6-2015

How Advancements in Aerodynamics Improves the Performance of Formula 1 Racecars

Joshua Fields
Union College - Schenectady, NY

How Advancements in Aerodynamics Improves the Performance of Formula 1 Racecars

By

Joshua Fields

****

Submitted in partial fulfillment of the requirements for

Honors in the Department of Mechanical Engineering

UNION COLLEGE

June, 2015

ABSTRACT

FIELDS, JOSHUA How Advancements in Aerodynamics Improves the Performance of Formula 1 Racecars. Department of Mechanical Engineering, June 2015.

ADVISOR: Prof. Andrew Rapoff

The purpose of this paper is to review how knowledge of aerodynamics improved the performance of Formula 1 racing cars since the beginnings of Formula 1 racing after World War II. Formula 1 racing places each competitive team on a similar level in regulating the cars to be safe while driving above 350 kph. This paper begins with how Formula 1 racing began and how race cars were designed and looked. Then each decade of racing will be discussed and remarks on major advancements and changes in aerodynamics. Also some computational fluid dynamics (CFD) will also be discussed on how analyses are made and their impact on the sport.

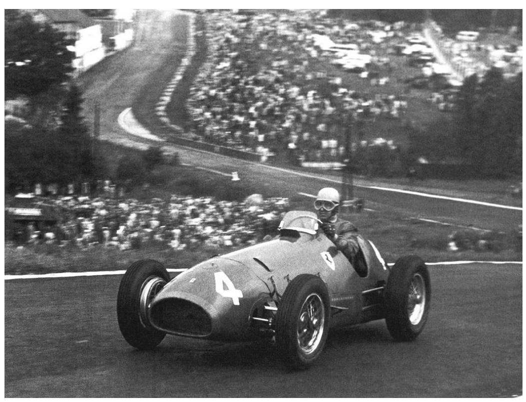

Figure 1: 1950 Formula 1 Racecar with long body and minimal aerodynamics (google.com)

Figure 2: 2015 Ferrari F1 Racecar with each component of the car engineered for aerodynamic downforce (bestfreejpg.com)

Introduction:

The first official Formula 1 race took place in May of 1950. Automobile racing had already been established but the "Formula", or set of rules and regulations enforced by the FIA (Federation Internationale de L'Automobile - International Automobile Federation), positioned automobile racing to the highest standard and class.

Automobile manufactures took pride in producing world class racing cars to reach the full potential of their engineering capabilities. Those who could afford it also bought and raced their own cars to compete for the prize money and title. Sometimes even great manufacturers such as Honda pull out due to high cost. (Formula 1, 2010)

Racing results depended on a number of factors, the main two being the driver's skill and the car. The driver's skill still continues to play an important role depending on their driving and racing experience. The car on the other hand somewhat differs between manufactures, and how they approach the "Formula" and produce a competitive racecar balancing a variety of tradeoffs.

Since there are many components to a Formula 1 car, each one plays a role in making the car go faster in the turns and accelerate in the straights. Two of the main components of driving a Formula 1 car are the engine supplying power to the car and the shape (aerodynamics) of the car itself. Initially, Formula 1 cars were designed to look like fighter jet airplanes to have a streamline body such as the Alfa Romeo 159. (Figure 3)

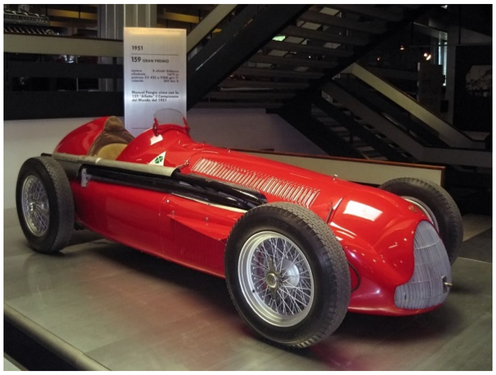

Figure 3: 1951 Alfa Romeo 159 with streamlined body (italiaspeed.com)

It had a 1.5 L L8 (inline) engine which produced 425 bhp (brake horse power) and reached a top speed of 305 kph (190 mph). As the advancements in the understanding of aerodynamics progressed, race cars with the same engine could go drive at higher cornering speeds which resulted in faster lap times leading to many victories. Along with engine regulations, the performance of Formula 1 cars reached such high capacities that drivers found themselves losing control at great speeds that resulted in multiple crashes and fatalities. In turn further regulations were placed on the aerodynamic design of Formula 1 cars that set all of the competing teams on a level playing field to ensure the safety of the drivers.

Some interesting facts about Formula 1 racing are as follows; A Formula 1 racecar can accelerate and decelerate in four seconds from 0 to 160 kph (100 mph) and back to 0. Formula 1 engine intakes about 450 liters of air every second and also burns 75 liters of fuel per 100 km. During a F1 season 200,000 liters of fuel is used for testing and racing. The fastest speed recorded in Formula 1 was 369.9 kph (230 mph) at the Italian Grand Prix in 2004 by Antonio Pizzonia for BMW. Formula 1 racecars are made with 80,000 components and are built 100% to how they are designed. If Formula 1 racecars are built 99.9% correctly, 80 parts would be out of place. Due to the high G forces that drivers encounter while racing, they lose about 4 kg of mass after one race. This is mainly 2 to 3 liters of water, and when racing in hotter climates, drivers can drink up to 8 liters of water during a day. When racing in streets of cities, manhole covers need to be welded down because the downforce of racing over them. It can cause lift on the manhole covers and they can shoot up in the air. (Jagran Post 2011)

Aerodynamics through the Decades

The fundamental purpose of the aerodynamics of a Formula 1 car is to increase the downforce acting on the vehicle. Without aerodynamic downforce, Formula 1 cars generate enough lift to “fly” while traveling at 160 kph (100 mph) alone. Considering, Formula 1 racecars usually race at an average speed of 300 kph (185 mph). (Jagran Post 2011) This culminates where the “rubber hits the road” and gives traction to the tires to travel at immense speeds and high g’s (acceleration of gravity). With aerodynamic downforce, at top speed a Formula 1 racecar can achieve a downforce of 2.5 times the car’s weight. (Jagran Post 2011) With the implementation of a front wing, rear wing, the body and engine placement, all of these aerodynamic modifications changed since the beginnings of Formula 1 racing.

In the 1950s when Formula 1 began, all of the cars had a front engine. The aerodynamic shape of the cars were streamlined. Streamline is a design with a form that presents little resistance to fluid flow, increasing speed and ease of movement. (Figure 4) The main two types of designs for inline front engines in Formula 1 during the 1950s resembled those of both the Mercedes-Benz W 196 R and the Maserati 250F. The Mercedes-Benz had an eight-cylinder in-line engine with a top speed of 300 kph and the Maserati had a six-cylinder in-line engine. These similar streamlined aerodynamic shapes continued until the late sixties. (Figure 5)

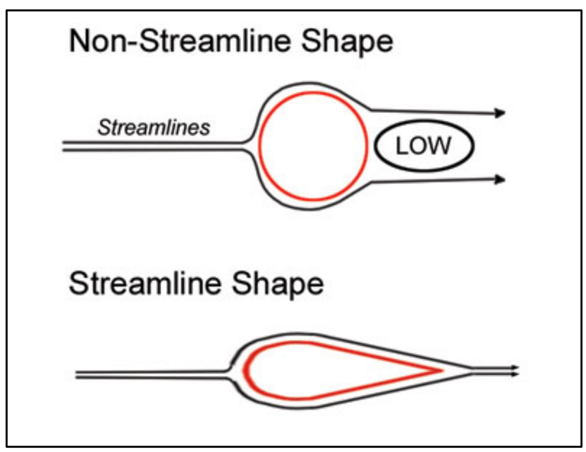

Figure 4: Streamline Design with “smoother” shape on the bottom with low resistance to the flow of fluid. In the case of racing, the fluid would be air. (swimright23.webs.com)

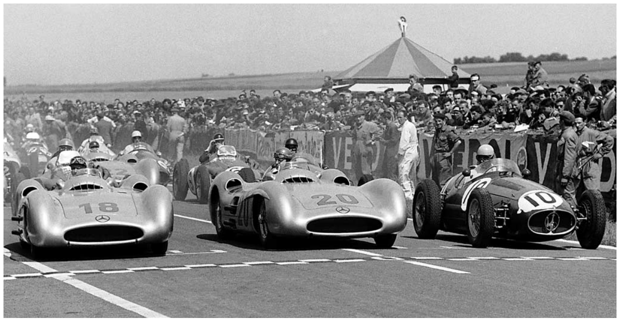

Figure 5: Starting Line at 1954 F1 Race (f1fanatic.co.uk)

Towards the late 1950s, placement of the engine in relation to the car's body itself began to change. In 1958 the car company Cooper introduced mid-engined racecars in Formula 1 with V8 engines behind the driver. Afterwards other manufactures began to lose races with front engines and changed to rear mid-engined racecars as well. Soon most Formula 1 racecars had a cigar tube shape such as the 1962 Lotus Climax 25 with a 1.5 L V8 engine located right behind the driver. (Figure 6 & 7)

Figure 6: 1962 Lotus-Climax 25 (f1fanatic.co.uk)

Figure 7: BRM P261, Lotus 33 and Honda RA 272 at Starting Line with cigar shaped racecars (1965) (f1fanatic.co.uk)

Adding downforce on the tires improves tire traction and allows the racecar to travel at higher speeds around corners before sliding. Figure 9 entails a visual representation. In this depiction, the vehicle is traveling in the –x direction and the the downforce is acting in the $+F_z$ direction while the lateral force is in the $+F_y$ direction. The angle at which the vehicle slides is $\boldsymbol{\beta}$.

When β is above five degrees, that is when slippage occurs. When a driver choses to travel at a certain speed, (where point *A* and *B* are in line) creating a certain downforce, with aerodynamic downforce a driver could now corner at a higher speed at point *C* to create the same angle of slippage. (Katz 2006) From this innovation in the mid-1960s aerodynamics of racing improved the competitiveness of the sport to reach high lateral forces.

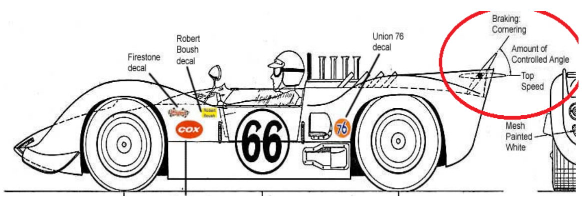

Figure 8: Variable Rear Wing on Chaparral 2C (gtplanet.net)

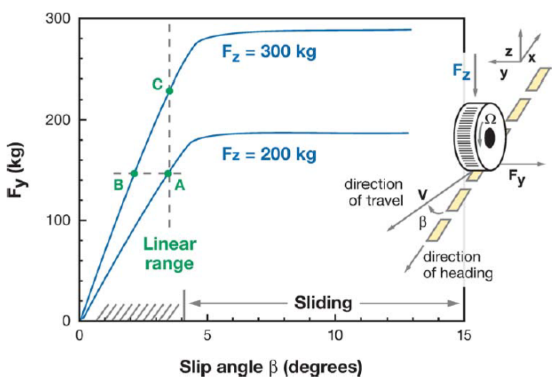

Figure 9: Downforce as a function of slip angle (Katz 2006)

It wasn't until the 1970s that aerodynamics impacted lateral acceleration as seen in the following figure. (Figure 10) With the addition of front and rear wings, Formula 1 racecars were able to reach up to 4Gs of lateral acceleration. Today drivers can experience up to 5Gs while driving which causes drivers to not only be skilled on the track but also athletic to regulate their body fat and muscle to physically tolerate these forces. The regulations began to be stricter as front and rear wings began to take effect. Tires were also a major change with larger rear wheels and also racing slick tires. The following figures show the changes in aerodynamics in the 1970s. (Figure 11 & 12)

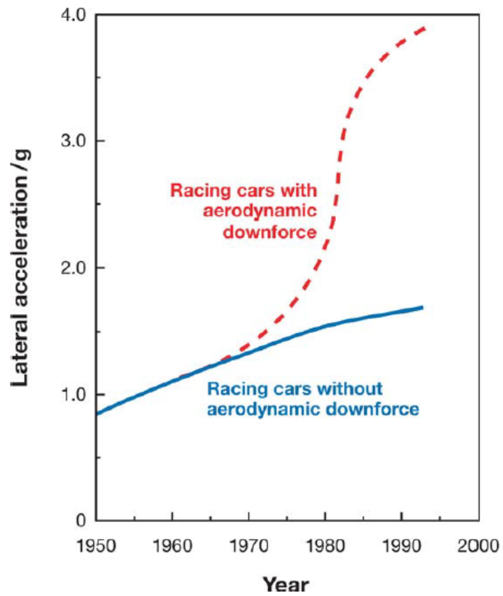

Figure 10: Progression of lateral acceleration using aerodynamic downforce (Katz 2006)

Figure 11: 1972 Lotus 72E (f1fanatic.co.uk)

Figure 12: 1977 Renault RS01 (f1fanatic.co.uk)

As the sport changed in the 1980s, turbo chargers were used by the competitive manufacturing teams to make Formula 1 cars as the ones seen in the following figure. (Figure 13) Turbo-charged engines were banned at the end of the 1980s in 1989 and from then on V10 engines were used. As technology began to become more advanced with the implementation of computing power and computational fluid dynamics, towards the late 90s and up until today, Formula 1 cars began to pay attention to every aspect of the car and how it affected the overall aerodynamics of theses race cars. (Figure 14)

Figure 13: 1984 Williams FW09B, McLaren MP4/2 (f1fanatic.co.uk)

Figure 14: 1997 Ferrari F310B (f1fanatic.co.uk)

The FIA also began to regulate engines in order for teams to remain close contenders for the title. As a result V10 engines were banned in 2005. This transitioned Formula 1 racing to focus even more on the aerodynamics to enter the age where each component of a Formula 1 racecar were designed to give the most downforce as possible.

Formula 1 Aerodynamic Fundamentals

The two main parts of a Formula 1 racing car that affects the aerodynamic shape of the car itself are the wings and the body. Primary considerations of the wings are the ground effect in the front, and the interactions between the wings and the body.

In relation to the ground effect of the front wing an inverted airfoil is used to provide negative lift, is proportional with the length of the chord (c) and the height (h) of the vehicle above the ground. Most race cars have an h/c value of 0.1 to 0.3 to maximize the downforce and minimize drag. The following figure, (Figure 15), the sizing of the front wing airfoil and its position above the ground determine certain values for the coefficient of drag and lift.

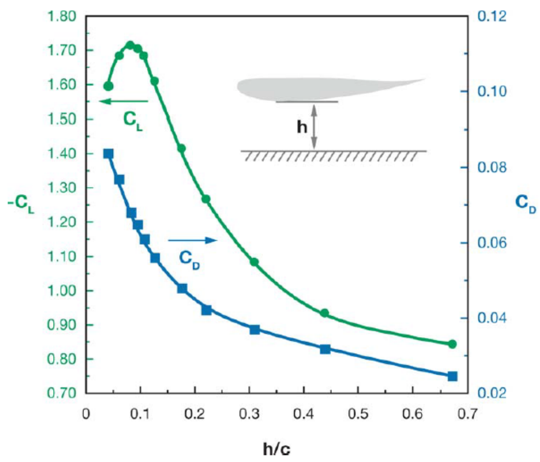

Figure 15: Coefficient of Lift as a function of front wing chord length and ride height (Katz 2006)

The shape of the body of the car in relation to the ground affects the aerodynamics as well. Depending on its overall shape, the key is to reduce the flow under the vehicles body. Since most automobile shapes have a tendency to generate lift Formula 1 racecars create a low pressure under the racecars body. This in turn creates a higher pressure above the race car that generates downforce. One concept used was putting a suction fan on the back of the car to decrease the air pressure under the car. This concept was implemented in a Formula 1 race car the 1978 Brabham BT46B. It once won one race and was immediately outlawed. The following figures (Figures 16 & 17) displays the car and the suction fan in the back.

Figure 16: 1978 Brabham BT46B (beautifullyengineered.tumbler.com)

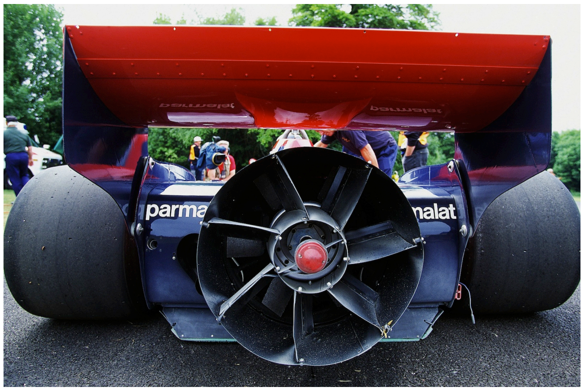

Figure 17: Rear suction fan on 1978 Brabham BT46B (jalopnik.com)

Since the fan in the back was banned, side flap skirts were used instead on most Formula 1 cars. It is slightly visible to see the side skirts on the Lotus 78 depicted next. (Figure 18) In 1977, Mario Andretti won the four championship races ending in 3rd place

overall driving the Lotus 78. The following figure (Figure 19) also shows the effect of the skirt gap height and coefficient of lift. As the gap between the skirt and the ground increase, there is a loss in downforce.

Figure 18: 1977 Lotus 78 with side skirts (f1technical.net)

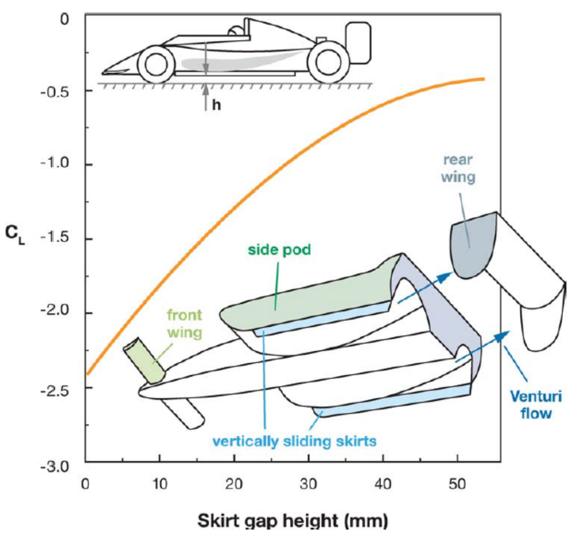

Figure 19: Coefficient of lift as a function of skirt gap height (Katz 2006)

After skirt failures due to bumps in the road, it caused the height to be raised which caused losses in downforce. Side flap skirts were banned by 1983. In order to maintain a negative "airfoil" profile of the car body itself, diffusers are used in the rear underbody of the Formula 1 race car. They create vortices that are quite effective to decrease drag and create a negative lifting profile of the car's body. The following figures show a diagram of how these diffusers are used to generate a low pressure of airflow under the car's body. (Figures 20-21)

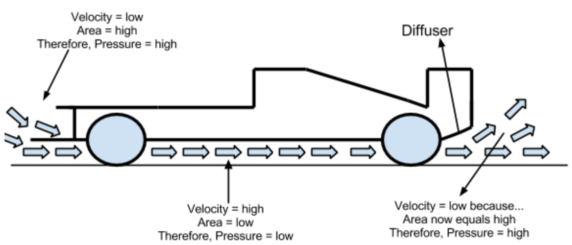

Figure 200: Simple diagram of airflow under the car (f1insight.co.uk)

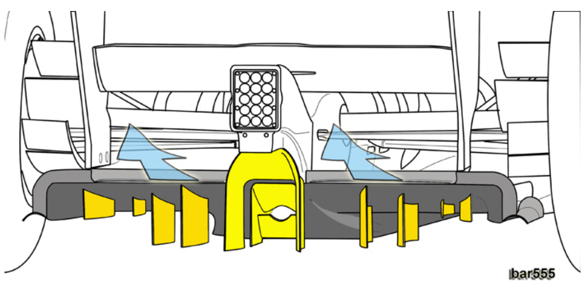

Figure 211: Diffusers at back of a Formula 1 racecar (formula1techandart.wordpress.com)

The rear wing also plays a major role in the downforce on the rear tires pushing it into the ground for traction. One interesting point is that in the rear wing there is a change in the angle of attack in each section of the rear wing for a higher pressure distribution.(Figure 24) Also the addition of rear wings increase the downforce with minimal increase in the overall drag of the rear wing. The following figure depicts a general rear wing shape with the data to support using side fins. (Figure 25)

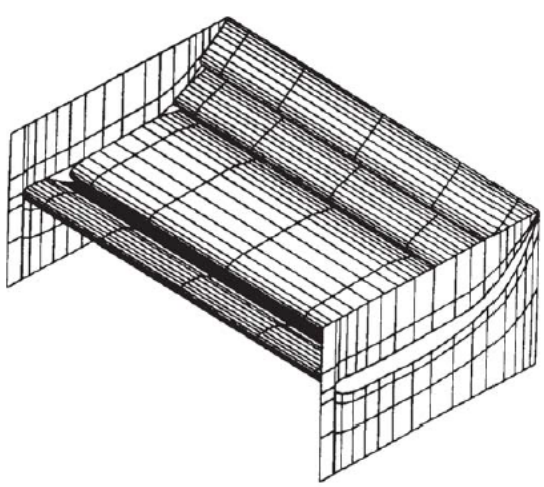

Figure 222: Rear wing discretized (Katz 2006)

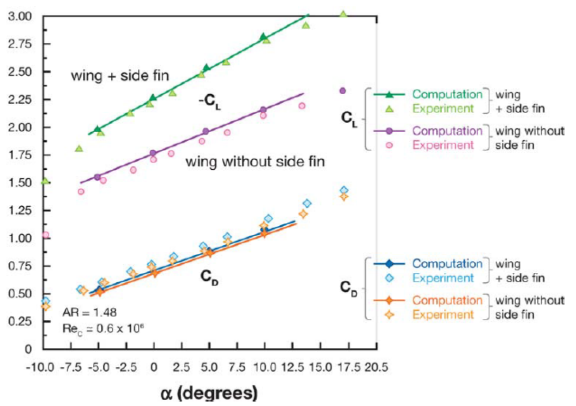

Figure 233: Coefficient of lift with and w/o side fins (Katz 2006)

The height of the position of the rear wing above the car also is an important factor when designing Formula 1 race cars. The root chord length of the rear wing and its height above the vehicles body determines the coefficients of lift and drag to attain a certain calculated downforce. (Figure 24)

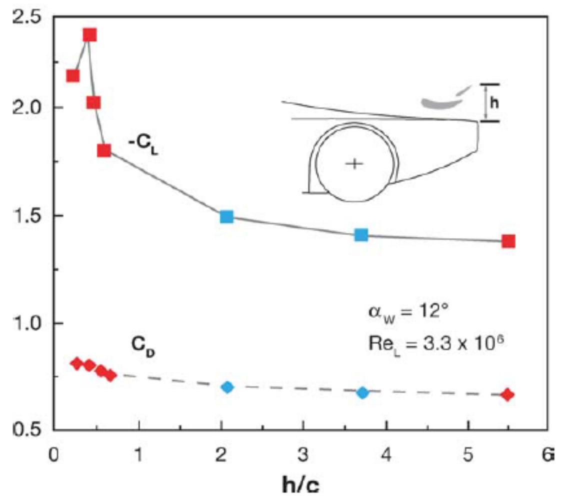

Figure 244: Coefficient of lift as a function of size and position of rear wing (Katz 2006)

In relating all the wings and body together, if the front wing is damaged, more air travels over the car losing the overall down force on the car. If the rear wing is damaged, there is a loss of downforce over the rear tires and a major reduction in traction. If part of the side of the body of the car is demolished, airflow towards the rear wing will be less than optimal (Wang et al. 2010).

Computational Fluid Dynamic Analyses

There have been many computational fluid dynamics (CFD) analysis tests on the design of Formula 1 race cars. In initial testing the results are very useful. As design is further tested in the wind tunnel and the actual track, the results are not as accurate as initially designed but still provide effective results nonetheless. Also it is easier to make changes on a computer model compared to wind tunnel testing and revising the final design of the car. (Vickers 2008)

When using CFD, there is always an uncertainty in the final analysis. To minimize error between computed results and actual results in the wind tunnel and on the track, different computational methods are used. For instance the Monte Carlo Method (MCM) is accurate and robust but is very time consuming compared to the probabilistic collocation method (PCM). (Bradford & D'Ammaro 2014) The MCM uses random sampling to generate data values to obtain numerical results. Like the MCM, the PCM uses lattice sampling in which data value are generated from a discrete set of points. This in turn saves time

when running tests, up to three orders of magnitude. In a CFD analysis of the airflow around the front wheel using the front wing there were several aspects that were studied. One was the difference in endplate variation and the other was the position of the endplate in relation to the tire. The following figures and tables show the mesh that was used and each variation. The table shows the actual results of wind tunnel experiments and the coefficient of drag which was the lowest at position C which confirmed CFD analysis. (Figures 25- 27 & Table 1) Due to the uncertainty of CFD, the results were not exactly the same but still comparable quantitative results nonetheless. The table shows the measurements for the coefficient of drag (C_d), relative wing downforce (W_r) and performance index (P).

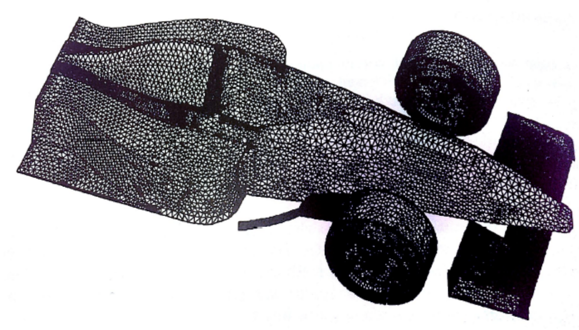

Figure 255: Initial CFD Model for front wing testing (Subic & Haake 2000)

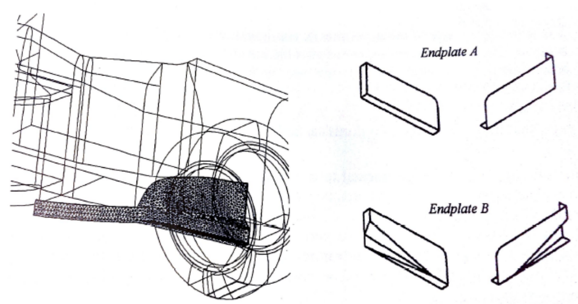

Figure 266: Endplate variations of front wing (Subic & Haake 2000)

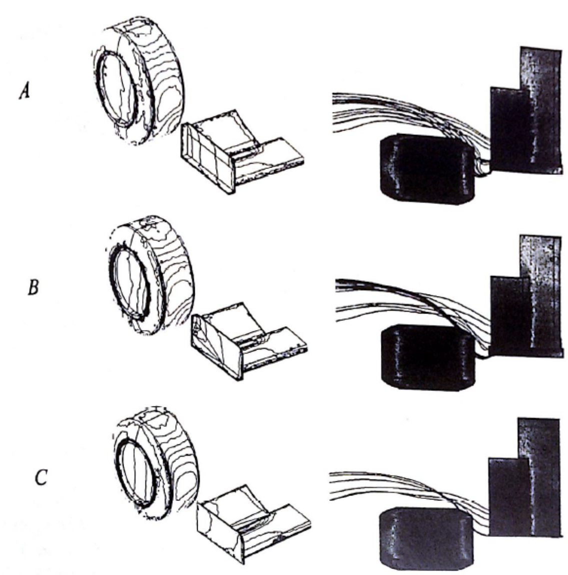

Figure 277: Different endplate positions relative to front tires (Subic & Haake 2000)

Table 1: Wind Tunnel Results of Testing (Subic & Haake 2000)

Configuration	C_d	W_r	$P = W_r/C_d$
A	0.518	0.800	1.544
B	0.565	0.863	1.527
C	0.486	0.820	1.687

CFD was also used on the BMW Sauber F1.09. In the following figure (Figure 30), the fabrication of a longer front wing and slimmer body influenced the streamlines of the flow behind the car making it more aerodynamic. In the top portion of the figure the streamlines flow initially wider around the Formula 1 car in 2009 compared to 2008 which in turn causes less drag over the car's body itself.

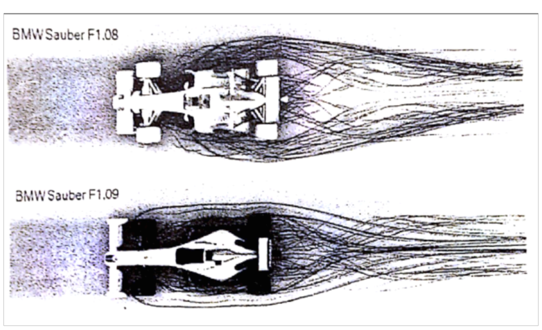

Figure 288: BMW Sauber F1.08 to F1.09 (Larsson 2009)

Discussion and Conclusions

As a result of all of the many factors of designing a Formula 1 race car, aerodynamics play a major role in the sport of Formula 1 racing and is a quantitative competition of engineering at its finest level. The "Formula" regulations enforced by the FIA are for the safety of the drivers but also push the sport to reach great engineering achievements. This multinational sport includes the best manufacturers and drivers from around the world. Since automobile gasoline engines are being integrated with and other forms of "clean" energy, Formula 1 racecar aerodynamics can add a certain extent of downforce to go around corners at higher speeds. Engineers on the manufacturing teams are constantly testing and modeling the aerodynamics to change various parameters of the body to gain as much downforce as possible. The body and the wings are redesigned every year and sometimes prove results when having the

right driver to win the championship races. Currently redesigning parts to increase aerodynamic downforce is the progressing towards the pinnacle of the aerodynamic age in the sport. In order for another considerable change to come to the sport it would have to be the FIA changing the energy source of the engines such as going electric or having hybrid racecars due to the amount of fuel consumption.

For future work and study, a deeper look at how the specifications of Formula 1 engines changed and progressed since its beginnings. The technology behind these powerful engines with the crankshaft rotating at a rate of 18000 RPMs is an accomplishment in itself. Also the implementation of electronics in the engine and the control system is highly sophisticated and essential component of Formula 1 racing. Engineers are still learning more about aerodynamics and the "Fomula" continues to change pushing to achieve great engineering accomplishments. Continuing to find the best solution to the "Formula" is the thrill of watching and appreciating Formula 1 racing.

REFERENCES

Bradford, J., F. Montomoli, and A. D'Ammaro. "Uncertainty Quantification and Race Car Aerodynamics." *Proceedings of the Institution of Mechanical Engineers Part D-Journal of Automobile Engineering* 228.4 (2014): 403-11.

"Formula One: Facts and Trivia", JAGRAN Post (2011)

Katz J, Aerodynamics of Race Cars, *Annual Review of Fluid Mechanics* 2006: 38(1) : 27-63

Larsson, Torbjom "2009 Formula One Aerodynamics: BMW Sauber F1.09-Fundamentally Different", *4th European Automotive Simulation Conference*, 2009; Pg. 1-7

Subic, A.J. and Haake, S.J, *The Engineering of SPORT-Research, Development and Innovation-* Pg. 353-60W.P Kellar, G.J. Targett, Am Savill & W.N Dawes CFD Laboratory, Cambridge University Engineering Dept., Cambridge, UK

"The 'Formula' Behind Formula One." JAGRAN Post (2011)

Vickers, Keith. Racing Green. 249 Vol. H.W. Wilson - Applied Science & Technology Abstracts, 2008.

Wang, Y.-N.; Tseng, C. –Y.; Huang Y.-L.; Leong, J. C., *Investigation of 2004 Ferrari Formula One race car wing effects,* 2010 International Symposium on Computer, Communication, Control and Automation (3CA), 2010; Vol. 1, Pg. 85-8