DESIGN OF SUSPENSION TO PREVENT PULLING TO ONE SIDE AND SKIDDING DURING BRAKING-PARTICULARLY ON A SURFACE WITH DIFFERING COEFFICIENT OF FRICTION

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Front suspension geometry and the splitting of the dual brake circuits can be so designed as to achieve optimal braking stability both on a straight course and when cornering. This paper sets out to demonstrate that front suspension geometry incorporating outboard scrub radius together with diagonally split dual brake circuits - especially with wheels on surface with different skid number - can considerably improve directional stability under braking.

Introduction

Skidding during braking is particularly dangerous, because many braking maneuvers are caused by emergency situations, at least they were not started voluntarily. If in such a situation, which would completely occupy the driver, the vehicle behaves unexpectedly and skids, he is most likely unable to retain control of the vehicle.

The directional stability under braking frequently determines if there will be an accident or not. Brakes which pull to one side are a frequent cause of serious accidents.

Extended brake testing under many different conditions - also with anti-lock systems - has shown up the weaknesses of conventional brake systems and led to a requirement for improved braking stability:

1. The vehicle should be able to brake from either straight ahead motion or cornering motion without pulling to one side, i.e., without deviating from the desired course, even if the coefficient of friction of the road surface varies from one side to the other and even if there are differing friction coefficients in the brakes themselves: this should be possible both with the brake system intact and when one circuit is out of action.
2. The understeer/oversteer behavior of the vehicle should remain unaltered, or change only slightly, during braking even if one brake circuit is out of action.
3. If at all possible, the vehicle should still retain steering control when one brake circuit is cut off and the braked wheels lock.

Two factors threaten to reduce the directional stability of the vehicle during braking: unequal braking forces on one side or the other, and locked wheels or axles (both front wheels or both rear wheels).

Nowadays it is possible to go a long way towards preventing the wheels from locking by the use of expensive anti-lock systems. But uneven braking forces will always occur even when anti-lock systems are used, since it is to be expected that the front wheels will in all cases be controlled independently of each other.

One of the most urgent requirements for increasing active safety must therefore be to reduce the effect of unequal braking forces on the directional stability of the vehicle to a minimum.

Cause and Effect of Asymmetric Braking Forces

Uneven distribution of braking forces can be caused by many factors:

a. varying friction characteristics of brake pads

b. friction between brake pad and brake disc reduced on one side by the presence of oil, water or ice

c. tire adhesion on the road surface varying from one side to the other, e.g., one wheel on a dry road and the other on water, ice, oil or grass

Asymmetric braking forces of this kind may have very different effects on the directional stability of the vehicle, depending on the front suspension geometry and the location of the front wheel brakes.

The factor which determines whether the vehicle pulls to one side or retains good braking stability is the length, or more accurately, the direction of the lever arm of the braking force on the front wheels.

Inboard Scrub Radius

With a conventional front suspension design with outboard brakes this distance is determined by the inboard scrub radius (king pin offset at the ground, slide 1). In the case of inboard brakes (slide 2) the braking force acts through the center of the wheel with a positive lever arm a (king pin offset at the wheel center), because the moment Mvs = P.r does not react on the front suspension but is transferred to react on the mountings of the engine and transmission assembly.

The poor directional stability of vehicles of this design when braking forces are applied on one side only is due to the following factors (slide 3):

1. Braking force P_1, acting on one side, turns the vehicle about its center of gravity towards the side which is being braked.

2. In addition, braking force P_1, acting on one side, turns the front wheels towards the side which is being braked as a result of the positive lever arm of the braking force.

3. The resulting slip angles α_1 and α_2 generate the lateral forces S_1 and S_2, whose direction is such as to intensify the effect of the braking force which tends to make the vehicle yaw to one side. In addition to this, the lateral force S_1 increases the lever arm y_{g1} of the braking force by the amount of lateral tire deformation so that the deflecting torque on the steering is exaggerated.

4. The lateral forces S_1 to S_4, generated by the increasing sideslip angle of the vehicle, are all directed to the side which is being braked and tend to displace the vehicle to this side.

The result is therefore a chain of reactions which all contribute to the same effect, i.e., the vehicle yaws and drifts.

Keeping the vehicle to the desired course under these conditions demands steering forces of such magnitude and a reaction time which is so short that the driver, particularly in emergency situations, can not retain control of the vehicle.

Zero Scrub Radius

If the inboard scrub radius is reduced to zero, the tendency to pull to one side is also reduced, but not fully compensated even with zero scrub radius (slide 4).

Braking force P_1, acting on one side, admittedly does not turn the front wheel immediately because there is no lever arm from the king pin center line during the initial braking phase, but the disproportionate braking force on one side turns the whole vehicle about its vertical axis (Sp) towards the side on which the braking force is greater (slide 5).

As soon as this turning motion is imparted to the vehicle, slip angles and therefore lateral forces are created at the wheels which then exaggerate the tendency of the vehicle to turn to the side on which the braking forces are greater.

In other words, when disproportionate braking forces are acting on one side, a vehicle with zero scrub radius exhibits similar characteristics to those of a vehicle with inboard scrub radius, except that the steering torque is not so great.

A self-stabilizing effect can not be obtained from the steering when the scrub radius is zero. A reaction at the steering wheel and on the whole vehicle will still be present when uneven braking forces are applied.

Outboard Scrub Radius - Stablilizing Effect Under Braking

The yaw effect of uneven braking forces can only be counteracted by the use of outboard scrub radius (negative lever arm of braking force).

Since it is extremely difficult to design a system with inboard brakes where dimension "a" (king pin offset at the wheel center, slide 2) is negative, it is necessary to incorporate outboard brakes together with outboard scrub radius to achieve a negative braking force lever arm (slide 6).

The good directional stability of such vehicles, even when disproportionate braking forces are applied on one side, is due to the following factors (slide 7):

Braking force P_1, acting on one side, tries to turn the vehicle towards the side which is being braked in this case as well, but since the inboard scrub radius has now been converted to outboard scrub radius the front wheels are now turned towards the side which is not being braked.

As a result of the lateral elastic deformation of the tire caused by lateral force S_1 acting on front wheel 1 (braked), the outboard scrub radius incorporated in the design is increased by the amount of lateral dynamic tire deformation, thus also increasing the stabilizing moment $P_1 \cdot y_{g1}$.

Lateral forces S_1 and S_2 thus generated at the front wheels are now also directed towards the side which is not being braked and so compensate the deflecting moment $P_1 \cdot e_R$ of the braking forces about the center of gravity Sp, so that the sum of the moments of all the forces acting at the tire contact areas about the center of gravity is reduced to zero or a minimal value.

$$M_{(Sp)} = R_1 \cdot e_R + (S_3 + S_4) \cdot e_3 - S_2 \cdot e_2 = 0$$

Under these conditions, the vehicle no longer yaws (turns).

This yaw compensation also involves a self-stabilizing steering effect: unlike conventional front suspension designs, where the road wheels are turned to full lock if the steering wheel is released (free control) and a braking force is applied on one side, with a front suspension with outboard scrub radius the wheels will, under the same conditions, take up a stable position, applying steering correction. When braking forces are applied on one side, the front wheels turn only until the forces acting at the tire contact areas about the king pin center lines (points L) are in balance: $P_1 \cdot y_{g1} = S_1 \cdot x_{g1} + S_2 \cdot x_{g2}$ (slide 7). There is now no torque on the steering and the front wheels remain stable in the corrective position. The torques required on the steering to keep the vehicle exactly on the desired course are almost zero.

Yaw can always be effectively compensated if at least one front wheel is not locked and if there is sufficient elasticity in the steering system. Tests have shown that full braking compensation can be achieved even with very inelastic steering designs (rack and pinion) because the greatest elasticity in the complete system is always provided by the driver's arms.

Experimental Results

The tests were carried out with a conventional front suspension with an inboard scrub radius of 62 mm (2.4 in.) and with a McPherson front suspension with an outboard scrub radius of 18 mm (.7 in.) and floating caliper brakes (slide 8).

Slide 9 shows the front wheel angle of two vehicles on which the front left wheel was braked with the steering wheel released. In the case of vehicle a with a conventional front suspension, the wheel turns to full lock inside 2 sec. But with vehicle b with outboard scrub radius the braked front wheel turns approximately 1° to 2° in the opposite direction and remains stable in this position (self-stabilization).

Slide 10 shows how the same vehicles a and b turn about their vertical axes (skid) during braking.

After 3.5 sec. the conventional vehicle has already spun through 90^{o} and after 6 sec. has almost completed a 180^{o} spin. Vehicle b with outboard scrub radius turns hardly at all. It maintains a stable course.

Slide 11 shows the steering torques required to maintain course, i.e., the forces which the driver must exert on the steering wheel if he is to hold the vehicle precisely on the desired course when unequal braking forces are applied. The sharply rising (0.5 sec.) steering torques required for conventional front suspensions with inboard scrub radius are immediately obvious, and similarly the increasing steering torques for vehicle c with zero scrub radius. Only in the case of vehicle b with outboard scrub radius does the steering torque remain practically zero, i.e., the steering is self-stabilizing.

This braking compensation is influenced very little by the type of tire construction (slide 9, 10 and 11).

To sum up: a vehicle with outboard scrub radius can be kept exactly on the desired course with very little steering effort, even when excessive braking force is applied on one side, as a result of its self-stabilizing characteristics.

The effect of this feature on directional stability can be observed not only when a braking force is applied on one side, but also when the vehicle is braked after a front tire is suddenly deflated (slide 12). The lateral deformation resulting from the braking force on the deflated tire means that the outboard scrub radius changes, so that the braking force has a short positive lever arm.

However, in the case of inboard scrub radius with normal king pin inclinations, the lever arm of the braking force is increased considerably (slide 13).

The steering torques required to keep the vehicle on the desired course under braking with a deflated front tire vary accordingly (slide 14). The correcting forces needed at the steering wheel in the case of outboard scrub radius are considerably reduced. They amount to only about a fifth of the steering torques required in the case of inboard scrub radius.

Diagonally Split Brake Circuits with Outboard Scrub Radius on Front Wheels

A diagonal split of the brake circuits takes on a completely new significance when considered with regard to the compensation of asymmetric braking forces, since it enables braking stability to be greatly improved when one circuit fails.

It is well known that if the brake circuits are split so that it is possible for both wheels on one axle to lock at the same time when one circuit is out of action, this has an adverse effect on directional stability. If both front wheels lock, steering control is lost; and if both rear wheels lock the vehicle becomes unstable. If this happens during cornering motion, the understeer/oversteer characteristics of the vehicle change to such an extent that the average driver can hardly retain control of the vehicle.

In contrast, diagonally split dual brake circuits together with outboard scrub radius at the front wheels offer important advantages over all other methods of splitting the brake circuits which have previously been put into practice:

1. Vehicle behavior under braking remains constant when one circuit fails, because it is still the braked front wheel which will lock first.
2. The vehicle does not pull to one side even when two diagonally opposite wheels are braked because yaw is compensated by the outboard scrub radius.
3. Neither braking stability nor steering control is lost when one circuit fails because two wheels always generate lateral forces even when the two braked wheels have locked.

Slide 15 shows the stabilizing effect of lateral forces S_1 and S_2 on the front wheels when two diagonally opposite wheels only are braked. Even when both wheels on a diagonal circuit lock (P_1 sliding, P_4 sliding), braking stability is still provided by lateral forces S_2 and S_3 on the wheels which are not braked.

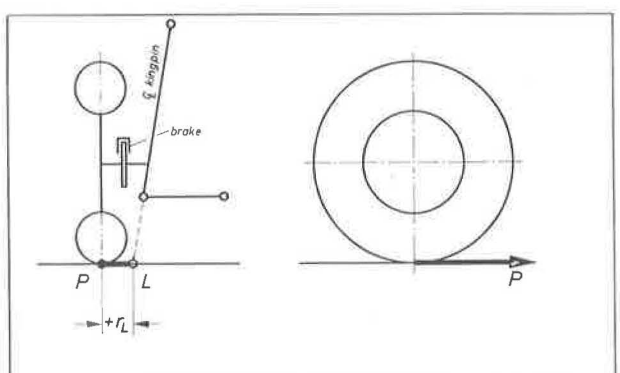
The oversteer/understeer behavior of a vehicle incorporating outboard scrub radius change only slightly; this applies not only to straight ahead motion but even to cornering motion when one diagonal brake circuit fails. The vehicle still handles well and control is retained.

When the outer front wheel and the inner rear wheel are braked (slide 16) an understeering moment is generated about the vertical axis by the braking forces and this moment is increased in the case of inboard scrub radius, but is partly compensated by the elastic oversteering correction imparted by both front wheels in the case of outboard scrub radius. This applies irrespective of whether the wheels lock or not.

When the other diagonal circuit is braked (slide 17) the oversteering moment generated by the braking forces is again exaggerated in the case of inboard scrub radius, but is partly compensated by the elastic understeering correction imparted by the front wheels in the case of outboard scrub radius.

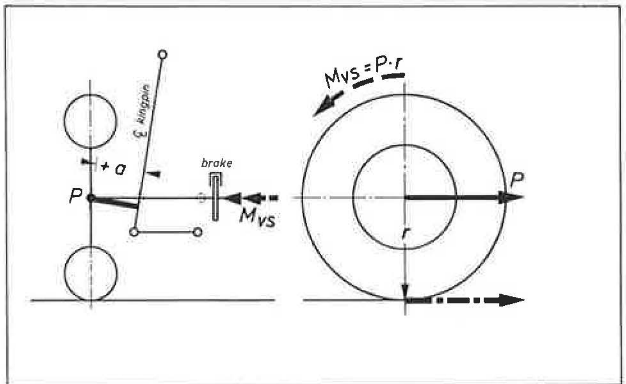
Tests have shown that a medium-sized passenger car with diagonally split brake circuits and an outboard scrub radius on the front wheels of 10 - 20 mm (.39 - .79 inches) possesses exceptional braking stability and controllability in all braking maneuvers. In addition, this combination of design elements requires a minimum of driver reaction to shortcomings and defects both in the brake system and the road surface.

This not only contributes to the active safety of the vehicle but also minimizes driver fatigue.



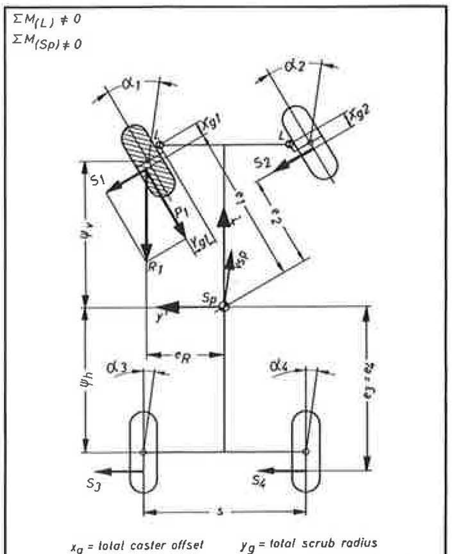
Outboard brake and inboard scrub radius r_L :
Braking force creates a toe - out moment $M_0 = P \cdot r_L$

Slide 1



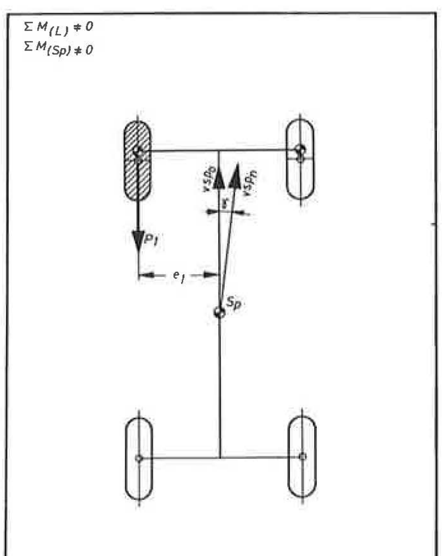
Inboard brake and positive kingpin offset at the wheel center "+a"
Braking force creates a toe-out moment $M_o = P \cdot a$

Slide 2



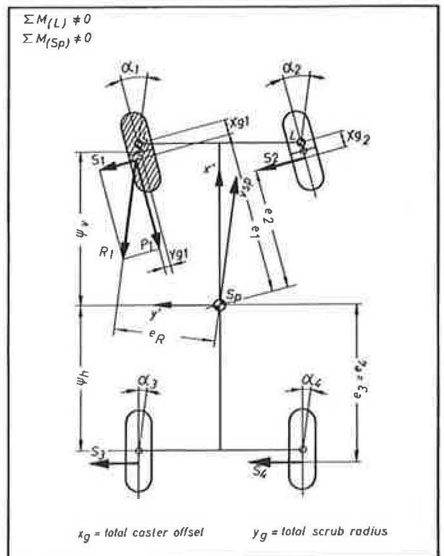
Forces acting on vehicle with inboard scrub radius, one front wheel braked

Slide 3



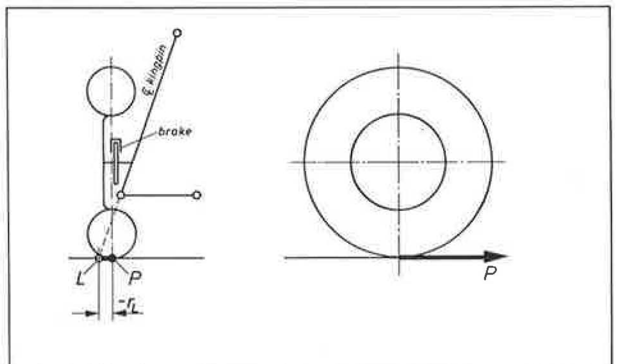
Forces acting on vehicle with zero scrub radius, braking initiated on one front wheel

Slide 4



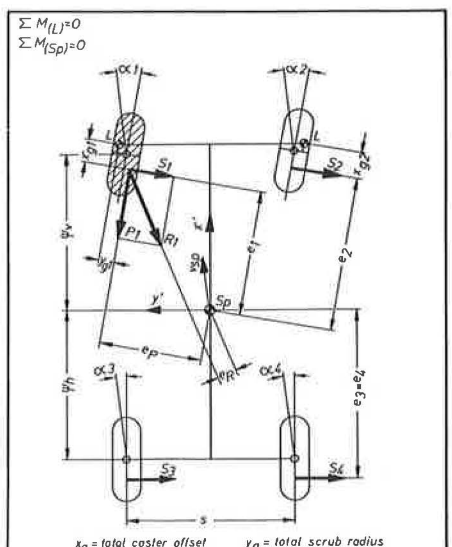
Forces acting on vehicle with zero scrub radius, one front wheel braked

Slide 5



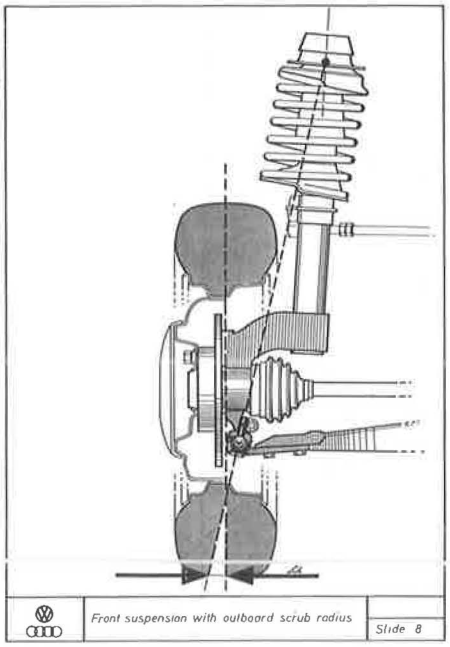
Outboard brake and outboard scrub radius $-r_L$:
Braking force creates a toe-in moment $M_i = P \cdot r_L$

Slide 6



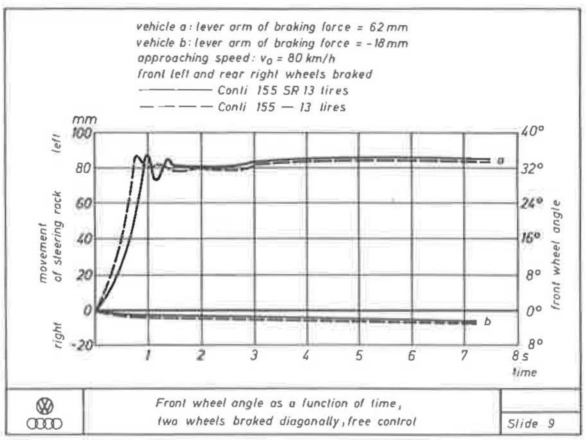
Forces acting on vehicle with outboard scrub radius, one front wheel braked

Slide 7



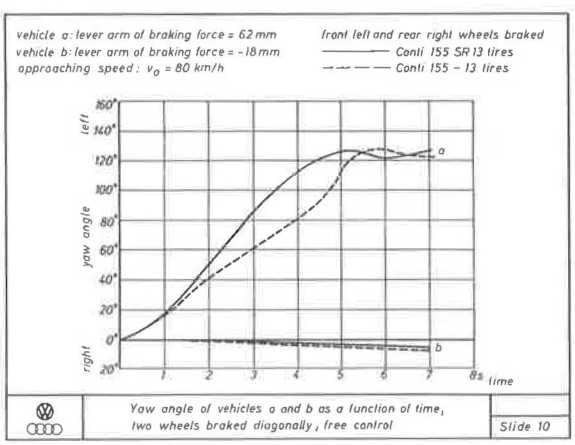
Front suspension with outboard scrub radius

Slide 8



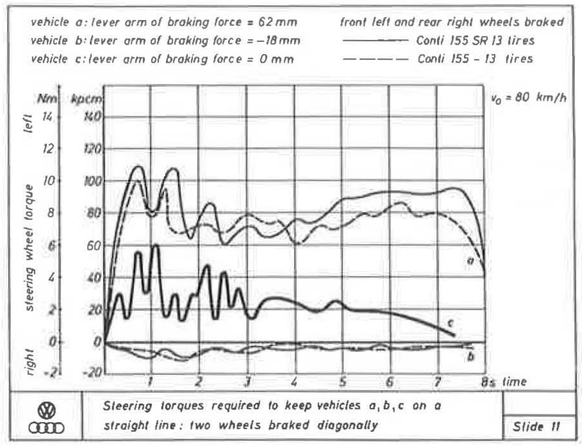
Front wheel angle as a function of time, two wheels braked diagonally, free control

Slide 9



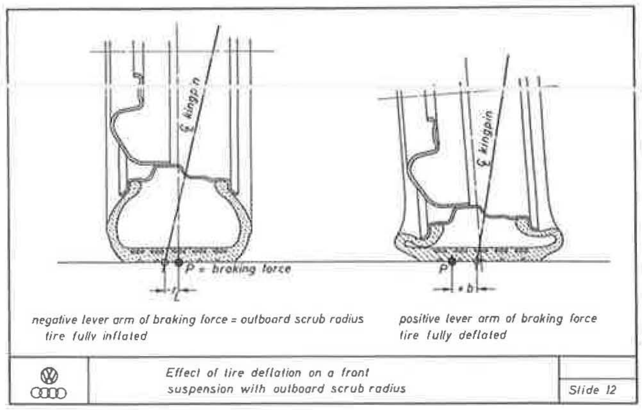
Yaw angle of vehicles a and b as a function of time, two wheels braked diagonally, free control

Slide 10



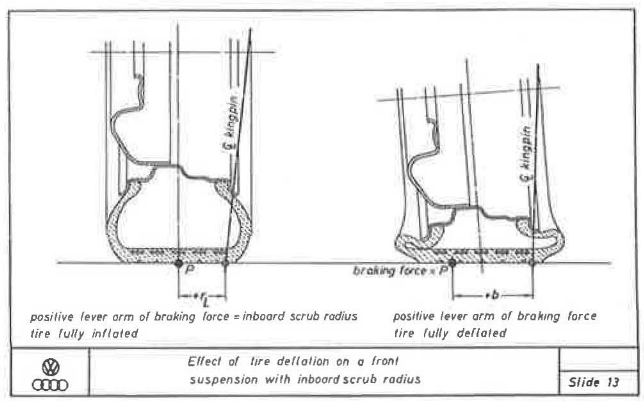
Steering torques required to keep vehicles a, b, c on a straight line: two wheels braked diagonally

Slide 11



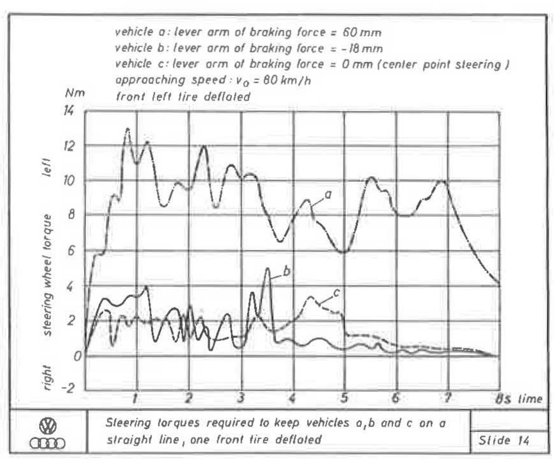
Effect of tire deflation on a front suspension with outboard scrub radius

Slide 12



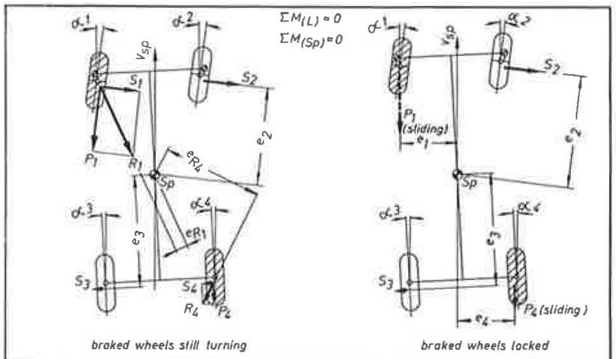
Effect of tire deflation on a front suspension with inboard scrub radius

Slide 13



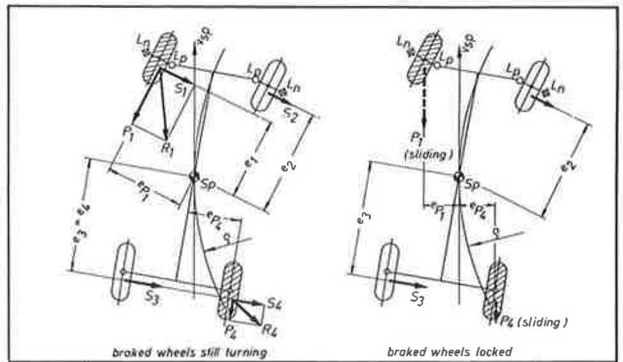
Steering torques required to keep vehicles a, b and c on a straight line, one front tire deflated

Slide 14



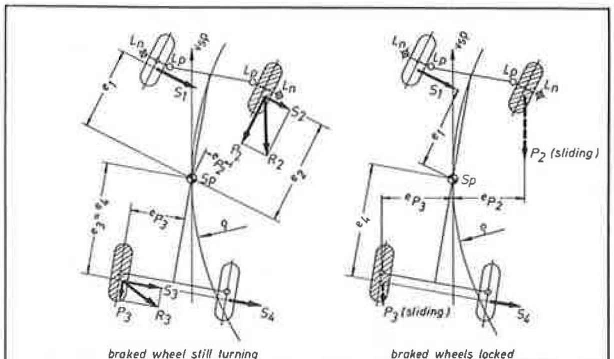
Forces acting on vehicle with outboard scrub radius with one diagonal brake circuit cut off

Slide 15



Braking stability, steering control and oversteer / understeer behavior when cornering with one diagonal brake circuit cut off: front inner / rear outer

Slide 16



Braking stability, steering control and oversteer / understeer behavior when cornering with one diagonal brake circuit cut off: front outer / rear inner

Slide 17