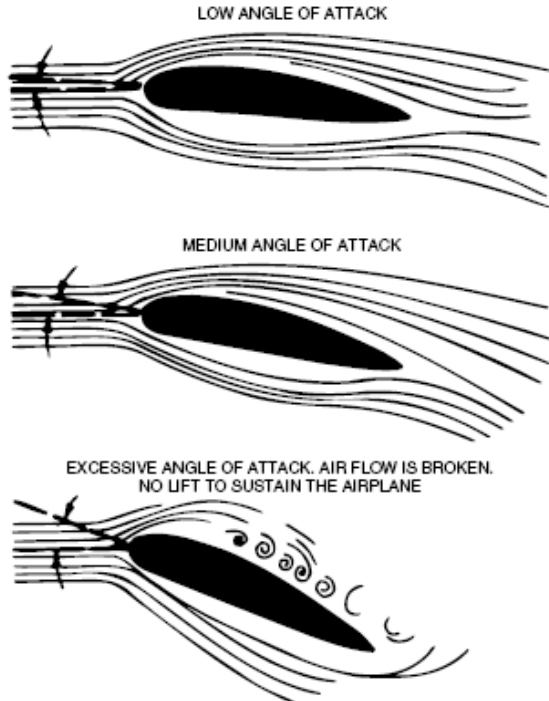


Figure 2-16 Airplane Wing in different Angle of Attack (Admin, 2020)

A stall is a rapid decrease of lift caused by separation of airflow, this can happen either the speed of flow is insufficient to allow the flow to attach to the wing surface, or that the angle of attack of the wing is too steep causing the boundary layer to enlarge quickly, resulting in separation of flow.

Air in boundary layer loses kinetic energy because of viscous friction, the flow direction immediately adjacent to the body surface will reverse to form a recirculating “separation bubble”.

Turbulent boundary layer may delay the onset of flow separation in certain circumstances, or even cause the reattachment of a separated flow, this is because the turbulent layer can actually reintroduce some fresh energy into the boundary layer (McBeath, 2015). This can have important positive benefits for drag reduction and at the same time more downforce creation.

While laminar boundary layer is beneficial in some circumstances, “Vortex Generator” as can be found in some race car designs today, may be of good use to re-energise or even create a turbulent boundary layer to prevent separation.



Figure 2-17 Image of boundary created by turbulent (Autosport, 2017)

For race car to maintain low drag, large regions of thin laminar boundary layers must be maintained and “the transition” be delayed. However, in the case where flow separation is likely, it is often more desirable to have a turbulent boundary layer with some drag penalty, rather than to have the painful flow separation which leads to the loss of downforce (Katz, 2006).

2.8 The Venturi Effect

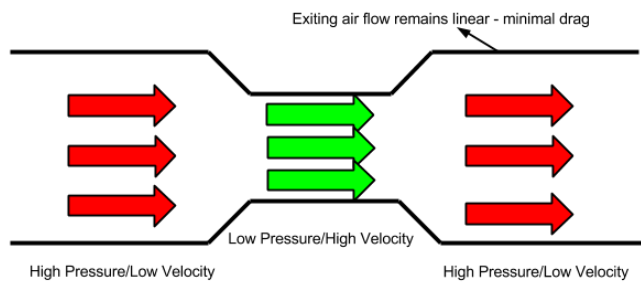


Figure 2-18 Venturi Effect (F1nsight, 2020)

The Venturi effect was published in 1797 by Giovanni Venturi, by applying Bernoulli's Principle to fluid that flows through a tube with a constricted section (or choke) of a pipe, and observed the reduction in fluid pressure at the choke.

In fluid dynamics, an incompressible fluid's velocity must increase as it passes through a constriction in accordance to the principle of mass continuity, meanwhile its static pressure must decrease in accordance to the principle of conservation of mechanical energy (Bernoulli's principle). Thus, any gain in kinetic energy a fluid may attain by its increased velocity through a constriction is balanced by a drop in pressure.

2.9 The Ground Effect

While the installation of wings at the rear of race cars can create drag, the alternative of increasing downforce for race car is to generate low pressure towards the bottom of the car, thus results in the suction effect.

One of the ways to generate even more downforce for race car is to capitalize on the ground effect. It is achieved by using the smooth out underbody of the race car, together with the road surface to form a tunnel like structure to create the ideal venturi effect, the race car gains the downforce due to the pressure difference created by the tunnels, these tunnels are literally sucking the race car downward towards the ground.

Schematic of how underbody tunnels can be integrated into race cars

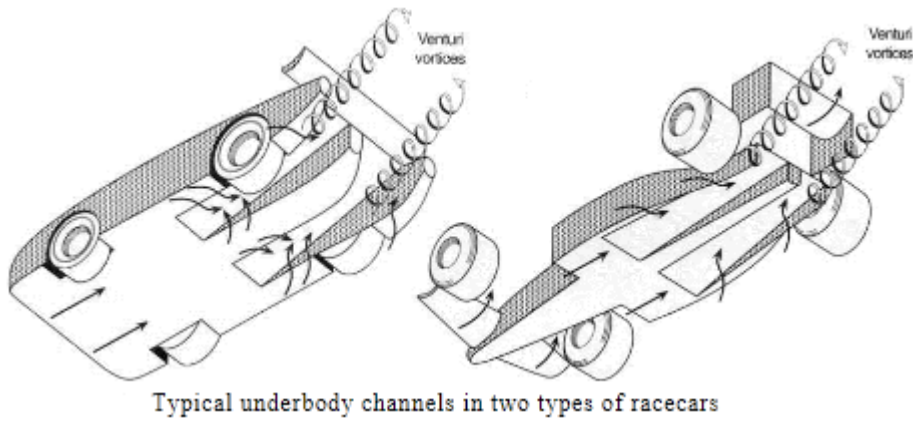


Figure 2-19 Race cars underbody schematic (Katz, 2006)

Schematic of 2021 F1 underbody tunnels to be reintroduce

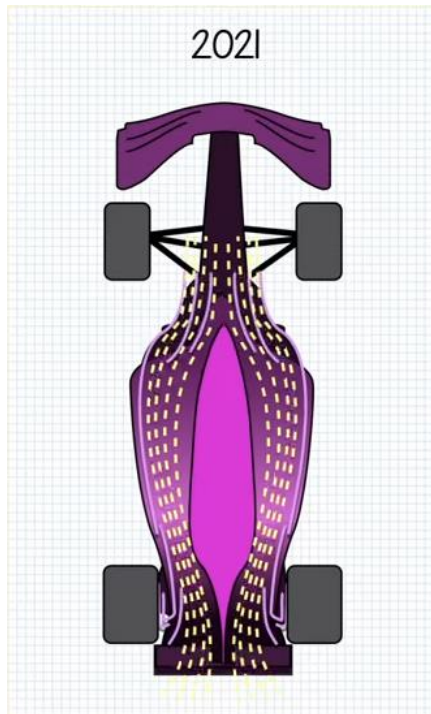


Figure 2-20 New 2021 F1 Underbody (Formula 1, 2019)

2.10 Balancing

Aerodynamic balancing in the form of centre of pressure is very important for race car because it can affect the stability of the car, thus affecting its handling.

The most optimum levels of downforce is not necessary the solution to a winning race car, instead the best downforce for the race car is one that is balanced and meets the race team's needs.

2.10.1 Round a Corner

Think of a square object on a flat plane, in order to set it in motion, apply a horizontal force so that it can act against its frictional force, where the friction is what is preventing the square from going into motion in the first place.

Apply the frictional equation:

$$F = \mu R$$

Where F is the frictional force, μ is the coefficient of friction and R is the perpendicular force.

The perpendicular force can be the gravitational force on weight alone. Or it can be the sum of weight and the additional downforce that the race car aerodynamic assist system can help generate when the race car is travelling at speed. R_W is from Weight and R_A is the sum of aerodynamic generated downforce.

$$R = R_W + R_A$$

Now think of the race car turning a corner say at constant speed with m as Mass, V as velocity and r as the radius of the turning circle.

We can then apply the motion force equation:

$$F = \frac{mV^2}{r} \quad \text{substitute "F", then} \quad \mu R = \frac{mV^2}{r}$$

$$V = \sqrt{\frac{\mu R r}{m}}$$

V is the maximum speed that the race car can travel around the corner before it loses traction and start to go out of control.

From the above equation, the larger the R, so will V be increased.

If $(R_W + R_A) > R_W$ is true, then the additional aerodynamic downforce R_A will result in the race car being able to accelerate and brake harder, and so be able to travel at a higher speed around corners.

The above calculation is based on an ideal world situation, but unfortunately the atmosphere on earth is filled with air which behave like a fluid, as a by-product of the race car travelling in speed through the air, must also take into account the drag this creates and also any positive lift as a result.

2.10.2 Front and Rear Downforce Distribution

In race car competitions, there are two major areas where the race car can be tuned to match the circuit characteristics so that the driver stands a better chance of winning, they are in the area of Mechanical Balancing and Aerodynamic Balancing.

Of the latter which involves the centre of pressure of the race car, much effort must be spent by race car engineer to tweak all the aerodynamic assisting systems so that the race car can match what the driver wants and what the racing track condition demands.

The first thing race car engineers will look at is what speed the driver wants to tackle at a corner, with low downforce to the front, the race car is exposed to under steering, and may run wide as a result, yet with too much downforce to the front, the race car is likely to over-steer, destabilising the whole race car launching it into a free tail spin.

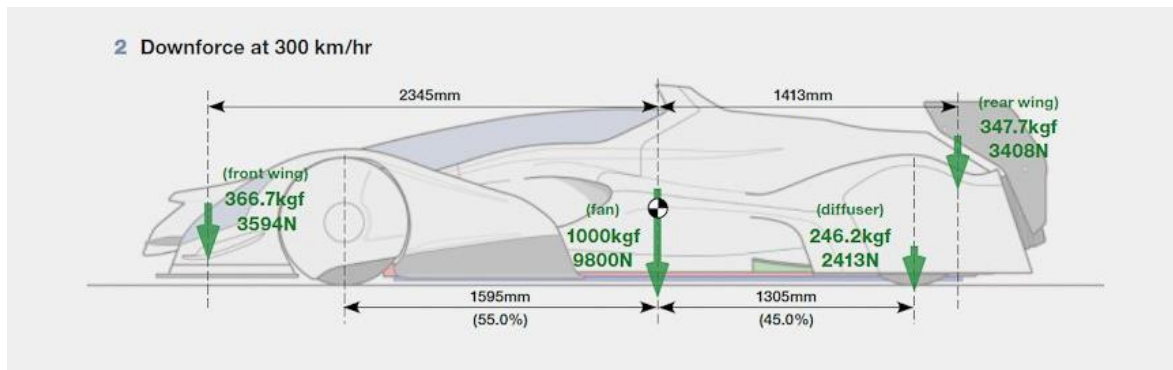


Figure 2-21 Race Car Downforce at speed (*Exorcet, 2011*)

The above diagram shows how the various different aerodynamic assisting systems can help generate the additional downforce when the race car is travelling at speed, but notice the forces are not necessarily generated at the wheel axis where the race car tyre is in contact with the track. The designed centre of pressure for aerodynamic balance must be maintained, that is why tweaking of these assisting systems are necessary.

Applying Newton's third law and considering the downforce at both front F and back B wheels, and then have their reaction forces represented by R_F and R_B .

First take the downforce generated by the **Front Wing** represented by W_F

- (1) Considering Moments **About F**

$$-R_B \times L_{FB} = W_F \times L_{W_F F} \quad (\text{Negative } R_B \text{ as its direction is towards the ground})$$

$$-R_B \times (1.595 + 1.305) = 3594 \times 0.75$$

$$R_B = -929.48$$

- (2) Considering Moments **About B**

$$R_A \times L_{FB} = W_F \times L_{W_F B}$$

$$R_A \times (1.595 + 1.305) = 3594 \times (1.595 + 1.305 + 0.75)$$

$$R_A = 4523.48$$

- (3) Then by Vertical Equilibrium Check

$$W_F = R_A + R_B$$

$$W_F = 4523.48 - 929.48 = 3594 \text{ Newton} \quad \textbf{(CHECKED)}$$

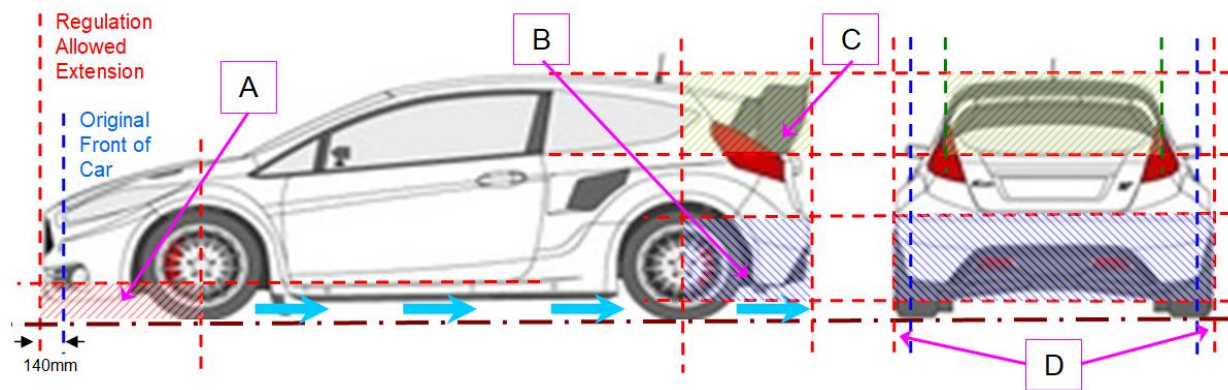
Also working on the downforce distribution of the Fan, the Diffuser and the Rear Wing, it was found that the total downforce exerted on to the front wheels totalled 8806.58N, and on to the rear wheels totalled 10408.44N.

With a lower aerodynamic downforce towards the front of the race car, the driver will have to be mindful of understeering at corners on this particular aerodynamic pressure setting.

2.11 Regulations

This project takes reference to the British Rallycross Championship Regulations, the Regulations for Autocross and Rallycross Racing(N), which itself reference to the Technical Regulations for Rallycross Cars published by the FIA on 6th December 2018, under the 2019 Appendix J - Article 279 regulation.

In accordance to these regulations and rules, this project focuses on area under the subsection Bodywork and Chassis, where the study will look at the air flow passing beneath the race car, and the project also looks at the development within the constrain and bounds of the regulations to the aerodynamic assisting systems. The project will implement design changes to the vehicle's fenders, air dam, rear wing, front and rear bumpers to see how the design change can further help improve the rallycross car's aerodynamic performance.



A. The first area of study is the front splitter near the ground, as part of the front bumper structure the regulation allows its extension by 140mm in front of the original bumper found on its homologated car.

B. Translating the revised regulation on the rear bumper, where its width must be the same as the body width of the rallycross car. Mudguards of 4mm thick flexible plastic material with minimum 100mm hanging from the ground had been used to meet this requirement.

C. Looking at possible improvements from the spoiler(air dam) and wing, though the dimensions of this rear aerodynamic device is already well defined, but the shape and material use are of free design, which opens to creativity and worth the effort to further explore.

D. The rallycross car can have a wider body versus the homologated car, the added width comes from the fenders, when the car is seen from above, the complete wheels of the car must not be visible above the wheel centreline. Height wise, the vender must not be higher than 400mm from the centre of the wheel.

3 Computational Fluid Dynamics (CFD)

3.1 History of CFD

CFD is the key area of computer simulation in fluid mechanics. CFD began in the 1960s and grew fast in parallel with the increase in computing power. CFD for Motorsport started in the Mid- 1990s, in 2004 engineers working on a budget were able to take advantage of some free CFD software such as the "OPENFOAM". CFD software continue to evolve into its very user friendly and easy to use characteristic of today.

3.2 How CFD works

There are 5 stages to CFD, they are ...

1. Generation of the Model (Geometry) – often engineers use CAD to help with the initial design, and with the model's CAD digital form the model can easily be imported to CFD directly.
2. The setting up of conditions (Domain Size) – such as air density, viscosity, velocity and the prerequisite of turbulence model, and if appropriate to apply the boundary conditions, indicating whether the test model is stationary or in motion.
3. Meshing (Verification) – the plotting action of thousands to millions of cells in some cases, cells are denser around the shape where its gradient is steep, cells are reduced at less critical areas. The available computation time must also be taken into consideration.
4. Solver –the actual calculation is performed and converge to a solution, here again the computation power also matters. Engineers can exercise balancing till solution is reached.
5. Post Processing (Validation) – analysis, images for analysis can also be created depending on the visualization tools available.

3.3 Benefits Limitations and the Future

CFD is fast, it is responsive to geometry changes to the design, CFD reduce the exposure to dangerous physical testing. Full scale simulation (no matter what size) in CFD is possible, and its data is portable between systems. But its parameter input is not perfect and can be limiting, that is why wind tunnels and practical tracking results are still perform and used to help validate.

With increasing computer power, eddy-resolving simulations may well be available in the near future, CFD may change from being a **postdictive** to a more trusting **predictive** tool.

3.4 Y Plus and Wall Function

The behaviour of flow near the wall is a complicated phenomenon, to distinguish the different regions near the wall, the concept of wall y^+ in the boundary layer has been formulated.

y^+ is a dimensionless quantity and is the distance from the wall measured in terms of viscous length.

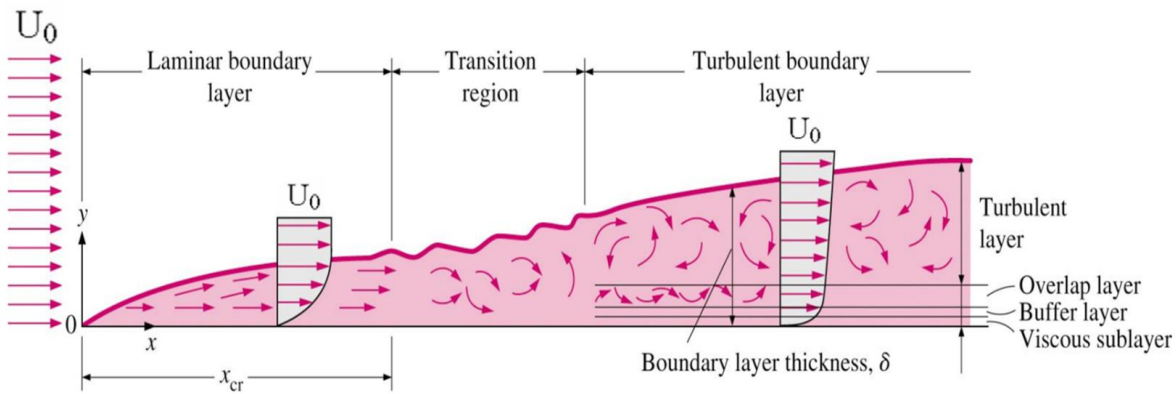


Figure 3-1 Different Regions in Boundary Layer Structure over a Flat Plate (LearnCAx, 2020)

Focusing on turbulent flow, from the above figure the flow near the wall has been divided into three major layers:

- The outer layer, or turbulent layer, large scale turbulent eddy shear dominates.
- The overlap layer (or Log Layer), velocity profiles exhibit a logarithmic variation.
- The inner layers, or the buffer layer and the sublayer, viscous shear dominates.

In order to represent the close to wall behaviour, it would be ideal if the gradient in velocity can be represented by assigning many cells as is shown in the figure below.

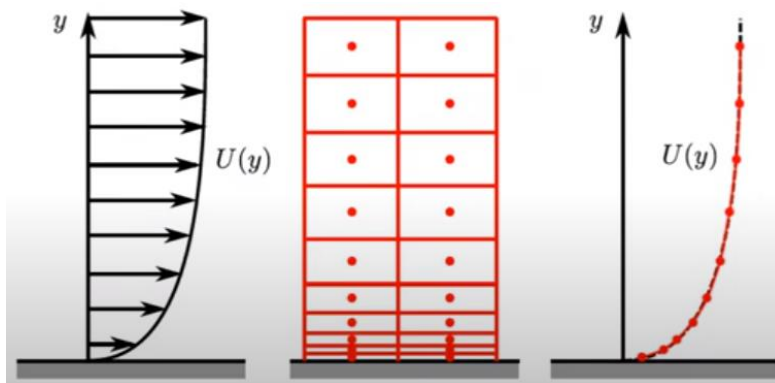


Figure 3-2 Gradient in Velocity and Proposed Meshing Cells (Wimshurst, 2018)

But moving closer to the wall, the cells used become thinner and thinner, the thin cells can have poor cell quality, which is not ideal for the CFD solver, the increase in the number of cells will also slow down the calculation and increase the time needed to reach solution.

An alternative would be to just use one cell to represent all the cells near to the wall, and it will have to be representative of the non-linear behaviour close to the wall.

Wall functions are the empirical functions that are fitted to the observed behaviour close to the wall.

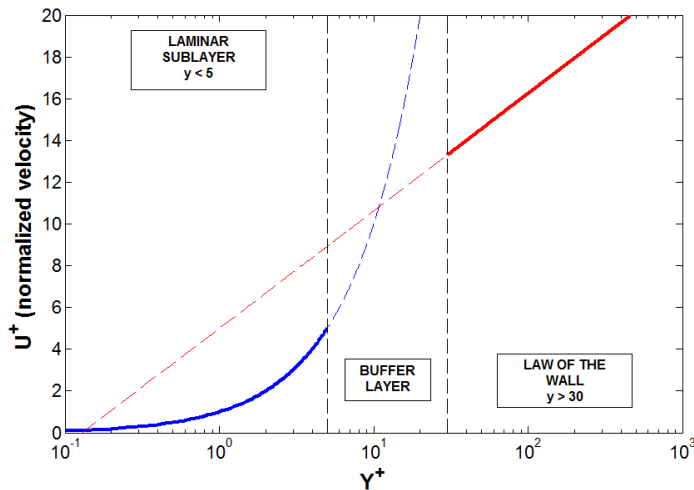


Figure 3-3 Wall Functions – Composite Regions of the Turbulent Boundary Layer (LEAP CFD Team, 2013)

In the diagram above, the **Blue Line** represents the equation (1) and the **Red Line** represents equation (2).

The Standard Wall Functions tells us that:

Equation (1) $u^+ = y^+$ where $y^+ < 5$

Equation (2) $u^+ = \frac{1}{k} \log(Ey^+)$ where $30 < y^+ < 200$

Where k and E are empirical coefficients (observed to be approximately k = 0.42, E = 9.1)

3.4.1 Spalding's Wall Function

But both Wall Function curves do not closely match the behaviour in the buffer region, that is why when performing CFD coding, placing cells in the buffer region should be avoided as it will give large errors, because neither of the two equations shown above are representative of the empirical curve at the buffer layer from experiments.

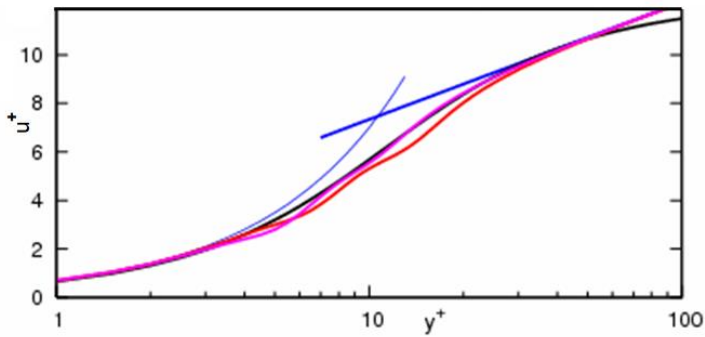


Figure 3-4 Sample Y Plus U Plus findings from Experimental Observations

An alternative is to use a single smooth continuous function that is representative of the behaviour of all the data even at the buffer layer.

It was found that the Spalding's Wall Function was able to match such requirement, provided y^+ is less than 300.

Spalding's Wall Function:

$$y^+ = u^+ + \frac{1}{E} \left[e^{ku^+} - 1 - ku^+ - \frac{1}{2}(ku^+)^2 - \frac{1}{6}(ku^+)^3 \right]$$

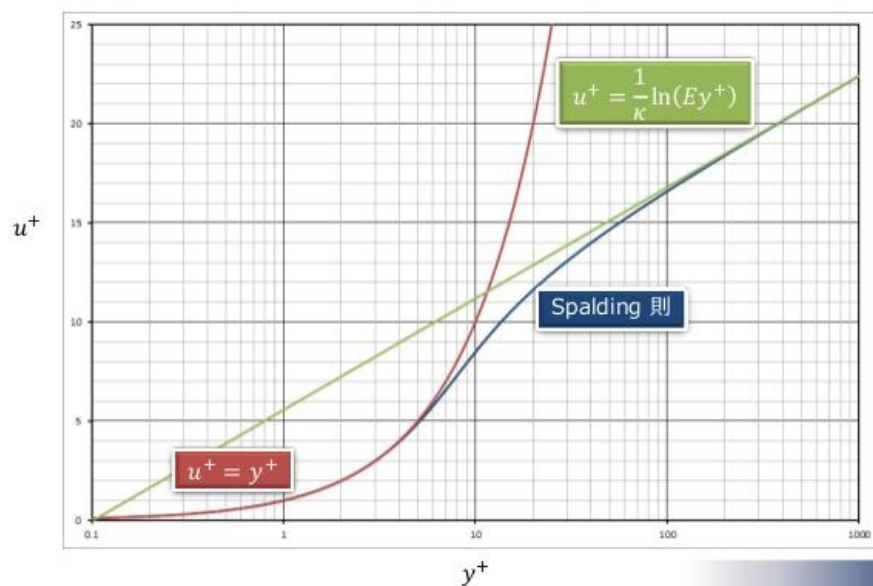


Figure 3-5 Spalding's Wall Function (SlideShare, 2020)

The major advantage of using such an unified wall function is that the first cell from the wall can be placed in the buffer or viscous region without the loss of accuracy, even if the logarithmic profiles is used to derive the figures. This also means that local refinement near the wall need not be switching from having to implementing one wall function and then to the other. Though in CFD coding some systems are already with an automatic function, where the system is able to choose between the two wall functions (also known as blending) for best results when calculating different cells.

3.4.2 Wall Functions on Turbulent Flow

Consider Turbulent flow in terms of Energy, where large eddy and whorls supports smaller eddy and whorls, and eventually that lesser whorls is affected by the viscosity force.

The famous Rhyme of Richardson:

Big whorls have little whorls,
which feed on their velocity,
and little whorls have lesser whorls,
and so on to viscosity. (in the molecular sense)

There are two eddy-viscosity model used in aerodynamic, they are the k-omega model which is well suited for simulating flow in the viscous sub-layer, and the k-epsilon model which is ideal for predicting flow behaviour in the regions away from the wall.

These turbulent models are about energy, where “k” from the equation represents the turbulence kinetic energy, while “E” represents the turbulence dissipation (i.e. the kinetic energy dissipation rate).

For CFD coding, the use of the e-epsilon model is favoured by the writer because according to the industry wide understanding, it has been proven to be a more accurate model to use. The epsilon value is calculated from the wall function by the system, the use of k-epsilon model is good when $y^+ > 30$ because there will be no viscous sublayer consideration, and that the k-epsilon model is able to resolve all the boundary layer within the log-layer, while the y^+ value is between 20 and to approximately 200 for closure. If y^+ value is too high, the boundary layer will become under resolved, and the mesh should be refined normal to the wall. y^+ must be clipped at 11.06, so it is not possible to over refine the meshing, and this can help protect the result's integrity.

3.5 CFD Practical Research Findings

An earlier assignment by the writer on CFD, where the findings and techniques were referenced by this project. The aim of the earlier CFD practical research was to investigate the optimal setting for CFD software to simulate accurate aero forces acting on the MIRA notch vehicle.

To achieve optimal setting for this project, the data from the MIRA wind tunnel with the same vehicle geometry was also used for validation.

There were multiple factors of setting, to get the best setting, the method used was to find the best results for each factor and continuing with the optimal settings until the results are representative.

3.5.1 Modelling and Geometry

To achieve high accuracy, maintaining the geometry quality was very important. The geometry of the CAD model must be very similar to the real object, but with a complicated model, the mesh reflecting the model must be even more detail to match the geometry of the CAD model, which can lead to a longer calculation time.

The geometry could be simplified, if CFD processing time was a constrain, but the accuracy can be lowered as a result. Another option was to divide the domain into sets of control volumes.

3.5.2 Domain size

If the actual wind tunnel test section area of the domain size was too small, it would have a Blockage Effect. With CFD software, symmetry or slip wall function can be selected to release and minimise the Blockage Effect.

Since the wind tunnel test section was of a confined volume, the aerodynamic measurements obtained from the wind tunnel test do not resemble those obtained in the infinitely spaced boundaries, such as the case of a vehicle moving on a plane road (Sahini, 2004).

On the type of modelling option selected, the degree of accuracy will define the pressure, temperature, flow rate etc. that are acceptable and can be used.

3.5.3 Mesh quality

There are different shapes of mesh cells, the main three shape are tetrahedral, hexahedral and polyhedral. Hexahedral and polyhedral can be constructed from tetrahedral, that is why tetrahedral cells are able to capture most data and was solely used in this practical research.

The mesh on the Mira data car was not very detailed, as less cells are needed in Mira data car study than the study on a real car.

Skewness was a measurement of the quality of the mesh in the CAD geometry, it identifies how well the regular mesh elements fit into the geometry profile. If cells are generated to have shape angle, the quality of cells would be lower (Baker, 2019).

Prism layer applies boundary condition on the model to CFD, although the quality of cells would go down, adding of boundary layer could improve the accuracy of the study.

The mesh used was design and created with reference to the computer power available, the solver was set up with the physical model, boundary and zone together with the initial value and previous solution findings. It was also necessary to set up solver controls and convergence monitoring in this exercise.

3.5.4 Turbulence Model

Turbulence Models are equations design to simulate turbulence between cells, the different models are de-sign for different purposes. They can only be selected at validation testing.

3.6 Mire notch car Validation

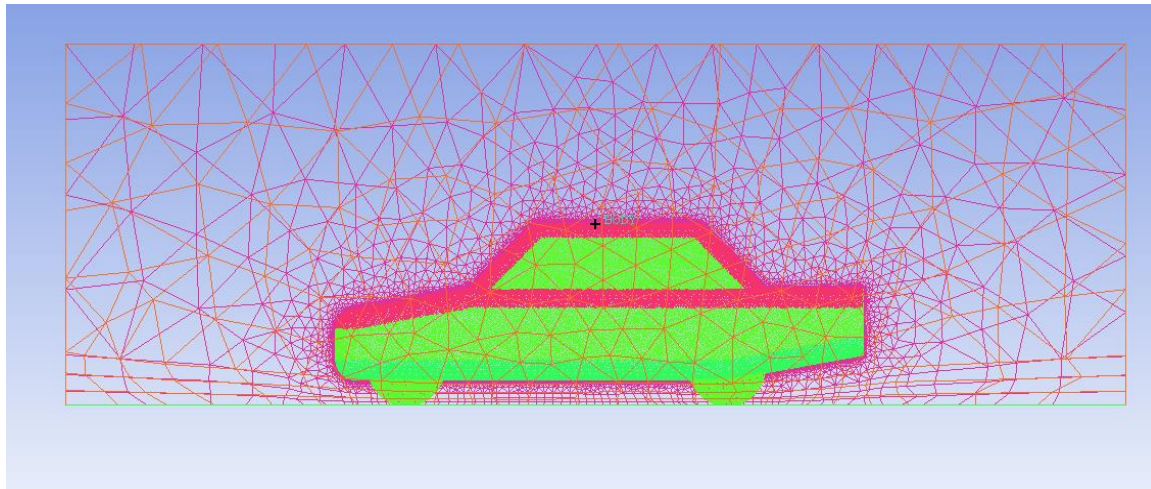


Figure 3-6 Mire notch car Mesh

To move on to the practical in this project, It was necessary to validate what results were found from the earlier CFD practical research.

It was found that the CFD result on the Mire notch car was very close to those data resulted from the wind tunnel test. The figures in the table below was derived from the earlier CFD practical research by the writer carried out in January 2019 (Hau, 2019), which was subsequently used in this project.

Table 2 Basic Set Up table

Mesh method	Robust octree
Domain size	26x5x3.5m ³
Density box mesh size	0.08m
Global element seed size	1m
Mesh size on CAR	0.01m
Mesh size on wing	0.008m
Number of prism layer	3
Turbulence Model	k-epsilon, realizable, non-equilibrium wall

The Mira notch car is symmetric left to right. To reduce calculation time, the test was run with half of a vehicle and half a wind tunnel due to the symmetry wall function. To prevent skew cell, the car model had also been sunk into the floor by 10mm.

The validated Mira notch car result was found to be inaccurate when it was applied to the Actual Vehicle on test, the problem believed to be mesh size being too big. It was therefore decided that a finer mesh was needed for this project to ensure an accurate solution can be generated.

4 CAD Model Refinement

The given rally car model from Spencer Sports for the study of this project was not exactly a RX Supercar model, so it was necessary to change the geometry to match that of the same needed RX Supercar model. First it was to merge the new facelift front bumper to the model, then the missing geometry of the 4 wheels and the underbody were also added to the model (See diagram below of the - Mark1 RallyCar).

Checks on effectiveness and efficiency were then conducted on all the proposed changes separately, these changes were carried out in a progressive manner. That is to say the model will adopt a single proposed change, say to the car's wing, the model with several variation of changed wing designs are then tested, when the most effective or efficient variation was selected, then the testing move on to the next design change, with the previous selected variation as the new Base-line Model for the next test. The test will end when all the changes had been carried out and a final best effective and efficient geometry found.

The model in the below diagram is the initial rally car model from Spencer Sport, the Mitsubishi Mirage R5.

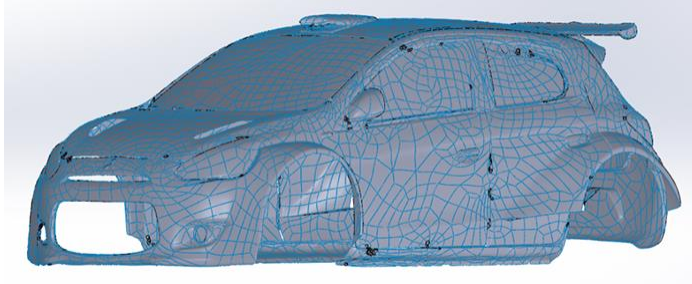


Figure 4-1 Mitsubishi Mirage R5 model

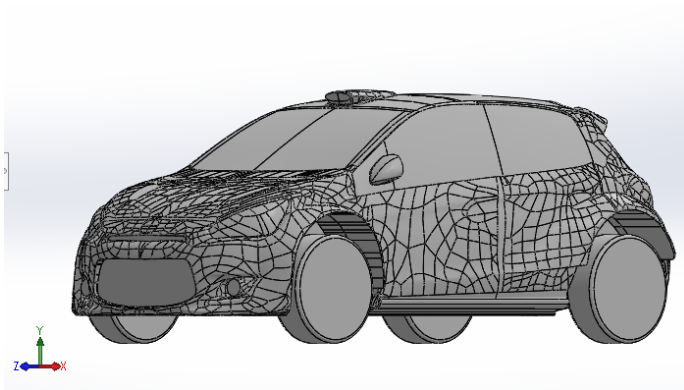


Figure 4-2 Model Mark1 RallyCar

4.1 Face Lifted Front Bumper

The aerodynamic efficiency of both bumpers both new (after having the facelift) and old had minor differences, of the new bumper there was higher pressure towards the lower part of the bumper causing a gain in downforce, which forces faster airflow to the bottom of the car, thus sucking the car downward even more than the old design.

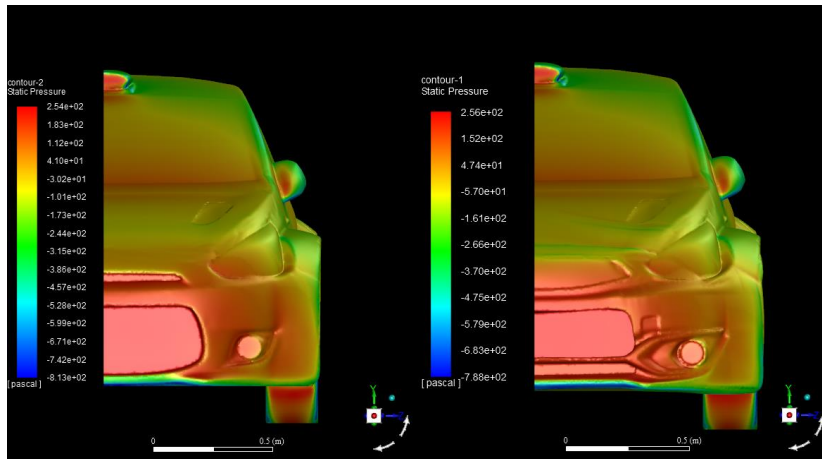


Figure 4-3 Mark1 and Mark2 RallyCar Front Bumper Test

Table 3 Front Bumper Test

	CL	CD
Mark1 RallyCar	-0.033	0.4
Mark2 RallyCar with Face lifted front bumper	-0.05	0.407

4.2 Air Scoop Removal

Since rallycross do not use Air Scoop (which is a contraption for supplying air to the driver), so it was removed.

By removing the air scoop there had been less turbulent at the roof of the rally car, this is shown in the diagram below. Without the air scoop, drag performance had improved slightly.

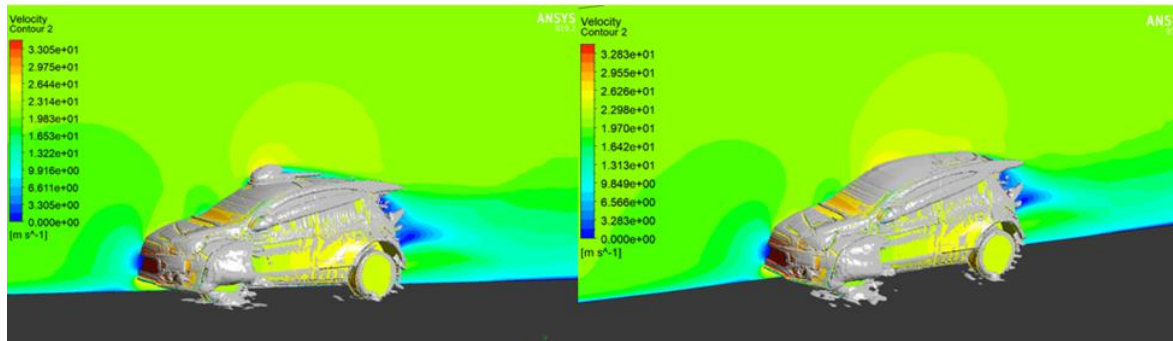


Figure 4-4 Mark2 and Mark3 RallyCar Air Scoop Removed Test

Table 4 Air Scoop Removal Test

	CL	CD
Mark2 With Air Scoop	-0.05	0.407
Mark3 Without Air Scoop	-0.039	0.394

4.3 Bottom Rear Fender

After the addition of fenders, airflow had been diverted away from the wheel by the fenders, with less air hitting the front of the tyre, the pressure on the surface of the tyre had been reduced, an improvement to the drag performance was noted.

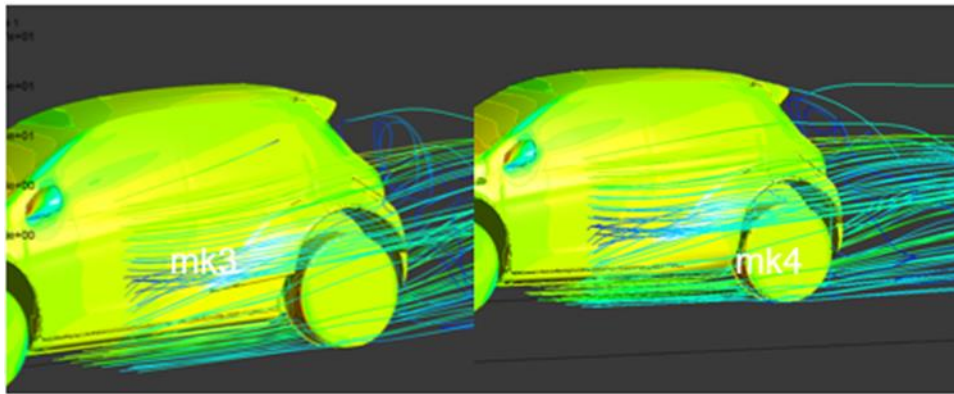


Figure 4-5 Mark3 and Mark4 Bottom Rear Fender Test

Table 5 Bottom Rear Fender Test

	CL	CD
Mark3 No Fender	-0.039	0.394
Mark4 With Fender	-0.035	0.377

4.4 Front Bumper Air Dam

Air dam had been added to the front bumper, since the air dam is designed to be close to the floor creating a smaller entrance to the bottom of the race car. The air dam is fused to the front bumper as one piece, with the added air dam, the bumper is experiencing greater pressure near the air dam region as air is being squeezed through the air dam to the underbody of the car, the air accelerates just like the Venturi Effect.

The experiment shows a gain in downforce, the airflow was able to be energized.

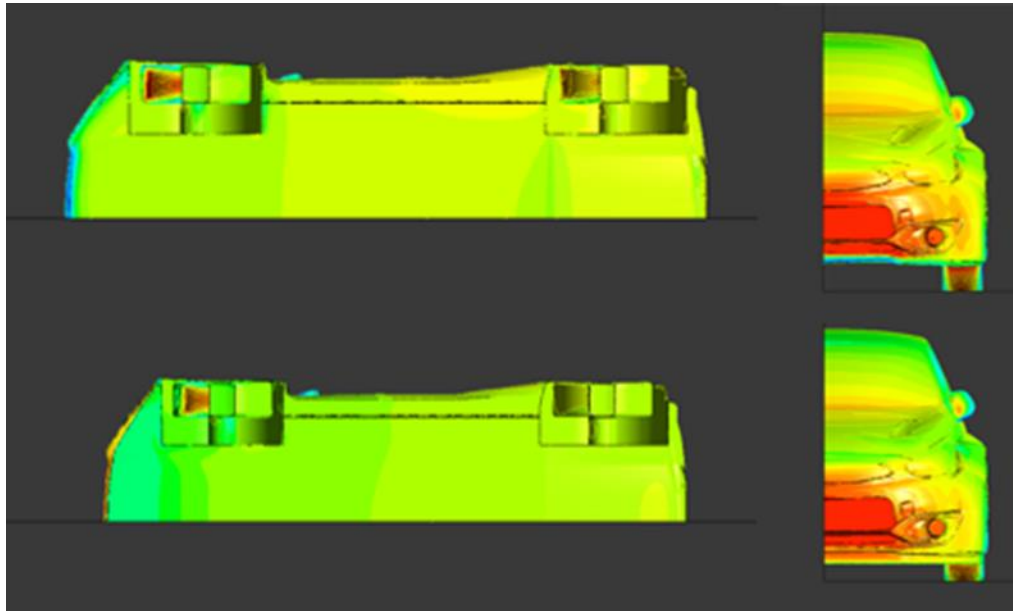


Figure 4-6 Top Mark4 and Bottom Mark5 Air Dam Test

Table 6 Front Air Dam Test

	CL	CD
Mark4 No Air Dam	-0.035	0.377
Mark5 With Air Dam	-0.063	0.371

4.5 Mud Guards

Though the mud guard was installed according to regulation, but when the race car is travelling at speed, it is understood that the mud guard will deflect backward in a curve. This feature was also built into the testing model to better illustrate the curved mud guard effect.

The result shows that greater amount of turbulence was created due to the mud guard, noted that the wheels was stationary in the simulation, if the vehicle wheels were in motion, this turbulence would be amplified due to the wheel spinning effect.

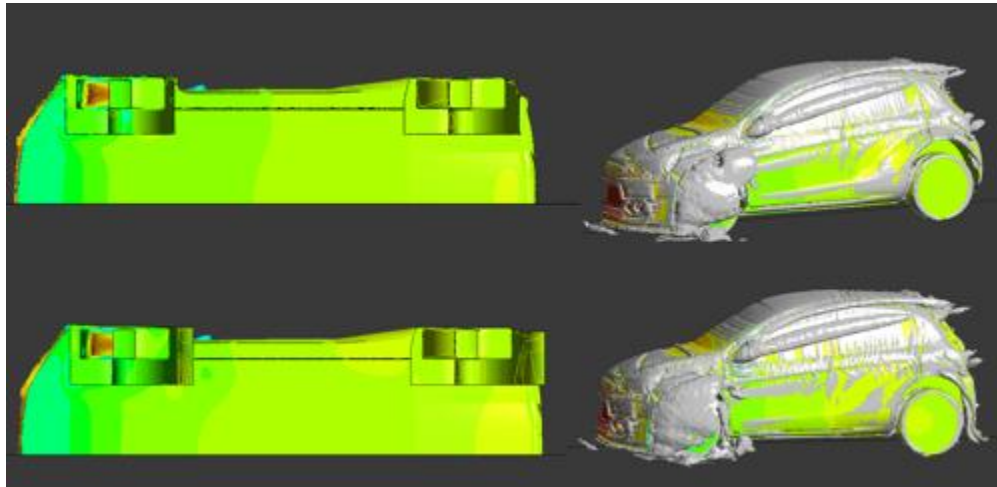


Figure 4-7 Mark5 and Mark6 Mud Guards Test

Table 7 Mud Guards Test

	CL	CD
Mark5 Without Mud Guards	-0.063	0.371
Mark6 With Mud Guards	-0.056	0.367

4.6 Wing Mirror

Spencer Sports has decided to change their rally car mirrors to a smaller size, as they wanted to lower the drag of the vehicle. With the mirror change, it was found that the trailing turbulent airflow from the wing mirror was much smaller, and it had also changed its flow direction from pointing up to pointing horizontally in line with the other airflow around the vehicle. So the change will improve the drag of the vehicle, but it will also decrease the downforce.

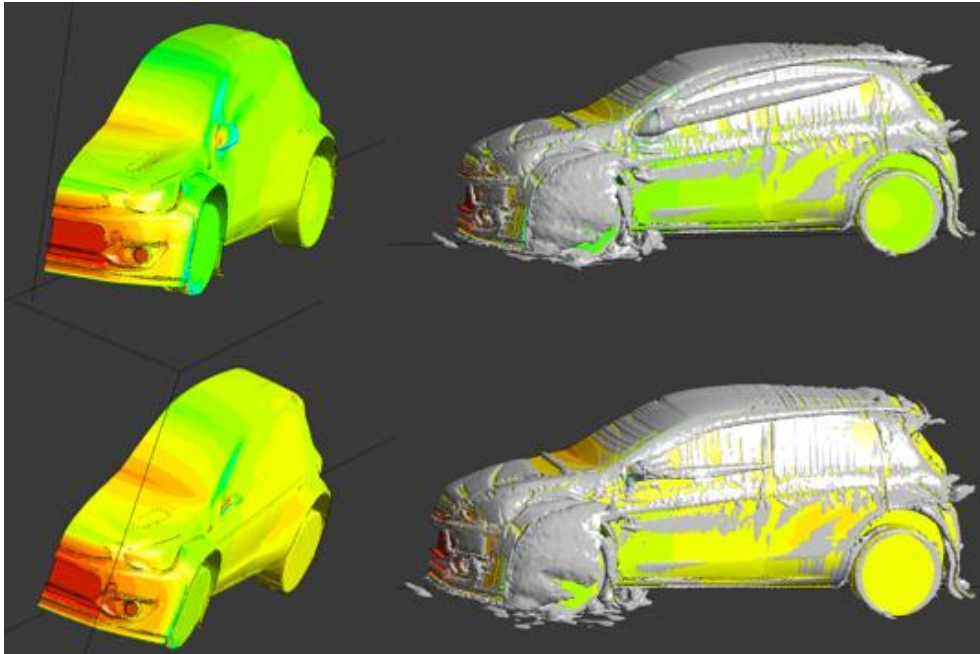


Figure 4-8 Top Mark6 and Bottom Mark7 Wing Mirror Test

Table 8 Wing Mirror Test

	CL	CD
Mark6 Old Wing Mirror	-0.056	0.367
Mark7 New Wing Mirror	-0.024	0.349

4.7 Underbody

The underbody of the race car model was refined twice since the initial refinement had failed to capture enough data for measurement. The initial test model shows a very smooth underbody with airflow pointing upward at the back of the vehicle, as if there was an assisting diffuser at work.

The actual vehicle with the added features in compliance to regulations, shows that the airflow under the body was not smooth, there was an underbody tunnel to house the drive shaft and the exhaust pipes, with the tunnel turbulence must exist at the belly of the vehicle, and the efficiency shown is way worse than the model vehicle.

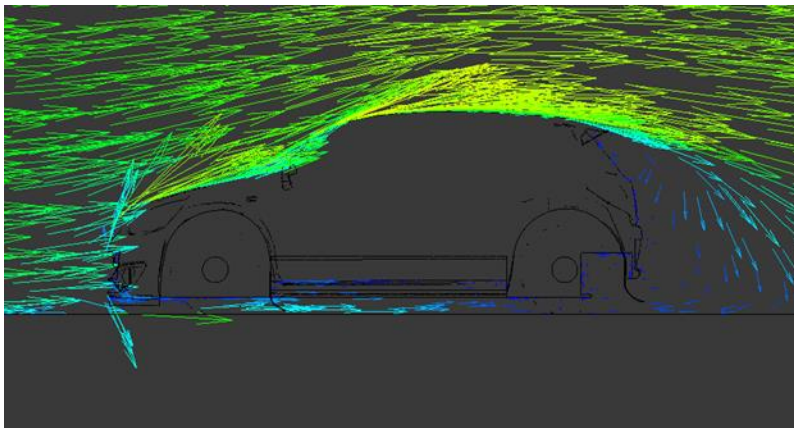


Figure 4-9 Model with Driveshaft and Exhaust Tunnel

Above diagram shows airflow is entering the driveshaft and exhaust tunnel beneath the race car, which is causing turbulence and increasing overall drag.

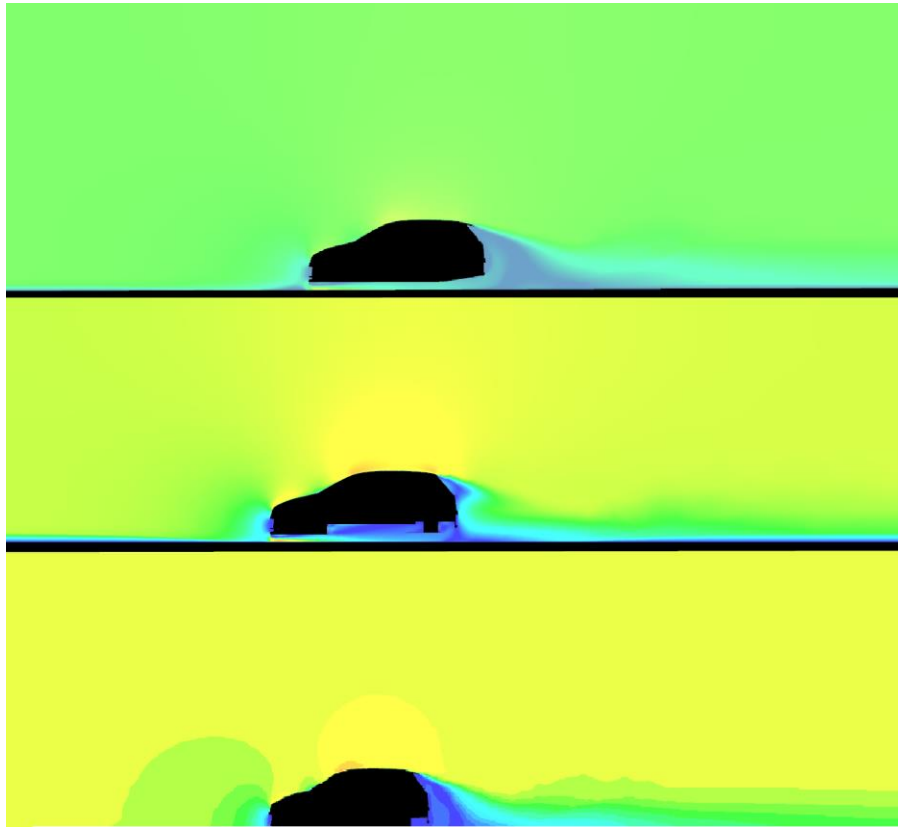


Figure 4-10 Top Mark7 Middle Mark8 and Bottom Mark9 Floor Refinement Test-1

With the floor test, Mark7 model was with a smooth under body, in the above velocity graph diagram, though models Mark8 and Mark9 are showing less tail end turbulence following the car, but turbulence was much greater underneath the vehicle as airflow has become slower causing lift.

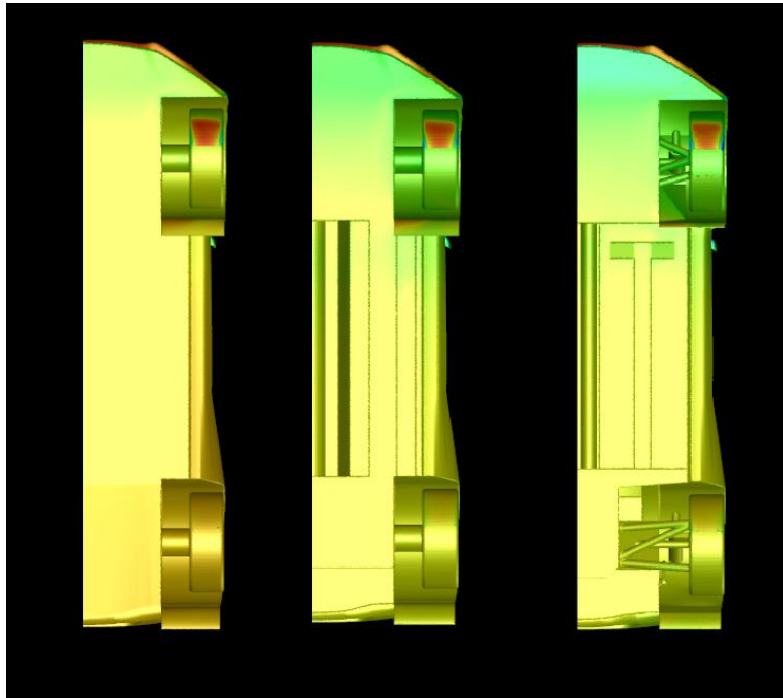


Figure 4-11 Mark7 Mark8 and Mark9 Floor Refinement Test-2

In model Mark9 where the rear wheel area is even smaller than in the refinement for Mark8, the test shows that lift for Mark9 was much greater.

Table 9 Floor Refinement Test

	CL	CD
Mark7 Original Underbody	-0.024	0.349
Mark8 First Underbody Refinement	0.065	0.376
Mark9 Second Underbody Refinement	0.177	0.467

4.8 Spoiler and Wing

The rallycross car will be fitted with regulation rear aerodynamic assist system of spoiler and wing. Scan model of the spoiler and wing was not readily available, so a physical measurement exercise was carried out on site at Spencer Sports to create the needed CAD model for testing.

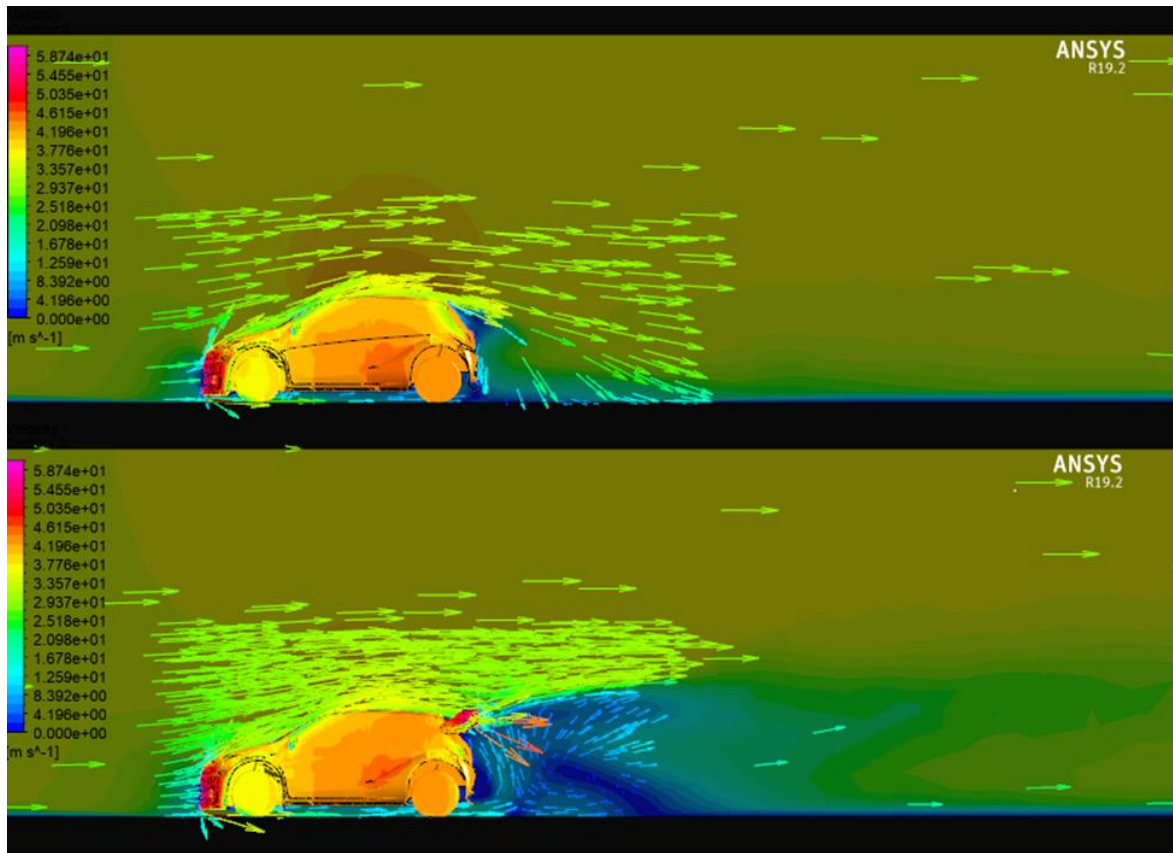


Figure 4-12 Top Mark9 Bottom Mark10 Spoiler and Wing Test-1

From the result, it can be seen that with model Mark10, high pressure region trails the back of the vehicle creating much downforce, airflow was jetting upward and resulted in vortices trailing the rally car, which compares to the calm and smooth air flow shown in the model Mark9.

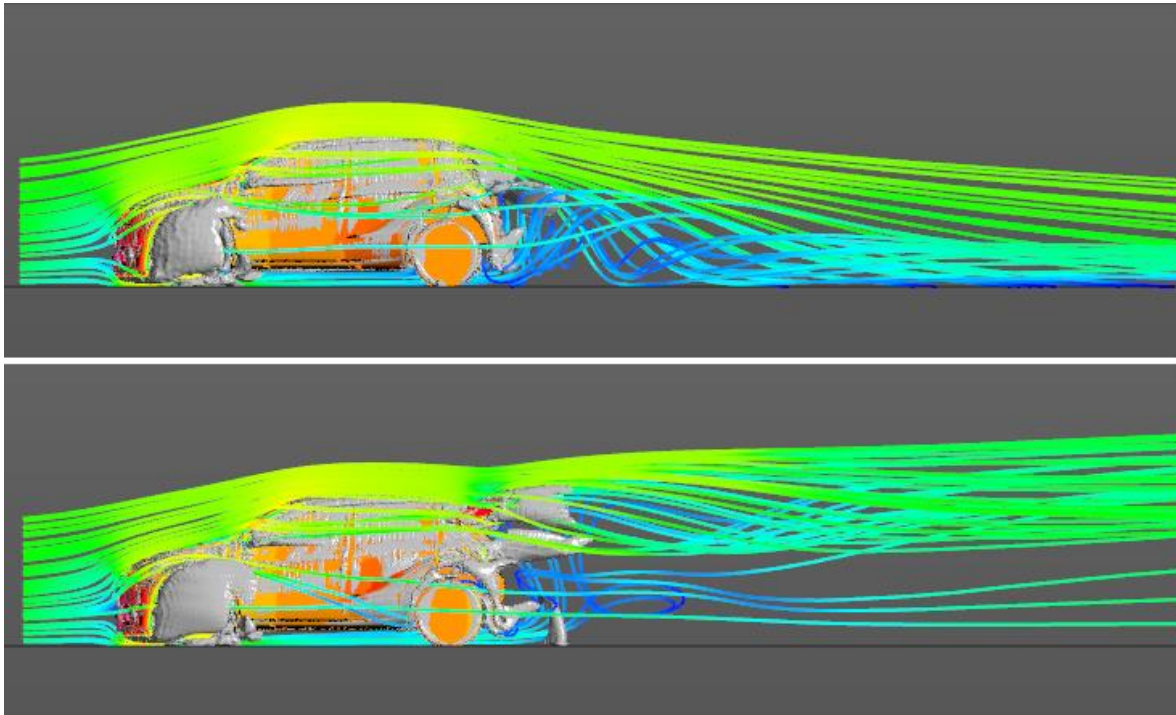


Figure 4-13 Top Mark9 Bottom Mark10 Spoiler and Wing Test-2

Normally the airflow after passing over the top of the vehicle will flow downward creating lift as is shown by model Mark9 in the diagram above.

When the vehicle has installed spoiler and wing as is with model Mark10, the elongated vortexes are guided upward by the spoiler and wing to meet the upper airstream of the vehicle, the vortexes had been elongated and is creating more drag.

Table 10 Spoiler and Wing Test

	CL	CD	COP
Mark9 Without Spoiler and Wing	0.177	0.467	4.99
Mark10 Added Spoiler and Wing	-0.437	0.551	1.35

5 1/24 Scale Wind Tunnel Validation

This validation is to show the flow characteristic of the vehicle, to help confirm that CFD data does match with the data the wind tunnel generates.

Unfortunately since the university wind tunnel was damaged, where it was no longer able to generate accurate lift and drag figures, otherwise CL and CD can be calculated from the wind tunnel output to help validate our findings.

But the wind tunnel visual output was still working, when checking the pictures produced, found they do match CFD visual output.

Note from the below diagram showing airflow from the front of the vehicle, after having passed the front wheel does start to flow upward shown in both systems.

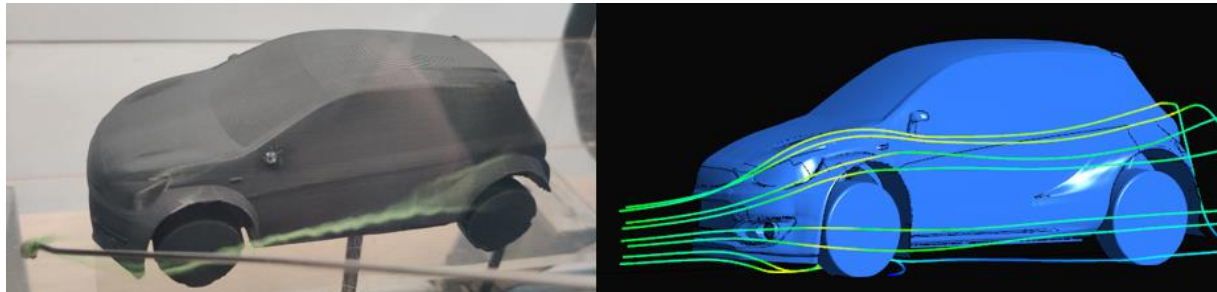


Figure 5-1 Mark9 and Mark10 Wind Tunnel Validation-1

Below diagram shows airflow from front car door, the airflow will travel over the rear venter towards back of the car before being discharged



Figure 5-2 Mark9 and Mark10 Wind Tunnel Validation-2

For model Mark9 shown in below diagram, the airflow starting from just in front of the vehicle bonnet has flow smoothly over the windscreen and roof, assisted by the spoiler and wing has directed the flow upward.

For model Mark10 flow was directed downward creating a separation bubble just behind the vehicle.

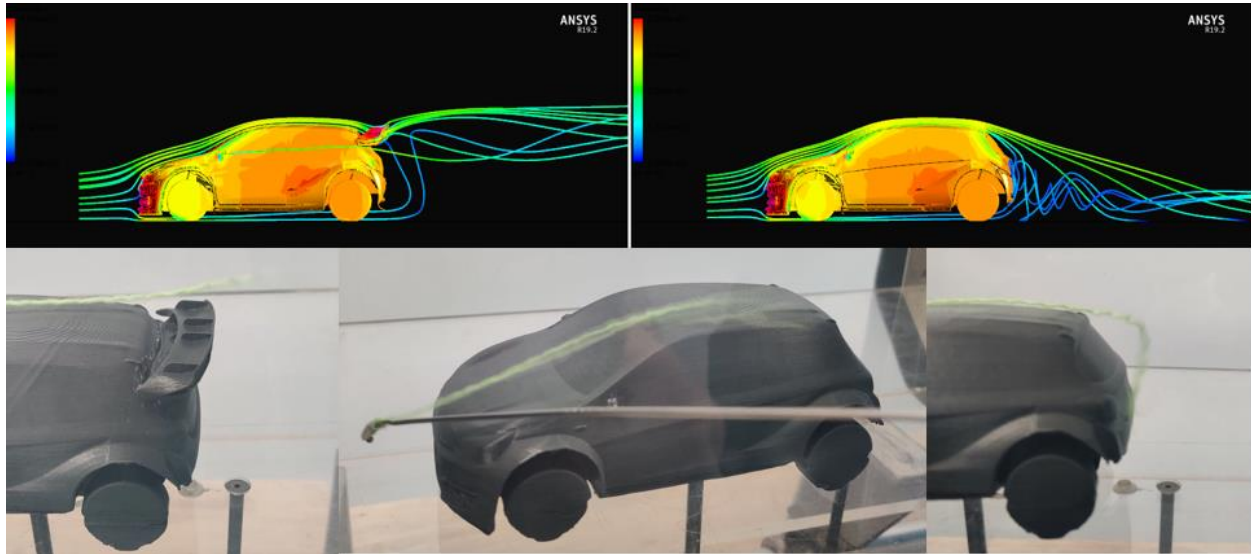


Figure 5-3 Mark9 and Mark10 Wind Tunnel Validation-3

6 Development

6.1 Underbody Modification

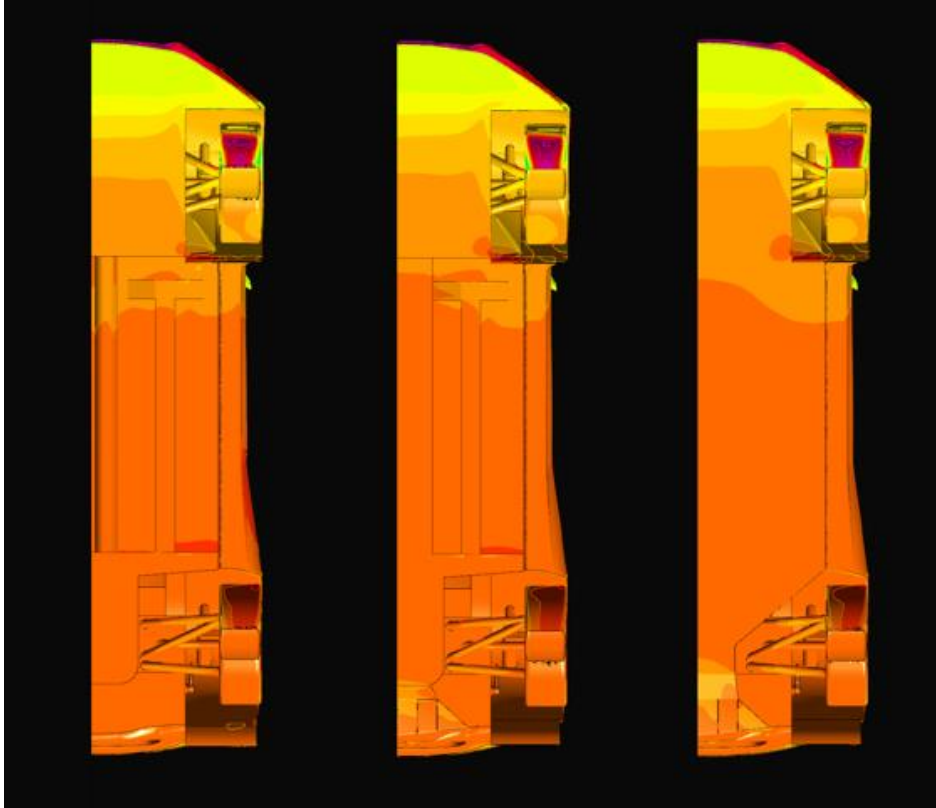


Figure 6-1 Mark10 Mark11 and Mark12 Underbody Modification Test-1

The model Mark10 in the above diagram has been modified by having its drive shaft and exhaust tunnel being boarded up to form a smoother underbody, but the testing result shows that the efficiency had in fact deteriorated. After investigation, it was found that the tunnel was not fully boarded up, which is believed must have been the cause for the wrong results. The race car floor must be very smooth in order to take advantage of the installed back diffuser effect.

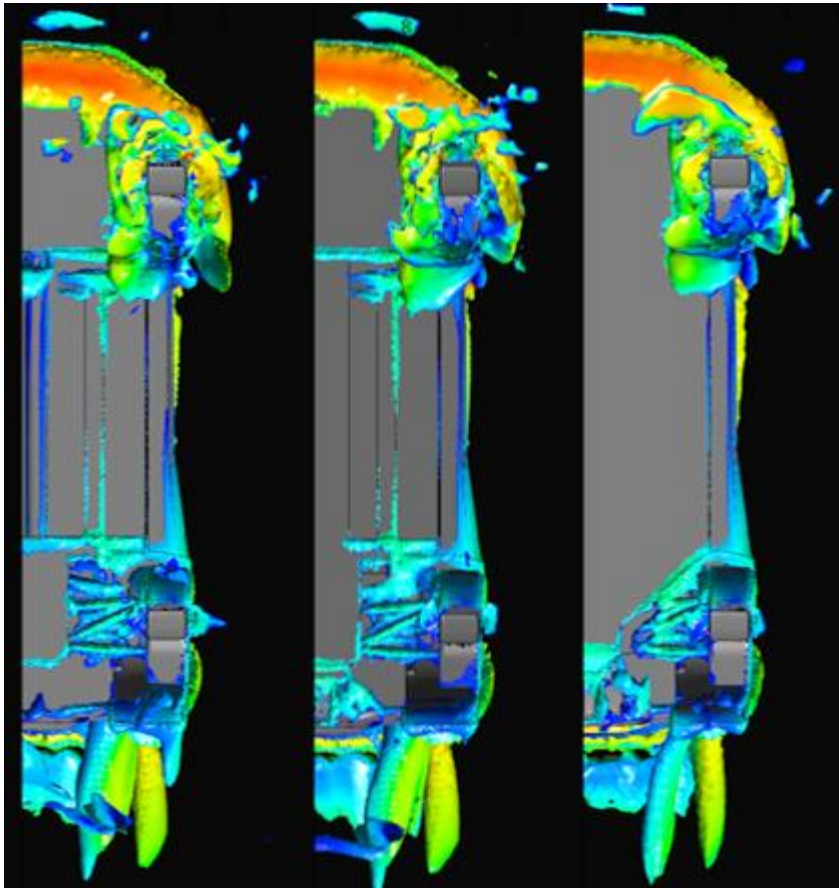


Figure 6-2 Mark10 Mark11 and Mark12 Underbody Modification Test-2

The model Mark12 does have a smooth flat underbody, working together with diffuser it did not experience any sudden pressure change, so there was not much turbulence that can slow down its underbody airflow.

Since Mark12 was the better design, Mark12 was used as the baseline model for the next design change of Mark12.2, Mark12.3 and Mark12.4 as shown below.

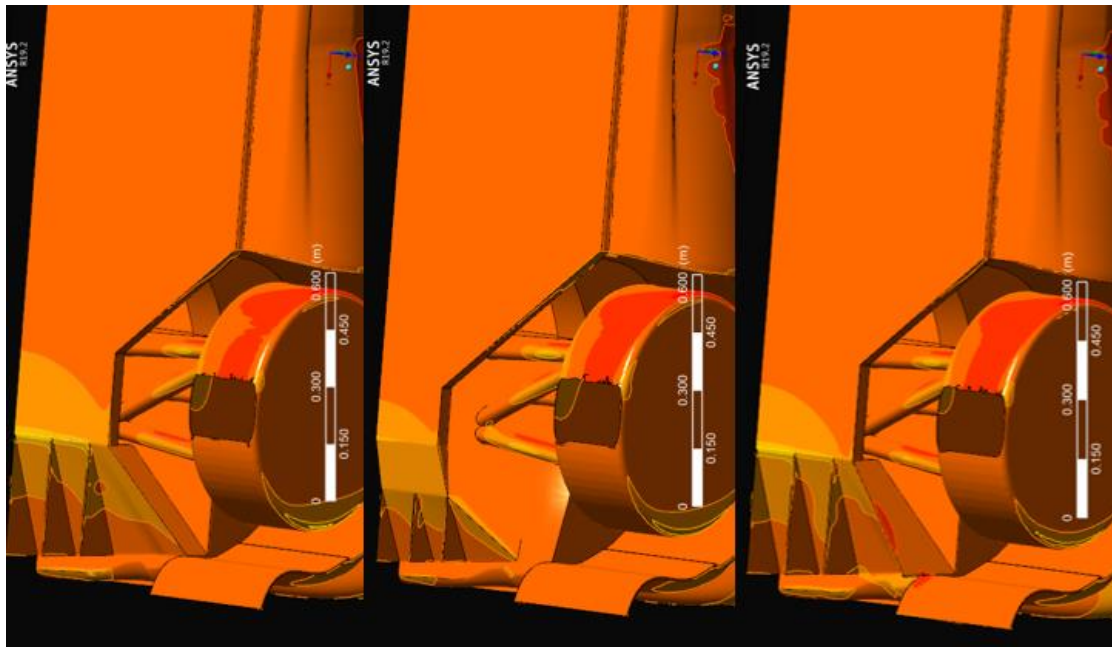


Figure 6-3 Mark12.2 Mark12.3 and Mark12.4 Underbody Modification Test-3

The Model Mark12.2 design has a barrier built to prevent air flow between the wheel and underbody main stream flow area next to the diffuser.

Model Mark12.3 was a simple barrier design which tries to cover up the empty areas within similar vicinity as the above model, also trying to smooth flow.

The Model Mark12.4 design was similar to Mark12.2, but its barrier extends towards the floor like a fin, this had been shown as not efficient, since its length is stopping airflow or diverting air to where it is not needed, high pressure built up can be seen from the diagram in this region.

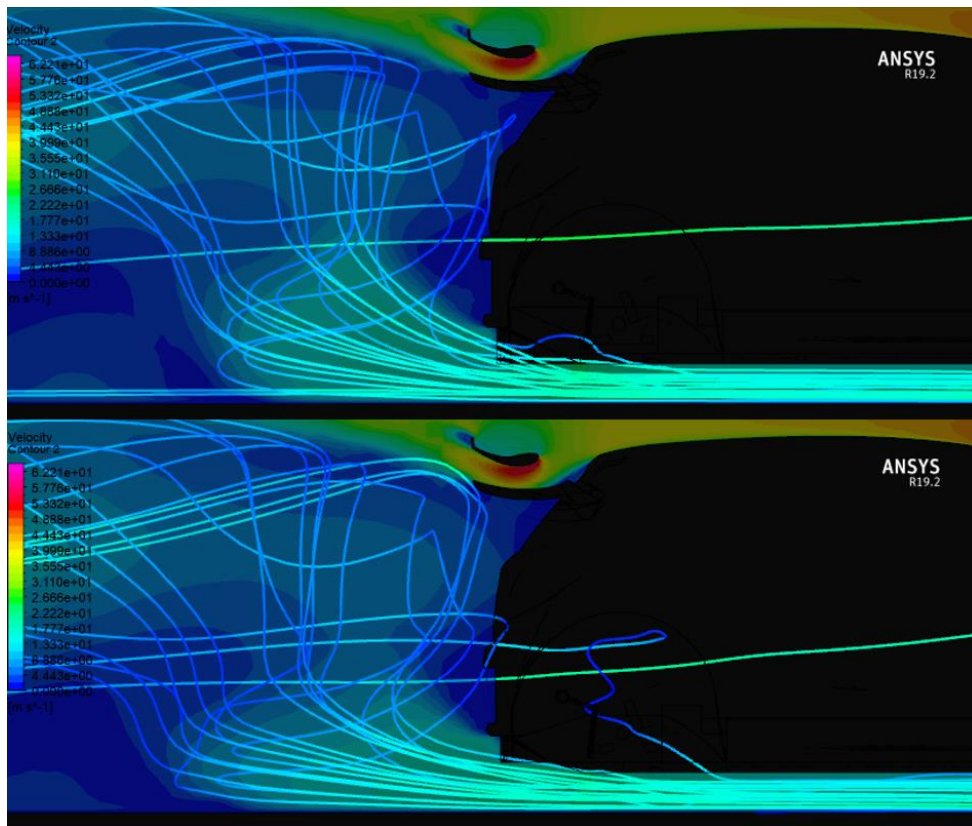


Figure 6-4 Top Mark12.2 and Bottom Mark12.3 Underbody Modification Test-4

Model Mark12.2 airflow has better exit than Mark12.3, noting the steep climb of airflow upward.

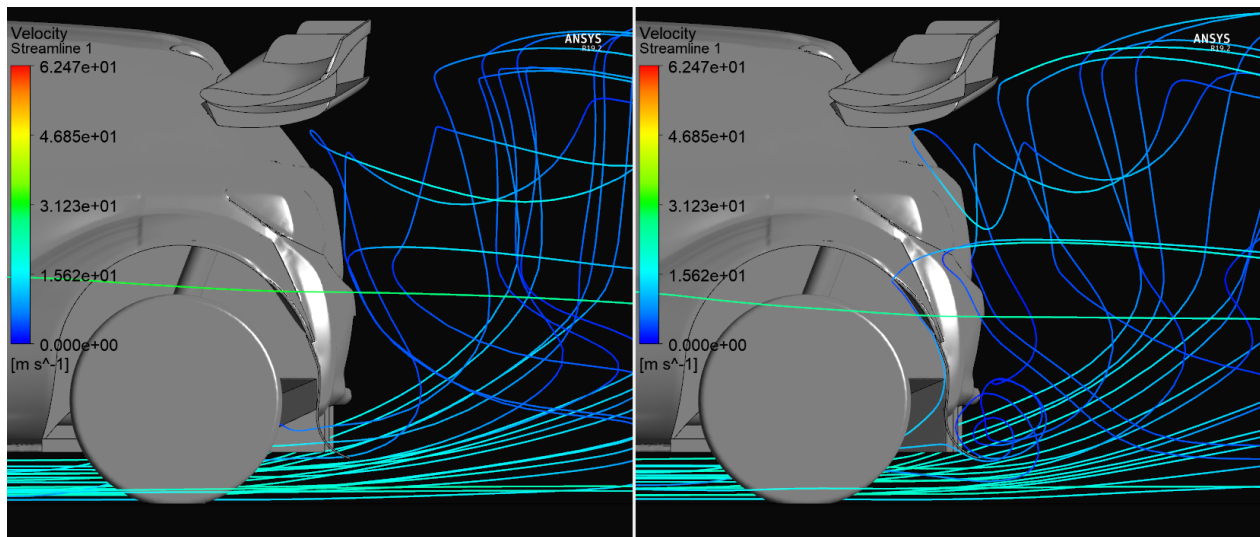


Figure 6-5 Mark12.2 and Mark12.4 Underbody Modification Test-5

Turbulence can be seen in Model Mark12.4 where drag increase had resulted.

Table 11 Underbody Modification Test

	CL	CD	COP (behind front axle)
Mark10	-0.43	0.55	1.35m
Mark11 Minor Modification	-0.42	0.55	1.53m
Mark12 Underbody Modification 1	-0.44	0.55	1.51m
Mark12.2 Underbody Modification 2	-0.44	0.55	1.48m
Mark12.3 Underbody Modification 3	-0.43	0.56	1.5m
Mark12.4 Underbody Modification 4	-0.41	0.57	1.56m

Model Mark12.2 was picked because this design shows best performance. Downforce had gained 2% from model Mark10.

6.2 Front Fender and Bumper Design

Using earlier selected model Mark12.2 as test model

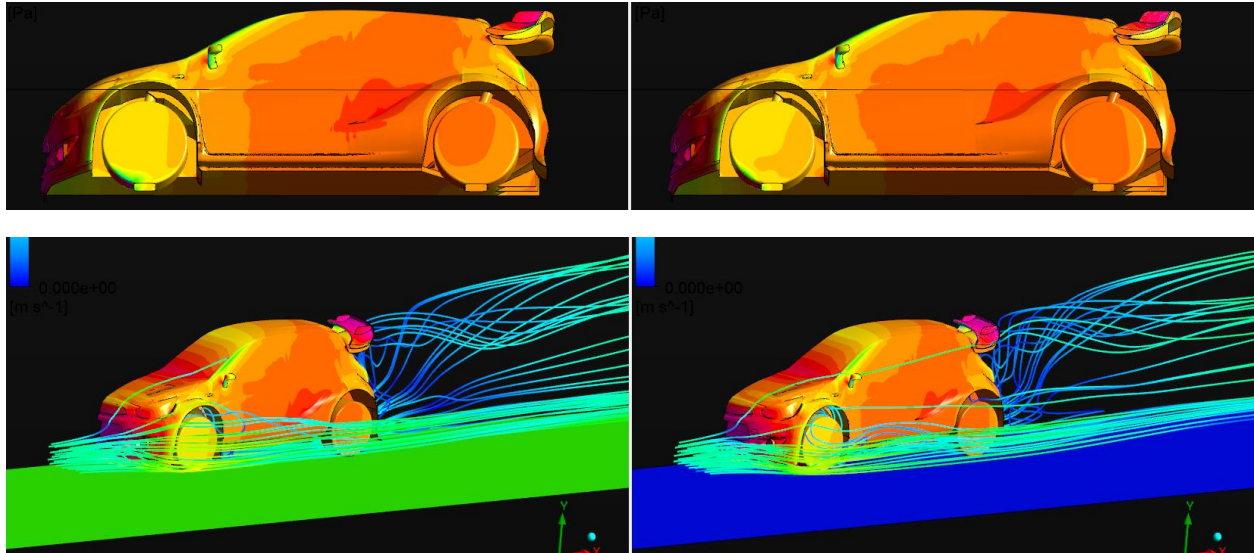


Figure 6-6 Left In Motion and Right Stand Still Testing

The wheel dynamic will affect the Fender, so Fender design must take wheel motion into consideration. In this test for vehicle in motion the wheel rotation, vehicle motion and floor motion had all been taken into consideration.

The result does show some difference in pressure, but airflow characteristic of the two models remain similar, COP, CL and CD are the same to two decimal points. Possible cause for the indifference in the result could had been since rally car wheels are covered, unlike formula race car which has their wheels exposed.

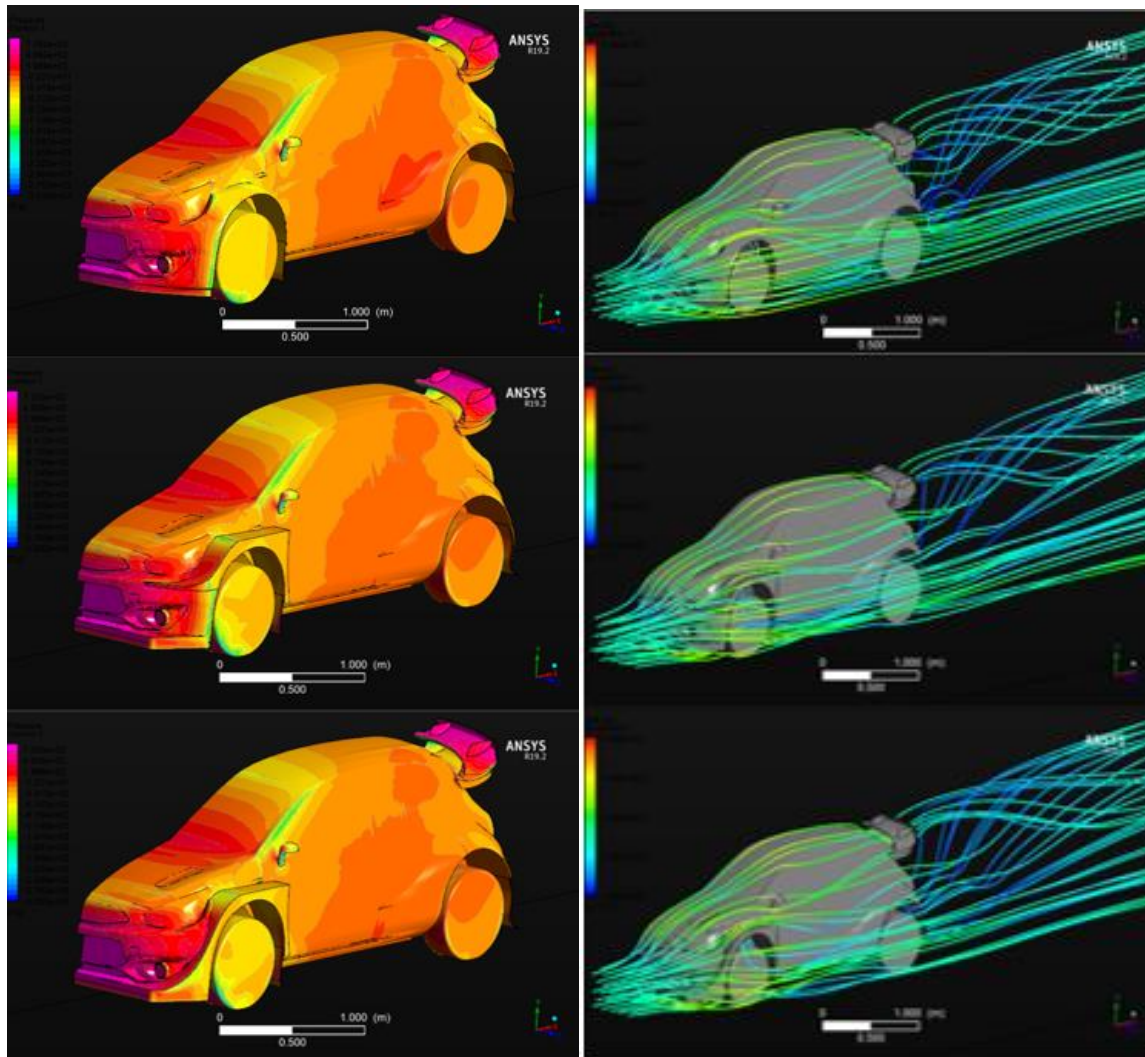


Figure 6-7 Top Mark12.2 Middle Mark13.1 Bottom Mark13.2 Front Fender and Bumper Test

Model Mark13.2 has its fender running all the way down to the bottom of the extended front bumper, while Mark13.1 has its fender slide down to top of the front bumper.

The test is with the car wheel, vehicle and the floor all in motion, both modified models are showing high pressure regions building up at the front bumper. The cause of this could be the extension of the underbody floor length due to the extended front bumper, where underbody airflow was further energized.

With the new fenders, airflow to the sides of the race car were directed upward, more continuous flow until the end of the vehicle was reached, noted smoother airflow exit at end of car.

Table 12 Front Fender and Bumper Test

	CL	CD	COP (behind front axle)
Mark12.2	-0.44	0.55	1.48m
Mark13.1 Modification 1	-0.5	0.61	1.15m
Mark13.2 Modification 2	-0.5	0.61	1.16m

Looking at the results from the table above, the CL figure has a 13% efficiency gained, the overall lift drag efficiency had gained by 2%, both models Mark13.1 and Mark13.2 has shown a shift of their COP figures by more than 0.3m towards the front of the vehicle.

Model Mark13.2 was selected as the baseline model for the next design change testing.

6.3 Rear Fenders and Bumper Design

According to the new regulation, the rear bumper used by Spencer Sport was no longer acceptable. Even if that rear bumper design performance was desirable, a change to the bumper was necessary to continue competing in the competition.

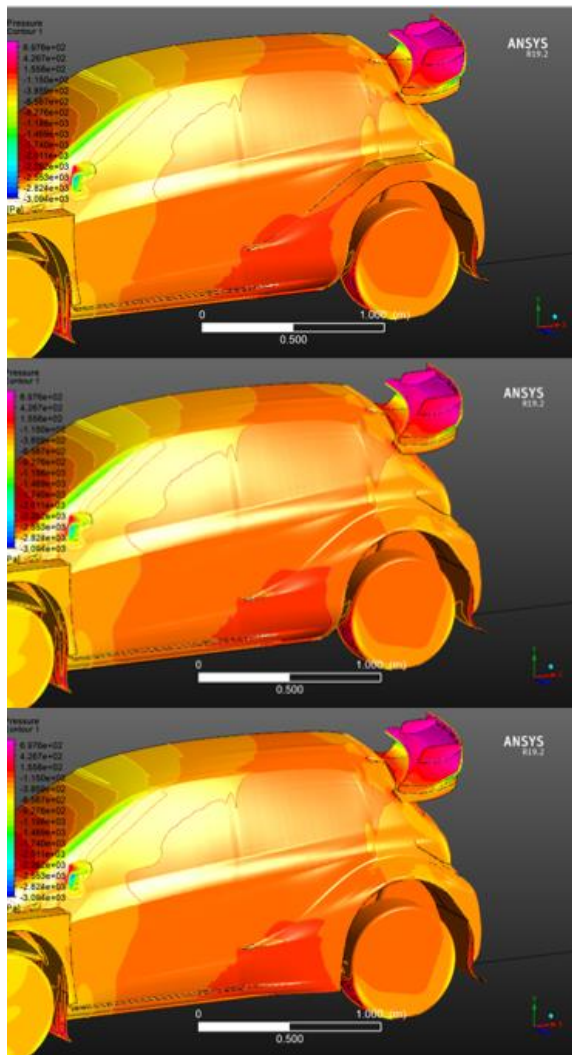


Figure 6-8 Mark13.3 Mark13.4 Mark13.5 Rear Fender and Bumper Test-1

The model Mark13.3 design try to guide airflow to discharge towards the top of the vehicle.

The model Mark13.4 design was based on the old rear bumper and fender design but has slight modification which are within the new regulation. The model Mark13.5 design is based on the model Mark13.4 design, but this time the side rear fenders has extend out a little further, yet still within regulations.

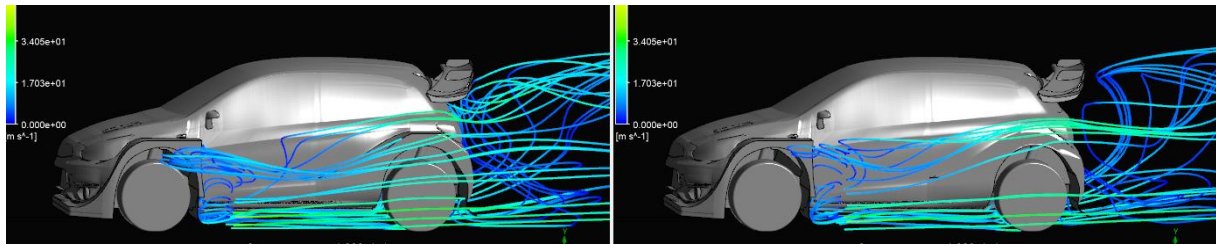


Figure 6-9 Mark13.3 Mark13.4 Rear Fender and Bumper Test-2

Model Mark13.3 design failed to guide the airflow toward the top, and airflow separation had resulted. Model Mark13.4 design airflow was successful in diverting air to the top, there was no separation and the spoiler and wing were able to use the diverted airflow.

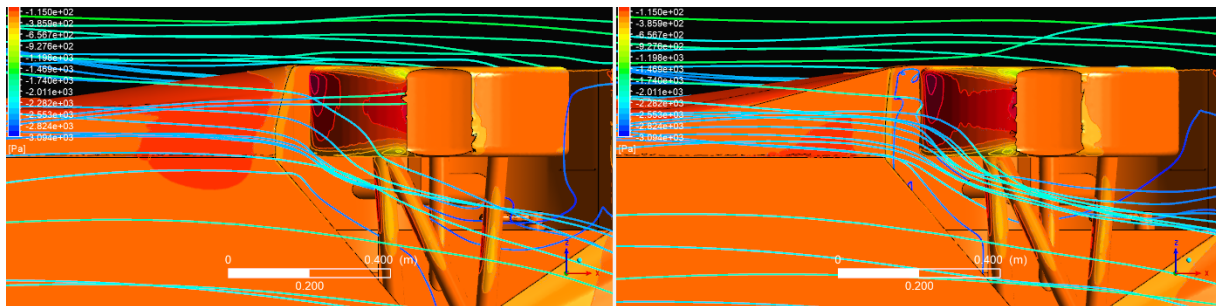


Figure 6-10 Mark13.4 Mark13.5 Rear Fender and Bumper Test-3

Model Mark13.4 design with its fender extended out, airflow was being drawn from the side, all the way into the wheel arches area, result in pressure built up at the forward facing side of the rear wheel, causing COP to move further forward to front axle.

Table 13 Rear Fender and Bumper Test

	CL	CD	COP (behind front axle)
Mark13.2	-0.5	0.61	1.16m
Mark13.3 Modification 1	-0.48	0.63	1.09m
Mark13.4 Modification 2	-0.5	0.61	1.09m
Mark13.5 Modification 3	-0.5	0.61	1.04m

Model Mark13.4 design was selected because this design gives best CL and CD results, and its COP was less front bias.

6.4 Front Fender Louvers

Trying to minimise wheel wake, Louvers holes were cut in the fender just behind the front wheel. Model Mark13.4 design has no Louvers, while model Mark14.1 design was with downward flowing Louvers and model Mark14.2 design was with upward flowing Louvers

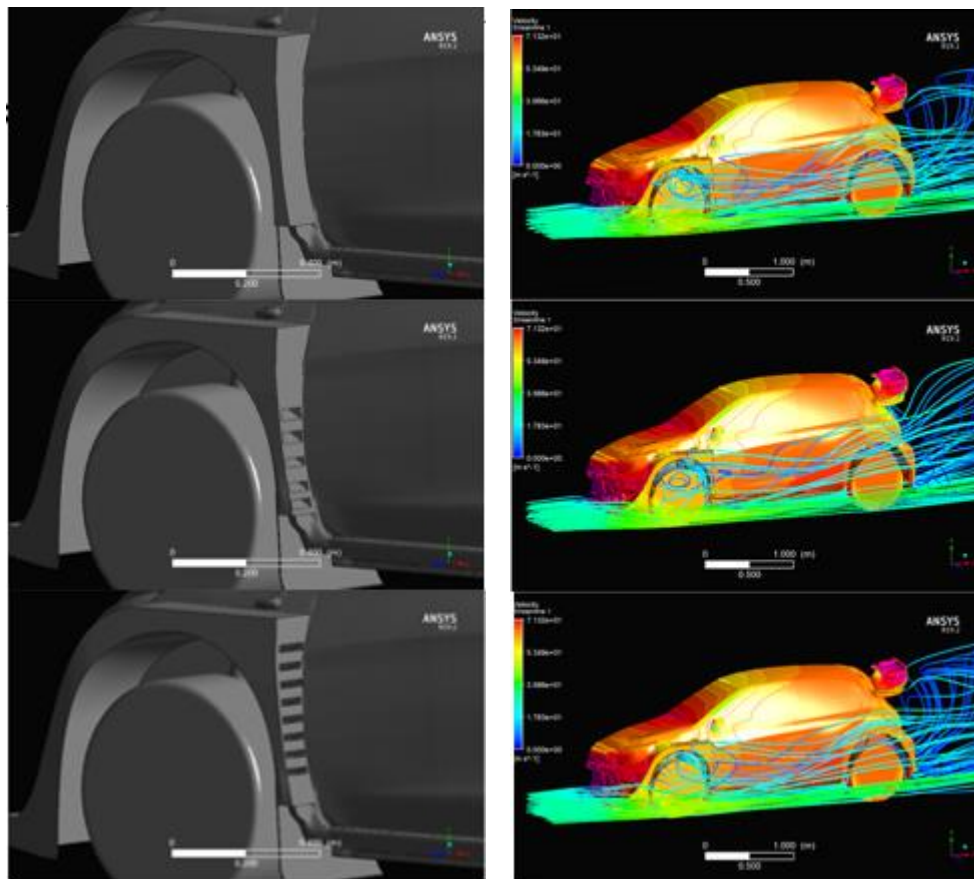


Figure 6-11 Top Mark13.4 Middle 14.1 Bottom 14.2 Front Fender Louvers Test

These simple louvers modification as you can see in the above diagram did not bring any improvement to the airflow, believe more sophisticated design of Louvers profile are needed. Further research into this area is called for.

Table 14 Front Fender Louvers Test

	CL	CD	COP (behind front axle)
Mark13.4	-0.5	0.61	1.09m
Mark14.1 Modification 1	-0.5	0.61	1.01m
Mark14.2 Modification 2	-0.5	0.61	1.00m

6.5 Wing Angle Study

Model Mark15.1 design has its angle of attack modified by 1 degree, while model Mark15.2 has its angle of attack modified by 2 degrees. According to the regulation specifying height of the rear wing which can not be higher than the roof of the vehicle, thus the whole wing structure must be lower accordingly to accommodate the angle of attack adjustments.

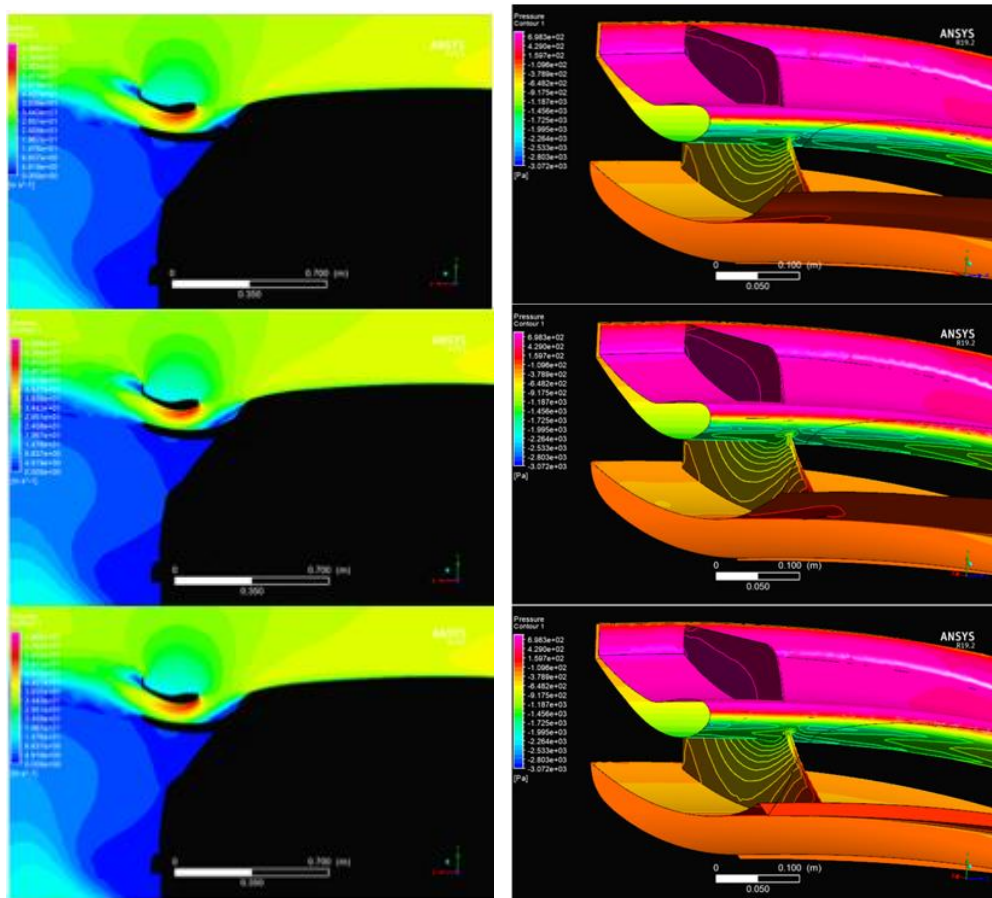


Figure 6-12 Top Mark13.4 Middle Mark15.1 Bottom Mark15.2 Wing Angle Test

For model Mark15.2 design airflow under the wing is starting to separate, so further exploration to any higher angle was not carried out.

For model Mark15.1 design, due to the change in the angle of attack of the wing, separation between high pressure and low pressure area had also changed accordingly.

Table 15 Wing Angle Test

	CL	CD	COP (behind front axle)
Mark13.4	-0.5	0.61	1.09m
Mark15.1 - 1 Degree	-0.5	0.61	1.1m
Mark15.2 - 2 Degree	-0.52	0.63	1.05m

7 Altitude Study

This is a study done on the refined model Mark9 with no spoiler and no wing. The same study pattern was planned by using the final baseline model with spoiler and with wing.

Due to the pandemic, this study was no longer possible. Below sharing what was found.

Table 16 Altitude Study

Ride Hight	CL	CD
+40mm	0.039	0.388
+20mm	0.062	0.377
+0mm	0.065	0.376
-20mm	0.085	0.394
-40mm	0.085	0.375

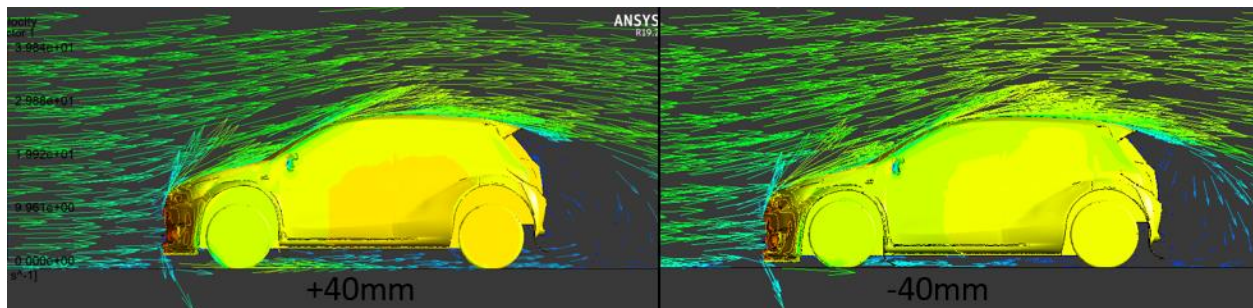


Figure 7-1 Mark9 Altitude Study

This study was found to be not very useful, since there was a drive shaft and exhaust tunnel at the underbody of this baseline model Mark9 vehicle, thus the finding was distorted.

8 Roll Pitch and Yaw Angle Study

Model Mark9 design was used in this study, like the altitude study, due to the pandemic, this study was no longer possible. Below sharing what was found.

This was a DOE study of how roll pitch and yaw angle can affect the baseline model.

Yaw angle at 15 degrees, lift becomes way more aggressive if the roll and pitch are also changing at the same time when compare to when Yaw angle is at zero degrees, the trend of drag does not change, but the whole graph will be lifted upward in proportion.

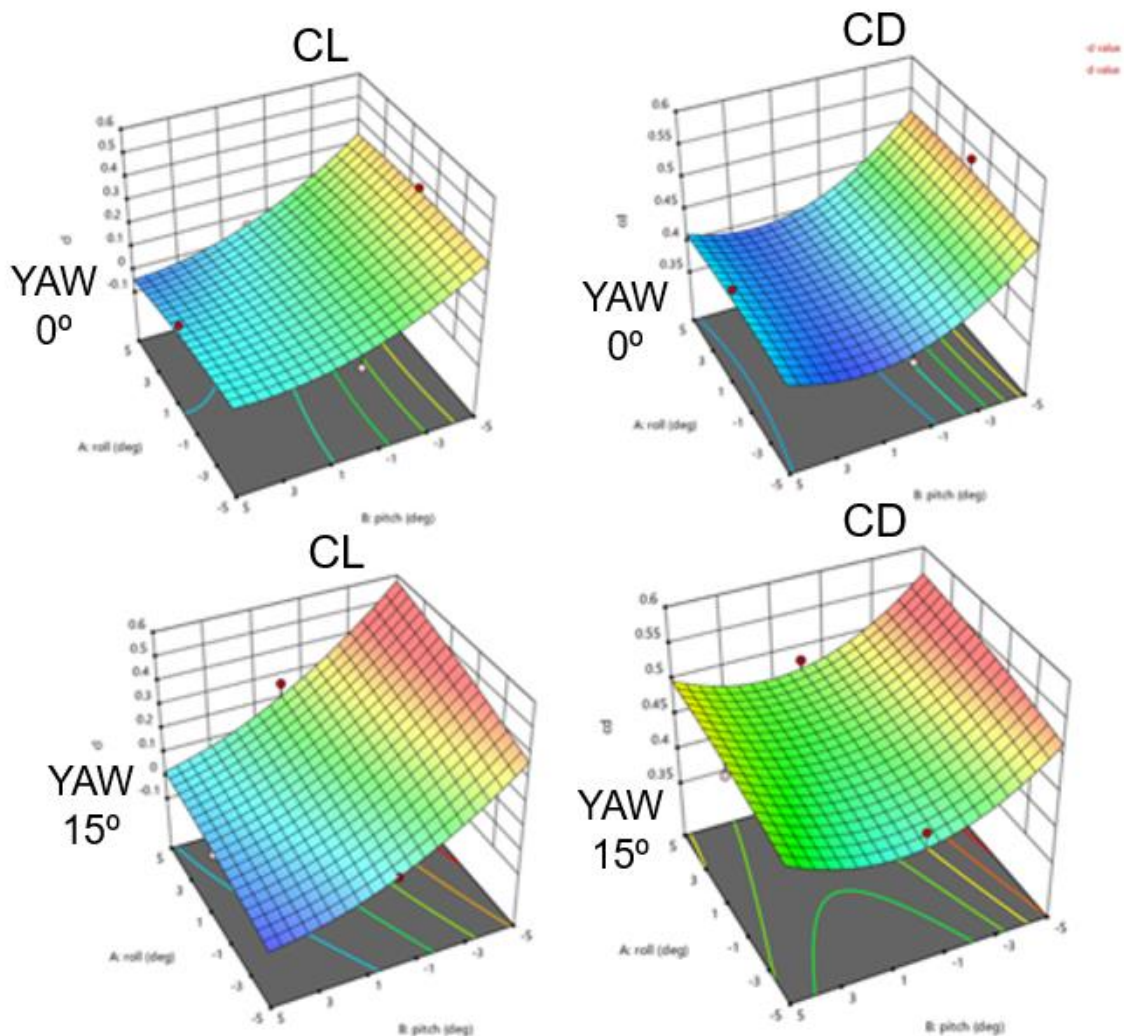


Figure 8-1 Roll Pitch and Yaw Angle Study

9 Pandemic Impact

Due to COVID-19 social distancing guideline from the Government, access to University resources had not been readily available for this project since Mid-March 2020. Other than on-line research, other case study support and resources had been limiting.

9.1 Book Research

Due to the closure of the University Library, further book research had not been possible. The literal review for this project had mainly depended on a couple of textbooks and information found on the website.

9.2 1/24 Scale Wind Tunnel Validation

There was a fault in the Wind Tunnel, where lift and drag data was not available for tests, only visual images on the behaviour of airflow was available. The Wind Tunnel remain faulty just before the COVID-19 lockdown had commenced.

9.3 Altitude Study, Roll Pitch and Yaw Angle Study

Yaw angle study is very important to rally car because the car often needs to go sideways.

The above studies were not possible because access to university computer with Ansys software was not available to the writer since mid-March 2020.

Free student version of Ansys software is restrictive, it allows CFD simulation results to be view, but does not allow new complicated CFD simulations to run. Without new simulation results, it was not possible to carry out simulation on Mark 10 and the final model Mark 15 W-1 on the above topics.

10 Conclusion

Wind tunnel testing results on the Mira notch car had been very useful in helping to validate simulation results by CFD analysis, this had also enable the project to move forward to the next stage.

The new under body has allowed the rally car to gain 2% downforce with no changes in drag, the COP was also shifted 0.1m to the back of the vehicle. This COP shift could be counter by a more aggressive front bumper design.

Complying to the front bumper regulation, further model design and testing had indicated that the new front bumper and fender design had managed to gain 13% of down force with 10% more drag, where the overall lift drag coefficient was still 2% better than the old rally car design.

There was one problem which needs to take into consideration, that was the installation of the front bumper to regulation, after installation the COP had moved forward by 0.3m compare to the final baseline model, such a COP change can affect the vehicle's overall balancing. This may become an area worthy of further investigation, perhaps the call for further validation through the use of simulator or life testing by the race car driver. Another area worthy of further investigation is towards the louvers design for rally cars, which this project had failed to identify any positive result from the installation of this contraption in our test model car.

In general, the aim of the project had been achieved. The study has shown that the rally car's bodywork can be further improved, especially toward the front of the vehicle.

This research exercise has shown that motorsport is not just a sport where driver skill dominates, on the contrary, the project's result has proven that innovation and the application of science to the sport can bring rewarding results to the whole sporting team, motorsport is truly a team game.

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