

Major Project Report

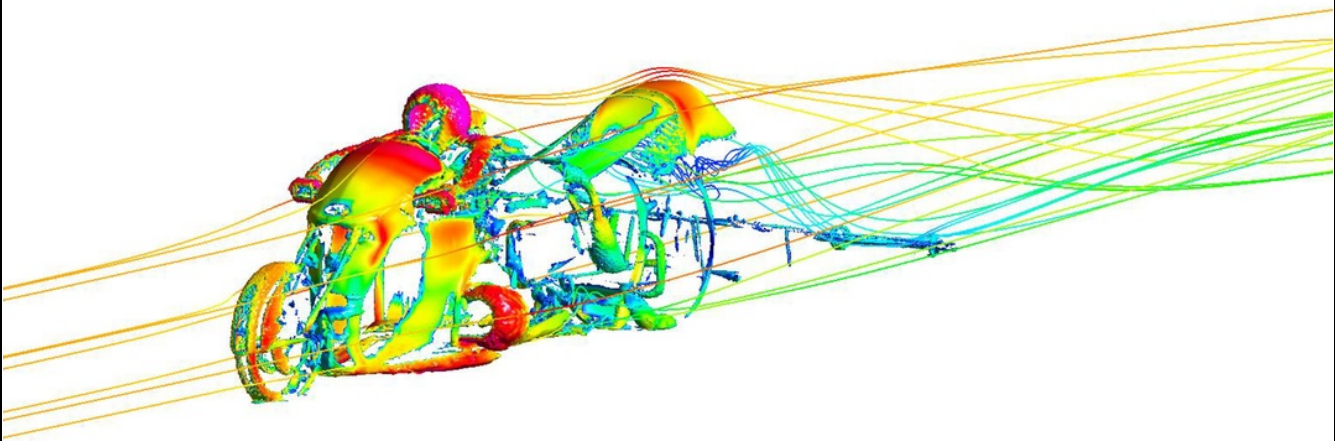
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Aerodynamic Development of the Storm Drag Bike using Computational Fluid Dynamics



Major Project: M6X00417

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Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Abstract

To summarise, this project was completed after Storm asked University of Wales Trinity Saint David Swansea if a student would like to develop the fairing of their drag bike, to gain more downforce on the rear wheel. This was taken on by the author and research was undertaken to find which aerodynamic profiles have been used for certain characteristics. Many studies were completed on different sections of the fairing which when completed, increased the downforce coefficient by almost 70%, and decreased the drag coefficient by almost 30% with a total efficiency increase of 12.23%. Most of these improvements formed from the latest tail designs which were inspired by the Suzuki Hayabusa which was made to break top speed records. The rest of the developments around the geometry proved to be positive, bar one. A mistake was made with the developed front fairing which proved to make efficiency worse rather than better. If that mistake was noticed sooner it could have been rectified however, more geometry developments were completed prior to finding the error. The largest visual improvements to be seen are in the wake region of the drag bike, where pressure and velocity differences have been minimized.



Acknowledgments

Throughout this dissertation I have received support and inspiration. Firstly, I would like to thank Mr Tim Tudor, my supervisor, for his continuous support, enthusiasm and invaluable experience in this particular field. Whom without would have made this project very difficult.

Next I would like to thank John Hughes for his great understanding of aerodynamic principles. His support has helped me to understand many aspects of aerodynamics which I previously had no experience with. I would also like to say how John inspired me to carry on even when certain parts of the project were not working out, for this I am truly grateful.

I would also like to thank Gavin Spring-Benyon for the amount of time he assisted me in developing my understanding and use of surfacing in Solidworks. This helped me to achieve my desired geometries and has given me valuable skills to take with me into my future.

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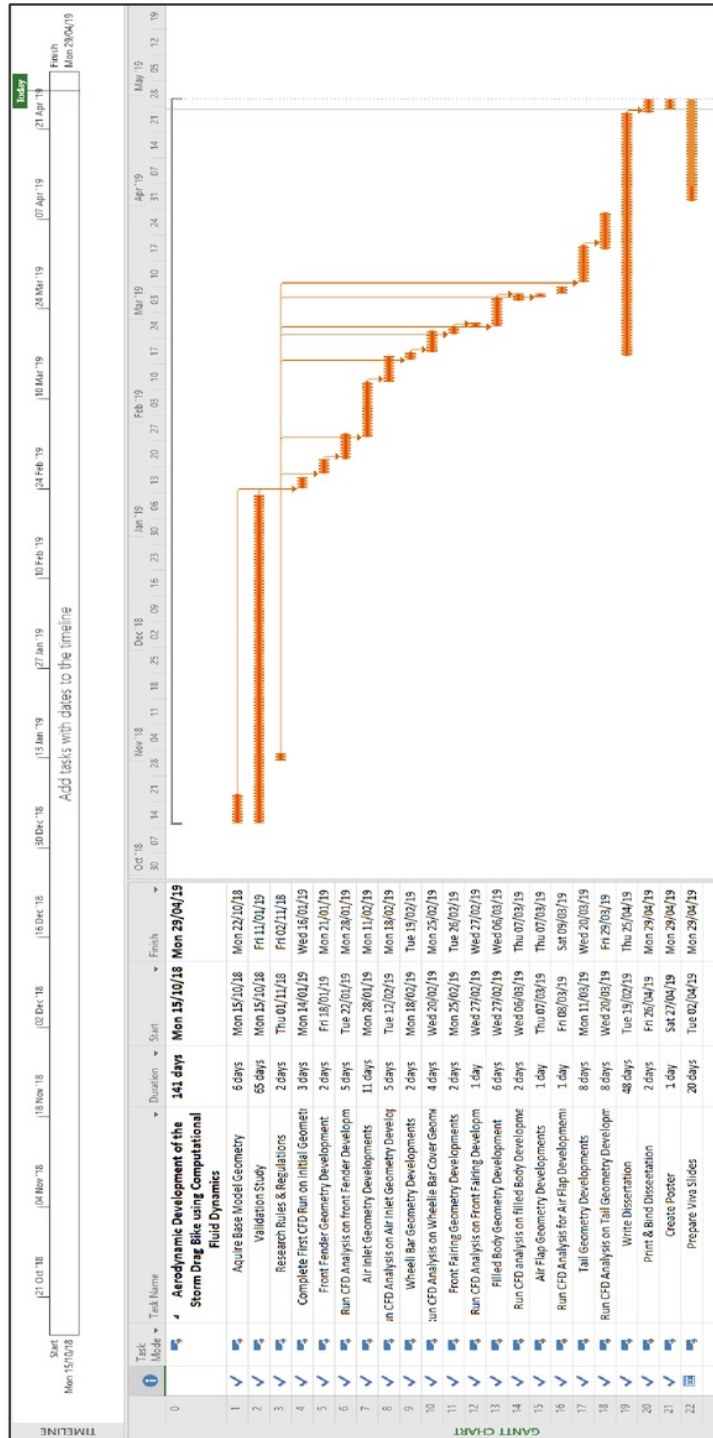
Abbreviations

- Cd – Coefficient of drag
- Cl – Coefficient of lift
- -Cl – Coefficient of downforce
- CFD – Computation fluid dynamics
- Ps – Static pressure
- P – Air density
- V – Velocity
- Pt – Total Pressure
- F -Force
- M – Mass
- a – Acceleration
- MGH – Mass, gravity & height
- Re – Reynolds Number
- RND – Research and development
- Cp – Centre of pressure



Timing Plan

Gantt Chart





1.0 Introduction

The development of aerodynamics has significantly progressed since the early 1900s'. Vehicles back then were not powerful, and people were used to the horse and carriage design that kept them dry and protected from the wind, so a streamline body wasn't necessary. It was only when better roads were made, enabling higher speeds that aerodynamics became a concern due to the economic benefits. (Schuetz, Aerodynamics of Road Vehicles, 2016).

The creation of the Storm drag bike and its team was fairly simple. A group of people got together and decided to create the "quickest turbo bike" they could imagine (Parnell, About Storm, 2013). Storm was introduced after the team found out the limits of the older Honda CBX engine. They decided that the best option would be to use a "top fuel engine" with a compound turbo setup which used methanol due to its capability to prevent knock (Parnell, About Storm, 2013). A top fuel engine is simply an engine designed to run with nitromethane rather than gasoline (How Stuff Works, 2001). The compound turbo setup utilizes two turbos, one large turbo to pull in lots of air, and then a smaller turbo further down the line to multiply the pressure. Unfortunately, there is currently no information about the aerodynamic properties of the Storm drag bike, however this project has been completed for that very purpose, with added geometry developments to improve the aerodynamic characteristics.

Aerodynamic characteristics are dependent on the purpose of the vehicle, for instance an aeroplane is required to generate a certain amount of lift whilst maintaining low drag. In the motor industry aerodynamic properties should be contemplated but are not as important as other economic issues, unless referring to motorsport. Aesthetically pleasing characteristics are considered more important than aspects such as aerodynamics (Schuetz, Aerodynamics of Road Vehicles, 2016). However, when it comes to motorsport, aerodynamics now play a more important role in achieving the fastest time around a lap or down a drag strip. As motorsport is not confined to a singular shape of vehicle, vehicle aerodynamics must adapt to the constant changes in shape and design (Schuetz, Aerodynamics of Road Vehicles, 2016). Figure 1 shows in detail how aerodynamics work with and around different vehicle types.

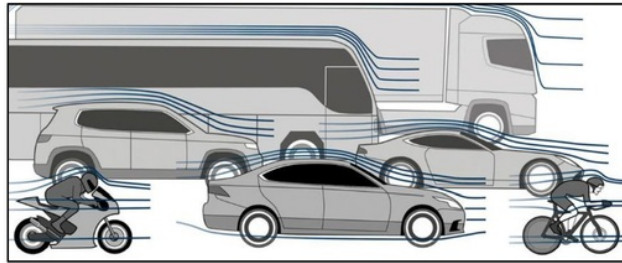


Figure 1 - Aerodynamic flow around different vehicle types, (Imeché, 2018)

If a race team wants to achieve better results in the form of lap times or quarter mile runs then eventually aerodynamic properties must be investigated. Storm is a small race team that enter drag competitions with their drag bike and have recently become interested in developing the aerodynamic characteristics of their bike, this is in hope of achieving a faster time down the drag strip.

This report will examine the principals of aerodynamics and research will be conducted to find suitable methods to achieve the aims set by the team members of Storm. The methods found will be used to develop the geometry of the drag bike fairing, which will then be analysed using computational methods to see if they are beneficial in terms of reducing the drag and increasing the downforce of Storm's drag bike.

2.0 Aims of the Project

- Increase Downforce
- Reduce Drag Force
- Improve Geometry Efficiency



3.0 Literature Review

3.1 Aerodynamic Principles

3.1.1 Bernoulli's Equation

When air is travelling from an area of high pressure to low pressure, Bernoulli's equation states there must be a change in velocity as the change in pressure creates a force. This law can be written in the form below, although it is often written in other ways, road vehicle aerodynamicists prefer this form. (Barnard, 2001)

$$P_s + \frac{1}{2} \cdot \rho \cdot V^2 = P_t$$

Equation 1 – Bernoulli's Equation

Where P_s is static pressure, ρ is the air density, V is the relative velocity and P_t is the total pressure. Together these terms form the dynamic pressure of the flow field when compared to a still body. This equation states that if the pressure increases then the velocity must decrease and vice versa. It has been stated above that road vehicle aerodynamicists prefer this method because potential energy (mgh) has been taken from this equation as road vehicle events such as testing and racing are usually near enough to sea level for altitude to be insignificant. The derivation of Bernoulli's equation has come from the assumption that pressure has no effect on air density, this is true in part but for vehicles moving at high enough speeds (supersonic) this would become invalid due to the compressive effects on air (Barnard, 2001).

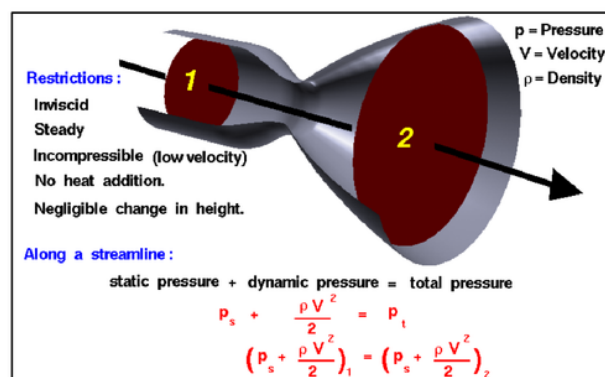


Figure 2 - Bernoulli's Equation, (Hall, Bernoulli's Equation, 2015)



If Bernoulli's equation is taken as true then at any point it can be said that where the velocity of the fluid is at its lowest value (zero), the pressure at that point must be at its maximum. These 'stagnant conditions' are treated as stagnation pressure as there is no velocity. This should not be confused with static pressure which is merely the pressure in the flow, therefore the stagnant pressure is only present where the velocity is very low (Barnard, 2001).

3.1.2 Newton's Laws

"For every action, there is an equal and opposite reaction" is a famous quote by Isaac Newton. Newton helped revolutionize science with his laws of gravitation and motion and these laws are still used within the aeronautical domain. Newton stated that an object remains in uniform motion or at rest in a straightforward direction until it is forced to act otherwise by an external force (Hall, Newtons Laws of Motion, 2015). This goes to show that if there are no external forces or if all external forces cancel out then the object will remain at a fixed velocity, including when the object is at rest. Therefore, it can be said that objects only change velocity when an outside force is applied to them, this force is commonly known as inertia.

Following on from Newton's first law comes Newton's second law which states how an external force changes the velocity of an object. Momentum is defined as mass multiplied by velocity, Newton defines that the force acting on an object is equal to the change in momentum of the object. From this we get the equation below where F is the force, m is mass and " a " is the acceleration. (Hall, Newtons Laws of Motion, 2015)

$$F = ma$$

Equation 2 – Newton's Law

Newton's third law shows that for every force there is an equal opposing force (Hall, Newtons Laws of Motion, 2015). This law can be used to describe how lift is generated on a wing of an aeroplane which can be adapted to use within motorsport as inverted wings are used to create downforce. However, Newton's equation was not quite complete and in reality, trying to quantify lift and drag using Newtonian law isn't acceptable as he never considered how much influence, for example, an inclined plate extended to. It was only in

1907 when a Russian scientist, Joukowski, found that air was affected a considerable distance away from the plate therefore the flow characteristics couldn't be determined by the forces alone (see figure 3) (McBeath, 1998).

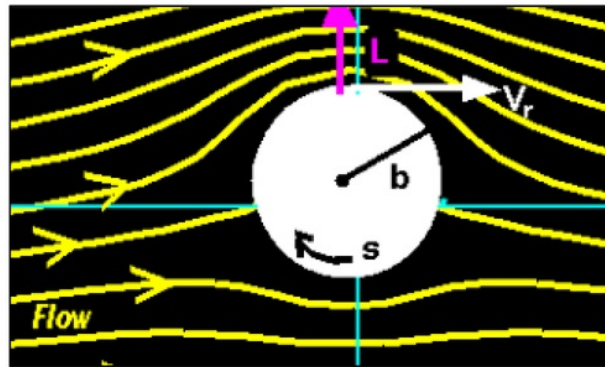


Figure 3 - Joukowski Lift Theorem, (Hall, Lift of Rotating Cylinder, 2018)

Albeit as it may, the force acting on the body is a result of the pressure multiplied by the area. As the resultant force works perpendicular to the surface it is acting on, it can be defined as lift whereas drag is the result of the net force acting along the fluid flow trajectory. When these forces are combined, they are defined as an integrated force due to varying pressure along the body. This is called the centre of pressure and is known commonly as aerodynamic force (Anderson & D, 1999).

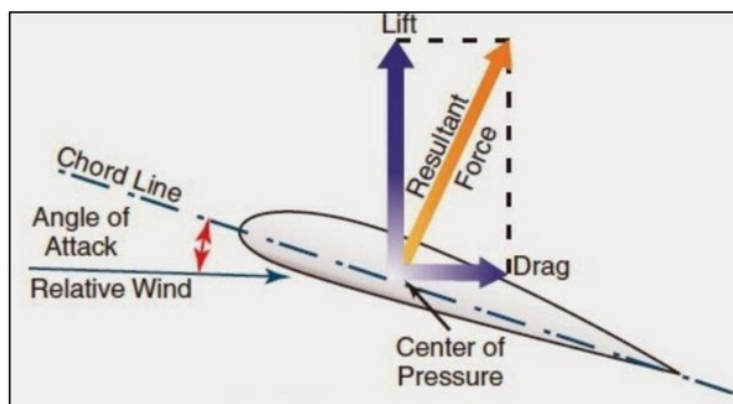


Figure 4 - Resultant force, (Prabakaran , 2013)



When a body moves through a given fluid, the pressure along the surface of the body is constantly varying due to velocity changes in the fluid. Using the equation below (see figure 3), the centre of pressure (C_p) can be determined which reveals where the lifting force (resultant force) and drag force are acting from. Integrating the pressures along the body multiplied by the surface area defines the amount of lift force. By calculating the average location of the varying pressure, the point where the lift and drag force are acting from can be found (C_p). If looking at a wing, the location of the centre of pressure would vary depending on the angle of attack (Nasa, 2015).

$$C_p = \frac{\int x \times p(x) \times dx}{\int p(x) \times dx}$$

Equation 3 - Centre of Pressure

Where $p(x)$ is the average location of pressure, dx is constant to denote the continuous integration function.

3.1.3 Euler's & Navier Stokes Equation

Leonard Euler's equation is used to describe how the pressure, velocity and density of a fluid are related. Figure 5 shows these coupled differential equations, meaning the equations are solved simultaneously, are solved via calculus. However, these equations are simpler versions of the more commonly known Navier Stokes' equations of fluid dynamics. This means Euler's equation can only be taken as an approximation as viscosity is not considered. Although, for testing a thin airfoil with a relatively low angle of attack, Euler's equations will offer a quicker solution with high accuracy (Hall, Eulers Equation, 2018).



2 - Dimensional, Steady Form:

Coordinates: (x,y)	Continuity:	$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0$
Velocity Components: (u,v)	X - Momentum:	$\frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} = -\frac{\partial p}{\partial x}$
Pressure: p	Y - Momentum:	$\frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} = -\frac{\partial p}{\partial y}$
Density: ρ		

Incompressible Form:

Continuity:	$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$
X - Momentum:	$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x}$
Y - Momentum:	$u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y}$

Figure 5 – Euler's Equations, (Hall, Eulers Equation, 2018)

For fluid flow, the Navier Stokes' equation is more complete than Euler's equation (see figure 6), with viscosity considered. With this, boundary layers (see chapter 3.1.4) can be taken into account which allows for accurate solutions to larger fluid problems. These problems are generally too difficult to solve analytically, which is why they are completed using numerical solutions via Computational Fluid Dynamics (Tucker, 2016).

Coordinates: (x,y,z)	Time: t	Pressure: p	Heat Flux: q
Velocity Components: (u,v,w)	Density: ρ	Stress: τ	Reynolds Number: Re
	Total Energy: Et		Prandtl Number: Pr

Continuity: $\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$

X - Momentum: $\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} \right]$

Y - Momentum: $\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} \right]$

Z - Momentum: $\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \right]$

Energy: $\frac{\partial(E_t)}{\partial t} + \frac{\partial(uE_t)}{\partial x} + \frac{\partial(vE_t)}{\partial y} + \frac{\partial(wE_t)}{\partial z} = -\frac{\partial(u p)}{\partial x} - \frac{\partial(v p)}{\partial y} - \frac{\partial(w p)}{\partial z} - \frac{1}{Re_r Pr_r} \left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right] + \frac{1}{Re_r} \left[\frac{\partial}{\partial x} (u \tau_{xx} + v \tau_{xy} + w \tau_{xz}) + \frac{\partial}{\partial y} (u \tau_{xy} + v \tau_{yy} + w \tau_{yz}) + \frac{\partial}{\partial z} (u \tau_{xz} + v \tau_{yz} + w \tau_{zz}) \right]$

Figure 6 - Navier Stokes Equation, (Hall, Navier-Stokes Equations, 2015)



3.1.4 Boundary Layers

Boundary layers are formed nearest the surface that a fluid is acting against. It appears that air sticks to the surface, though this is not true. However, the air in the boundary has no velocity (no-slip) relative to the body parallel against the surface (Barnard, 2001). Figure 7 shows how a boundary layer grows and how the velocity increases as it transitions back into the freestream flow.

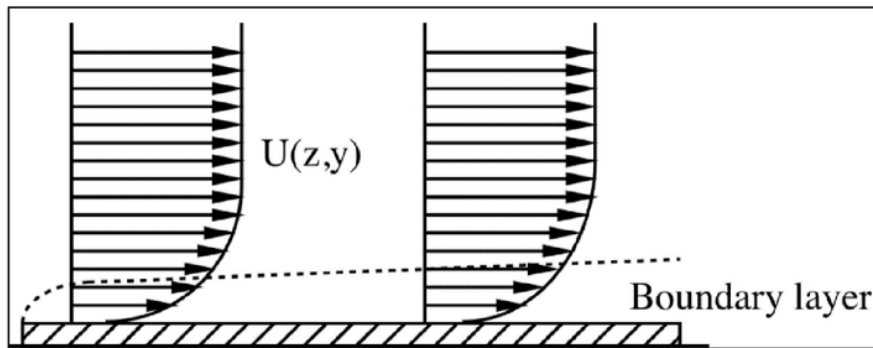


Figure 7 - Boundary Layer Growth & Velocity Increase, (Stokes, 2019)

These properties are important to understand as "skin friction drag" occurs which plays a role in how much drag will occur around the body. Boundary layers that have a laminar flow are considered to have a relatively low Reynold's number (see chapter 3.1.5) which allows for the velocity change throughout the layer to be uniform. Whereas, a boundary layer with a higher Reynold's number means that the stream wise velocity deviates unsteadily, causing eddying (see chapter 3.1.7) flow patterns in the boundary layer (Hall, Boundary Layer, 2005). The state of the boundary layer also has a large impact on how much or how early separation (see chapter 3.1.7) will occur, due to it being more easily affected by pressure differences. This is a result of a lower amount of available energy in the flow (compared with the freestream), meaning the effective shape of a body can vary significantly depending on the size of the boundary layer. Generally, this occurs more at higher angles of attack (Hall, Boundary Layer, 2005).

3.1.5 Reynolds Number

Reynolds number (Re) is calculated to predict the patterns of fluid behaviour. In viscous flow, Re is used to foresee if the fluid flow will be either be in a laminar or turbulent state, which is an important parameter to understand when choosing a numerical method in CFD. This is because turbulence models have a pre-set range of Re (SimScale, 2017). If the inertia forces and viscous forces are known, then Re can be calculated by dividing the inertia force by the viscous force. For sub-sonic viscous flow, if the Re is calculated to be under 1×10^5 , the viscous forces dominate therefore the flow is considered laminar. If Re is above 1×10^5 then the flow will be in a state of transition until it reaches 5×10^5 where the flow is expressed as turbulent due to the inertia forces dominating the viscous forces. (David Darling, 2016). From this information it can be said Re is simply the behaviour of the flow in the fluid. Osbourne Reynolds studied this phenomenon in 1883 by releasing dye into the centre of a clear pipe with flowing water and analysed the behaviour of the dye. A visual representation of the experiment is shown in figure 8.

$$\text{Reynolds Number} = \frac{\text{Inertia Force (N)}}{\text{Viscous Force (N)}} = \frac{\text{Fluid Properties} + \text{Flow Properties}}{\text{Fluid Properties}}$$

Equation 4 - Reynolds Number

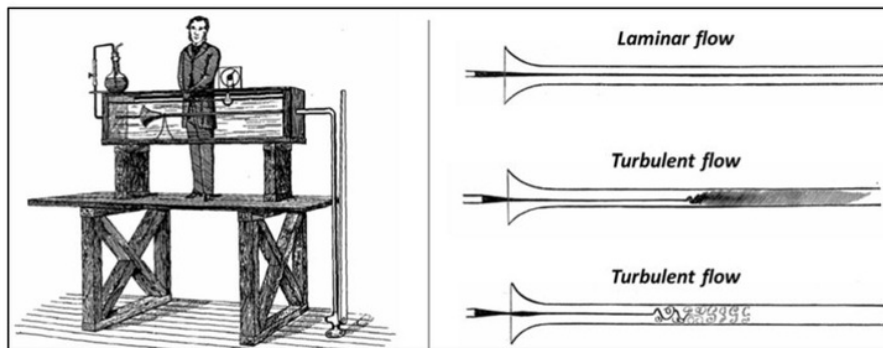


Figure 8 - Representation of Osbourne Reynolds Experiment, (SimScale, 2017)



3.1.6 K-epsilon

K-epsilon is known as one of the standard turbulence models to use for subsonic fluid flow analysis (Wasserman, 2016). Marra says the model utilises wall functions which allow it to predict the fluid behaviour near to walls, meaning in the viscous sub-layer (Wasserman, 2016). The benefit of this turbulence model is that it doesn't require a huge amount of memory to solve, for this reason, it is often used for external flow analysis (Wasserman, 2016). This is because CFD is used in many different industries which include automotive, construction and aerospace. These industries often build bodies with a large surface area, having the use of a turbulence model which doesn't require excessive amounts of memory is beneficial. The Realizable K-epsilon model is an improvement of the standard model because it is better at calculating boundary flow, swirling flows and works well with big curvatures. However, it is not as stable as the standard model (Rodriguez, 2014) therefore achieving convergence, giving suitable answers, can be difficult.

3.1.7 Turbulence, Eddies & Separation

It is important to appreciate the difference between flow separation and a turbulent boundary layer. A turbulent boundary layer still has flow attached to the surface, the shear forces are high, so a lot of kinetic energy is lost and many small eddies are formed, however this is not called separation (Barnard, 2001). Viscous friction is produced by air moving over a body, this is because the air is not only slowing down because of friction between itself and the surface, but also because the air is trying to carry the surface with it due to friction (Barnard, 2001). When looking at a wing profile with a low angle of attack, the adverse pressure gradient is not as high as that with a higher angle of attack because of larger velocity differences. When the angle of attack is too large, the pressure gradient along that wing is high which can result in flow separation due to the air failing to stay attached as the gradient of the surface curvature is too high.

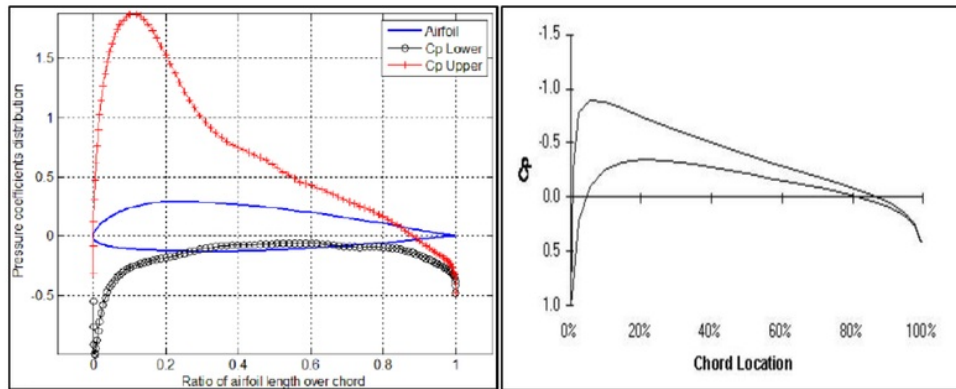


Figure 9 - Comparison between a wing with a high pressure gradient (left) (Hirsch, 2018) and wing with low pressure gradient (right) (Erb, 1997)

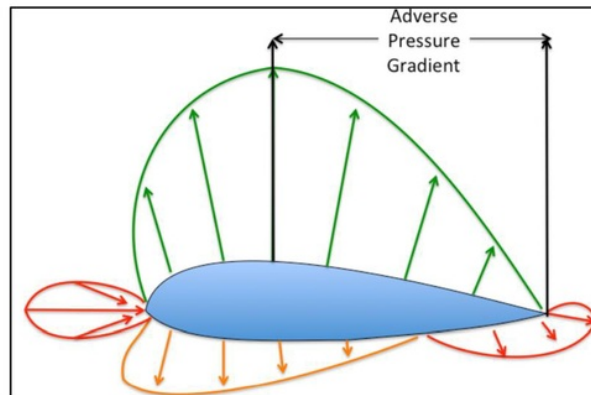


Figure 10 - Wing pressure gradient example, (Code7700, 2018)

Separation occurs because too much energy is being lost from the air trying to stay attached to the surface, resulting in small eddies. If the difference in pressure between the surface flow and the free stream flow is too great, the energy transfer will become too slow, this results in the lower part of the boundary layer decreasing in velocity. This energy drop stops the boundary layer forming on the surface so the flow separates, this is separation (Schuetz, Aerodynamics of Road Vehicles, 2016). As more energy is lost, the eddies move closer to the highest velocity point (lowest pressure) of the wing (Barnard, 2001). From this point onwards turbulence is being formed which leads to drag but can also pass useful energy to other areas.

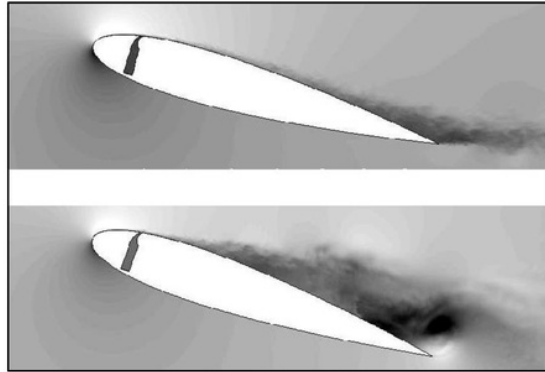


Figure 11 - Examples of how angle of attack effects point of separation, (Moin, 2007)

Eddies are a form of turbulence, which is caused from a spike in kinetic energy in a flow field. Usually this means a body has caused a fluid to move out of its original path, the result is a chaotic scenario between the varying pressures and velocities in said fluid. These constant changes are unpredictable and have been attempted to be solved many times, with equations derived from Newton's laws. Unfortunately, it is currently impossible to determine exactly how much turbulence will occur in any given situation. This is due to the sheer amount of calculations that need to be solved in order to how each atom collides with each other (Davidson, 2015).

3.1.8 Tear Drop

The teardrop is one of the most naturally occurring efficient aerodynamic shapes. It was first utilised for its aerodynamic properties in 1921 by a German inventor named Edmund Rumpler who launched the "teardrop car" (see figure 12).



Figure 12 - Teardrop car invented by Edmund Rumpler, (DON-BUR, 2019)



Since then, the teardrop shape has been used in the automotive industry to lower the drag of the vehicle. Perhaps the most iconic of these vehicles is the latest Toyota Prius, which has an astonishing drag coefficient of 0.24 (Toyota, 2019). However, it has also been used to reduce the drag of trucks hauling a trailer, which has in some cases accomplished a decrease in drag of 10% whilst increasing the haulage capacity by 10%, with fuel savings of around 11.3% (DON-BUR, 2019). It is safe to say that this idea has been used for many vehicles over the years which has slowly left “brick” shaped vehicles behind, especially with race engineers identifying the benefits of a higher speed rather than stability (DON-BUR, 2019). Implementing the teardrop shape into certain areas of the drag bike geometry could improve certain aspects of the aerodynamic characteristics.

3.1.9 Lift & Drag

In the motorsport industry, aerodynamic properties such as lift and drag have become increasingly important due to restrictions in other areas such as engine tuning (Racecar Engineering, 2019). Negative lift, also known as downforce has had a significant role in how fast a vehicle can move around a track. For example, in the motorsport world, diffusers are made to increase the flow velocity underneath the vehicle (see figure 13). This creates an area of low pressure and effectively sucks the air out from underneath the vehicle which in turn pulls the vehicle towards the ground (Racecar Engineering, 2019). This allows these vehicles to turn into a corner faster than before which means the minimum corner speed is increased which in turn, allows for higher corner exit speeds which overall decreases lap times.

The equations for lift and drag force are the same apart from the fact that they are multiplied by their respective coefficients (see equations 4&5).

$$D = C_d \times \frac{\rho \times V^2}{2} \times A$$

Equation 5 - Drag Force

$$L = C_l \times \frac{\rho \times V^2}{2} \times A$$

Equation 6 - Lift Force



For these equations, ρ is air density, V is velocity and A is the reference area. From these equations it can be said there is a direct relationship between lift and drag force. Each term of the equations are the same apart from the coefficients. However, if any of the terms were to change, the respective force, in general, would change proportionately. From this, it can be said that more downforce will result in more drag. However the only term that will affect the lift or drag will be its coefficient, respectively.

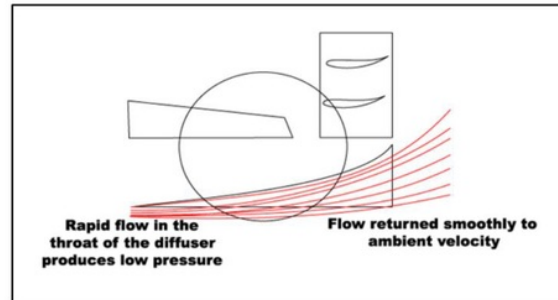


Figure 13 - How a Diffuser Works, (Racecar Engineering, 2019)

Downforce (negative lift) is often gained by the use of a wing. Many studies have been completed to see which wing design is most efficient, in order to increase the amount of downforce without gaining too much drag. However, understanding the concept of how a wing works is probably the best place to start. It's a common myth that wings cause lift because the air velocity is forced to move faster on the top of the wing to meet up with the air flow underneath, at the trailing edge of the wing, this is not accurate. A study by Holger Babinski at the university of Cambridge has "set the record straight" (Babinsky, 2012) by releasing a video which proves that the air travelling over the top of the wing passes the trailing edge before the air travelling underneath (see figure 14). Knowing that diffusers create downforce, this design could be applied to the drag bike to improve the efficiency of the geometry.

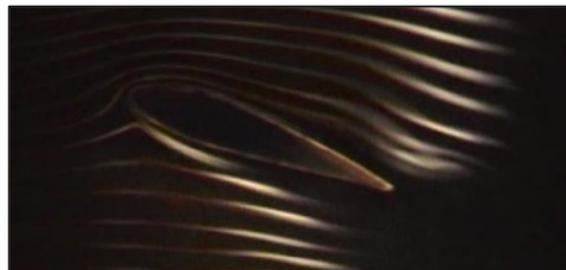


Figure 14 - Air flow passing a wing, (Babinsky, 2012)



Looking at figure 14, it is true the air is moving faster over the top of the wing than it is underneath, but the two flows do not meet again. From Bernoulli's equation, this states that pressure must be lower on the top surface of the wing. The difference in the pressure between the top surface and bottom surface is what "lifts" the wing, as high pressure likes to move to low pressure or ambient pressure (Walker , 2019).

3.2 Wind Tunnels

Wind tunnels are quite special, they allow for real world testing of how a body will act aerodynamically, generally using a model. However, it is difficult to replicate the Reynolds number of the full scale body when testing a model (Woodford, 2019). For an aeroplane, wind tunnels cannot match the air velocity which occurs in real flight. Due to this, to get an accurate Reynolds number, the European transonic wind tunnel changes the dynamic pressure of the air and evaporates nitrogen into the closed loop tunnel (European, 2019) (see figure 15). As the equation for inertial forces is calculated by multiplying the air density by the velocity (Benson, 2014), if the pressure is raised, the velocity can be decreased. This allows for a relatively accurate Reynolds number without having to create realistic conditions.

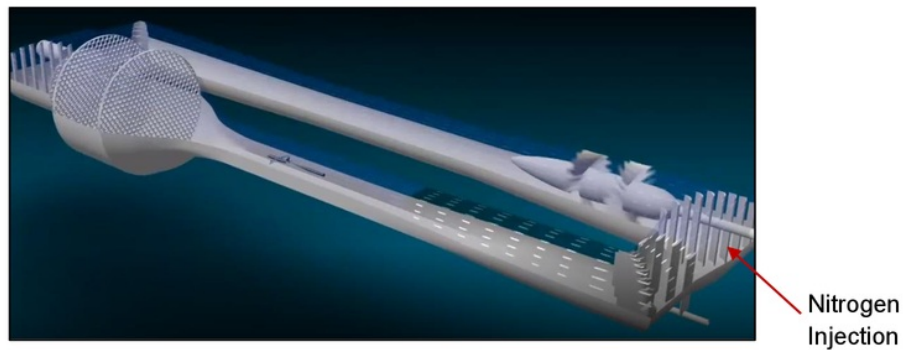


Figure 15 - Nitrogen Injection Wind Tunnel, (European, 2019)

For the automotive industry, these conditions aren't as difficult to achieve. Fortunately, full size wind tunnels such as the MIRA wind tunnel can achieve wind speeds of up to 36m/s which equates to roughly 80mph (Horiba MIRA, 2019). At these velocities, accurate solutions for lift and drag can be obtained for road vehicles. When trying to calculate lift and drag forces over these speeds, only approximations can be calculated unless the density of air is changed to match the difference in velocity.



3.3 Drag Racing

3.3.1 History

Drag racing was introduced shortly after Henry Ford started mass producing vehicles which were less expensive than before (McDonald, 2011). Flat areas of land were used to create drag strips where racing took place. Of course this was considered illegal until around 1950 where Cloyce J Hart opened the first drag strip in California (McDonald, 2011).

People saw the opportunity of having a set place to have sanctioned races, this is where drag racing was born. Unfortunately, Hart was ushered away by a group of U.S marines, however the manager of an airport in the orange county offered up the use of an unused air strip. The airport manager asked for 10% of the proceedings as well as insurance, so Hart, his wife Peggy and two other sponsors opened the first official drag strip, Santa Ana Drag, all for under \$1000 (Wallace, 1999). From there drag racing became popular and within ten years there were multiple events being held all over the United States (McDonald, 2011). Since this period, drag racing has become popular, with events being held all over the world.

3.3.2 Hayabusa

The Suzuki Hayabusa (see figure 16) held the top spot for the fastest motorbike to ever be mass produced in 1999 (Hughes, 2018). Even the name of this iconic bike means speed. Hayabusa, which in Japanese translates as peregrine falcon, the fastest land animal on the earth, reaching speeds up to 200mph when “stooping” to catch prey (The Wildlife Trusts, 2012).



Figure 16 - Suzuki Hayabusa, (Hughes, 2018)



The reason that the Hayabusa was able to reach such speeds is not only due to the power from the 1.3lt engine (Suzuki, 2019). The fairing of the bike was sculpted in such a way to cut through the air as efficiently as possible. When the rider is fully slouched, the teardrop design is visible which can be seen below which is sourced from Suzuki's RND department. Looking at figure 17, it can be seen that the fairing has been created in this way to force the air to move around the bike in the smoothest way p. Extensive wind tunnel testing was completed to achieve this shape which has made the bike a legend in its own right (Suzuki, 2019). Not everyone appreciated the aesthetics of the Hayabusa, but none could question its performance. For this reason, the Hayabusa has often been used as a drag bike for its streamline design and highly tuned engine.



Figure 17 - Suzuki Hayabusa Streamlines, (Suzuki, 2019)

Looking at figure 17, the tail of the Hayabusa has been aerodynamically shaped to reduce the amount of turbulent wake (Suzuki, 2019). In effect this reduces drag, therefore this approach could be utilized to try and reduce the wake region of Storm's bike.

3.3.3 Jade Warrior

In the drag racing industry, the Jade Warrior drag bike is iconic for its unique design, the only reason it could be called a bike is because it had two wheels. Apart from that it looked like a rocket (see figure 18). Its low-profile design includes a small frontal area, long body and uses an exhaust blowing method, which provided downforce even whilst the bike was stationary. This allowed the bike to run the quarter mile in under eight seconds (Wolf, 2010). This was very impressive at the time (1985) and was described as "riding on the tip of a bullet" by Andrew Wolf of Dragzine (Wolf, 2010).

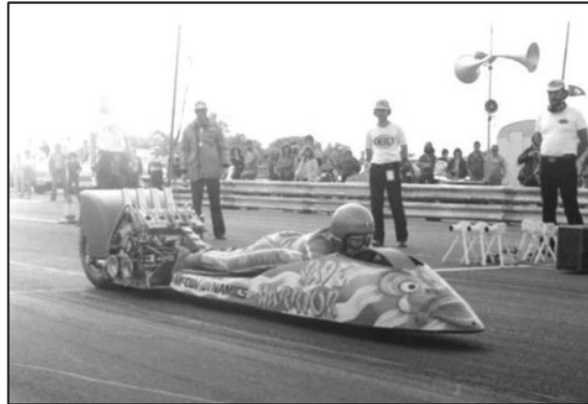


Figure 18 - Jade Warrior Drag Bike, (Wolf, 2010)

It's a shame iconic designs like the Jade Warrior are not around anymore, however teams such as Storm strive to get their bike to run the quarter mile as fast as they can which has led to this project. Angus MacPhail is part of the team that runs Storm, he worked on the Jade Warrior and it seems some of the engine characteristics from the Jade Warrior have been carried through to Storm which has led to some impressive quarter mile times (Parnell, About Us, 2018).

3.3.4 Wheelie Bars

Wheelie bars are quite self-explanatory; they are used to stop a drag bike from flipping over itself (see figure 20). Not only do they do this, they also allow for some improvements of geometry on the bike. For example, a bike with wheelie bars will generally have a higher rake angle on the front forks (see figure 19).



Figure 19 - Comparison of Rake Angle, with Wheelie Bars (Left) (Storm, 2013) and without Wheelie Bars (Right) (Dragbike.com, 2018)



Being able to have a higher rake angle makes the bike more stable at high speeds (Calfee Design, 2019) which can in turn help with aerodynamic characteristics. If a bike is slightly weaving back and forth across the drag strip due to harsh acceleration, it's constantly trying to move air around more than if the bike was moving consistently straight. So wheelie bars are good, but can they be better? Do they have a negative impact on the aerodynamics characteristics of the bike? If so, can they have less of a negative impact? This is studied further on in the report with results to conclude this question.



Figure 20 - Effect of Wheelie Bars, (Hinchliffe, 2016)

3.3.5 Land Speed Record Vehicles

When looking to develop the shape of a body so it is more aerodynamically useful, land speed record vehicles are a good place to start looking for some inspiration. Seeing as some of these vehicles are reaching velocities over the speed of sound (Vijayenthiran, 2018), the shape of the outer body must be cutting through the air efficiently. When looking at the Bloodhound SSC, its design is similar to a rocket. Looking at some computational simulation work completed by Ben Evans of the aerodynamics team (see figure 21), there are only a select few areas on the Bloodhound that have points of high pressure, the nose, inlet and rear wheels.

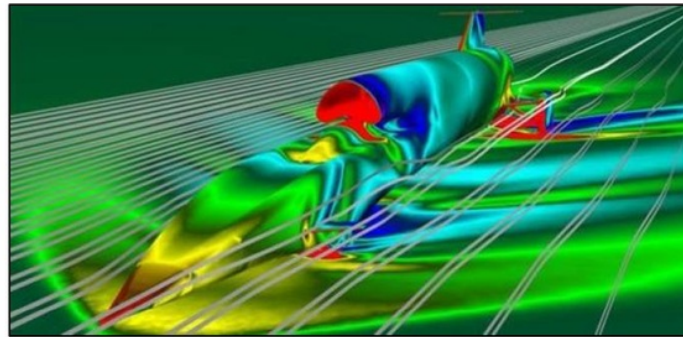


Figure 21 - CFD solution of the Bloodhound, (Evans, 2013)

This goes to show that keeping the outer geometry of the Bloodhound as clean and smooth as possible is helping achieve these tremendous speeds. Other factors which help achieve these velocities safely are the pitch of the vehicle and ride height (Evans, 2013). Land speed motorbikes can't achieve as high a speed as the jet powered vehicles, however the current speed record holder for motorbikes, the Ack Attack, still reaches a speed of 394mph. It uses two Hayabusa engines utilising a large turbo to gain the power needed for these velocities (Guinness World Records, 2019). However, looking at the body of the bike, it has as much covered up as possible and has a similar shape to the bloodhound (see figure 22).



Figure 22 - Ack Attack Land Speed Motorbike, (Guinness World Records, 2019)

After looking at these design, it is obvious that streamlining the body of a land speed vehicle is beneficial to gaining a high top speed. This could prove to be useful on the drag bike, helping to decrease drag by making the geometry more streamlined.



4.0 Storm Drag Bike

4.1 Rules & Regulations

Storm currently race in the “funny bike” series. The rules and regulations that need to be followed for the development of the fairing are as follows...

6.14 STREAMLINING...

- 1. There must be clearance of at least 20mm between the streamlining and the extremities of the handlebars or steering device, including any attachment thereto, whatever the position of the handlebars.
- 2. It must not be possible for the front wheel to make contact with the streamlining whatever the position of the handlebars.
- 3. The streamlining must be constructed of metal or other suitable material and fitted to allow complete liberty of movement of the rider, both when riding and when getting on and off the machine, without the streamlining or any part of it having to be displaced.
- 6.24 GROUND CLEARANCE... Where no particular class rules apply. Immediately after a run machines must have a minimum ground clearance of 50mm with the rider sitting on the machine in the normal riding position with their feet off the ground. Failure to comply will result in disqualification of the run.
- 7.3 HELMETS... Helmets bearing the current ACU gold stamp and in sound condition and properly fitted must be worn by all riders and passengers while practicing and racing. Overseas riders may use helmets as approved by their own FMN.

(AUTO CYCLE UNION , 2018)

4.2 CAD Modelling

To start analysing the aerodynamic properties of Storm, the first step was to create a fairly representative model. A base model was provided by a previous student which can be seen in figure 23.

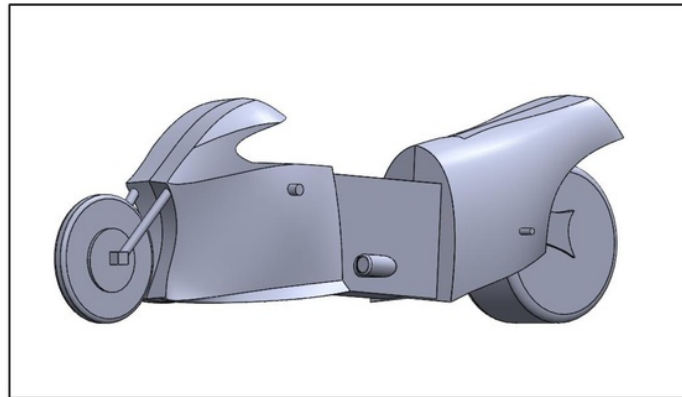


Figure 23 - Base Model Provided by Craig Welch, (Welch, 2018)

This required learning totally new techniques such as surfacing. This is where shapes are drawn using 3D sketching, then converted into surfaces by using surfacing tools. Which tool to use depends entirely on what has been sketched and how complicated the geometry of that sketch is. These surfaces then need to be converted into a 3D model. For this to be achieved, the model must be closed, meaning there are not any open faces or edges anywhere on the model, which can be difficult. If these conditions are not met, the separate surfaces cannot be stitched together. A comparison between good and bad surfacing is shown below in figure 23.

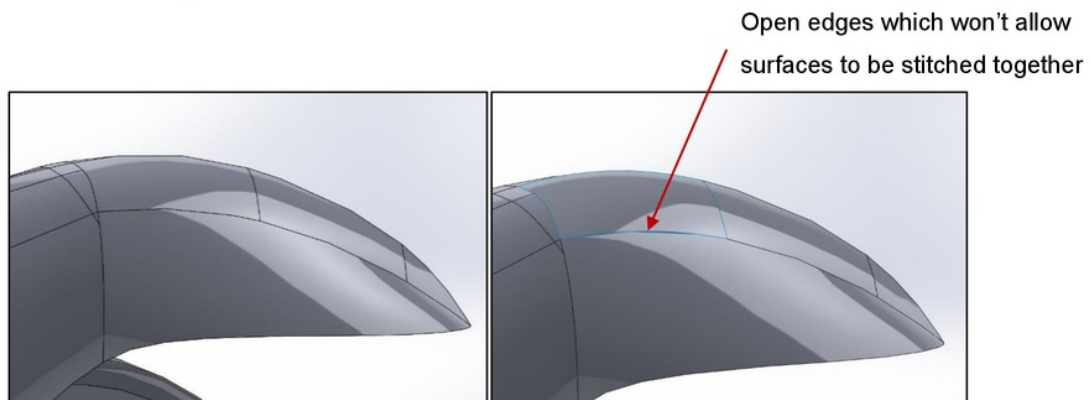


Figure 24 - Comparison of Good Surfacing (Left) and Bad Surfacing (Right) Using Different Methods

As previously stated, the model of Storm needed to represent the real bike to get some relatively accurate results. As there's a rider on the bike as it moves down the strip, a rider was modelled (see figure 25). As well as this, the wheelie bars and other details on the bike



were modelled. This required using more surfacing techniques to create geometries with more complexity, for example the legs. Once this process was complete, initial analysis could be started. A comparison between the base model provided by Craig and the authors more representative model is shown below, with a picture of Storm for clarification below (see figure 26)

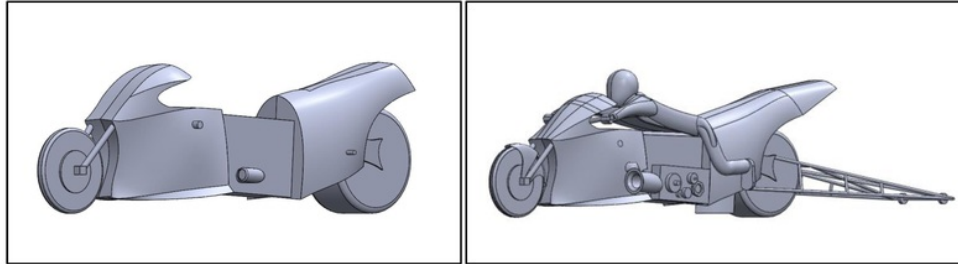


Figure 25 - Base Model (Left) (Welch, 2018) and the Authors more representative Model (Right)



Figure 26 - Current Storm Geometry, (Storm, 2018)



5.0 CFD Validation

Computational fluid dynamics (CFD) is computer software that can analyse aerodynamic characteristics of a body by using numerical methods to calculate fluid flow. CFD is used extensively in the world today not just for the automotive industry, but also for construction, aerospace, plumbing and much more. However, as fluid is unpredictable and CFD software has many variables, using the software correctly is important. To ensure results are usable, a validation study of an ahmed body was completed prior to this report. It should also be noted that CFD results should only ever be taken as an estimate, and that real wind tunnel tests should be completed to validate the CFD results.

The Horiba Mira car has been used by many to validate CFD settings due to its simple geometry along with valid wind tunnel results for lift and drag which can be received from Horiba Mira. The following table and graph show the results of the prior study against the data received from Horiba Mira and provided by Tim Tudor.

Table 1 - Comparison between Real Mira Results and CFD Results

Method	Cd	Cl	Difference	
Wind Tunnel Data	0.2963	-0.0845		
K-Epsilon, Realizable, Non-Equilibrium Wall Functions	0.3040	-0.0800	Drag: 2.6%	Lift: 4.85%

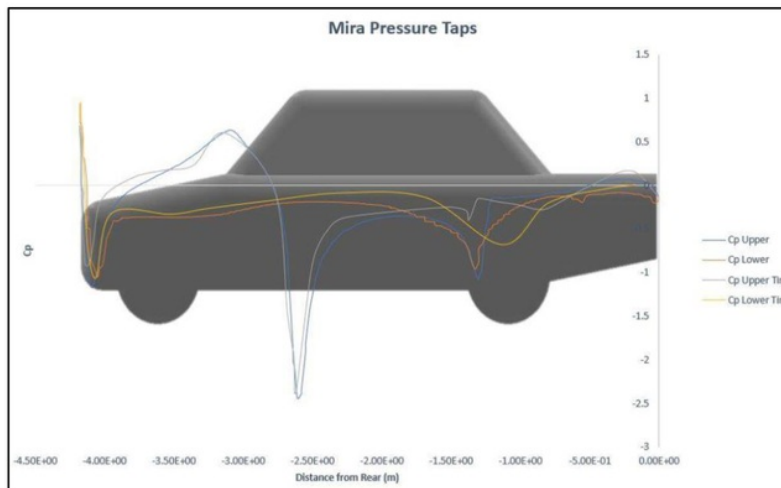


Figure 27 - Mira Validation Study Results, (Randall, Results from Mira Validation Study, 2019)



To obtain these results, studies were conducted on many parameters which include the domain size, car placement, mesh for both domain and car, density box, prism layers and turbulence model. From table, it can be seen that the results obtained from CFD are fairly accurate with a difference in drag of 2.6% and a difference in lift of 4.85%. In the authors eyes these are acceptable margins as any results under 5% are going to be fairly accurate. Backing up the results are the pressure tap plots which can be seen in figure 27 which plots the pressure coefficient against distance from the rear of the car. The trends for both the upper and lower surface generally follow the trends of the real results obtained from Tim Tudor, which clarifies the use of settings and chosen turbulence model. As mentioned in the report for this validation study, the k-epsilon realizable non-equilibrium wall functions turbulence model struggles to predict realistic data in the boundary layer which is why the pressure taps differ around the rear slope of the car where separation occurs. However, the settings listed above in table 1 have been carried forward to use with the development of the aerodynamic package on the Storm drag bike.



6.0 Development, Results & Analysis

6.1 Front Fender

It should be noted that the results from here on are in a step process, where each result is either an increase or decrease in the drag/lift coefficients from the previous development, for the whole geometry. Graphical results have been provided in the main body of work for any studies with more than one development. For studies with one development, graphical results are shown in the appendix.

The first area of development was the front fender of the bike. As previously stated, land speed record vehicles cover up as much as possible. Looking at the geometry as it is currently, the front fender is a stock version, which is only there to stop water and stones flicking up onto the radiator and nose cone of the bike. As the rules and regulations state there must be a ground clearance of at least 50mm after a run is complete and that the front wheel must be able to completely turn without coming into contact with any extremities, the front fender was adapted to completely cover the top half of the front wheel. A comparison between the two are below in figure 28.

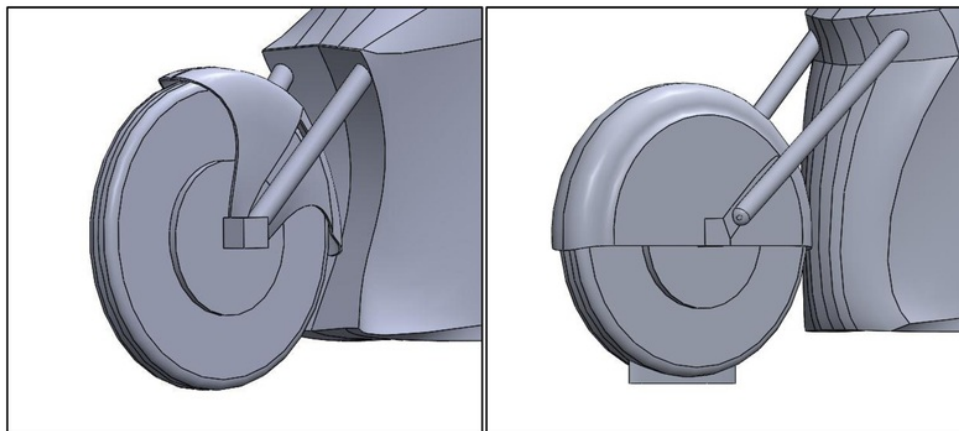


Figure 28 - Front Fender Before (Left) and After (Right) Modification

Table 2 - Results for Front Fender Modification

Front Fender						
Model	Cd	Drag Force (N)	Cl	(-Cl)	Downforce (N)	Efficiency (%/100)
Realistic	0.677	650.38	-0.059	0.059	56.68	0.09
Modified Fender	0.617	592.74	-0.0727	0.0727	69.84	0.12

From table 2, the results show a decrease in Cd by 0.06 and an increase in -Cl of 0.0137. With this development, the efficiency of the geometry has risen by 3%. For a graphical representation of the results, see appendix.

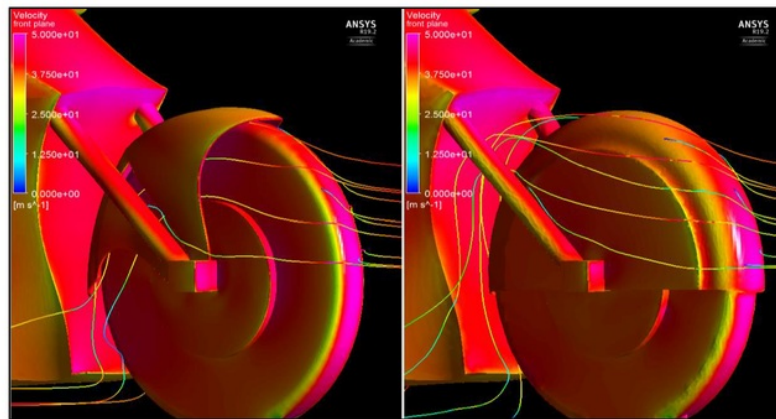


Figure 29 - Front Fender Pressure Comparison, Original (Left) and Modified (Right)

Looking at figure 29, the original fender is allowing air to flow in-between the wheel and the fender, this creates a region of high pressure under the fender which is then leaking out into the freestream causing vortices to form due to sudden changes in the flow direction (see figure 30) causing spikes in kinetic energy, hence more drag. The modified version of the fender blocks any air from entering the fender.

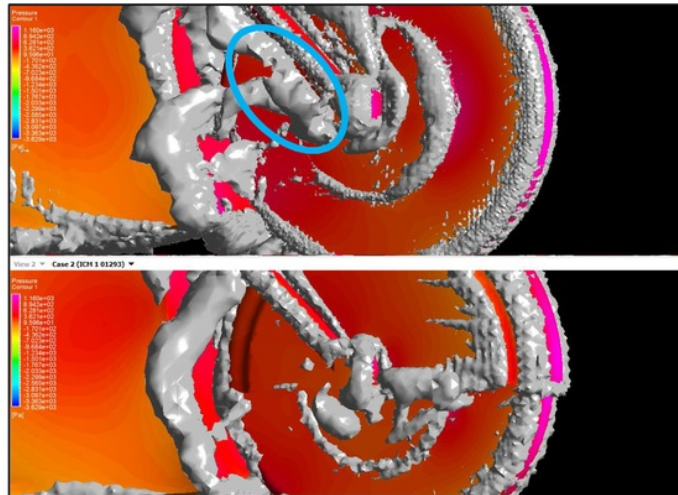


Figure 30 - Front Fender Vortices Comparison, Original (Top) and Modified (Bottom)

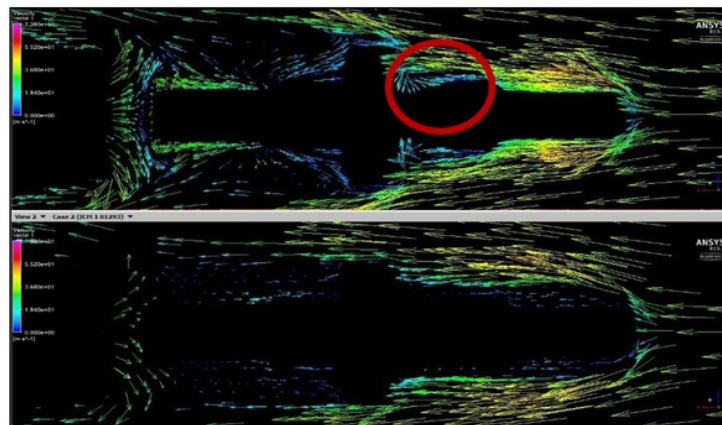


Figure 31 - Fender Velocity Vector Comparison, Original (Top) and Modified (Bottom)

From figure 31, there are more locations on the original fender geometry where recirculation occurs. This mainly happens where there are sudden obstacles, examples of this are circled above. Recirculation causes turbulence which is a cause of drag, therefore with less recirculation occurring, the amount of drag is decreased.



6.2 Air Inlet

The air inlet needs to be in an area where it can collect as much air as possible, therefore it requires as little restriction as possible. As the stock inlet is protruding out of the side of the bike, obstructing the free stream flow, four geometry developments were completed. The thoughts behind the final development came from the teardrop shape as previously mentioned, and a bullet. The shape of both a teardrop and bullet because they have very good drag coefficients (Shelke, 1997).

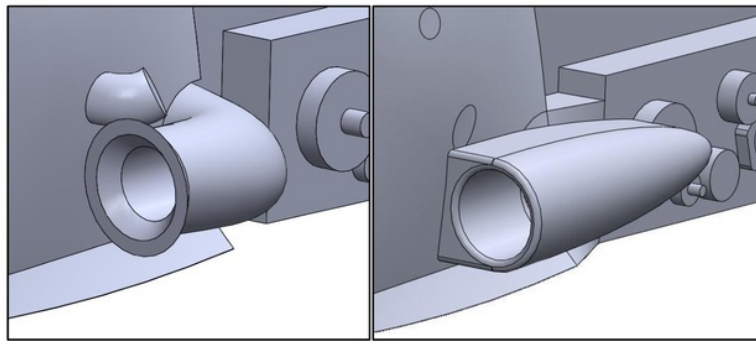
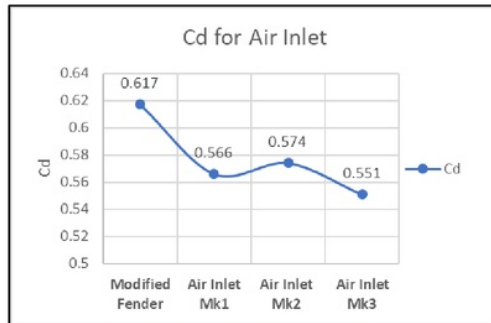


Figure 32 – Air Inlet Before (Left) & After (Right) Development

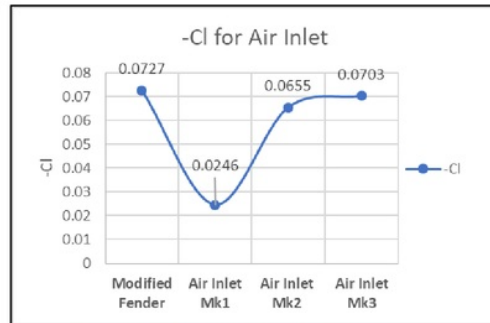
Table 3 – Results for Air Inlet Development

Air Inlet						
Model	Cd	Drag Force (N)	Cl	(-Cl)	Downforce (N)	Efficiency (%/100)
Modified Fender	0.617	592.74	-0.0727	0.0727	69.84	0.12
Air Inlet Mk1	0.566	543.74	-0.0246	0.0246	23.63	0.04
Air Inlet Mk2	0.574	551.43	-0.0655	0.0655	62.92	0.11
Air Inlet Mk3	0.551	529.33	-0.0703	0.0703	67.54	0.13

From the results in table 3, the drag coefficient for “Air Inlet Mk3” has decreased by 0.066 with the downforce very similar to the original design. This has had little effect on efficiency over all with a rise of 1%, however lowering the amount of drag will allow the bike to accelerate faster.



Graph 1 - C_d for Air Inlet Development



Graph 2 - $-C_l$ for Air Inlet Development

From graph 1, the trend of the line shows a general decrease in drag coefficient with a total decrease of 0.066. Graph 2 shows a sudden drop in the downforce coefficient, it then rises again to a similar position where it started. This sudden drop was due to the second air inlet development where the frontal area was increased to attempt to create a venturi for the inlet, to accelerate the air flowing into the intake (see figure 33). Post processing revealed a higher concentration of pressure on the top surfaces of the inlet, creating a higher pressure gradient when compared to the lower surfaces. This extra pressure was due to the pressure bleeding from the nose of the bike. However, the model was not ran with air flowing into the engine so in reality, the outcome would be different.

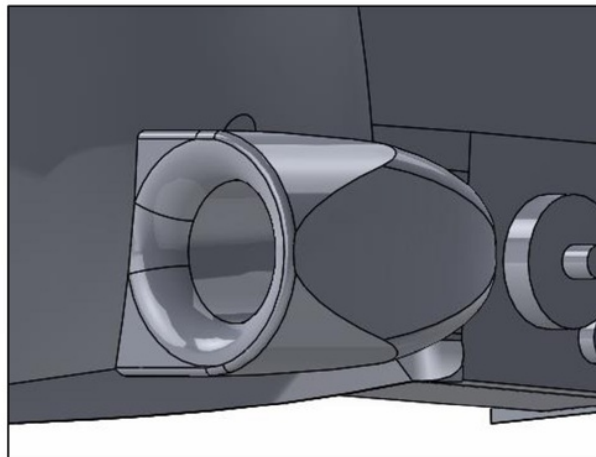
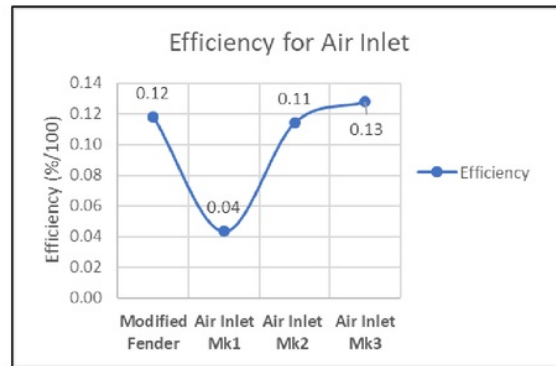


Figure 33 - Air Inlet Mk1



Graph 3 - Efficiency for Air Inlet Development

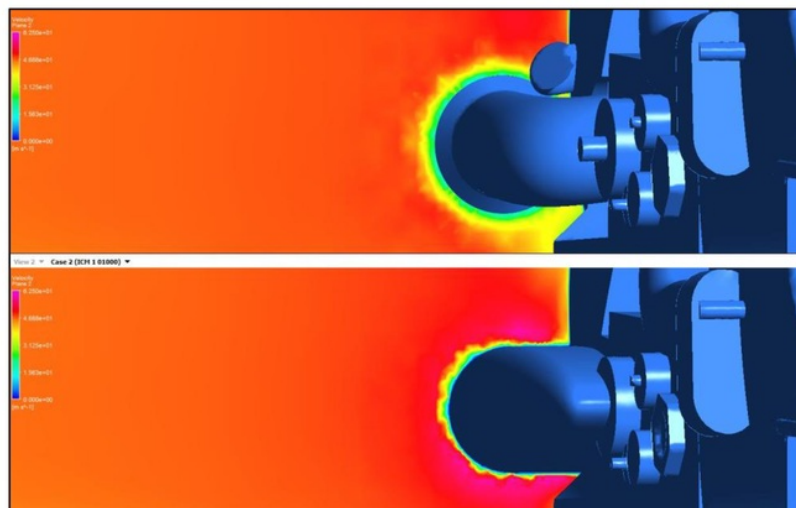


Figure 34 - Velocity Plane Comparison of Original Inlet (Top) and Developed Inlet (Bottom)

Looking at figure 34, there is a noticeable difference between how streamlined the finalized inlet is compared to the original. This is mainly due to removing the trumpet design seen in the original model which caused separation to occur almost right away. This is allowing the air-flow passing the inlet to re-enter the freestream sooner which has decreased the amount of turbulent energy in that area. Recirculation causes turbulence to form which increases drag (see figure 35). More improvements could be made here to utilize the air flow that is passing under the inlet here to improve $-C_l$, which in turn would improve the efficiency of the inlet. However it should be stated that these models have not accounted for air flowing into the engine, therefore there would be some difference in reality.

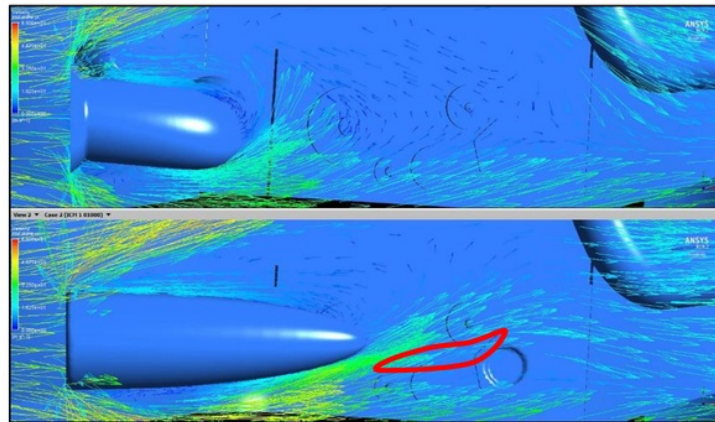


Figure 35 - Velocity Contour Comparison between Original Inlet (Top) and Finalized Inlet (Bottom)

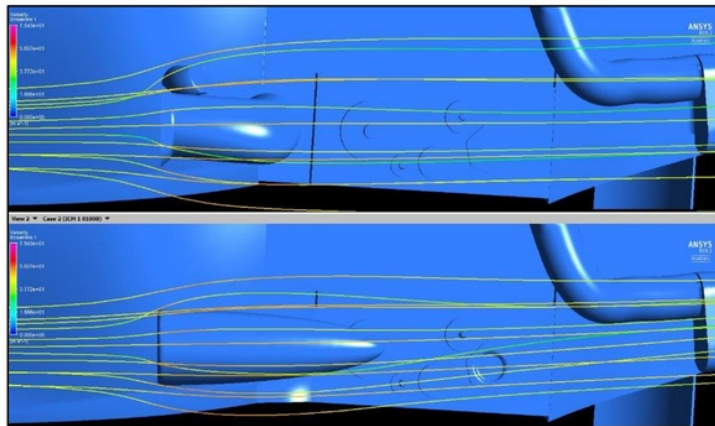


Figure 36 - Streamline Comparison between Original Inlet (Top) and Finalized Inlet (Bottom)

Figure 36 again shows how the finalized inlet geometry has improved the streamline airflow in that area, less air flow is dispersing. This area could possibly be improved by inserting an aerofoil style plate to use the now extra flow that has stayed attached to the underside of the air inlet, see example on figure 35.



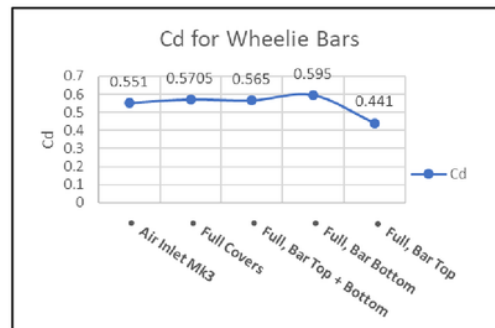
6.3 Wheelie Bars

Following some research, the only noticeable information about how to cover up wheelie bars was taken from pictures of different drag bikes. If any sides of the wheelie bars were covered, it was always the left and right side, therefore a study was conducted to see which layout would benefit the bike the most. A table of the results can be seen below in table 4.

Table 4 - Wheelie Bar Study Results

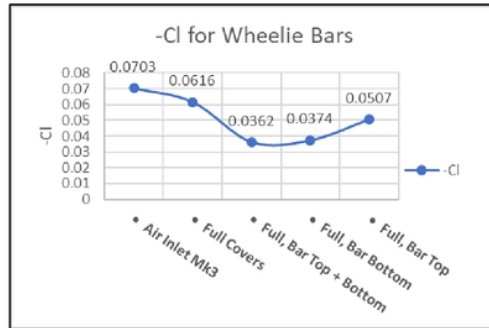
Wheelie Bar Covers						
Model	Cd	Drag Force (N)	CI	(-CI)	Downforce (N)	Efficiency (%/100)
Air Inlet Mk3	0.551	529.33	-0.0605	0.0703	67.54	0.13
Full Covers	0.5705	548.07	-0.0616	0.0616	59.18	0.11
Full, Bar Top + Bottom	0.565	542.78	-0.0362	0.0362	34.78	0.06
Full, Bar Bottom	0.595	571.60	-0.0374	0.0374	35.93	0.06
Full, Bar Top	0.441	423.66	-0.0507	0.0507	48.71	0.11

Table 4 shows that removing the top cover from the wheelie bars decreased Cd, but also decreases $-CI$, when compared to the initial geometry. This is unfortunate however the writer believed the tail would be the best area to increase the downforce, therefore Cd was considered here over $-CI$. With this, the drag coefficient dropped by 0.11.



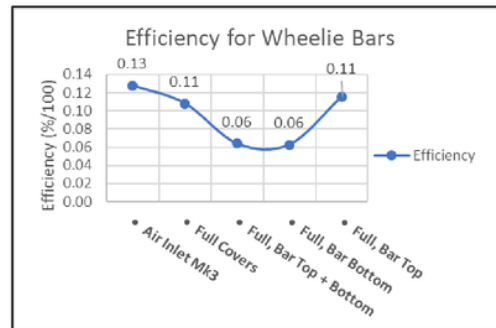
Graph 4 - Drag coefficient for Wheelie Bar Development

Graph 4 shows the trend of the line is fairly stable for Cd apart from "Full, Bar Top" where Cd drops suddenly. This is explained through post processing further on.



Graph 5 - Downforce coefficient for Wheelie Bar Development

From graph 5, the trend of $-CI$ lowers until "Full, Bar Top" where the $-CI$ rises again. Although the $-CI$ is higher than other geometries, the C_d for "Full, Bar Top" is significantly lower (see graph 4) so this geometry was chosen to move ahead with.



Graph 6 - Efficiency for Wheelie Bar Development

The efficiency for the wheelie bar studies generally follows the same trend as $-CI$, this is due to the fact C_d does not change drastically until the final study. As efficiency is calculated by dividing the $-CI$ by C_d , the final efficiency figure rises more than $-CI$ due to the drop in C_d .

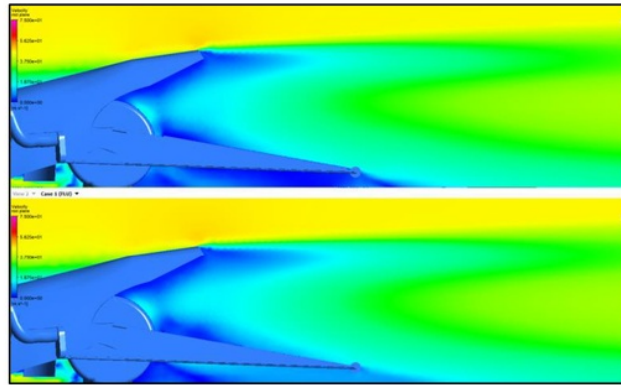


Figure 37 - Velocity Contours for Fully Covered Wheelie Bars (Top) and Fully Covered Wheelie Bars Bar Top (Bottom)

The main noticeable difference in figure 37 is the difference underneath the wheelie bars. The lower geometry shows there is less of a difference in velocity compared with the underneath of the wheelie bars and the freestream, compared to the fully covered wheelie bars.

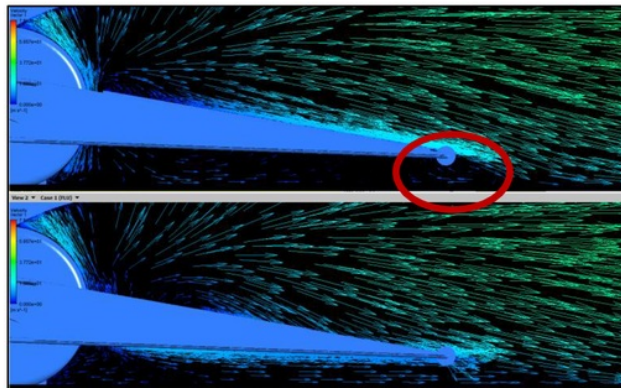


Figure 38 - Velocity Vector Comparison between Fully Covered Wheelie Bars (Top) and Fully Covered Wheelie Bars Bar Top (Bottom)

Figure 38 shows the velocity vectors of how the air flow is passing the wheelie bars. This clearly shows there is less air flow in general under the fully covered wheelie bars (top). This shows that air was getting trapped in the fully covered wheelie bars which was creating a larger velocity/pressure difference between inside the wheelie bars and the wake region, hence why C_d was higher. As this was fixed by removing the top cover of the wheelie bars, and less recirculation on the trailing edge is forming underneath the wheelie bars (circled), the C_d decreased.

6.4 Front Fairing

Looking back at figure 28 (original fender), the fairing on the front of the bike was causing high pressure to build up due to its shape. Therefore, this was the next area chosen to be developed. Creating a cleaner, more streamline shape was key to allowing the air flow to move past this point with more efficiency. Unfortunately, this was not the case, the new design made the efficiency of the model worse, rather than better. This mistake was not noticed soon enough and other geometry changes were made before the mistake could be rectified, therefore this geometry was carried forward.

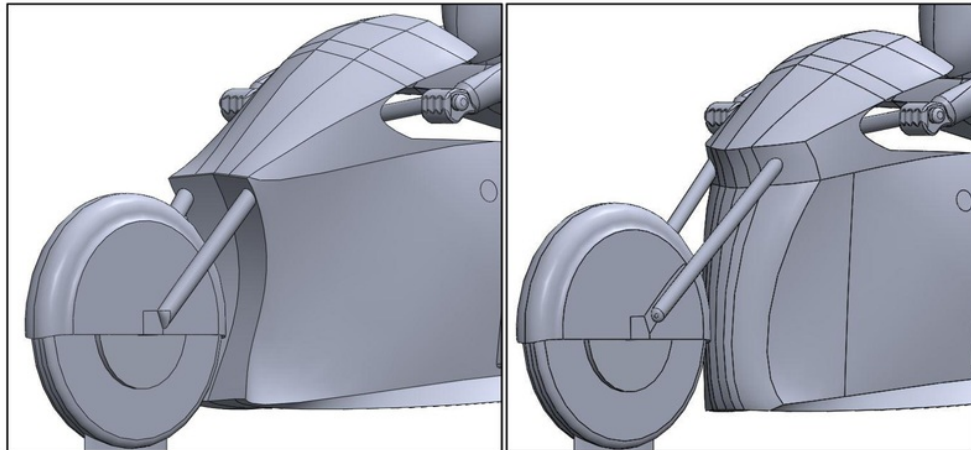


Figure 39 – Front Fairing Before (Left) & After (Right) Development

Table 5 - Modified Front Fairing Results

Front Fairing						
Model	Cd	Drag Force (N)	Cl	(-Cl)	Downforce (N)	Efficiency (%/100)
Full Wheelie covers Bar Top	0.441	423.66	-0.0507	0.0507	48.71	0.11
New Front Fairing	0.5568	534.91	-0.0267	0.0267	25.65	0.05

From table 5, both the drag and lift coefficients of the model increased. This made for less efficiency which if noticed sooner may have been rectified, which could have made for a much better outcome overall. For a graphical representation of the results, see appendix.

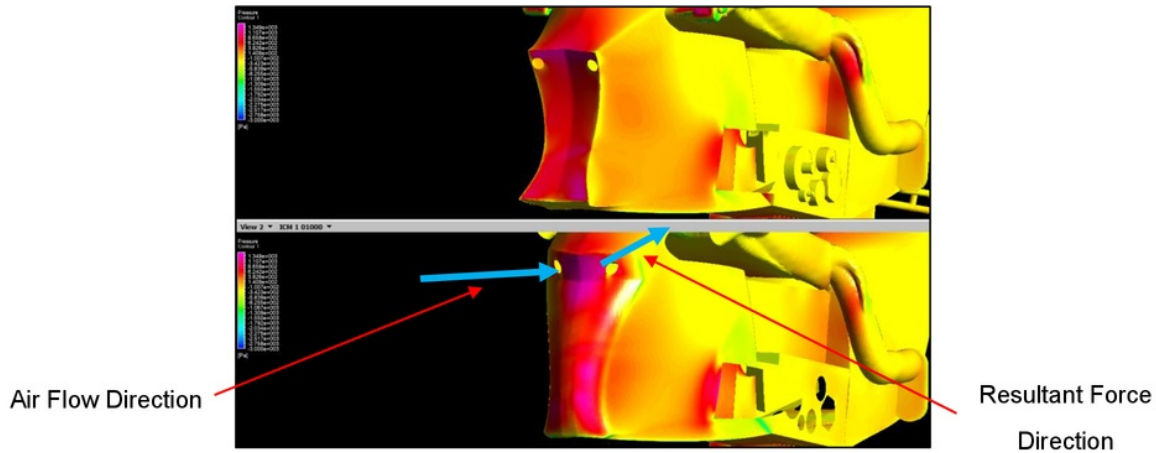


Figure 40 – Front Fairing Pressure Contours Before (Top) & After (Bottom) Modification

Figure 38 shows that the new front fairing design has made the pressure build up worse on the front of the bike. The reason lift has increased can be seen clearly by the pressure contours at the top of the nose where there is a higher concentration of high pressure compared with the previous geometry. Looking back at section 3.1.2 where resultant force was said to act perpendicular to the surface, it can be said that the top of the front surface is directed towards the road. From this the resultant force (lift force) is working towards the sky (see arrows). This is the same concept of how a splitter works, a region of high pressure builds on top of the splitter due to air flow restriction which results in a lower pressure region underneath the splitter. As pressure is always trying to equalize, or become ambient, the splitter is “sucked” to the road.

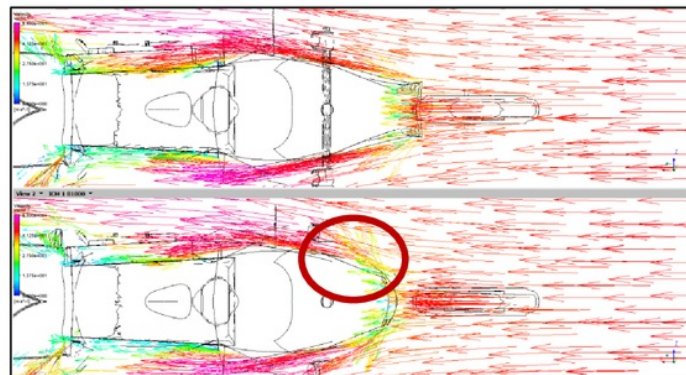


Figure 41 – Front Fairing Velocity Vectors Before (Top) & After (Bottom) Modification



Figure 41 shows the air is being deflected more severely from the modified front fairing compared to the original design. This air will be forcing the air around it to deviate from its path which is causing turbulence to build around the side of the front fairing and the air inlet which can be seen circled.

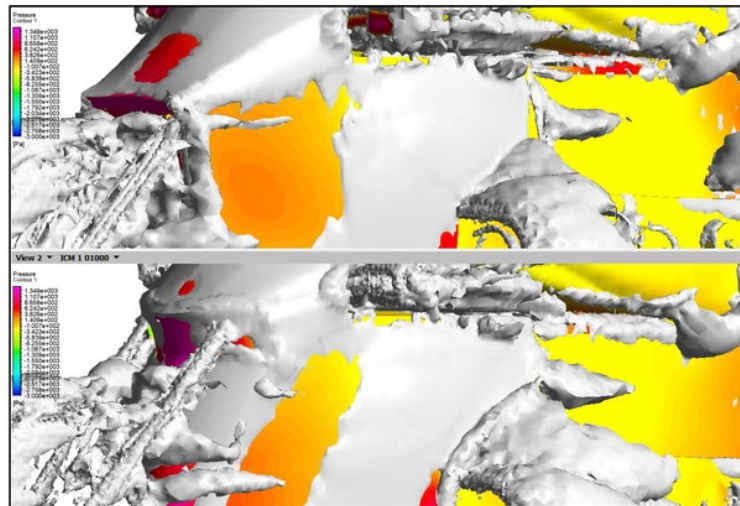


Figure 42 – Front Fairing Vortices Before (Top) & After (Bottom) Modification

Figure 42 shows how turbulence is building more severely as the flow rolls off the front face. This shows how the boundary layer has more turbulent energy which means more energy is being lost due to high shear forces.

6.5 Streamlining

As mentioned before, making the general shape of a body streamlined is a good way of lowering the drag of said body. The original geometry of Storm has a sudden step in the geometry where the front fairing meets the main body of the bike toward the centre (see figure 43). There was also a large pressure build up where the rider's leg met the body so it was decided that that area would be looked at for improvements. The main idea was simple, fill the centre of the geometry so it was smooth to remove said "steps".

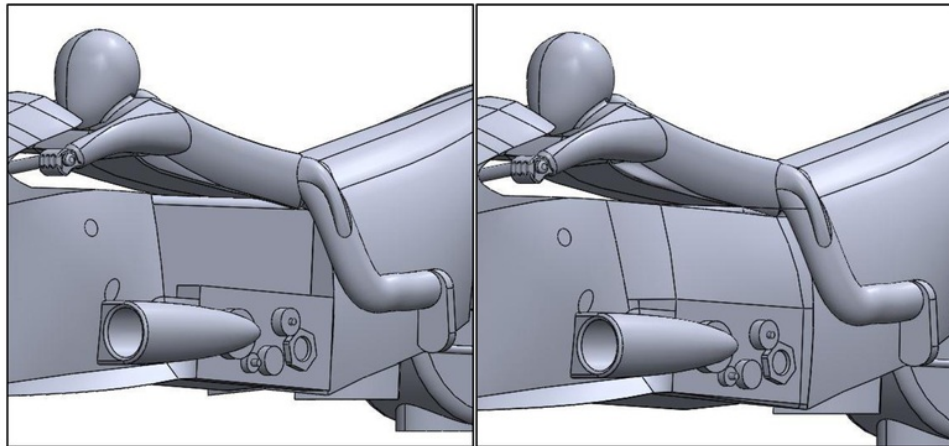


Figure 43 – Main Body Before (left) & After (right) Development

Table 6 – Filled Body Results

Model	Body					
	Cd	Drag Force (N)	Cl	(-Cl)	Downforce (N)	Efficiency (%/100)
New Front Fairing	0.5568	534.91	-0.0267	0.0267	25.65	0.05
Filled Body	0.5375	516.36	-0.0244	0.0244	23.44	0.05

This idea worked in part, drag decreased 0.0193, however downforce also decreased. As the drag only decreased with a very small reduction in downforce, this geometry development was chosen to move ahead with. Again, the majority of downforce gains were expected to be made on the tail of the bike whilst trying to make the rest of the geometry more streamline. For a graphical representation of the results, see appendix.

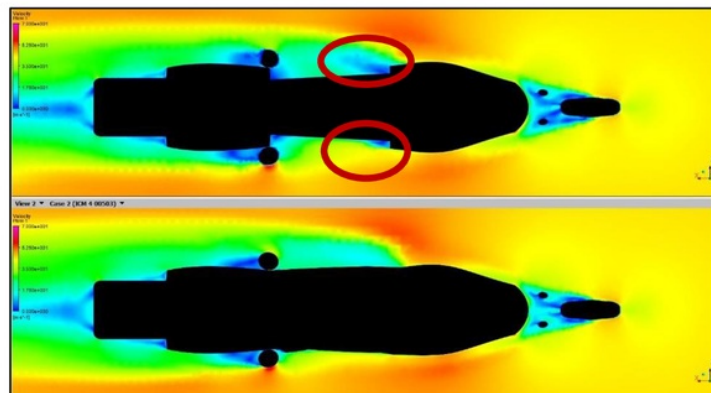


Figure 44 - Velocity Contours Before (Top) & After (Bottom) Modification

The reason for less drag occurring with the modified geometry can be seen in figure 44, the areas circled show zones of low velocity which were causing some recirculation, causing drag which can be seen in figure 45. After taking away these sudden steps, by essentially filling the body, these areas of recirculation have been removed.

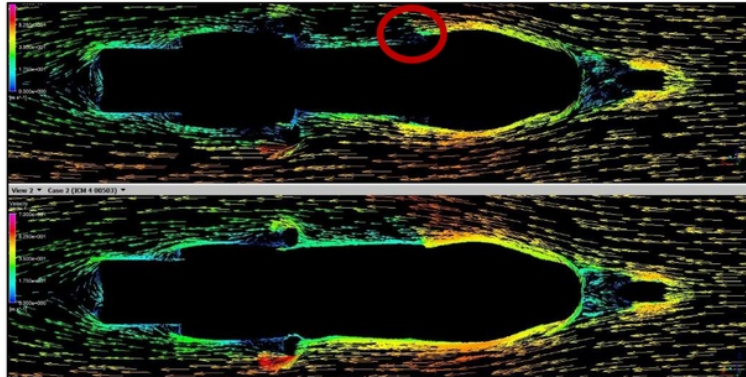


Figure 45 - Velocity Vectors Before (Top) & After (Bottom) Modification

There could be some improvements made to this design. Although the areas of recirculation have disappeared where the front fairing meets the main body of the bike, more air flow has stayed attached. This has caused more air to build up around the legs of the rider which has slightly increased the amount of recirculation around the back of the legs. Developing the geometry before the legs could prove useful if the built up air around the legs could be pushed away. Analysis would need to be completed to see if this would be a positive action to take.

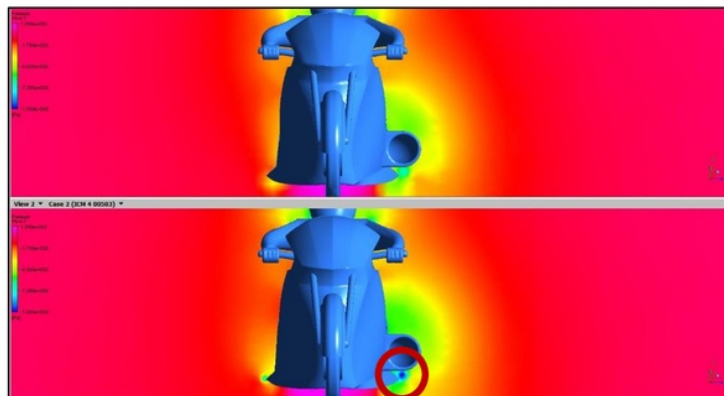


Figure 46 – Pressure Contours Before (Top) & After (Bottom) Modification

Figure 46 shows a small area (circled) of low pressure. This is evidence of a vortex being created which can be seen in figure 47 below. The air that was being pulled into the body before is being swept off the angled lip of the front fairing (arrowed) causing a build-up of swirling air which is trying to keep some attachment to the rear of the air inlet, pushing the vortex up.

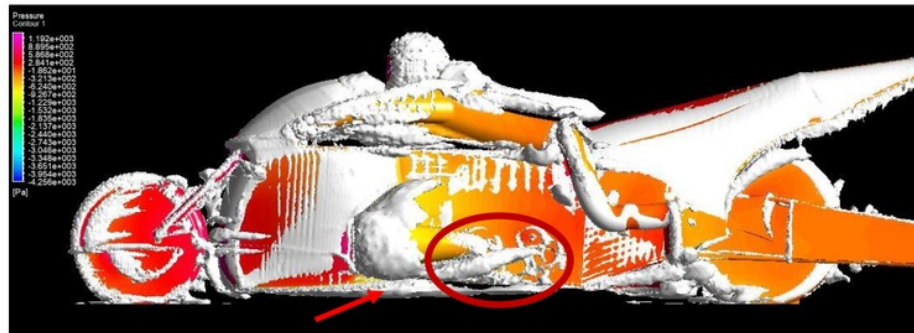


Figure 47 - Vortex Core Regions for Filled Body

This vortex was not present on the previous geometry, if extra work were to be carried out it would be a good idea to try and adapt the geometry in this area to either remove the vortices or to try and utilize it.

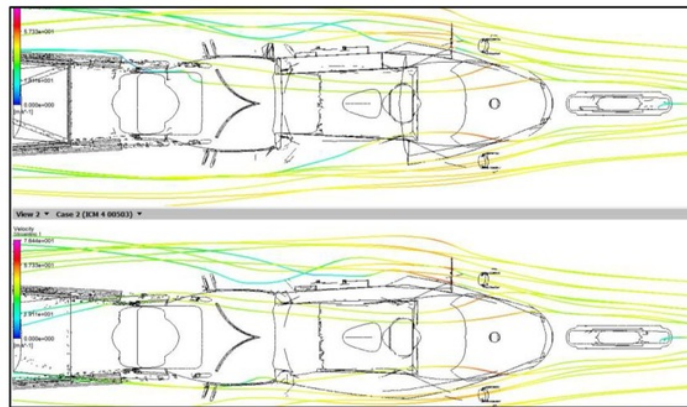


Figure 48 - Streamlines Before (Top) & After (Bottom) Modification

After the main body was filled, the streamlines towards the rear of the bike are being pulled in over the wheelie bars. This is another area that could be looked at as further work to try and utilize this new flow pattern.

6.6 Air Flaps

The air flaps underneath the bike near the rear wheel are used to deflect air away from the rear tyre. The problem with this in computational analysis is that they are treated as solid walls, whereas in reality they literally flap around. Therefore for analysis purposes, these have been treated as static turning veins which are used in formula 1 to deflect air to different parts of the cars.

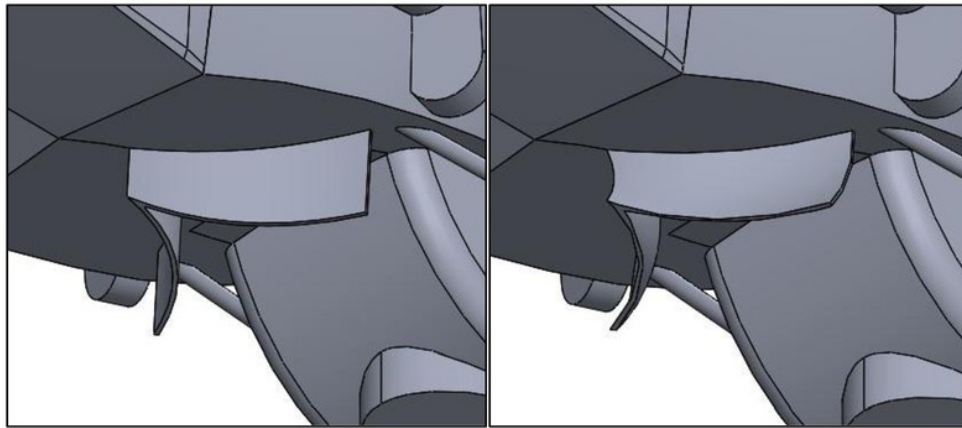


Figure 49 – Air Flaps Before (left) & After (right) Development

Table 7 – Air Flap Results

Air Flaps						
Model	Cd	Drag Force (N)	Cl	(-Cl)	Downforce (N)	Efficiency (%/100)
Filled Body	0.5375	516.36	-0.0244	0.0244	23.44	0.05
Filled Body New Flaps	0.5447	523.28	-0.0315	0.0315	30.26	0.06

A small improvement in efficiency has been made with the modified air flaps, after looking at some post processing, the main cause of this is the slightly higher build-up of pressure on the lower part of the air flaps which can be seen in figure 50. As this part of the air flap is angled slightly upwards, the downforce acting perpendicular to the surface is pushing the flaps towards the ground, similar to how a wing makes its downforce. However as the modified air flaps are diverting more of the air's energy to create this downforce, so some drag is introduced. For a graphical representation of the results, see appendix.

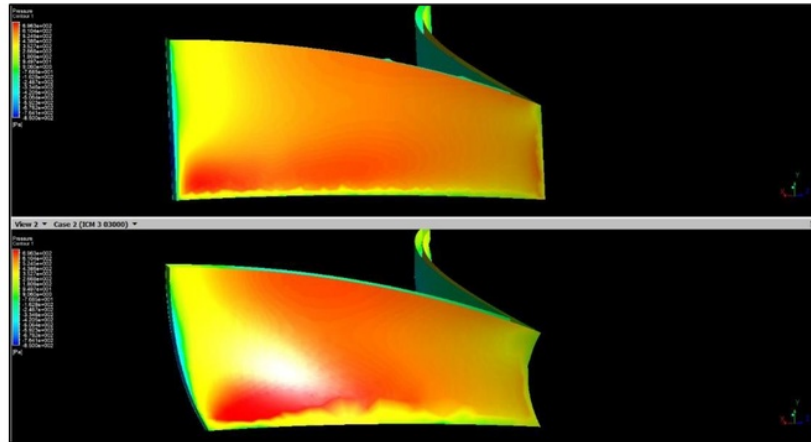


Figure 50 – Air Flap Pressure Contours (Top) & After (Bottom) Modification

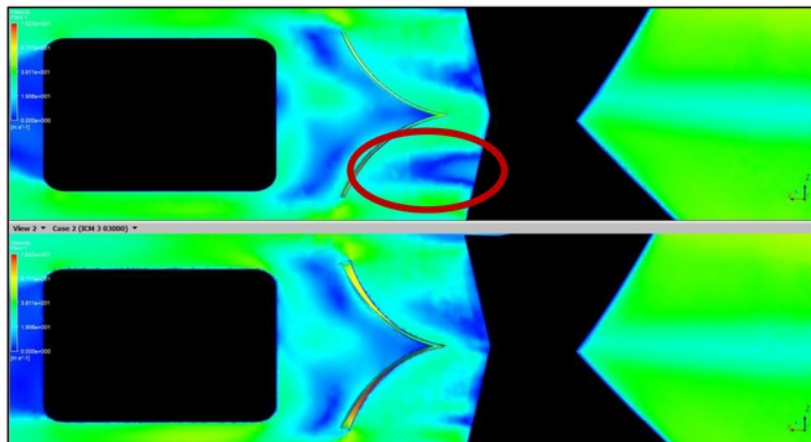


Figure 51 – Air Flap Plane Velocity Contours Before (Top) & After (Bottom) Modification

Figure 51 shows that a small region of low velocity that has almost disappeared (circled) with the modified air flaps. This is allowing a more uniform flow to pass under this area of the bike, however this is a relatively small difference hence why there is not a significant difference in drag and lift.

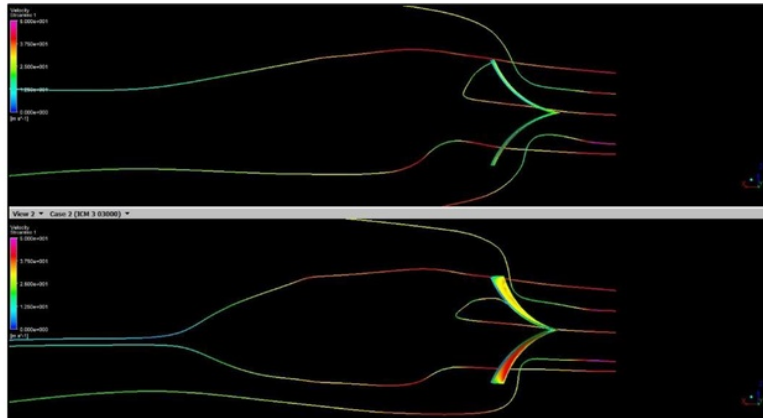


Figure 52 – Air Flap Streamlines Before (Top) & After (Bottom) Modification

The streamlines passing the air flaps before and after modification show very small differences in the air flow patterns (see figure 52). Be that as it may, the streamline coming off the right-hand side (lower part of image) of the air flaps show the flow has not been pushed as far outwards, meaning the outer flow properties are not being affected as much as before.

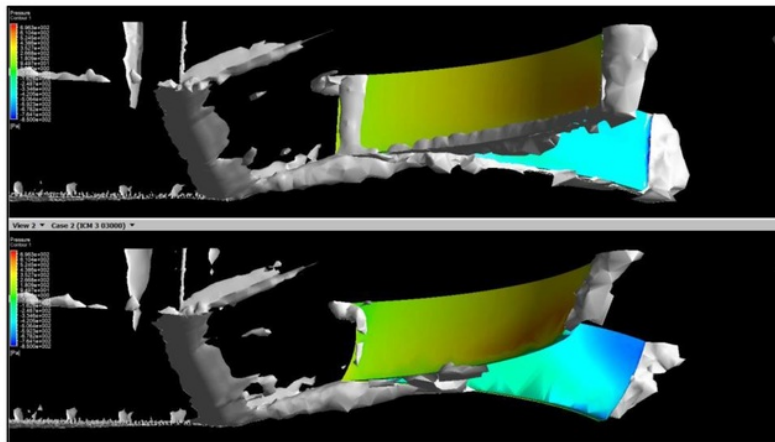


Figure 53 – Air Flap Turbulence Before (Top) & After (Bottom) Modification

Figure 53 shows there is not as much turbulence building on the trailing edges of the modified air flaps. Normally this would suggest less drag, but as mentioned above, more downforce is being created which means there is more drag, so the decreased amount of turbulence doesn't have a significant effect.

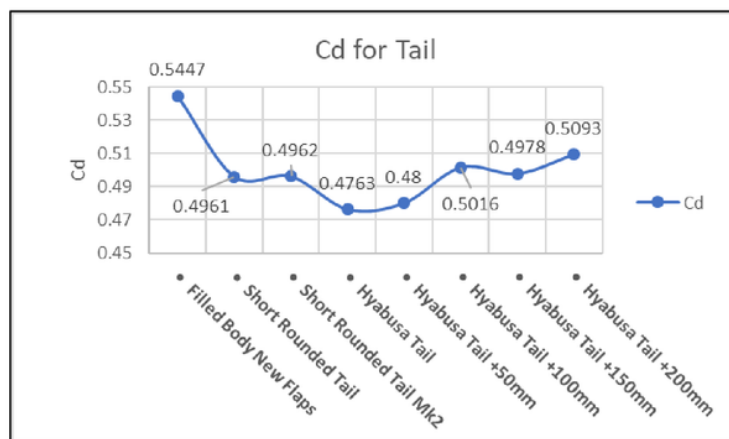


6.7 Tail

The tail of the bike was the main area to focus on when looking at increasing downforce efficiently. Initially, the design of the tail was modified to have a rounded end, so that sudden separation would not occur. This did increase the efficiency of the geometry by lowering the drag and increasing the downforce. Then it was decided to create a similar tail design to that of the Suzuki Hayabusa to see the difference in flow characteristics, which was a success. Once this was concluded, a number of studies were completed to see what effect increasing the length of the tail had in terms of downforce. The theory being the tail would have more working surface area with increased length, this was not the case. A comparison between the initial and final geometry can be seen in figures 52 and 53. The results for the studies are shown in the tables and graphs below.

Table 8 - Tail Study Results

Model	Tail					
	Cd	Drag Force (N)	Cl	(-Cl)	Downforce (N)	Efficiency (%/100)
Filled Body New Flaps	0.5447	523.28	-0.0315	0.0315	30.26	0.06
Short Rounded Tail	0.4961	476.59	-0.09822	0.09822	94.36	0.20
Short Rounded Tail Mk2	0.4962	476.69	-0.0982	0.0982	94.34	0.20
Hyabusa Tail	0.4763	457.57	-0.09974	0.09974	95.82	0.21
Hyabusa Tail +50mm	0.48	461.13	-0.08308	0.08308	79.81	0.17
Hyabusa Tail +100mm	0.5016	481.88	-0.08532	0.08532	81.96	0.17
Hyabusa Tail +150mm	0.4978	478.23	-0.09062	0.09062	87.06	0.18
Hyabusa Tail +200mm	0.5093	489.27	-0.08786	0.08786	84.41	0.17



Graph 7 - Drag coefficient for Tail Development



From graph 7, the trend for C_d decreases until the tail extension studies were undertaken. From there, the trend rises where the tail is extended. Looking at figure 54, the streamlines show how the air flow doesn't stay attached on the sides of the extended tail. This would mean that the force on the wheelie bars from the flow coming off the tail would be lower which is evident in figure 55. The air that has separated from the body flows under the tail and adds energy to the vortices under the tail. Hence the C_d is increase with a lower downforce coefficient.

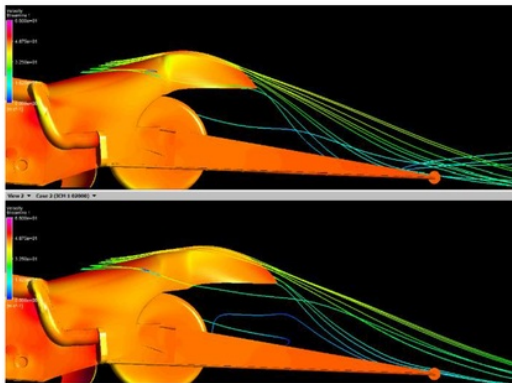


Figure 54 - Comparison for Standard Hayabusa Style Tail (Top) against Hayabusa +200mm (Bottom)

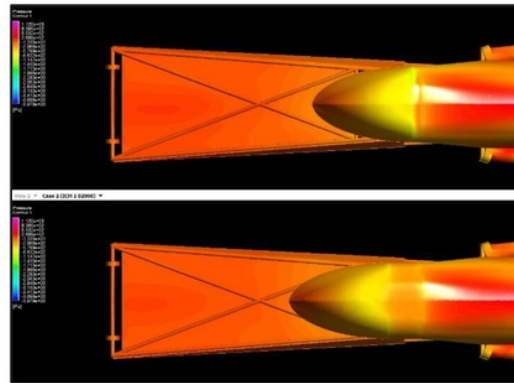
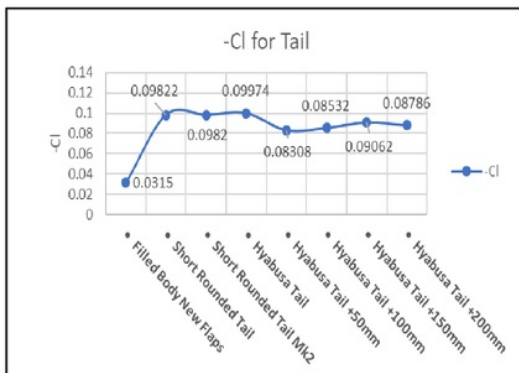
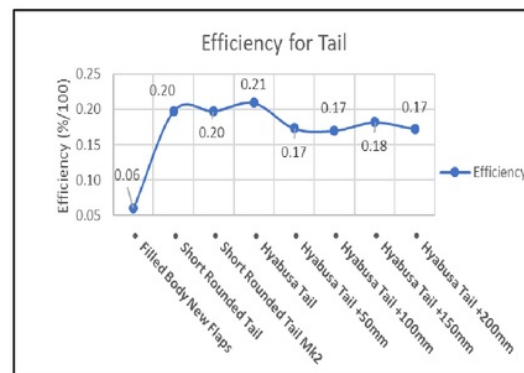


Figure 55 - Comparison for Standard Hayabusa Style Tail (Top) against Hayabusa +200mm (Bottom)



Graph 8 - $-C_l$ for Tail Development



Graph 9 - Efficiency for Tail Development

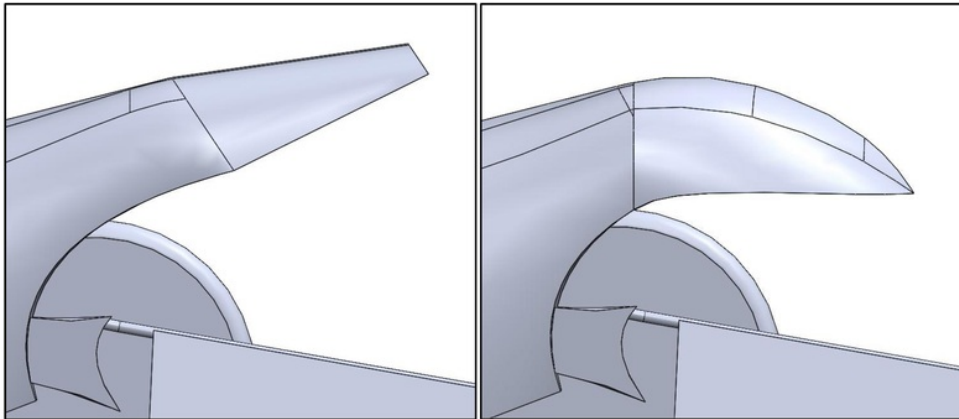


Figure 56 - Tail Design Before (left) & After (right) Development

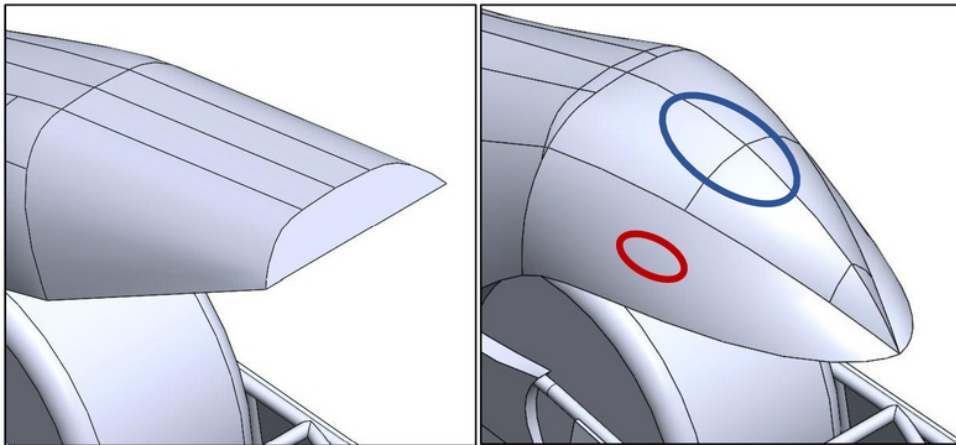


Figure 57 – Tail Design Before (left) & After (right) development

To try and help the air flow to stay attached, the tail is designed with two characteristics. The protruding surfaces on the sides (circled in red) to try and stop air flow getting sucked underneath the tail before it reaches the end of the body. The middle surfaces (circled in blue) were to try and keep the air flow moving over the top of the tail attached as the lower outer surfaces were angled too severely.

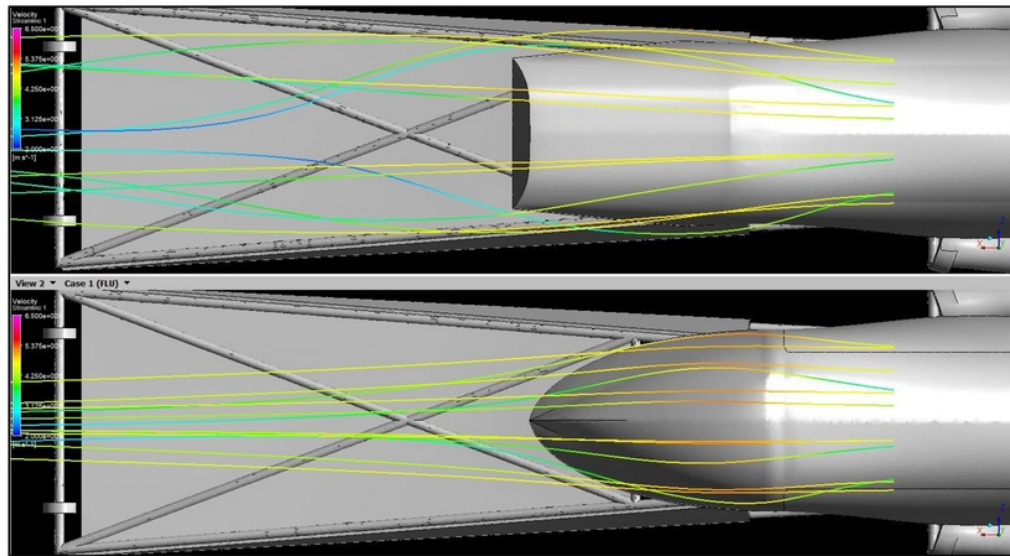


Figure 58 - Tail Streamlines Before (Top) & After (Bottom) Development

Both of these characteristics helped each other which was an unanticipated, better result. The faster moving air over the middle surfaces pulled the air flow from the outer surfaces with it (see figure 58) which kept the air flow moving over the outer surfaces from spilling underneath. The wake region, which is the area behind a body after the body had moved through a fluid, has some significant changes which can be seen in figure 59.

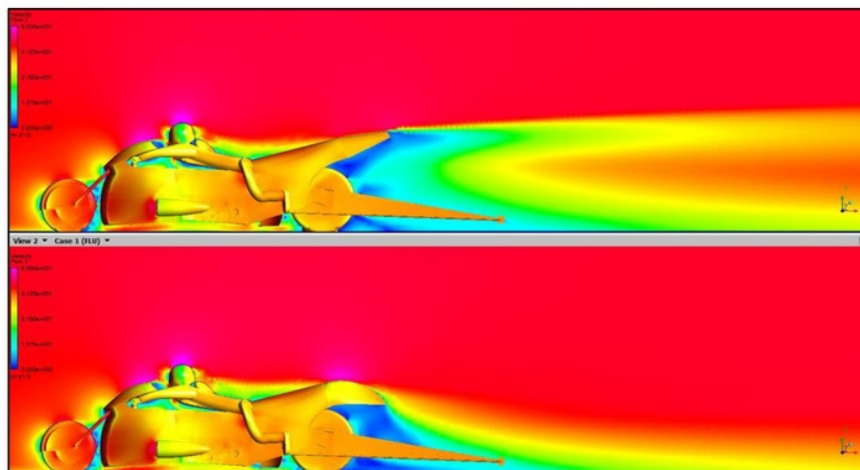


Figure 59 - Velocity Contours Before (Top) & After (Bottom) Development



From figure 59, the difference in velocities in the wake region has reduced dramatically, reducing the drag on the bike. This is due to the air flow on the developed tail design staying attached almost until the tip of the tail. As the angle at this position is pointing towards the rear end of the wheelie bars, the air follows that direction so is essentially pushed down. The area of low velocity under the tail does however have an effect on the air flow coming off the tail, in essence pulling on it, which creates a small amount of recirculation seen circled in figure 58.

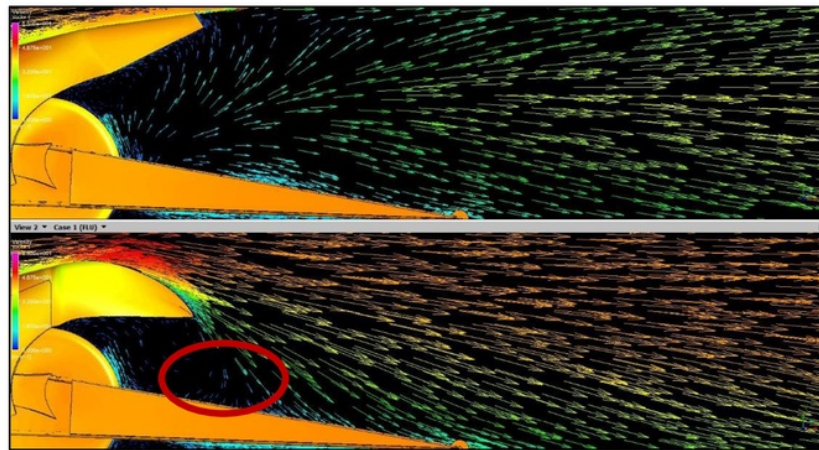


Figure 60 - Velocity Vectors Before (Top) & After (Bottom) Development

With the flow coming off the tail now moving towards the rear of the wheelie bars, the up wash from the previous geometry has been neutralized with some of it being pushed down on to the top of the wheelie bars. This will also be creating some downforce on the wheelie bars due to the new pressure difference between the top and the underside of the wheelie bar cover. Which in reality may cause some disruption to the steering on the front, by making the steering lighter due to the bike trying to pivot around the rear wheel axle. Using Newton's law of equal and opposite reaction, it could also be said that the force being created by the downwash could also cause lift.

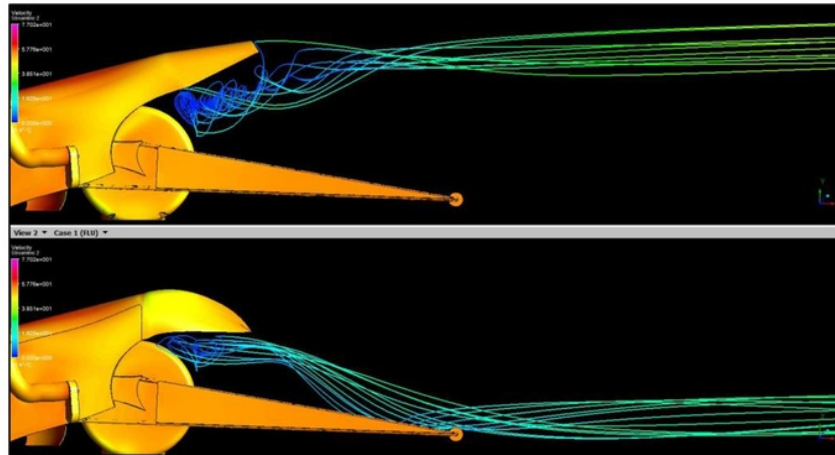


Figure 61 - Velocity Streamlines Before (Top) & After (Bottom) Development

Figure 61 shows how the turbulent up wash has been transformed into a more laminar flow with the developed tail design. The streamlines show how the air flow moving over the top of the tail effect the flow characteristics underneath the tail. The streamlines are now in a downwash state which has significantly reduced the pressure differences in the wake region, this is in part the reason the coefficient of drag has reduced with increased downforce due to the force acting on the wheelie bars.

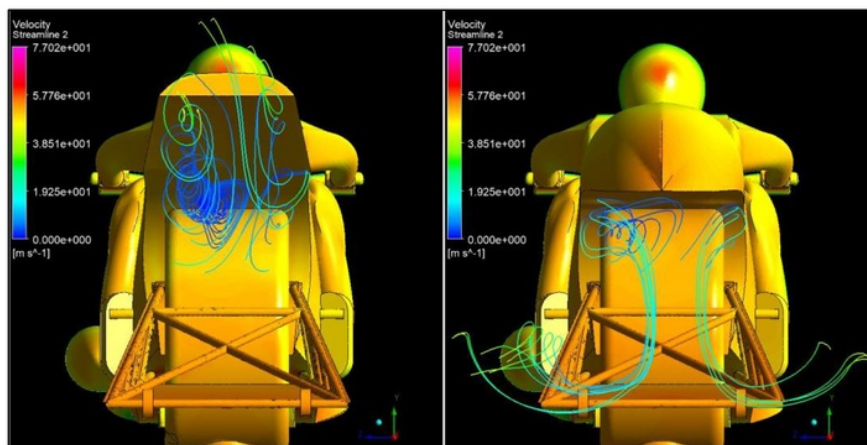


Figure 62 – Velocity Streamlines Before (Left) & After (Right) Tail Development



Looking at figure 62, viewing the streamlines from this point of view shows just how significant the new tail design is. Previously, a lot of energy was being lost to vortices forming, there is still some recirculation occurring but it is significantly lower.

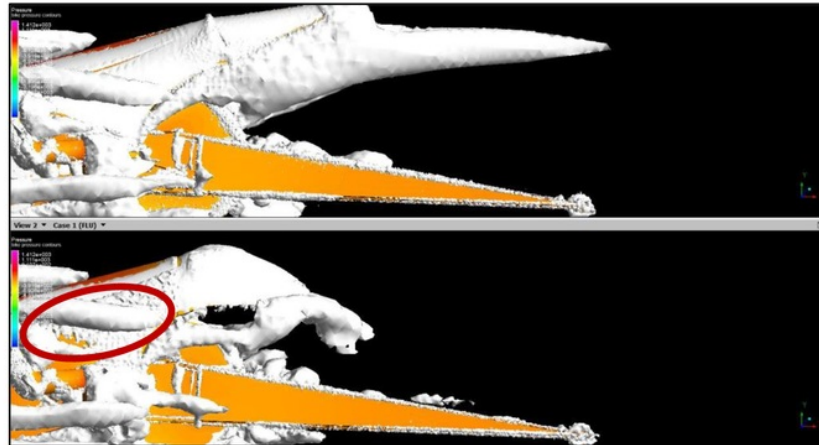


Figure 63 - Turbulence Before (Top) & After (Bottom) Tail Development

Figure 63 shows again how little turbulence is forming compared with the previous tail design. The large vortices coming from under the tail due to air spilling over the tail has been in most part eliminated. The vortices seen in the developed tail design is coming from the back of the body (circled). Further work could be taken on to develop the rear body of the bike to try and stop this. Keeping the air flow in that region attached to the body could feed more energy to the tail, which could prove to produce more downforce. However, the extra energy flowing off the tail may prove too much for the current tail design, resulting in the flow separating earlier which would increase the velocity and pressure differences in the wake region, producing more drag.

Albeit as it may, the final results are shown below and on the tables on the next page.

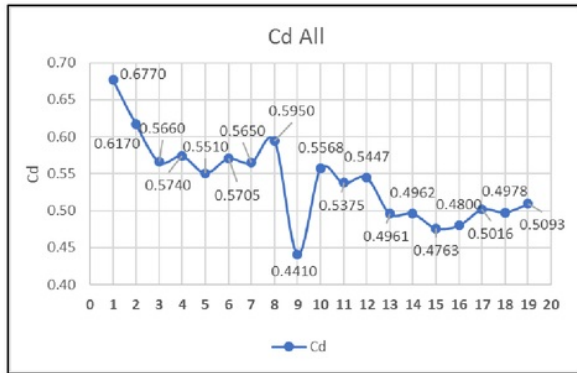
Table 9 - Results from the Start & End of Project

Final Results						
Model	C_d	Drag Force (N)	C_l	$(-C_l)$	Downforce (N)	Efficiency (%/100)
Realistic	0.677	650.38	-0.059	0.059	56.68	0.09
Finalized Design	0.4763	457.57	-0.0997	0.0997	95.82	0.21

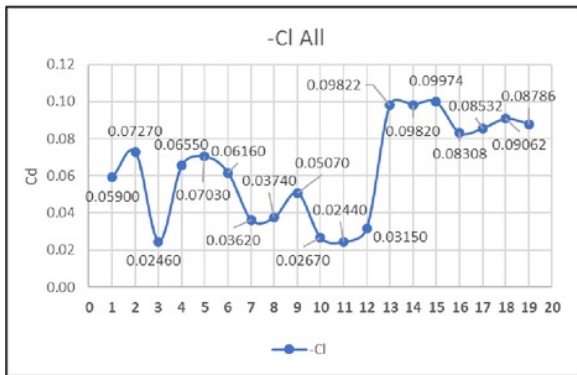


Table 10 – Table of improvements from Realistic Geometry to Developed Geometry

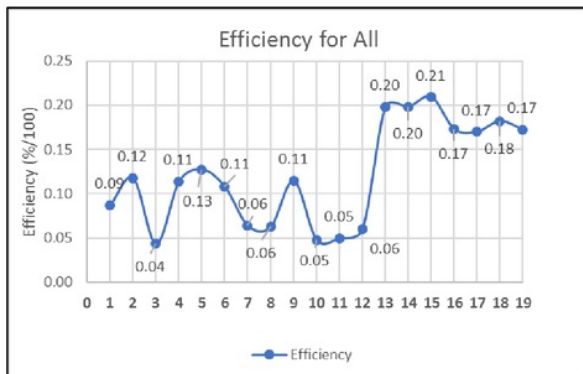
Improvements						
Cd	Cd (%)	Drag Force (N)	-Cl	-Cl(%)	Downforce (N)	Efficiency (%)
-0.2007	29.65	192.81	0.0407	69.05	39.14	12.23



Graph 10 - Drag coefficient for All Developments



Graph 11 - Downforce coefficient for All Developments



Graph 12 - Efficiency for All Developments

Table 11 - Legend for "All Developments" Graphs

X Axis	
1	Realistic
2	Modified Fender
3	Air Inlet Mk1
4	Air Inlet Mk2
5	Air Inlet Mk3
6	Full Covers
7	Full, Bar Top + Bottom
8	Full, Bar Bottom
9	Full, Bar Top
10	New Front Fairing
11	Filled Body
12	Filled Body New Flaps
13	Short Rounded Tail
14	Short Rounded Tail Mk2
15	Hyabusa Tail
16	Hyabusa Tail +50mm
17	Hyabusa Tail +100mm
18	Hyabusa Tail +150mm
19	Hyabusa Tail +200mm



7.0 Conclusion

The project on a whole has been a success. The aims that were set have been achieved even with mistakes being made. If post processing analysis was conducted before the mistake was noticed, it may have been able to be fixed. The results show the drag coefficient is now 0.4763, a decrease in C_d of 0.2007 which is quite significant seeing that the difference in C_d between a sphere and a cube is 0.58 (Churazova, 2017). The total drag force has reduced by 192.8N which is the equivalent to 19.65kg less pulling resistance. The developed geometry has a downforce coefficient of 0.0997 which is an increase of 69.05% compared to the geometry's initial downforce coefficient of 0.059. This has increased the downforce by 39.14N which is equivalent to 3.99kg of extra force pushing down. These results are not as high of an increase that was anticipated or desired. Be that as it may, any increase is a bonus. With this, the geometry efficiency has increased by 12.23% with a total efficiency of 21% which is not perfect by any means but is better than the previous efficiency of 9%. The majority of improvements came from the developed tail design where the largest reduction of drag and largest increase in downforce appeared. This is mainly due to the fact that the wake region is more equalized than before and that the air flow characteristics near the tail have been put to better use, creating less turbulence and cleaner streamline characteristics.

8.0 Further Work

Many more studies could be completed to increase the efficiency of each part of the geometry of the drag bike. One idea would be to increase the arch length of the tail further and cover the sides so no air can get pulled into the wheel wake region. This could also help with the early separation on the tail. It is also believed that it would be a good idea to simulate the final geometry with air passing through the air inlet, moving wheels and a moving road to see what differences this would make to the air flow characteristics. This would also make the simulation more realistic. One aspect the author wished to study and develop on the drag bike was the exhaust blowing method, this would create downforce when the bike is stationary, which would help with launching the bike off the line. It would have been interesting to see how this affected the final results.

Word Count: 10,186



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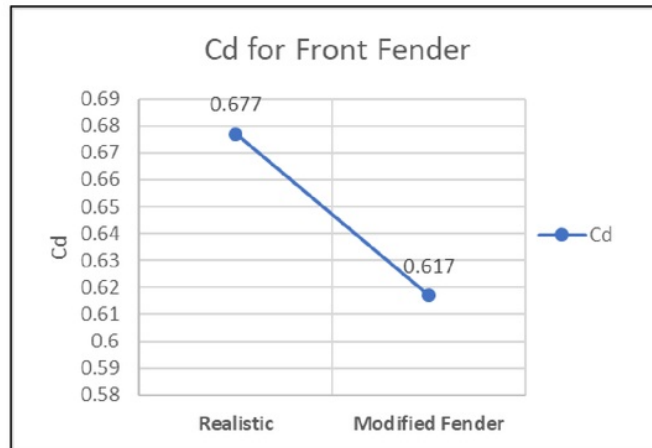
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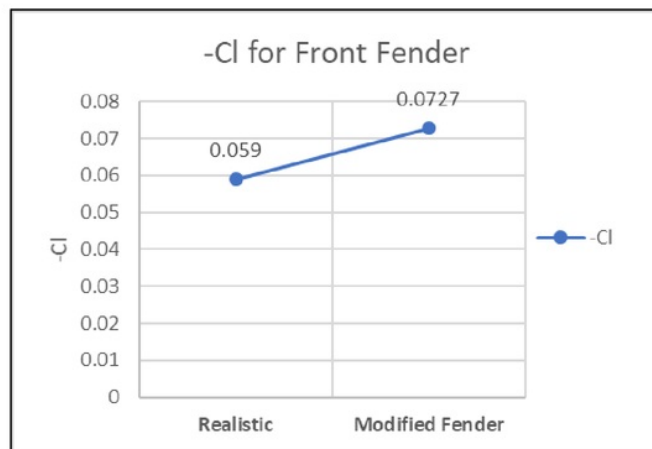
Appendix

Results

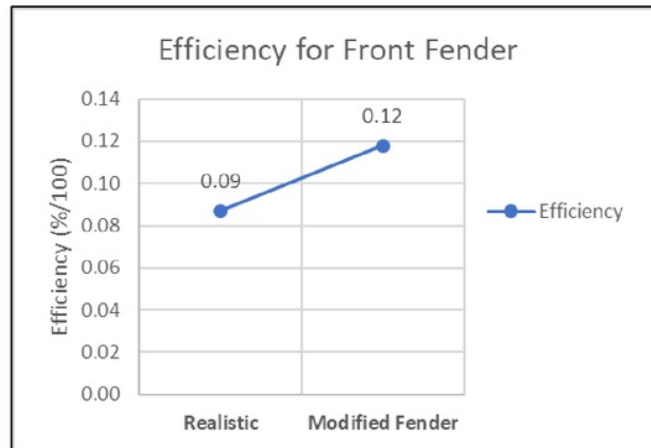
Front Fender Results



Graph 13 - Drag coefficient for front Fender Development

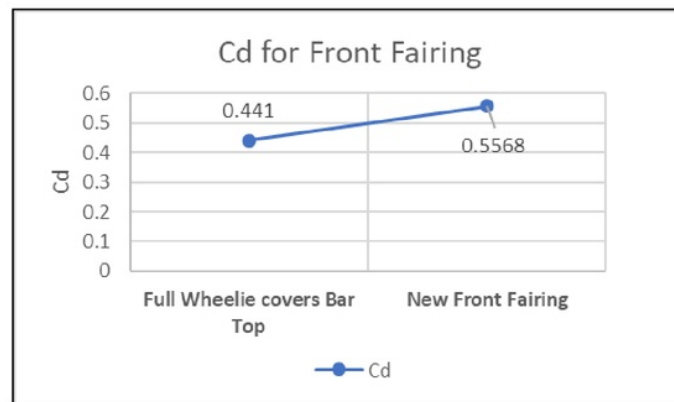


Graph 14 - Downforce coefficient for Front Fender Development

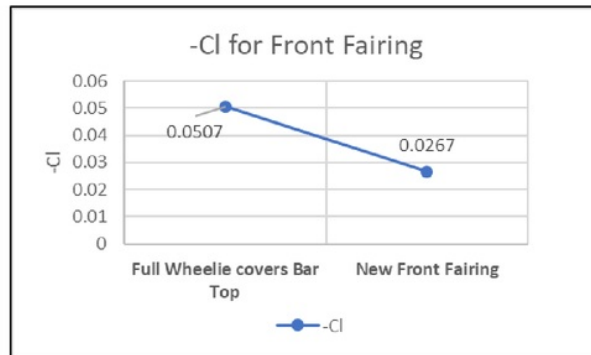


Graph 15 - Efficiency for front Fender Development

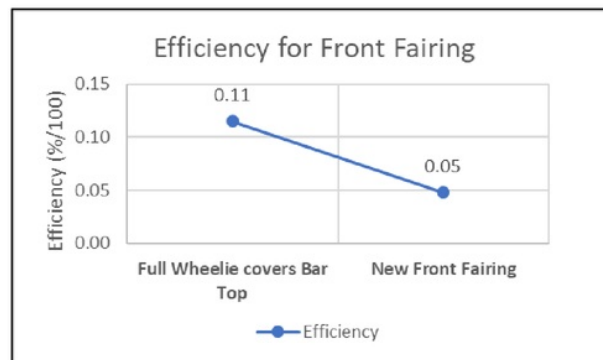
Front Fairing Results



Graph 16 - Drag coefficient for Front Fairing Development

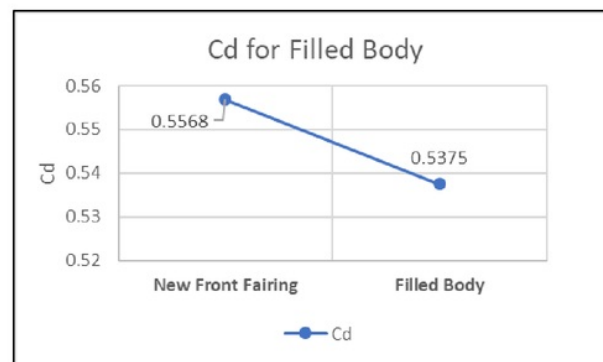


Graph 17 - Downforce coefficient for Front Fairing Development

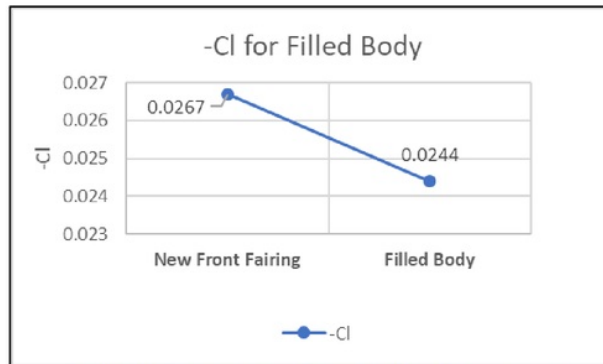


Graph 18 - Efficiency for Front Fairing Development

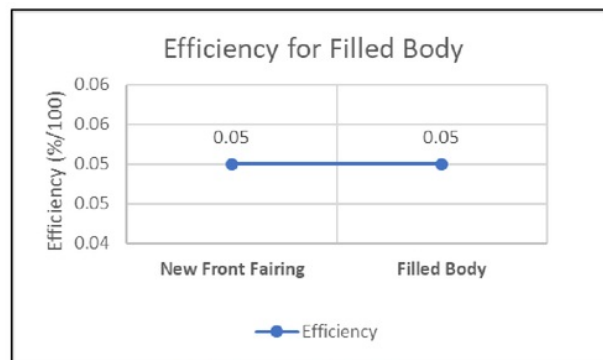
Streamlining Results



Graph 19 - Drag coefficient for Body Development

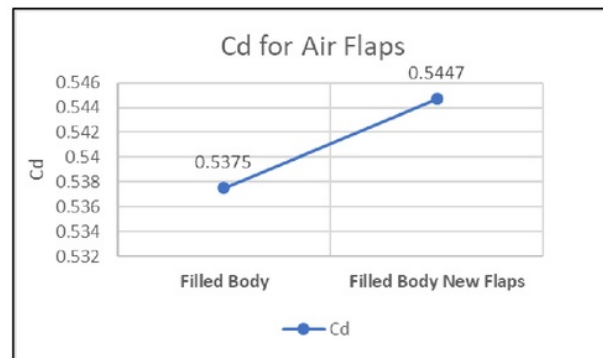


Graph 20 - Downforce coefficient for Body Development

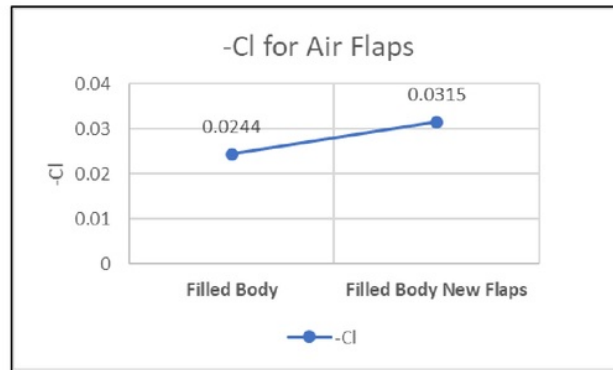


Graph 21 - Efficiency for Body Development

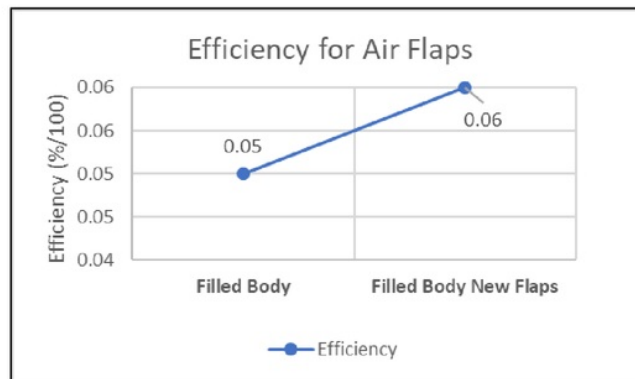
Air flap Results



Graph 22 - Drag coefficient for Air flap Development



Graph 23 - Downforce coefficient for Air Flap Development



Graph 24 - Efficiency for Air Flap Development

Other

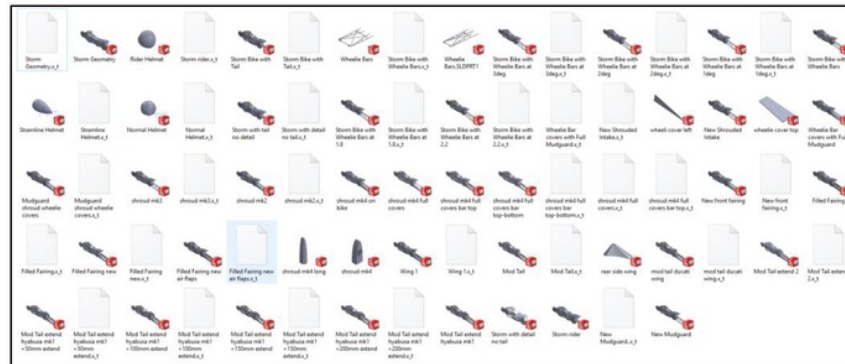


Figure 64 - Storm Geometries

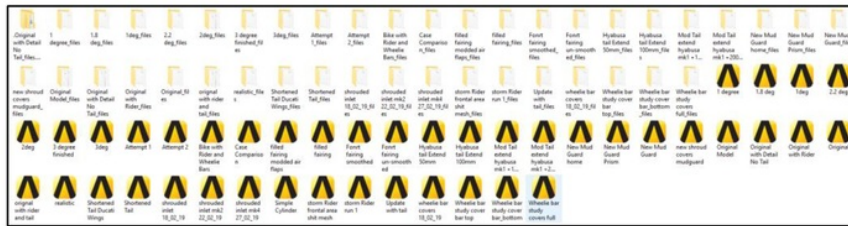


Figure 65 - Ansys Fluent Folders

Storm Domain Info			Generic Mesh Settings			Generic Box Info			Wake Mesh Settings		
Size (m)			Location			Size (m)			Element		
X	20	From Origin (m)	Domain	1.5		X	2		Box	0.02	
Y	4	7 in Wind	Domain	0.3		Y	1.5		Exhaust	0.02	
Z	3.5 Buns		Price Layers	5		Z	2		Flags	0.008	
			Height	0.51		Placement			Front End	0.008	
Inlet Layers			Height	0.51		X	0		Inlet	0.02	
No Inlet Layers			Height	0.51		Y	0		Flags	0.008	
			Height	0.51		Z	0		Flow Inlet	0.02	
			Height	0.51		Wake Mesh Settings			Box	0.02	
			Height	0.51					Exhaust	0.02	
			Height	0.51					Flags	0.008	
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			Height	0.51					Exhaust	0.02	
			Height	0.51					Flags	0.008	
			Height	0.51					Front End	0.008	
			Height	0.51					Inlet	0.02	
			Height	0.51					Flags	0.008	
			Height	0.51					Flow Inlet	0.02	
			Height	0.51					Box	0.02	
			Height	0.51					Exhaust	0.02	
			Height	0.51					Flags	0.008	
			Height	0.51					Front End	0.008	
			Height	0.51					Inlet	0.02	
			Height	0.51					Flags	0.008	
			Height	0.51					Flow Inlet	0.02	
			Height	0.51					Box	0.02	
			Height	0.51					Exhaust	0.02	
			Height	0.51					Flags	0.008	
			Height	0.51					Front End	0.008	
			Height	0.51					Inlet	0.02	
			Height	0.51					Flags	0.008	
			Height	0.51					Flow Inlet	0.02	
			Height	0.51					Box	0.02	
			Height	0.51					Exhaust	0.02	
			Height	0.51					Flags	0.008	
			Height	0.51					Front End	0.00	