



# Automobile Steering and Brake Technologies

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# Table of Contents

- Chapter 1 - Steering and Vehicle Brake
- Chapter 2 - Power Steering
- Chapter 3 - Ackermann Steering Geometry and Caster Angle
- Chapter 4 - Kingpin (Automotive Part) and Oversteer
- Chapter 5 - Torque Steering and Understeer
- Chapter 6 - Automatic Braking and Brake Bleeding
- Chapter 7 - Anti-Lock Braking System
- Chapter 8 - Brake Fade and Brake Fluid
- Chapter 9 - Brake Lining and Electronic Brakeforce Distribution
- Chapter 10 - Disc Brake
- Chapter 11 - Electronic Stability Control
- Chapter 12 - Engine Braking and Vacuum Servo
- Chapter 13 - Regenerative Brake
- Chapter 14 - Inboard Brake and Hydraulic Brake
- Chapter 15 - Parking Brake

## Chapter 1

# Steering and Vehicle Brake

## Steering

**Steering** is the term applied to the collection of components, linkages, etc. which will allow a vessel (ship, boat) or vehicle (car, motorcycle, bicycle) to follow the desired course. An exception is the case of rail transport by which rail tracks combined together with railroad switches (and also known as 'points' in British English) provide the steering function.



Part of car steering mechanism: tie rod, steering arm, king pin axis (using ball joints).

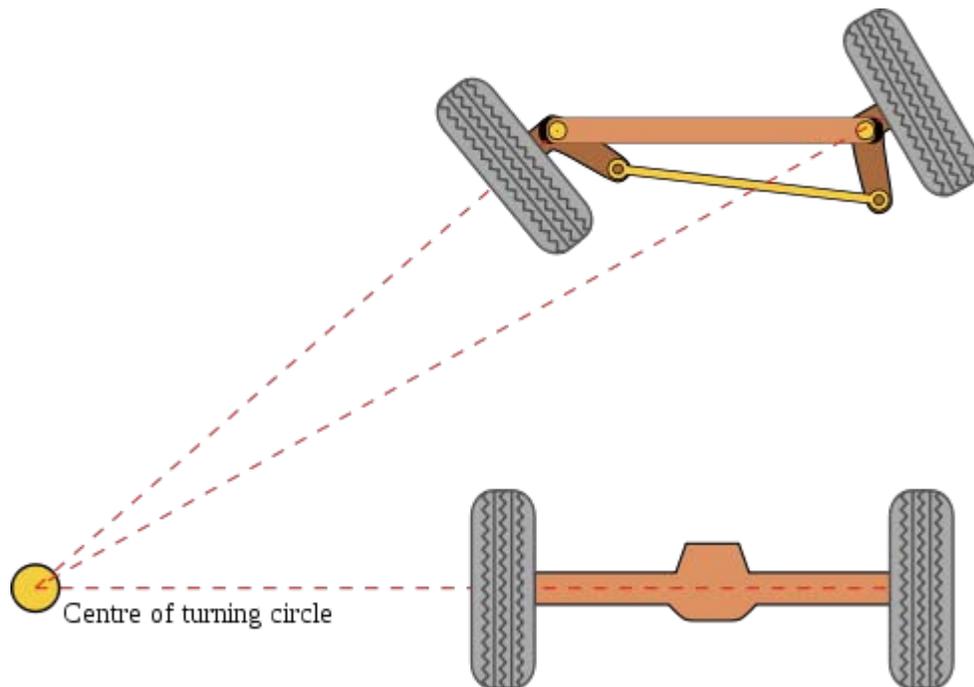
## Introduction

The most conventional steering arrangement is to turn the front wheels using a hand-operated steering wheel which is positioned in front of the driver, via the steering column, which may contain universal joints (which may also be part of the collapsible steering column design), to allow it to deviate somewhat from a straight line. Other arrangements are sometimes found on different types of vehicles, for example, a tiller or rear-wheel steering. Tracked vehicles such as tanks usually employ differential steering — that is, the tracks are made to move at different speeds or even in opposite directions to bring about a change of course or direction.

## Wheeled vehicle steering

### Basic geometry

The basic aim of steering is to ensure that the wheels are pointing in the desired directions. This is typically achieved by a series of linkages, rods, pivots and gears. One of the fundamental concepts is that of *caster angle*- each wheel is steered with a pivot point ahead of the wheel; this makes the steering tend to be self-centering towards the direction travel.

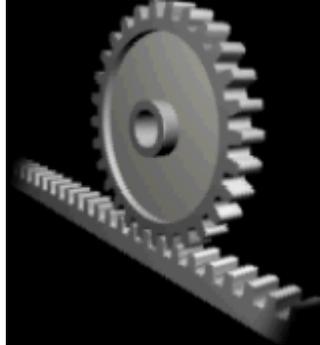


Ackermann steering geometry

The steering linkages connecting the steering box and the wheels usually conform to a variation of Ackermann steering geometry, to account for the fact that in a turn, the inner

wheel is actually travelling a path of smaller radius than the outer wheel, so that the degree of toe suitable for driving in a straight path is not suitable for turns.

### **Rack and pinion, recirculating ball, worm and sector**



Rack and pinion



Rack and pinion unit mounted in the cockpit of an Ariel Atom sports car chassis. For most high volume production, this is usually mounted on the other side of this panel

Many modern cars use rack and pinion steering mechanisms, where the steering wheel turns the pinion gear; the pinion moves the rack, which is a linear gear that meshes with

the pinion, converting circular motion into linear motion along the transverse axis of the car (side to side motion). This motion applies steering torque to the swivel pin ball joints that replaced previously used kingpins of the stub axle of the steered wheels via tie rods and a short lever arm called the steering arm.

The rack and pinion design has the advantages of a large degree of feedback and direct steering "feel". A disadvantage is that it is not adjustable, so that when it does wear and develop lash, the only cure is replacement.

Older designs often use the recirculating ball mechanism, which is still found on trucks and utility vehicles. This is a variation on the older worm and sector design; the steering column turns a large screw (the "worm gear") which meshes with a sector of a gear, causing it to rotate about its axis as the worm gear is turned; an arm attached to the axis of the sector moves the Pitman arm, which is connected to the steering linkage and thus steers the wheels. The recirculating ball version of this apparatus reduces the considerable friction by placing large ball bearings between the teeth of the worm and those of the screw; at either end of the apparatus the balls exit from between the two pieces into a channel internal to the box which connects them with the other end of the apparatus, thus they are "recirculated".

The recirculating ball mechanism has the advantage of a much greater mechanical advantage, so that it was found on larger, heavier vehicles while the rack and pinion was originally limited to smaller and lighter ones; due to the almost universal adoption of power steering, however, this is no longer an important advantage, leading to the increasing use of rack and pinion on newer cars. The recirculating ball design also has a perceptible lash, or "dead spot" on center, where a minute turn of the steering wheel in either direction does not move the steering apparatus; this is easily adjustable via a screw on the end of the steering box to account for wear, but it cannot be entirely eliminated because it will create excessive internal forces at other positions and the mechanism will wear very rapidly. This design is still in use in trucks and other large vehicles, where rapidity of steering and direct feel are less important than robustness, maintainability, and mechanical advantage. The much smaller degree of feedback with this design can also sometimes be an advantage; drivers of vehicles with rack and pinion steering can have their thumbs broken when a front wheel hits a bump, causing the steering wheel to kick to one side suddenly (leading to driving instructors telling students to keep their thumbs on the front of the steering wheel, rather than wrapping around the inside of the rim). This effect is even stronger with a heavy vehicle like a truck; recirculating ball steering prevents this degree of feedback, just as it prevents desirable feedback under normal circumstances.

The worm and sector was an older design, used for example in Willys and Chrysler vehicles, and the Ford Falcon (1960s).

Other systems for steering exist, but are uncommon on road vehicles. Children's toys and go karts often use a very direct linkage in the form of a bellcrank (also commonly known as a Pitman arm) attached directly between the steering column and the steering arms,

and the use of cable-operated steering linkages (e.g. the Capstan and Bowstring mechanism) is also found on some home-built vehicles such as soapbox cars and recumbent tricycles.

## **Power steering**

Power steering, assists the driver of an automobile in steering by directing a portion of the vehicle's power to traverse the axis of one or more of the roadwheels. As vehicles have become heavier and switched to front wheel drive, particularly using negative offset geometry, along with increases in tire width and diameter, the effort needed to turn the steering wheel manually has increased — often to the point where major physical exertion is required. To alleviate this, auto makers have developed power steering systems: or more correctly power-assisted steering — on road going vehicles there has to be a mechanical linkage as a fail safe. There are two types of power steering systems—hydraulic and electric/electronic. A hydraulic-electric hybrid system is also possible.

A hydraulic power steering (HPS) uses hydraulic pressure supplied by an engine-driven pump to assist the motion of turning the steering wheel. Electric power steering (EPS) is more efficient than the hydraulic power steering, since the electric power steering motor only needs to provide assistance when the steering wheel is turned, whereas the hydraulic pump must run constantly. In EPS, the assist level is easily tunable to the vehicle type, road speed, and even driver preference. An added benefit is the elimination of environmental hazard posed by leakage and disposal of hydraulic power steering fluid. Also in the event of the engine cutting out, assist will not be lost - whereas hydraulic will stop working, as well as making the steering doubly heavy as the driver has to turn the power-assist mechanism on top of the steering system itself.

## **Speed Sensitive Steering**

An outgrowth of power steering is speed sensitive steering, where the steering is heavily assisted at low speed and lightly assisted at high speed. The auto makers perceive that motorists might need to make large steering inputs while manoeuvring for parking, but not while traveling at high speed. The first vehicle with this feature was the Citroën SM with its Diravi layout, although rather than altering the amount of assistance as in modern power steering systems, it altered the pressure on a centring cam which made the steering wheel try to "spring" back to the straight-ahead position. Modern speed-sensitive power steering systems reduce the mechanical or electrical assistance as the vehicle speed increases, giving a more direct feel. This feature is gradually becoming more common.

## **Four-wheel steering**

Four-wheel steering (or all-wheel steering) is a system employed by some vehicles to improve steering response, increase vehicle stability while maneuvering at high speed, or to decrease turning radius at low speed.



Sierra Denali with QuadraSteer, rear steering angle

In most *active* four-wheel steering systems, the rear wheels are steered by a computer and actuators. The rear wheels generally cannot turn as far as the front wheels. Some systems, including Delphi's QuadraSteer and the system in Honda's Prelude line, allow the rear wheels to be steered in the opposite direction as the front wheels during low speeds. This allows the vehicle to turn in a significantly smaller radius — sometimes critical for large trucks or tractors and vehicles with trailers.

Many modern vehicles offer a form of *passive* rear steering to counteract normal vehicle tendencies. For example, Subaru used a passive steering system to correct for the rear wheel's tendency to toe-out. On many vehicles, when cornering, the rear wheels tend to steer slightly to the outside of a turn, which can reduce stability. The passive steering system uses the lateral forces generated in a turn (through suspension geometry) and the bushings to correct this tendency and steer the wheels slightly to the inside of the corner. This improves the stability of the car, through the turn. This effect is called compliance understeer and it, or its opposite, is present on all suspensions. Typical methods of achieving compliance understeer are to use a Watt's Link on a live rear axle, or the use of toe control bushings on a twist beam suspension. On an independent rear suspension it is normally achieved by changing the rates of the rubber bushings in the suspension. Some suspensions will always have compliance oversteer due to geometry, such as Hotchkiss live axles or a semi-trailing arm IRS.

Passive rear wheel steering is not a new concept, as it has been in use for many years, although not always recognised as such. For example, Jaguar independent rear suspension incorporated a small amount of passive rear wheel steering since 1961.

### **Recent application**

In an active four-wheel steering system, all four wheels turn at the same time when the driver steers. There can be controls to switch off the rear steer and options to steer only the rear wheel independent of the front wheels. At slow speeds (*e.g.* parking) the rear wheels turn opposite of the front wheels, reducing the turning radius by up to twenty-five percent, while at higher speeds both front and rear wheels turn alike (electronically controlled), so that the vehicle may change position with less yaw, enhancing straight-line stability. The "Snaking effect" experienced during motorway drives while towing a travel trailer is thus largely nullified. Four-wheel steering found its most widespread use in monster trucks, where maneuverability in small arenas is critical, and it is also popular in large farm vehicles and trucks. Some of the modern European Intercity buses also utilize four-wheel steering to assist maneuverability in bus terminals, and also to improve road stability.

General Motors offers Delphi's Quadrasteer in their consumer Silverado/Sierra and Suburban/Yukon. However, only 16,500 vehicles have been sold with this system since its introduction in 2002 through 2004. Due to this low demand, GM discontinued the technology at the end of the 2005 model year.

Previously, Honda had four-wheel steering as an option in their 1987-2000 Prelude, and Mazda also offered four-wheel steering on the 626 and MX6 in 1988.

A new "Active Drive" system is introduced on the 2008 version of the Renault Laguna line. It was designed as one of several measures to increase security and stability. The Active Drive should lower the effects of under steer and decrease the chances of spinning by diverting part of the G-forces generated in a turn from the front to the rear tires. At low speeds the turning circle can be tightened so parking and maneuvering is easier.

## Articulated steering



A front loader with articulated steering.

Articulated steering is a system by which a four-wheel drive vehicle is split into front and rear halves which are connected by a vertical hinge. The front and rear halves are connected with one or more hydraulic cylinders that change the angle between the halves, including the front and rear axles and wheels, thus steering the vehicle. This system does not use steering arms, king pins, tie rods, etc. as does four-wheel steering. If the vertical hinge is placed equidistant between the two axles, it also eliminates the need for a central differential, as both front and rear axles will follow the same path, and thus rotate at the same speed.

## Rear wheel steering

A few types of vehicle use rear wheel steering, notably fork lift trucks, early pay loaders, Buckminster Fuller's Dymaxion car, and the ThrustSSC.

Rear wheel steering can tend to be unstable because in turns the steering geometry tends to decrease the turn radius (oversteer), rather than increase it (understeer). A rear wheel steered automobile exhibits non-minimum phase behavior. It turns in the direction opposite of how it is initially steered. A rapid steering input will cause two accelerations, first in the direction that the wheel is steered, and then in the opposite direction: a

"reverse response." This makes it harder to steer a rear wheel steered vehicle at high speed than a front wheel steered vehicle.

## **Steer-by-wire**

The aim of *steer-by-wire* technology is to completely do away with as many mechanical components (steering shaft, column, gear reduction mechanism, etc.) as possible. Completely replacing conventional steering system with steer-by-wire holds several advantages, such as:

- The absence of steering column simplifies the car interior design.
- The absence of steering shaft, column and gear reduction mechanism allows much better space utilization in the engine compartment.
- The steering mechanism can be designed and installed as a modular unit.
- Without mechanical connection between the steering wheel and the road wheel, it is less likely that the impact of a frontal crash will force the steering wheel to intrude into the driver's survival space.
- Steering system characteristics can easily and infinitely be adjusted to optimize the steering response and feel.

As of 2007 there are no production cars available that rely solely on steer-by-wire technology due to safety, reliability and economic concerns, but this technology has been demonstrated in numerous concept cars and the similar *fly-by-wire* technology is in use in both military and civilian aviation applications. Removing the mechanical steering linkage in road going vehicles would require new legislation in most countries.

## **Safety**

For safety reasons all modern cars feature a collapsible steering column (energy absorbing steering column) which will collapse in the event of a heavy frontal impact to avoid excessive injuries to the driver. Airbags are also generally fitted as standard. Non-collapsible steering columns fitted to older vehicles very often impaled drivers in frontal crashes, particularly when the steering box or rack was mounted in front of the front axle line, at the front of the crumple zone. This was particularly a problem on vehicles that had a rigid separate chassis frame, with no crumple zone. Most modern vehicle steering boxes/racks are mounted behind the front axle on the front bulkhead, at the rear of the front crumple zone.

Audi used a retractable steering wheel and seat belt tensioning system called procon-ten, but it has since been discontinued in favor of airbags and pyrotechnic seat belt pretensioners.

Collapsible steering columns were invented by Bela Barenyi and were introduced in the 1959 Mercedes-Benz W111 Fintail, along with Crumple zones.

This safety feature first appeared on cars built by General Motors after an extensive and very public lobbying campaign enacted by Ralph Nader.

Ford started to install collapsible steering columns in 1968.

## **Cycles**

Steering is crucial to the stability of bicycles and motorcycles.

## ***Ship and boat steering***

Ships and boats are usually steered with a rudder. Depending on the size of the vessel, rudders can be manually actuated, or operated using a servomechanism, or a trim tab/servo tab system.

# **Vehicle brake**

A **vehicle brake** is a brake used to slow down a vehicle by converting its kinetic energy into heat. The basic hydraulic system, most commonly used, usually has six main stages. The brake pedal, the brake boost (vacuum servo), the master cylinder, the apportioning valves and finally the roadwheel brakes themselves.

## ***Friction brake***

A friction brake is a type of automotive brake that slows or stops a vehicle by converting kinetic energy into heat energy, via friction. The heat energy is then dissipated into the atmosphere. In most systems, the brake acts on the vehicle's roadwheel hubs, but some vehicles use brakes which act on the axles or transmission. Friction brakes may be of either drum or disc type.

## **Drum brake**

A drum brake is a brake in which the friction is caused by a set of brake shoes that press against the inner surface of a rotating drum. The drum is connected to the rotating roadwheel hub.

## **Disc brake**

The disc brake is a device for slowing or stopping the rotation of a roadwheel. A brake disc (or rotor in U.S. English), usually made of cast iron or ceramic, is connected to the wheel or the axle. To stop the wheel, friction material in the form of brake pads (mounted in a device called a brake caliper) is forced mechanically, hydraulically, pneumatically or electromagnetically against both sides of the disc. Friction causes the disc and attached wheel to slow or stop.

## ***Electromagnetic brake***

Electromagnetic brakes slow an object through electromagnetic induction, which creates resistance and in turn either heat or electricity. Friction brakes apply pressure on two separate objects to slow the vehicle in a controlled manner.

## Chapter 2

# Power Steering

The term **power steering** is usually used to describe a system that provides mechanical steering assistance to the driver of a land vehicle, for example, a car or truck. The power steering system in a vehicle is a type of servomechanism.

For many drivers, turning the steering wheel in a vehicle that doesn't have power steering requires more force (torque) than the driver finds comfortable, especially when the vehicle is moving at a very slow speed. Steering force is very sensitive to the weight of the vehicle, and nearly so much to its length, so this is most important for large vehicles. In a vehicle equipped with power steering, when the driver turns the steering wheel, he feels only a slight retarding force, so a vehicle equipped with power steering can be driven by any healthy driver, even when the vehicle is being parked. This is because the power steering system furnishes most of the energy required to turn the steered wheels of the car.

Most power steering systems in cars and light trucks today are hydraulic (that is, the force to turn the wheels is provided by a hydraulic piston, which is powered by high pressure hydraulic fluid), but in some cars and trucks, the steering force is provided by an electric motor.

### ***History***

A steam-powered ship's steering engine, similar in many ways to the power steering system used in modern cars and trucks, was first installed in the SS Great Eastern in 1866.

The earliest known patent for a power steering system for a land vehicle was granted to Frederick W. Lanchester in the UK in February 1902. His invention was to "cause the steering mechanism to be actuated by hydraulic power". R.E. Twyford included a mechanical power steering mechanism as part of his patent for the first four wheel drive

system (U.S. Patent 646,477 April 3, 1900). The next design was filed as recorded by the US Patent Office on August 30, 1932, by Klara Gailis, from Belmont, Massachusetts. There is another inventor credited with the invention of power steering by the name of Charles F. Hammond an American, born in Detroit, who filed similar patents, the first of which was filed as recorded by the Canadian Intellectual Property Office.

Francis W. Davis, an engineer of the truck division of Pierce Arrow began exploring how steering could be made easier, and in 1926 demonstrated the first power steering system. Davis moved to General Motors and refined the hydraulic-assisted power steering system, but the automaker calculated it would be too expensive to produce. Davis then signed up with Bendix, a parts manufacturer for automakers. Military needs during World War II for easier steering on heavy vehicles boosted the need for power assistance on armored cars and tank-recovery vehicles for the British and American armies.

Chrysler Corporation introduced the first commercially available passenger car power steering system on the 1951 Chrysler Imperial under the name "Hydraguide". The Chrysler system was based on some of Davis' expired patents. General Motors introduced the 1952 Cadillac with a power steering system using the work Davis had done for the company almost twenty years earlier.

Most new vehicles now have power steering, owing to the trends toward front wheel drive, greater vehicle mass, and wider tires, which all increase the required steering effort. Heavier vehicles as common in some countries would be extremely difficult to maneuver at low speeds, while vehicles of lighter weight may not need power assisted steering at all.

## ***Hydraulic systems***



A power steering fluid reservoir and pulley driven pump

Most power steering systems work by using a hydraulic system to turn the vehicle's wheels. The hydraulic pressure is usually provided by a gerotor or rotary vane pump driven by the vehicle's engine. A double-acting hydraulic cylinder applies a force to the steering gear, which in turn applies a torque to the steering axis of the roadwheels. The flow to the cylinder is controlled by valves operated by the steering wheel; the more torque the driver applies to the steering wheel and the shaft it is attached to, the more fluid the valves allow through to the cylinder, and so the more force is applied to steer the wheels in the appropriate direction.

One design for measuring the torque applied to the steering wheel is to fix a torsion bar to the end of the steering shaft. As the steering wheel rotates, so does the attached steering shaft, and so does the top end of the attached torsion bar. Since the torsion bar is relatively thin and flexible and the bottom end is not completely free to rotate, the bar will soak up some of the torque; the bottom end will not rotate as far as the top end. The difference in rotation between the top and bottom ends of the torsion bar can be used to control the valve that allows fluid to flow to the cylinder which provides steering assistance; the greater the "twist" of the torsion bar, the more steering assistance will be provided.

Since the pumps employed are of the positive displacement type, the flow rate they deliver is directly proportional to the speed of the engine. This means that at high engine speeds the steering would naturally operate faster than at low engine speeds. Because this would be undesirable, a restricting orifice and flow control valve are used to direct some of the pump's output back to the hydraulic reservoir at high engine speeds. A pressure relief valve is also used to prevent a dangerous build-up of pressure when the hydraulic cylinder's piston reaches the end of the cylinder.

Some modern implementations also include an electronic pressure relief valve which can reduce the hydraulic pressure in the power steering lines as the vehicle's speed increases (this is known as variable assist power steering).

Some heavy machines use hydraulic-only systems where there is no backup if the pump motor fails.

## **DIRAVI**

In the DIRAVI system invented by Citroën, the force turning the wheels comes from the car's high pressure hydraulic system and is always the same no matter what the road speed is. As the steering wheel is turned, the wheels are turned simultaneously to a corresponding angle by a hydraulic piston. In order to give some artificial steering feel, there is a separate hydraulically operated system that tries to turn the steering wheel back to centre position. The amount of pressure applied is proportional to road speed, so that at low speeds the steering is very light, and at high speeds it is very difficult to move more than a small amount from the centre position.

As long as there is pressure in the car's hydraulic system, there is no mechanical connection between the steering wheel and the roadwheels. This system was first introduced in the Citroën SM in 1970, and was known as 'VariPower' in the UK and 'SpeedFeel' in the U.S.

While DIRAVI is not the mechanical template for all modern power steering arrangements, it did innovate the now common benefit of speed sensitive steering. The force of the centering device increases as the car's road speed increases.

In the late 1960s, General Motors offered a variable ratio power steering system as an option on Pontiac and other vehicles.

### ***Electro-hydraulic systems***

Electro-hydraulic power steering systems, sometimes abbreviated EHPS, and also sometimes called "hybrid" systems, use the same hydraulic assist technology as standard systems, but the hydraulic pressure is provided by a pump driven by an electric motor instead of being belt-driven by the engine.

In 1965, Ford experimented with a fleet of "wrist-twist instant steering" equipped Mercury Park Lanes that replaced the conventional large steering wheel with two 5-inch (127 mm) rings, a fast 15:1 gear ratio, and an electric hydraulic pump in case the engine stalled.

In 1990, Toyota introduced its second-generation MR2 with electro-hydraulic power steering. This was to avoid running hydraulic lines from the engine (which were located behind the driver in the MR2) up to the steering rack. In 1994 Volkswagen produced the Mark 3 Golf Ecomatic, which utilized an electric pump so that the power steering could operate while the engine had been turned off by the computer to save fuel. Electro-hydraulic systems can be found in some cars by Ford, Volkswagen, Audi, Peugeot, Citroen, SEAT, Skoda, Suzuki, Opel, MINI, Toyota, Honda, and Mazda.

### **Servotronic**

Servotronic offers true speed-dependent power steering, in which the amount of servo assist depends on road speed, and thus provides even more comfort for the driver. The amount of power assist is greatest at low speeds, for example when parking the car. The greater assist makes it easier to maneuver the car. At higher speeds, an electronic sensing system gradually reduces the level of power assist. In this way, the driver can control the car even more precisely than with conventional power steering. Servotronic is used by a number of automakers, including Audi, General Motors, BMW, Volkswagen, Volvo, SEAT and Porsche. Servotronic is a trademark of AM General Corp.

### ***Electric systems***

**Electric power steering (EPS or EPAS)** is designed to use an electric motor to reduce effort by providing steering assist to the driver of a vehicle. Sensors detect the motion and torque of the steering column, and a computer module applies assistive torque via an electric motor coupled directly to either the steering gear or steering column. This allows varying amounts of assistance to be applied depending on driving conditions. The system allows engineers to tailor steering-gear response to variable-rate and variable-damping suspension systems achieving an ideal blend of ride, handling, and steering for each vehicle. On Fiat group cars the amount of assistance can be regulated using a button named "CITY" that switches between two different assist curves, while most other EPS systems have variable assist, which allows for more assistance as the speed of a vehicle

decreases and less assistance from the system during high-speed situations. In the event of component failure, a mechanical linkage such as a rack and pinion serves as a back-up in a manner similar to that of hydraulic systems. Electric power steering should not be confused with drive-by-wire or steer-by-wire systems which use electric motors for steering, but without any mechanical linkage to the steering wheel.

Electric systems have a slight advantage in fuel efficiency because there is no belt-driven hydraulic pump constantly running, whether assistance is required or not, and this is a major reason for their introduction. Another major advantage is the elimination of a belt-driven engine accessory, and several high-pressure hydraulic hoses between the hydraulic pump, mounted on the engine, and the steering gear, mounted on the chassis. This greatly simplifies manufacturing and maintenance. By incorporating electronic stability control electric power steering systems can instantly vary torque assist levels to aid the driver in evasive manoeuvres.

The first electric power steering systems appeared on the Honda NSX in 1990, the FIAT Punto Mk2 in 1999, the Honda S2000 in 1999, and on the BMW Z4 in 2002. Today a number of manufacturers use electric power steering.

Reviews in the automotive press often comment that certain steering systems with electric assist do not have a satisfactory amount of "road feel". Road feel refers to the relationship between the force needed to steer the vehicle and the force that the driver exerts on the steering wheel. Road feel gives the driver the subjective perception that they are engaged in steering the vehicle. The amount of road feel is controlled by the computer module that operates the electric power steering system. In theory, the software should be able to adjust the amount of road feel to satisfy drivers. In practice, it has been difficult to reconcile various design constraints while producing a more pronounced road feel. The same argument has been applied to hydraulic power steering as well.

### **Variable gear ratios**

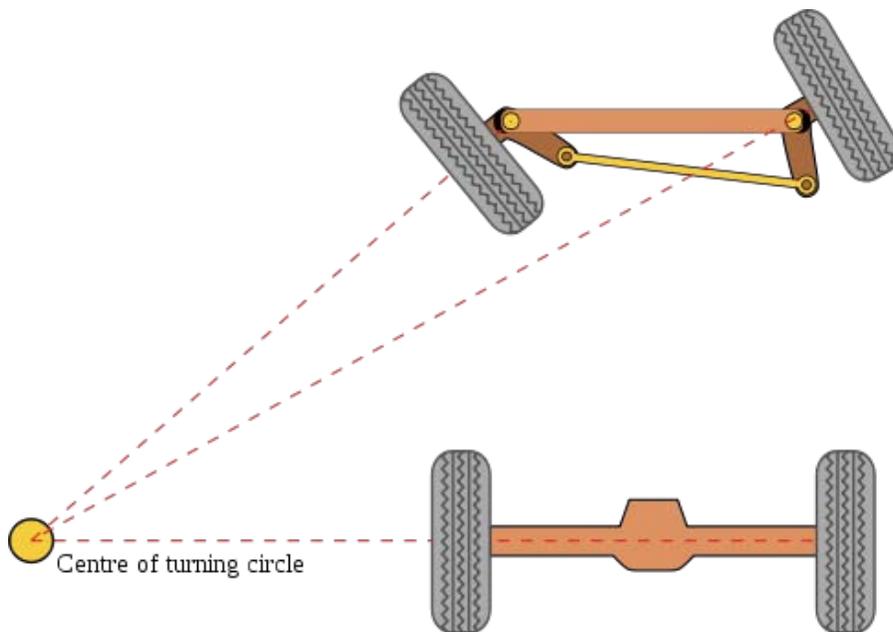
In 2000, Honda launched the S2000 Type V equipped with the world's first electric power variable gear ratio steering (VGS) system. In 2002, Toyota introduced their own "Variable Gear Ratio Steering (VGRS)" system introduced on the Lexus LX 470 and Landcruiser Cygnus, and also incorporated the electronic stability control system to alter steering gear ratios and steering assist levels. In 2003, BMW introduced their "Active Steering" system on the 5-series.

This system should not be confused with variable assist power steering which varies steering assist torque not steering ratios, nor with systems where the gear ratio is only varied as a function of steering angle.

## Chapter 3

# Ackermann Steering Geometry and Caster Angle

## Ackermann steering geometry

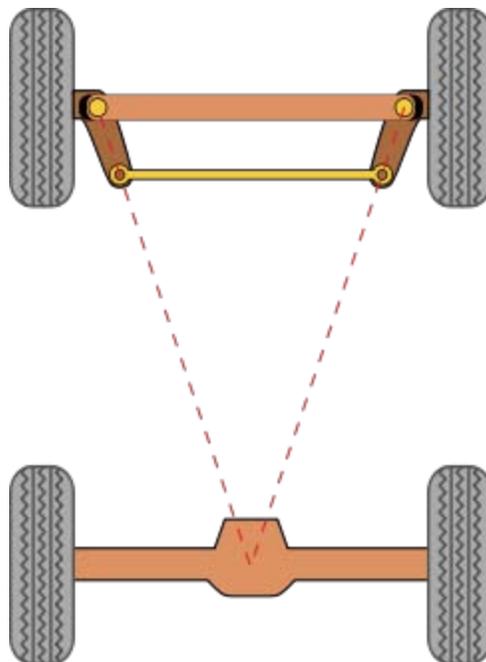


Ackermann geometry

**Ackermann steering geometry** is a geometric arrangement of linkages in the steering of a car or other vehicle designed to solve the problem of wheels on the inside and outside of a turn needing to trace out circles of different radii. It was invented by the German Carriage Builder "Lankensperger" in 1817, then patented by his agent in England Rudolph Ackermann (1764–1834) in 1818 for horse drawn carriages. Erasmus Darwin may have a prior claim as the inventor dating from 1758.

The intention of Ackermann geometry is to avoid the need for tyres to slip sideways when following the path around a curve. The geometrical solution to this is for all wheels to have their axles arranged as radii of a circle with a common centre point. As the rear wheels are fixed, this centre point must be on a line extended from the rear axle. Intersecting the axes of the front wheels on this line as well requires that the inside front wheel is turned, when steering, through a greater angle than the outside wheel.

Rather than the preceding "turntable" steering, where both front wheels turned around a common pivot, each wheel gained its own pivot, close to its own hub. A linkage between these hubs moved the two wheels together, and by careful arrangement of the linkage dimensions the Ackermann geometry could be approximated. This was achieved by making the linkage *not* a simple parallelogram, but by making the length of the track rod (the moving link between the hubs) shorter than that of the axle, so that the steering arms of the hubs appeared to "toe out". As the steering moved, the wheels turned according to Ackermann, with the inner wheel turning further. If the track rod is placed ahead of the axle, it should instead be longer in comparison, thus preserving this same "toe out".

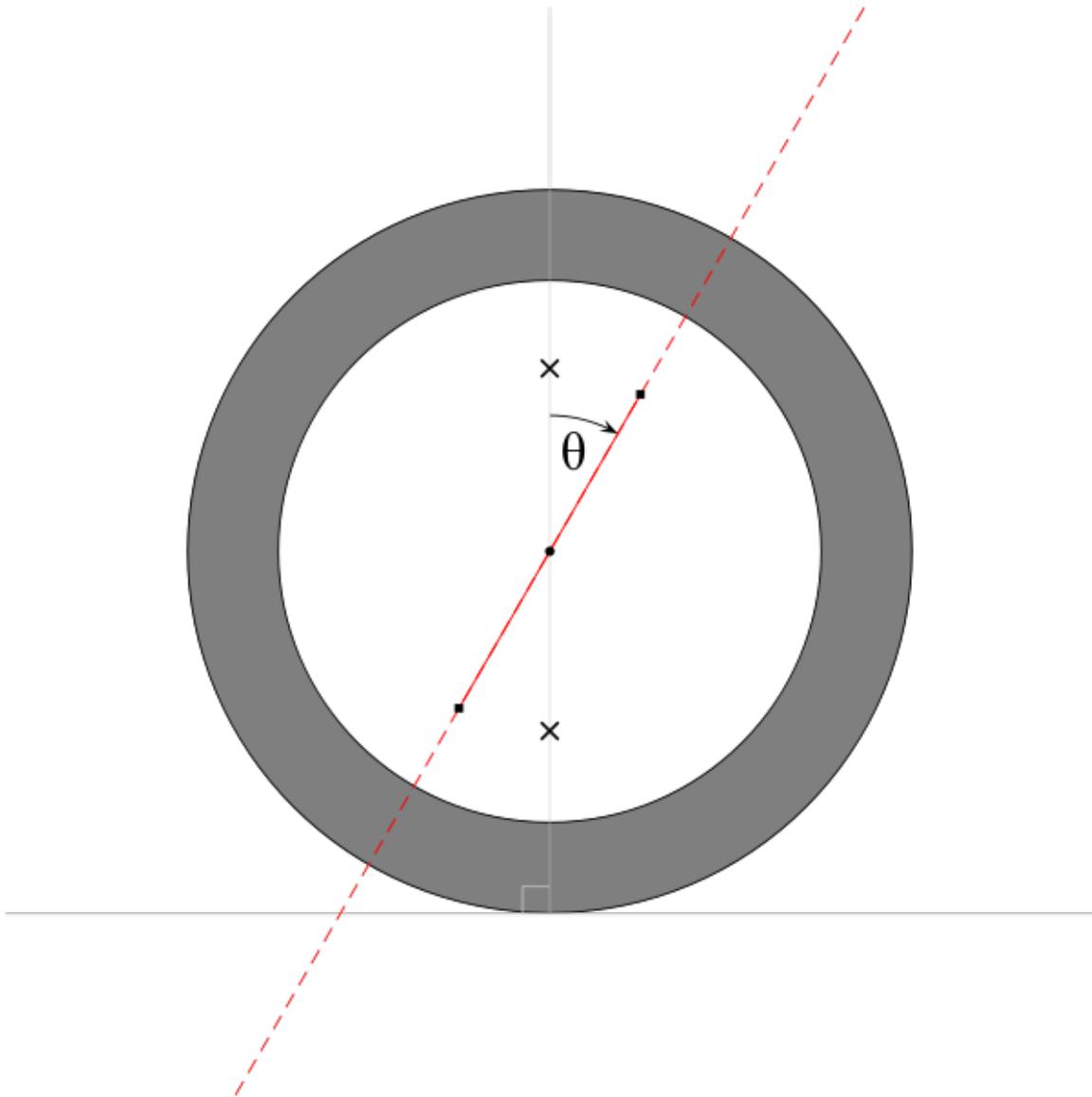


Simple approximation for designing Ackermann geometry

A simple approximation to perfect Ackermann steering geometry may be generated by moving the steering pivot points inward so as to lie on a line drawn between the steering kingpins and the centre of the rear axle. The steering pivot points are joined by a rigid bar called the tie rod which can also be part of the steering mechanism, in the form of a rack and pinion for instance. With perfect Ackermann, at any angle of steering, the centre point of all of the circles traced by all wheels will lie at a common point. Note that this may be difficult to arrange in practice with simple linkages, and designers are advised to draw or analyze their steering systems over the full range of steering angles.

Modern cars do not use *pure* Ackermann steering, partly because it ignores important dynamic and compliant effects, but the principle is sound for low speed manoeuvres. Some race cars use *reverse* Ackermann geometry to compensate for the large difference in slip angle between the inner and outer front tyres while cornering at high speed. The use of such geometry helps reduce tyre temperatures during high-speed cornering but compromises performance in low speed maneuvers.

# Caster angle



$\theta$  is the caster angle, red line is the pivot line, grey area is the tire. A positive caster angle is shown with the front of the vehicle being to the left.



A motorcycle's front wheel pivot angle is easily visualized. Choppers sometimes have an extreme **caster angle** for aesthetic reasons

**Caster angle** or **castor angle** is the angular displacement from the vertical axis of the suspension of a steered wheel in a car, bicycle or other vehicle, measured in the longitudinal direction. It is the angle between the pivot line (in a car - an imaginary line that runs through the center of the upper ball joint to the center of the lower ball joint) and vertical. Car racers sometimes adjust caster angle to optimize their car's handling characteristics in particular driving situations.

## ***Bikes***

When applied to bicycles and motorcycles, caster is more commonly referred to as rake and trail.

## ***Front end alignment***

When an automotive vehicle's front suspension is aligned, caster is adjusted to achieve the self-centering action of steering, which affects the vehicle's straight-line stability. Improper caster settings will cause the driver to move the steering wheel both into and out of each turn, making it difficult to maintain a straight line.

## ***Positive caster angle***

The pivot points of the steering are angled such that a line drawn through them intersects the road surface slightly ahead of the contact point of the wheel. The purpose of this is to provide a degree of self-centering for the steering - the wheel casters around so as to trail behind the axis of steering. This makes a car easier to drive and improves its directional stability (reducing its tendency to wander). Excessive caster angle will make the steering heavier and less responsive, although, in racing, large caster angles are used to improve camber gain in cornering. Caster angles over 10 degrees with radial tires are common. Power steering is usually necessary to overcome the jacking effect from the high caster angle.

## ***Trail or trailing***

The steering axis (the dotted line in the diagram above) does not have to pass through the center of the wheel, so the caster can be set independently of the mechanical trail, which is the distance between where the steering axis hits the ground, in side view, and the point directly below the axle. The interaction between caster angle and trail is complex, but roughly speaking they both aid steering, caster tends to add damping, while trail adds 'feel', and returnability. In the extreme case of the shopping trolley wheel, the system is undamped but stable, as the wheel oscillates around the 'correct' path. The shopping trolley/cart setup has a great deal of trail, but no caster. Complicating this still further is that the lateral forces at the tire do not act at the center of the contact patch, but at a distance behind the nominal contact patch. This distance is called the pneumatic trail and varies with speed, load, steer angle, surface, tire type, tire pressure and time. A good starting point for this is 30 mm behind the nominal contact patch.

## ***History***

Arthur Krebs applied the first positive caster angle to automotive front-train in his 1896 car, English patent : "To ensure stability of direction by means of a special arrangement of fore-carriage, that is to say, to re-establish automatically the parallelism of the two axles of the vehicle when there is no tendency to keep them in any other direction, or after a temporary effort has caused them to diverge from said parallelism. [...] The axle of the fore-carriage is situated a suitable distance behind the projection of the axis of the pivot-pin in order to ensure the stability of direction above referred to."

## Chapter 4

# Kingpin (Automotive Part) and Oversteer

## Kingpin (automotive part)



Part of car front suspension and steering mechanism: kingpin axis, tie rod, and steering arm (using ball joints).

The **kingpin**, also **king-pin** and **king pin**, is the main pivot in the steering mechanism of a car or other vehicle. Originally this was literally a steel pin on which the moveable, steerable wheel was mounted to the suspension. Free to rotate on a single axis, it limited the degrees of freedom of motion of the rest of the front suspension. When its bearings were replaced starting in the 1950s by ball joints, more complicated suspension designs became available to designers. It is usually made of metal.

Although they are largely obsolete, kingpin suspensions have the advantage of being able to carry much heavier weights, which is why they are still featured on some heavy trucks.

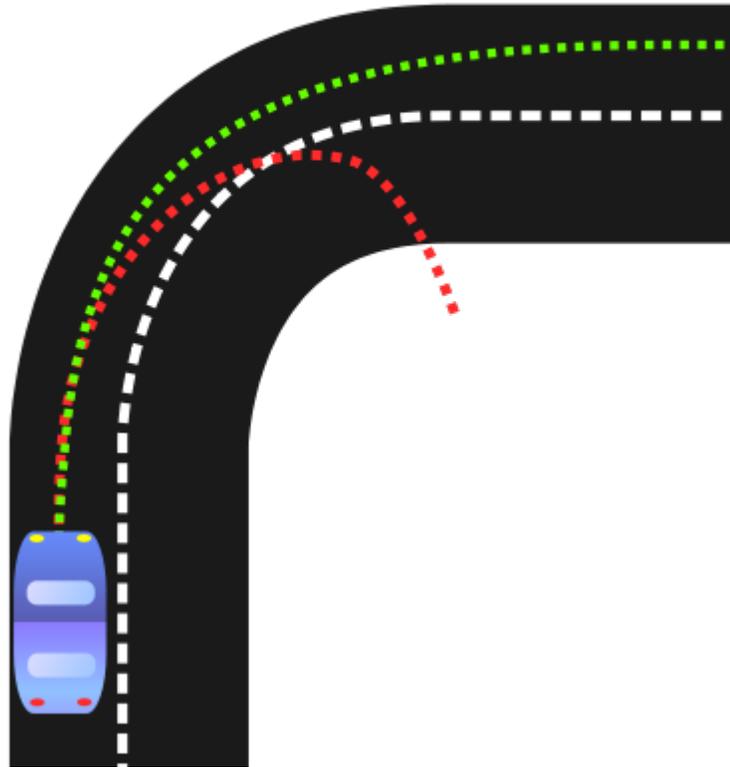
No longer restricted to moving like a pin, the part was not necessarily still called a kingpin; but in newer designs, the term may be used not for an actual pin but the axis around which the steered wheels pivot.

The nipple at the front of a semi-trailer to connect to a fifth wheel coupling is also known as a kingpin.

### ***Kingpin Inclination***

On most modern designs, the kingpin is set at an angle relative to the true vertical line, as viewed from the front or back of the vehicle. This is the kingpin inclination or KPI (also called steering axis inclination, or SAI). This has an important effect on the steering, making it tend to return to the straight ahead or centre position. This is because the straight ahead position is where the wheel is at its highest point relative to the suspended body of the vehicle - the weight of the vehicle tends to turn the kingpin to this position. A second effect of the kingpin inclination is to set the scrub radius of the steered wheel. This is the offset between the tyre's contact point with the road surface and the projected axis of the steering down through the kingpin. If these points coincide, the scrub radius is zero. Zero scrub radius is possible without an inclined kingpin, but requires a deeply dished wheel so that the kingpin is at the centerline of the wheel. It's much more practical to incline the kingpin and use a less dished wheel, which also gives the self-centering effect. Zero scrub radius is not necessarily desirable - larger scrub radii lead to less steering effort (especially on vehicles without power steering) but more force applied to the steering components by road surface imperfections, braking, etc. Zero scrub radius isolates the steering from these effects but can lead to a "dead" feel for the driver which is undesirable, especially on performance vehicles.

# Oversteer



Oversteer

**Oversteer** is a term for a car handling condition in which the slip angle of the rear tires is greater than the slip angle of the front tires. In other words, the amount that the car *steers* is *over* that commanded by the driver. The effect is opposite to that of understeer.

An oversteering car is referred to as "loose" or "free". Oversteer is a dynamically unstable condition; in other words, if control is lost, the vehicle will spin.

## Causes

The tendency of a car to oversteer is affected by several factors such as mechanical traction, aerodynamics and suspension, and driver control, and may be applicable at any level of lateral acceleration. Generally, oversteer is the condition when the slip angle of the rear tires exceeds that of the front tires, even when they are both small. *Limit oversteer* occurs when the rear tires reach the limits of their lateral traction during a cornering situation but the front tires have not, thus causing the rear of the vehicle to head towards the outside of the corner. The driving technique called opposite lock is meant to cope in this circumstance. *Trailing Throttle Oversteer* (TTO), a.k.a. "snap-oversteer" is induced by the weight balance of the car shifting from the rear to the front, this may happen if the car is cornering under throttle, causing the car to settle on the rear, if the throttle application would be removed—e.g. as to reduce the radius of the turn—the balance would suddenly shift to the front, giving less traction on the rear, if the car was already at the traction limit before the driver lifted the throttle it is very likely to cause a TTO. Rear wheel drive cars are more prone to oversteer, in particular when applying power in a tight corner. This occurs because the rear tires must handle both the lateral cornering force and engine torque.

## Yaw rate

The terms oversteer and understeer are related to yaw rate and not to *sideways movement*. A car undergoes a circular spinning motion (yaw) as it turns, as well as *sideways movement* (towards the inside of the corner). Understeer and oversteer refer to the yaw motion. The difference between yaw and sideways movement is best demonstrated by practising turning an aircraft, because separate controls control each of the two movement types in aircraft. Consider a car with its steering wheel turned part way to one side and locked in that position. Now imagine that car rolling forward very slowly on a flat surface. It will move along an arc of a circle whose radius is determined solely by the position of the wheels, since centrifugal force is minimal. Its sideways motion and yaw rate are hence interlinked and set by the steering wheel position. However, the wheels can only provide a limited amount of sideways force before they slide. This sliding will happen at a larger radius as either the speed increases, the friction coefficient decreases, or the normal force decreases. Once this sliding occurs, the sideways movement and yaw rate may become unlinked. If the yaw rate of the car tends towards a larger radius than the radius set by the wheels, it is said to understeer. If the yaw rate radius is smaller (spinning too fast), it is called oversteer. During oversteer or understeer the sideways movement of the car may also follow a different radius to that set by the steering wheel, but this does not affect the definition of oversteer or understeer.

## Critical speed

Oversteering cars have an associated instability mode, which occurs at and above the critical speed. As this speed is approached, with the car on an approximately straight course, the steering becomes progressively more sensitive. At the critical speed the yaw velocity gain becomes infinite, that is, the car will turn violently in response to the

slightest steering input or external disturbance. Above the critical speed analysis shows that the yaw response will be reversed for a given steering wheel input, such as a car turning left in response to turning the wheel to the right. This is an oversimplification, however, as the model used is linearised in many important ways. Understeering cars do not suffer from this, which is one of the reasons why high speed cars tend to be set up to understeer.

### ***In road cars***



A Mercedes-Benz CLS AMG 55 oversteering on a wet surface

Contrary to popular opinion, modern rear-wheel-drive cars are much more user-friendly in regard to oversteer. Their suspension is not balanced heavily toward understeer, in fact with today's experience in making cars, most manufacturers try to achieve neutrality from the respective configurations so that they are largely capable of oversteering especially when the driver attempts to invoke it on purpose.

The natural reaction of most drivers to the perception of loss of control during oversteer is to immediately lift their foot off the gas pedal. Cutting the power mid-corner can induce more oversteer, known as lift-off oversteer. The correct reaction to oversteer is to gently steer into the slide and take the power away as needed without pitching the car forward. Indeed, "trail braking", or continuing to apply brake pressure after turning into a curve, can induce oversteer by transferring weight off the rear tires, regardless of whether the car is front, rear or all-wheel drive.

Braking may or may not improve the situation. Most modern cars have a brake bias which tends to straighten out the car. However, there are two factors working against this. Most drivers must lift their foot from the gas pedal in order to press the brake, inducing the spin as described above. The second is that braking transfers more of the vehicle's weight forward which tends to worsen oversteer. Even so, the brake bias may be enough to help or at least not make it worse.

### ***In race cars***

A car that tends neither to oversteer nor understeer when pushed to the limit is said to have neutral handling. It seems intuitive that race drivers would prefer a slight oversteer condition to rotate the car around a corner, but this isn't usually the case for two reasons. Accelerating early as the car passes the apex of a corner allows it to gain extra speed down the following straight. The driver who accelerates sooner and/or harder has a large advantage. The rear tires need some excess traction to accelerate the car in this critical phase of the corner, while the front tires can devote all their traction to turning. So the car must be set up with a slight understeer or "tight" tendency. Also, an oversteering car tends to be twitchy and ill tempered, making a race car driver more likely to lose control during a long race or when reacting to sudden situations in traffic.

Carroll Smith, in his book "Drive to Win", provides a detailed explanation of why a fast race car must have a bit of understeer. Note that this applies only to road racing. Dirt racing is a different matter.

Even so, some successful race car drivers do prefer a bit of oversteer in their cars, preferring a car which is less sedate and more willing to turn into corners (or inside their opponents). The judgement of a car's handling balance is not an objective one. Driving style is a major factor in the apparent balance of a car. This is why two drivers with identical cars on the same race team often run with rather different balance settings from each other. And both may call the balance of their cars 'neutral'.

### **Aerodynamic stability**

The importance of the position of a fast car's aerodynamic centre of pressure to its directional stability was not understood at first. In the late 1950s, cars such as the 120 mph Jaguar 3.4-litre saloon / sedan were reported to feel directionally unstable at high speeds, and were badly affected by gusts.

Simple streamlining tends to lift the back of a car, reducing the downforce on its back wheels relative to the front wheels, resulting in oversteer. Streamlining also moves the centre of pressure well forward, causing directional instability in cross winds.

At first, aerodynamic oversteer was counteracted by setting the cars up with strong mechanical understeer, resulting in excessive understeer at lower speeds. Various means of achieving aerodynamic stability have since been developed, such as tail fins to move the centre of pressure back, the Kamm tail and the spoiler to reduce lift, rear wings to

generate downward acting lift force, and air dams and skirts to reduce air pressure under the car, causing down force due to ground effect. Most of those features improve stability but increase drag, reducing top speed and increasing fuel consumption. However an early example of a fin used for directional stability without reducing top speed is provided by the Jaguar D-Type.

Usually these features are little more than styling gimmicks, the cars not being fast enough to benefit from them.

In modern race cars, especially open-wheel race cars, oversteering in high speed turns is caused mainly by aerodynamic configuration. A heavier aerodynamic load on the front of the car relative to the rear causes it to oversteer. Oversteer in low speed turns is often reduced or eliminated electronically through traction control (if the sanctioning body allows their use). The front/rear balance required to make the cars fast through corners is obtained by setting up the aerodynamics and balancing the suspension. The car's tendency toward oversteer is generally increased by softening the front suspension or stiffening the rear suspension in roll. The suspension's roll stiffness may be adjusted independently of pitch stiffness by means of adjustable or interchangeable anti-roll bars at one or both ends of the car. Camber angle, ride height, and tire pressures can also be used to tune the balance of the car.

## Chapter 5

# Torque Steering and Understeer

## Torque steering

**Torque steering** is the influence of the engine torque on the steering for some front-wheel drive vehicles. For example, during full acceleration the steering may pull to one side, which may be disturbing to the driver. This either causes a tugging sensation in the steering wheel, or else the car veers from the intended path. As the torque steer effect is directly related to the engine torque capabilities, this problem becomes more and more evident with high output engines with strong torque in the low RPM range.

Torque steering may be confused with steering kickback.

### ***Causes***

Root causes for torque steer are:

- Unequal driveshaft length (or more accurately, unequal driveshaft angles, also caused by body roll or single wheel bump)
- Incorrect sidewall ply design allowing deformation of the tire sidewall.
- Nonsymmetric driveshaft angles, e.g. due to
  - Transient movement of the engine
  - Tolerances in engine mounts
- Different driveshaft torques left to right (due to wheel bearing or differential problems)
- Suspension geometry tolerances
- Unequal traction forces due to road surface ( $\mu$ -Split) in combination with kingpin offset

### ***Ways to reduce the effect of torque steer***

- Employ the use of a tire with proper sidewall ply design, mitigating the sidewall deformation.

- Have both driveshafts of the equal length by using an intermediate shaft (or "lay shaft") on one side of the transmission. This is already implemented on most modern cars. When the driveshafts have different length and excessive torque is applied, the longer half shaft flexes more than the shorter one. However, this is a short term transient effect. To avoid fatigue failure, the amount of drive shaft torsional deflection must necessarily be small. Effects due to one wheel spinning more slowly than the other usually result in negligible effect. Equal lengths of the driveshafts, in the case of no asymmetric suspension deflection due to roll or bump, keep the drive shaft angles equal. The main component of torque steer occurs when the torques in the driveshaft and the hub are summed vectorially, giving a resultant torque vector around the steering pivot axis (king pin). These torques can be substantial, and in the case of shafts making equal angles to the hub shafts, will oppose one another at the steering rack, and so will cancel. These torques are strongly influenced by the position of the driveshaft universal joint (CV joint) in relation to the steering axis, however due to other requirements such as achieving a small or negative scrub radius an optimum solution is not generally possible with simple suspension configurations such as Macpherson strut.
- Equalise the torque better between the driveshafts by using a low friction differential. The torque difference is zero if the differential is frictionless, and limited slip differentials, intended to increase power transfer, actually make torque steer much worse. For this reason, limited slip differentials by automobile transmission manufacturers like Quaife, Torsen, TrueTrac, Gold Trac have not been much used until recently, and require other measures to be implemented, such as careful positioning of suspension pivot points and driveshaft CV joints, in order to keep the resultant torque steer to a manageable amount. Limited slip differentials do not improve cornering, or steering feel, however they will improve power transfer in situations where one wheel experiences limited adhesion, and so may improve overall performance.
- Reduce the amount torque from the front axle by passing part of torque to the rear axle. This is achieved on all-wheel-drive (AWD) vehicles with full-time AWD, e.g. with mechanical gear-based transaxle differential, e.g. Audi AWD cars equipped by Torsen transaxle differential.
- Power assisted steering (set on most modern cars) make the torque steer effect less noticeable to the driver. Steer-by-wire also hides the effect of torque steer from the driver.

Rear-wheel-drive vehicles still are affected by torque steer in the sense that any of the above situations will still apply a steering moment to the car (though from the rear wheels instead of the front). However, the torque-steer effect at the rear wheels will not send any torque response back through the steering column, so the driver will not have to fight the steering wheel. Additionally, basically all rear-drive vehicles are designed with equal-length halfshafts (the most common cause of torque steer), so it is a rare and/or minor occurrence on rear-drive vehicles.

# Understeer

**Understeer** and **oversteer** are vehicle dynamics terms used to describe the sensitivity of a vehicle to steering. Automotive engineers originally defined understeer and oversteer based on the gradient of the steering needed to make a turn in a steady-state condition (constant speed, constant radius) on a flat and level ground surface. Car and motorsport enthusiasts often use the terminology more generally in magazines and blogs to describe vehicle response to steering in all kinds of maneuvers, even on banked turns. Simply put, oversteer is what occurs when a car turns (steers) by more than (over) the amount commanded by the driver. Conversely, understeer is what occurs when a car steers under the amount commanded by the driver.

## ***Vehicle Dynamics Terminology***

In standard terminology defined by the Society of Automotive Engineers (SAE) J670 and the International Organization for Standardization (ISO) 8855, understeer and oversteer are based on differences in steady-state conditions where the vehicle is following a constant-radius path at a constant speed with a constant steering wheel angle, on a flat and level surface. If the speed is increased slightly for the same radius path and, after settling into steady state, the same steering is measured, then the vehicle is said to have neutral steer. If more steering is needed at the higher speed to maintain the same radius of curvature, then the vehicle is said to have understeer. If less steering is needed at the higher speed, then the vehicle is said to have oversteer.

Understeer and oversteer are defined by an understeer gradient  $U$  that is the difference between a reference steer angle gradient and the Ackerman steer angle gradient. The reference steer angle ( $\delta_R$ ) is the average steer of the front axle wheels minus the average steer of the rear axle wheels. The Ackerman steer angle ( $\delta_A$ ) is defined for a given radius of turn as the reference steer angle that would be used at a very low speed. For a four-wheeled vehicle with steering only at the front wheels, the Ackerman angle  $\delta_A$  (at the wheels) is the arctangent of the wheelbase divided by the turn radius (at the center of the rear axle).

Understeer and oversteer are formally defined using the gradient  $U$ : if  $U$  is positive, the vehicle is understeer; if  $U$  is negative, the vehicle is oversteer; if  $U$  is zero, the vehicle is neutral.

Different companies and organizations have different test procedures for defining  $U$ . In all cases, the gradient is taken by comparing measures from steady state tests, and expressed with units of degrees of steer (at the road wheels) divided by lateral acceleration  $A_y$  expressed in g's. In steady-state conditions,  $A_y = V^2/R/G$ , where  $V$  is the vehicle speed,  $R$  is the radius of the turn, and  $G$  is the gravitational scaling factor.

SAE J670 describes three methods for measuring  $U$ :

1. Constant radius: tests are repeated at different speeds for a given constant-radius track. In this kind of procedure, the Ackerman steering is always the same, so the gradient is:  $U = d(\delta_R)/d(Ay)$
2. Constant steer angle: tests are repeated at different speeds for a given reference steer angle. In this kind of procedure, the reference steer is always the same so the gradient is:  $U = -d(\delta_A)/d(Ay)$
3. Constant speed: tests are repeated with different reference steer angles for a given speed. In this kind of procedure, the gradient is:  $U = d(\delta_R)/d(Ay) - d(\delta_A)/d(Ay)$

Gillespie goes into more detail on applying the first and third measurement methods.

Results depend on the type of test, so just giving a deg/g value is not sufficient; it is also necessary to indicate the type of procedure used to measure the gradient.

Vehicles are inherently nonlinear systems, and it is normal for  $U$  to vary over the range of testing. It is possible for a vehicle to be understeer in some conditions and oversteer in others. Therefore, it is necessary to specify the speed and lateral acceleration whenever reporting understeer/oversteer characteristics.

## **Contributions to understeer**

Many properties of the vehicle affect the understeer gradient, including tire cornering stiffness, camber thrust, lateral force compliance steer, aligning torque, lateral load transfer, and compliance in the steering system. These individual contributions can be identified analytically or by measurement in a Bundorf analysis.

## ***Limit conditions***

When an understeer vehicle is taken to frictional limits where it is no longer possible to increase lateral acceleration, the vehicle will follow a path with a radius larger than intended. Although the vehicle cannot increase lateral acceleration, it is dynamically stable.

When an oversteer vehicle is taken to frictional limits, it becomes dynamically unstable with a tendency to spin out. Although the vehicle is unstable in open-loop control, a skilled driver can maintain control a little past the point of instability with counter-steering. However, at some limit in lateral acceleration, it is not physically possible for even the most skilled driver to maintain a steady state and spinout will occur.

## ***Related measures***

Understeer gradient is one of the main measures for characterizing steady-state cornering behavior. It is involved in other properties such as characteristic speed (the speed for an understeer vehicle where the steer angle needed to negotiate a turn is twice the Ackerman angle), lateral acceleration gain (g's/deg), yaw velocity gain (1/s), and critical speed (the speed where an oversteer vehicle has infinite lateral acceleration gain).

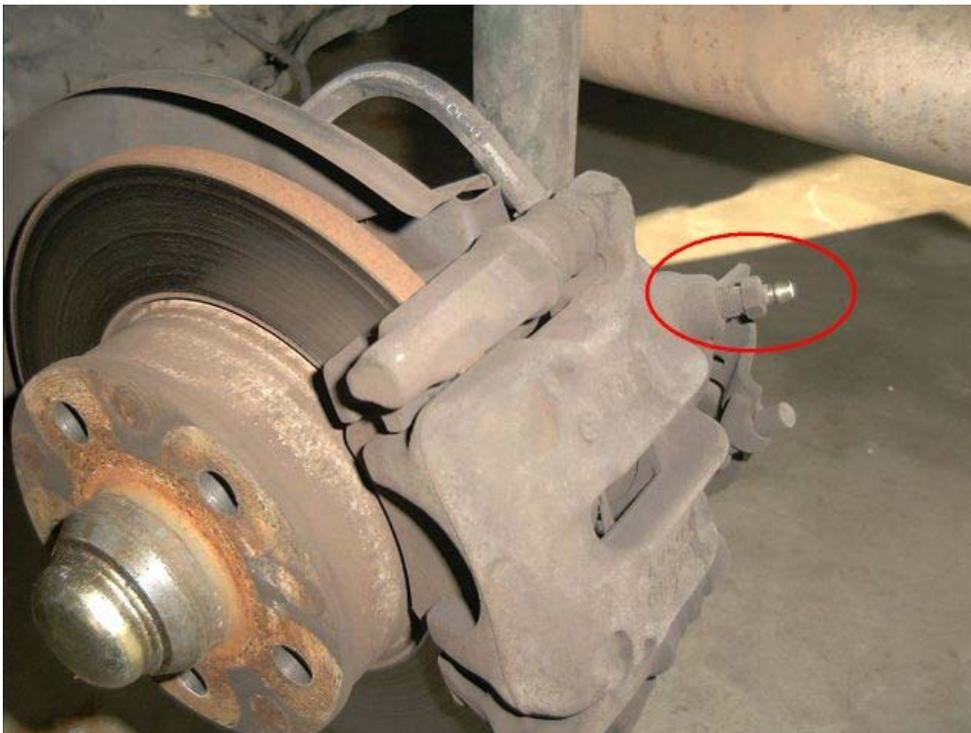
## Chapter 6

# Automatic Braking and Brake Bleeding

## Automatic Braking

**Automatic Braking** is a technology for automobiles to sense an imminent collision with another vehicle, person or obstacle; or a danger such as a high speed approach to a stop sign and to respond with the braking system by either precharging the brakes or by applying the brakes to slow the vehicle without any driver input. Sensors to detect other vehicles or obstacles can include radar, video, infrared, ultrasonic or other technologies. GPS sensors can detect fixed dangers such as approaching stop signs through a location database.

## Brake bleeding



Close-up of a disk brake bleed screw



Vacuum bleeding a disk brake caliper



Pressure bleeding a brake system

**Brake bleeding** is the procedure performed on hydraulic brake systems whereby the brake lines (the pipes and hoses containing the brake fluid) are purged of any air bubbles. This is necessary because, while the brake fluid is an incompressible liquid, air bubbles are compressible gas and their presence in the brake system greatly reduces the hydraulic pressure that can be developed within the system. The same methods used for bleeding are also used for purging, where the old fluid is replaced with new fluid, which is necessary maintenance.

The brake fluid capacity of a typical automobile is around 250ml. Brake fluid is toxic, and must be handled carefully and disposed of properly. Most cars use DOT 3 or 4 Brake fluids, which may be mixed, but DOT 5 is silicone based and not compatible with DOT 3 or 4. One word of caution, most types of brake fluid harm paint and plastics on contact, so be careful. Brake fluid is water soluble so it may be rinsed with water.

The process is performed by forcing clean, bubble-free brake fluid through the entire system, usually from the master cylinder(s) to the calipers of disc brakes (or the wheel cylinders of drum brakes), but in certain cases in the opposite direction. A brake bleed screw is normally mounted at the highest point on each cylinder or caliper.

*Please note that the following description of brake bleeding techniques is intended only to provide an overview of the common methods, and is NOT to be used as specific instruction. The actual procedure varies from one vehicle to another and the manufacturers' shop manual procedure should be used.*

There are four main methods of bleeding: Pump & Hold (2 variations), Vacuum, Pressure, and Reversed Pressure. Pump & Hold generally requires two people, the other methods can be done by a single person.

- Pump and Hold Method, two people: One person pumps the brake pedal to compress the air, then holds pressure on it. The other person opens the bleeder valve to let out fluid and air, then closes the valve after the pedal has landed (to prevent air being sucked back in through the valve on the upstroke). The process is repeated, usually many times, for each wheel. Typically a length of clear tubing is connected to the bleeder valve and run to a container during the process, both to collect the toxic brake fluid and to better view the fluid and bubbles. The master cylinder reservoir must be replenished frequently, for if it goes dry the entire process must be redone. The cover must be left loose so that the fluid may be drawn, but should be in place so that fluid does not squirt out on the return stroke. A block may be placed under the pedal so that it does not bottom out during this procedure, as the master cylinder seals could be damaged by encountering accumulated sediment and / or corrosion.
- Pump and Hold Method, One Person Option: This uses either a "one man" bleeder tool, consisting of a one way valve at the end of a length of tubing which is attached to the bleeder valve, or a special one way bleeder valve. These methods have the disadvantage that air is sometimes sucked back into the system via the bleeder valve threads, this can be alleviated to a degree by using Teflon tape on those threads. This method is not recommended because with only one person there is no way to verify if indeed the fluid that is coming out of the bleeder valve has any air present, such as from a bad master cylinder or improper/incomplete bleeding.
- Vacuum Method: The master cylinder is topped off and the cover left loose. A specialized vacuum pump is attached to the bleeder valve, which is opened and fluid extracted with the pump until it runs clear of bubbles. Once again, the master cylinder reservoir level must be maintained. The vacuum method can also draw in air via the bleeder threads, so the bubbles will never clear. However, this does not mean there is still air in the brake lines. Using Teflon tape on the bleeder threads will alleviate this issue and allow you to accurately determine when you have evacuated all air from the system.
- Pressure Method: A specialized pressure pump, is attached to the master cylinder and filled with fluid. The pump is used to pressurize the system to about 10psi, and the bleeder valves are opened one at a time until the fluid is clear of air. One

advantage to this system is that the pump reservoir usually holds enough fluid that running dry is not likely. This is the method most professional shops use.

- Reverse Pressure Method: In this method, a pump is used to force fluid through the bleeder valve to the master cylinder. This method may have advantages in some cases, however it is not in common usage.
- Gravity method: This method is most simple. Just loosen the bleeder valve and the cap of the master cylinder reservoir. The fluid will drip slowly by the force of gravity. The bleeder valve is designed to be top point of the fluid in the caliper. The air will not enter the caliper downward from the physics law.

The order in which the wheels are bled is specified in the specific vehicle's shop manual. Typically the wheel farthest from the master cylinder is done first, working toward the closest wheel last.

If bleeding brakes because of master cylinder replacement the master cylinder is usually "bench bled" before installation. Typically by securing it on the bench, filling it with fluid, connecting fittings and hoses to route fluid from the outlet ports on the master cylinder back to its reservoir, and repeatedly depressing the master cylinder plunger until bubbles are no longer seen coming from the hoses.

## Chapter 7

# Anti-Lock Braking System

An **anti-lock braking system (ABS)** is a safety system that allows the wheels on a motor vehicle to continue interacting tractively with the road surface as directed by driver steering inputs while braking, preventing the wheels from locking up (that is, ceasing rotation) and therefore avoiding skidding.

An ABS generally offers improved vehicle control and decreases stopping distances on dry and slippery surfaces for many drivers; however, on loose surfaces like gravel or snow-covered pavement, an ABS can significantly increase braking distance, although still improving vehicle control.

Since initial widespread use in production cars, anti-lock braking systems have evolved considerably. Recent versions not only prevent wheel lock under braking, but also electronically control the front-to-rear brake bias. This function, depending on its specific capabilities and implementation, is known as electronic brakeforce distribution (EBD), traction control system, emergency brake assist, or electronic stability control (ESC).

### ***History***

#### **Early systems**

The ABS was first developed for aircraft use in 1929 by the French automobile and aircraft pioneer, Gabriel Voisin, as threshold braking on airplanes is nearly impossible. An early system was Dunlop's Maxaret system, which was introduced in the 1950s and is still in use on some aircraft models. These systems use a flywheel and valve attached to a hydraulic line that feeds the brake cylinders. The flywheel is attached to a drum that runs at the same speed as the wheel. In normal braking, the drum and flywheel should spin at the same speed. However, if a wheel were to slow down, then the drum would do the same, leaving the flywheel spinning at a faster rate. This causes the valve to open, allowing a small amount of brake fluid to bypass the master cylinder into a local

reservoir, lowering the pressure on the cylinder and releasing the brakes. The use of the drum and flywheel meant the valve only opened when the wheel was turning. In testing, a 30% improvement in braking performance was noted, because the pilots immediately applied full brakes instead of slowly increasing pressure in order to find the skid point. An additional benefit was the elimination of burned or burst tires.

In 1958, a Royal Enfield Super Meteor motorcycle was used by the Road Research Laboratory to test the Maxaret anti-lock brake. The experiments demonstrated that anti-lock brakes can be of great value to motorcycles, for which skidding is involved in a high proportion of accidents. Stopping distances were reduced in most of the tests compared with locked wheel braking, particularly on slippery surfaces, in which the improvement could be as much as 30 percent. Enfield's technical director at the time, Tony Wilson-Jones, saw little future in the system, however, and it was not put into production by the company.

A fully mechanical system saw limited automobile use in the 1960s in the Ferguson P99 racing car, the Jensen FF, and the experimental all wheel drive Ford Zodiac, but saw no further use; the system proved expensive and unreliable in automobile use.

### **Modern systems**

Chrysler, together with the Bendix Corporation, introduced a computerized, three-channel, four-sensor all-wheel ABS called "Sure Brake" for its 1971 Imperial. It was available for several years thereafter, functioned as intended, and proved reliable. In 1971, General Motors introduced the "Trackmaster" rear-wheel only ABS as an option on their Rear-wheel drive Cadillac models. In the same year, Nissan offered an EAL (Electro Anti-lock System) as an option on the Nissan President, which became Japan's first electronic ABS.



ABS brakes on a BMW motorcycle

In 1988, BMW introduced the first motorcycle with an electronic-hydraulic ABS: the BMW K100. Honda followed suit in 1992 with the launch of its first motorcycle ABS on the ST1100 Pan European. In 2007, Suzuki launched its GSF1200SA (Bandit) with an ABS. In 2005, Harley-Davidson began offering ABS as an option for police bikes. In 2008, ABS became a factory-installed option on all Harley-Davidson Touring motorcycles and standard equipment on select models.

## ***Operation***

The anti-lock brake controller is also known as the CAB (Controller Anti-lock Brake).

A typical ABS includes a central electronic control unit (ECU), four wheel speed sensors, and at least two hydraulic valves within the brake hydraulics. The ECU constantly monitors the rotational speed of each wheel; if it detects a wheel rotating significantly slower than the others, a condition indicative of impending wheel lock, it actuates the valves to reduce hydraulic pressure to the brake at the affected wheel, thus reducing the braking force on that wheel; the wheel then turns faster. Conversely, if the ECU detects a wheel turning significantly faster than the others, brake hydraulic pressure to the wheel is increased so the braking force is reapplied, slowing down the wheel. This process is repeated continuously and can be detected by the driver via brake pedal pulsation. Some anti-lock system can apply or release braking pressure 16 times per second.

The ECU is programmed to disregard differences in wheel rotative speed below a critical threshold, because when the car is turning, the two wheels towards the center of the curve turn slower than the outer two. For this same reason, a differential is used in virtually all roadgoing vehicles.

If a fault develops in any part of the ABS, a warning light will usually be illuminated on the vehicle instrument panel, and the ABS will be disabled until the fault is rectified.

The modern ABS applies individual brake pressure to all four wheels through a control system of hub-mounted sensors and a dedicated micro-controller. ABS is offered or comes standard on most road vehicles produced today and is the foundation for ESC systems, which are rapidly increasing in popularity due to the vast reduction in price of vehicle electronics over the years.

Modern electronic stability control (ESC or ESP) systems are an evolution of the ABS concept. Here, a minimum of two additional sensors are added to help the system work: these are a steering wheel angle sensor, and a gyroscopic sensor. The theory of operation is simple: when the gyroscopic sensor detects that the direction taken by the car does not coincide with what the steering wheel sensor reports, the ESC software will brake the necessary individual wheel(s) (up to three with the most sophisticated systems), so that the vehicle goes the way the driver intends. The steering wheel sensor also helps in the operation of Cornering Brake Control (CBC), since this will tell the ABS that wheels on the inside of the curve should brake more than wheels on the outside, and by how much.

The ABS equipment may also be used to implement a traction control system(TCS) on acceleration of the vehicle. If, when accelerating, the tire loses traction, the ABS controller can detect the situation and take suitable action so that traction is regained. More sophisticated versions of this can also control throttle levels and brakes simultaneously.

## **Components**

There are four main components to an ABS: speed sensors, valves, a pump, and a controller.

### Speed sensors

The anti-lock braking system needs some way of knowing when a wheel is about to lock up. The speed sensors, which are located at each wheel, or in some cases in the differential, provide this information.

### Valves

There is a valve in the brake line of each brake controlled by the ABS. On some systems, the valve has three positions:

- In position one, the valve is open; pressure from the master cylinder is passed right through to the brake.
- In position two, the valve blocks the line, isolating that brake from the master cylinder. This prevents the pressure from rising further should the driver push the brake pedal harder.
- In position three, the valve releases some of the pressure from the brake.

### Pump

Since the valve is able to release pressure from the brakes, there has to be some way to put that pressure back. That is what the pump does; when a valve reduces the pressure in a line, the pump is there to get the pressure back up.

### Controller

The controller is an ECU type unit in the car which receives information from each individual wheel speed sensor, in turn if a wheel loses traction the signal is sent to the controller, the controller will then limit the brakeforce (EBD) and activate the ABS modulator which actuates the braking valves on and off.

## **Use**

There are many different variations and control algorithms for use in an ABS. One of the simpler systems works as follows:

1. The controller monitors the speed sensors at all times. It is looking for decelerations in the wheel that are out of the ordinary. Right before a wheel locks up, it will experience a rapid deceleration. If left unchecked, the wheel would stop

- much more quickly than any car could. It might take a car five seconds to stop from 60 mph (96.6 km/h) under ideal conditions, but a wheel that locks up could stop spinning in less than a second.
2. The ABS controller knows that such a rapid deceleration is impossible, so it reduces the pressure to that brake until it sees an acceleration, then it increases the pressure until it sees the deceleration again. It can do this very quickly, before the tire can actually significantly change speed. The result is that the tire slows down at the same rate as the car, with the brakes keeping the tires very near the point at which they will start to lock up. This gives the system maximum braking power.
  3. When the ABS system is in operation the driver will feel a pulsing in the brake pedal; this comes from the rapid opening and closing of the valves. This pulsing also tells the driver that the ABS has been triggered. Some ABS systems can cycle up to 16 times per second.

## ***Brake types***

Anti-lock braking systems use different schemes depending on the type of brakes in use. They can be differentiated by the number of channels: that is, how many valves that are individually controlled—and the number of speed sensors.

### Four-channel, four-sensor ABS

This is the best scheme. There is a speed sensor on all four wheels and a separate valve for all four wheels. With this setup, the controller monitors each wheel individually to make sure it is achieving maximum braking force.

### Three-channel, three-sensor ABS

This scheme, commonly found on pickup trucks with four-wheel ABS, has a speed sensor and a valve for each of the front wheels, with one valve and one sensor for both rear wheels. The speed sensor for the rear wheels is located in the rear axle. This system provides individual control of the front wheels, so they can both achieve maximum braking force. The rear wheels, however, are monitored together; they both have to start to lock up before the ABS will activate on the rear. With this system, it is possible that one of the rear wheels will lock during a stop, reducing brake effectiveness.

### One-channel, one-sensor ABS

This system is commonly found on pickup trucks with rear-wheel ABS. It has one valve, which controls both rear wheels, and one speed sensor, located in the rear axle. This system operates the same as the rear end of a three-channel system. The rear wheels are monitored together and they both have to start to lock up before the ABS kicks in. In this system it is also possible that one of the rear wheels will lock, reducing brake effectiveness. This system is easy to identify. Usually there will be one brake line going through a T-fitting to both rear wheels.

## **Effectiveness**

A 2003 Australian study by Monash University Accident Research Centre found that ABS:

- Reduced the risk of multiple vehicle crashes by 18 percent,
- Reduced the risk of run-off-road crashes by 35 percent.

On high-traction surfaces such as bitumen, or concrete, many (though not all) ABS-equipped cars are able to attain braking distances better (i.e. shorter) than those that would be easily possible without the benefit of ABS. In real world conditions even an alert, skilled driver without ABS would find it difficult, even through the use of techniques like threshold braking, to match or improve on the performance of a typical driver with a modern ABS-equipped vehicle. ABS reduces chances of crashing, and/or the severity of impact. The recommended technique for non-expert drivers in an ABS-equipped car, in a typical full-braking emergency, is to press the brake pedal as firmly as possible and, where appropriate, to steer around obstructions. In such situations, ABS will significantly reduce the chances of a skid and subsequent loss of control.

In gravel, sand and deep snow, ABS tends to increase braking distances. On these surfaces, locked wheels dig in and stop the vehicle more quickly. ABS prevents this from occurring. Some ABS calibrations reduce this problem by slowing the cycling time, thus letting the wheels repeatedly briefly lock and unlock. Some vehicle manufacturers provide an "off-road" button to turn ABS function off. The primary benefit of ABS on such surfaces is to increase the ability of the driver to maintain control of the car rather than go into a skid, though loss of control remains more likely on soft surfaces like gravel or slippery surfaces like snow or ice. On a very slippery surface such as sheet ice or gravel, it is possible to lock multiple wheels at once, and this can defeat ABS (which relies on comparing all four wheels, and detecting individual wheels skidding). Availability of ABS relieves most drivers from learning threshold braking.

A June 1999 National Highway Traffic Safety Administration (NHTSA) study found that ABS increased stopping distances on loose gravel by an average of 22 percent.

According to the NHTSA,

"ABS works with your regular braking system by automatically pumping them. In vehicles not equipped with ABS, the driver has to manually pump the brakes to prevent wheel lockup. In vehicles equipped with ABS, your foot should remain firmly planted on the brake pedal, while ABS pumps the brakes for you so you can concentrate on steering to safety."

When activated, some earlier ABS systems caused the brake pedal to pulse noticeably. As most drivers rarely or never brake hard enough to cause brake lock-up, and a significant number rarely bother to read the car's manual, this may not be discovered until

an emergency. When drivers do encounter an emergency that causes them to brake hard, and thus encounter this pulsing for the first time, many are believed to reduce pedal pressure, and thus lengthen braking distances, contributing to a higher level of accidents than the superior emergency stopping capabilities of ABS would otherwise promise. Some manufacturers have therefore implemented a brake assist system that determines that the driver is attempting a "panic stop" (by detecting that the brake pedal was depressed very fast, unlike a normal stop where the pedal pressure would usually be gradually increased, Some systems additionally monitor the rate at the accelerator was released) and the system automatically increases braking force where not enough pressure is applied. Hard or panic braking on bumpy surfaces, because of the bumps causing the speed of the wheel(s) to become erratic may also trigger the ABS. Nevertheless, ABS significantly improves safety and control for drivers in most on-road situations.

Anti-lock brakes are the subject of some experiments centred around risk compensation theory, which asserts that drivers adapt to the safety benefit of ABS by driving more aggressively. In a Munich study, half a fleet of taxicabs was equipped with anti-lock brakes, while the other half had conventional brake systems. The crash rate was substantially the same for both types of cab, and Wilde concludes this was due to drivers of ABS-equipped cabs taking more risks, assuming that ABS would take care of them, while the non-ABS drivers drove more carefully since ABS would not be there to help in case of a dangerous situation. A similar study was carried out in Oslo, with similar results.

## Chapter 8

# Brake Fade and Brake Fluid

## Brake fade

Vehicle braking system **fade**, or **brake fade**, is the reduction in stopping power that can occur after repeated or sustained application of the brakes, especially in high load or high speed conditions. Brake fade can be a factor in any vehicle that utilizes a friction braking system including automobiles, trucks, motorcycles, airplanes, and even bicycles.

Brake fade is caused by a buildup of heat in the braking surfaces and the subsequent changes and reactions in the brake system components and can be experienced with both drum brakes and disc brakes. Loss of stopping power, or fade, can be caused by friction fade, mechanical fade, or fluid fade. Brake fade can be significantly reduced by appropriate equipment and materials design and selection, as well as good cooling.

Brake fade occurs most often during high performance driving or when going down a long, steep hill. Owing to their configuration fade is more prevalent in drum brakes. Disc brakes are much more resistant to brake fade and have come to be a standard feature in front brakes for most vehicles.

### ***Causes of brake fade***

The reduction of friction termed brake fade is caused when the temperature reaches the "kneepoint" on the temperature-friction curve. [*All brake lining is cured under mechanical pressure following a heating & cooling curve, heating the friction material up to 450°F to "cure" (cross-link) the phenolic resin thermoset polymers: There is no melting of the binding resins, because phenolic resins are thermoset, not thermoplastic*] In this form of fade, the brake pedal feels firm but there is reduced stopping ability. Fade can also be caused by the brake fluid boiling, with attendant release of compressible gases. In this type of fade, the brake pedal feels "spongy". This condition is worsened

when there are contaminants in the fluid, such as water, which most types of brake fluids are prone to absorbing to varying degrees. For this reason brake fluid replacement is standard maintenance.

### ***Fade in self-assisting brakes***

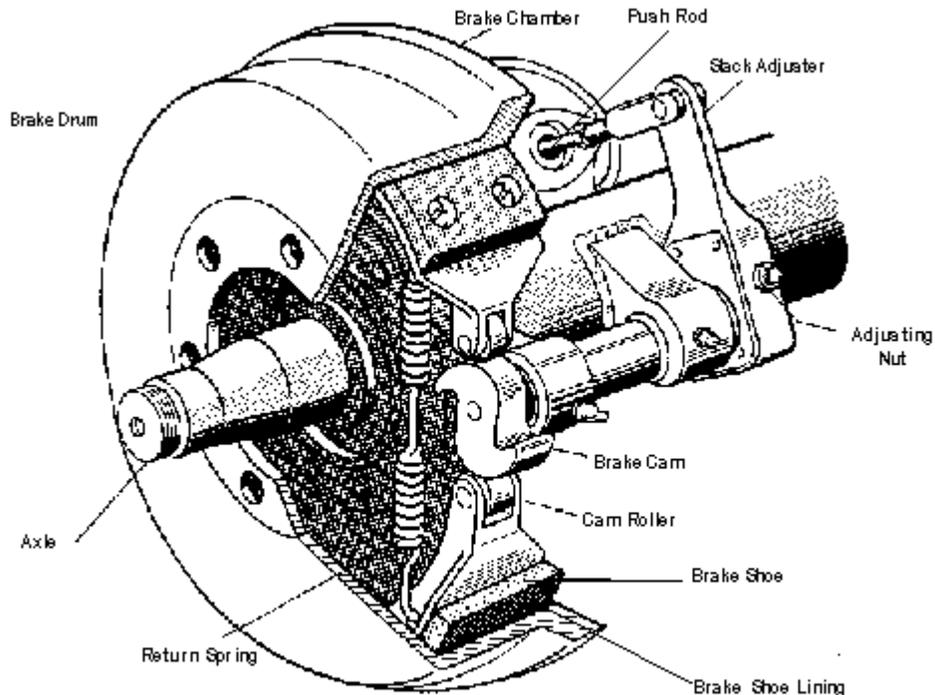


Figure 5-2 S-cam Air Brake

Truck air brakes can fade due to expansion if improperly adjusted

Various brake designs such as band brakes and many drum brakes are self-assisting: when the brake is applied, some of the braking force feeds back in to the brake mechanism to further self-apply the brake. This is called "positive feedback" or "self-servo". Self-assist reduces the input force needed to apply the brake, but exaggerates fade, since a reduction in pad friction also reduces pad force. In contrast, for a brake without self-assist, such as a conventional disc brake, a loss of pad friction does not change the pad force, so the loss of braking is proportional to just the loss of pad friction.

The self-assist mechanism affects the amount of fade. For example, the Ausco Lambert and Murphy brakes have self-assist roughly proportional to pad friction, so total braking is reduced as roughly the square of the loss in friction. Many other self-assist designs, such as band brakes and many common drum brakes, have exponential self-assist, described by  $e^{\mu\theta}$ , where  $e$  is the natural logarithm base,  $\mu$  is the coefficient of friction between shoes and drum, and  $\theta$  is the angle of engagement between shoes and drum. A small change in friction causes an exponential change in self assist. In many common brakes, a slight increase in friction can lead to wheel lockup with even light application.

For example, on damp mornings, drum brakes can lock on first application, skidding to a stop even after the brake pedal has been released. Conversely, a slight decrease in friction can lead to severe brake fade.

### ***Factors contributing to fade***

Brake fade failures can cascade. For example, a typical 5-axle truck/trailer combination has 10 brakes. If one brake fades, brake load is transferred to the remaining 9 brakes, causing them to work harder, get hotter, and thus fade more. Where fade is non-uniform, fade may cause a vehicle to swerve. Because of this, heavy vehicles often use disproportionately weak brakes on steered wheels, which hurts the stopping distance and causes brakes on non-steered wheels to work harder, worsening fade. An advantage of low-fade brakes such as disc brakes is steered wheels can do more braking without causing brake steer.

Brake fade typically occurs during heavy or sustained braking. Many high-speed vehicles use disc brakes, and many European heavy vehicles use disc brakes. Many U.S. and third-world heavy vehicles use drum brakes due to their lower purchase price. On heavy vehicles, air drag is often small compared to the weight, so the brakes dissipate proportionally more energy than on a typical car or motorcycle. Thus, heavy vehicles often need to use engine compression braking, and slow down so braking energy is dissipated over a longer interval. Even so, heavy vehicle drum brakes may fade significantly in a single stop on flat ground from highway speeds.

Brake failure is also caused by brake drum thermal expansion in which brake shoe clearance becomes excessive from wear. This was largely remedied in the 1950s by self-adjusting brakes. Maladjustment with wear is still a factor in trucks with drum air brakes. A Canadian survey of randomly-stopped heavy trucks found over 10% of trucks using self-adjusting brakes had at least one brake out of adjustment, due either to failure of the self-adjust mechanism or wear beyond the capacity of the self adjuster. Newer brake pistons ("cans") extend stroke from about 65 mm to about 75 mm; since about 30 mm of stroke is used just putting the pads in contact with the drum, the added 10 mm of stroke is over 25% increase in useful stroke. Longer stroke reduces especially wear-related fade, but drum brakes are still fundamentally prone to fade when hot.

After cooling, faded brakes usually perform as well as before, with no visible change to the brake shoes and/or pads. However if the brakes have been excessively hot for a prolonged period of time, glazing can occur on both of the friction linings of the shoes and pads. When this happens, the contacting surfaces of the linings will have a smooth, shiny appearance, and will not perform as efficiently to slow the vehicle under braking. This glazing can be easily removed by either gently using emery paper on them, or by driving the vehicle carefully whilst implementing light use of the brakes for several miles.

An incorrect explanation sometimes given for brake fade is heated brake shoes evaporate to generate gas that separate them from the drum. Such effects are easy to imagine, but

physically impossible, due to the large volume of gas that would be required for such an effect. A gas bearing would need gas replenishment as fast as the disc or drum moves, since it has no gas on its surface as it approaches the pad or shoe. Also, disc brakes use much the same materials and operate well with little fade, even when the discs are glowing hot. (color vs. temperature) If brake materials outgassed at drum temperatures, they would also outgas at disc temperatures and would fade substantially. Since discs have little fade, the also demonstrate outgassing is not a source of fade. Some disc brakes are drilled or slotted, but smooth discs show no more fade.

Long dual-tire skid marks on highways, made by trucks with drum brakes, are visible examples of non-linearity between brake response and pedal pressure. Large trucks still use drum brakes because they are economical and fit easily where an equivalent disc brake does not. More recently disc brakes for trucks have been promoted listing features such as no fade, possible because they have no self-assist (self-servo).

## ***Railroads***

Railroads have been using disk brakes on passenger cars for more than 60 years, but coupled with a *Rolokron* anti-lock system to avoid the creation of *flat spots* (or “*square wheels*”) when wheels lock and skid on the rail surface (audible as rhythmic *bang-bang-bang* noise as a train goes by). Usually, brake disks are installed in the center of the axle, but in some applications (such as Bombardier Bi Level commuter cars), only one disk is used, mounted on the axle end outside the truck frame. High speed trains (such as the TGV) may use four disks per axle.

Freight cars (and some passenger cars like multiple-unit cars whose traction motors do not yield room on axles to allow the placement of disk brakes) are equipped with *clasp brakes* which directly grab the rolling surface of the wheels (much like the old horse buggy brakes of yesteryear). Such brakes are an external-shoe drum brake; but unlike band brakes and many internal-shoe drum brakes, there is no self-assist/self-servo effect, and so they are far less susceptible to locking than self-assist brakes. Due to high stiffness and relatively low power, these clasp brakes are even less prone to lockup than many disc brakes, and so freight cars using them are not equipped with anti-lock systems.

## ***Controlling fade through driving technique***

Brake fade and rotor warping can be reduced through proper braking technique; when running down a long downgrade that would require braking simply select a lower gear (for automatic transmissions this may necessitate a brief application of the throttle after selecting the gear). Also, periodic, rather than continuous application of the brakes will allow them to cool between applications. Continuous light application of the brakes can be particularly destructive in both wear and adding heat to the brake system. Finally, new brakes are prone to a phenomenon termed “green fade”, where resin on the brake pad evaporates at the high temperatures involved in heavy braking and the resulting pressurised gas forces the brake lining away from the disk, reducing friction. New brakes

should therefore be used as gently as possible for the first 100 miles or so to "break them in" and eliminate "green fade".

### ***Brake modification to reduce fade***

High performance brake components provide enhanced stopping power by improving friction while reducing brake fade. Improved friction is provided by lining materials that have a higher coefficient of friction than standard brake pads, while brake fade is reduced through the use of more expensive binding resins with a higher melting point, along with slotted, drilled, or dimpled discs/rotors that reduce the gaseous boundary layer, in addition to providing enhanced heat dissipation. Heat buildup in brakes can be further addressed by body modifications that direct cold air to the brakes.

The "gaseous boundary layer" is a hot rod mechanics explanation for failing self servo effect of drum brakes because it felt like a brick under the brake pedal when it occurred. To counter this effect, brake shoes were drilled and slotted to vent gas. In spite of that, drum brakes were abandoned for their self-servo effect. Disks do not have that because application force is applied at right angles to the resulting braking force. There is no interaction.

Adherents of gas emission have carried that belief to motorcycles, bicycles and "sports" cars, while all other disk brake users from the same automotive companies have no holes through the faces of their discs, although internal radial air passages are used. Vents to release gas have not been found on railway, aircraft and passenger car brakes because there is no gas to vent. Meanwhile, heavy trucks still use drum brakes because they offer more heat dissipation than disks that would fit in the same space. Railways have never used internal expanding drum brakes because they cause skidding, causing expensive flat spots on steel wheels.

Both disc and drum brakes can be improved by any technique that removes heat from the braking surfaces.

Drum brake fade can be reduced and overall performance enhanced somewhat by an old "hot rod" technique of drum drilling. A carefully chosen pattern of holes is drilled through the drum working section; drum rotation centrifugally pumps a small amount air through the shoe to drum gap, removing heat; fade caused by water-wet brakes is reduced since the water is centrifugally driven out; and some brake-material dust exits the holes. Brake drum drilling requires careful detailed knowledge of brake drum physics and is an advanced technique probably best left to professionals. There are performance-brake shops that will make the necessary modifications safely.

The Bugatti Veyron for example has turbine-cooled brakes that reduce fade to almost nothing considering the speeds it is braking from.

Brake fade caused by overheating brake fluid (often called Pedal Fade) can also be reduced through the use of thermal barriers that are placed between the brake pad and the

brake caliper piston, these reduce the transfer of heat from the pad to the caliper and in turn hydraulic brake fluid. Some high-performance racing calipers already include such brake heat shields made from titanium or ceramic materials. However, it is also possible to purchase aftermarket titanium brake heat shields that will fit your existing brake system to provide protection from brake heat. These inserts are precision cut to cover as much of the pad as possible. These Titanium Brake shims are an easy to install, low cost solution that are popular with racers and track day enthusiasts.

Another technique employed to prevent brake fade is the incorporation of fade stop brake coolers. Like titanium heat shields the brake coolers are designed to slide between the brake pad backing plate and the caliper piston. They are constructed from a high thermal conductivity, high yield strength metal composite which conducts the heat from the interface to a heat sink which is external to the caliper and in the airflow. They have been shown to decrease caliper piston temperatures by over twenty percent and to also significantly decrease the time needed to cool down. Unlike titanium heat shields, however, the brake coolers actually transfer the heat to the surrounding environment and thus keep the pads cooler.

## Brake fluid

**Brake fluid** is a type of hydraulic fluid used in hydraulic brake applications in automobiles, motorcycles, light trucks, and some advanced bicycles. It is used to transfer force into pressure. It works because liquids are not appreciably compressible - in their natural state the component molecules do not have internal voids and the molecules pack together well, so bulk forces are directly transferred to trying to compress the fluid's chemical bonds.

Brake fluid is also commonly used in hydraulic clutches.

Because oils damage rubber seals and hoses in the braking system, brake fluids are not petroleum-based. Most brake fluids used today are glycol-ether based, but mineral oil (*Citroën liquide hydraulique minéral* LHM) and silicone (DOT 5) based fluids are also available. Brake fluids must meet certain requirements as defined by various standards set by organizations such as the SAE, or local government equivalents. For example, most brake fluid sold in North America is classified by the US Department of Transportation (DOT) under their own ratings such as "DOT 3" and "DOT 4". Their classifications broadly reflect the concerns addressed by the SAE's specifications, but with local details - Alaska and the Azores have different normal temperature and humidity ranges to consider, for example. Many countries defer explicitly to the SAE specifications, or simply refer to "best practice" which in practice would defer to the SAE.

## Characteristics

Brake fluids must have certain characteristics and meet certain quality standards for the braking system to work properly.

### Boiling point

Brake fluid is subjected to very high temperatures, especially in the wheel cylinders of drum brakes and disk brake calipers. It must have a high boiling point to avoid vaporizing in the lines. This vaporization is a problem because vapor is compressible and negates hydraulic fluid transfer of braking force.

Quality standards refer to a brake fluid's "dry" and "wet" boiling points. Wet boiling point, which is usually much lower (although above most normal service temperatures), refers to the fluid's boiling point after absorbing a certain amount of moisture. This is several (single digit) percent, varying from formulation to formulation. Glycol-ether/dot three/dot four/dot five point one brake fluids are hygroscopic (water absorbing), which means they absorb moisture from the atmosphere under normal humidity levels. Non-hygroscopic fluids (e.g. silicone/DOT 5-based formulations), are hydrophobic, and can maintain an acceptable boiling point over the fluid's service life, although at the cost of potential phase separation/water pooling and freezing/boiling in the system over time - the main reason single phase hygroscopic fluids are used.

Boiling points for common braking fluids

	<b>Dry boiling point</b>	<b>Wet boiling point</b>
DOT 3	205 °C (401 °F)	140 °C (284 °F)
DOT 4	230 °C (446 °F)	155 °C (311 °F)
DOT 5	260 °C (500 °F)	180 °C (356 °F)
DOT 5.1	270 °C (518 °F)	190 °C (374 °F)

*Wet boiling point defined as 3.7% water by volume.*

### Viscosity

For reliable, consistent brake system operation, brake fluid must maintain a constant viscosity under a wide range of temperatures, including extreme cold. This is especially important in systems with an anti-lock braking system (ABS), traction control, and stability control (ESP).

### Corrosion

Brakes fluids must not corrode the metals used inside components such as calipers, master cylinders, etc. They must also protect against corrosion as moisture enters the system. Additives (corrosion inhibitors) are added to the base fluid to accomplish this.

## **Compressibility**

Brake fluids must maintain a low level of compressibility that remains low, even with varying temperatures.

## ***Service and maintenance***

Most automotive professionals agree that glycol-based brake fluid, (DOT 3, DOT 4, DOT 5.1) should be flushed, or changed, every 1–2 years. Many manufacturers also require periodic fluid changes to ensure reliability and safety. Once installed, moisture diffuses into the fluid through brake hoses and rubber seals and, eventually, the fluid will have to be replaced when the water content becomes too high. Electronic testers and test strips are commercially available to measure moisture content. The corrosion inhibitors also degrade over time. New fluid should always be stored in a sealed container to avoid moisture intrusion.

DOT 5 is silicone fluid and the above does not apply. Ideally, silicone fluid should be used only to fill non-ABS systems that have not been previously filled with glycol based fluid. Any system that has used glycol based fluid will contain moisture, glycol fluid disperses the moisture throughout the system and contains corrosion inhibitors. Silicone fluid does not allow moisture to enter the system, but does not disperse any that is already there either. A system filled from dry with silicone fluid, does not require the fluid to be changed at intervals, only when the system has been disturbed for a component repair or renewal. The United States armed forces have standardised on silicone brake fluid since the 1990s.

Brake fluid is not considered a "top up" fluid. If it is low, there is usually a problem. Brake fluid level in the master cylinder will drop as the linings (pads or shoes) wear and the calipers or wheel cylinders extend further to compensate. This added fluid may need to be removed when renewing pads or shoes. Overspill from pushing back pistons should be avoided, because glycol based fluid will quickly lift or strip paints and other coatings on contact (it can be removed by quickly washing with water, not wiping). Brake fluid level may also be low because of a leak, which could result in a loss of hydraulic pressure and consequently, a significant loss of braking ability. Modern cars have split hydraulic circuits to ensure against total hydraulic failure. Brake fluids with different DOT ratings should not be mixed, not all DOT fluid is compatible. This is because it will dilute and reduce the properties of the higher specification DOT fluid, or in the case of mixing of glycol with silicone fluid may cause corrosion due to trapped moisture.

Brake fluid can be dangerous as it is toxic and highly flammable.

## ***Components***

### **Glycol-based (DOT 3, 4, 5.1)**

- Alkyl ester

- Aliphatic amine
- Diethylene glycol
- Diethylene glycol monoethyl ether
- Diethylene glycol monomethyl ether
- Dimethyl dipropylene glycol
- Polyethylene glycol monobutyl ether
- Polyethylene glycol monomethyl ether
- Polyethylene oxide
- Triethylene glycol monobutyl ether
- Triethylene glycol monoethyl ether
- Triethylene glycol monomethyl ether

### **Silicone-based (DOT 5)**

- Di-2-ethylhexyl sebacate
- Dimethyl polysiloxane
- Tributyl phosphate

## Chapter 9

# Brake Lining and Electronic Brakeforce Distribution

## Brake lining

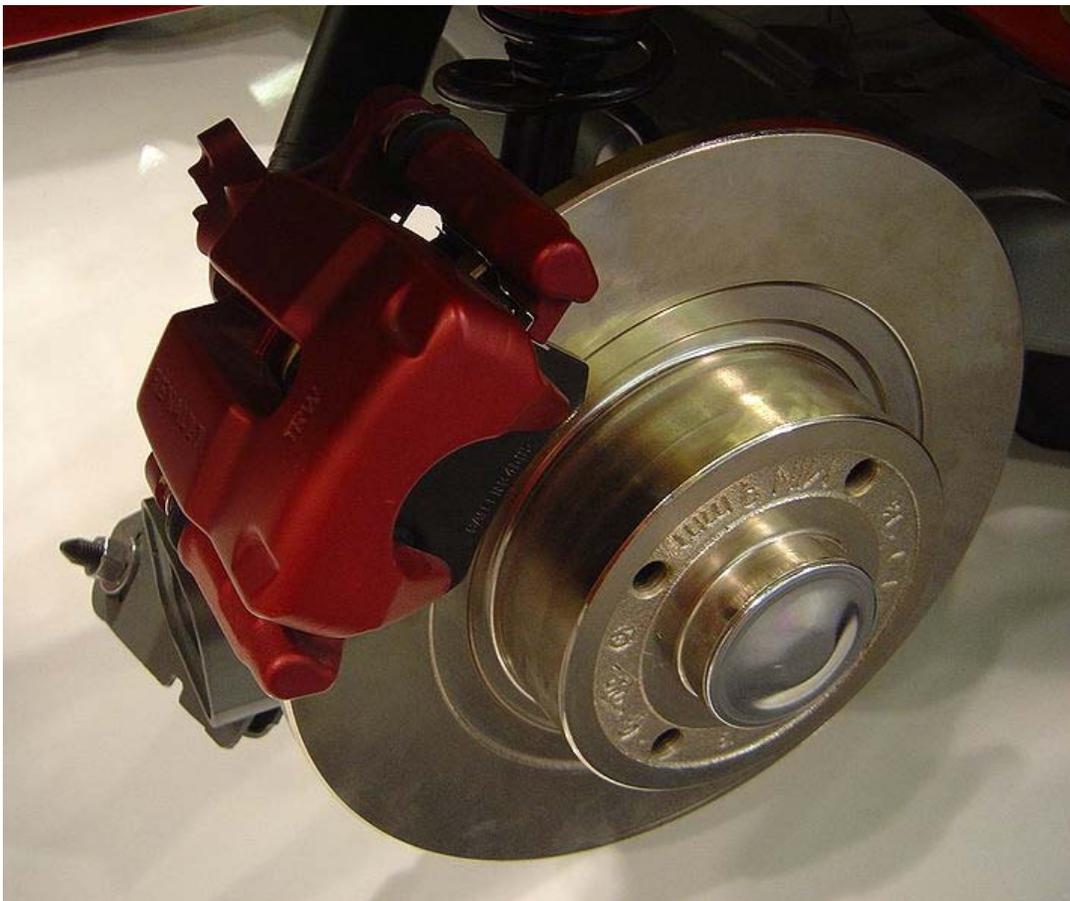


Drum shoes with linings

**Brake linings** are the consumable surfaces in brake systems, especially drum brakes as those used in vehicles.

### ***Structure and function***

Brake linings are composed of a relatively soft but tough and heat-resistant material with a high coefficient of dynamic friction (and ideally an identical coefficient of static friction) typically mounted to a solid metal backing using high-temperature adhesives or rivets. The complete assembly (including lining and backing) is then often called a brake pad or brake shoe. The dynamic friction coefficient " $\mu$ " for most standard brake pads is usually in the range of 0.35 to 0.42. This means that a force of 1000 Newtons (or pounds) on the pad will give a resulting brake force close to 400 Newtons (or pounds). There are some racing pads that have a very high  $\mu$  of 0.55 to 0.62 with excellent high temperature behaviour. These pads have high iron content and will usually outperform any other pad used with iron discs. Unfortunately nothing comes for free, and these high  $\mu$  pads wear fast and also wear down the discs at a rather fast rate. However they are a very cost effective alternative to more exotic/expensive materials.



In this view of an automobile disc brake, the **brake pad** is the black material held by the red metal component (the **brake caliper**). The **brake lining** is that part of the brake pad which actually contacts the metal disc when the brake is engaged.

Using a typical bicycle brake as an example, the backing would be the metal shell which provides mechanical support, and the lining would be the rubbery portion which contacts the rims when the brakes are applied. In most modern vehicular applications the system is conceptually identical, except the rims would be replaced with solid steel (or sometimes exotic metal) disc. Furthermore, a metal tang is usually incorporated into the pad assembly. The tang contacts the rotors when the linings are worn out, causing an annoying noise designed to alert the motorist that brake servicing is required.

Since the lining is the portion of the braking system which converts the vehicle's kinetic energy into heat, the lining must be capable of surviving high temperatures without excessive wear (leading to frequent replacement) or outgassing (which causes *brake fade*, a decrease in the stopping power of the brake).

Due to its suitability, asbestos was often a component in brake linings; as a result, brake dust should never be inhaled. Brake linings or pads have not used asbestos since 2003, having been replaced by aramid.

## ***Maintenance***

When the lining is worn out, the backing or rivets will contact the rotors or drums during braking, often causing damage requiring remachining or replacement of the drums or rotors. An annoying squeal caused by the warning tang is the typical alert that the pads need to be replaced; if the squeal is ignored for too long, drum or rotor damage (usually accompanied by an unpleasant grinding sound or sensation) will be the typical result.

The lining may also become contaminated by oil or leaked brake fluid. Typical symptoms will be brake chatter, where the pads vibrate as the lining grabs and releases the rotor's surface. The solution is to repair the source of the contamination and replace the damaged pads.

In the automotive repair industry, many consumers purchase brake pads with a lifetime warranty. These pads use a much harder lining than traditional brake pads and tend to cause excessive wear of the much more expensive rotors or drums. For that reason, consumers should ensure that the new brake pads installed are those specified or supplied by the vehicle's manufacturer. Relined brake pads are usually inexpensive and perfectly acceptable, with new lining material attached to reconditioned (cleaned, inspected and painted) backing assemblies.

Brake pads must always be replaced simultaneously on both ends of a vehicle's axle, as the different lining thicknesses (and possibly material types) will cause uneven braking, making the vehicle pull in the direction of the more effective brake. For most vehicles, replacing pads (and therefore linings) is very easy, requiring a minimum of tools and time — the linings are designed to be consumable and should therefore be easy to service.

Brake linings can also be found just about everywhere there are braking systems, from elevator safety brakes to spindle brakes inside a VCR. The form and materials are frequently different, but the principle is the same.

## ***Cataloguing***

There are different systems for the cataloguing of brake linings. The most frequently used system in Europe is the WVA numbering system.

# **Electronic brakeforce distribution**

**Electronic brakeforce distribution (EBD or EBFD), Electronic brakeforce limitation (EBL)** is an automobile brake technology that automatically varies the amount of force applied to each of a vehicle's brakes, based on road conditions, speed, loading, etc. Always coupled with anti-lock braking systems, EBD can apply more or less braking pressure to each wheel in order to maximize stopping power whilst maintaining vehicular control. Typically, the front end carries the most weight and EBD distributes less braking pressure to the rear brakes so the rear brakes do not lock up and cause a skid. In some systems, EBD distributes more braking pressure at the rear brakes during initial brake application before the effects of weight transfer become apparent.

## ***How ABS works***

Under heavy braking, vehicle wheels may lock-up. The anti-lock braking system (ABS) monitors wheel speeds and releases pressure on individual wheel brake lines, rapidly pulsing individual brakes to prevent lock-up. During heavy braking, preventing wheel lock-up helps the driver maintain steering control. Modern ABS has an individual brake line for each of the four wheels, enabling different braking pressure on different road surfaces. For example, less braking pressure is needed to lock a wheel on ice than a wheel which is on bare asphalt. If the left wheels are on asphalt and the right wheels are on ice, during an emergency stop, ABS detects the right wheels about to lock and reduces braking force on the right wheels, helping to avoid lock-up and loss of vehicle control.

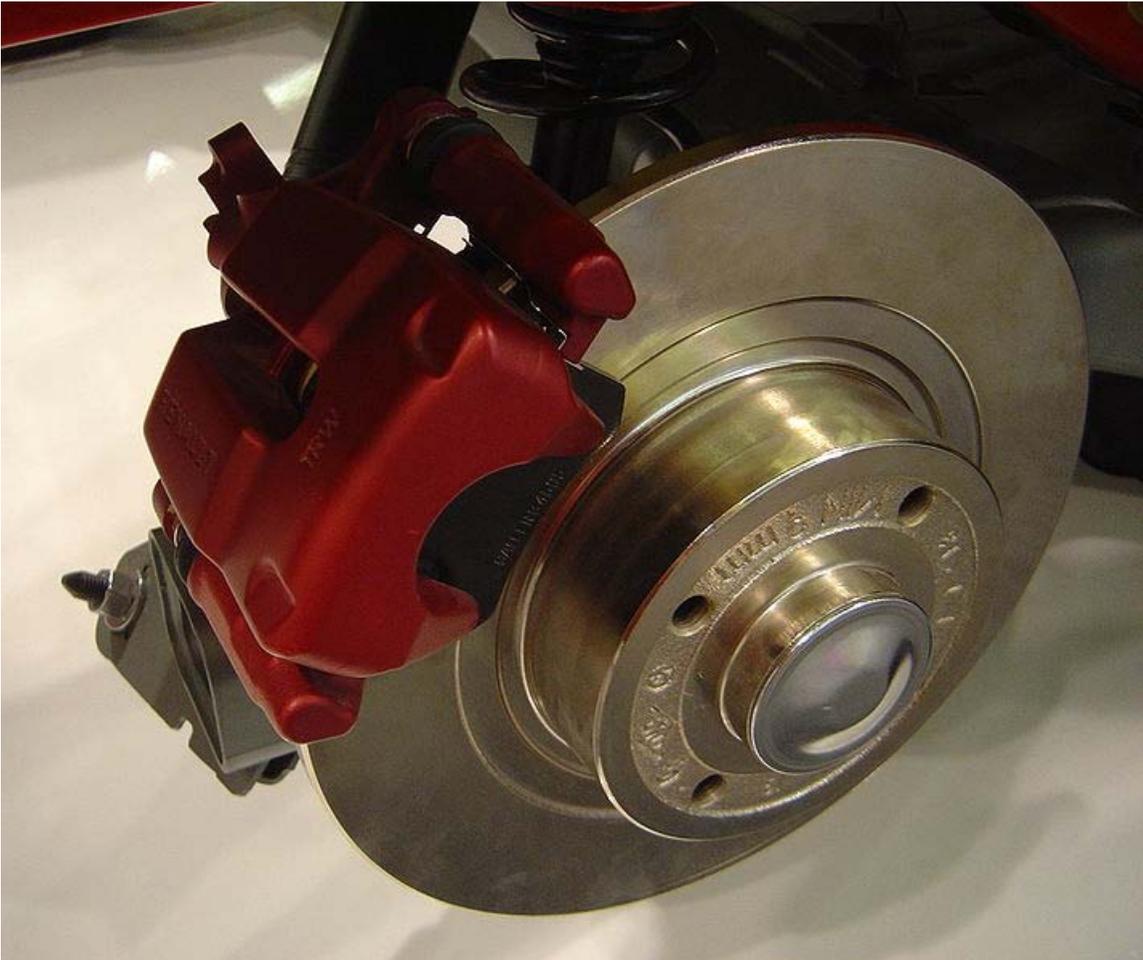
## ***How EBD works***

As per SAE technical paper #920646 - Buschmann et al. "The job of the EBD as a subsystem of the ABS system is to control the effective adhesion utilization by the rear wheels. The pressure of the rear wheels is approximated to the ideal brake force distribution in a partial braking operation. To do so, the conventional brake design is modified in the direction of rear axle overbraking, and the components of the ABS are used. EBD reduces the strain on the hydraulic brake force proportioning valve in the vehicle. EBD optimizes the brake design with regard to: adhesion utilization; driving stability; wear; temperature stress; and pedal force."

EBD may work in conjunction with ABS and Electronic Stability Control ("ESC") to minimize yaw accelerations during turns. ESC compares the steering wheel angle to vehicle turning rate using a yaw rate sensor. "Yaw" is the vehicle's rotation around its vertical center of gravity (turning left or right). If the yaw sensor detects more/less yaw than the steering wheel angle should create, the car is understeering or oversteering and ESC activates one of the front or rear brakes to rotate the car back onto its intended course. For example, if a car is making a left turn and begins to understeer (the car plows forward to the outside of the turn) ESC activates the left rear brake, which will help turn the car left. The sensors are so sensitive, and the actuation is so quick that the system may correct direction before the driver reacts. ABS helps prevent wheel lock-up and EBD helps apply appropriate brake force to make ESC work effectively.

## Chapter 10

# Disc Brake



Close-up of a disc brake on a car



On automobiles, disc brakes are often located within the wheel

The **disc brake** or **disk brake** is a device for slowing or stopping the rotation of a wheel while it is in motion. A brake disc (or *rotor* in U.S. English) is usually made of cast iron, but may in some cases be made of composites such as reinforced carbon-carbon or ceramic-matrix composites. This is connected to the wheel and/or the axle. To stop the wheel, friction material in the form of brake pads (mounted on a device called a **brake caliper**) is forced mechanically, hydraulically, pneumatically or electromagnetically against both sides of the disc. Friction causes the disc and attached wheel to slow or stop. Brakes convert motion to heat, and if the brakes get too hot, they become less effective, a phenomenon known as brake fade.

## **History**

Disc-style brakes development and use began in England in the 1890s. The first caliper-type automobile disc brake was patented by Frederick William Lanchester in his Birmingham, UK factory in 1902 and used successfully on Lanchester cars. However, the limited choice of metals in this period, meant that he had to use copper as the braking medium acting on the disc. The poor state of the roads at this time, no more than dusty, rough tracks, meant that the copper wore quickly making the disc brake system non-viable (as recorded in *The Lanchester Legacy*). It took another half century for his innovation to be widely adopted.

Modern-style disc brakes first appeared on the low-volume Crosley Hotshot in 1949, although they had to be discontinued in 1950 due to design problems. Chrysler's Imperial also offered a type of disc brake from 1949 through 1953, though in this instance they were enclosed with dual internal-expanding, full-circle pressure plates. Reliable modern disc brakes were developed in the UK by Dunlop and first appeared in 1953 on the Jaguar C-Type racing car. The Citroën DS of 1955, with powered inboard front disc brakes was the first foreign, whilst the 1956 Triumph TR3 was the first English production car to feature modern disc brakes. The first production car to feature disc brakes at all 4 wheels was the Austin-Healey 100S in 1954. The first British company to market a production saloon fitted with disc brakes to all four wheels was Jensen Motors with the introduction of a Deluxe version of the Jensen 541 with Dunlop disc brakes. The first German production car with disc brakes was the 1961 Mercedes-Benz 220SE coupe featuring British-built Girling units on the front. The next American production automobile equipped with caliper-type disc brakes was the 1963 model year Studebaker Avanti (the Bendix system optional on some of the other Studebaker models). Front disk brakes became standard equipment in 1965 on the Rambler Marlin (the Bendix units were optional on all American Motors "senior" platform models), the Ford Thunderbird, and the Lincoln Continental. A four-wheel disc brake system was also introduced in 1965 on the Chevrolet Corvette Stingray.

Compared to drum brakes, disc brakes offer better stopping performance, because the disc is more readily cooled. As a consequence discs are less prone to the "brake fade" caused when brake components overheat; and disc brakes recover more quickly from immersion (wet brakes are less effective). A drum brake will have at least one leading shoe, which gives a servo-effect. By contrast, a disc brake has no self-servo effect and its braking force is always proportional to the pressure placed on the brake pad by the braking system via any brake servo, braking pedal or lever.

Many early implementations for automobiles located the brakes on the inboard side of the driveshaft, near the differential, but most brakes today are located inside the road wheels. (An inboard location reduces the unsprung weight and eliminates a source of heat transfer to the tires.)

Disc brakes were most popular on sports cars when they were first introduced, since these vehicles are more demanding about brake performance. Discs have now become the more

common form in most passenger vehicles, although many (particularly light weight vehicles) use drum brakes on the rear wheels to keep costs and weight down as well as to simplify the provisions for a parking brake. As the front brakes perform most of the braking effort, this can be a reasonable compromise.

## ***Discs***



A cross-drilled disc on a modern motorcycle

The design of the disc varies somewhat. Some are simply solid cast iron, but others are hollowed out with fins or vanes joining together the disc's two contact surfaces (usually included as part of a casting process). The weight and power of the vehicle will determine the need for ventilated discs. The "ventilated" disc design helps to dissipate the generated heat and is commonly used on the more-heavily-loaded front discs. The front brakes provide most of the stopping power.

Many higher performance brakes have holes drilled through them. This is known as cross-drilling and was originally done in the 1960s on racing cars. For heat dissipation purposes, cross drilling is still used on some braking components, but is not favored for racing or other hard use as the holes are a source of stress cracks under severe conditions.

Discs may also be slotted, where shallow channels are machined into the disc to aid in removing dust and gas. Slotting is the preferred method in most racing environments to remove gas, water, and de-glaze brake pads. Some discs are both drilled and slotted. Slotted discs are generally not used on standard vehicles because they quickly wear down

brake pads; however, this removal of material is beneficial to race vehicles since it keeps the pads soft and avoids vitrification of their surfaces. As a way of avoiding thermal stress, cracking and warping of the disc these are sometimes mounted in a half loose way to the hub with coarse splines. This allows the disc to expand in a controlled symmetrical way and with less unwanted heat transfer to the hub.



A mountain bike disc brake

On the road, drilled or slotted discs still have a positive effect in wet conditions because the holes or slots prevent a film of water building up between the disc and the pads. Crossdrilled discs may eventually crack at the holes due to metal fatigue. Cross-drilled brakes that are manufactured poorly or subjected to high stresses will crack much sooner and more severely.

The first motorcycles to use disc brakes were racing machines. The first mass-produced road-going motorcycle to sport a disc-brake was the 1969 Honda CB750. Disc brakes are now common on motorcycles, mopeds and even bicycles. Motorcycle disc brakes have become increasingly sophisticated, partly through marketing. Their discs are usually drilled and occasionally slotted. Calipers have evolved from simple "single-pot" units to 2-, 4- and even 6-pot items. It is debatable whether the modern fashions of "radially-mounted calipers" and "wavy discs" significantly improve braking. Since (compared to cars) motorcycles have a higher centre of gravity:wheelbase ratio, they experience more

weight transference when braking. A modern sports bike will typically have twin front discs of large diameter, but only a single rear disc that is very much smaller (or even a small rear drum brake). The front brake(s) provide most of the required deceleration; the rear brake serves mainly as to "balance" the motorcycle during braking. If too much braking force is applied to the rear brake, the rear wheel is liable to lock up; so motorcycles should not have oversize rear brakes.

Mountain bike disc brakes range from simple, mechanical (cable) systems, to expensive and powerful, 6-pot (piston) hydraulic disc systems, commonly used on downhill racing bikes. Improved technology has seen the creation of the first vented discs for use on mountain bikes, similar to those on cars, introduced to help avoid heat fade on fast alpine descents. Although less common, discs are also used on road bicycles for all-weather cycling with predictable braking, although drums are sometimes preferred as harder to damage in crowded parking, where discs are sometimes bent. Most bicycle brake discs are made of stainless steel, although some lightweight discs are made of titanium or aluminium. Discs are thin, often about 2 mm. Some use a two-piece floating disc style, others use a floating caliper, others use pads that float in the caliper, and some use one moving pad that makes the caliper slide on its mounts, pulling the other pad into contact with the disc. Because the "motor" is small, an uncommon feature of bicycle brakes is pads that retract to eliminate residual drag when the brake is released. In contrast, most other brakes drag the pads lightly when released.

Disc brakes are increasingly used on very large and heavy road vehicles, where previously large drum brakes were nearly universal. One reason is the disc's lack of self-assist makes brake force much more predictable, so peak brake force can be raised without more risk of braking-induced steering or jackknife on articulated vehicles. Another is disk brakes fade less when hot, and in a heavy vehicle air and rolling drag and engine braking are small parts of total braking force, so brakes are used harder than on lighter vehicles, and drum brake fade can occur in a single stop. For these reasons, a heavy truck with disc brakes can stop in about 120% the distance of a passenger car, but with drums stopping takes about 150% the distance. In Europe, stopping distance regulations essentially require disc brakes for heavy vehicles. In the U.S., drums are allowed and are typically preferred for their lower purchase price, despite higher total lifetime cost and more frequent service intervals.



A railroad bogie and disc brakes

Yet larger discs are used for railroads and some airplanes. Passenger rail cars and light rail often use disc brakes outboard of the wheels, which helps ensure a free flow of cooling air. In contrast, some airplanes have the brake mounted with very little cooling and the brake gets quite hot in a stop, but this is acceptable as the maximum braking energy is very predictable.

For auto use, disc brake discs are commonly manufactured out of a material called grey iron. The SAE maintains a specification for the manufacture of grey iron for various applications. For normal car and light truck applications, the SAE specification is J431 G3000 (superseded to G10). This specification dictates the correct range of hardness, chemical composition, tensile strength, and other properties necessary for the intended use. Some racing cars and airplanes use brakes with carbon fiber discs and carbon fiber pads to reduce weight. Wear rates tend to be high, and braking may be poor or grabby until the brake is hot.

Historically, brake discs were manufactured throughout the world with a strong concentration in Europe, and America. Between 1989 and 2005, manufacturing of brake discs is migrating predominantly to China.

## ***Racing***



A reinforced carbon brake disc installed on a Ferrari F430 Challenge race car

In racing and very high performance road cars, other disc materials have been employed. Reinforced carbon discs and pads inspired by aircraft braking systems were introduced in Formula One by Brabham in conjunction with Dunlop in 1976. Carbon-Carbon braking is now used in most top-level motorsport worldwide, reducing unsprung weight, giving better frictional performance and improved structural properties at high temperatures, compared to cast iron. Carbon brakes have occasionally been applied to road cars, by the French Venturi sports car manufacturer in the mid 1990s for example, but need to reach a very high operating temperature before becoming truly effective and so are not well suited to road use. The extreme heat generated in these systems is easily visible during night racing, especially at shorter tracks. It is not uncommon to be able to look at the cars, either live in person or on television and see the brake discs glowing red during application.

### ***Ceramic composites***

Ceramic discs are used in some high-performance cars and heavy vehicles.

The first development of the modern ceramic brake was made by British Engineers working in the railway industry for TGV applications in 1988. The objective was to reduce weight, the number of brakes per axle, as well as provide stable friction from very high speeds and all temperatures. The result was a carbon fibre reinforced ceramic process which is now used in various forms for automotive, railway, and aircraft brake applications.

The requirement for a large section of ceramic composite material having very high heat tolerance and mechanical strength often relegates ceramic discs to exotic vehicles where the cost is not prohibitive to the application, and industrial use where the ceramic disc's light weight and low maintenance properties justify the cost relative to alternatives. Composite brakes can withstand temperatures that would make steel discs bendable.



Mercedes Benz AMG Carbon Ceramic brake

Porsche's ceramic composite brakes, known as PCCB (Porsche Composite Ceramic Brakes), are siliconized carbon fiber, with very high temperature capability, a 50% weight reduction over iron rotors (therefore reducing the unsprung weight of the vehicle), a significant reduction in dust generation, substantially increased maintenance intervals, and enhanced durability in corrosive environments over conventional iron rotors. Found on some of their more expensive models, e.g., the Carrera GT, 911 GT2, etc. it is also an

optional brake for all street Porsches at added expense. It is generally recognized by the bright yellow paintwork on the aluminum 6-piston calipers that are matched with the rotors. The rotors are internally vented much like cast iron rotors, and also cross-drilled.

### ***Disc damage modes***

Discs are usually damaged in one of four ways: scarring, cracking, warping or excessive rusting. Service shops will sometimes respond to any disc problem by changing out the discs entirely. This is done mainly where the cost of a new disc may actually be lower than the cost of labour to resurface the original disc. Mechanically this is unnecessary unless the discs have reached manufacturer's minimum recommended thickness, which would make it unsafe to use them, or vane rusting is severe (ventilated discs only). Most leading vehicle manufacturers recommend brake disc skimming (US: rotor turning) as a solution for lateral run-out, vibration issues and brake noises. The machining process is performed in a brake lathe, which removes a very thin layer off the disc surface to clean off minor damage and restore uniform thickness. Machining the disc as necessary will maximise the mileage out of the current discs on the vehicle.

### **Excessive lateral run-out (warping)**

Measuring this is accomplished using a dial indicator on a fixed rigid base, with the tip perpendicular to the brake disc's face. It is typically measured about 1/2" (12 mm) from the outside diameter of the disc. The disc is spun. The difference between minimum and maximum value on the dial is called lateral runout. Typical hub/disc assembly runout specifications for passenger vehicles are around 0.0020" or 50 micrometers. Runout can be caused either by deformation of the disc itself or by runout in the underlying wheel hub face or by contamination between the disc surface and the underlying hub mounting surface. Determining the root cause of the indicator displacement (lateral runout) requires disassembly of the disc from the hub. Disc face runout due to hub face runout or contamination will typically have a period of 1 minimum and 1 maximum per revolution of the brake disc.

Discs can be machined to eliminate thickness variation and lateral runout. Machining can be done in-situ (on-car) or off-car (bench lathe). Both methods will eliminate thickness variation. Machining on-car with proper equipment can also eliminate lateral runout due to hub-face non-perpendicularity.

Incorrect fitting can distort (warp) discs; the disc's retaining bolts (or the wheel/lug nuts, if the disc is simply sandwiched in place by the wheel, as on many cars) must be tightened progressively and evenly. The use of air tools to fasten lug nuts is extremely bad practice, unless a torque tube is also used. The vehicle manual will indicate the proper pattern for tightening as well as a torque rating for the bolts. Lug nuts should never be tightened in a circle. Some vehicles are sensitive to the force the bolts apply and tightening should be done with a torque wrench.

Often uneven pad transfer is confused for disc warping. In reality, the majority of brake discs which are diagnosed as "warped" are actually simply the product of uneven transfer of pad material.

Uneven pad transfer will often lead to a thickness variation of the disc. When the thicker section of the disc passes between the pads, the pads will move apart and the brake pedal will raise slightly; this is pedal pulsation. The thickness variation can be felt by the driver when it is approximately 0.17 mm or greater (on automobile discs).

This type of thickness variation has many causes, but there are three primary mechanisms which contribute the most to the propagation of disc thickness variations connected to uneven pad transfer. The first is improper selection of brake pads for a given application. Pads which are effective at low temperatures, such as when braking for the first time in cold weather, often are made of materials which decompose unevenly at higher temperatures. This uneven decomposition results in uneven deposition of material onto the brake disc. Another cause of uneven material transfer is improper break in of a pad/disc combination. For proper break in, the disc surface should be refreshed (either by machining the contact surface or by replacing the disc as a whole) every time the pads are changed on a vehicle. Once this is done, the brakes are heavily applied multiple times in succession. This creates a smooth, even interface between the pad and the disc. When this is not done properly the brake pads will see an uneven distribution of stress and heat, resulting in an uneven, seemingly random, deposition of pad material. The third primary mechanism of uneven pad material transfer is known as "pad imprinting." This occurs when the brake pads are heated to the point that the material begins to break-down and transfer to the disc. In a properly broken in brake system (with properly selected pads), this transfer is natural and actually is a major contributor to the braking force generated by the brake pads. However, if the vehicle comes to a stop and the driver continues to apply the brakes, the pads will deposit a layer of material in the shape of the brake pad. This small thickness variation can begin the cycle of uneven pad transfer.

Once the disc has some level of variation in thickness, uneven pad deposition can accelerate, sometimes resulting in changes to the crystal structure of the metal that composes the disc in extreme situations. As the brakes are applied, the pads slide over the varying disc surface. As the pads pass by the thicker section of the disc, they are forced outwards. The foot of the driver applied to the brake pedal naturally resists this change, and thus more force is applied to the pads. The result is that the thicker sections see higher levels of stress. This causes an uneven heating of the surface of the disc, which causes two major issues. As the brake disc heats unevenly it also expands unevenly. The thicker sections of the disc expand more than the thinner sections due to seeing more heat, and thus the difference in thickness is magnified. Also, the uneven distribution of heat results in further uneven transfer of pad material. The result is that the thicker-hotter sections receive even more pad material than the thinner-cooler sections, contributing to a further increase in the variation in the disk's thickness. In extreme situations, this uneven heating can actually cause the crystal structure of the disc material to change. When the hotter sections of the discs reach extremely high temperatures(1200-1300 degrees Fahrenheit), the carbon within the cast iron of the disc will react with the iron molecules

to form a carbide known as cementite. This iron carbide is very different from the cast iron the rest of the disc is composed of. It is extremely hard, very brittle, and does not absorb heat well. After cementite is formed, the integrity of the disc is compromised. Even if the disc surface is machined, the cementite within the disc will not wear or absorb heat at the same rate as the cast iron surrounding it, causing the uneven thickness and uneven heating characteristics of the disc to return.

## Scarring



Brake discs being polished after scarring occurred

Scarring (US: Scoring) can occur if brake pads are not changed promptly when they reach the end of their service life and are considered worn out. Once enough of the friction material has worn away, the pad's steel backing plate (for glued pads) or the pad

retainer rivets (for riveted pads) will bear directly upon the disc's wear surface, reducing braking power and making scratches on the disc. Generally a moderately scarred / scored disc, which operated satisfactorily with existing brake pads, will be equally usable with new pads. If the scarring is deeper but not excessive, it can be repaired by machining off a layer of the disc's surface. This can only be done a limited number of times as the disc has a minimum rated safe thickness. The minimum thickness value is typically cast into the disc during manufacturing on the hub or the edge of the disc. In Pennsylvania, which has one of the most rigorous auto safety inspection programs in North America, an automotive disc cannot pass safety inspection if any scoring is deeper than .015 inches (0.38 mm), and must be replaced if machining will reduce the disc below its minimum safe thickness.

To prevent scarring, it is prudent to periodically inspect the brake pads for wear. A tire rotation is a logical time for inspection, since rotation must be performed regularly based on vehicle operation time and all wheels must be removed, allowing ready visual access to the brake pads. Some types of alloy wheels and brake arrangements will provide enough open space to view the pads without removing the wheel. When practical, pads that are near the wear-out point should be replaced immediately, as complete wear out leads to scarring damage and unsafe braking. Many disc brake pads will include some sort of soft steel spring or drag tab as part of the pad assembly, which is designed to start dragging on the disc when the pad is nearly worn out. The result is a moderately loud metallic squealing noise, alerting the vehicle user that service is required, and this will not normally scar the disc if the brakes are serviced promptly. A set of pads can be considered for replacement if the thickness of the pad material is the same or less than the thickness of the backing steel. In Pennsylvania, the standard is 1/32".

## **Cracking**

Cracking is limited mostly to drilled discs, which may develop small cracks around edges of holes drilled near the edge of the disc due to the disc's uneven rate of expansion in severe duty environments. Manufacturers that use drilled discs as OEM typically do so for two reasons: appearance, if they determine that the average owner of the vehicle model will prefer the look while not overly stressing the hardware; or as a function of reducing the unsprung weight of the brake assembly, with the engineering assumption that enough brake disc mass remains to absorb racing temperatures and stresses. A brake disc is a heat sink, but the loss of heat sink mass may be balanced by increased surface area to radiate away heat. Small hairline cracks may appear in any cross drilled metal disc as a normal wear mechanism, but in the severe case the disc will fail catastrophically. No repair is possible for the cracks, and if cracking becomes severe, the disc must be replaced.

## **Rusting**

The discs are commonly made from cast iron and a certain amount of what is known as "surface rust" is normal. The disc contact area for the brake pads will be kept clean by regular use, but a vehicle that is stored for an extended period can develop significant rust

in the contact area that may reduce braking power for a time until the rusted layer is worn off again. Over time, vented brake discs may develop severe rust corrosion inside the ventilation slots, compromising the strength of the structure and needing replacement.

## **Calipers**



Disc brake caliper (twin-pot, floating) removed from brake pad for changing pads

The **brake caliper** is the assembly which houses the brake pads and pistons. The pistons are usually made of aluminium or chrome-plated steel. There are two types of calipers: floating or fixed. A fixed caliper does not move relative to the disc and is, thus, less tolerant of disc imperfections. It uses one or more single or pairs of opposing pistons to clamp from each side of the disc, and is more complex and expensive than a floating caliper. A floating caliper (also called a "sliding caliper") moves with respect to the disc, along a line parallel to the axis of rotation of the disc; a piston on one side of the disc pushes the inner brake pad until it makes contact with the braking surface, then pulls the caliper body with the outer brake pad so pressure is applied to both sides of the disc.

Floating caliper (single piston) designs are subject to sticking failure, which can occur due to dirt or corrosion entering at least one mounting mechanism and stopping its normal movement. This can cause the pad attached to the caliper to rub on the disc when the brake is not engaged, or cause it to engage at an angle. Sticking can occur due to infrequent vehicle use, failure of a seal or rubber protection boot allowing debris entry, dry-out of the grease in the mounting mechanism and subsequent moisture incursion leading to corrosion, or some combination of these factors. Consequences may include reduced fuel efficiency and excessive wear on the affected pad.

Various types of brake calipers are also used on bicycle rim brakes.

## **Pistons and cylinders**

The most common caliper design uses a single hydraulically actuated piston within a cylinder, although high performance brakes use as many as twelve. Modern cars use different hydraulic circuits to actuate the brakes on each set of wheels as a safety measure. The hydraulic design also helps multiply braking force. The number of pistons in a caliper is often referred to as the number of 'pots', so if a vehicle has 'six pot' calipers it means that each caliper houses six pistons.

Brake failure can occur due to failure of the piston to retract - this is usually a consequence of not operating the vehicle during a time that it is stored outdoors in adverse conditions. On high mileage vehicles the piston seals may leak, which must be promptly corrected. The brake disc must have enough surface to perform well and the **coefficient of friction** is the most important factor to be considered when designing a brake system.

## ***Brake pads***

The brake pads are designed for high friction with brake pad material embedded in the disc in the process of bedding while wearing evenly. Although it is commonly thought that the pad material contacts the metal of the disc to stop the car, the pads work with a very thin layer of their own material and generate a semi-liquid friction boundary that creates the actual braking force. Friction can be divided into two parts: Adhesive and abrasive. Of course, depending on the properties of the material of both the pad and the disc and the configuration and the usage, pad and disc wear rates will vary considerably. The properties that determine material wear involve trade-offs between performance and longevity. The friction coefficient for most standard pads will be in the region of .40 when used with cast iron discs. Racing pads with high iron content designed for use with cast iron brake discs reach .55 to .60 which gives a very significant increase in braking power and high temperature performance. High iron content racing pads wear down discs very quickly and usually when the pads are worn out so are the discs.

The brake pads must usually be replaced regularly (depending on pad material), and some are equipped with a mechanism that alerts drivers that replacement is needed. Some have a thin piece of soft metal that rubs against the disc when the pads are too thin, causing the brakes to squeal, while others have a soft metal tab embedded in the pad material that closes an electric circuit and lights a warning light when the brake pad gets thin. More expensive cars may use an electronic sensor.

Generally road-going vehicles have two brake pads per caliper, while up to six are installed on each racing caliper, with varying frictional properties in a staggered pattern for optimum performance.

Early brake pads (and linings) contained asbestos. When working on an older car's brakes, care must be taken not to inhale any dust present on the caliper (or drum).

Although newer pads can be made of exotic materials like ceramics, kevlar and other plastics, inhalation of brake dust should still be avoided regardless of material.

## ***Brake squeal***

Sometimes a loud noise or high pitch squeal occurs when the brakes are applied. Most brake squeal is produced by vibration (resonance instability) of the brake components, especially the pads and discs (known as *force-coupled excitation*). This type of squeal should not negatively affect brake stopping performance. Simple techniques like adding chamfers to linings, greasing or gluing the contact between caliper and the pads (finger to backplate, piston to backplate), bonding insulators (damping material) to pad backplate, inclusion of a brake shim between the brake pad and back plate, etc. may help to reduce squeal. Cold weather combined with high early morning humidity (dew) often makes brake-squeal worse, although the squeal stops when the lining reaches regular operating temperatures. Dust on the brakes may also cause squeal; there are many commercial brake cleaning products that can be used to remove dust and contaminants. Finally, some lining wear indicators, located either as a semi-metallic layer within the brake pad material or with an external squealer "sensor", are also designed to squeal when the lining is due for replacement. The typical external sensor is fundamentally different because it occurs when the brakes are off, and goes away when the brakes are on.

Overall brake squeal can be annoying to the vehicle passengers, passers-by, pedestrians, etc. especially as vehicle designs become quieter. Noise, vibration, and harshness (NVH) are among the most important priorities for today's vehicle manufacturers.

Apart from noise generated from squeal, brakes may also develop a phenomenon called *brake judder* or *shudder*.

## ***Brake judder***

Brake judder is usually perceived by the driver as minor to severe vibrations transferred through the chassis during braking.

The judder phenomenon can be classified into two distinct subgroups: *hot* (or *thermal*), or *cold* judder.

Hot judder is usually produced as a result of longer, more moderate braking from high speed where the vehicle does not come to a complete stop. It commonly occurs when a motorist decelerates from speeds of around 120 km/h (74.6 MPH) to about 60 km/h (37.3 MPH), which results in severe vibrations being transmitted to the driver. These vibrations are the result of uneven thermal distributions, or *hot spots*. Hot spots are classified as concentrated thermal regions that alternate between both sides of a disc that distort it in such a way that produces a sinusoidal waviness around its edges. Once the brake pads (friction material/brake lining) comes in contact with the sinusoidal surface during braking, severe vibrations are induced, and can produce hazardous conditions for the person driving the vehicle.

Cold judder, on the other hand, is the result of uneven disc wear patterns or disc thickness variation (DTV). These variations in the disc surface are usually the result of extensive vehicle road usage. DTV is usually attributed to the following causes: waviness of disc surface, misalignment of axis (runout), elastic deflection, wear and friction material transfers.

### ***Brake dust***

When braking force is applied, small amounts of material are gradually ground off the brake pads. This material is known as "brake dust" and a fair amount of it usually deposits itself on the braking system and the surrounding wheel. Brake dust can badly damage the finish of most wheels if not washed off. Airborne brake dust is known to be a health hazard, so most repair manuals recommend the use of a chemical 'brake cleaner' instead of compressed air to remove the dust. Different brake pad formulations create different amounts of dust, and some formulations, particularly metallic brake pads, are much more damaging than others. Ceramic brake pads contain significantly fewer metal particles, and therefore produce less corrosion of surrounding metal parts.

## Chapter 11

# Electronic Stability Control

**Electronic stability control (ESC)** is a computerized technology that improves safety of a vehicle's stability by detecting and minimizing skids. When ESC detects loss of steering control, it automatically applies the brakes to help "steer" the vehicle where the driver intends to go. Braking is automatically applied to wheels individually, such as the outer front wheel to counter oversteer or the inner rear wheel to counter understeer. Some ESC systems also reduce engine power until control is regained. ESC does not improve a vehicle's cornering performance; instead, it helps to minimize the loss of control. According to IIHS and NHTSA, one-third of fatal accidents could have been prevented by the technology.

### ***History***

In 1987, the earliest innovators of ESC, Mercedes-Benz and BMW, introduced their first traction control systems. Traction control works by applying individual wheel braking and throttle to keep traction while accelerating but, unlike the ESC, it is not designed to aid in steering.

Named simply TCL in 1990, the system has since evolved into Mitsubishi's modern *Active Skid and Traction Control (ASTC)* system. Developed to help the driver maintain the intended path through a corner, an onboard computer monitored several vehicle operating parameters through the use of various sensors. When too much throttle has been used, while taking a curve, engine output and braking are automatically regulated to ensure the proper path through a curve and to provide the proper amount of traction under various road surface conditions. While conventional traction control systems at the time featured only a slip control function, Mitsubishi developed a TCL system which had a preventive (active) safety feature. This improved the course tracing performance by automatically adjusting the traction force, thereby restraining the development of excessive lateral acceleration, while turning. Although not a 'true' modern stability control system, trace control monitors steering angle, throttle position and individual wheel speeds and there is no yaw rate input. The TCL system's standard wheel slip

control function improves traction on slippery surfaces or during cornering. In addition to the TCL's traction control feature, it also works together with Diamante's electronic controlled suspension and four-wheel steering that Mitsubishi had equipped to improve total handling and performance.

BMW, working with Robert Bosch GmbH and Continental Automotive Systems, developed a system to reduce engine torque to prevent loss of control and applied it to the entire BMW model line for 1992. From 1987 to 1992, Mercedes-Benz and Robert Bosch GmbH co-developed a system called Elektronisches Stabilitätsprogramm (Ger. "Electronic Stability Programme" trademarked as ESP) a lateral slippage control system, the electronic stability control (ESC).

GM worked with Delphi Corporation and introduced its version of ESC called "StabiliTrak" in 1997 for select Cadillac models. StabiliTrak was made standard equipment on all GM SUVs and vans sold in the U.S. and Canada by 2007 except for certain commercial and fleet vehicles. While the "StabiliTrak" name is used on most General Motors vehicles for the U.S. market, the "Electronic Stability Control" identity is used for GM overseas brands, such as Opel, Holden and Saab, except in the case of Saab's 9-7X which also uses the "StabiliTrak" name. Ford's version of ESC, called AdvanceTrac, was launched in the year 2000. Ford later added Roll Stability Control to AdvanceTrac which was first introduced in Volvo XC90 in 2003 when Volvo Cars was fully owned by Ford and it is now being implemented in many Ford vehicles.

## ***Introduction***

In 1995, automobile manufacturers introduced ESC systems. Mercedes-Benz, supplied by Bosch, was the first to implement this with their W140 S-Class model. That same year BMW, supplied by Bosch and ITT Automotive (later acquired by Continental Automotive Systems). Volvo Cars began to offer their version of ESC called DSTC in 1998 on the new S80. Toyota's Vehicle Stability Control system (also in 2004, a preventive system called VDIM) appeared on the Crown Majesta in 1995. Meanwhile others investigated and developed their own systems.

During a moose test (swerving to avoid an obstacle) which became famous in Germany as "the Elk test" the Swedish journalist Robert Collin of Teknikens Värld (World of Technology) in October 1997 rolled a Mercedes A-Class (without ESC) at 78 km/h. Because Mercedes-Benz promotes a reputation for safety, they recalled and retrofitted 130,000 A-Class cars with ESC. This produced a significant reduction in crashes and the number of vehicles with ESC rose. Today virtually all premium brands have made ESC standard on all vehicles, and the number of models with ESC continues to increase. Ford and Toyota announced that all their North American vehicles would be equipped with ESC standard by the end of 2009 (it was standard on Toyota SUVs as of 2004, and after the 2011 model-year, All Lexus, Toyota, and Scion vehicles have ESC; the last one to get it was the 2011 model-year Scion tC). However, as recent as November 2010, Ford still sells models in North America without ESC. General Motors had made a similar announcement for the end of 2010. The NHTSA requires all passenger vehicles to be

equipped with ESC by 2012 and estimates it will prevent 5,300-9,600 annual fatalities once all passenger vehicles are equipped with the system.

## **Operation**

During normal driving, ESC works in the background and continuously monitors steering and vehicle direction. It compares the driver's intended direction (determined through the measured steering wheel angle) to the vehicle's actual direction (determined through measured lateral acceleration, vehicle rotation (yaw), and individual road wheel speeds).

ESC intervenes only when it detects loss of steering control, i.e. when the vehicle is not going where the driver is steering. This may happen, for example, when skidding during emergency evasive swerves, understeer or oversteer during poorly judged turns on slippery roads, or hydroplaning. ESC estimates the direction of the skid, and then applies the brakes to individual wheels asymmetrically in order to create torque about the vehicle's vertical axis, opposing the skid and bringing the vehicle back in line with the driver's commanded direction. Additionally, the system may reduce engine power or operate the transmission to slow the vehicle down.

ESC can work on any surface, from dry pavement to frozen lakes. It reacts to and corrects skidding much faster and more effectively than the typical human driver, often before the driver is even aware of any imminent loss of control. In fact, this led to some concern that ESC could allow drivers to become overconfident in their vehicle's handling and/or their own driving skills. For this reason, ESC systems typically inform the driver when they intervene, so that the driver knows that the vehicle's handling limits have been approached. Most activate a dashboard indicator light and/or alert tone; some intentionally allow the vehicle's corrected course to deviate very slightly from the driver-commanded direction, even if it is possible to more precisely match it.

Indeed, all ESC manufacturers emphasize that the system is not a performance enhancement nor a replacement for safe driving practices, but rather a safety technology to assist the driver in recovering from dangerous situations. ESC does not increase traction, so it does not enable faster cornering (although it can facilitate better-controlled cornering). More generally, ESC works within inherent limits of the vehicle's handling and available traction between the tires and road. A reckless maneuver can still exceed these limits, resulting in loss of control. For example, in a severe hydroplaning scenario, the wheels that ESC would use to correct a skid may not even initially be in contact with the road, reducing its effectiveness.

In July 2004, on the Crown Majesta, Toyota offered a Vehicle Dynamics Integrated Management (VDIM) system that incorporated formerly independent systems, including ESC. This worked not only after the skid was detected but also to prevent the skid from occurring in the first place. Using electric variable gear ratio steering power steering this more advanced system could also alter steering gear ratios and steering torque levels to assist the driver in evasive maneuvers.

## **Effectiveness**

Numerous studies around the world confirm that ESC is highly effective in helping the driver maintain control of the car, thereby saving lives and reducing the severity of crashes. In the fall of 2004 in the U.S., the National Highway and Traffic Safety Administration confirmed the international studies, releasing results of a field study in the U.S. of ESC effectiveness. The NHTSA in United States concluded that ESC reduces crashes by 35%. Additionally, Sport utility vehicles (SUVs) with stability control are involved in 67% fewer accidents than SUVs without the system. The United States Insurance Institute for Highway Safety (IIHS) issued its own study in June 2006 showing that up to 10,000 fatal US crashes could be avoided annually if all vehicles were equipped with ESC. The IIHS study concluded that ESC reduces the likelihood of all fatal crashes by 43%, fatal single-vehicle crashes by 56%, and fatal single-vehicle rollovers by 77-80%.

ESC is described as the most important advance in auto safety by many experts, including Nicole Nason, Administrator of the NHTSA, Jim Guest and David Champion of Consumers Union of the Fédération Internationale de l'Automobile (FIA), E-Safety Aware, Csaba Csere, editor of Car and Driver, and Jim Gill, long time ESC proponent of Continental Automotive Systems. The European New Car Assessment Program (EuroNCAP) "strongly recommends" that people buy cars fitted with stability control.

The IIHS requires that a vehicle must have ESC as an available option in order for it to qualify for their *Top Safety Pick* award for occupant protection and accident avoidance.

## **Components and design**

ESC incorporates yaw rate control into the anti-lock braking system (ABS). Yaw is a rotation around the vertical axis; i.e. spinning left or right. Anti-lock brakes enable ESC to brake individual wheels. Many ESC systems also incorporate a traction control system (TCS or ASR), which senses drive-wheel slip under acceleration and individually brakes the slipping wheel or wheels and/or reduces excess engine power until control is regained. However, ESC achieves a different purpose than ABS or Traction Control.

The ESC system uses several sensors to determine what the driver wants (input). Other sensors indicate the actual state of the vehicle (response). The control algorithm compares driver input to vehicle response and decides, when necessary, to apply brakes and/or reduce throttle by the amounts calculated through the state space (set of equations used to model the dynamics of the vehicle). The ESC controller can also receive data from and issue commands to other controllers on the vehicle such as an all wheel drive system or an active suspension system to improve vehicle stability and controllability.

The sensors used for ESC have to send data at all times in order to detect possible defects as soon as possible. They have to be resistant to possible forms of interference (rain, holes in the road, etc.). The most important sensors are:

- Steering wheel angle sensor: determines the driver's intended rotation; i.e. where the driver wants to steer. This kind of sensor is often based on AMR-elements.
- Yaw rate sensor : measures the rotation rate of the car; i.e. how much the car is actually turning. The data from the yaw sensor is compared with the data from the steering wheel angle sensor to determine regulating action.
- Lateral acceleration sensor: often based on the Hall effect. Measures the lateral acceleration of the vehicle.
- Wheel speed sensor : measures the wheel speed.

Other sensors can include:

- Longitudinal acceleration sensor: similar to the lateral acceleration sensor in design but can offer additional information about road pitch and also provide another source of vehicle acceleration and speed.
- Roll rate sensor: similar to the yaw rate sensor in design but improves the fidelity of the controller's vehicle model and correct for errors when estimating vehicle behavior from the other sensors alone.

ESC uses a hydraulic modulator to assure that each wheel receives the correct brake force. A similar modulator is used in ABS. ABS needs to reduce pressure during braking, only. ESC additionally needs to increase pressure in certain situations and an active vacuum brake booster unit may be utilized in addition to the hydraulic pump to meet these demanding pressure gradients.

The brain of the ESC system is the Electronic Control Unit (ECU). The various control techniques are embedded in it. Often, the same ECU is used for diverse systems at the same time (ABS, Traction control system, climate control, etc.). The input signals are sent through the input-circuit to the digital controller. The desired vehicle state is determined based upon the steering wheel angle, its gradient and the wheel speed. Simultaneously, the yaw sensor measures the actual state. The controller computes the needed brake or acceleration force for each wheel and directs via the driver circuits the valves of the hydraulic modulator. Via a CAN interface the ECU is connected with other systems (ABS, etc.) in order to avoid giving contradictory commands.

Many ESC systems have an "off" override switch so the driver can disable ESC, which may be desirable when badly stuck in mud or snow, or driving on a beach, or if using a smaller-sized spare tire which would interfere with the sensors. Some systems also offer an additional mode with raised thresholds so that a driver can utilize the limits of adhesion with less electronic intervention. However, ESC defaults to "On" when the ignition is re-started. Some ESC systems that lack an "off switch", such as on many recent Toyota and Lexus vehicles, can be temporarily disabled through an undocumented series of brake pedal and handbrake operations. Furthermore, unplugging a wheel speed sensor is another method of disabling most ESC systems. The ESC implementation on newer Ford vehicles cannot be completely disabled even through the use of the "off switch". The ESC will automatically reactivate at highway speeds, and below that if it detects a skid with the brake pedal depressed.

## ***Availability and cost***

ESC is built on top of an anti-lock brake (ABS) system, and all ESC-equipped vehicles are fitted with traction control. The ESC components include a yaw rate sensor, a lateral acceleration sensor, a steering wheel sensor, and an upgraded integrated control unit. According to National Highway Traffic Safety Administration research, ABS in 2005 cost an estimated US\$368; ESC cost a further US\$111. The retail price of ESC varies; as a stand-alone option it retails for as little as \$250 USD. However, ESC is rarely offered as a sole option, and is generally not available for aftermarket installation. Instead, it is frequently bundled with other features or more expensive trims, so the cost of a package that includes ESC could be several thousand dollars. Nonetheless, ESC is considered highly cost-effective and it might pay for itself in reduced insurance premiums. When new federal regulations requiring a safety tool called electronic stability control kick in during 2012, all cars will employ it.

Availability of ESC in passenger vehicles varies between manufacturers and countries. In 2007, ESC was available in roughly 50% of new North American models compared to about 75% in Sweden. However, consumer awareness affects buying patterns so that roughly 45% of vehicles sold in North America and the UK are purchased with ESC, contrasting with 78-96% in other European countries such as Germany, Denmark, and Sweden. While few vehicles had ESC prior to 2004, increased awareness will increase the number of vehicles with ESC on the used car market.

ESC is available on cars, SUVs and pickup trucks from all major auto makers. Luxury cars, sports cars, SUVs, and crossovers are usually equipped with ESC. Midsize cars are also gradually catching on, though the 2008 model years of the, Nissan Altima and Ford Fusion only offered ESC on their V6 engine-equipped cars. While ESC includes traction control, there are vehicles such as the 2008 Chevrolet Malibu LS and 2008 Mazda6 that have traction control but not ESC. ESC is rare among subcompact cars as of 2008. The 2009 Toyota Corolla in the United States (but not Canada) has stability control as a \$250 option on all trims below that of the XRS which has it as standard. In Canada, for the 2010 Mazda3, ESC is as an option on the midrange GS trim as part of the moonroof package, and is standard on the top-of-the-line GT version. The 2009 Ford Focus has ESC as an option for the S and SE models, and standard on the SEL and SES models

ESC is also available on some motor homes. Elaborate ESC and ESP systems (including Roll Stability Control (RSC)) are available for many commercial vehicles, including transport trucks, trailers, and buses from manufacturers such as Bendix Corporation, WABCO Daimler, Scania AB, and Prevost, and light passenger vehicles.

The *ChooseESC!* campaign, run by the EU's *eSafetyAware!* project, provides a global perspective on ESC. One *ChooseESC!* publication shows the availability of ESC in EU member countries.

In the US, the Insurance Institute for Highway Safety (IIHS) website shows availability of ESC in individual US models and the National Highway Traffic Safety Administration (NHTSA website) lists US models with ESC.

In Australia, the *National Roads and Motorists' Association* NRMA shows the availability of ESC in Australian models.

## **Future**

The market for ESC is growing quickly, especially in European countries such as Sweden, Denmark, and Germany. For example, in 2003 in Sweden the purchase rate on new cars with ESC was 15%. The Swedish road safety administration issued a strong ESC recommendation and in September 2004, 16 months later, the purchase rate was 58%. A stronger ESC recommendation was then given and in December 2004, the purchase rate on new cars had reached 69% and by 2008 it had grown to 96%. ESC advocates around the world are promoting increased ESC use through legislation and public awareness campaigns and by 2012, most new vehicles should be equipped with ESC.

Just as ESC is founded on the Anti-lock braking system (ABS), ESC is the foundation for new advances such as Roll Stability Control (RSC) that works in the vertical plane much like ESC works in the horizontal plane. When RSC detects impending rollover (usually on transport trucks or SUVs), RSC applies brakes, reduces throttle, induces understeer, and/or slows down the vehicle.

The computing power of ESC facilitates the networking of active and passive safety systems, addressing other causes of crashes. For example, sensors may detect when a vehicle is following too closely and slow down the vehicle, straighten up seat backs, and tighten seat belts, avoiding and/or preparing for a crash.

## **Regulation**

While Sweden used public awareness campaigns to promote ESC use, others implemented or proposed legislation.

The Canadian province of Quebec was the first jurisdiction to implement an ESC law, making it compulsory for carriers of dangerous goods (without data recorders) in 2005.

The United States was next, requiring ESC for all passenger vehicles under 10,000 pounds (4536 kg), phasing in the regulation starting with 55% of 2009 models (effective 1 September 2008), 75% of 2010 models, 95% of 2011 models, and all 2012 models.

Canada will require all new passenger vehicles to have ESC from 1 September 2011.

The Australian Government announced on 23 June 2009 that ESC would be compulsory from 1 November 2011 for all new passenger vehicles sold in Australia, and for all new vehicles from November 2013.

The European Parliament has also called for the accelerated introduction of ESC. The European Commission has confirmed a proposal for the mandatory introduction of ESC on all new cars and commercial vehicle models sold in the EU from 2012, with all new cars being equipped by 2014.

The United Nations Economic Commission for Europe has passed a Global Technical Regulation to harmonize ESC standards.

## Chapter 12

# Engine Braking and Vacuum Servo

## Engine braking

**Engine braking** or **Jake braking** is the act of using the retarding forces within an engine to slow a vehicle down, as opposed to using an external braking mechanism, for example friction brakes or magnetic brakes.

### ***Petrol (gasoline) engines***

The term engine braking usually refers to the braking effect caused by throttle position induced vacuum in petrol (gasoline) engines. While some of the braking force is due to friction in the drive train, this is negligible compared to the effect from vacuum.

When the throttle is lifted less air is allowed to pass through the intake manifold, and the engine works against this vacuum. It is the deceleration of the engine against this vacuum which provides the braking effect.

### ***Diesel engines***

Diesel engines vary fuel flow to control power rather than throttling air intake and maintaining a constant fuel ratio as petrol engines do. As they do not maintain a throttle vacuum, they are not subject to the same engine braking effects as petrol engines are.

However, there are several other mechanisms which diesel engines use that could also technically fall under the term engine braking:

An engine retarder/engine brake

A compression release brake, which is used mainly in large diesel trucks. It works by opening the exhaust valves at the top of the compression stroke, resulting in

adiabatic expansion of the compressed air so that the large amount of energy which is stored in it is not returned to the crankshaft but is released into the atmosphere. This creates a sound similar to automatic gunfire, although not as loud; consequently some areas have laws banning the use of unmuffled engine brakes. The vacuum that is subsequently created when the piston moves down again also adds to the immense amounts of braking force. A 565 hp (421 kW) diesel engine can produce up to 600 hp (450 kW) of braking power.

An exhaust brake

This works by causing a restriction in the exhaust much like the intake throttle causes in a gasoline engine. Nearly all of these brakes are butterfly valves mounted downstream of the turbocharger.

A mechanism related to the exhaust brake is back-pressure from a turbocharger. In turbo diesels with variable-vane turbos, the vanes will close when the accelerator is released which creates a back pressure braking effect similar to an exhaust brake.

## ***Two-stroke engines***

Engine braking in a premix two-stroke engine can be extremely harmful to the engine, because cylinder and piston lubricant is delivered to each cylinder mixed with fuel. Consequently, during engine braking, the engine starves not only of fuel but also lubricant, while parts reciprocate wear rapidly. Many old two-stroke cars (Saab, Wartburg etc.) had a freewheel device on the transmission to make engine braking optional. Most two-stroke motorcycle engines since the 1970s have had lubrication by an oil pump, independent of the throttle and fuel system, such as Suzuki's Posi-Force system.

## ***Applications***

Engine braking passively reduces wear on brakes and helps a driver maintain control of the vehicle. Active use of engine braking (shifting into a lower gear) is advantageous when it is necessary to control speed while driving down very steep and long slopes. It should be applied before regular disk or drum brakes have been used, leaving the brakes available to make emergency stops. The desired speed is maintained by using engine braking to counteract the gravitational acceleration.

Improper engine braking technique can cause the wheels to skid (also called shift-locking), especially on slippery surfaces such as ice or snow, as a result of too much deceleration. As in a skid caused by over-braking, the vehicle will not regain traction until the wheels are allowed to turn more quickly; the driver must reduce engine braking (shifting back up) to regain traction.

Engine braking is intrinsically available in non-hybrid vehicles with gasoline-powered internal combustion engines, regardless of transmission type. In almost all cases, it is active when the foot is lifted off the accelerator, the transmission is not in neutral, the clutch is engaged and a freewheel is not engaged.

In hybrid electric vehicles like the Toyota Prius, engine braking is simulated by the computer software to match the feel of a traditional automatic transmission. For long downhill runs, the "B" mode acts like a lower gear, using higher RPMs in the internal combustion engine to waste energy, preventing the battery from becoming overcharged.

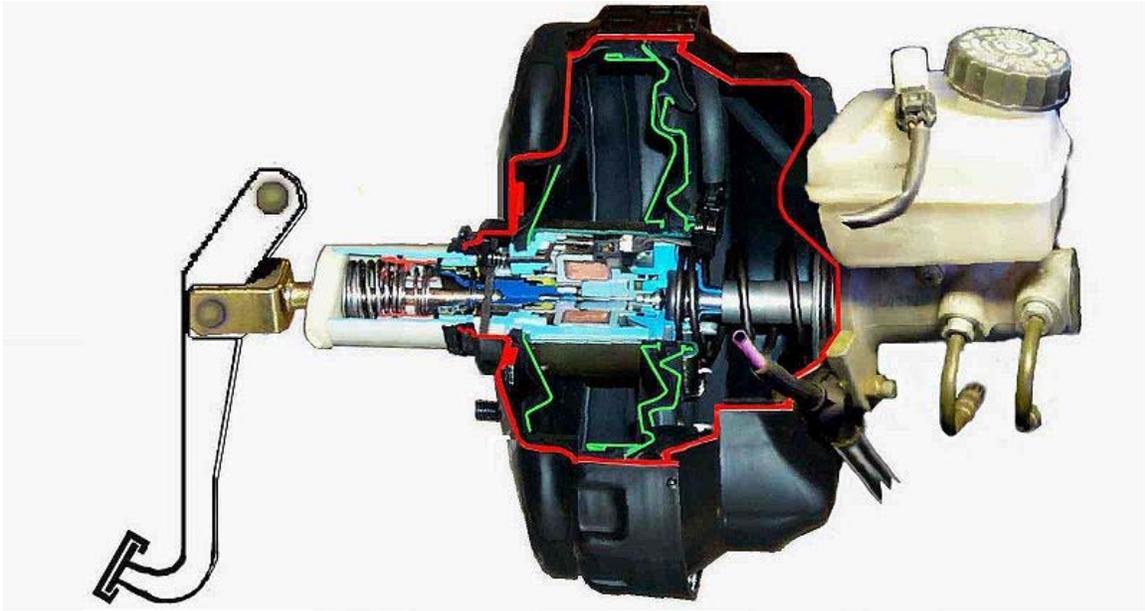
### ***Legal implications***

Compression braking, a form of engine braking, produces extreme amounts of noise pollution if there is no muffler on the intake manifold of the engine. Use of an exhaust brake produces similar effects, due to release of compressed gasses, but the mechanism is distinct from regular car engine braking. Anecdotally, it sounds similar to a jackhammer, however the loudness is between 10-20 times the sound pressure level of a jackhammer. Numerous cities, municipalities, states, and provinces have banned the use of unmuffled compression brakes, which are typically only legal in roads away from populations. In Australia, traffic enforcement cameras are currently being tested that automatically photograph heavy vehicles that use compression braking.

## **Vacuum servo**



Brake booster from a Geo Storm.



Brake vacuum servo section

A **vacuum servo** is a component used on motor vehicles in their braking system, to provide assistance to the driver by decreasing the braking effort.

It is used on virtually all vehicles which use hydraulic brakes for their primary braking circuit. Vacuum servos are not used on vehicles which use cables, rods (or other mechanical linkages), or pressurized air systems for their primary brake circuits.

It uses a stored vacuum to multiply braking force applied by the driver to the brake pedal, before applying the transferred force to the brake master cylinder.

The vacuum is generated in two distinct methods, dependent on the type of internal combustion engine, or other motive force (as in electric vehicles). In petrol engines, the manifold vacuum is utilized, whereas in diesel engines, a separate vacuum pump is used. The vacuum is transferred to the servo along semi-rigid plastic lines, and is stored in the servo by using a non-return valve.

The vacuum booster or vacuum servo is used in most modern hydraulic brake systems which contain four wheels. The vacuum booster is attached between the master cylinder and the brake pedal and multiplies the braking force applied by the driver. These units consist of a hollow housing with a movable rubber diaphragm across the center, creating two chambers. When attached to the low-pressure portion of the throttle body or intake manifold of the engine, the pressure in both chambers of the unit is lowered. The equilibrium created by the low pressure in both chambers keeps the diaphragm from moving until the brake pedal is depressed. A return spring keeps the diaphragm in the starting position until the brake pedal is applied. When the brake pedal is applied, the movement opens an air valve which lets in atmospheric pressure air to one chamber of the booster. Since the pressure becomes higher in one chamber, the diaphragm moves

toward the lower pressure chamber with a force created by the area of the diaphragm and the differential pressure. This force, in addition to the driver's foot force, pushes on the master cylinder piston. A relatively small diameter booster unit is required; for a very conservative 50% manifold vacuum, an assisting force of about 1500 N (150 kgf) is produced by a 20cm diaphragm with an area of 0.03 square meters. The diaphragm will stop moving when the forces on both sides of the chamber reach equilibrium. This can be caused by either the air valve closing (due to the pedal apply stopping) or if "run out" is reached. Run out occurs when the pressure in one chamber reaches atmospheric pressure and no additional force can be generated by the now stagnant differential pressure. After the run out point is reached, only the driver's foot force can be used to further apply the master cylinder piston.

## Chapter 13

# Regenerative Brake



Mechanism for regenerative brake on the roof of a Škoda Astra tram.

A **regenerative brake** is an energy recovery mechanism which slows a vehicle by converting its kinetic energy into another form, which can be either used immediately or stored until needed. This contrasts with conventional braking systems, where the excess kinetic energy is converted to heat by friction in the brake linings and therefore wasted.

The most common form of regenerative brake involves using an electric motor as an electric generator. In electric railways the generated electricity is fed back into the supply system, whereas in battery electric and hybrid electric vehicles, the energy is stored in a battery or bank of capacitors for later use. Energy may also be stored via pneumatics, hydraulics or the kinetic energy of a rotating flywheel.

### ***The motor as a generator***

Vehicles driven by electric motors use the motor as a generator when using regenerative braking: it is operated as a generator during braking and its output is supplied to an electrical load; the transfer of energy to the load provides the braking effect.

Regenerative braking is used on hybrid gas/electric automobiles to recoup some of the energy lost during stopping. This energy is saved in a storage battery and used later to power the motor whenever the car is in electric mode.

Early examples of this system were the front-wheel drive conversions of horse-drawn cabs by Louis Antoine Krieger (1868–1951). The Krieger electric landaulet had a drive motor in each front wheel with a second set of parallel windings (bifilar coil) for regenerative braking. In England, the Raworth system of "regenerative control" was introduced by tramway operators in the early 1900s, since it offered them economic and operational benefits as explained by A. Raworth of Leeds in some detail. These included tramway systems at Devonport (1903), Rawtenstall, Birmingham, Crystal Palace-Croydon (1906) and many others. Slowing down the speed of the cars or keeping it in hand on descending gradients, the motors worked as generators and braked the vehicles. The tram cars also had wheel brakes and track slipper brakes which could stop the tram should the electric braking systems fail. In several cases the tram car motors were shunt wound instead of series wound, and the systems on the Crystal Palace line utilized series-parallel controllers. Following a serious accident at Rawtenstall, an embargo was placed on this form of traction in 1911. Twenty years later, the regenerative braking system was reintroduced.

Regenerative braking has been in extensive use on railways for many decades. The Baku-Tbilisi-Batumi railway (Transcaucasian railway or Georgian railway) started utilizing regenerative braking in the early 1930s. This was especially effective on the steep and dangerous Surami Pass. In Scandinavia the Kiruna to Narvik railway carries iron ore from the mines in Kiruna in the north of Sweden down to the port of Narvik in Norway to this day. The rail cars are full of thousands of tons of iron ore on the way down to Narvik, and these trains generate large amounts of electricity by their regenerative braking. From Riksgränsen on the national border to the Port of Narvik, the trains use only a fifth of the power they regenerate. The regenerated energy is sufficient to power the empty trains

back up to the national border. Any excess energy from the railway is pumped into the power grid to supply homes and businesses in the region, and the railway is a net generator of electricity.

An Energy Regeneration Brake was developed in 1967 for the AMC Amitron. This was a completely battery powered urban concept car whose batteries were recharged by regenerative braking, thus increasing the range of the automobile.

Many modern hybrid and electric vehicles use this technique to extend the range of the battery pack. Examples include the Toyota Prius, Honda Insight, the Vectrix electric maxi-scooter, and the Chevrolet Volt.

## ***Limitations***

Traditional friction-based braking is used in conjunction with mechanical regenerative braking for the following reasons:

- The regenerative braking effect drops off at lower speeds; therefore the friction brake is still required in order to bring the vehicle to a complete halt. Physical locking of the rotor is also required to prevent vehicles from rolling down hills.
- The friction brake is a necessary back-up in the event of failure of the regenerative brake.
- Most road vehicles with regenerative braking only have power on some wheels (as in a two-wheel drive car) and regenerative braking power only applies to such wheels, so in order to provide controlled braking under difficult conditions (such as in wet roads) friction based braking is necessary on the other wheels.
- The amount of electrical energy capable of dissipation is limited by either the capacity of the supply system to absorb this energy or on the state of charge of the battery or capacitors. No regenerative braking effect can occur if another electrical component on the same supply system is not currently drawing power and if the battery or capacitors are already charged. For this reason, it is normal to also incorporate dynamic braking to absorb the excess energy.
- Under emergency braking it is desirable that the braking force exerted be the maximum allowed by the friction between the wheels and the surface without slipping, over the entire speed range from the vehicle's maximum speed down to zero. The maximum force available for acceleration is typically much less than this except in the case of extreme high-performance vehicles. Therefore, the power required to be dissipated by the braking system under emergency braking conditions may be many times the maximum power which is delivered under acceleration. Traction motors sized to handle the drive power may not be able to cope with the extra load and the battery may not be able to accept charge at a sufficiently high rate. Friction braking is required to absorb the surplus energy in order to allow an acceptable emergency braking performance.

For these reasons there is typically the need to control the regenerative braking and match the friction and regenerative braking to produce the desired total braking output. The GM

EV-1 was the first commercial car to do this. Engineers Abraham Farag and Loren Majersik were issued two patents for this *brake-by-wire* technology.

### ***Electric railway vehicle operation***

During braking, the traction motor connections are altered to turn them into electrical generators. The motor fields are connected across the main traction generator (MG) and the motor armatures are connected across the load. The MG now excites the motor fields. The rolling locomotive or multiple unit wheels turn the motor armatures, and the motors act as generators, either sending the generated current through onboard resistors (dynamic braking) or back into the supply (regenerative braking).

For a given direction of travel, current flow through the motor armatures during braking will be opposite to that during motoring. Therefore, the motor exerts torque in a direction that is opposite from the rolling direction.

Braking effort is proportional to the product of the magnetic strength of the field windings, times that of the armature windings.

Savings of 17% are claimed for Virgin Trains Pendolinos. There is also less wear on friction braking components. The Delhi Metro saved around 90,000 tons of carbon dioxide (CO<sub>2</sub>) from being released into the atmosphere by regenerating 112,500 megawatt hours of electricity through the use of regenerative braking systems between 2004 and 2007. It is expected that the Delhi Metro will save over 100,000 tons of CO<sub>2</sub> from being emitted per year once its phase II is complete through the use of regenerative braking.

Another form of simple, yet effective regenerative braking is used on the London Underground which is achieved by having small slopes leading up and down from stations. The train is slowed by the climb, and then leaves down a slope, so kinetic energy is converted to "stored" potential energy in the station.

Electricity generated by regenerative braking may be fed back into the traction power supply; either offset against other electrical demand on the network at that instant, or stored in lineside storage systems for later use.

### ***Comparison of dynamic and regenerative brakes***

Dynamic brakes ("rheostatic brakes" in the UK), unlike regenerative brakes, dissipate the electric energy as heat by passing the current through large banks of variable resistors. Vehicles that use dynamic brakes include forklifts, Diesel-electric locomotives, and streetcars. This heat can be used to warm the vehicle interior, or dissipated externally by large radiator-like cowls to house the resistor banks.

The main disadvantage of regenerative brakes when compared with dynamic brakes is the need to closely match the generated current with the supply characteristics and increased

maintenance cost of the lines. With DC supplies, this requires that the voltage be closely controlled. Only with the development of power electronics has this been possible with AC supplies, where the supply frequency must also be matched (this mainly applies to locomotives where an AC supply is rectified for DC motors).

A small number of mountain railways have used 3-phase power supplies and 3-phase induction motors. This results in a near constant speed for all trains as the motors rotate with the supply frequency both when motoring and braking.

### ***Kinetic Energy Recovery Systems***

Kinetic Energy Recovery Systems (KERS) were used for the motor sport Formula One's 2009 season, and under development for road vehicles. However, KERS was abandoned for the 2010 Formula One season. The Formula One Teams that used Kinetic Energy Recovery Systems in the 2009 season are Ferrari, Renault, BMW, and McLaren. One of the main reasons that not all cars use KERS is because it adds an extra 25 kilograms of weight, while not adding to the total car weight, it does incur a penalty particularly seen in the qualifying rounds, as it raises the car's center of gravity, and reduces the amount of ballast that is available to balance the car so that it is more predictable when turning. FIA rules also limit the exploitation of the system. Eventually, during the season, Renault and BMW stopped using the system. Williams is developing a flywheel-KERS system. The concept of transferring the vehicle's kinetic energy using Flywheel energy storage was postulated by physicist Richard Feynman in the 1950s and is exemplified in complex high end systems such as the ZyteK, Flybrid, Torotrak and Xtrac used in F1 and simple, easily manufactured and integrated differential based systems such as the Cambridge Passenger/Commercial Vehicle Kinetic Energy Recovery System (CPC-KERS)

Xtrac and Flybrid are both licensees of Torotrak's technologies, which employ a small and sophisticated ancillary gearbox incorporating a continuously variable transmission (CVT). The CPC-KERS is similar as it also forms part of the driveline assembly. However, the whole mechanism including the flywheel sits entirely in the vehicle's hub (looking like a drum brake). In the CPC-KERS, a differential replaces the CVT and transfers torque between the flywheel, drive wheel and road wheel.

## Use in motor sport

### History



A Flybrid Systems Kinetic Energy Recovery System

The first of these systems to be revealed was the Flybrid. This system weighs 24 kg and has an energy capacity of 400 kJ after allowing for internal losses. A maximum power boost of 60 kW (81.6 PS, 80.4 HP) for 6.67 s is available. The 240 mm diameter flywheel weighs 5.0 kg and revolves at up to 64,500 rpm. Maximum torque is 18 Nm (13.3 ftlbs). The system occupies a volume of 13 litres.

Two minor incidents have been reported during testing of KERS systems in 2008. The first occurred when the Red Bull Racing team tested their KERS battery for the first time in July: it malfunctioned and caused a fire scare that led to the team's factory being evacuated. The second was less than a week later when a BMW Sauber mechanic was given an electric shock when he touched Christian Klien's KERS-equipped car during a test at the Jerez circuit.

**FIA**



A KERS flywheel

Formula One have stated that they support responsible solutions to the world's environmental challenges, and the FIA allowed the use of 81 hp (60 kW; 82 PS) KERS in the regulations for the 2009 Formula One season. Teams began testing systems in 2008: energy can either be stored as mechanical energy (as in a flywheel) or as electrical energy (as in a battery or supercapacitor). Due to high cost, FOTA teams agreed to drop KERS from the 2010 season onwards, but this is still an open issue as Williams F1 said it will use KERS in 2010 and changes to the regulations must be agreed by all teams.

Vodafone McLaren Mercedes became the first team to win a F1 GP using a KERS equipped car when Lewis Hamilton won the Hungarian Grand Prix on July 26, 2009. Their second KERS equipped car finished fifth. At the following race, Lewis Hamilton became the first driver to take pole position with a KERS car, his team mate, Heikki Kovalainen qualifying second. This was also the first instance of an all KERS front row. On August 30, 2009, Kimi Räikkönen won the Belgian Grand Prix with his KERS equipped Ferrari. It was the first time that KERS contributed directly to a race victory, with second placed Giancarlo Fisichella claiming "Actually, I was quicker than Kimi. He only took me because of KERS at the beginning". New rules for the 2011 F1 season raise the minimum weight limit of the car and driver by 20 kg to 640 kg. This is to prepare the way for a return of the KERS power-boost and energy storage systems which featured in 2009. Although KERS is still legal in F1, for the 2010 season all the teams have agreed not to use it. As of 2013 it is possible that F1 will require KERS again as FIA rules force F1 to use greener methods to power their cars. The proposal is to increase the power storage from 60 kW to 120 kW. The FIA release of the 2011 rule changes with both FOTA, FOM and the FIA have agreed that F1 will have KERS for the 2011 season at 80 hp (60 kW), with this value rising in 2013 to coincide with smaller engines. This is still optional as it was in the 2009 season and can be battery or flywheel based.

### **Autopart makers**

Bosch Motorsport Service is developing a KERS for use in motor racing. These electricity storage systems for hybrid and engine functions include a lithium-ion battery with scalable capacity or a flywheel, a four to eight kilogram electric motor (with a maximum power level of 60 kW/80 hp), as well as the KERS controller for power and battery management. Bosch also offers a range of electric hybrid systems for commercial and light-duty applications.

### **Carmakers**

Automakers including Honda have been testing KERS systems. At the 2008 1,000 km of Silverstone, Peugeot Sport unveiled the Peugeot 908 HY, a hybrid electric variant of the diesel 908, with KERS. Peugeot plans to campaign the car in the 2009 Le Mans Series season, although it will not be capable of scoring championship points.

Vodafone McLaren Mercedes began testing of their KERS in September 2008 at the Jerez test track in preparation for the 2009 F1 season, although at that time it was not yet known if they would be operating an electrical or mechanical system. In November 2008 it was announced that Freescale Semiconductor would collaborate with McLaren Electronic Systems to further develop its KERS for McLaren's Formula One car from 2010 onwards. Both parties believed this collaboration would improve McLaren's KERS system and help the system filter down to road car technology.

Toyota has used a supercapacitor for regeneration on Supra HV-R hybrid race car that won the 24 Hours of Tokachi race in July 2007.

## **Motorcycles**

KTM racing boss Harald Bartol has revealed that the factory raced with a secret Kinetic Energy Recovery System (KERS) fitted to Tommy Koyama's motorcycle during the 2008 season-ending 125cc Valencian Grand Prix. This was illegal and against the rules, so they were later banned from doing it afterwards.

## **Races**

Automobile Club de l'Ouest, the organizer behind the annual 24 Hours of Le Mans event and the Le Mans Series is currently "studying specific rules for LMP1 that will be equipped with a kinetic energy recovery system." Peugeot was the first manufacturer to unveil a fully functioning LMP1 car in the form of the 908 HY at the 2008 Autosport 1000 km race at Silverstone.

## ***Use in compressed air cars***

Regenerative brakes could be employed in compressed air cars to refill the air tank during braking.

## Chapter 14

# Inboard Brake and Hydraulic Brake

## Inboard brake

An **inboard braking system** is an automobile technology wherein the brakes are mounted between the bearings of the wheels that constitute an axle.

Excepting the case of vehicles with beam axles and vehicles having no suspension, in practice it is normal for inboard brakes to be mounted rigidly with respect to the body of the vehicle, often to the differential casing. This is done to move the weight of the braking mechanism from being carried by the wheels directly (unsprung weight), to being carried indirectly by the wheels via the suspension (sprung mass). This then necessitates a means of transferring braking torque from the brake mechanism to the wheel, which is capable of operating despite the relative movement between body and wheel. Driven wheels already have shafting (or in older vehicles chains) which serve this purpose so there is no penalty for them, but undriven wheels require a similar mechanism which is then called a brake shaft.

The benefit of such a system is primarily the reduction of unsprung weight which improves handling and ride. The suspension does not have to resist twisting when the brakes are applied. The wheels don't enclose the brake mechanism allowing greater flexibility in wheel offset, and placement of suspension members. It is also much easier to protect the brake mechanism from the outside environment, and protect it from water, dust, and oil. Of secondary importance is flexible brake pipes are avoided and rigid pipes allow increases in brake fluid pressure, allowing a smaller disks for a given braking torque.

The mechanical disadvantages are largely those of added complexity. Undriven wheels require a brake shaft. It is more difficult to arrange for cooling air to flow over the wheel, and air ducting can be required, to prevent brake fade.

There can be practical difficulties, in servicing the brake mechanism. Instead of simply removing a wheel to renew pads and discs, the vehicle may need to be jacked up, so a mechanic can work underneath the vehicle. Additionally renewing brake discs can require dismantling the half axle. This greatly discourages their use in motorsport, and the additional time makes for greater labour cost when servicing these parts.

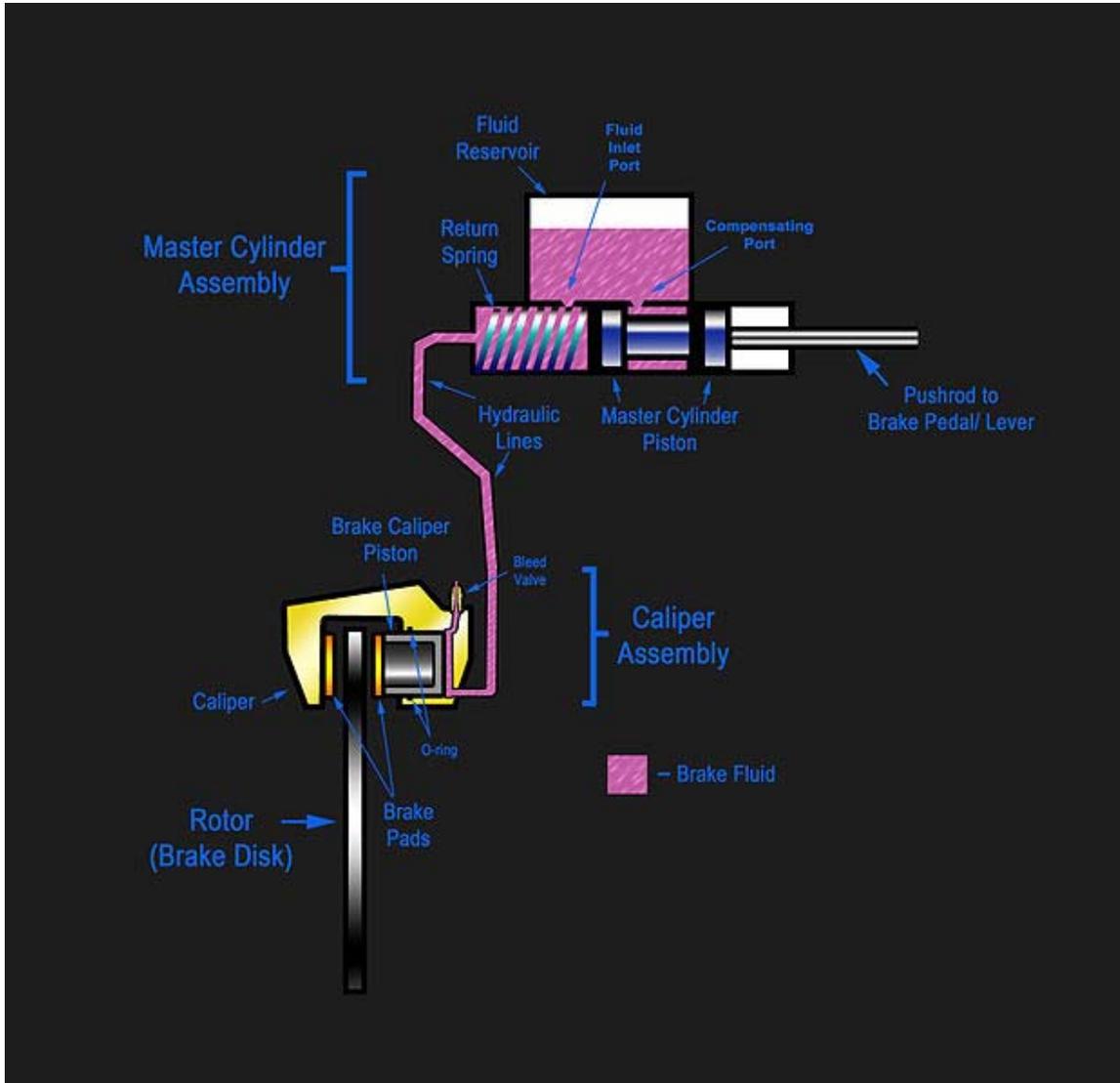
This system was more common in the 1960s, found on such cars as the Jaguar E-Type and Citroën 2CV. The Hummer H1 is one of the few modern vehicles fitted with inboard brakes, to accommodate each wheel's portal gear system.

Hybrid gasoline/electric vehicles may be considered to have partial inboard braking, because the devices used for the regenerative part of the braking are usually mounted inboard.

### ***Cars with inboard brakes***

- Alfa Romeo Alfasud Alfetta GTV GTV6 Giulietta 75 90 SZ Milano
- Audi 100 LS
- British Racing Motors: Some BRM racing cars had a single inboard disk brake, acting on both back wheels.
- Citroën 2CV, DS, GS, SM, Ami, Dyane, Axel and other Citroën models
- DKW Junior plus other models
- Hummer H1
- Jaguar E-Type, Jaguar XJ (until XJ40), Jaguar XJ-S
- Lancia Aurelia
- Lotus 72 Formula One racing car
- Lotus Elite, Elan and Esprit
- Mercedes-Benz W196 and 300SLR
- Monteverdi Hai 450 SS
- Oldsmobile Toronado
- Olcit
- Rover P6
- Subaru G

# Hydraulic brake



A schematic illustrating the major components of a hydraulic disc brake system

The **hydraulic brake** is an arrangement of braking mechanism which uses brake fluid, typically containing ethylene glycol, to transfer pressure from the controlling unit, which is usually near the operator of the vehicle, to the actual brake mechanism, which is usually at or near the wheel of the vehicle.

## **Construction**

The most common arrangement of hydraulic brakes for passenger vehicles, motorcycles, scooters, and mopeds, consists of the following:

- Brake pedal or lever
- A pushrod (also called an *actuating rod*)
- A master cylinder assembly containing a piston assembly (made up of either one or two pistons, a return spring, a series of gaskets/ O-rings and a fluid reservoir)
- Reinforced hydraulic lines
- Brake caliper assembly usually consisting of one or two hollow aluminum or chrome-plated steel pistons (called *caliper pistons*), a set of thermally conductive brake pads and a rotor (also called a *brake disc*) or drum attached to an axle.

The system is usually filled with a glycol-ether based brake fluid (other fluids may also be used).

At one time, passenger vehicles commonly employed disc brakes on the front wheels and drum brakes on the rear wheels. However, because disc brakes have shown a better stopping performance and are therefore generally safer and more effective than drum brakes, four-wheel disc brakes have become increasingly popular, replacing drums on all but the most basic vehicles. Many two-wheel vehicle designs, however, continue to employ a drum brake for the rear wheel.

For simplicity, the braking system described hereafter uses the terminology and configuration for a simple *disc brake*.

## **System Operation**

Within a hydraulic brake system, as the brake pedal is pressed/ brake lever is squeezed, a pushrod exerts force on the piston(s) in the master cylinder causing fluid from the brake fluid reservoir to flow into a pressure chamber through a compensating port which results in an increase in the pressure of the entire hydraulic system. This forces fluid through the hydraulic lines toward one or more calipers where it acts upon one or two additional caliper pistons secured by one or more seated O-rings which prevent the escape of any fluid from around the piston.

The brake caliper piston(s) then apply force to the brake pads. This causes them to be pushed against the spinning rotor, and the friction between the pads and the rotor causes a braking torque to be generated, slowing the vehicle. Heat generated from this friction is often dissipated through vents and channels in the rotor and through the pads themselves which are made of specialized heat-tolerant materials (kevlar, sintered glass, et al.).

Subsequent release of the brake pedal/ lever allows the spring(s) within the master cylinder assembly to return that assembly's piston(s) back into position. This relieves the hydraulic pressure on the caliper allowing the brake piston in the caliper assembly to

slide back into its housing and the brake pads to release the rotor. Unless there is a leak somewhere in the system, at no point does any of the brake fluid enter or leave.

### ***An example of a hydraulic brake system***

When using hydraulics, we can transfer a huge amount of energy, to stop a spinning object. Let us imagine a very simple brake system, with just two cylinders and a disc brake. The cylinders are connected via tubes and inside the cylinders is a piston. The cylinders and tubes are filled with oil, which is incompressible. Notice that the two cylinders have the same volume, but has a different diameter, therefore a different surface area. The one with the smallest diameter is called the master cylinder. The spinning disc brake, will be placed down at the piston with the larger surface area. Let us say that the diameter of the master cylinder is  $x$  and the diameter of the other cylinder is  $4x$ . If  $x$  is 1, the surface area of the master cylinder is 3,14 and the other cylinder will have a surface area of 50,24, which is 16 times larger. Now, if we push the piston in the master cylinder down 16 cm, with  $x$  kg of force, the other piston will then move 1 cm, with a force of  $16 \cdot x$  kg. So if we push the piston in the master cylinder down with 10 kg of force, the other piston with the larger surface area, will then push against the spinning disc brake with 160 kg of force.

We can easily multiply this force by adding a lever, which is connected to the piston in the master cylinder. At the end of the lever we'll place a pedal, in the other end is the pivot and somewhere between the two, we'll connect the lever to the piston. Let us say the distance from the pedal to the pivot is  $3y$  and the distance from the pivot to the connected piston is  $y$ . Because the distance from the pedal to the pivot is 3 times larger than from the pivot to the piston, we are multiplying our force with a factor of 3, when pushing down on the pedal. Now, if we push down on the pedal with 10 kg of force, 30 kg of force will then be applied to the piston in the master cylinder and the other piston will then push against the spinning disc brake, with a total force of 480 kg. With this system we are all in all multiplying our force with a factor of 48.

### ***Component specifics***

(For typical light duty automotive braking systems)

The **brake pedal** is a simple lever. One end is attached to the framework of the vehicle, a pushrod extends from a point along its length, and the foot pad is at the other end of the lever. The rod either extends to the master cylinder (manual brakes) or to the vacuum booster (power brakes).

In a four-wheel car, the master cylinder is divided internally into two sections, each of which pressurizes a separate hydraulic circuit. Each section supplies pressure to one circuit. Passenger vehicles typically have either a front/rear split brake system or a diagonal **split brake system** (the master cylinder in a motorcycle or scooter may only pressurize a single unit, which will be the front brake).

A front/rear split system uses one master cylinder section to pressurize the front caliper pistons and the other section to pressurize the rear caliper pistons. A split circuit braking system is now required by law in most countries for safety reasons; if one circuit fails, the other circuit can stop the vehicle.

**Diagonal split systems** were used initially on American Motors automobiles in the 1967 production year. The right front and left rear are served by one actuating piston while the left front and the right rear are served, exclusively, by a second actuating piston (both pistons pressurize their respective coupled lines from a single foot pedal). If either circuit fails, the other, with at least one front wheel braking (the front brakes provide most of the speed reduction) remains intact to stop the mechanically-damaged vehicle. Just before 1970, diagonally split systems had become universal for automobiles sold in the United States.

The diameter and length of the master cylinder has a significant effect on the performance of the brake system. A larger diameter master cylinder delivers more hydraulic fluid to the caliper pistons, yet requires more brake pedal force and less brake pedal stroke to achieve a given deceleration. A smaller diameter master cylinder has the opposite effect.

A master cylinder may also use differing diameters between the two sections to allow for increased fluid volume to one set of caliper pistons or the other.

## **Power brakes**

The **vacuum booster** or **vacuum servo** is used in most modern hydraulic brake systems which contain four wheels. The vacuum booster is attached between the master cylinder and the brake pedal and multiplies the braking force applied by the driver. These units consist of a hollow housing with a movable rubber diaphragm across the center, creating two chambers. When attached to the low-pressure portion of the throttle body or intake manifold of the engine, the pressure in both chambers of the unit is lowered. The equilibrium created by the low pressure in both chambers keeps the diaphragm from moving until the brake pedal is depressed. A return spring keeps the diaphragm in the starting position until the brake pedal is applied. When the brake pedal is applied, the movement opens an air valve which lets in atmospheric pressure air to one chamber of the booster. Since the pressure becomes higher in one chamber, the diaphragm moves toward the lower pressure chamber with a force created by the area of the diaphragm and the differential pressure. This force, in addition to the driver's foot force, pushes on the master cylinder piston. A relatively small diameter booster unit is required; for a very conservative 50% manifold vacuum, an assisting force of about 1500 N (200n) is produced by a 20 cm diaphragm with an area of 0.03 square meters. The diaphragm will stop moving when the forces on both sides of the chamber reach equilibrium. This can be caused by either the air valve closing (due to the pedal apply stopping) or if "run out" is reached. Run out occurs when the pressure in one chamber reaches atmospheric pressure and no additional force can be generated by the now stagnant differential pressure. After

the run out point is reached, only the driver's foot force can be used to further apply the master cylinder piston.

The fluid pressure from the master cylinder travels through a pair of steel brake tubes to a **pressure differential valve**, sometimes referred to as a "brake failure valve", which performs two functions: it equalizes pressure between the two systems, and it provides a warning if one system loses pressure. The pressure differential valve has two chambers (to which the hydraulic lines attach) with a piston between them. When the pressure in either line is balanced, the piston does not move. If the pressure on one side is lost, the pressure from the other side moves the piston. When the piston makes contact with a simple electrical probe in the center of the unit, a circuit is completed, and the operator is warned of a failure in the brake system.

From the pressure differential valve, brake tubing carries the pressure to the brake units at the wheels. Since the wheels do not maintain a fixed relation to the automobile, it is necessary to use hydraulic brake hose from the end of the steel line at the vehicle frame to the caliper at the wheel. Allowing steel brake tubing to flex invites metal fatigue and, ultimately, brake failure. A common upgrade is to replace the standard rubber hoses with a set which are externally reinforced with braided stainless-steel wires; these have negligible expansion under pressure and can give a firmer feel to the brake pedal with less pedal travel for a given braking effort.

### ***Special considerations***

Air brake systems are bulky, and require air compressors and reservoir tanks. Hydraulic systems are smaller and less expensive.

Hydraulic fluid must be non-compressible. Unlike air brakes, where a valve is opened and air flows into the lines and brake chambers until the pressure rises sufficiently, hydraulic systems rely on a single stroke of a piston to force fluid through the system. If any vapor is introduced into the system it will compress, and the pressure may not rise sufficiently to actuate the brakes.

Hydraulic braking systems are sometimes subjected to high temperatures during operation, such as when descending steep grades. For this reason, hydraulic fluid must resist vaporization at high temperatures.

Water vaporizes easily with heat and can corrode the metal parts of the system. If it gets into the brake lines, it can degrade brake performance dramatically. This is why light oils are often used as hydraulic fluids. Oil displaces water, protects plastic parts against corrosion, and can tolerate much higher temperatures before vaporizing.

"Brake fade" is a condition caused by overheating in which braking effectiveness reduces, and may be lost. It may occur for many reasons. The pads which engage the rotating part may become overheated and "glaze over", becoming so smooth and hard that they cannot grip sufficiently to slow the vehicle, vaporization of the hydraulic fluid

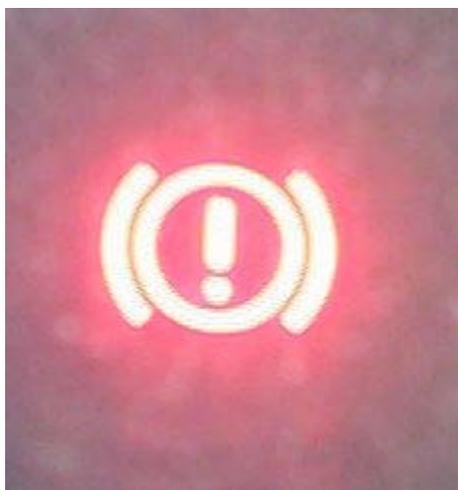
under temperature extremes, and thermal distortion may cause the linings to change their shape and engage less surface area of the rotating part. Thermal distortion may also cause permanent changes in the shape of the metal components, resulting in a reduction in braking capability that requires replacement of the affected parts.

## Chapter 15

# Parking Brake



Hand brake lever from a Geo Storm.



Brake warning light. The light is turned on, indicating that the brake is engaged.

In cars, the **hand brake** (also known as the **emergency brake**, **e-brake**, or **parking brake**) is a latching brake usually used to keep the car stationary. Automobile e-brakes usually consist of a cable (usually adjustable for length) directly connected to the brake mechanism on one end and to some type of mechanism that can be actuated by the driver on the other end. The mechanism is often a hand-operated lever (hence the *hand brake* name), on the floor on either side of the driver, or a pull handle located below and near the steering wheel column, or a (foot-operated) pedal located far apart from the other pedals.

Although sometimes known as an emergency brake, using it in any emergency where the footbrake is still operational is likely to badly upset the brake balance of the car and vastly increase the likelihood of loss of control of the vehicle, for example by initiating a rear-wheel skid. Additionally, the stopping force provided by using the handbrake instead of or in addition to the footbrake is usually small and would not significantly aid in stopping the vehicle, again because it usually operates on the rear wheels; they suffer reduced traction compared to the front wheels while braking. The emergency brake is instead intended for use in case of mechanical failure where the regular footbrake is inoperable or compromised, hopefully with opportunity to apply the brake in a controlled manner to bring the vehicle to a safe, if gentle halt before seeking service assistance. Modern brake systems are typically very reliable and engineered with failsafe (e.g. dual-circuit hydraulics) and failure-warning (e.g. low brake fluid sensor) systems, meaning the handbrake is no longer often called on for its original purpose.

The most common use for an automobile emergency brake is to keep the vehicle motionless when it is parked, thus the alternative name, *parking brake*. Car emergency brakes have a ratchet locking mechanism that will keep them engaged until a release button is pressed. On vehicles with automatic transmissions, this is usually used in concert with a parking pawl in the transmission. Automotive safety experts recommend the use of both systems to immobilize a parked car, and the use of both systems is required by law in some jurisdictions, yet many individuals use only the "Park" position

on the automatic transmission and not the parking brake. It's similar with manual transmission cars: They are recommended always to be left with the handbrake engaged, in concert with their lowest gear (usually either first or reverse). The use of both systems is also required by law in some jurisdictions. However, when parking on level ground, many people either only engage the handbrake (gear lever in neutral), or only select a gear (handbrake released).

### ***Types of brakes***



The hand brake lever in a Saab 9-5 automobile

School buses which are equipped with a hydraulic brake system will have a hand brake lever to the left of the driver (in left hand drive buses) near the floor. It is operated by pushing the lever down with one's hand to apply the brake, and pulling it upwards to release it. However, this has been known to cause severe back problems in drivers who do this regularly, and many choose to push it up with their feet.

Some cars with automatic transmissions are fitted with automatically releasing parking brakes. Later models require the foot brake to be depressed before the car's transmission can be moved from park. When reverse or drive is selected, the parking brake automatically releases. Earlier models would release the parking brake when the gear selector was placed in a forward or reverse gear without requiring any input on the brake

pedal at all. These earlier automatic release systems were a safety hazard, since there would be no protection against accidentally knocking the transmission into gear.

In cars with rear drum brakes, the emergency brake cable usually actuates these drums mechanically with much less force than is available through the hydraulic system. In cars with rear disc brakes, the emergency brake either actuates the disc calipers (again, with much less force) or a small drum brake housed within the hub assembly.

Hudson automobiles used an unusual hybrid hydraulic-mechanical dual-brake system which operated the rear brakes through the otherwise conventional mechanical emergency-brake system when a failure of the hydraulic system allowed the pedal to travel beyond its normal limit.

A number of production vehicles, light and medium duty trucks, and motor homes have been made with a separate drum brake on the transmission output shaft; called a driveline parking brake. This has an advantage of being completely independent of other braking systems. This is effective as long as the drive train is intact — propeller shaft, differential, and axle shafts. In many vehicles, this type of parking brake is operated by either a foot pedal or a hydraulic cylinder controlled by the transmission gear selector, or by both.

## ***Large vehicles***

Large vehicles are usually fitted with power operated or power assisted handbrakes. Power assisted handbrakes are usually found on large vans as well as some older heavy vehicles. These operate in the same way as a conventional handbrake, but pulling the lever will operate a valve that allows air or hydraulic pressure or vacuum into a cylinder which applies force to the brake shoes and makes applying the handbrake easier. When releasing the handbrake, the same mechanism also provides assistance to the driver in disengaging the ratchet. Particularly on commercial vehicles with air operated brakes, this has the added benefit of making it much harder or even impossible to release the parking brake when insufficient air pressure is available to operate the brakes. A reservoir or accumulator is usually provided so a limited amount of power assistance is available with the engine off. Power operated handbrakes are fitted to heavy commercial vehicles with air brakes, such as trucks and buses. These usually are spring applied, with air pressure being used to hold the brake off and powerful springs holding the brakes on. In most cases, a small lever in the cab is connected to a valve which can admit air to the parking brake cylinders to release the parking brake, or release the air to apply the brake. On some modern vehicles the valve is operated electrically from a lever or button in the cab. The system is relatively safe since if air pressure is lost the springs will apply the brakes. Also, the system prevents the parking brake being released if there is insufficient air pressure to apply the foot brake. A disadvantage to this system is that if a vehicle requires towing and can not provide its own air supply, an external supply must be provided to allow the parking brake to be released, or the brake shoes must be manually wound off against the springs.

## **New system: electric parking brake**

A recent variation is the electric parking brake. First installed in the 2001 Renault Vel Satis, electric brakes have since appeared in a number of vehicles, including the Audi A4, A5, A6 and A8, the 2010 Subaru Legacy and Subaru Outback, the 2002 BMW 7 Series, Lincoln LS, Jaguar S-Type, XF and XJ, Renault Scénic, Espace , Laguna II.phase II , Opel/Vauxhall Insignia , Volkswagen Passat, Citroen C6 the new Citroen C5, and the new 2011 Buick Regal

Two variations are available: In the more-traditional "cable-pulling" type, an electric motor simply pulls the emergency brake cable rather than a mechanical handle in the cabin. A more complex unit uses two computer-controlled motors attached to the rear brake calipers to activate it.

It is expected that these systems will incorporate other features in the future. BMW, Renault and VW already have a system where the emergency brake initiates when the car stops and then goes off as soon as the gas pedal is pressed preventing the car from rolling. The vehicle operator can easily turn off the system.

There is also a single un-verified report of the brake disengaging randomly.

## **Jacking**

It is important to know which wheels are providing the braking action when lifting the car with a jack. Typically the rear wheels are the ones that are stopped with parking brakes. The Alfasud, Saab 99s, Pre-Facelift 900's, the Citroen Xantia and most early Subarus applied the handbrake force to the front wheels, which makes them notable exceptions. If one lifts the braking wheels off the ground then the car can move and fall off the jack. This is why makers recommend that jacking be conducted on level ground and with chocks immobilizing the wheels that remain on the ground.

## ***Railroad hand brakes***

Virtually all railroad rolling stock is equipped with manually-operated mechanical hand brake devices that set and release the brakes. Most of these involve a chain linked to the brake rigging, most often at the brake cylinder, that when tightened pull the piston out against the releasing springs, thus applying the brakes on the car (if there is only one brake cylinder per car) or bogie (if there is more than once cylinder per car). Newer locomotives have electric systems that simply place an electric motor in place of the chain winding mechanism. This brake acts independent of the action of the automatic air brakes, which function collectively when coupled in a train and are under the control of the locomotive engineer.

Manual hand brakes serve to keep a piece of rolling stock stationary after it has been spotted in a rail yard or at a customer for unloading and/or loading. They are also used to secure a parked train from inadvertent movement, especially while unmanned.

Before the development of locomotive-actuated train braking systems, designated railroad employees known as brakemen would move about the tops of cars, setting hand brakes in an effort to stop the train in a timely manner, this process was imprecise and extremely dangerous. Many brakemen lost life and limb as a result of falling from a moving train, icy and wet conditions often adding to the hazards involved in negotiating the top of a swaying boxcar.