

The race cars
aerodynamics
engineering essay



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Race car performance depends on elements such as the engine, chassis, road, tires, suspension and of course, the driver. However, it is essential to consider the principles of aerodynamics, as they play a vital role in determining the performance and efficiency of a race car. Due to the complex geometry of race cars, the aerodynamic interactions between the various body components are significant. Different methods to generate downforce such as inverted wings, diffusers, and vortex generators are enumerated. Conventional testing techniques like wind tunnel testing, Computational Fluid Dynamics, track testing and their relevance to race car developments are also discussed.

Automotive racing started becoming popular in the 20th century. The design and working of cars then were completely different from the race cars today. First, racing cars were primarily designed to achieve high top speeds and the main goal was to minimize the air drag. In order to improve their stability and handling, engineers mounted inverted wing profiles generating negative lift. Even though car racing is often referred to as a “pure sport” it is not really justified. There is a lot of science behind it. Technology and developments in the field of automotives paved way for numerous forms of racing which in turn resulted in diverse designs. By the start of 21st century, a lot of associations and organizations started conducting races and soon racing became popular. National Association for Stock Car Auto

Racing (NASCAR) and Formula One (F1) are pioneers in automotive racing.

Speed becomes an integral part of racing. The urge to achieve higher speeds started growing with time, as automotive racing started witnessing developments. The NASCAR race car enters turn three at an average speed

of 170 mph, which is extremely fast. It is even more interesting when we get to know that a Boeing 757 touches down a runway at roughly the same speed. Comparing an airplane and a race car is not really possible. But, in this case it is even more complicated. A Boeing isn't positioned like a race car, just inches away from another vehicle while it travels at such a high speed. How are these vehicles designed to protect the driver and maintain shape in such high speeds? This is when aerodynamics comes into play. The motion of air around a moving vehicle affects all of its components in one form or another. Engine intake and cooling flow, internal ventilation, tire cooling, and overall external flow over rear wings, side pods, vertically sliding skirts, diffusers, fall under the category of vehicle aerodynamics.

The discussion on race car aerodynamics cannot be complete without briefly discussing tire characteristics. Although it is clear that airplanes fly on wings, the fact that race cars “ fly” on their tires is less obvious and requires adequate explanation. The other factors influencing the performance of race cars are: downforce, race car wings, aspect ratio, wing-vehicle interactions, diffusers, and add-ons like: vortex generators, spoilers etc. Some of the methods used to evaluate the working of race cars are also discussed in the following sections.

2. Aerodynamic forces

2. 1 Downforce

Downforce is a downward force produced by air pressure, which creates a stronger pressure between the tire and the surface of the road. The principle involved is the same as the one that gives lift to airplanes, but in reverse.

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Aerodynamic force results from differences in pressure on the sides of the moving object. The most common methods for increasing the downforce of a vehicle involve reducing the air pressure underneath the vehicle. For the most part, any increase in downforce will also bring an accompanying increase in aerodynamic drag. For the speed of these race cars, more drag means lower speeds on the straight-ways, but more downforce means better handling on turns since the tires grip the track more securely.

2. 2 Lift

The wings of a bird or an aircraft are the most obvious producers of lift. But lift doesn't necessarily mean an upward force countering gravity. In fact, downforce is a form of lift- negative lift. Lift is the aerodynamic force perpendicular to the direction of the body in motion. Lift is usually present to one degree or another in a moving object. Because lift and downforce are opposing forces, part of the effort to build a race car with a strong downforce involves overcoming lift. Race cars occasionally become airborne despite these devices. The danger is especially present when a car is spinning, which radically alters the aerodynamic forces in play.

2. 3 Drag

Aerodynamic drag is the force of air along the length of the traveling car, opposing the car's force. As the car cuts a path through the air, some air molecules collide with the front bumper, producing resistance. Other molecules flow along the hood, only to come up against the wind shield, which is another source of drag. The air that glides smoothly over the roof grows turbulent above the rear window and behind the car, exerting a

backward force on the vehicle. Drag is the major obstacle to acceleration and racing speed. Overcoming drag was the first major focus of automotive aerodynamics, beginning in the 1960s. It is still the most important variable in racing conditions that plays a smaller premium on downforce, such as longer tracks with more straight-ways.

2. 4 Generating downforce with the help of inverted wings

The foremost and simplest approach to generate downforce was to add inverted wings to the existing race cars. However, this newly discovered advantage was not free of complications.

The aerodynamic downforce increases with the square of the vehicle's speed whereas tires depend far less on speed. Consequently, if the inverted wings are attached to the vehicle then the suspension spring rate must be stiffened to allow for the additional high-speed loads. Variable downforce-generating devices followed, mostly based on reducing wing or flap angle of attack at higher speeds.

There a number of ways to generate aerodynamic downforce. But the best results were observed by adding wings or by using the vehicle's body. The following sections elaborate the significance of adding wings and various methods of using the vehicle's body to generate downforce.

3. Race car wings and how they are different from Airplane wings

A race car lifting surface design is different from a typical airplane wing design because (a) a race car's front wings operate within strong ground effect, (b) open-wheel race car rear wings have very small aspect ratio, and <https://assignbuster.com/the-race-cars-aerodynamics-engineering-essay/>

(c) there are strong interactions between the wings and other vehicle components (e. g. body, wheels, or other wings).

3. 1 Ground effect

Race-car (front) wings operate very close to the ground, resulting in a significant increase in downforce. This increase is a manifestation of a phenomenon known as the wing-in-ground effect, which interestingly is favorable for the performance of both ordinary airfoils creating lift and inverted airfoils creating downforce. Of course, the effect has its own demerits because of the amount of drag it produces. Since many race cars use front wings mounted close to the ground, this principle is widely utilized in race-car design.

3. 2 Small aspect ratio wings

Figure 1: An Indy car with Airfoil shape wings. In most forms of motor racing a large rear wing is used.

In the case of open-wheel race cars such as Indy cars (figure 1) these wings have very small aspect ratio (span/chord ratio), contrary to the much higher aspect ratio of airplane wings. The first result of the smaller aspect ratio was a significantly higher drag. This penalty could be reduced by adding very large end plates, seen on most race cars, which indeed improve the lift-to-drag ratio.

A second problem resulted from borrowing airfoil shapes from airplanes having several elements (flaps and slots). The main problem was, these airfoils were developed for airplanes having very wide wings (high aspect

ratio), and therefore their performance was not optimized for race-car application. Nowadays, custom-designed airfoil shapes have been used to overcome this problem.

3. 3 Wing-vehicle interactions

The third major difference between aircraft and race-car wings is the strong interaction between the lifting surface and the other body components. The horizontal positioning (such as fore-aft) of the wing also has a strong effect on the vehicle's aerodynamics (usually downforce increases as the wing is shifted backward). But, racing regulations state that the wing trailing edge cannot extend behind the vehicle body (from top view). The very large change in the downforce of this prototype car is due to the increased underbody diffuser flow, but the effect remains clear with sedan or even open-wheel race cars as well.

3. 4 Effect of Gurney flaps

Initially, race car wings were based on airplane airfoil shapes and their design was based on aerospace experience. However, a small trailing edge flap defying aerodynamic logic momentarily reversed this order because it was used on race cars prior to the transfer of this technology to aerospace applications. At the very early stages of using wings on race cars, a thick Newman airfoil was added to an Indy car. Because of the high speed and structural considerations, a small vertical reinforcement was added on top of the airfoil, at the trailing edge, spanning the whole width. It serves essentially the same purpose as the complex flap on an aircraft wing. It increases lift or, in this instance, downforce. After adding this structural

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reinforcement, the car lapped at a higher speed, indicating a lower drag. The Gurney Flap is still widely utilized in motorsport as an inexpensive and effective aerodynamic addition.

4. Creating downforce with the vehicle's body

Once the importance of aerodynamic downforce in win races was realized, engineers started experimenting other ways to achieve effective downforce. It was obvious that the larger planform area of the body (compared to an add-on wing), significant levels of downforce could be generated. However, the nature of flow under the vehicle must be considered. An ellipsoid (figure 2) and a semi-ellipse shape (figure 3) were considered. In the case of ellipsoid, flow accelerates under the ellipsoid and a downforce, with reduced proximity is created. However if the same area distribution (along the length) is distributed in a semi-ellipse shape, the opposite (e. g., lift) is measured due to the reduced flow under the body.

Figure 2: A symmetric ellipsoid shape.

Figure 3: A semi-ellipse shape.

So, clearly, the shape in the figure 3 (which resembles automotive shapes) will have lift that will increase with reduced ground clearance. The conclusions are simple: One option is to streamline the underbody to generate lower pressures there (as a result of higher speed), and another option is to create low pressure under the car by effects not directly related to the basic inverted wing model. Another method to generate this effect is to seal the gap between the ground and the car entirely, leaving only the

rear portion open. Then the low base pressure behind the vehicle dictates the pressure under the car. In this case, lowering the rear deck reduces the base area and the drag component (due to the base pressure), improving the downforce to drag ratio.

4. 1 Use of Suction fans

The next important development focused on actively controlling the low pressure under the car independently of vehicle's speed. This car used auxiliary engines to drive two large suction fans behind the vehicle. The whole periphery around the car underbody and the ground was sealed and the fans were used to suck the leaking air through the seals to maintain the controllable low pressure. Another benefit from this design was that the ejected underbody flow (backward) reduced the base pressure and therefore the vehicle's drag penalty was not high. In terms of performance, the downforce was controlled by the auxiliary motors and did not increase with the square of speed, making the car quite comfortable (no stiff suspension) and competitive. Needless to say, the design was winning from day one, which was not well received by the competition (e. g. regulations almost immediately outlawed such designs). Because the suction car concept was banned by the sanctioning bodies, the only other alternative was to use the old fashioned ground effect to create downforce by the vehicle's body.

4. 2 Alternative methods of creating downforce with vehicle's body

Since the suction car concept was banned by the sanctioning bodies, the only other alternative was to use the old fashioned ground effect to create downforce by the vehicle's body. Colin Chapman, designer of the famous <https://assignbuster.com/the-race-cars-aerodynamics-engineering-essay/>

Lotus 78 (Hoefer 1978), developed this concept to fit F1 race car geometry. In his design the vehicle's side pods had an inverted airfoil shape (in ground effect) and the two sides of the car were sealed by sliding 'skirts'. These side seals created a two-dimensional environment for the small AR inverted-wing-shaped side pods. The concept (as shown in figure 4) worked very well, resulting in large suction forces under the car.

Figure 4: Effect of side skirt to ground gap clearance on vehicle's total downforce coefficient. A year after this model came into existence Hoefer (1978) documented Chapman's approach for integrating the inverted airfoil idea into the vehicle side pods using the sliding skirts. This concept was turned out to be highly successful and the Lotus 78 won the world championship in 1977. By the end of the 1980s this method was used in many forms of racing, resulting in downforce values exceeding the weight of the vehicle. However, the sliding seals at the vehicle sides were not trouble free. Irregularities in the road surface occasionally resulted in seal failure and the immediate loss of downforce with catastrophic consequences. This led to the banning of all sliding seals by 1983, and in most forms of racing the only part of the vehicle allowed to be in contact with the ground are the tires. Once the sliding skirts concept was banned it was realized that an inverted airfoil shaped underbody can still generate downforce. Because the only area that this approach could fit in (under the car) was between the wheels, so diffusers or tunnels were created. These diffusers could be viewed as the logical replacement for the banned "skirted, inverted airfoil-shaped side pods" concept.

4. 3 Underbody Diffusers

Once the sliding skirts were banned the suction under the car was significantly reduced. A logical evolution of this concept led to underbody “tunnels” formed under the sidepods, which sometimes were called diffusers. A diffuser allows the air traveling underneath the car a place to expand and decelerate back to road speed as well as providing wake infill. As the air enters towards the front of the car it accelerates and reduces pressure. There is a second suction peak at the transition of the flat bottom and diffuser. The diffuser then eases this “high velocity” air back to normal velocity and also helps fill in the area behind the race car making the whole underbody a more efficient downforce producing device by reducing drag and increasing downforce.

Figure 5: Creation of downforce with underbody diffusers (tunnels). The existence of the side vortices responsible for reattaching the flow in the tunnels (diffusers) is also seen.

A flat bottomed car (one without a diffuser) will produce downforce in and of itself when run in rake. Essentially the entire flat bottom becomes one large diffuser. It too has two suction peaks, one upon entrance, the second at the trailing edge of the flat undertray. A diffuser acts like a pump, encouraging better flow under the car. The integration of this concept into an actual race-car underbody is depicted in figure 5. Flow visualizations clearly show the existence of the side vortices responsible for reattaching the flow in the tunnels (diffusers). Of course, the downforce usually increases with reduced ground clearance, an effect that continues down to very small ground clearance values.

5. Add-ons

5. 1 Vortex generators

Figure 6: Schematic description of Vortex Generators in the underbody. In this section we discuss simple modifications that can be added to an existing car to increase downforce. One of the simplest add-ons is the vortex generator. Vortex generators were used for many years on aircraft, mainly to control boundary-layer flows. The size of Vortex generators in such applications was on the order of the local boundary-layer thickness, and apart from influencing boundary-layer transition, they served to delay the flow separation on a wing's suction side. The use of such devices in automotive racing is quite different. Here the focus is on creating a stable and long-tip vortex, which in turn can reduce the pressure along its trail.

A simple option is to add Vortex generators at the front of the underbody and the long vortex trails of the Vortex generators can induce low pressure under the vehicle. This principle is widely used for open-wheel race cars (e. g. Indy car), and a typical integration of such Vortex generators into the vehicle underbody is shown in Figure 6. In such an application the Vortex Generator is much taller than the local boundary-layer thickness and the objective is to create a strong and stable vortex which, as noted, can generate suction loads along its trail.

Flow visualizations with these models indicate that with reduced ground clearance not only does vortex strength seem to increase but the two vortices per side untangle and get closer to the vehicle's surface (e. g., increasing suction force). This increase in vortex strength and the reduced

distance from the underbody (of the vortex) explain the increase in both lift and drag as ground clearance is reduced. At the very low ground clearance values however, a maximum in the downforce is reached due to possible breakdown effects in the trailing vortices.

5. 2 Spoilers

Spoilers used on a race car reduce its lift and drag, as well as increase the amount of force pushing the vehicle's tires to the road surface. These, in turn, would ensure to boost traction, permitting the car to brake, turn, and accelerate properly and more forcefully. Spoilers function by disrupting airflow passing over and around a moving vehicle. This diffusion is accomplished by increasing amounts of turbulence flowing over the shape, "spoiling" the laminar flow and providing a cushion for the laminar boundary layer.

Race cars are built to generate as much downforce as possible. At the speeds they're traveling, and with their extremely light weight, these cars actually begin to experience lift at some speeds and forces make them take off like an airplane. Obviously, cars aren't intended to fly through the air, and if a car goes airborne it could mean a devastating crash. For this reason, downforce must be maximized to keep the car on the ground at high speeds, and this means a high co-efficient of drag is required. Race cars achieve this by using wings or spoilers mounted onto the front and rear of the vehicle. These wings channel the flow into currents of air that hold the car to the ground increasing the downforce. This maximizes cornering speed, but it has

to be carefully balanced with lift to also allow the car the appropriate amount of straight-line speed.

Figure 7: A sedan type race car with front and rear spoilers. Tests made on spoilers under the chin of the car on a sedan-type vehicle (Figure 7), showed positive effects on front downforce. Apart from reducing the pressure below the front underbody of the car, they have a positive effect on the flow across front-mounted radiators. Among several other studies, the work of Good et al. (1995) is one of the most interesting. He investigated the combined effect of front and boot spoilers on sedans of various sizes and compared the results of track and wind tunnel testing. The trends were similar but the track drag data were higher. Their focus was more on drag reduction and validation of wind tunnel tests, but an increase in downforce resulted in more drag.

6. Methods used for evaluating Aerodynamics of Race cars

Aerodynamic evaluation and refinement is a continuous process and an integral part of race car engineering, which is not limited to the vehicle initial design phase only. Typical analysis and evaluation tools used in this process may include wind tunnel testing, computational prediction, or track testing. Each of these methods may be more suitable for a particular need. Wind tunnel testing or a numeric model can be used during the initial design stage prior to the vehicle being built. Once a vehicle exists, it can be instrumented and tested on the track. In the following sections the three basic methods (wind tunnel testing, computational methods, and track testing) and their applicability for aerodynamic prediction and validation are discussed.

6. 1 Wind Tunnel Methods

Wind tunnels can provide race car drivers with a huge amount of information on how to make their cars aerodynamic. They help answer questions about how the cars should be shaped, what angle their spoilers should be set at, and where the air inlets should be placed. When it comes to aerodynamic development, wind tunnels are hard to beat. It's a good bet that with their ability to provide accurate and efficient results, wind tunnels will play a central role in the advancement of aerodynamic design for years to come. As a result of the increased use of wind tunnels for race car development, customized facilities were rapidly developed, all with rolling ground simulation. Most of these facilities were planned for 30% to 50% scale models with rolling ground simulation capabilities near the 200-km/h range.

Figure 8: Typical Indy car model as tested in a wind tunnel. A rolling belt on the floor is used to simulate the moving road. The wheels are mounted separately and rotated by the belt, with the 40%-scale race car's body being positioned.

Typically, the model is mounted on an internal six-component balance attached to the wind tunnel ceiling via an aerodynamic strut and the wheels are driven by the rotating belt (figure 8). The wheels can be attached to the vehicle by using a soft suspension or mounted from the sides using separate balances. The main advantage of this setup is that both ground clearance and a body's angle of attack could be changed easily. However, yaw simulation and wheel lift measurement were more difficult. Model size was also a major consideration while developing these facilities. On one hand,

cost and space considerations lead to small models, but fabrication difficulties with a too-small model and Reynolds number effects required the largest model affordable. Testing full scale models will eliminate duplicate small-scale model fabrication, but will add to the cost of the facility.

6. 2 Computational Fluid Dynamic Methods

CFD is a computer-based technology that studies the dynamics of various flows over a body. Contrary to wind tunnel tests, the data can be viewed, investigated, and analyzed over and over, after the experiment ends.

Furthermore, such virtual solutions can be created before a vehicle is built and can provide information on aerodynamic loads on various components, flow visualization, etc. In car racing, CFD involves building a computer-simulated model of a race car and then applying the laws of physics to the virtual prototype to predict what the downforce or drag may be on various components of the car or how the car will respond in various wind conditions, changing environmental conditions or on different road surfaces.

Aerodynamicists can use CFD to better visualize and enhance their understanding of how various designs will perform. It also allows them to experiment with more design variables in a shorter amount of time until they arrive at optimal results.

CFD allows engineers to use computer software to divide components of a race car into specific cells or grids. For each of those cells, supercomputers are then used to calculate mathematical equations that compute the velocity and air pressure of the wind as it rushes over, under and around the specified components of the race car (Figure 9). Aerodynamicists can use the

resulting data to compute the downforce, drag and balance the race car will experience, depending on different environmental and road conditions and different design variables. When the calculations are finished, the aerodynamicists can analyze the results either numerically or graphically.

Figure 9: Streamline patterns under a stock car observed using CFD. CFD is very useful in the preliminary design phase, before a wind tunnel model exists. It is almost the only approach for effective wing airfoil shape developments because of the detailed pressure and skin friction information. It is a powerful tool for calculating vortex flows and for providing valuable flow visualizations.

Its advantage also lies in the fact that the results can be viewed over and over again and new aspects of the solution can be investigated. As most of the recent studies indicate, CFD is an excellent complementary tool along with other methods such as wind tunnel testing. Its weakness is rooted in scaling issues such as the prediction of transition from laminar to turbulent flows (e. g., boundary layers) or the calculation of separated flow and unsteady wakes. The main drawback of this method is that, the flow field cannot be modeled economically.

6. 3 Track Testing

Some difficulties inherent to wind tunnel testing are simply nonexistent in full-scale aerodynamic testing on the race track. Problems relating to rolling wheels, moving ground, and wind tunnel blockages are solved. Because of the above-mentioned advantages, and in spite of the uncontrolled weather and cost issues, this form of aerodynamic testing has improved considerably

in recent years. With the advance in computer and sensor technology, by the end of the 1990s the desirable forces, moments, or pressures were measured and transmitted via wireless communication at a reasonable cost. Sensors to measure suspension displacement, various stress/strains, drive shaft torques, pressures, temperatures, etc. are available off the shelves. Data acquisition systems can rapidly analyze loads and provide information such as temperature or pressure drop across the cooling system, downforce, and drag of various components (including wings and wheels). Even flow visualizations can be conducted by installing miniature cameras at various locations to provide information on flow separation, vortex trails, or unplanned recirculation in the cooling system. In spite of the technology becoming highly effective and affordable, race track renting is still quite expensive, and to save cost in many forms of racing the organizers simply limit the number of track test days and some even forbid using telemetry during the race.

7. Safety concerns

Racing organizations work continuously to make the sport safer, and some of their measures are aimed at reducing racing speed. Consequently, some of the research is not directly related to improving vehicle performance but rather to make it safer under unplanned conditions. One example is related to stock car racing (e. g. NASCAR), where the cars race in close formations and contact between vehicles during the race is not an uncommon event. Such is the regulation requiring the use of flat underbody (without tunnels), which is mandated in many forms of racing (also to reduce vehicle development cost). Open wheel race cars have a distinct front wing they

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were less likely (although not immune) to experience blow over at high speeds compared to prototype race cars. The aerodynamic interaction between two or more vehicles can alter vehicle balance and directly affects all safety aspects. The other initiative by the Motorsport organizers is the use of Safety cars. A safety car is one which limits the speed of competing cars on a racetrack in the case of a caution period such as an obstruction on the track. During a caution period the safety car enters the track ahead of the leader. Competitors are not allowed to pass the safety car or other competitors during a caution period, and the safety car leads the field at a pre-determined safe speed, which may vary by series and circuit. At the end of the caution period, the safety car leaves the track and the competitors may resume racing. Even after so many initiatives taken, NASCAR car racing and F1 racing still remain unsafe.

8. Conclusion

The complexity of automobile and race car aerodynamics is comparable to airplane aerodynamics and is not limited to drag reduction only. The generation of downforce and its effect on lateral stability has a major effect on race car performance, particularly when high-speed turns are involved. In the process of designing and refining current race car shapes, all aerospace-type design tools are used. Because of effects such as flow separations, vortex flows, or boundary-layer transition, the flow over most types of race cars is not always easily predictable. Due to the competitive nature of this sport and the short design cycles, engineering decisions must rely on combined information from track, wind tunnel, and CFD tests