ABS : Principles and Technology

Pierre Duysinx

Research Center in Sustainable Automotive Technologies of University of Liege

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Lay-out

- Introduction
- Historical perspective
- Functions and specifications of Anti Lock Braking Systems ABS
- ABS Concept
- Control Problem of wheel locking
  - Estimation of the vehicle speed
  - Prediction of locking
- ABS components

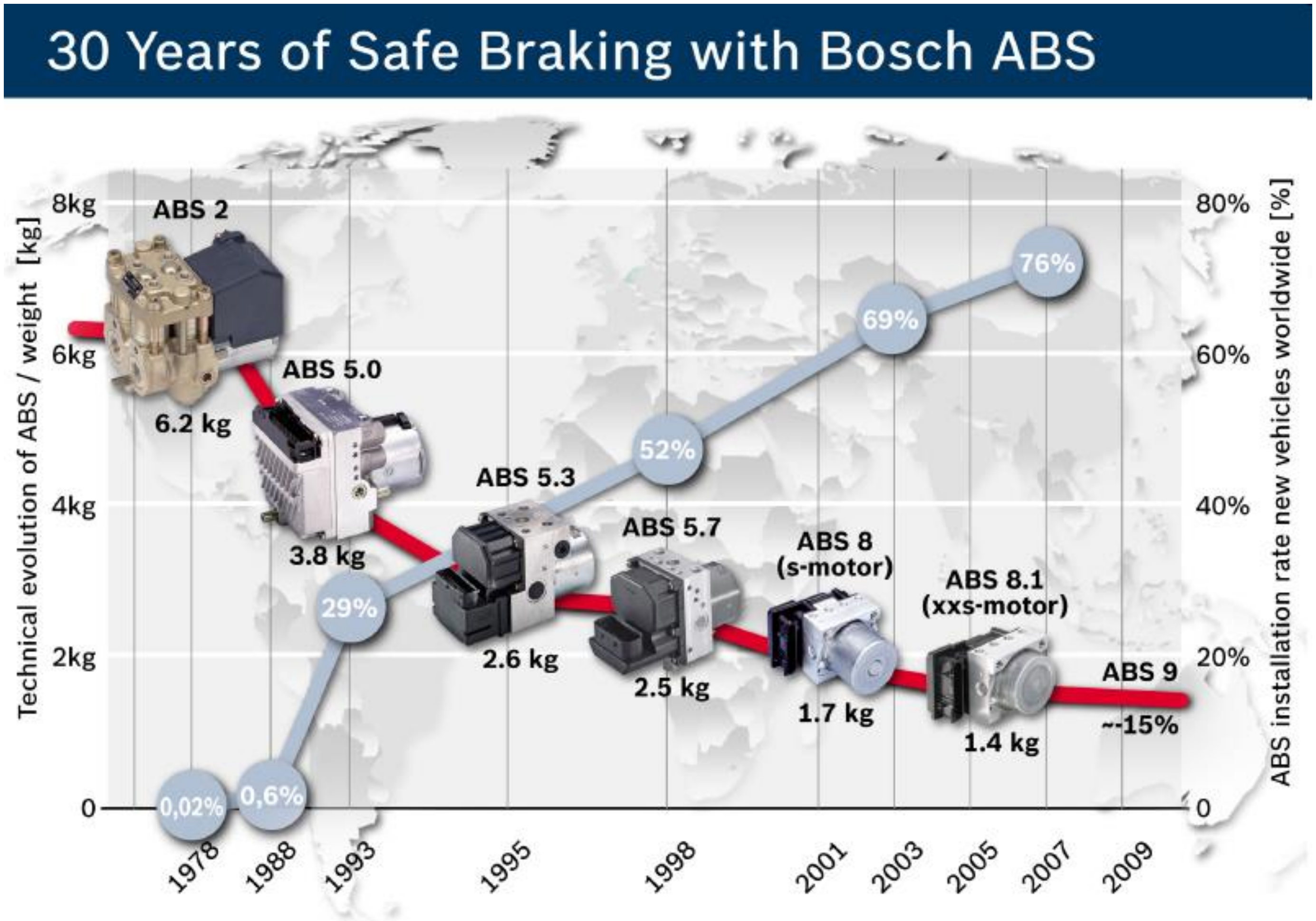
Historical Perspective

- 1900: Appearance of the concept ant blocking systems for locomotives to minimize the flats in the (steel) wheels.
- The system also reduces the braking distance.
- 1936: Bosch in Germany patents a system called ABS.
- 1948: Boeing B47 airplanes are equipped with ABS to prevent wheel explosion on dry runways and slipping on icy runways.
- 1954: Ford equips an experimental Lincoln with an experimental anti lock braking system.
- 1968: Kessey-Hayes develops ABS for the rear wheel braking system only.
- In Europe the development of ABS for automotive applications started in the 1960s in a company called Teldix (a contraction of Telefunken and Bendix, partners in this project).

Historical Perspective

- The poor performance of the electronics at the time prevented the implementation of a system that was not reliable enough for automobiles.
- The Citroën SM was almost equipped with ABS, but the financial difficulties of "Automobiles Citroën" and the first oil shock put an end to the project.
- 1970: Legal issues stop ABS implementation in the USA.
- 1970 The patents and licenses of Teldix are acquired by Bosch, which continues the developments
- 1980: Bosch and European manufacturers such as Mercedes (1978: Mercedes S-Class) and BMW take the lead.
- 1990: Explosion of demand
  - 1988: ABS on 7% of new cars and 32% of trucks
  - 1997: ABS on 59% of new cars and 90% of trucks

Historical Perspective



Introduction

- ABS stands for Anti-lock Braking Systems
- ABS are systems that manage braking operating conditions and modify the braking torque by modulating the brake pressure through apply/release cycles.
- The system attempts to keep the operating point within a range around the maximum coefficient of friction.
- Generally, slip rates between 10 and 30%.
- The system prevents wheel lock-up during braking, thereby maintaining the ability to generate sufficient lateral forces to provide directional control and lateral stability.

Introduction

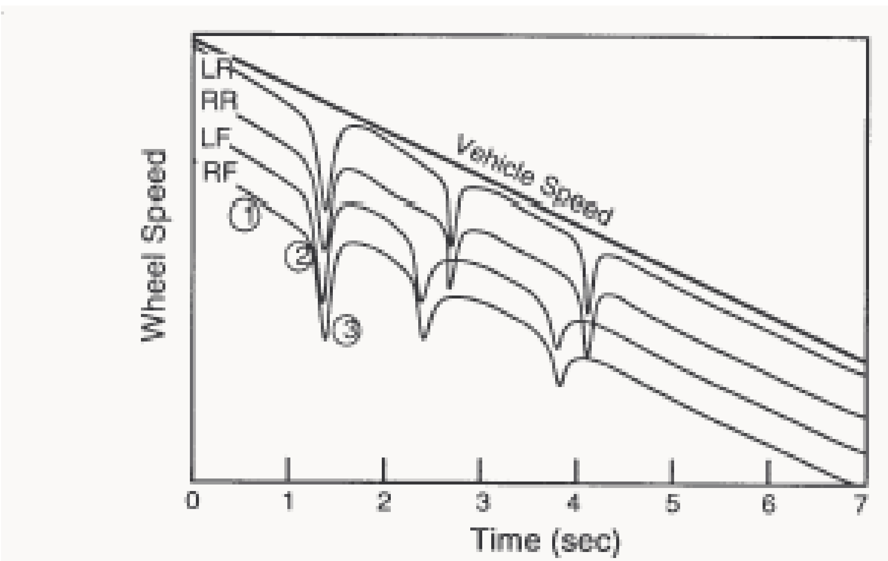


Fig. 3.10 Wheel speed cycling during ABS operation.

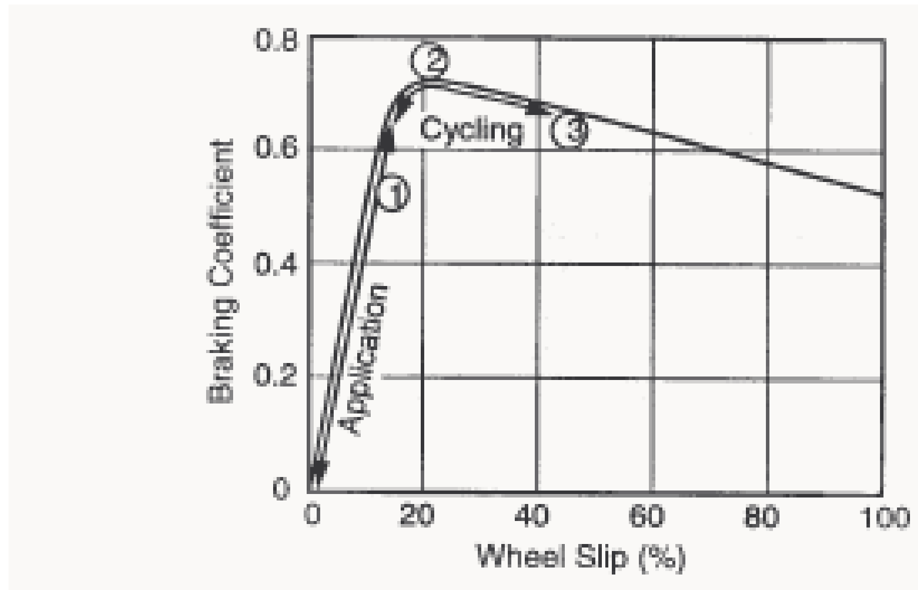


Fig 3.11 ABS operation to stay at the peak braking coefficient.

Gillespie (1992) Fig 3.10: Wheel cycling during ABS operations

Gillespie (1992) Fig 3.11: ABS operation to stay at the peak braking coefficient

Introduction

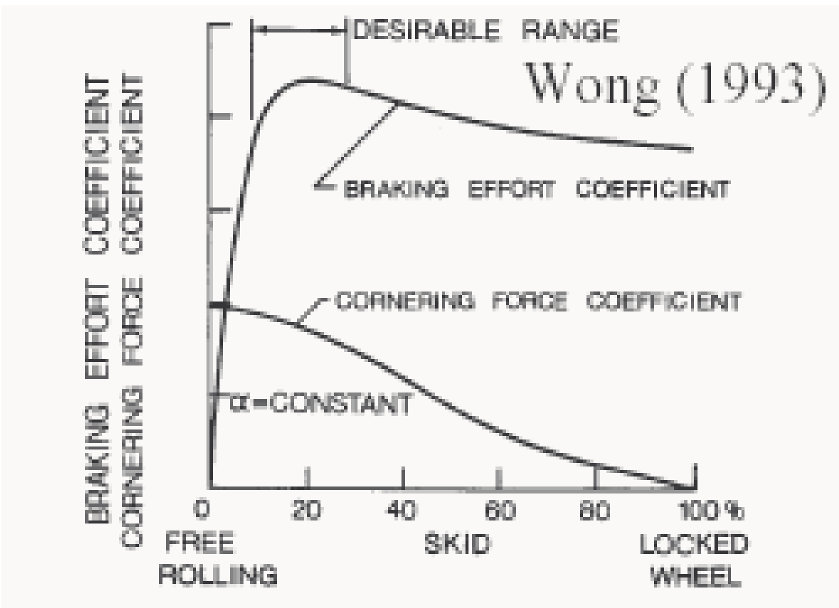
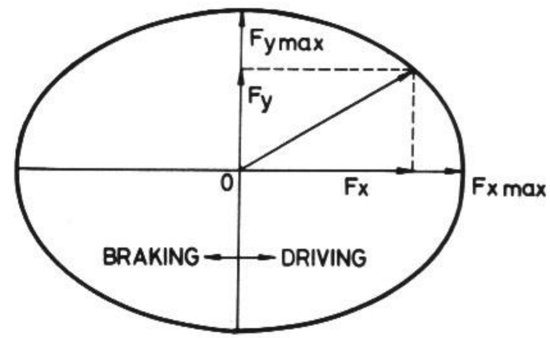


Fig. 3.54 Effect of skid on cornering force coefficient of a tire.

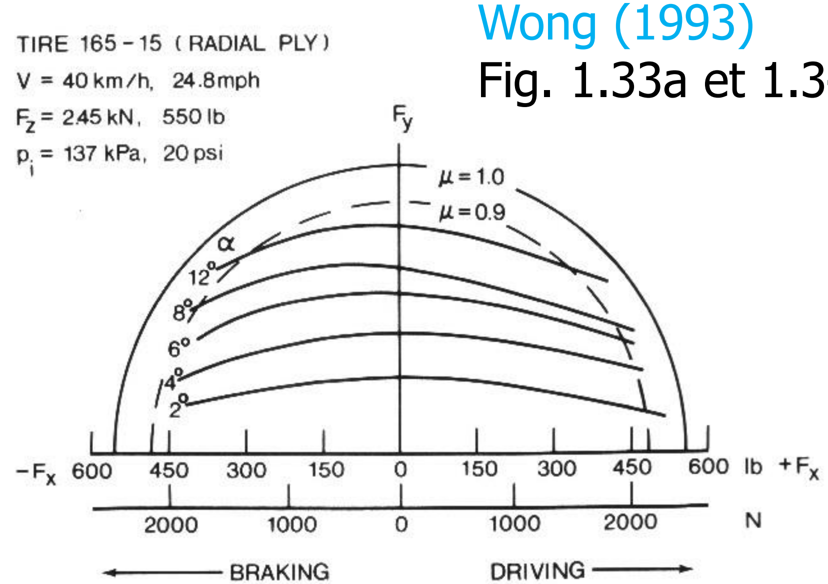
Wong (1993) Fig 3.54

Effect of longitudinal slip on cornering force



Wong (1993)

Fig. 1.33a et 1.34



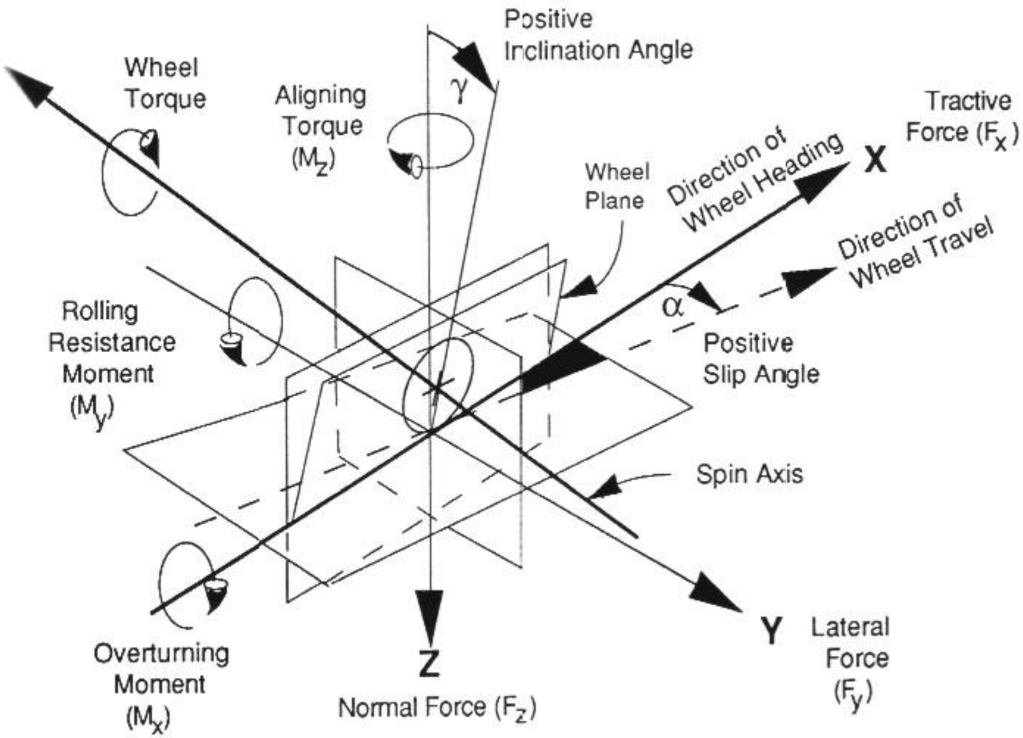
Introduction

- ABS is a servo system included in the braking system.
  - Its activation depends on the driver applying the brakes.

- Corollary: the ABS system has other advantages:
  - The system automatically distributes braking between the front and rear wheels
  - In addition to the front/rear distribution, it deals with the problem of load variation and left/right adhesion (μ slip problem).
  - ➔ ABS replaces the brake distribution systems

Basics of Tire Mechanics

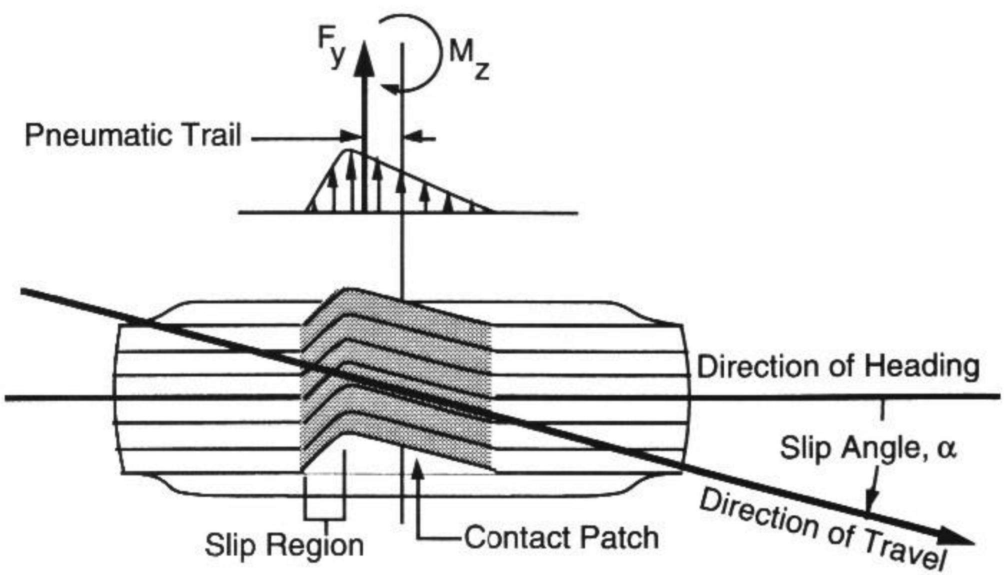
Summary of Tire Mechanics



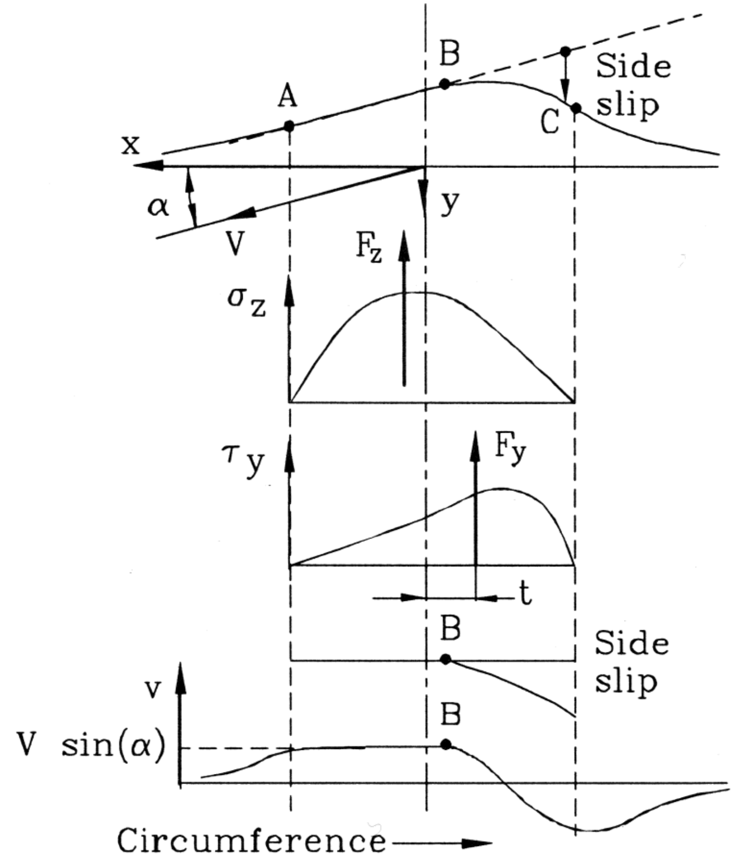
- Side slip angle (α): angle between the heading direction of the wheel and the travel direction of the wheel.
- A positive side slip angle corresponds to a tire moving to the right when driving forward.

Origin of lateral forces

- The origin of the phenomenon is the deformation of the tire under the effect of lateral loads developed at the tire road contact patch



Gillespie, Fig 10.10

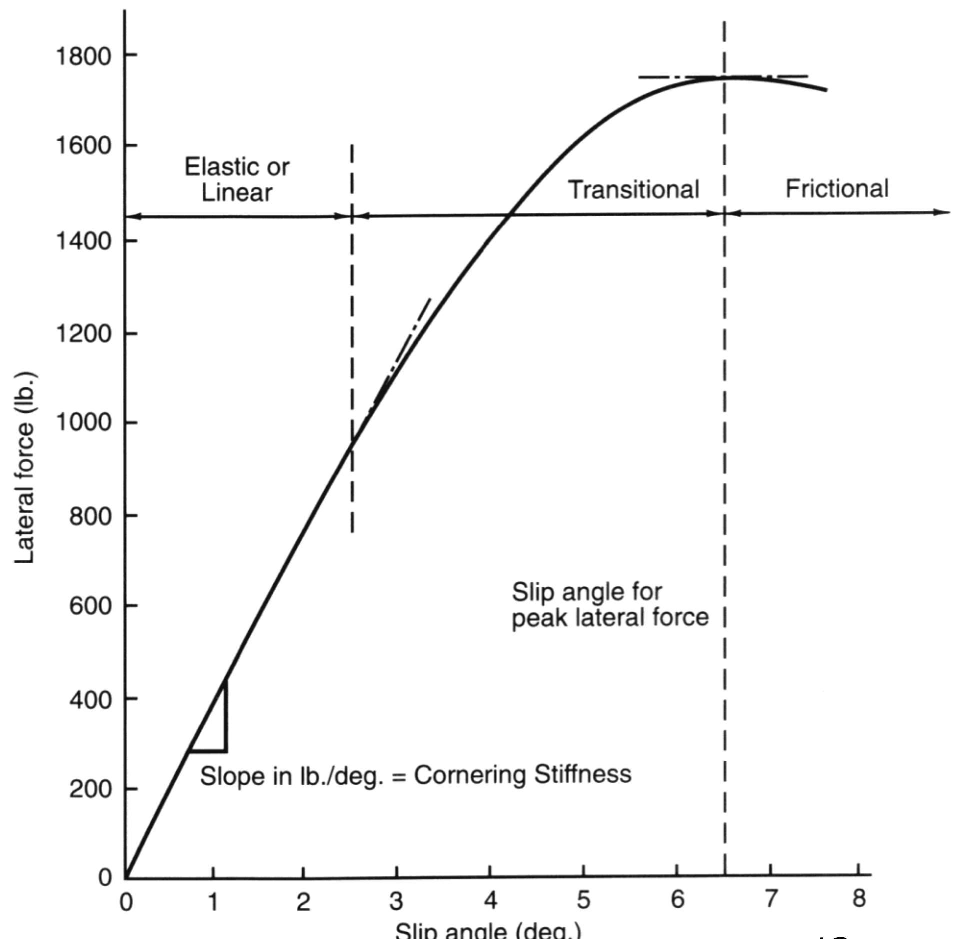


Genta Fig 2.24: Lateral displacement, the distribution of stresses σ_z and τ_{zy}, the lateral side slip, lateral speed for a tire with lateral side slip α

Lateral Forces

Milliken. Fig. 2.7
P215/60 R15 GoodYear Eagle GT-S (shaved for racing) 31 psi
For a vertical load of 1800 lb

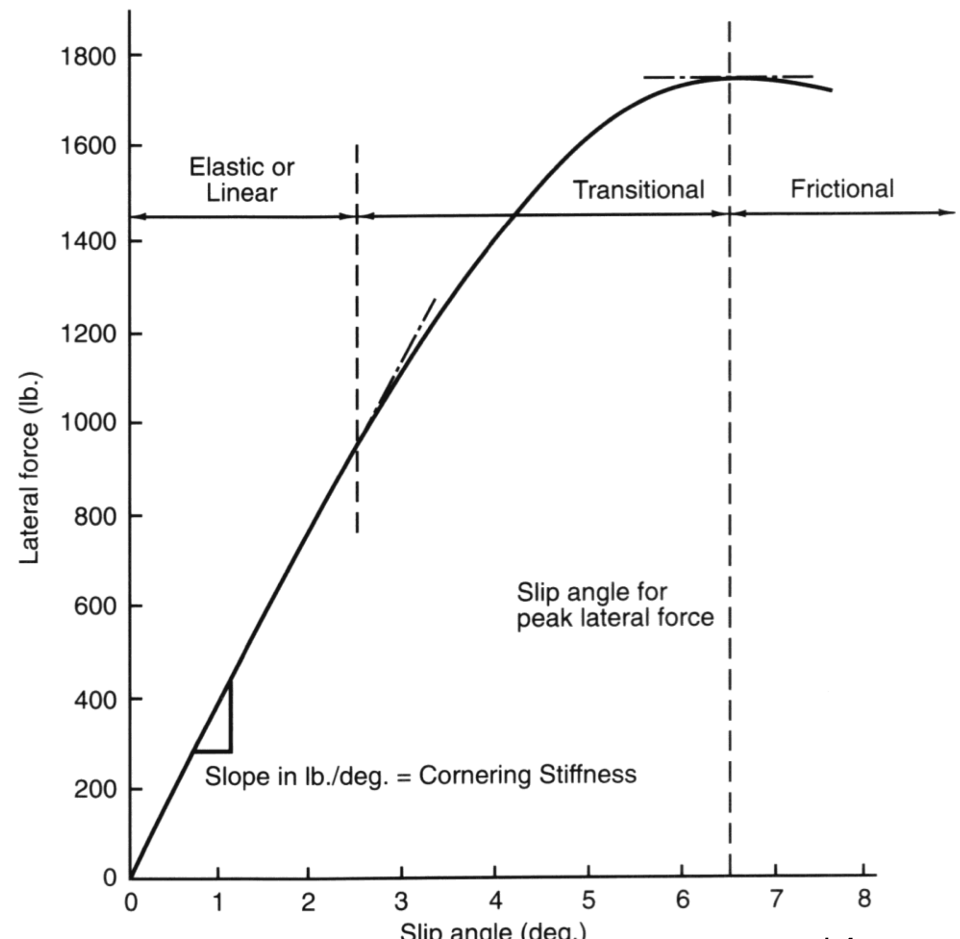
- Three parts in the F_y curve as a function of the sliding angle α: linear, transition and friction.
- Below 3°, the lateral force is linear in the side slip angle. The slope is the cornering coefficient.
- Between 3° and 7°, one has a transitional part of the curve. The nonlinearity increases gradually.
- Over 5 to 10° the curves reaches a peak.



Lateral Forces

Milliken. Fig. 2.7
P215/60 R15 GoodYear Eagle GT-S
(shaved for racing) 31 psi
For a vertical load of 1800 lb

- After the peak, the curve may remain constant or fall.
- On wet ground, one observes a reduction of the maximum value and a faster fall afterwards.
- At peak and beyond, the major part of the footprint is subject slippery conditions, and the resulting force comes from dry friction between the tire and the road.

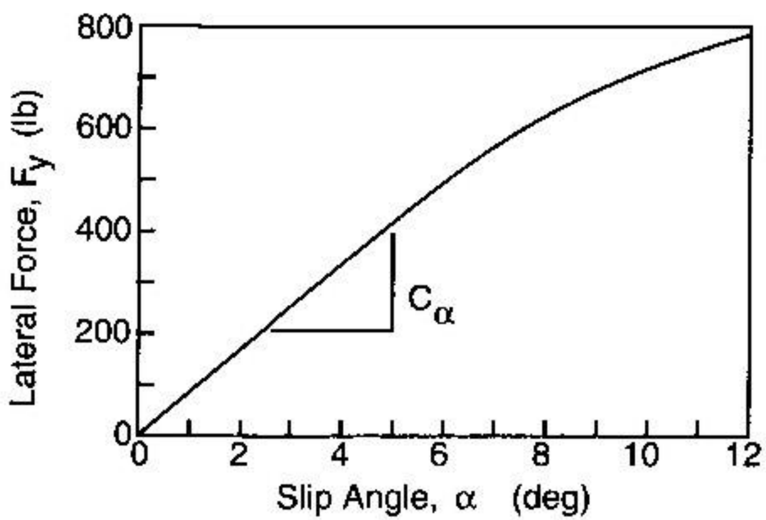


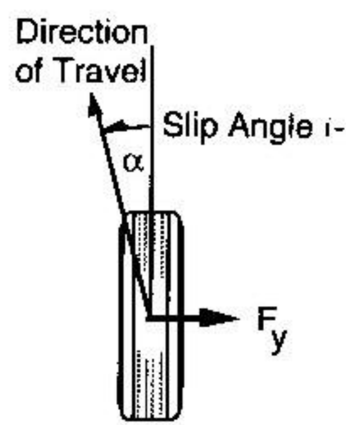
Cornering stiffness

- In the linear part (small drift angles), the curve giving the lateral force as a function of the drift angle is a linear function and it can be written:

$$F_y = -C_\alpha \, \alpha \qquad\qquad C_\alpha = \left. \frac{\partial F_y}{\partial \alpha} \right|_{\alpha=0}$$

- C_α is the cornering stiffness.





Gillespie Fig. 6.2

Braking forces

- Longitudinal Slip Ratio

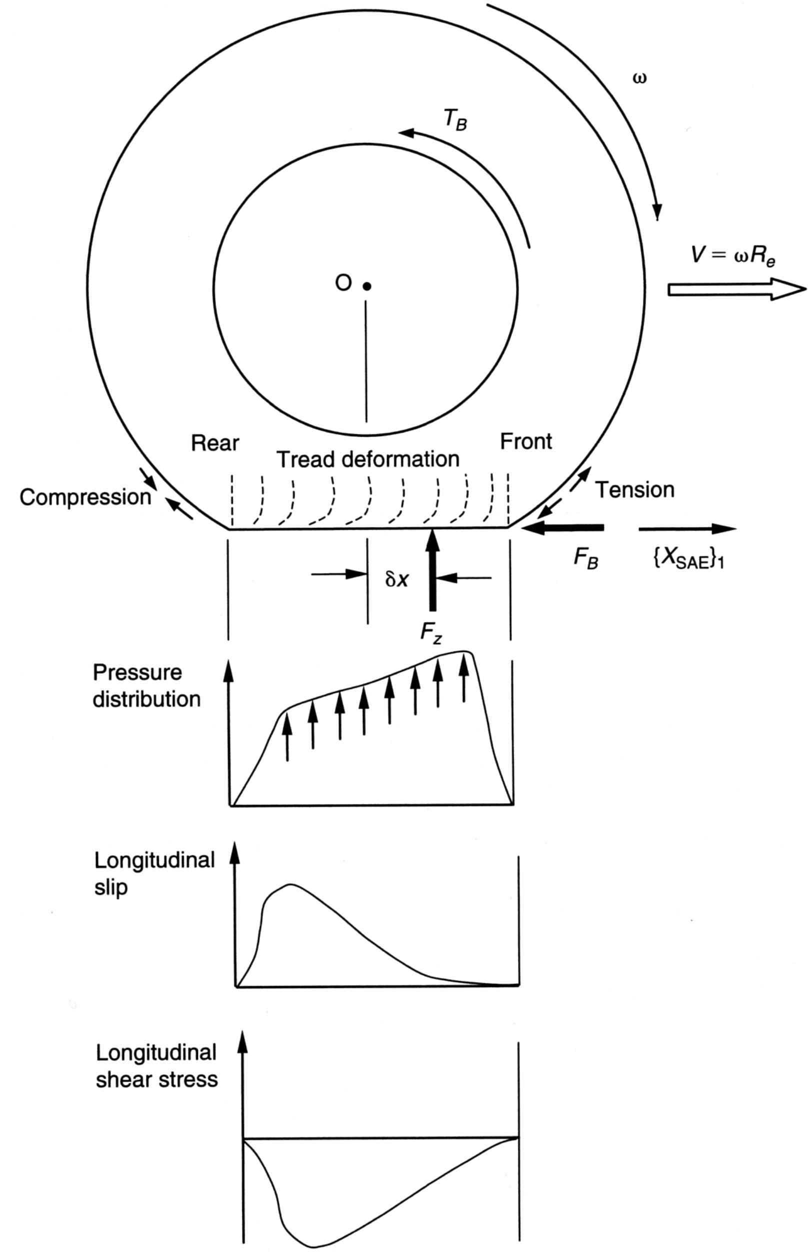
$$SR = \frac{\Omega - \Omega_0}{\Omega_0} = \frac{\Omega}{\Omega_0} - 1$$

- If R_e is the effective rolling radius of the freewheel

$$\lambda = SR = \frac{\Omega\, R_e}{V} - 1$$

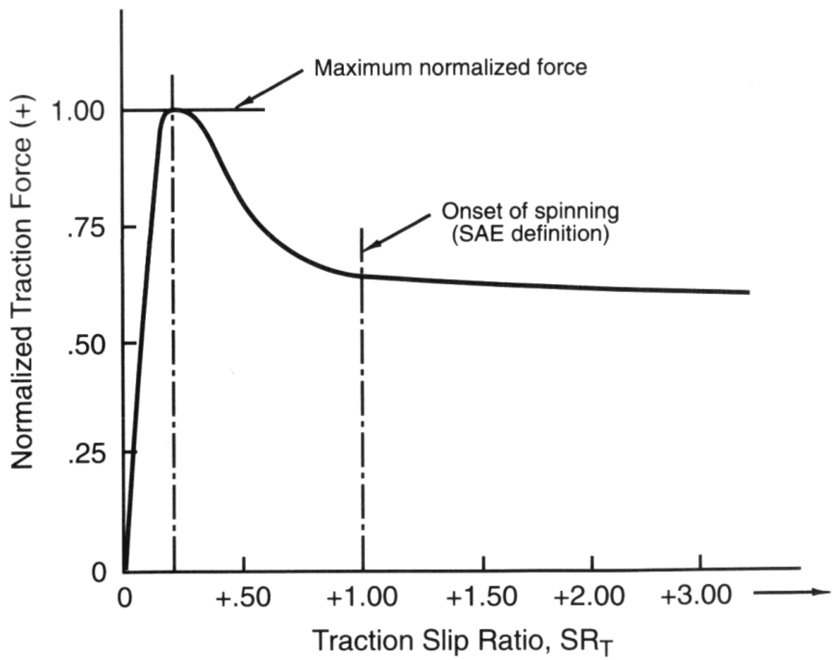
  - Freewheel SR = 0
  - Wheel locked during braking SR = -1
  - Spinning: SR = +1

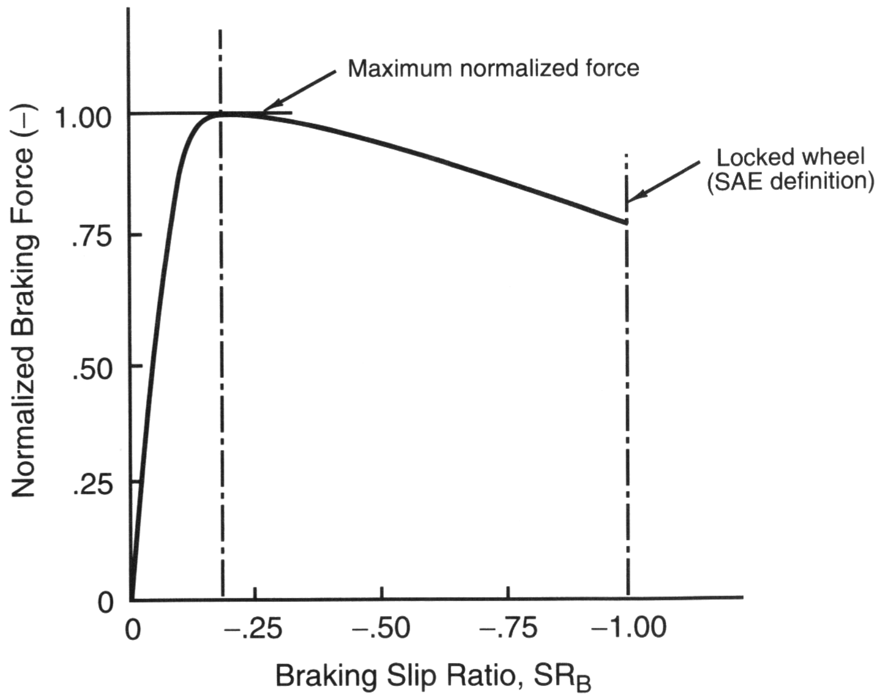
- Traction and braking forces are functions of longitudinal slip ratio SR



Blundel. Fig. 5.18

Longitudinal forces



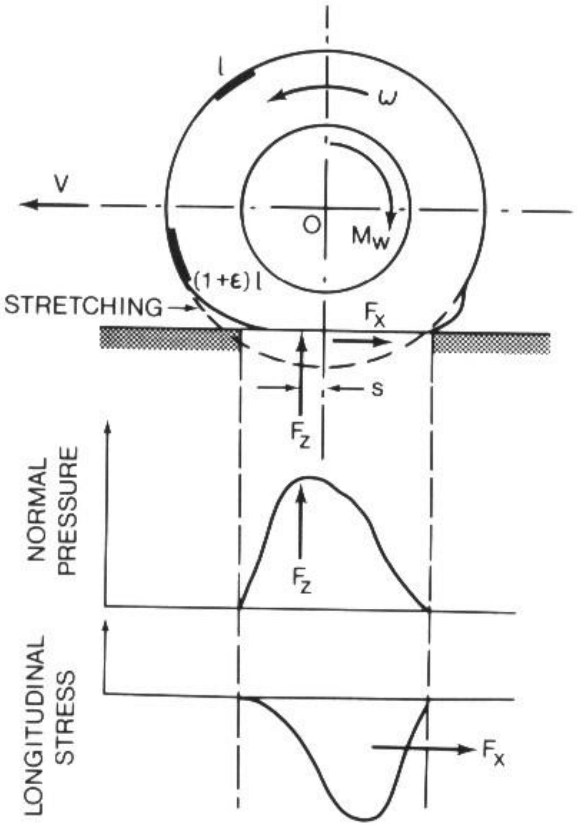


Milliken. Fig. 2.16

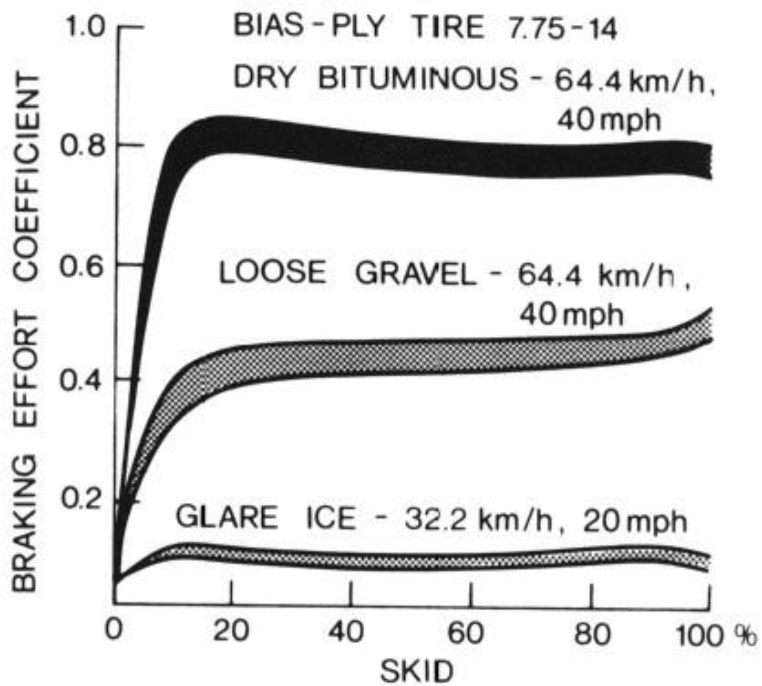
Milliken. Fig. 2.17

Touring tire with bias ply carcass

Longitudinal forces



Wong Fig 1.17



Wong Fig 1.18

Combined operations

- Sakai's experience conducted at Japan Automotive Research Institute (JARI)
  - One of the only complete data sets available to the public
  - Small tire for passenger vehicles with a load of 400 kg (882 lbs) and a speed of 20 km/h (12.4 mph)
- Definition of longitudinal slip ratio adopted in this study
  - Traction

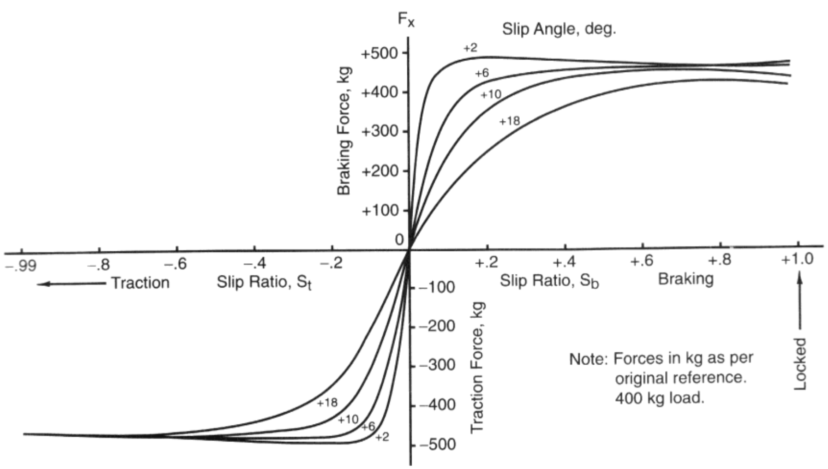
$$S_t = \frac{V \cos \alpha}{\Omega \, R_e} - 1$$

  - Braking

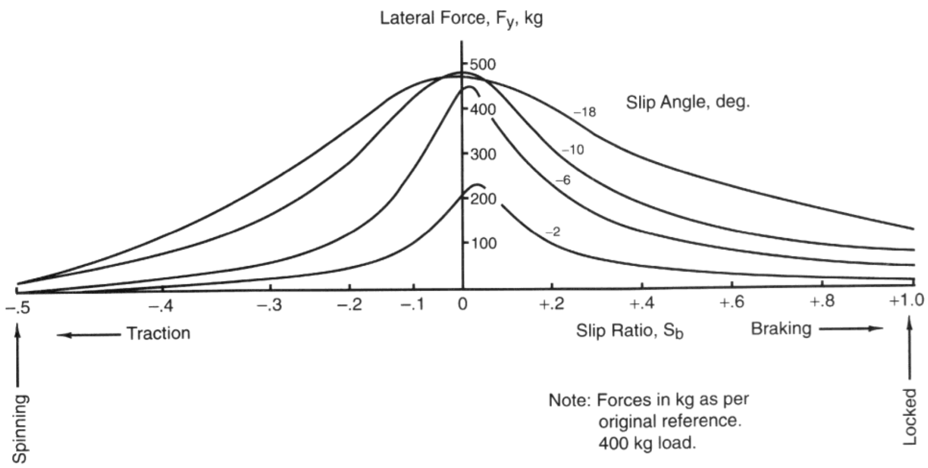
$$S_b = \frac{\Omega \, R_e}{V \cos \alpha} - 1$$

  - Free rolling $S_t = S_b = 0$
  - Wheel locked during braking $S_b = -1$
  - Spinning wheel (acceleration) $S_t = -\frac{1}{2}$
  - Blocked wheel (acceleration) $S_t = -1$

Combined operations



Braking / tractive forces vs. longitudinal slip ratio, the side slip angle as parameter
Milliken Fig 2.18



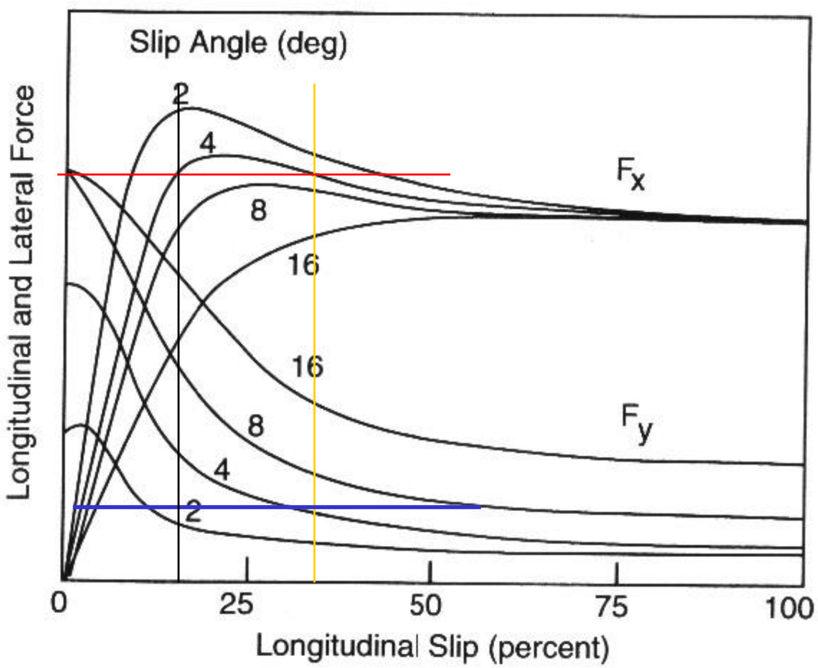
Lateral forces vs. longitudinal slip ratio, the side slip angle as a parameter
Milliken Fig 2.19

Friction circle and ellipsis

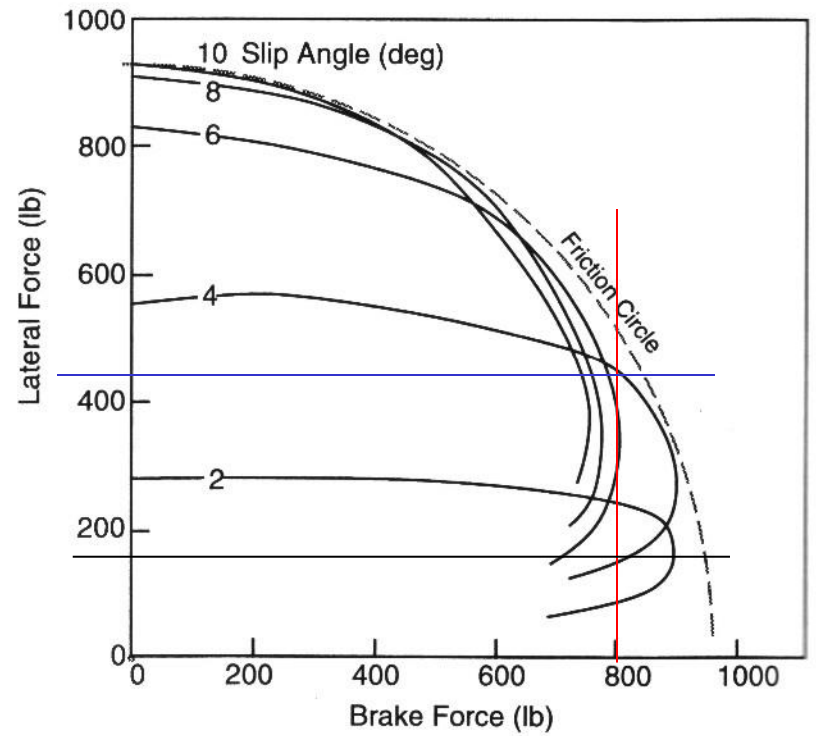
- The goal is to combine the two graphs of the lateral and longitudinal forces into a single diagram for any side slip angles and the longitudinal slip ratios.

- The friction circle represents the limit of the forces that the tire can produce under given operational conditions (vertical load, temperature, surface, etc.).

Friction circle and ellipsis



Braking and lateral forces in function the longitudinal slip ratio
Gillespie Fig. 10.22

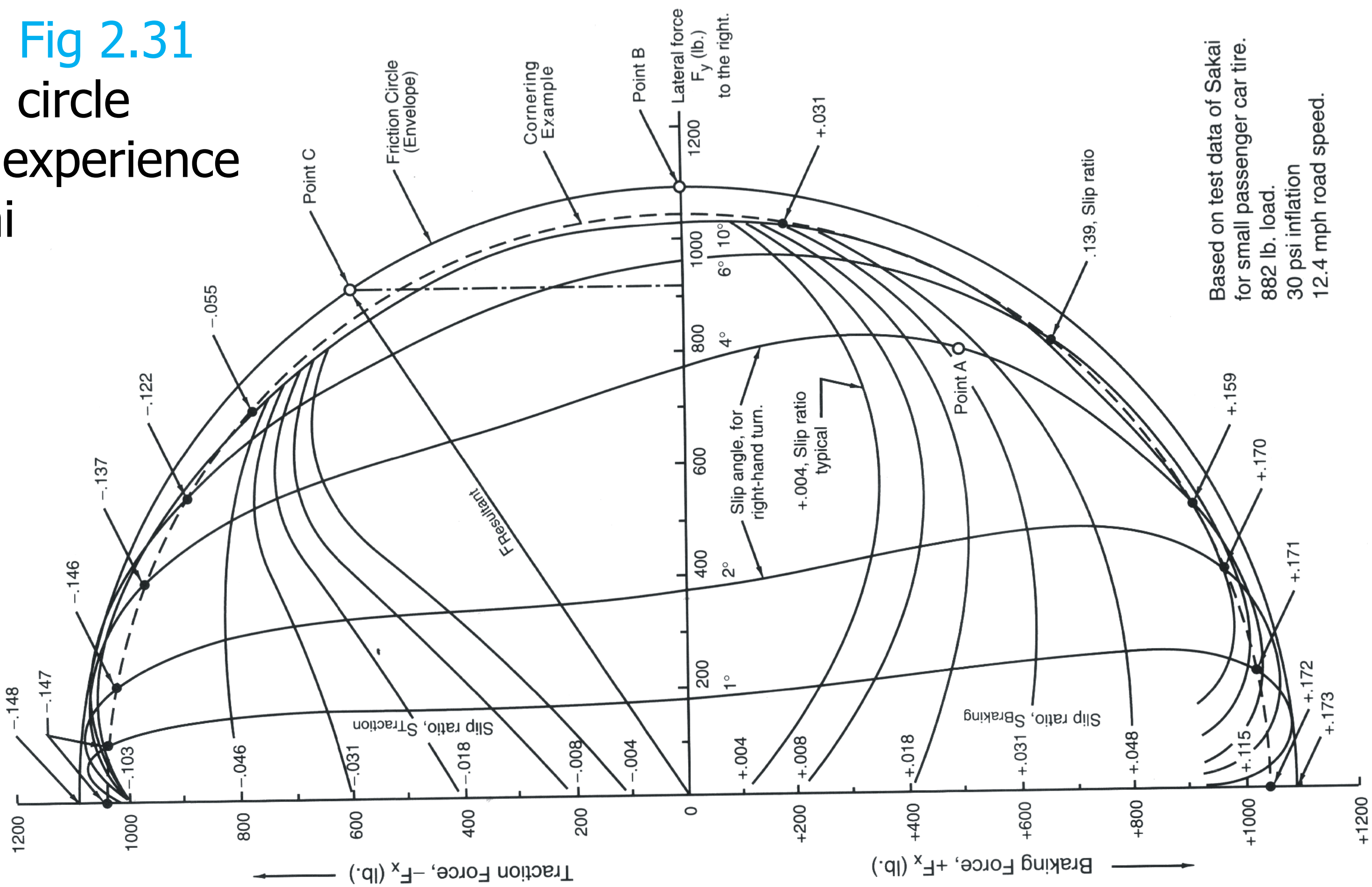


Lateral force as a function of braking force and side slip angle
Gillespie Fig. 10.23

Friction circle and ellipsis

Milliken Fig 2.31

Friction circle for the experience of Sakai

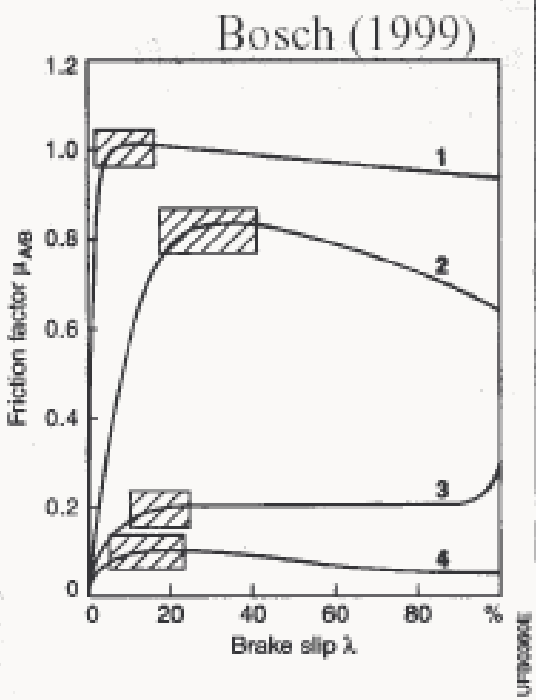


MOTIVATION OF ABS

Range variation of the braking forces with the side slip and the longitudinal slip ratio

Friction factor μ_{HF} as function of slip λ during braking

1 Radial tire on dry concrete,
2 Cross-ply winter tire on wet asphalt,
3 Radial tire on loose snow,
4 Radial tire on wet black ice.
Cross-hatched surfaces:
Transition from stable to instable range.



The tough aspect of friction control: the strong variation of the friction coefficients with the road condition

Coefficient of friction μ_{HF} between tire and road surface

Vehicle speed km/h	Tire condition	Dry road surface μ_{HF}	Wet road surface (water-depth 0.2 mm) μ_{HF}	Heavy rain (water-depth 1 mm) μ_{HF}	Puddles (water-depth 2 mm) μ_{HF}	Surface ice (black ice) μ_{HF}
50	new	0.85	0.65	0.55	0.5	0.1 and lower
	worn out	1	0.5	0.4	0.25	
90	new	0.8	0.6	0.3	0.05	
	worn out	0.95	0.2	0.1	0.0	
130	new	0.75	0.55	0.2	0	
	worn out	0.9	0.2	0.1	0	

Specifications of ABS systems

- Maintain a good directional control at all times and for all road conditions.
- Seek and exploit the highest braking friction coefficient, but with a main focus on the stability and the directional control rather than on searching for the minimum stopping distance, regardless of how the driver applies pedal force.
- Efficiency over a wide range of speeds.
- Yaw control for variable friction conditions (left/right and front/rear braking force distribution).
- Self-adjusting.
- Self-diagnosis.

Concept of the feedback controller

Controlled variables:

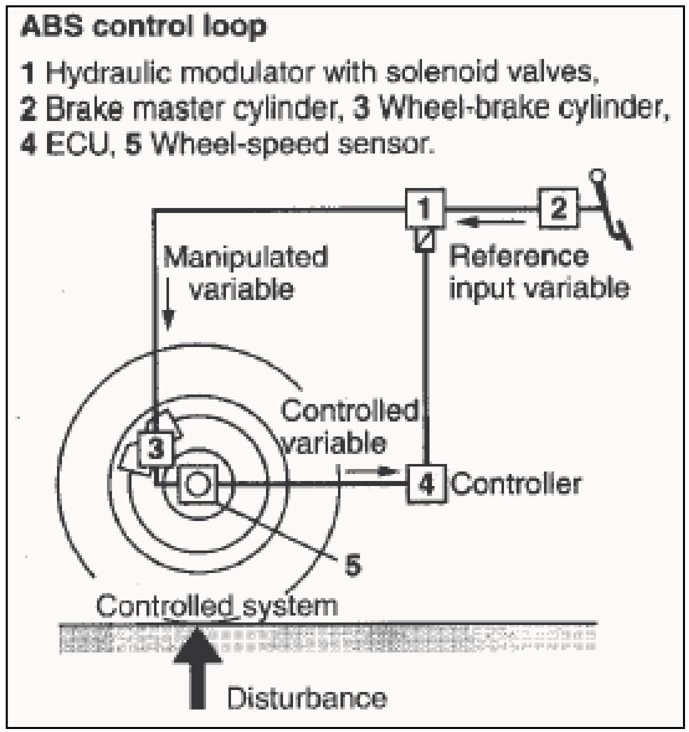
Angular rotation speeds of the wheels and the measured info at wheels (3)

Manipulated variables:

The pressure of the wheel brake cylinders (1-3)

Perturbations:

Road conditions, braking conditions, vehicle mass and mass distribution, and tire characteristics



Bosch (1999)

Controller:

Wheel-speed sensors and the ABS control unit (4)

Reference values / input:

The pressure applied at the brake pedal (2)

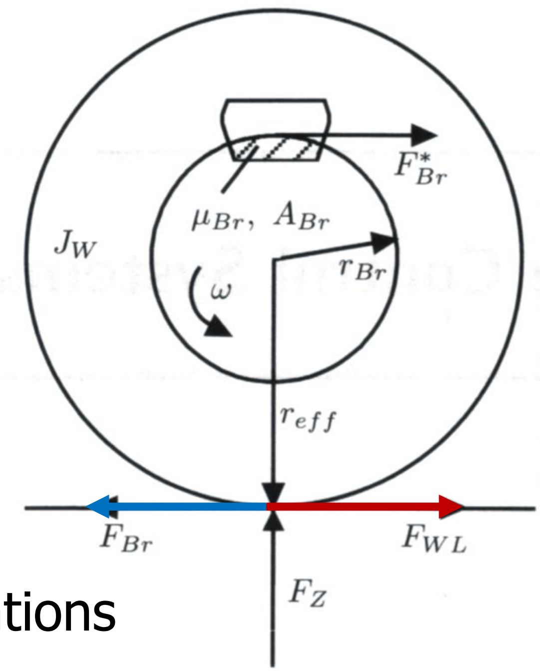
Controlled system:

The vehicle with its wheels, its brakes, the friction between the tires and the road

ABS simplified model

- Braking torque:

$$
\begin{aligned}
T_{Br} &= F_{Br}\, r_{eff} \\
&= r_{Br}\, \mu_{Br}\, A_{Br}\, p_{Br} \\
&= r_{eff}\, k_{Br}\, p_{Br}
\end{aligned}
$$



F^*_{Br}	*braking force at brake disc*
r_{Br}	*effective braking radius*
μ_{Br}	*Friction co − efficient of brakes*
A_{Br}	*brake area*
p_{Br}	*braking pressure*
F_{Br}	$= F^*_{Br} \cdot \frac{r_{Br}}{r_{eff}}$ *brake force at wheel contact*
T_{Br}	*brake torque at wheel contact*
ω	*rotational wheel speed*
J_W	*wheel moment of inertia*
F_Z	*wheel ground contact force*
F_{WL}	$= \mu_L(s) \cdot F_Z$ *friction force*
T_{WL}	$= reff \cdot F_{WL}$ *friction torque*

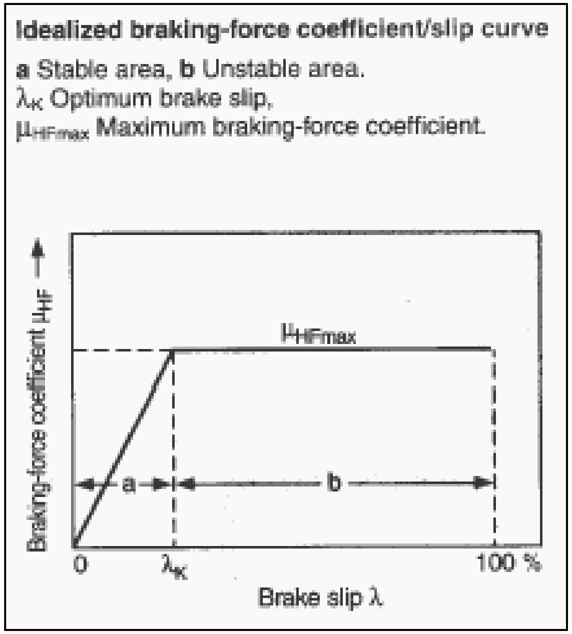
- Wheel equilibrium equations

$$J_w \dot{\omega} = \underline{F_{wL}\, r_{eff}} - \underline{T_{Br}} + T_{Driveline}$$

$$J_w \dot{\omega} = r_{eff}\, \mu_L(\lambda)\, F_Z - r_{eff}\, k_{Br}\, p_{Br}$$

ABS simplified model

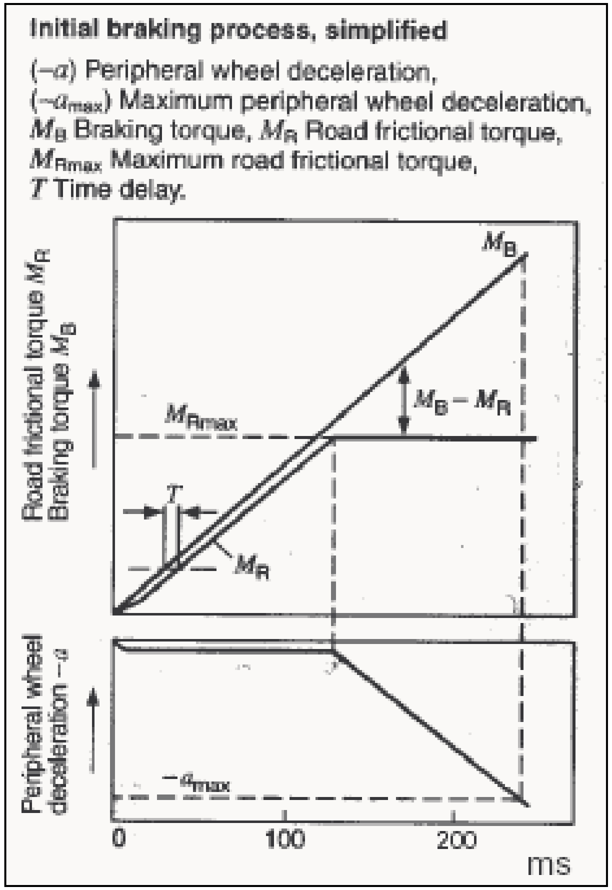
Ideal system: non driven wheel, 1/4 of the vehicle mass, simplified friction curve with a stable part (linear) and unstable (constant)



Firstly, the applied braking torque increases linearly over time.

The torque developed by the frictional force between the wheel and the ground follows with a little delay, before reaching saturation (maximum).

When arriving at saturation, the friction forces reaches its maximum, while braking roque can still grow.

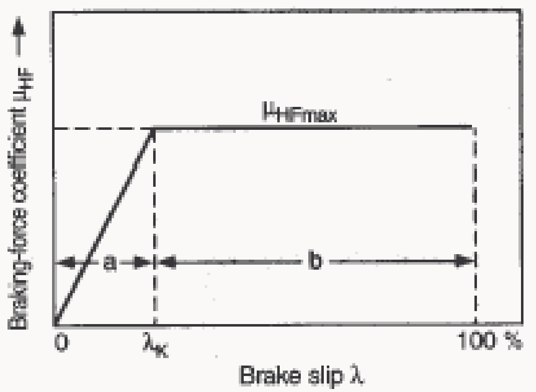


ABS simplified model

<u>Ideal system</u>: non driven wheel, 1/4 of the vehicle mass, simplified friction curve with a stable part (linear) and unstable (constant)

Idealized braking-force coefficient/slip curve

a Stable area, **b** Unstable area.
λ_K Optimum brake slip,
μ_{HFmax} Maximum braking-force coefficient.



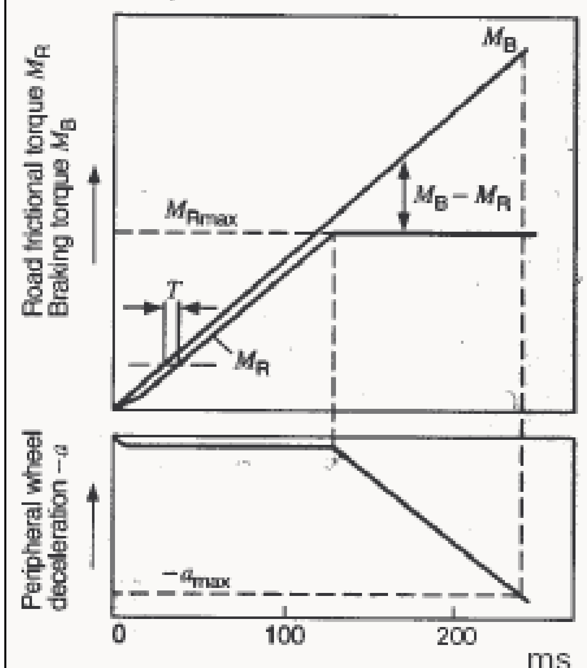
Torque difference between friction and braking forces leads to a wheel speed reduction till locking

Torque difference provides a measure of angular acceleration

The torque response of the road is a good estimate of friction.

Initial braking process, simplified

$(-a)$ Peripheral wheel deceleration,
$(-a_{max})$ Maximum peripheral wheel deceleration,
M_B Braking torque, M_R Road frictional torque,
M_{Rmax} Maximum road frictional torque,
T Time delay.



Questions to be solved by control

- Wheel speed sensors must be used to determine :
  - The linear acceleration/deceleration at the wheel rim
  - The longitudinal slip in braking
  - The reference speeds and deceleration of the vehicle

- Difficulty to define a reliable estimation of the variables: ➔ It is not easy to use the wheel accelerations and decelerations or the longitudinal slip ratio as a controlled variable.

- How to use the measured information?
- How to work with this information to derive other quantities?
- Control algorithms?

ABS control principles

Control Algorithm

- The system is highly non-linear because of
  - The μ-λ friction characteristic curves (slip, longitudinal and lateral coefficients of friction)
  - The equations of motion
- Linear controllers are not very effective
- Non-linear controllers are necessary to predict the braking torque modulation and to achieve the desired target
  - Nonlinear controller based on rules and sometimes even tabulated solutions. They are difficult to set up (setting parameters)
  - Complex nonlinear controllers: sliding mode controllers by Slotine
  - A very simple non-linear system: the bang-bang controller

Example of ABS controller action

- Example of a heavy vehicle with air actuated brakes on wet road (Wong, 1993)
- The brake pressure reduction and restoration cycle can be repeated between 5 to 16 times per second.
- The ABS function is disengaged when the vehicle speed is below 5-6 km/h.

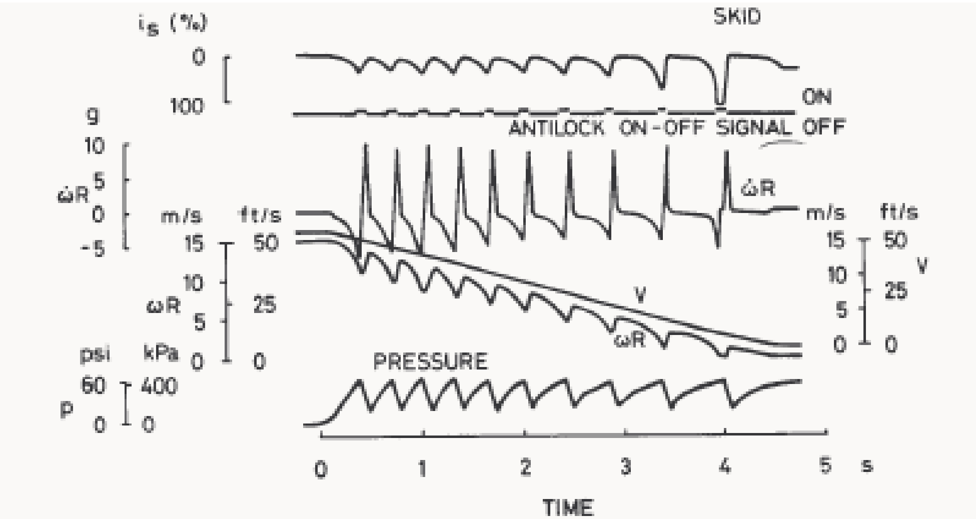


Fig. 3.57 Operating characteristics of an antilock system for heavy commercial vehicles with pneumatic braking systems.

Estimating the vehicle reference speed

- Since the vehicle speed cannot be measured directly, the ECU (Electronic Control Unit) must estimate this value appropriately.

- When the ABS is not operating (no wheel locking), Bosch's ABS system, for instance, uses the information of wheel speeds on along diagonal and forms an estimate based on this information.

- For moderate braking, the ECU will estimate the value of the reference speed on the fastest wheel on the diagonal.

- For emergency braking, the ECU proceeds by using and extrapolation based on a ramp function using the speed values calculated at the start of the cycle.

Predicting wheel blocking (Wong, 1993)

- The anti-blocking must be activated when the angular deceleration at the wheel periphery exceeds a certain threshold value (typically 1 to 1.6 g):

$$|R_e\,\dot{\omega}| > 1.6\,g$$

- In passenger cars, ABS often includes a track-and-hold circuit that memorizes wheel decelerations above 1.6 g for a given period of time (e.g. 140 ms)
- If during this period, the angular velocity decreases by more than 5% below the stored value AND if the longitudinal acceleration of the vehicle measured by an accelerometer sensor is less than 0.5g then the wheel is blocked.
- If the measured vehicle deceleration is greater than 0.5 g, the lock is always predicted as blocked and the brake is released whenever the angular velocity falls below 15% of its recorded value.

Predicting wheel blocking (Wong, 1993)

- In some other anti-blocking systems, the brake system pressure is released (because wheel blocking) whenever

- The estimated slip rate λ_s of the tire is above a threshold λ_0 (e.g. 10%)

$$\lambda = 1 - \frac{\omega \, R_e}{V} \; > \; \lambda_0$$

AND

- Linear deceleration is greater than a critical value (typically 1 to 1.6 g).

$$\dot{v}_w = |R_e \, \dot{\omega}| > 1.6 \, g$$

Criteria to re-apply braking pressure (Wong 1993)

- In some systems: as soon as the criteria for releasing the pressure have disappeared.
- In some devices, a fixed delay is introduced to introduce hysteresis to prevent pumping.
- In other systems, braking is re-applied when the momentum of the vehicle has restored sufficient angular acceleration.
- Braking is applied as soon as the angular acceleration times the wheel radius is greater than a threshold typically 2.2 to 3 g.

$$\dot{v}_w = R_e \dot{\omega} \; > \; 2.2 - 3\, g$$

- Other times the fluid pressure is controlled by the angular acceleration of the wheel.

Control cycles of a typical ABS

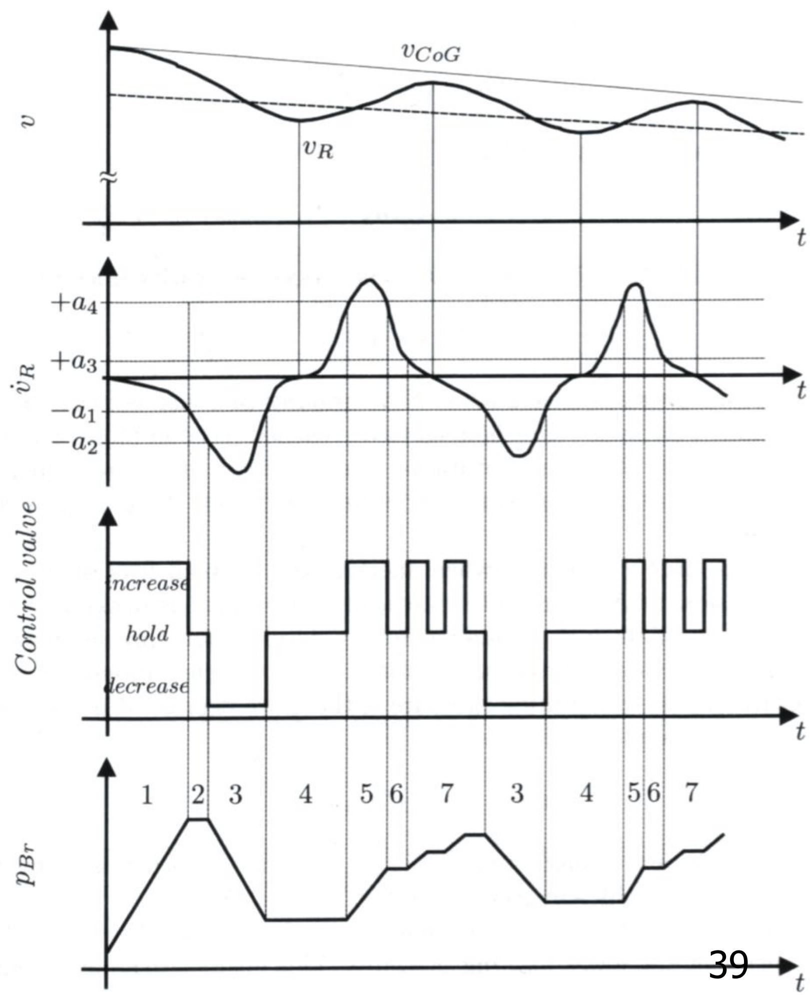
- The equivalent wheel speed is measured and differentiated to obtain the equivalent wheel acceleration.
- **Phase 1:** The point of maximum friction is exceeded when

$$\dot{v}_w < -a_1$$

- **Phase 2:** during the first cycle a lower threshold is applied to suppress the effect of noise.

$$\dot{v}_w < -a_2$$

- Between a_1 and a_2 the pressure is maintained but no longer increases.



Control cycles of a typical ABS

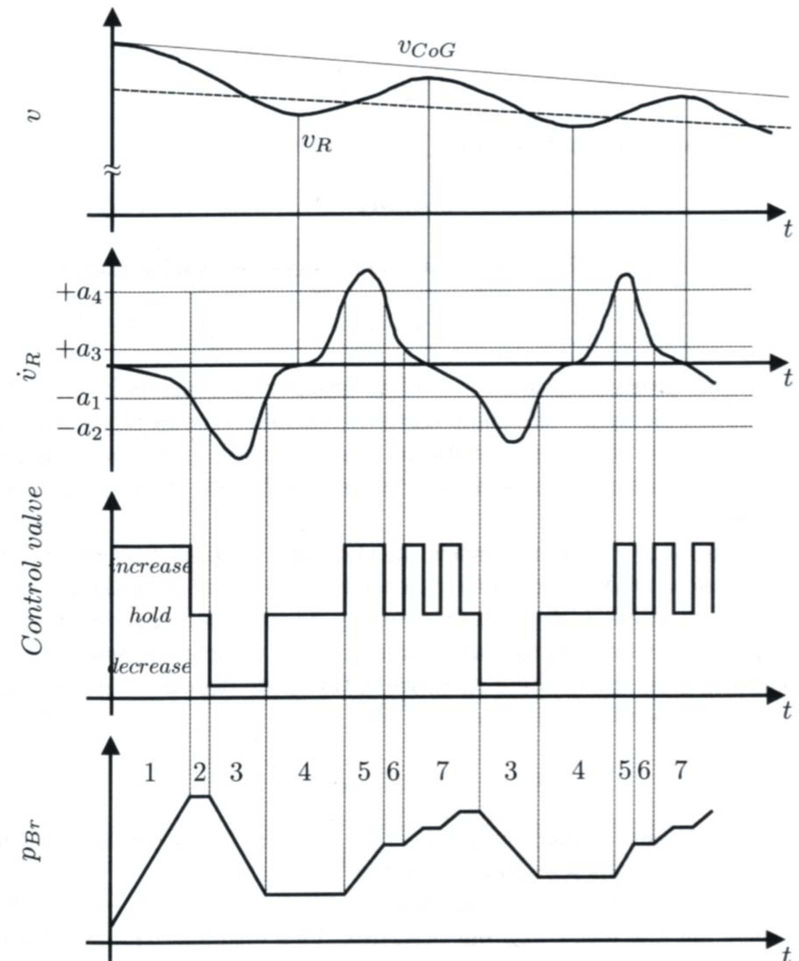
- **Phase 3:** when

$$\dot{v}_w < -a_2$$

- the pressure is released. The wheel regains speed.
- **Step 4:** When the threshold -a_1 is reached again, the pressure drop is stopped, and the pressure is maintained.
- **Phase 5:** The pressure is only increased when the wheel accelerates beyond the threshold.

$$\dot{v}_w > +a_4$$

- to avoid coming back into operation with a too low friction coefficient



Control cycles of a typical ABS

- **Phase 6:** in the range

$$a_4 > \dot{v}_w > a_3$$

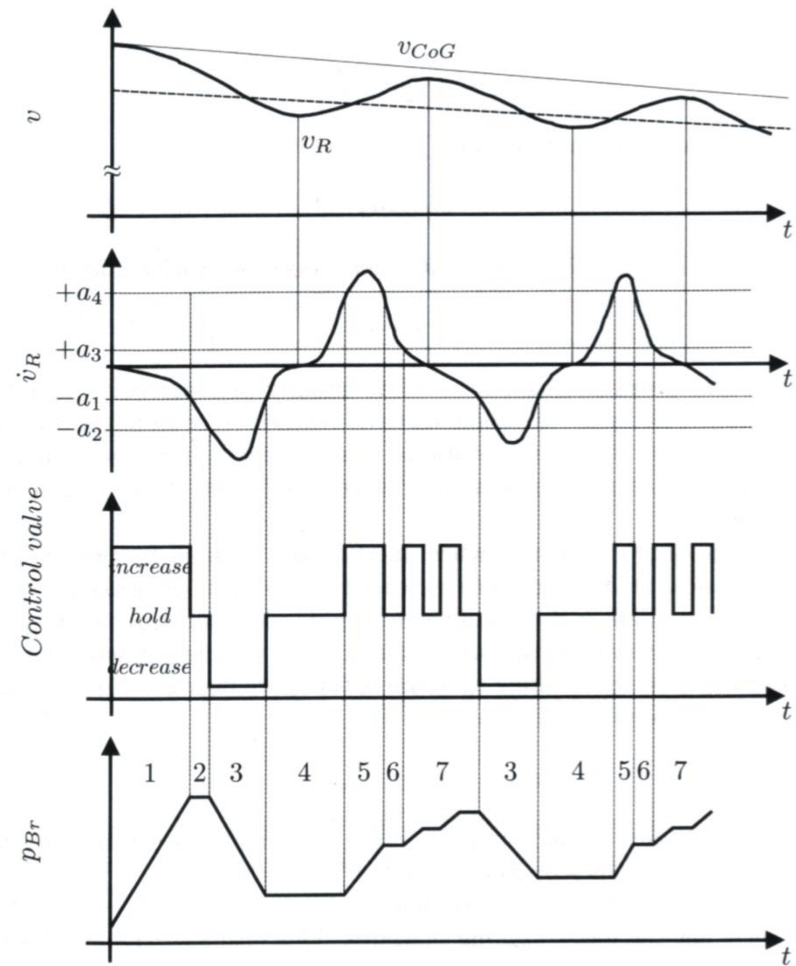
- the pressure is kept constant.
- **Phase 7:** in the range

$$a_3 \geq \dot{v}_w > -a_1$$

- the pressure is increased slowly. Pressure increase is made in stages with time delays.
- **Phase 3:** When the threshold $-a_1$ is reached again:

$$\dot{v}_w < -a_1$$

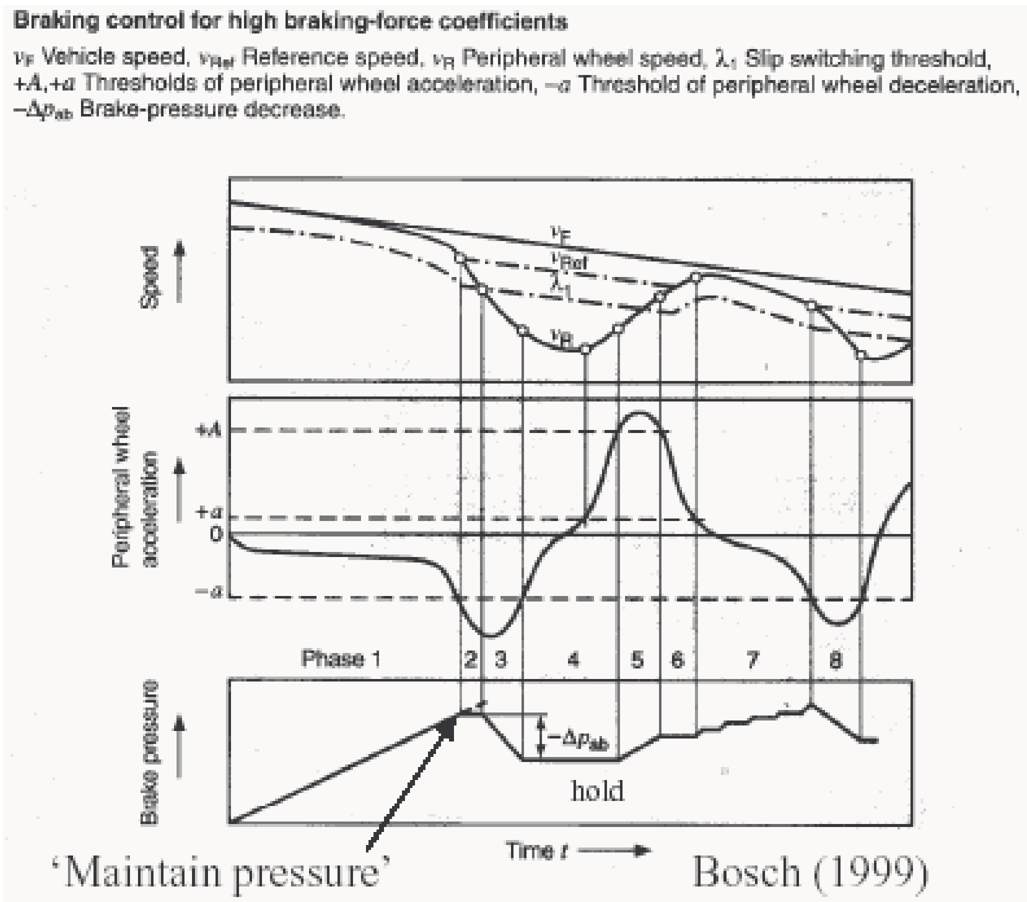
- the second cycle starts. This time, one doesn't wait for reaching the threshold a_2 before reducing the pressure.



Control cycles of a typical ABS

Bosch proprietary solution (Bosch, 1999)

- Illustration of the cycle for a surface with a high coefficient of friction
- Reference speed used to determine the slip ratio threshold
- The pressure is released as long as the peripheral acceleration is below the threshold.
- Increasing acceleration causes pressure to increase but in a stepped manner (system wait time)



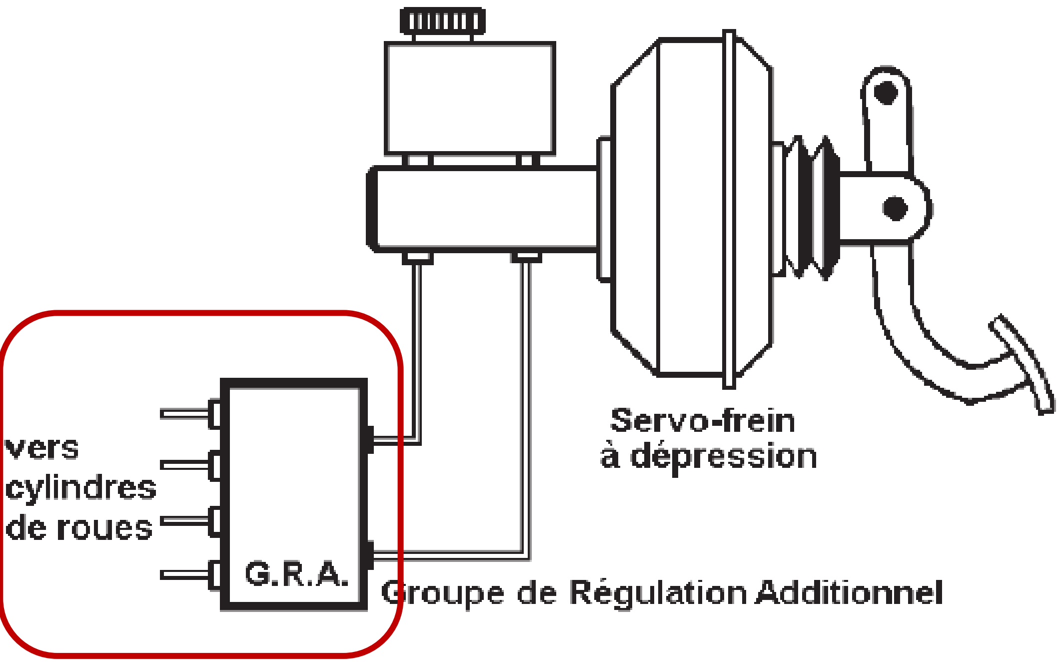
ABS components

The ABS components

- Implementations
  - Additional systems with respect to the classical braking system
  - Integrated systems

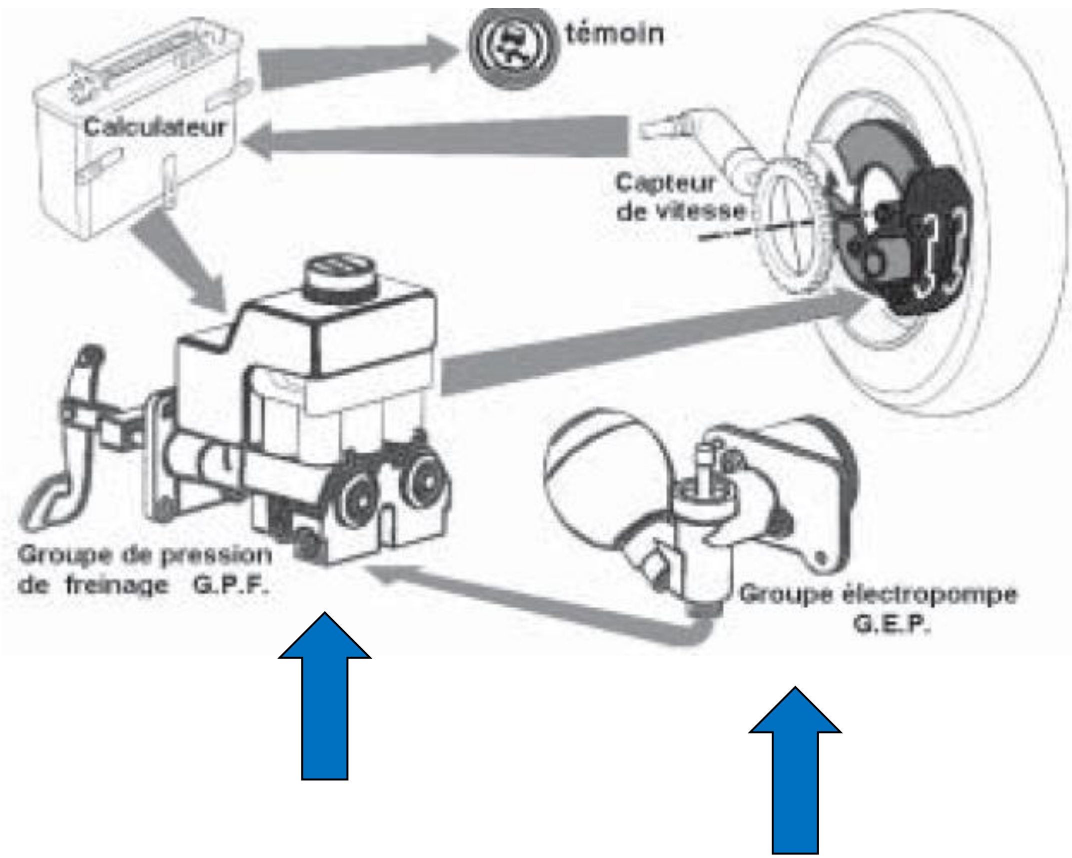
- The components
  - The Electronic Control Unit (ECU)
  - Wheel speed sensors
  - Brake wheel pressure modulation

ABS as an additional systems



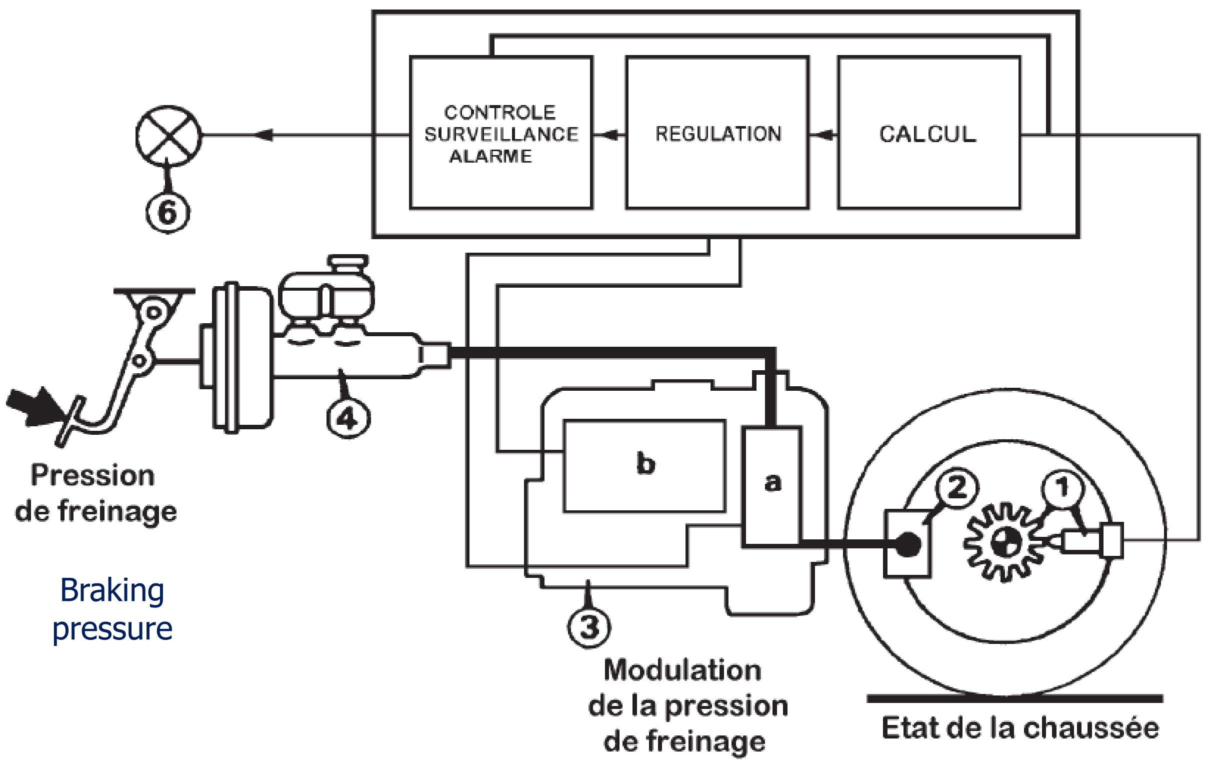
- Conventional braking elements are used.
- A hydraulic brake pressure regulating unit is interposed between the master cylinder and the receivers.
- This regulation is carried out by a variable number of solenoid valves.
- Brake assist is retained.

ABS integrated systems



- Identical to the conventional braking system except that the brake-assist and the master cylinder are replaced by a high-pressure pump and a hydraulic distributor.
- The pressure is regulated by means of solenoid valves.

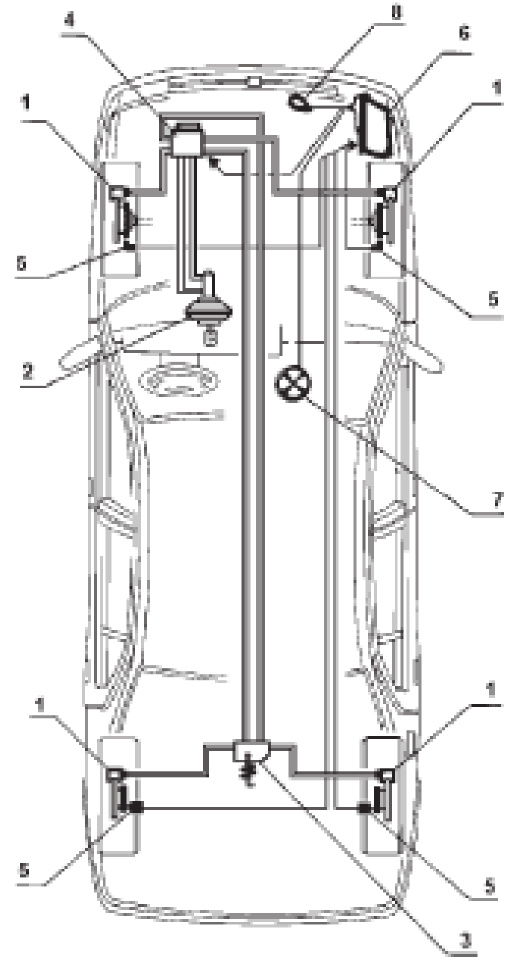
ABS as an additional systems



Braking pressure

Modulation of braking pressure

Road conditions



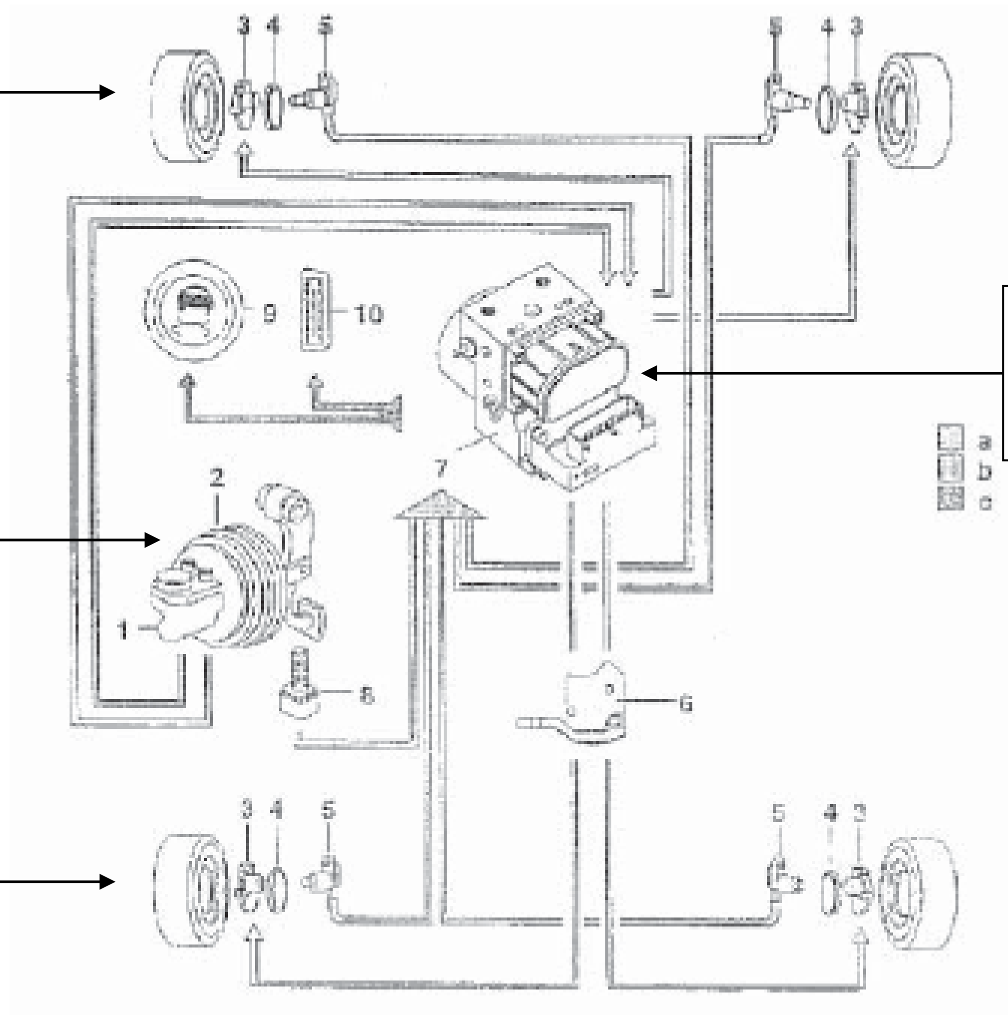
System layout and subsystem connections

Brake pistons

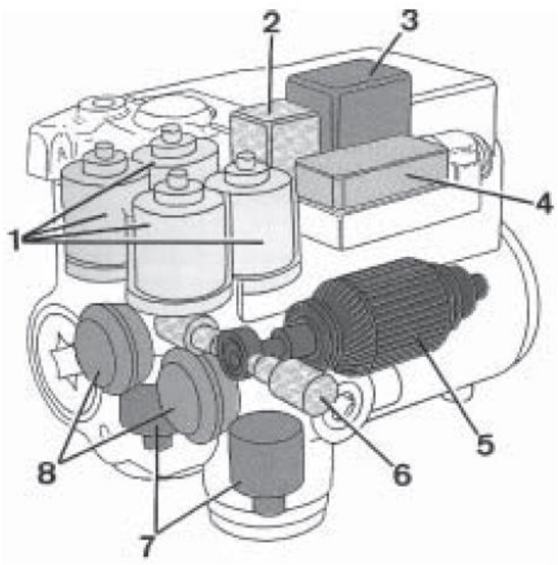
Master Vac

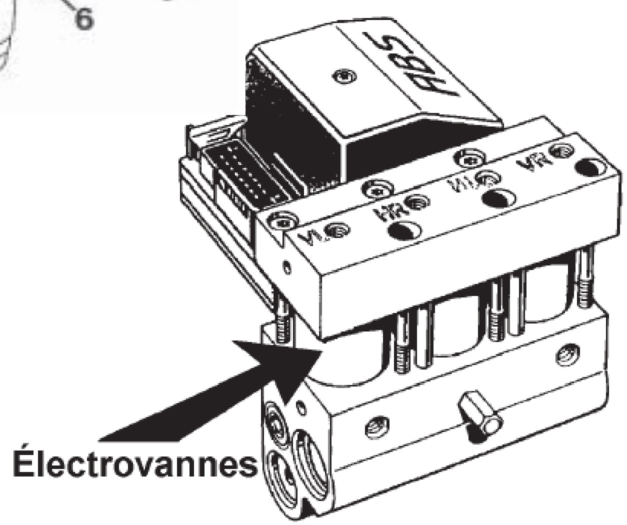
Brake pistons

Brake pressure modulator using solenoid valves



Servo control group





- The hydraulic power pack, in an additional system, has the advantage of being able to be placed anywhere according to the available free space in the engine compartment.

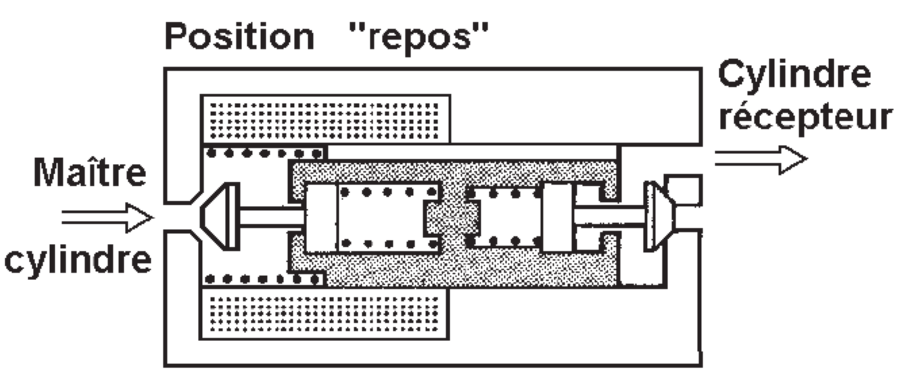
- It consists of a re-injection pump (6), an electric motor (5) to drive the pump, one accumulator (1) per brake circuit, several solenoid valves and a relay board (pump and solenoid valve relay) and, more and more often, an integrated control unit (3).

Solenoid valves

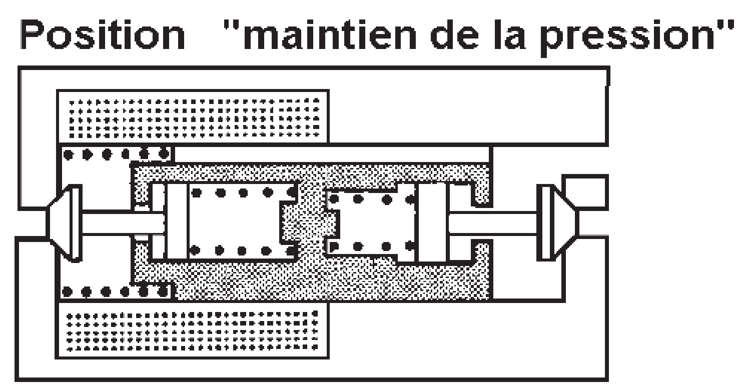
- This additional system uses three-way solenoid valves that allow either:
  - to put the master cylinder and the receiver cylinders in communication. (normal braking)
  - to cut off this communication, thus prohibiting the increase of pressure in the cylinder.
  - to put the receiving cylinder in communication with a delivery pump, this causes the pressure in the cylinder to drop and thus decelerates the wheel.
- The solenoid valves consist of a coil that is powered and grounded by the computer. The current passed through depends on the desired displacement of the core-piston. The stroke of the core-piston is a few tenths of a millimeter. There can be 3 or 4 solenoid valves.

Solenoid valves

- **I= 0A:** Idle position, the pressure from the master cylinder goes directly to the receivers.
- **I=2A:** Position "pressure hold", the communication is cut off, a current of 2A flows through the winding, the core-piston moves to close the pressure supply from the master cylinder.



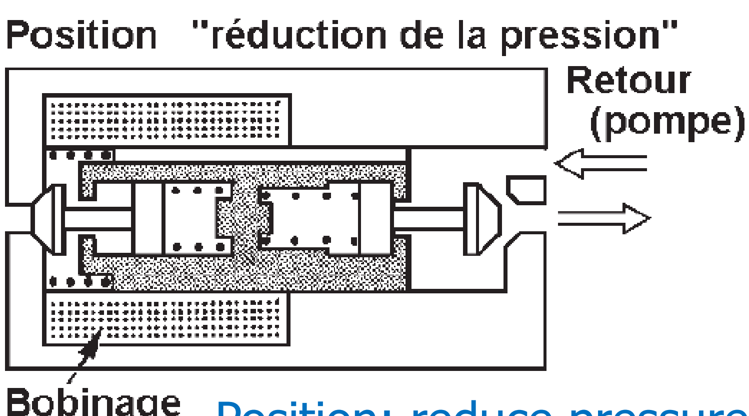
Rest position



Position: hold pressure

Solenoid valves

- **I=5A:** Position "pressure reduction", a current of 5A flows through the winding, the piston core moves further and opens the channel which allows the connection between the brake cylinders and the re-injection pump.

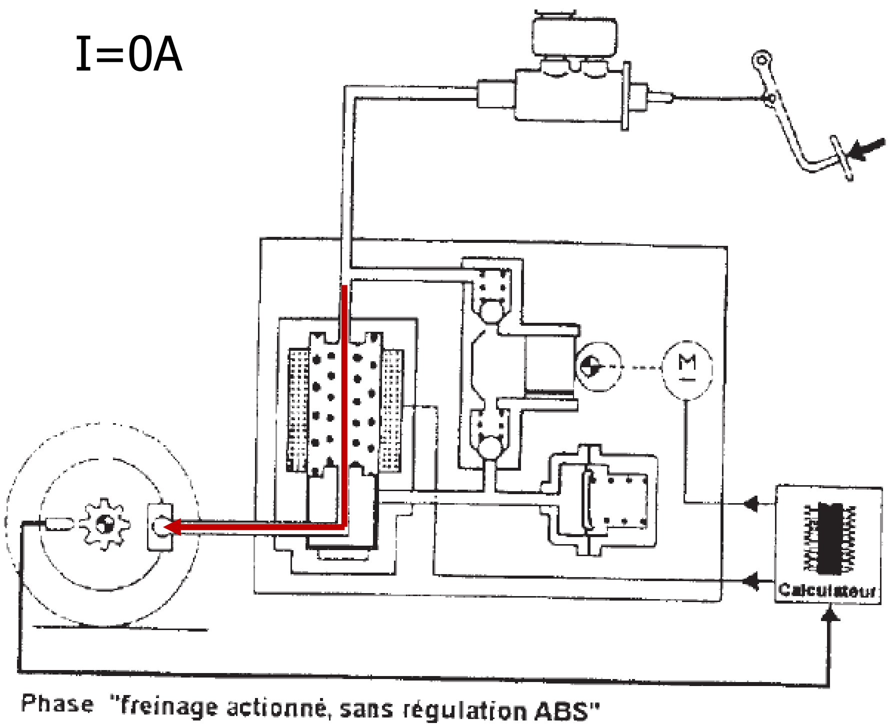


Position: reduce pressure

- When the computer controls the solenoid valve(s) with a current of 5A, it simultaneously controls the re-injection pump relay. The role of this pump is to transfer the liquid from the accumulator to the master cylinder line to prevent the brake pedal from being depressed during regulation. The driver may feel a pulsation at the pedal. One or more accumulators can be used to alleviate this phenomenon.

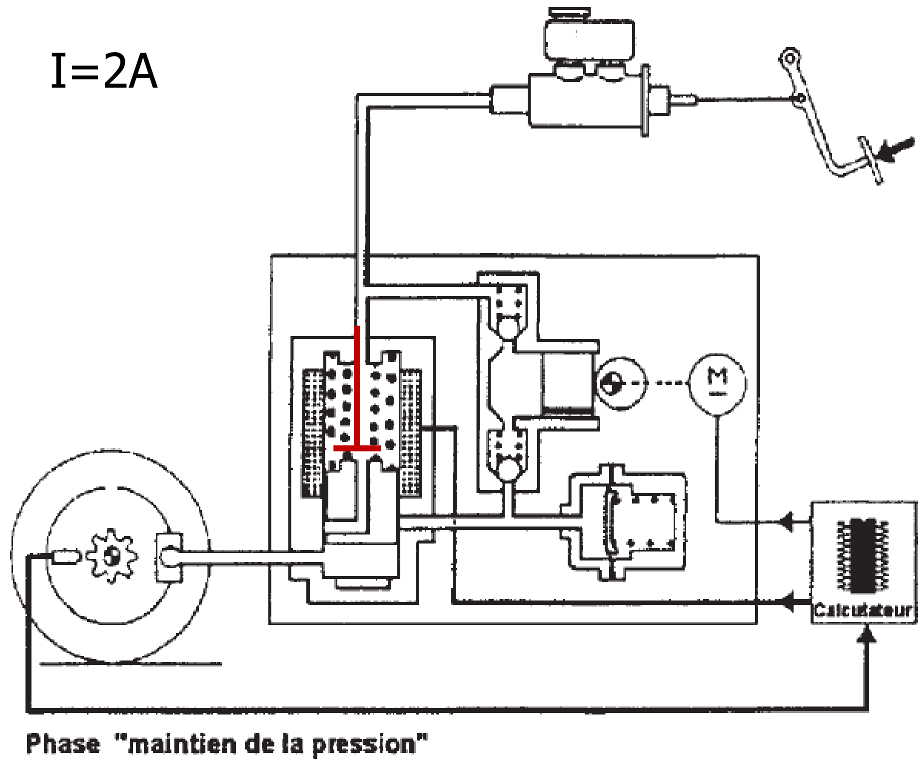
Solenoid valves

I=0A



Phase: Braking is operated, without ABS

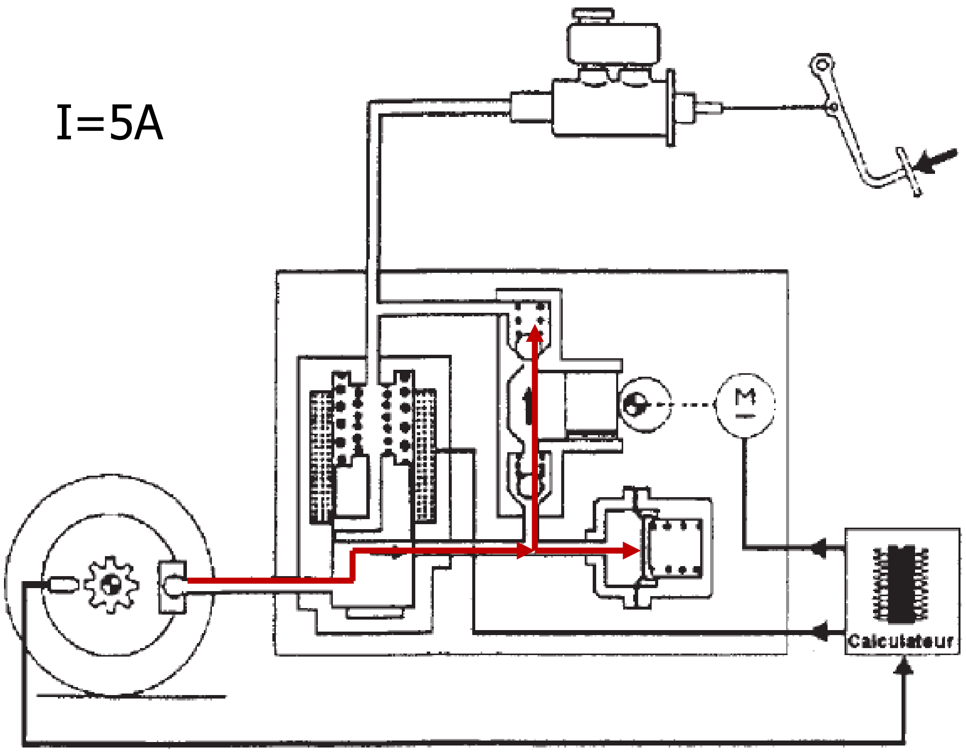
I=2A



Phase: Holding the pressure

Solenoid valves

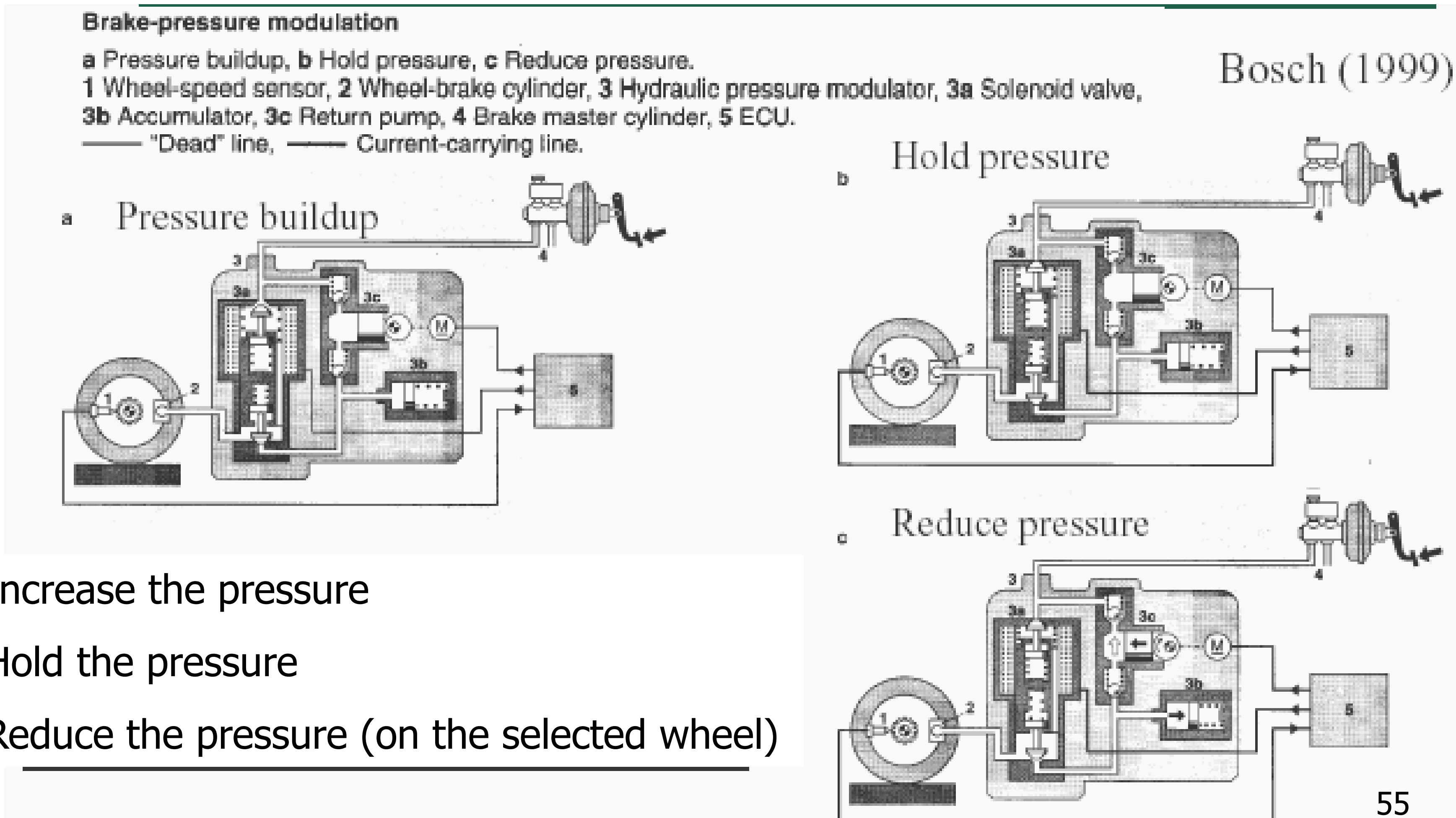
I=5A



Phase "baisse de la pression"

Phase: Reducing the pressure

Modulating the braking pressure

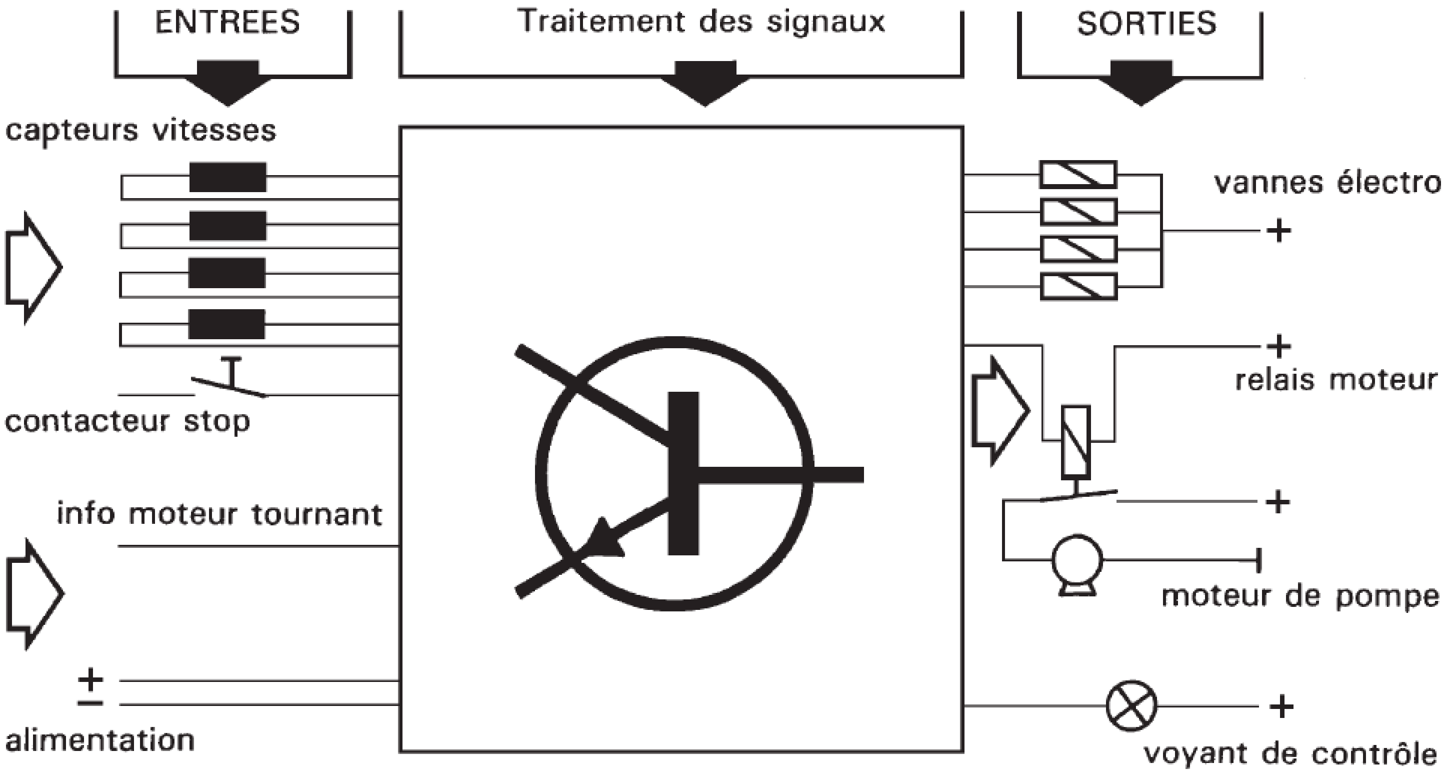


A/ Increase the pressure

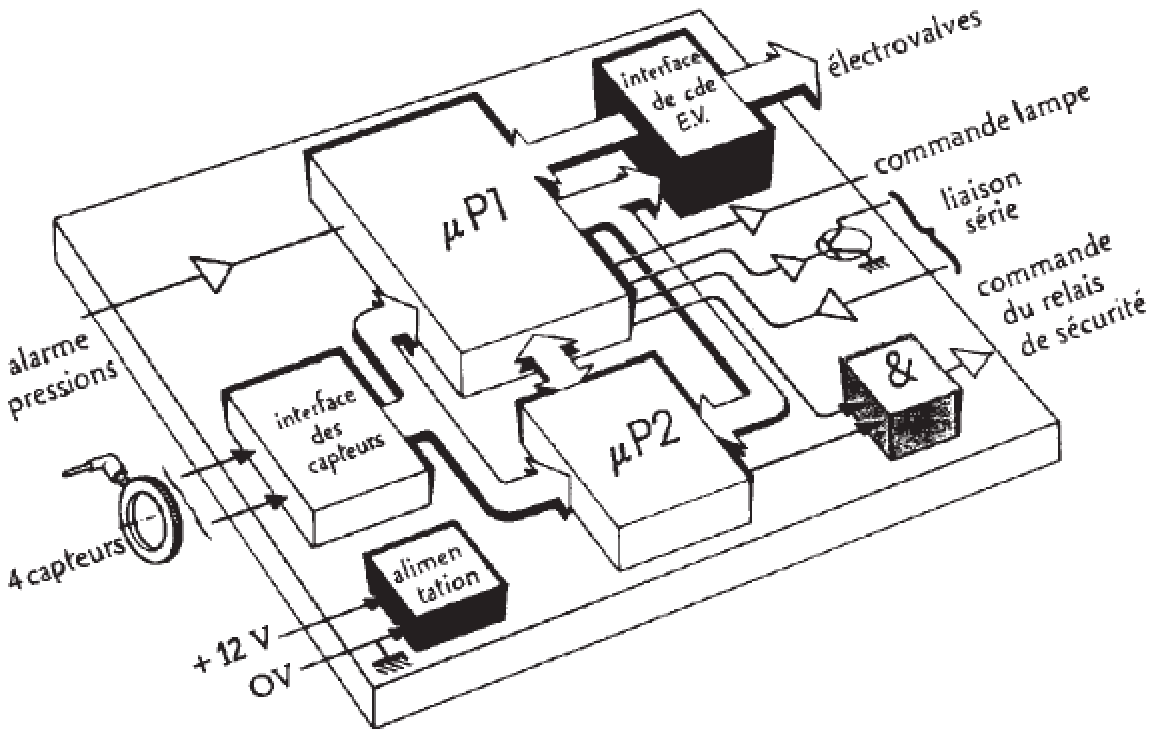
B/ Hold the pressure

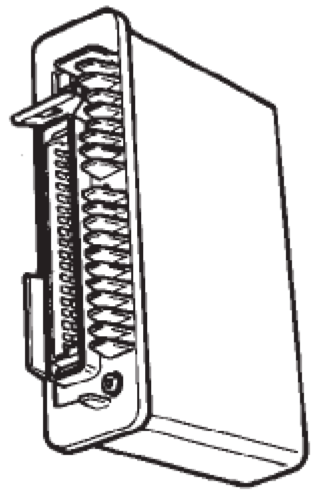
C/ Reduce the pressure (on the selected wheel)

Electronic Control Unit



Electronic Control Unit





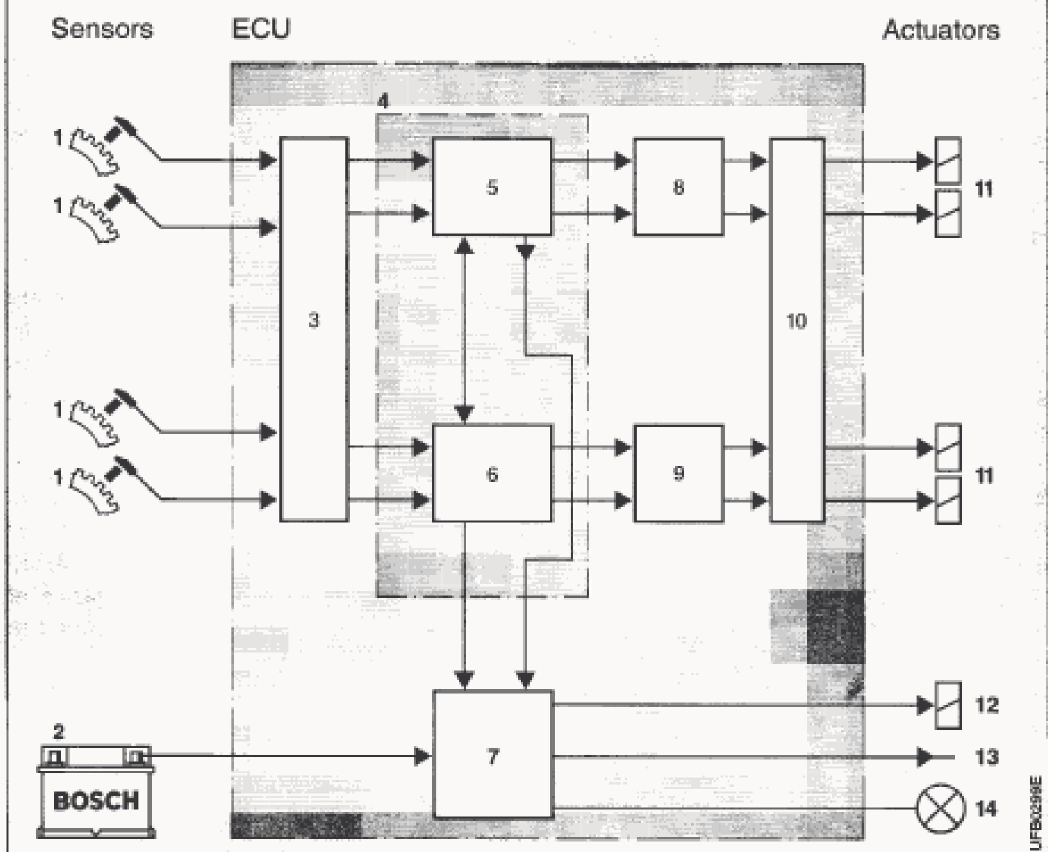
Electronic Control Unit

- The ECU receives information from the wheel speed sensors and the stop switch on the brake pedal (the system has to distinguish slip when braking and slip when acceleration).
- It also receives a connection to power supply and a ground connection.
- In return, it controls the solenoid valves, the control light on the dashboard and the relay of the re-injection pump.
- When the ignition is switched on, it performs a "self-diagnosis" of the device. If a system fault occurs while driving, the indicator light on the dashboard lights up and the computer shuts down the A.B.S. device (fail safe mode).
- In this case, the traditional braking system is available. The ECU also save all faults in memory and allows them to be read with the diagnostic station.

Electronic Control Unit

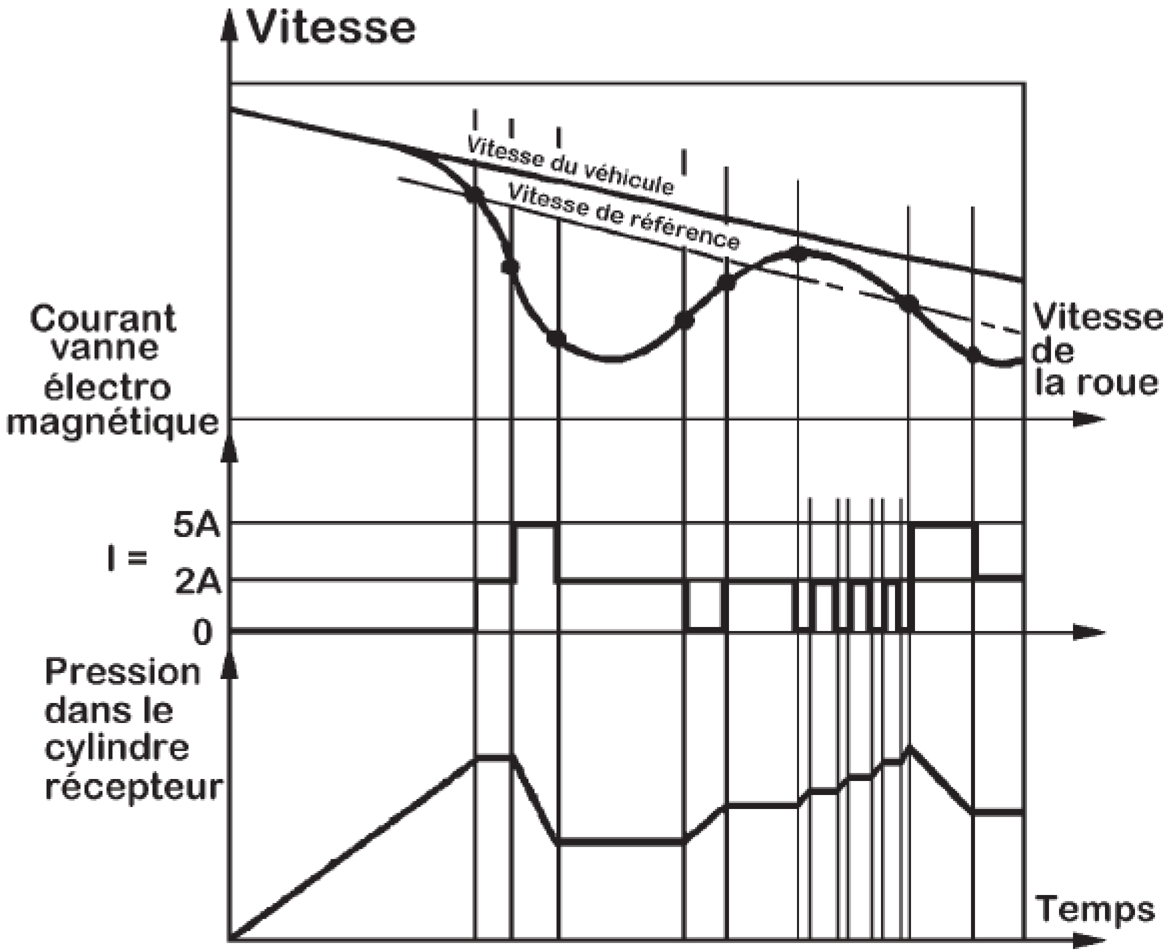
ABS2S control unit (ECU)

1 Wheel-speed sensors (wheel frequencies), **2** Battery, **3** Input circuit, **4** Digital controller, **5** LSI circuit (1), **6** LSI circuit (2), **7** Voltage stabilizer/fault memory, **8** Output circuit (1), **9** Output circuit (2), **10** Output stage, **11** Solenoid valves, **12** Safety relay, **13** Stabilized battery voltage, **14** Indicator lamp.



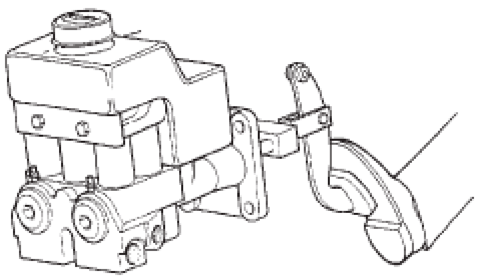
Bosch, 1999
Fig. 4 page 65

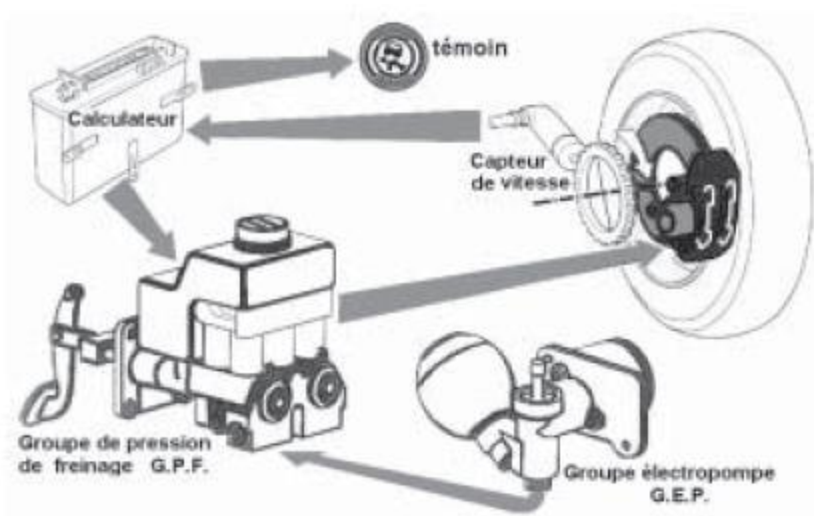
Electronic Control Unit

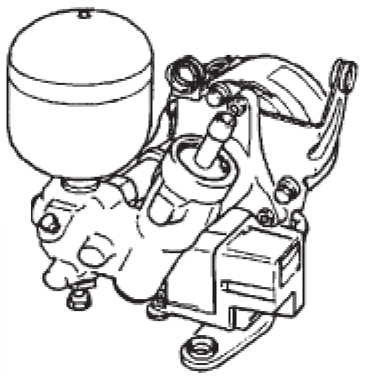


ABS integrated systems

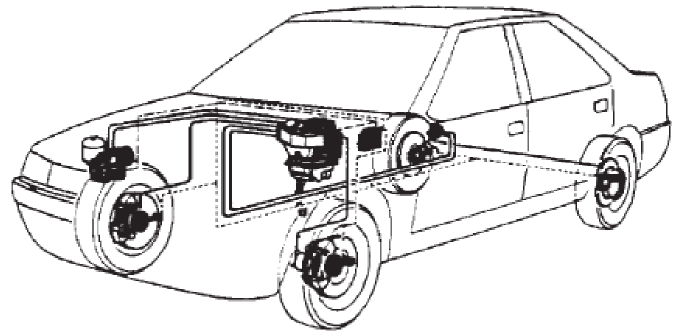
- In this system, which works on the same principle as the additional system, the creation of the high pressure is different, and it offers a slightly different operation of the solenoid valves.

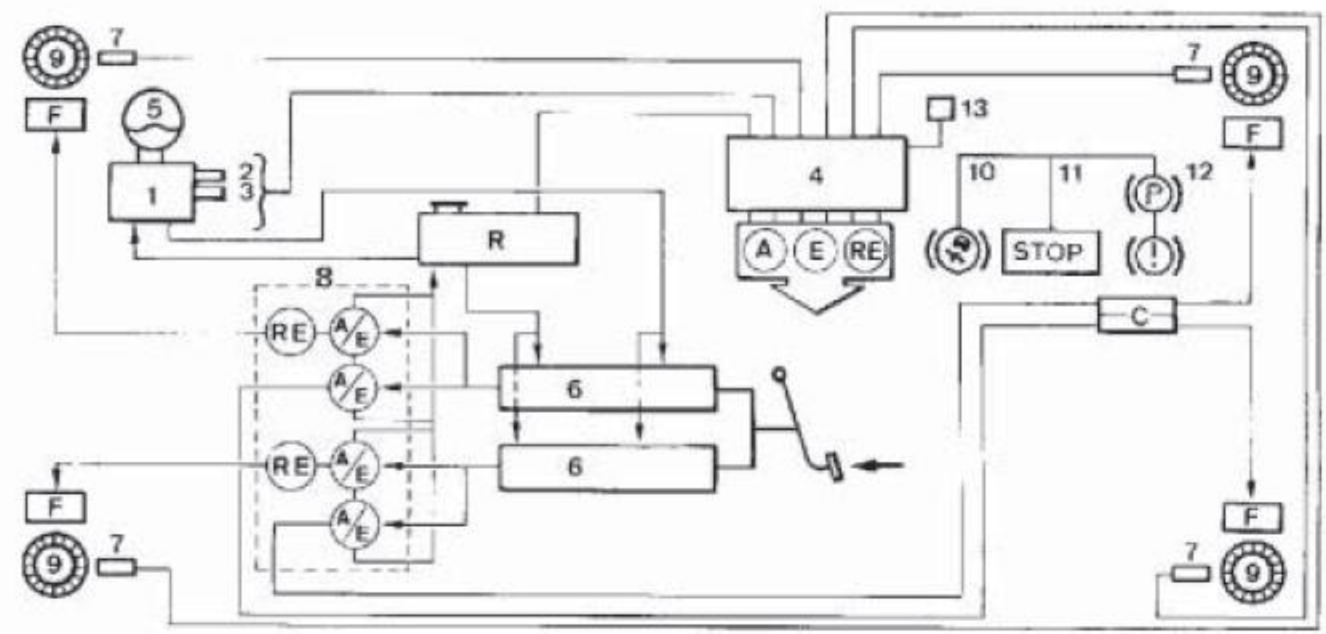




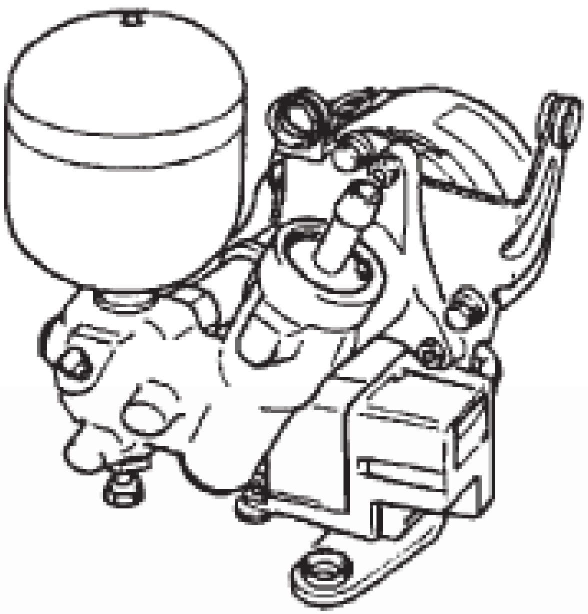


ABS integrated systems



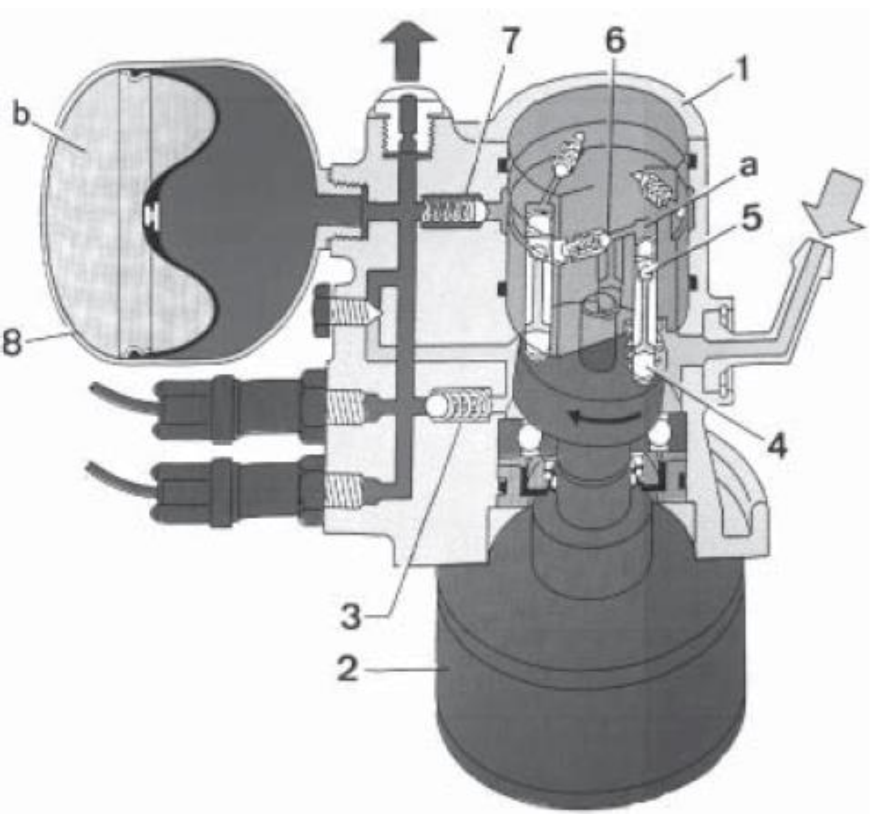


Operation of the integrated ABS system



- The braking device uses the high pressure supplied by a hydraulic pump as a pressure source.
- The braking pressure is, in all cases, proportional to the user's action on the brake pedal.

Operation of the integrated ABS system

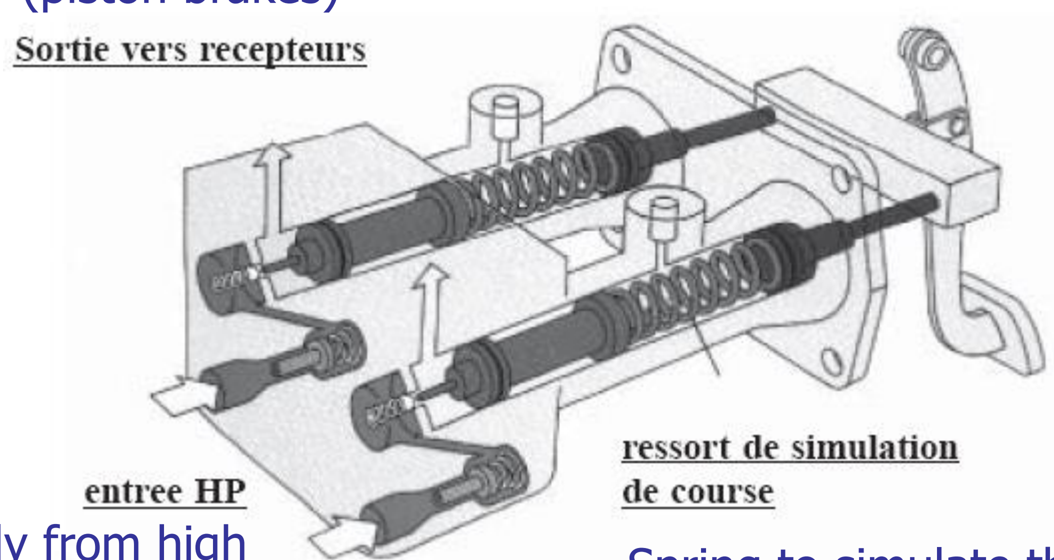


- This hydraulic pump (1) and electric motor (2) delivers a pressure regulated by two pressure switches between 160 and 180 bars.
- As soon as the pressure drops below 80 bar, the pressure switches alert the computer that the pressure is too low. The computer supplies the pump with electrical energy via a relay.
- An accumulator (8) (ball) is used to build up a pressure reserve.

Hydraulic distributor

- The role of the hydraulic distributor is to transmit to the brakes a braking pressure proportional to the braking effort.

Exit to receptors
(piston brakes)



Supply from high
pressure

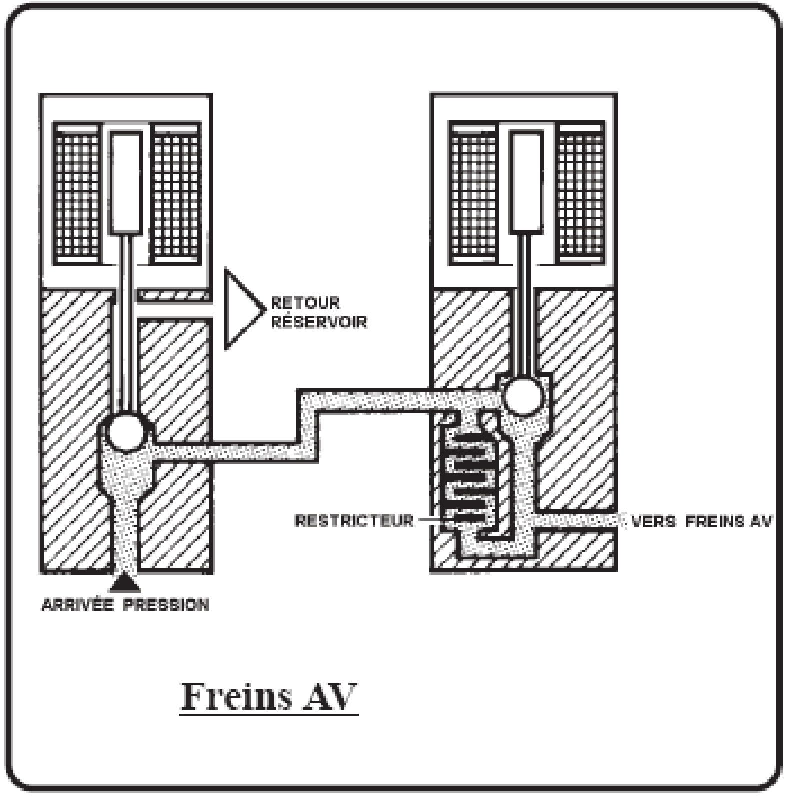
Spring to simulate the
piston displacement

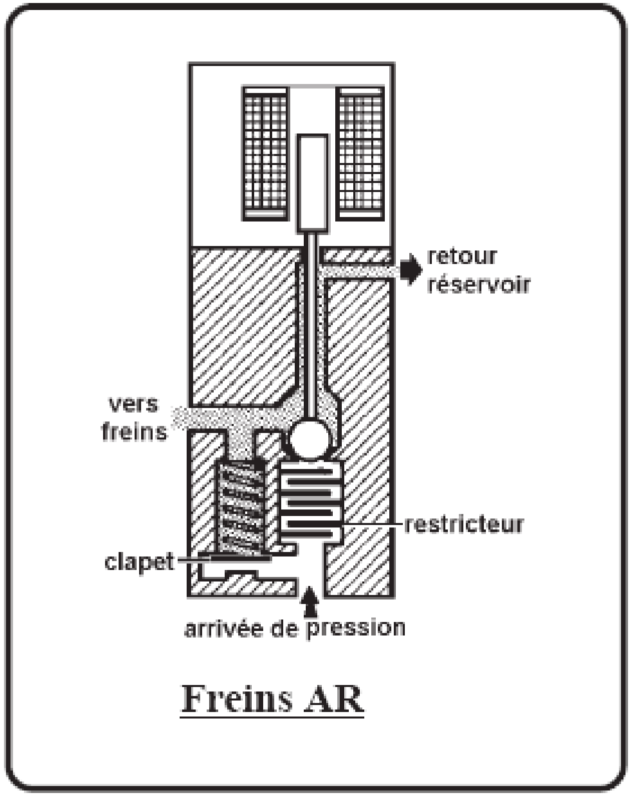
Solenoid valve operation

- Four possible cases:
  - Rapid pressure build-up
  - Rapid pressure drop
  - Slow pressure increase
  - Slow pressure drop

- On each front brake circuit, there are 2 solenoid valves:
  - One 3-way solenoid valve
  - And one 2-way solenoid valve.
- On each rear brake circuit there is
  - One 3-way solenoid valve.

Solenoid valve operation



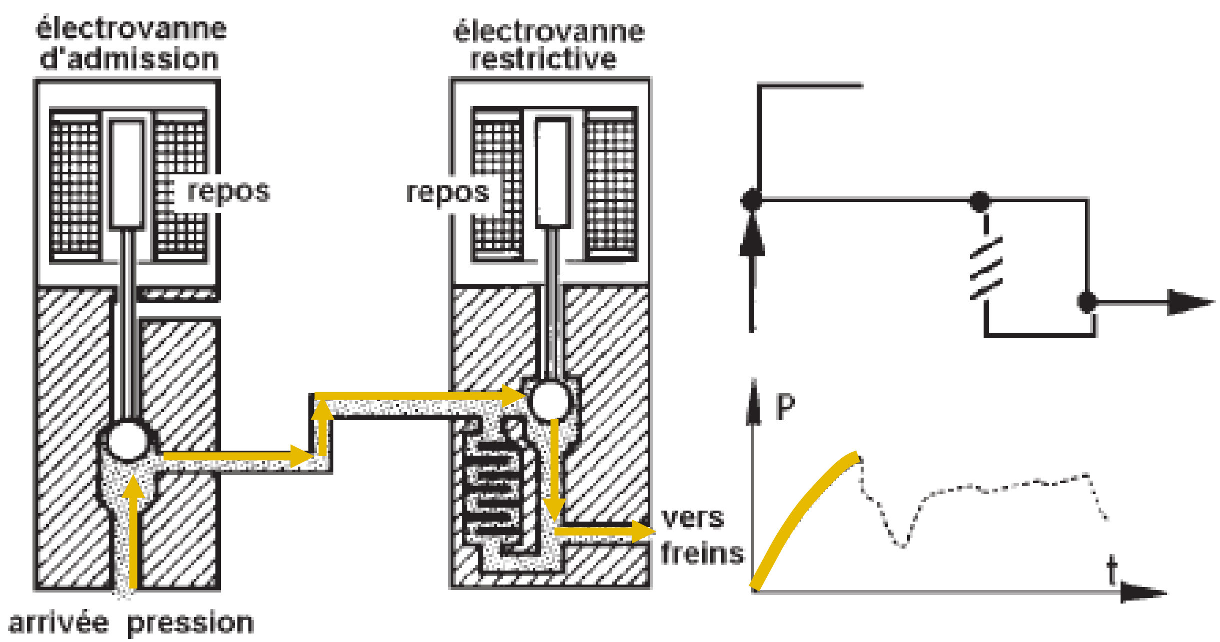


Front brakes

Rear brakes

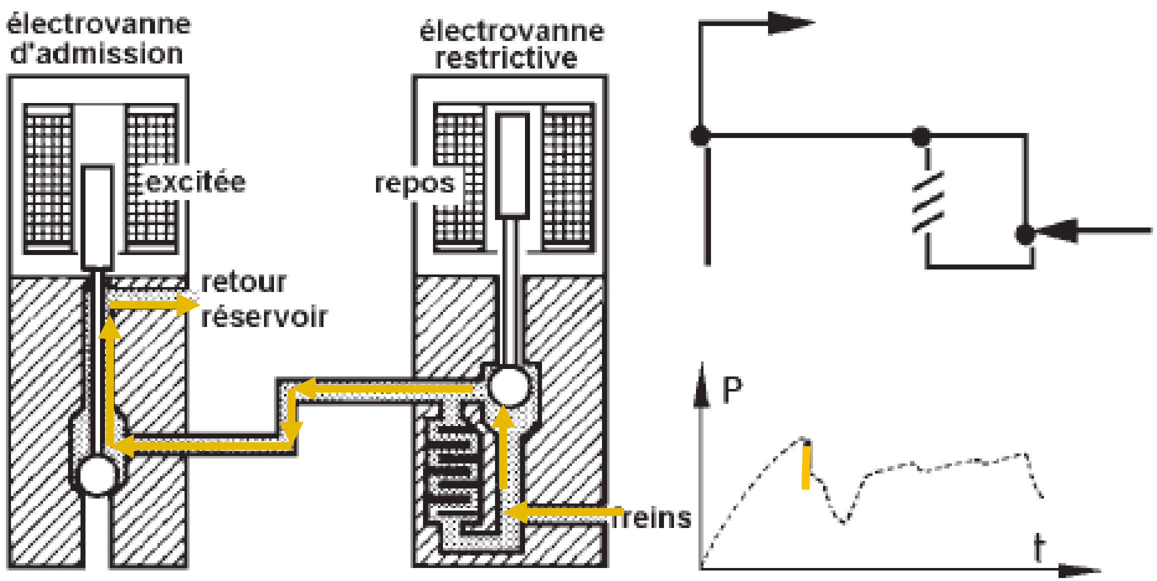
Solenoid valve operation

- <u>Front brakes: </u>phase 1 → Fast intake (without ABS)
- The solenoid valves are not powered. Hydraulic pressure is supplied directly to the front brakes.



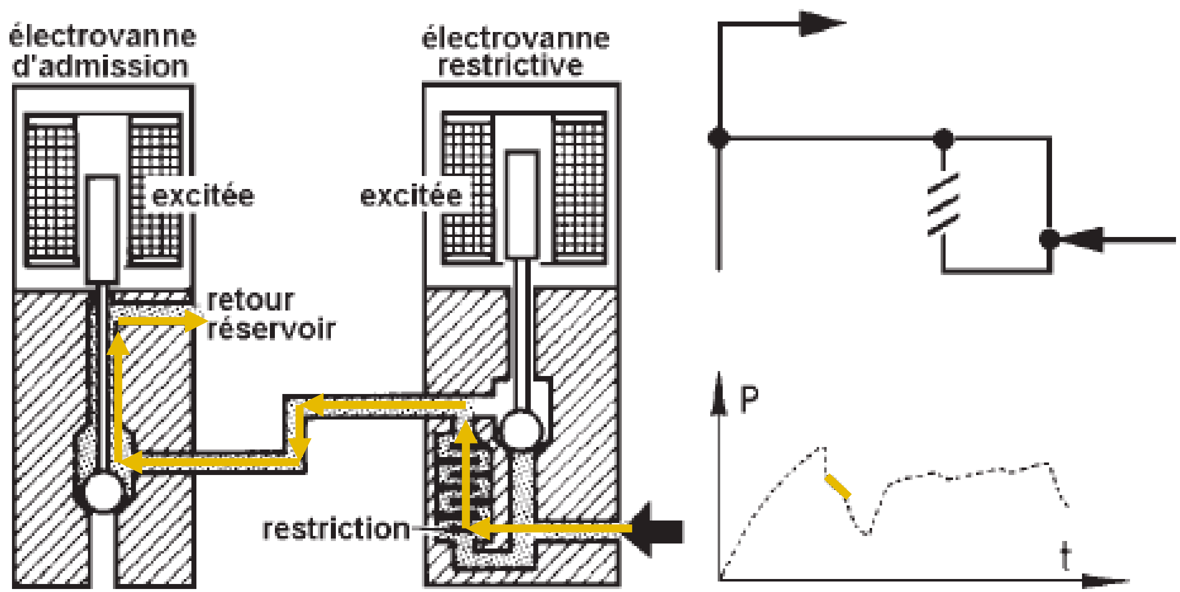
Solenoid valve operation

- <u>Front brakes</u>: phase 2 Quick release (locking of one or more wheels - ABS)
- The inlet solenoid valve is energized. There is no more high-pressure supply, the pressure in the circuit drops because the liquid can return to the reservoir.



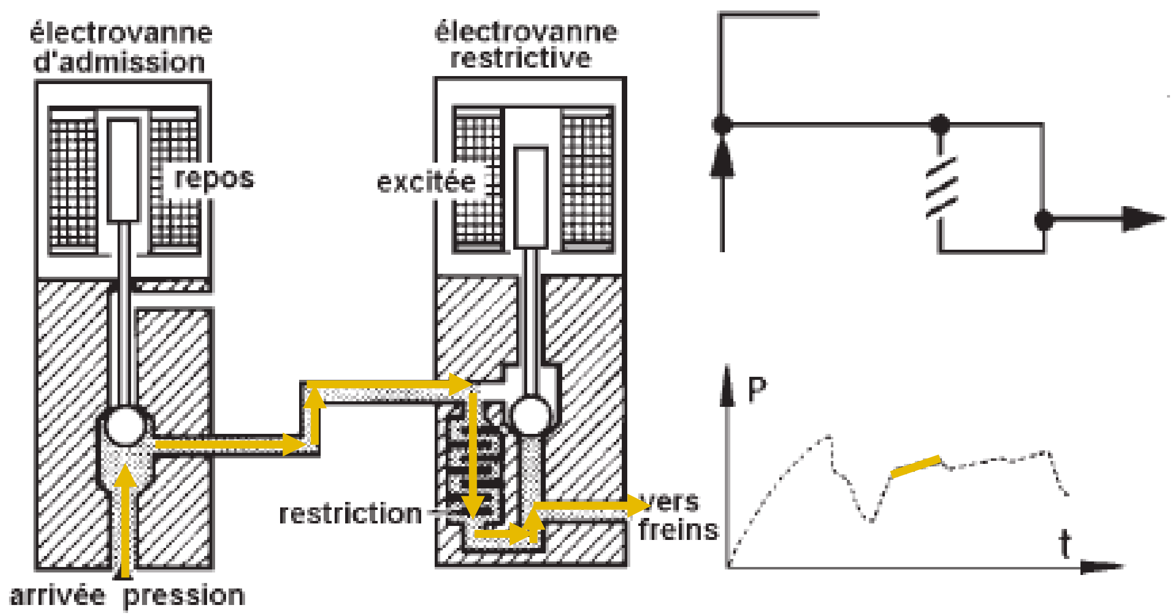
Solenoid valve operation

- <u>Front brakes</u>: phase 3 Slow release
- The two solenoid valves are powered. The circuit is still in communication with the return to the reservoir, but the pressure drop is slower because the flow has to go through the restrictor.



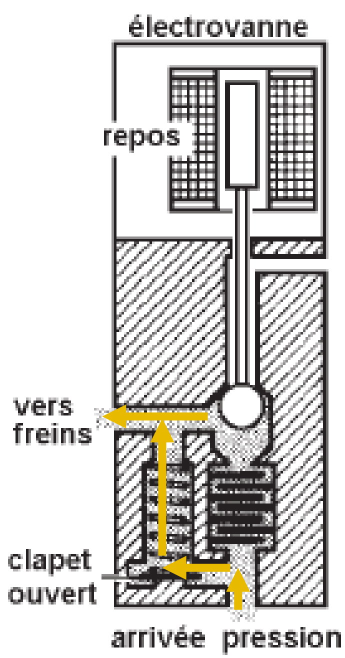
Solenoid valve operation

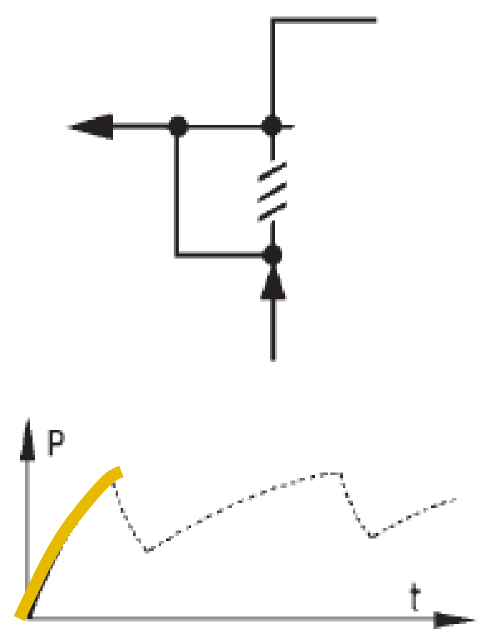
- Front brakes: phase 4 Slow admission
- The solenoid restriction valve is always energized. The pressure supply to the brakes is slow because of the restrictor. Braking is resumed in stages.



Solenoid valve operation

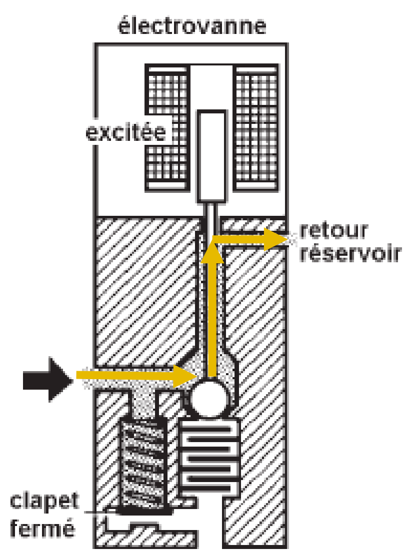
- <u>Rear brakes</u>: phase 1 Quick admission (without ABS)
- The solenoid valve is not powered. The valve is open, so the brake circuit is supplied normally, which causes a rapid build-up of pressure.

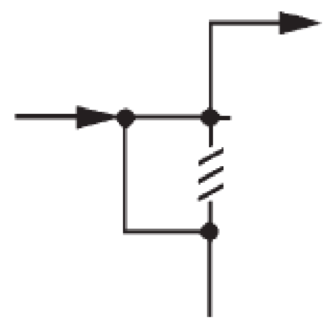


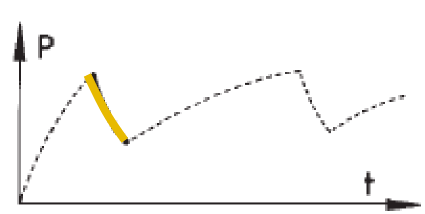


Solenoid valve operation

- <u>Rear brakes</u>: phase 2 Quick release (locking of one or more wheels)
- Beginning of blocking, as the supply pressure is higher than the operating pressure, the valve closes. The solenoid valve is energized, the brake circuit is in communication with the return to the reservoir, so this causes a rapid pressure drop.

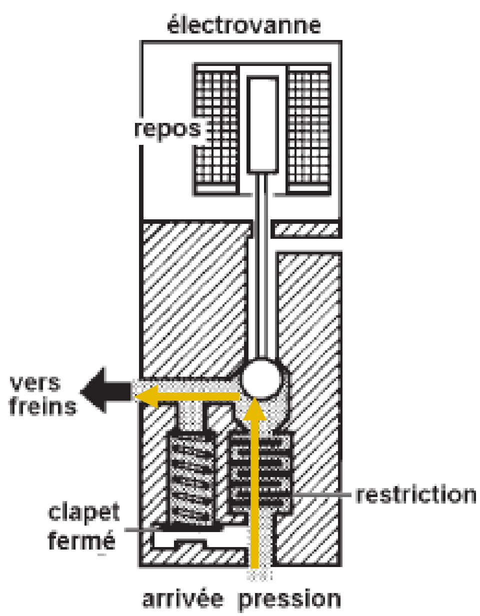


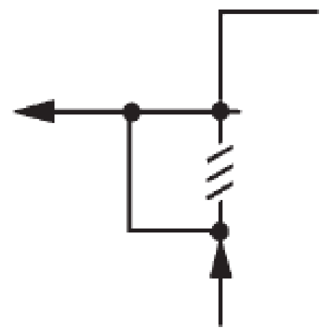


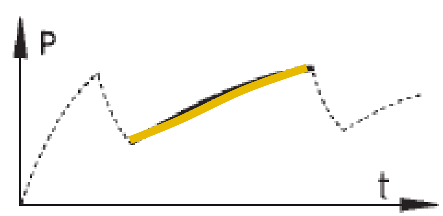


Solenoid valve operation

- Rear brakes: phase 3 Slow admission
- The solenoid valve is no longer powered. The valve remains closed because the supply pressure is higher than the operating pressure. The brakes are supplied again, but more slowly because the fluid passes through the restrictor.







The pressure modulator

The hydraulic pressure variator contains an accumulator, a return pump, and a solenoid valve.

ABS2S hydraulic pressure modulator

1 Accumulator, **2** Return pump, **3** Solenoid valve.

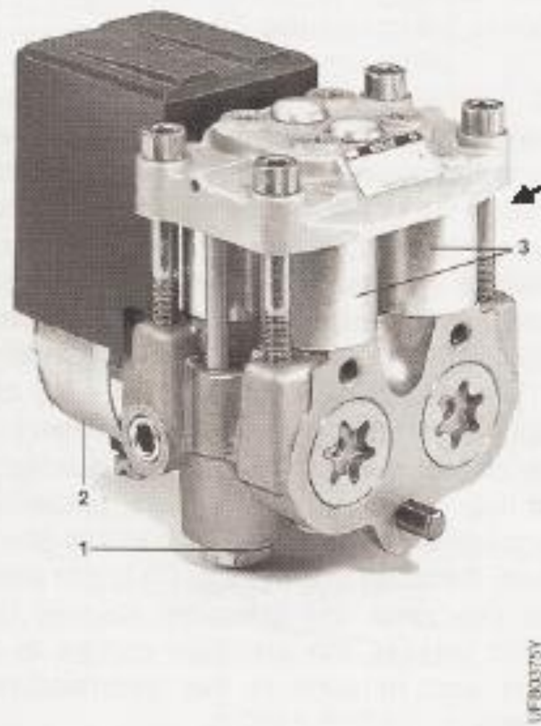
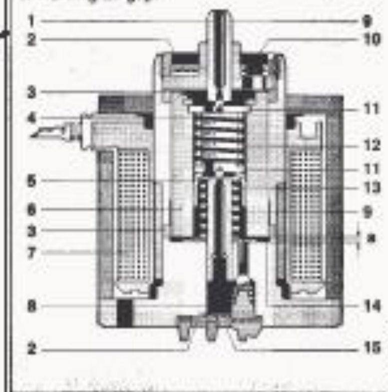


Fig. 7

ABS2S 3/3 solenoid valve

1 To the return line, **2** Filter, **3** Non-magnetic bearing ring, **4** Outlet valve, **5** Input valve, **6** Armature, **7** Winding, **8** Check valve, **9** Valve body, **10** To the wheel-brake cylinder, **11** Carrier plate, **12** Auxiliary spring, **13** Main spring, **14** Recess step, **15** From brake master cylinder. **a** Working air gap.



Wheel speed sensors

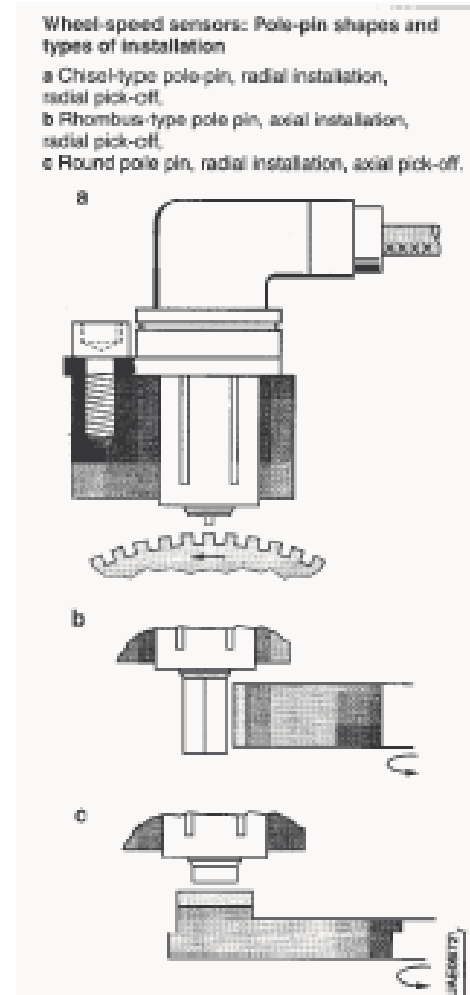
The sensor can generate between 90 and 100 pulses per revolution.

Bosch 1999
Fig. 1 & 2, page 63

Wheel speed sensors are inductive sensors. The sensor is a fixed wound equipped with a core with an extended pole and a permanent magnet. It is located directly above the sensor crown.

The rim is covered with salient poles. It is attached to the wheel hub or is placed on the differential shaft.

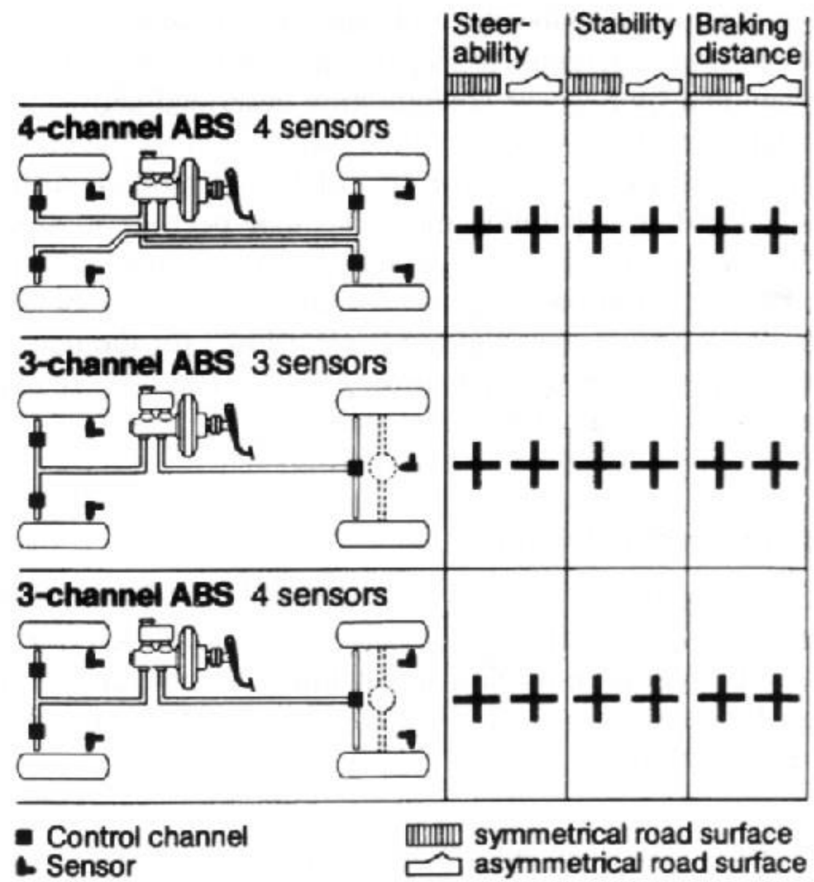
When the ring gear spins, the reluctance of the magnetic circuit varies alternately and creates a variable voltage whose frequency is proportional to the speed of rotation.



Layout of ABS (Wong)

- Several ABS architectures commonly found in passenger vehicles:
  - 4 channels - 4 sensors,
  - 3 channels - 3 sensors,
  - 3 channels - 4 sensors

- One channel = portion of the braking system that can be controlled independently of the rest of the braking system.



In all systems, the rear wheels are controlled together according to the »select-low« principle. In the first system, control was by synchronous triggering of both solenoid valves.

Layout of ABS (Wong)

- The primary objective is to ensure directional control and stability in straight and curved braking, as well as in braking on roads with asymmetrical coefficients of friction between right and left sides.
- The two front wheels can always be controlled individually according to the information from their speed sensor.
- The two rear wheels are often controlled together:
  - Strategy: "select low" uses the information from the slower wheel to control the brake pressure of the rear wheels.
  - Strategy "select high" uses the information from the fastest wheel to regulate the braking of both wheels.

Layout of ABS (Wong)

- Strategy select low:
  - Provides directional control when braking on asymmetrical road surfaces and in curves.
  - Lengthens the braking distance, as it reduces the braking power.
- Select high strategy:
  - May cause loss of directional control when cornering or on asymmetrical roads. It locks the inner wheel or the wheel on the low friction coefficient while the other wheel still develops a high braking force. This leads to a reduction of the lateral force potential and results in a yawing moment contrary to directional stability.

Layout of ABS (Wong)

- Dispositif 4 canaux – 4 capteurs: le contrôle indépendant des 4 roues peut entraîner l'apparition de moments de lacet importants peu favorables au contrôle directionnel.
- Dispositif 3 canaux – 3 capteurs:
  - Train arrière contrôlé par la vitesse moyenne du train arrière
  - Généralement adopté sur pick-up
- Dispositif 3 canaux – 4 capteurs + stratégie « select low »:
  - Résultat assez semblable au 4 canaux – 4 capteurs si stratégie «select low».
- Dispositif 2 canaux – 4 capteurs
  - Stratégie « select high » à l'avant et «select low» à l'arrière
  - Compromis entre distance d'arrêt et contrôle directionnel

Layout of ABS (Wong)

- 4-channel - 4-sensor system:
  - The independent control of the 4 wheels can lead to high yawing moments which are not favorable for directional control.
- 3-channel - 3-sensor system:
  - Rear axle controlled by average rear axle speed
  - Generally adopted on pick-up trucks
- 3 channel device - 4 sensors + "select low" strategy:
  - Result quite similar to the 4 channels - 4 sensors if "select low" strategy.
- 2-channel device - 4 sensors
  - Select high" strategy in the front and "select low" strategy in the back
  - Compromise between stopping distance and directional control

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