Basics of Vehicle Dynamics

Module H2

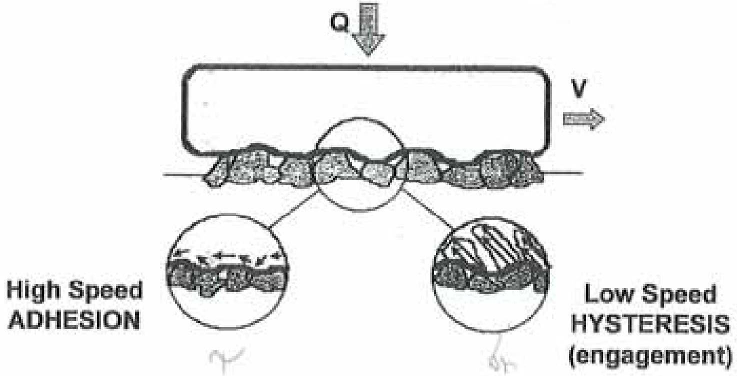
Tyre Behaviour

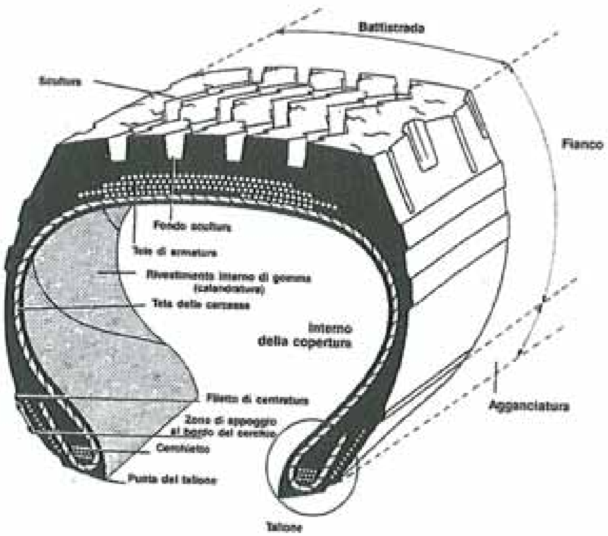
- Forces generated by tyre
- Tyre effects
- Tyre transient response
- Handling tyre models

TYRES FUNCTIONS ARE:

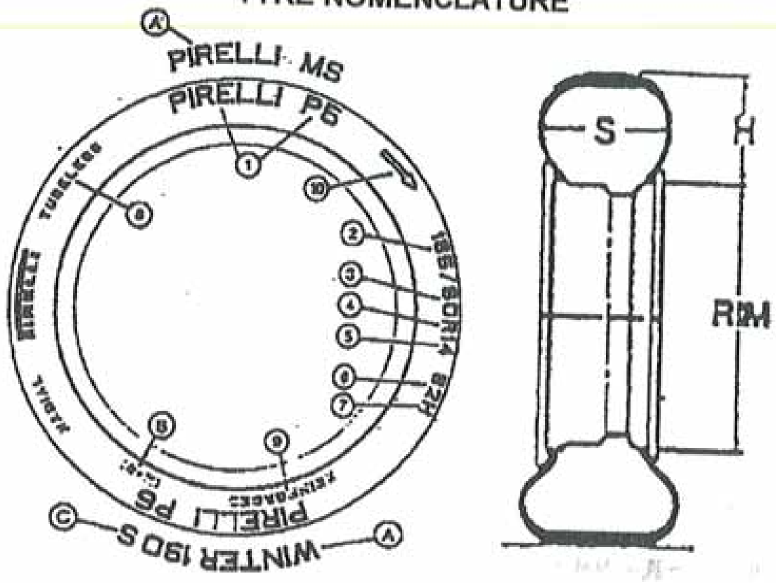
- ❖ Supplying forces for controlling and stabilizing the vehicle
- ❖ Transmitting torque to the ground (TRACTION)
- ❖ Filtering road roughness (COMFORT)

ADHESION AND HYSTERESIS





TYRE NOMENCLATURE



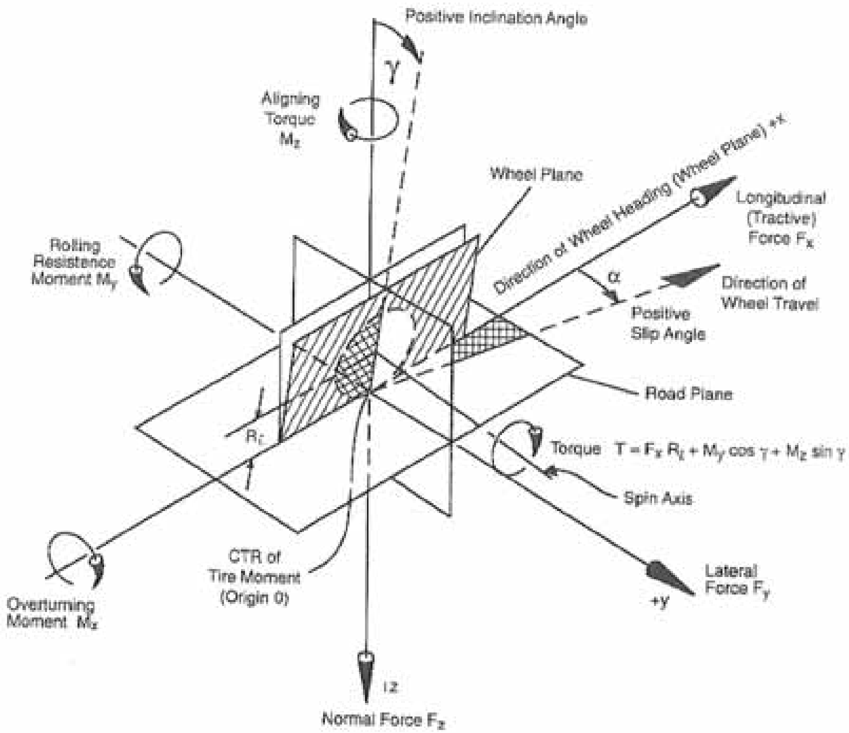
1 Manufacturer name and tread type
2 Section nominal width in mm
3 Ratio between sidewall height H and section width S, usually not given if it equals 80
4 Type of structure (R if radial, - conventional)
5 Shrinking diameter in inches
6 Related to load capacity
7 Tyre maximum speed code
8 Tubeless tyre. Tyres with tube have the writing TUBE TYPE
9 Reinforced internal structure for weight higher than usual
10 The arrow shows the preferential rolling direction

Winter tyres marking

A Manufacturer name and product name
B "Mud and Snow" indicates a tyre fit to that specific duty
C Letter S means pits

TYRE REFERENCE SYSTEM

GEOMETRICAL VARIABLES and CONTACT FORCES (SAE J670)



Forces generated by tyre

Lateral Force
Longitudinal Force
Aligning Torque

LATERAL FORCE

A lateral tire force originates at the "center" of the tire contact with the road, lies in the horizontal road plane and is perpendicular to the direction in which the wheel is headed

⇩

A vehicle turns because of the applied lateral tire forces

1 - How the tyre interacts with the ground

- Constant vertical force
- Lateral force push the tyre

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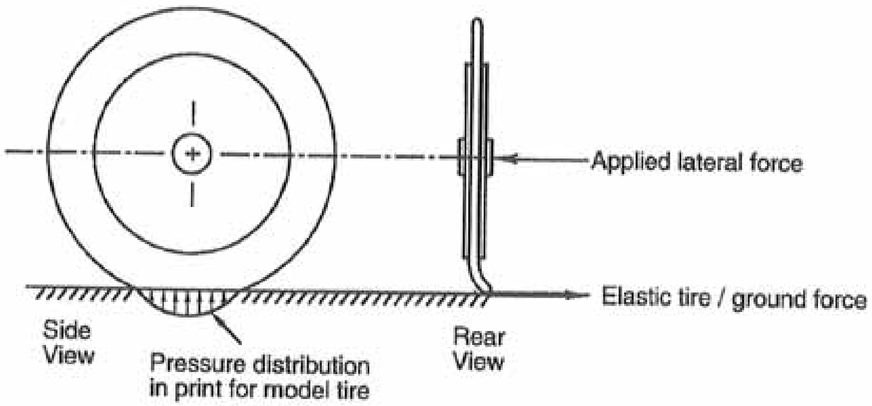
The tyre acts like a spring
Sidewalls bent elastically



FORCES AND MOMENTS

The external forces acting on the vehicle can be summed into one force vector having the following components

Longitudinal Force (Fx): is the force component in the x-direction

Lateral Force (Fy): is the force component in the y-direction

Normal Force (Fz): is the force component in the z-direction

The external moment acting on the vehicle can be summed into one moment vector having the following components

Rolling Moment (Mx): is the moment component tending to rotate the vehicle about the x-axis, positive clockwise when looking in the positive direction of the x-axis

Pitching Moment (My): is the moment component tending to rotate the vehicle about the y-axis, positive clockwise when looking in the positive direction of the y-axis

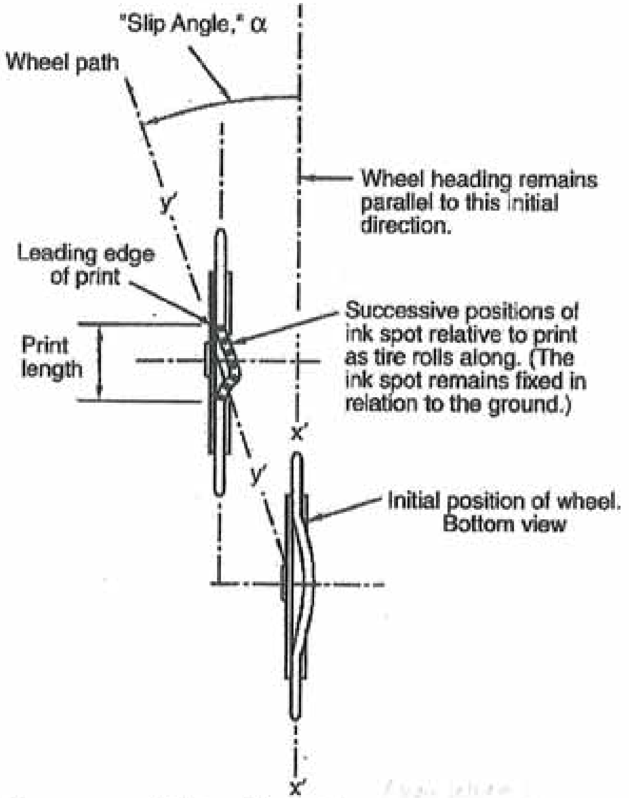
Yawing Moment (Mz): is the moment component tending to rotate the vehicle about the z-axis, positive clockwise when looking in the positive direction of the z-axis

2 - How the tyre interacts with the ground

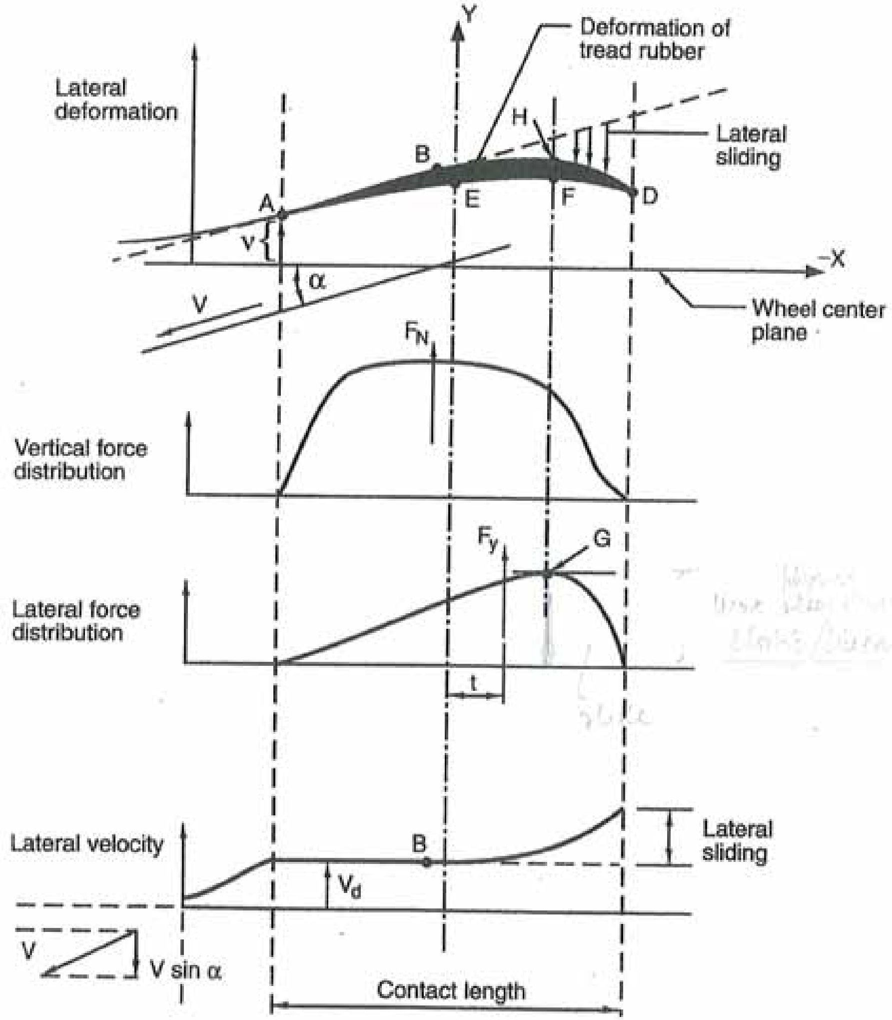
• Tyre is rolled

⇩

α angle between velocity vector and the wheel plane
Each tread unit enters the print and moves aft to the print and also sideways because of the lateral deflection in the print



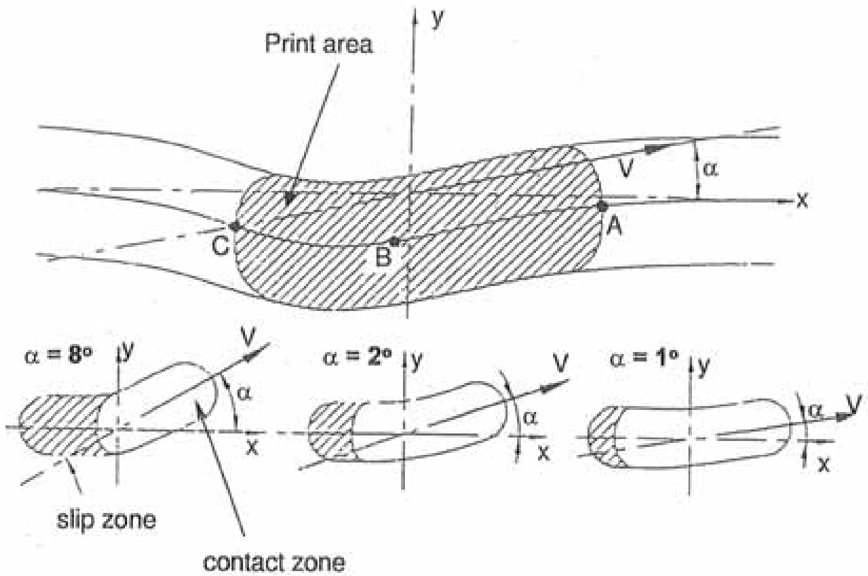
Slip angle increases with lateral force, in a progressive process.
When the print slides, the lateral force is determined by the coefficient of friction.



Distribution of forces and lateral velocity over the contact length.

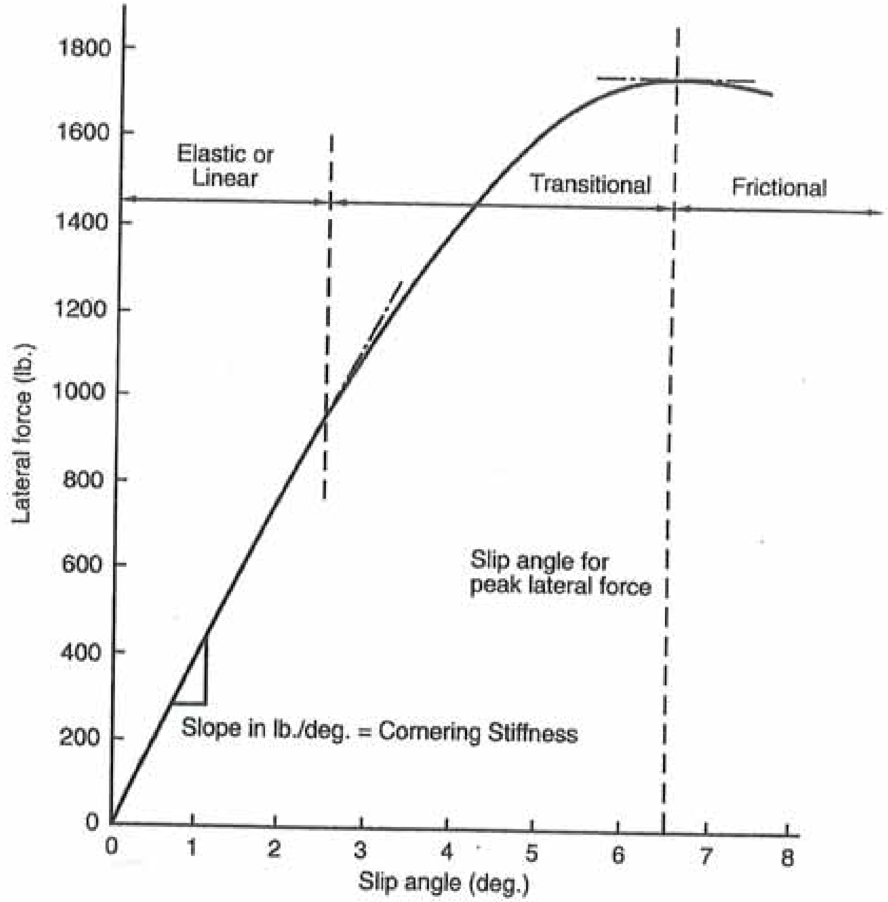
SLIP ANGLE DEFINITION

A)



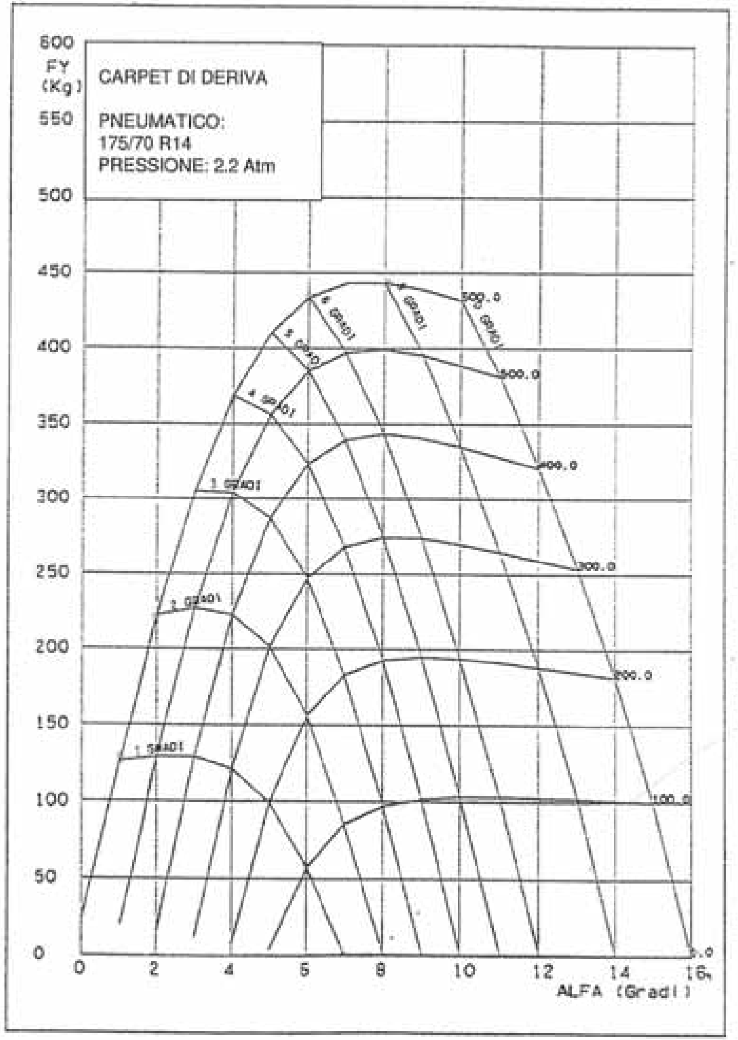
LATERAL FORCE vs SLIP ANGLE

For a given load.



Lateral force vs. slip angle.

LATERAL FORCE CARPET



ALIGNING TORQUE

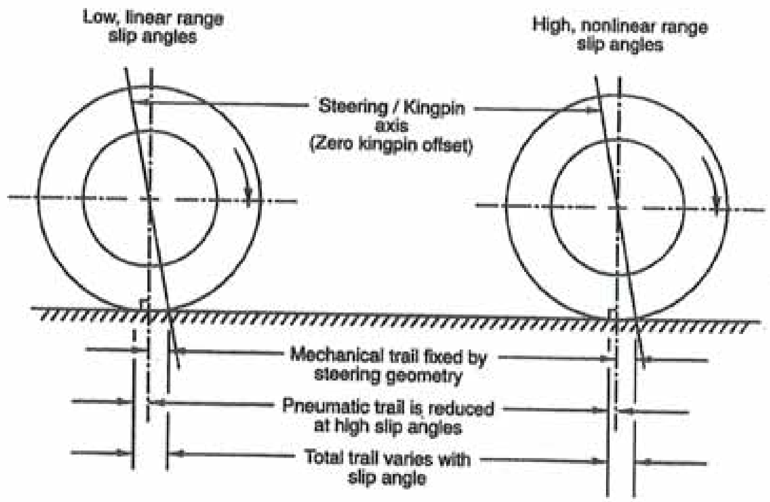
Aligning Torque (SAE J670): describe a tyre's tendency to steer about a vertical axis through the "center" of the print.
At low and medium slip angles the tyre tends to align its heading with its path.

Pneumatic Trail: distance from the fore-aft center of the print to the center of action of the lateral force due to uneven distribuition of these.
IT CHANGES WITH TYRE OPERATING CONDITIONS.

ALIGNING TORQUE = LATERAL FORCE TIMES PNEUMATIC TRAIL

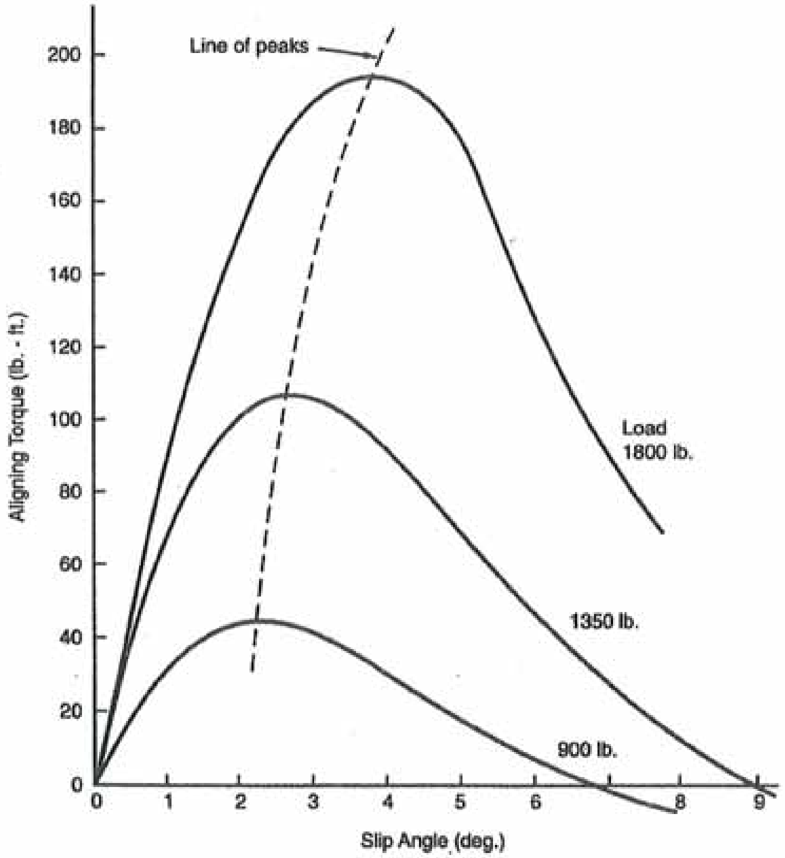
Mechanical Trail: steering pivot obtained by caster angle and kingpin offset

STEERING TORQUE = (PNEUMATIC_trail + MECH_trail)*FY



Pneumatic and mechanical trail

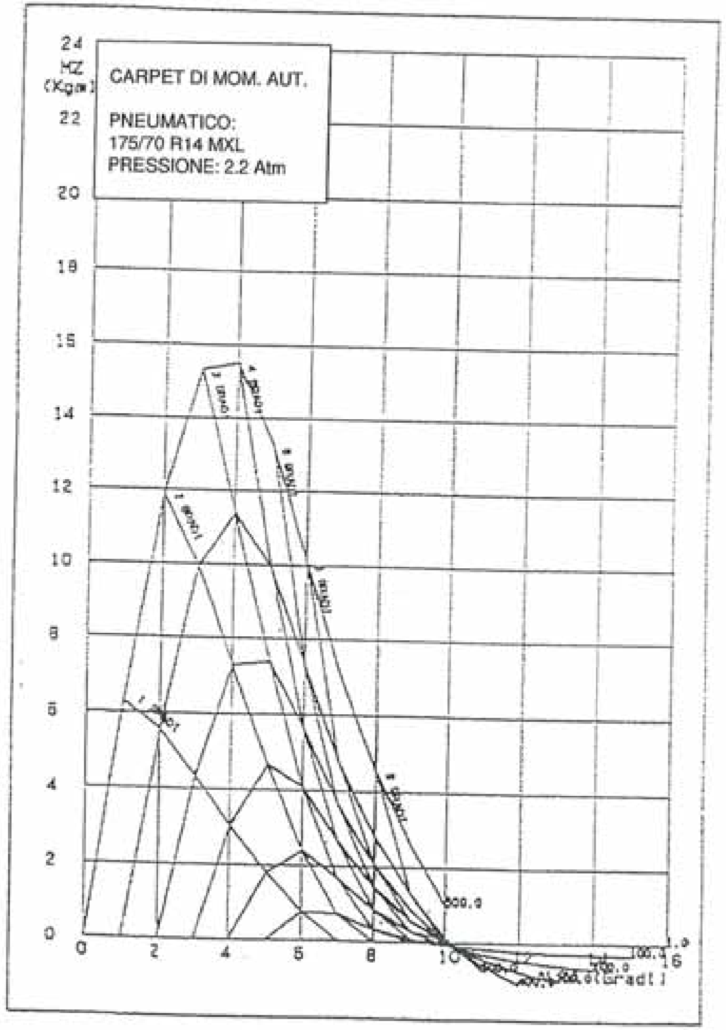
ALIGNING TORQUE vs SLIP ANGLE



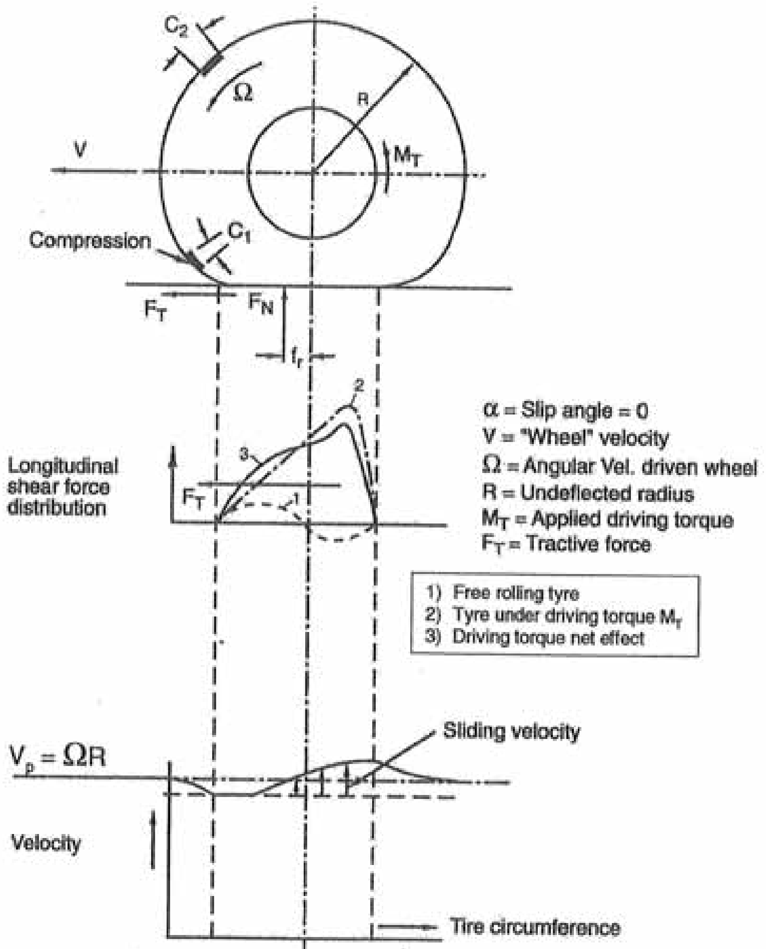
Aligning torque vs. slip angle for several loads.

BASICS OF VEHICLE DYNAMICS
Module H2
Tyre Behaviour

ALIGNING TORQUE CARPET



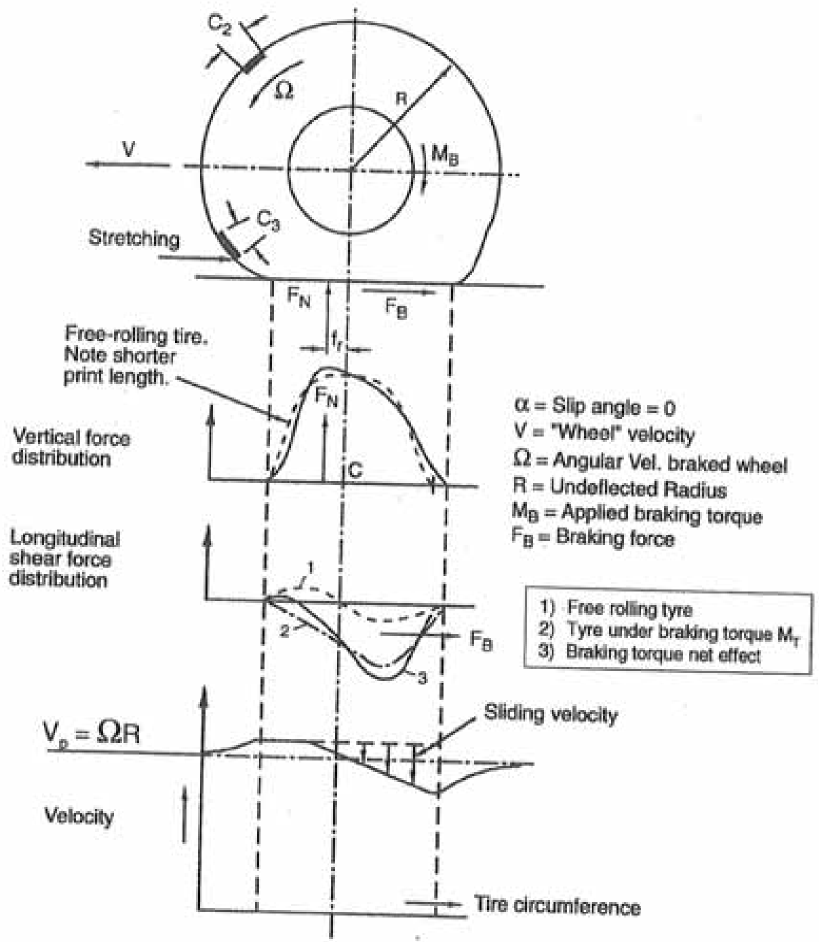
LONGITUDINAL FORCE: TRACTION



Distribution of forces and sliding velocity, over the contact length of a tire under the action of a driving torque M_T.

Tyre print characteristics - traction

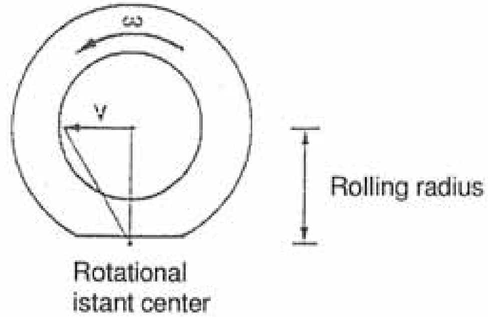
LONGITUDINAL FORCE: BRAKING

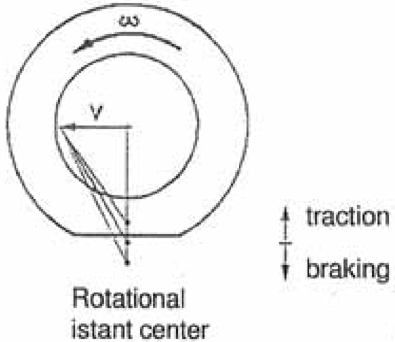


Distribution of forces and sliding velocity over the contact length of a tire under the action of a braking torque M_B.

Tire print characteristics—braking

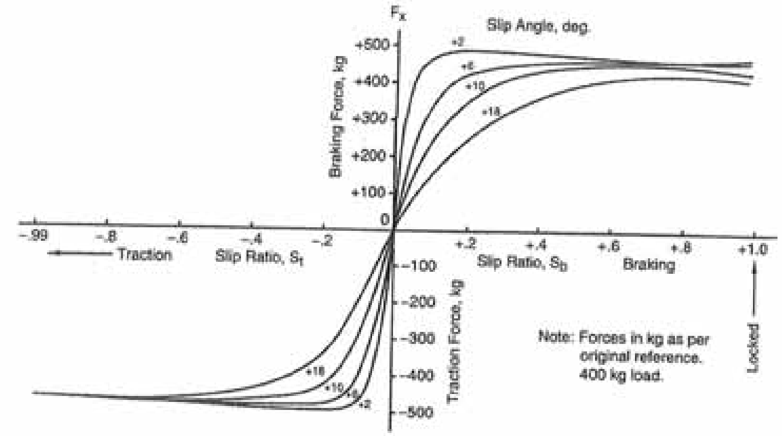
SLIP RATIO



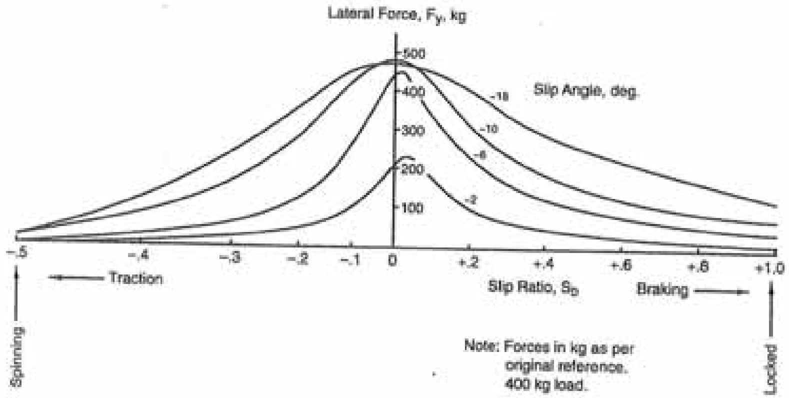


$$S = \frac{\omega \cdot R - V}{\omega \cdot R}$$ *traction*

$$S = \frac{\omega \cdot R - V}{V}$$ *braking*

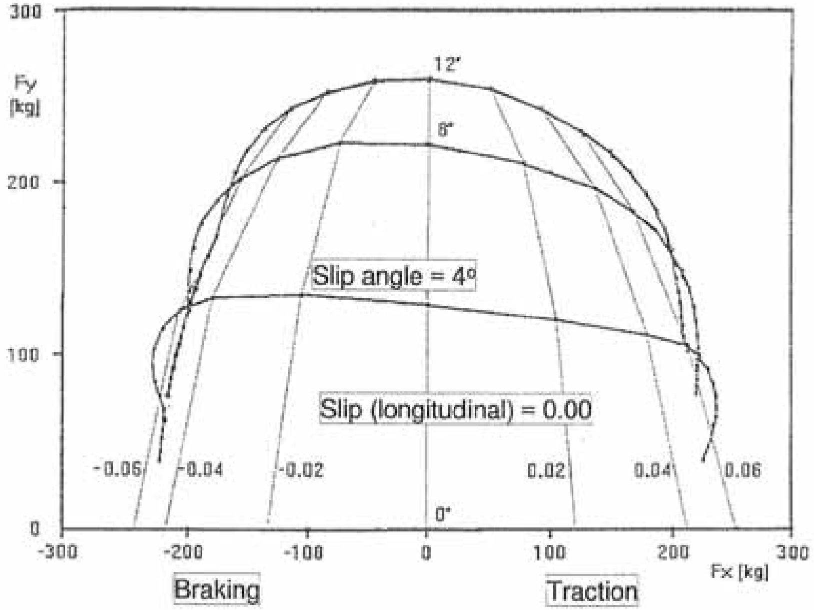


Braking and traction forces vs. slip ration and slip angle



Lateral force vs. slip ration and slip angle

LONGITUDINAL and LATERAL FORCES INTERACTION

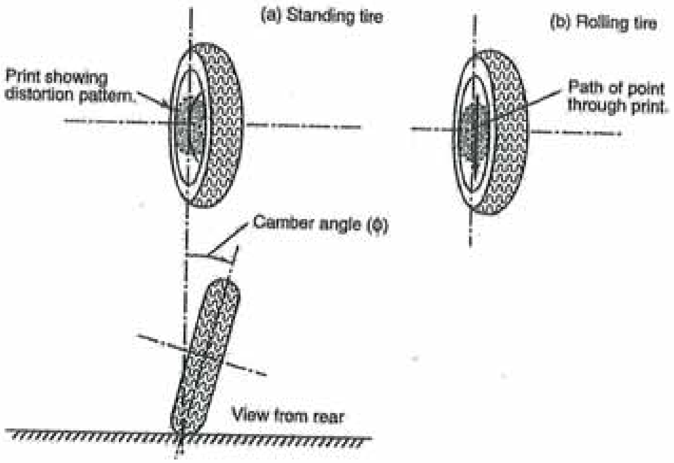


Tyre Effects

CAMBER EFFECTS

Camber angle is defined as the angle between a tilted wheel plane and the vertical.

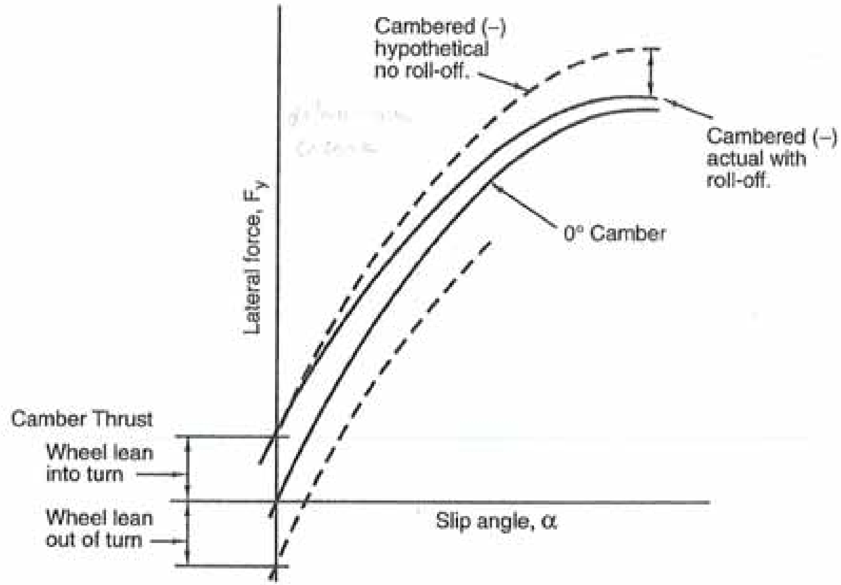
Camber thrust: lateral force produced by a cambered rolling pneumatic-tired wheel; it arises from lateral distortion in the print.



Distortion in print of a tire at a camber angle.

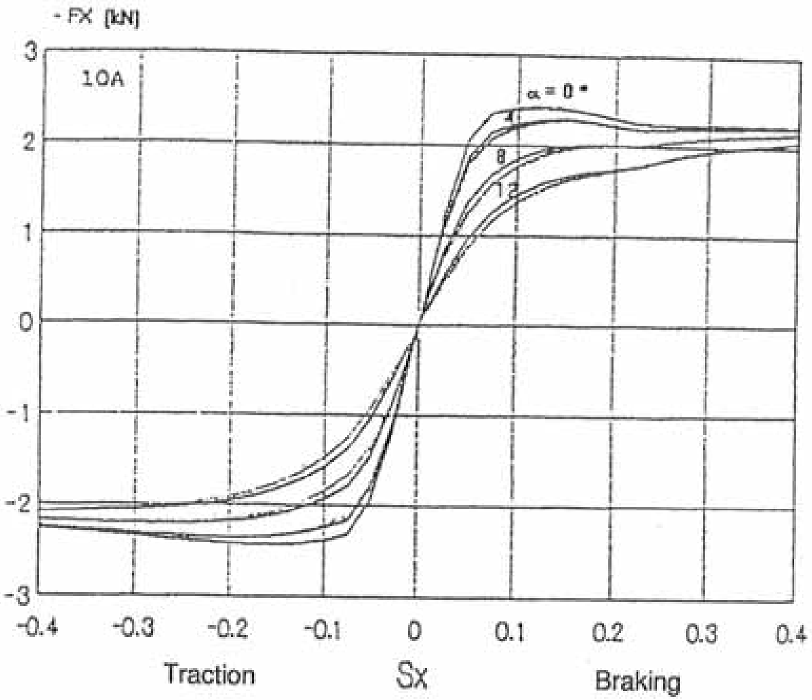
For traditional bias tires cornering stiffness is generally five to six times greater than the camber stiffness.
For radial tires the effect may be quite small since the lateral stiffness of the belt and the flexibility of radial cord sidewall inhibit the print distortion

CAMBER EFFECTS

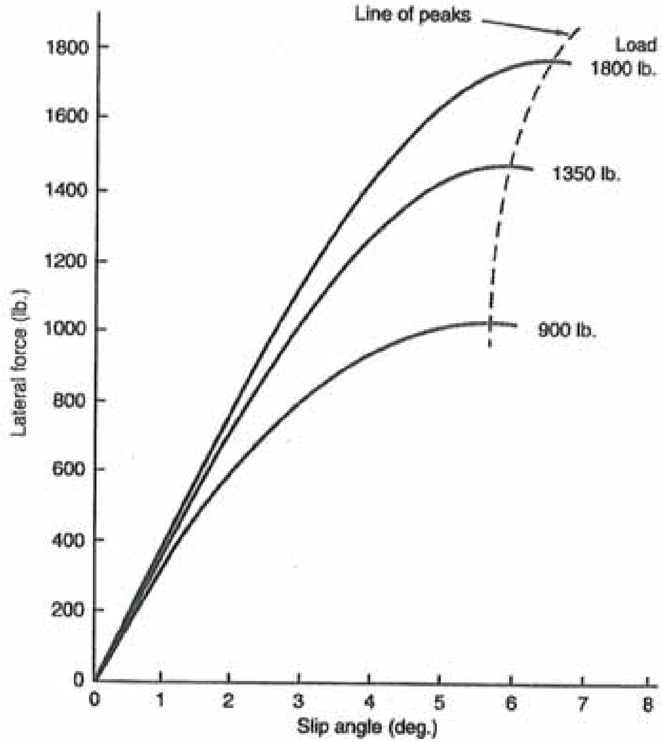


Camber thrust and camber roll-off at constant load.

CAMBER vs. LONGITUDINAL FORCE

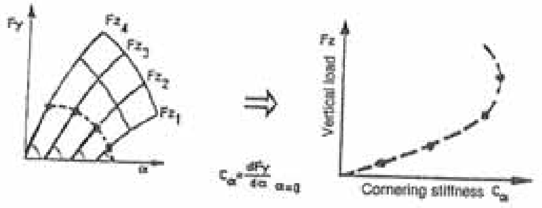


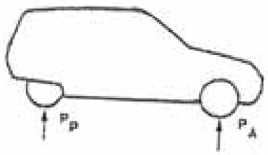
LOAD EFFECTS (Lateral Force)

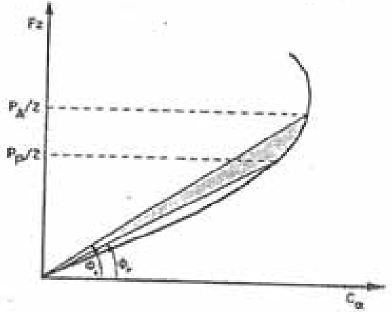


Lateral force vs. slip angle for several loads.

TYRES UNDERSTEER GRADIENT



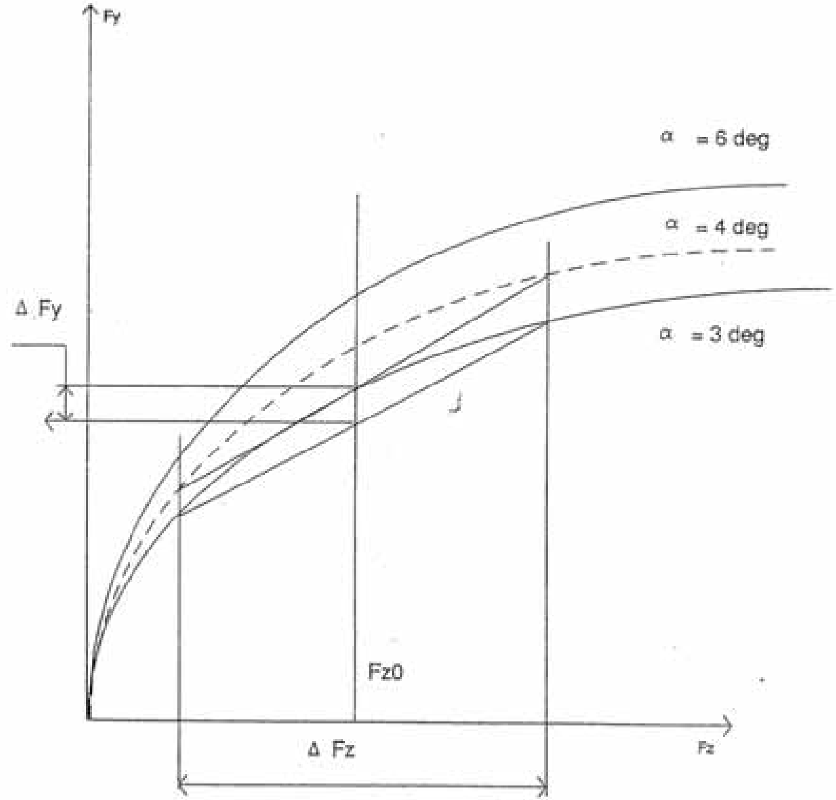




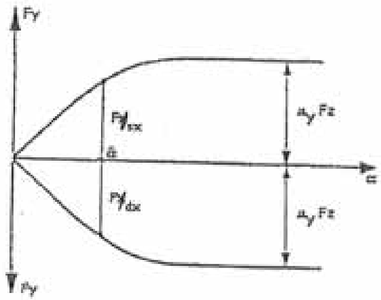
$$KUS = \left(\frac{d\delta_{vol}}{da_y}\right)_{a_y=0} = \left(\frac{d\alpha_A}{da_y} - \frac{d\alpha_P}{da_y}\right)_{a_y=0} \cdot \tau_{vol} =$$

$$= \left(\frac{d(F_{y_A}/C_{\alpha_A})}{d(2 \cdot F_{y_A}/P_A)} - \frac{d(F_{y_P}/C_{\alpha_P})}{d(2 \cdot F_{y_P}/P_P)}\right)_{a_y=0} \cdot \tau_{vol} = \frac{1}{2} \cdot \left(\frac{P_A}{C_{\alpha_A}} - \frac{P_P}{C_{\alpha_P}}\right) \cdot \tau_{vol} = (tg\phi_A - tg\phi_P) \cdot \tau_{vol}$$

TYRES NON LINEARITIES vs. VERTICAL LOAD : Single axle



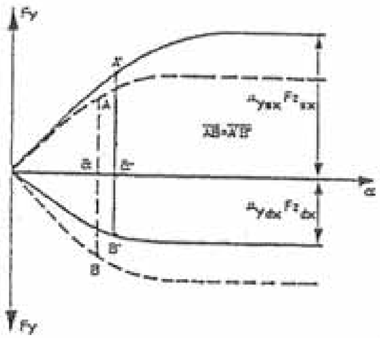
LOAD TRANSFER



NO LOAD TRANSFER

$\bar{\alpha}$ slip angle to generate load
$Fy = Fy_{sx} + Fy_{dx}$

Fz vertical load on single wheels



LOAD TRANSFER

$\bar{\alpha}'$ slip angle to generate load
$Fy = Fy_{SX} + Fy_{DX}$

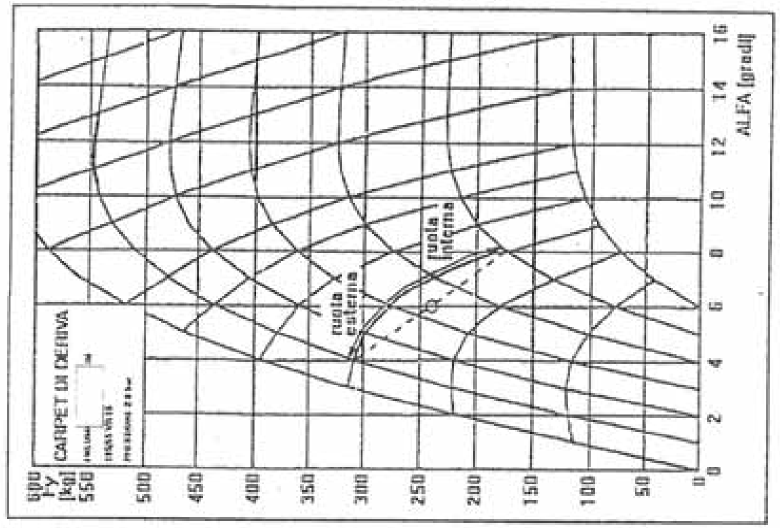
Fz_{SX} vertical load on left wheel

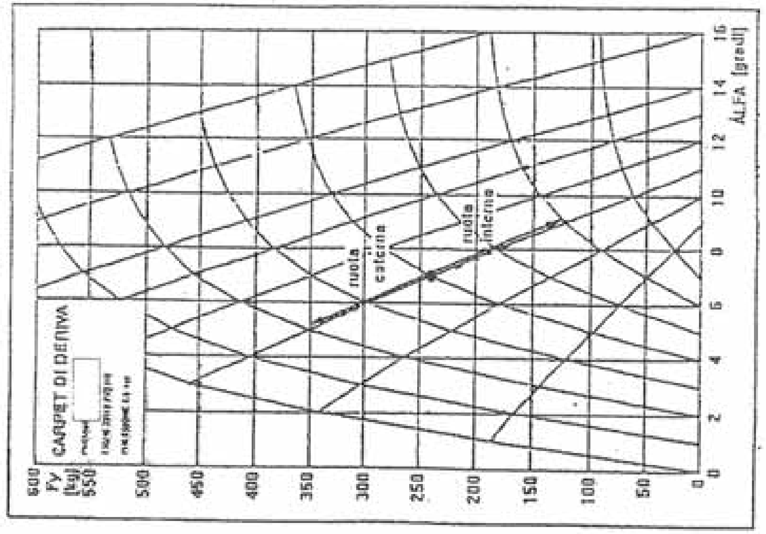
Fz_{DX} vertical load on right wheel

$\bar{\alpha}' > \bar{\alpha}$

BASICS OF VEHICLE DYNAMICS
Module H2
Tyre Behaviour

TYRE SENSITIVITY vs. LOAD TRANSFER





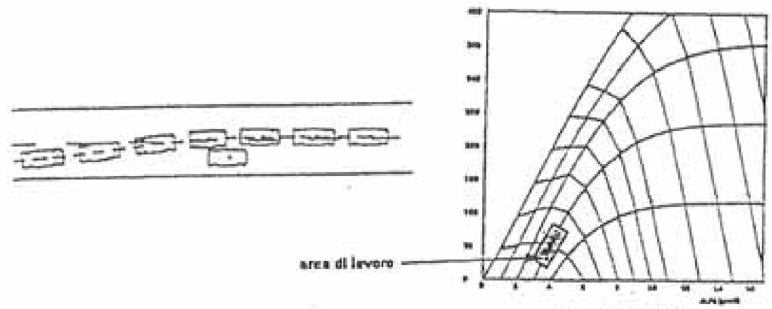
Tyre transient response

TYRES DYNAMIC BEHAVIOUR

SLIP ANGLE TRANSIENT CONDITIONS

NORMAL DRIVING

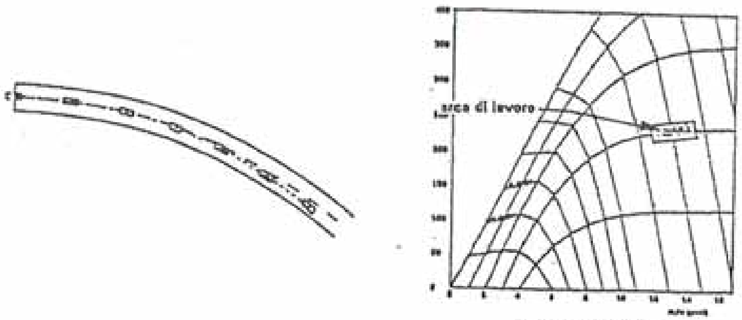
1. Variable slip angle around small initial values, at roughly constant vertical load



CARPET DI DERIVA

LIMIT CONDITION

2. Variable slip angle around large initial values, at roughly constant vertical load



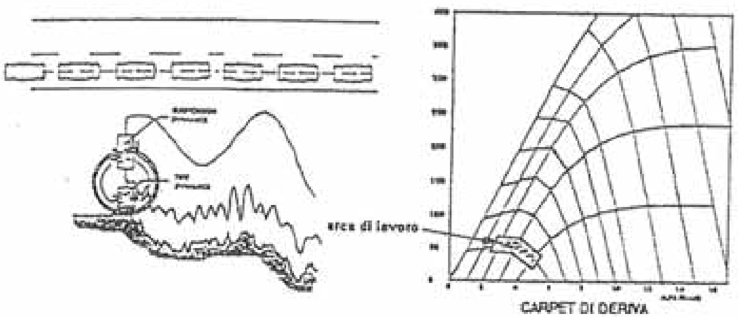
CARPET DI DERIVA

TYRES DYNAMIC BEHAVIOUR

VERTICAL LOAD TRANSIENT CONDITIONS

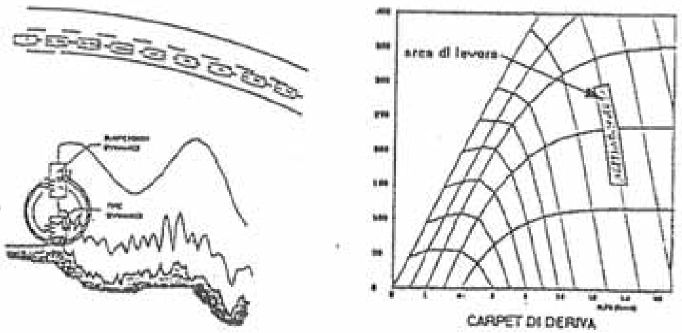
CENTER FEEL ON UNEVEN ROAD

1. Variable vertical load, roughly constant small, slip angle



GRIP ON UNEVEN ROAD

2. Variable vertical load, roughly constant large slip angle



TYRE TRANSIENT EQUATION

$$\dot{F}_y = \frac{V}{S_0(F_z)} \cdot [F_{yss}(\alpha, F_z) - F_y]$$

Fy	= lateral force
Fyss	= steady lateral force
V	= speed
So	= relaxation length
α	= slip angle
Fz	= vertical load

Handling Tyre Models

MODEL GOAL :

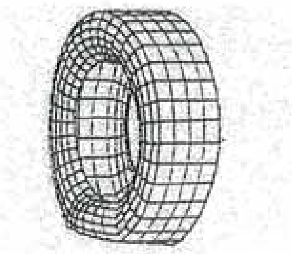
MATHEMATICAL SIMULATION
of TYRE BEHAVIOUR in HANDLING

- Steady state conditions
- Transient conditions
- Different working conditions:
  - High adhesion
  - Low adhesion
  - Pressure
  - Temperature

MODEL KINDS

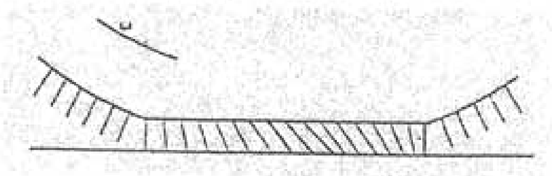
1) PHYSIC

To get handling characteristics vs. tyre physic characteristics (dimensions, tread types, carcass structure, ecc.)



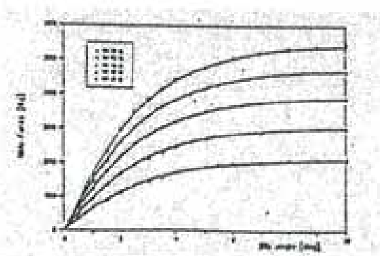
2) SEMI-PHYSIC

To get handling characteristics vs. physic equivalent parameters (carcass and tread stiffness, adhesion coeff., ecc.)

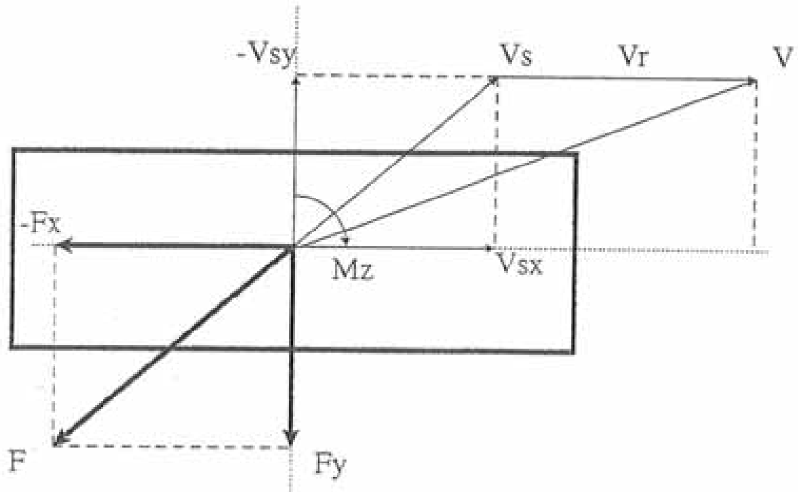


3) INTERPOLATION

To get handling characteristics by mathematical interpolation of characteristics obtained by testing or physical models



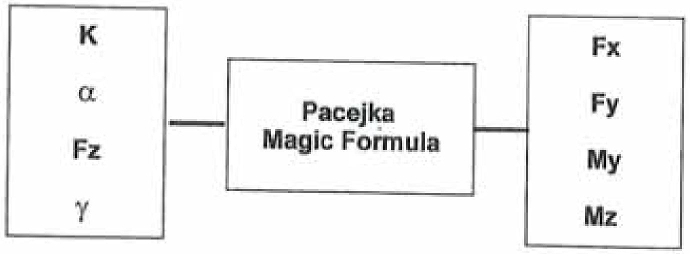
PACEJKA MAGIC FORMULA



Tyre view during simultaneous action of lateral and longitudinal loads, showing force and speed vectors

Longitudinal Slip : $k = \frac{V_{sx}}{V_x}$

Slip angle: $\tan\alpha = -\frac{V_{sx}}{V_x}$



VEHICLE APPLIED FORCES

$$Y = D \cdot \sin[C \cdot \arctan(B \cdot (x+Sh) - E \cdot (B \cdot (x+Sh) - \arctan(B \cdot (x+Sh))))] + Sv$$

dove per $Y = F_y$ *e* $x = \alpha$

$$D = a1 \cdot F_z^2 + a2 \cdot F_z$$

$$B \cdot C \cdot D = a3 \cdot \sin[2 \cdot \arctan(\frac{F_z}{a4})] \cdot (1 - a5 \cdot |\gamma|)$$

$$C = a0 \; ; \qquad E = a6 \cdot F_z + a7$$

$$Sh = a8 \cdot \gamma + a9 \cdot F_z + a10$$

$$Sv = (a112 \cdot F_z^2 + a111 \cdot F_z) \cdot \gamma + a12 \cdot F_z + a13$$

mentre per $Y = M_z$ *e* $x = \alpha$

$$D = c1 \cdot F_z^2 + c2 \cdot F_z$$

$$B \cdot C \cdot D = (c3 \cdot F_z^2 + c4 \cdot F_z) \cdot (1 - c6 \cdot |\gamma|) \, e^{-c5 \cdot F_z}$$

$$C = c0 \; ; \qquad E = (c7 \cdot F_z^2 + c8 \cdot F_z + c9) \cdot (1 - c10 \cdot |\gamma|)$$

$$Sh = c11 \cdot \gamma + c12 \cdot F_z + c13$$

$$Sv = (c14 \cdot F_z^2 + c15 \cdot F_z) \cdot \gamma + c16 \cdot F_z + c17$$

PACEJKA INTERPOLATION MODEL EXAMPLES