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RESEARCH UPDATE

Race-car aerodynamics

In recent years motor racing has become one of the most popular of sports, attracting record numbers of followers. In some racing categories the vehicles resemble production sedans while in others they look more like fighter airplanes, and there is also a great variety of tracks that range from paved to unpaved and from straight to oval or regular road courses. In all forms of racing, however, aerodynamics eventually surfaced as a significant design parameter, and nowadays all race-car designs have some level of aerodynamic element.

The complexity of race-car aerodynamics is comparable to airplane aerodynamics and is not limited to drag reduction. The generation of aerodynamic downforce (force directed downward, or negative lift) and its effect on lateral stability result in a major enhancement in race-car performance, particularly when high-speed turns are involved. In the process of designing and refining current race-car shapes, all available aerospace-type design tools are used. Because of effects such as flow separation, vortex flows, and boundary-layer transitions, the flow over most types of race cars is not easily predictable. Owing to the competitive nature of this sport and the short design cycles, engineering decisions must rely on information gathered from track and wind-tunnel testing, and even computational fluid dynamics.

Although the foundations of aerodynamics were formulated over the past 200 years, not all its principles were immediately utilized by race-car designers. Naturally, the desire for low drag was recognized first, and early designers focused mainly on streamlining their race cars. Although there was some experimentation with the addition of wings to influence the vertical load on the vehicle during the late 1920s, this major innovation was completely ignored for the following 35 years. Once designers realized the significance of aerodynamic downforce and its effect on vehicle performance, fixtures such as inverted wings or even underbody diffusers were added. The benefits of aerodynamic downforce and the improved performance are basically a result of increasing the tire adhesion by simply pushing the tires more toward the ground. Because of this additional load, larger friction (traction) levels can be achieved, and the vehicle can turn, accelerate, and brake more quickly. Furthermore, by controlling the fore/aft downforce ratio, vehicle handling can be easily modified to meet the needs of a particular race track.

The foremost and simplest approach to generate downforce was of course to add inverted wings to existing race cars. But almost immediately it was realized that the vehicle body may be used to generate downforce as well. The main advantage of this approach is that even small values of negative pressure under the vehicle can result in a sizable aerodynamic downforce because of the large planview area of the vehicle. **Figure 1** shows a modern Indy (Indianapolis Motor Speedway) car as tested in a wind tunnel. The large front and rear wings are immediately visible. However, underbody diffusers and vortex generators are hidden below the car and cannot easily be detected by the competition. The principles of these and some other downforce generating methods will be discussed.

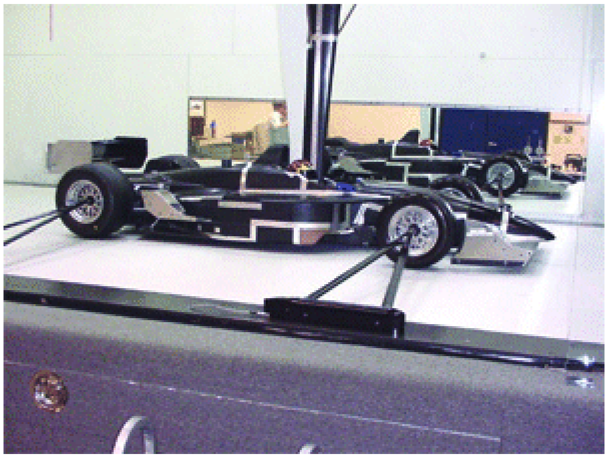


Fig. 1 Typical Indy (Indianapolis Motor Speedway) car model as tested in a wind tunnel. A rolling belt on the floor is used to simulate the moving road. The wheels are mounted separately and rotated by the belt, while the 40%-scale race car's body positioned is changed from above. (*Mark Page; Swift Engineering*)

Race-car wings

Airplane wing design matured by the middle of the twentieth century and it was only natural that race-car designers borrowed successful airplane wing profiles to use on their vehicles. This approach, however, was not entirely successful due to the inherent differences between these two applications. A race-car lifting surface design is different from a typical airplane wing design for the following reasons:

1. 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 does not come freely because a similar increase in drag is measured. Since many race cars use front wings mounted close to the ground, this principle is widely utilized in race-car design.

2. In most forms of motor racing a large rear wing is used. In the case of open-wheel race cars such as Indy cars 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, but with the fringe benefit of delaying wing stall (the sudden drop of lift). 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 basing early designs on existing high-lift airfoil shapes, borrowed from airplanes having several elements (flaps and slots). But as noted, these airfoils were developed for airplanes having very wide wings (high aspect ratio), and therefore their performance was not optimized for race-car application. Recently, quite different, custom-designed airfoil shapes have been used to address this problem.

3. The third major difference between aircraft and race-car wings is the strong interaction between the lifting surface and the other body components. As an example, the data for a prototype race car with large underbody diffusers is presented in **Fig. 2**. In this case the wing height (*h*) was varied up to a height where the interaction is minimal. Clearly, the combined downforce increases as the wing approaches the vehicle's rear deck. At a very close proximity the flow separates between the rear deck and the wing and the downforce is reduced. 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.

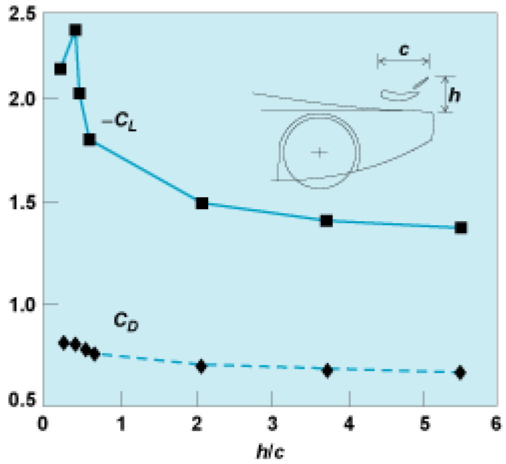


Fig. 2 Effect of rear-wing vertical position on the lift and drag coefficients, C_L and C_D, of a prototype race car. The rear-wing vertical position is expressed as h/c, where the wing height h and chord c are defined in the inset diagram. The rear-wing negative incidence $\alpha_w = 12°$, and the lift and drag coefficients are based on the planview area of the vehicle. (*From J. Katz, Race-Car Aerodynamics, 2d ed., Robert Bentley Inc., Cambridge, Massachusetts, 2006*)

Creating downforce with the vehicle's body

Once the potential of using aerodynamic downforce to win races was realized, designers began experimenting with methods other than simply attaching inverted wings. One approach is quite similar to the previously mentioned wing-in-ground-effect model. Colin Chapman, designer of the famous Lotus 78, developed this concept to fit Formula One (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-aspect-ratio inverted-wing- shaped side pods (resulting in air speeds much higher than the vehicle's speed). The concept (as shown in the lower inset to **Fig. 3**) worked very well, resulting in large suction forces under the car (in accord with the Bernoulli principle that higher flow speeds result in lower pressure). The “skirted car” was 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. The sliding seals, however, were not trouble-free. Irregularities in the road surface occasionally resulted in seal failure and the immediate loss of downforce, with catastrophic consequences. [The effect of increasing the gap between the ground and the seal on the downforce is shown in Fig. 3; a 20-mm (0.8-in.) gap could result in loss of 50% of the downforce.] This problem led to the banning of all sliding seals in F1 cars by 1983. In the following years, this ruling was mandated in most other forms of racing as well, and the only parts of the vehicle allowed to be in contact with the ground were the tires.

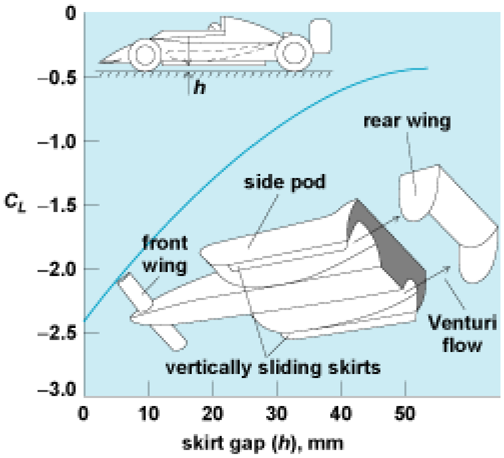
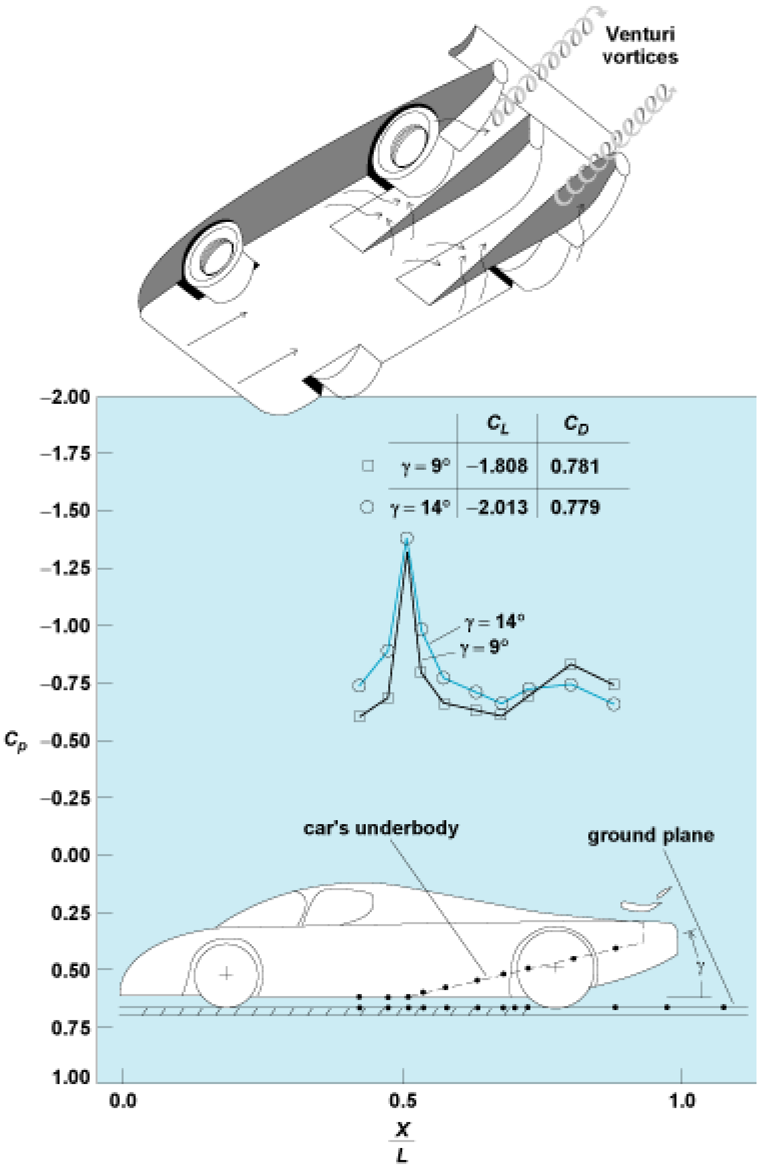


Fig. 3 Creation of downforce with side skirts. Graph shows effect of side-skirt-to-ground gap *h* on a vehicle's total downforce coefficient, $-C_L$. The gap *h* is defined in the upper inset diagram, and the underbody of the race car is diagrammed in the lower inset. 1 mm = 0.04 in. (*From J. Katz, Aerodynamics of race cars, Annu. Rev. Fluid Mech., 38:27–64, 2006, Annual Reviews*)

Another approach that worked well is based on controlling the low pressure under the car, independent of the vehicle's speed. This approach resulted in the so-called suction cars. The first was the 1969 Chaparral 2J. 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 flow separation behind the vehicle, and therefore the vehicle's drag was reduced. 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. The design was immediately successful. However, this success was not well received by the competition, and regulation almost immediately outlawed such designs.

Underbody diffusers (tunnels)

Once the sliding skirts were banned the suction under the car was significantly reduced (Fig. 3). A logical evolution of this concept led to underbody “tunnels” formed under the sidepods, which sometimes were called diffusers. The integration of this concept into an actual race-car underbody is depicted in the upper part of **Fig. 4**. Flow visualizations clearly show the existence of the side vortices responsible for reattaching the flow in the tunnels (diffusers). Surface pressures measured along the tunnel centerlines are shown in Fig. 4 as well, and a sharp suction peak at the tunnel entrance is evident. In this study several diffuser angles were used and the resulting downforce and drag coefficients for the complete vehicle are shown in the table inserted in the figure. For this particular geometry, diffuser angles larger than 14° caused the flow to separate from the diffuser walls with the result of less downforce. The significance of the pressure peak at the diffuser entrance for race-car application is that the location of the vehicle's center of pressure could be controlled by the fore-aft shifting of the diffuser entrance. Of course, the downforce usually increases with reduced ground clearance, an effect that continues down to very small ground clearance values.



	C_L	C_D
□ γ = 9°	−1.808	0.781
○ γ = 14°	−2.013	0.779

Fig. 4 Creation of downforce with underbody diffusers (tunnels). Upper drawing shows race-car underbody. Graph shows effect of underbody diffuser angle γ on the diffuser centerline pressure distribution. Here, C_p is a nondimensional pressure coefficient, and negative values mean pressures below the ambient level. Resulting downforce coefficients, $-C_L$, and drag coefficients C_D for the complete vehicle are shown in the table. Lower diagram defines the diffuser angle γ, and locates measurement points, whose fore-aft positions are graphed in terms of X/L, where X is distance from front of car and L is length of car. Rear-wing negative incidence $\alpha_w = 12°$. (*From J. Katz, Race-Car Aerodynamics, 2d ed., Robert Bentley Inc., Cambridge, Massachusetts, 2006*)

Add-ons

Simple modifications can be added to an existing car to increase downforce. One of the simplest add-ons is the vortex generator. These devices can take the form of small triangular plates or resemble miniature wings, and they are not always visible. A simple option is to add such vortex generators at the front of the underbody where their long vortex trails can induce low pressure under the vehicle. This principle is widely used for open-wheel race cars (such as Indy or F1 cars).

The discussion of vehicle-body-related downforce would not be complete without mentioning some of the widely used add-ons such as spoilers and dive plates. One of the earliest types of “spoilers” mounted on the rear deck of sedan-type vehicles is quite effective and widely used. Current stock cars use them, and the rear downforce that they generate has been shown to increase with increasing angle (measured from the horizontal plane). A 60° rear spoiler causes a change of about −0.20 in the lift coefficient C_L. Spoilers under the chin of a sedan-type vehicle were tested in the 1970s, and showed a positive effect 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.

For background information See also: Aerodynamic force; Aerodynamics; Aileron; Air-cushion vehicle; Airfoil; Automobile; Bernoulli's theorem; Vortex; Wing in the McGraw-Hill Encyclopedia of Science & Technology

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