



Session-6

Friday, 18-12-2006, 4.00PM -5.30 PM

Steady State Handling and Transient Handling



Handling

- Ackermann Steering Geometry
- Low Speed Turning
- High Speed Cornering
- Tire Cornering Stiffness
- Cornering equations
- Static Margin
- Suspension effects on Cornering
 - Roll Moment Distribution
 - Camber Thrust
 - Roll Steer
 - Lateral Force Compliance Steer
 - Aligning Torque
- Effect of Tractive Forces on Cornering
- Experimental Measurements of Understeer Gradient
- Transient Response of vehicles
- Roll Over
- Vehicle Dynamic Tests
- Electronic Stability Control

Ackerman Steering Geometry

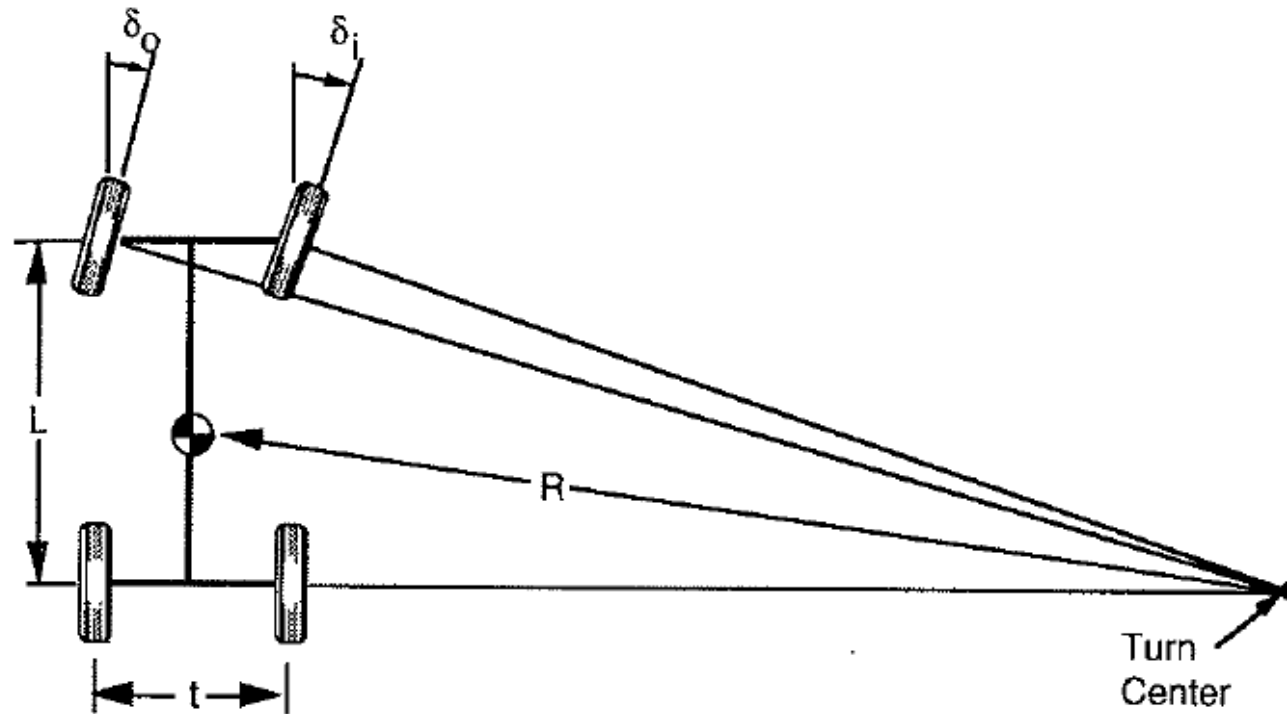


Fig. 6.1 p. 197 Gillespie



Ackerman Steering Geometry

- Inner front wheel steer angles

$$\delta_i = \frac{L}{\left(R - \frac{t}{2}\right)}$$

- Outer front wheel steer angle

$$\delta_o = \frac{L}{\left(R + \frac{t}{2}\right)}$$

- Average Steer angle
Assume small angles!

$$\delta_{ave} = \frac{L}{R}$$



Low Speed Turning

- During Low speed Turning Centrifugal forces are neglected
- Steering is normally effected by changing the heading of the front wheels
- During turn all tires should be in pure rolling without the lateral sliding
- To satisfy pure rolling the wheels should follow curved paths with different radii originating from a common turn centre



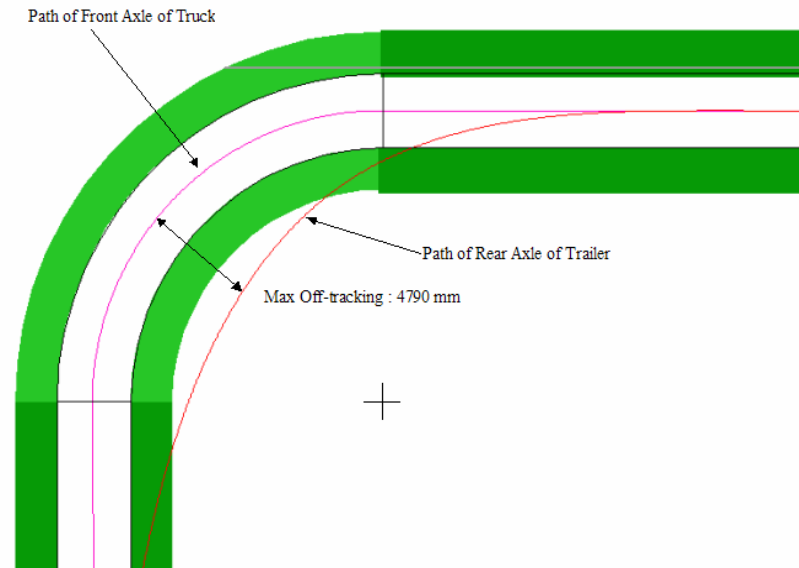
Low Speed Turning

- The terms “Ackerman Steering” or “Ackerman Geometry” are often used to denote the exact geometry of the front wheels
- The correct angles are dependent on the wheelbase of the vehicle and the angle of turn
- The other significant aspect of low-speed turning is the off-tracking that occurs at the rear wheels.
- The off-tracking distance, Δ , may be calculated from simple geometry relationships as:

$$\Delta = R - R \cos\left(\frac{L}{R}\right) = R \left[1 - \left(1 - \frac{\left\{ \frac{L}{R} \right\}^2}{2!} + \frac{\left\{ \frac{L}{R} \right\}^4}{4!} - \dots \right) \right] \cong \frac{L^2}{2R}$$



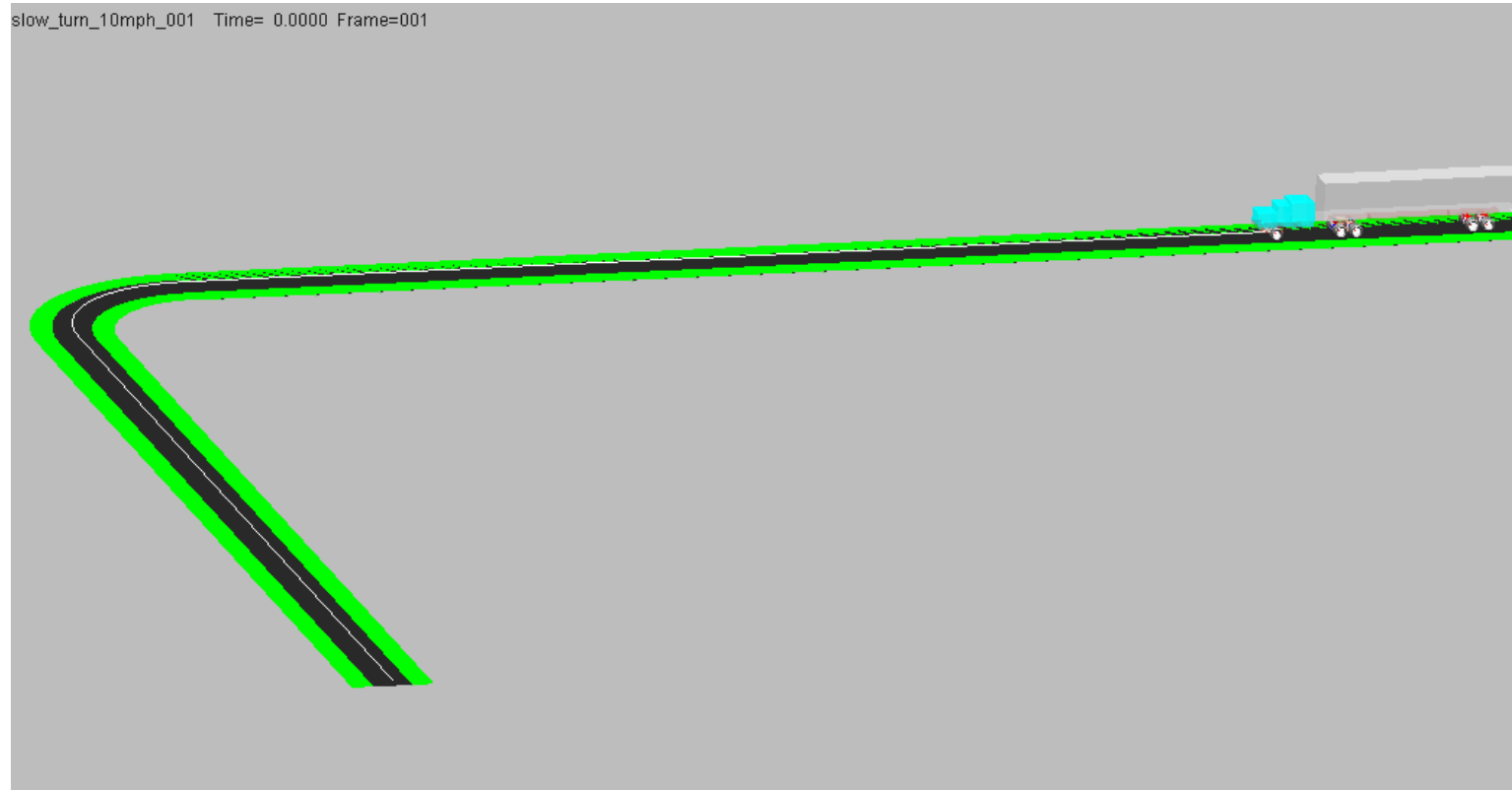
Low Speed Off tracking



Max Off tracking : 4790 mm



Low Speed Off tracking





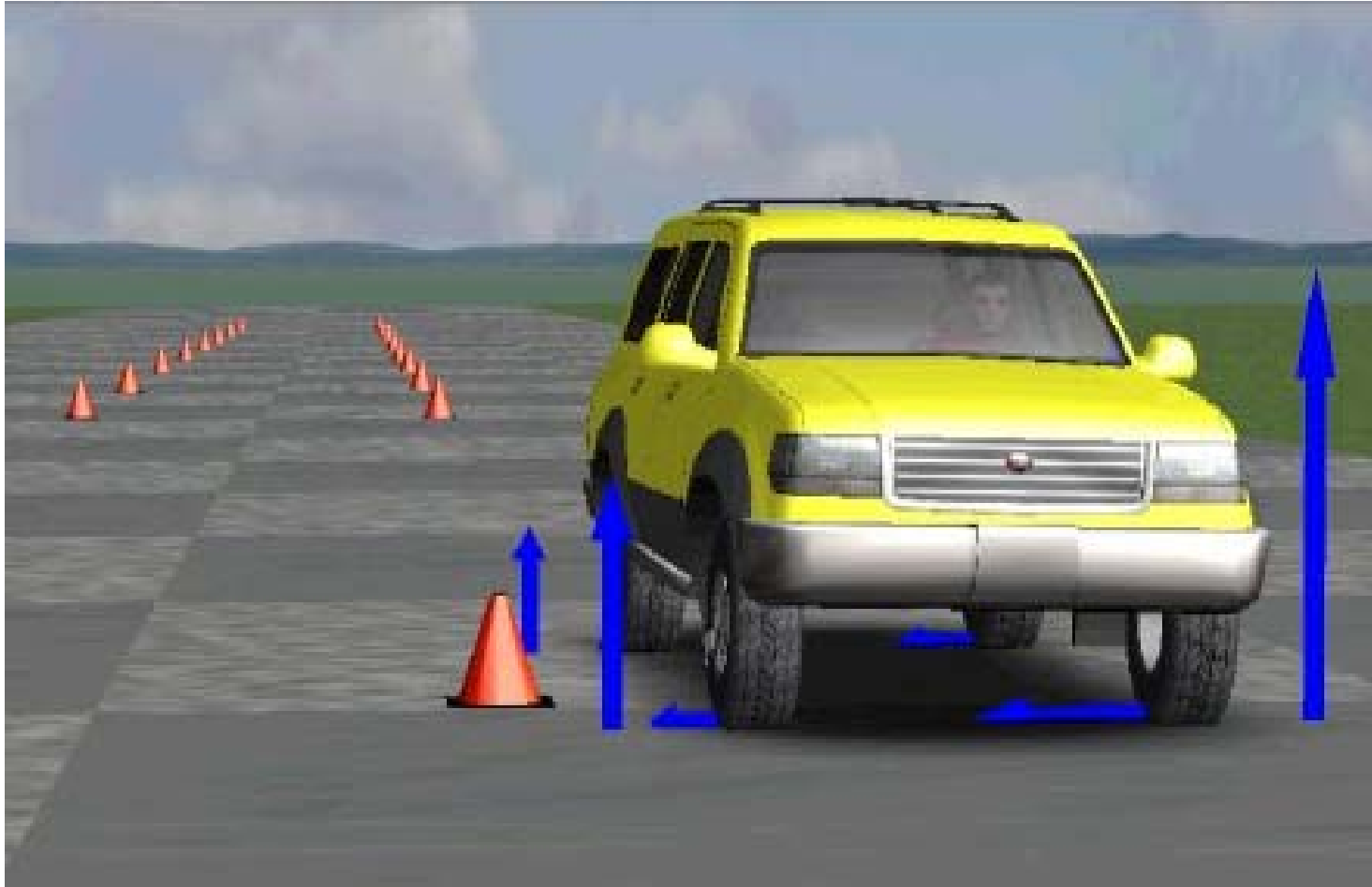
Steady State Handling

- Steady state handling performance is concerned with the directional behaviour of a vehicle during a turn under nontime-varying conditions
- Vehicle negotiating a curve with constant radius at a constant forward speed
- In the steady state handling behaviour the inertia properties of the vehicle are not involved
- Steady state Handling Simulation [Click](#)



High Speed Cornering

- When a vehicle is negotiating a turn at moderate or higher speeds, the effect of the centrifugal force acting at the centre of gravity is to be considered
- To balance the centrifugal force, the tires must develop appropriate cornering forces
- A side force acting on a tire produces a side slip angle
- When a vehicle is negotiating a turn at moderate or higher speeds, the four tires will develop appropriate slip angles
- The handling characteristics of the vehicle depend to a great extent on the relationship between the slip angles of the front and rear tires.
- Side forces while cornering-Next slide



High Speed Cornering

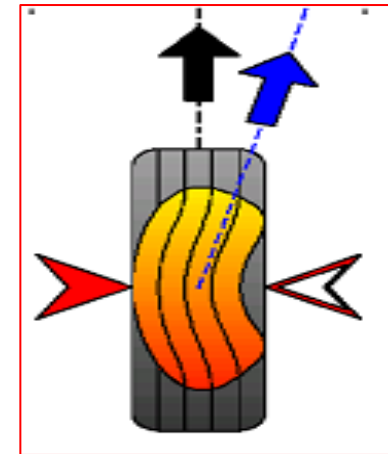
- When a vehicle is negotiating a turn at moderate or higher speeds, the effect of the centrifugal force acting at the centre of gravity is to be considered
- To balance the centrifugal force, the tires must develop appropriate cornering forces



Centrifugal Force
 mV^2/R

High Speed Cornering

- A side force acting on a tire produces a side slip angle
- When a vehicle is negotiating a turn at moderate or higher speeds, the four tires will develop appropriate slip angles
- The handling characteristics of the vehicle depend to a great extent on the relationship between the slip angles of the front and rear tires.
- Simulation of side forces [Click](#)

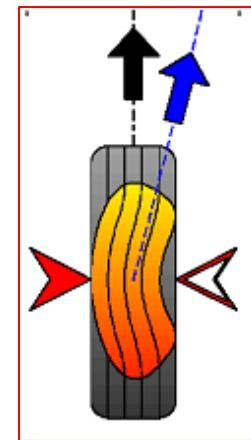
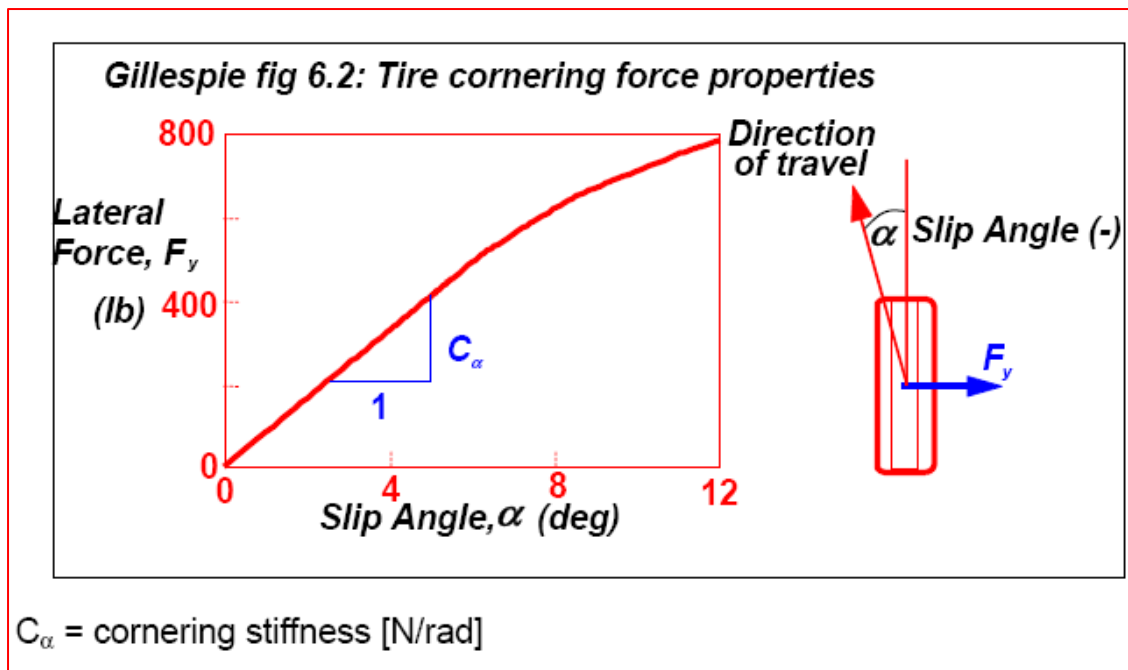




High Speed Cornering

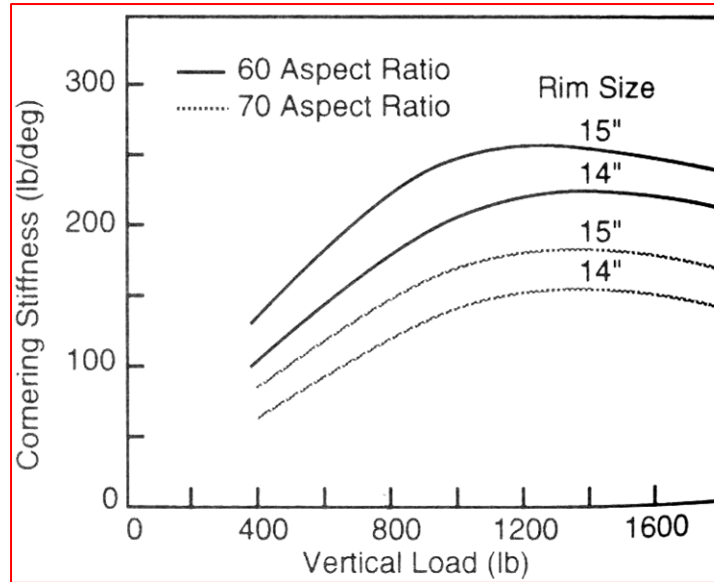
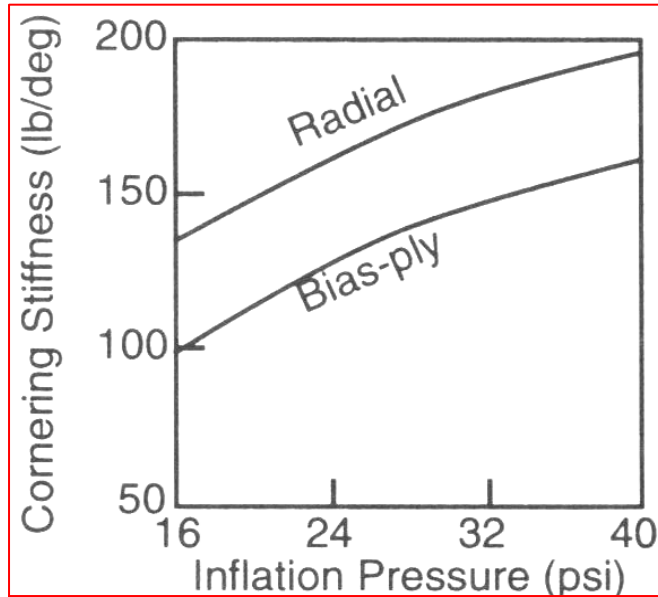
- Cornering Stiffness

$$C_{\alpha} = \frac{F_y}{\alpha} (N / rad)$$





Factors Affecting Cornering Stiffness



Cornering coefficient

$$CC_{\alpha} = C_{\alpha} / F_z$$

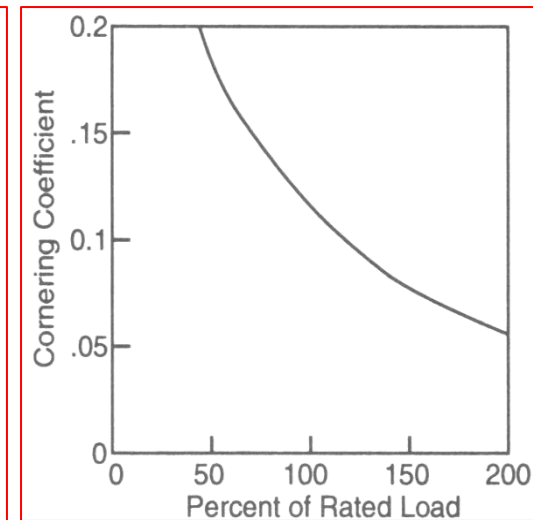
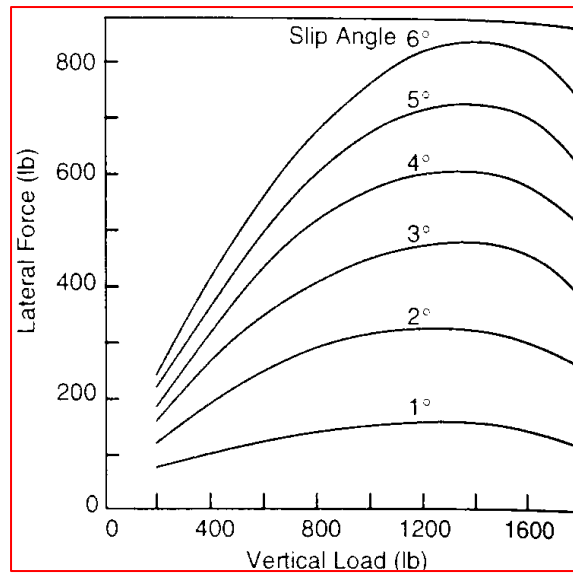
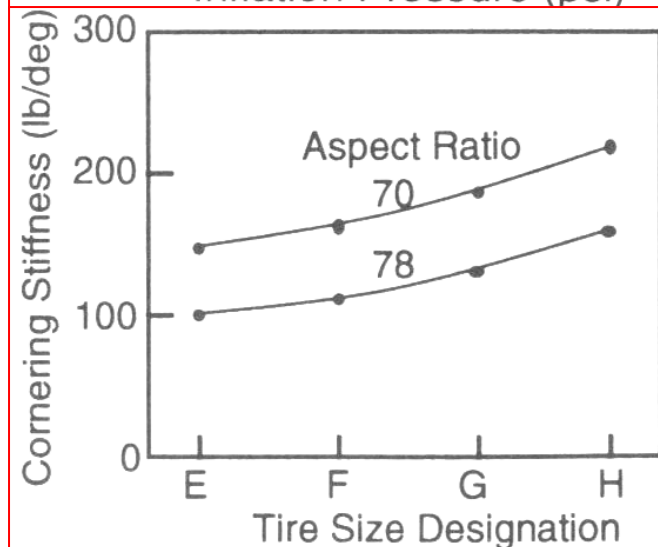
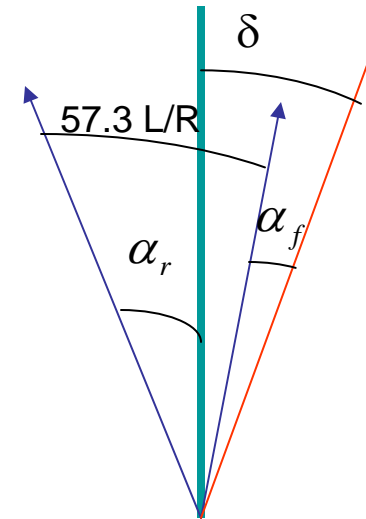
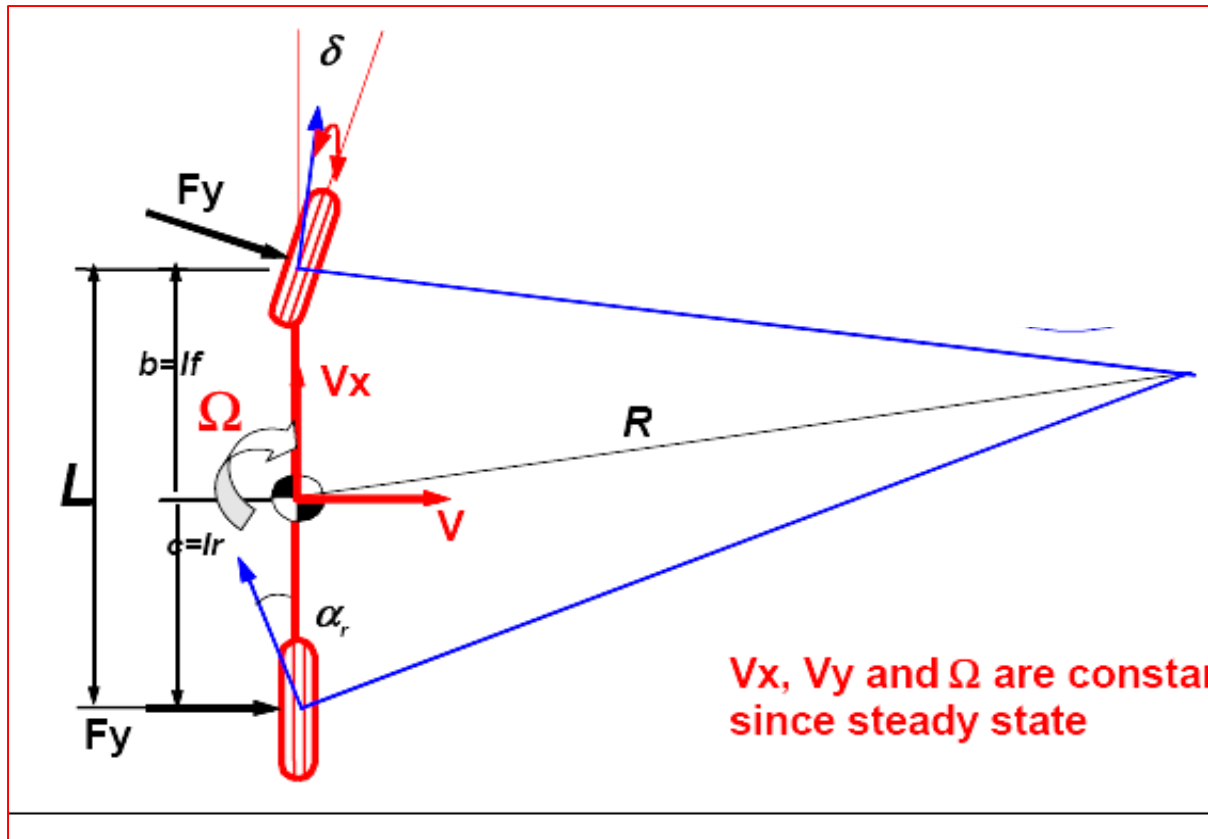


Fig: 15.5a, b, c, d & e

Cornering Equations



Steer Angle required to negotiate a given curve

$$\delta = 57.3 \frac{L}{R} + (\alpha_f - \alpha_r)$$



Cornering Equations

$$F_{yr} = \left[M \frac{b}{L} \right] \frac{V^2}{R} = \frac{W_r}{g} \frac{V^2}{R}$$

$$F_{yf} = \left[M \frac{c}{L} \right] \frac{V^2}{R} = \frac{W_f}{g} \frac{V^2}{R}$$

$$F_{yf} = C_{\alpha f} \alpha_f$$

$$\alpha_f = \frac{F_{yf}}{C_{\alpha f}} = \frac{1}{C_{\alpha f}} \frac{W_f}{g} \frac{V^2}{R}$$

$$F_{yr} = C_{\alpha r} \alpha_r$$

$$\alpha_r = \frac{F_{yr}}{C_{\alpha r}} = \frac{1}{C_{\alpha r}} \frac{W_r}{g} \frac{V^2}{R}$$

$$\delta = 57.3 \frac{L}{R} + (\alpha_f - \alpha_r)$$

$$\delta = 57.3 \frac{L}{R} + \frac{W_f V^2}{C_{\alpha f} g R} - \frac{W_r V^2}{C_{\alpha r} g R}$$

$$\delta = 57.3 \frac{L}{R} + \left(\frac{W_f}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}} \right) \frac{V^2}{g R}$$

$$\delta = 57.3 \frac{L}{R} + K a_y \dots\dots\dots(a)$$

Where:

K = Understeer gradient(deg/g)

a_y = Lateral acceleration(g)

K is a measure of the steady-state handling behavior.



Understeer Gradient

$$K = \left(\frac{W_f}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}} \right)$$

Understeer Gradient due to tire cornering stiffness



Understeer Gradient

- Understeer gradient is a function of the weight distribution and tire cornering stiffness
- Depending on the value of K , the steady state handling characteristics can be classified as
 - Neutral steer
 - Understeer
 - Oversteer



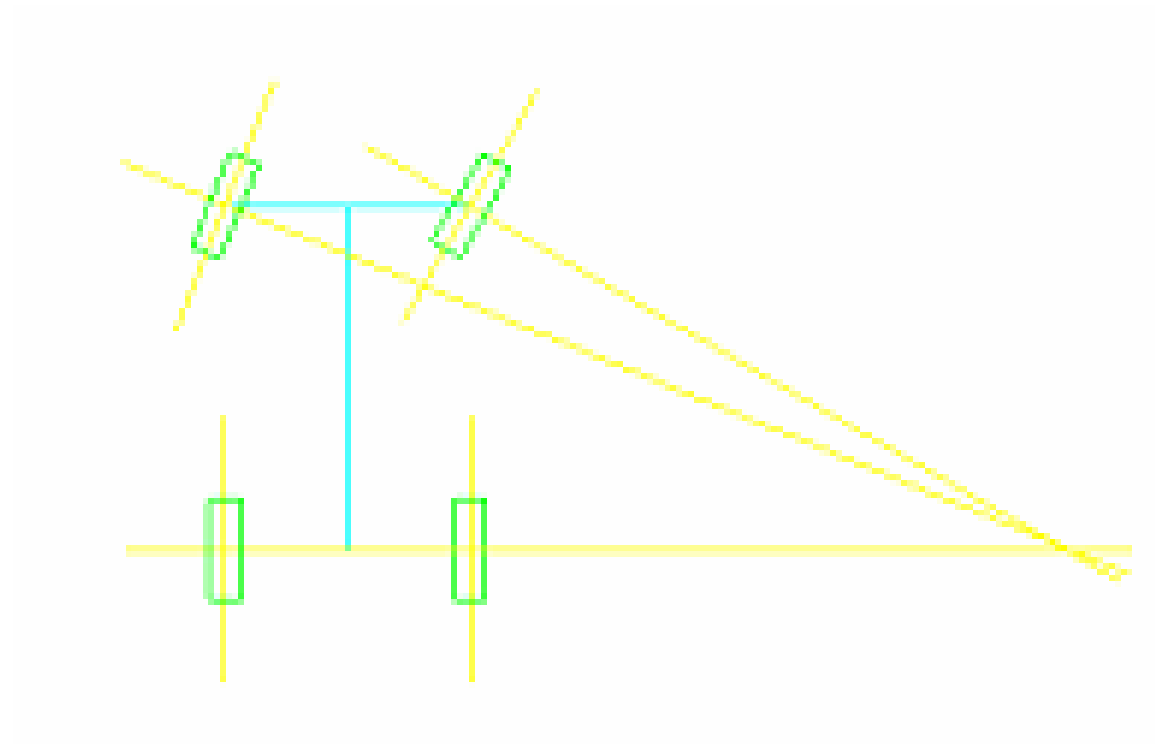
Neutral Steer

$$K = 0 ; \frac{W_f}{C_{\alpha f}} = \frac{W_r}{C_{\alpha r}} \rightarrow \alpha_f = \alpha_r$$

$$\delta = 57.3 \frac{L}{R}$$

- The steer angle required to make the turn will be equivalent to the Ackerman Angle, 57.3 L/R.
- Physically, the neutral steer case corresponds to a balance on the vehicle such that the “force” of the lateral acceleration at the CG causes an identical increase in slip angle at both the front and rear wheels.
- This is a typical situation when cornering speed is low, and all four tires have more or less the same weight on them.
- No slipping

Neutral Steer





Understeer

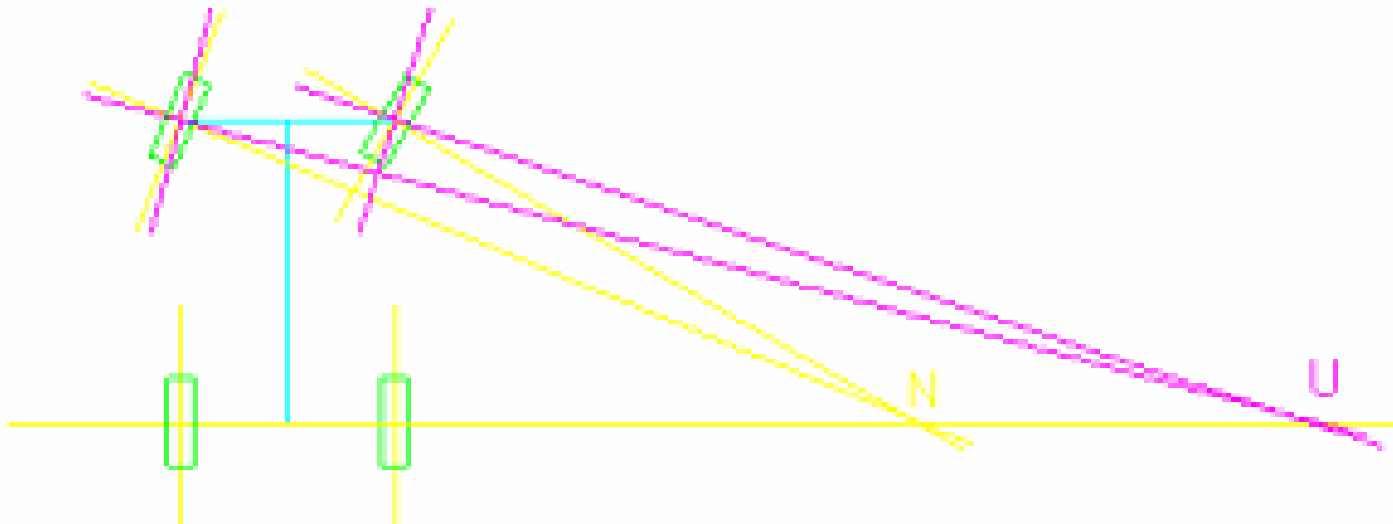
$$\frac{W_f}{C_{\alpha f}} > \frac{W_r}{C_{\alpha r}}; \quad K > 0; \quad \alpha_f > \alpha_r$$

- On a constant-radius turn, the steer angle will have to increase with speed in proportion to K (deg/g) times the lateral acceleration in g's. Thus it increases linearly with the lateral acceleration and with the square of the speed.
- In the understeer case, the lateral acceleration at the CG causes the front wheels to slip sideways to a greater extent than at the rear wheels.
- Thus to develop the lateral force at the front wheels necessary to maintain the radius of turn, the front wheels must be steered to a greater angle.



Understeer

- Front wheels slipping. The car is not turning around the expected point N
- Instead, it's turning around the intersection point U, which makes for a larger turning radius than expected.





Oversteer

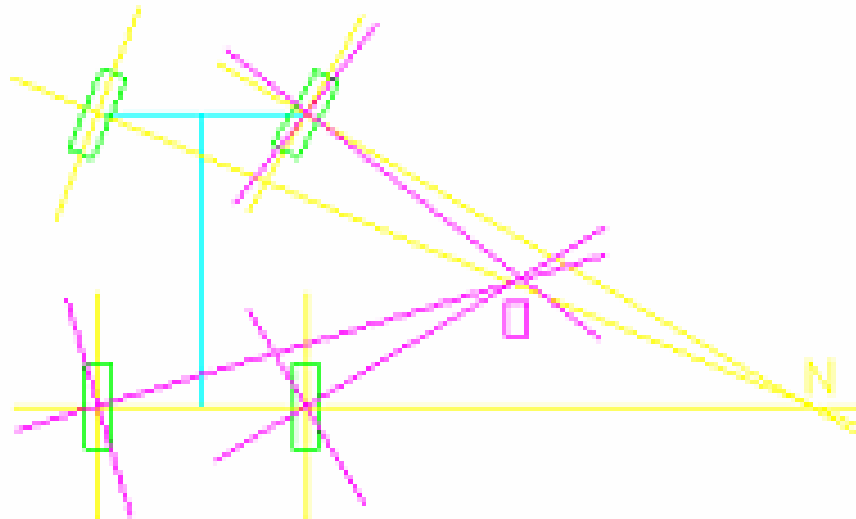
$$\frac{W_f}{C_{\alpha f}} < \frac{W_r}{C_{\alpha r}}; \quad K < 0; \quad \alpha_f < \alpha_r$$

- On a constant-radius turn, the steer angle will have to decrease as the speed (and lateral acceleration) is increased. In this case, the lateral acceleration at the CG causes the slip angle on the rear wheels to increase more than at the front.
- The outward drift at the rear of the vehicle turns the front wheels inward, thus diminishing the radius of turn.
- The increase in lateral acceleration that follows causes the rear to drift out even further and the process continues unless the steer angle is reduced to maintain the radius of turn.



Oversteer

- Rear wheels slipping. This leads to a condition called **oversteer**, where the turning radius is smaller than expected.

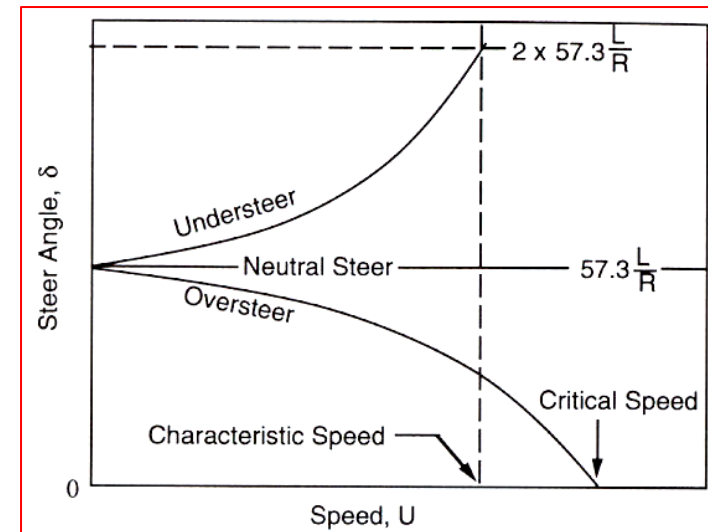


Demo [Click](#)



Steer Angle with Speed

- The way in which steer angle changes with speed on a constant-radius turn for each of these cases is illustrated in **Fig.** With a neutral steer vehicle, the steer angle to follow the curve at any speed is simply the Ackerman Angle.
- With understeer the angle increases with the square of the speed, reaching twice the initial angle at the characteristic speed.
- In the oversteer case, the steer angle decreases with the square of the speed and becomes zero at the critical speed value.





Characteristic Speed

- Characteristic speed is simply the speed at which the steer angle required to negotiate any turn is twice the Ackerman Angle.

$$2 * 57.3L / R = 57.3L / R + Ka_y$$

$$Ka_y = 57.3L / R$$

$$K \frac{V^2}{gR} = 57.3 \frac{L}{R}$$

$$V_{char} = \sqrt{57.3Lg / K}$$

- For an understeer vehicle, the understeer level may be quantified by characteristic speed.



Critical Speed

- In an oversteer vehicle, critical speed is the speed above which the vehicle becomes unstable

$$0 = 57.3L / R + Ka_y$$

$$Ka_y = -57.3L / R$$

$$K \frac{V^2}{gR} = 57.3 \frac{L}{R}$$

$$V_{crit} = \sqrt{-57.3Lg / K}$$

- An Oversteer vehicle can be driven at speeds less than the critical



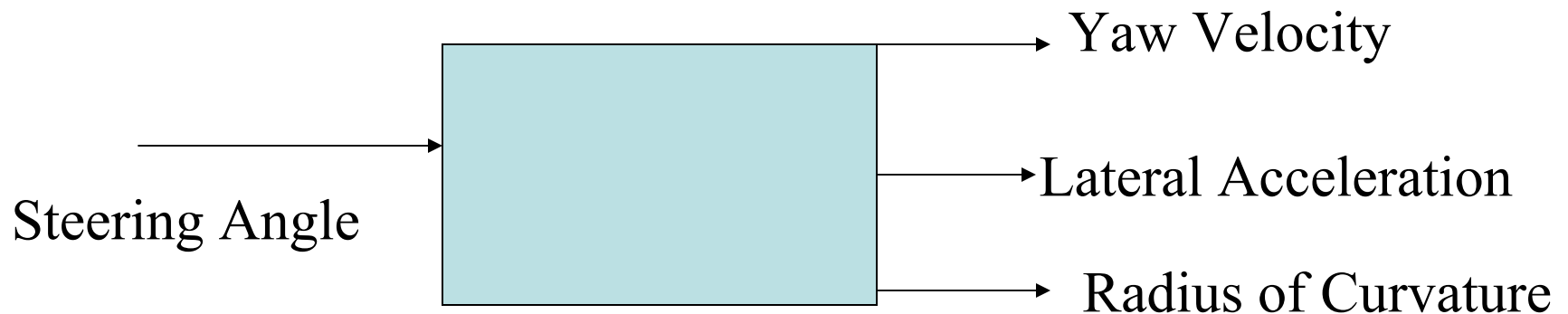
Comments

- The primary factors controlling the steady state handling characteristics of a vehicle are the weight distribution of the vehicle and cornering stiffness of the tires
- A front engined, front wheel drive vehicle with a large portion of the vehicle weight on the front tires may tend to exhibit understeer behaviour
- A rear-engined, rear-wheel drive car with a large portion of the vehicle weight on the rear tires may tend to have oversteer characteristics
- Changes in the load distribution will alter the handling behaviour of a vehicle
- It is necessary choose right type of tire to have right handling characteristics



Steady State Response to Steering Input

- During a turning maneuver, the steer angle induced by the driver can be considered as input to the system and the motion variables of the vehicle such as yaw velocity, lateral acceleration, and curvature may be regarded as outputs.
- The ratio of yaw velocity, lateral acceleration, or curvature to the steering input can then be used for comparing the response characteristics of different vehicles





Lateral Acceleration Gain

- The ratio of lateral acceleration, a_y , to the steering angle, δ , is the lateral acceleration gain,

$$\begin{aligned}\frac{a_y}{\delta} &= \frac{\frac{V^2}{gR}}{57.3 \frac{L}{R} + K a_y} \\ &= \frac{\frac{V^2}{gR}}{57.3 \frac{L}{R} + K \frac{V^2}{gR}} = \frac{\frac{V^2}{gR}}{1 + \frac{KV^2}{57.3Lg}}\end{aligned}$$

- Note that when K is zero (neutral steer), the lateral acceleration gain is determined only by the numerator and is directly proportional to speed squared.
- When K is *positive* (understeer), the gain is diminished by the second term in the denominator, and is always less than that of a neutral steer vehicle.
- Finally, when K is *negative* (oversteer), the second term in the denominator subtracts from 1, increasing the lateral acceleration gain.



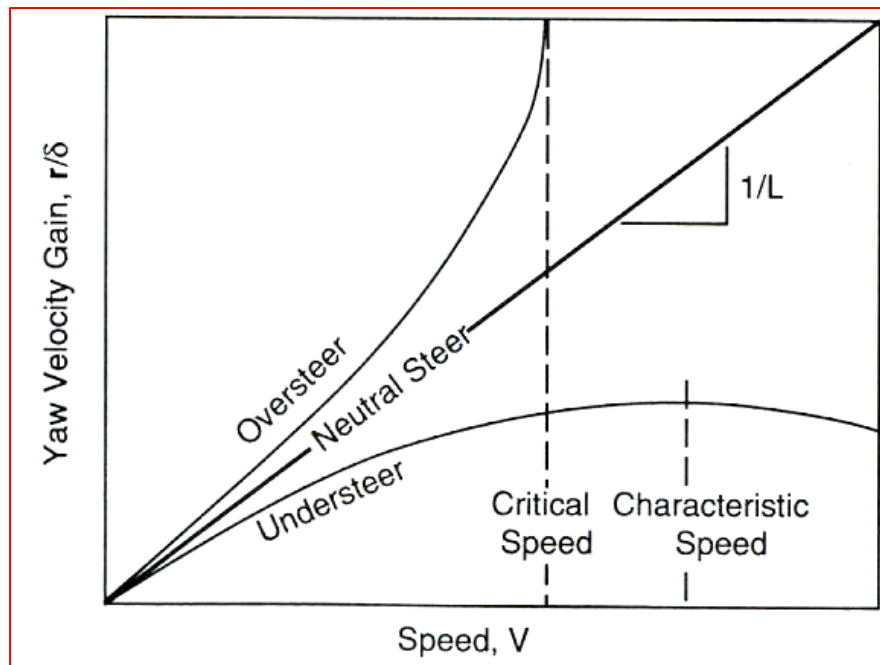
Yaw Velocity Gain

Yaw Velocity r is the rate of rotation in heading angle and is given by $r = 57.3 \frac{V}{R}$

$$\text{Yaw velocity} = \text{rate of rotation in heading angle} = 57.3 \frac{V}{R} \text{ deg/s}$$

$$\frac{r}{\delta} = \frac{V/L}{1 + \frac{KV^2}{57.3Lg}} = \text{Yaw velocity gain}$$

- In the case of the understeer vehicle, the yaw velocity increases with speed up to the characteristic speed, then begins to decrease thereafter. Thus the characteristic speed has significance as the speed at which the vehicle is most responsive in yaw.





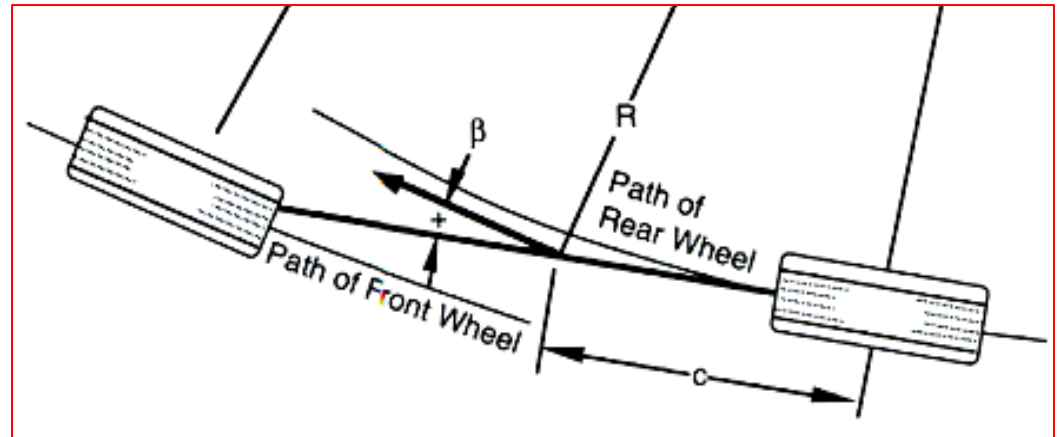
Curvature Response

$$\frac{1/R}{\delta} = \frac{1}{L + KV^2 / g}$$

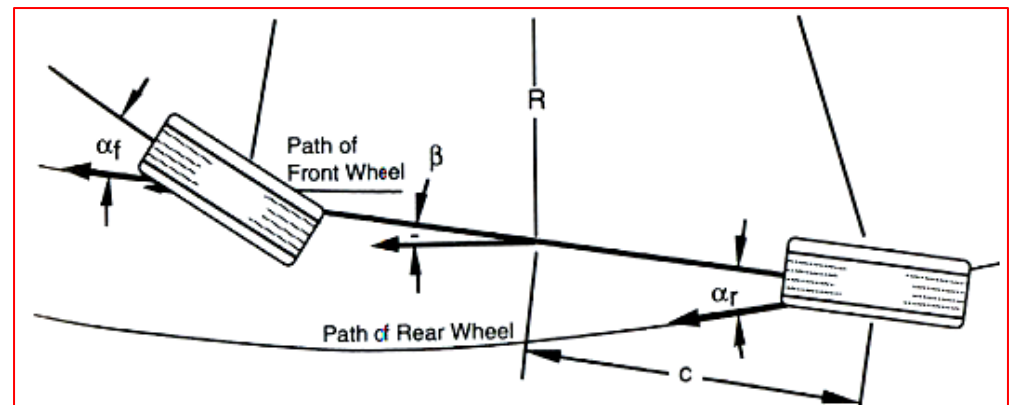
- The ratio of the steady state curvature $1/R$ to the steer angle is another parameter commonly used for evaluating the response characteristics of a vehicle
- From the steering response point of view, the oversteer vehicle has the most sensitive handling characteristics, while the understeer vehicle is the least responsive

Side Slip Angle (β)

- When the lateral acceleration is negligible, the rear wheel tracks inboard of the front wheel. But as lateral acceleration increases, the rear of the vehicle must drift outboard to develop the necessary slip angles on the rear tires.



Low speed Turning



High speed Turning



Directional Stability

- The directional stability of a vehicle refers to its ability to stabilise its direction of motion against disturbances.
- A vehicle is considered to be directionally stable if, following a disturbance, it returns to a steady state regime within a finite time
- A directionally unstable vehicle diverges more and more from the original path, even after the disturbance is removed
- The disturbances may arise from crosswind, momentary forces acting on the tires from the road, slight movement of the steering wheel, and a variety of causes



Condition for Stability

$$L + \frac{V_x^2}{g} K > 0 \quad \text{if}$$

If K is positive (understeer vehicle) the vehicle is always stable

If K is negative, the vehicle will be stable only

$$V_x < \sqrt{\frac{gL}{-K}}$$

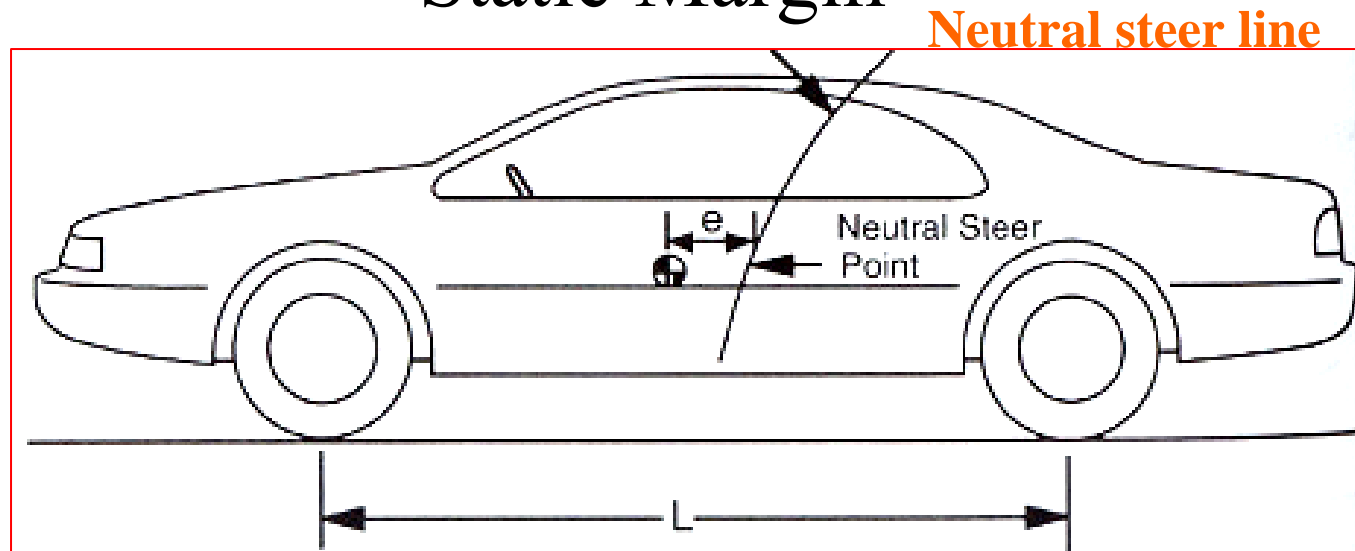
Vehicle Velocity must be less than critical velocity



Static Margin

- **Static margin** like understeer coefficient or characteristic speed, provides a measure of the steady-state handling behavior.
- Static margin is determined by the point on the vehicle where a side force will produce no steady-state yaw velocity (i.e., the neutral steer point).
- The neutral steer line is the locus of points in the x-z plane along which external lateral forces produce no steady-state yaw velocity.

Static Margin



- The static margin is defined as the distance the neutral steer points falls behind the CG, normalized by the wheelbase. That is:

$$\text{Static Margin} = e/L$$

- When the point is behind the CG the static margin is positive and the vehicle is understeer. At the CG the margin is zero and the vehicle is neutral steer. When ahead of the CG, the vehicle is oversteer. On typical vehicles the static margin falls in the range of 0.05 to 0.07 behind the CG.



Conclusions

- At Low Speed Tires do not develop lateral forces, Ackermann steering formula holds good
- At higher speeds because tire slip, lateral forces are developed, the steering angle is different from Ackermann steering equation
- Depending on the sign of steering gradient K , steering can be neutral, under and over steering.
- Oversteering makes a vehicle unstable at high speeds
- Positive Static Margin makes the vehicle understeer



Suspension Effects On Cornering

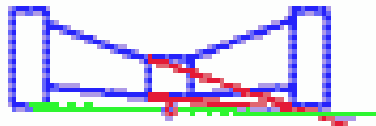
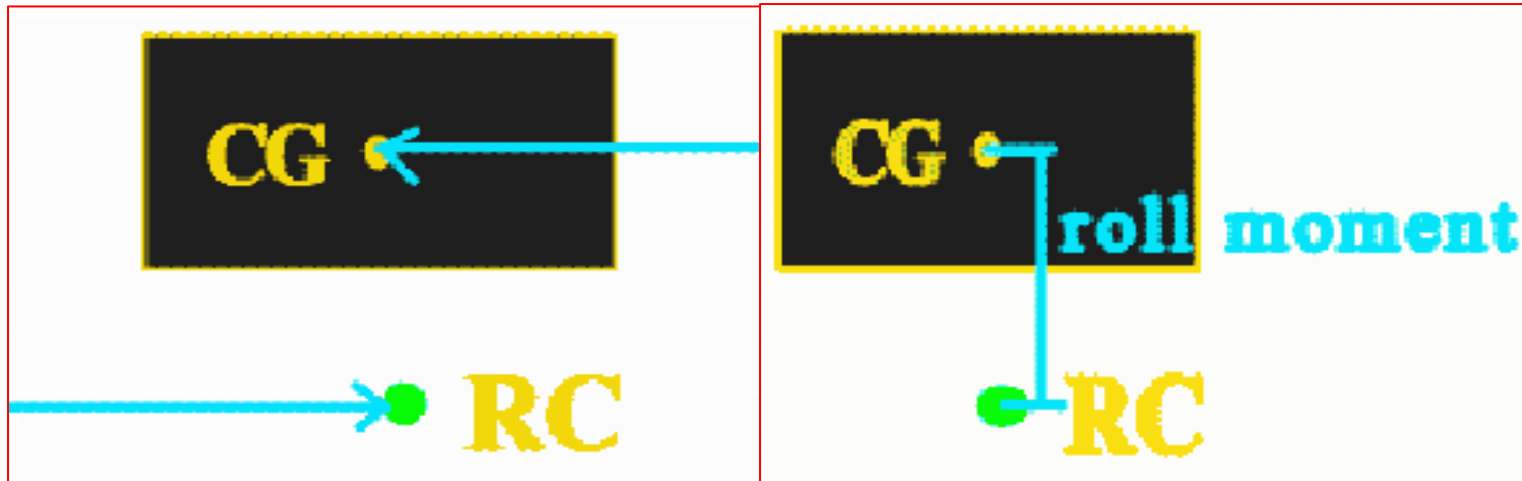
- Although tire cornering stiffness was used as the basis for developing the equations for understeer/oversteer, there are multiple factors in vehicle design that may influence the cornering forces developed in the presence of a lateral acceleration.
- Any design factor that influences the cornering force developed at a wheel will have a direct effect on directional response.
- The **suspensions and steering system** are the primary sources of these influences



Suspension Effects on Cornering

- Roll Moment Distribution
- Camber Change
- Roll Steer
- Lateral Force Compliance Steer
- Aligning Torque
- Effect of Tractive Forces on Cornering

Roll Moment and Roll Axis



Roll Axis

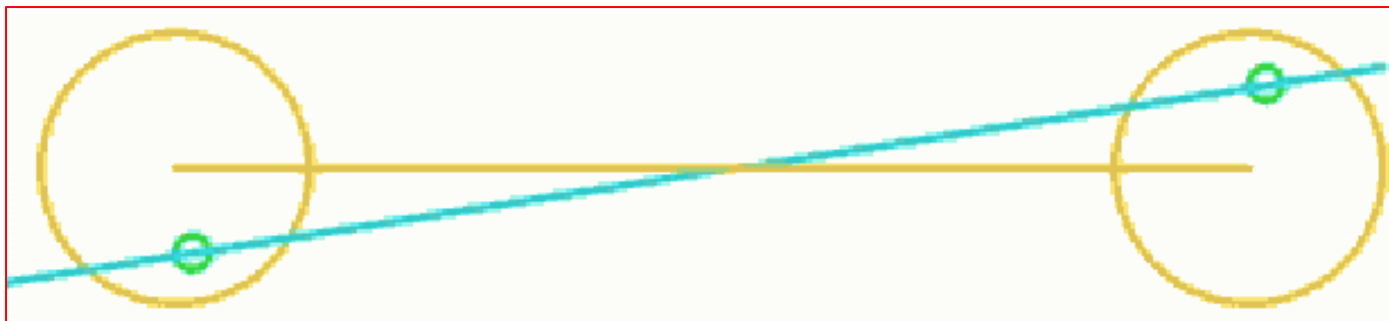
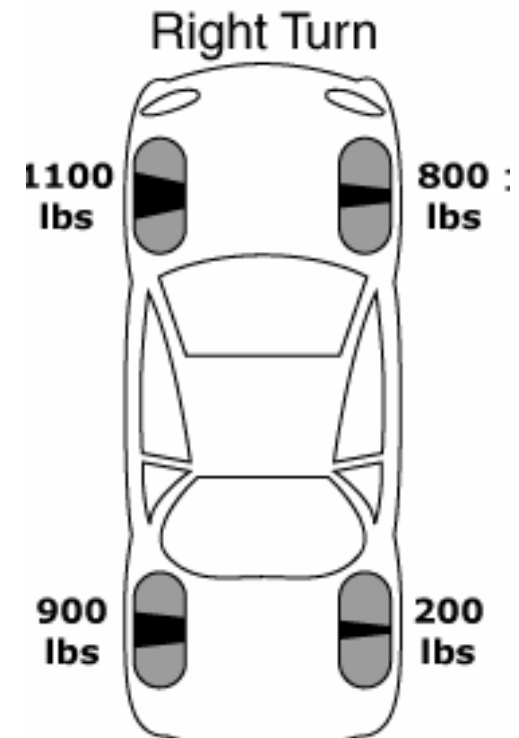
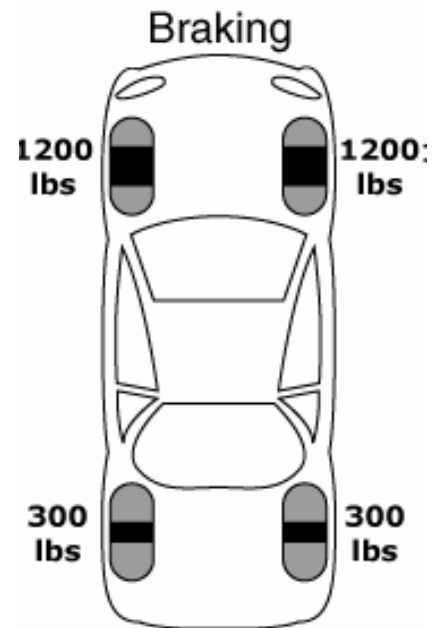
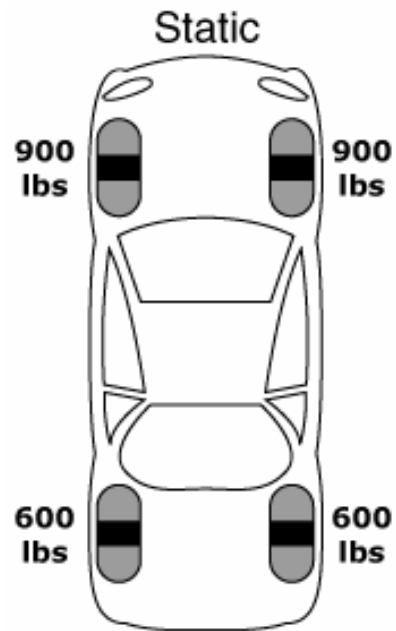
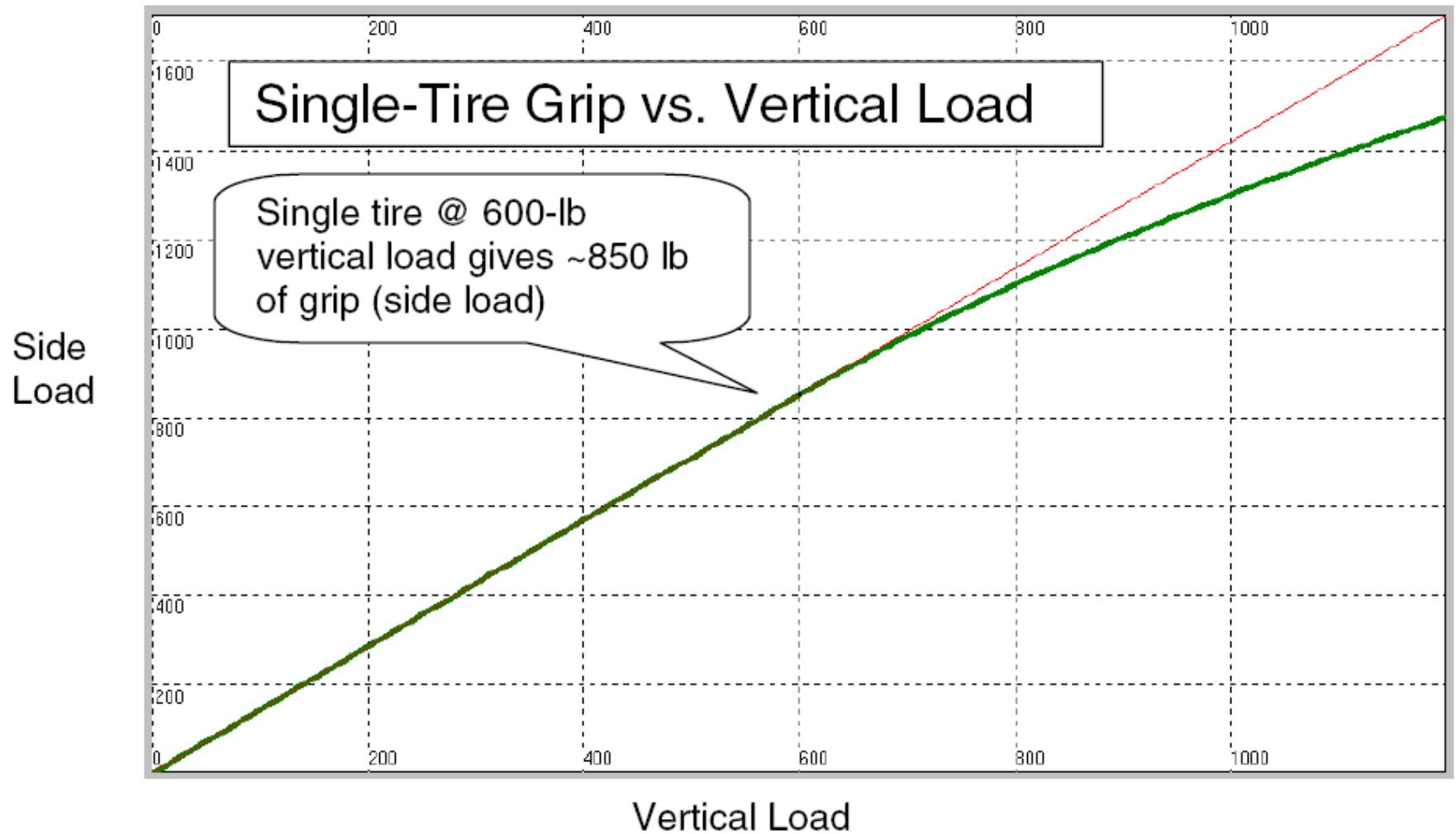


Fig: 16.4

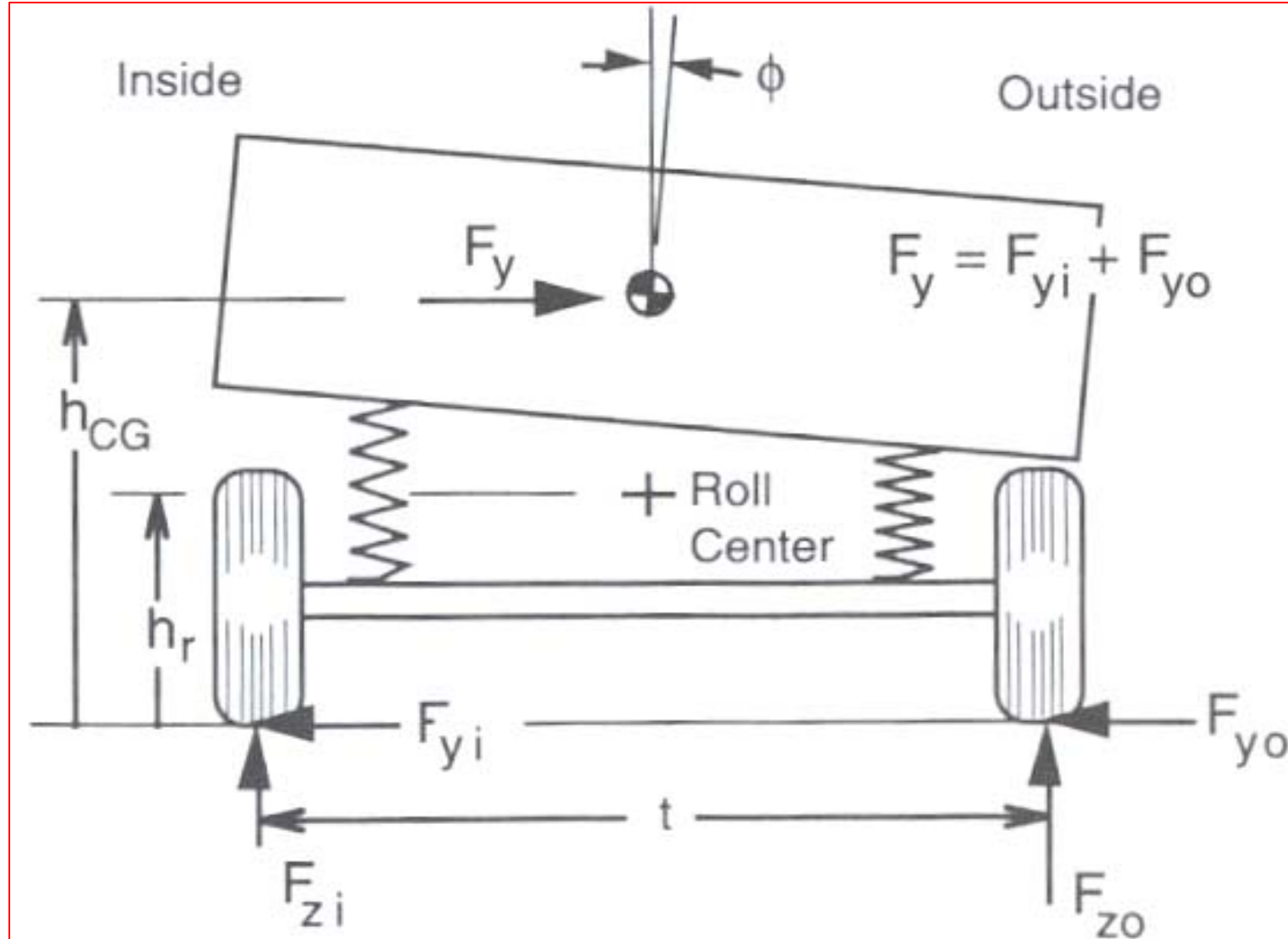






Body Roll

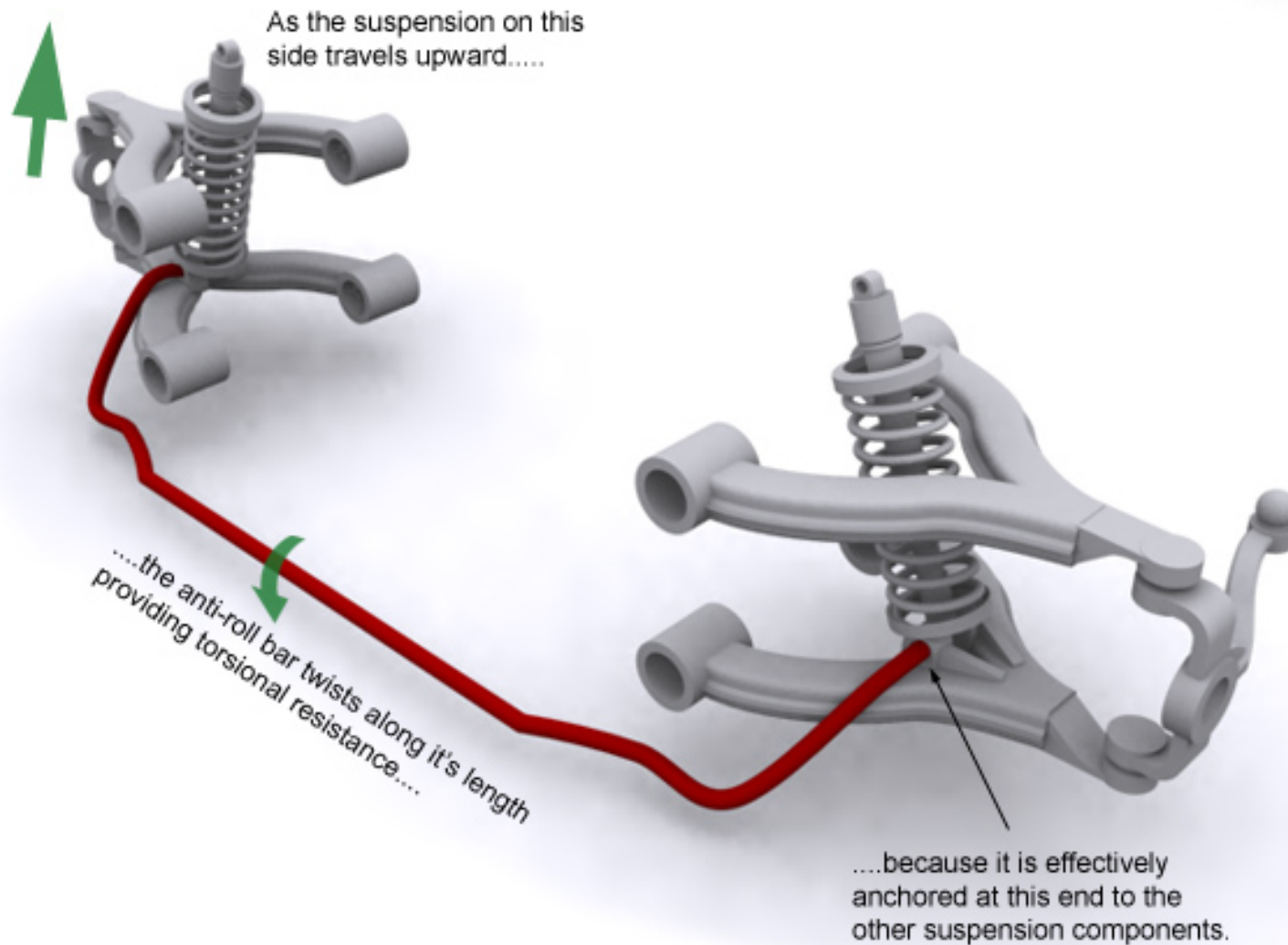
- When thinking of load transfer it may help to consider body roll.
- As the body rolls the outside springs are compressed and place more load on the outside tires.
- In reality, body roll is a result of cornering force, not a cause of load transfer.
- If you double the spring rate you will NOT significantly change the load transfer, but you will reduce body roll.





- If the lateral force, we are talking about, happens on the front wheels, then the vehicle understeers, if happens on the rear wheels, then the vehicle oversteers
- Roll moment distribution changes vehicle handling characteristics. If roll moment distribution is high on front axle, the vehicle understeers, it oversteers if the roll moment distribution is high on rear axle
- Auxiliary roll stiffeners (Stabilising bars) alter handling characteristics
- Using stabilising bar, the roll moment on the front axle can be increased, thus making vehicle understeer
- Using stabilising bars at the rear increase the roll moment on the rear side making the vehicle oversteer

Stabilising (Anti Roll) Bar





Mechanics of Roll Moment Distribution

- All suspensions are functionally equivalent to the two springs.
- The lateral separation of the springs causes them to develop a roll resisting moment proportional to the difference in roll angle between the body and axle

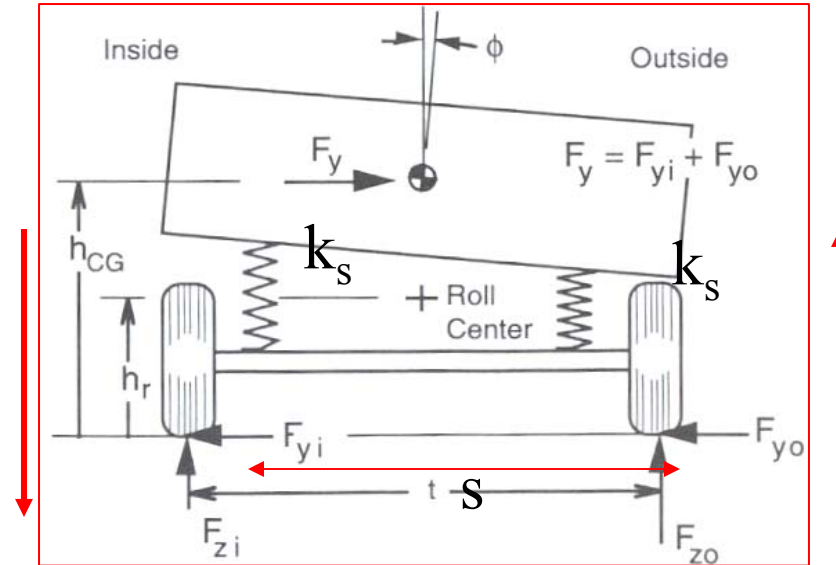
K_ϕ : Roll stiffness of the suspension

K_s : Vertical Spring rate of the left and right springs

s : Lateral separation between the springs

ϕ ; Roll angle of the body

Mechanics of Roll Moment



$$\sum M_{cG} = \left(k_s \left(\frac{s}{2} \right) \phi \right) \frac{s}{2} + \left(k_s \left(\frac{s}{2} \right) \phi \right) \frac{s}{2} = \frac{1}{2} k_s s^2 \phi = k_\phi \phi$$

If a roll bar is included then

$$\sum M_{cG} = \frac{1}{2} k_s s^2 \phi + k_r \phi = (k_\phi + k_r) \phi$$

$$K_\phi = \text{Roll stiffness of the suspension} = 0.5 k_s s^2$$



Lateral Load Transfer

To Determine the Load coming on the left and Right Wheels

Assume a vehicle is taking a turn

F_{z0} = vertical load on the outside wheel
in turn

F_{zi} = Vertical load on the inside wheel
in turn

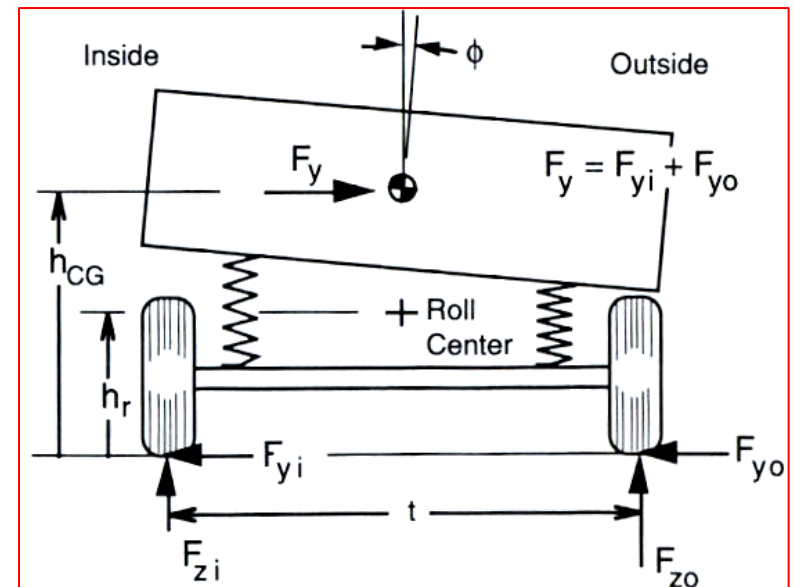
F_y = lateral force = $F_{yi} + F_{yo}$

h_r = Roll Centre height

t = Track width

K_ϕ = Roll stiffness of the suspension

ϕ = Roll angle of the body





Taking moment about the Roll Centre

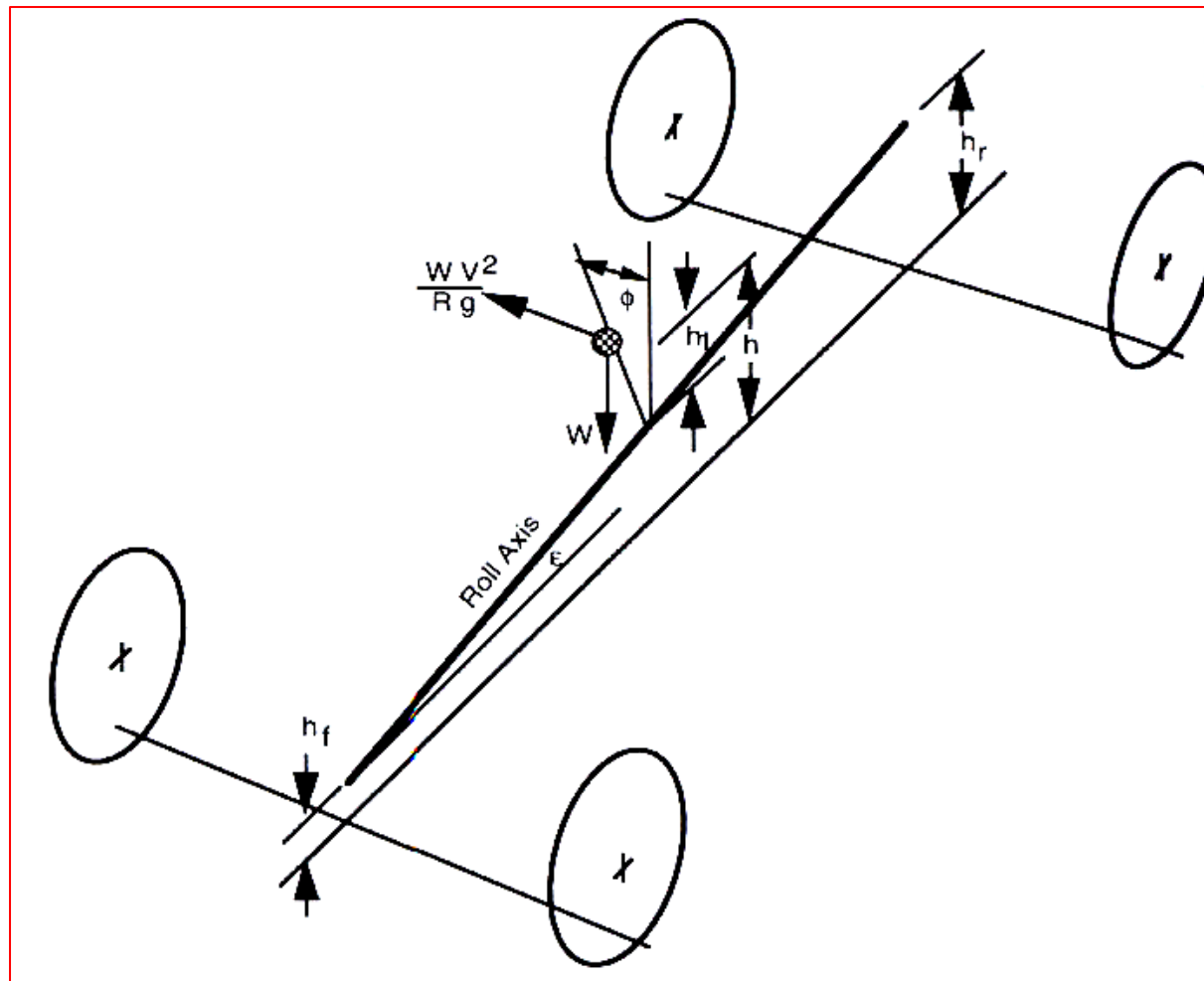
$$(F_{z0} - F_{zi}) \frac{t}{2} - (F_{y0} + F_{yi}) h_r - K_\phi \phi = 0$$

$$\begin{aligned} F_{z0} - F_{zi} &= 2(F_{y0} + F_{yi}) \frac{h_r}{t} + 2 \frac{K_\phi}{t} \phi \\ &= 2 F_y \frac{h_r}{t} + 2 \frac{K_\phi \phi}{t} \end{aligned}$$

$$\text{Lateral load transfer due to cornering force} = \frac{2 F_y h_r}{t}$$

$$\text{Lateral load transfer due to vehicle roll} = \frac{2 K_\phi \phi}{t}$$

Roll Angle ϕ





$$K_{\phi} = \text{Roll stiffness of the suspension} = 0.5k_s s^2$$

ϕ = Roll Angle

$$\phi = \frac{Wh_1 V^2 / Rg}{K_{\phi f} + K_{\phi r} - Wh_1} = \frac{Wh_1 a_y}{K_{\phi f} + K_{\phi r} - Wh_1}$$



Roll Rate

$$\text{Roll Rate} = \frac{d\phi}{da_y} = \frac{Wh_1}{K_{\phi f} + K_{\phi r} - Wh_1}$$

*The roll rate is usually ...in the range of 3to7 degrees / g
on typical passenger cars*

From foregoing equations



Roll Moment

Roll Moments

$$M'_{\phi_f} = K_{\phi_f} \frac{Wh_1 V^2 / (Rg)}{K_{\phi_f} + K_{\phi_r} - Wh_1} + W_f h_f \frac{V^2}{Rg} = \Delta F_{zf} t_f$$

$$M'_{\phi_r} = K_{\phi_r} \frac{Wh_1 V^2 / (Rg)}{K_{\phi_f} + K_{\phi_r} - Wh_1} + W_r h_r \frac{V^2}{Rg} = \Delta F_{zr} t_r$$

The Roll moments magnitude depend on K_{ϕ_f} and K_{ϕ_t} which in turn depend on suspension stiffness



Lateral Forces F_{yf} and F_{yr}

$$F_{yf} = [C_{\alpha f} - 2b\Delta F_z^2]\alpha_f = \frac{W_f V^2}{gR}$$

on the rear tires

$$F_{yr} = [C_{\alpha r} - 2b\Delta F_z^2]\alpha_r = \frac{W_r V^2}{gR}$$

b is the second coefficient in the cornering stiffness polynomial



Slip Angles due to Lateral Force

$$F_{yf} = [C_{\alpha f} - 2b\Delta F_z^2]\alpha_f = \frac{W_f V^2}{gR}$$

$$\alpha_f = \frac{W_f V^2}{gR[C_{\alpha f} - 2b\Delta F_z^2]}$$

$$F_{yr} = [C_{\alpha r} - 2b\Delta F_z^2]\alpha_r = \frac{W_r V^2}{gR}$$

$$\alpha_r = \frac{W_r V^2}{gR[C_{\alpha r} - 2b\Delta F_z^2]}$$



Understeer Gradient Due to Roll Moment Distribution

$$\delta = 57.3 \frac{L}{R} + (\alpha_f - \alpha_r)$$

$$\delta = 57.3 \frac{L}{R} + \frac{W_f V^2 / Rg}{(C_{\alpha f} - 2b\Delta F_{zf}^2)} - \frac{W_r V^2 / Rg}{(C_{\alpha r} - 2b\Delta F_{zr}^2)}$$

$$C_{\alpha} \gg 2b\Delta F_z^2$$

$$\frac{1}{(C_{\alpha} - 2b\Delta F_z^2)} = \frac{1}{C_{\alpha} (1 - \frac{2b\Delta F_z^2}{C_{\alpha}})} \approx \frac{1}{C_{\alpha}} (1 + \frac{2b\Delta F_z^2}{C_{\alpha}})$$

$$\delta = 57.3 \frac{L}{R} + \left[\left(\frac{W_f}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}} \right) + \left(\frac{W_f}{C_{\alpha f}} \frac{2b\Delta F_{zf}^2}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}} \frac{2b\Delta F_{zr}^2}{C_{\alpha r}} \right) \right] \frac{V^2}{gR}$$

$$K_{lt} = \frac{W_f}{C_{\alpha f}} \frac{2b\Delta F_{zf}^2}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}} \frac{2b\Delta F_{zr}^2}{C_{\alpha r}}$$



Understeer Gradient

$$K_{llt} = \frac{W_f}{C_{\alpha f}} \frac{2b\Delta F_{zf}^2}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}} \frac{2b\Delta F_{zr}^2}{C_{\alpha r}}$$

Understeer Gradient due
to lateral load transfer

It is the understeer gradient that arises due to lateral load transfer



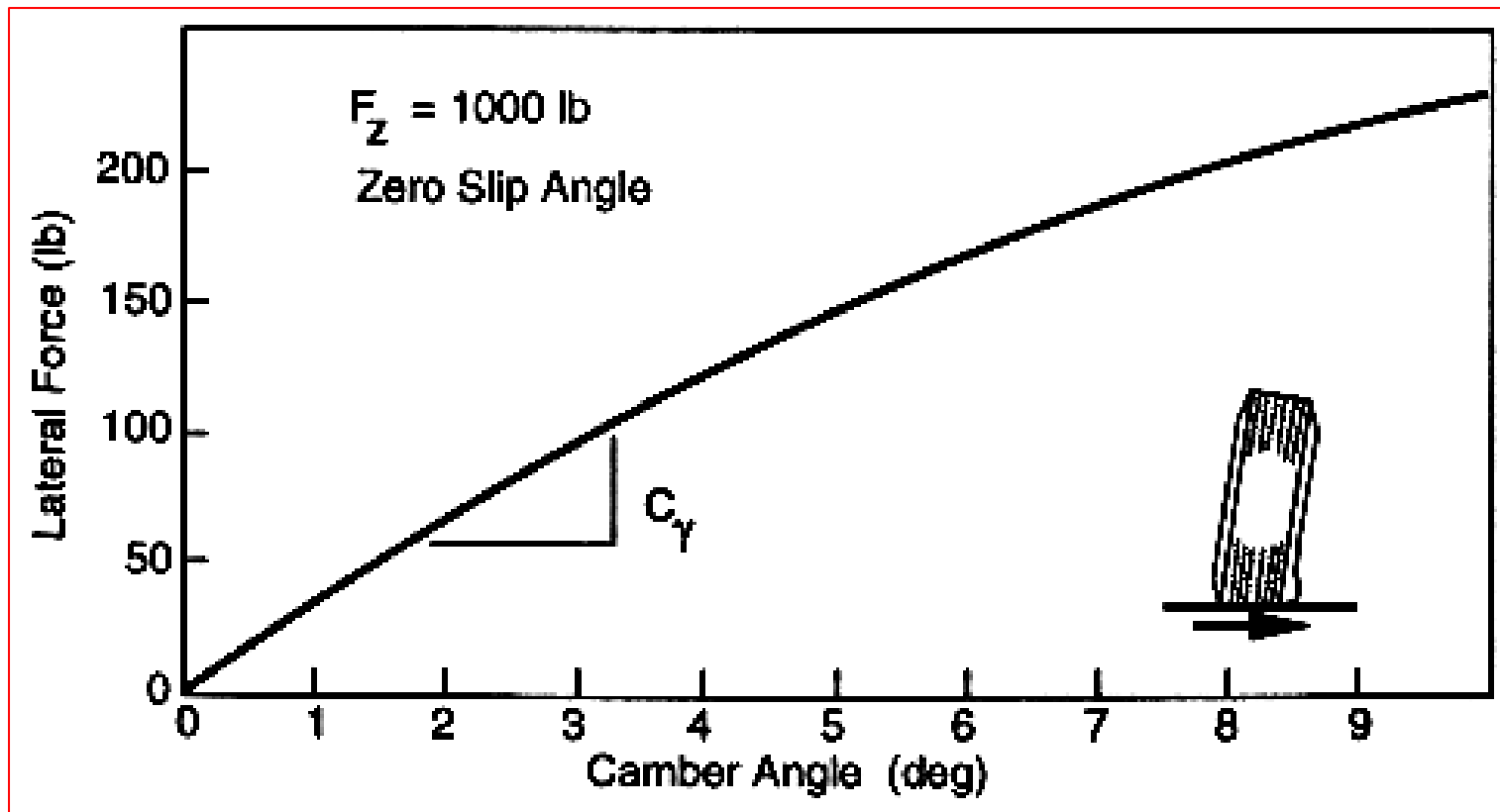
In general, the roll moment distribution on vehicles tends to be biased toward the front wheels due to a number of factors:

- **Relative to load, the front spring rate is usually slightly lower than that at the rear (for flat ride), which produces a bias toward higher roll stiffness at the rear.** However, independent front suspensions used on virtually all cars enhance front roll stiffness because of the effectively greater spread on the front suspension springs (increased s , but less k_s).
- Designers usually strive for higher front roll stiffness to ensure under-steer in the limit of cornering.
- **Stabilizer bars are often used on the front axle to obtain higher front roll stiffness.**
- If stabilizer bars are needed to reduce body lean, they may be installed on the front or the front and rear. Caution should be used when adding a stabilizer bar only to the rear because of the potential to induce unwanted oversteer.



Camber Change

- The inclination of a wheel outward from the body is known as the camber angle. **Camber on a wheel will produce a lateral force known as “camber thrust.”** **Fig:** shows a typical camber thrust curve.





Camber Change

- Camber angle produces much less lateral force than slip angle. About 4 to 6 degrees of camber are required to produce the same lateral force as 1 degree of slip angle on a bias-ply tire.
- Camber stiffness of radial tires is generally lower than that for bias-ply tires; hence, as much as 10 to 15 degrees are required on a radial. Nevertheless, camber thrust is additive to the cornering force from slip angle, thus affecting understeer gradient.
- Camber thrust of bias-ply tires is strongly affected by inflation pressure, although not so for radial tires, and it is relatively insensitive to load and speed for both radial and bias tires.



Camber Change

- Camber angles are small on solid axles, and at best only change the lateral forces by 10% or less. On independent wheel suspensions, however, camber can play an important role in cornering.
- Camber changes both as a result of body roll and the normal camber change in jounce/rebound.
- The understeer gradient deriving from camber angles on each axle is given by:

$$K_{camber} = \left(\frac{C_{\gamma f}}{C_{\alpha f}} \frac{\partial \gamma_f}{\partial \phi} - \frac{C_{\gamma r}}{C_{\alpha r}} \frac{\partial \gamma_r}{\partial \phi} \right) \frac{\partial \phi}{\partial a_y}$$

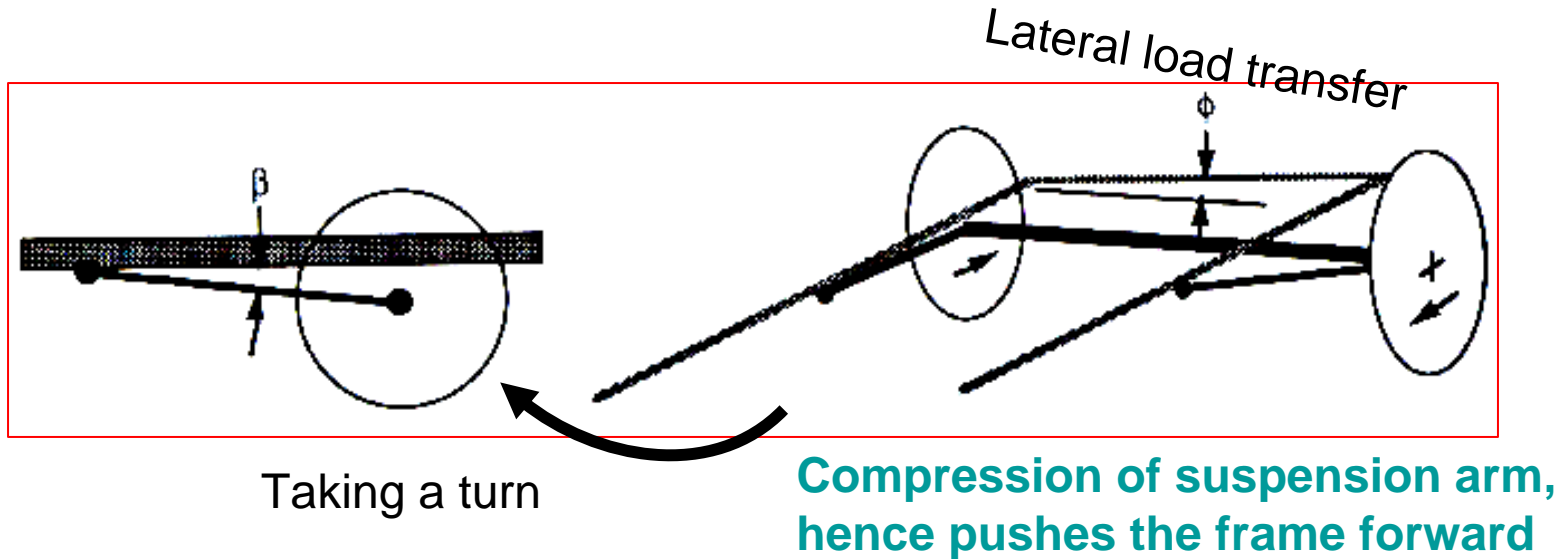
$$C_{\gamma} = \text{Tire Camber Stiffness} = \frac{F_y}{\gamma}$$



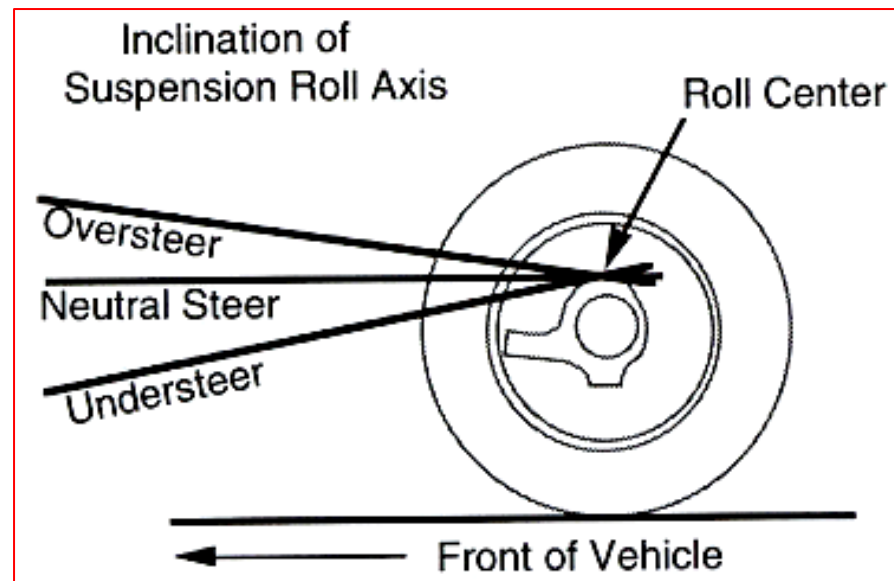
Roll Steer

- When a vehicle rolls in cornering, the suspension kinematics may be such that the wheels steer. Roll steer is defined as the steering motion of the front or rear wheels with respect to the sprung mass that is due to the rolling motion of the sprung mass. Consequently, roll steer effects on handling lag the steer input, awaiting roll of the sprung mass.
- The steer angle directly affects handling as it alters the angle of the wheels with respect to the direction of travel. **Let “ ϵ ” be the roll steer coefficient on an axle (degrees steer/degree roll).**
- The understeer gradient resulting due to roll steer

$$K_{roll\ steer} = (\epsilon_f - \epsilon_r) \frac{\partial \phi}{\partial a_y}$$



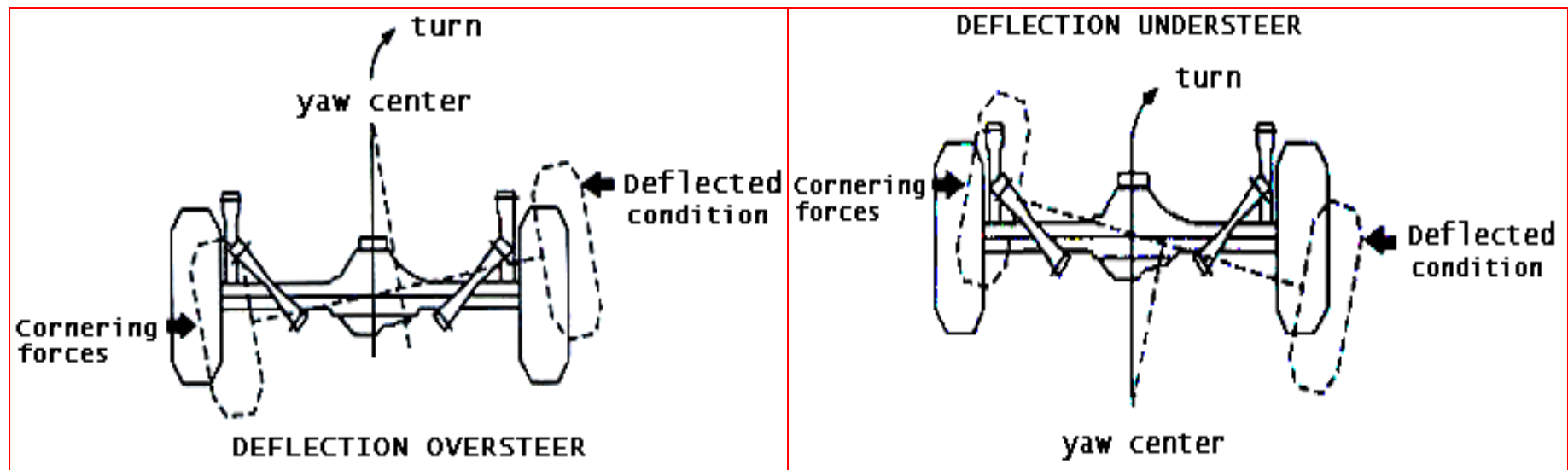
- Positive roll steer on the rear axle oversteers the vehicle
- Positive roll steer on the front axle understeers the vehicle





Lateral Force Compliance Steer

- With the soft bushings used in suspension linkages for NVH reasons, there is the possibility of steer arising from lateral compliance in the suspension.
- With the simple solid axle, compliance steer can be represented as rotation about a yaw center as illustrated in





- With a forward yaw center on a rear axle, the compliance allows the axle to steer toward the outside of the turn, thus causing oversteer. Conversely, a rearward yaw center results in understeer
- On a front axle, just the opposite is true - a rearward yaw center is oversteer, and a forward yaw center is understeer
- The lateral force understeer gradient is given by

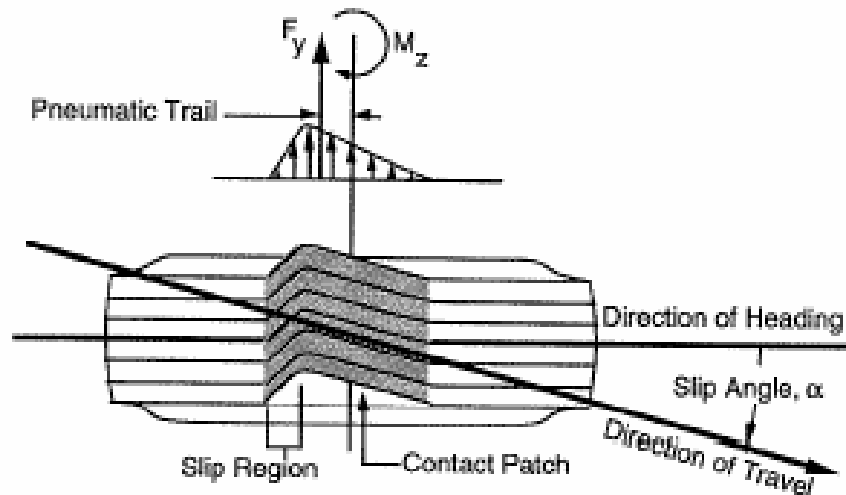
$$K_{lfcs} = A_f W_f - A_r W_r$$

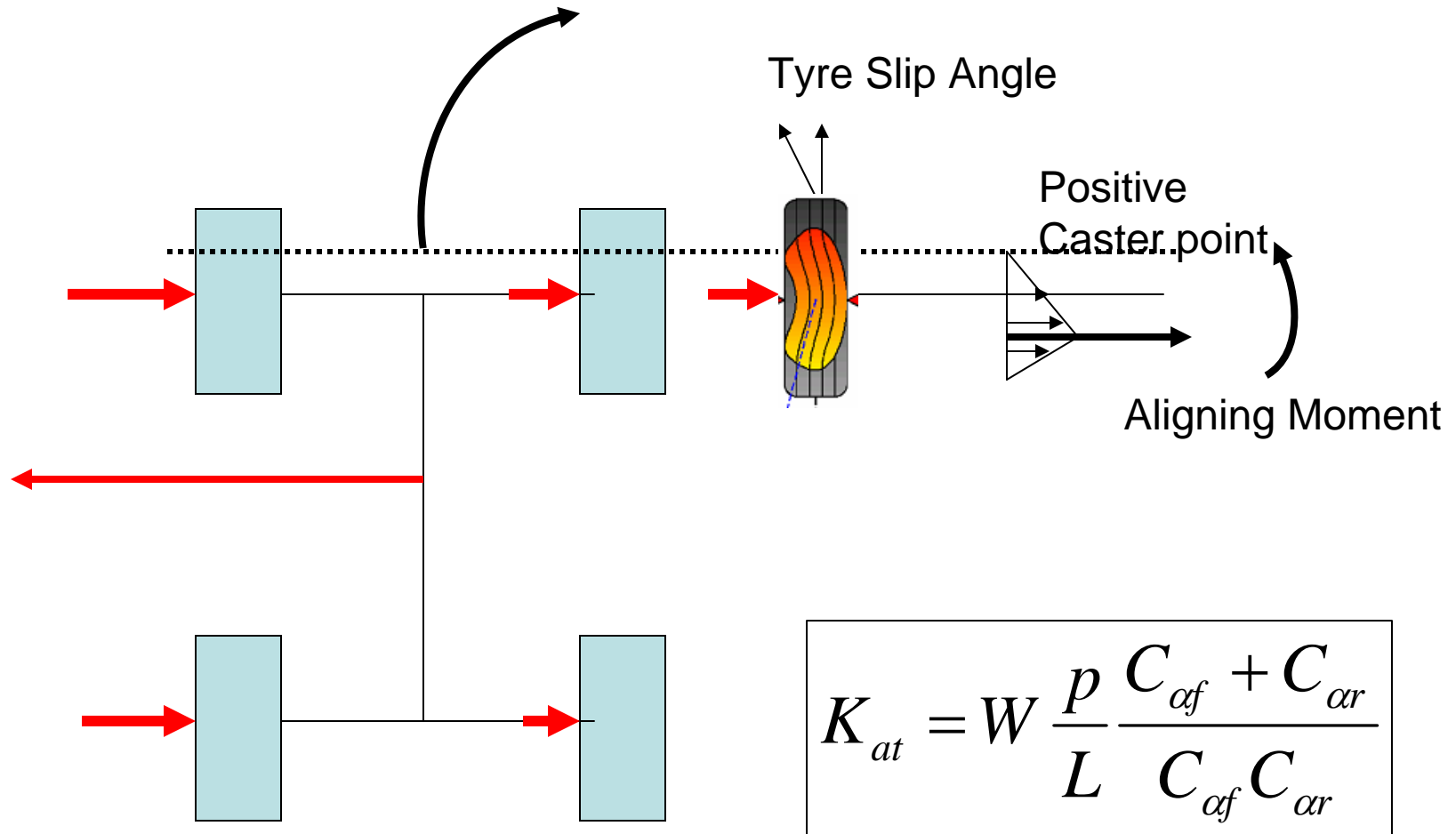
- $A = \text{Lateral force compliance} = \delta / F_y$



Aligning Torque

- When a side force applied at the wheel centre and the cornering force developed in the ground plane are usually not coplanar. At some slip angle, the cornering force in the ground plane is normally behind the applied side force giving rise to a torque called aligning torque. The distance is known as the “pneumatic trail (p).”
- The aligning torque experienced by the tires on a vehicle always resists the attempted turn, thus it is the source of an understeer effect.







- Because the C_{α} values are positive, the aligning torque effect is positive (understeer) and cannot ever be negative (oversteer).
- The understeer due to this mechanism is normally less than 0.5 deg/g. However, aligning torque is indirectly responsible for additional, and more significant, understeer mechanisms through its influence on the steering system.

Effect of Tractive Forces on Cornering

- Considering tractive forces , the Understeer gradient equation can be written as follows:

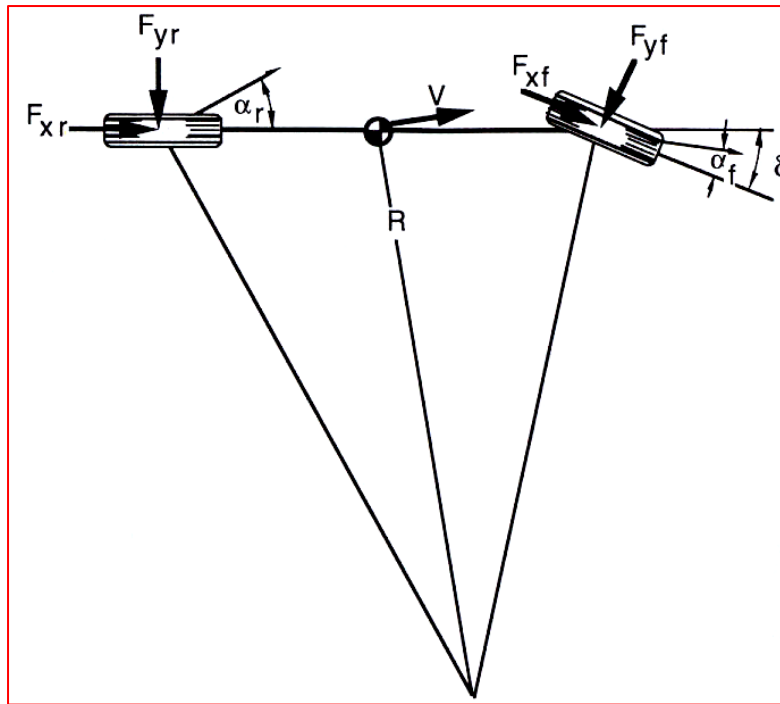


Fig: 16.10

$$K_{tf} = -\left(\frac{W_f}{C_{\alpha f}} \frac{F_{xf}}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}} \frac{F_{xr}}{C_{\alpha r}}\right)$$



- If F_{xf} is positive it causes an oversteer influence (pulls the front of the vehicle into the turn). Thus this mechanism is an oversteer influence with a FWD in the throttle-on case.
- If F_{xr} is positive it causes an understeer influence by the same reasoning on a RWD.
- On a 4WD these mechanisms would suggest that the rear axle should “over drive” the front axle to ensure understeer behavior.



FWD Understeer Influences

- In a front wheel drive vehicle, as per the equation derived the vehicle oversteers

$$K_{tf} = -\left(\frac{W_f}{C_{\alpha f}} \frac{F_{xf}}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}} \frac{F_{xr}}{C_{\alpha r}}\right)$$

- But in most cases, throttle-on produces understeer, and throttle-off produces oversteer



FWD Understeer Influences

- The primary mechanisms responsible for throttle on/off changes in understeer of a FWD vehicle are:
 - The lateral component of drive thrust – While this mechanism is relatively weak (<0.5 deg/g), it is oversteer in direction.
 - Drive torque acting about the steer axis – Highly dependent on driveline geometry and the degree of body roll in cornering, this mechanism is understeer in direction (about 1 deg/g).
 - Loss of lateral force – A tire property which causes understeer (about 1 – 1.5 deg/g).
 - Increase in aligning moment – A tire property which causes under-steer (about 0.5-1 deg/g).
 - Fore/aft load transfer – Although present on FWD and RWD vehicle, it is always understeer in direction (about 1 deg/g).



SUMMARY OF UNDERSTEER EFFECTS

- The understeer coefficient, K , for a vehicle is the result of tire, vehicle and steering system parameters. Its total value is computed as the sum of a number of effects as summarized in the following table.

UNDERSTEER COMPONENT

SOURCE

$$K_{cornering\ stiffness} = \frac{W_f}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}}$$

Tire cornering stiffness

$$K_{llt} = \frac{W_f}{C_{\alpha f}} \frac{2b\Delta F_z^2}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}} \frac{2b\Delta F_z^2}{C_{\alpha r}}$$

Lateral load transfer

$$K_{camber} = \left(\frac{C_{\gamma f}}{C_{\alpha f}} \frac{\partial \gamma_f}{\partial \Phi} - \frac{C_{\gamma r}}{C_{\alpha r}} \frac{\partial \gamma_r}{\partial \Phi} \right) \frac{\partial \Phi}{\partial a_y}$$

Camber thrust

$$K_{roll\ steer} = (\varepsilon_f - \varepsilon_r) \partial \Phi / \partial a_y$$

Roll steer



UNDERSTEER COMPONENT

SOURCE

$$K_{lf_{cs}} = A_f W_f - A_r W_r$$

Lateral force compliance steer

$$K_{at} = W \frac{p}{l} \frac{C_{\alpha f} + C_{\alpha r}}{C_{\alpha f} C_{\alpha r}}$$

Aligning torque

$$K_{tf} = -\left(\frac{W_f}{C_{\alpha f}} \frac{F_{xf}}{C_{\alpha f}} - \frac{W_r}{C_{\alpha r}} \frac{F_{xr}}{C_{\alpha r}}\right)$$

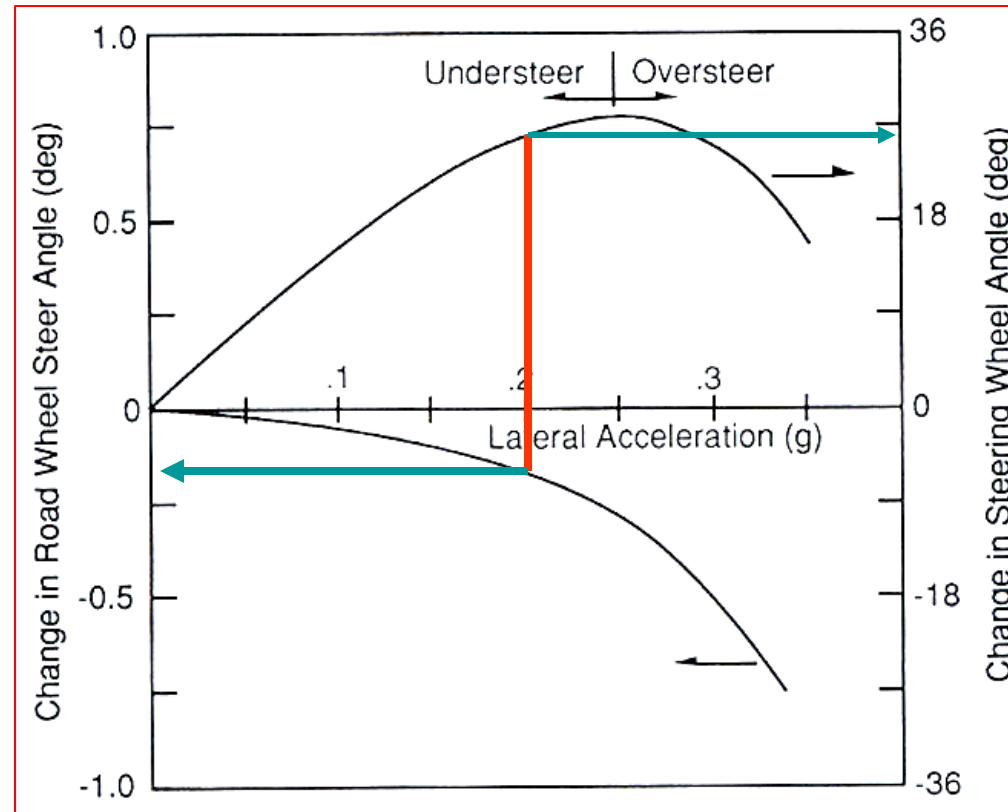
Tractive Forces

$$K_{strg} = W_f \frac{r v + p}{K_{ss}}$$

Steering system

v = caster angle, K_{ss} – Steering System stiffness

How much Understeer Gradient



K- Understeer Gradient value is dependent on Steering ratio desired for different class of vehicles



Testing of Handling Characteristics

- To test handling under steady state conditions, various types of tests can be conducted on a skid pad, which in essence is a large, flat, paved area.
- Three types of tests can be distinguished
 - Constant radius test
 - Constant forward speed test
 - Constant steer angle test
- During the tests, the steer angle, forward speed and yaw velocity or lateral acceleration of the vehicle are measured
- Yaw velocity measured by a rate gyro or lateral acceleration/forward speed
- Lateral acceleration can be measured by an accelerometer or yaw velocity x forward speed
- Based on the relationship between the steer angle and lateral acceleration or yaw velocity obtained handling characteristics can be evaluated



Constant Radius Test

- Vehicle is driven along a constant radius at various speeds
- The steer angle required to maintain the vehicle on course at various forward speeds together with the corresponding lateral acceleration are measured
- Results are plotted
- The handling behaviour of the vehicle can then be determined from the slope of steer angle-lateral acceleration curve

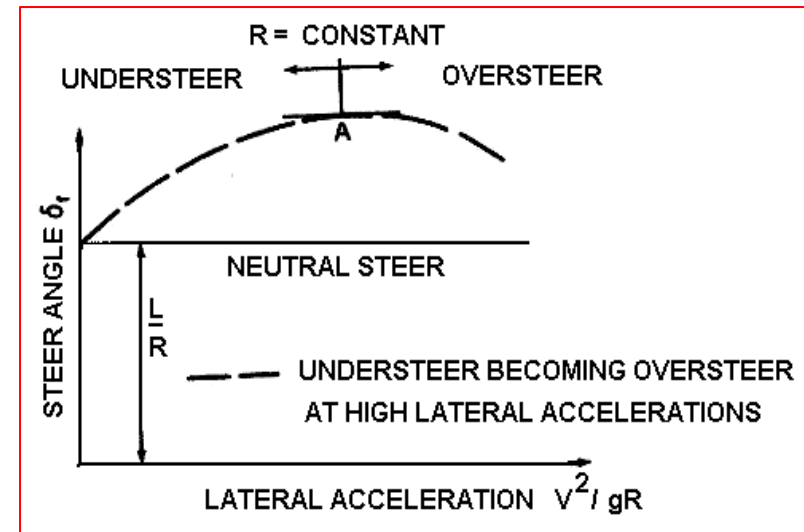


Fig: 15.20



Constant Speed Test

- The vehicle is driven at a constant forward speed at various turning radii.
- The steer angle and the lateral acceleration are measured
- The handling behaviour of the vehicle can then be determined from the slope of the steer angle-lateral acceleration curve
- The vehicle is understeer when the slope is greater than that of neutral steer slope, vehicle is oversteer when the slope is less than neutral steer curve slope

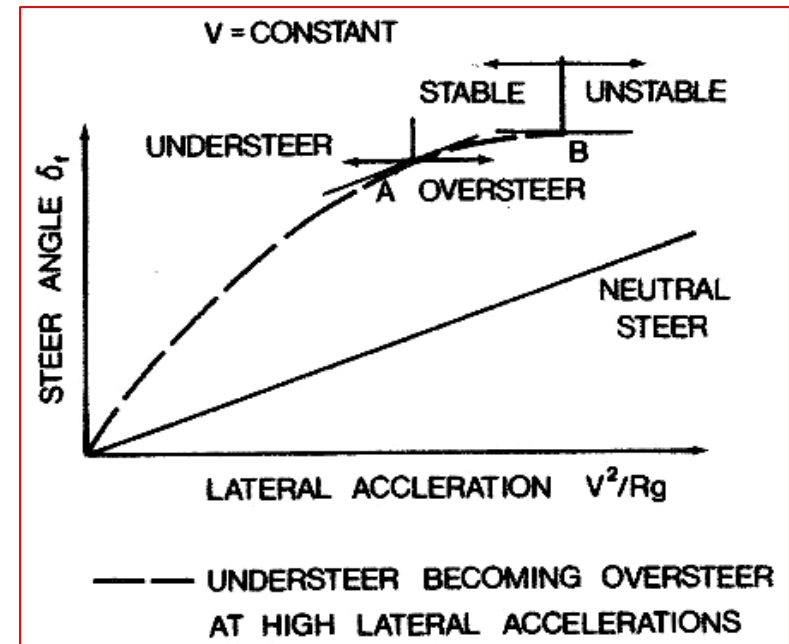


Fig: 15.21



Constant Steer Angle Test

- The vehicle is driven with a fixed steering wheel angle at various forward speeds.
- Curvature Vs lateral acceleration curve is drawn and the handling characteristic is determined
- The constant radius test is simplest and requires little instrumentation, constant speed test is more representative of the actual road behaviour of a vehicle than the constant radius test as the driver usually maintains a more or less constant speed in a turn and turns the steering wheel by the required amount to negotiate the curve. The constant steer angle test is easy to execute.

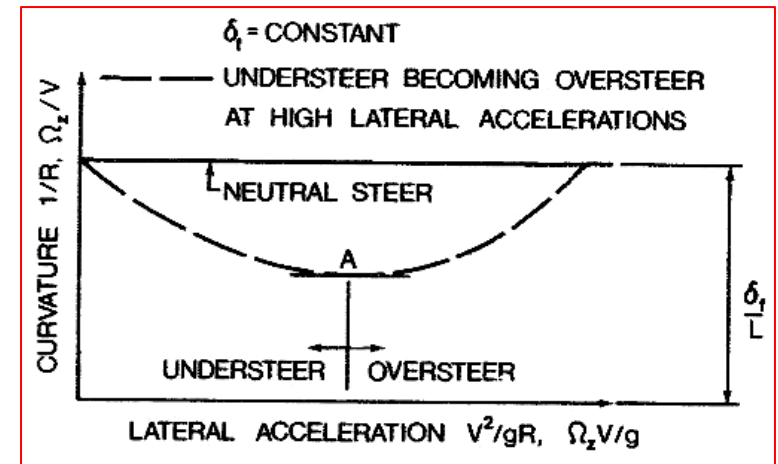
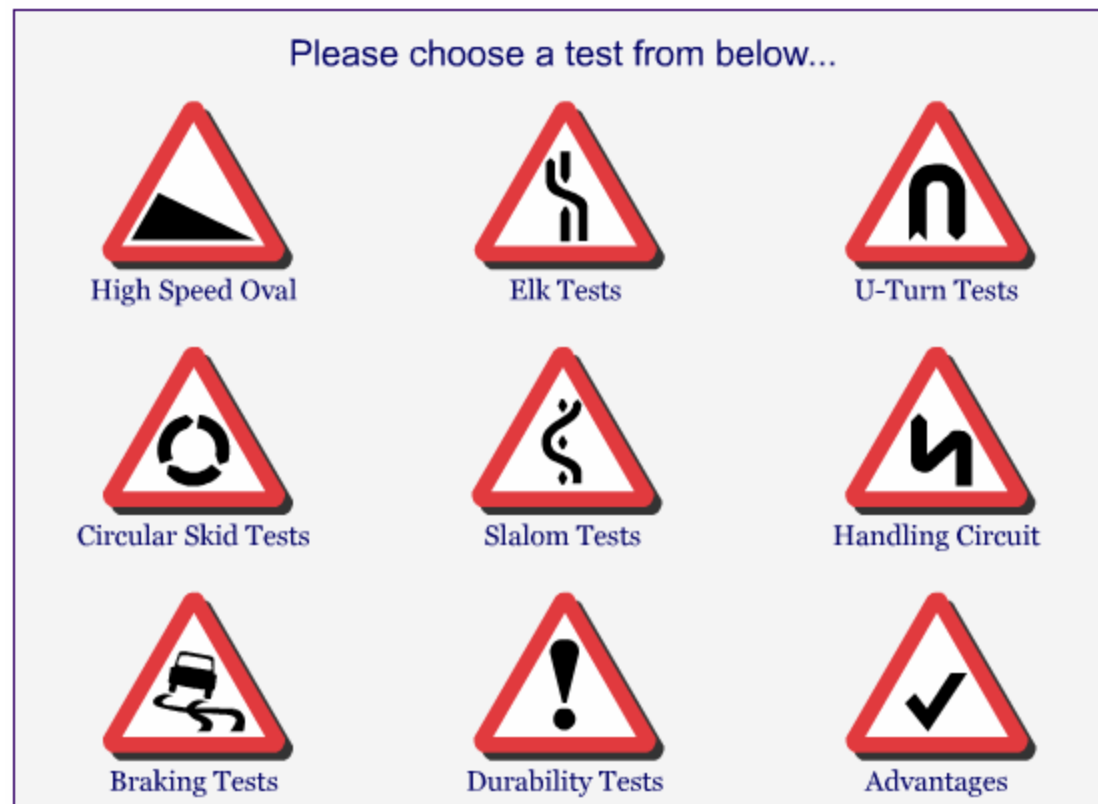


Fig: 15.22



Vehicle Dynamic Tests

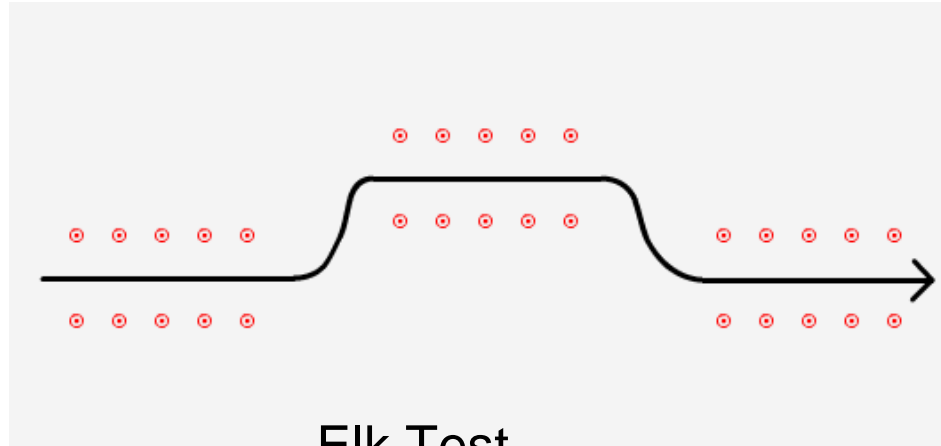
- The intent of these test procedure is to subjectively determine the road holding ability and handling characteristics of a vehicle.



Vehicle Dynamic Tests



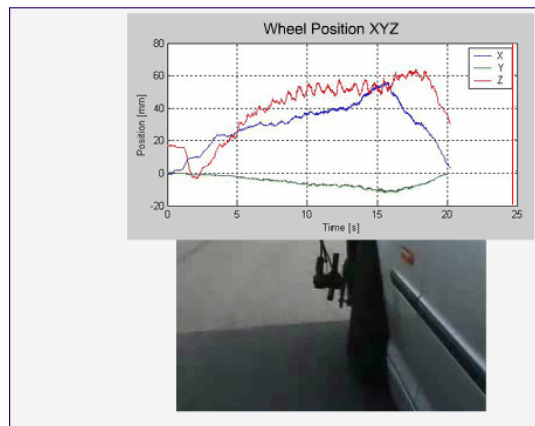
High Speed Oval



Elk Test



U-Turn Test



Circular Test



Slalom Test



Vehicle Dynamic Tests

Test	Purpose
High Speed Oval	Wheel Motion Data Recording
Elk Test (Double Lane Change)	Vehicle Handling during fast lane change
U-Turn	Body Roll, Roll steer, Lateral Compliance
Circular Skid Test	To test understeer and oversteer
Slalom Test	Vehicle Dynamic Analysis, Wheel Packaging Calculations-like camber change

Elk (Double Lane Change) Test

Figure 2 – Placement of cones for marking the lane change track

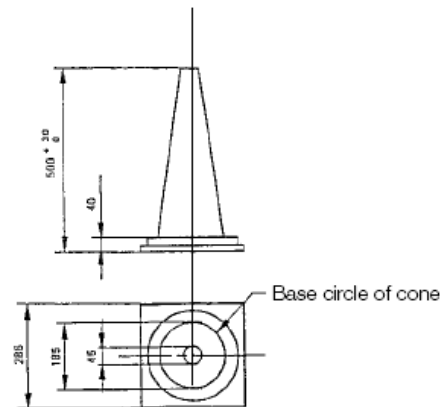
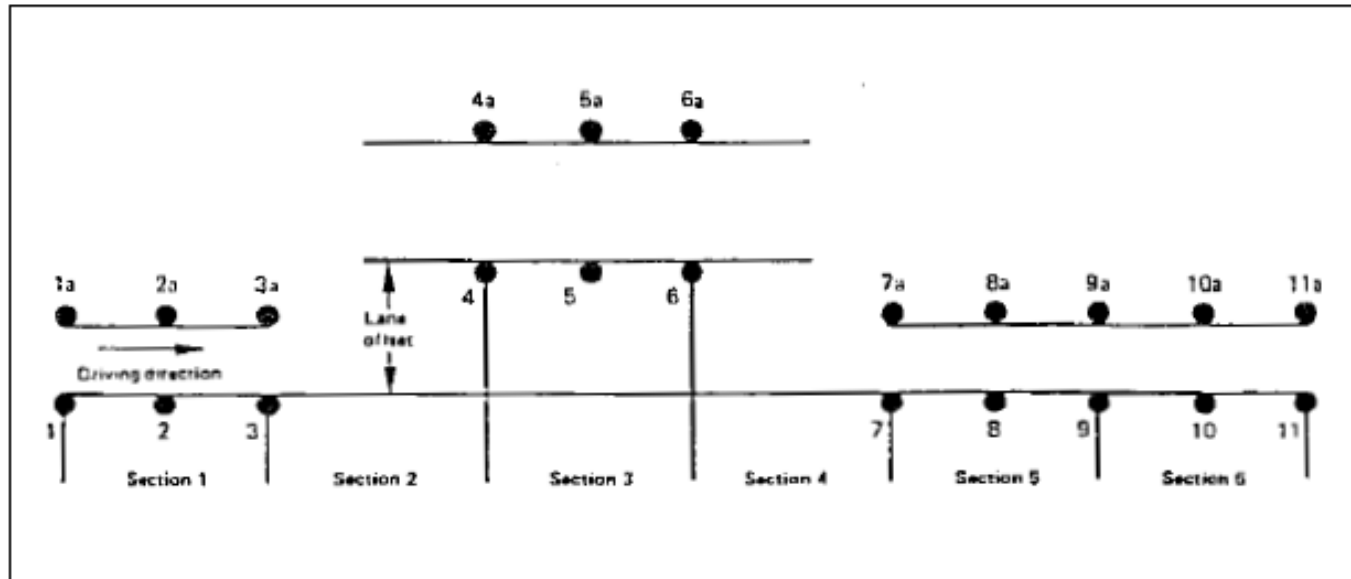


Figure 1 – Cones used for lane change delineation



Elk (Double Lane Change) Test

Lane change track dimensions

The dimensions of the track are specified in the appropriate ISO standard.

Section	Length of Section	Section Width
1	15.0 m	1.1 x vehicle width plus 0.25m
2	30.0 m	
3	25.0 m	1.2 x vehicle width plus 0.25m
4	25.0 m	
5	15.0 m	1.3 x vehicle width plus 0.25m
Lane Offset 3.5 m		

Track surface

The track surface shall be sealed, dry and as hard and as planar as possible.

The anti-skid property during the test shall correspond to a skid number of at least 70, according to ASTM.

Longitudinal deviation from horizontal shall not be more than 1 degree.

Transverse deviation from horizontal shall not be more than 2 degrees.

Ambient conditions

Wind speed shall not exceed 3m/s (11 kph).



Elk (Double Lane Change) Test

Vehicle 'test tare mass'

The test vehicle must be equipped with all optional equipment that is likely to increase the tare mass of the vehicle. The vehicle must also have full complement of:

- lubricants
- coolant (if required)
- washer fluid
- fuel (tank to be filled to at least 90% of the capacity specified by the manufacture).

If offered as standard equipment, the following equipment must also be included in the vehicle;

- spare wheel
- fire extinguisher
- wheel chocks
- standard tool kit.

The mass of a vehicle equipped as described above, is the 'test tare mass'.

Test mass

The vehicle shall be tested under two loaded conditions, unless the engineer can provide suitable justification for the deletion of one of the tests.

Vehicle test mass 1

The test tare mass as defined above, to which the driver's mass is to be added. When tested at this mass a driver being of at least 68kg will meet this requirement. Alternatively, additional mass can be added to the vehicle to achieve a combined mass of load mass and driver mass of 68kg.



Elk (Double Lane Change) Test

Vehicle test mass 2

The test tare mass as per 1, plus

68kg x number of seating positions in the passenger compartment and 7kg x number of seating positions, uniformly distributed over the luggage compartment(s).

Loading of the passenger compartment shall be such that wheel loads obtained correspond to wheel loads that would be obtained with loading each seat with 68kg at its "H" point. Masses used for loading may be placed on the passenger compartment floor.

In no case must the permissible axle loads be exceeded.

Masses must be placed in such a way as not to substantially alter the vehicle's moment of inertia around the vertical axis.

Testing

An experienced and skilled driver must conduct the tests.

To ensure the safety of all concerned, the driver must commence testing at a speed not exceeding 80kph. Test speed can then be incrementally increased up to the 'maximum test speed', as the driver and engineer deem it safe to do so.

The 'maximum test speed' shall be lower of the following:

- The maximum speed the vehicle can obtain, or
- 110 +/- 3kph

The vehicle must be driven through the lane-change track according to the following conditions;

The vehicle must be driven into the redesignated test track at the 'maximum test speed' for the vehicle and the exit speed must be stated in the test report.



Elk (Double Lane Change) Test

Over the test course the throttle position must be held as steady as possible and the gear position engaged during the test shall be stated in the test report.

A successful pass through the lane-change track requires that none of the cones be displaced during the test.

Subjective assessment

Further to the above testing, a subjective report assessing the overall handling characteristics of the subject vehicle must be prepared by the test driver.

The assessment shall cover the general handling of the vehicle up to legal speed limits.



Transient Response Characteristic

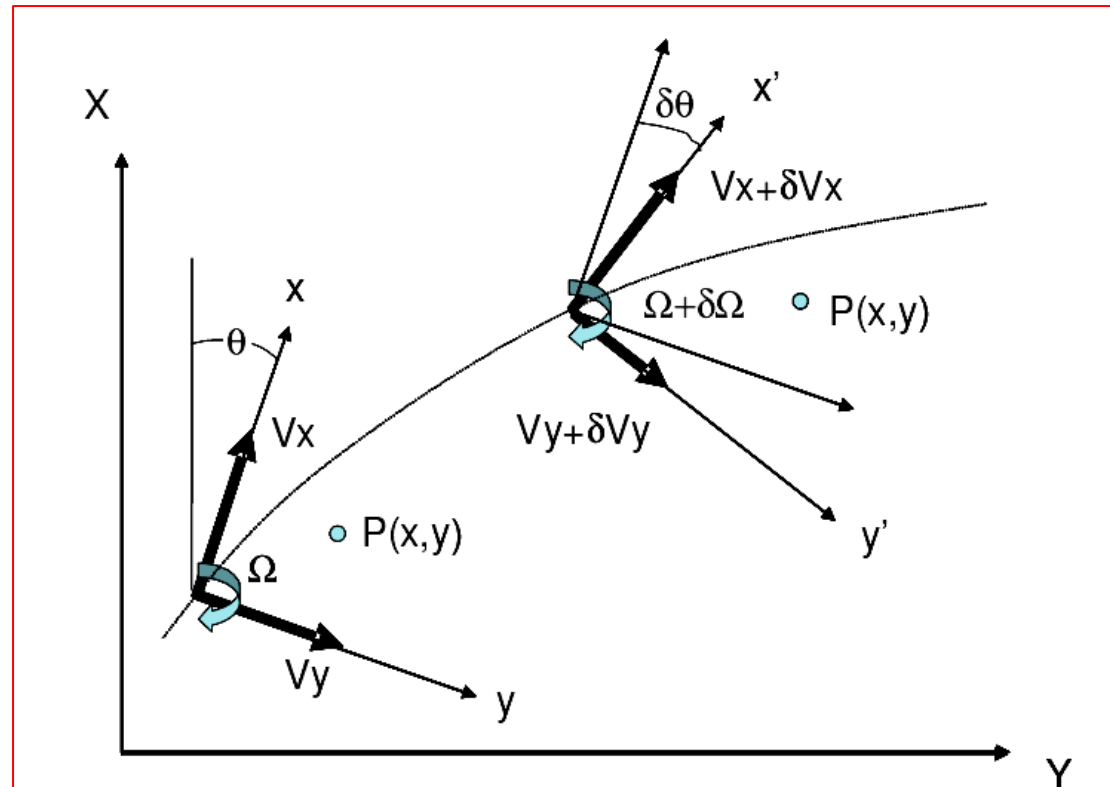
- Vehicle will be in a transient state between the application of steering input and the attainment of steady state motion
- The behaviour of the vehicle in this period is usually referred to as transient response characteristics
- The overall handling quality of a vehicle depends to a great extent on its transient behaviour
- The optimum transient response of a vehicle is that which has the fastest response with a minimum of oscillation in the process of approaching the steady state motion



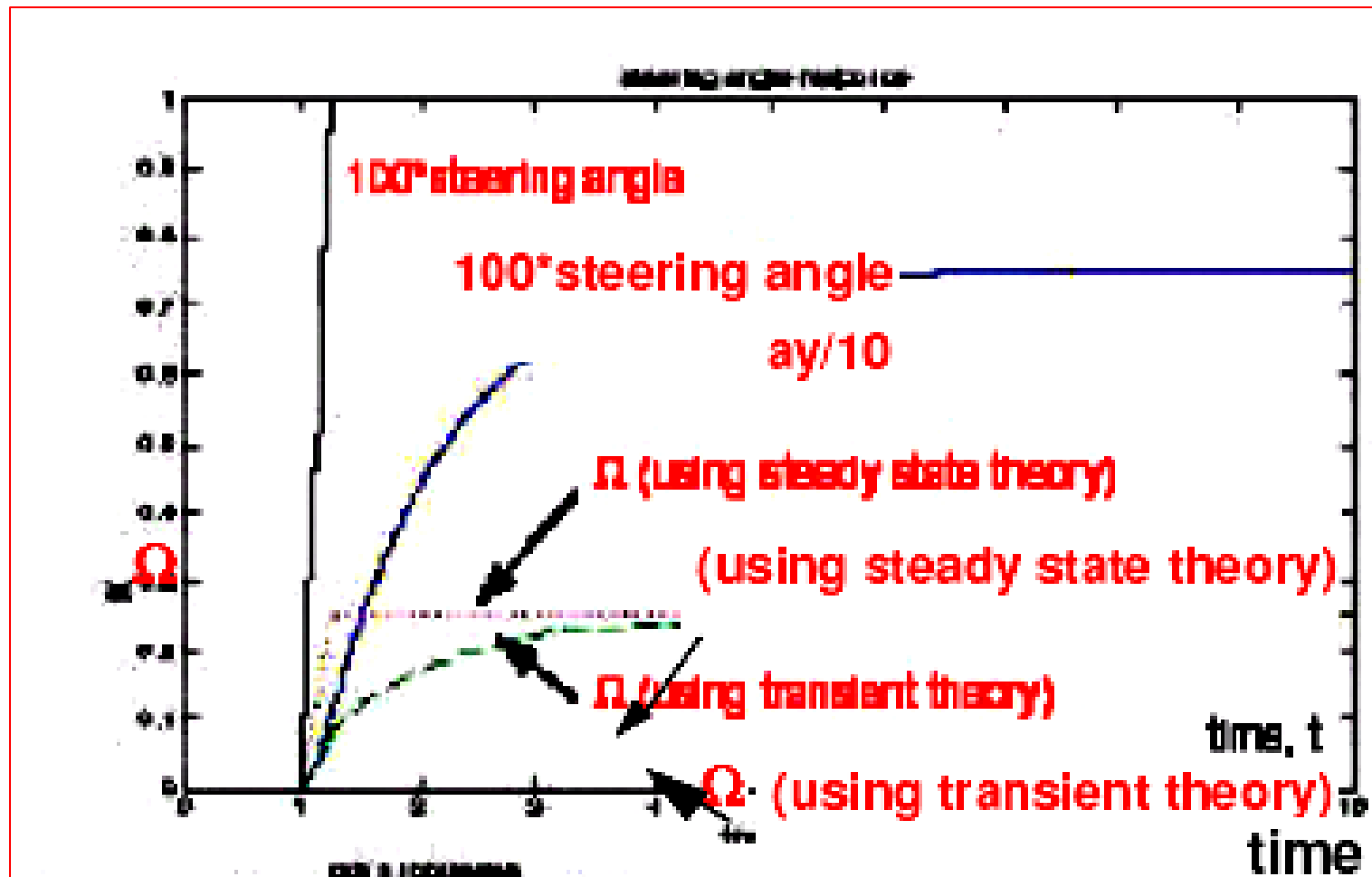
Transient Response Characteristic

- While analysing for transient response, the inertia properties of the vehicle must be taken into consideration
- To describe its motion, it is convenient to use a set of axes fixed to and moving with the vehicle body because with respect to these axes, the mass moment of inertia of the vehicle are constant, where as with respect to axes fixed to earth, the mass moments of inertia vary as the vehicle changes its position

Formulation of Transient Motion Equations



$$\begin{bmatrix} m & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} dV_y / dt \\ d\Omega / dt \end{bmatrix} + \begin{bmatrix} 2 \times 2 \text{ matrix, dependent of } V_x, \text{ cornering stiffness and geometry} \end{bmatrix} \begin{bmatrix} V_y \\ \Omega \end{bmatrix} = \begin{bmatrix} C_{af} \\ C_{af} \cdot b \end{bmatrix} \cdot \delta$$



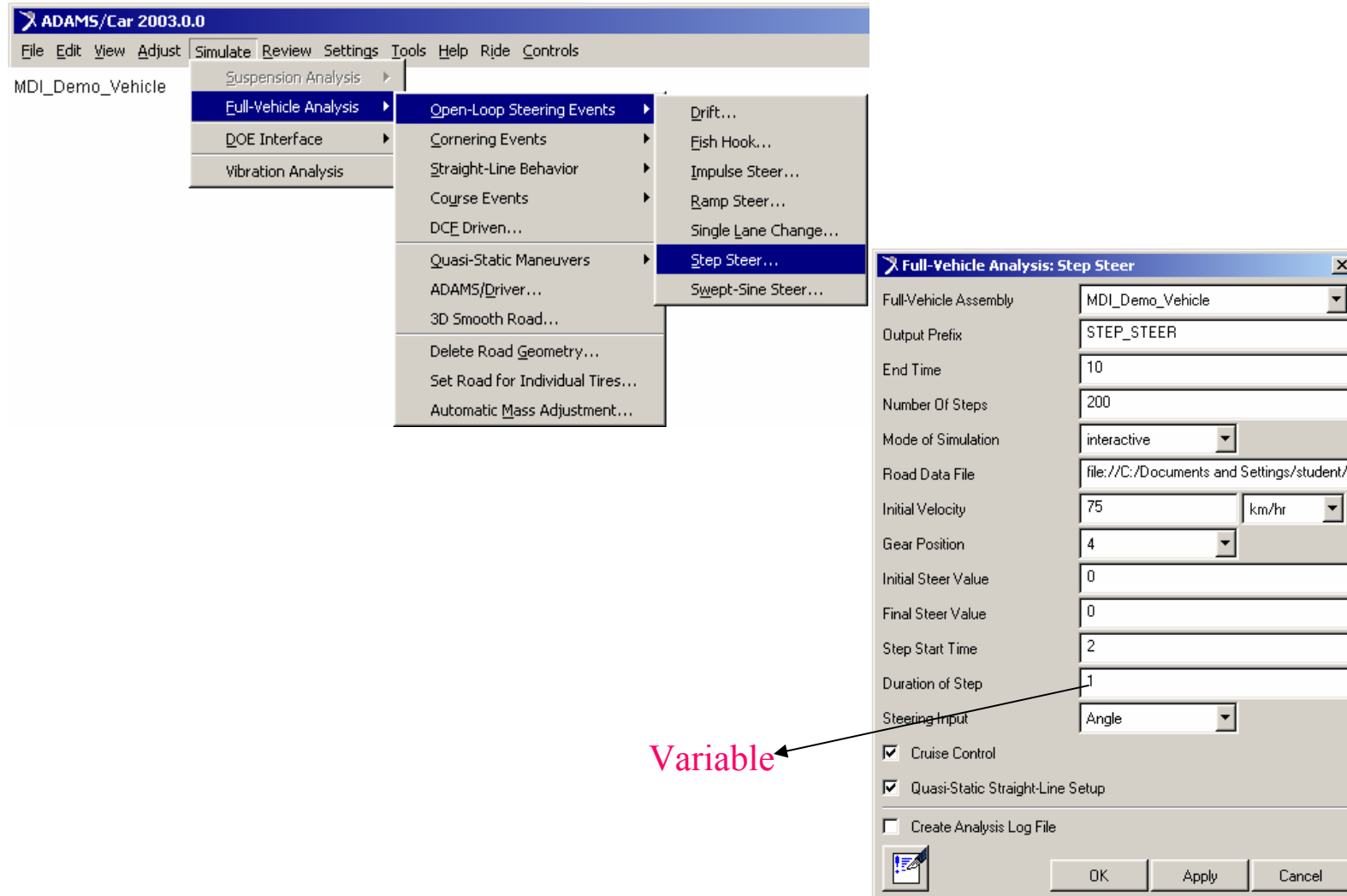


ADAMS Simulations

- Transient Inputs
 - Step steer
 - Ramp Steer
 - Sinusoidal input



Inputs (Step steer)



Step steer

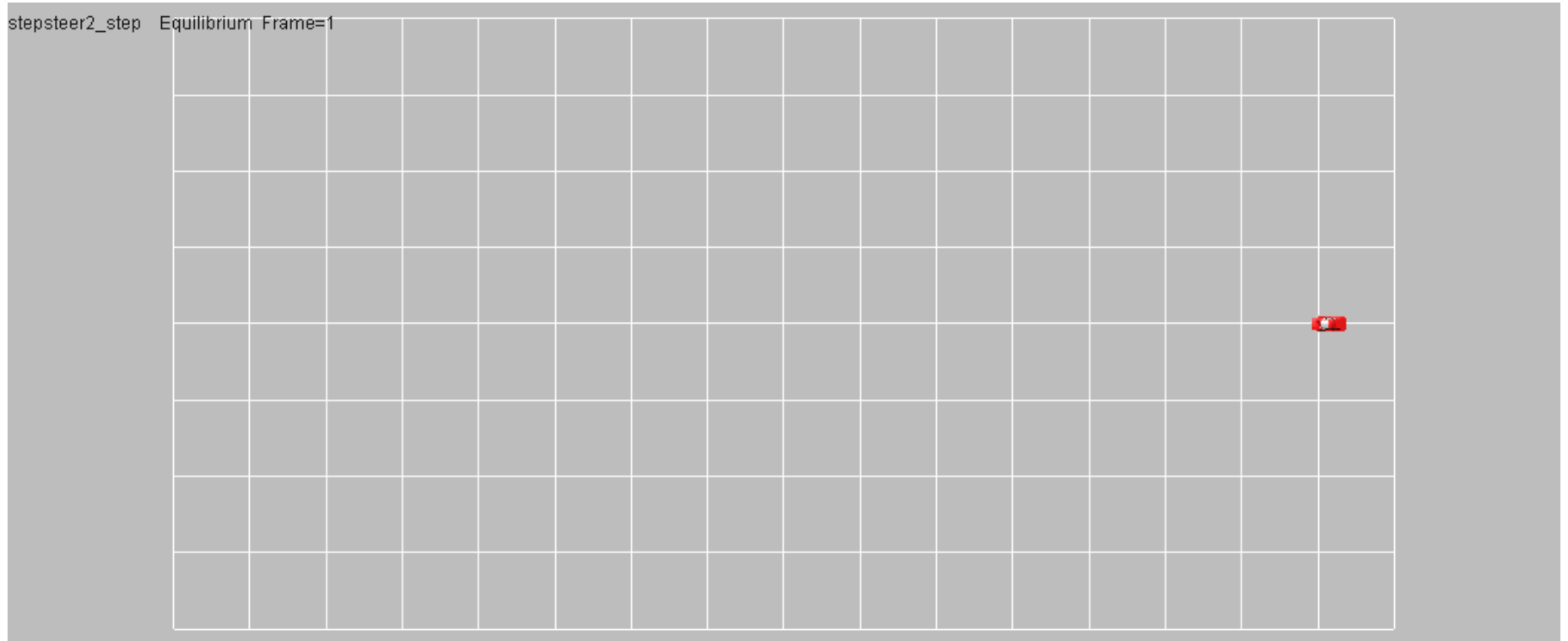
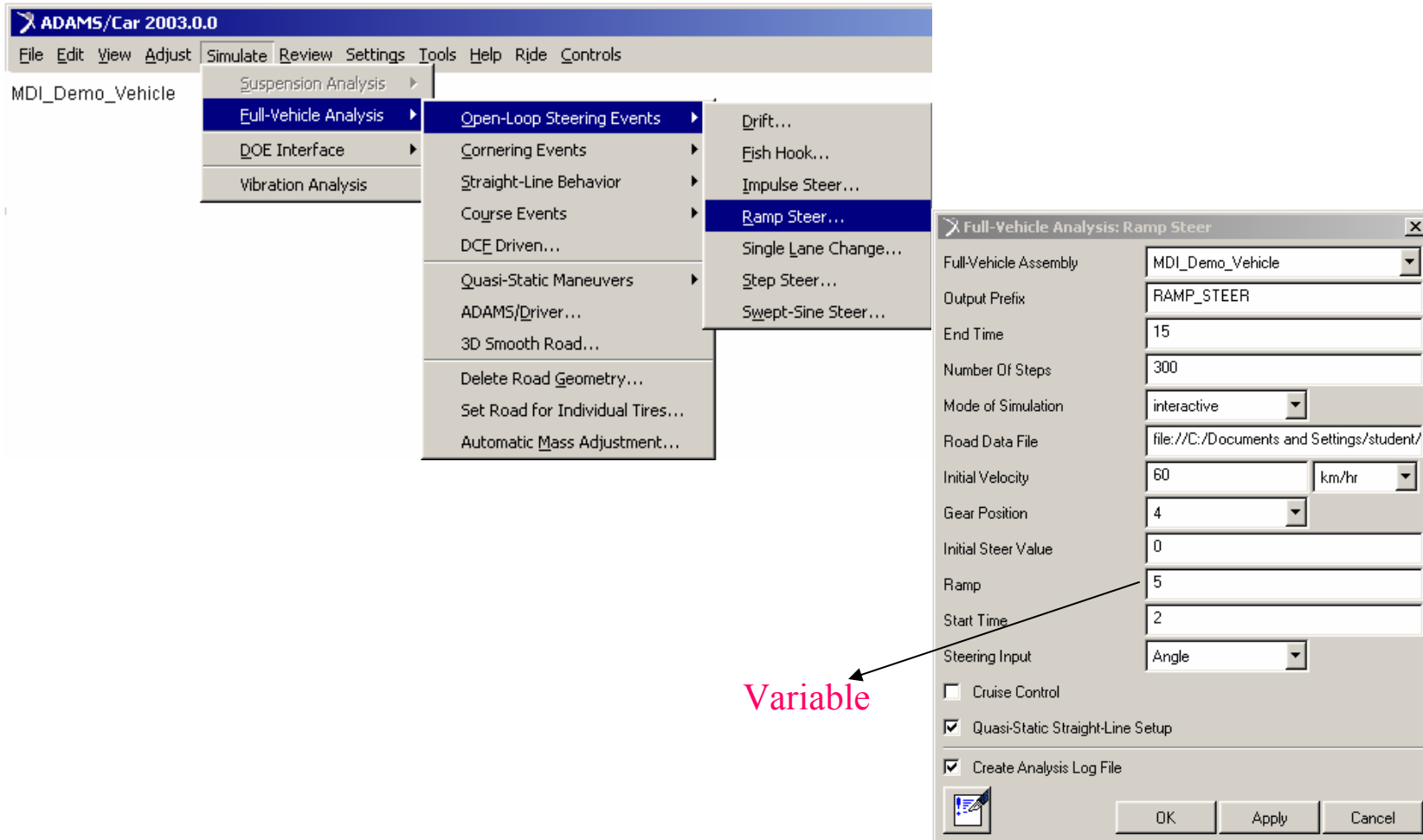


Fig: 15.25



Inputs (Ramp Steer)





Ramp steer Simulation

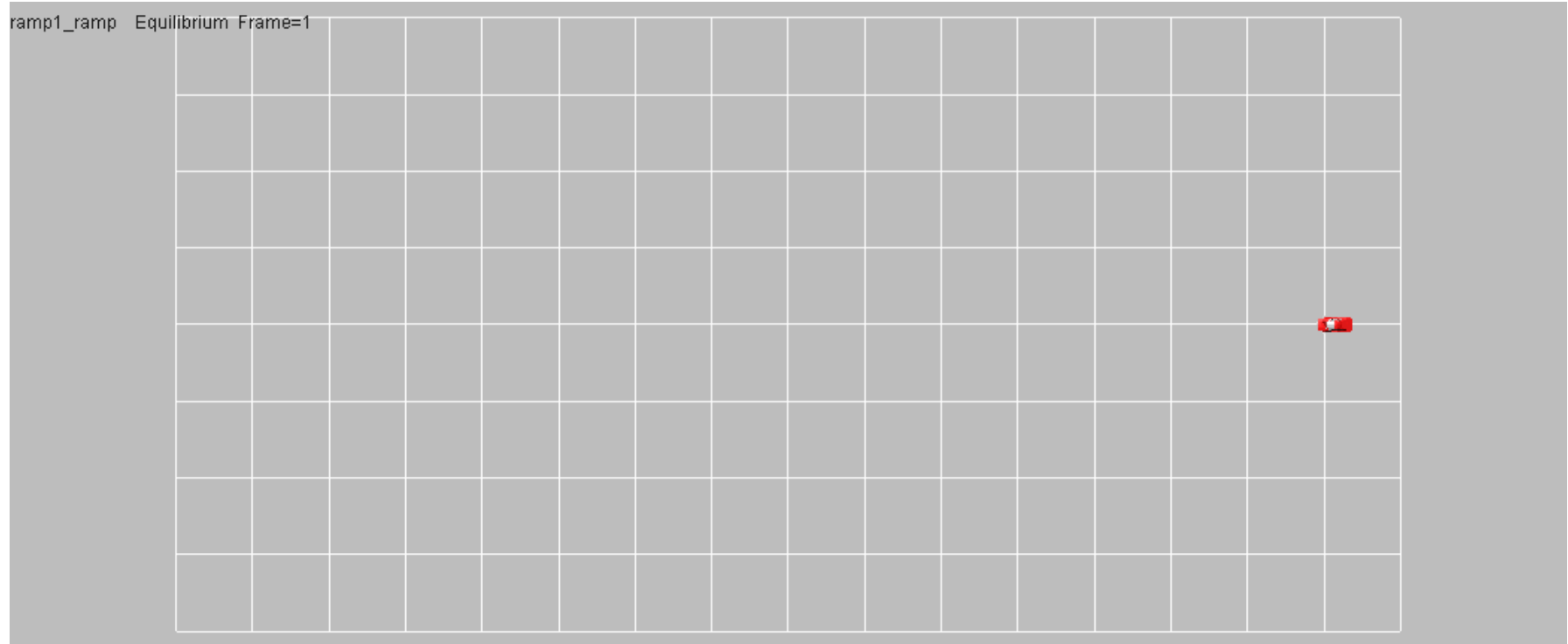
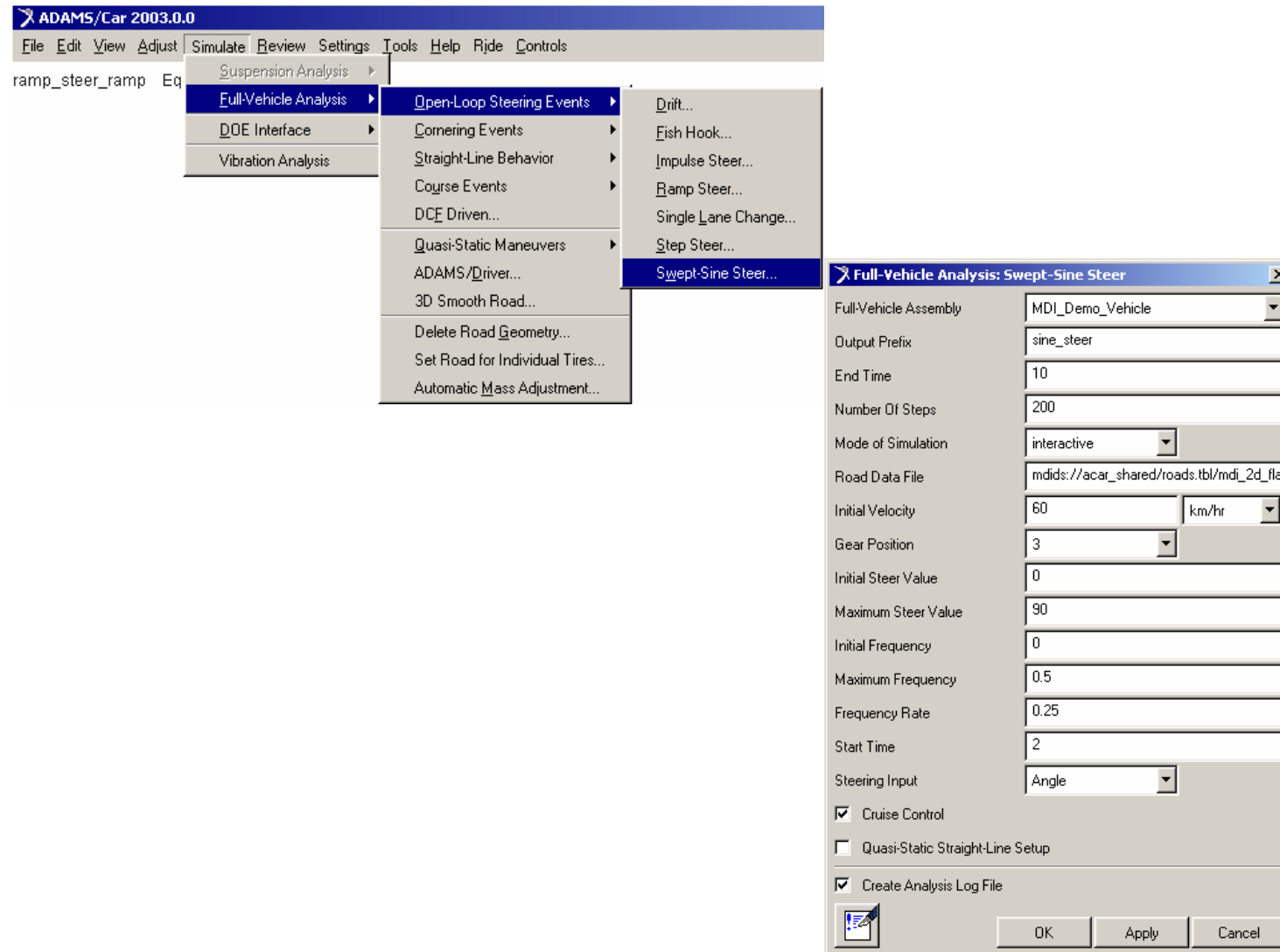


Fig: 15.26

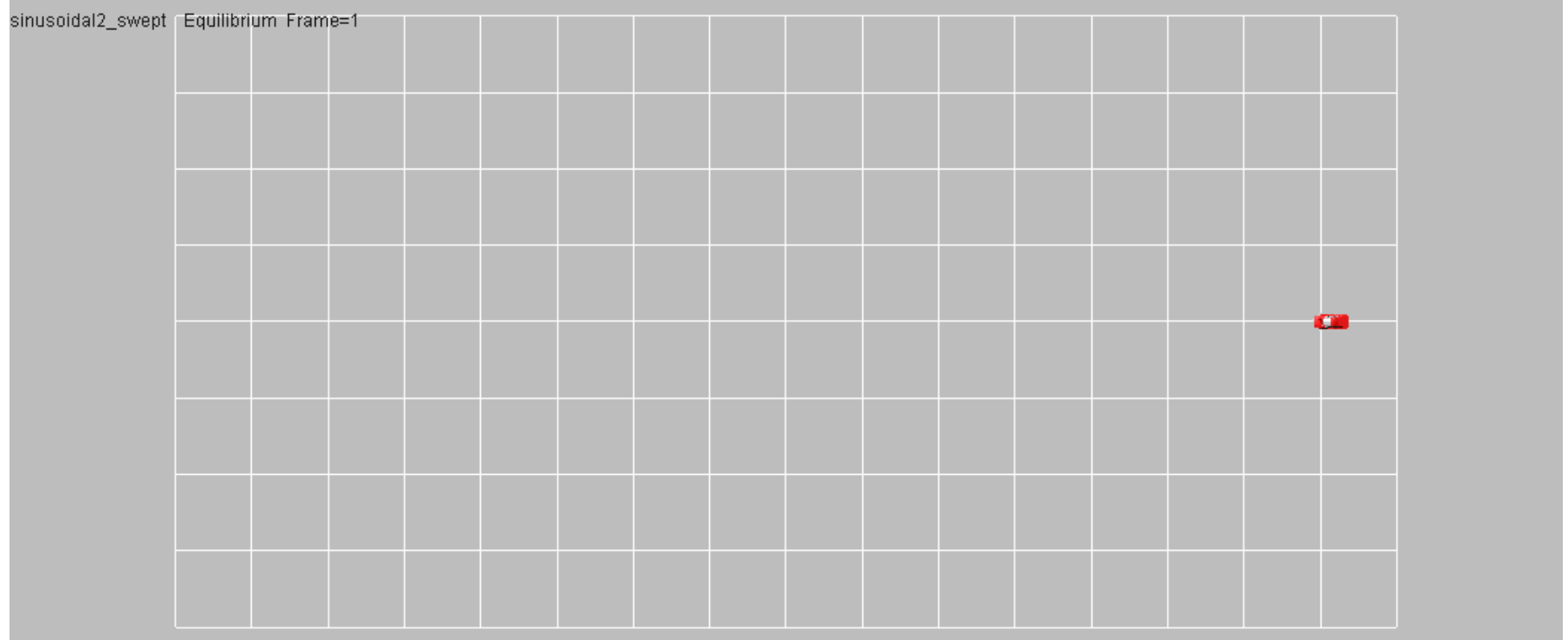


Input (sinusoidal steer input)





Sinusoidal steer





Chapter 10

Roll Over

- Introduction to rollover
- Causes of rollover
- Avoidance of rollover
- Roll over demonstrations
- Simulation-Demonstration (plots/animations etc)

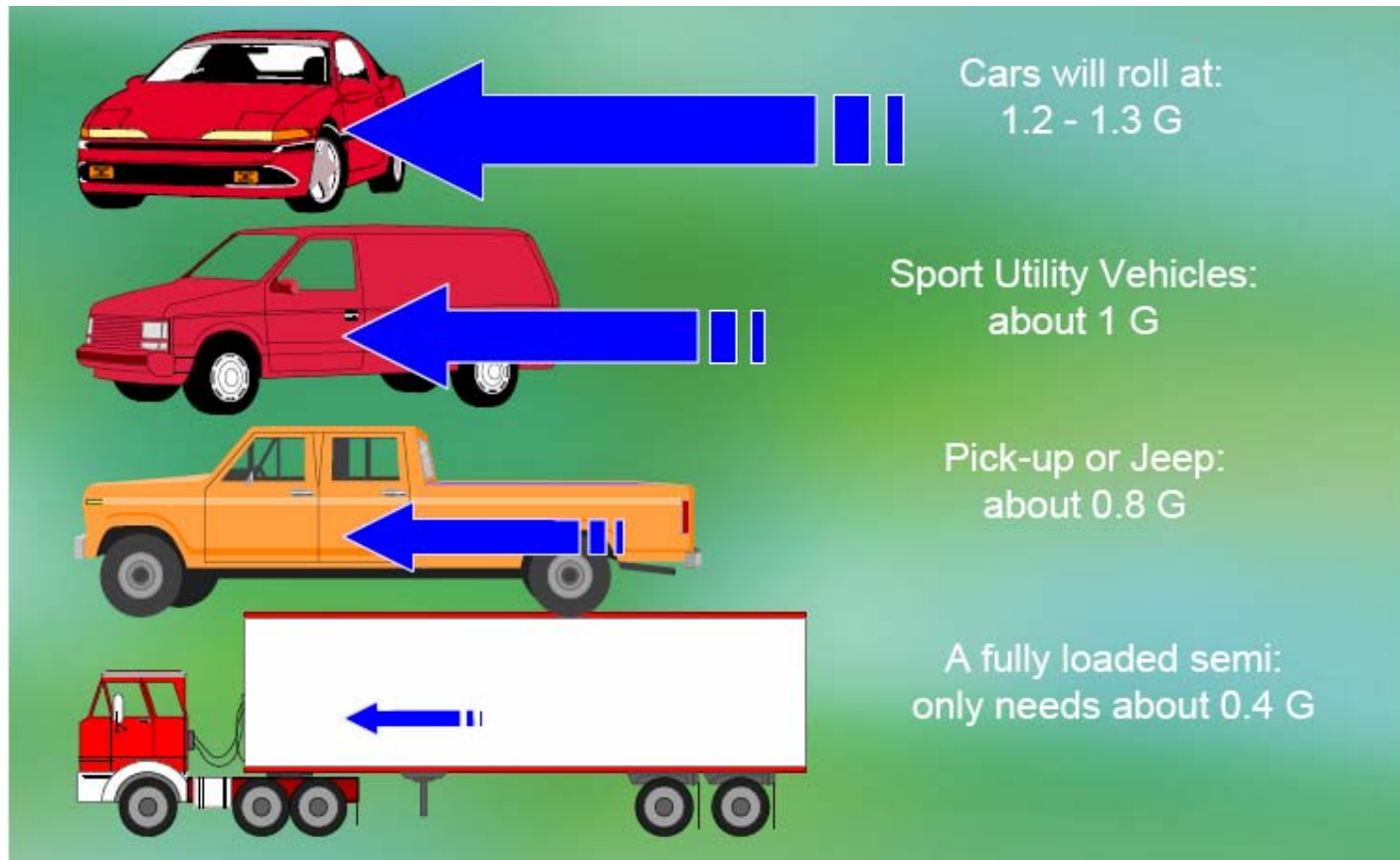
Introduction

- Rollover is a type of vehicle accident, where a vehicle turns over on its side or roof
- The vehicle rotates 90 degrees or more about its longitudinal axis (x-axis) such that the body makes contact with the ground



Introduction

- It may occur on flat and level surfaces when the lateral accelerations on a vehicle reach a level beyond that which can be compensated by lateral weight shift on the tires

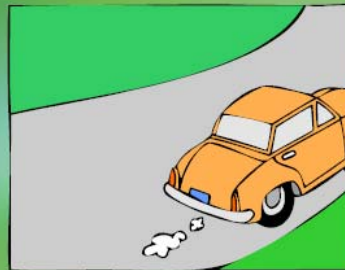




Cars will roll at:
1.2 - 1.3 G

It is very difficult for a car to generate 1.3 G's in cornering.

Because of this inherent stability, cars will slide out of a curve before they will roll over.



A fully loaded semi will
roll at:
about 0.4 G

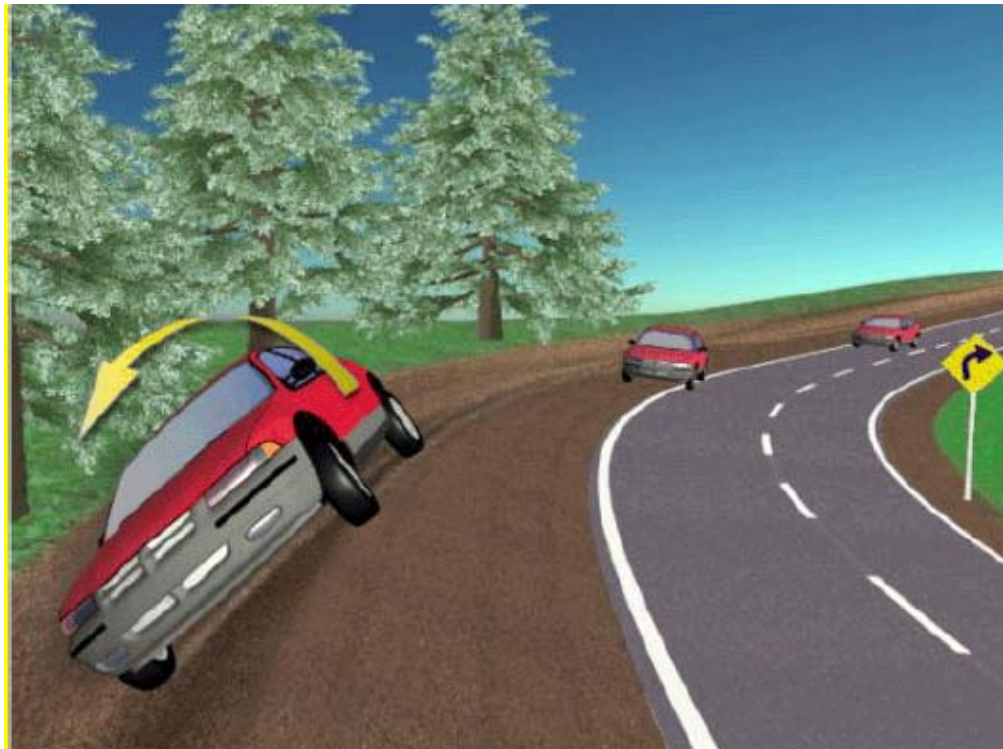
It is fairly easy for a fully loaded truck to generate more than 0.4 G's.

Now we can see: cars will skid before they roll over.

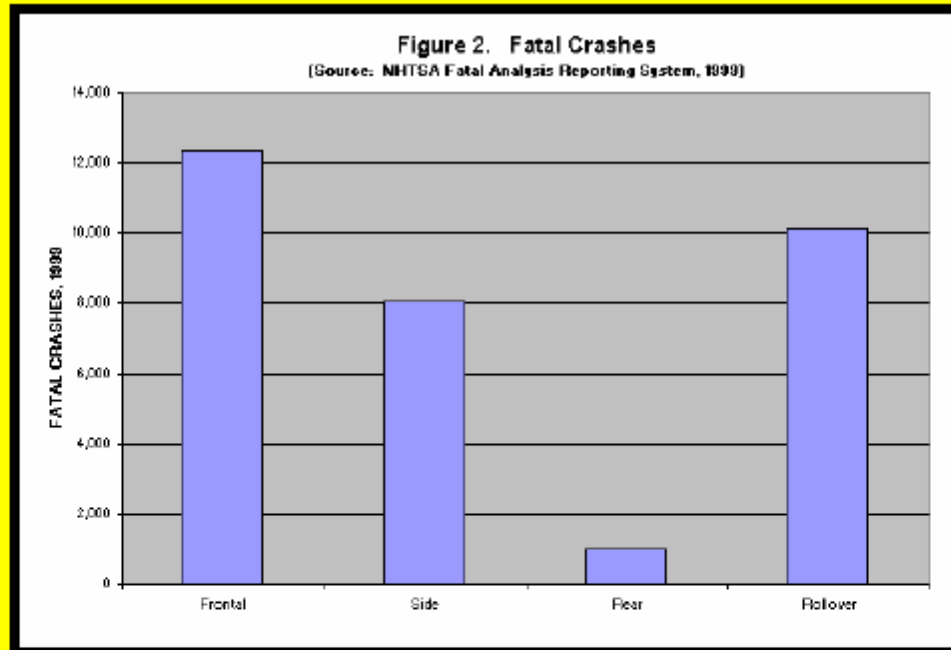
Trucks will roll over
before they will skid.

Introduction

- Cross-slope of the road (or off-road) surface may contribute along with disturbance to the lateral forces arising from curb impacts, soft ground or other obstructions that may “trip” the vehicle



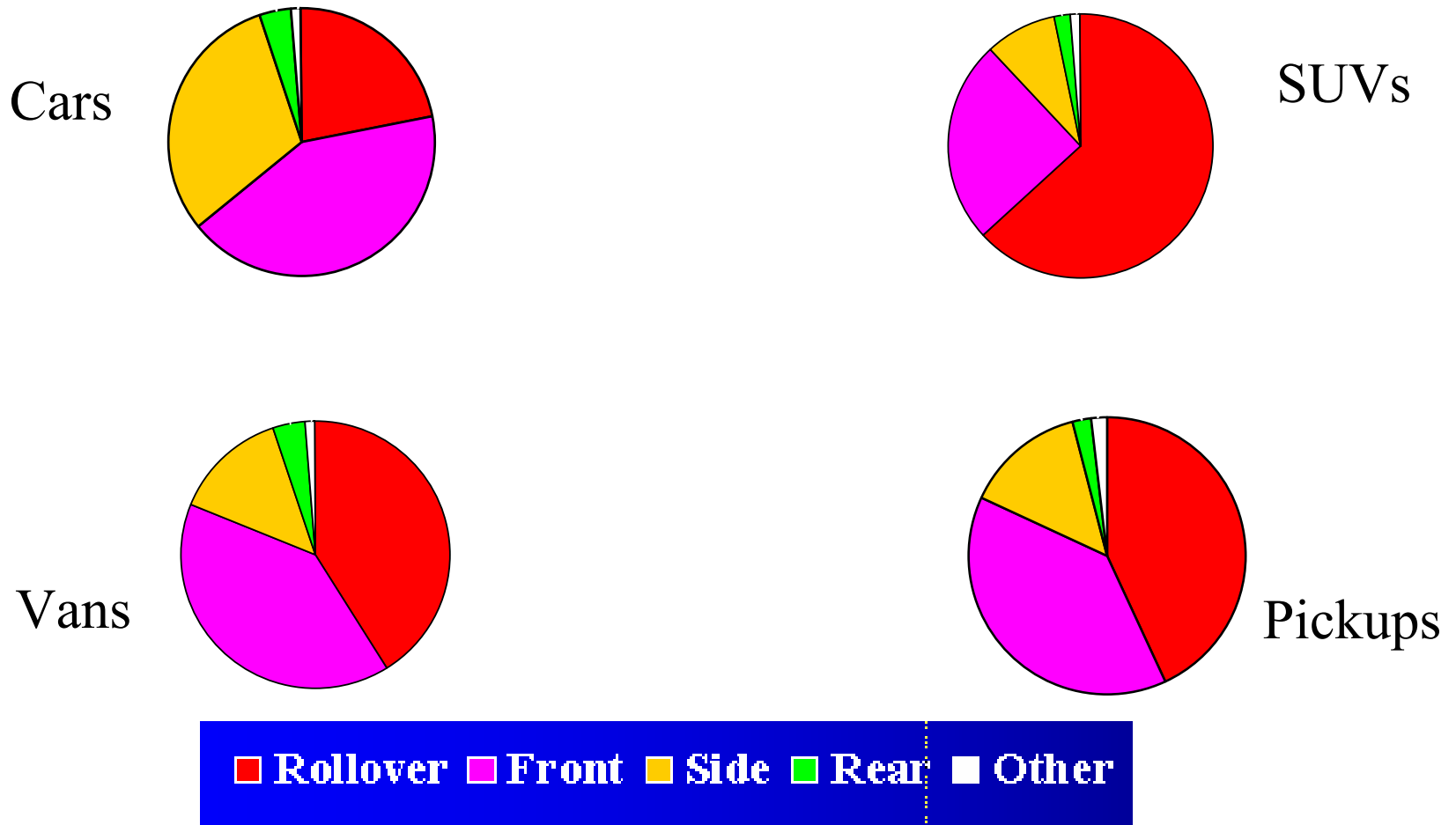
Roll Over Fatalities



Rollovers accounted for more than 10,000 fatalities in the United States in 1999, more than side and rear crashes combined. They also resulted in thousands of serious injuries.



Roll Over Fatalities in Different Types of Vehicles



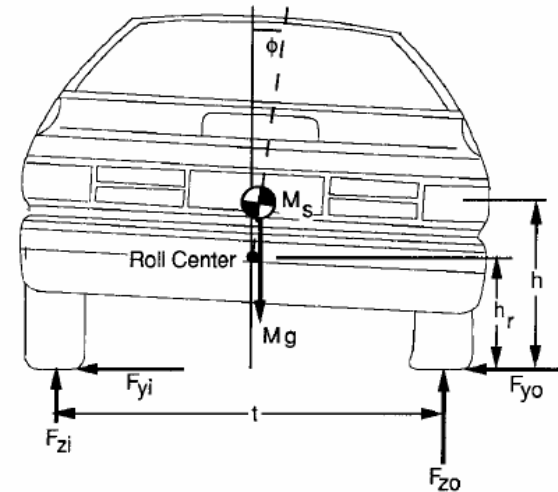
Roll Over Models-First Order

(Quasi-Static Roll)

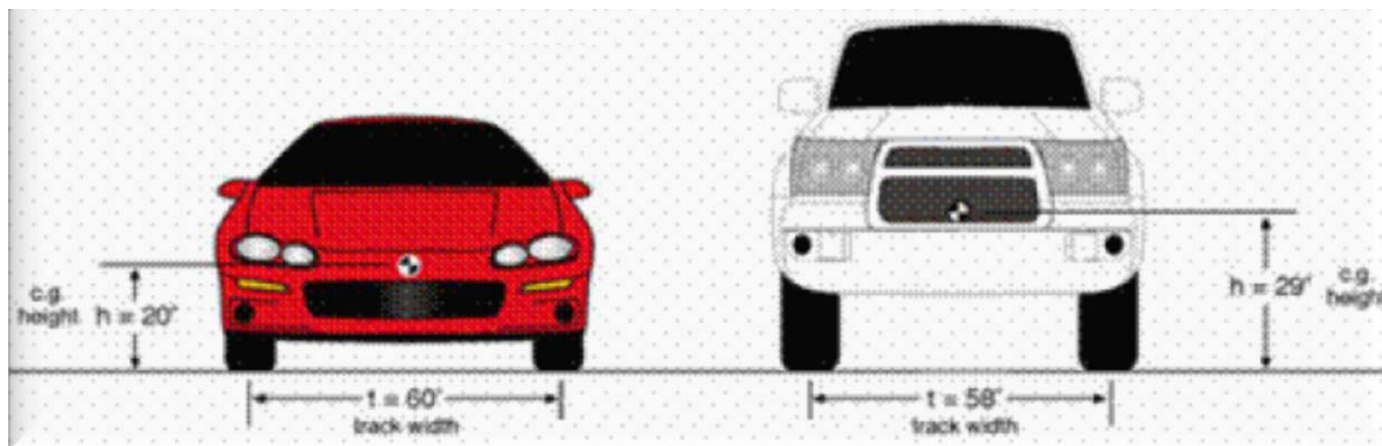


Height of CG -h

Track Width-t

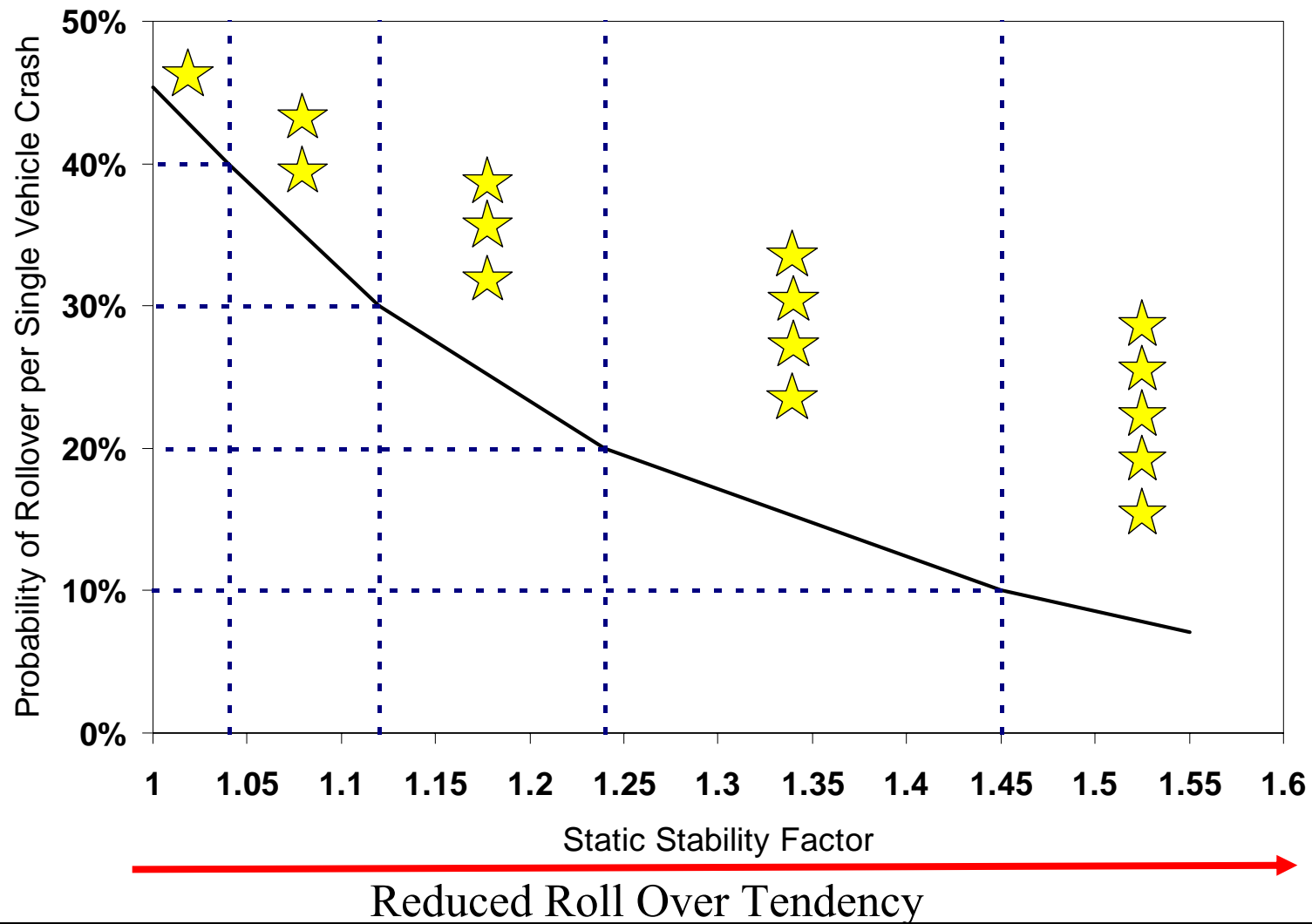


SSF= Static Stability Factor= $t/2h$

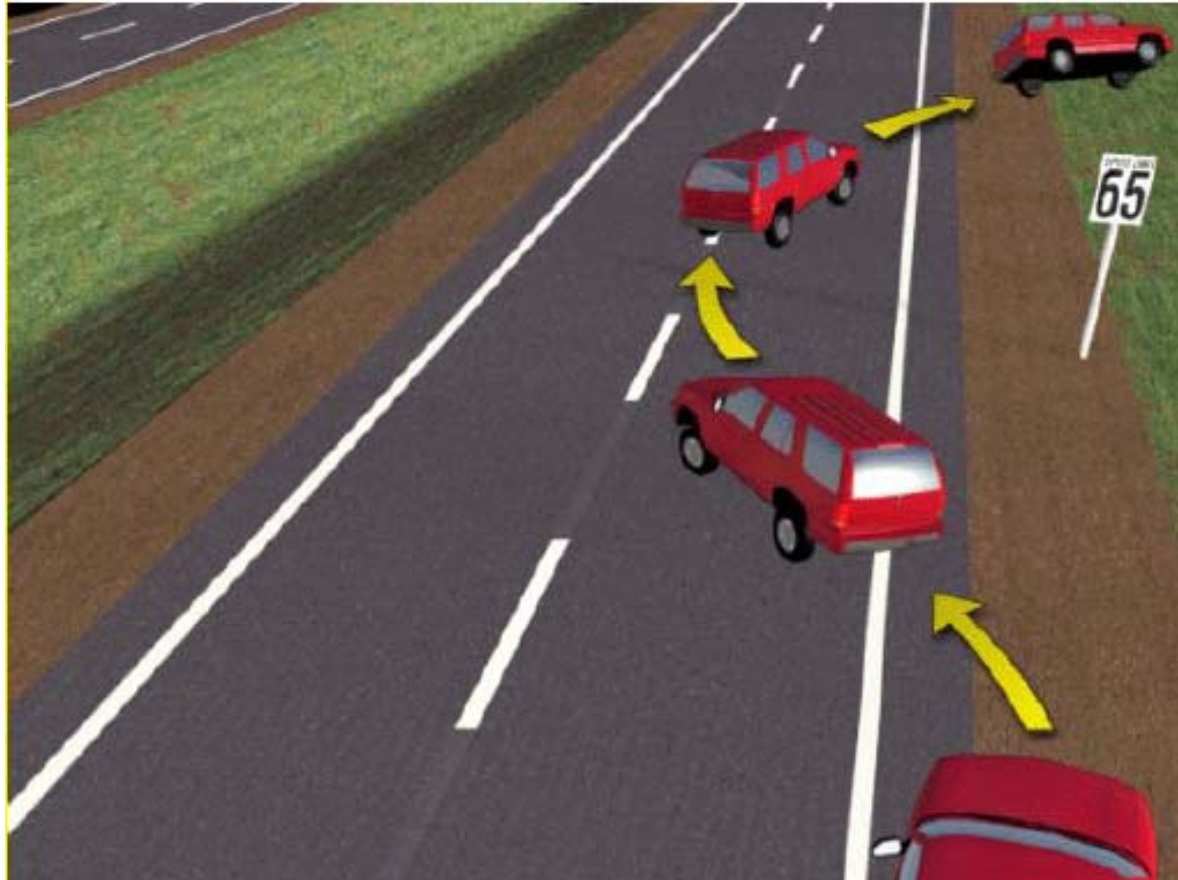




Rollover Probability V/S Static Stability Factor



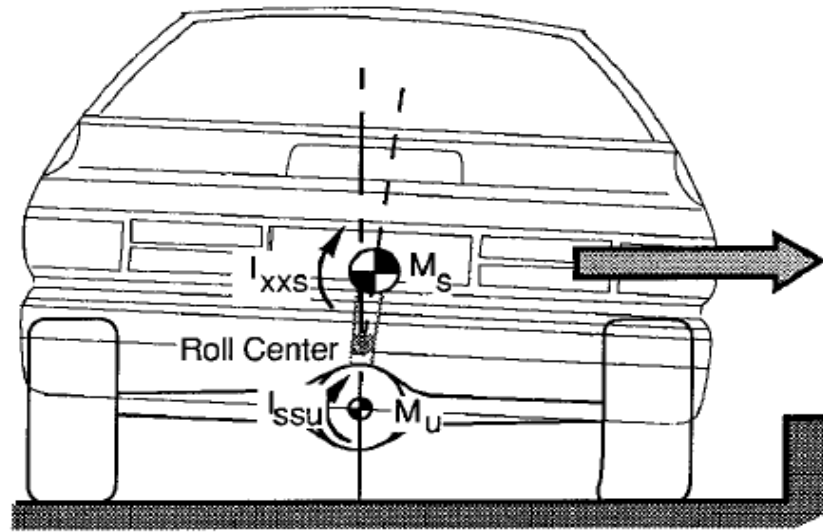
Roll Over-Transient Maneuvers



It can happen during Step Steer

Tripping

- NHTSA data show that 95% of single-vehicle rollovers are tripped
- This happens when a vehicle leaves the roadway and slides sideways, digging its tires into soft soil or striking an object such as a curb or guardrail
- The high tripping force applied to the tires in these situations can cause the vehicle to roll over



Tripping





Causes of Rollover

- Increased height of CG will increase the tendency to roll over
- The vehicle can overturn when it strikes a ditch or embankment, or is tripped by soft soil
- High Lateral forces cause vehicle Roll over

Active Safety System

Incorporating active safety systems like ESC (Electronic stability Control) can reduce the chances of rollover



Avoidance of Roll Over

Tire Pressure

1. Improperly inflated and worn tires can be especially dangerous because they inhibit the ability to maintain vehicle control
2. Worn tires may cause the vehicle to slide sideways on wet or slippery pavement, sliding the vehicle off the road and increasing its risk of rolling over

Loading the vehicle

1. If the vehicle is overloaded and the load distribution is improper, it increases the tendency to rollover
2. Roof rack should be fitted by considering weight limits
3. Any load placed on the roof will be above the vehicle's centre of gravity, and will increase the vehicle's likelihood of rolling over



Vehicle Type

- All types of vehicles can rollover. However, taller, narrower vehicles such as SUVs, pickups, and vans have higher centres of gravity, and thus are more susceptible to rollover if involved in a single-vehicle crash

Panic-like Steering

- Many rollovers occur when drivers overcorrect their steering as a panic reaction to an emergency—or even to a wheel going off the pavement's edge
- At highway speeds, overcorrecting or excessive steering can cause the driver to lose control which can force the vehicle to slide sideways and roll over

Aerodynamics

- Improper pressure distribution may give rise to side forces

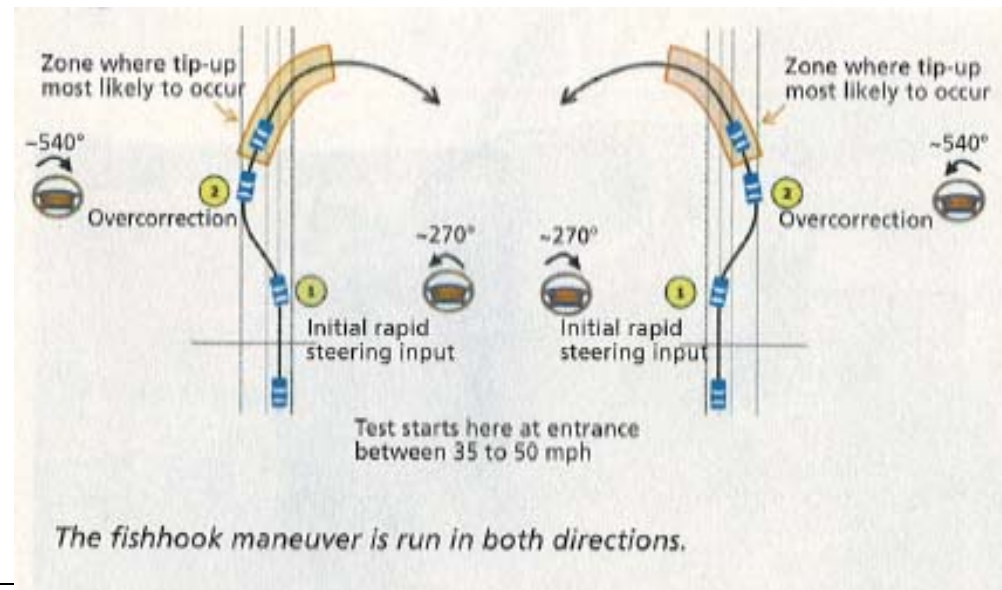
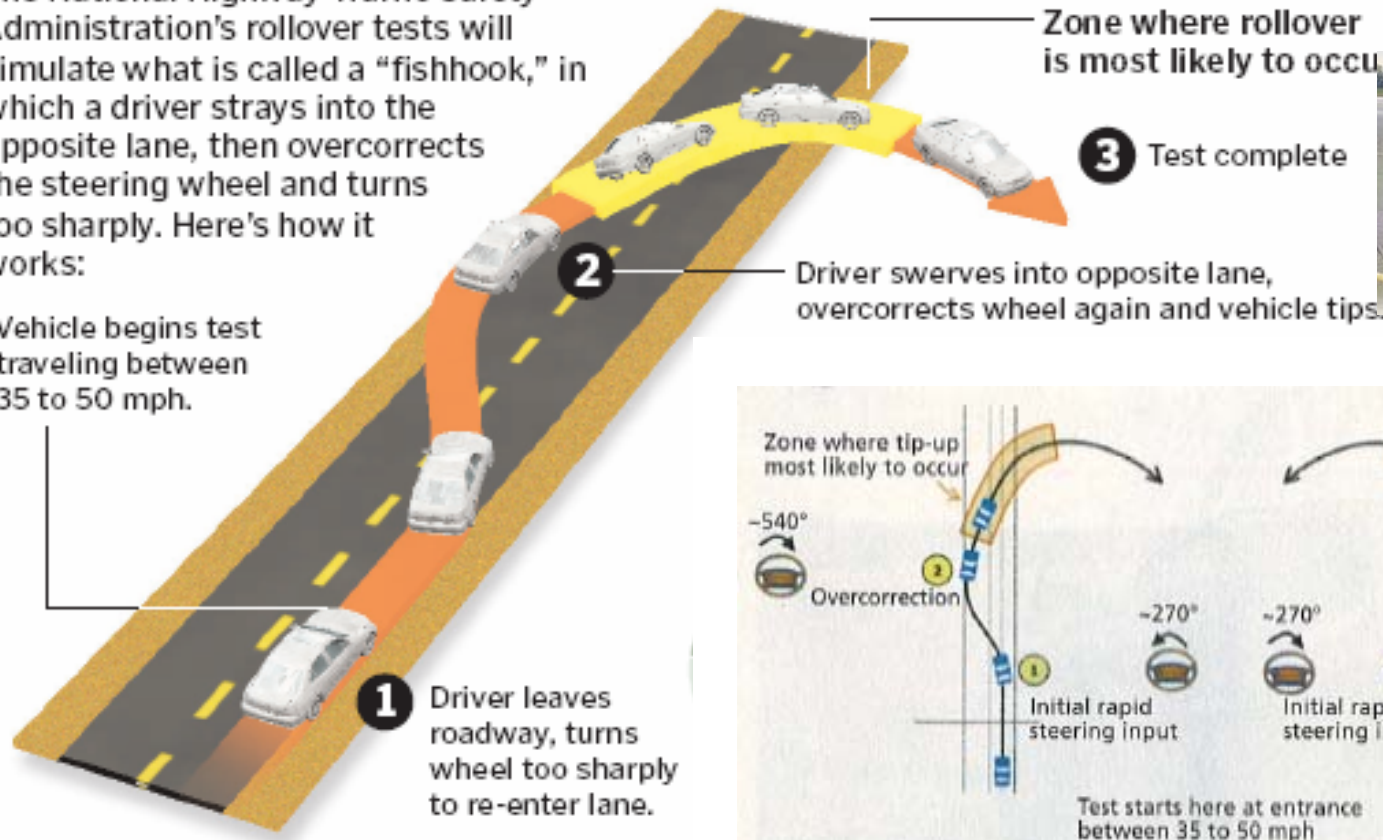
Testing For Rollover

NHTSA Fish Hook Test

Testing for a rollover

The National Highway Traffic Safety Administration's rollover tests will simulate what is called a "fishhook," in which a driver strays into the opposite lane, then overcorrects the steering wheel and turns too sharply. Here's how it works:

Vehicle begins test traveling between 35 to 50 mph.



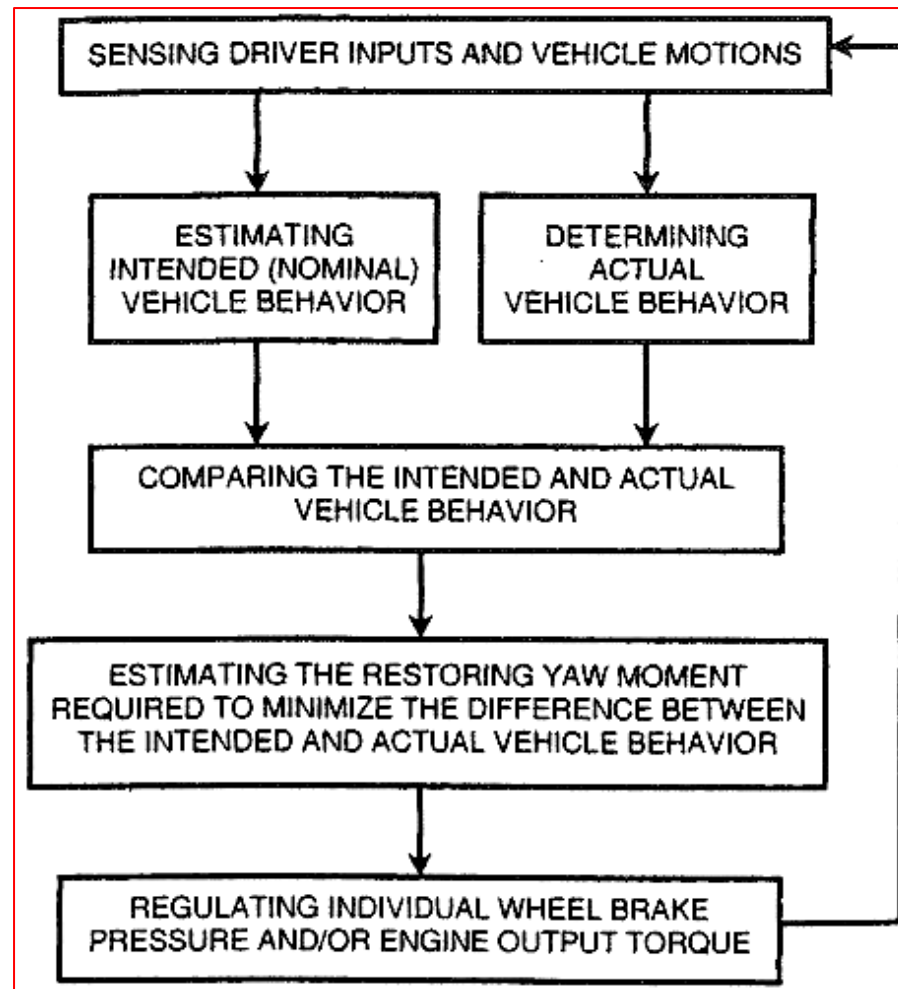


Vehicle Stability Control

- Vehicle stability control system is used to enhance the active safety of the vehicles. They are known as
 - Vehicle Dynamics Control (VDC)
 - Electronic Stability Program (ESP)
 - Vehicle Stability Assist(VSA)
 - Advanced Stability Control (ASTC)
 - Direct yaw moment control (DYC)
- Vehicle stability control is normally integrated with the brake system and power train and usually shares components with the antilock brake system and traction control system



Operating Principle of a Vehicle Stability Control



ESP

Fig: 15.28



Operating Principle of a Vehicle Stability Control

- Intended motion of the vehicle-steering wheel angle, accelerator pedal position, brake pressure, angular speed of the wheels
- Actual directional behaviour- yaw rate sensor, lateral and longitudinal acceleration of the vehicle
- Vehicle stability control system will regulate the brake pressure on select tyres and reduce engine torque transmitted to the driven wheels so as to generate a restoring yaw moment to minimise the deviation from the intended motion
- In all yaw rate control and sideslip angles need to be controlled.



What is Vehicle Stability

- Vehicle instability is characterized by Skid, Slide or Spin (yaw)
- Yaw is rotation around the vertical axis; i.e. spinning left or right.
- Skidding, Sliding and Spinning of vehicle may happen due to panic braking, high speed cornering, loss of traction and due to dynamic (transient) maneuvering
- Vehicle stability control systems must help drivers maintain control when a vehicle starts to skid, slide or spin

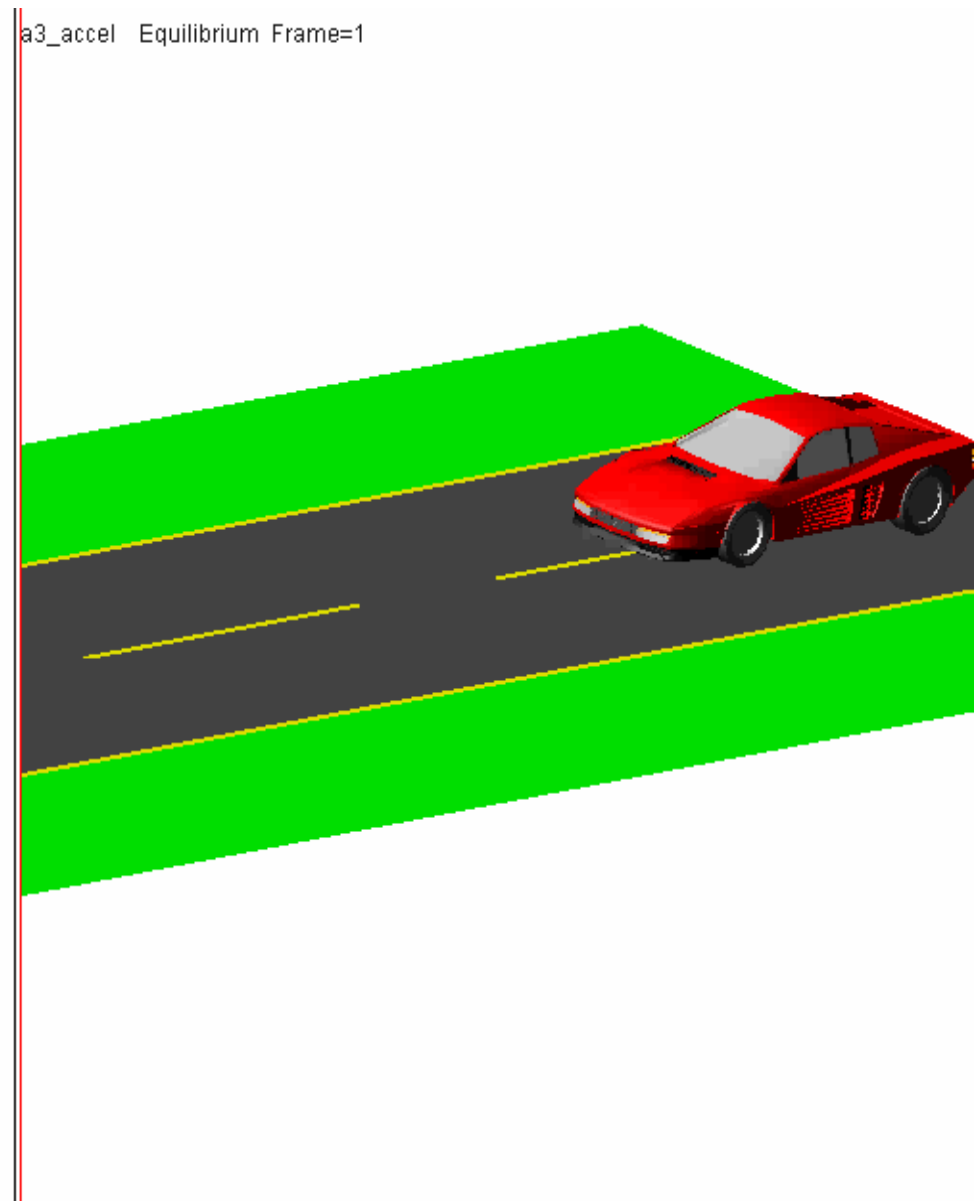
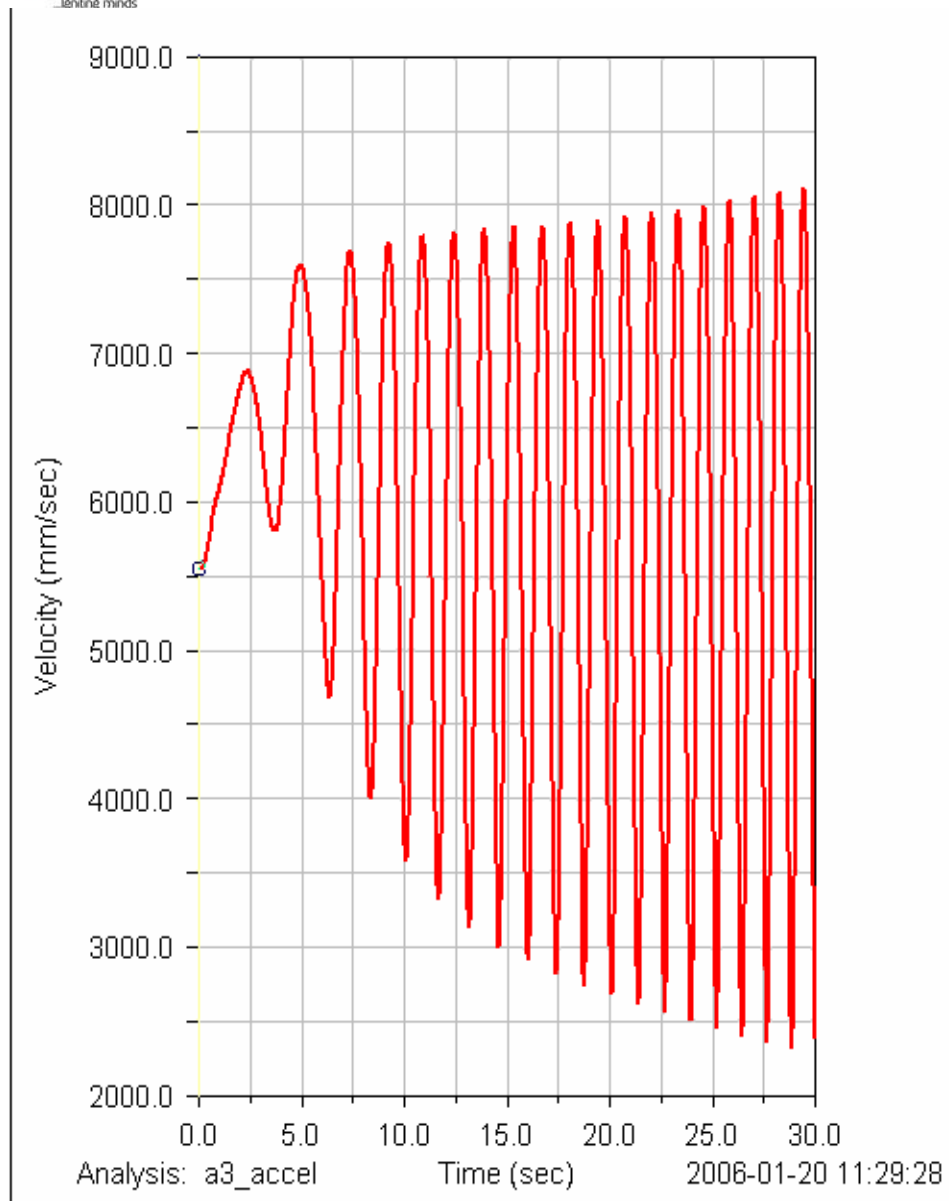
Skidding [demo](#) – wheel locking

Sliding [Demo](#) – steering (Over Steering)

Spinning demo –Next Slide- loss of traction



With Road $\mu = 0.05$





Condition for Stability

$$L + \frac{V_x^2}{g} K > 0 \quad \text{if}$$

If K is positive (understeer vehicle) the vehicle is always stable

If K is negative, the vehicle will be stable only

$$V_x < \sqrt{\frac{gL}{-K}}$$



Electronic Stability Control

- **Electronic Stability control (ESC)** is a technology that improves the safety of a vehicle's handling by detecting and preventing skids
- When ESC detects loss of steering control, ESC automatically applies individual brakes to help "steer" the vehicle where the driver wants to go.
- Braking is automatically applied to individual wheels, such as the outer front wheel to counter oversteer, or the inner rear wheel to counter understeer.
- Some ESC systems also reduce engine power until control is regained

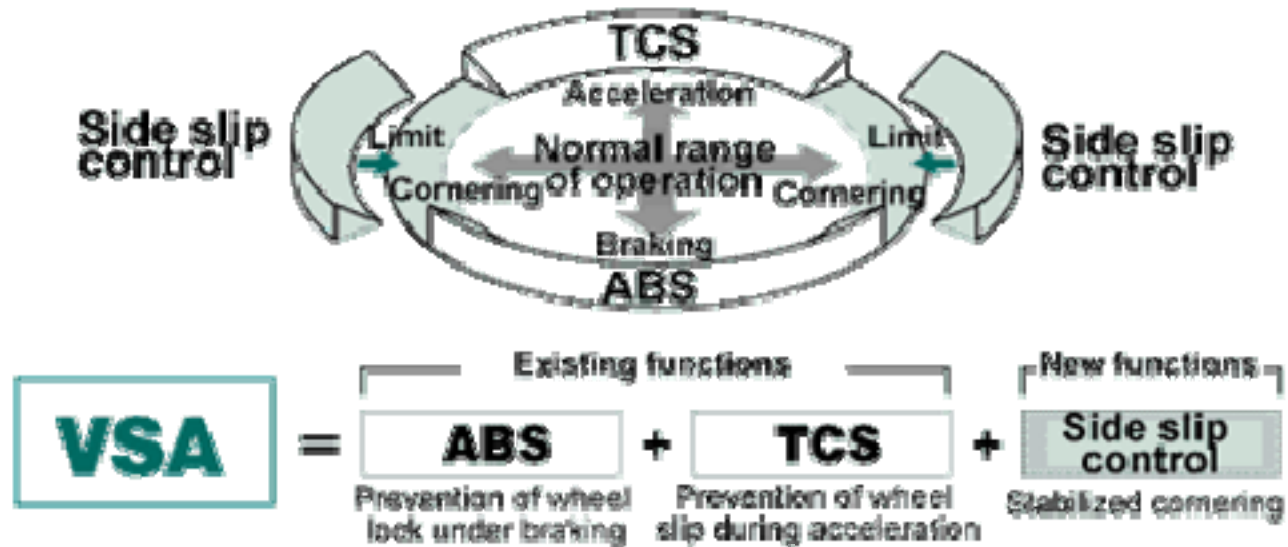


Electronic Stability Control (ESC)

- **Electronic Stability Control (ESC)** is the generic term for systems designed to improve a vehicle's handling, particularly at the limits where the driver might lose control of the vehicle
- Other nomenclatures
 - Vehicle Dynamics Control (VDC)
 - Electronic Stability Program (ESP)
 - Vehicle Stability Assist(VSA)
 - Advanced Stability Control (ASTC)
 - Direct yaw moment control (DYC)

Electronic Stability Control

VSA's concept



Vehicle Stability Control - Algorithm

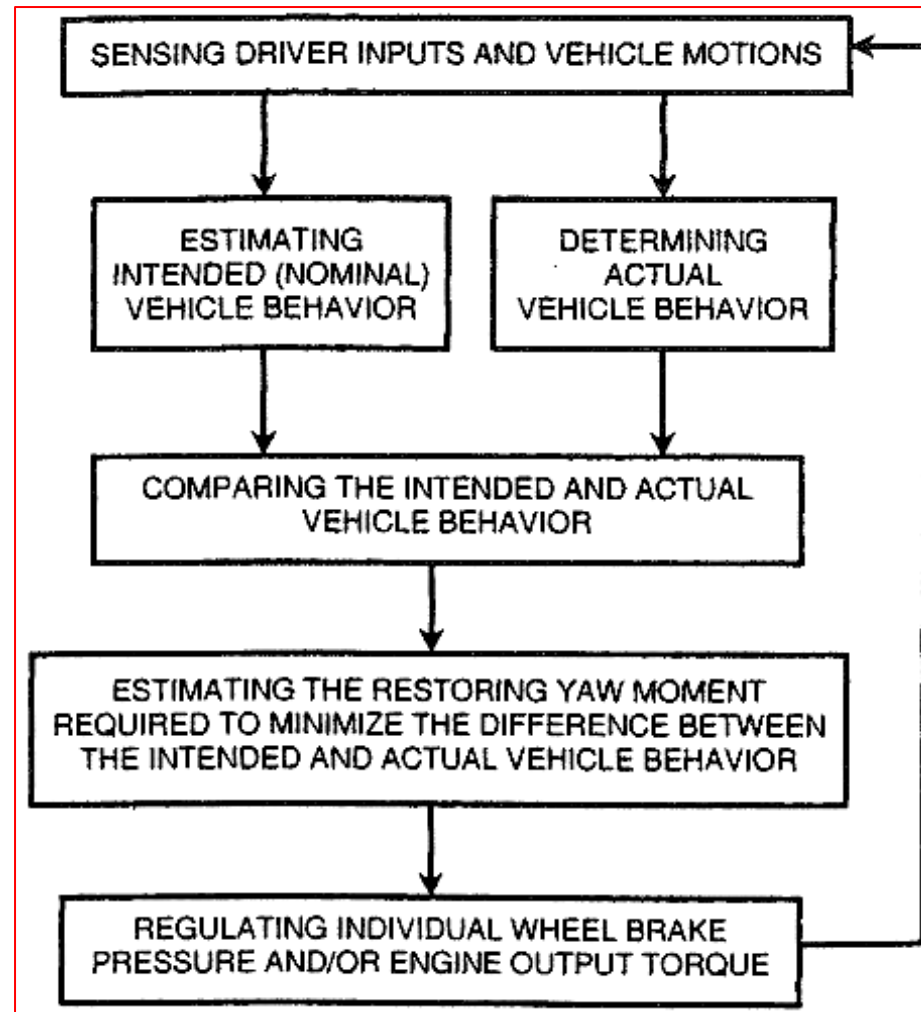
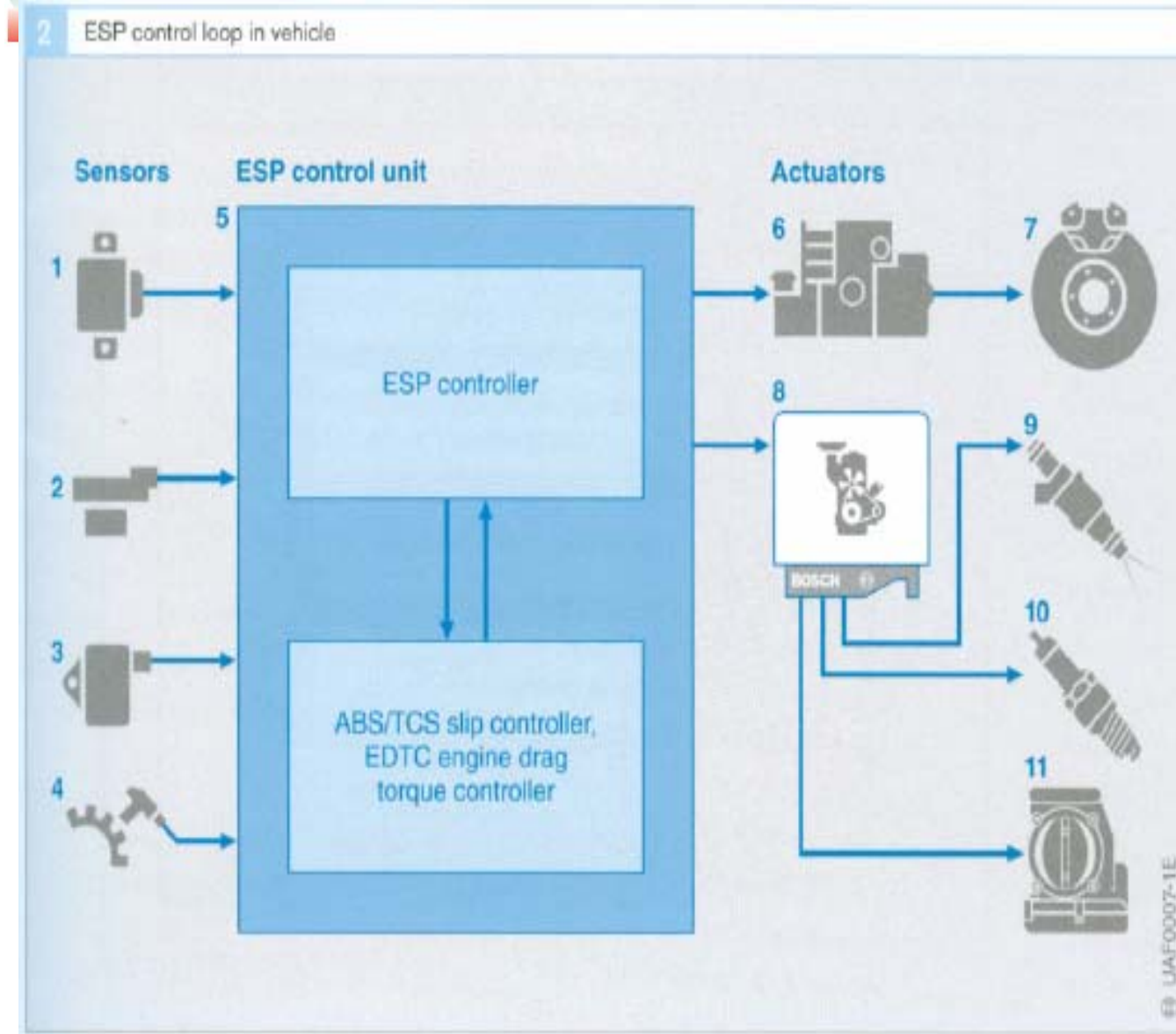


Fig: 8.4

ESP – Control Loop



1. Yaw-rate sensor with lateral-acceleration sensor
2. Steering-wheel-angle sensor
3. Primary-pressure sensor
4. Wheel-speed sensor
5. ESP control unit
6. Hydraulic modulator
7. Wheel brakes
8. Engine management
9. Fuel injection – only for gasoline engine:
10. Ignition-timing intervention
11. Throttle-valve intervention (ETC)

Fig: 8.6

Vehicle Dynamics and Safety

ESP – Control Loop

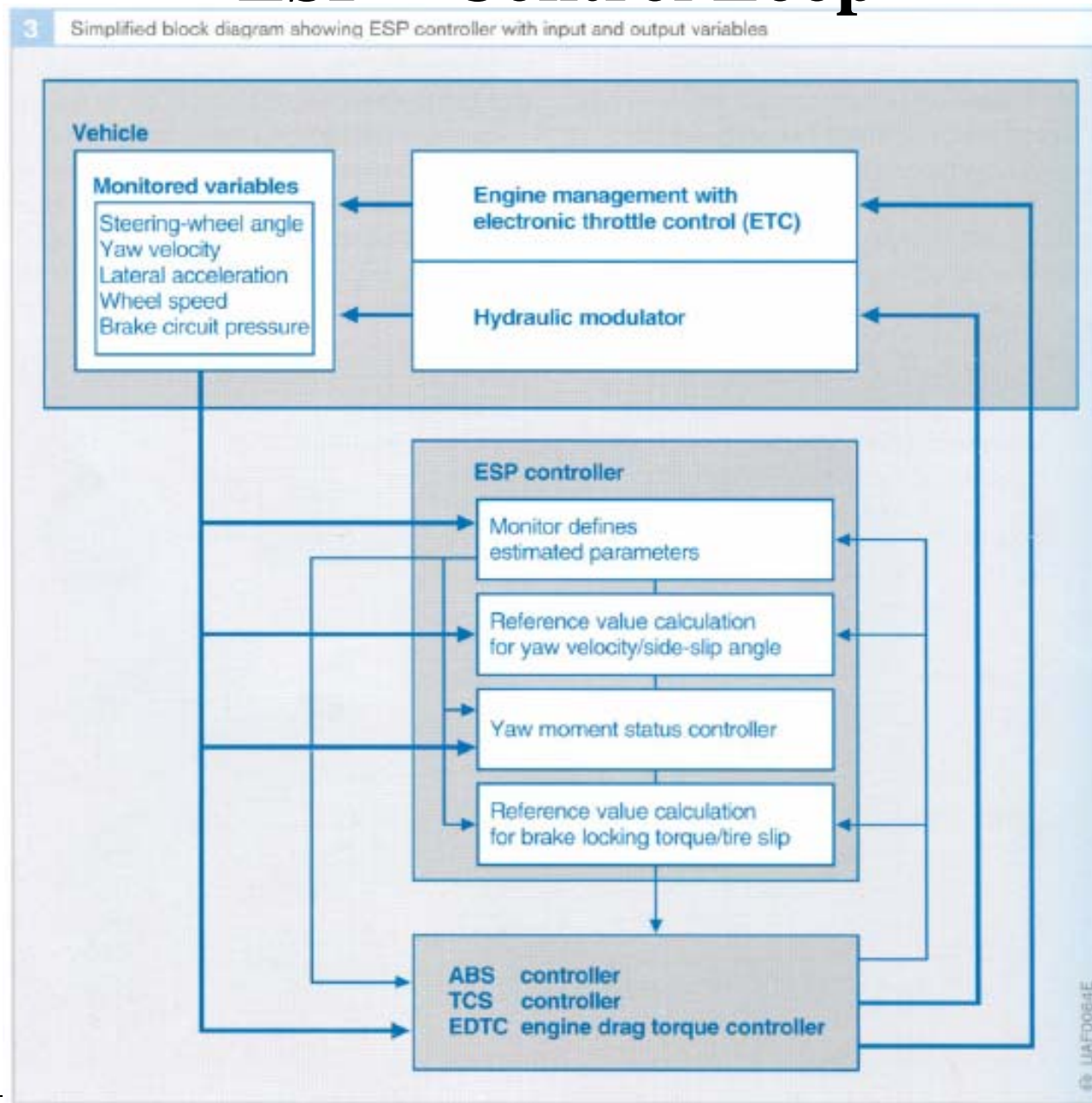


Fig: 8.7

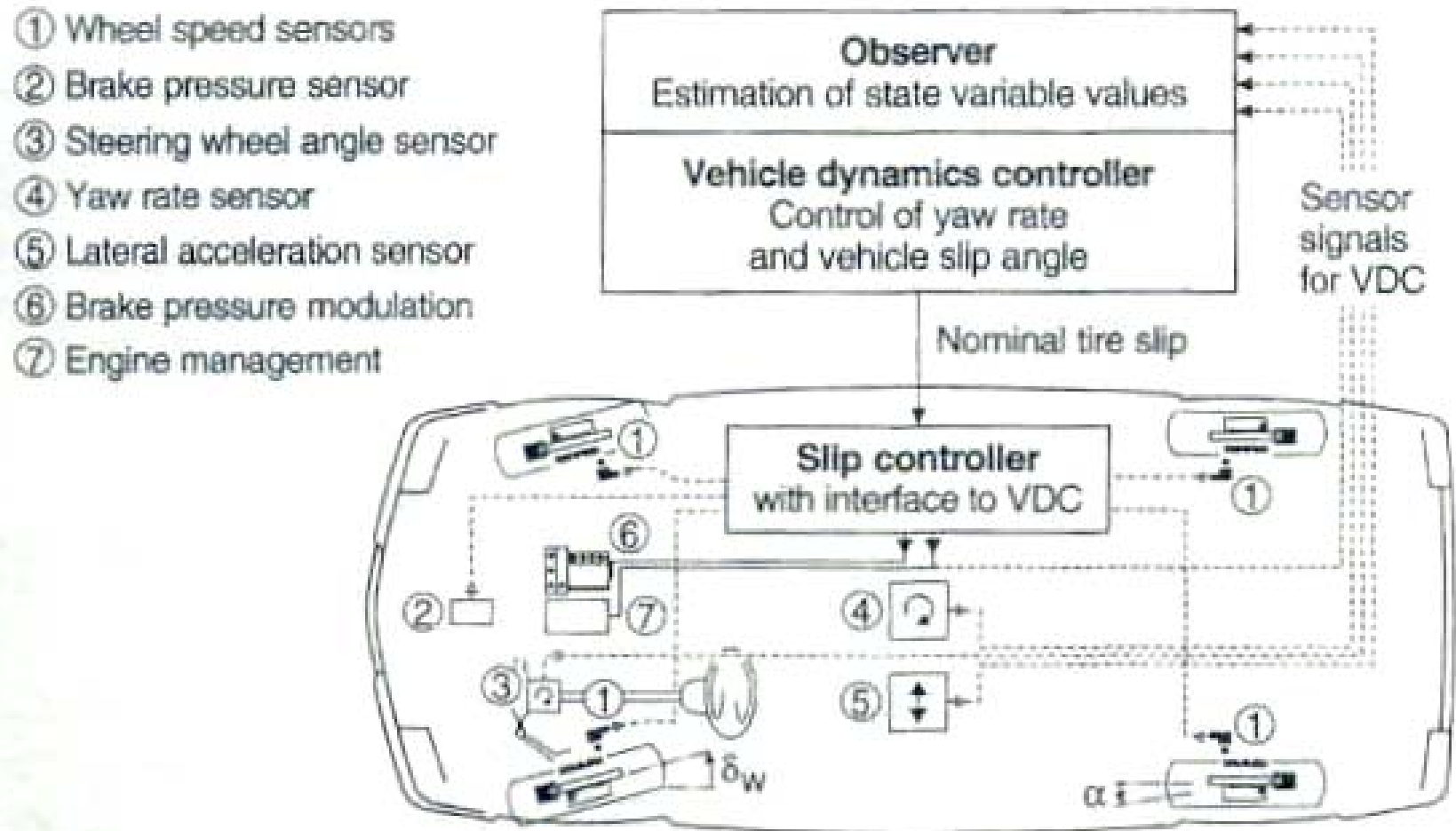
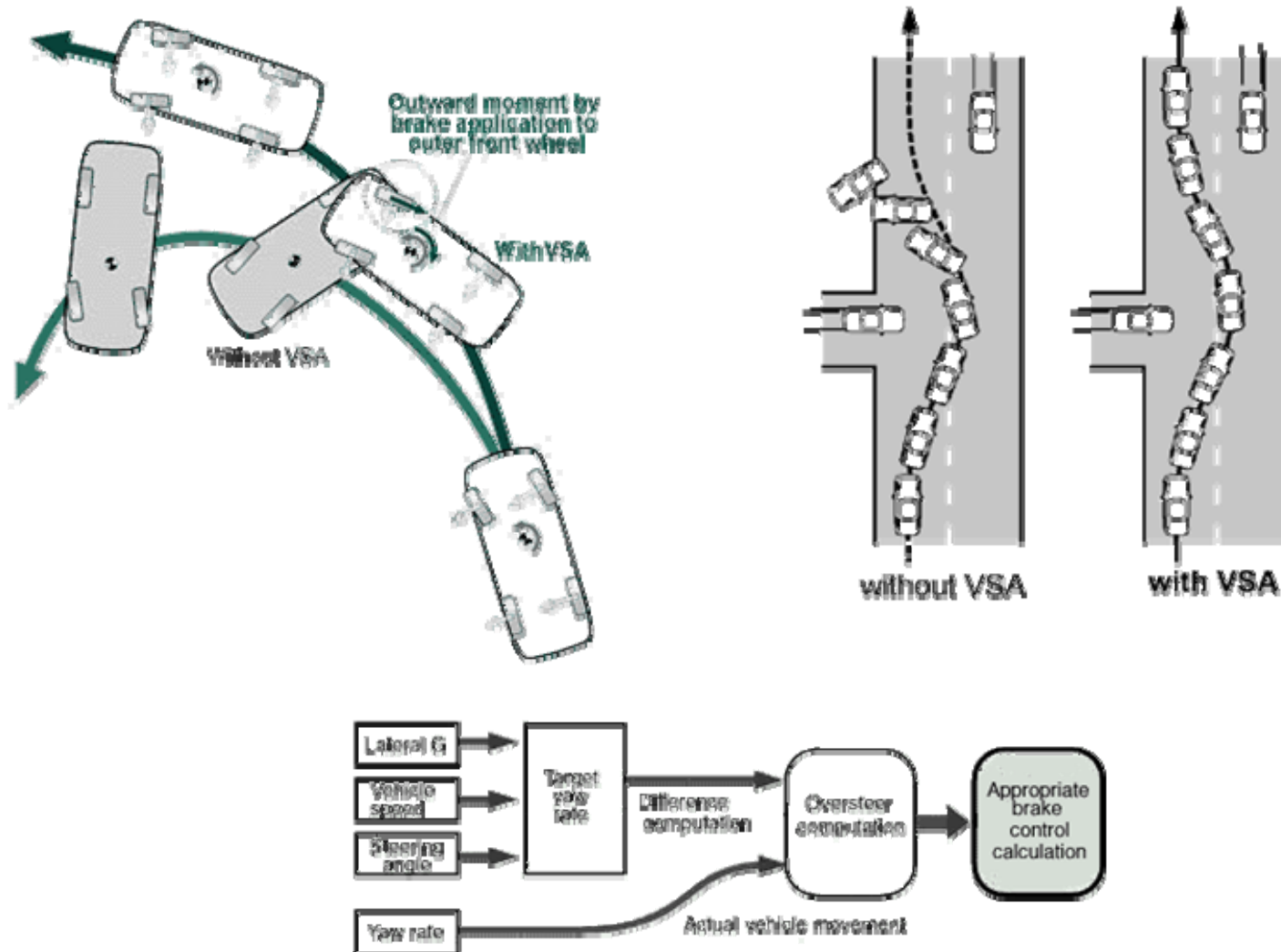
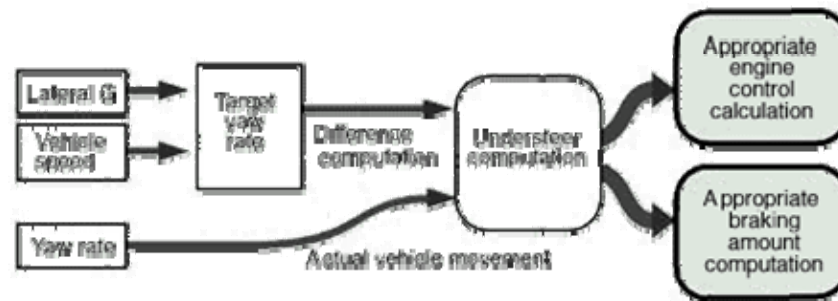
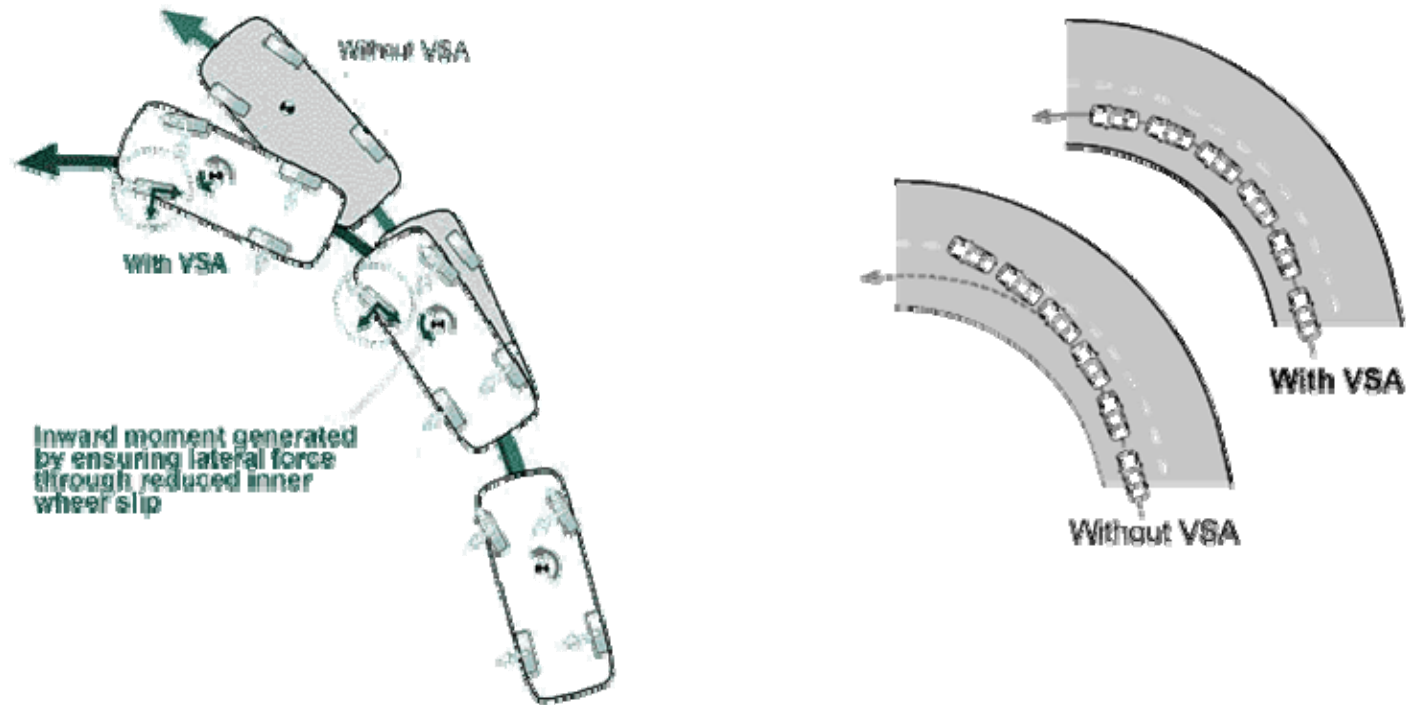


Fig: 8.5

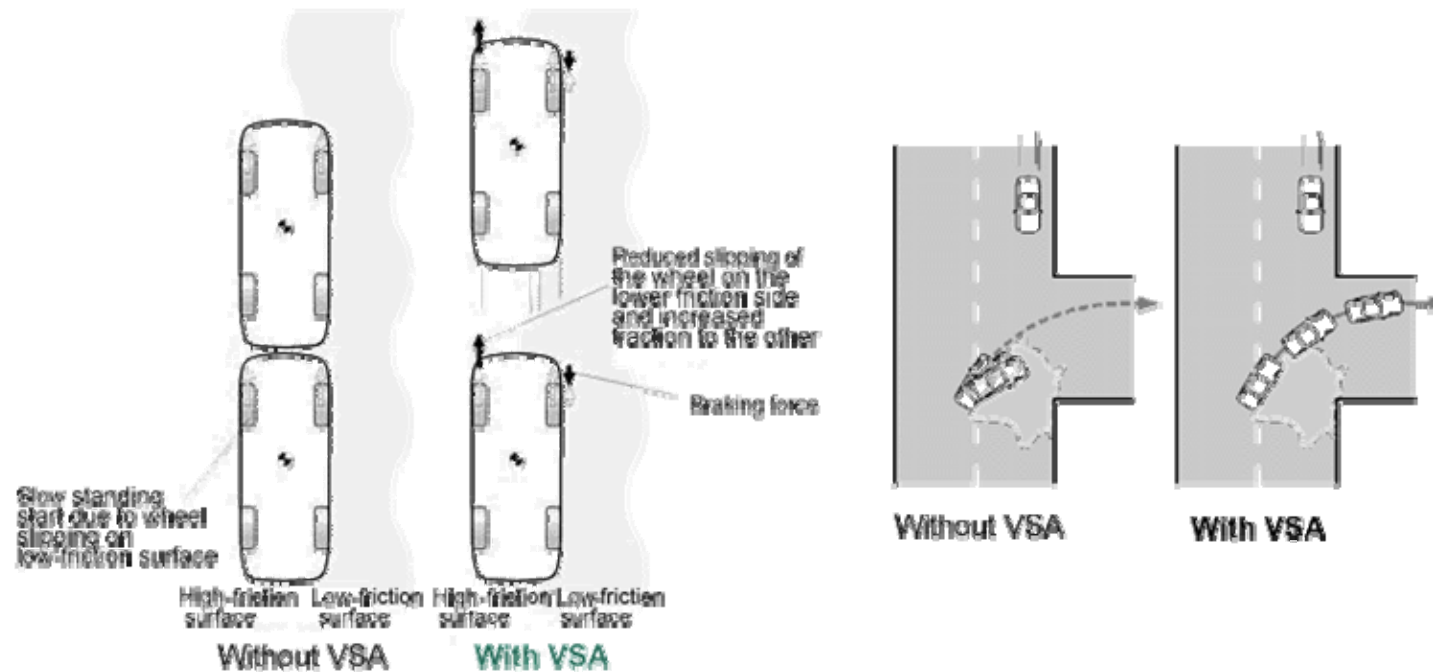
Operation-Oversteer Control



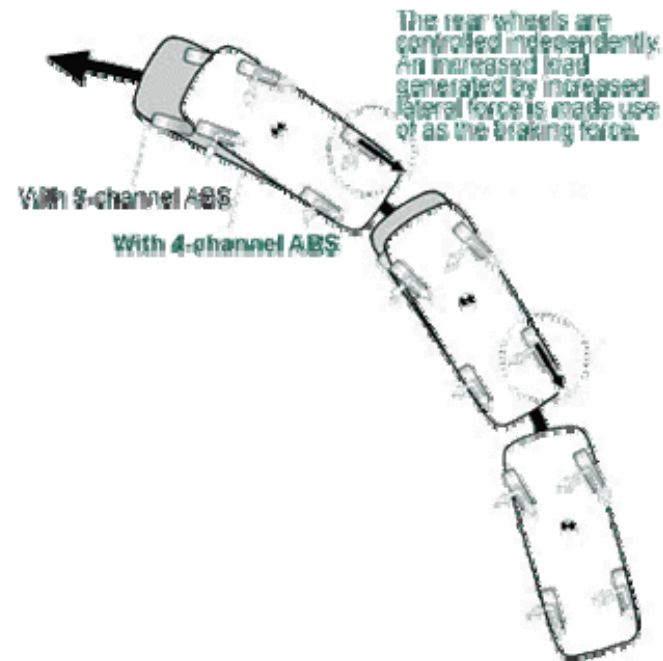
Operation-Understeer Control



Standing Start Slip Control

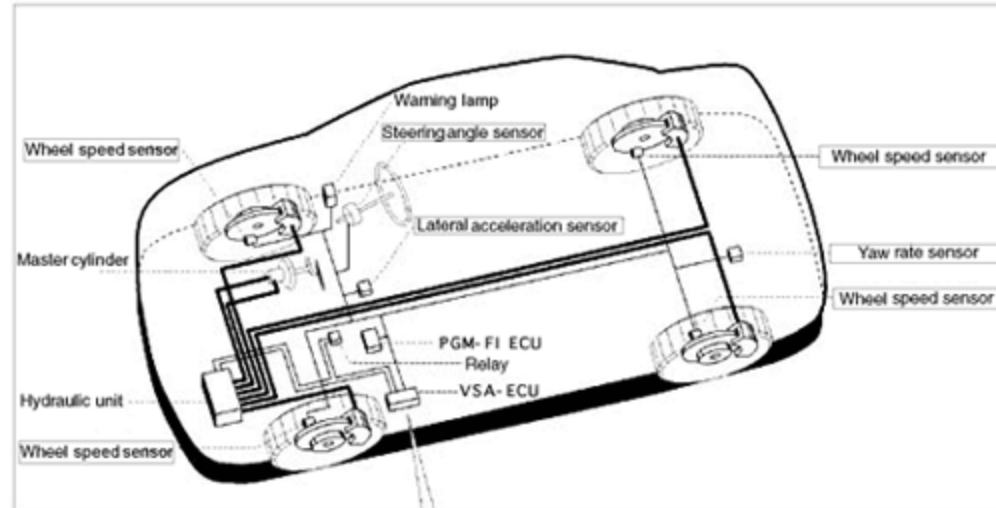


Braking Control Under Cornering



System Configuration

System Configuration



ECU circuit diagram

