Session-4

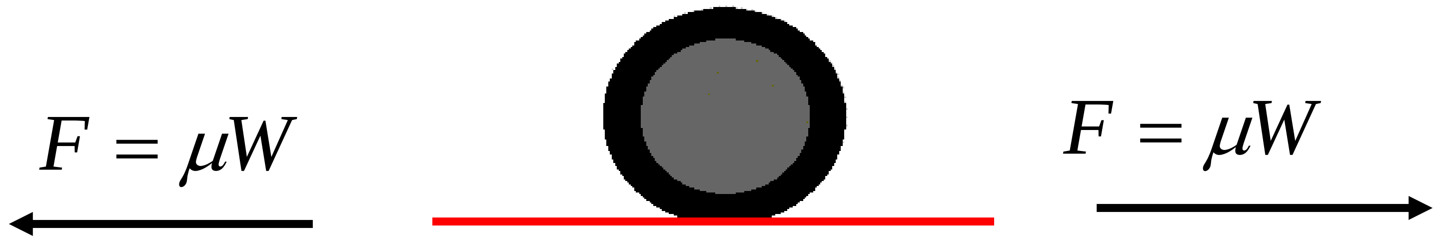
Friday, 9.30 AM-11.00 AM

Tyre Dynamics

- Role of Tyres in Vehicle Performance

Friction Circle

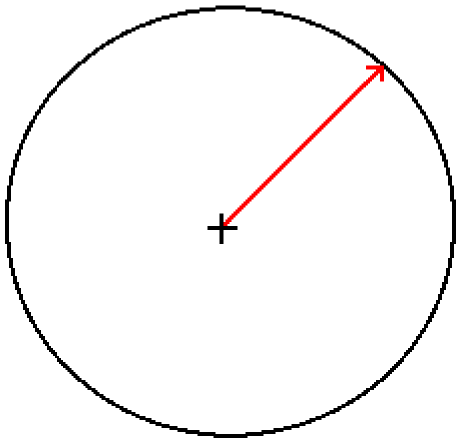
Friction Circle is a tool that can be used with any type of car (or truck) to graphically represent traction capacity of a ground vehicle



The illustration above shows the traction force to the front or rear; however, the traction force can be generated to the side or any other direction in the horizontal plane. Because the tire can develop the force in any direction on the horizontal plane, it provides the basis for the friction circle theory.

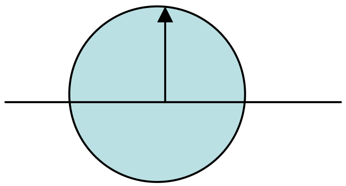
Friction Circle

The tire's traction force can be in any direction, the force arrow can also point in any direction. So now imagine the force arrow was to sweep 360 degrees, like the hands on a clock. The limit of the arrow would then describe a circle

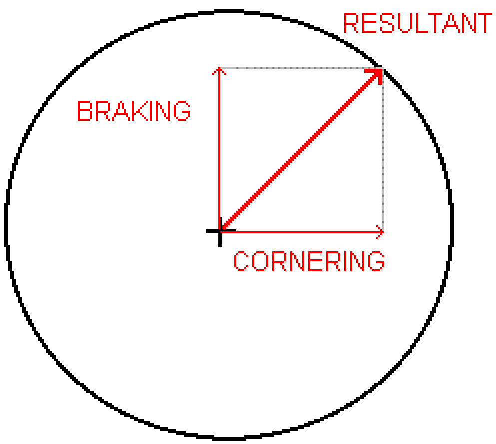


The circle is simply a graphic means of illustrating that the tire's maximum traction can be developed in any direction.

Application of Friction Circle Theory



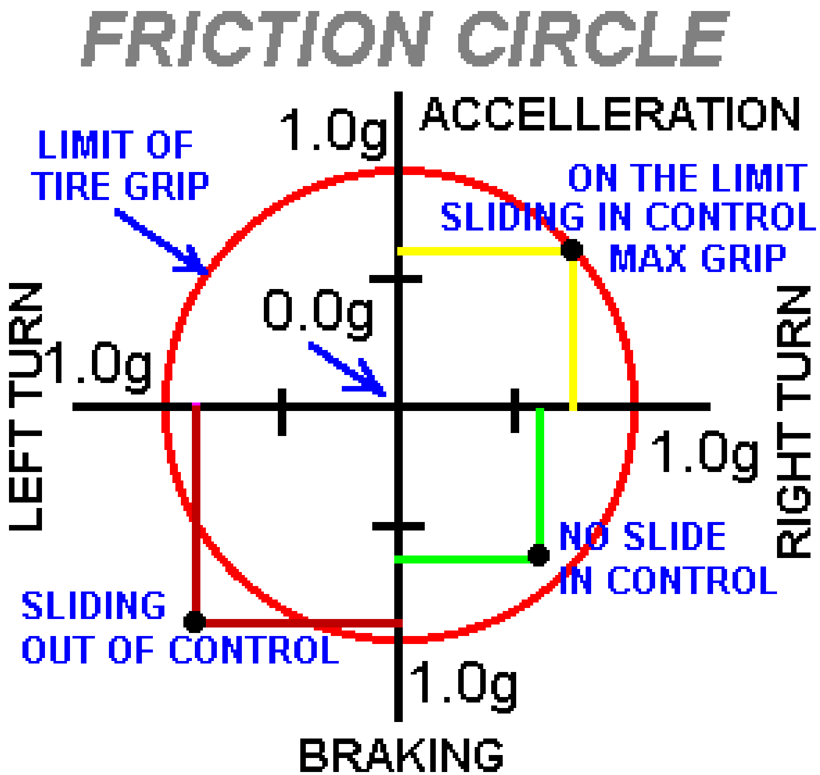
- Now, imagine that you are driving your car in a straight line and you slam on the brakes to the point that the wheels almost lock up. The tires are now at the limit of their traction and the arrow on the friction circle would be pointing to the front and at the limit of the circle

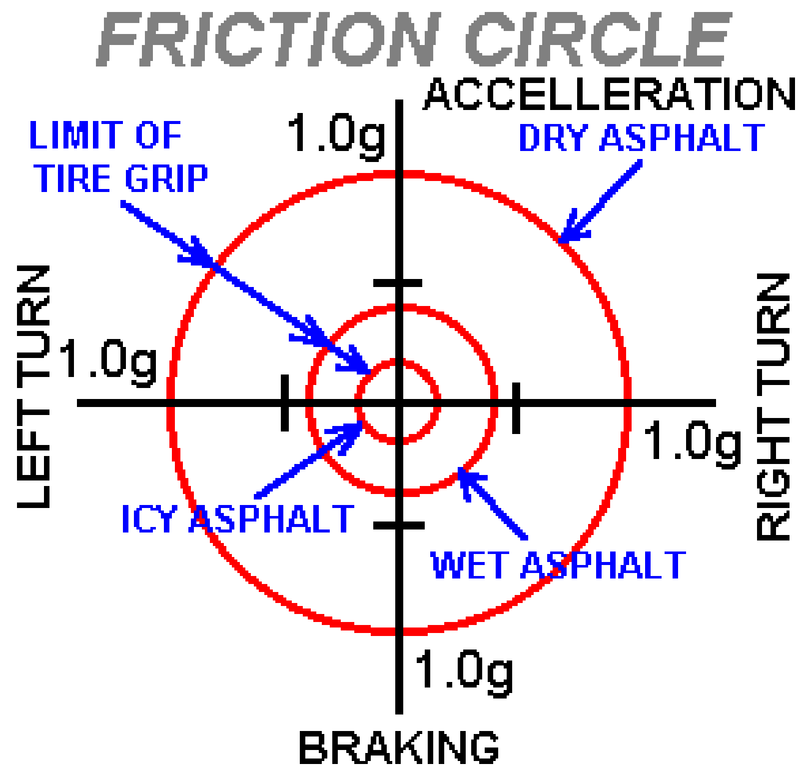


- If you try to turn the steering wheel in this condition, the tires will start to slide because there is no lateral force available. However, if less brake was applied so that the force arrow did not reach the limit of the circle, then some traction force would be available for turning

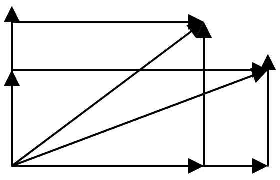
- As long as the combination of forces (braking and turning or acceleration and turning) create a resulting force that is inside the friction circle, then the tire will have traction. If the resulting force tries to exceed the friction circle, then the tire will break traction and start to slide.

Friction Circle





- Tractive force and lateral load can be combined in vector form to determine cornering and or braking/acceleration capacity at any point.
- Lateral loads decrease braking/acceleration limits



decreased acceleration

Increased cornering

Friction Circle

Acceleration/Deceleration

$$F = \mu W = m\frac{dV}{dt}$$

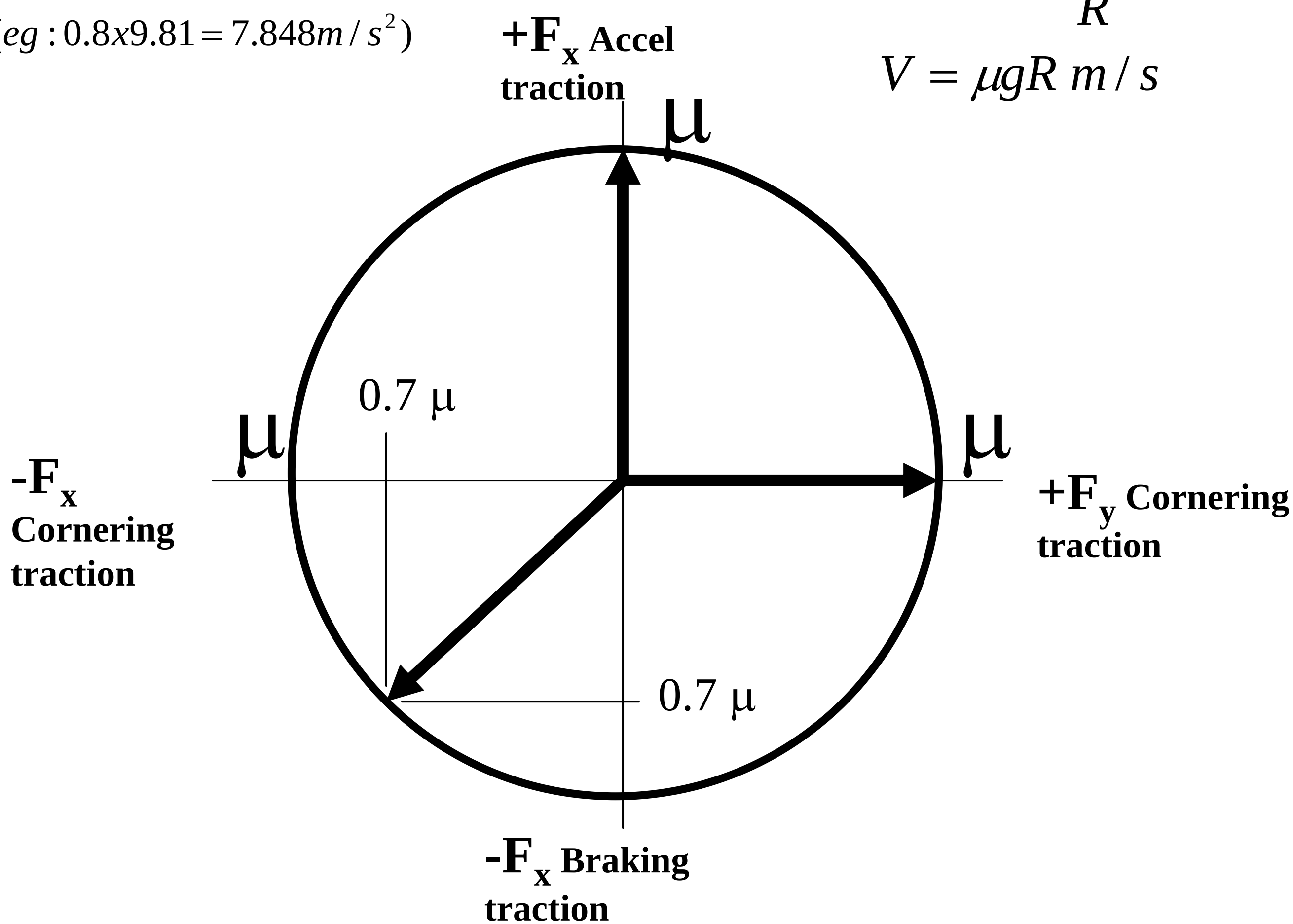
$$\frac{dV}{dt} = \mu W / m = \mu g \ (eg: 0.8x9.81 = 7.848 m/s^2)$$

$$V = \int \mu g dt$$

Cornering Velocity

$$\mu W = m\frac{V^2}{R}(Cornering)$$

$$V = \mu g R \ m/s$$



Tire Friction Characteristics

- Slip Velocity
  - The difference between the angular velocity of the driven (braked) wheel and the angular velocity of the free rolling wheel.

- Slip Ratio

$$s = \omega - \omega_o$$

  - Slip ratio is defined as the slip velocity as a percentage of the free rolling velocity.

$$SR = \frac{\omega - \omega_o}{\omega_o} = \frac{\omega}{\omega_o} - 1$$

Tire Friction Characteristics

- Slip Ratio
  - Slip ratio is defined as the slip velocity as a percentage of the free rolling velocity.
  - Since $$SR = \frac{\omega r_r - V}{V} = \frac{\omega - \omega_o}{\omega_o} = \frac{\omega}{\omega_o} - 1$$
  - then $$\omega_o = \frac{V}{r_r} \qquad r_r = \text{tire rolling radius}$$

$$SR = \frac{\omega\, r_r}{V} - 1 \quad @\, \alpha = 0$$

Tire Friction Characteristics

- Slip Ratio
  - If spinning is arbitrarily assigned a slip ratio of 1 then at spinning

$$SR_{sp} = 1 \quad then, \quad \frac{\omega\, r_r}{V} = 2$$

  - This implies the peripheral speed is twice that of the free rolling tire and twice the forward velocity.
  - The onset of spinning is usually much earlier usually ≈ 0.10-0.15

Tire Friction Characteristics

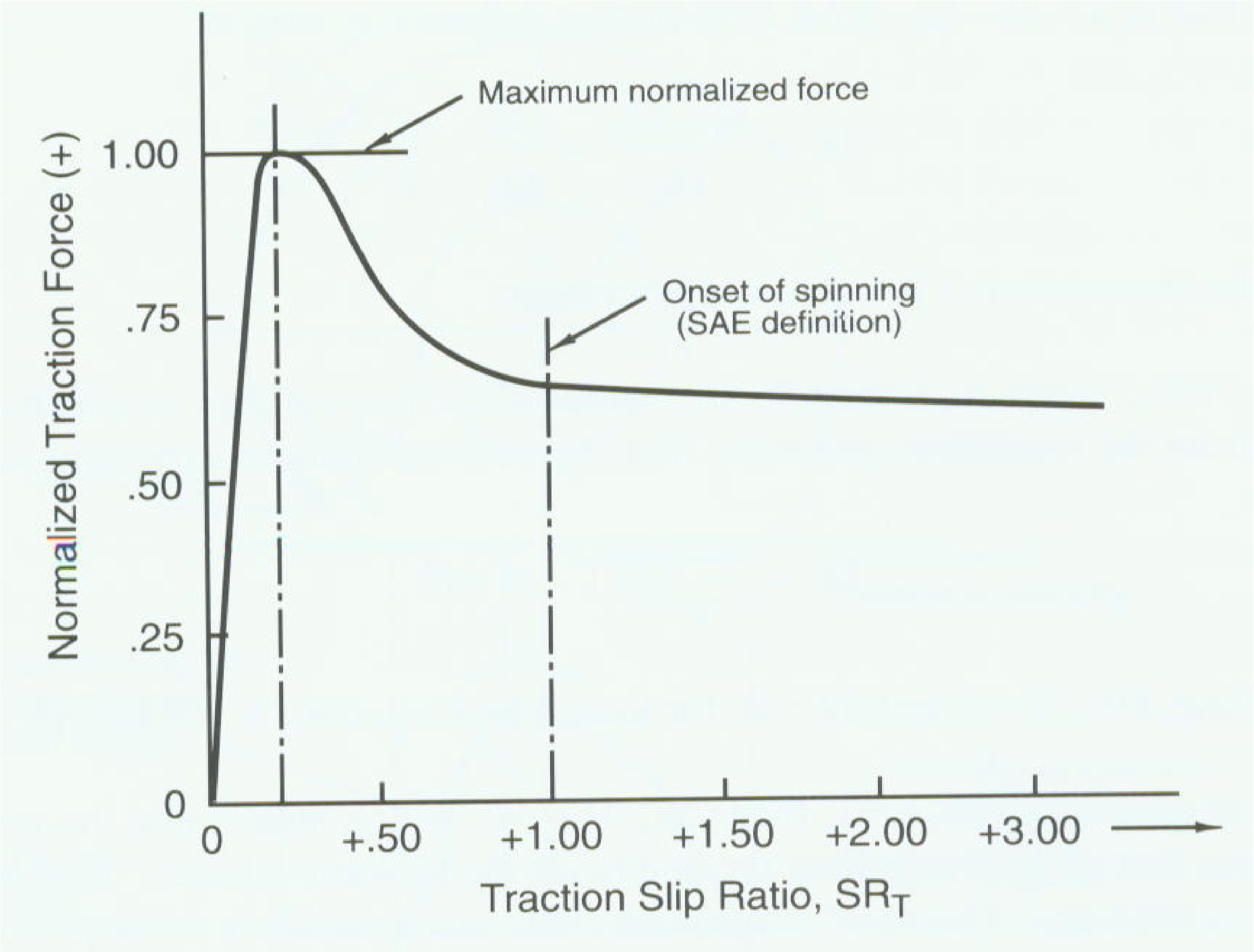
- Slip Ratio definitions
  - SAE J670

$$SR = \left(\frac{\omega\, r_e}{V\, Cos\,\alpha}\right) - 1$$

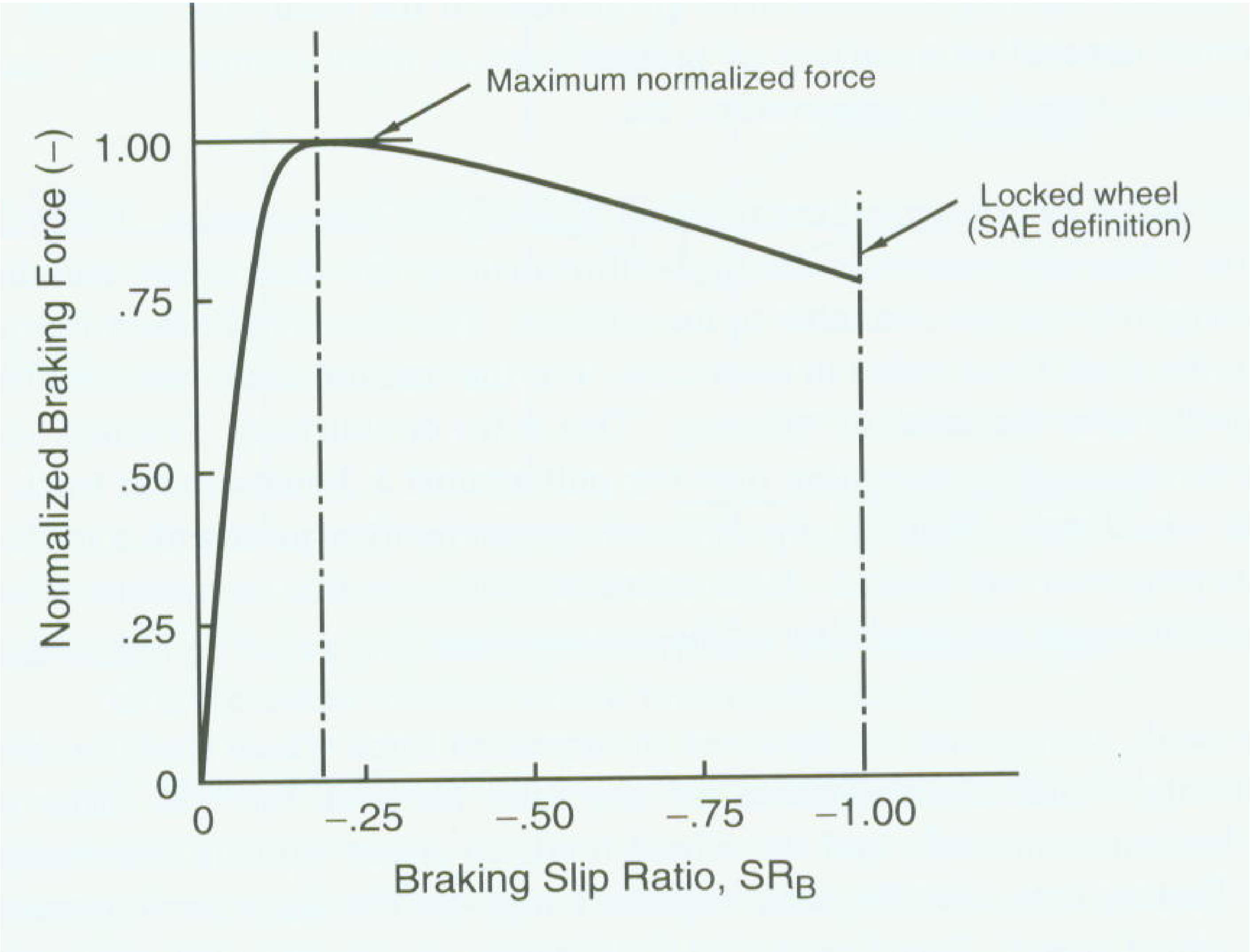
r_e = effective rolling radius for free rolling @ $\alpha = 0$

α = slip angle

Tire Slip Ratio (acceleration)



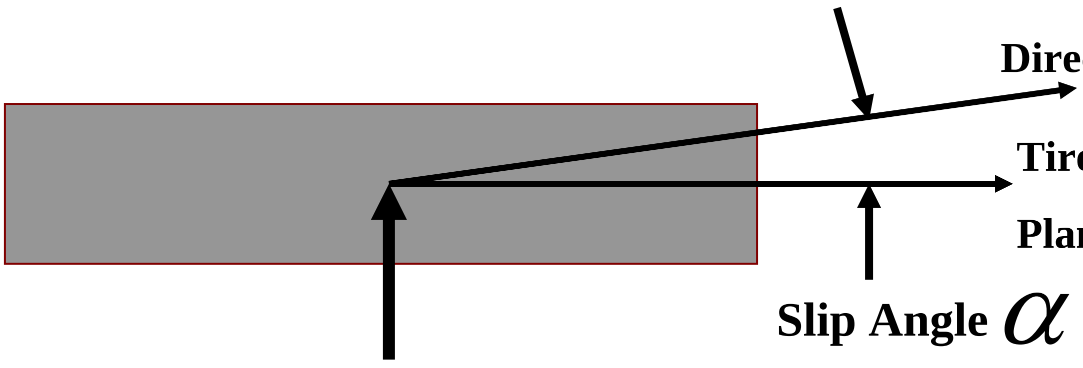
Tire Slip Ratio (braking)



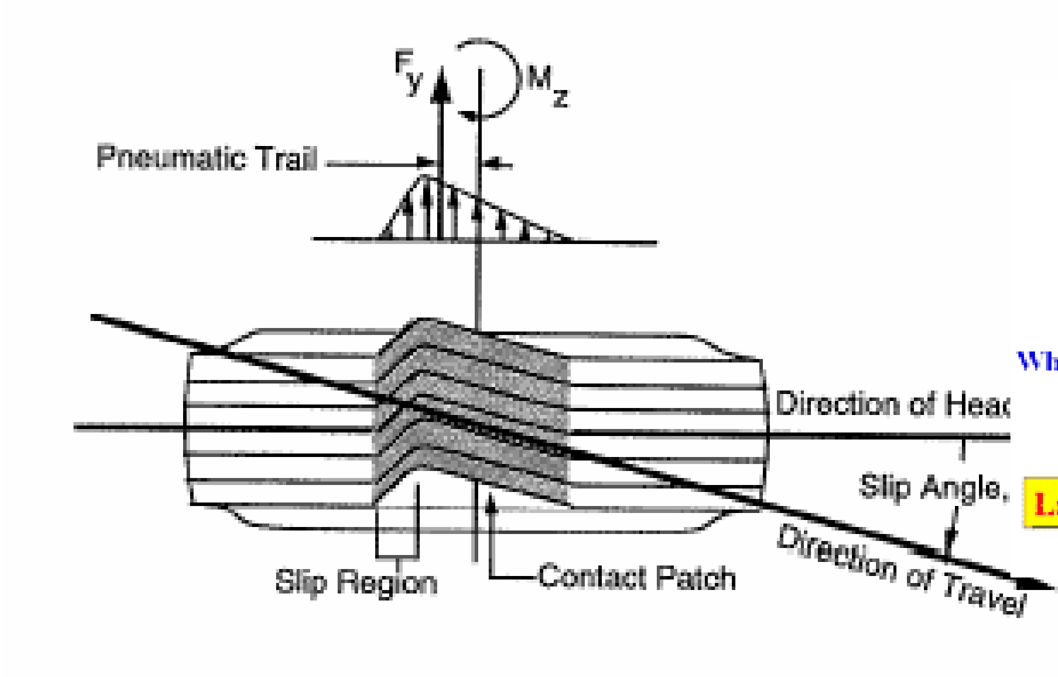
Slip Angle

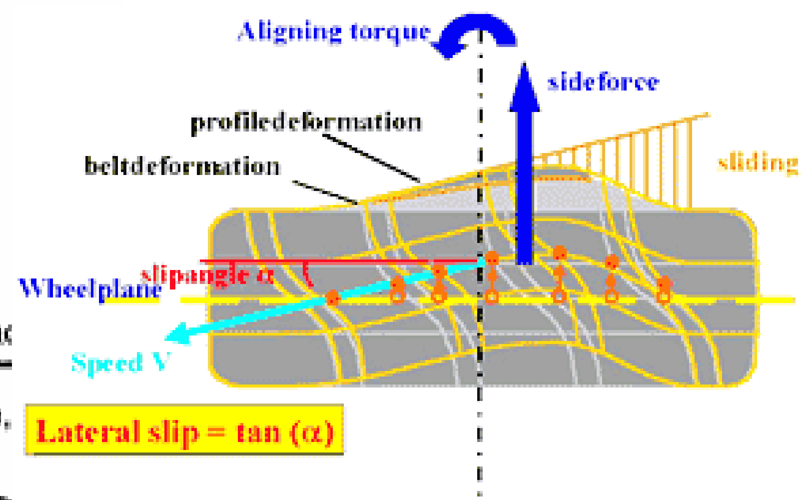
- Slip angle is defined as the angle between the rotational plane of the tire and the tire heading direction.

- Lateral loads on a tire introduce a slip angle.



Tire Rolling Deformation





- If a side force operates on the tire, a lateral deformation appears in the tire belt and its tread. Points on the running surface experience the belt deformation before they make contact with the road at which point the tire first attempts to maintain contact with the road surface.

Tire Rolling Deformation

1. This corresponds to a gradually increasing shear stress in lateral direction. Once the adhesion limits are reached, the rubber will start to slide relative to the road with a lateral motion, perpendicular to the wheel plane. The asymmetry in the distribution of shear stress causes the resulting force not to grip exactly in the middle of the contact area just under the wheel centre. Rather there is a pneumatic trail which, in combination with the side force, produces an aligning torque which tries to push the tire in the direction of the wheel speed.

2. The tangent of the slip angle between wheelplane and wheel speed, denoted as side slip -sy :

$$sy = \tan(\alpha)$$

in conjunction with the wheel load and the camber angle, are decisive for the side force and the aligning torque

Tire Characteristics

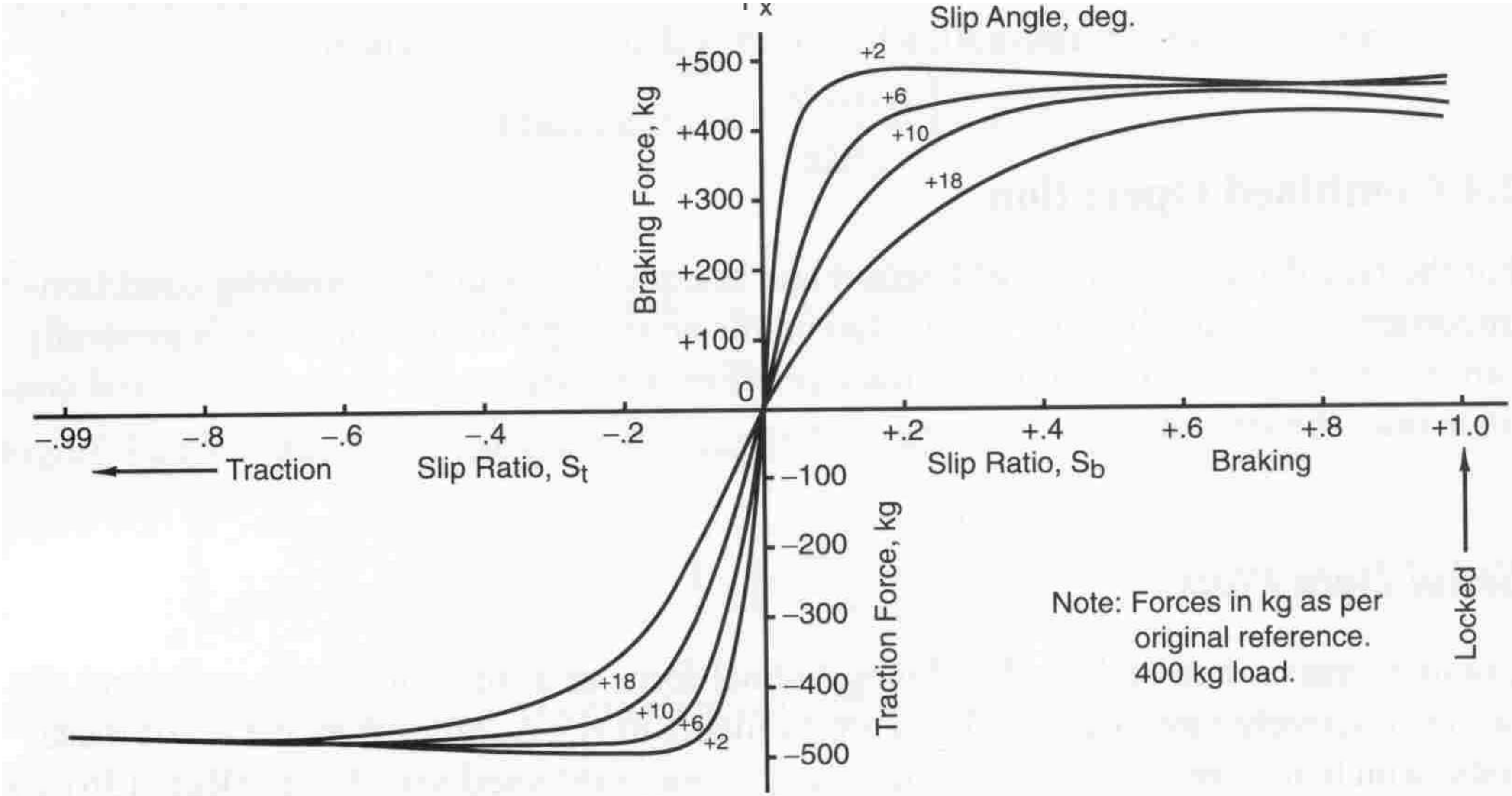
- Analysis of the Slip Ratio and Lateral Force behavior at given slip angles.

  - At a given slip angle as the slip ratio increases the tires capacity to support a lateral load diminishes.

  - Peak tractive forces are present at slip ratios that differ slightly between braking and forward traction.

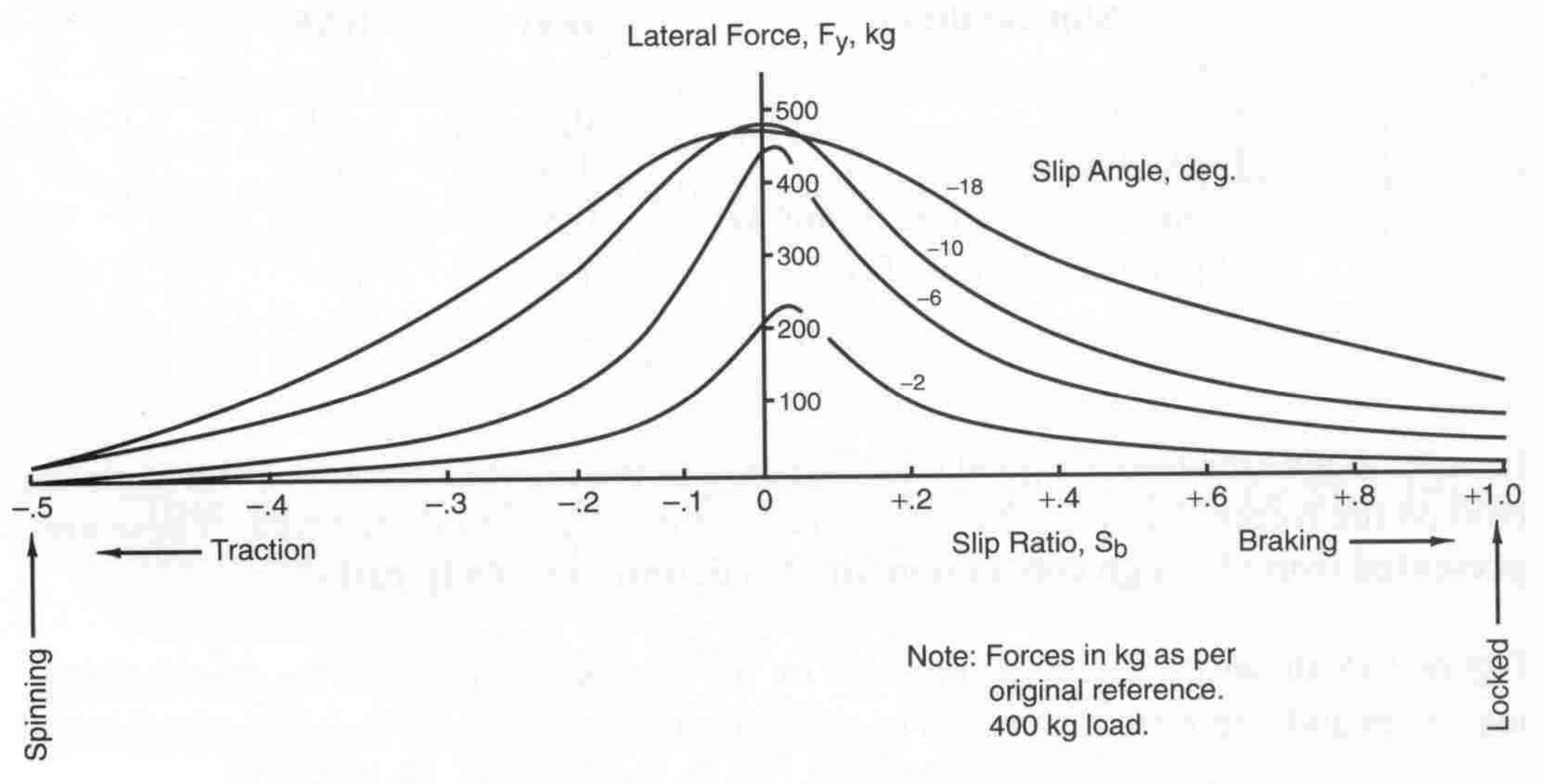
  - At any given slip ratio, the lateral force capacity increases with increasing slip angles.

Tire Characteristics



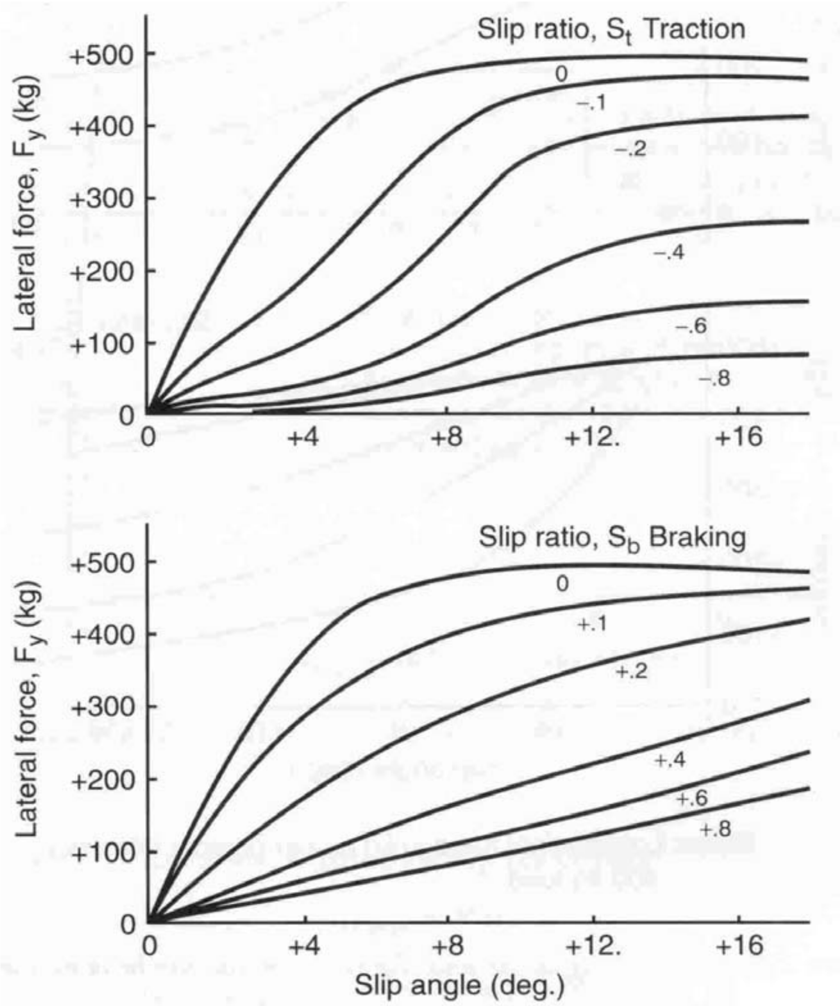
Braking and Tractive forces @ given Slip Angles vs. Slip Ratio

Tire Characteristics



Slip Ratio vs. Lateral Force @ given Slip Angles

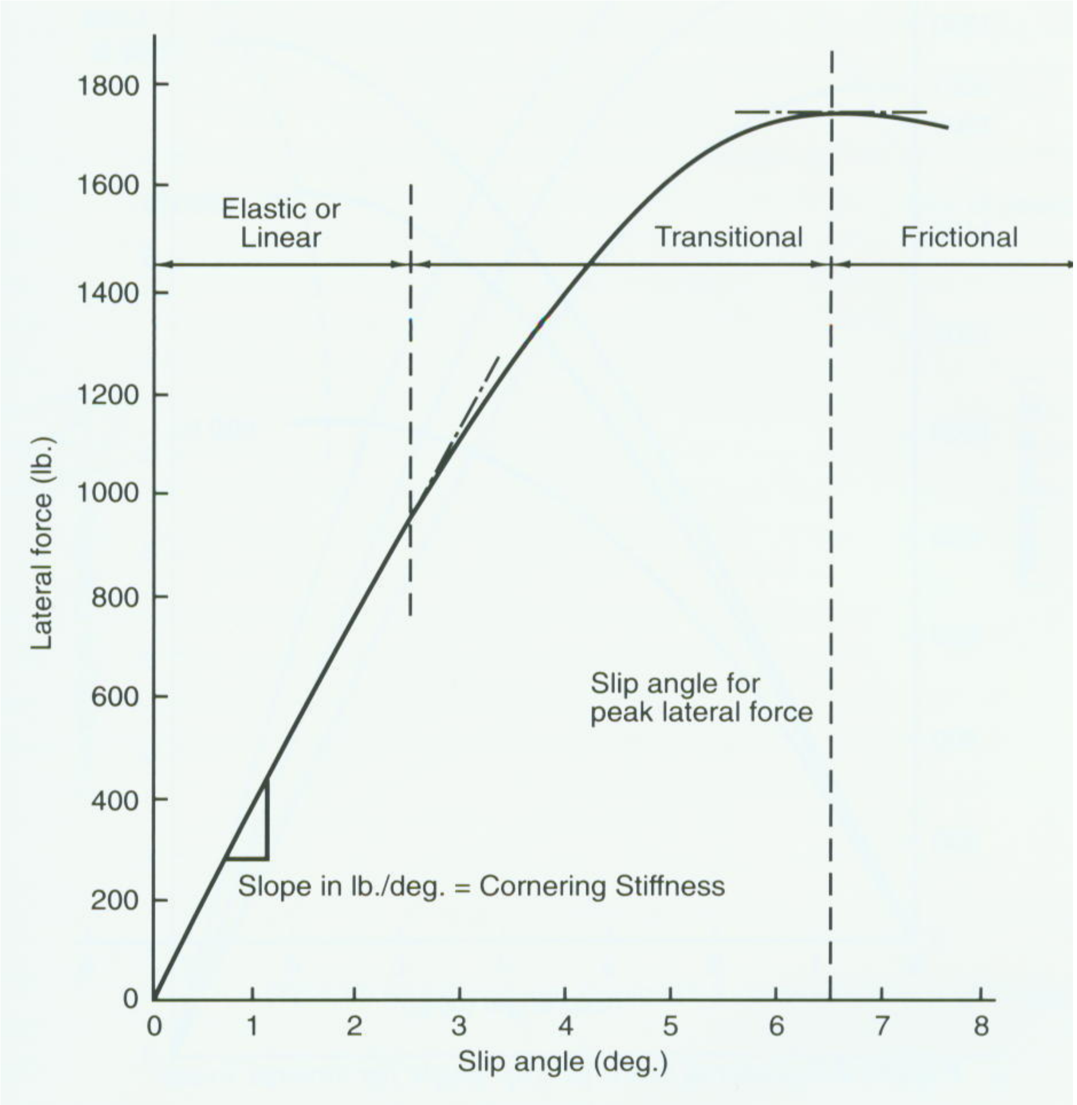
Lateral Force Capacity



Lateral Force vs. Slip Ratio @ range of Slip Angles

(400 kg Normal Load)

Slip Angle vs Lateral Load



Goodyear Eagle GT-S F_z=1800 lb

Fig.2.7 p.25 Milliken

Tire Cornering Stiffness

- Cornering stiffness is the change in lateral force per unit slip angle change at a specified normal load in the linear range of the tire.

$$C_\alpha = \frac{d\ F_{y\alpha}}{d\alpha}$$

Slip Angle vs Lateral Load

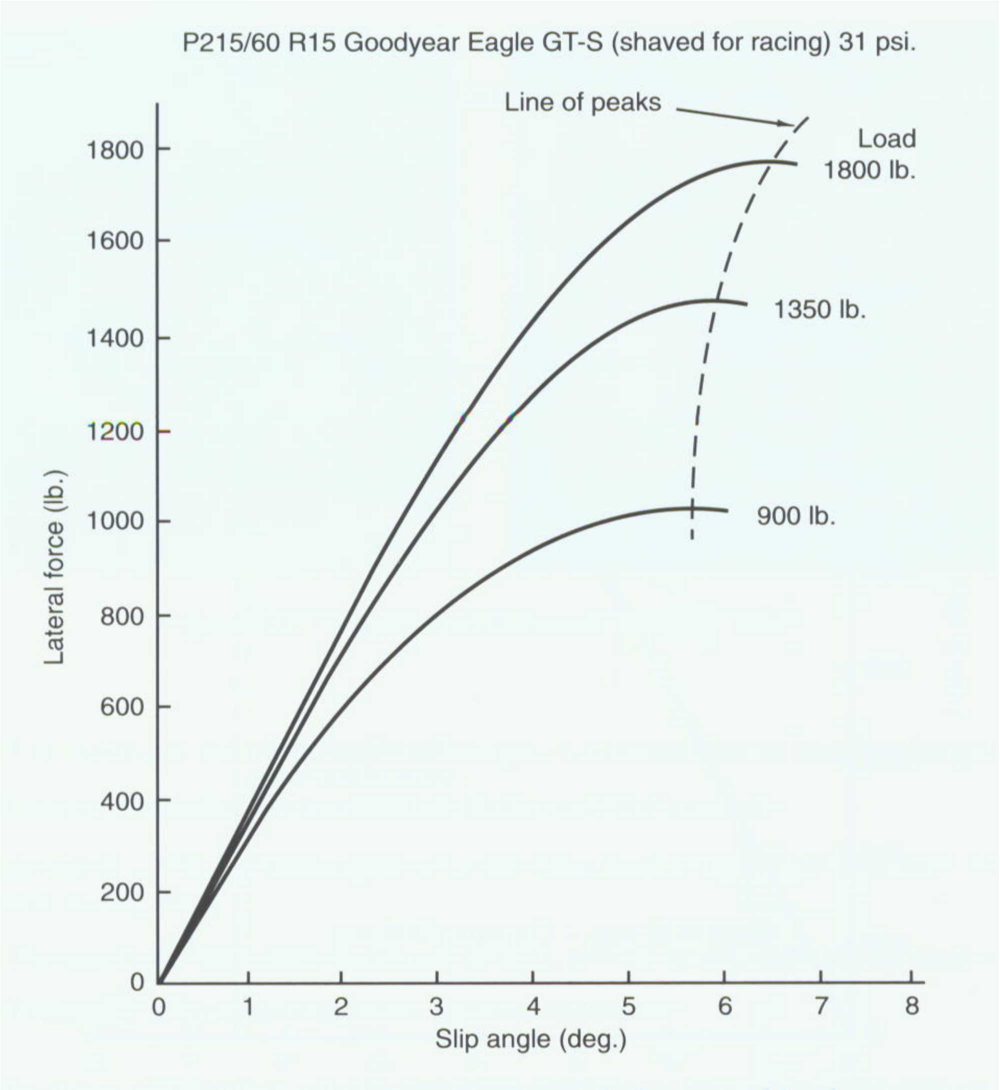


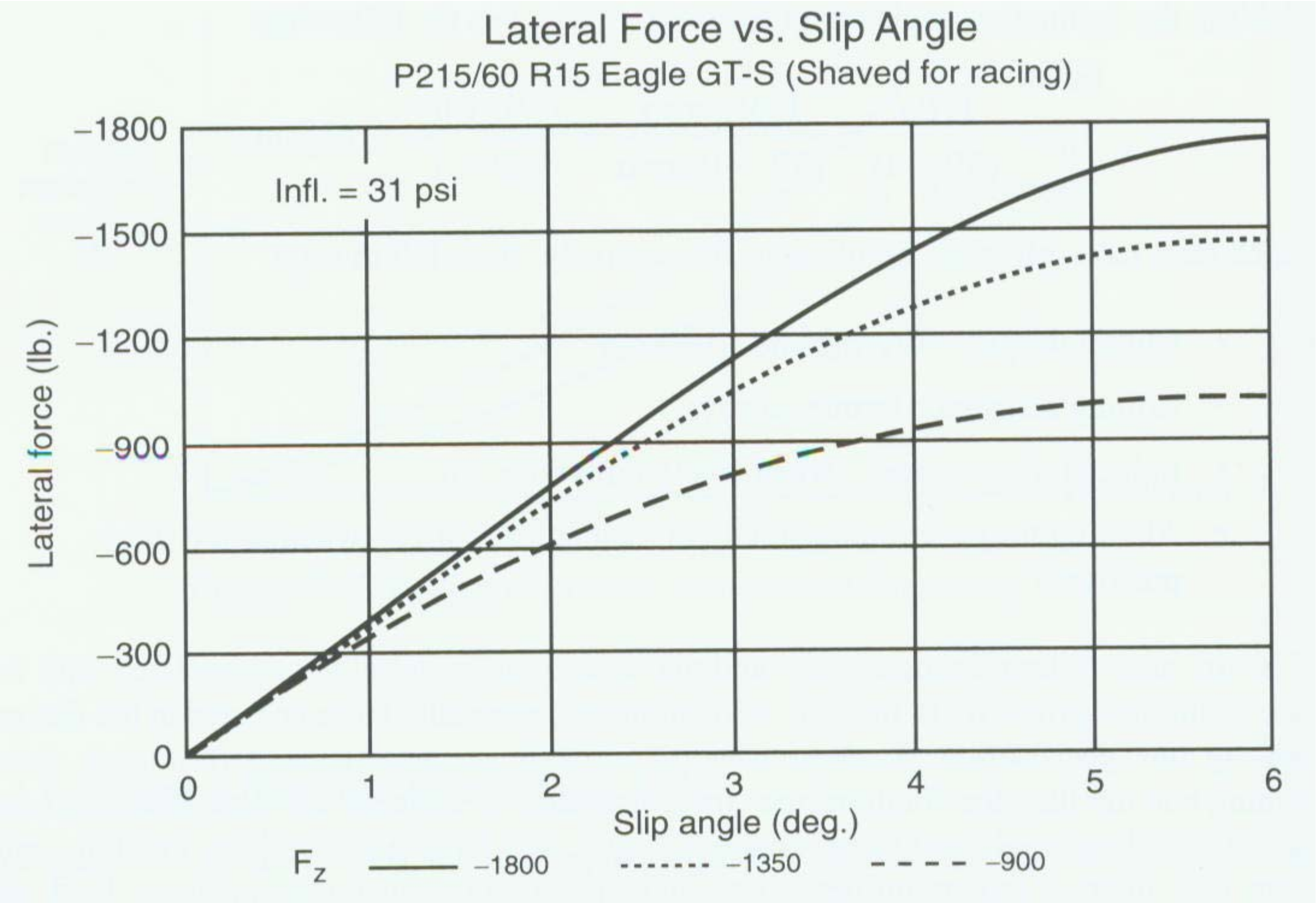
Fig.2.8 p.26
Milliken

Cornering Stiffness Comparison

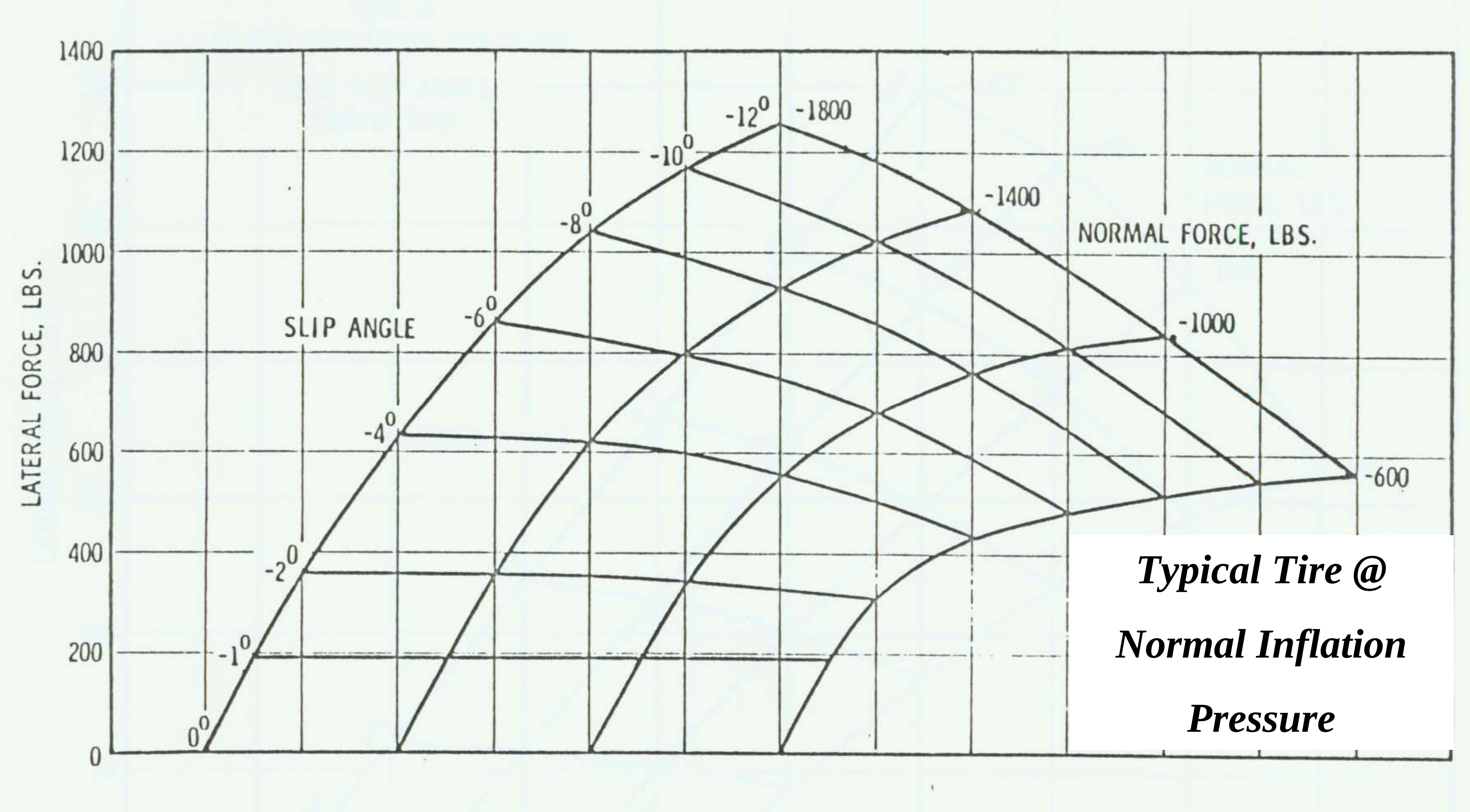
Table 2.2 Calculated C_α for Five Race Tires

Tire	Figure	Load lb.	Calculated C_α lb./deg.	lb./rad.
Eagle GT-S	2.42	1800	383	21,950
Short Track	2.43	2000	667	38,200
Eagle ZR	2.44	1955	533	30,600
Indy Road	2.45	1800	833	47,750
Formula 1	2.46	1000	750	42,975

Tire Lateral Force Plot

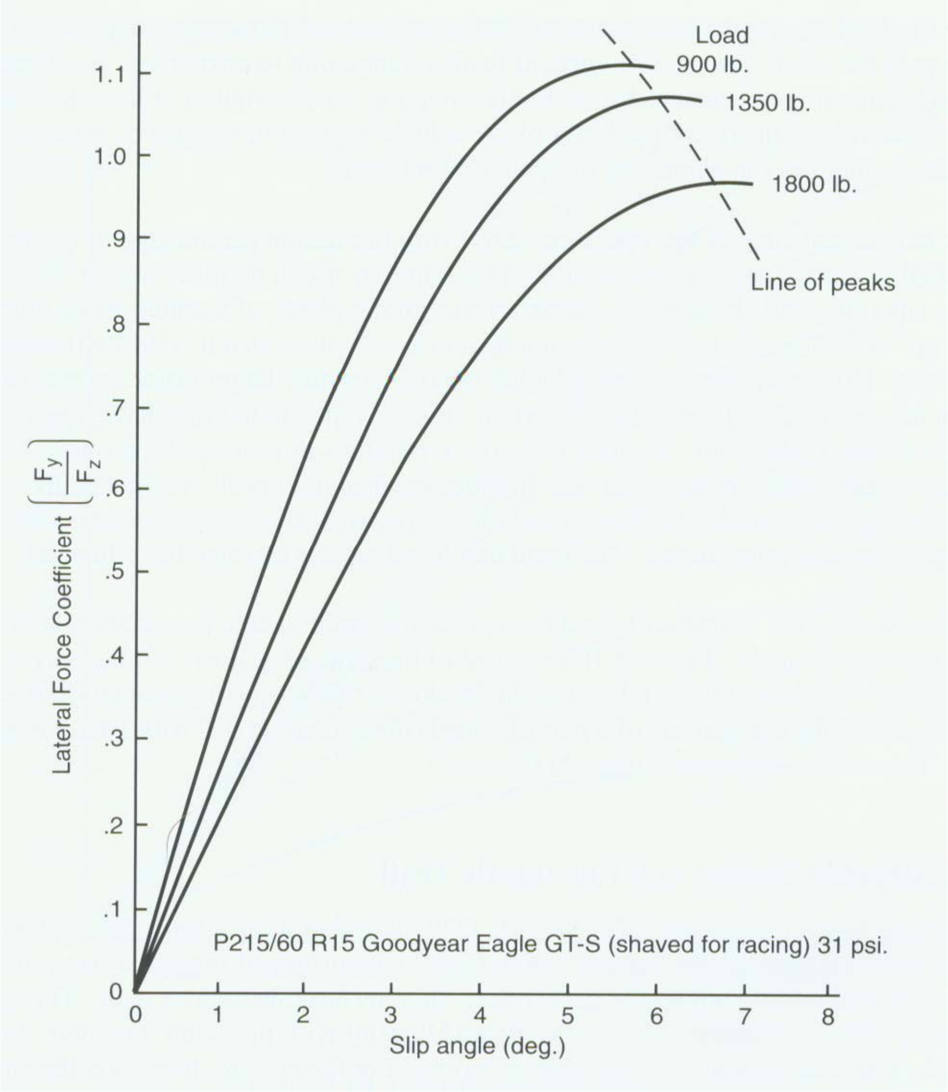


Tire Carpet Plot



Typical Tire @ Normal Inflation Pressure

Slip Angle vs Lateral Force Coefficient



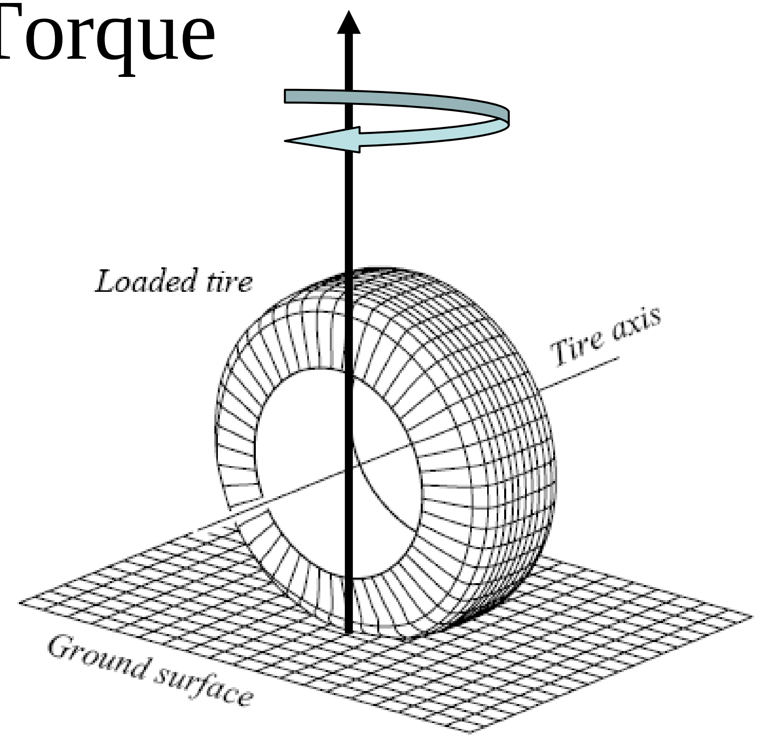
Lateral Force Coefficient

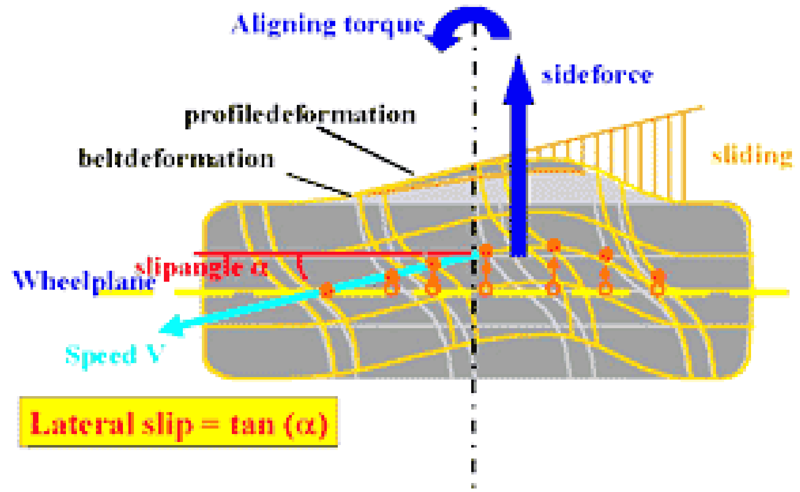
- Lateral Force Coefficient is a normalized Tire Cornering Stiffness (dimensionless) obtained by dividing the lateral cornering force by the vertical load in the tire

$$\text{Lateral Force Coefficient} = \frac{F_y}{F_z}$$

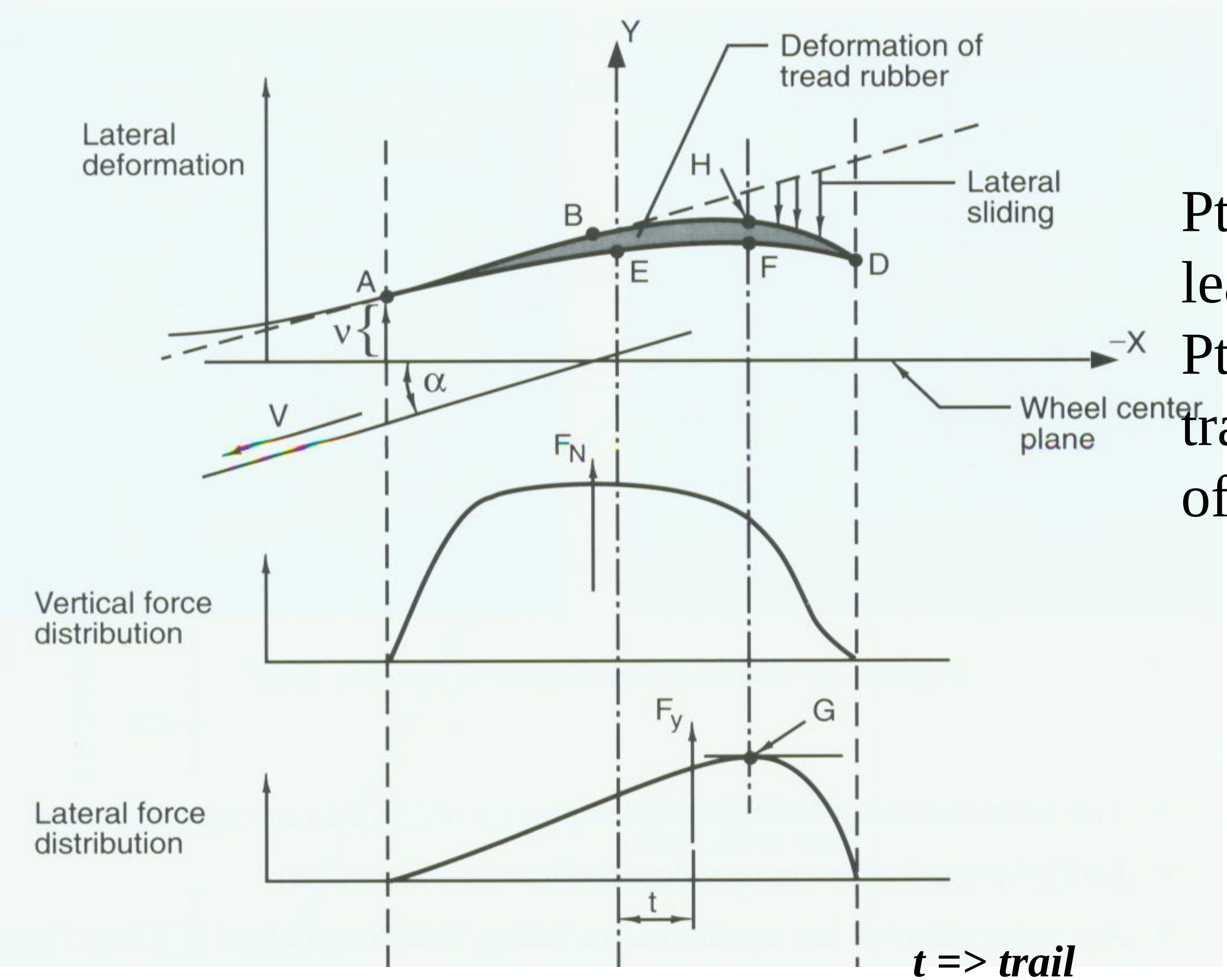
Self-Aligning Torque

- Self-Aligning Torque is derived from a combination of caster trail and the tires own pneumatic trail.
- If the mechanical (caster) trail is small the tires aligning torque (Pneumatic Trail) will dominate the steering effect.
    - If Pneumatic trail effects dominate the limits of traction are more obvious to the driver of the vehicle.
- Pneumatic trail is derived from the shear force distribution in the tire footprint.





Self-Aligning Torque

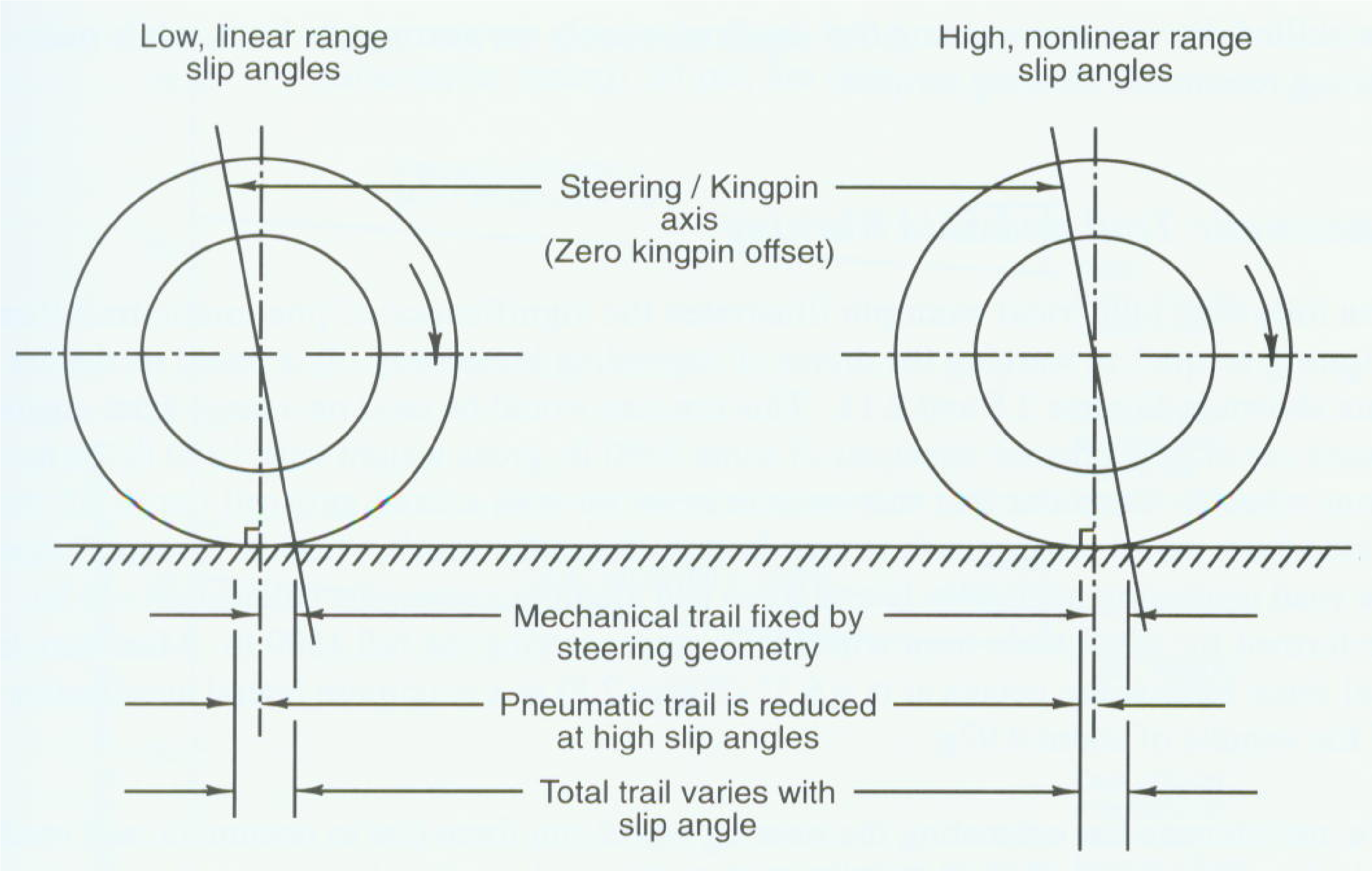


Pt A is leading edge

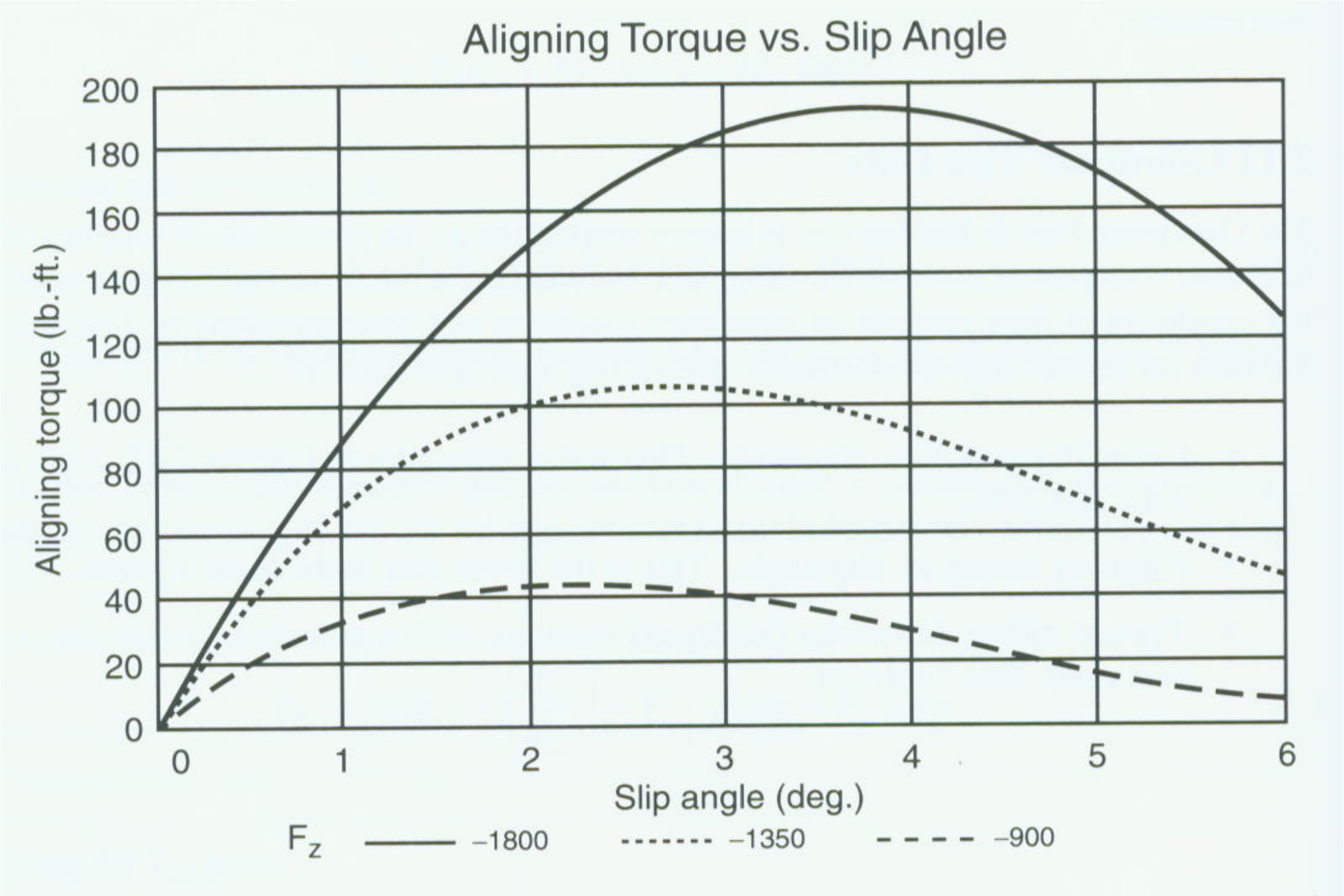
Pt D is trailing edge of tire patch

t => trail

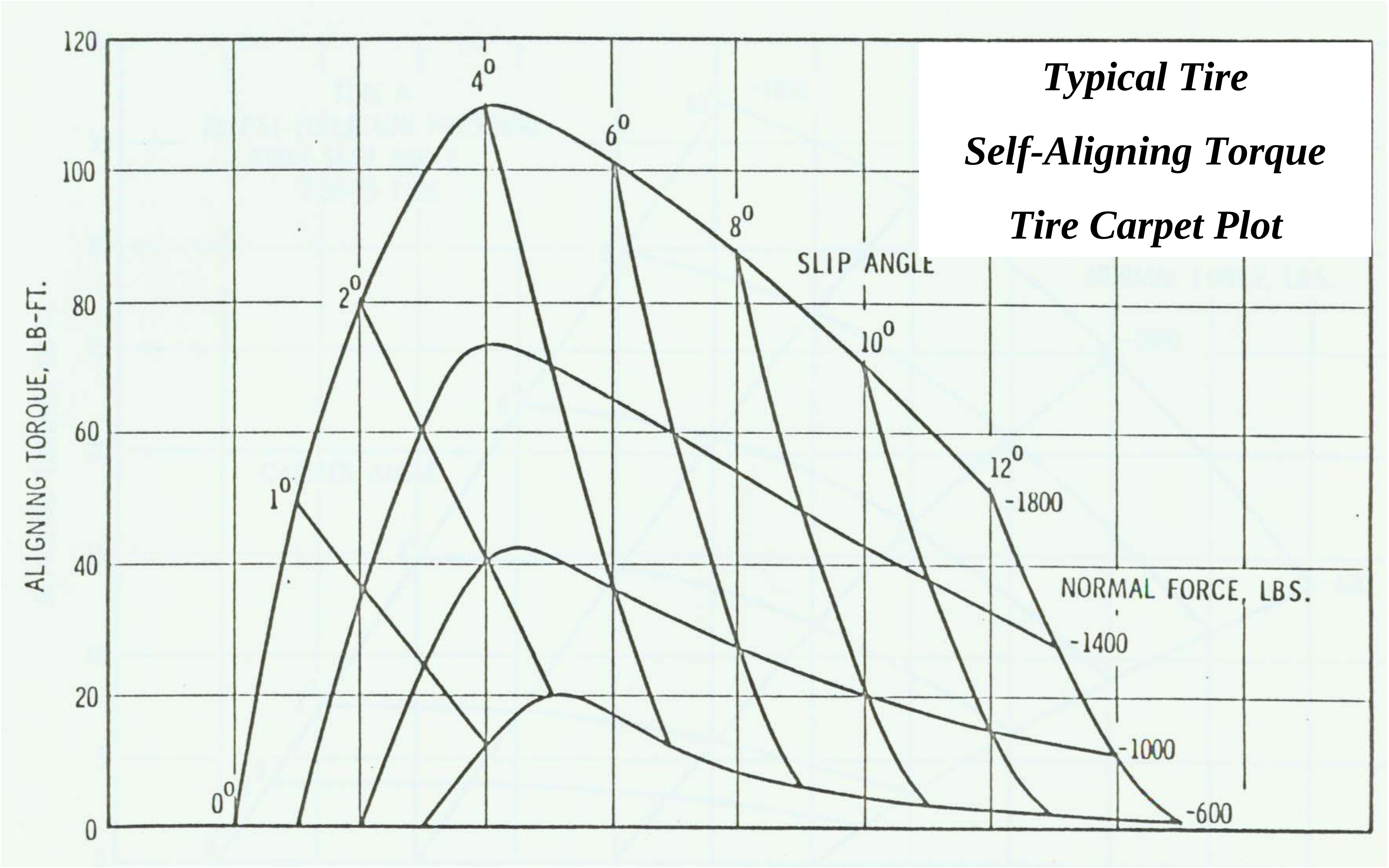
Self-Aligning Torque



Tire Self Aligning Torque



Tire Self Aligning Torque Carpet Plot



Camber Thrust

A second means of lateral force generation in a tire derives from rolling at a non-vertical orientation, the inclination angle being known as camber angle. With camber, a lateral force known as "camber thrust" is produced. The

- Camber force is directed towards the direction the tire is inclined

In absolute value, the camber stiffness of a tire is typically in the range of 10 to 20 percent of the cornering stiffness. Figure 10.16 provides a carpet plot of lateral force as a function of camber and load for a typical passenger-car tire.

- Camber stiffness

$$C_\gamma = \left.\frac{\partial F_y}{\partial \gamma}\right|_{\gamma = 0}$$

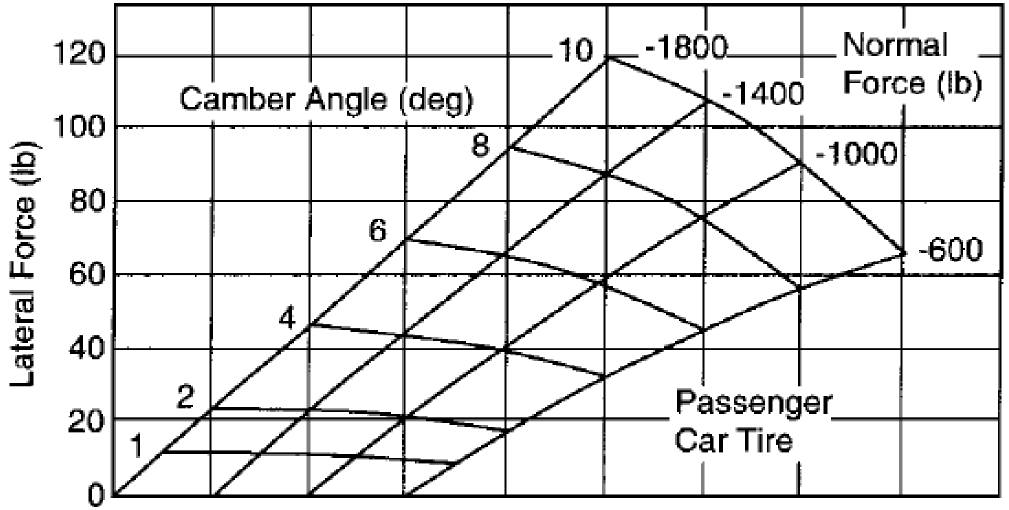
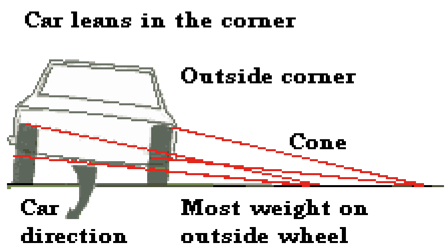
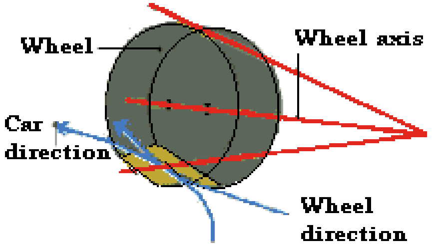


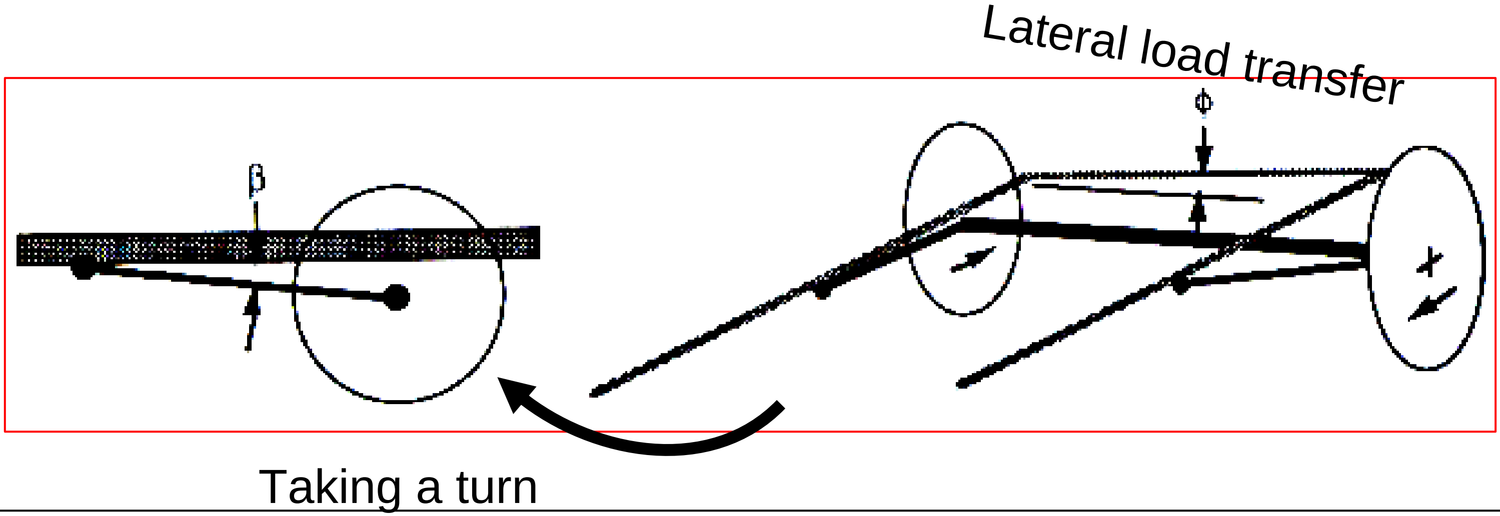
Fig. 10.16 Carpet plot of lateral force due to camber angle for a bias-ply tire.

Roll Steer





Roll steering



Friction Circle

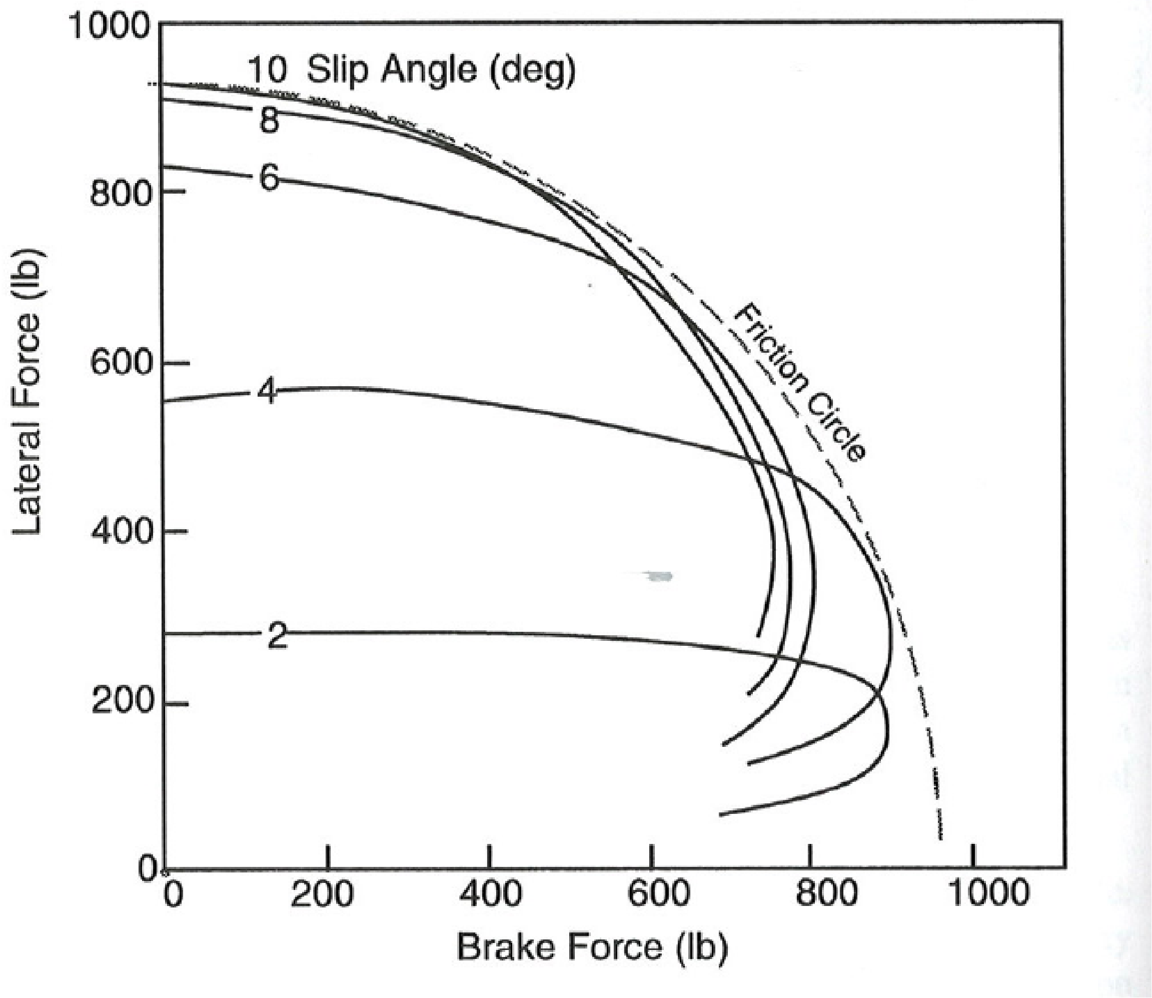
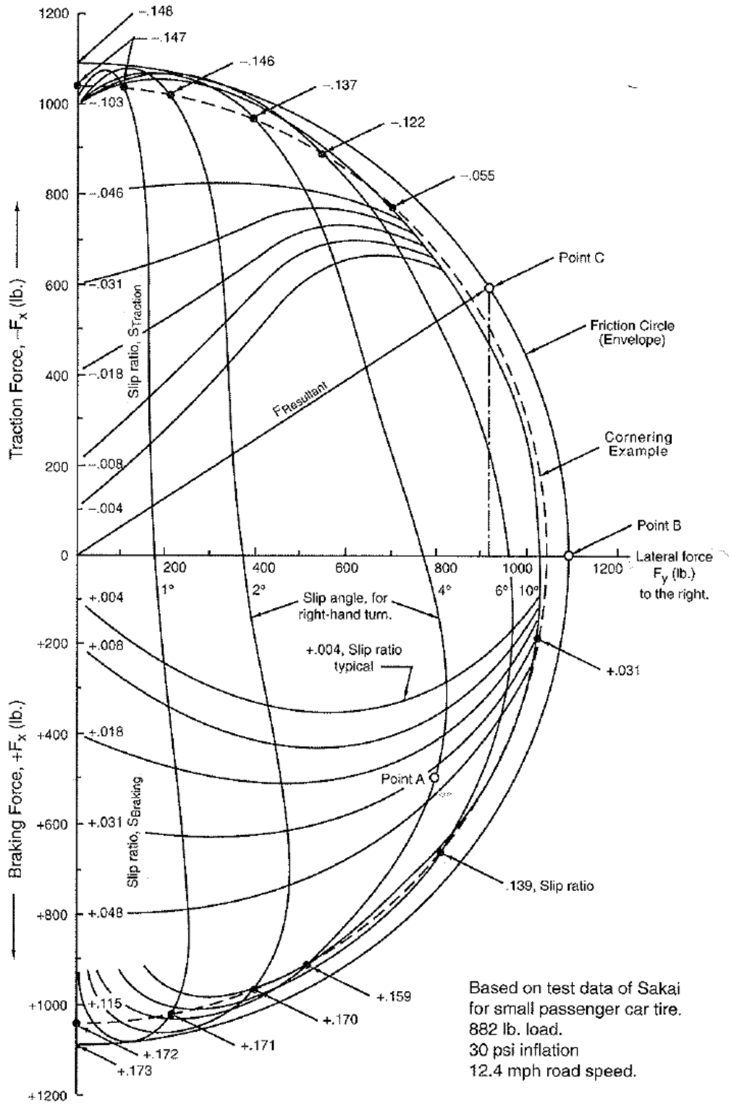
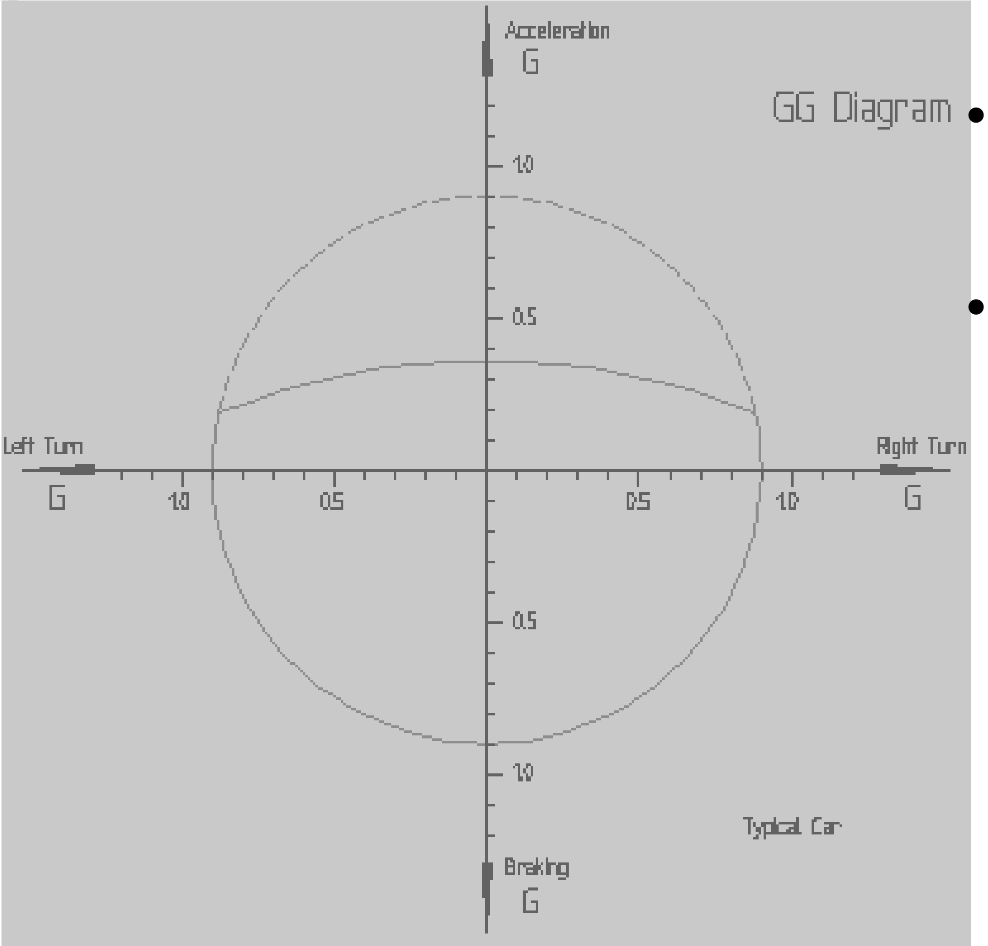


Fig. 10.23 p. 364 Gillespie

Friction Circle

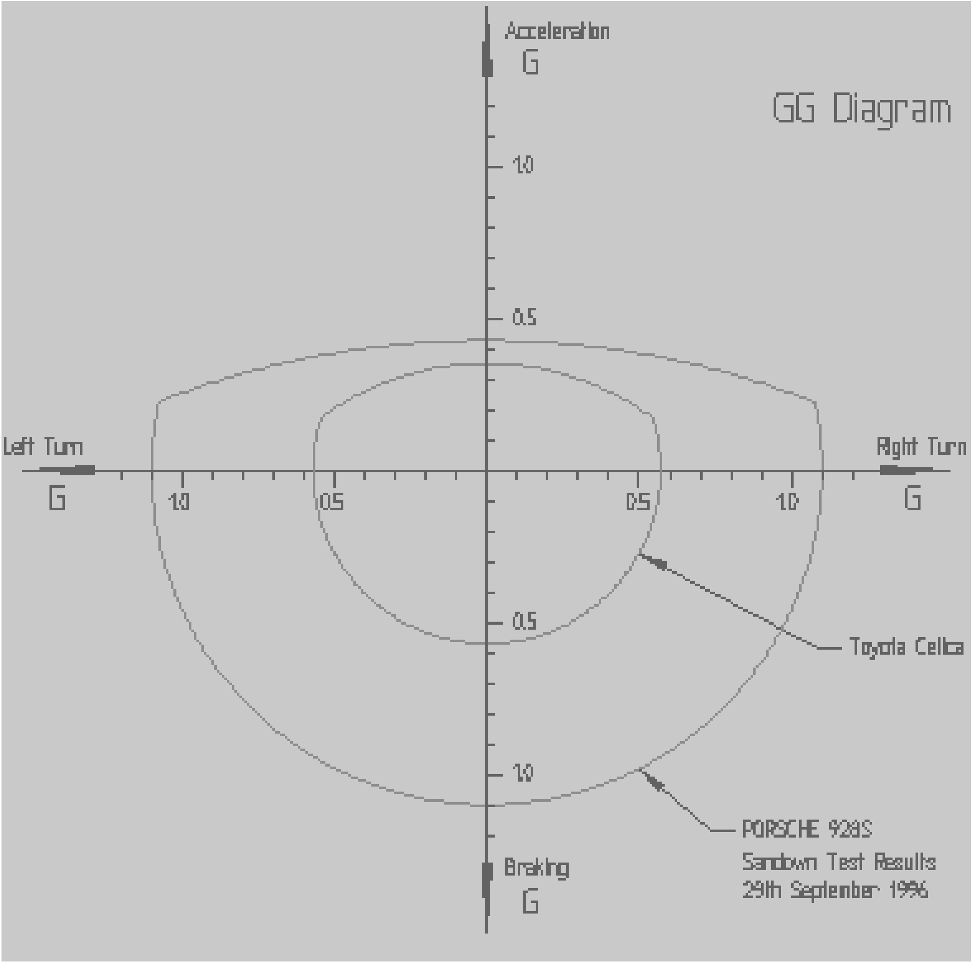


g-g Diagram



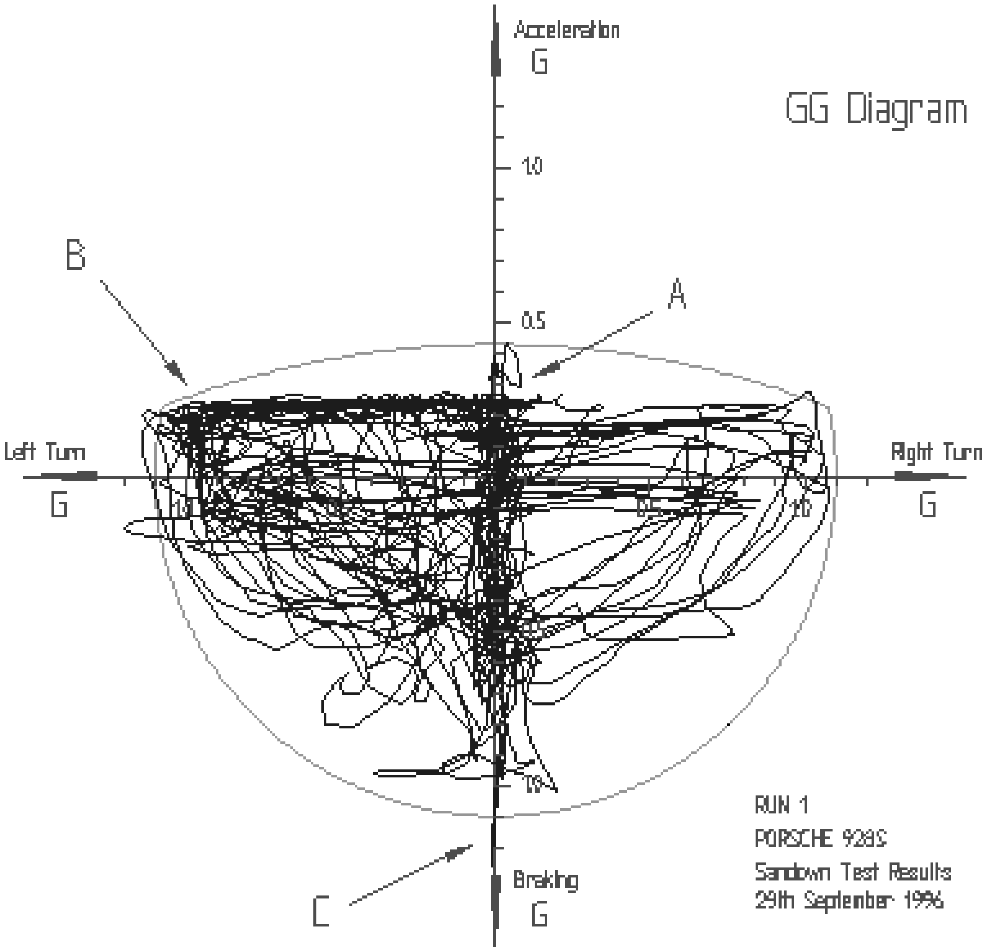
- Acceleration, Braking, Cornering all 0.9 g
- It is not possible to achieve 0.9g in acceleration, at lower gears higher acceleration possible, at higher gears engine power becomes limiting factor, Dotted circle is what we want but what we can achieve is solid line circle
- gg diagram represents performance envelope of a car

g-g Diagram



- Figure shows a dramatic example of the effect tires can have on a car's overall performance. It shows how the grip of the tires is a crucial factor in performance, and what you may be getting when you pay that little bit extra for high performance tires.

g-g Diagram



- Figure presents a gg Diagram displaying 8 minutes of recorded accelerometer data around Sandown Motor Raceway. Data was recorded at 10 samples per second to generate the trace shown. The car's performance envelope is also overlaid. Although initially appearing as a meaningless tangle of lines, a number of interesting things can be read from this chart.

g-g Diagram

- Point A is a small spike of forward acceleration above what appears to be a fairly consistent horizontal boundary. The recording of the acceleration data commenced before the car began moving. This spike represents the acceleration of the car away from rest. Once moving, particularly around a high speed circuit like Sandown, the car has less acceleration capability. It is operating in a region where it cannot attain as high a forward acceleration. This is the reason for the apparent boundary of forward acceleration shown on the diagram.

g-g Diagram

- Point B highlights that there is far more data displayed on the left side of the GG Diagram than the right. This is not surprising as Sandown is made up primarily of left hand corners, so a car will spend much more time turning left than right. It is also apparent that data occasionally appears beyond the curve defining the performance envelope. The performance envelope indicates the sustained capabilities of a vehicle. Dynamic manoevres can exceed these capabilities, though only briefly

g-g Diagram

- Point C indicates a spike arising from a dedicated maximum braking maneuver, executed specifically to obtain an extreme value on the GG Diagram for later analysis. It's interesting to contemplate whether this is a point arising from a dynamic maneuver, or a sustained deceleration point, or some combination of both. The point itself peaked at a deceleration value of 1.25 G, which is quite an impressive figure for a road car.

g-g diagram

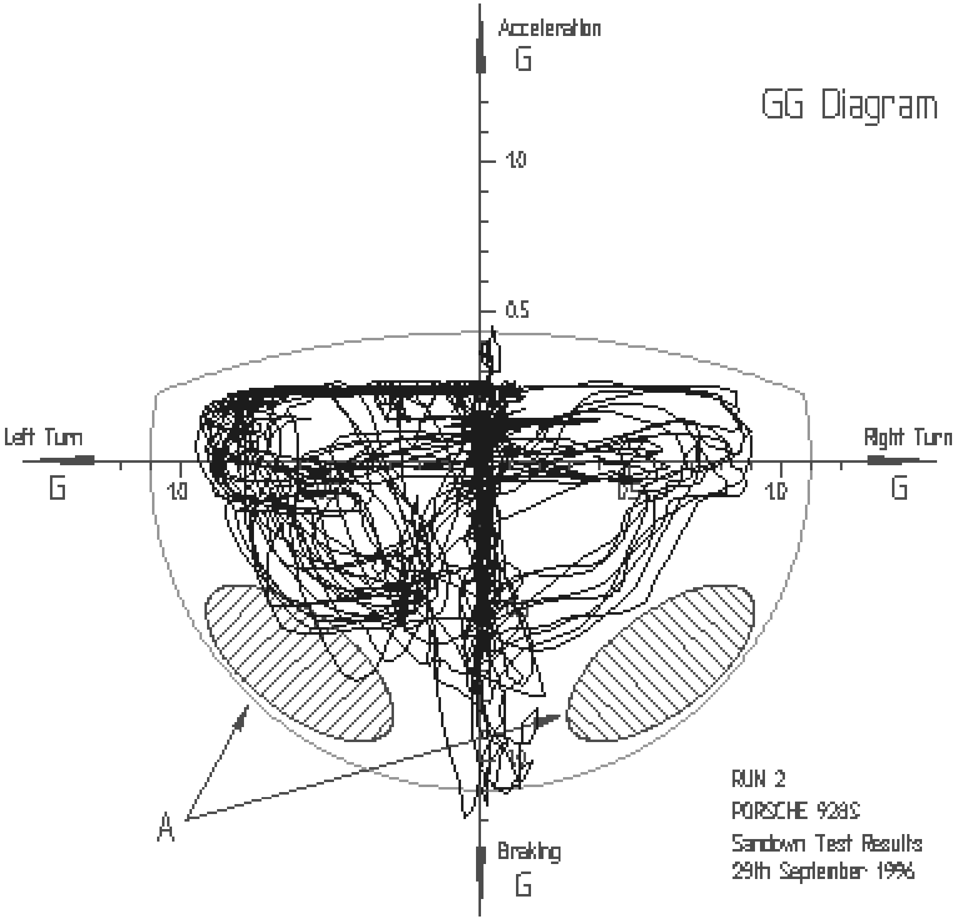


Figure shows another gg Diagram recorded at Sandown. This shows a number of similarities to previous Figure and also a number of interesting differences. This diagram clearly indicates a very useful aspect of the gg Diagram; how it can display where a driver or car can be improved to better utilize the capabilities available. Two hatched area, labeled A, indicate areas of the diagram where very little of the recorded data appears.

g-g diagram

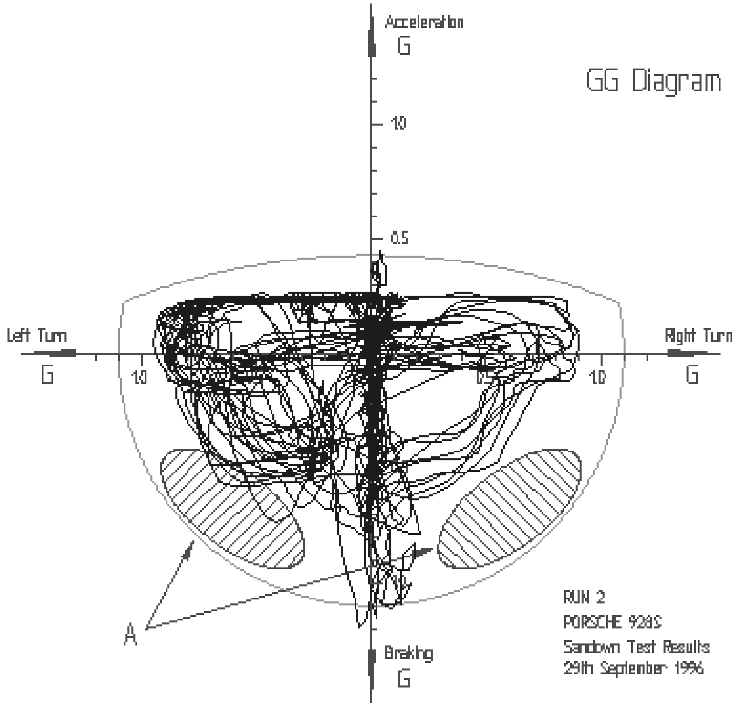
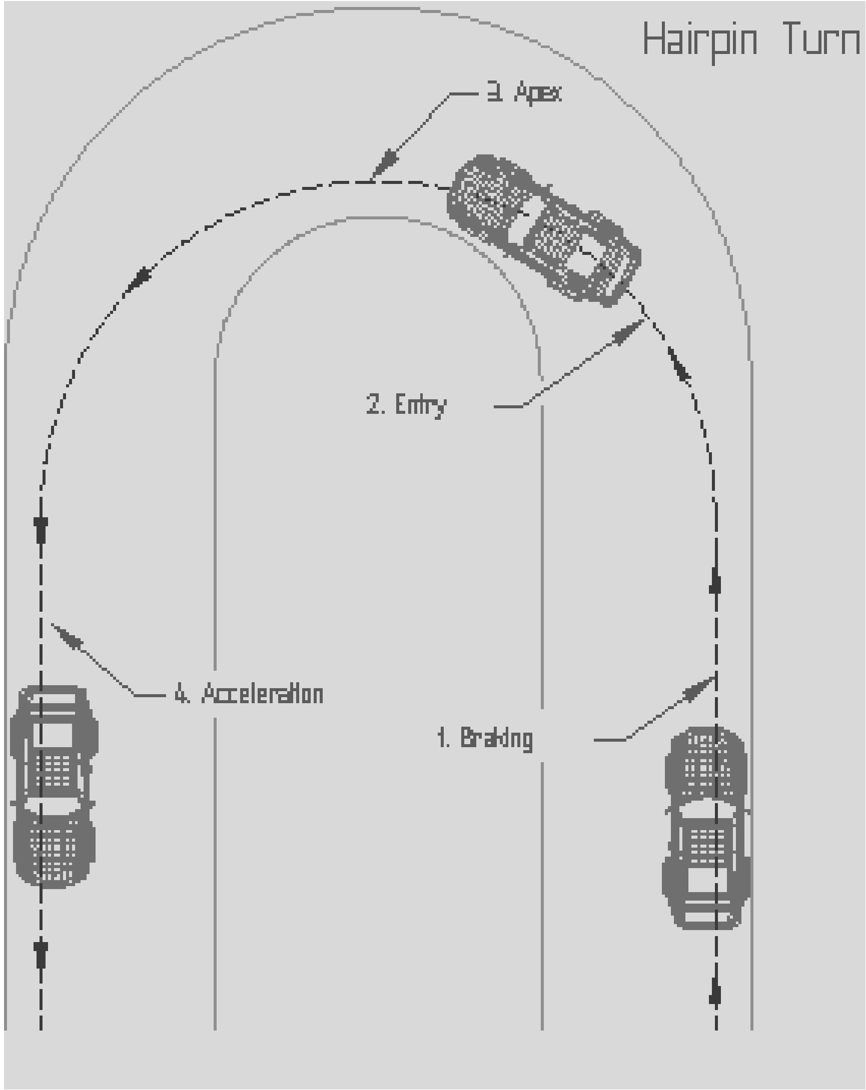


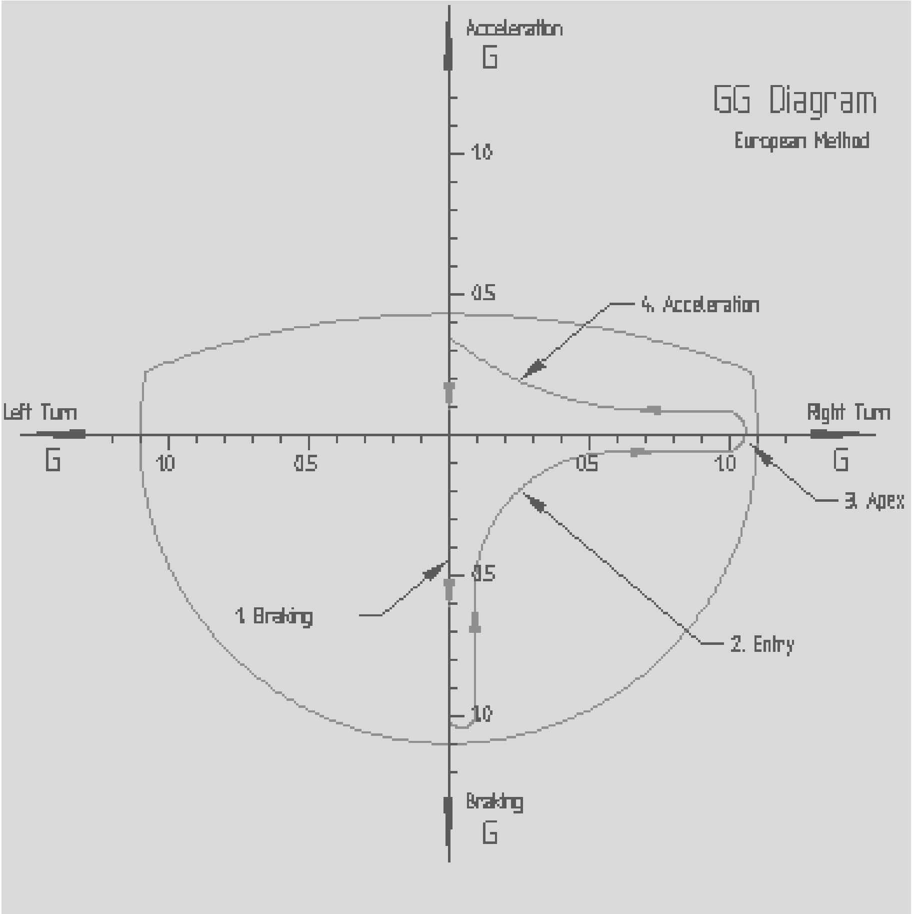
Figure 4

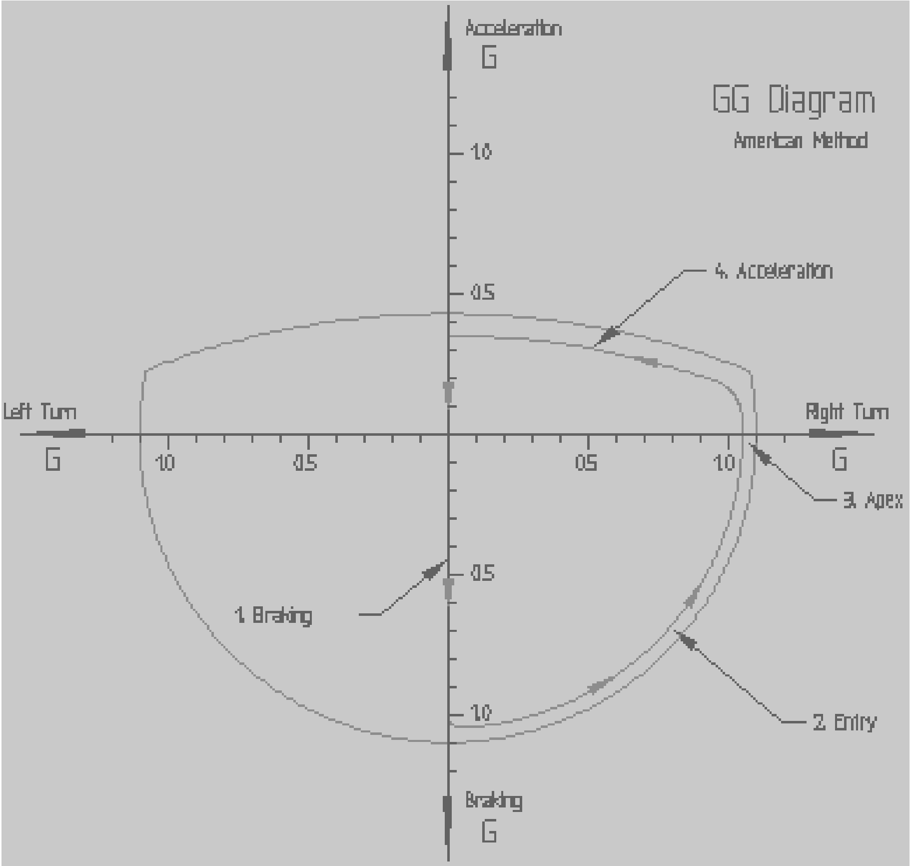
So, what are these areas ? These represent a region where the car would be braking into a corner. One of the classic rules of high performance driving is that one should never brake and turn at the same time, yet the GG Diagram is telling us to do just that. This is one of the more fascinating features of the gg Diagram. It leads us to re-evaluate how to approach the task of driving rapidly. It has resulted in two fundamentally different approaches to driving being proposed, which some have termed "The European Method" and "The American Method".

Application of g-g diagram

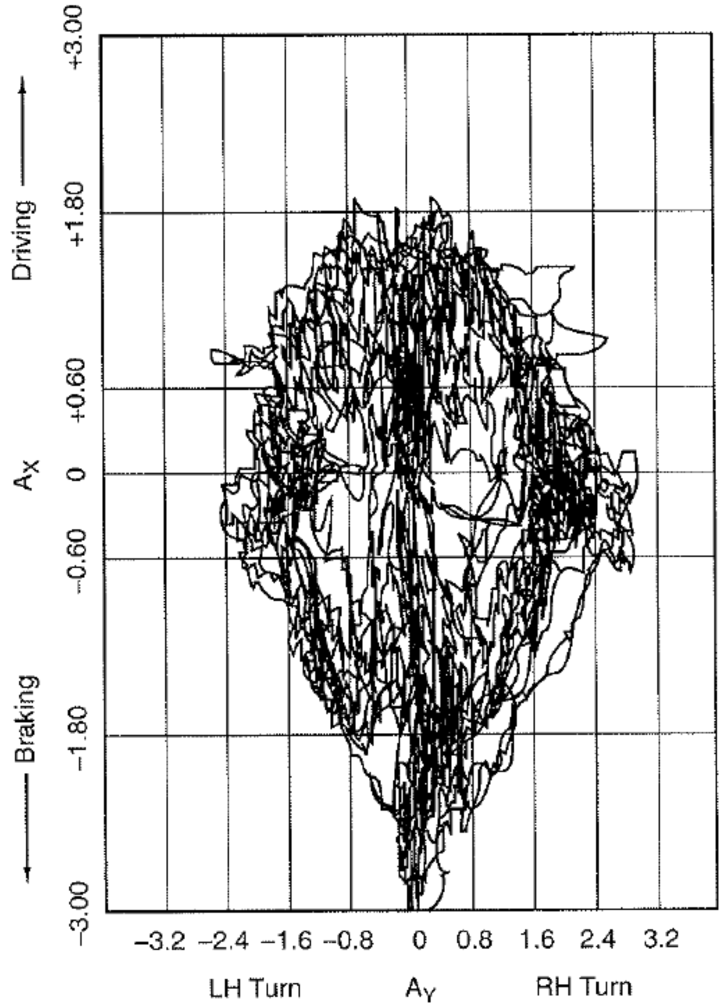


Application of g-g diagram





“g-g” Diagram



Practice on dry circuit.
(Reference personal communication
Peter Wright, Team Lotus.)