The Tire Chapters

A Brief Introduction to Tires

Editing Comment by Bill Ball Senior Engineer for GM

“This is as good a place as any for me to mention the obvious fact that data acquisition tells us as much about the driver as the car. In my testing for the GM Series etc., I have been frustrated by working with good and even great race drivers who were either very inconsistent ("err... well, yes, I started driving over the curb on turn 3 about then; maybe that's why the times got faster even though the tires were going off..."), or, who blissfully "drove around" all sorts of evil set up mistakes without even consciously noticing them. As a matter of fact, out of the 20 or so I tapped for testing over the years, including ------- -------, ----- ----, ----- -son-of- ------ -----, -- -----, ---- ---- and assorted past champions, stock car and road course specialists, etc., I can count on the thumbs of one hand the number who could drive the cars consistently and report clearly on what was happening! (**Ron Fellows** was that one).”

Driver names withheld for the sake of bruised egos.



Vince Aiello – A very smart person

2

TIRES - Part One

Design and Performance Parameters

(It's just not this simple!)



Figure 2-1



Figure 2-2



Figure 2-3



Figure 2-4

The Contact Patch - Everything begins and ends at the tire's contact patches. Take a long careful look at Figures (2-5 / 2-7). The three contact patches are actual full scale tire contact patch prints. The lighter areas are the points of greatest loading while the darker areas indicate less loading. I find it quite enlightening to look at contact patch prints and realize that this is all there is between the car and the track.

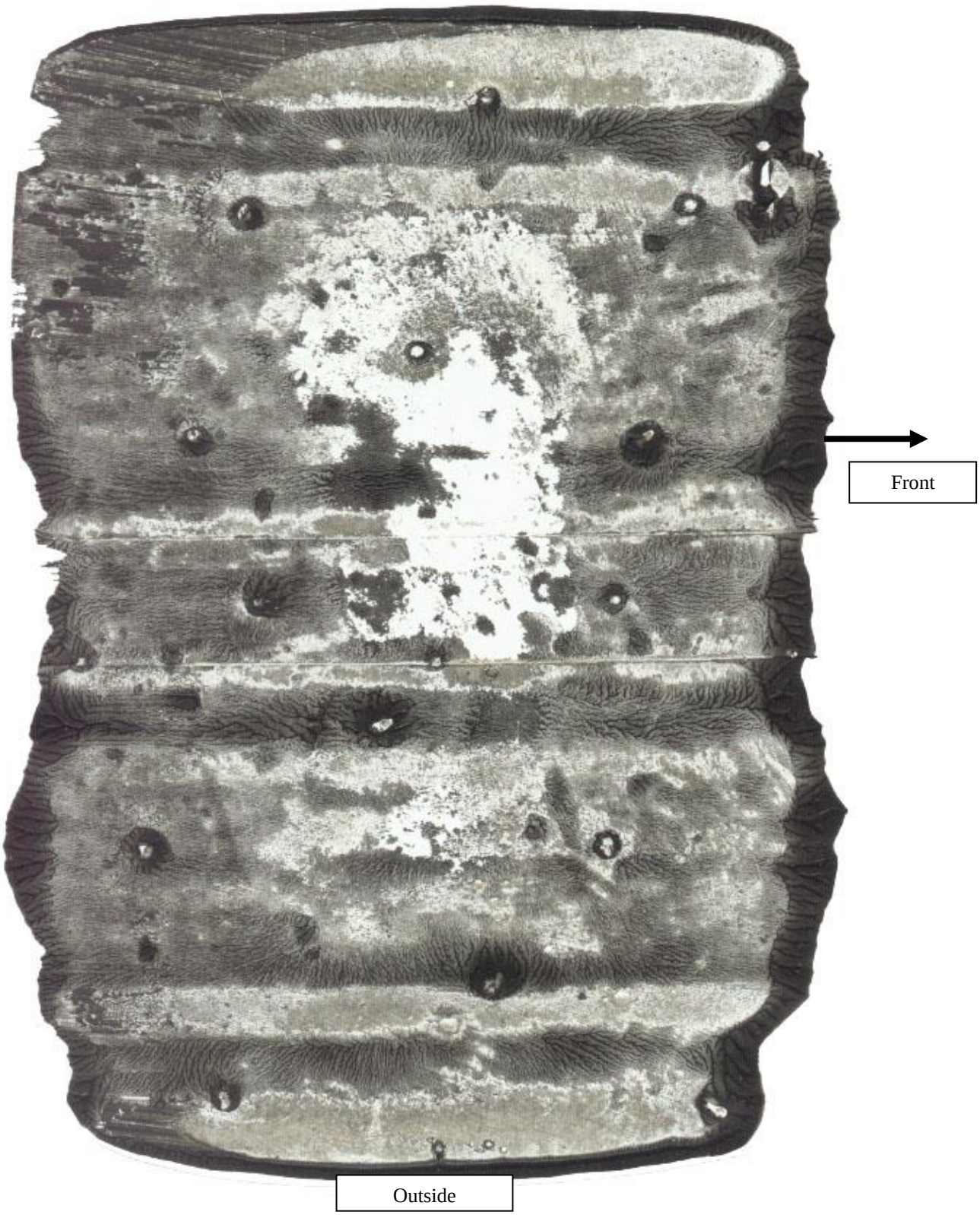


Figure 2-5 - Illustrates to-scale contact patch from a short track stock car racing slick. This was the only tire that was a perfect fit for the page. The patch illustration is made from a 26.0 - 9 - 15 tire with an aspect ratio of 61.0. At 20 psi, it carries a load of 1000 lb. and camber is set at zero. Its total contact area is approximately 50 square inches. The right side of the print is the front of the tire and the bottom of the print is the outside of the tire. (CP6). I have combinations of patches from every major North American racing series.

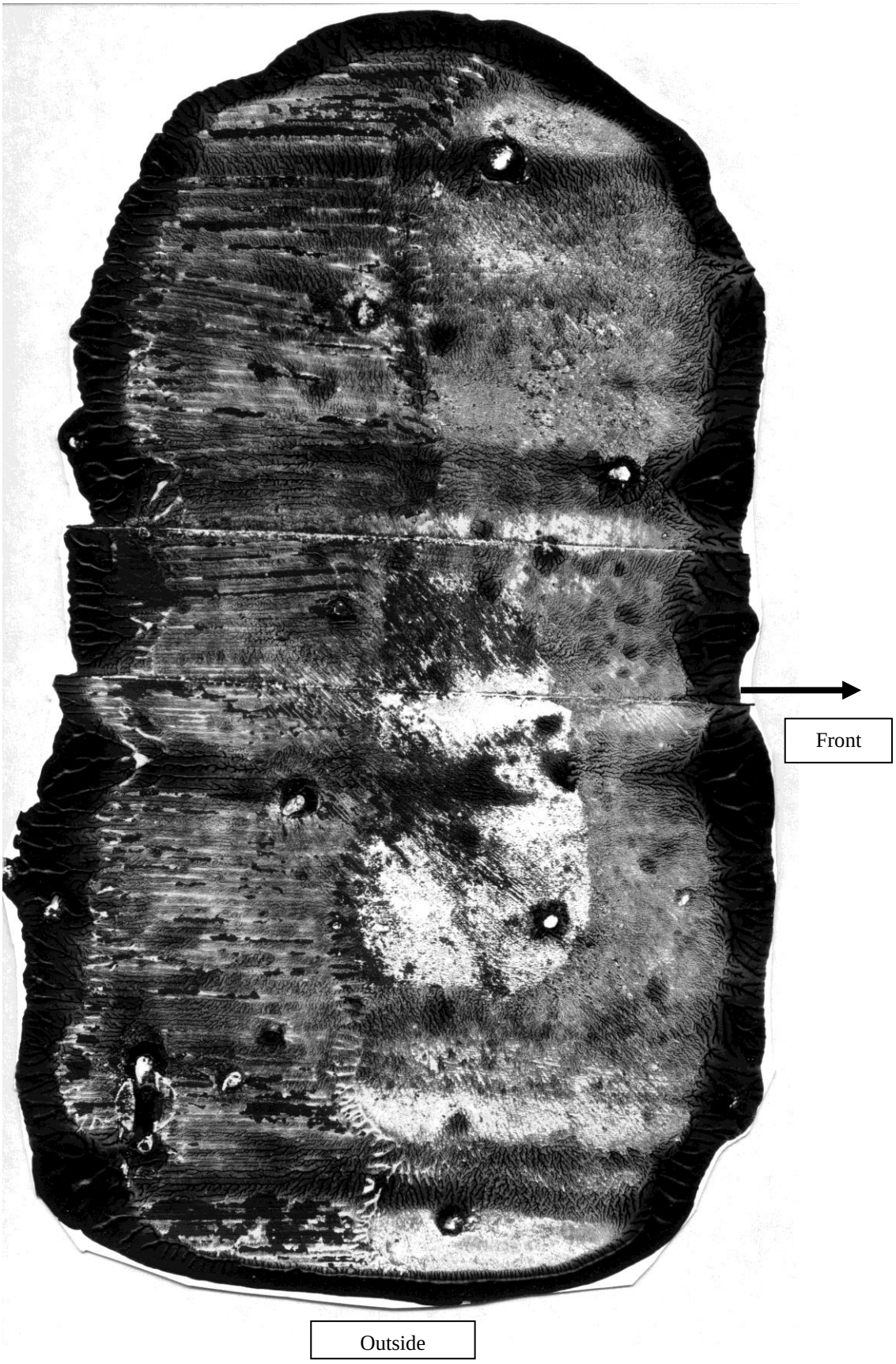


Figure 2-6 - Illustrates to-scale contact patch from a short track stock car racing slick. The patch illustration is made from a 26.0 - 9 - 15 tire with an aspect ratio of 61.0. It is the same tire and conditions as Figure 5 except pressure is 40 psi. Its total contact area is approximately 25 square inches. The right side of the print is the front of the tire and the bottom of the print is the outside of the tire.

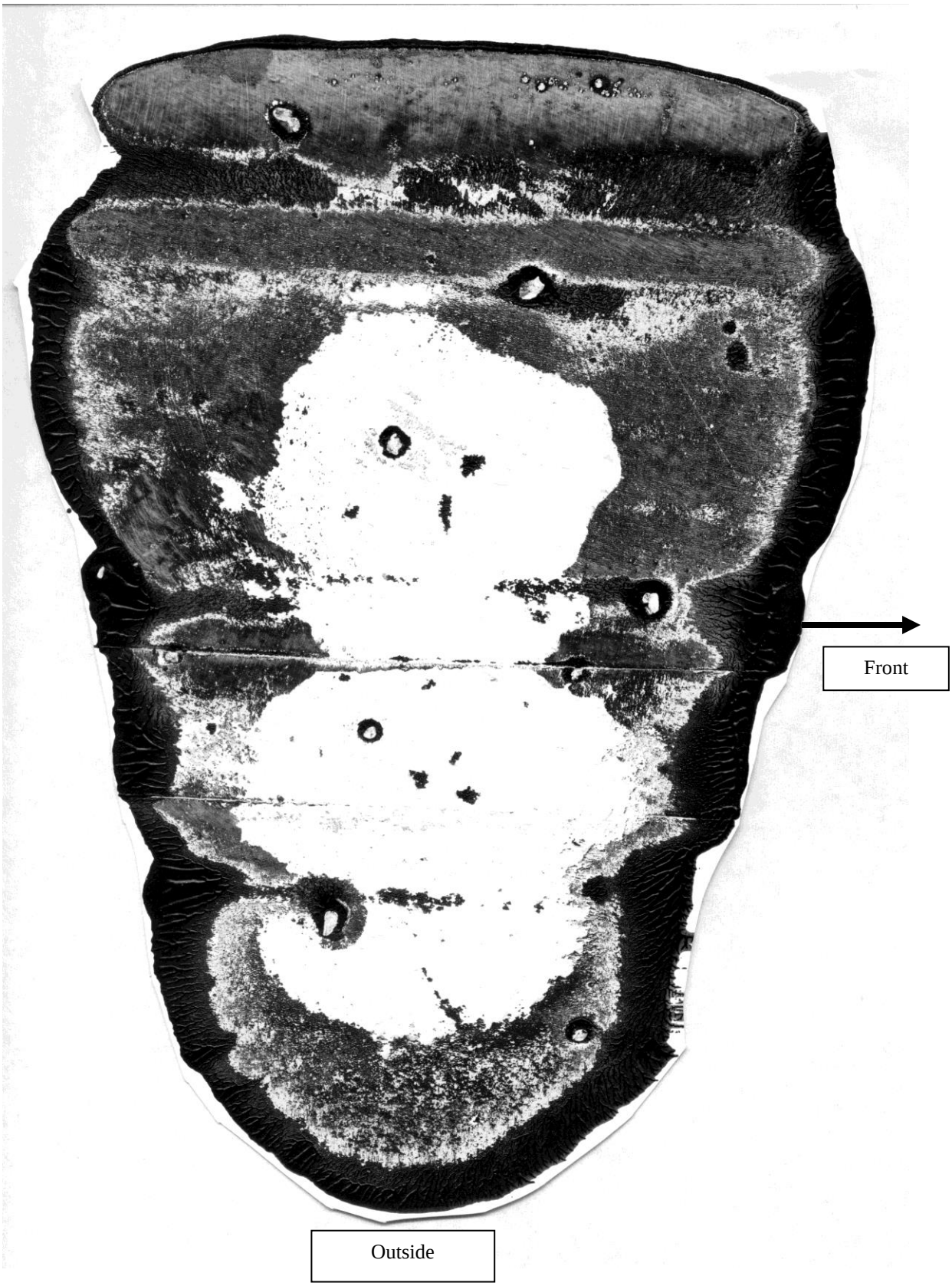


Figure 2-7 - Illustrates to-scale contact patch from a short track stock car racing slick. The patch illustration is made from a 26.0 - 9 - 15 tire with an aspect ratio of 61.0. It is the same tire and conditions as Figure 6 except camber is set at -5º. Its total contact area is approximately 24.8 square inches. The right side of the print is the front of the tire and the bottom of the print is the outside of the tire.

Part One - A Tire Construction Primer

Everything begins and ends at the tire contact patch - easily said but often not so easily remembered. How racing tires work is still a developing science (even tire companies don't have all the answers, particularly the on-track answers) and many of the tire manufacturers are still very reluctant to share their knowledge with race teams because they are afraid of losing their competitive edge. Fortunately, over the past few years, tire data is finally becoming somewhat more accessible to the teams, both by a number of the race tire manufacturers, and, to a much greater extent, by private test facilities. Designing test equipment at MTS Systems Corporation ™ must be like having Christmas every day - *Mechanical Testing, Simulation, Analysis, and Factory Automation*.

At the upper echelons of racing, most tire manufacturers share knowledge on a multi-tiered system with the back markers receiving the least amount of technical data and so on up to the top teams that have testing agreements with the tire manufacturers. But even the teams on tier one get only a portion of the manufacturer's data.

The race engineer needs to obtain as much information from the tire manufacturer's as possible in order to compare it with their own track test data. Manufacturer's data helps both in the design of on-track tests and in validating on-track data. Chapter 19 develops a number of tire test scenarios of the type all race teams need to run.

Tire Design - The modern tire engineer has thousands upon thousands of choices to make when developing a new tire design. The major tire companies have large databases from which they can draw both in-house and track testing information. Before beginning the design process, the engineer will look at the car type (weight, performance windows etc.) and the track (turn radius, track surface make-up, wear factor, coefficient of friction factor, banking, probable race day temperature etc.).

Tire Types - There are two primary types of modern racing tires: the bias ply tire and the radial tire. Both construction types are used extensively. The bias tire is used primarily in the junior classes of racing while the radial tire is found in most of the top racing classes such as ChampCar, Formula One, IRL, NASCAR etc. The mid-level racing classes often have to use radial tires that have their design origins in passenger car tires, which, in turn, end up being rather poor excuses for race tires (In my Humble Opinion - "IMHO"). Within these two types, there are a thousandfold variations and qualities from mega-expensive Formula One tires to short track stock car retreads. The tire performance characteristics depend primarily on the design, construction material and construction quality. Both design and construction quality vary a great deal from series to series as well as from manufacturer to manufacturer. Obviously there is considerably more research, design and construction development going into Formula 1, ChampCar or NASCAR tires than into a short track stock car tire or a Formula 1600 tire. Not all tire manufacturers are equal. Companies such as Goodyear, Firestone/Bridgestone and Michelin with their vast budgets, research teams and facilities can, when they want to or need to, produce a superior tire to the many small tire manufacturers. However, within the junior ranks, the smaller manufacturers often produce a comparable bias ply tire.

When a series changes tire manufacturers, the teams will often need to make major set up changes in order to accommodate the new design parameters. A change of tire manufacturer is much easier for those teams that have the budget and ability to test while the remaining teams may take considerable time to work out the new set ups. This is also the case during a tire war between manufacturers when each manufacturer will bring out a new tire design for each race. This can be particularly interesting when the rubber laid down on the track from the two tire compounds don't mix well.

Tire Construction - The modern racing tire is an extremely complex **visco-elastic** system. The term visco-elastic simply means that when a force is applied to the tire, its elastic qualities produce a reaction force which is able to store that energy (potential energy) over a period of time. The stored energy pushes back with an equal and opposite force. "Visco" within the term visco-elastic means the stored energy or a portion of that stored energy will, at some point in time, begin to relax (flow out) i.e. it is viscous.

The primary structure of a racing tire is its flexible carcass. The carcass consists of high tensile strength cords which are woven into a specific pattern and then molded into various rubber compounds. The cords and rubber casing, in most cases, are attached at each end to a steel cable bead. The bead is used to seat or anchor the carcass to the rim. Air pressure in the tire creates a reaction force that both supports the carcass and holds the bead in place against the rim.

Depending on the tire's intended use, the carcass will be of a composite construction using a variety of different fiber materials and rubber compounds. The fibers may consist of any number of wound fiber cords such as cotton, nylon, polyester, S glass, E glass, carbon, Kevlar™, steel, etc. The composite of materials used and the way the materials are combined and laid up (bundled and orientated) will determine the tire's performance envelopes. The compounding of the rubber also plays a major role in the tire's ultimate performance envelopes. The rubber compound near the bead (shoulder) may well be quite different than the compound used at the thinnest point of the sidewall (knee) and different again below the tread area.

Bias Ply Carcass Construction - Bias ply carcass construction consists of a series of two or more plies running from bead to bead at some angle to the circumference of the tire. This angle is often in the 25 to 45 degree range with each successive ply altered in its layup direction. Inherent problems with the bias ply tire are:

- It tends to allow the sidewall to roll under during heavy lateral loading.
- The carcass in the contact patch area tends to squirm when the tire is rolling.
- The tire circumference and radius tends to grow when air pressure is increased.

Radial Construction - Traditional radial ply construction consists of a series of two or more plies running from bead to bead at a ninety degree angle to the circumference of the tire. Radial sidewalls are stiff in tension but inherently even more flexible in bending than a bias ply tire, which, in turn, provides very little directional stability. Therefore, radial tires require an additional **belt** that runs around the circumference of the tire between the carcass and the tread to provide the needed stability - Figure 2-8. The cord angle of the belt varies from 10 degrees to around 30 degrees and is constructed with each successive ply altered in its lay up direction. Depending on the tire's design parameters, the fibers used in the belt can range from steel to cotton to Kevlar™ composites. The belt provides rolling stability under lateral and longitudinal loading.

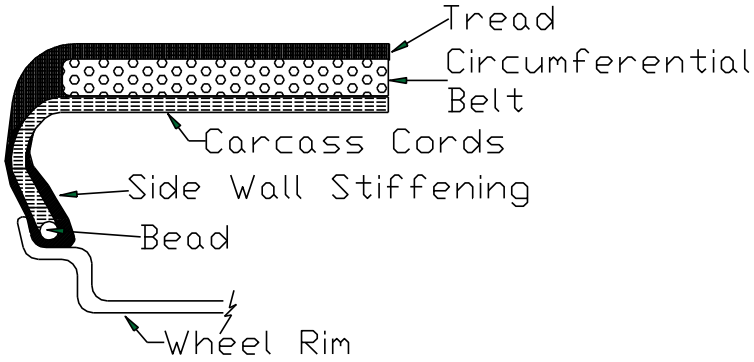


Figure 2-8

The fiber cords and rubber matrix that make up the carcass must also transmit torque which causes the carcass to twist on the wheel, and, as most race tires have to transmit large amounts of torque, this torque would result in the carcass twisting excessively. Therefore, high-torque radial racing tires are also constructed with their cords alternating between some negative and positive bias angle. Without the cord running at a bias angle, torque twisting within the radial tire would cause severe torsional oscillations during hard forward and braking acceleration - Figure 2-9. Without the belt and some bias to the cord angle, a radial tire's performance parameters would be very poor in both lateral loading and torque.

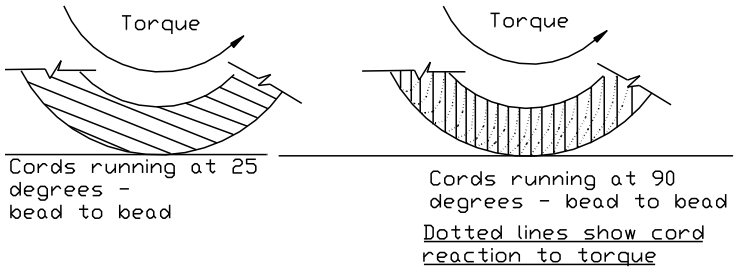


Figure 2-9

Figures 2-10 to 2-14 show a variety of different tire designs.

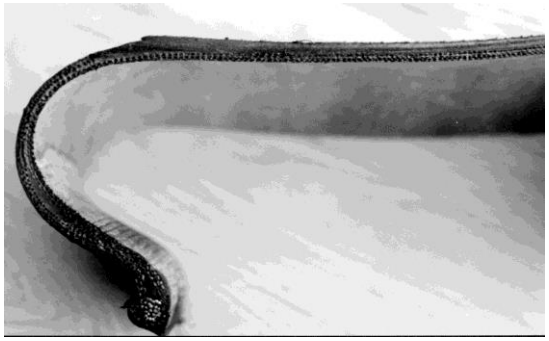


Figure 2-10

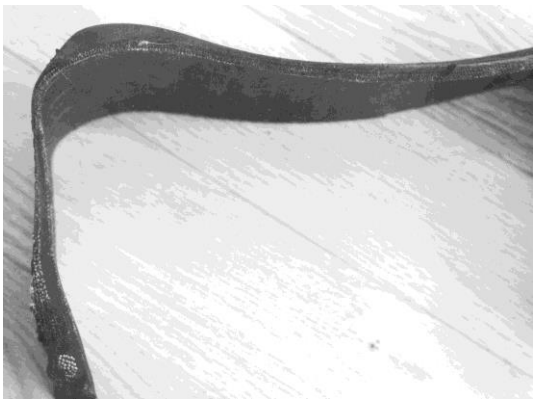


Figure 2-11

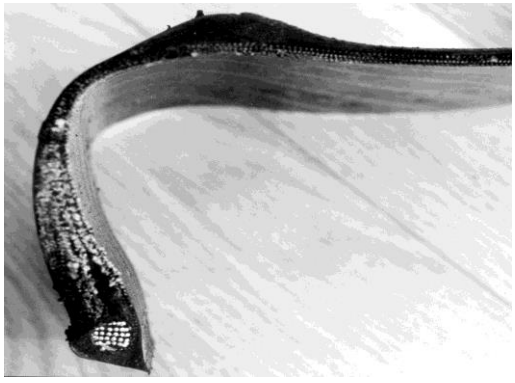


Figure 2-12

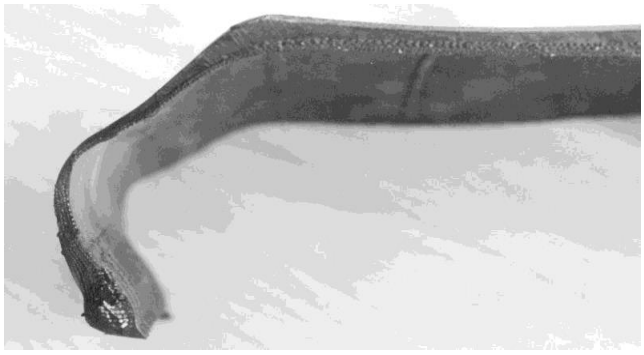


Figure 2-13

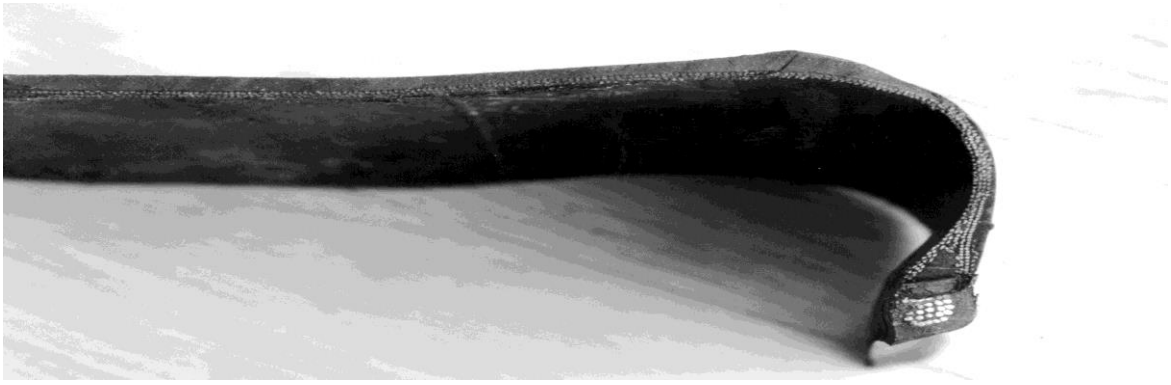


Figure 2-14

Tread Compound - The tread is a complex mix of components and without the molded sidewall serial numbers, even the at-track tire engineers would be unable to discern the tire's composition. The rubber composition of a tire varies not only between the tread and the sidewall but often within different parts of the sidewall and tread. The tread rubber composition (formula) is primarily concerned with frictional and heating properties while the sidewall properties are geared towards stiffness and damping coefficients.

The tread is made up of four primary constituents and a large number of secondary constituents. The four primary components are rubber, carbon black, processing resins and curatives (accelerators, curing agents, catalysts etc.). The tread compound rubber is primarily developed from synthetic polymers (styrene-butadiene, polybutadiene, etc.), and, as stated previously, is a visco-elastic material.

Carbon black is a reinforcing filler which is used to regulate the tire's coefficient of friction and sets sensitivity to temperature. Carbon black itself is a complex mix of materials and can be designed to vary in particle size and how it chemically reacts with the rubber compounds, resins, curatives and the vulcanization process. Carbon black is a black powder developed from heating various viscosities and types of oils in a furnace. Its chemical composition and particle size(s) are defined by the oils used in the process in addition to the heating process. The heating process, in itself, can be quite involved and complex. Carbon black design is constantly evolving with new types being developed on a track by track basis at the upper echelons of racing. There are hundreds of carbon black formulas. A smaller carbon black particle size combined with the tread's other compounds will increase the tire's ultimate surface area (higher coefficient of friction), which, in turn, produces a higher heat factor.

Processing resins (oils) such as plasticizers and tackifiers (the sticky stuff) when combined with the synthetic rubber polymers and carbon black further defines the particular characteristics of a tire. Amongst other things, the processing resins are important in defining the tread's heat and adhesion factors.

Curatives (accelerators) when combined with heat (vulcanization process) cause the many tread components to develop molecular cross-linking, which, in turn, produce one homogeneous compound. Different levels of cross-linking can greatly affect the stiffness and hardness (durometer reading) of the compound.

Tire Size - Tire size is defined in several ways - Figure 2-15. The tire and rim size determines the tire load rating:

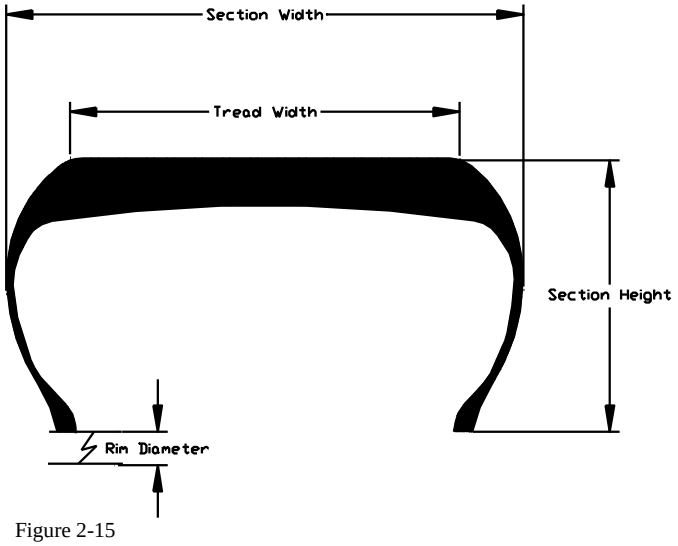


Figure 2-15

- Section Height - Distance from the bead seat to the outer edge of the tread
- Section Width - Maximum width of the carcass (from shoulder to shoulder). Section width can be given in either inches or mm
- Aspect Ratio - Ratio of section height to section width
- Rim Diameter - Diameter of rim at bead seat

The following are two examples of modern race tire designations; however, there are a great number of different tire designations so it's best to measure the tire yourself and then do the aspect ratio calculations. The various units are frequently mixed up.

- 325/35/R16 - where 325 = section width in mm, 35 = aspect ratio, R = radial and 16" = rim diameter
- 25 x 13 x 16F - where 25 = tire diameter at recommended inflation pressure, 13 = tread width, 16" = rim diameter and F = front

  Figure 2-16 illustrates a Goodyear racing tire used in the NASCAR Nextel Cup stock car series. It has a tire diameter of 27.5", a tread width of 12" and a rim diameter of 15".

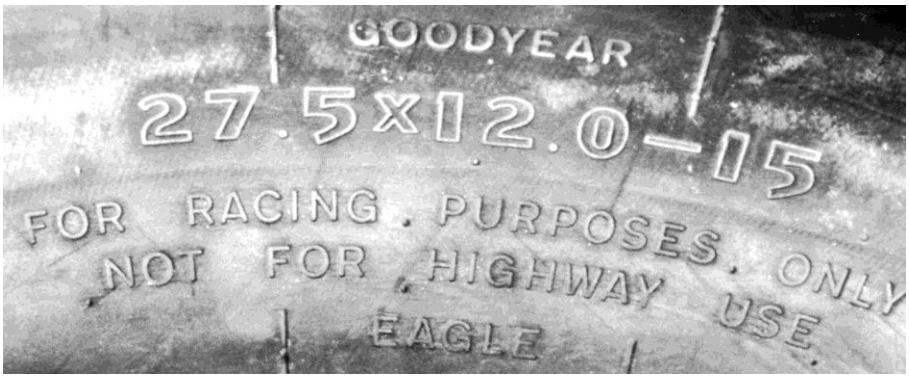


Figure 2-16

Aspect Ratio - The aspect ratio is an important physical factor in determining the performance envelope of modern racing tires which tend to have quite small aspect ratios when compared to street tires. The exceptions are stock car and Formula 1 tires because of mandated rim size and drag racing tires. Figures 2-17 & 2-18 show a variety of modern race tire outlines.



Figure 2-17



Figure 2-18

The aspect ratios in Figure 2-19 are as follows:

- Top Tire (GT - rear) = 32.0
- Second from top (Atlantic - rear) = 40.9
- Middle (USF 2000 - rear) = 53.3
- Second from bottom (Atlantic - front) = 29.
- Bottom (short track stock car) = 75.0



Figure 2-19

The stock car tire in Figures 2-20 to 2-22 is designated as 26.5 x 10 x 15 with an aspect ratio of 55.0.

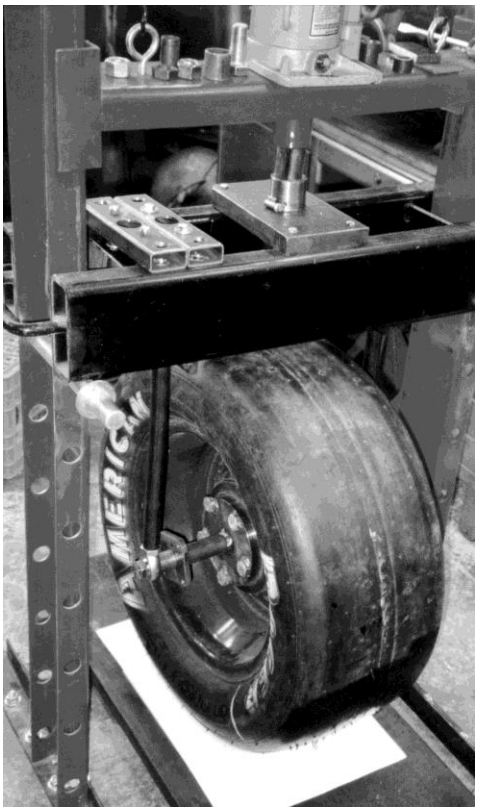


Figure 2-20



Figure 2-21



Figure 2-22

Differences in Aspect Ratios - Figures 2-23 & 2-24 show the aspect ratio of a 2001 sports car tire while Figure 2-25 shows a current dragster tire.



Figure 2-23



Figure 2-24



Figure 2-25

Tire Design Concepts - A tire is a flexible membrane supported by air pressure, which, when subjected to a vertical load, will deform at the point of contact between the tire and the track surface. As the load is increased, the size of the contact patch between the tire and the track surface will also increase - Area = Load/Pressure. If a load of 1000 lb. is applied to a tire with 20 psi, the resultant contact patch will be approximately 50 square inches (1000lb./20 psi). If the pressure is increased to 25 psi, the contact patch area will be reduced to approximately 40 square inches. This formula is independent of the tire's diameter and tread section width. For a given load and tire pressure, both the drag tire and the sports car tire will have approximately the same size of contact patch except the drag racing tire foot print will normally be

longer than it is wide while the sports car tire will normally be just the opposite. The height and width of the tire design is always a compromise between longitudinal and lateral acceleration performance i.e. **tread surface cooling rates**. Though the load on the tire and the pressure within the tire are the two primary factors determining the size of the resultant contact patch, the tire side wall and carcass design also play a small role in determining the contact patch, size. If the tires' sidewalls are sufficiently stiff to support a portion of the load on their own, this formula would need a correction factor added to compensate for the sidewall support. The (A=L/P) calculation is only true when the tire is entirely reliant on air pressure to maintain its shape. Though not completely accurate for **dynamic** conditions, static prints as shown in Figures 2-26 & 2-27 are quite revealing.

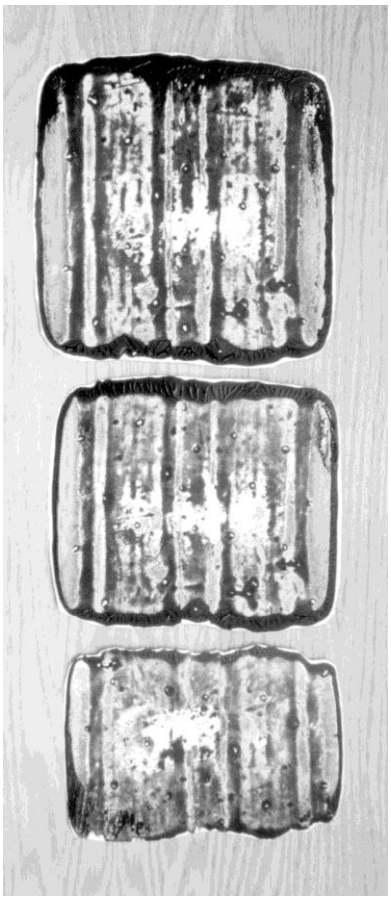


Figure 2-26 - The three contact patches are from the same tire at 35psi but with 500, 1000, and 1500 lb. load respectively.

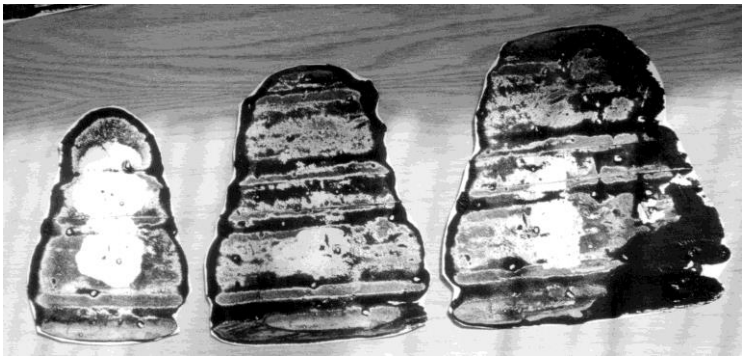


Figure 2-27 - The three contact patches are from the same tire at 35 psi, with -5 degrees of camber but with 500, 1000, and 1500 lb. load respectively.

Table 2-1

TIRE - SWEEP SHEET	TEST NO.	PSI INCREASE - PER - LOAD INCREASE	
Tire ID #33-A-7	Note		
Tread Width 10"	Aspect Ratio 55.0	Tire Diameter 26.520	Datum PSI 20
Load in lb..	PSI	PSI Change	Total Change
0	20	0	0
250	20.1	0.1	0.1
500	20.2	0.1	0.2
750	20.3	0.1	0.3
1000	20.4	0.1	0.4
1250	20.5	0.1	0.5
1500	20.6	0.1	0.6

Like a balloon, when a vertical load is applied to a tire's contact patch, the total volume will decrease, and, as a result, the pressure in the tire will increase, but, in the case of a tire, the increase in pressure is very small. As seen in Table (2-1) a tire pressure gauge attached to the tire can record the air pressure increase as load is applied to the tire. For tires with low aspect ratios and stiff sidewalls, the pressure change for a 100 pound load change is very, very small. Nevertheless, for teams that are looking for that last 1% of performance, knowing the tire pressure change per load change will help explain small handling anomalies resulting from the pressure differences. As will be seen later in this chapter, adding pressure to a tire and observing the load change yields quite a different result.

LATERAL AND LONGITUDINAL FORCES

In order to make a car turn and/or increase or decrease its linear velocity, you need to generate a force that will accelerate the car's mass. In a lateral and/or longitudinal sense (direction), the forces generated through the tire's coefficient of friction are achieved through three phenomena:

- Conventional Friction
- Hysteresis - (also referred to as Gearing and Mechanical Interlocking)
- Molecular Bonding

Conventional Friction Forces - These are force effects which are produced when two smooth bodies whose surfaces are in contact have sliding motion relative to one another (equal and opposite). Unlike engines, transmissions, rear ends and wheel bearings where we want a very low coefficient of friction, with tires we want the highest possible coefficient of friction maintained at a constant level during lateral and/or longitudinal acceleration. Conversely, we want the lowest possible rolling resistance when the car is not accelerating. Conventional friction as described by Issac Newton can be defined as the resistance to relative motion between two smooth objects where such resistance is dependent on load. The greater the load, the higher the friction force is.

Hysteresis - Using the Conventional Law of Friction, a tire would only be capable of producing a coefficient of friction of 1.0 g. But Newton's Laws are for friction between smooth hard bodies and though a tire and track surface may appear smooth, they are not. The tire and its contact patch are an elastic material, which, when subjected to a vertical load, will deform and recover very quickly. This allows the tire to conform to the small imperfections on the track's surface. Engineers call this process **"hysteresis, gearing or interlocking"** - Figure 2-28. Rubber with a high level of hysteresis releases its stored energy quite slowly compared to the type of rubber used in a child's play ball which is developed to release its stored energy very quickly i.e. bounces back very quickly.

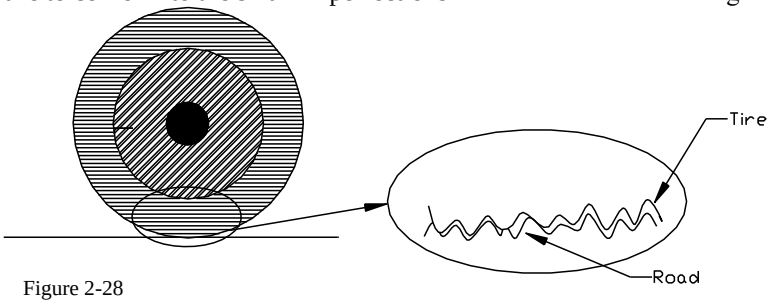


Figure 2-28

This interlocking (gearing) of the tread particles with the track surface greatly enhances the forces produced by conventional friction. The amount the coefficient of friction is increased by hysteresis depends on the track surface (aggregate to filler percentage), the softness of the tread compound and the track and tread temperature. However, if the tread compound is too soft, the track too abrasive and/or the temperature too high, the tread will be degraded very quickly i.e. the tire will blister and/or have chunks of tread ripped off. As will be discussed later in this chapter, tire temperature plays a major role in a tire's performance parameters and longevity. Hysteresis adhesion is not as affected by water on the track surface as is that of conventional friction or molecular bonding. Therefore, hysteresis qualities, as you might imagine, are of

primary importance when developing rain tires. For peak hysteresis performance, chemical compounding of the tread needs to be tailored to each track surface.

Even when a tire is locked up, it will produce a coefficient of friction as a result of conventional and hysteresis friction forces - Figure 2-29.

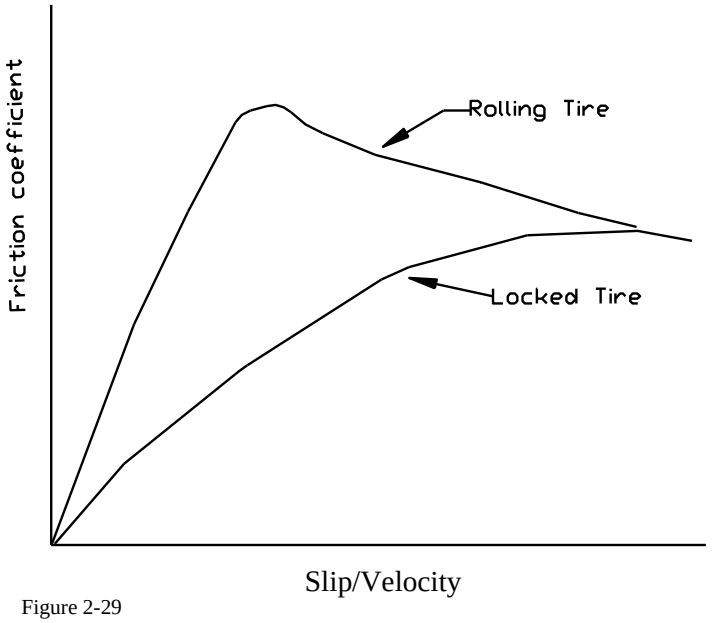


Figure 2-29

Molecular Bonding (Adhesion) - This is the force which tends to hold dissimilar track and tire molecules together. Adhesion works because of the interlocking of molecules, much the same as an adhesive. However, molecular adhesion only adds to the overall coefficient of friction when under some degree of vertical and lateral and/or longitudinal loading. A good example of molecular bonding is seen in the 3M product *"Post It Notes™"*. The interlocking of the note and the surface to which it is stuck is strong enough to affix the note but not so strong that it will tear the paper when the note is removed. The molecular bonding component of a tire's coefficient of friction is of primary importance under dry conditions but is substantially reduced under wet track conditions. For peak molecular bonding performance, chemical compounding of the tread needs to be tailored to the chemical components of each track surface. Additionally, if a race series visits a track twice, once when the ambient temperature is much lower than the second time, different tire compounds would need to be developed for peak performance. A soft compound used in the spring would not last during the high heat of summer.

COEFFICIENT OF FRICTION AND ITS RELATED FORCES – Lateral Acceleration

A tire's coefficient of friction is a percentage that relates to the lateral forces a tire can develop as the result of two variables, for example, the relation between shear angle and traction or vertical load and traction. Traction can be expressed as a force (lateral force) or a coefficient. During lateral acceleration, the forces that move the chassis laterally are a function of the coefficient of friction, which is defined as the ratio of lateral force divided by vertical load i.e. a vertical load of 1000 lb. and a lateral force of 900 lb. produces a 0.9 coefficient. Figure 2-30 shows an example of a typical coefficient of friction versus shear graph (left side) and a traction versus load graph (right side). Notice that in the shear versus coefficient graph, up to a point, the friction forces increase as the tire's tread molecule sheared angle increases. Past that point, the tire loses cornering force very quickly. A tire's lateral coefficient of friction is found by dividing its lateral acceleration force by the normal load applied to the tire. The graph on the right titled, "Tire Performance Curve", shows the relation between lateral acceleration traction force and the normal load applied to the tire.

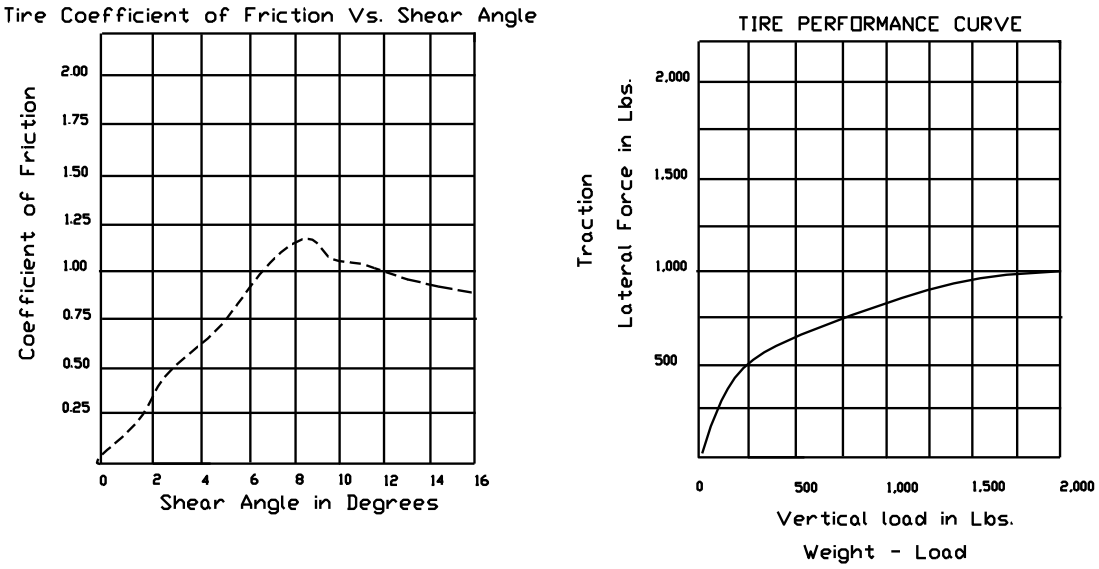


Figure 2-30

Centripetal versus Centrifugal - When a car is turning, it is, in fact, accelerating laterally. It is accelerating towards the center of the arc of its path (center seeking) - Figure 2-31. Centripetal forces are those forces that generate the lateral or deflective forces which try to push the car inwards towards the center of its arc while centrifugal forces (chassis forces) are trying to fling the car out away from the center of the arc (center fleeing). These two forces must be balanced in order for the chassis to corner in a balanced, steady state condition.

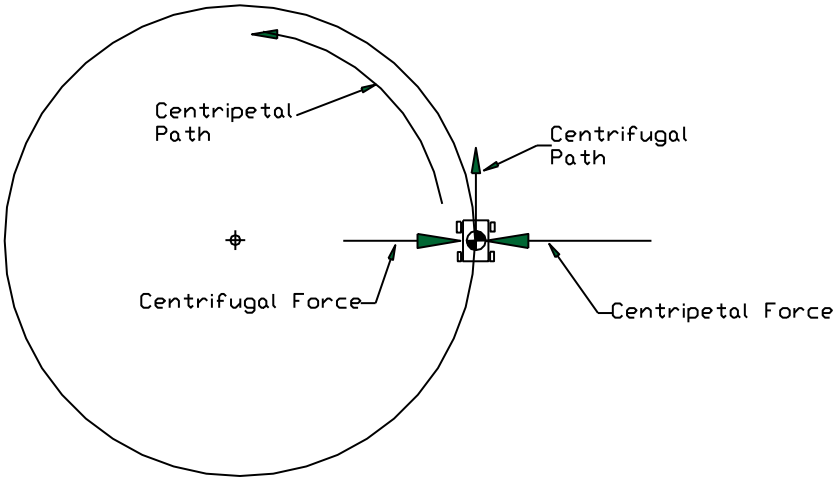


Figure 2-31

The driver feels centrifugal force as a lateral outward force, but, in actuality, this force is simply the body trying to maintain its original inline path. A good example of centrifugal force is to place a small paper box on the dash of your road car and then make a quick turn. As a result, the box looks like it has been flung across the dash, while, in fact, it is the car that has moved, not the box which is simply trying to maintain its original inline direction.

It is the process of **conventional friction**, **hysteresis** and **molecular adhesion** that allows a tire to reach a coefficient of friction greater than one. What this means for the racer is that the tire's resistance to motion between it and the track can be greater than the load applied through the tire onto the surface of the track. If a tire supporting a normal load of 1000 lb. can develop a lateral force of 800 lb., it is said to have a lateral force 0.8 coefficient - 800/1000; if, on the other hand, it develops 1300 lb. of lateral force with 1000 lb. of normal load, it is said to have a coefficient of 1.3 "g" - 1300/1000. Four race tires can produce a

coefficient of friction great enough to laterally accelerate an aero chassis at a constant rate (for 500 milliseconds or more) of over 3 “g” and for very short periods up to 5 “g”.

Lateral Acceleration

As all physics texts will tell you, everything, no matter how it is made, will deflect under an applied load. In the end, everything turns out to be a spring, and, when deflected, it will generate a resisting force - of course some things deflect a great deal more than others. A tire is specifically designed to generate a resisting force when deflected.

It takes a force to accelerate an object (Newton’s First Law) - “A body which is acted on by a resultant force will experience an acceleration directly proportional to this force”. This acceleration, which is a vector quantity, will have the same direction and sense as the resultant force. The amount of force required is determined by the object’s mass. A vector is a quantity which requires three distinctive characteristics in order to be completely defined:

- Magnitude
- Direction
- Sense

An excellent reference book for Vector Mechanics is, *“Vector Mechanics For Engineers Volume I and II”, by* Joseph F. Shelley. It is published by Schaum/McGraw-Hill Inc.

Lateral Force - The cornering forces generated by a tire are referred to as **lateral forces** with their efficiency described by the coefficient of friction. A tire can not produce its peak amount of lateral force without being deformed (sheared).

In order to create a lateral force, the tire must first be turned/steered (except in the case of aligning forces and/or cross winds or other aero phenomena) at some angle away from the steady-state direction of travel, at which point, Newton’s Third law comes into effect - “For every force action of a body on a second body, there is an equal and opposite force action of the second body on the first body”, or, “ For every action there is an equal and opposite action”. Because the tire has a lateral coefficient of friction and is running at an angle to the car’s steady-state direction, a series of action and reaction forces are created. The tire contact patch sticks to the ground but the car’s mass wants to keep moving in a straight line causing the track surface to push back and deform the tire. The tire’s resistance to deformation is what generates the lateral forces needed to move the chassis laterally, hence, lateral acceleration.

Terms, Definitions and Explanations

Important Note: The term “slip”, in reference to tire performance, is often used to describe **two** completely different types of actions. It can mean the amount the tread particles are sheared (cantilevered, pushed aside, offset, deformed or bent) and/or the act of the tread particles slipping back to their at rest position. The first action denotes an amount of force/grip while the second action denotes a lack of force/grip. The term slip angle is also often interchanged with the amount the tire is steered. In this book **slip** refers to the action of the tread particles slipping back to or towards their at rest position while **shear** refers to the amount the tread particles are sheared (offset from their at rest position) during acceleration. Steer refers to the amount the steered wheel is turned from its straight ahead position.

I realize this is not in accordance with the current automotive convention and I apologize to those who find the use of the word “shear” to describe the forced deformation of the tread particles under acceleration offensive. I sincerely hope the academic racers will not think too harshly of me for this deviation from convention. It is definitely not my intention or wish to be seen swimming upstream in terms of academic protocol and if I can be convinced that the use of the term “shear” does not make educational, manufacturing and/or racing sense, I would most certainly be willing to “scrub it”. My whole goal in using the word “shear” was to decrease the levels of confusion I routinely find racers, manufacturers and academics have when using “slip” to describe two opposite functions.

Tire Shear - The bending/deforming of the tread particles, the sidewall and/or the tire carcass during acceleration.

Sidewall Shear Displacement - The amount the sidewalls are displaced from their at rest center line.

Tread Shear Displacement - The amount the tread particles are displaced from their at rest center.

Total Shear Displacement - The combined amount the tread, sidewall/carcass and belt are displaced from their at rest center line - Figure (2-32).

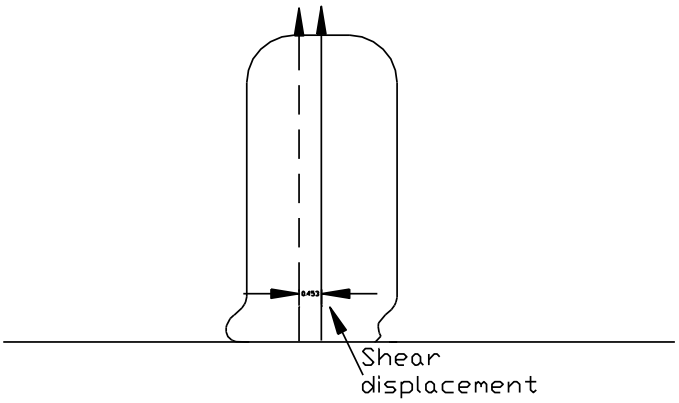


Figure 2-32

Tread Shear Angle - The angle of tread particle displacement within the contact patch - Figure 2-33.

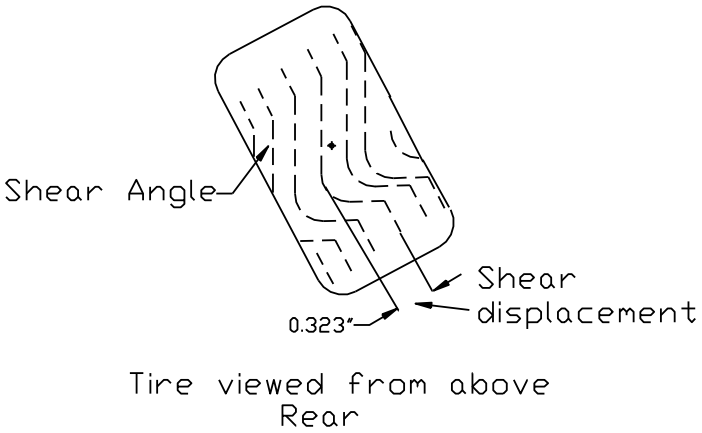


Figure 2-33

Sidewall Shear Angle - The angle of sidewall, carcass and belt (radial tire) displacement from their at rest center line - Figure 2-34.

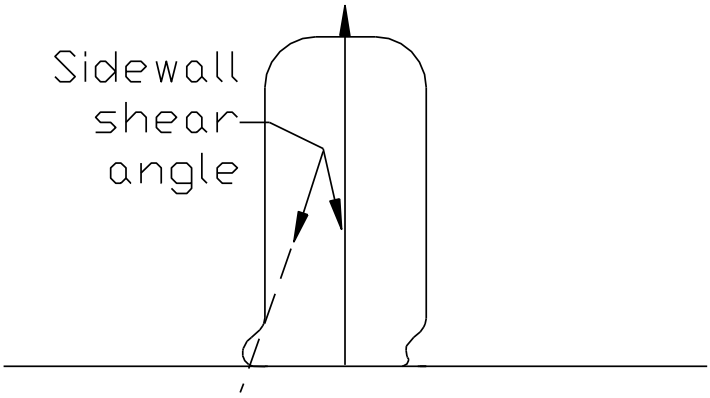


Figure 2-34

Total Shear Angle - The combined tread and sidewall/carcass angle of shear - Figure 2-35.

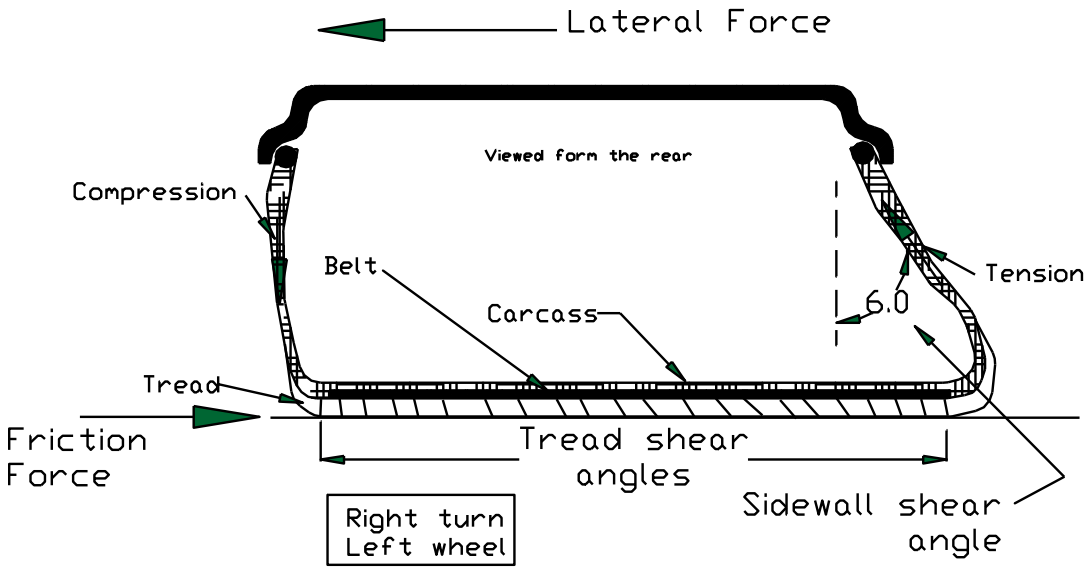


Figure 2-35

Slip - Slip is when the tread particles have stretched past the point of maximum deflection, are losing grip and begin to slip back to their original at rest position. At or near the peak of tire performance, this process is taking place on a continuous basis.

Slip Angle - The difference between steer angle and combined shear angle is slip angle - Figure 2-36. Slip angle represents the difference between the amount the tire is turned compared to the combined shear angle the tire is able to produce without **slipping (losing grip)**. For example, with 7 degrees of steer angle, if the tread shears 2 degrees and the sidewall 3 degrees, the slip angle would be 2 degrees – [7-(2+3)] = 2. The tire is turned 2 degrees past the amount the combined tread and sidewall can shear.

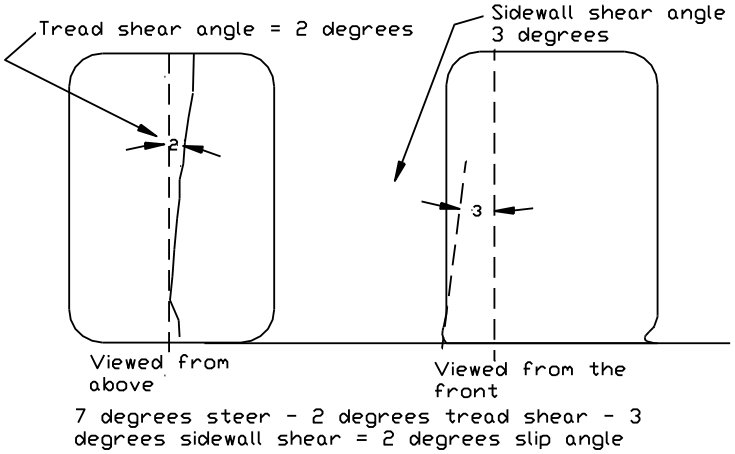


Figure 2-36

Trailing Edge Slip Percentage - The percentage of tread particles that have exceeded their coefficient of friction at the trailing edge of the contact patch in relation to the contact patch's length is referred to as the slip percentage - Figure 2-37. As the slip percentage increases past a certain point, for example 30%, some of the tire's tread particles will begin to slide. At 50% the tire is sliding enough to produce whiffs of tire smoke i.e. the **sliding** tread particles are unable to grip the track sufficiently to shear, but, instead are simply sliding across the track surface without producing significant amounts of molecular adhesion.

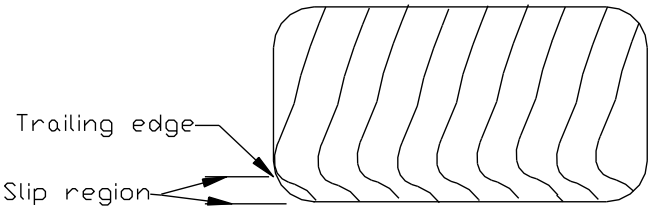


Figure 2-37

Lateral Shear Forces Versus Lateral Acceleration - As the steered wheel rolls forward, the tread molecules in the contact patch are displaced sideways relative to the tire's center line. The visco-elastic forces within each successive contact patch, in turn, tend to pull the centerline of the rim towards the center of the contact patch displacement, thereby laterally accelerating the chassis. Depending on a great number of factors, the amount the chassis laterally accelerates can be greater or less than the steer angle. The amount that the tire is laterally displaced per contact patch is primarily a factor of the tire's coefficient of friction in relation to the combined **tread** and **sidewall** shear displacement. A coefficient graph can be developed to determine the amount of lateral acceleration per amount of combined tread and sidewall deflection.

Tread Shear Angle - As the tire deforms, the tread particles are moved (sheared) in the direction of the lateral forces. The angle at which these tread particles are sheared is known as the **Shear Angle** - Figure 2-38. The tire's contact patch can be forced to point in one direction while it is headed in a slightly different direction. The angle of shear at the front tire is primarily controlled by the steering input angle versus the tread's depth and modulus of elasticity. Tire design and construction, normal load, track conditions, amounts of tractive or braking forces, etc. all help determine the resultant shear angle of the tread particles. Though exaggerated in the illustrations for clarity, remember the individual tread particles are only able to stretch (cantilever) a small amount in regards to total tread particle displacement.

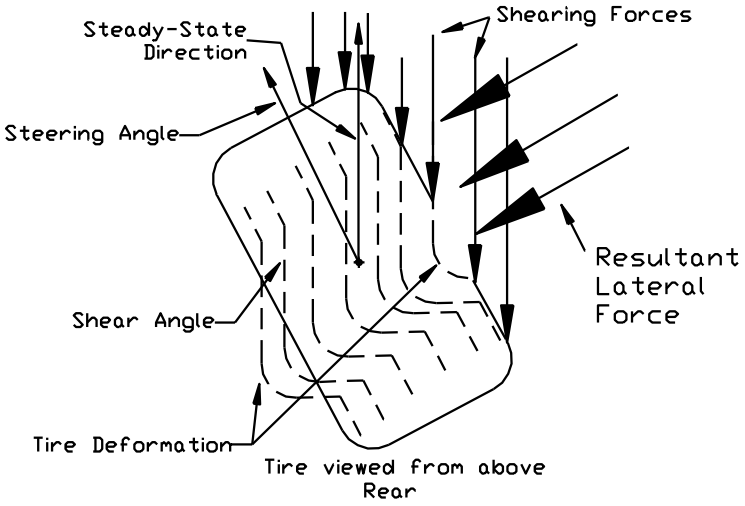


Figure 2-38

Tread Particles - The tread particles do not act independently of each other but instead push and pull one against the next much like the fibers in a cleaning brush - Figure 2-39. The fiber particles in Figure 2-40 require a higher force to move a prescribed amount than the softer fibers in Figure 2-39. This is also the case with different tread compounds. As in the case of tire tread depth, a shorter fiber of equal strength will produce a higher force for an equal amount of shear - Figure 2-41.



Figure 2-39



Figure 2-40

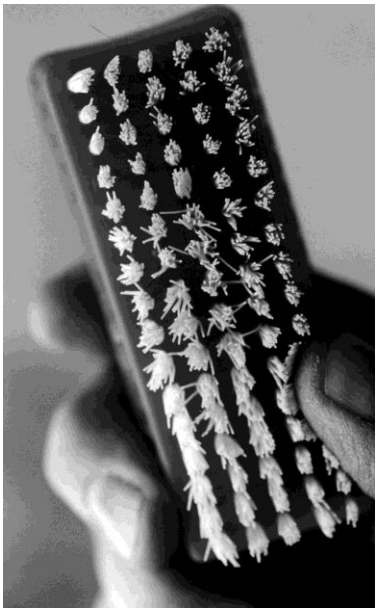


Figure 2-41

Chassis reaction (centrifugal) forces also control the size, shape and coefficient of the tread shear pattern - Figure 2-42. The centrifugal chassis reaction forces tend to increase both the tread and sidewall shear angle. In so doing, they tend to stretch the tread and sidewall particles past their elastic limit, which, in turn, leads to slip and a lowering of the tire coefficient of friction. If not for the chassis reaction forces, the combined sidewall and tread shear angle would be quite similar to the steer angle providing the tread and sidewall combined modulus of elasticity was great enough. Once the steer angle is greater than the tire's combined shear potential, the tire will begin to develop slip within the body of the contact patch.

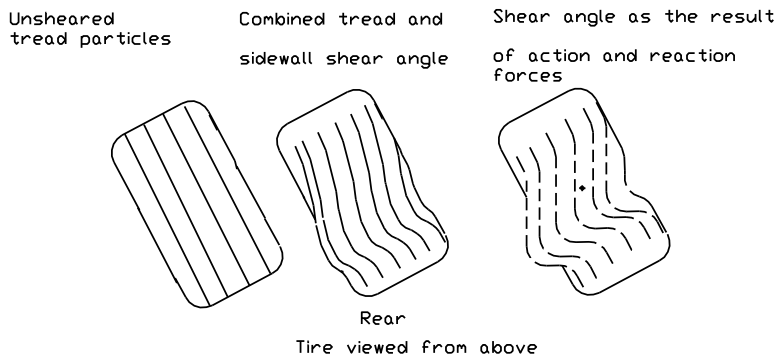


Figure 2-42

The lateral reaction forces resulting from tire deflection (shear) reacts to the track surface at more or less 90 degrees to the tire steered plane - Figure 2-43. If the tread particles are already deflected to their maximum shear angle as the result of steered action forces, they will be unable to sustain any further lateral reaction forces unless the reaction forces also increase the tire's vertical loading, which, of course, will be the case. How much additional load is added to the tire is part of the endless search for the ultimate set up. As will be discussed ad infinitum throughout the five book series, adding load to an outside tire while losing load from an inside tire only degrades the chassis' overall performance i.e. the increase in inside tire coefficient of friction is not proportional to the outside tire's loss in coefficient of friction. In almost all cases, the combined inside and outside lateral force is less than if the vertical tire loads were more evenly balanced.

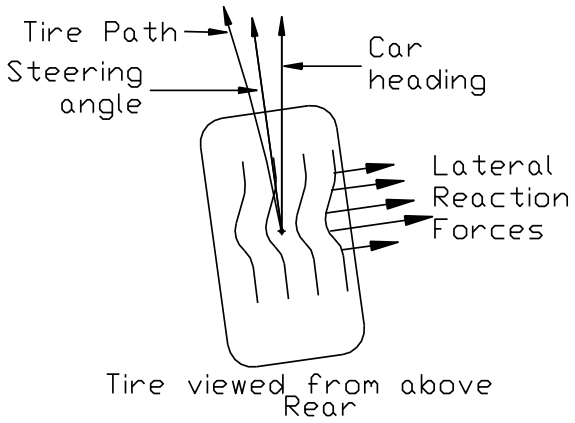


Figure 2-43 Yes, under the right circumstances the tire path can be outside the steer angle.

Tread Shear Displacement - Shear displacement is the amount of tread particle displacement within the contact patch due to shearing forces. The amount the tread particles are deflected (sheared) vary a great deal from point to point within the contact patch as well as from moment to moment in time. Additionally, the peak vertical load placement is constantly moving under dynamic conditions.

Percentage of Shear Displacement - Shear percent is the percentage the tread particles are displaced in relation to the contact patch length (looking up at the tire contact patch from the road surface). 7% shear with a contact patch length of 5.218" = 0.365" (7%*5.218). *The 7 % shear is an arbitrary chosen number used for this example*.

Shear Angle - Shear angle is the angle of the shear from the leading edge to the point of maximum acceleration force (looking up at the tire contact patch from the road surface). With a contact patch length of 5.218" and 7 % shear, the shear angle = 3.9967 degrees - Figure 2-44.

Shear Displacement - Shear displacement with a contact patch length of 5.218" and 7% shear = 0.365" Figure 2-44. If shear is kept at 7 percent and the contact patch length is increased to 8.566", tread displacement is now 0.6" and shear angle increases to 4.012 degrees - Figure 2-45.

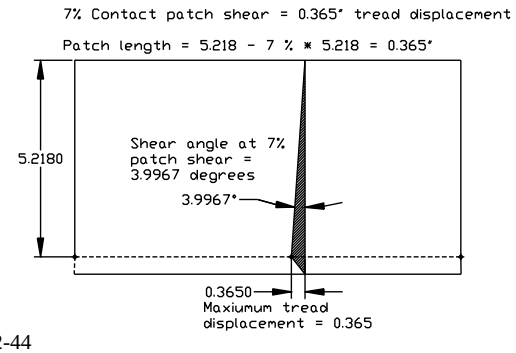


Figure 2-44

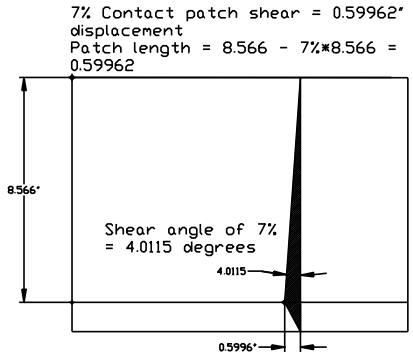


Figure 2-45

Tread Cantilever Displacement Angle - The cantilever displacement angle is the angle of deflection of the tread particles from their at rest position in reference to tread depth. Considering a tread depth of 1/4", a contact patch of 5.218 and 7% contact patch shear, the tread from its at rest position would be displaced 0.365". The cantilevered angle of the tread would be 55.5523 degrees - Figure 2-46.

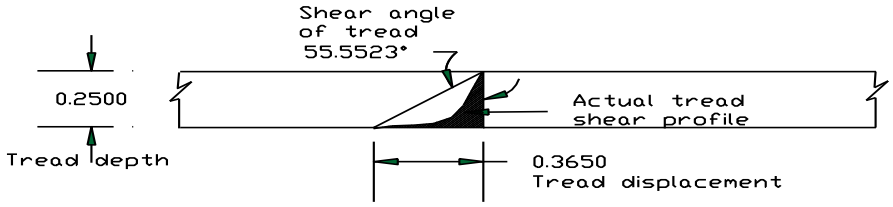


Figure 2-46

If, on the other hand, the tread particles were only able to cantilever 0.100", they would exhibit an angle of 20.172 degrees - Figure 2-47.

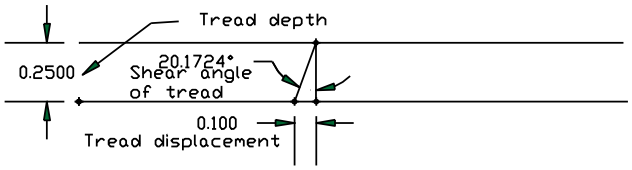


Figure 2-47

A thinner tread will not need to cantilever as far in order to achieve the same acceleration forces, or, conversely, a thicker tread depth requires a higher angle of cantilever to achieve a comparable acceleration force. Of course, a thinner tread will exceed its cantilever limit at a lower angle. As one can imagine, there are an endless number of play offs between using a thicker or thinner tread depth.

Sidewall Shear /Deflection - Sidewall shear (deflection) of a tire also produces lateral acceleration forces as a result of its elastic deformation. As in the case of the tread's coefficient of friction versus shear angle, the sidewall also has a coefficient of friction versus shear angle. It is the combination of tread and sidewall forces that determine the tire's ultimate lateral acceleration potential. Modern racing tires with their lower aspect ratios are producing significantly higher coefficients of friction than in the recent past.

Sidewall Shear Displacement - Seven degrees of sidewall deflection (shear) for a tire with a section height of 6 inches results in a shear of 0.7354" while 7 degrees of deflection for a tire with a section height of 3 inches is much less at only 0.3768" - Figures 2-48 & 2-49. Obviously, a shorter section height makes the sidewall a great deal stiffer. However, as in the case of tread depth, a shorter sidewall will produce a higher acceleration force per angle of deflection but will be able to shear less before it exceeds its shear limit. *The integer of 7 degrees is an arbitrarily chosen number.*

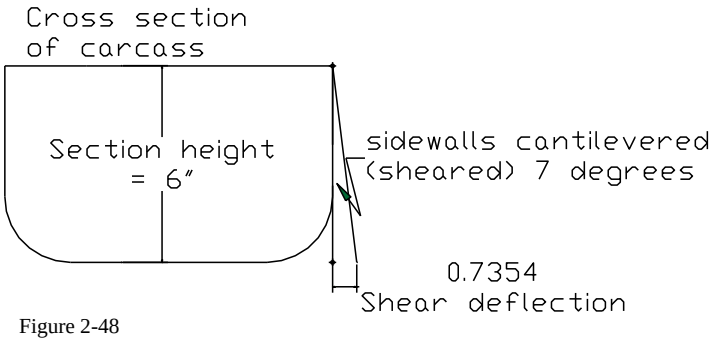


Figure 2-48

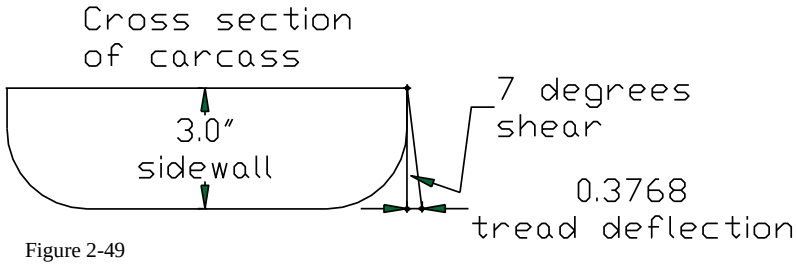


Figure 2-49

Maximum Tread Shear Angle Versus Maximum Tread Shear Force - Maximum force within the tread particles will be produced at a shear angle **less** than the maximum shear angle. Depending on tire design, the maximum tread shear force will typically occur at between 1 and 5 degrees of shear i.e. while the tread particles may be able to sustain a shear angle of 7 degrees, the peak shear forces may occur at only 2 degrees.

Measuring Tread and Sidewall Shear - If this type of information cannot be obtained from the tire companies, then a series of measuring devices as described below can be used. Static force and shear measurements are never as good as dynamic information, but, either way, it is obvious various correction factors will need to be added to correlate with on track performance. Measurement of the various shear angles is not all that easy to do with any sort of complete accuracy. Having said that, the information you do glean is still more than worth the time and effort. This type of information helps explain anomalies in the on-track performance. Book Three documents the design, building and use of these types of devices while Book Four makes considerable use of the related information.

Measuring Tread Shear - The jig in Figure 2-50 is used to apply a prescribed vertical and lateral load/force. The inner part of the carcass is first machined flat and epoxied to the steel base. After the tread is epoxied to the base, grid lines are scribed into the bottom and side of the tread using a razor blade and a spring steel template with fine gridlines laser cut, hot wire cut or electrode cut into it - Figure 2-51. The steel base and carcass, tread down, is then placed on the glass plate. A camera is affixed under the glass plate to record the shear movement for the various vertical and lateral load combinations.

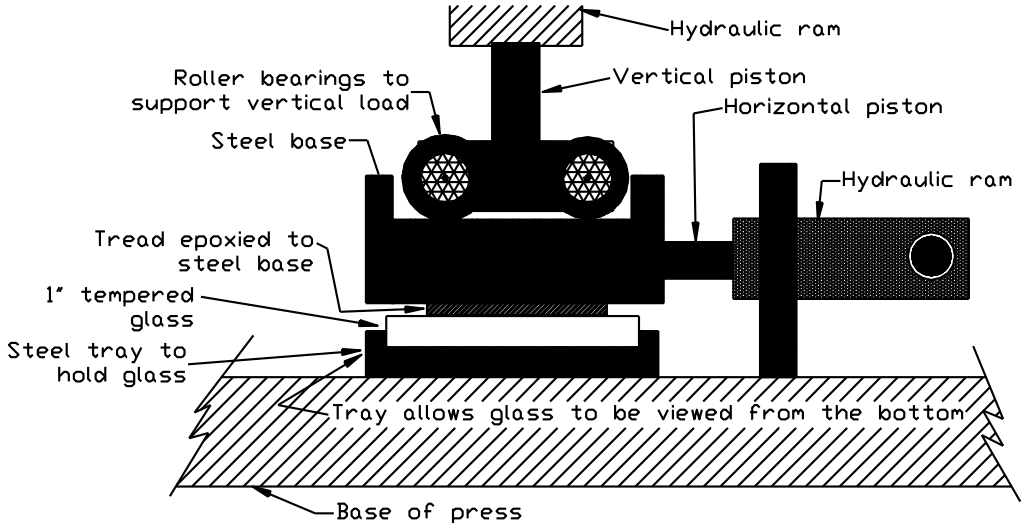


Figure 2-50

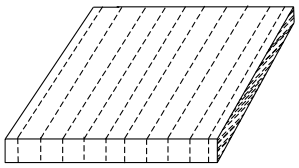


Figure 2-51

Measuring Sidewall Shear Angle - The jig used to measure sidewall shear is shown in Figure 2-52. It applies a prescribed lateral and vertical load/force at the hub centerline. Measuring sidewall deflection is a fair bit more complex than the drawing would indicate. Unless you have lots of time and money, leave the strain gauge development for measuring the shear forces to someone with **considerable** knowledge in this area. Even better, make friends with the tire engineers and while buying them copious amounts of beer, ply them with those ponderous little tire questions.

One could spend millions building or purchasing test equipment of this type and in today's racing world, many teams do.

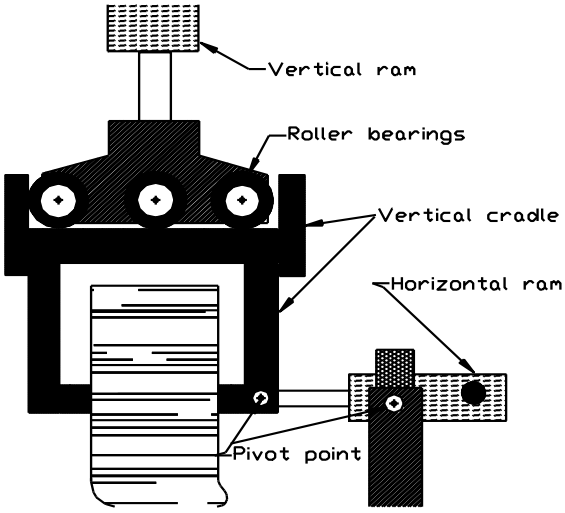


Figure 2-52

The difference between different vertical and lateral load combinations even using simple machines as described above is quite mind boggling let alone comparing a range of different tire designs. Using software to control the ram motion provides a much more accurate picture. There are a growing number of equipment manufacturers and independent test facilities that would be more than happy to provide this type of equipment and/or testing.

The Turning Process - *Revisited*

As the steering wheel is turned, the tire is pointed away from the car's steady-state direction. Once the tire starts to turn, it almost immediately begins to deform at the contact patch and sidewall with peak shear occurring somewhere between one and one and a half revolutions of the tire. The elastic resistance to this deformation generates the initial lateral force. Up to a point, each increase in steering angle will increase the tread and sidewall shear angle, which, in turn, will increase the car's cornering forces, much the same as the amount of potential energy stored in an elastic band can be increased as the elastic is stretched further and further up to the point where its elastic limit is exceeded. As in the case of an elastic band, if the pneumatic tire has its elastic compounds stretched past its elastic limit, it will yield no further potential energy gains. At this point, one of two things happens:

- The tread particle loses grip and begins to slip back to its at rest position until it reaches a point where it is able to regrip
- The particle is ripped from the tire surface and deposited onto the track surface

Tread Forces - As the tire rotates, its tread particles gradually begin to deform and stretch at the contact patch's leading edge, reaching its maximum deformation just before the trailing edge. As the tread particles rotate past the trailing edge, they quickly snap back into line. As the tire rotates, this process is continuously repeated. The peak lateral forces are generated just before the trailing edge, which, incidentally, is seldom the point of highest vertical load. As each set of tread particles rotate past the trailing edge, the vertical load is released. At this point, a small amount of slide occurs as the tread particles snap back in line. If, for some reason, the tire's coefficient of friction is exceeded, this sliding begins to migrate from the trailing edge towards the leading edge, further lowering the tires coefficient of friction.

Path - As the tire rolls forward, the laterally deflected forces within the tread, belt and carcass push the chassis laterally at an angle to the steady-state direction, creating lateral acceleration. This sideways motion is referred to as the tire's **path** - much the same as if you were trying to walk in a straight line but someone kept pushing you off line. "The ability of the tire to travel outside its plane without appreciable slippage is the result of laying down successive prints, each laterally displaced because of the sideways tire distortion. It is equivalent to heading in a given direction but walking at an angle to that direction by placing each foot laterally as it is put on the ground. The tire behaves as if it had an infinite number of feet around its periphery"[1] - Figure 2-53 & 2-54.

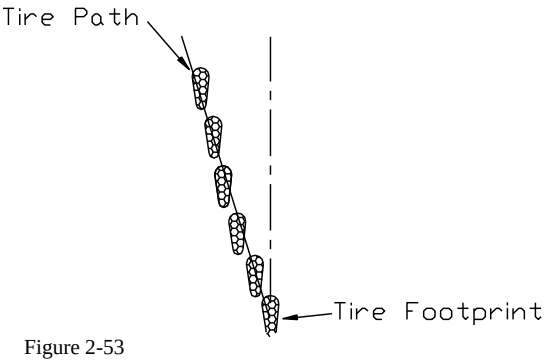


Figure 2-53

[1] *Milliken , W.F. and Milliken., D.L. (1995) Race Car Vehicle Dynamics. USA; SAE International, pg.*

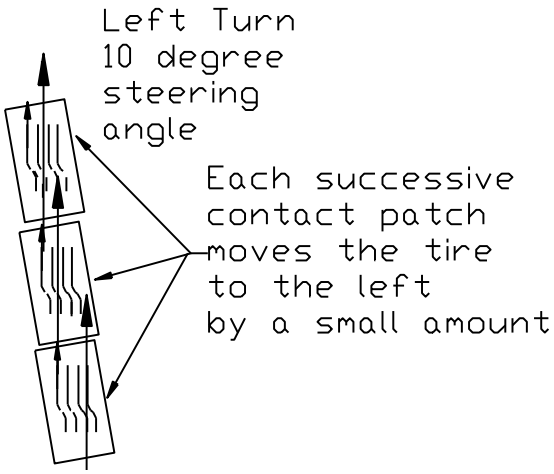


Figure 2-54

Figures 2-55 & 2-56 illustrate the resulting footprint from a small tire sprayed with black paint and run at a right turn shear angle i.e. the tire is rolled straight ahead (per arrowed line) while a lateral force is applied producing a right turn shear angle.

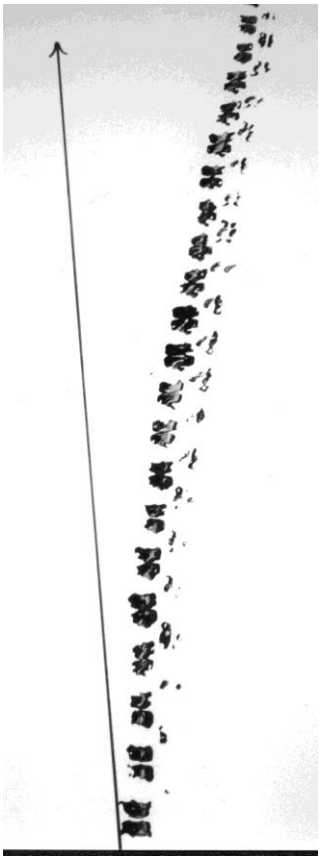


Figure 2-55



Figure 2-56

Shear Angle Versus Heat Generation. - The higher the shear angle, the higher the heat factor. The amount of heat the tire generates is directly related to the shear angle versus lateral force. If the lateral force is doubled for a given speed, the shear angle (ratio) will need to be halved to maintain the same heat factor. **Work produces heat**. As discussed in subsequent chapters, a tire's heat factor is an important tuning tool.

Remember that a particular steer angle, shear angle, tire heading and chassis heading, though closely related, will not necessarily be the same for any particular coefficient of friction number. For example, an increase in camber angle can lower the required steering input, and, subsequently, its related shear angle, while still obtaining the same amount of chassis lateral acceleration.

Speed - When running on a dry track, both the peak and sliding (hysteresis) coefficients decrease with an increase in speed (velocity) - Figure 2-57. "If you ever tried to push a heavy cardboard box on the sidewalk you would have noticed that it is harder to start it moving than to keep it moving once it starts. This kinetic coefficient of friction is always smaller than the static coefficient of friction. As any farm boy knows it is better to drive fast and skip over the tips of the bumps on a rough road than to drive slow and ride the peaks and valleys." Dr J. J. Salinas

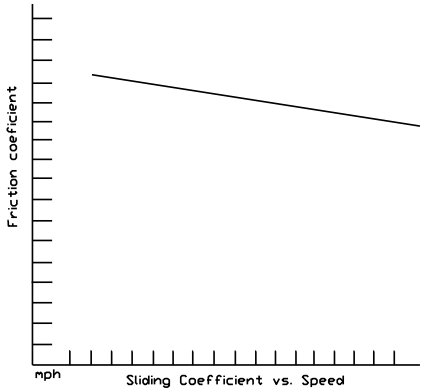


Figure 1

Track Surface Friction - The makeup of the track surface and its condition play an important role in a tire's ultimate achievable coefficient of friction, both in regards to hysteresis and molecular adhesion.

Tire Path - Tire path is the angular difference between the tire heading or plane of rotation and the tire's actual direction of motion.

Car Path - Car path is the angular difference between the car's initial heading and its present path. An individual tire path is seldom the same as the car's path which is the result of forces created at all four contact patches.

Figure 2-58 illustrates some of the planes and paths involved in the steering process.

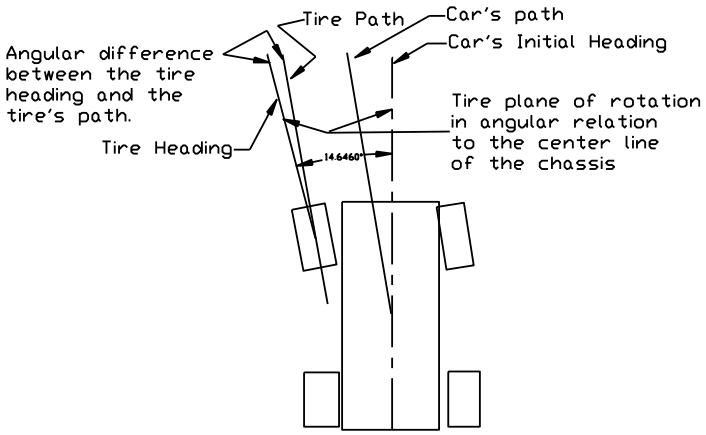


Figure 2-58