NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY

BE Mechanical Project Report

We hereby recommend that the report prepared under our supervision by:

Student Name: **Quratulain** Regn No. **2010-NUST-SMME-BE-ME-102**

Titled: **Exterior Body Design, Analysis and Experimental Testing of Formula Student Race Car** be accepted in partial fulfillment of the requirements for the award of BE degree.

Examination Committee Members

1. Name: **Dr. Muhammad Sajid** Signature: ________________________
2. Name: **Dr Samiur Rahman Shah** Signature: ________________________
3. Name: **Mr Abdul Naeem Khan** Signature: ________________________

Supervisor's Name: **Dr. Muhammad Sajid** Signature: ___________________________

Dated: _____________________________

____
(**Head of Department**)

____
(Date)

COUNTERSIGNED

Dated: _________________

____
(Dean/ Principal)

Exterior Body Design, Analysis and Experimental Testing of Formula Student Race Car

Author

Quratulain

Registration Number

2010-NUST-SMME-BE-ME-102

A report submitted in partial fulfillment of the requirements for the degree of

BE Mechanical Engineering

Supervisor:

Dr. Muhammad Sajid

Supervisor's Signature:____

DEPARTMENT OF MECHANICAL ENGINEERING

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY,

ISLAMABAD

JUNE, 2014

Declaration

I certify that this report titled "*Exterior Body Design, Analysis and Experimental Testing of Formula Student Race Car"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

Signature of Student

Quratulain

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Copyright Statement

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I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was Your will, so indeed none be worthy of praise but You.

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ABSTRACT

In automotive racing world, improvements in aerodynamics can have a substantial effect on vehicle performance. Aerodynamic devices' design and implementation i.e. inverted wings, under trays and side pods meliorate race vehicles' performance. The project involves comparison of selected cars of formula student competition and assessment of their design to optimize bodywork that will cover the chassis constructed by NUST bolts racing (NBR) team for FS competition 2014. The external aerodynamics of selected FS cars is evaluated, by applying concepts of Computational Fluid Dynamics (CFD) while keeping the same environment for the car as it will experience on a race track. The CFD tool, "OpenFOAM" was used for iterative solution of the designed model's aerodynamic characteristics, to discover the trend of aerodynamic parameters including lift and drag with and without aerodynamic devices. Using this trend and NBR chassis size limitations exterior shape of a car is optimized. Small scale model of the finalized car, formula style body, is fabricated and tested in a wind tunnel to experimentally quantify the results prior to actual fabrication. Rear spoilers are not a part of this project. For lift, only limitation is to have a zero or negligible lift.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

NUST	National University of Sciences and Technology
SMME	School of Mechanical and Manufacturing Engineering
FS	Formula student
NBR	NUST bolts racing
CFD	Computational fluid dynamics
3D	Three dimensional
CAE	Center of Aeronautical Engineering
EME	Electrical and Mechanical Engineering
IST	Institute of Space Technology
GIKI	Gulam Ishaq Khan Institute

1. Introduction

1.1. Objective

The objective of this project is to develop a methodology to design bodywork and optimize it according to given specifications, rules and regulations using Computational Fluid Dynamics (CFD) tool and experimental testing.

1.2. Background

Formula student, also known as FSAE (Formula Society of Automotive Engineers) is an engineering design competition which gives engineering students a platform, to design, build, test and race a single seated car. Students compete with over 400 teams from all over the world. A competition is based on three static events (cost, presentation, design) and five dynamic events (acceleration, skid pad, sprint, endurance, efficiency) having different points for each event.

School of Mechanical and Manufacturing Engineering (SMME) of National University of Sciences and Technology (NUST), Pakistan is going to partake for the year 2014. Twenty seven students from SMME will show their engineering skills in formula student (FS) competition 2014. Complete team is divided into six technical teams i.e. engine, transmission, turbo charging, chassis, suspension, bodywork, Electronic Control Unit (ECU) , engine mapping, instrumentation. It also carries two departments i.e. resource management and quality assurance each comprising of sub teams.

1.3. Importance of Aerodynamics in Formula student competition

In automobile world the most significant factor that has the influence on power consumption is drag offered by air. Aerodynamics study has become decisive to make best use of the power of engine. It came when flight technology was making progress. Aeronautical practice and naval architecture were the early attempts to streamline cars. Particularly in racing world where the high speed is the aim, reduction of drag demands most aerodynamic bodywork design. Among manufacturers consideration is being given more on this aspect.

To achieve success in race all aspects of the car design and development process must be carefully balanced [3]. Team with the fastest car does not necessarily win rather it requires a complete overall package of design, race performance, cost management and sales planning. Exterior shape of a car and aerodynamic devices used, tell a lot where about where a car stands in winning race, besides other factors.

The increasing trend of the use of aerodynamic devices is observed in leading cars [4] and is summarized in *Table. I*. It is essential to unveil the reason of increasing trend. Chalmers University of Technology was ranked first position in 2012 competition and has used rear and front spoilers, underbody diffuser and side pods. This shows aerodynamics is one of the important aspects to ensure winning a race.

Table 1-1: aerodynamic devices usage trend by leading FS cars

Rank 2012	**Team**	**Year**	**wings**	**Underbody diffuser**	**Sidepod**
1	Chalmers University of Technology	2012	✔	✔	✔
		2013	✔	✔	✔
2	Delft University of Technology	2012	X	x	X
		2013	✔	✔	✔
3	Monash University	2012	✔	✔	✔
		2013	No participation		
4	TU Munich	2012	X	✔	✔
		2013	✔	✔	✔
5	University of Stuttgart	2012	X	x	✔
		2013	✔	✔	✔
6	Tallinn University of Applied Sciences	2012	✔	✔	✔
		2013	No participation		
7	Oxford Brookes University	2012	X	x	✔
		2013	X	✔	✔

1.4. Outline

The first chapter of this report includes objective, background and emphasis on the fact i.e. aerodynamic consideration is important to win race. In addition, it instigates formula student competition and shows aerodynamic devices employment trend in Formula Student (FS) competition 2012.

The second chapter provides information about the history of computational fluid dynamics (CFD), fluid mechanics applications in road vehicles. In this chapter general aerodynamics principles used in automobile industry will be under consideration. It also throws light on the aerodynamic devices and some tips to design race car aerodynamically.

In chapter three methodologies followed to optimize the bodywork that will cover the chassis and meet the objectives will be explained. It incorporates two dimensional and three dimensional analysis of race car. In addition to this experimental testing followed before going for fabrication will be presented.

In chapter four the results of aerodynamic parameters i.e. downforce, drag developed from computational fluid dynamics (CFD) tool will be under consideration.

In the last chapter conclusions and recommendations are provided followed by the additional specific information which is presented in the appendixes.

2. Vehicle Aerodynamics

2.1. History

There was no concept of aerodynamics 100 years ago, when carriage horse was replaced by thermal engine. It came much later when flight technology was making progress. Aeronautical practice and naval architecture were the early attempts to streamline cars. Acceptance of aerodynamics in automobile industry has been described in detail (Wolf Heinrich Hucho, 1993). In the beginning better flow over the car i.e. lower drag was the only consideration. Later on two oil crises in 1970s forced to improve fuel economy drastically and provided an area of development through vehicle aerodynamics. The efforts resulted in drag coefficients reduction dramatically.

2.2. Road vehicles and fluid mechanics

Road vehicles are defined as blunt body not remote to the ground in fluid dynamics. Components of a vehicle that are exposed to the external flow (engine compartment, wheel wells) and rotating wheels add complexity in geometry and fluid mechanics perspective. Three dimensional flows over road vehicles are turbulent and phenomenon of flow separation and reattachment can be observed commonly. Longitudinal trailing vortices and large turbulent wakes are formed at the rear of vehicle.

2.3. General aerodynamic principles

2.3.1. Drag

Flow of air around and through a vehicle mainly when it is in motion comes under the study of aerodynamics. Some energy is required to vehicle for its motion through air as it faces the opposing

$$F_d = \frac{1}{2} \rho v^2 C_d A \qquad [2.1]$$

Where F_d is the drag force, ρ is density of the fluid, v is the velocity of the object relative to the fluid, A is the reference area, and C_D is the drag coefficient.

In vehicle aerodynamics drag force is of two types which are frontal pressure and skin friction drag

2.3.1.1. Frontal pressure

Millions molecules of air compress in front grill of the car, raising air pressure in that region. This is known as frontal pressure. The air molecules which are moving along car sides are at atmospheric pressure which is low compared to the molecules at car front. The high pressure air molecules explore the way to flow towards lower pressure zone. Doing so, they move to the sides, top and bottom of the car.

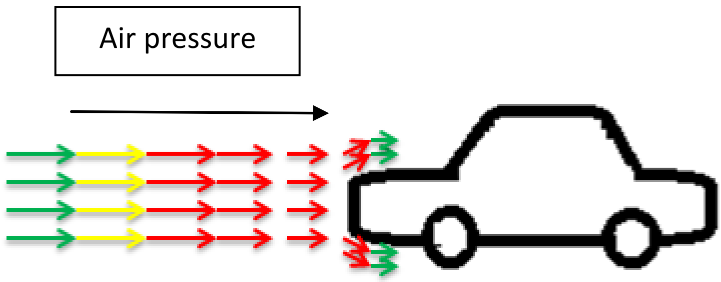


Figure 2-1: frontal pressure

2.3.1.2. Skin friction drag

Consider air flow in terms of layers. The layer close to the surface of car encounter friction due to rough surface and its speed slightly goes down. The layer above this affected layer would be slowed down as well. This process goes on to some layers and at certain level top layer of air is not affected by the disturbance in bottom layer. The force that is cause by friction of fluid with the surface of moving object is known as skin friction drag.

Skin friction drag can be calculated as

$$C_f = \frac{\tau w}{2\rho U \infty 2} \qquad [2.2]$$

where τ_w is the local wall shear stress, ρ is the fluid density, and U_∞ is the free stream velocity

2.3.1.2.1. Flow detachment

The region in which this disturbance prevails is called boundary layer. Boundary result phenomenon results in a hole at the rear of the car called *rear vacuum*. To envision this we can take an example of a bus traveling at a high speed. A big hole in the air is punched by it, with the air molecules rushing around a bus. The space behind the bus will be empty or like a vacuum. This emptiness results due to inability of air molecules to fill that space compared to the velocity of bus which is high. So there is a continuous vacuum region right behind the bus. In technical terms this inability of air molecules is termed as *flow detachment.*

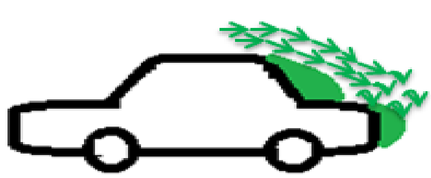


Figure 2-2: rear vacuum

2.3.1.2.2. Turbulence

Flow detachment results in a phenomenon called turbulence. This is the case when the force created by the vacuum exceeds the force created by frontal pressure. Hence to converge the flow into the vacuum, smoothly along the shape of car is very important. For example in Le Mans race cars tail of cars are extended well at the back of rear wheels and is made narrow when viewed from side or top. Doing this extra bodywork let on converge the air molecules back to the vacuum minimizing turbulence. Generally turbulence affects the “rear vacuum” portion but it can be observed wherever vacuum is created due to blunt shape. For example turbulence can be observed at the back of car mirror. Air flow separates from the flat side of mirror and faces to back of the car. This turbulence affects the car components in the close vicinity of mirror. Efficiency of intake duct is affected by this as the flow entering into the duct is disturbed by the turbulence generated by the mirror.

2.3.1.3. Drag on blunt and streamlined bodies

In case of blunt vehicles pressure drag is dominating parameter which is to avoid or to control in vehicle aerodynamics. It can be avoided only in case of no separation of flow. While friction drag is important parameter particularly in race car vehicles that are made very close to the ground and streamlined.

2.3.2. Lift / Down force

Another term used in race car world for lift is down force. An aero plane wings experiences lift, down force is similar to this but press down instead of lifting up. These two forces i.e. lift force and downforce is created by every object that flows in air. Race car use inverted wings to generate this downforce. Down force is needed in race cars for two reasons. Firstly it is required to help the tires staying on track and secondly to improve cornering forces.

Existence of lift and downforce in vehicles is according to Bernoulli theorem. According to Bernoulli theorem, for an in viscid flow, higher the speed air molecules lower the air pressure in that region and vice versa. This is related to air in motion across a still body, or to a vehicle in motion, moving through still air.

Car having a lift or downforce is decided by taking summation of all forces that are present above and below the car body. The resultant will dictate either car is experiencing lift or a downforce. In figure you can observe at certain locations lift force is present while at some locations car is experiencing a downforce. At the front grill of the car air pressure is high due to the fact air molecules are going towards zero speed by the front grill. These air molecules go towards low pressure regions like top, side and bottom of the car. These locations i.e. side, top and bottom will generate lift force due to lower pressure regions except one region. This region can be observed close to the windscreen. The air molecules again experience barrier and it becomes high pressure region, generating downforce.

Lift created on the large surface area of car's roof, due to the high pressure area, closed to windscreen cause a problem for road cars. Low pressure area lifts car's roof when air passes through it. Another problem is faced when air pass to the rear window. Rear vacuum is created due to window dropping down to the trunk. Flow get separates and this lower pressure region generate lift which is experienced by the whole surface area of the trunk. This trend can be observed in sedan cars of 1950's. Sedan travelling at high speed makes its driver feel that car is becoming light in the rear.

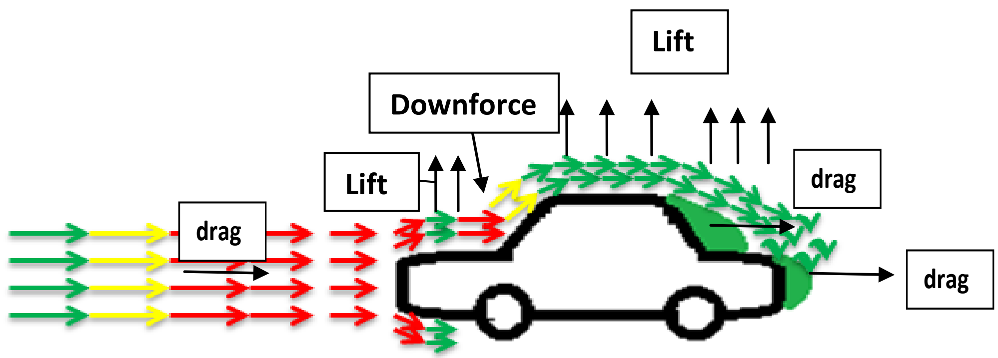


Figure 2-3: lift and downforce above car surface

Now if we talk about underside of the car it is also responsible to create lift or downforce. Front end of a car is kept lower than the rear end. Vacuum is generated between the underbody of a car and road due to widening gap created by difference in height of front and rear end. This vacuum or lower pressure region creates downforce. See figure to see downforce generated by underside of a car.

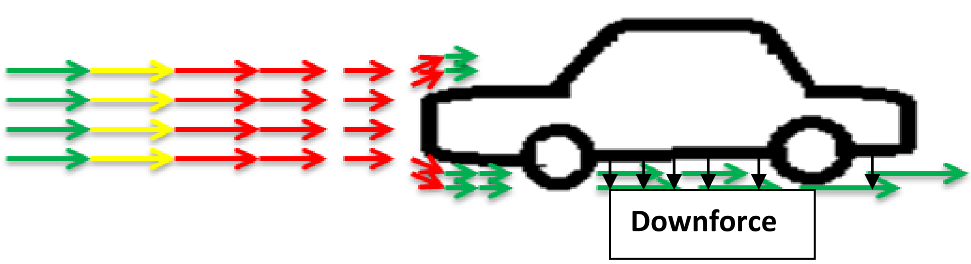


Figure 2-4: downforce at underbody of a car

Hence the flow of air over a car is not uniform rather combination of high and lower pressure regions. Taking summation of the forces created by these regions, it can be concluded what force a car is generating naturally.

2.3.3. Drag Coefficient

From above theory of aerodynamics it is cleared that shape of car plays an important role to determine drag of a car. Some conclusions can be drawn with reference to above discussion. Flowing things should be kept in mind while deciding shape of a car.

- Frontal pressure should be kept minimum, by keeping small front grill
- To minimize air flow under the car, ground clearance below the grill should be small.
- To avoid pressure build up at front keep the windshield more steep.
- To keep the air flow attached to the rear surface use “fastback” style window which is basically a shape, at rear of a car, where roofline slopes continuously goes down at the back.
- Also use a converging “tail” to keep air flow attached to rear surface.
- To create low pressure under the car, keep underside slightly raked.

These were some of the considerations that should be kept in mind while designing a race car. Ideally race car should be like a tear drop shape (Figure 2-5) as even the best designed race car experiences flow separation. Air separates and goes under and over a car at a point called stagnation point. Tear drop shape of a race car practically is not possible for the area where it operates i.e. close to the ground. This is the reason tear drop shape is applicable to airplanes design. Tear drop shape as shown in figure has a drag coefficient of 0.05. The reason for such a low drag coefficient is its smooth profile that allows air to smoothly flow over it after a stagnation point. At the end air experiences very small turbulence and then attach again like before.

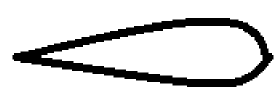


Figure 2-5: tear drop shape

Drag coefficient (C_d) is stacked up by these ideal characteristics. Common car design wisdom says that a low coefficient of drag is desirable to increase fuel economy and allow for engine downsizing Coefficient of drag for best road cars is estimated to 0.28. A minimum of 0.75 drag coefficient is estimated for formula 1 cars which have wings and open wheels. Wings and open wheels of formula 1 race car are massive drag components.

If coefficient of drag for flat plate is considered 1 then formula 1 car really seems inefficient. On the other hand if formula 1 race car is poor in aerodynamic drag efficiency then this weakness is compensated by the downforce and horsepower.

2.3.4. Frontal Area

Drag force produced by the vehicle not only depends on drag coefficient but also on frontal area of a vehicle and can be seen in drag force equation. Drag coefficient of new aerodynamic semi-trailer trucks may have low value but its frontal area is very large. So by just having the value of drag coefficient one cannot conclude any results regarding drag force created by any vehicle. Frontal area is calculated by multiplying the height and width of car. There is a laminar flow of air over the car. Separation of air makes the flow turbulent from laminar and hence inducing drag.

2.4. Aerodynamic devices

2.4.1. Scoops/Positive pressure intakes

When high volume air flow is required scoops or positive intakes are used. Every type of race car makes use of this device. Constant flow of air, available at inlet is compressed inside an air box. The opening of air box allows enough volume of air to enter. Pressure inside the box is increased as it slows down passing through expanding air box. This is the basic principle of scoops. See figure indicating air flow through scoops or positive pressure intakes.

2.4.2. NACA Ducts

These devices are useful to draw air into inaccessible areas. They are far better than scoops owing to the capacity to access areas which would otherwise have been difficult to have air flow by any other aerodynamic device. NACA ducts are placed along the sides of a car. It takes advantage of the boundary layer. It prevails where car profile is flatten and does not accelerate and decelerates the air flow. The longer such profile the thicker the boundary layer. The NACA duct has a specially designed intake. It scavenges the slow incoming air and drop in toward the inside of the bodywork. The typical application of this device is in engine air intakes and cooling.

2.4.3. Spoilers

They offer obstruction to air flow. As a consequence high pressure region develops in front of the spoiler. They are used principally on sedan-type race cars. Sedan car inclines light at the rear side as low pressure region above trunk tends to lift the rear side of car. Front air dams are similar to spoilers. They are aimed to restrain air flow from going under the car.

2.4.4. Wings

In all likelihood the most renowned form of aerodynamic assistance is the wing. They basically generate abundant downforce on little cost of increase in drag. In formula student cars lot of downforce is required at cornering. Primarily focus is given to increase downforce rather to reduce drag. Their importance is long familiar for improved performance of race car [7].

Several constraints are there in yielding downforce in formula student competition. Some restrictions are on the maximum size of the wings, the minimum distance between front wing and the ground [7]. Wheel base and track width limits the size of the wing or its plan area.[3,7] a) Vertical envelop developed by the rear of the rear tires, b) the tires outside edge, c) and a line 460 mm forward of the front of the front tires restrains the location of aerodynamic wing [3]. The space limitations mentioned above is only applicable on wings. Other aerodynamic devices like diffuser can be placed outside this limited region [3].

The wings work on the principle of differentiating pressure on upper and lower surface of the wing. Bernoulli theorem is applied over here which is, the higher the speed of a given volume of air, the lower the pressure in that volume, and vice versa.

In race car application air molecules approaching to the leading edge are forced to separate out. The air molecules under the wings travel a larger distance than the air molecules over the wings. They meet up at the trailing edge. During its progression higher pressure region develops over the surface and low pressure region under the surface of wings. Consequently downforce is generated serving the main purpose of using wings.

Effectiveness of wings requires no obstruction between the lower surface of wings and road. So mounting a wing above a trunk affects its effectiveness.

2.5. Aerodynamic Design Tips

2.5.1. Cover open wheels

Open wheels are a source of lot of drag and air flow turbulence. Similar effects are observed as described above in case of mirror. Keeping this in mind proposed solution is to fully covered bodywork if allowed by rules. If rules allow partial covering bodywork, using a converging fairing at back of the wings also provides notable benefit.

2.5.2. Minimize frontal area

Narrow race cars are much better aerodynamically e.g. formula 1 race cars. It helps a lot to reduce frontal area than Cd (drag coefficient). It is also a source of much better top aped and acceleration.

2.5.3. Bodywork converging slowly

A great deal of turbulence and drag is generated if bodywork quickly converges or truncated. It can also reduce the effectiveness of other aerodynamic devices like diffuser. For flow attachment bodywork is required to converge slowly.

2.5.4. Spoilers usage

They are mainly used to create downforce by creating an obstruction at the top rear side of trunk. It works on the same pattern of wind shield, only it generates higher pressure region top of the trunk. They are mainly used in sedan type cars such as NASCAR stock cars.

2.5.5. Wings usage

They work in opposite fashion to the wings on aircraft. It work efficiently and generate downforce on a large scale than a drag. Spoilers and wings occupy same locations and defeat each other's purpose so both are not used simultaneously on race cars.

2.5.6. Front air dams usage

They also serve the purpose of generating downforce. They create low pressure region at the underside of car be restricting the air flow from going under the surface of car.

2.6. Vehicles characteristics affected by aerodynamics

2.6.1. Performance and fuel economy

Market situation is one of the factors that allow aerodynamics to influence the shape of vehicle. Key factors to have low drag worldwide are fuel economy and increasingly global warming. Fuel consumption is a process of demand and supply. On demand side mechanical energy required for different purpose is seen for propulsion, while supply side is the efficiency of getting this energy by power plants and deliver to the points of application. Aerodynamics parameter i.e. drag force has a strong effect on propulsive part.

The tractive force required at road tire interface at any instant is

$$F_{TR} = \underbrace{R + D}_{\text{Road}} + \underbrace{M\frac{dV}{dt}}_{\text{Inertia}} + \underbrace{Mg\sin\theta}_{\text{Grade}} \qquad [2.3]$$

Where F_{TR} is tractive force, R is tire rolling resistance, D is aerodynamic drag, M is vehicle mass, g acceleration of gravity, ø is the inclination of the angle.

The tractive power is

$$P_{TR} = F_{TR}\,V \qquad [2.4]$$

For propulsion required tractive energy during any given driving period is

$$E_{TR} = \int_0^T P_{TR}\,dt \qquad [2.5]$$

Writing an equation for instantaneous fuel consumption, integrating it over a total driving duration, and using the mean value theorem to introduce proper averages for some of the integrands, the following fundamental equation for the average fuel consumed per unit distance travelled, g^* can be obtained (Sovran 1983)

$$g^* = \underbrace{\frac{k}{(\eta_b \eta_d S)} + E_{TR} + E_{ACC}}_{\text{Propulsion}} + \underbrace{g_u}_{\text{Braking and idle}} \qquad [2.6]$$

Where k is fuel dependent constant η_b is average engine efficiency during propulsion, η_d is average drive train efficiency, S is the total distance traveled, E_{ACC} is the energy required by vehicle accessories, and g_u is the fuel consumption during idling and braking.

Aerodynamic drag effects $E_{TR.}$ However E_{TR} is only part of the propulsive fuel consumption which is only part of the total fuel consumption. The impact of drag on total vehicle fuel consumption therefore depends on the relative magnitudes of these contributions.

Reduction of drag results in reduced fuel consumption, increased acceleration capability and increased top speed. When the only target is maximum fuel economy, the increased acceleration and top speed capabilities can contribute to further reduction in fuel consumption. Regearing the drive train converts the increased acceleration quality while reduction in installed engine power and corresponding percentage reduction in vehicle mass converts top speed quality of vehicle.

2.6.2. Race Car's behavior in still air:

Race car during traveling not only experiences drag force but in actual aerodynamic force has components in six degrees of freedom. These are lift force, drag force, side force, rolling moment about drag force, pitching moment about side force, yaw moment about lift force. Its behavior is different in still air and in presence of cross wind.

In still air flow is symmetric about car's plane of symmetry. In this configuration lift force drag force and pitching moment are the only components of aerodynamic force. Race car tends to lift off if special measures are not taken because of positive lift force on the car near the ground. Reduction in load on tires causes handling a difficult task. This is because maximum side force that a tire can generate decreases when tire load is reduced. For a typical European car with a typical lift coefficient of 0.3, lifts amounts to less than 3 % at 60 mph, and only 10% at 120 mph.

Pitching moment changes the load distribution between front and rear axles so is counted instead of lift in vehicle dynamics. The steering properties are affected by the difference in load distribution. Nose down pitching moment cause over steering at increasing speeds. This effect is undesirable so European manufacturers keep lift on rear axle as low as possible in car design process.

Cornering capability of race car vehicles depend on down force. To keep down force maximum is good but drag force also increases so we have to trade off between these two parameters. The trade off depends on type of race track. Low drag is preferred at high speed race track with few bends like LeMans (Fance) and speed during cornering is less important. On the other side, race track with large number of bends like Brands Hatch (Greeat Britain), consideration is given to have a high down force for short lap times.

2.6.3. Race car's behavior in crosswind:

From numerical simulations and experience of vehicle dynamics, it is said yawing moment and side force are the only two components that are significant to vehicle's behavior in cross wind.

First indication of sensitivity to cross wind is given by yawing moment associated to vehicle's center of gravity. Yawing moment impelled to twist the vehicle further away from the wind as it is unstable for almost any vehicle. It causes further increase in yaw angle, yawing moment and side force.

Development in road vehicles smoothly transferred the center of gravity of passenger's cars forward. This is done for two reasons. First, rear engines cars have become rare; second, front wheel drive trend shifted load from the rear to front axle. Therefore yawing moment referred to the center of the wheelbase has remained relatively constant, that referred to the centre of gravity has decreased. As a result matter of crosswind sensitivity analyses lost its significance.

2.6.4. Functional:

Functional is a term that takes effects other than aerodynamic forces and moments cause by the air flow over a vehicle. Same attention should be given to these effects as one give to forces and moments. One of the many functional effects is forces on body parts. Large flat plans are used in vehicle body. They should cope up ample aerodynamic loading. At all conditions hoods, doors, and frameless windows have to be tight. Light weight structures face down flutter. To handle it add on parts like air shields and various type of spoilers are used.

2.7. Computational fluid dynamics:

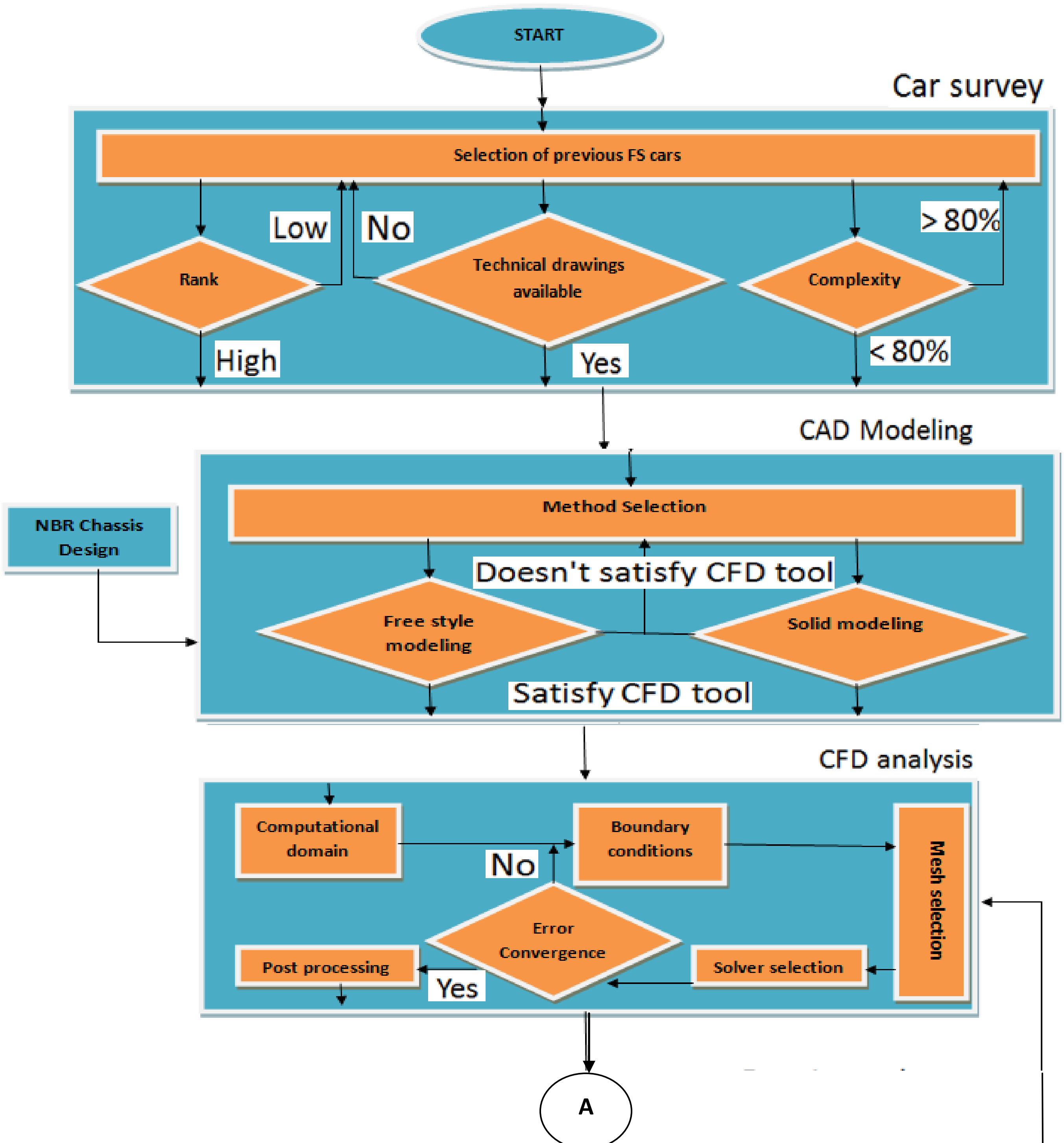
Time saving in product development is very important. This is the reason automobiles industries are very keen to use numerical methods. An expedetive acknowledgment to relentlessly changing demands of market is high priority than cost saving techniques. Two things are expected to be satisfied from all numerical methods. These are:

1. They should reflect the related physics with acceptable accuracy.
2. Numerical results should be produced faster than the experiment procedures.

Only to some extent computational fluid dynamics in vehicle's application fulfills both of these conditions. Accuracy in terms of computational fluid dynamics is defined as CFD must be able to detect a drag change as small as of 0.002 magnitudes.

Computational fluid dynamics has various advantages over experimental procedure using wind tunnel. First of all it deduces results and all information prior to existence of physical test model. Secondly we can modify the domain as needed to solve problem while wind tunnel has limitations. For example blockage effects can be eliminated by just increasing the computational space rather to change the physical model of wind tunnel and hence it is cost saving. Also simulations can be easily performed for relative motion between vehicle and road and for rotation of wheels as well. Finally much more information we can get than the routine experiments once the equations of physics are solved.

3. Methodology



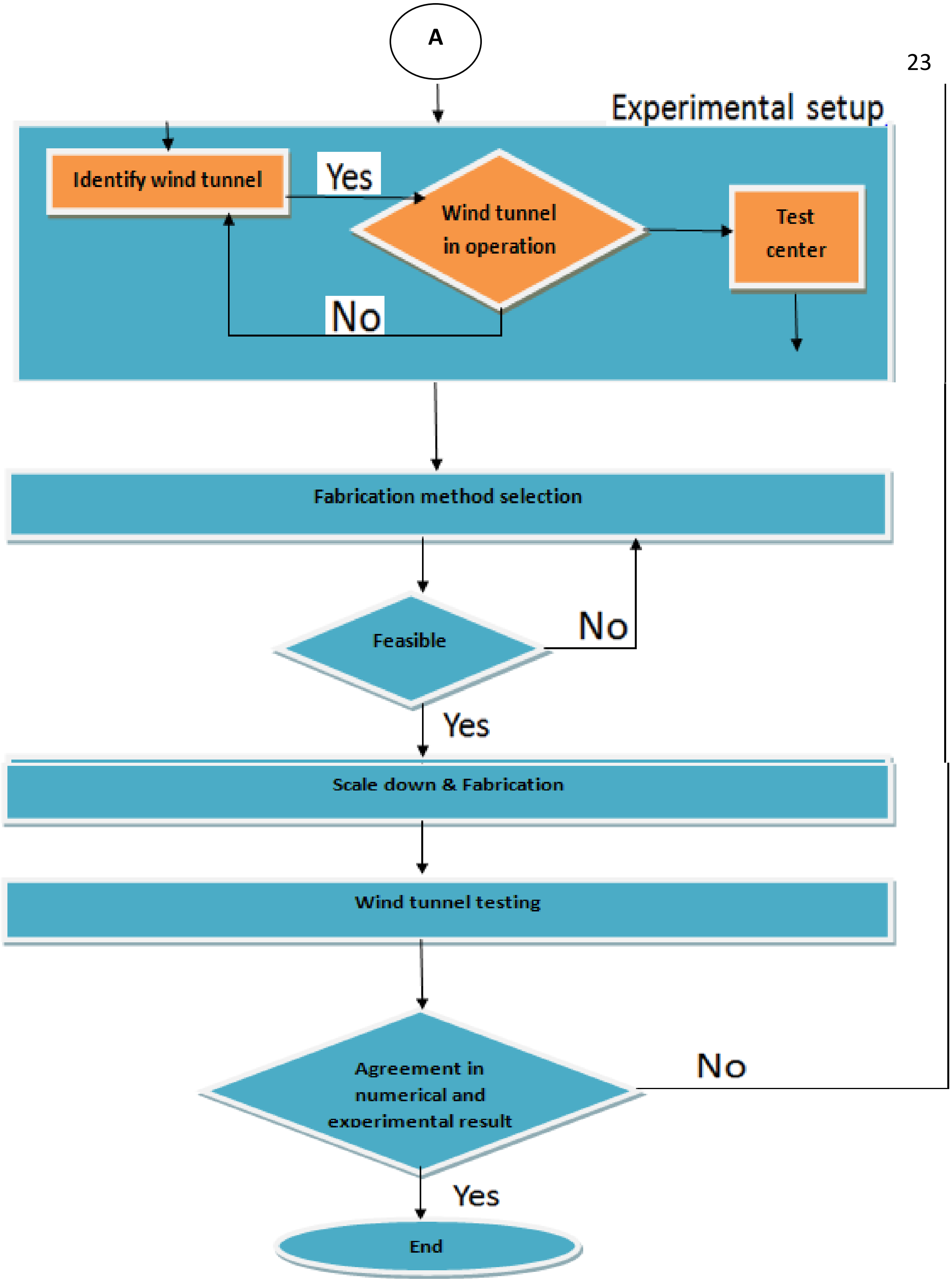


Figure 3-1 flow chart

Figure 3-1 shows the methodology followed throughout project. To have optimized exterior shape first extensive car survey was carried out to select leading cars that had raced in 2012 FS competition. Following the survey, Cad modeling of selected cars was done in Creo Parametric. After solid modeling in CAD software numerical simulations have been performed in CFD package OpenFOAM. Trial version of COMSOL Multiphysics simulated two dimensional domains of selected FS cars. Later on simulations were performed in open license CFD package i.e. OpenFOAM due to limitations of processor speed requirements in COMSOL Multiphysics. Physics involved in external fluid flow over a race car is reviewed. Another basic model of car was prepared according to chassis provided by NBR team. Basic model was optimized using skills obtained by analyzing previous FS cars. Numerical results of the physics over the computational domains selected have been quantified experimentally using a small scale model in wind tunnel.

3.1. Car Survey

Online leading motorsport magazine "Race car engineering" provided vast information about formula student competition and teams participated in it. Details of ninety eight class 1 teams and seventeen class 2 teams that had raced in 2012 competition are available in it. The complete particulars like orthographic views, isometric view, and technical details of most of the teams are available. Only team with the rear wing profile available is Monash University, Australia. Also both the views (Isometric and orthographic) of most cars are available in this magazine for the year 2013.

3.1.1. Comparison of leading FS cars

To access various aerodynamic parameters two leading FS cars have been selected based on the

I. Availability of technical drawings
II. Complexity involved
III. Aerodynamic devices used

Based on drawing details available two dimensional analyses is preliminary carried out before going to three dimensional analyses. Orthographic views available for Monash University's car have wing profile but lack profile of its exterior shape rather focusing on chassis and its inside components, therefore exterior shape of the car has been approximated and it is expected that modeling errors will be less in a two dimensional analyses as compare to the propagation of these errors in a three dimensional analyses. Also the computational cost of a three dimensional analyses was deemed too expensive at this stage of preliminary analyses of formula student cars, and therefore two dimensional analyses is adopted focusing on effectiveness of rear and front wings. Methodology followed and conclusions drawn for two dimensional simulations are presented in a conference paper in International Conference on Modeling and Simulations (ICOMS 2013) and are attached in Appendix E.

Three dimensional analyses is required to fully infer aerodynamics involved in Monash and TU Graz car. Due to complexity of constructing 3D geometry in OpenFOAM it is imported in stereo-lithography (.stl) format from Creo Parametric 1.0. Very high resolution of triangular surface is kept to have accurate approximated 3D geometry in OpenFOAM.

3.2. CAD Modeling

Two methods were considered initially to model formula student cars in CAD software, Creo Parametric 1.0. First method was using free style modeling while other was using solid modeling. The method which satisfies CFD most is selected. Meanwhile another CAD model of car for chassis design received by NBR team has been made.

Modeling using free style did not satisfy CFD tool due to the complexity involved in car. Spaces between different surfaces will alter the solution to great extent. So free style modeling was not preferred.

Solid modeling gave the model best suited for CFD analysis. No problem related to spaces between surfaces was encountered in this method. The whole car was of solid. The space behind driver seat was made solid so that physics assigned to problem in simulation relate to actual scenario. In reality engine and other devices fill the frame attached at the back of driver seat.

FS rules followed during CAD modeling are

3.2.1. Vehicle Configuration

The vehicle must be open-wheeled and open-cockpit (a formula style body) with four (4) wheels that are not in a straight line.

Definition of "Open Wheel" – Open Wheel vehicles must satisfy all of the following criteria:

a. *The top 180 degrees of the wheels/tires must be unobstructed when viewed 68.6mm (2.7 inches) above the plane formed by the tops of the front and rear tires.*

b. *The wheels/tires must be unobstructed when viewed from the side.*
c. *No part of the vehicle may enter a keep-out-zone defined as a circle 68.6mm (2.7 inches) larger radially than the outside diameter of the tire with the tires steered straight ahead with a 77kg (170 pound) driver seated in the normal driving position. The inner sidewall of the tire (vehicle side) is not included in this assessment.*

3.2.2. Bodywork

There must be no openings through the bodywork into the driver compartment from the front of the vehicle back to the roll bar main hoop or firewall other than that required for the cockpit opening. Minimal openings around the front suspension components are allowed.

3.2.3. Wheel Base

The car must have a wheelbase of at least 1525 mm (60 inches). The wheelbase is measured from the center of ground contact of the front and rear tires with the wheels pointed straight ahead.

3.2.4. Vehicle Track

The smaller track of the vehicle (front or rear) must be no less than 75% of the larger track.

3.2.5. 95th Percentile Male Template Dimensions

A two dimensional template used to represent the 95th percentile male is made to the following dimensions:

a. A circle of diameter 200 mm (7.87 inch) will represent the hips and buttocks.
b. A circle of diameter 200 mm (7.87 inch) will represent the shoulder/cervical region.
c. A circle of diameter 300 mm (11.81 inch) will represent the head (with helmet).
d. A straight line measuring 490 mm (19.29 inch) will connect the centers of the two 200 mm circles.
e. A straight line measuring 280 mm (11.02 inch) will connect the centers of the upper 200 mm circle and the 300 mm head circle.

3.3. CFD Analysis

Computational fluid dynamics code consists of three main elements to solve fluid problem numerically

- Pre processing
    - Computational domain
    - Boundary conditions

- meshing
- Solution
  - Selection of solver
  - Error convergence check
- Post processing
  - Pressure surface plot
  - Velocity streamlines

3.3.1. Pre Processing

Pre processing includes selection of computational domain, meshing, setting material properties and lastly application of boundary conditions according to the physics involved in fluid problem.

Snappy Hex Mesh is used to generate complex meshes of hexahedral and split-hexahedral cells from triangular surface of car model imported from CAD software in stereo lithography (stl) format. It requires background mesh which defines the extent of computational domain and a base level mesh density.

3.3.2. Solution

In solution phase solver in accordance to physics involved in problem was selected. Error convergence check was performed to know how solver is computing aerodynamic properties.

Steady state solver "SimpleFOAM" was used to iterate fluid problem using equation of fluid dynamics. This solver incorporates physics law regarding conservation of mass, momentum and energy. Governing equations which define fluid flow are given below

$$\rho \, \partial \mathbf{u} / \partial t + \rho(\mathbf{u}.\nabla)\mathbf{u} = \nabla.[-p \, \mathbf{I} + \mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^T) - 2/3\mu(\nabla.\mathbf{u}) \, \mathbf{I}] + \mathbf{F} \qquad [3.1]$$

$$\rho\nabla.\mathbf{u} = 0 \qquad [3.2]$$

Where ρ is the density (kg/m3), **u** is the velocity (m/s), p is the pressure (Pa) and F is the volume force vector (N/m3)

Pressure and velocity equations used in OpenFoam solver "simpleFoam" are provided in *Appendix D*

In any fluid flow problem turbulence cannot be ignored. Turbulence effects have been taken into account in the process of finalizing exterior shape.

K-ω (k omega) turbulence model is used to predict turbulence effects. This model predicts turbulence by using two partial differential equations containing two variables (*equation 3.3* *and 3.4*). First variable is kinetic energy (k) and second variable is specific rate of dissipation of kinetic energy (ω).

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial xj} = P_k - \beta^* k\,\omega + \frac{\partial}{\partial xj}\left[(v + 6_k\, v_T)\frac{\partial k}{\partial xj}\right] \quad [3.3]$$

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial xj} = \alpha s^2 - \beta\,\omega^2 + \frac{\partial}{\partial xj}\left[(v + \sigma_\omega\, v_T)\frac{\partial \omega}{\partial xj}\right] + 2(1\text{-F1})\,\sigma\,\omega^2 \frac{1}{\omega}\frac{\partial k}{\partial xi}\frac{\partial \omega}{\partial xi} \quad [3.4]$$

3.3.3. Post Processing

Post processing has been performed to visualize the fluid behavior across car. Stream lines showed the flow separation around car vicinity. Pressure contour plot indicated pressure gradient. Vector plot has been used to indicate the fluid characteristics, pressure and velocity.

3.4. Experimental setup

After CFD analysis next step was to look for experimental testing. Survey for wind tunnel availability was carried out. Status of wind tunnel i.e. either it is in use or not and test centre size are important parameters to select wind tunnel suitable for some particular problem.

3.5. Fabrication method selection

Two methods were given consideration for fabrication.

- Rapid prototyping
- Wood model

Both facilities are available in NUST School of Mechanical and manufacturing engineering. The technique which is feasible in terms of minimum cost was selected. Wood model satisfied the conditions. Final scale down model was made using deodar wood.

3.6. Scale down and fabrication

CAD model of car selected on the basis of skills gained by analyzing previous FS cars, and limitations set by NBR chassis design was scaled down and fabricated.

Prior to actual fabrication it was necessary to perform experiment on its small scale model. Actual model of design 2 has been reduced dimensionally by eight times. It has been fabricated using deodar wood.

3.7. Wind tunnel testing

Wind tunnel testing was carried out on small scale model. This is necessary before going to actual fabrication of FS car. Results were compared with the simulations. Trend for lift and drag co efficient were analyzed.

Options available for wind tunnel testing were presented in the following

Table 3-1

Table 3-1 : wind tunnel availability

Organization	**Wind tunnel status**	**Test centre size [l x w x h]**
CAE, Risalpur	In operation	6 x 3 x 2 ft^3
College of EME, Rawalpindi	Not in use	2 x 1 x 1 ft^3
IST, Islamabad	Not in use	2 x 1 x 1 ft^3
GIKI, KPK	In operation	5 x 2 x 2 ft^3

Sub sonic wind tunnel of Risalpur was used for wind tunnel testing.

4. Results

4.1. Previous FS cars

For obtaining most relevant results it is pertinent to select race car of Monash University as its wing profile is known and compared it with a wingless car of TU Graz University to have distinct difference and clear idea of using front and rear wings and its effect on drag and lift co-efficient. Details available for both cars are given in Table 4-1 and Table 4-2.Table 4-2 Details of extensive survey of 123 cars are provided *in Appendix A.* For technical details of Monash and Tu Graz FS car see *Appendix B.*

Table 4-1 selected cars information

Car No.	Team	Rank 2012	Isometric view	Orthographic views
1.	Monash University	third	✔	✔
2.	TU Graz	tenth	✔	✔

Table 4-2: dimensions of Monash and TU Graz car

	Monash	TU Graz
Length (mm)	3085	2678
Width (mm)	1300	1375
Height (mm)	1470	1022
Wheel base (mm)	1530	1550

4.2. Computational Domain

Quantity of triangles kept for Monash and TU Graz is 32258 and 5328 respectively and is shown in Figure 4-1. Large number of triangles for Monash is due to its aerodynamic devices which include side pod, front and rear spoilers, and underbody diffuser.

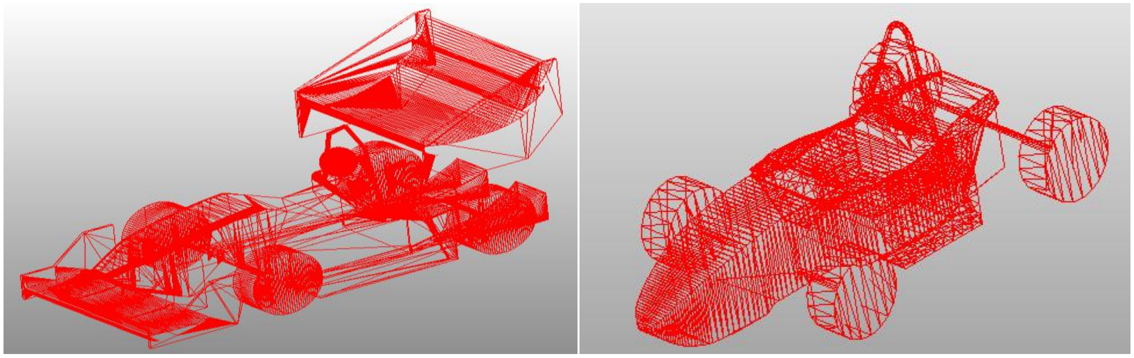


Figure 4-1: triangular surfaces of Monash (left) and TU Graz (right)

Size of the domain is shown in Table 4-3 and ***Error! Reference source not found.*** respectively. Figure 4-2 illustrates the extent of domain selected.

Table 4-3: domain size of Monash and TU Graz

	Direction	**Magnitude**		
			Monash	**TU Graz**
Length (mm)	Z	**7 x length $_{car}$**	21595	18746
Width (mm)	X	**5 x width $_{car}$**	6500	6875
Height (mm)	Y	**3 x length $_{car}$**	7350	8034

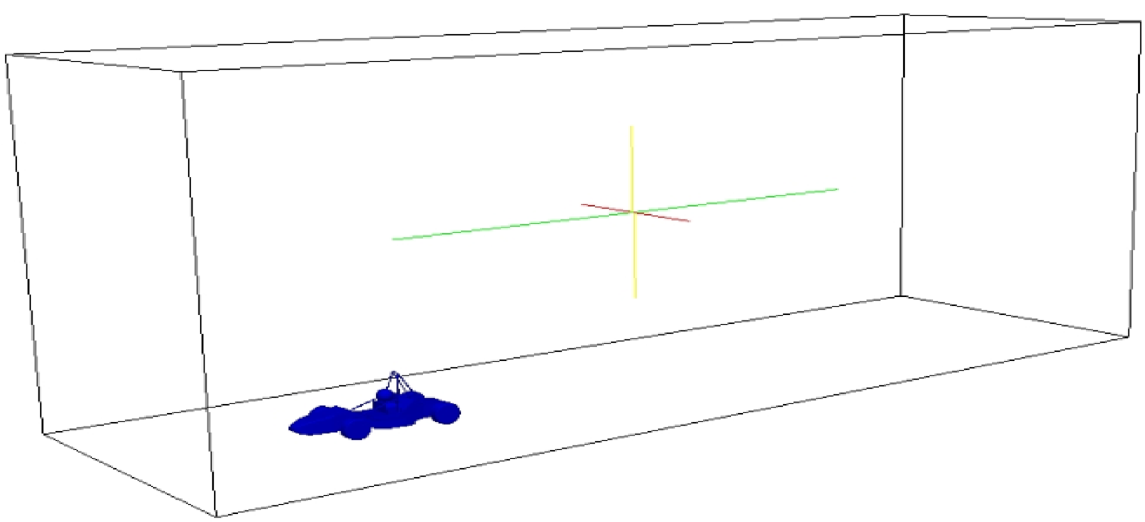


Figure 4-2: domain selected for both cars

It can be seen from Table 4-3 domain width is kept 5 times the width of a car, while height and length is kept three and seven times the length of a car respectively. Such large size domain ensures reliable and real results having uniform flow far away from the vehicle. The gradients of pressure and velocity are covered in this domain. So design can be optimized analyzing these gradients.

4.3. Boundary Conditions

In Open Foam following boundary conditions are defined for both models

Table 4-4: Boundary conditions for selected cars

Boundaries	U	P	k	ω
Inlet	Free stream	Zero gradient	Fixed value	Fixed value
Outlet	Free stream	0	Zero gradient	Fixed value
Car exterior profile	No slip	Zero gradient	kqRwallfunction	Omega wall function
Top	Zero gradient	Zero gradient	Symmetry plane	Symmetry plane
Ground	No slip	Zero gradient	kqRwallfunction	Symmetry plane
Front and Back	Zero gradient	Zero gradient	Symmetry plane	Symmetry plane

The pressure at the outlet was set at zero Pa for all the test cases. The symmetry condition at the top wall was selected to indicate the state of uniform flow sufficiently far away from the vehicle. While the velocity was varied from 30 km/hr to 130 km/hr with intervals of 20 in order to evaluate the relation of the drag forces with the speed of the vehicle.

4.4. Mesh Statistics

Block structured mesh of hexahedral shape is used for background mesh. Background mesh density is kept 10 cm^3. Further increase in density does not satisfy memory requirements of computer. Number of block structured mesh cells allocated to domain is provided in Table 4-5 for selected cars.

Table 4-5: number of block structured mesh cells

Direction	Monash	TU Graz
X	65	69
Y	74	80
Z	216	187

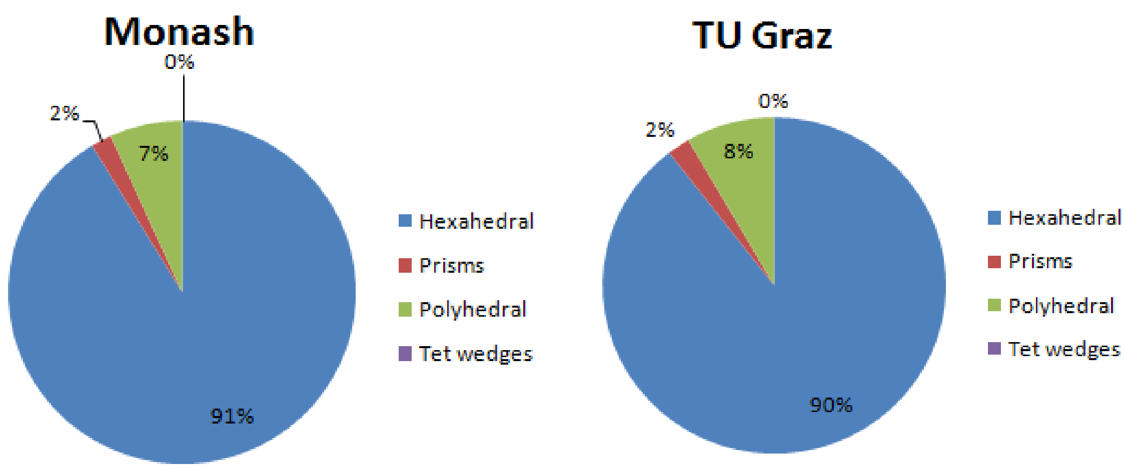
Statistics of the generated meshes and type of mesh cells for both cars are shown in **Table 4-6** and

Figure 4-3 respectively.

Table 4-6: Mesh statistics

	Monash	TU Graz
Points	3885811	6144619
Faces	10487346	16369781
Internal faces	9925756	15420207
Cells	3301962	5122409
Faces per cell	6.18211	6.20606
Boundary patches	6	6
Point zones	0	0
Face zones	0	0
Cell zones	0	0

Figure 4-3: overall number of block structured mesh cells



In OpenFOAM high dense mesh is necessary to capture minor changes in gradients of velocity and pressure. Figure 4-4 depicts the extent of dense mesh for both selected cars.

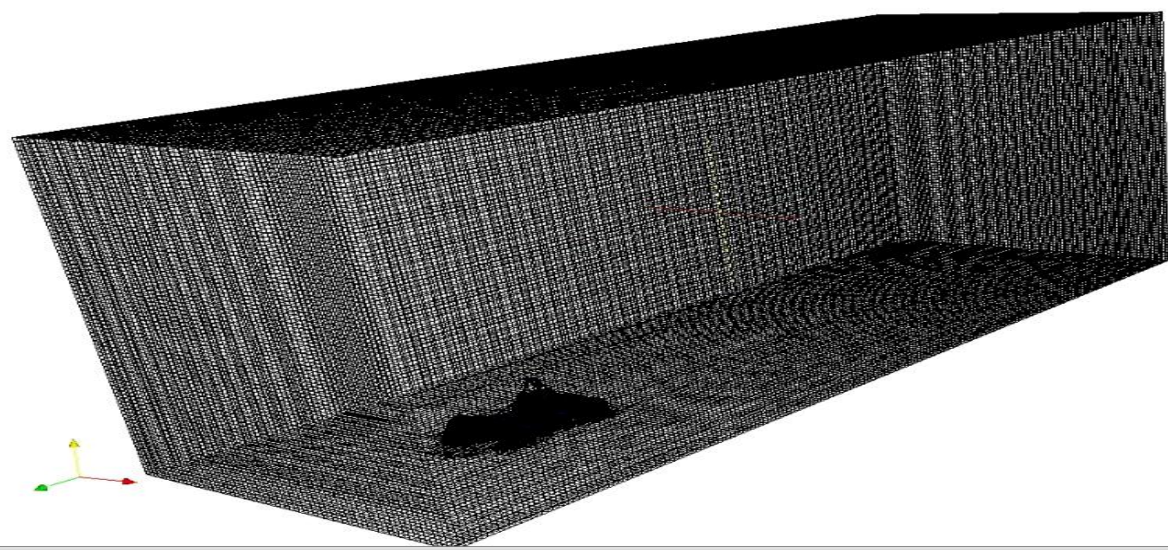


Figure 4-4: dense mesh of domain

4.4. Monash and TU Graz Results

Figures given below are showing aerodynamic properties of fluid as a function of car velocity.

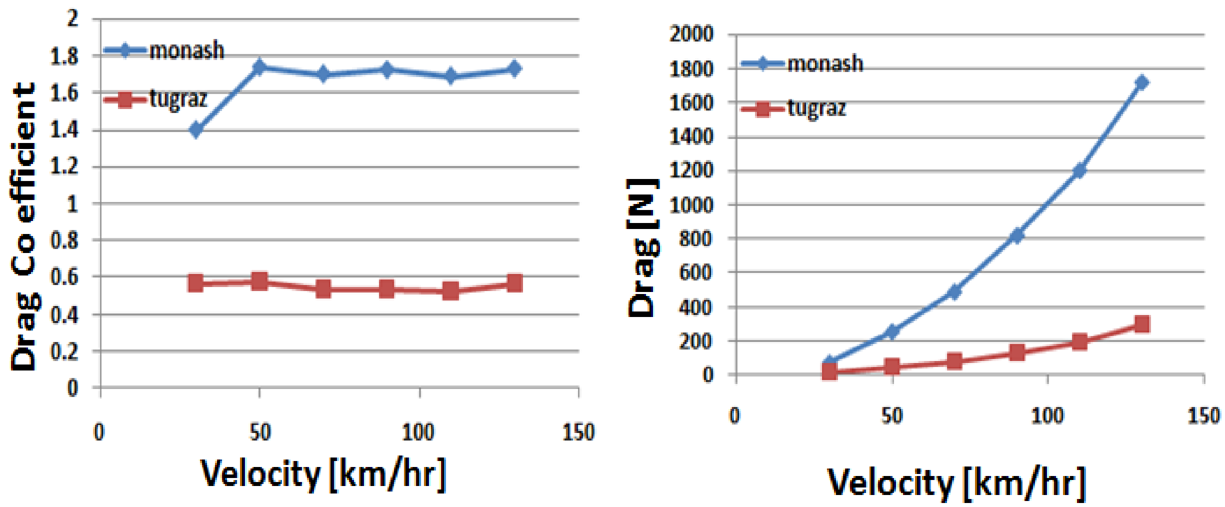


Figure 4-5 (a): C_d as a function of car velocity (b): C_d as a function of car velocity

Figure 4-5 shows drag force experienced by both cars. It is obtained by integration of pressure component along the surface of the car in the direction of air flow. Monash has significantly large drag as compare to TU Graz car due to large contact area offered by side pod, front and rear spoilers at all velocities. The plot of drag coefficients dictates the low drag features of TU Graz car. However at increasing velocity difference in drag forces also increases.

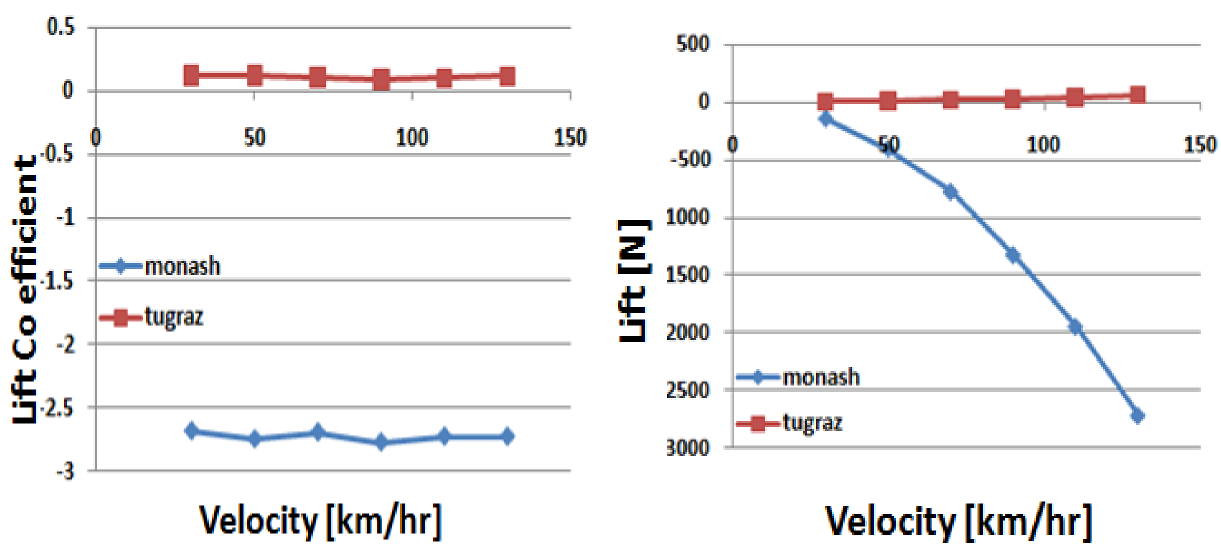


Figure 4-6 (a): C_l as a function of car velocity (b): C_l as a function of car velocity

Integration of pressure component at the surface of car, normal to the air flow direction results in calculation of lift. Above figure shows negative lift coefficient for Monash car representing down force. Rear spoilers of Monash are source of negative lift coefficient. While little positive lift coefficient of TU Graz car does not produce significance lift.

Based on the skills gained by comparing Monash and TU Graz and chassis size limitation three models of FS car were analyzed. Their description has been described in Table 4-7. Dimension of FS cars have been shown in Table 4-8. Drawings of NBR final version have been provided in *Appendix C*

Table 4-7: NUST Bolts Racing (NBR) versions characteristics

Design	**Modeling**	**Frontal Area [m^2]**	**Aero device**
NBR version I	Laminar	2.408	No
NBR version II	Laminar	2.523	Side pod
NBR final version	Turbulent	2.523	Side pod

Table 4-8: dimensions of FS cars

Dimension	**Monash**	**TU Graz**	**NBR versions**
Length [mm]	3085	2678	2905
Width [mm]	1300	1375	1300
Height [mm]	1470	1022	1258
Wheel base [mm]	1530	1550	1750

Rear spoilers are not a part of this project. For lift only limitation is to have a zero or negligible lift.

4.5. NBR version I

Based on the results obtained from comparison of Monash and TU Graz car, certain characteristics of fluid have been identified that helped in finalizing the profile of car. Also NBR version I was limited by the chassis dimensions. This design includes no aerodynamic device. Frontal area of the car is 2.408 m^2. Aerodynamic properties are shown in the following figures.

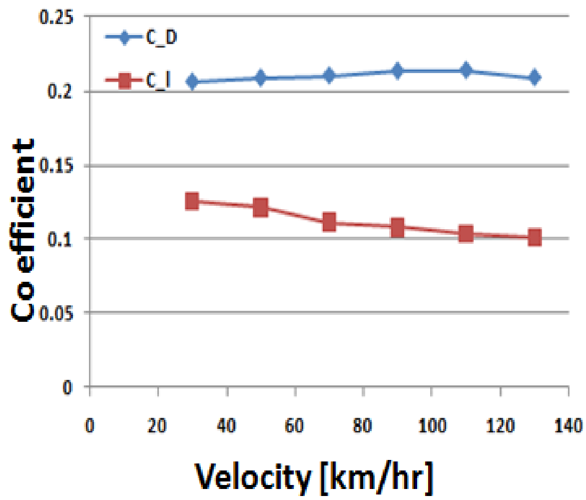


Figure 4-7 (a): coefficients of NBR Version I (b): forces on NBR Version I

Figure 4-7 show positive lift coefficient but lift force induced by this coefficient can be ignored. Drag force is 100 units larger then TU Graz car but 800 units less than Monash car. There is a significant difference in size of TU Graz car and chassis designed by NBR. Considering limitations by Chassis size, drag force offered to design 1 sound quite good.

4.6. NBR version II

NBR version II of formula student car with side pod yielded following results.

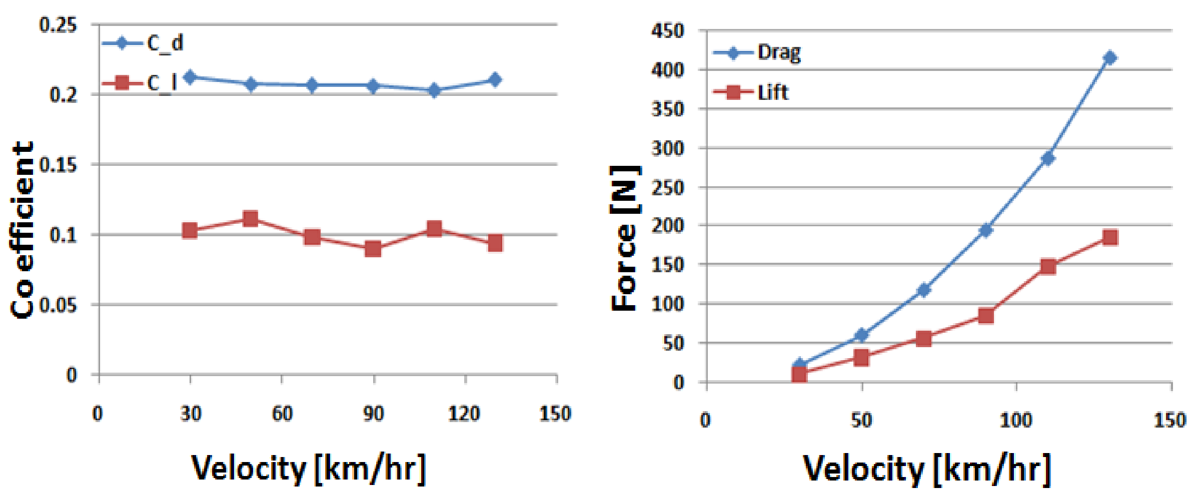


Figure 4-8 (a): coefficients of NBR Version II (b) forces on NBR Version II

Drag force is increased by 7 % while down force by 3 % when side pod is employed in FS car. Side pod is a tradeoff between better engine cooling and increase in drag. Only one side pod is preferred in the final design i.e. design 2 for this reason. Installing side pods on both sides of a car would have been introduced more drag as frontal area would increase.

4.7. NBR final version

NBR final car incorporates an aerodynamic device i.e. Side pod and turbulence. Side pod was needed to direct air flow towards engine placed at the rear of a car to enhance cooling system performance. Circulations were observed at the rear of car so it was necessary to include turbulence modeling for greater accuracy of results.

Final design of FS car takes into account turbulence effects. Equations used in turbulence modeling are presented in section 3.3.2. It also includes one aerodynamic device i.e. side pod for effective engine cooling by directing air flow on the rear of car. Combine effects of turbulence and side pod on aerodynamic parameters are shown in following figures.

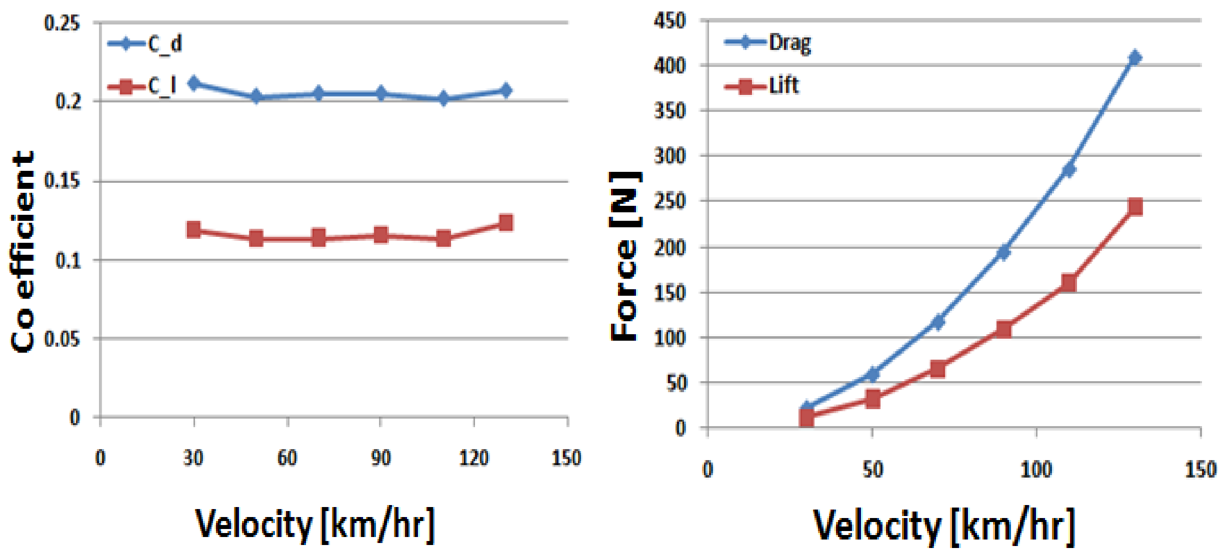


Figure 4-9 (a): coefficients of Final Version (b) forces on NBR Final Version

Drag and lift experience by final design FS car is 410 N and 244 N respectively at maximum velocity. Turbulence reduces drag by 2% compared to NBR version II.

4.8. Error Convergence

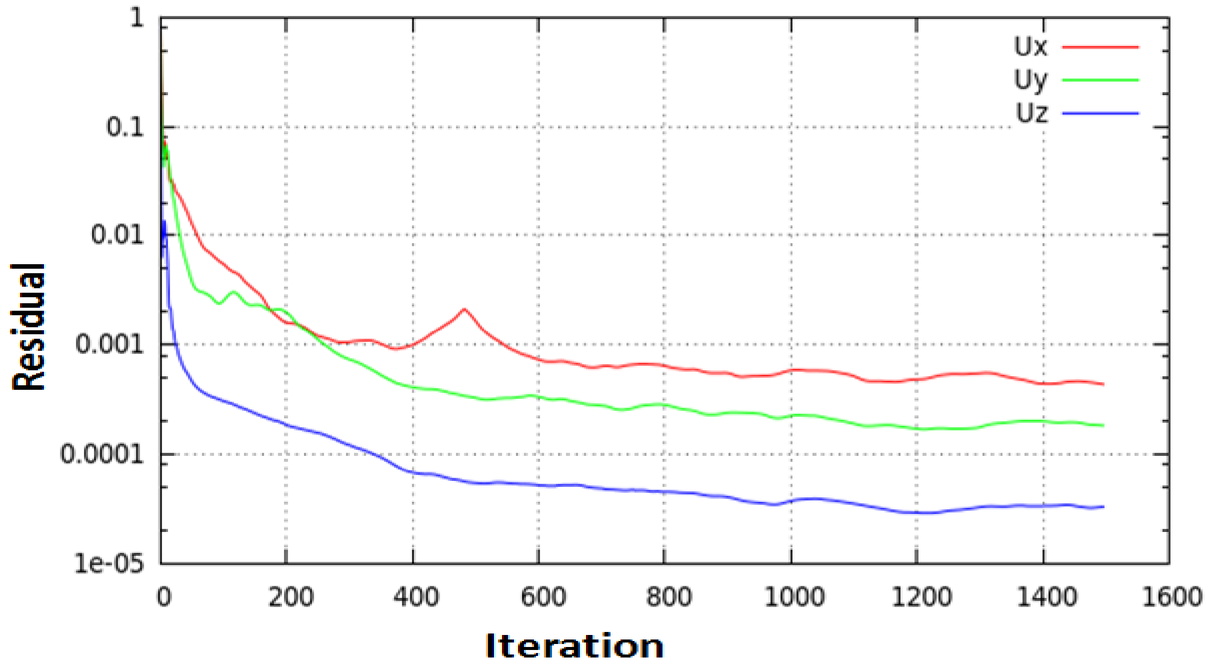


Figure 4-10: error plot in NBR car simulation

Results are computed using an incompressible flow solver "SimpleFOAM" to obtain a steady state solution in OpenFOAM. Error plot for NBR cars is shown in **Error! Reference source not found.**Figure 4-10

4.9. Post Processing

4.9.1. Velocity Streamlines

Figure 4-11, Figure 4-12 and Figure 4-13 shows streamlines of TU Graz, Monash and NBR final version respectively. Flow separation can be identified in above figures. At the rear of car circulations are large in the wake region while some circulations are also observed in front of driver and at wheels vicinity.

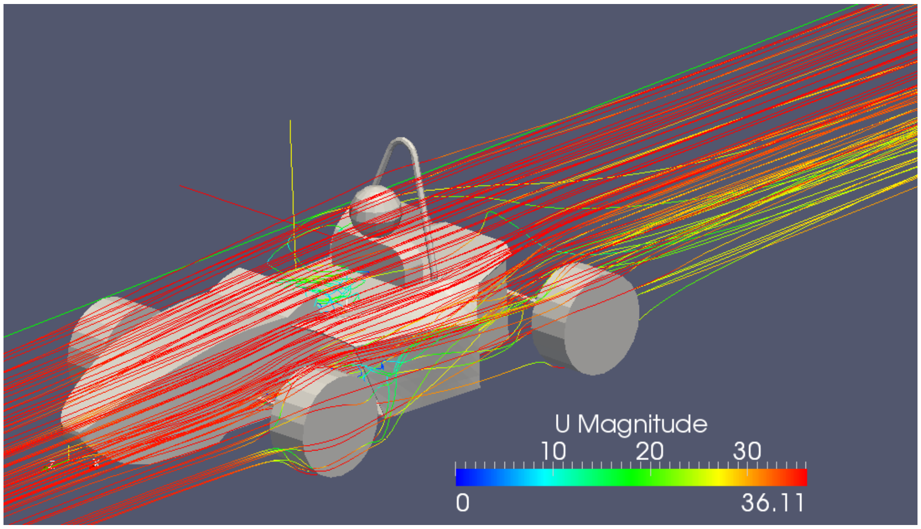


Figure 4-11: TU Graz car streamlines

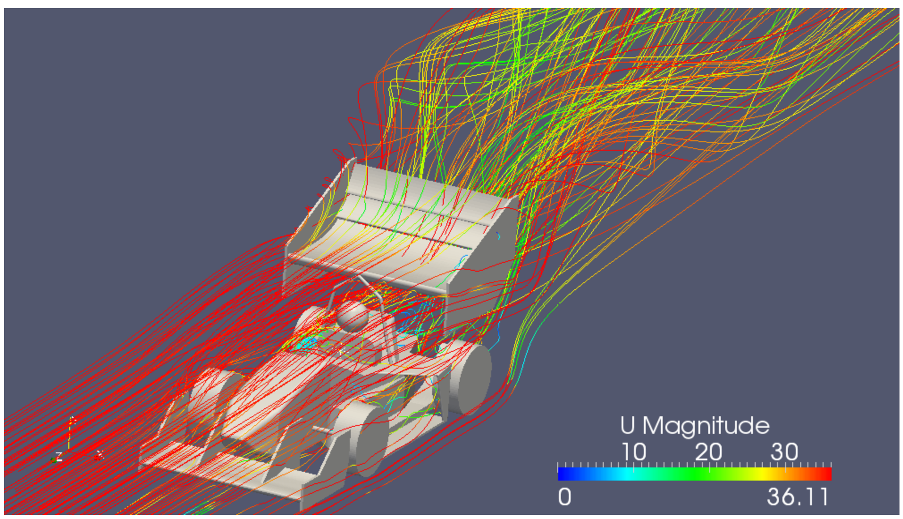


Figure 4-12: Monash car streamlines

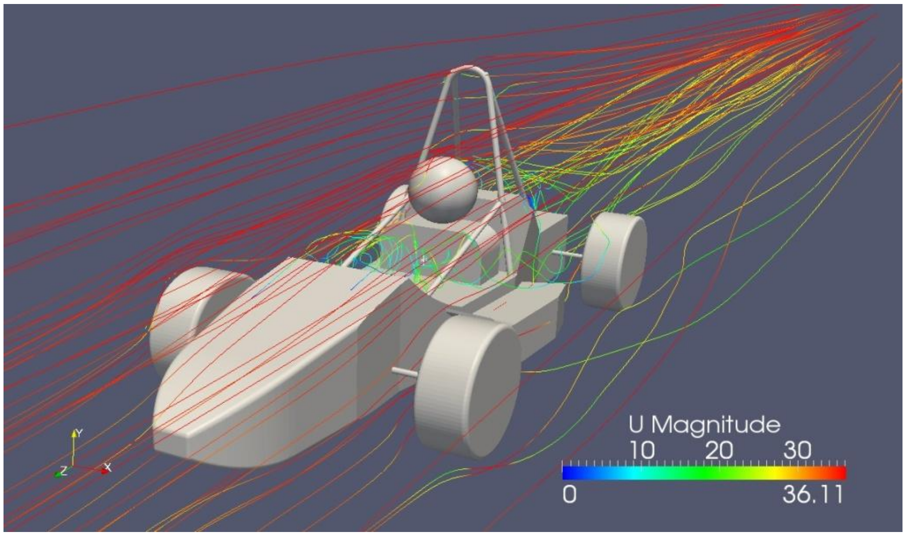


Figure 4-13: NBR final version streamlines

4.9.2. Pressure surface plots

Figure 4-14, Figure 4-15 and Figure 4-16 shows pressure surface plots of TU Graz, Monash and NBR final version respectively. High pressure zones can be identified at the direct exposed surfaces to flow like nose cone, driver head, and front area of wheels. In Monash car pressure above the spoilers is large than pressure below rear spoilers, creating downforce. Main hoop of car is tilted and experiencing less pressure drag.

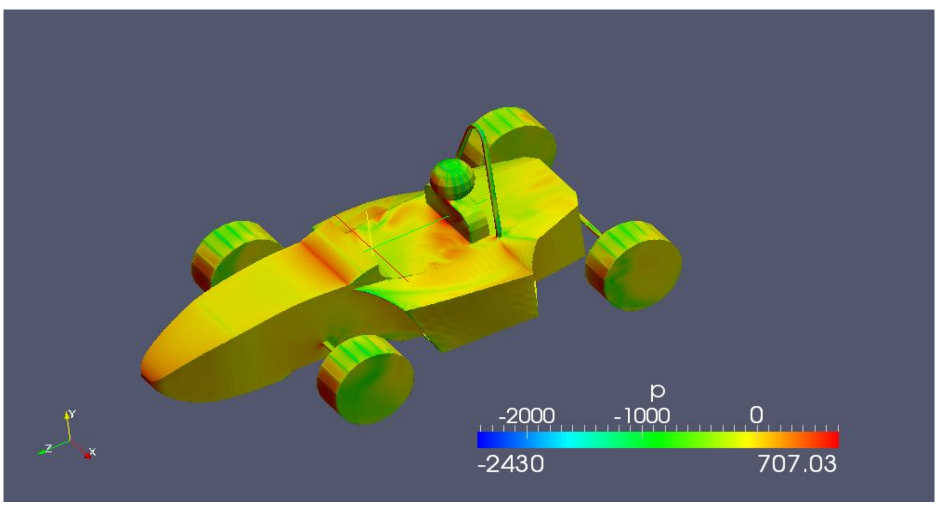


Figure 4-14: TU Graz pressure surface plot

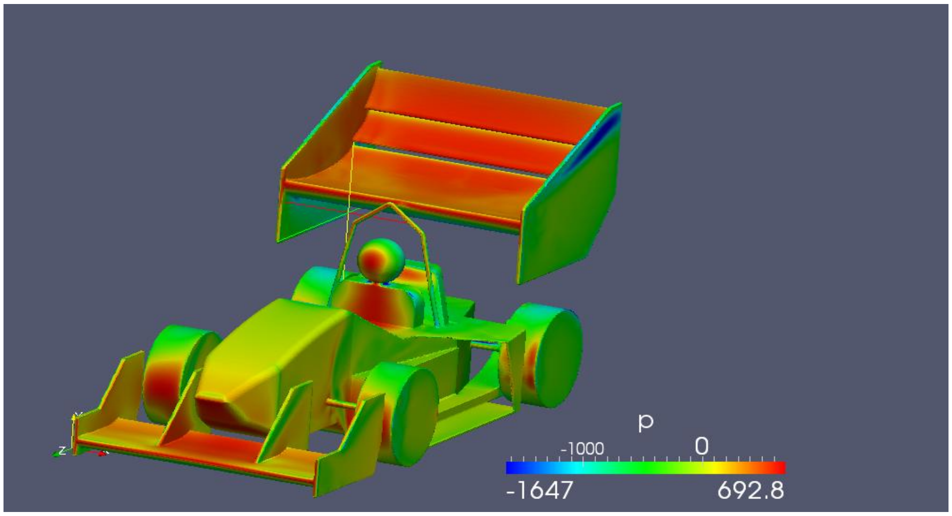


Figure 4-15: Monash pressure surface plot

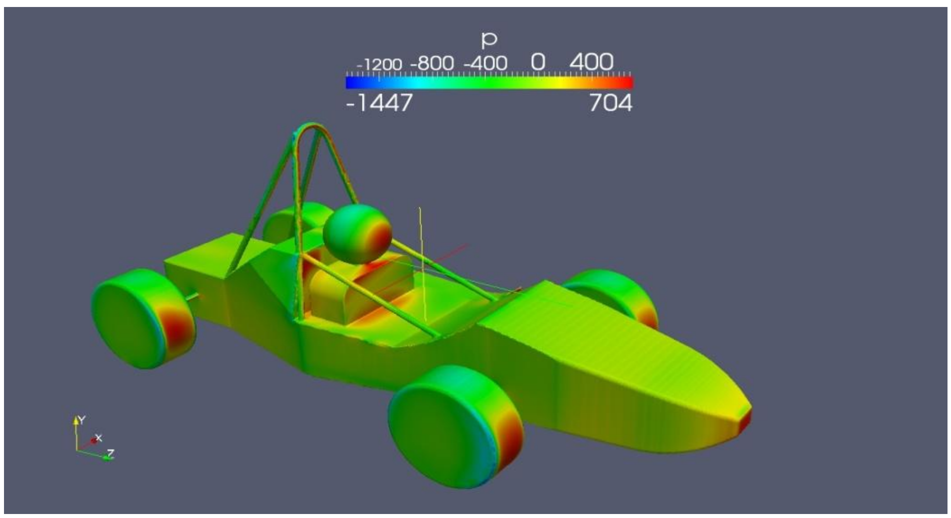


Figure 4-16: NBR final version pressure surface plot

4.10. Wind Tunnel Testing

Subsonic close loop wind tunnel of Centre of Aeronautical Engineering (CAE), Risalpur was used for experimental testing of NBR final version FS car small scale model. NBR final version FS car was scaled down to factor of 1/8 and have dimensions as shown in Table 4-9.

Table 4-9: Dimensions of NBR final version small scale model

Dimensions	Small scale model of NBR final version
Length [mm]	363
Width [mm]	163
Height [mm]	157
Wheel base [mm]	219

Instrumentation for measuring aerodynamic parameters was load cell configuration. It gives 6 aerodynamic parameters

1. Drag coefficient
2. Lift coefficient
3. Side force reaction
4. Yaw moment reaction
5. Pitch moment reaction
6. Rolling moment reaction

Experiment was carried out in three phases. In first phase car was placed straight. Vertical mountings have two dummies to reduce the effect of bluntness of mountings. Remaining two phases were required to cancel the effect of mountings and dummies used in the first phase. Second phase contain car in inverted position with same configuration of mountings and dummies as were in phase 1. In the last phase two more inverted mountings and dummies were added. Results were obtained using equation 4.1

Result= phase 1 – (phase 3- phase 2) [4.1]

SeeFigure 4-17, Figure 4-18 and Figure 4-19 for three phases of wind tunnel experiment.

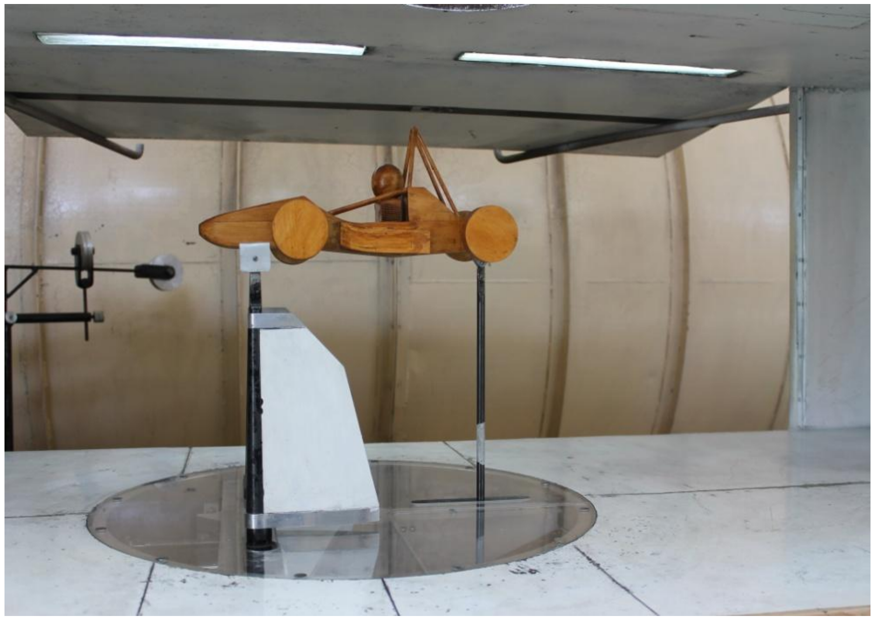


Figure 4-17: wind tunnel “straight” analysis

Figure 4-18: wind tunnel “inverted” analysis

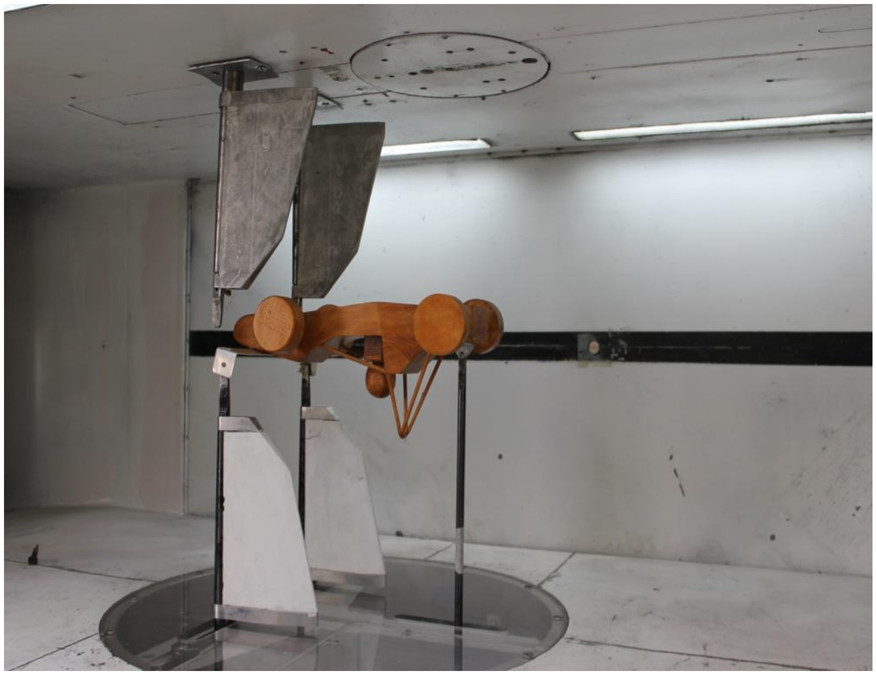


Figure 4-19: wind tunnel "inverted with dummies" analysis

4.10.1. Wind Tunnel Results

Figure 4-20 shows the difference between numerical and experimental results of NBR final version small scale model.

Figure 4-20 gives positive lift coefficient. Comparing with Monash it is negligible, unable to produce any significant lift. Rear spoilers of Monash FS car gave downforce of 2700 N, dictating the importance of rear spoilers for traction. Also at low velocities results are quite agreeable. Reasons for difference in results are

1. Dimensional error in fabrication
2. Surface roughness of wood model
3. High clearance in wind tunnel
4. Mounting problem in wind tunnel
5. Single wind tunnel run introduce large error

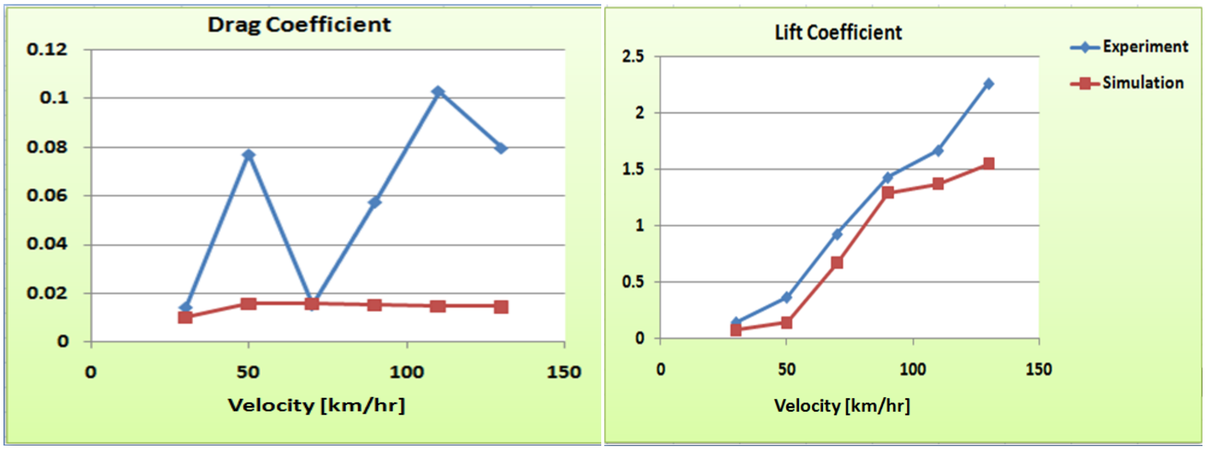


Figure 4-20: experimental and numerical results comparison of small scale model.

6. Conclusions and Recommendations

CFD analysis of TU Graz car and Monash car revealed relationships of certain factors which contribute in external aerodynamics of race cars. Dimensions of car are directly related to drag force because of larger contact area of surface inducing skin friction drag. In the same context wingless car has less drag than winged car. Frontal area is another factor on which drag force depends. Monash car has greater frontal area and has therefore large drag than TU Graz car. For downforce rear and front spoilers are needed. They also ensure greater traction for race cars. Monash has a down force of 2700 N created by rear and front spoilers.

Some aerodynamic characteristics were identified regarding chassis. Main hoop of car must be tilted to have less pressure drag. Underbody design of a chassis must have varying areas to have a balance of lift and downforce to avoid lifting of car in case of no spoilers, and best downforce when spoilers are employed at the rear and front of a car. Height of a car is important. Additional height adds extra weight and increase contact area of a car.

Following the NBR versions certain conclusions can be drawn. Addition of sidepod in version II adds drag force but it is required for effective cooling of engine through radiator. It has also increased frontal area causing more drag. Total increase in drag was 7 % and in lift was 2 %. Trade off has been made between increase in drag force and extent of cooling of engine. In final version turbulence modeling was included that reduces drag to 2 % of drag enforced on NBR version II.

Experimental testing revealed that results obtained through simulations agree to more extent at low velocities than at higher velocities. Also it has indicated the importance of accuracy in dimensions of physical model used for wind tunnel testing. The accurate model will give results closer to the numerical results.

Conclusions of this project can be summarized in following points

- Frontal area, contact areas are directly related to drag force.
- Aerodynamic devices increase the total drag on car.
- Spoilers are required for maximum downforce and greater traction of race cars, particularly while corning at race track.
- Varying areas at underbody of car balance out drag and lift in absence of spoilers.
- Tilted main hoop of FS cars induce less pressure drag
- In case of side pods trade off has to make between increase in drag and extent of cooling of engine through radiator in FS race cars.
- At low velocities numerical and experimental results are more agreeable.

The findings of this research can be improved by

- Including rear and front spoilers for required downforce while cornering at FS race track.
- Including underbody diffuser that will contribute in increase of downforce.
- Reducing the chassis size for less drag.
- Having multiple runs of wind tunnel for more accurate experimental results.

REFERENCES

[1]. Silver Stone 13-15 July 2012, Official Program, Institute of Mechanical Engineers, 2012

[2]. S.Sayovitz, Formula SAE Scoring Template, Institute of Mechanical Engineers, 2013

[3]. S.Wordley and J.Saunders, Aerodynamics for Formula SAE: Initial design and performance prediction, SAE International, 2006-01-0806, 2006

[4]. A.Deakin, Overall Results, Formula Student Institute of Mechanical Engineers 2012

[5]. Website: http://www.racecar-engineering.com/formulastudent/ (Accessed on: June 26,2013)

[6]. M. Shahmal, Study of F1 Car Aerodynamic Rear Wing Using Computational Fluid Dynamic (CFD), 2011

[7] Noah J.Mckay and Ashok Gopalarathnam, The effects of wing Aerodynamics on Race Vehicle Performance, SAE Paper 2002-0103294

[8] Wolf-Heinrich Hucho, Aerodynamics of Road Vehicles, Annu. Rev. Fluid Mech. 1993.25 : 485-537, 1993

[9] S.PEhan and B. Kegl, Aerodynamics Aspects of Formula Racing Car, International Design Conference- Design, Dubrovnik, May 14-17, 2002

[10] Daum, 2013 Formula SAE rules, 2013

APPENDIX A

Extensive survey of previous FS cars

S.No	Team Name	University Name	Location	Iso-metric views	Orthog-raphic views	Tech-nical detail
1	ENIM Formula Student	National Engineering School of Metz	France	✔	x	✔
2	ESTACA Formula Team	ESTACA Engineering School	France	✔	x	✔
3	ISAT Formula Team	University of Burgugy ISAT	Germany	✔	x	x
4	e-gnition Hamburg	Hamburg University of Technology	Germany	✔	x	✔
5	KA-RaceIng E	Karlsruhe Institute of Technology (KIT)	Germany	✔	x	✔
6	KA-RaceIng C	Karlsruhe Institute of Technology (KIT)	Germany	✔	x	x
7	Horsepower Hannover	Leibniz Universität Hannover	Germany	✔	x	✔
8	Ecurie Aix Formula Student Team RWTH Aachen e.V	RWTH Aachen	Germany	✔	x	✔
9	TU Darmstadt Racing Team e.V.	TU Darmstadt	Germany	✔	x	✔
10	Elbflorace Formula Student Team TU Dresden e.V.	TU Dresden	Germany	x	x	✔
11	Kaiserslautern Racing Team	TU Kaiserslautern	Germany	✔	x	✔
12	TU Fast Racing Team	TU Munich	Germany	✔	✔	✔

13	Running Snail Racing Team	UAS Amberg-Wieden	Germany	✔	x	✔
14	CAT-Racing	UAS CoburgFachhochschule Coburg	Germany	✔	x	✔
15	Race-Ing. Team	UAS Dortmund	Germany	✔	✔	✔
16	Raceyard E	UAS Kiel	Germany	✔	x	✔
17	Regenics e.V.	UAS Regensburg	Germany	✔	x	✔
18	Dynamics e.V.	UAS Regensburg	Germany	✔	x	✔
19	Saar Racing Team	UAS Saarbrücken	Germany	✔	x	✔
20	WHZ Racing Team	UAS Zwickau	Germany	✔	x	✔
21	Herkules Racing Team	University of Kassel	Germany	✔	x	✔
22	UPBracing Team e.V	University of Paderborn	Germany	✔	x	✔
23	GreenTeam Uni Stuttgart	University of Stuttgart	Germany	✔	x	✔
24	Aristotle Racing Team	Aristotle University of Thessaloniki	Greece	✔	x	✔
25	Revanta Racing	Bangalore Institute of Technology	India	x	x	x
26	IIT Bombay Racing	Indian Institute of Technology Bombay	India	✔	x	✔
27	KART	Indian Institute of Technology Kharagpur	India	✔	x	✔
28	IIT Roorkee Motorsports	National Institute of Technology Roorkee	India	x	x	x
29	Team Unwired	National Institute of	India	✔	x	✔

		Technology				
30	Team Ojas	Vellore Institute of Technology	India	✔	x	✔
31	Formula DIT	Dublin Institute of Technology	Ireland	✔	x	✔
32	University of Limerick Racing	University of Limerick	Ireland	✔	✔	✔
33	Universita di Bologna	UniBo Motorsport	Italy	✔	x	✔
34	Unicar	University of Cagliari	Italy	✔	x	✔
35	Race UP Team	University of Padova	Italy	✔	x	✔
36	UUJ FS2013	University of Ulster	Northern Ireland	✔	x	✔
37	Revolve NTNU	Norwegian University of Science and Technology	Norway	✔	✔	✔
38	Formula Student Team UiS	University of Stavanger	Norway	x	✔	✔
39	Caledonian Team Oryx	Caledonian College of Engineering	Oman	✔	x	✔
40	Formula NUST Racing	National University of Sciences & Technology	Pakistan	✔	✔	✔
41	AGH Racing	AGH University of Science & Technology	Poland	✔	x	✔
42	PWR Racing Team	Wroclaw University of Technology	Poland	✔	✔	✔
43	BlueStreamLine	Transilvania University of Brasov	Romania	✔	x	✔
44	Formula Neftegaz	Tyumen State Oil and	Russia	✔	x	✔

		Gas University				
45	Road Arrow Team	University of Belgrade	Serbia	✔	x	✔
46	STUBA Green Team	Slovak University of Technology	Slovenia	✔	x	✔
47	Uni Maribor Grand Prix Engineering	University of Maribor	Slovenia	✔	x	✔
48	Tecnun Motorsport	Tecnun – University of Navarra	Spain	✔	x	✔
49	Formula UEM	Universidad Europea de Madrid	Spain	✔	x	✔
50	Formula Student Bizkaia	University of the Basque Country (UPV/EHU)	Spain	✔	x	✔
51	Chalmers Formula Student	Chalmers University of Technology	UK	✔	x	✔
52	Clear River Racing	Karlstad University	Sweden	✔	x	✔
53	KTH Racing	KTH Royal Institute of Technology	Sweden	✔	x	✔
54	ELiTH Racing	Linkoping University	Sweden	x	x	✔
55	LURacing	Lund University	Sweden	✔	x	✔
56	AMZ Racing	ETH Zurich	Switzerland	✔	x	✔
57	Cardiff Racing	Cardiff University	UK	✔	✔	✔
58	Brunel Racing	Brunel University	UK	✔	x	✔
59	BCU Racing	Birmingham City University	UK	✔	x	✔
60	City Racing	City University London	UK	✔	x	✔

61	Phoenix Racing	Coventry University	UK	✔	x	✔
62	DMU Racing	De Montfort Racing	UK	✔	x	✔
63	GlyndwrRacing	Glyndŵr University	UK	x	x	✔
64	HWRacing	Heriot-Watt Racing	UK	✔	x	✔
65	KU e-Racing	Kingston University	UK	✔	x	✔
66	Lancaster Racing Team	Lancaster University	UK	✔	x	✔
67	LJMU Racing	Liverpool John Moores University	UK	✔	x	✔
68	LUMotorsport	Loughborough University	UK	✔	x	✔
69	MMU Racing	Manchester Metropolitan University	UK	✔	x	✔
70	Oxford Brookes Racing	Oxford Brookes University	UK	✔	x	✔
71	Queen Mary Racers	Queen Mary University of London	UK	x	x	x
72	UCL Racing	University College London	UK	✔	✔	✔
73	TAU Racing	University of Aberdeen	UK			
74	Team Bath Racing	University of Bath	UK	✔	x	✔
75	Exeter Racing	University of Exeter	UK	✔	x	✔
76	UGRacing	University of Hertfordshire	UK	✔	x	✔
77	UH Racing	University of Hertfordshire	UK	✔	x	✔
78	Team HARE	University of	UK	✔	✔	✔

		Huddersfield				
79	UCLan Race Engineering URE13	University of Central Lancashire	UK	✔	x	✔
80	Hull University Formula Student	University of Hull	UK	✔	x	✔
81	Leeds Formula Race Team	University Leeds	UK	✔	✔	✔
82	University of Leicester	University of Leicester Racing	UK	✔	x	✔
83	University of Liverpool Motorsport	University of Liverpool	UK	✔	x	✔
84	UPRacing	University of Portsmouth	UK	✔	✔	✔
85	Sheffield Formula Student	University of Sheffield	UK	✔	x	✔
86	Southampton University Formula Student Team	University of Southampton	UK	✔	x	✔
87	University of Strathclyde Motorsport	University of Strathclyde	UK	✔	x	✔
88	Mobil 1 Team Sussex	University of Sussex	UK	✔	✔	✔
89	Warwick Racing	University of Warwick	UK	✔	x	✔
90	SDU Vikings	University of Southern Denmark	Denmark	✔	x	✔
91	Racing Team Pilsen	University of West Bohemia	Czech Republic	✔	✔	✔
92	FSB Racing Team	University of Zagreb	Croatia	x	x	✔
93	Dalhousie Formula SAE	Dalhousie University	Canada	x	x	✔

94	Thomas More Innovation	Thomas More Mechelen – De Nayer	Belgium	x	x	x
95	Fastrada	Karel de Grote University College	Belgium	x	x	✔
96	Formula Group T	Group T International University College	Belgium	✔	x	✔
97	Joanneum Racing Graz	UAS Graz	Austria	✔	✔	✔
98	TUG Racing	TU Graz	Austria	✔	✔	✔
99	ASU Racing Team	Ain Shams University	Egypt	✔	x	✔
100	Cairo University Racing Team	Cairo University	Egypt	x	x	x
101	AUC Racing Team	American University in Cairo	Egypt	x	x	x
102	Swansea University Race Engineering	Swansea University	UK	✔	x	✔
103	HFS Racing Team	Helwan University	Egypt	x	x	✔
104	Minoufyia University	Menoufiya University Team	Egypt	x	x	✔
105	MEC Auto FS Team	Tanta University	Egypt	x	x	✔
106	Nuta_Bolts Team	Anambra State University	Nigeria	✔	x	✔
107	SKEMA Racing Team	SKEMA Business School	France	x	x	✔
108	Firenze Race Team	Università degli studi di Firenze	Italy	x	x	✔
109	Formula IPLeiria	Politechnic Institute of Leiria	Portugal	x	x	✔
110	Clear River Racing	Karlstad University	Sweden	✔	x	✔

	Electric Division					
111	Aston Racing	Aston University	UK	x	x	✔
112	Brunel Masters Motorsport	Brunel University	UK	x	x	✔
113	Durham University Formula Student	Durham University	UK	x	x	✔
114	Team Bath Racing	University of Bath	UK	✔	x	✔
115	Newcastle Racing	Newcastle University	UK	x	x	✔
116	Full Blue Racing	University of Cambridge	UK	x	x	✔
117	Drammo Engineering	University of Warwick	UK	x	x	✔
118	UG Racing	University of Glasgow	UK	x	x	✔
119	UH Racing	University of Hertfordshire	UK	x	x	x
120	University of Manchester	University of Manchester Formula Student	UK	x	x	✔
121	University of Northampton	University of Northampton	UK	x	x	✔
122	UWE Racing	University of the West of England	UK	x	x	✔
123	Warwick Racing Class 2	University of Warwick	UK	x	x	x

APPENDIX B

TU Graz FS car technical details

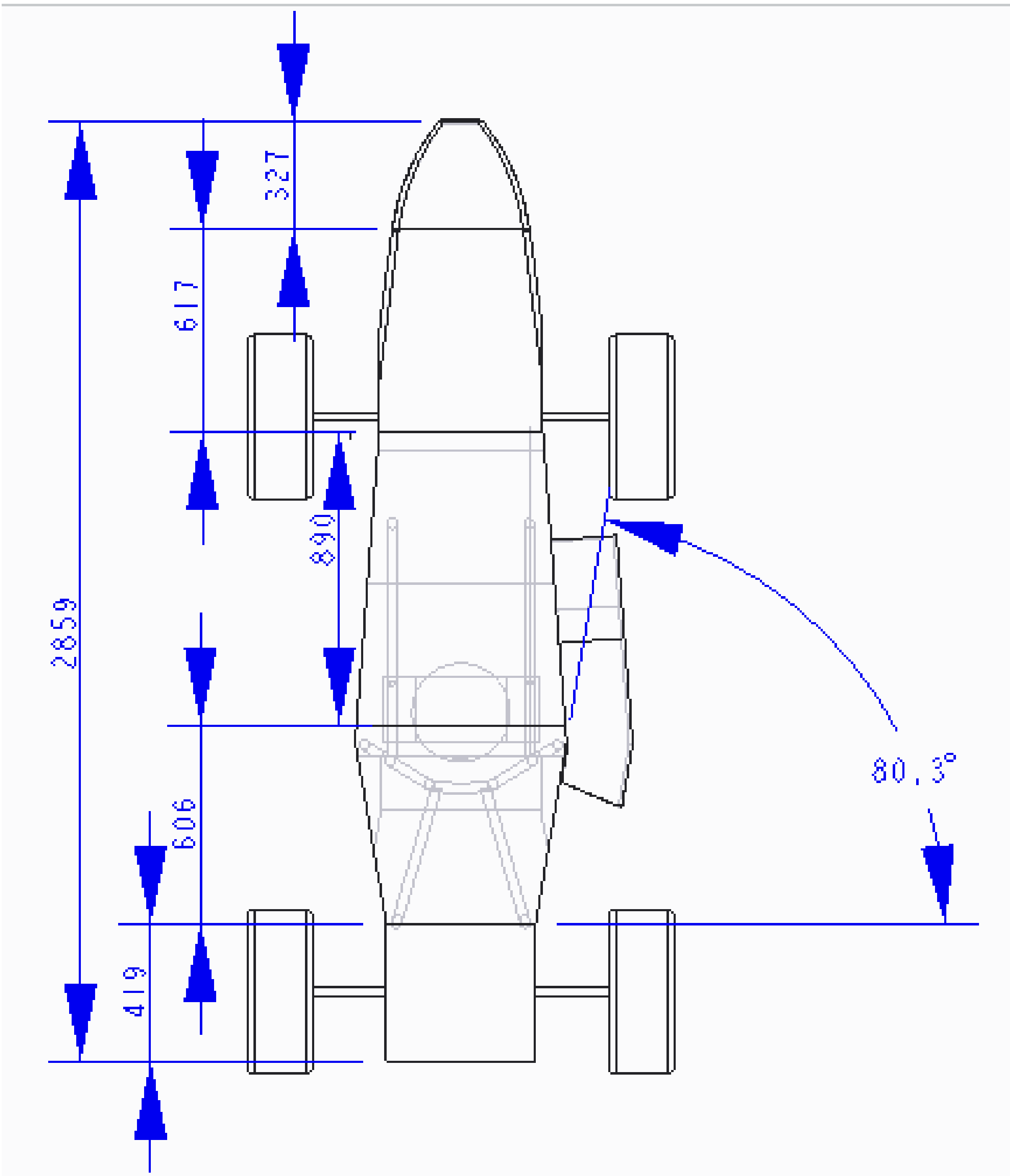
Length: 2678
Width: 1375
Height: 1022
Wheelbase: 1550
Track: 1180/1150
Weight – no driver: 141
Weight - distribution including driver:107/102
Suspension: unequal length a-arms, front pull/rear push rod and bell crank actuated 4-way adjustable dampers
Tyres: 18×6.0-10 Hoosier LCO
Wheels: 6,5″ wide, 2pc CFRP-rim
Brakes: 4-disc system, self designed steel rotors, adjustable brake balance
Chassis construction: - one piece CFRP monocoque
Engine: 2013/KTM 500 EXC
Bore: 95
Stroke: 72
Cylinders: 1
CC: 500
Fuel Type: 100 RON unleaded
Fuel System: student designed and built fuel injection, 2-spray preparation
Max Power: 61
Max Torque: 9500
Transmission: Single 520 Chain
Differential: Drexler, multiplate limited slip differential
Final Drive: 12:32

Monash FS car technical details

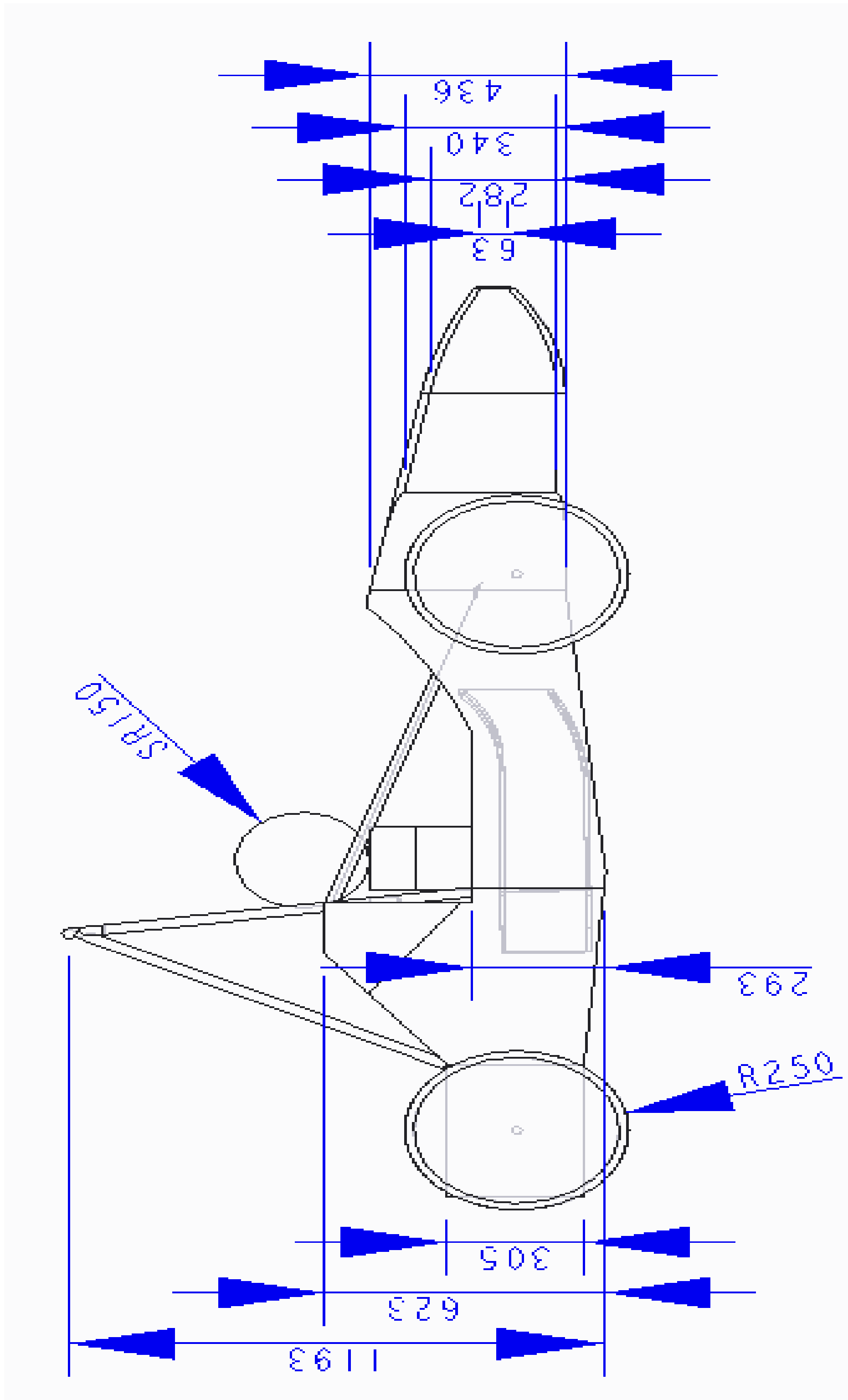
Length: 3085
Width: 1300
Height: 1470
Wheelbase: 1530
Track: 1100mm/1050mm
Weight – no driver: 200kg
Weight – distribution including driver: 133kg/135kg
Suspension: Double unequal length A-Arm. Pull rod/Push rod actuated longitudinally/horizontally oriented spring and damper
Tyres: 20×7-13 D2704 Goodyear
Wheels: 7 inch wide, 3 pc Al
Brakes: Floating Bisalloy, 207mm/172.5mm dia cross drilled
Chassis construction: Steel tube spaceframe with bonded composite panels, aluminium rear bulkhead
Engine: 2011 / KTM 450 SX-F single
Bore: 97
Stroke: 60.8
Cylinders: 1
CC: 449.3
Fuel Type: 99 RON
Fuel System: MoTeC M400 ECU, sequential injection
Max Power: 40 kW @ 9,000rpm
Max Torque: 54 Nm @ 7,000rpm
Transmission: Single 428 Chain
Differential: Drexler Formula Student Clutch Pack LSD
Final Drive: 3.38:1

APPENDIX C

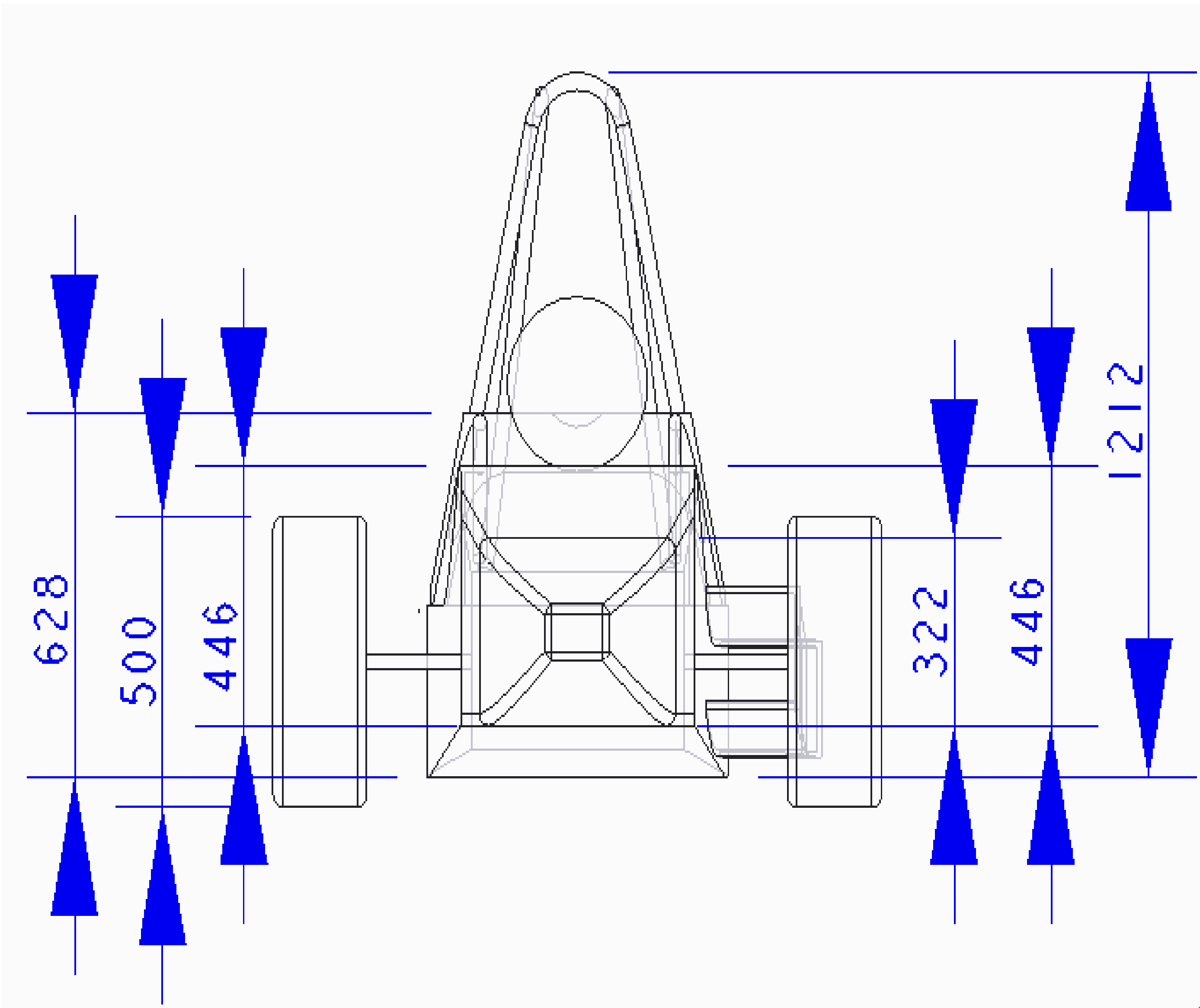
NBR final version top view (all dimensions are in mm)



NBR final version side view (all dimensions are in mm)



NBR final version front view (all dimensions are in mm)



APPENDIX D

Pressure equations in SimpleFOAM solver

```
{
    volScalarField rAU(1.0/UEqn().A());
    volVectorField HbyA("HbyA", U);
    HbyA = rAU*UEqn().H();
    UEqn.clear();

    surfaceScalarField   phiHbyA("phiHbyA",   fvc::interpolate(HbyA)   &
mesh.Sf());
    adjustPhi(phiHbyA, U, p);

    fvOptions.relativeFlux(phiHbyA);

    // Non-orthogonal pressure corrector loop
    while (simple.correctNonOrthogonal())
    {
        fvScalarMatrix pEqn
        (
            fvm::laplacian(rAU, p) == fvc::div(phiHbyA)
        );

        pEqn.setReference(pRefCell, pRefValue);

        pEqn.solve();

        if (simple.finalNonOrthogonalIter())
        {
            phi = phiHbyA - pEqn.flux();
        }
    }

    #include "continuityErrs.H"

    // Explicitly relax pressure for momentum corrector
    p.relax();

    // Momentum corrector
    U = HbyA - rAU*fvc::grad(p);
    U.correctBoundaryConditions();
    fvOptions.correct(U);
```

Velocity equations in simpleFOAM solver

```
// Momentum predictor

    tmp<fvVectorMatrix> UEqn
    (
        fvm::div(phi, U)
      + turbulence->divDevReff(U)
      ==
        fvOptions(U)
    );

    UEqn().relax();

    fvOptions.constrain(UEqn());

    solve(UEqn() == -fvc::grad(p));

    fvOptions.correct(U);
```

APPENDIX E

APPENDIX E

A Comparative Study of Exterior Body shapes of Formula Student Cars

Quratulain
Department of Mechanical Engineering
School of Mechanical and Manufacturing Engineering
National University of Sciences and Technology
Islamabad, Pakistan

Muhammad Sajid
Department of Mechanical Engineering
School of Mechanical and Manufacturing Engineering
National University of Sciences and Technology
Islamabad, Pakistan
m.sajid@smme.nust.edu.pk

Samiur Rahman Shah
Department of Mechanical Engineering
School of Mechanical and Manufacturing Engineering
National University of Sciences and Technology
Islamabad, Pakistan

Abstract— **Formula Student is a student engineering competition held annually in the UK and run by the Institution of Mechanical Engineers (IMECHE). Student teams from around the world design, build, test, and race a small single seat-race car. Body work design of a single seat race car should be aesthetic, allow ease of ingress/egress for driver, allow easy access to components for inspection and access to ports for replenishment / verification of level of fluids (coolant, oil etc.), airflows for cooling for different components of the vehicle, addition of aerodynamic devices for front, rear and underbody of a car and analyzing aerodynamic performance. The external aerodynamics of selected formula student cars was analyzed, using Computational Fluid Dynamics (CFD) for relevant parameters including lift, drag while keeping the same environment for the car as it will experience on a race track. A comparison of the performance parameters obtained for these cars is presented in this paper.**

Keywords—computational fluid dynamics; formula student; external flow

INTRODUCTION

In automobile world the most significant factor that has the influence on power consumption is the drag offered by air. Aerodynamics study has become decisive to make best use of the power of engine. Particularly in racing world where the high speed is the aim, reduction of drag demands most aerodynamic bodywork design. Among manufacturers consideration is being given more on this aspect. This paper focuses on formula student competition [1]. It is a design competition which gives engineering students, a platform to design, build, test and race a single seated car. A competition is based on three static events (cost, presentation, design) and five dynamic events (acceleration, skid pad, sprint, endurance, efficiency) having different points for each event [2]. To achieve success all aspects of the car design and development process must be carefully balanced [3]. Exterior shape of a car and aerodynamic devices used, tell a lot where about where a car stands in winning race, besides other factors. The increasing trend of the use of aerodynamic devices is observed in leading cars [4] and is summarized in *Table. I*. It is essential to unveil the reason of increasing trend. This paper presents comparison of selected formula student race cars in order to unveil the reason of this growing tendency.

TABLE I. ADOPTION OF AERODYNAMIC DEVICES BY LEADING CARS

Rank 2012	Team	Year	wings	diff-user	Side-pod
1	Chalmers University of Technology	2012	✔	✔	✔
		2013	✔	✔	✔
2	Delft University of Technology	2012	x	x	X
		2013	✔	✔	✔
3	Monash University	2012	✔	✔	✔
		2013	No participation		
4	TU Munich	2012	x	✔	✔
		2013	✔	✔	✔
5	University of	2012	x	x	✔

	Stuttgart	2013	✔	✔	✔
6	Tallinn University of Applied Sciences	2012	✔	✔	✔
		2013	No participation		
7	Oxford Brookes University	2012	x	x	✔
		2013	x	✔	✔

I. Research Approach

The first step in this research was to carry out a survey of formula student cars, their selection strategy, two dimensional analysis details, review of the physics involved, definition of computational domain and numerical solution of the physics over the domain. In the end results of comparison of lift and drag coefficients are presented. This paper illustrates factors to take into account while designing exterior shape of a car and shows how advantageous it is to utilize aerodynamic devices in race cars.

A. Selection of cars

Drawings of formula student cars can be found from an online magazine "Racecar Engineering" [5]. It is the world's leading technology magazine for motorsport. Detailed views are available for most of the cars except specifics of wing profile. The only car with wing profile details available is of Monash University. Also both the views (Isometric and orthographic) of most cars are available in this magazine for the year 2013.

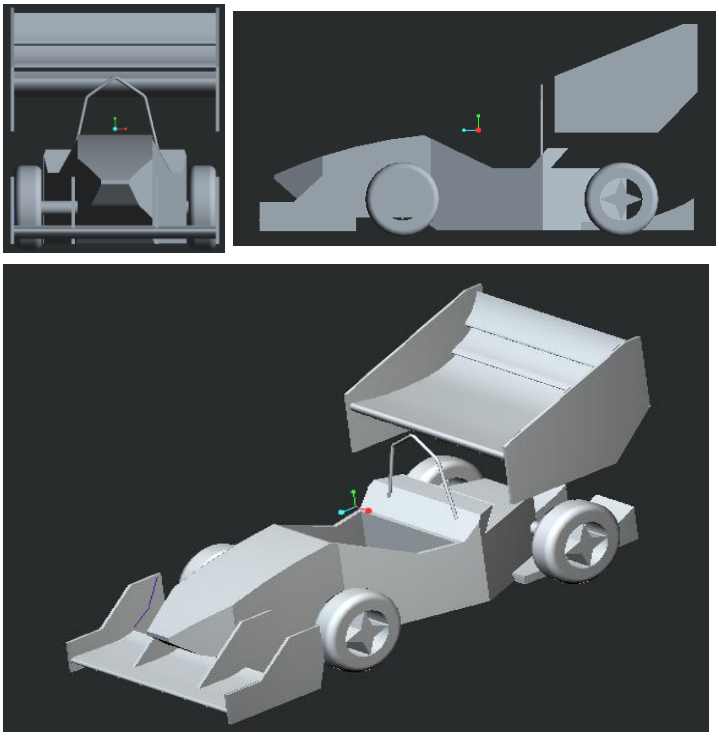
Cars are selected on the basis of their position obtained in last year's competition, availability of required information, level of complexity of making solid models from their orthographic views and the number and type of aerodynamic devices used by the teams. For obtaining most relevant results it is pertinent to select race car of Monash University as its wing profile is known and compare it with a car which is using no wings to have distinct difference and clear idea of using front and rear wings and its effect on drag and lift co-efficient. Details available for both cars are given in *table II* . *See figure 1* for detailed views of both cars.

TABLE II. Available Details

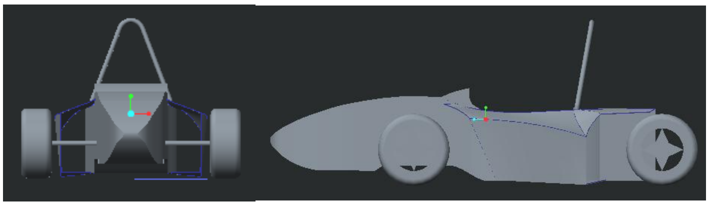
Car No.	Team	Rank 2012	Isometric view	Orthographic views
1.	Monash University	Third	✔	✔
2.	TU Graz	tenth	✔	✔

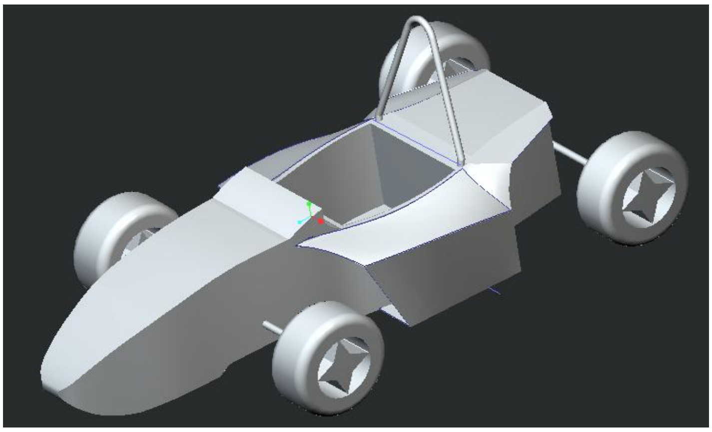
B. Computational Domain

Based on available drawing details two dimensional analyses is preliminary carried out before going to three dimensional analyses as outlined in [3] [6]. Orthographic views available for Monash University's car have wing profile but lack profile of its exterior shape rather focusing on chassis and its inside components, therefore exterior shape of the car has been approximated and it is expected that modeling errors will be less in a two dimensional analyses as compare to the propagation of these errors in a three dimensional analyses. Also the computational cost of a three dimensional analyses was deemed too expensive at this stage of preliminary analyses of formula student cars, and therefore two dimensional analyses is adopted focusing on effectiveness of rear and front wings.



a. Front, Side and Orthographic Views of Monash University car





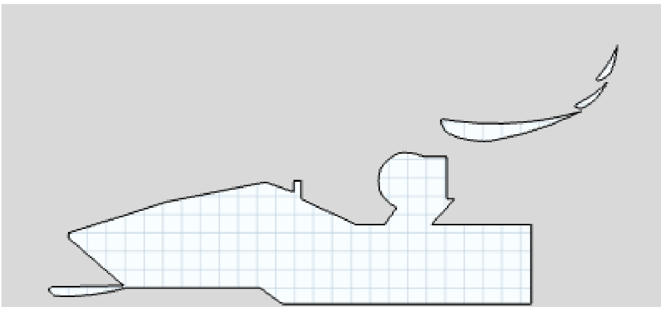
b. Front, Side and Orthographic Views of TU Graz car

Fig.1. Detailed views of cars

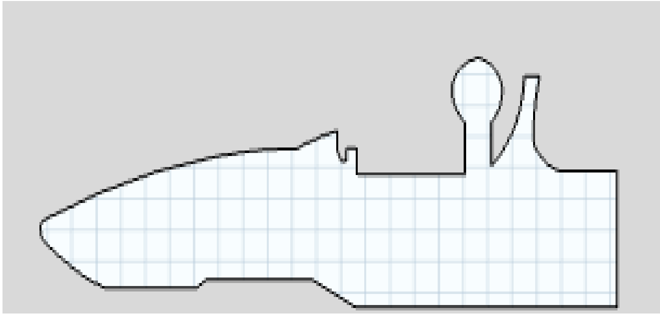
Three dimensional Analysis of remaining devices i.e. side pod, underbody diffuser is required but due to incomplete available drawing of Monash University car this paper is limited to only two dimensional analysis, comparing front and rear wings of Monash University car with non winged car of Tu Graz University.

For sketching Creo Parametric 1.0 is used. Central plane of both cars are sketched with the help of available side view of cars. Dimensions are noted by the sketch made in this software. With the help of these dimensions geometry is constructed for simulation. Two simulation softwares are used to predict the better results i) Comsol Multiphysics and ii) OpenFOAM for Computational fluid Dynamics (CFD) simulation.

Figure 2 shows centre plane sketch of both cars. Selected domain length is seven times while domain height is two times the length of respective cars in Comsol Multiphysics .



c. Two dimensional sketch of Monash University car



b. Two dimensional sketch of TU Graz car

Fig.2. Two dimensional sketches

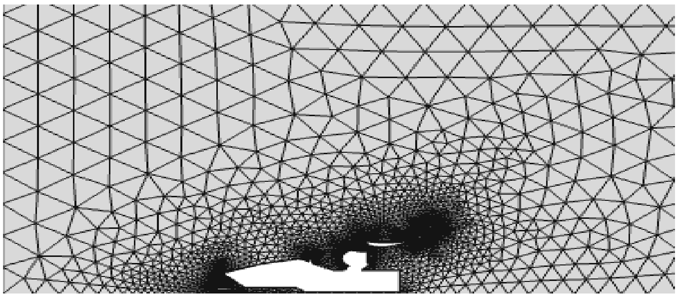
While COMSOL uses a finite element discretization over an unstructured grid a structured hexahedral mesh is discretized using the finite volume method in OpenFOAM. The later software utility is an open source package and allows easy modification of the solver as well as simpler integration of post processing functions. This aspect facilitated the integration of normal pressure distribution over the complex domain in order to calculate the lift and drag forces as well as their coefficients and was the prime motivation for using OpenFOAM.
In OpenFOAM the extent of the computational domain is thirteen times the length of respective cars while the domain height is five times the height of respective cars. The larger size of computational domain in leads to better results without a detectable increase in computational cost in term of performance of computer.

C. Mesh Structure

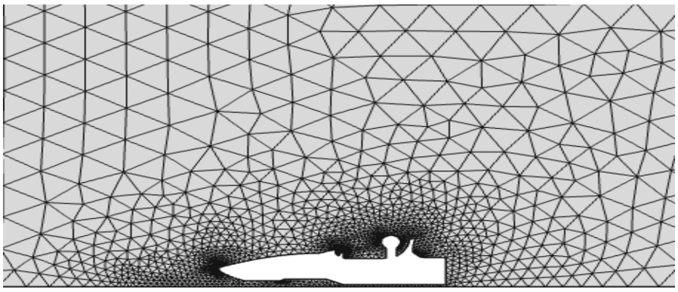
Free triangular meshing is used to create an unstructured mesh with triangular elements for the two dimensional models of both cars. High mesh density was ensured in regions where gradients of velocity and pressure were expected to be higher based on the physics of the problem. Statistics of the generated meshes for both cars are shown in *table III* while *Figure 3* depicts the mesh structure in close vicinity to the cars.

TABLE III. MESH STATISTICS IN COMSOL MULTIPHYSICS

Statistics	**Monash**	**TU Graz**
Triangular elements	9143	4307
Edge elements	577	353
Vertex elements	48	30
Number of elements	9143	4307
Minimum element quality	0.7625	0.7754
Average element quality	0.9709	0.9742
Element area ratio	1.077e-5	2.818e-5
Mesh area	1.319e8mm2	9.939e7 mm2



a. Monash



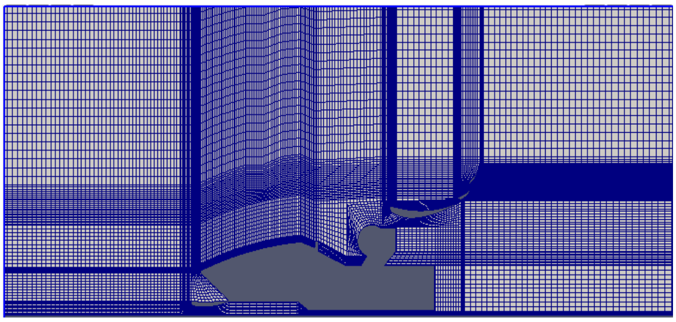
b. TU Graz

Fig.3. Free triangular meshing (Comsol Multiphysics)

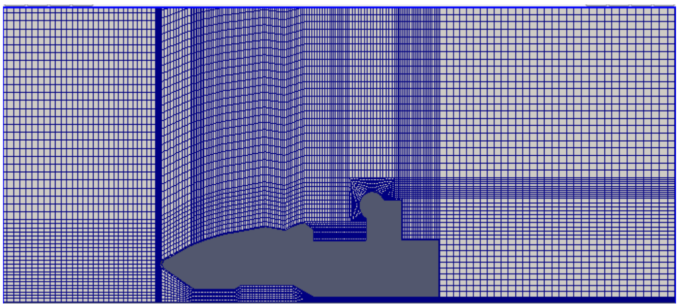
In OpenFOAM block structured meshing is used with hexahedral elements for the two dimensional models of both cars. In close vicinity of the cars, larger mesh density is used to ensure accuracy of results and to capture minor changes in gradients of velocity and pressure. Aspect ratio of cells is kept close to one in this region while farther away from the cars variations in aspect ratio are allowed in the direction of the flow. Due to the structured nature of the mesh non-orthogonality of the mesh is limited. Statistics of the generated meshes for both cars are shown in *table IV* while *Figure 4* depicts the mesh structure in close vicinity to the cars.

TABLE IV. MESH STATISTICS IN OPEN FOAM

Statistics	**Monash**	**TU Graz**
Points	181880	100006
Internal points	0	0
Faces	361078	197873
Internal faces	179192	97867
Cells	90045	49290
Boundary patches	6	6



a. Monash



b. TU Graz

Fig.4. Block structured meshing (OpenFOAM)

D. Boundary Conditions

Following conditions are defined for both car models in Comsol Multiphysics

TABLE V. BOUNDARY CONDITIONS FOR BOTH CASES IN COMSOL MULTIPHYSICS

Boundary	**Boundary Condition**	**Equation**
Inlet	Velocity	$\mathbf{u}=-U_o\ \mathbf{n}$
Outlet	Pressure	$p=p_o$
Top wall	Symmetry	$\mathbf{u}.\mathbf{n} = 0$ $\mathbf{K}-(\mathbf{K}.\mathbf{n}).\mathbf{n}=0$ $\mathbf{K}=[\mu(\nabla\mathbf{u})+(\nabla\mathbf{u})^T)\quad]\mathbf{n}$
Remaining	No slip	$\mathbf{u} = 0$

In Open Foam following boundary conditions are defined for both models

TABLE VI. BOUNDARY CONDITIONS FOR BOTH CASES IN OPEN FOAM

boundaries	**Velocity**	**Pressure**
Inlet	Fixed value	Zero gradient
Outlet	Zero gradient	0
Car exterior profile	Fixed value	Zero gradient
Top	Symmetry plane	Symmetry plane

Ground	Fixed value	Zero gradient
Front and Back	Empty	Empty

The pressure at the outlet was set at zero Pa for all the test cases. The symmetry condition at the top wall was selected to indicate the state of uniform flow sufficiently far away from the vehicle. While the velocity was varied from 5 m/s to 45 m/s with intervals of 5 in order to evaluate the relation of the drag forces with the speed of the vehicle.

E. Governing Equations

Incompressible Navier Stokes equations which define the physics of the fluid flow for the case taking into account viscous forces and time rate of change of momentum, are given below;

$$\rho\, \partial \mathbf{u} /\partial t + \rho(\mathbf{u}.\nabla)\mathbf{u}=\nabla.[-p\, \mathbf{I} + \mu(\nabla\mathbf{u} + (\nabla\mathbf{u})^T) - 2/3\mu(\nabla.\mathbf{u})\, \mathbf{I}] + \mathbf{F} \quad (1)$$

$$\rho\nabla.\mathbf{u} = 0 \quad (2)$$

where ρ is the density (kg/m3), **u** is the velocity (m/s), p is the pressure (Pa) and F is the volume force vector (N/m3)

Non-dimensionalization of both equations is carried out using the following dimensionless variables;

$$L_* = L/L_R$$
$$u_* = u_{in}/u_R$$
$$t_* = (t.u_R) / L_R$$
$$p_* = p/(\rho/u_R^2)$$
$$\nabla_* = \nabla.L_R$$

Reference values are given in *table.VII*

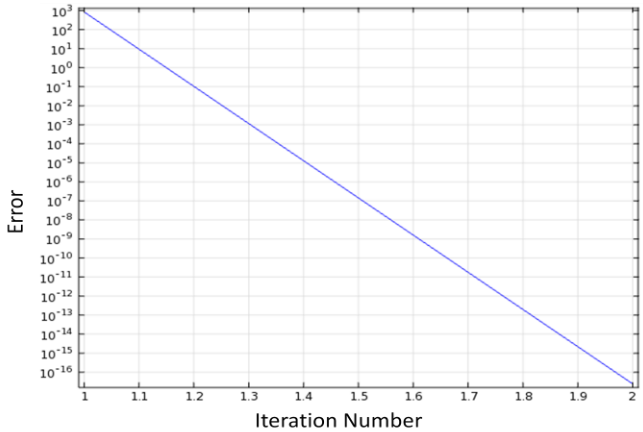
TABLE VII. Reference values

Parameter	Value
L_R	0.001 m
u_R	10 m/s
ρ_R	1.23 kg/m3
μ_R	1.79e-5 Pa.s

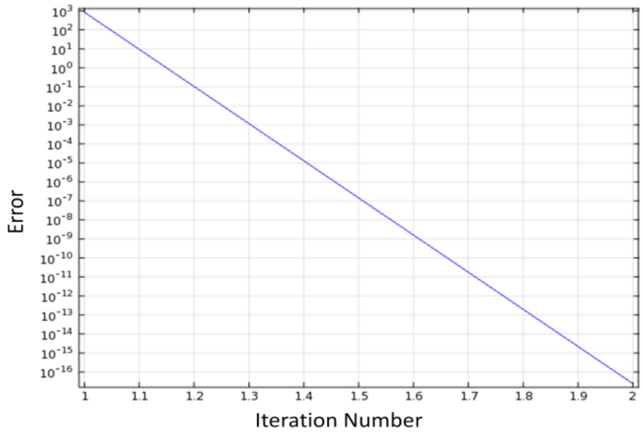
F. Solution and Results

Relative tolerance for both cases is 0.01 while results are computed using direct solver MUMPS to obtain a steady state solution in comsol multiphysics utility. While in OpenFOAM an incompressible flow solver based on the 'simple' approach is employed.

Error plot for both the cars at an inlet velocity of 45 m/s is shown in *fig. 5*.



a. Error in non linear solver of Monash



b. Error in non linear solver of Tu Graz

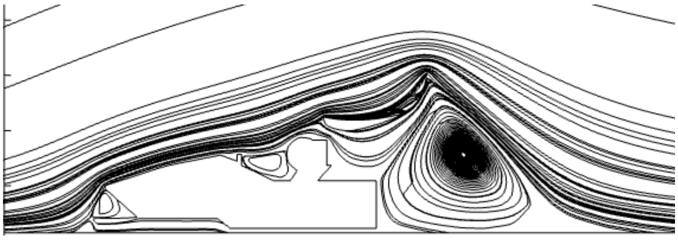
Fig.5. Relative Error (Comsol Multiphysics Solver)

The lift and drag forces can be computed using line integration of pressure in y and x directions respectively. From the forces the coefficients can be calculated using the following expressions.

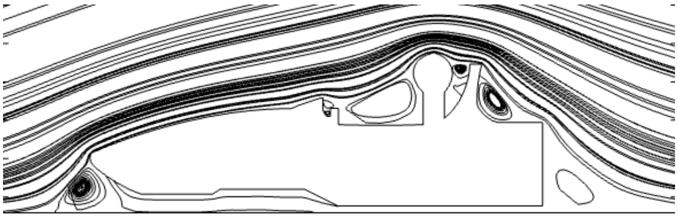
$C_L = F_L / 0.5\rho\, u^2 A$ (3)
$C_D = F_D / 0.5\rho\, u^2 A$ (4)

Where C_L and C_D are lift and drag coefficients respectively, ρ is the density (kg/m3), u is the upstream velocity (m/s), A (m2) is the frontal area.

In Monash car, circulation is observed at the rear and front side of a car while small circulation at the front is also observed in TU Graz car. See *fig. 6* for streamline plots.



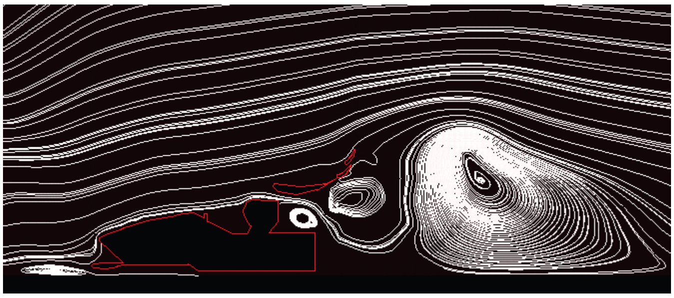
a. Streamlines around Monash



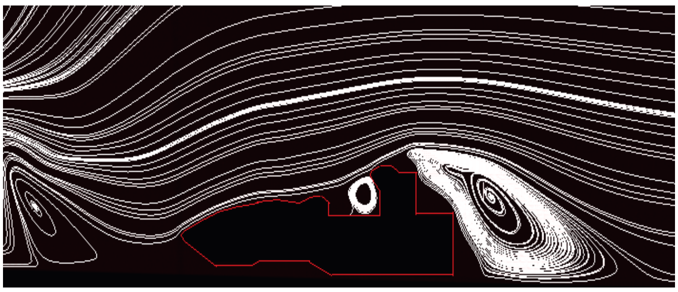
b. Streamlines around TU Graz

Fig.6. Stream line plot in Comsol Multiphysics

Similar streamlines were observed while carrying out the simulation in OpenFOAM under the same conditions, and large size circulation was observed in the wake region behind both cars. See *fig. 7* for streamline plots.



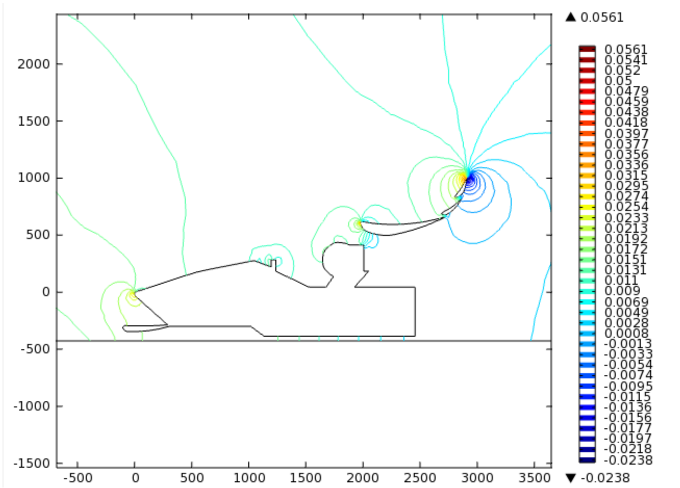
a. Streamlines around Monash



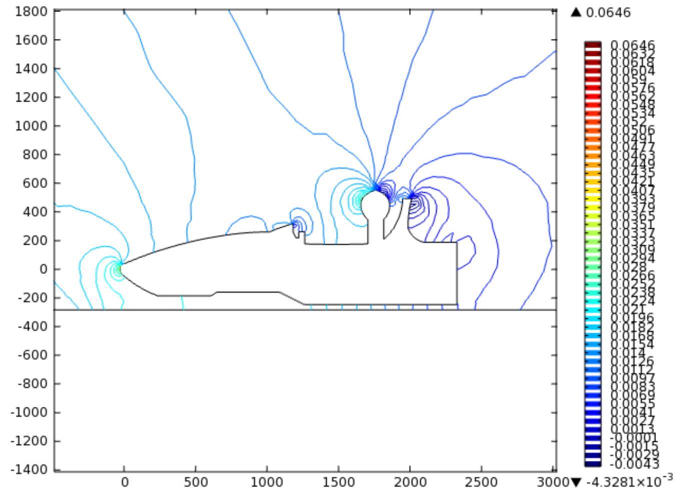
b. Streamlines around TU Graz

Fig.7. Stream line plot in Open Foam

Wings are designed with larger thickness at front-lower side, which increases flow speed and decrease pressure, creating pressure difference between top and lower side of wing as shown in the following pressure contour plot.



a. Monash



b. Tu Graz

Fig.8. Pressure Contour Plot (Comsol)

In Monash car it can be observed (*fig. 8a*) that pressure at the top of wing is higher than the lower side. This pressure difference generates downward force which is a basic purpose of using inverted wings in race cars. Similar observations were made while simulating in OpenFOAM.

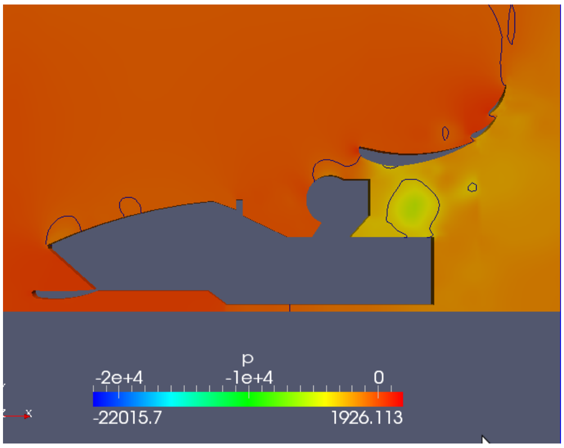


Fig.9. Pressure distribution over Monash in OpenFOAM.

Tu Graz car lacks this down force as it has no wings. Furthermore a pressure gradient along the horizontal direction is also observable in both vehicles indicating presence of drag forces.

In order to quantify the drag force on the cars, the pressure normal to the horizontal and vertical projections of the surface of the vehicle are integrated over the outline of the vehicle. This gives us an estimate of the drag force per unit depth of the two cars as a function of the car velocity.

The following figures show the evolution of the coefficients of lift and drag for both cars at various speeds as obtained from the OpenFOAM solver.

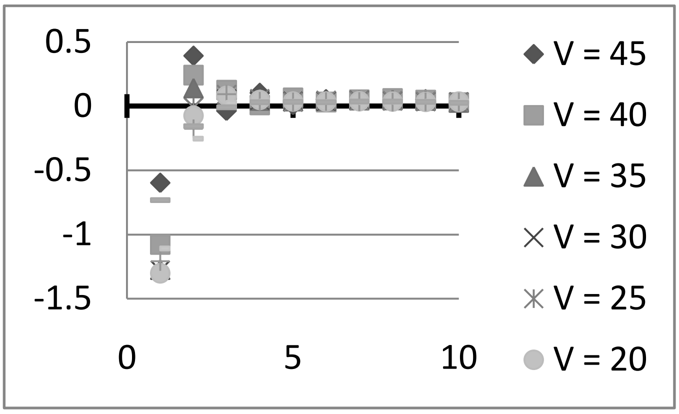


Fig.9. Drag coefficient, Cd for TU Graz vs. time steps taken by solver at various velocities.

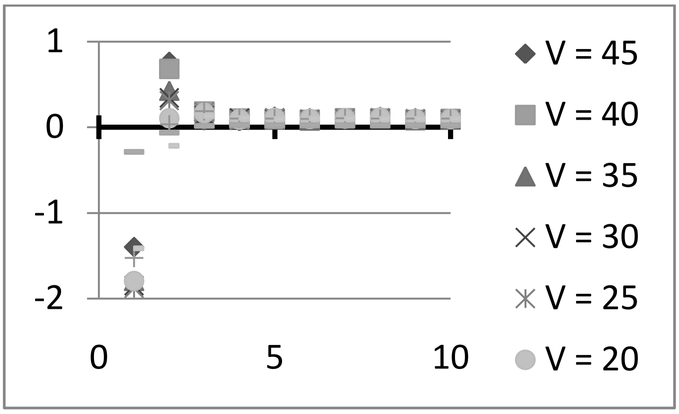


Fig.10. Drag coefficient, Cd for Monash vs. time steps taken by solver at various velocities.

These figures indicate that the values of the drag coefficient have converged, while the range of the graph does not permit an accurate assessment of the drag coefficient. For this purpose the following figure is presented.

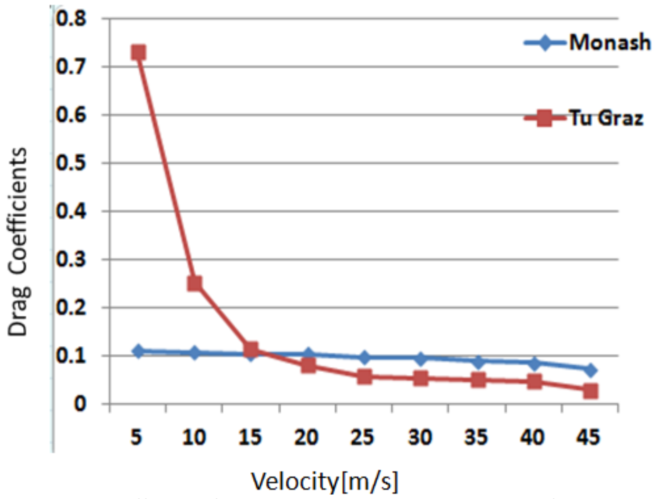


Fig.11. Drag co efficient of Monash and TU Graz per unit depth of vehicle.

Similarly the evolution of the lift coefficient for the two cars are as follows;

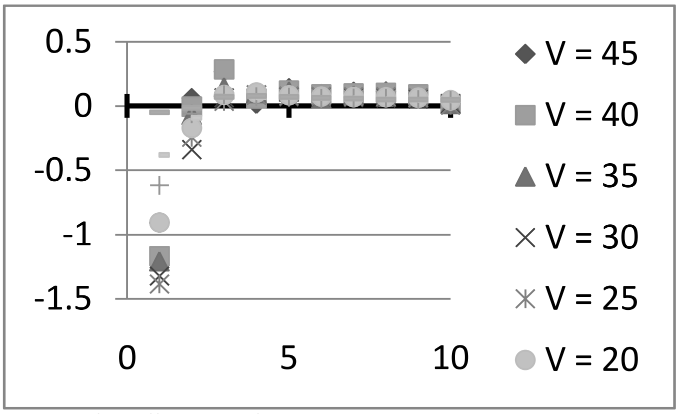


Fig.12. Lift coefficient, Cl for TU Graz vs. time steps taken by solver at various velocities.

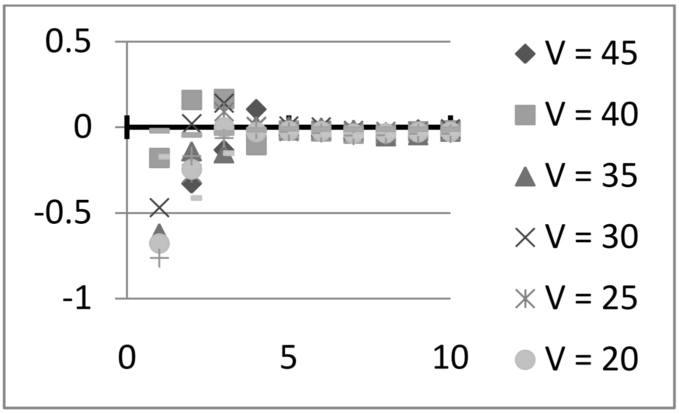


Fig.13. Lift coefficient, Cl for Monash vs. time steps taken by solver at various velocities.

We observe in these two figures that the lift coefficient for the TU Graz car converges towards a net positive value close to zero, indicating a small upward lift. Whereas for the Monash car, a negative lift coefficient indicating a net downward force is observed.

By integrating the vertical components of the pressure normal to the surface of the car at various velocities the magnitude of the expected downward force can be obtained. This is shown in the following figure.

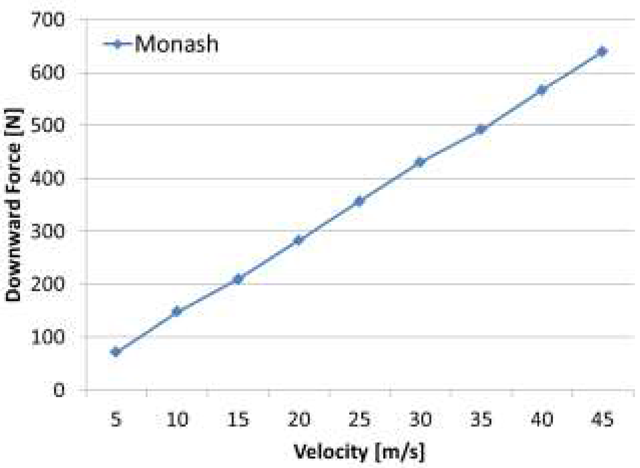


Fig.14. Negative Lift Force of Monash

While the drag force experienced by the two cars as shown in the next figure. The net drag force on Monash car is greater than the net drag force on the TU Graz car at all speeds. While both drag forces appear to increase in a linear fashion. Since this is a two dimensional case, the drag force and drag coefficients are calculated per unit depth of the cars into the paper. The plot of drag coefficients reinforces the low drag features of the TU Graz car. However, it is still interesting to note that drag coefficients of both cars are very close at high speeds even though the drag force on Monash car is significantly greater than the drag force on TU Graz car.

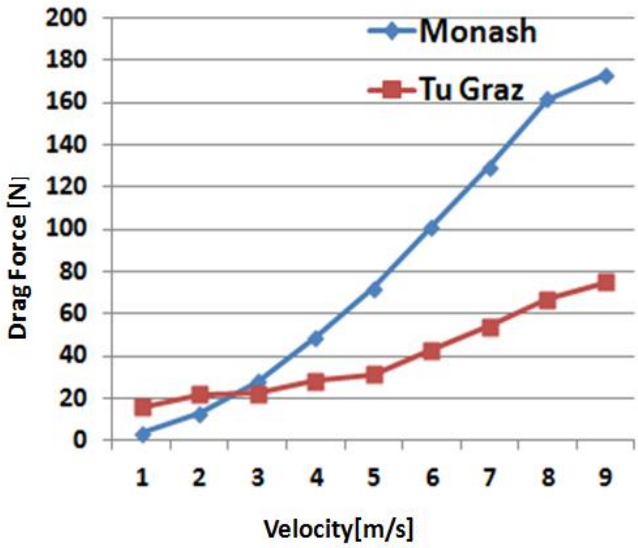


Fig.10. Drag force of Monash and Tu Graz

II. Conclusions and Recommendation

While the drag force on the wing-less formula student cars is less than on cars with aerodynamic devices due to less contact area, the increase in downward force provided by these wings ensures greater traction for these cars. The findings of this research can be improved by further investigating winged and wingless formula student race cars by;

- A full three dimensional analysis, taking into account the aerodynamic drag due to wheel wells.
- Inclusion of other devices i.e. side pods and underbody diffuser is required.
- Addition of a suitable turbulence model in order to accurately capture the effect of wake region on the cars.
- Incorporation of other leading formula student cars into the study.

Acknowledgment

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References

[1]. Silver Stone 13-15 July 2012, Official Programme, Institute of Mechanical Engineers, 2012
[2]. S.Sayovitz, Formula SAE Scoring Template, Institute of Mechanical Engineers, 2013
[3]. S.Wordley and J.Saunders, Aerodynamics for Formula SAE: Initial design and performance prediction, SAE International, 2006-01-0806, 2006
[4]. A.Deakin, Overall Results, Formula Student Institute of Mechanical Engineers 2012
[5]. Website: http://www.racecar-engineering.com/formulastudent/ (Accessed on: June 26,2013)
[6]. M. Shahmal, Study of F1 Car Aerodynamic Rear Wing Using Computational Fluid Dynamic (CFD), 2011