Car braking systems

Braking systems are indispensable for the roadworthiness and safe operation of a motor vehicle in road traffic conditions. They are therefore subject to strict legal requirements. The increasing effectiveness and sophistication demanded of braking systems over the course of time has meant that the mechanical systems have been continually improved. With the advent of microelectronics, the braking system has become a complex electronic system.

Overview

Car braking systems must perform the following fundamental tasks:
- Reduce the speed of the vehicle
- Bring the vehicle to a halt
- Prevent unwanted acceleration during downhill driving
- Keep the vehicle stationary when it is stopped

The first three of those tasks are performed by the service brakes. The driver controls the service brakes by operating the brake pedal. The parking brake ("hand brake") keeps the vehicle stationary once it is at a standstill.

Conventional braking systems

On conventional braking systems, the braking sequence is initiated exclusively by means of force applied to the brake pedal. In the braking system's master cylinder, that force is converted into hydraulic pressure. Brake fluid acts as the transmission medium between the master cylinder and the brakes (Figure 1).

On power-assisted braking systems such as are most frequently used on cars and light commercial vehicles, the actuation pressure is amplified by a brake servo unit (brake booster).

1 Example of a power-assisted car braking system

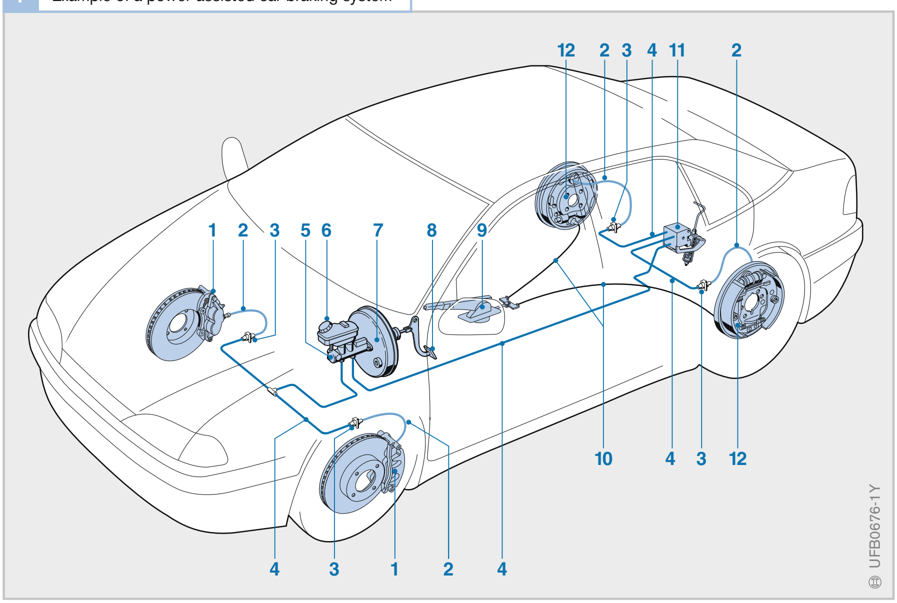

Fig. 1
1 Front brake (disc brake)
2 Brake hose
3 Connecting union between brake pipe and brake hose
4 Brake pipe
5 Master cylinder
6 Brake-fluid reservoir
7 Brake servo unit
8 Brake pedal
9 Handbrake lever
10 Brake cable (parking brake)
11 Braking-force reducer
12 Rear brake (drum brake in this case)

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Electronic braking systems

Antilock braking system (ABS)

An electronic braking system was first used on a volume-production vehicle in 1978. ABS (**A**ntilock **B**raking **S**ystem) prevents the wheels locking up and the vehicle becoming uncontrollable under heavy braking.

As with conventional systems, an ABS system has a mechanical link between the brake pedal and the brakes. But it also incorporates an additional component, the hydraulic modulator. Solenoid valves in the hydraulic modulator are controlled in such a way that if the degree of wheel slip exceeds a certain amount, the brake pressure in the individual wheel cylinders is selectively limited to prevent the wheels locking.

ABS has been continually improved and developed to the extent that it is now standard equipment on virtually all new vehicles sold in western Europe.

Electrohydraulic brakes (SBC)

SBC (**S**ensotronic **B**rake **C**ontrol) represents a new generation of braking systems. Under normal operating conditions, it has no mechanical link between the brake pedal and the wheel cylinders. The SBC electrohydraulic system detects the brake pedal travel electronically using duplicated sensor systems and analyses the sensor signals in an ECU. This method of operation is sometimes referred to as "brake by wire". The hydraulic modulator controls the pressure in the individual brakes by means of solenoid valves. Operation of the brakes is still effected hydraulically using brake fluid as the transmission medium.

Electromechanical brakes (EMB)

In the future there will be another electronic braking system, EMB (**E**lectro**m**echanical **B**rakes), which will operate electromechanically rather than employing hydraulics. Electric motors will force the brake pads against the discs in order to provide the braking action. The link between the brake pedal and the brakes will be purely electronic.

Electronic vehicle-dynamics systems

Continuing development of the ABS system led to the creation of TCS (**T**raction **C**ontrol **S**ystem). This system, which was first seen on volume-production cars in 1987, prevents wheel spin under acceleration and thus improves vehicle handling. Consequently, it is not a braking system in the strict sense of the word. Nevertheless, it makes use of and actively operates the braking system to prevent a wheel from spinning.

Another vehicle-dynamics system is the ESP (**E**lectronic **S**tability **P**rogram), which prevents the vehicle entering a skid within physically determined parameters. It too makes use of and actively controls the braking system in order to stabilise the vehicle.

Ancillary functions of electronic systems

Electronic processing of data also makes possible a number of ancillary functions that can be integrated in the overall electronic braking and vehicle-dynamics systems.

- **B**rake **A**ssistant (BA) increases brake pressure if the driver is hesitant in applying the full force of the brakes in an emergency.
- Electronic **B**raking-force distribution controls the braking force at the rear wheels so that the best possible balance between front and rear wheel braking is achieved.
- **H**ill **D**escent **C**ontrol (HDC) automatically brakes the vehicle on steep descents.

History of the brake

Origin and development

The first use of the wheel is dated to 5,000 B.C. Usually, cattle were used as draft animals; later, horses and donkeys were also used. The invention of the wheel made it necessary to invent the brake. After all, a horse-drawn carriage traveling downhill had to be slowed down, not only to keep its speed within controllable limits, but also to prevent it running into the back of the horses. This was likely done using wooden rods braced against the ground or the wheel disks. Beginning around 700 B.C., wheels acquired iron tires to prevent premature wear of the wheel rim.

Beginning in 1690, coach drivers used a "chock" to brake their carriages. While driving downhill, they used its handle push it under a wheel, which then was immobilized and slid onto the chock.

In 1817, at the dawn of the industrial age, Baron Karl Drais rode from Karlsruhe in southern Germany to Kehl, proving to a stunned public that it is possible to ride on two wheels without falling over. As he surely had difficulty stopping when driving downhill, his last, 1820 model featured a friction brake on the rear wheel (Fig. 1).

Finally, in 1850, the iron axle was introduced in carriage construction, along with the shoe brake. In this type of brake, brake shoes were pressed against the metallic running surface of the iron-coated wooden wheels. The shoe brake could be operated from the driver's seat with the aid of a crank handle and a gear linkage (Fig. 2).

The low speed and sluggish drive train of the first automobiles did not place any great demands on the effectiveness of the brakes. In the early days, the shoe, band and wedge brakes, which were manually or foot-operated using levers, hinges and cables on the fixed rear axles, were sufficient for this purpose.

At first, the rear wheels were braked; occasionally, an intermediate shaft or only the cardan shaft was braked. Only about 35 years after the automobile was invented were the front wheels equipped with (cable-operated) brakes. Even more years passed before automobiles began to be equipped with hydraulically operated brakes, which, at the time, were only drum brakes. Use of the old method of cable activation continued in a few models, such as the VW Beetle, until after World War II. Other important milestones were the use of disk brakes and, in the present era, the introduction and incremental development of various driving stability systems.

1 Baron Karl Drais' wheel with friction brake, 1820

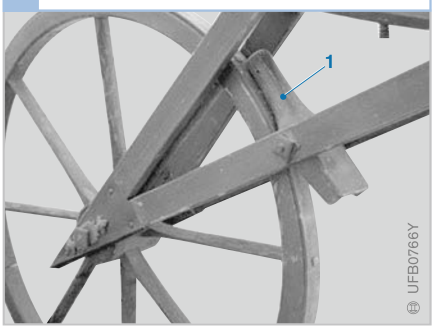
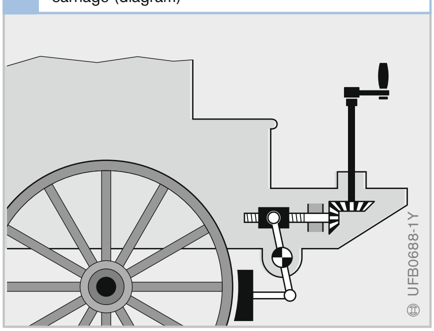


Fig. 1
1 Friction brake on wheel

2 Shoe brake with crank and linkage on a carriage (diagram)



Shoe and external shoe brakes on the wheel running surfaces

The first motor vehicles drove on wooden wheels with steel or rubber tires, or rubber-tired, spoked steel wheels. For braking, levers (as for the horse-drawn carriages) pushed brake shoes or external shoe brakes with friction linings against the running surfaces of the rear wheels. An initial example is the "riding carriage" developed by Gottlieb Daimler as an experimental vehicle in 1885 (the first motorcycle, with an engine performance of 0.5 horsepower and a top speed of 12 km/h). A cable led from the brake actuating lever, located at the front, close to the steering arm, to the *external shoe brake* on the rear wheel (Figures 3a, b).

In 1886, the first passenger cars with internal combustion engines were introduced: the Daimler motor carriage (1.1 hp, 16 km/h), which was derived from the horse carriage, and the Benz motorcar, which was newly designed as an automobile. Both of them had shoe brakes, as did the world's first truck, built in 1896. The shoe brake was installed in front of the rear wheels of each vehicle (Figures 3c, d, e, f.).

3 Historic motor vehicles and their wheel brakes (examples)

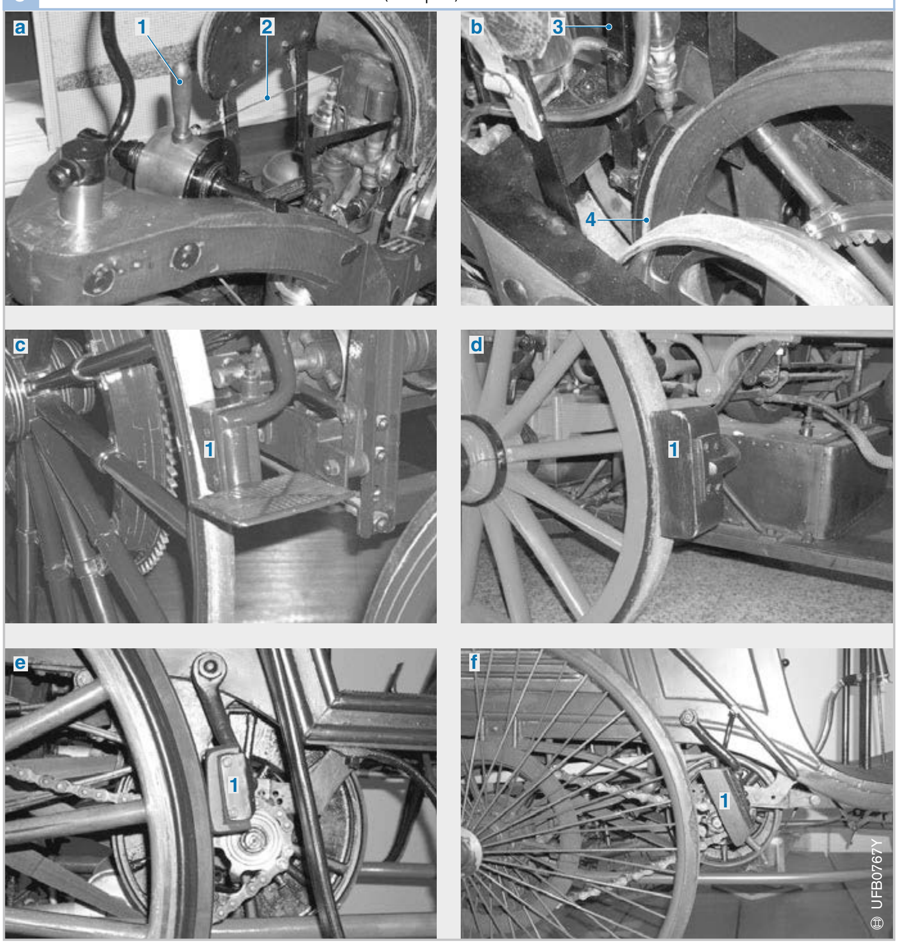


Fig. 3

a, b Daimler riding carriage 1885
1 Brake actuating lever
2 Cable to brake lever
3 Brake lever
4 External shoe brake on rear wheel

c Daimler motor carriage, 1886
1 Shoe brake, which also braked in "automatic" state when the flanged step was stepped on

d Daimler fire truck, 1890
1 Shoe brake

e Benz Viktoria, 1893
1 Shoe brake

f Benz Velo, 1894
1 Shoe brake

4 Daimler steel-wheeled car with band brake, 1889

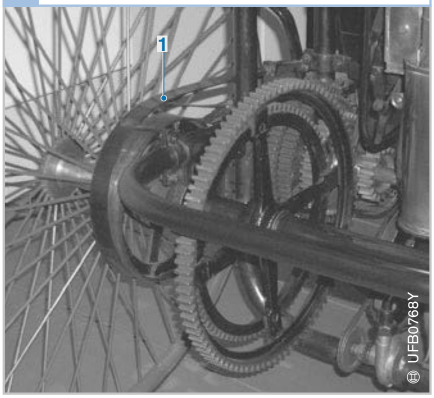


Fig. 4
1 Band brake on the rear axle

5 Daimler Phoenix, 1889, drive shaft (front view)

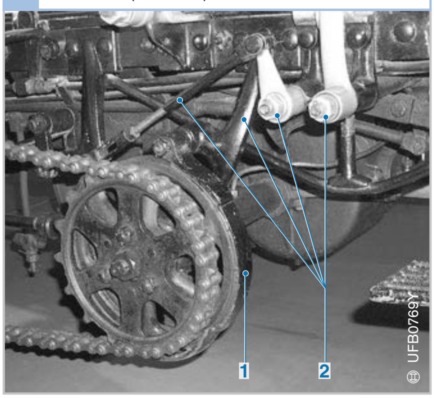


Fig. 5
1 External shoe brake, front section
2 Brake lever and brake linkage

6 Daimler Phoenix, 1889, drive shaft (rear view)

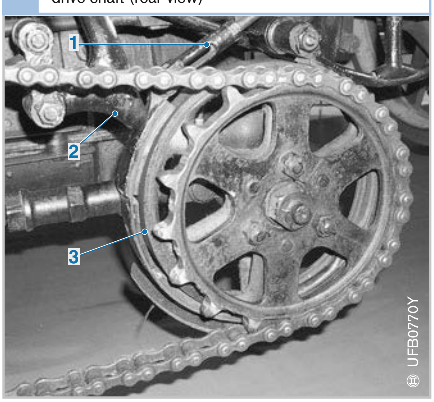


Fig. 6
1 Brake rod
2 Brake lever
3 External shoe brake, rear section

Band and external shoe brakes

As solid rubber tires quickly became established for motor vehicles (beginning with the triangular Benz motorcar in 1886 and the Daimler steel-wheeled car of 1889) and were soon replaced by air-filled rubber tires for a more comfortable ride, the era of the shoe brake in automobiles had already come to an end.

From then on, *band brakes* (flexible steel brake bands that braked either directly or via several brake shoes riveted to the inside) or *external shoe brakes* (rigid cast iron or steel brake shoes with brake linings) began to be used. These pedal-operated brakes worked with external brake drums that were normally installed at the front on the intermediate drive shaft or on the drive axle in the rear wheel area.

For example, the Fahrzeugfabrik Eisenach produced the first Wartburg motorcar in 1898. Model 1 featured an exposed transmission and drive pinions. *Band brakes* braked both the axle drive and the two rear wheels.

In 1899, the Daimler steel-wheeled car had solid rubber tires and *steel band brakes* on the rear wheels (Fig. 4). The Daimler "Phoenix", also dating from 1899, still had solid rubber tires, but these were soon replaced by air-filled tires. A footbrake acted as an *external shoe brake* on the front drive shaft (Figures 5 and 6), and the handbrake acted on the rear wheels. In addition, this car featured – as did, for example, the Benz racing car of 1899 (Fig. 7) – a "sprag brake", a strong rod mounted on the rear that had the purpose of being driven into the (usually relatively soft) road.

An excerpt from the original text of the user manual for the "Phaeton" by Benz & Co. Rheinische Gasmotoren-Fabrik A.G. Mannheim from 1902 reads as follows: "In addition to a handbrake attached to its left side, the car is braked primarily by depressing the left foot pedal, which acts as a band brake on the brake disks fastened to the two rear wheels. Simultaneously, as mentioned above, the belt is automatically moved out. To stop the car immediately, both the left and the right pedals are depressed at the same time, which causes the band brake connected to the right pedal to act on the brake disk and thus brake the reduction gear."

Internal shoe drum brakes with mechanical cable activation

Over time, vehicles became faster and heavier. Therefore, they required a more effective brake system. Thus band and external shoe brakes soon gave way to the *internal shoe drum brake,* for which Louis Renault applied for a patent in 1902. A spreading mechanism pushed two crescent-shaped brake shoes against the inner surface of the cast iron or steel brake drums, which were connected to the wheel. Due to its self-reinforcing effect, the drum brake features low operating forces compared to the braking forces, long maintenance periods and long-lasting linings.

At first, the braking force was transmitted to the two drum brakes of the rear wheels using brake cables.

For example, the Mercedes Simplex already featured additional, *cable-operated rear wheel drum brakes* (Fig. 8) in addition to the cardan shaft band brake. Due to higher engine performance (40 horsepower), a second footbrake (Fig. 9) was added, which also acted as a *band brake* on the intermediate shaft of the chain drive. By the way, all four brakes were cooled by a water spray which, during braking, dripped onto the friction surfaces from a reservoir.

Beginning in about 1920, vehicles were fitted with *drum brakes on all four wheels.* The braking force was still transmitted using mechanical means, i.e. *levers, joints and brake cables.*

7 Benz racecar, 1899, with external band brake and suspended "sprag brake"

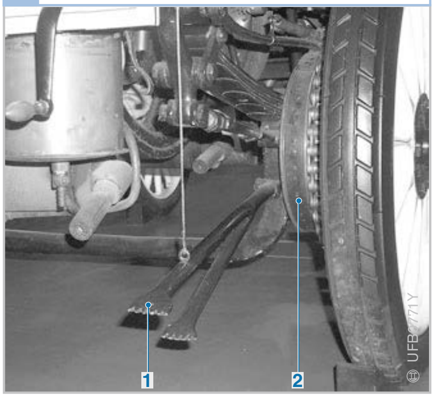


Fig. 7
1 "Sprag brake"
2 External band brake with brake shoes riveted to the inside

8 Daimler-Simplex, 1902, with cable-operated drum brake on the rear wheel

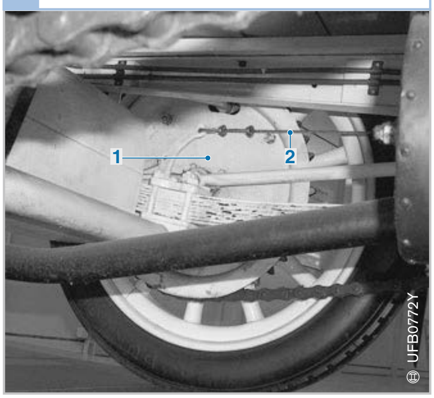


Fig. 8
1 Drum brake
2 Bowden cable

9 Daimler-Simplex, 1902, pedal and lever mechanism on the driver's seat

These cable-operated drum brakes remained in use for a long time. One example was the standard VW model of the 1950s (Fig. 10):

The primary element of this brake system was a brake pressure rail (Item 1). The four brake cables (2) attached to this element ran backwards through cable sleeves to the wheel brakes (drum brakes) of the four wheels (3). The rear part of the rail was supported by a short lever that sat on the brake pedal shaft. When the brake pedal of the footbrake (4) was depressed, the brake pressure rail was pushed forwards along with the four cables. The cables transmitted the force to the wheel brakes.

The lever for the handbrake (5) was further back in the car. However, via a decoupled rod, the handbrake ultimately acted on the same mechanism as the footbrake, and thus likewise acted on all four wheels.

10 Standard model VW, cable brake

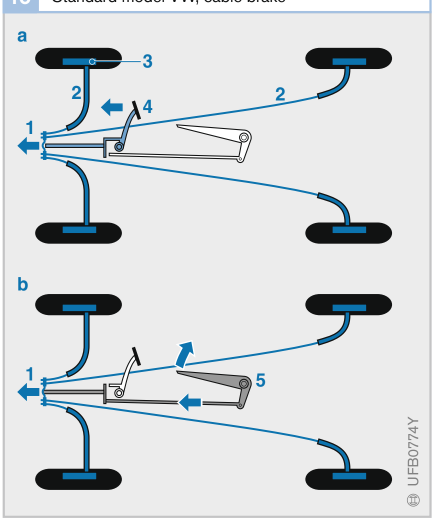


Fig. 10
- a Activation of the footbrake
- b Activation of the handbrake

1. Brake pressure rail
2. Brake cables
3. Wheel brakes
4. Brake pedal of the footbrake
5. Lever of the handbrake

Hydraulic brake activation

The main problem of the cable brake was the great maintenance effort and the uneven braking effect caused by uneven friction during mechanical transmission.

This was remedied when Lockheed introduced a hydraulically actuated brake in 1919. A special brake fluid now transmitted the brake pedal force uniformly to the actuating cylinders of the wheel brakes over metal lines and hoses, without the need for levers, joints and cables.

Hydraulic brake activation also made it possible to amplify the foot pressure applied by the driver by using intake manifold depression as a source of power for a brake servo system. The principle was patented in 1919 by Hispano-Suiza.

On commercial vehicles and railway rolling stock, air brakes established themselves as the system of choice.

In 1926, the “Adler Standard” was the first car in Europe to be equipped with a hydraulic brake system. The first hydraulic braking force reinforcement in auto racing were used in the Mercedes-Benz “Silver Arrows” in 1954. This ultimately became standard equipment for many mass-production vehicles.

Because a possible failure of the brake circuit could completely disable the early single-circuit brakes, the dual-circuit brake was later prescribed by law. According to VW Golf developer Dr. Ernst Fiala, the early “Beetles” (the standard model VWs) still had a cable-operated brake for that very reason: at the time it was feared that a hose in the hydraulic brakes could explode. Later, however – if only for competitive reasons – the VW Export and VW Transporter featured hydraulic braking systems.

Disk brake

Although British automaker Lancaster had patented the disk brake in 1902, it was a long time until this type of brake was introduced. Not until some fifty years later, beginning in 1955, did the legendary Citroën DS-19 become the first mass-produced car to be fitted with disk brakes. The disk brake was derived from the multi-plate brake and was initially developed for the aircraft industry.

In the disk brake, one brake lining presses the brake disk from the inside and outside. The brake disk (which is normally made of cast iron or, less commonly, of steel) is connected to the wheel. Its advantage is its simple and easy-to-assemble structure. It also counteracts the reduction in braking effect caused by overheating and prevents misalignment of the wheels of an axle.

The first German car with disk brakes on the front wheels was the BMW 502 in 1959. The first German cars to have disk brakes on all four wheels were the Mercedes 300 SE, the Lancia Flavia and the Fiat 2300 in 1961. Today, virtually all cars have a disk braking system, at least on the front wheels. In 1974, the first Formula 1 racecars with carbon fiber composite brake disks were introduced. These disks are considered especially light and heat resistant and thus have gained widespread use in motorsports and aviation.

Brake pads and shoes

Suitable brake linings had to be developed for drum and disk brakes, for which asbestos proved to be particularly effective. Not until it became known that asbestos fibers were harmful to health was the material replaced by plastic fiber.

Driving stability systems

The age of electronic brake systems dawned in 1978 with the arrival of the antilock braking system (ABS) for cars developed by Bosch. During braking, ABS provides early detection of the incipient lock of one or more wheels and prevents wheel locking. It ensures the steerability of the vehicle and substantially reduces the danger of skidding. In 1986, it was followed by the traction control system (TCS) with which Bosch extended system capability to the control of wheel spin under acceleration.
Fig. 11 shows road tests of these systems on the Bosch proving grounds in Boxberg in southern Germany.

As a further improvement of driving safety, Bosch introduced the electronic stability program (ESP) in 1995, which integrates the functions of ABS and TCS. It not only prevents the vehicle wheels from locking and spinning, it also keeps the vehicle from pulling to the side. Alternative systems, such as four-wheel steering and rear-axle kinematics, which were developed in the 1980s and 90s and were installed in some mass-production vehicles, did not catch on because they weighed too much, cost too much or were not effective enough.

Meanwhile, the (electrohydraulic) sensotronic brake control has found its place in automobile construction. It provides all of the ESP functions and decouples the mechanical operation of the brake pedal by means of an electronic control system. For safety purposes, a hydraulic fallback system is automatically available.

11 Steep uphill drive in the Bosch proving grounds in Boxberg for testing the driving stability systems of passenger cars and commercial vehicles

Classification of car braking systems

The entirety of the braking systems on a vehicle is referred to as braking equipment. Car braking systems can be classified on the basis of
- design and
- method of operation

Designs

Based on legal requirements, the functions of the braking equipment are shared among three braking systems:
- the service brakes,
- the secondary-brake system, and
- the parking brake

On commercial vehicles, the braking equipment also includes a continuous-operation braking system (e.g. retarder) that allows the driver to keep the vehicle at a steady speed on a long descent. The braking equipment of a commercial vehicle also includes an automatic braking system that operates the brakes of a trailer if it is detached from its towing vehicle either deliberately or by accident.

Service brakes

The service-brake system ("foot brake") is used to slow down the vehicle, to keep its speed constant on a descent, or to bring it completely to a halt.

The driver can infinitely vary the braking effect by means of the pressure applied to the brake pedal.
The service-brake system applies the brakes on all four wheels.

Secondary-brake system

The secondary-brake system must be capable of providing at least some degree of braking if the service-brake system fails. It must be possible to infinitely vary the level of braking applied.

The secondary-brake system does not have to be an entirely separate third braking system (in addition to the service brakes and the parking brake) with its own separate actuation device. It can consist of the remaining intact circuit of a dual-circuit service-brake system on which one circuit has failed, or it can be a parking-brake that is capable of graduated application.

Parking-brake system

The parking brake (hand brake) performs the third function required of the braking equipment. It must prevent the vehicle from moving when stopped or parked, even on a gradient and when the vehicle is unattended.

According to the legal requirements, the parking-brake system must also have an unbroken mechanical link, e.g. a rod linkage or a cable, between the actuation device and the brakes that it operates.
The parking-brake system is generally operated by means of a hand-brake lever positioned near the driver's seat, or in some cases by a foot pedal. This means that the service and parking-brake systems of a motor vehicle have separate actuation devices and means of force transmission.

The parking-brake system is capable of graduated application and operates the brakes on one pair of wheels (front or rear) only.

Methods of operation

Depending on whether they are operated entirely or partially by human effort or by another source of energy, braking systems can be classed either as

- muscular-energy (unassisted) braking systems,
- power-assisted braking systems, or
- power-brake systems,

Muscular-energy braking systems

On this type of braking system frequently found on cars and motorcycles, the effort applied to the brake pedal or hand-brake lever is transmitted to the brakes either mechanically (by means of a rod linkage or cable) or hydraulically. The energy by which the braking force is generated is produced entirely by the physical strength of the driver.

Power-assisted braking systems

The power-assisted braking system is the type most commonly used on cars and light commercial vehicles.
It amplifies the force applied by the driver by means of a brake servo which utilises another source of energy (vacuum or hydraulic power). The amplified muscle power is transmitted hydraulically to the brakes.

Power-brake systems

Power-brake systems are generally used on commercial vehicles but are occasionally fitted on large cars in conjunction with an integral ABS facility. This type of braking system is operated entirely without muscular-energy.

The system is operated by hydraulic power (which is based on fluid pressure) transmitted by hydraulic means. The brake fluid is stored in energy accumulators (hydraulic accumulators) which also contain a compressed gas (usually nitrogen). The gas and the fluid are kept apart by a flexible diaphragm (diaphragm accumulator) or a piston with a rubber seal (piston accumulator). A hydraulic pump generates the fluid pressure, which is always in equilibrium with the gas pressure in the energy accumulator. A pressure regulator switches the hydraulic pump to idle as soon as the maximum pressure is reached.

Since brake fluid can be regarded as practically incompressible, small volumes of brake fluid can transmit large brake-system pressures.

Components of a car braking system

Figure 1 shows the schematic layout of a car braking system. It consists of the following main component groups:

- Energy supply system,
- Actuation device,
- Force transmission system, and
- Wheel brakes.

Energy supply system

The energy supply system encompasses those parts of the braking system that provide, control and (in some cases) condition the energy required to operate the brakes. It ends at the point where the force transmission system begins, i.e. where the various circuits of the braking system are isolated from the energy supply system or from each other.

Car braking systems are in the main power-assisted braking systems in which the physical effort of the driver, amplified by the vacuum in the brake servo unit, provides the energy for braking.

Actuation device

The actuation device encompasses those parts of a braking system that are used to initiate and control the action of that braking system. The control signal may be transmitted within the actuation device, and the use of an additional energy source is also possible.

The actuation device starts at the point at which the actuation force is directly applied. It may be operated in the following ways:

- by direct application of force by hand or foot by the driver,
- by indirect control of force by the driver.

The actuation device ends at the point where distribution of the braking-system energy begins or where a portion of that energy is diverted for the purpose of controlling braking. Among the essential components of the actuation device are the vacuum servo unit and the master cylinder.

Force transmission system

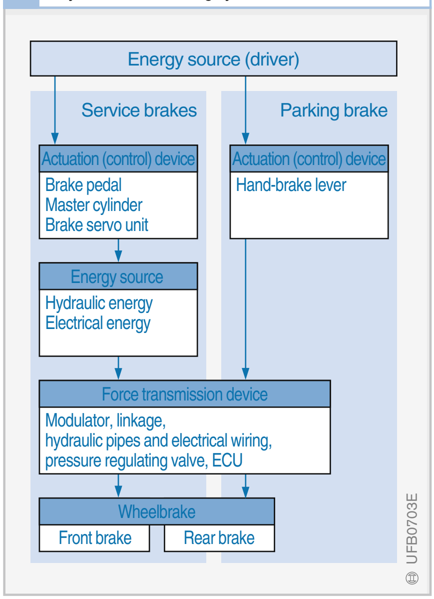
The force transmission system encompasses those parts of the braking system that transmit the energy introduced by the energy supply system(s) and controlled by the actuation device. It starts at the point where the actuation device and the energy supply system end. It ends at the point where it interfaces with those parts of the braking system that generate the forces that inhibit or retard vehicle motion. It may be mechanical or hydromechanical in design.

The components of the force transmission system include the transmission medium, hoses, pipes and, on some systems, a pressure regulating valve for limiting the braking force at the rear wheels.

Wheelbrakes

The wheelbrakes consist of those parts of the braking system in which the forces that inhibit or retard the movement of the vehicle are generated. On car braking systems, they are friction brakes (disc or drum brakes).

1 Layout of a car braking system



Brake-circuit configuration

Legal requirements demand that braking systems incorporate a dual-circuit forcetransmission system.

According to DIN 74 000, there are five ways in which the two brake circuits can be split (Figure 1). It uses the following combinations of letters to designate the five different configurations: II, X, HI, LL and HH. Those letters are chosen because their shapes roughly approximate to the layout of the brake lines connecting the master cylinder and the brakes.

Of those five possibilities, the II and X configurations, which involve the minimum amount of brake piping, hoses, disconnectable joints and static or dynamic seals, have become the most widely established. That characteristic means that the risk of failure of each of the individual circuits due to fluid leakage is as low as it is for a single-circuit braking system. In the event of brake-circuit failure due to overheating of one of the brakes, the HI, LL and HH configurations have a critical weakness because the connection of individual brakes to both circuits means that failure of one brake can result in total failure of the braking system as a whole.

In order to satisfy the legal requirements regarding secondary-braking effectiveness, vehicles with a forward weight-distribution bias are fitted with the X configuration. The II configuration is particularly suited to use on cars with a rearward weight-distribution bias.

II configuration

This layout involves a front-axle/rear-axle split – one circuit operates the rear brakes, the other operates the front brakes.

X configuration

This layout involves a diagonal split – each circuit operates one front brake and its diagonally opposed rear brake.

HI configuration

This layout involves a front/front-and-rear split - one brake circuit operates the front and rear brakes, the other operates only the front brakes.

LL configuration

This arrangement involves a two-front/one-rear split. Each circuit operates both front wheels and one rear wheel.

HH configuration

The circuits are split front-and-rear/front-and-rear. Each circuit operates all four wheels.

1 Brake-circuit configuration

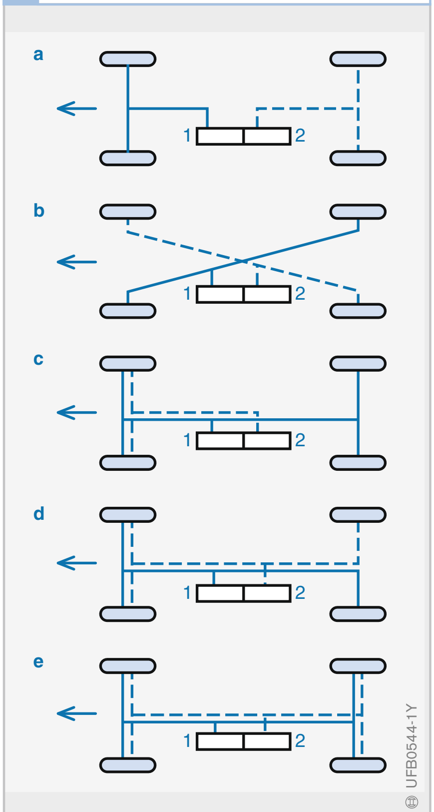


Fig. 1
a II configuration
b X configuration
c HI configuration
d LL configuration
e HH configuration
1 Brake circuit 1
2 Brake circuit 2
← Direction of travel