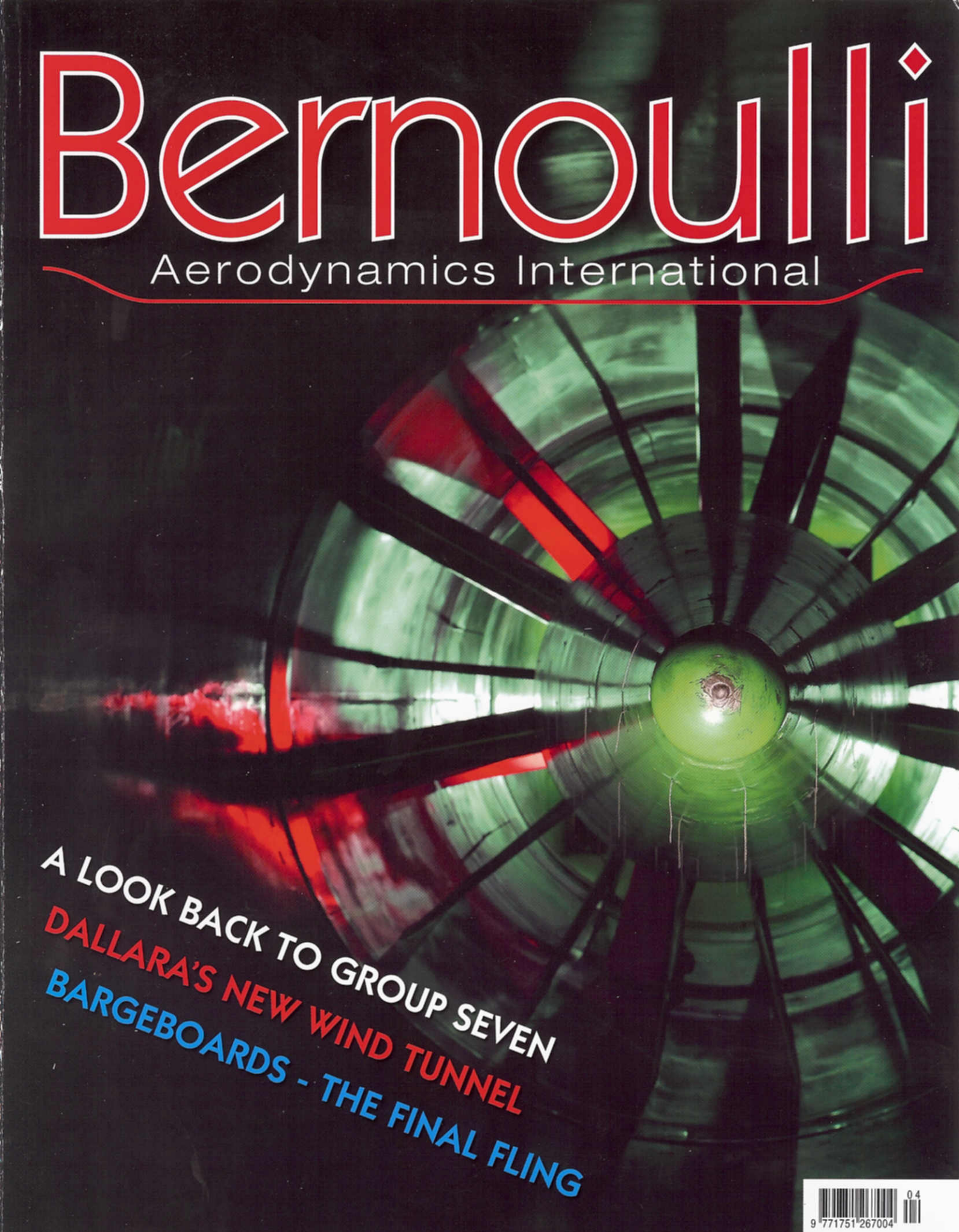
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Aerodynamics International



A LOOK BACK TO GROUP SEVEN

DALLARA'S NEW WIND TUNNEL

BARGEBOARDS - THE FINAL FLING

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The science of flying on the ground

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Aerodynamics & the Group Seven Sports Car

The interaction of aerodynamic normal and drag forces with tire and chassis characteristic of a Group 7 sports car and their effect on static stability and steady state turning are considered. Analytic techniques and objective data are applied to the analysis of vehicle motion. The influence of aerodynamic drag and download are identified and various methods of applying aerodynamic download are examined. The author's personal subjective experiences related to dynamic stability, transient response and frequency response of the Chaparral Group 7 car are recounted. **Paul Lamar**



ABOVE The 1967 24 Hours of Daytona with Phil Hill at the wheel of the Chaparral 2F that was the class of the field until it got sidelined when it hit a concrete wall. Author Paul Lamar can be seen in the foreground holding the fire bottle

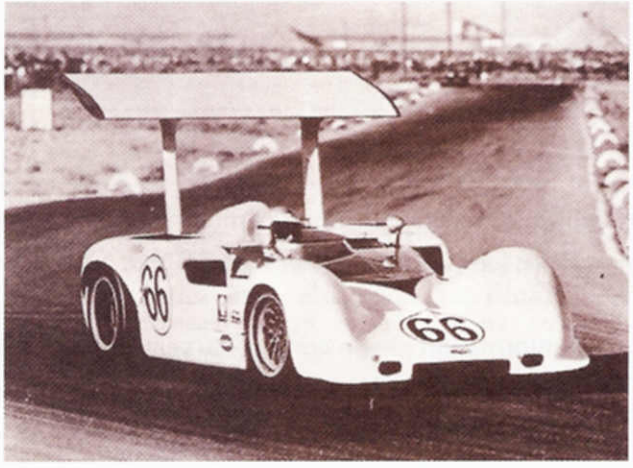
Editor's Note: This paper was originally published in 1968 but the fundamental lessons and solutions remain valid to this day although this paper was written before wind tunnel testing became the norm and CFD was not even a small twinkle in the software firmament. Paul Lamar, who remains an active engineer to this day, was heavily involved with the ground-breaking Chaparral team.

To retain the authenticity the US spelling has been retained.

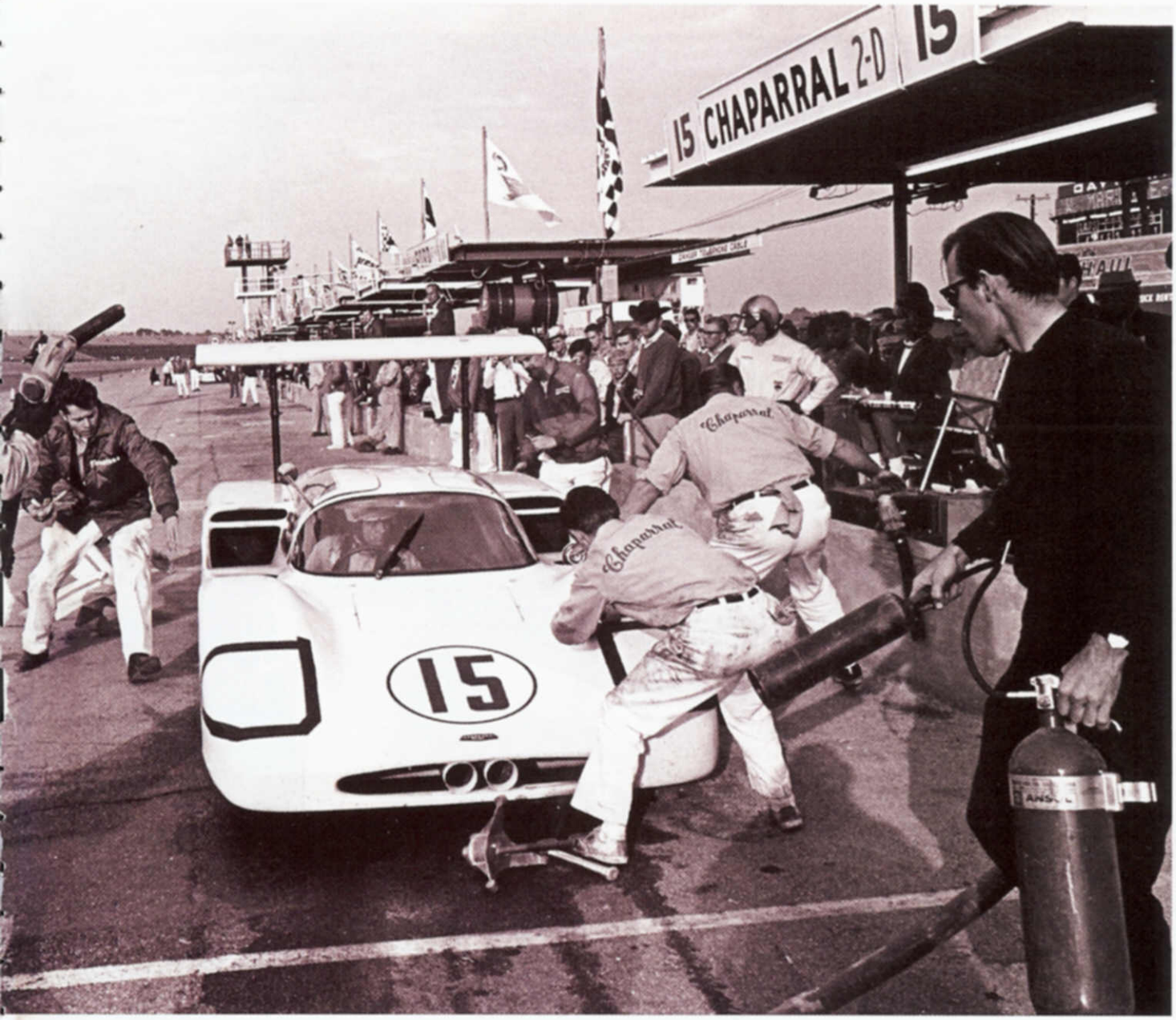
1. INTRODUCTION

A Group 7 racing car is (according to the Sports Car Club of America) a car "designed and constructed for road racing competition, offering provisions for driver and a passenger, basically suitable for driving over normal roads". Other than certain minimum cockpit dimensions designed to eliminate the proliferation of single seat cars, there are no rules that limit minimum size or weight or rules that arbitrarily limit the maximum size of the engine. A typical Group 7 car is shown in Figure 1(right).

The current Group 7 racing car is typically 135" long, 65" wide, 30" high, and has a ground clearance of 3". It weighs approximately 1,400 lb empty and is powered through 5-speed spur rear transmission by a 350 to 430 cubic inch V8 engine, mounted in the rear, developing 500 to 600 hp. The center of gravity is located 14" to 15" above ground level and 65% of the 90" wheelbase behind the front wheel centerline. It carries 45 to 55 gallons of 100 octane gasoline (pump gasoline is required by rule) and gets 4 mpg at racing speeds of 30 to 190 mph. A typical race length for Group 7 cars is 200 miles with no pit stops required. The average speed of a typical race is 110 mph.



LEFT The Chaparral 2C of 1965 featured the first in-car adjustable rear wing that was designed to be flat on the straight and tipped up to add rear downforce under braking and in corners



Racing tires used on these cars are mounted on 8.5" to 10" wide wheel rims at the front and 12" to 15" wide wheel rims at the rear. The diameter of the rims is 15" in both cases. The outside diameter of the front wheels is approximately 24" and that at the rear, 26". Tire and wheel weigh an average of 40 lb each.

From an aerodynamic point of view a Group 7 car has a frontal area of about 13 ft^2 and a drag coefficient of 5. In plan view, it has an aspect ratio of 0.4, a projected area of 60 ft^2 and a "wing loading" of 25 lb/ft^2. I mention these analogies because the lift characteristics of the Group 7 racing car are proving more important than the drag characteristics. This is a direct result of the relatively low wing loading.

This paper will attempt to give insights to the aerodynamic factors that affect the maximum steady-state cornering ability of the Group 7 racing car and will consider simple stability criteria, a general treatment of stability and control theory being beyond the scope of this paper. This subject is adequately covered, for example, in References (1) and (2).

2. STABILITY

For the purpose of this discussion it is assumed that a car will be directionally stable and comfortable to drive if the ratio of maximum available cornering stiffness (deviation of the lateral force with respect to slip angle) to static weight at the rear axle of the car is greater than the same ratio at the front axle. The car feels stable to the driver under these conditions because the lateral force as the result of a steering input produces a secondary inertial yawing moment which tends to resist the turn of the racecar. A slightly unstable car can be useful at low speeds as it usually has a faster transient response. This assumption ignores lateral aerodynamic forces due to yaw as they are negligible relative to the tire lateral forces and can be compensated for by small changes in maximum lateral tire forces.

Steady-state stability as opposed to ►



ABOVE Jim Hall in a Chaparral 2C negotiating the Monterey Corkscrew at Laguna Seca in 1967

dynamic stability and response is emphasized for several reasons. It is usually necessary to achieve steady-state stability or static stability before attempting to modify the dynamic stability. Achieving steady-state stability of an accelerating high-powered racecar is not easy. When steady-state stability is achieved there is a strong incentive to accept the damping and transient response inherent in the basic car. This is a result of the fact that some of the many parameters that affect these characteristics may not be changed by the designer of a Group 7 car. Wheelbase tread width, moments of inertia and tire characteristics are all determined by the more important criteria of minimum size, weight and maximum cornering speed. The interaction of these various parameters is discussed by Nordeen in Reference (3). Furthermore, the driver of a high-powered racecar affects the dynamic stability by his use of the brakes, accelerator pedal and the transmission gear ratio he chooses.

3. OPERATIONAL MODES

The operation of a Group 7 racecar can be broken down into five basic modes. Although there is some overlap, they will be considered individually for clarity. The first mode is full throttle acceleration from a speed of 30 mph, which is the speed of the slowest corner usually found on the majority of race tracks, to a speed of about 100 mph, which coincides with the cessation of potential spin of the drive wheels. During this mode positive longitudinal acceleration is limited to about 1g by the static weight on the rear driving wheels, longitudinal tire load transfer, the tire's coefficient of friction, and a little assistance from aerodynamic downforce above about 50 mph.

In the second mode, from 100 mph to the top speed of the vehicle, acceleration is limited by available hp and is approximately inversely proportional to speed, dropping to zero at the top speed ►

of the vehicle. Full throttle acceleration in a straight line occupies the majority of the time it takes to complete one lap.

Braking for an impending corner at the rate of about 1.1g is the third mode, and the fourth is partial throttle, constant speed operation from the end of braking to approximately the apex of the corner. The fifth mode is partial throttle acceleration from the apex to some point near the beginning of the straight where full throttle acceleration begins.

4. TIRE CHARACTERISTICS

To appreciate the role aerodynamic forces play in the cornering and stability of the racecar it is necessary to study the known characteristics of racecar tires. In the past, far too little consideration has been given to the interaction of aerodynamic forces with the characteristics of vehicle tires. This interaction has a profound influence on the handling characteristics of passenger cars as well as racecars. For example, references 4 and 5 show that pneumatic tires have a maximum lateral coefficient of friction that varies in nearly a linear manner with normal load. This variation takes the form of a linear reduction in coefficient of friction with an increase in normal load assuming variable slip angle and optimum constant camber angle. That is,

$$\mu = \mu_o - mP \quad (1)$$

where μo is an extrapolated zero load lateral coefficient of friction and m is the constant rate of the lateral coefficient of friction's reduction with load, P. The camber angle is usually held within insignificant variations of the optimum by suspension geometry and anti-roll bars.

The slip angle is the angle between the plane of the wheel and the tangent to its path of travel and is shown in Figure 2 along with the horizontal tire and vehicle forces. Figure 2 ignores the small geometrical difference in slip angle between individual wheels which results from finite wheelbase and tread width.





RIGHT The body design of the first Chaparral 2, Jim Hall's original racecar that featured revolutionary aerodynamic design and chassis engineering, was based on wind tunnel testing from General Motors styling

BELOW The 1967 24 Hours of Daytona featuring from left to right: Wesley Sweet, Bob Johnson, Franz Weis, Bruce Jennings, Phil Hill, Paul Lamar, Jim Hall and Mike Spence



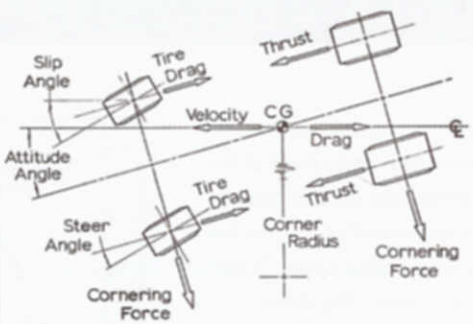


Figure 2. Schematic of Vehicle Force System

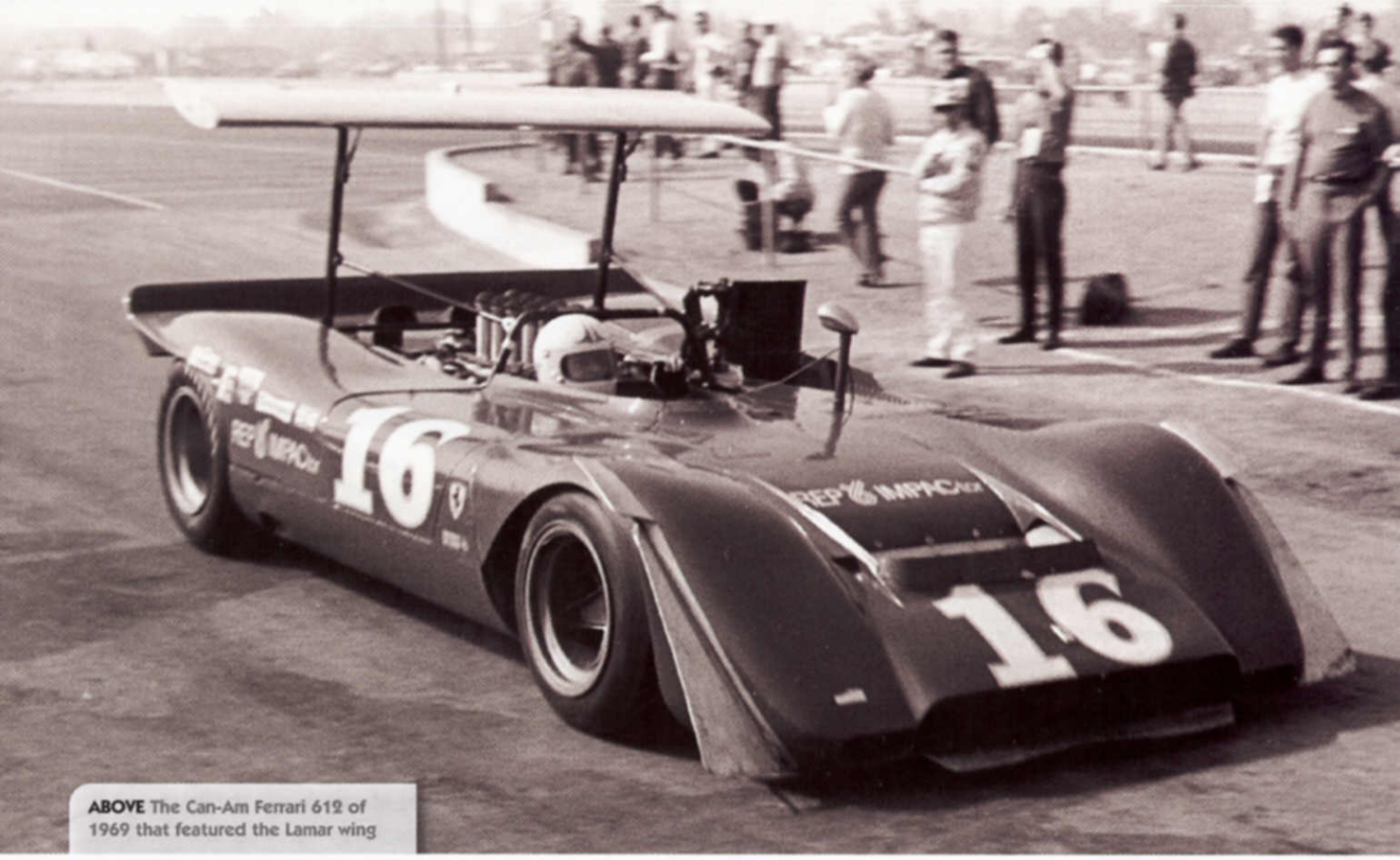
This is justified because these dimensions are very small relative to the majority of corner radii. The necessary slip angle of a tire developing a given lateral force is a complex function of normal load, tractive force, camber angle and the basic tire to road coefficient of friction. Some of these functions are, for the most part, unknown for racing tires. Roll steer, deflection steer (there is no longer any rubber in the suspension bearings of pure racecars) and bump steer are all minimized to prevent uneven road surfaces from steering the car and, therefore, so is their interaction with the changing slip angles that modify the transient handling behavior of the passenger car. Changes in the rear slip angle that affect the equilibrium are immediately compensated for by the driver's changes in throttle opening or steer angle to re-establish equilibrium. Changes in maximum possible lateral force will, in general, modify the cornering stiffness (the derivative of the lateral force with respect to slip angle) in the same direction, as shown in Reference (4).

Most analyses of automotive stability have traditionally employed slip angle as an integral part of their construction. The driver of a car is not directly aware of the exact magnitude of the slip angles at any given moment. It therefore would be far better to relate the handling of the car directly to its response to the controls or lateral acceleration rather than the slip angles. Furthermore, the non-linear nature of the slip angles severely complicates analysis when they are employed as independent variables. In the opinion of the author, a far better independent variable would be the lateral acceleration of the car. For these reasons every attempt has been made to factor out or bypass the discussion of slip angles in this paper.

The basic tire equation for the cornering ^ force is

$$CF = \sqrt{[(\mu_o - mP)P]^2 - F_x^2} \qquad (2)$$

It is seen that in addition to a sensitivity to normal load, the tires are also sensitive to transmitted torque or longitudinal thrust, Fx. This characteristic has been examined by Ellis in Reference 7. Mathematically the sensitivity takes the approximate form of a circular function at the variable slip angle and camber angle of maximum cornering force. Maximum cornering force for one tire is therefore a function of μo, m, P. and Fx where it is noted that the normal load P is in turn a function of static weight, tire load transfer and aerodynamic lift or downforce. The most significant factor is the longitudinal tractive force Fx, since a racecar is usually in a continual state of high acceleration. In addition to accelerative ►



ABOVE The Can-Am Ferrari 612 of 1969 that featured the Lamar wing

tractive force there is that tractive force required to overcome aerodynamic drag, rolling resistance and tire induced drag while cornering.

5. AERODYNAMIC INTERACTION

5.1 LOW-SPEED ACCELERATION

During the first mode of operation, the period of full throttle acceleration, and therefore large amounts of tractive force, from about 30 mph to 100 mph, the rear tires are capable of providing very little cornering stiffness. Therefore, the car is very unstable. Large demands are made upon the driver's ability to keep the car "pointed down the road".

Yaw disturbances in this mode are caused by local variations in the basic coefficient of friction, wind gusts and uneven road surfaces affecting the normal loads on the driving rear tires. Normal load change on one or the other of the rear tires affects the longitudinal tractive force on that rear tire which in turn causes a yaw moment and a path deviation. Low suspension spring rates lower tire normal load change with uneven road surfaces. A further reduction in steady-state instability in this mode of operation is caused by the reduction in normal load and therefore cornering stiffness at the front tire patches with an increase at the rear due to longitudinal tire load transfer. This reduction in normal load at the front is about 33% for a typical Group 7 car operating in this mode. The driver corrects for yaw disturbances by releasing some throttle opening which increases the lateral force and the cornering stiffness of the rear tires and/or by steering into the yaw. Some help is provided by the one-half of one degree toe-in generally used at the rear wheels. This acts much like outwardly offset thrust lines on twin engine aircraft would.

5.2 HIGH-SPEED ACCELERATION

In the second mode of operation full throttle acceleration from 100 mph to the top speed of the racecar, the magnitude of longitudinal acceleration is reduced linearly with velocity from about 1g to zero. Front cornering stiffness is increasing due to increasing normal load. Rear cornering stiffness is a complex function of aerodynamic downforce, drag and pitching, longitudinal acceleration, and thrust. Figure 3 is a plot of this relationship for a typical Group 7 racecar with and without aerodynamic downforce.

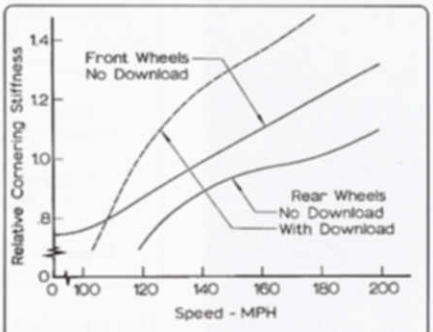


Figure 3. Relative Cornering Stiffness Variation With Speed for a Typical Group 7 Race Car.

At the higher speeds the designer can control the steady-state stability by use of aerodynamic normal forces. All rear-drive cars require either aerodynamic downforce at the rear or a lifting nose to prevent decreasing static stability with speed. The exact amount of downforce required on the rear wheels for a particular rear-drive car is a function of the ratio of car drag to static weight on the rear wheels. Otherwise equal cars with a higher percentage of static weight on the rear wheels require less downforce to insure stability. This usually results in a more rearward located center of gravity which generally results in an "aerodynamically" unstable vehicle in yaw.



BELOW In 1968, Lola produced the T160 for Can-Am with one of the modifications being the addition of a wing high above the rear bodywork

In this connection some attempts have been made to use tail fins to increase stability in these speed ranges. Most of these attempts have failed because the lateral restoring force per degree yaw or aerodynamic stiffness and the damping was not high enough. These failures are partially the result of considering the car an aerodynamic entity rather than a tire-aerodynamic system. It would require a tail fin of approximately 10 sq ft in area with an effective aspect ratio of 1 or better to approximately equal the cornering stiffness of a pair of undriven rear tires in this speed range. The same effect as undriven rear tires can be achieved at high speeds by a well designed small wing exerting down force.

Front engine, front-wheel drive would seem to offer a solution to this problem as the cornering stiffness of the driven front wheels is reduced with thrust and therefore stability is increased. Closer examination shows that this is not a desirable solution. The front-wheel drive car suffers from longitudinal tire load transfer towards the rear wheels while accelerating resulting in a loss of maximum traction at low speeds. Braking promotes tire load transfer to the front wheels resulting in a further decrease in overall coefficient of friction and hence an increase in stopping distances from any given speed. Furthermore, the driver must be placed high enough to have adequate visibility over the larger front wheels and the engine which must be placed at the front for the necessary static weight. This bulky arrangement results in additional frontal area, difficulty in achieving front aerodynamic downforce due to the shape of the car and a higher center of gravity. At the present time there are no successful front-wheel drive pure racing cars.

Four-wheel drive is another possible solution and a very admirable one in many ways. Further discussion of this arrangement is given in Reference 8. Four-wheel drive cars are less sensitive to poor road conditions such as water and oil than an aerodynamically compensated, rear-drive, rear-engined car would be. Four-wheel drive cars would need less aerodynamic downforce to achieve the same maximum cornering force. However, weight and size on Group 7 cars are very undesirable and both weight and wheelbase would be greater with four-wheel drive. On racing cars such as those used at Indianapolis, Le Mans and Grand Prix races, all of which have minimum weight limits, four-wheel drive may find applications, providing the racing car engineers can design them to be reliable at their minimum weight limits. At the present time they are finding that hard to do with only two-wheel drive. ►

BRAKING

During the third mode of operation, braking for a corner, the steady-state stability of the racecar is adjusted by changing the ratio of braking torque between the front and rear wheels. The longitudinal tire force Fx of Equation 2 which now applies to both front and rear wheels, represents braking tractive force in this mode of operation. The exact ratio, chosen in the pits for a specific course, is a function of aerodynamic longitudinal normal load distribution, which in general will vary with pitch as the result of braking. The braking torque ratio will also vary with static weight distribution, longitudinal tire load transfer and basic tire to road friction characteristics. A more detailed discussion of these effects is given in References 9 and 10.

An increase in braking torque on the front wheels increases steady-state stability. Lateral static weight distribution must be equalized to prevent yaw moments. Suspension spring rates must also be matched laterally to prevent unequal tire normal loads as the result of pitch that might also cause yaw moments while braking. Severe deceleration is seldom attempted while the car's lateral acceleration is appreciably different from zero because as shown in Reference 11, to do so would cause a loss in total lateral force and a yaw moment on the car due to lateral weight transfer.

Application of generous amounts of aerodynamic downforce can of course improve the overall braking performance of the racecar.

STEADY-STATE CORNERING

The fourth mode was stated to be neutral throttle coasting in gear from the cessation of severe braking to approximately the apex of the corner. This is not strictly true for all corners, drivers and cars. Some rear tire tractive force is usually necessary to overcome front tire and aerodynamic drag to maintain constant speed. Some drivers prefer to brake slightly during this mode while others may prefer slight acceleration. In general, however, very little longitudinal tractive force is applied to the tires in this mode.

The equation for maximum cornering force at the front wheels is

$$CF = \mu_{FO} P_{FO} + \mu_{FI} P_{FI}$$

$$CF = \left[\mu_{oF} - m_F\left(\frac{W_F}{2} + \delta y_{FO} \pm \frac{\delta_x}{2} + \frac{DF_F}{2}\right)\right] \times \left(\frac{W_F}{2} + \delta y_{FO} \pm \frac{\delta_x}{2} + \frac{DF_F}{2}\right) + \left[\mu_{oF} - m_F\left(\frac{W_F}{2} - \delta y_{FI} \pm \frac{\delta_x}{2} + \frac{DF_F}{2}\right)\right] \times \left(\frac{W_F}{2} + \delta y_{FI} \pm \frac{\delta_x}{2} + \frac{DF_F}{2}\right)$$

The cornering force on the front tires is seen to be a function of static weight distribution, aerodynamic download, drag and pitching moment and longitudinal acceleration.

In general, tire normal loads PO and P1 are not equal due to lateral tire load transfer while the car is cornering. The load increase on the outside tire is usually directly proportional to the lateral acceleration and that on the inside tire inversely proportional. At low speeds the aerodynamic loads are quite low and therefore the rate of lateral tire load transfer has a pronounced affect on the cornering force of the front suspension. This sensitivity has also been pointed out by Nordeen and Cortese, Reference 12. The designer has control of the front to rear ratio of this lateral rate of load transfer by means of the suspension springs and geometry he chooses and the size of the anti-roll bars. The use of the rate of lateral load transfer neatly bypasses any need to know details about the spring rates or suspension geometry of the vehicle in question. At speeds over approximately 80 mph the aerodynamic lift characteristics of the nose of the car is the predominating influence on the maximum cornering force developed at the front axle.

The situation at the rear in the steady-state cornering mode is quite similar to that at the front except that much more aerodynamic downforce is required to compensate for increased static weight and the tractive force required to overcome front tire and aerodynamic drag. Care must be used in applying large amounts of downforce as excessive induced aerodynamic drag can negate the benefits on long sweeping high-speed corners that require the driver to maintain speed through applied tractive force.

The equation for the maximum cornering force at the rear wheels is

$$CF_R = \mu_{RO} P_{RO} + \mu_{RI} P_{RI}$$

$$CF_R = \left[\left\{\left[\mu_{oR} - m_R\left(\frac{W_R}{2} + \delta y_{RO} \mp \frac{\delta_x}{2} + \frac{DF_R}{2}\right)\right] \times \left(\frac{W_R}{2} + \delta y_{RO} \mp \frac{\delta_x}{2} + \frac{DF_R}{2}\right)\right\}^2 - (F_{xO})^2\right] + \left[\left\{\left[\mu_{oR} - m_R\left(\frac{W_R}{2} + \delta y_{RI} \mp \frac{\delta_x}{2} + \frac{DF_R}{2}\right)\right] \times \left(\frac{W_R}{2} + \delta y_{RI} \mp \frac{\delta_x}{2} + \frac{DF_R}{2}\right)\right\}^2 - (F_{xI})^2\right]^{1/2}$$

It is important to note that the cornering force on the rear tires is strongly affected by the power applied.

Equation 4 is plotted in Figure 4 (overleaf) for a typical Group 7 racecar without downforce. The straight lines are plots of rear lateral tire load transfer and the intersection of these lines and the curves is the cornering force as a function of tractive force and is plotted in Figure 5 (overleaf). Again the individual tire normal loads (PRI' PRO) are functions of the static weight, the lateral acceleration of the vehicle, the longitudinal acceleration and aerodynamic normal loads.





BELOW & RIGHT
Author Paul Lamar in 2007 and (right) working on one of his wings in 1967 (Photo by Pete Lyons)

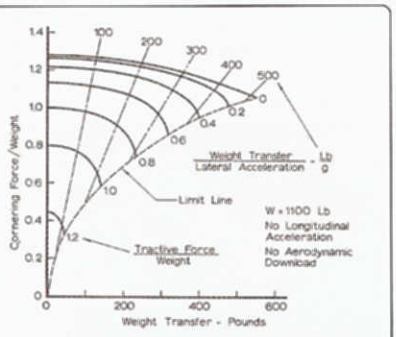


Figure 4. The Effect of Tractive Force and Weight Transfer on the Cornering Force of a Typical Group 7 Race Car

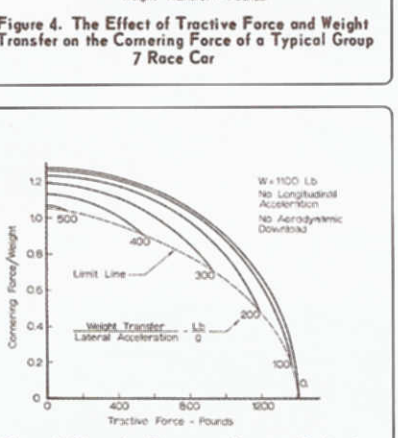


Figure 5. Cornering Force at a Constant Ratio of Weight Transfer to Lateral Acceleration

The designer can adjust the ratio of front rate of lateral load transfer to rear rate of lateral load transfer to adjust the low-speed handling characteristics of the racecar. Keeping the ratio of front rate to rear rate as high as possible maximizes the cornering force at the rear. This improves overall car performance as the rear cornering force is usually the limiting case. The optimum is complete front lateral load transfer (inside front wheel clear of the ground) on low-speed corners. It is then sometimes necessary to increase the front wheel rim and/or tire tread width to increase front lateral force. The balance of front to rear lateral forces is usually adjusted at low speeds for slight instability which promotes rapid transient response. On high-speed corners the aerodynamic downforce on the front of the car places the inside front wheel firmly in contact with the road and the disproportionately increased downforce at the rear promotes increased stability.

ACCELERATED TURN

The fifth mode, partial throttle acceleration while turning, is not always distinguishable from the fourth. If the driver enters the corner at a higher speed than that which would enable him to negotiate the corner without leaving the road, he may "throw" the car slightly more sideways than usual and scrub off speed with the lateral force capabilities of the tires. The path of the car's center of gravity would then be a decreasing radius spiral. If this scrubbing action is allowed to continue too long it then becomes necessary to accelerate while still turning. Variation in corner geometry such as an increasing radius can also lead to the need for longitudinal acceleration while the car is still turning. The equations are the same as in the fourth mode. The rear lateral force is increased slightly by longitudinal tire load transfer and decreased by the additional tractive force. The front lateral force is decreased rather more by positive longitudinal tractive force than the rear is increased relative to their static weights. The path of the car's center of gravity will be an increasing radius spiral.

5.6 AERODYNAMIC DOWNFORCE IN THE TURN

Ignoring stability, load transfer and variable lateral coefficient of friction with tractive force and load and using the maximum acceleration without downforce, the equation for the maximum cornering speed as a function of corner radius and aerodynamic downforce is at which an infinite cornering speed solution exists. This possibility may prove difficult to achieve in practice because of induced drag and reduction in U with the greatly increased normal loads. When applied to a typical, road race track situation infinite cornering speed may not always be necessary because the high-speed corners following the very low-speed corners are likely to be acceleration limited. That is, due to a limited weight and drag to horsepower ratio, the car is unable to accelerate to a speed before it reaches the high-speed corner that will appreciably tax its high cornering ability. In fact, some high-speed corners on certain race tracks are now acceleration limited for the Chaparral, which has a relatively sophisticated aerodynamic system. In the past it was necessary for the driver to slow down before attempting to negotiate certain corners. This is no longer true even though the cars are capable of greater acceleration between corners.

$$v_{max} = \sqrt{\frac{\bar{\eta}_y}{\frac{1}{gR} - \frac{\bar{\eta}_y \rho}{2}\left(\frac{SC_L}{W}\right)}} \qquad (5)$$

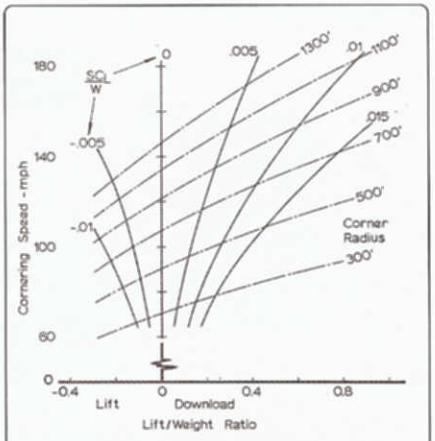


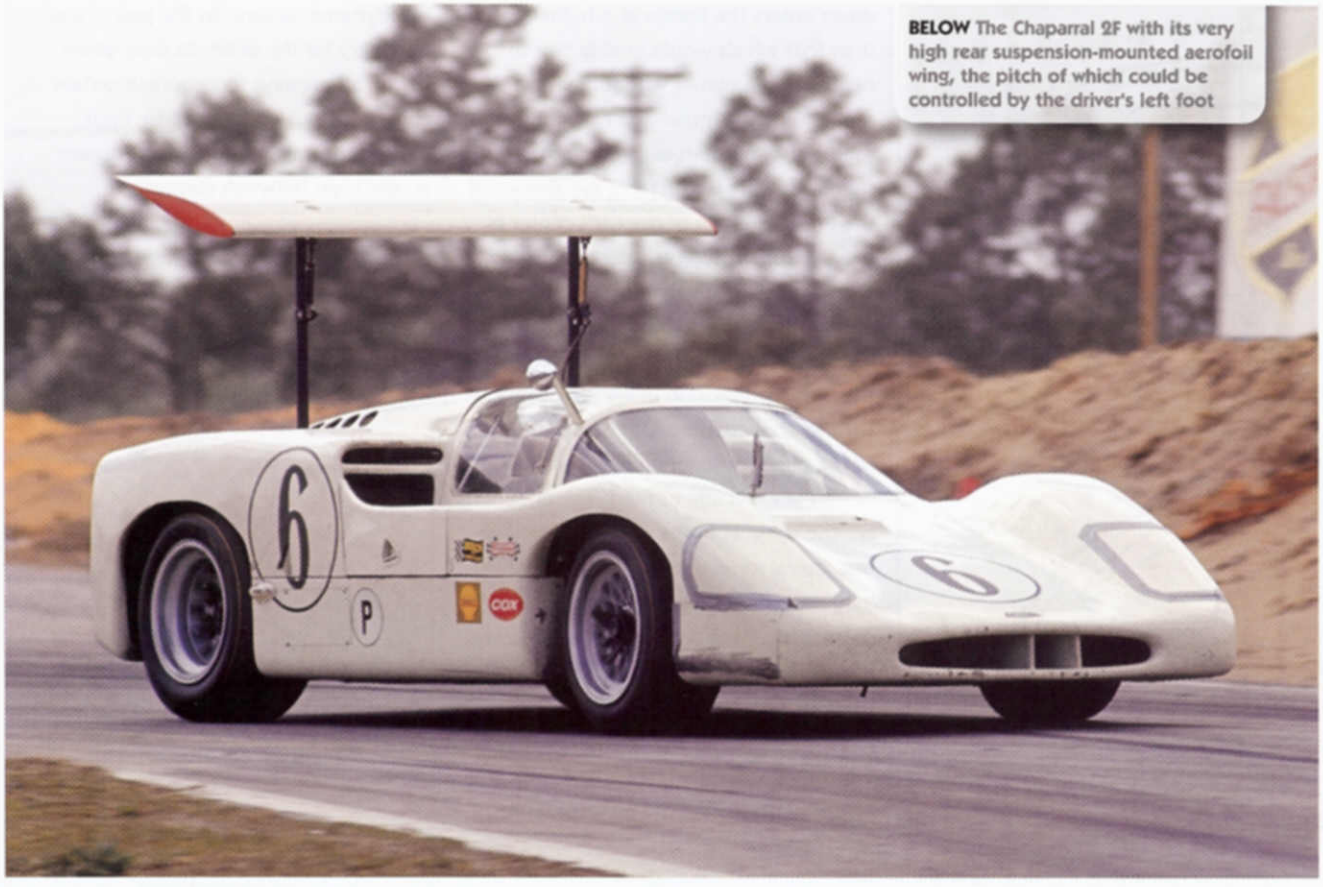
Figure 6. The Effect of Aerodynamic Download on Cornering Speed

TIMES THROUGH A 135 MPH TURN – STARDUST INTERNATIONAL RACEWAY GRAND PRIX CAN-AM SERIES QUALIFICATIONS, 1967

Driver / Car	Time - Seconds									
Andretti Honker	4.5	4.5	4.5	4.3	4.8	4.6	4.3			
McLaren McLaren	4.1	4.4	4.2	4.0	4.1	4.1	4.0	4.2	4.0	4.2
Hall Chaparral	4.1	3.8	3.8	3.8	3.8	3.8	3.7	3.7	3.8	
Gurney Lola	4.1	4.2	4.3							
Titus Cobra	4.8	4.3	4.1	4.0						

Figure 6 is a plot of Equation 5 for a typical Group 7 car for downforce loadings less than critical.

To further illustrate with actual data the increase in performance possible, Table 1 consists of hand stopwatch times taken at Stardust International Raceway, Las Vegas, Nevada in 1967 during the Stardust Grand Prix Can-Am series qualifying. The times are in seconds for an arbitrary distance through the approximately 135 mph turn one. To put these times in perspective it is necessary to realize that as little as one second (approximate lap time 1 minute, 30 seconds) separates one qualifying position from another and that it is only necessary to be several feet ►



BELOW The Chaparral 2F with its very high rear suspension-mounted aerofoil wing, the pitch of which could be controlled by the driver's left foot

ahead at the end of 200 miles to win the race. This data illustrates the clear superiority of the Chaparral relative to its competitors at high-speed cornering.

6. AERODYNAMICS AND SUSPENSION

There are many problems encountered when attempting to apply aerodynamic downforce to race cars. High values of downforce applied to the body depress the vehicle's suspension springs reducing suspension travel for bumps and reducing ground clearance. There are problems with wheel camber as well. Normal suspension design practice is to arrange the suspension linkage so that the wheel remains as nearly vertical to the road as possible when the body and chassis roll in high lateral acceleration corners. References (13), (14), and (15) treat the problems of suspension systems in more detail. Unfortunately the same suspension geometry that holds the wheels vertical also causes them to tilt inward at their tops when the chassis and body are deflected downward on the suspension springs. This leads to uneven tire wear and a reduction in cornering force. These problems have been partially solved in certain Group 7 cars by stiffening the suspension springs beyond that which would normally give the best road holding without downforce.

A second solution and one not quite so common but gaining favor is to compromise the suspension geometry so that the wheels do not tilt in quite so far and hence improve the overall average maximum cornering force and reduce uneven tire wear. Another possible solution is a constant ride height device that automatically keeps the chassis at a predetermined ground clearance.

The solution Chaparral chose was to apply downward force directly to the wheels with a wing and struts, thereby bypassing the suspension springs. However, this approach created more problems. The high vertical accelerations of the wheels caused the wing linkage to fail several times before it was fully developed to cope with these forces. The low pressure area between wing and the rear body work over the engine caused the rear of the body to lift. This rear body lift in conjunction with the downforce on the nose depressing the front springs caused the body to pitch nose down at the front. This nose down attitude had serious consequences as the downforce on the nose at any given speed is a sensitive function of the height from the ground of the stagnation point.

The result of all this was that the downforce on the nose was sometimes proportional to the car speed to the fourth and even the sixth power rather than the square of car speed as would normally be expected. This problem was attacked in several ways: by venting the rear engine cover thereby reducing lift on the rear of the body; by installing a small rear body air dam, the downforce of which helped balance the front downforce, therefore preventing body pitch; and by installing devices that relieved front downforce aerodynamic pressure at a predetermined speed.

7. LIFT/DRAG RATIO

The most important problem of all in applying aerodynamic downforce to the racing car is achieving a high ratio of ►

maximum lift to minimum drag. One solution is to employ a movable surface. This device must operate from minimum drag to full downforce on the order of a tenth of a second and not upset the balance of front to rear cornering force as severe instability would result. It must also be readily controlled by the driver who at the present time has plenty to keep him busy. Since weight and unreliability are undesirable in Group 7 cars, this degree of complication may not be worth the effort.

Another approach is to reshape the body to have as much fixed downforce as possible without incurring excessive induced drag as for example in Reference (16). Figure 7 is the approximate center line pressure distribution of a Group 7 car so shaped.

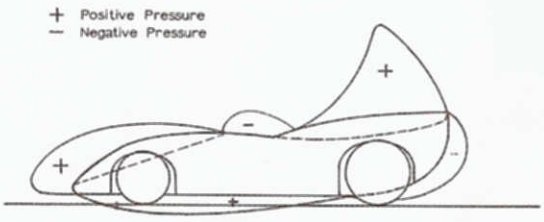


Figure 7. Schematic of the Pressure Distribution on a Typical Group 7 Race Car With Download

Raising the riding height at the rear of the car gives the body an attitude that is known to the hot rod fraternity as a "rake". This rake relieves the positive pressure under the front of the car and enhances the negative pressure under the extreme rear thereby promoting downforce. Rake is not used on Group 7 cars to any large extent because it raises the center of gravity and therefore reduces the low-speed cornering ability. Rake is used on stock cars because rules prohibit modifying the body and stock cars seldom corner at low speeds. Gaining a high inherent downforce to drag ratio will be hampered by the Group 7 race car's poor aspect ratio and necessarily small ground clearance.

8. AERODYNAMIC TESTING

Use of a conventional wind tunnel to develop a high downforce to drag ratio and stability has in the past resulted in rather poor results – references (17) and (18). These poor results are probably a consequence of the small ground clearance and the interaction of the longitudinal thrust characteristics of the tires with the aerodynamics of the vehicle. Figure 6 is an approximate plot of the car centerline pressure distribution that might be measured in a wind tunnel and the actual centerline pressure distribution of the same car as might be measured on full-scale road test. There will in general be an increase in positive pressure beneath the front of the car as a consequence of the changed air velocity gradient between the road and the car. This pressure difference results in poor correlation between tunnel lift and drag measurements and full-scale tests. The tendency of engineers to consider the car as an aerodynamic entity and not as a tire-aerodynamic system also leads to poor correlation because of the tractive effects on tire lateral cornering force. Perhaps a chassis dynamometer driving a high-speed movable ground plane at the speed of the tunnel air would help.

Full-scale road tests are probably the best method for developing the aerodynamic characteristics of the Group 7 racecar. Downforce or lift can be measured while the car is driven at steady specific speeds on windless days with suitable instrumentation that is capable of translating mean suspension deflection to downforce or lift.

Drag can be measured by the technique of "coast down" wherein the car is allowed to coast from a specific speed on a windless day while the deceleration is recorded as a function of speed. Knowing the weight and rolling resistance of the vehicle the drag can then be calculated. This technique is described in References (19) and (20). One way of measuring the rolling resistance is to place the car in a large box on wheels to protect it from aerodynamic drag and towing the car within with a dynamometer.

9. SUBJECTIVE HANDLING

My own subjective impression of driving the Chaparral at less than racing speeds on the Midland test track during several hundred miles of aerodynamic testing were quite enlightening. The Chaparral is an order of magnitude improvement above the average passenger car in transient response, frequency response and dynamic stability. The car feels better at a constant 120 mph than an average passenger car does at 60 mph. There is no tendency for the car to wander or drift out of its lane. The car responds to steering input immediately and without discernible overshoot or oscillations. The ride is quite comfortable due to the low suspension frequency used and the form fitting seats. At racing speeds the complexion of the car changes completely. Violent longitudinal and lateral accelerations make the car extremely uncomfortable for a passenger. High-speed corners are taken at what appears to be impossible speeds. Confidence in the driver is absolutely essential.

10. CONCLUSION

The racing car must be considered a complete system rather than just a mechanical entity or an aerodynamic entity to realize its full performance and stability potential. Specifically, an "aerodynamically" unstable car is not necessarily an unstable car since there is an interaction of tire and aerodynamic forces that determine overall car stability.

Aerodynamic normal force rather than drag is the critical design parameter since larger gains in overall lap time performance can be gained by reducing cornering times through use of aerodynamic download than by reducing drag. Significant overall performance gains can still be achieved even though applying aerodynamic download may lead to an increase in drag.

Much more tire data, cornering force as a function of thrust, slip angle, camber angle, normal load, trim width, etc is needed to reach a thorough understanding of the overall interaction of the aerodynamics of a

vehicle and its stability.

Methods must be found to improve the correlation of wind tunnel measurements with actual vehicle performance and stability.

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The discussion of this paper was deferred to the panel discussion period where the general subject of Group 7 car performance and handling qualities was treated in detail. ■

NOMENCLATURE

CF	=	cornering force - lbs.
C^	=	lift coefficient
DF	=	aerodynamic downforce - lbs.
F	=	longitudinal tire tractive force - lbs.
g	=	acceleration due to gravity - ft/sec?
m	=	d/t/dP - lbs.
P	=	tire normal load - lbs.
R	=	corner radius - ft.
=		surface area - ft.
v	=	velocity - ft/sec
W	=	vehicle static weight - lbs.
–	=	tire load transfer - lbs.
ŋ	=	acceleration - g's
M	=	coefficient of friction
MO	=	zero load coefficient of friction
P	=	mass density of air - slugs/ft?

Subscript

F	=	front wheels
R	=	rear wheels
1	=	inside wheels
O	=	outside wheels
x	=	longitudinal component
y	=	lateral component

Superscript = value with no aerodynamic download