Automobile Parts and Technology

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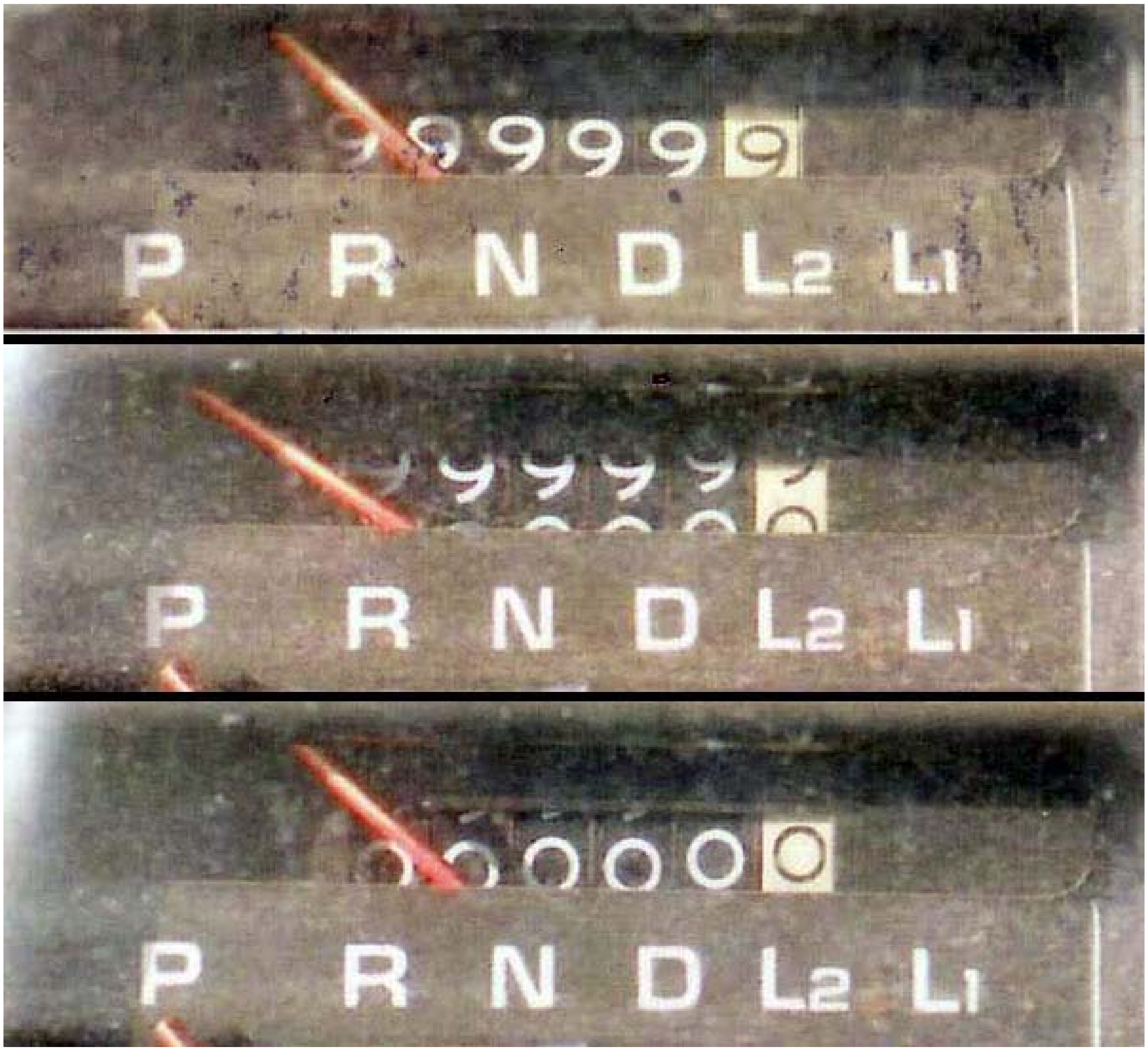
Chapter- 1

Odometer

A mechanical odometer with trip meter below.

An **odometer** (**mileometer**, **milometer**) indicates distance travelled by a bicycle, automobile, or other vehicle. The device may be electronic, mechanical, or a combination of the two. The word derives from the Greek words *hodós*, meaning "path" or gateway and "métron", "measure".

Description



Odometer rollover.

In the early cars a top reading of 99,999 was enough. With improvements, modern vehicles need an extra digit. At the top reading, an odometer restarts from zero (odometer rollover).

Most modern cars include a **trip meter** (**trip odometer**). Unlike the odometer, a trip meter is reset at any point in a journey, making it possible to record the distance travelled in any particular journey or part of a journey. It was traditionally a purely mechanical device but, in most modern vehicles, it is now electronic. Luxury vehicles often have multiple trip meters. Most trip meters will show a maximum value of 999.9. The trip meter may be used to record the distance travelled on each tank of fuel, making it very easy to accurately track the energy efficiency of the vehicle; another common use is resetting it to zero at each instruction in a sequence of driving directions, to be sure when one has arrived at the next turn.

History

A Smiths speedometer from the 1920s showing odometer and trip meter.

An electronic odometer with digital display

Classical Era

Possibly the first evidence for the use of an odometer can be found in the works of Pliny (NH 6. 61-62) and Strabo (11.8.9). Both authors list the distances of routes travelled by Alexander the Great (r. 336-323 BC) as measured by his bematists Diognetus and Baeton. However, the high precision of the bematists's measurements rather indicates the use of a mechanical device. For example, the section between the cities Hecatompylos and Alexandria Areion, which later became a part of the silk road, was given by Alexander's bematists as 529 English miles long, that is with a deviation of 0.4% from the actual distance (531 English miles). From the nine surviving bematists' measurements in Pliny's *Naturalis Historia* eight show a deviation of less than 5% from the actual distance, three of them being within 1%. Since these minor discrepancies can be adequately explained by slight changes in the tracks of roads during the last 2300 years, the overall accuracy of the measurements implies that the bematists already must have used a sophisticated device for measuring distances, although there is no direct mentioning of such a device.

An odometer for measuring distance was first described by Vitruvius around 27 and 23 BC, although the actual inventor may have been Archimedes of Syracuse during the First

Punic War. Hero of Alexandria describes a similar device in chapter 34 of his *Dioptra*. The machine was also used in the time of Roman Emperor Commodus (c. 192 AD), although after this point in time there seems to be a gap between its use in Roman times and that of the 15th century in Western Europe. Some researchers have speculated that the device might have included technology similar to that of the Greek Antikythera mechanism.

The odometer of Vitruvius was based on chariot wheels of 4 feet (1.2 m) diameter turning 400 times in one Roman mile (about 1400 m). For each revolution a pin on the axle engaged a 400 tooth cogwheel thus turning it one complete revolution per mile. This engaged another gear with holes along the circumference, where pebbles (*calculus*) were located, that were to drop one by one into a box. The distance travelled would thus be given simply by counting the number of pebbles. Whether this instrument was ever built at the time is disputed. Leonardo da Vinci later tried to build it himself according to the description, but failed. However, in 1981 engineer Andre Sleewyck built his own replica, replacing the square-toothed gear designs of da Vinci with the triangular, pointed teeth found in the *Antikythera mechanism*. With this modification, the Vitruvius odometer functioned perfectly.

Ancient China

The odometer was also later invented in ancient China, possibly by the profuse inventor and early scientist Zhang Heng (78–139 AD) of the Han Dynasty (202 BC–220 AD). Zhang Heng is often accredited with the invention of the first odometer device in China, an achievement alongside earlier contemporaries Archimedes and Heron of Alexandria from the Hellenized West. By the 3rd century (during the Three Kingdoms Period), the Chinese had termed the device as the 'jì lĭ gŭ chē' (記里鼓車) , or 'li-recording drum carriage' (Note: the modern measurement of li = 500 m/1640 ft). Chinese texts of the 3rd century tell of the mechanical carriage's functions, and as one li is traversed, a mechanical-driven wooden figure strikes a drum, and when ten li is traversed, another wooden figure would strike a gong or a bell with its mechanical-operated arm.

Despite its association with Zhang Heng or even the later Ma Jun (c. 200–265), there is evidence to suggest that the invention of the odometer was a gradual process in Han Dynasty China that centered around the *huang men* court people (i.e. eunuchs, palace officials, attendants and familiars, actors, acrobats, etc.) that would follow the musical procession of the royal 'drum-chariot'. The historian Joseph Needham asserts that it is no surprise this social group would have been responsible for such a device, since there is already other evidence of their craftsmenship with mechanical toys to delight the emperor and the court. There is speculation that some time in the 1st century BC (during the Western Han Dynasty), the beating of drums and gongs were mechanically-driven by working automatically off the rotation of the road-wheels. This might have actually been the design of one Loxia Hong (c. 110 BC), yet by 125 AD the mechanical odometer carriage in China was already known (depicted in a mural of the Xiao Tang Shan Tomb).

The odometer was used also in subsequent periods of Chinese history. In the historical text of the *Jin Shu* (635 AD), the oldest part of the compiled text, the book known as the *Cui Bao* (c. 300 AD), recorded the use of the odometer, providing description (and interestingly enough attributing it to the Western Han era, from 202 BC–9 AD). The passage in the *Jin Shu* expanded upon this, explaining that it took a similar form to the mechanical device of the South Pointing Chariot invented by Ma Jun (200–265). As recorded in the *Song Shi* of the Song Dynasty (960-1279 AD), the odometer and South Pointing Chariot were combined into one wheeled device by engineers of the 9th century, 11th century, and 12th century (refer to South Pointing Chariot). The *Sun Tzu Suan Ching* (Master Sun's Mathematical Manual), dated from the 3rd century to 5th century, presented a mathematical problem for students involving the odometer. It involved a given distance between two cities, the small distance needed for one rotation of the carriage's wheel, and the posed question of how many rotations the wheels would have in all if the carriage was to travel between point A and B.

Song Dynasty odometer

The historical text of the *Song Shi* (1345 AD), recording the people and events of the Chinese Song Dynasty (960–1279), also mentioned the odometer used in that period. However, unlike written sources of earlier periods, it provided a much more thoroughly detailed description of the device that harkens back to its ancient form (Wade-Giles spelling):

The odometer. [The mile-measuring carriage] is painted red, with pictures of flowers and birds on the four sides, and constructed in two storeys, handsomely adorned with carvings. At the completion of every li, the wooden figure of a man in the lower storey strikes a drum; at the completion of every ten li, the wooden figure in the upper storey strikes a bell. The carriage-pole ends in a phoenix-head, and the carriage is drawn by four horses. The escort was formerly of 18 men, but in the 4th year of the Yung-Hsi reign-period (987 AD) the emperor Thai Tsung increased it to 30. In the 5th year of the Thien-Sheng reign-period (1027 AD) the Chief Chamberlain Lu Tao-lung presented specifications for the construction of odometers as follows:

What follows is a long dissertation made by the Chief Chamberlain Lu Daolong on the ranging measurements and sizes of wheels and gears, along with a concluding description at the end of how the device ultimately functions:

The vehicle should have a single pole and two wheels. On the body are two storeys, each containing a carved wooden figure holding a drumstick. The road-wheels are each 6 ft in diameter, and 18 ft in circumference, one evolution covering 3 paces. According to ancient standards the pace was equal to 6 ft and 300 paces to a li; but now the li is reckoned as 360 paces of 5 ft each.

The vehicle wheel (li lun) is attached to the left road-wheel; it has a diameter of 1.38 ft with a circumference of 4.14 ft, and has 18 cogs (chhih) 2.3 inches apart. There is also a lower horizontal wheel (hsia phing lun), of diameter 4.14 ft and circumference 12.42 ft, with 54 cogs, the same distance apart as those on the vertical wheel (2.3 inches). (This engages with the former.)

Upon a vertical shaft turning with this wheel, there is fixed a bronze "turning-like-the-wind wheel" (hsuan feng lun) which has (only) 3 cogs, the distance between these being 1.2 inches. (This turns the following one.) In the middle is a horizontal wheel, 4 ft in diameter, and 12 ft circumference, with 100 cogs, the distance between these cogs being the same as on the "turning-like-the-wind wheel" (1.2 inches).

Next, there is fixed (on the same shaft) a small horizontal wheel (hsiao phing lun) 3.3 inches in diameter and 1 ft in circumference, having 10 cogs 1.5 inches apart. (Engaging with this) there is an upper horizontal wheel (shang phing lun) having a diameter of 3.3 ft and a circumference of 10 ft, with 100 cogs, the same distance apart as those of the small horizontal wheel (1.5 inches).

When the middle horizontal wheel has made 1 revolution, the carriage will have gone 1 li and the wooden figure in the lower story will strike the drum. When the upper horizontal wheel has made 1 revolution, the carriage will have gone 10 li and the figure in the upper storey will strike the bell. The number of wheels used, great and small, is 8 inches in all, with a total of 285 teeth. Thus the motion is transmitted as if by the links of a chain, the "dog-teeth" mutually engaging with each other, so that by due revolution everything comes back to its original starting point (ti hsiang kou so, chhuan ya hsiang chih, chou erh fu shih).

Subsequent Developments

Odometers were first developed in the 1600s for wagons and other horse-drawn vehicles in order to measure distances traveled. In 1645 Blaise Pascal invented the *pascaline*. The *pascaline* utilized gears to compute measurements. Each gear contained 10 teeth. The first gear advanced the next gear one position when moved one complete revolution, the same principle employed on modern mechanical odometers.

Odometers were developed for ships in 1698 with the odometer invented by the Englishman Thomas Savery. Benjamin Franklin, U.S. statesman and the first Postmaster General, built a prototype odometer in 1775 that he attached to his carriage to help measure the mileage of postal routes. In 1847, William Clayton, a Mormon traveller, invented the *Roadometer*, which he attached to a wagon used by American settlers heading west. The *Roadometer* recorded the distance travelled each day by the wagon trains.

In 1895 Curtis Hussey Veeder invented the *Cyclometer*. The *Cyclometer* was a mechanical device that counted the number of rotations of a bicycle wheel. A flexible cable transmitted the number of rotations of the wheel to an analog odometer visible to the rider, which converted the wheel rotations into the number of miles traveled according to a predetermined formula.

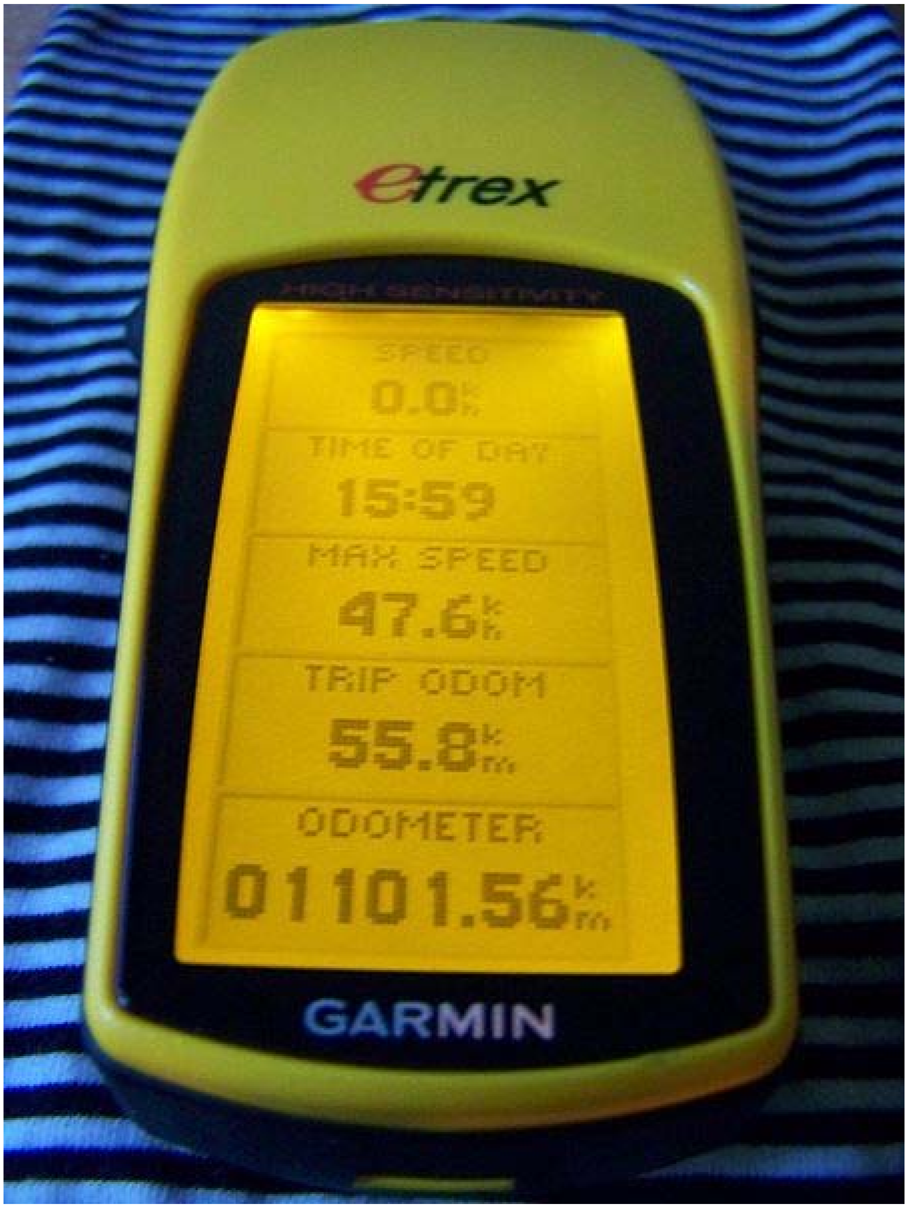
In 1903 Arthur P. and Charles H. Warner, two brothers from Beloit, Wisconsin, introduced their patented *Auto-meter*. The *Auto-Meter* used a magnet attached to a rotating shaft to induce a magnetic pull upon a thin metal disk. Measuring this pull provided accurate measurements of both distance and speed information to automobile drivers in a single instrument. The Warners sold their company in 1912 to the Stewart & Clark Company of Chicago. The new firm was renamed the Stewart-Warner Corporation. By 1925, Stewart-Warner magnetic speedometers were standard equipment on the vast majority of automobiles and motorcycles manufactured in the United States.

Clocking and legality

A common form of fraud is to tamper with the reading on an odometer; this is often referred to as clocking. This is done to make a car appear to have been driven less than it really has been, and thus increase its apparent market value. Many new cars sold today use digital odometers that store the mileage in the vehicle's engine control module making it difficult (but not impossible) to manipulate the mileage electronically. With mechanical odometers, the speedometer can be removed from the car dash board and the digits wound back, or the drive cable can be disconnected and connected to another odometer/speedometer pair while on the road. Modern odometers now add mileage driven in reverse to the total as if driven forward, to accurately reflect the true total wear and tear on the vehicle (older vehicles could be driven in reverse to subtract mileage).

The resale value of a vehicle is often strongly influenced by the number of miles or kilometres a passenger vehicle has on the odometer, yet odometers are inherently insecure because they are under the control of their owners. Many jurisdictions have chosen to enact laws which penalize people who are found to commit odometer fraud. In the US (and many other countries), vehicle mechanics are also required to keep records of the odometer any time a vehicle is serviced. Companies such as Carfax then use this data to help potential car buyers detect whether odometer rollback has occurred.

GPS used as odometer



A Garmin etrex H GPS receiver, showing an odometer, trip odometer as well as speed related information

Recently, exercise enthusiasts have observed that an advanced Global Positioning System receiver (GPSr) with an odometer mode serves as a very accurate pedometer for outdoor activities. While not truly counting steps (no pendulum is involved) an advanced GPS odometer can accurately reveal the distance traveled to within 1/100 of a mile (depending on the model, perhaps 1/1000 of a mile). 1/1000 of a mile is approximately the distance of a single pace or 2 steps (1.609 m). Precise metric odometers have a precision of 1/100 or 1/1000 km, 10 or 1 metre(s) respectively.

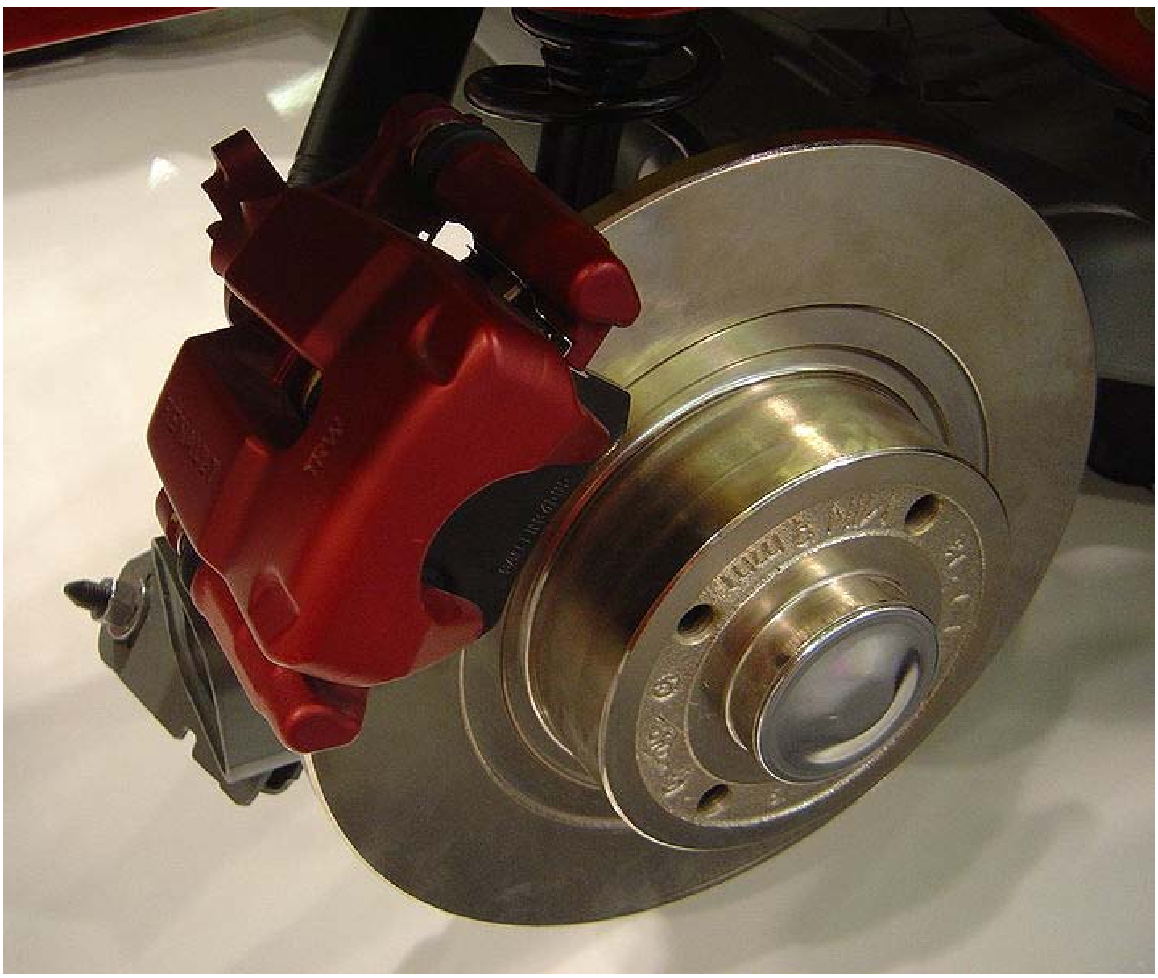
A GPS with odometer mode is also an excellent and inexpensive means to verify proper operation of both the speedometer and odometer mounted in a vehicle.

Odometer tax

This would be a road vehicle tax collected per distance unit of travel. This may become increasingly important with the increasing presence of gas burning vehicles & very fuel efficient electric models.

Chapter- 2

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- 3

Windscreen Wiper

A common windscreen wiper arm and blade

Windscreen wiper on a parked car. In this common design, the force from the arm is distributed evenly with a series of linkages known as a whippletree.

A common design for a "wiper" (also called a clear view screen) on a ship. A round portion of the windscreen has two layers, the outer one of which is spun at high speed.

A **windscreen wiper** or **windshield wiper** is a device used to remove rain and debris from a windscreen or windshield. Almost all motor vehicles, including trains, aircraft and watercraft, are equipped with such wipers, which are usually a legal requirement.

A wiper generally consists of an arm, pivoting at one end and with a long rubber blade attached to the other. The blade is swung back and forth over the glass, pushing water from its surface. The speed is normally adjustable, with several continuous speeds and often one or more "intermittent" settings. Most automobiles use two synchronized radial type arms, while many commercial vehicles use one or more pantograph arms.

History

In 1903, Mary Anderson is credited with inventing the first operational windshield wiper. In Anderson's patent, she called her invention a window cleaning device for electric cars and other vehicles. Operated via a lever from inside a vehicle, her version of windshield wipers closely resembles the windshield wiper found on many early car models. Anderson had a model of her design manufactured. She then filed a patent (U.S. patent number 743,801) on June 18, 1903 that was issued to her by the U.S. Patent Office on November 10, 1903.

Irish born Inventor James Henry Apjohn (1845–1914) devised a method of moving two brushes up and down on a vertical plate glass windscreen in 1903. This was patented in the UK.

In April 1911, a patent for windscreen wipers was registered by Sloan & Lloyd Barnes, patent agents of Liverpool, England, for Gladstone Adams of Whitley Bay. The first designs for the windscreen wiper are also credited to concert pianist Józef Hofmann, and Mills Munitions, Birmingham who also claimed to have been the first to patent windscreen wipers in England.

The company Oishei formed, the Tri-Continental Corporation, introduced the first windshield wiper, Rain Rubber, for the slotted, two-piece windshields found on many of the automobiles of the time. Today Trico Products is one of the world's leading manufacturers of windshield wiping systems, windshield wiper blades and refills, with wiper plants on five continents.

Inventor William M. Folberth, in 1919, applied for a patent for an automatic windscreen wiper apparatus. The patent was granted in 1922. It was the first automatic mechanism. Trico later settled a patent dispute with Folberth and purchased Folberth's Cleveland company, the Folberth Auto Specialty Co. The new vacuum-powered system quickly became standard equipment on automobiles, and the vacuum principle was in use until about 1960. In the late 1950s, a feature common on modern vehicles first appeared, operating the wipers automatically for two or three passes when the washer button was pressed, making it unnecessary to manually turn them on as well. Today, an electronic timer is used, but originally a small vacuum cylinder mechanically linked to a switch provided the delay as the vacuum leaked off.

In 1963, the first intermittent wipers were invented by Robert Kearns, an engineering professor at Wayne State University in Detroit. The road to intermittent wipers began on his wedding night earlier in 1953, when an errant champagne cork shot into Kearn's left eye, which eventually went almost completely blind. Nearly a decade later Kearns was driving his Ford Galaxie through a light rain, and the constant movement of the wiper blades irritated his already troubled vision. He got to thinking about the human eye, which has its own kind of wiper, the eyelid, that automatically closes and opens every few seconds. FInally in 1963, Kearns put his idea into action, building the first intermittent wiper system using off-the-shelf electronic components and offered it to Ford. The interval between wipes was determined by the rate of current flow into a capacitor. When the charge in the capacitor reached a certain voltage, the capacitor discharged, activating the wiper motor for one cycle. After extensive testing, Ford executives decided to offer Kearns's intermittent wipers as an option on the company's Mercury line beginning with the 1969 models. Kearns may not, in fact, be the original inventor. John Amos, an engineer for the UK automative engineering company, Lucas Industries was the first to file a patent for an intermittent wiper. United States Patent #3,262,042 was filed two years before Kearns filed United States Patent #3,351,836, and was issued in 1966 before Kearns' patent was issued in 1967. The difference is that the Amos patent describes an electromechanical device, whereas Kearns proposed a solid-state circuit.

In 1970, Saab Automobile introduced headlight wipers across the product range. These operated on a horizontal reciprocating mechanism, with a single motor. They were later superseded by a radial spindle action wiper mechanism, with individual motors on each headlamp. In March 1970, Citroën introduced rain-sensitive intermittent windscreen wipers on the SM model. When the intermittent function was selected, the wiper would make one swipe. If the windscreen was relatively dry, the wiper motor drew high current, which set the control circuit timer to delay the next wipe longest. If the motor drew little current, it indicated that the glass was wet, setting the timer to minimize the delay.

Bosch has the world's biggest windscreen wiper factory in Tienen, Belgium, which produces 350,000 wiper blades every day.

Power

Wipers may be powered by a variety of means, although most in existence today are powered by an electric motor through a series of mechanical components, typically two 4-bar linkages in series or parallel. Vehicles with air operated brakes sometimes use air operated wipers, run by bleeding a small amount of air pressure from the brake system to a small air operated motor mounted just above the windscreen. These wipers are activated by opening a valve which allows pressurized air to enter the motor.

Early wipers were often driven by a vacuum motor powered by manifold vacuum. This had the drawback that manifold vacuum alters depending on throttle position and is almost non-existent under wide-open throttle; the wipers would slow down or even stop. This problem was overcome somewhat by using a combined fuel/vacuum booster pump. Some cars, mostly from the 1960s and 1970s, had hydraulically driven wipers. On the earlier Citroën 2CV, the windscreen wipers were powered by a purely mechanical system: a cable connected to the transmission, to reduce cost this cable also powered the speedometer. The wipers' speed was therefore variable with car speed. When the car was waiting at a crossroad, the wipers were not powered, thus a handle under the speedometer allowed the driver to power them by hand.

Geometry

Most wipers are of the pivot (or radial) type: they are attached to a single arm, which in turn is attached to the motor. These are commonly found on many cars, trucks, trains, boats, airplanes, etc.

Another type of wipers are the pantograph-based (see Fig. 6), which are used on many commercial vehicles, especially buses with large windscreens. Pantograph wipers feature two arms for each blade, with the blade assembly itself supported on a horizontal bar connecting the two arms. One of the arms is attached to the motor, while the other is on an idle pivot. The pantograph mechanism, while being more complex, allows the blade to cover more of the windscreen on each wipe. However, it also usually requires the wiper to be "parked" in the middle of the windscreen, where it may partially obstruct the driver's view when not in use. Some larger cars in the late '70s and early '80s, especially LH driver American cars, had a pantograph wiper on the driver's side, with a conventional pivot on the passenger side.

Mercedes-Benz pioneered a system called the Monoblade, based on cantilevers (see Fig. 5), in which a single arm extends outward to reach the top corners of the windscreen, and pulls in at the ends and middle of the stroke, sweeping out a somewhat 'W'-shaped path. This way, a single blade is able to cover more of the windscreen, and displace the residual streaks away from the center of the windscreen.

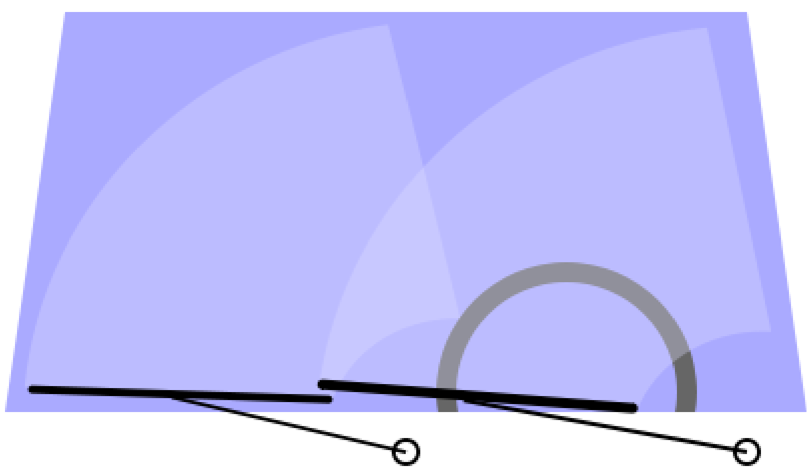


Fig. 1: most common geometry, found on vast majority of vehicles

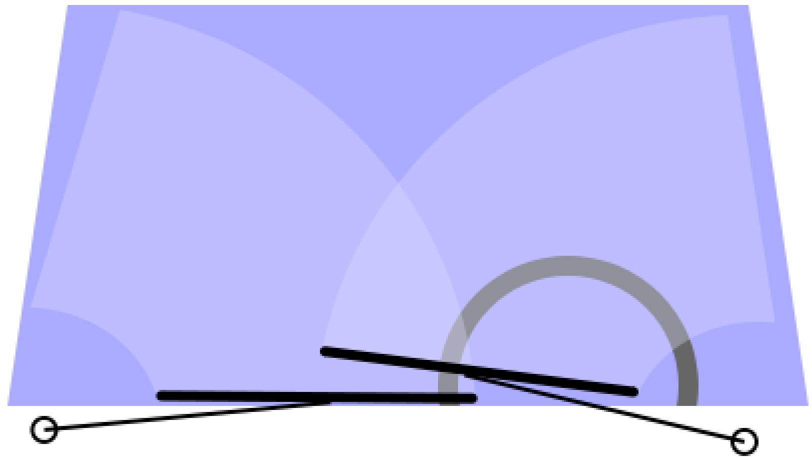


Fig. 2: Mercedes-Benz W114, W168, W169; VW Sharan, Honda Civic, some minivans, some school buses, Peugeot 307

Fig. 3: SEAT Altea, SEAT León Mk2, SEAT Toledo Mk3

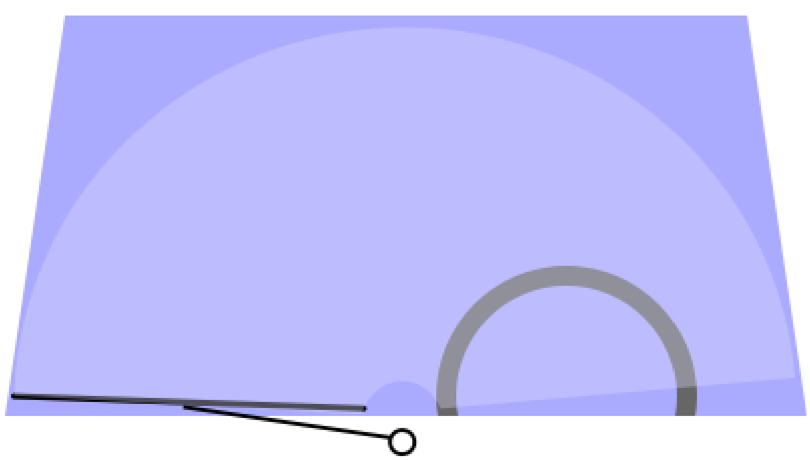


Fig. 4: VAZ-1111 Oka, 1990's Citroën Citroen AX

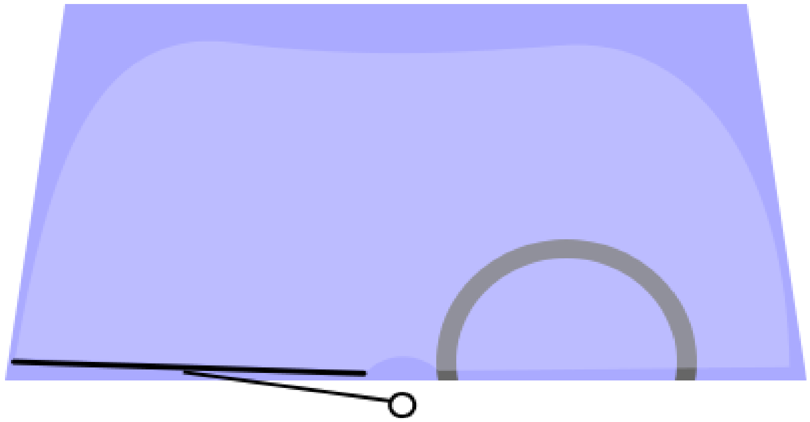


Fig. 5: Subaru XT, Mercedes-Benz W124, W201, W202, W210

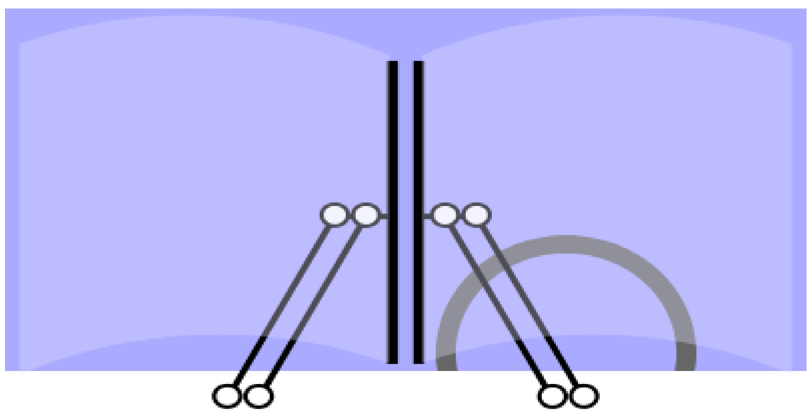


Fig. 6: Buses, some school buses, Mercedes-Benz O305

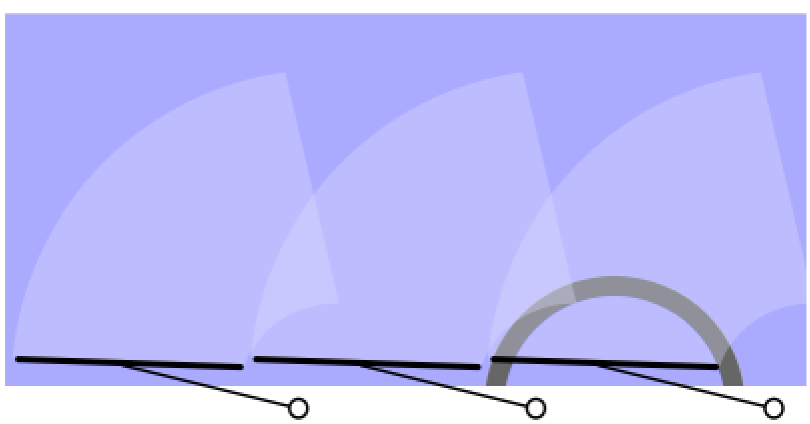


Fig. 7: MAN, Toyota FJ Cruiser, Jaguar E-type, MGB, MG Midget, Austin Healey Sprite, a 1968 US only ruling required a certain percentage of the windscreen to be wiped.

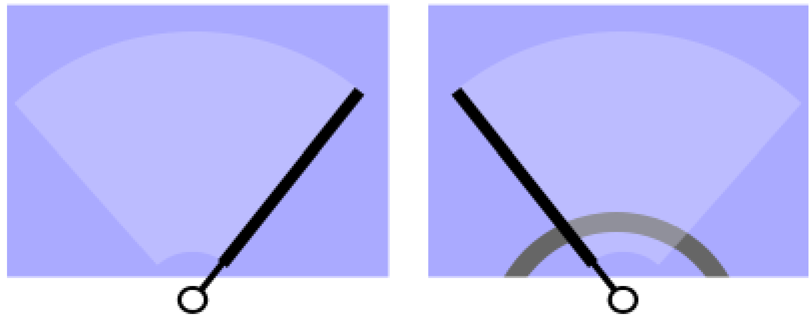


Fig. 8: obsolete, found on some older firetrucks

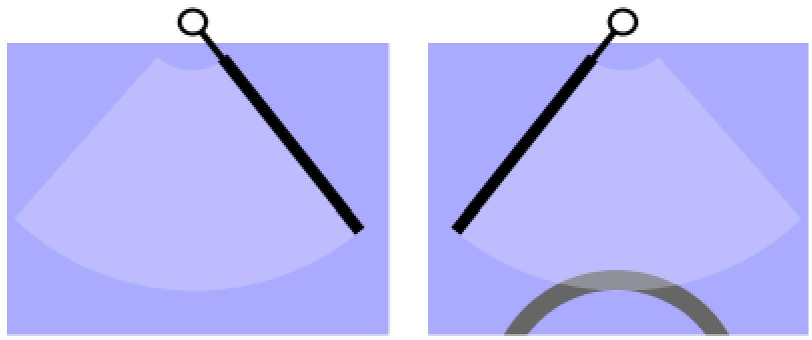


Fig. 9: US Military Wheeled Vehicles, some school buses

Other features

Some larger cars are equipped with "hidden" (or "depressed-park") wipers. When wipers are switched off, a "parking" mechanism or circuit moves the wipers to the lower extreme of the wiped area, near the bottom of the windscreen, but still in sight. To hide the wipers, the windscreen extends below the rear edge of the hood, and the wipers park themselves below the wiping range at the bottom of the windscreen, but out of sight.

Some vehicles have small wipers or washers on the headlights. In more modern vehicles, these have been replaced with a powerful jet spray, without wipers. Some vehicles are fitted with wipers (with or without washers) on the back window as well. Rear-window wipers are typically found on hatchbacks, station wagons, sport utility vehicles, minivans, and some sports cars. They were first implemented in the 1970s, but SUVs did not use them until the 1980s.

Windscreen washer

Most windscreen wipers operate together with a windscreen (or windshield) washer; a pump that supplies water and detergent (usually a blend called windshield washer fluid) from a tank to the windscreen through small nozzles, mounted on the hood or on the wipers, known as a 'wet-arm' system. In warmer climates, water may also work, but it can freeze in colder climates. Although automobile antifreeze is chemically similar to windscreen wiper fluid, it must not be used because it can damage paint. The earliest idea for having a windshield wiper unit hooked up to a windshield washer fluid reservoir was in 1931, Richland Auto Parts Co, Mansfield, Ohio

Rain-sensing wipers

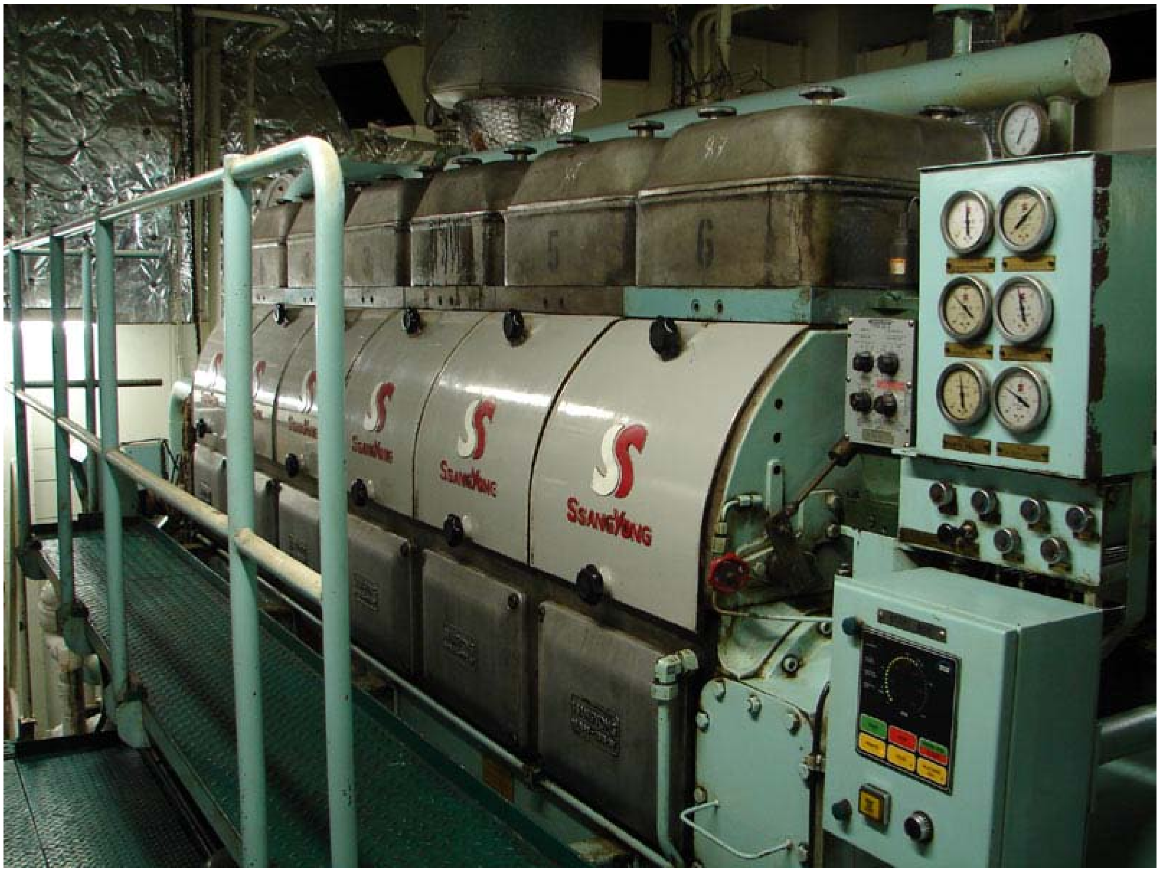
Vehicles are now available with driver-programmable *intelligent* (automatic) windscreen wipers that detect the presence and amount of rain using a rain sensor. The sensor automatically adjusts the speed of the blades according to the amount of rain detected. These usually have a manual override.

Rain-sensing windscreen wipers appeared on various models in the late 20th century, one of the first being Nissan's 200SX/Silvia. As of early 2006, rain-sensing wipers are optional or standard on all Cadillacs and most Volkswagen, and are available on many other main-stream manufacturers.

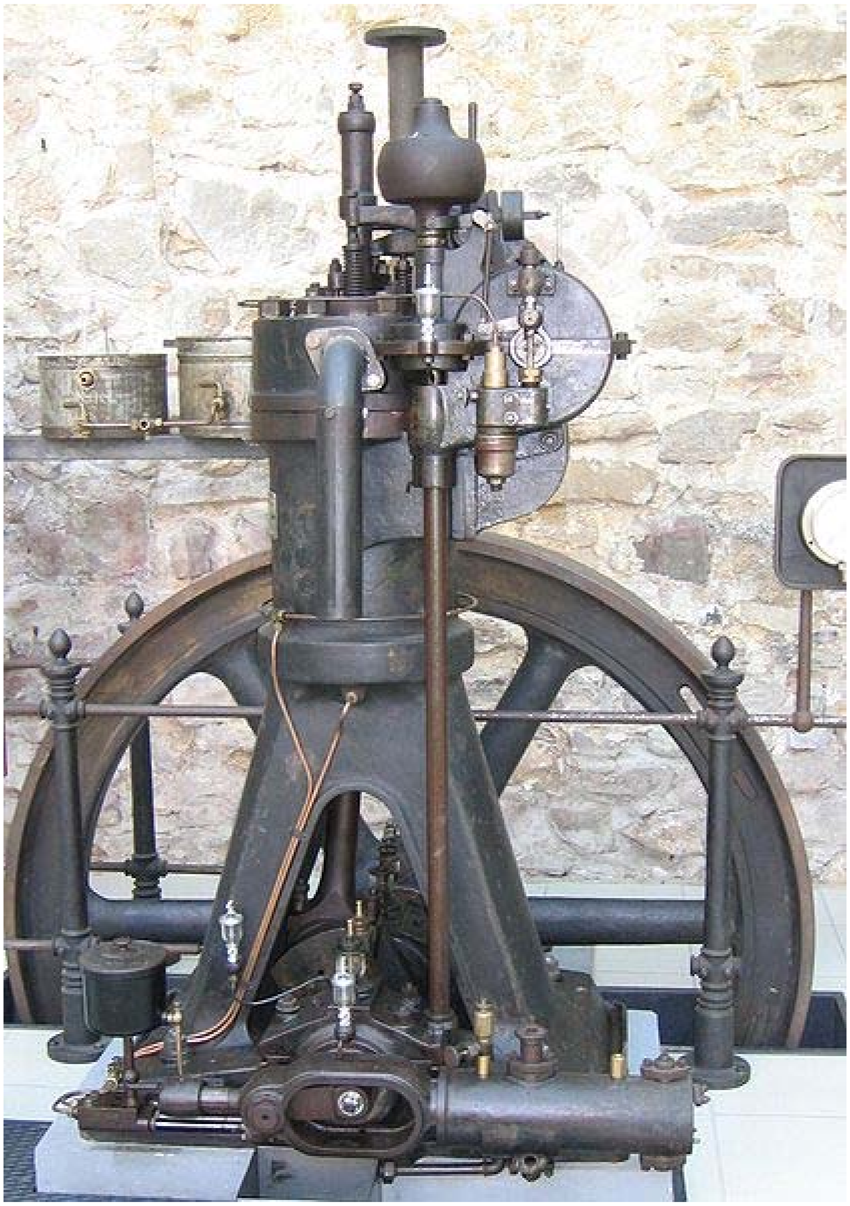
Chapter- 4

Diesel Engine

Diesel engines in a museum



Diesel generator on an oil tanker



A diesel engine built by MAN AG in 1906

A **diesel engine** (also known as a **compression-ignition engine** and sometimes capitalized as **Diesel engine**) is an internal combustion engine that uses the heat of compression to initiate ignition to burn the fuel, which is injected into the combustion chamber during the final stage of compression. This is in contrast to spark-ignition engines such as a petrol engine (gasoline engine) or gas engine (using a gaseous fuel as opposed to gasoline), which uses a spark plug to ignite an air-fuel mixture. The diesel engine is modeled on the Diesel cycle. The engine and thermodynamic cycle were both developed by Rudolf Diesel in 1897.

The diesel engine has the highest thermal efficiency of any regular internal or external combustion engine due to its very high compression ratio. Low-speed diesel engines (as used in ships and other applications where overall engine weight is relatively unimportant) often have a thermal efficiency which exceeds 50 percent.

Diesel engines are manufactured in two stroke and four stroke versions. They were originally used as a more efficient replacement for stationary steam engines. Since the 1910s they have been used in submarines and ships. Use in locomotives, large trucks and electric generating plants followed later. In the 1930s, they slowly began to be used in a few automobiles. Since the 1970s, the use of diesel engines in larger on-road and off-road vehicles in the USA increased. As of 2007, about 50 percent of all new car sales in Europe are diesel.

The world's largest diesel engine is currently a Wärtsilä marine diesel of about 80 MW output.

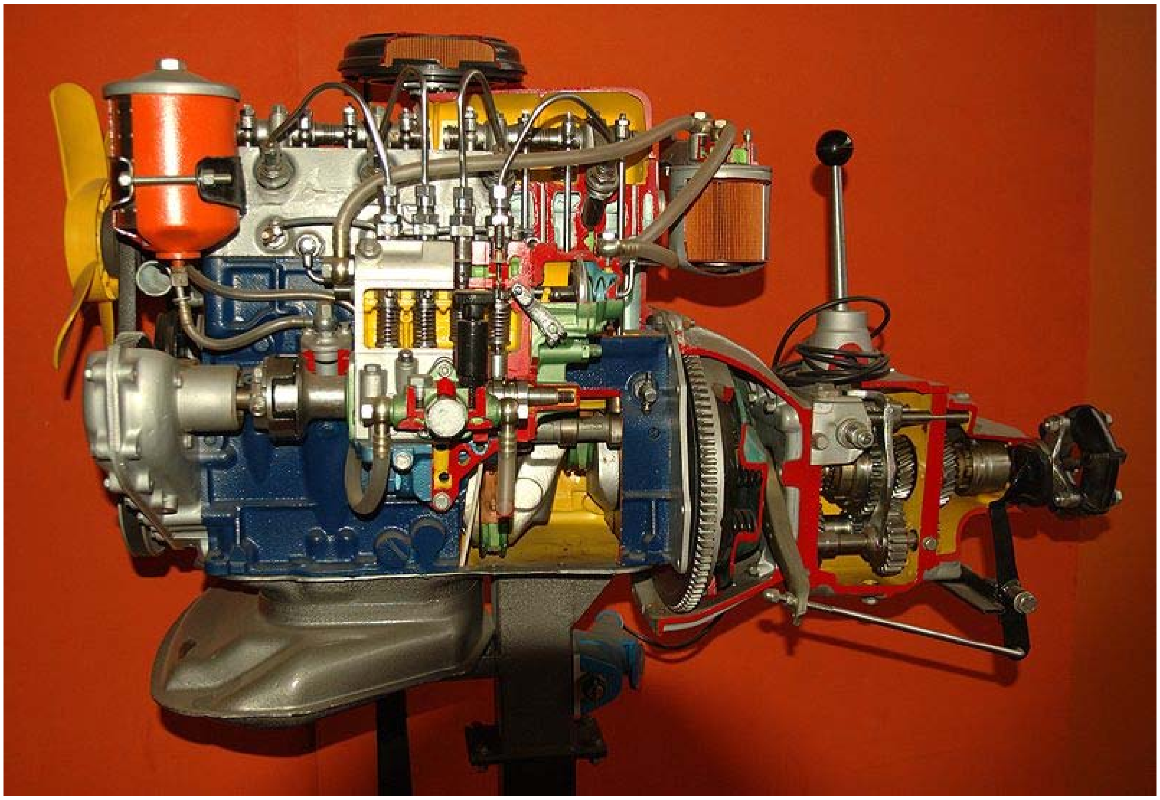
History

Rudolf Diesel, of German ethnicity, was born in 1858 in Paris where his parents were German immigrants. He was educated at Munich Polytechnic. After graduation he was employed as a refrigerator engineer, but his true love lay in engine design. Diesel designed many heat engines, including a solar-powered air engine. In 1892 he received patents in Germany, Switzerland, the United Kingdom and filed in the United States for "Method of and Apparatus for Converting Heat into Work". In 1893 he described a "slow-combustion engine" that first compressed air thereby raising its temperature above the igniting-point of the fuel, then gradually introducing fuel while letting the mixture expand "against resistance sufficiently to prevent an essential increase of temperature and pressure", then cutting off fuel and "expanding without transfer of heat". In 1894 and 1895 he filed patents and addenda in various countries for his Diesel engine; the first patents were issued in Spain (No.16,654), France (No.243,531) and Belgium (No.113,139) in December 1894, and in Germany (No.86,633) in 1895 and the United States (No.608,845) in 1898. He operated his first successful engine in 1897. His engine was the first to prove that fuel could be ignited without a spark.

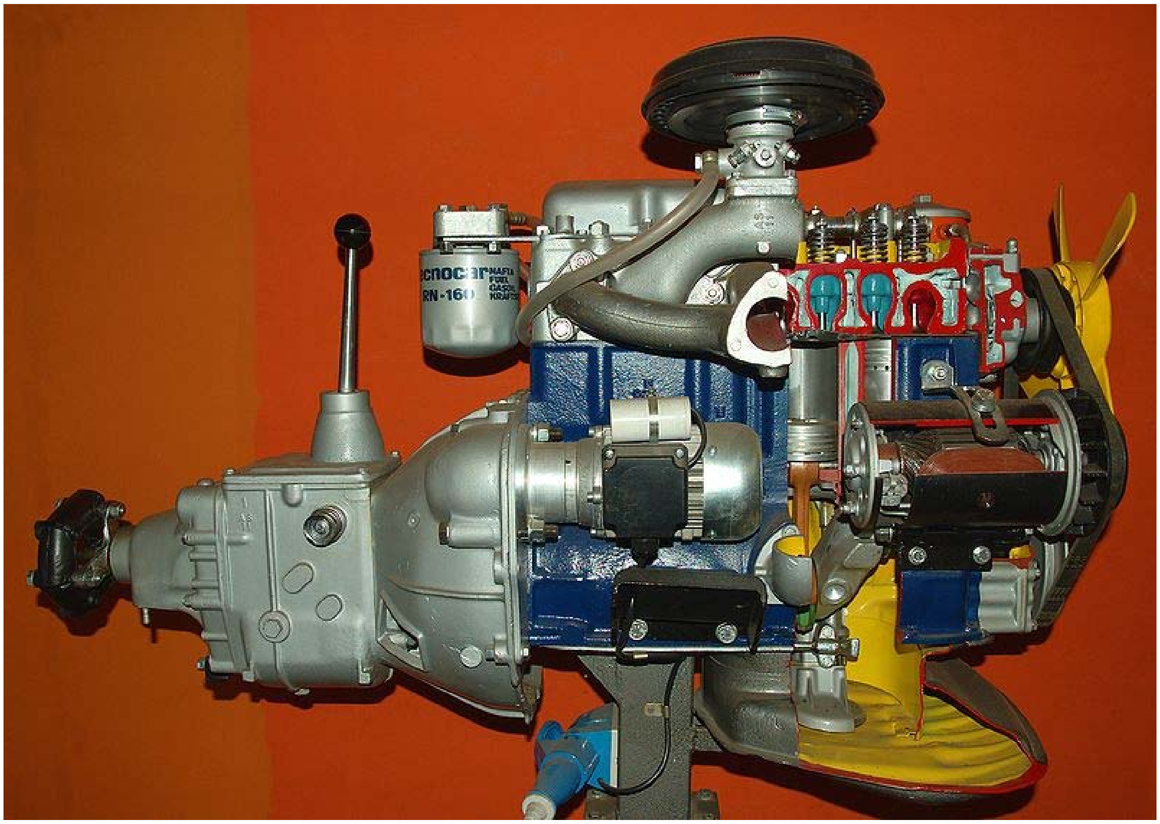
Though best known for his invention of the pressure-ignited heat engine that bears his name, Rudolf Diesel was also a well-respected thermal engineer and a social theorist. Diesel's inventions have three points in common: they relate to heat transfer by natural physical processes or laws; they involve markedly creative mechanical design; and they were initially motivated by the inventor's concept of sociological needs. Rudolf Diesel originally conceived the diesel engine to enable independent craftsmen and artisans to compete with industry.

At Augsburg, on August 10, 1893, Rudolf Diesel's prime model, a single 10-foot (3.0 m) iron cylinder with a flywheel at its base, ran on its own power for the first time. Diesel spent two more years making improvements and in 1896 demonstrated another model with a theoretical efficiency of 75 percent, in contrast to the 10 percent efficiency of the steam engine. By 1898, Diesel had become a millionaire. His engines were used to power pipelines, electric and water plants, automobiles and trucks, and marine craft. They were soon to be used in mines, oil fields, factories, and transoceanic shipping.

How diesel engines work



Diesel engine model, left side



Diesel engine model, right side

The diesel internal combustion engine differs from the gasoline powered Otto cycle by using highly compressed, hot air to ignite the fuel rather than using a spark plug (*compression ignition* rather than *spark ignition*).

In the true diesel engine, only air is initially introduced into the combustion chamber. The air is then compressed with a compression ratio typically between 15:1 and 22:1 resulting in 40-bar (4.0 MPa; 580 psi) pressure compared to 8 to 14 bars (0.80 to 1.4 MPa) (about 200 psi) in the petrol engine. This high compression heats the air to 550 °C (1,022 °F). At about the top of the compression stroke, fuel is injected directly into the compressed air in the combustion chamber. This may be into a (typically toroidal) void in the top of the piston or a *pre-chamber* depending upon the design of the engine. The fuel injector ensures that the fuel is broken down into small droplets, and that the fuel is distributed evenly. The heat of the compressed air vaporizes fuel from the surface of the droplets. The vapour is then ignited by the heat from the compressed air in the combustion chamber, the droplets continue to vaporise from their surfaces and burn, getting smaller, until all the fuel in the droplets has been burnt. The start of vaporisation causes a delay period during ignition, and the characteristic diesel knocking sound as the vapor reaches ignition temperature and causes an abrupt increase in pressure above the piston. The rapid expansion of combustion gases then drives the piston downward, supplying power to the crankshaft. Engines for scale-model aeroplanes use a variant of the Diesel principle but premix fuel and air via a carburation system external to the combustion chambers.

As well as the high level of compression allowing combustion to take place without a separate ignition system, a high compression ratio greatly increases the engine's efficiency. Increasing the compression ratio in a spark-ignition engine where fuel and air are mixed before entry to the cylinder is limited by the need to prevent damaging pre-ignition. Since only air is compressed in a diesel engine, and fuel is not introduced into the cylinder until shortly before top dead centre (TDC), premature detonation is not an issue and compression ratios are much higher.

Early fuel injection systems

Diesel's original engine injected fuel with the assistance of compressed air, which atomized the fuel and forced it into the engine through a nozzle (a similar principle to an aerosol spray). The nozzle opening was closed by a pin valve lifted by the camshaft to initiate the fuel injection before top dead centre (TDC). This is called an air-blast injection. Driving the three stage compressor used some power but the efficiency and net power output was more than any other combustion engine at that time.

Diesel engines in service today raise the fuel to extreme pressures by mechanical pumps and deliver it to the combustion chamber by pressure-activated injectors without compressed air. With direct injected diesels, injectors spray fuel through 4 to 12 small orifices in its nozzle. The early air injection diesels always had a superior combustion without the sharp increase in pressure during combustion. Research is now being performed and patents are being taken out to again use some form of air injection to reduce the nitrogen oxides and pollution, reverting to Diesel's original implementation with its superior combustion and possibly quieter operation. In all major aspects, the modern diesel engine holds true to Rudolf Diesel's original design, that of igniting fuel by compression at an extremely high pressure within the cylinder. With much higher pressures and high technology injectors, present-day diesel engines use the so-called solid injection system applied by Herbert Akroyd Stuart for his hot bulb engine. The indirect injection engine could be considered the latest development of these low speed *hot bulb* ignition engines.

Fuel delivery

A vital component of all diesel engines is a mechanical or electronic governor which regulates the idling speed and maximum speed of the engine by controlling the rate of fuel delivery. Unlike Otto-cycle engines, incoming air is not throttled and a diesel engine without a governor cannot have a stable idling speed and can easily overspeed, resulting in its destruction. Mechanically governed fuel injection systems are driven by the engine's gear train. These systems use a combination of springs and weights to control fuel delivery relative to both load and speed. Modern electronically controlled diesel engines control fuel delivery by use of an electronic control module (ECM) or electronic control unit (ECU). The ECM/ECU receives an engine speed signal, as well as other operating parameters such as intake manifold pressure and fuel temperature, from a sensor and controls the amount of fuel and start of injection timing through actuators to maximise power and efficiency and minimise emissions. Controlling the timing of the start of injection of fuel into the cylinder is a key to minimizing emissions, and maximizing fuel economy (efficiency), of the engine. The timing is measured in degrees of crank angle of the piston before top dead centre. For example, if the ECM/ECU initiates fuel injection when the piston is 10 degrees before TDC, the start of injection, or timing, is said to be 10° BTDC. Optimal timing will depend on the engine design as well as its speed and load.

Advancing the start of injection (injecting before the piston reaches to its SOI-TDC) results in higher in-cylinder pressure and temperature, and higher efficiency, but also results in elevated engine noise and increased oxides of nitrogen (NO_x) emissions due to higher combustion temperatures. Delaying start of injection causes incomplete combustion, reduced fuel efficiency and an increase in exhaust smoke, containing a considerable amount of particulate matter and unburned hydrocarbons.

Major advantages

Diesel engines have several advantages over other internal combustion engines:

- They burn less fuel than a petrol engine performing the same work, due to the engine's higher temperature of combustion and greater expansion ratio. Gasoline engines are typically 25 percent efficient while diesel engines can convert over 30 percent of the fuel energy into mechanical energy.
- They have no high-tension electrical ignition system to attend to, resulting in high reliability and easy adaptation to damp environments. The absence of coils, spark plug wires, etc., also eliminates a source of radio frequency emissions which can interfere with navigation and communication equipment, which is especially important in marine and aircraft applications.
- They can deliver much more of their rated power on a continuous basis than a petrol engine.
- The life of a diesel engine is generally about twice as long as that of a petrol engine due to the increased strength of parts used. Diesel fuel has better lubrication properties than petrol as well.

Bus powered by **biodiesel**

- Diesel fuel is considered safer than petrol in many applications. Although diesel fuel will burn in open air using a wick, it will not explode and does not release a large amount of flammable vapor. The low vapor pressure of diesel is especially advantageous in marine applications, where the accumulation of explosive fuel-air mixtures is a particular hazard. For the same reason, diesel engines are immune to vapor lock.
- For any given partial load the fuel efficiency (mass burned per energy produced) of a diesel engine remains nearly constant, as opposed to petrol and turbine engines which use proportionally more fuel with partial power outputs.
- They generate less waste heat in cooling and exhaust.
- Diesel engines can accept super- or turbo-charging pressure without any natural limit, constrained only by the strength of engine components. This is unlike petrol engines, which inevitably suffer detonation at higher pressure.
- The carbon monoxide content of the exhaust is minimal, therefore diesel engines are used in underground mines.
- Biodiesel is an easily synthesized, non-petroleum-based fuel (through transesterification) which can run directly in many diesel engines, while gasoline engines either need adaptation to run synthetic fuels or else use them as an additive to gasoline (e.g., ethanol added to gasohol), making diesel engines the clearly preferred choice for sustainability.

Mechanical and electronic injection

Many configurations of fuel injection have been used over the past century (1901–2000).

Most present day (2008) diesel engines make use of a camshaft, rotating at half crankshaft speed, lifted mechanical single plunger high pressure fuel pump driven by the engine crankshaft. For each cylinder, its plunger measures the amount of fuel and determines the timing of each injection. These engines use injectors that are very precise spring-loaded valves that open and close at a specific fuel pressure. For each cylinder a plunger pump is connected to an injector with a high pressure fuel line. Fuel volume for each single combustion is controlled by a slanted groove in the plunger which rotates only a few degrees releasing the pressure and is controlled by a mechanical governor, consisting of weights rotating at engine speed constrained by springs and a lever. The injectors are held open by the fuel pressure. On high speed engines the plunger pumps are together in one unit. Each fuel line should have the same length to obtain the same pressure delay.

A cheaper configuration on high speed engines with fewer than six cylinders is to use an axial-piston distributor pump, consisting of one rotating pump plunger delivering fuel to a valve and line for each cylinder (functionally analogous to points and distributor cap on an Otto engine). This contrasts with the more modern method of having a single fuel pump which supplies fuel constantly at high pressure with a common rail (single fuel line common) to each injector. Each injector has a solenoid operated by an electronic control unit, resulting in more accurate control of injector opening times that depend on other control conditions, such as engine speed and loading, and providing better engine performance and fuel economy. This design is also mechanically simpler than the combined pump and valve design, making it generally more reliable, and less noisy, than its mechanical counterpart.

Both mechanical and electronic injection systems can be used in either direct or indirect injection configurations.

Older diesel engines with mechanical injection pumps could be inadvertently run in reverse, albeit very inefficiently, as witnessed by massive amounts of soot being ejected from the air intake. This was often a consequence of push starting a vehicle using the wrong gear. Large ship diesels can run either way.

Indirect injection

An indirect injection diesel engine delivers fuel into a chamber off the combustion chamber, called a pre-chamber or ante-chamber, where combustion begins and then spreads into the main combustion chamber, assisted by turbulence created in the chamber. This system allows for a smoother, quieter running engine, and because combustion is assisted by turbulence, injector pressures can be lower, about 100 bar (10 MPa; 1,500 psi), using a single orifice tapered jet injector. Mechanical injection systems allowed high-speed running suitable for road vehicles (typically up to speeds of around 4,000 rpm). The pre-chamber had the disadvantage of increasing heat loss to the engine's cooling system, and restricting the combustion burn, which reduced the efficiency by 5–10 percent. Indirect injection engines were used in small-capacity, high-speed diesel engines in automotive, marine and construction uses from the 1950s, until direct injection technology advanced in the 1980s. Indirect injection engines are cheaper to build and it is easier to produce smooth, quiet-running vehicles with a simple mechanical system. In road-going vehicles most prefer the greater efficiency and better controlled emission levels of direct injection. Indirect injection diesels can still be found in the many ATV diesel applications.

Direct injection

Modern diesel engines make use of one of the following direct injection methods:

Direct injection injectors are mounted in the top of the combustion chamber. The problem with these vehicles was the harsh noise they produced. Fuel consumption was about 15 to 20 percent lower than indirect injection diesels, which for some buyers was enough to compensate for the extra noise.

This type of engine was transformed by electronic control of the injection pump, pioneered by Fiat in 1986 (Croma). The injection pressure was still only around 300 bar (30 MPa; 4,400 psi), but the injection timing, fuel quantity, EGR and turbo boost were all electronically controlled. This gave more precise control of these parameters which eased refinement and lowered emissions.

Unit direct injection

Unit direct injection also injects fuel directly into the cylinder of the engine. In this system the injector and the pump are combined into one unit positioned over each cylinder controlled by the camshaft. Each cylinder has its own unit eliminating the high pressure fuel lines, achieving a more consistent injection. This type of injection system, also developed by Bosch, is used by Volkswagen AG in cars (where it is called a *Pumpe-Düse-System*—literally *pump-nozzle system*) and by Mercedes Benz ("PLD") and most major diesel engine manufacturers in large commercial engines (CAT, Cummins, Detroit Diesel, Volvo). With recent advancements, the pump pressure has been raised to 2,400 bar (240 MPa; 35,000 psi), allowing injection parameters similar to common rail systems.

Common rail direct injection

In common rail systems, the separate pulsing high pressure fuel line to each cylinder's injector is also eliminated. Instead, a high-pressure pump pressurizes fuel at up to 2,500 bar (250 MPa; 36,000 psi), in a "common rail". The common rail is a tube that supplies each computer-controlled injector containing a precision-machined nozzle and a plunger driven by a solenoid or piezoelectric actuator.

Cold weather

Starting

In cold weather, high speed diesel engines that are pre-chambered can be difficult to start because the mass of the cylinder block and cylinder head absorb the heat of compression, preventing ignition due to the higher surface-to-volume ratio. Pre-chambered engines therefore make use of small electric heaters inside the pre-chambers called glowplugs. These engines also generally have a higher compression ratio of 19:1 to 21:1. Low-speed and compressed-air-started larger and intermediate-speed diesels do not have glowplugs and compression ratios are around 16:1.

Some engines (e.g., some Cummins models) use resistive grid heaters in the intake manifold to warm the inlet air until the engine reaches operating temperature. Engine block heaters (electric resistive heaters in the engine block) connected to the utility grid are often used when an engine is turned off for extended periods (more than an hour) in cold weather to reduce startup time and engine wear. In the past, a wider variety of cold-start methods were used. Some engines, such as Detroit Diesel engines and Lister-Petter engines, used a system to introduce small amounts of ether into the inlet manifold to start combustion. Saab-Scania marine engines, Field Marshall tractors (among others) used slow-burning solid-fuel 'cigarettes' which were fitted into the cylinder head as a primitive glow plug.

Lucas developed the *Thermostart*, where an electrical heating element was combined with a small fuel valve in the inlet manifold. Diesel fuel slowly dripped from the valve onto the hot element and ignited. The flame heated the inlet manifold and when the engine was cranked, the flame was drawn into the cylinders to start combustion.

International Harvester developed a tractor in the 1930s that had a 7-litre 4-cylinder engine which started as a gasoline engine and ran on diesel after warming up. The cylinder head had valves which opened for a portion of the compression stroke to reduce the effective compression ratio, and a magneto produced the spark. An automatic ratchet system automatically disengaged the ignition system and closed the valves once the engine had run for 30 seconds. The operator then switched off the petrol fuel system and opened the throttle on the diesel injection system.

Recent direct-injection systems are advanced to the extent that pre-chambers systems are not needed by using a common rail fuel system with electronic fuel injection.

Gelling

Diesel fuel is also prone to *waxing* or *gelling* in cold weather; both are terms for the solidification of diesel oil into a partially crystalline state. The crystals build up in the fuel line (especially in fuel filters), eventually starving the engine of fuel and causing it to stop running. Low-output electric heaters in fuel tanks and around fuel lines are used to solve this problem. Also, most engines have a *spill return* system, by which any excess fuel from the injector pump and injectors is returned to the fuel tank. Once the engine has warmed, returning warm fuel prevents waxing in the tank. Due to improvements in fuel technology with additives, waxing rarely occurs in all but the coldest weather when a mix of diesel and kerosene should be used to run a vehicle.

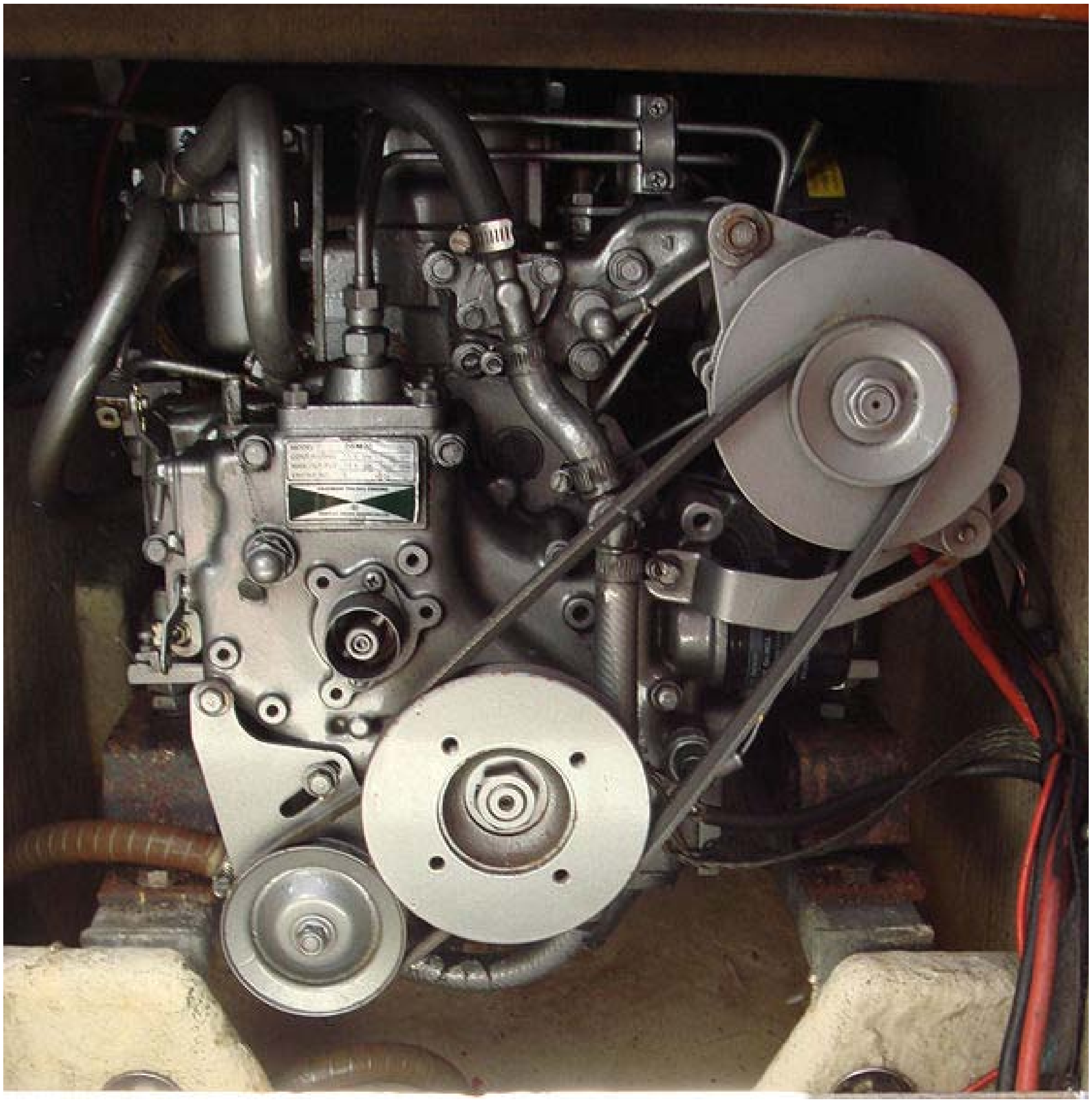
Types

Early

Rudolf Diesel intended his engine to replace the steam engine as the primary power source for industry. As such, diesel engines in the late 19th and early 20th centuries used the same basic layout and form as industrial steam engines, with long-bore cylinders, external valve gear, cross-head bearings and an open crankshaft connected to a large flywheel. Smaller engines would be built with vertical cylinders, while most medium- and large-sized industrial engines were built with horizontal cylinders, just as steam engines had been. Engines could be built with more than one cylinder in both cases. The largest early diesels resembled the triple-expansion steam reciprocating engine, being tens of feet high with vertical cylinders arranged in-line. These early engines ran at very slow speeds—partly due to the limitations of their air-blast injector equipment and partly so they would be compatible with the majority of industrial equipment designed for steam engines; maximum speeds of between 100 and 300 rpm were common. Engines were usually started by allowing compressed air into the cylinders to turn the engine, although smaller engines could be started by hand.

In the early decades of the 20th century, when large diesel engines were first being used, the engines took a form similar to the compound steam engines common at the time, with the piston being connected to the connecting rod by a crosshead bearing. Following steam engine practice some manufactures made double-acting two-stroke and four-stroke diesel engines to increase power output, with combustion taking place on both sides of the piston, with two sets of valve gear and fuel injection. While it produced large amounts of power and was very efficient, the double-acting diesel engine's main problem was producing a good seal where the piston rod passed through the bottom of the lower combustion chamber to the crosshead bearing, and no more were built. By the 1930s turbochargers were fitted to some engines. Crosshead bearings are still used to reduce the wear on the cylinders in large long-stroke main marine engines.

Modern



A Yanmar 2GM20 marine diesel engine, installed in a sailboat.

As with petrol engines, there are two classes of diesel engines in current use: two-stroke and four-stroke. The four-stroke type is the "classic" version, tracing its lineage back to Rudolf Diesel's prototype. It is also the most commonly used form, being the preferred power source for many motor vehicles, especially buses and trucks. Much larger engines, such as used for railroad locomotion and marine propulsion, are often two-stroke units, offering a more favourable power-to-weight ratio, as well as better fuel economy. The most powerful engines in the world are two-stroke diesels of mammoth dimensions.

Two-stroke diesel operation is similar to that of petrol counterparts, except that fuel is not mixed with air before induction, and the crankcase does not take an active role in the cycle. The traditional two-stroke design relies upon a mechanically driven positive displacement blower to charge the cylinders with air before compression and ignition. The charging process also assists in expelling (scavenging) combustion gases remaining from the previous power stroke. The archetype of the modern form of the two-stroke diesel is the Detroit Diesel engine, in which the blower pressurizes a chamber in the engine block that is often referred to as the "air box". The (much larger) Electromotive prime mover used in EMD diesel-electric locomotives is built to the same principle.

In a two-stroke diesel engine, as the cylinder's piston approaches the bottom dead centre exhaust ports or valves are opened relieving most of the excess pressure after which a passage between the air box and the cylinder is opened, permitting air flow into the cylinder. The air flow blows the remaining combustion gases from the cylinder—this is the scavenging process. As the piston passes through bottom centre and starts upward, the passage is closed and compression commences, culminating in fuel injection and ignition. Refer to two-stroke diesel engines for more detailed coverage of aspiration types and supercharging of two-stroke diesel engines.

Normally, the number of cylinders are used in multiples of two, although any number of cylinders can be used as long as the load on the crankshaft is counterbalanced to prevent excessive vibration. The inline-six cylinder design is the most prolific in light to medium-duty engines, though small V8 and larger inline-four displacement engines are also common. Small-capacity engines (generally considered to be those below five litres in capacity) are generally four or six cylinder types, with the four cylinder being the most common type found in automotive uses. Five cylinder diesel engines have also been produced, being a compromise between the smooth running of the six cylinder and the space-efficient dimensions of the four cylinder. Diesel engines for smaller plant machinery, boats, tractors, generators and pumps may be four, three or two cylinder types, with the single cylinder diesel engine remaining for light stationary work. Direct reversible two-stroke marine diesels need at least three cylinders for reliable restarting forwards and reverse, while four-stroke diesels need at least six cylinders.

The desire to improve the diesel engine's power-to-weight ratio produced several novel cylinder arrangements to extract more power from a given capacity. The uniflow opposed-piston engine uses two pistons in one cylinder with the combustion cavity in the middle and gas in- and outlets at the ends. This makes a comparatively light, powerful, swiftly running and economic engine suitable for use in aviation. An example is the Junkers Jumo 204/205. The Napier Deltic engine, with three cylinders arranged in a triangular formation, each containing two opposed pistons, the whole engine having three crankshafts, is one of the better known.

Gas generator

Before 1950, Sulzer started experimenting with two-stroke engines with boost pressures as high as 6 atmospheres, in which all the output power was taken from an exhaust gas turbine. The two-stroke pistons directly drove air compressor pistons to make a positive displacement gas generator. Opposed pistons were connected by linkages instead of crankshafts. Several of these units could be connected to provide power gas to one large output turbine. The overall thermal efficiency was roughly twice that of a simple gas turbine. This system was derived from Raúl Pateras Pescara's work on free-piston engines in the 1930s.

Advantages and disadvantages versus spark-ignition engines

Power and fuel economy

The MAN S80ME-C7 low speed diesel engines use 155 gram fuel per kWh for an overall energy conversion efficiency of 54.4 percent, which is the highest conversion of fuel into power by any internal or external combustion engine. Diesel engines are more efficient than gasoline (petrol) engines of the same power rating, resulting in lower fuel consumption. A common margin is 40 percent more miles per gallon for an efficient turbodiesel. For example, the current model Škoda Octavia, using Volkswagen Group engines, has a combined Euro rating of 6.2 L/100 km (38 miles per US gallon, 16 km/L) for the 102 bhp (76 kW) petrol engine and 4.4 L/100 km (54 mpg, 23 km/L) for the 105 bhp (78 kW) diesel engine.

However, such a comparison does not take into account that diesel fuel is denser and contains about 15 percent more energy by volume. Although the calorific value of the fuel is slightly lower at 45.3 MJ/kg (megajoules per kilogram) than petrol at 45.8 MJ/kg, liquid diesel fuel is significantly denser than liquid petrol. This is significant because volume of fuel, in addition to mass, is an important consideration in mobile applications. No vehicle has an unlimited volume available for fuel storage.

Adjusting the numbers to account for the energy density of diesel fuel, the overall energy efficiency is still about 20 percent greater for the diesel version.

While a higher compression ratio is helpful in raising efficiency, diesel engines are much more efficient than gasoline (petrol) engines when at low power and at engine idle. Unlike the petrol engine, diesels lack a butterfly valve (throttle) in the inlet system, which closes at idle. This creates parasitic loss and destruction of availability of the incoming air, reducing the efficiency of petrol engines at idle. In many applications, such as marine, agriculture, and railways, diesels are left idling and unattended for many hours, sometimes even days. These advantages are especially attractive in locomotives.

The average diesel engine has a poorer power-to-weight ratio than the petrol engine. This is because the diesel must operate at lower engine speeds and because it needs heavier, stronger parts to resist the operating pressure caused by the high compression ratio of the engine and the large amounts of torque generated to the crankshaft. In addition, diesels are often built with stronger parts to give them longer lives and better reliability, important considerations in industrial applications.

For most industrial or nautical applications, reliability is considered more important than light weight and high power. Diesel fuel is injected just before the power stroke. As a result, the fuel cannot burn completely unless it has a sufficient amount of oxygen. This can result in incomplete combustion and black smoke in the exhaust if more fuel is injected than there is air available for the combustion process. Modern engines with electronic fuel delivery can adjust the timing and amount of fuel delivery (by changing the duration of the injection pulse), and so operate with less waste of fuel. In a mechanical system, the injection timing and duration must be set to be efficient at the anticipated operating rpm and load, and so the settings are less than ideal when the engine is running at any other RPM than what it is timed for. The electronic injection can "sense" engine revs, load, even boost and temperature, and continuously alter the timing to match the given situation. In the petrol engine, air and fuel are mixed for the entire compression stroke, ensuring complete mixing even at higher engine speeds.

Diesel engines usually have longer stroke lengths in order to achieve the necessary compression ratios. As a result piston and connecting rods are heavier and more force must be transmitted through the connecting rods and crankshaft to change the momentum of the piston. This is another reason that a diesel engine must be stronger for the same power output as a petrol engine.

Yet it is this characteristic that has allowed some enthusiasts to acquire significant power increases with turbocharged engines by making fairly simple and inexpensive modifications. A petrol engine of similar size cannot put out a comparable power increase without extensive alterations because the stock components cannot withstand the higher stresses placed upon them. Since a diesel engine is already built to withstand higher levels of stress, it makes an ideal candidate for performance tuning at little expense. However, it should be said that any modification that raises the amount of fuel and air put through a diesel engine will increase its operating temperature, which will reduce its life and increase service requirements. These are issues with newer, lighter, *high performance* diesel engines which are not "overbuilt" to the degree of older engines and they are being pushed to provide greater power in smaller engines. The addition of a turbocharger or supercharger to the engine greatly assists in increasing fuel economy and power output, mitigating the fuel-air intake speed limit mentioned above for a given engine displacement. Boost pressures can be higher on diesels than on petrol engines, due to the latter's susceptibility to knock, and the higher compression ratio allows a diesel engine to be more efficient than a comparable spark ignition engine. Because the burned gases are expanded further in a diesel engine cylinder, the exhaust gas is cooler, meaning turbochargers require less cooling, and can be more reliable, than with spark-ignition engines.

With a diesel, boost pressure is essentially unlimited. It is literally possible to run as much boost as the engine will physically stand before breaking apart.

The increased fuel economy of the diesel engine over the petrol engine means that the diesel produces less carbon dioxide (CO_2) per unit distance. Recent advances in production and changes in the political climate have increased the availability and awareness of biodiesel, an alternative to petroleum-derived diesel fuel with a much lower net-sum emission of CO_2, due to the absorption of CO_2 by plants used to produce the fuel. Although concerns are now being raised as to the negative effect this is having on the world food supply, as the growing of crops specifically for biofuels takes up land that could be used for food crops and uses water that could be used by both humans and animals. The use of waste vegetable oil, sawmill waste from managed forests in Finland, and advances in the production of vegetable oil from algae demonstrate great promise in providing feed stocks for sustainable biodiesel that are not in competition with food production.

Diesel engines have a lower rotational speed than an equivalent size petrol engine because the diesel-air mixture burns slower than the petrol-air mixture. A combination of improved mechanical technology (such as multi-stage injectors which fire a short "pilot charge" of fuel into the cylinder to warm the combustion chamber before delivering the main fuel charge), higher injection pressures that have improved the atomisation of fuel into smaller droplets, and electronic control (which can adjust the timing and length of the injection process to optimise it for all speeds and temperatures) have mitigated most of these problems in the latest generation of common-rail designs, while greatly improving engine efficiency. Poor power and narrow torque bands have been addressed by superchargers, turbochargers, (especially variable geometry turbochargers), intercoolers, and a large efficiency increase from about 35 percent for IDI to 45 percent for the latest engines in the last 15 years.

Even though diesel engines have a theoretical fuel efficiency of 75 percent, in practice it is lower. Engines in large diesel trucks, buses, and newer diesel cars can achieve peak efficiencies around 45 percent, and could reach 55 percent efficiency in the near future. However, average efficiency over a driving cycle is lower than peak efficiency. For example, it might be 37 percent for an engine with a peak efficiency of 44 percent.

Emissions

Diesel exhaust has been found to contain a long list of toxic air contaminants. Among these pollutants, fine particle pollution is perhaps the most important as a cause of diesel's deleterious health effects.

Diesel engines produce very little carbon monoxide as they burn the fuel in excess air even at full load, at which point the quantity of fuel injected per cycle is still about 50 percent lean of stoichiometric. However, they can produce black soot (or more specifically diesel particulate matter) from their exhaust. The black smoke consists of carbon compounds that were not combusted, because of local low temperatures where the fuel is not fully atomized. These local low temperatures occur at the cylinder walls, and at the outside of large droplets of fuel. At these areas where it is relatively cold, the mixture is rich (contrary to the overall mixture which is lean). The rich mixture has less air to burn and some of the fuel turns into a carbon deposit. Modern car engines use a diesel particulate filter (DPF) to capture carbon particles and then intermittently burn them using extra fuel injected directly into the filter. This prevents carbon buildup at the expense of wasting a small quantity of fuel.

The full load limit of a diesel engine in normal service is defined by the "black smoke limit", beyond which point the fuel cannot be completely combusted. As the "black smoke limit" is still considerably lean of stoichiometric, it is possible to obtain more power by exceeding it, but the resultant inefficient combustion means that the extra power comes at the price of reduced combustion efficiency, high fuel consumption and dense clouds of smoke. This is only done in specialized applications (such as tractor pulling competitions) where these disadvantages are of little concern.

Likewise, when starting from cold, the engine's combustion efficiency is reduced because the cold engine block draws heat out of the cylinder in the compression stroke. The result is that fuel is not combusted fully, resulting in blue and white smoke and lower power outputs until the engine has warmed. This is especially the case with indirect injection engines, which are less thermally efficient. With electronic injection, the timing and length of the injection sequence can be altered to compensate for this. Older engines with mechanical injection can have mechanical and hydraulic governor control to alter the timing, and multi-phase electrically controlled glow plugs, that stay on for a period after start-up to ensure clean combustion—the plugs are automatically switched to a lower power to prevent their burning out.

Particles of the size normally called PM10 (particles of 10 micrometres or smaller) have been implicated in health problems, especially in cities. Some modern diesel engines feature diesel particulate filters, which catch the black soot and when saturated are automatically regenerated by burning the particles. Other problems associated with the exhaust gases (nitrogen oxides, sulfur oxides) can be mitigated with further investment and equipment; some diesel cars now have catalytic converters in the exhaust.

All diesel engine exhaust emissions can be significantly reduced by using biodiesel fuel. Oxides of nitrogen do increase from a vehicle using biodiesel, but they too can be reduced to levels below that of fossil fuel diesel, by changing fuel injection timing.

Power and torque

For commercial uses requiring towing, load carrying and other tractive tasks, diesel engines tend to have better torque characteristics. Diesel engines tend to have their torque peak quite low in their speed range (usually between 1600 and 2000 rpm for a small-capacity unit, lower for a larger engine used in a truck). This provides smoother control over heavy loads when starting from rest, and, crucially, allows the diesel engine to be given higher loads at low speeds than a petrol engine, making them much more economical for these applications. This characteristic is not so desirable in private cars, so most modern diesels used in such vehicles use electronic control, variable geometry turbochargers and shorter piston strokes to achieve a wider spread of torque over the engine's speed range, typically peaking at around 2500–3000 rpm.

While diesel engines tend to have more torque at lower engine speeds than petrol engines, diesel engines tend to have a narrower power band than petrol engines. Naturally aspirated diesels tend to lack power and torque at the top of their speed range. This narrow band is a reason why a vehicle such as a truck may have a gearbox with as many as 18 or more gears, to allow the engine's power to be used effectively at all speeds. Turbochargers tend to improve power at high engine speeds; superchargers improve power at lower speeds; and variable geometry turbochargers improve the engine's performance equally by flattening the torque curve.

Noise

The characteristic noise of a diesel engine is variably called diesel clatter, diesel nailing, or diesel knock. Diesel clatter is caused largely by the diesel combustion process, the sudden ignition of the diesel fuel when injected into the combustion chamber causes a pressure wave. Engine designers can reduce diesel clatter through: indirect injection; pilot or pre-injection; injection timing; injection rate; compression ratio; turbo boost; and exhaust gas recirculation (EGR). Common rail diesel injection systems permit multiple injection events as an aid to noise reduction. Diesel fuels with a higher cetane rating modify the combustion process and reduce diesel clatter. CN (Cetane number) can be raised by distilling higher quality crude oil, by catalyzing a higher quality product or by using a cetane improving additive. Some oil companies market high cetane or premium diesel. Biodiesel has a higher cetane number than petrodiesel, typically 55CN for 100% biodiesel.

A combination of improved mechanical technology such as multi-stage injectors which fire a short "pilot charge" of fuel into the cylinder to initiate combustion before delivering the main fuel charge, higher injection pressures that have improved the atomisation of fuel into smaller droplets, and electronic control (which can adjust the timing and length of the injection process to optimise it for all speeds and temperatures), have mostly mitigated these problems in the latest generation of common-rail designs, while improving engine efficiency.

Reliability

The lack of an electrical ignition system greatly improves the reliability. The high durability of a diesel engine is also due to its overbuilt nature, a benefit that is magnified by the lower rotating speeds in diesels. Diesel fuel is a better lubricant than petrol so is less harmful to the oil film on piston rings and cylinder bores; it is routine for diesel engines to cover 250,000 miles (400,000 km) or more without a rebuild.

Due to the greater compression force required and the increased weight of the stronger components, starting a diesel engine is harder. More torque is required to push the engine through compression.

Either an electrical starter or an air-start system is used to start the engine turning. On large engines, pre-lubrication and slow turning of an engine, as well as heating, are required to minimise the amount of engine damage during initial start-up and running. Some smaller military diesels can be started with an explosive cartridge, called a Coffman starter, which provides the extra power required to get the machine turning. In the past, Caterpillar and John Deere used a small petrol *pony* engine in their tractors to start the primary diesel engine. The pony engine heated the diesel to aid in ignition and used a small clutch and transmission to spin up the diesel engine. Even more unusual was an International Harvester design in which the diesel engine had its own carburetor and ignition system, and started on petrol. Once warmed up, the operator moved two levers to switch the engine to diesel operation, and work could begin. These engines had very complex cylinder heads, with their own petrol combustion chambers, and were vulnerable to expensive damage if special care was not taken (especially in letting the engine cool before turning it off).

Quality and variety of fuels

Petrol/gasoline engines are limited in the variety and quality of the fuels they can burn. Older petrol engines fitted with a carburetor required a volatile fuel that would vaporise easily to create the necessary air-fuel ratio for combustion. Because both air and fuel are admitted to the cylinder, if the compression ratio of the engine is too high or the fuel too volatile (with too low an octane rating), the fuel will ignite under compression, as in a diesel engine, before the piston reaches the top of its stroke. This pre-ignition causes a power loss and over time major damage to the piston and cylinder. The need for a fuel that is volatile enough to vaporise but not too volatile (to avoid pre-ignition) means that petrol engines will only run on a narrow range of fuels. There has been some success at dual-fuel engines that use petrol and ethanol, petrol and propane, and petrol and methane.

In diesel engines, a mechanical injector system vaporizes the fuel directly into the combustion chamber or a pre-combustion chamber (as opposed to a Venturi jet in a carburetor, or a Fuel injector in a fuel injection system vaporising fuel into the intake manifold or intake runners as in a petrol engine). This *forced vaporisation* means that less-volatile fuels can be used. More crucially, because only air is inducted into the cylinder in a diesel engine, the compression ratio can be much higher as there is no risk of pre-ignition provided the injection process is accurately timed. This means that cylinder temperatures are much higher in a diesel engine than a petrol engine, allowing less volatile fuels to be used.

Diesel fuel is a form of light fuel oil, very similar to kerosene/paraffin, but diesel engines, especially older or simple designs that lack precision electronic injection systems, can run on a wide variety of other fuels. Some of the most common alternatives are Jet A-1 type jet fuel or vegetable oil from a very wide variety of plants. Some engines can be run on vegetable oil without modification, and most others require fairly basic alterations. Biodiesel is a pure diesel-like fuel refined from vegetable oil and can be used in nearly all diesel engines. Requirements for fuels to be used in diesel engines are the ability of the fuel to flow along the fuel lines, the ability of the fuel to lubricate the injector pump and injectors adequately, and its ignition qualities (ignition delay, cetane number). Inline mechanical injector pumps generally tolerate poor-quality or bio-fuels better than distributor-type pumps. Also, indirect injection engines generally run more satisfactorily on bio-fuels than direct injection engines. This is partly because an indirect injection engine has a much greater 'swirl' effect, improving vaporisation and combustion of fuel, and because (in the case of vegetable oil-type fuels) lipid depositions can condense on the cylinder walls of a direct-injection engine if combustion temperatures are too low (such as starting the engine from cold).

It is often reported that Diesel designed his engine to run on peanut oil, but this is not the case. Diesel stated in his published papers, "at the Paris Exhibition in 1900 (*Exposition Universelle*) there was shown by the Otto Company a small diesel engine, which, at the request of the French Government ran on Arachide (earth-nut or pea-nut) oil, and worked so smoothly that only a few people were aware of it. The engine was constructed for using mineral oil, and was then worked on vegetable oil without any alterations being made. The French Government at the time thought of testing the applicability to power production of the Arachide, or earth-nut, which grows in considerable quantities in their African colonies, and can easily be cultivated there." Diesel himself later conducted related tests and appeared supportive of the idea.

Most large marine diesels (often called *cathedral engines* due to their size) run on heavy fuel oil (sometimes called "bunker oil"), which is a thick, viscous and almost flameproof fuel which is very safe to store and cheap to buy in bulk as it is a waste product from the petroleum refining industry. The fuel must be heated to thin it out (often by the exhaust header) and is often passed through multiple injection stages to vaporise it.

Fuel and fluid characteristics

Diesel engines can operate on a variety of different fuels, depending on configuration, though the eponymous diesel fuel derived from crude oil is most common. The engines can work with the full spectrum of crude oil distillates, from natural gas, alcohols, petrol, wood gas to the *fuel oils* from diesel oil to residual fuels.

The type of fuel used is a combination of service requirements, and fuel costs. Good-quality diesel fuel can be synthesised from vegetable oil and alcohol. Diesel fuel can be made from coal or other carbon base using the Fischer-Tropsch process. Biodiesel is growing in popularity since it can frequently be used in unmodified engines, though production remains limited. Recently, biodiesel from coconut, which can produce a very promising coco methyl ester (CME), has characteristics which enhance lubricity and combustion giving a regular diesel engine without any modification more power, less particulate matter or black smoke, and smoother engine performance. The Philippines pioneers in the research on Coconut based CME with the help of German and American scientists. Petroleum-derived diesel is often called *petrodiesel* if there is need to distinguish the source of the fuel.

Pure plant oils are increasingly being used as a fuel for cars, trucks and remote combined heat and power generation especially in Germany where hundreds of decentralised small- and medium-sized oil presses cold press oilseed, mainly rapeseed, for fuel. There is a Deutsches Institut für Normung fuel standard for rapeseed oil fuel.

Residual fuels are the "dregs" of the distillation process and are a thicker, heavier oil, or oil with higher viscosity, which are so thick that they are not readily pumpable unless heated. Residual fuel oils are cheaper than clean, refined diesel oil, although they are dirtier. Their main considerations are for use in ships and very large generation sets, due to the cost of the large volume of fuel consumed, frequently amounting to many tonnes per hour. The poorly refined biofuels straight vegetable oil (SVO) and waste vegetable oil (WVO) can fall into this category, but can be viable fuels on non common rail or TDI PD diesels with the simple conversion of fuel heating to 80 to 100 degrees Celsius to reduce viscosity, and adequate filtration to OEM standards. Engines using these heavy oils have to start and shut down on standard diesel fuel, as these fuels will not flow through fuel lines at low temperatures. Moving beyond that, use of low-grade fuels can lead to serious maintenance problems because of their high sulphur and lower lubrication properties. Most diesel engines that power ships like supertankers are built so that the engine can safely use low-grade fuels due to their separate cylinder and crankcase lubrication.

Normal diesel fuel is more difficult to ignite and slower in developing fire than petrol because of its higher flash point, but once burning, a diesel fire can be fierce.

Fuel contaminants such as dirt and water are often more problematic in diesel engines than in petrol engines. Water can cause serious damage, due to corrosion, to the injection pump and injectors; and dirt, even very fine particulate matter, can damage the injection pumps due to the close tolerances that the pumps are machined to. All diesel engines will have a fuel filter (usually much finer than a filter on a petrol engine), and a water trap. The water trap (which is sometimes part of the fuel filter) often has a float connected to a warning light, which warns when there is too much water in the trap, and must be drained before damage to the engine can result. The fuel filter must be replaced much more often on a diesel engine than on a petrol engine, changing the fuel filter every 2-4 oil changes is not uncommon for some vehicles.

Safety

Fuel flammability

Diesel fuel has low flammability, leading to a low risk of fire caused by fuel in a vehicle equipped with a diesel engine.

In yachts diesels are used because petrol engines generate combustible vapors, which can accumulate in the bottom of the vessel, sometimes causing explosions. Therefore ventilation systems on petrol powered vessels are required.

The United States Army and NATO use only diesel engines and turbines because of fire hazard. Although neither Gasoline nor Diesel is explosive in liquid form, both can create an explosive air/vapor mix under the right conditions. However, Diesel fuel is less prone due to its lower vapor pressure, which is an indication of evaporation rate. The Material Safety Data Sheet for Ultra-Low Sulfur Diesel fuel indicates a vapor explosion hazard for Diesel indoors, outdoors, or in sewers.

US Army gasoline-engined tanks during World War II were nicknamed Ronsons, because of their greater likelihood of catching fire when damaged by enemy fire. (Although tank fires were usually caused by detonation of the ammunition rather than fuel.)

Maintenance hazards

Fuel injection introduces potential hazards in engine maintenance due to the high fuel pressures used. Residual pressure can remain in the fuel lines long after an injection-equipped engine has been shut down. This residual pressure must be relieved, and if it is done so by external bleed-off, the fuel must be safely contained. If a high-pressure diesel fuel injector is removed from its seat and operated in open air, there is a risk to the operator of injury by hypodermic jet-injection, even with only 100 psi pressure. The first known such injury occurred in 1937 during a diesel engine maintenance operation.

Diesel applications

The characteristics of diesel have different advantages for different applications.

Passenger cars

Diesel engines have long been popular in bigger cars and this is spreading to smaller cars. Diesel engines tend to be more economical at regular driving speeds and are much better at city speeds. Their reliability and life-span tend to be better (as detailed). Some 40% or more of all cars sold in Europe are diesel-powered where they are considered a low CO_2 option. Mercedes-Benz in conjunction with Robert Bosch GmbH produced diesel-powered passenger cars starting in 1936 and very large numbers are used all over the world (often as "Grande Taxis" in the Third World).

Railroad rolling stock

Diesel engines have eclipsed steam engines as the prime mover on all non-electrified railroads in the industrialized world. The first diesel locomotives appeared in the early 20th century, and diesel multiple units soon after.

While electric locomotives have now replaced the diesel locomotive almost completely on passenger traffic in Europe and Asia, diesel is still today very popular for cargo-hauling freight trains and on tracks where electrification is not feasible.

Most modern diesel locomotives are actually diesel-electric locomotives: the diesel engine is used to power an electric generator that in turn powers electric traction engines with no mechanical connection between diesel engine and traction.

Other transport uses

Larger transport applications (trucks, buses, etc.) also benefit from the diesel's reliability and high torque output. Diesel displaced paraffin (or tractor vaporising oil, TVO) in most parts of the world by the end of the 1950s with the U.S. following some 20 years later.

In merchant ships and boats, the same advantages apply with the relative safety of diesel fuel an additional benefit. The German pocket battleships were the largest diesel warships, but the German torpedo-boats known as E-boats (*Schnellboot*) of the Second World War were also diesel craft. Conventional submarines have used them since before the First World War, relying on the almost total absence of carbon monoxide in the exhaust. American World War II diesel-electric submarines operated on two-stroke cycle as opposed to the four-stroke cycle that other navies used.

Military fuel standardisation

NATO has a single vehicle fuel policy and has selected diesel for this purpose. The use of a single fuel simplifies wartime logistics. NATO and the United States Marine Corps have even been developing a diesel military motorcycle based on a Kawasaki off road motorcycle, with a purpose designed naturally aspirated direct injection diesel at Cranfield University in England, to be produced in the USA, because motorcycles were the last remaining gasoline-powered vehicle in their inventory. Before this, a few civilian motorcycles had been built using adapted stationary diesel engines, but the weight and cost disadvantages generally outweighed the efficiency gains.

Engine speeds

Within the diesel engine industry, engines are often categorized by their rotational speeds into three unofficial groups:

- High speed engines,
- medium speed engines, and
- slow speed engines

High and medium speed engines are predominantly four stroke engines. Medium speed engines are physically larger than high speed engines and can burn lower grade (slower burning) fuel than high speed engines. Slow speed engines are predominantly large two stroke crosshead engines, hence very different from high and medium speed engines. Due to the lower rotational speed of slow and medium speed engines, there is more time for combustion during the power stroke of the cycle, and these engine are capable of utilising lower fuel grades (slower burning) fuels than high speed engines.

High-speed engines

High-speed (approximately 1,000 rpm and greater) engines are used to power trucks (lorries), buses, tractors, cars, yachts, compressors, pumps and small electrical generators.

As of 2008, most high-speed engines have direct injection. Many modern engines, particularly in on-highway applications, have common rail direct injection, which is cleaner burning.

Medium-speed engines

Medium speed engines are used in large electrical generators, ship propulsion and mechanical drive applications such as large compressors or pumps. Medium speed diesel engines operate on either diesel fuel or heavy fuel oil by direct injection in the same manner as low speed engines.

Engines used in electrical generators run at approximately 300 to 1000 rpm and are optimized to run at a set synchronous speed depending on the generation frequency (50 or 60 hertz) and provide a rapid response to load changes. Typical synchronous speeds for modern medium speed engines are 500/514 rpm (50/60 Hz), 600 rpm (both 50 and 60 Hz), 720/750 rpm, and 900/1000 rpm.

As of 2009, the largest medium speed engines in current production have outputs up to approximately 20 MW (27,000 hp). and are supplied by companies like MAN B&W, Wärtsilä, and Rolls-Royce (who acquired Ulstein Bergen Diesel in 1999). Most medium speed engines produced are four-stroke machines, however there are some two-stroke medium speed engines such as by EMD (Electro-Motive Diesel), and the Fairbanks Morse OP (Opposed-piston engine) type.

Typical cylinder bore size for medium speed engines ranges from 20 cm to 50 cm, and engine configurations typically are offered ranging from in-line 4 cylinder units to V configuration 20 cylinder units. Most larger medium speed engines are started with compressed air direct on pistons, using an air distributor, as opposed to a pneumatic starting motor acting on the flywheel, which tends to be used for smaller engines. There is no definitive engine size cut-off point for this.

It should also be noted that most major manufacturers of medium speed engines make natural gas fueled versions of their diesel engines, which in fact operate on the Otto cycle, and require spark ignition, typically provided with a spark plug. There are also dual (diesel/natural gas/coal gas) fuel versions of medium and low speed diesel engines using a lean fuel air mixture and a small injection of diesel fuel (so called "pilot fuel") for ignition. In case of a gas supply failure or maximum power demand these engines will instantly switch back to full diesel fuel operation.

Low-speed engines

The MAN B&W 5S50MC 5-cylinder, 2-stroke, low-speed marine diesel engine. This particular engine is found aboard a 29,000 tonne chemical carrier.

Also known as *slow-speed*, or traditionally *oil engines*, the largest diesel engines are primarily used to power ships, although there are a few land-based power generation units as well. These extremely large two-stroke engines have power outputs up to approximately 85 MW (114,000 hp), operate in the range from approximately 60 to 200 rpm and are up to 15 m (50 ft) tall, and can weigh over 2,000 short tons (1,800 t). They typically use direct injection running on cheap low-grade heavy fuel, also known as *Bunker C* fuel, which requires heating in the ship for tanking and before injection due to the fuel's high viscosity. The heat for fuel heating is often provided by waste heat recovery boilers located in the exhaust ducting of the engine, which produce the steam required for fuel heating. Provided the heavy fuel system is kept warm and circulating, engines can be started and stopped on heavy fuel.

Large and medium marine engines are started with compressed air directly applied to the pistons. Air is applied to cylinders to start the engine forwards or backwards because they are normally directly connected to the propeller without clutch or gearbox, and to provide reverse propulsion either the engine must be run backwards or the ship will utilise an adjustable propeller. At least three cylinders are required with two-stroke engines and at least six cylinders with four-stroke engines to provide torque every 120 degrees.

Companies such as MAN B&W Diesel, (formerly Burmeister & Wain) and Wärtsilä (which acquired Sulzer Diesel) design such large low speed engines. They are unusually narrow and tall due to the addition of a crosshead bearing. As of 2007, the 14 cylinder Wärtsilä-Sulzer 14RTFLEX96-C turbocharged two-stroke diesel engine built by Wärtsilä licensee Doosan in Korea is the most powerful diesel engine put into service, with a cylinder bore of 960 mm (37.8 in) delivering 114,800 hp (85.6 MW). It was put into service in September 2006, aboard the world's largest container ship *Emma Maersk* which belongs to the A.P. Moller-Maersk Group. Typical bore size for low speed engines ranges from approximately 35 to 98 cm (14 to 39 in). As of 2008, all produced low speed engines with crosshead bearings are in-line configurations; no Vee versions have been produced.

Supercharging and turbocharging

Most diesels are now turbocharged and some are both turbo charged and supercharged. Because diesels do not have fuel in the cylinder before combustion is initiated, more than one bar (100 kPa) of air can be loaded in the cylinder without preignition. A turbocharged engine can produce significantly more power than a naturally aspirated engine of the same configuration, as having more air in the cylinders allows more fuel to be burned and thus more power to be produced. A supercharger is powered mechanically by the engine's crankshaft, while a turbocharger is powered by the engine exhaust, not requiring any mechanical power. Turbocharging can improve the fuel economy of diesel engines by recovering waste heat from the exhaust, increasing the excess air factor, and increasing the ratio of engine output to friction losses. A two-stroke engine does not have an exhaust and intake stroke. These are performed when the piston is at the bottom of the cylinder. Therefore large two-stroke engines have a piston pump, or electrical driven turbo at startup. Smaller two stroke engines (for example, Detroit 71 series) are fitted with turbochargers and a mechanically driven supercharger. Because turbocharged or supercharged engines produce more power for a given engine size as compared to naturally aspirated engines, attention must be paid to the mechanical design of components, lubrication, and cooling to handle the power. Pistons are usually cooled with lubrication oil sprayed on the bottom of the piston. Large diesels may use water, sea water, or oil supplied through telescoping pipes attached to the cross head.

Other applications

- Aircraft diesel engine
- Motorcycles

Current and future developments

As of 2008, many common rail and unit injection systems already employ new injectors using stacked piezoelectric wafers in lieu of a solenoid, giving finer control of the injection event.

Variable geometry turbochargers have flexible vanes, which move and let more air into the engine depending on load. This technology increases both performance and fuel economy. Boost lag is reduced as turbo impeller inertia is compensated for.

Accelerometer pilot control (APC) uses an accelerometer to provide feedback on the engine's level of noise and vibration and thus instruct the ECU to inject the minimum amount of fuel that will produce quiet combustion and still provide the required power (especially while idling).

The next generation of common rail diesels is expected to use variable injection geometry, which allows the amount of fuel injected to be varied over a wider range, and variable valve timing similar to that on petrol engines. Particularly in the United States, coming tougher emissions regulations present a considerable challenge to diesel engine manufacturers. Ford's HyTrans Project has developed a system which starts the ignition in 400 ms, saving a significant amount of fuel on city routes, and there are other methods to achieve even more efficient combustion, such as homogeneous charge compression ignition, being studied.

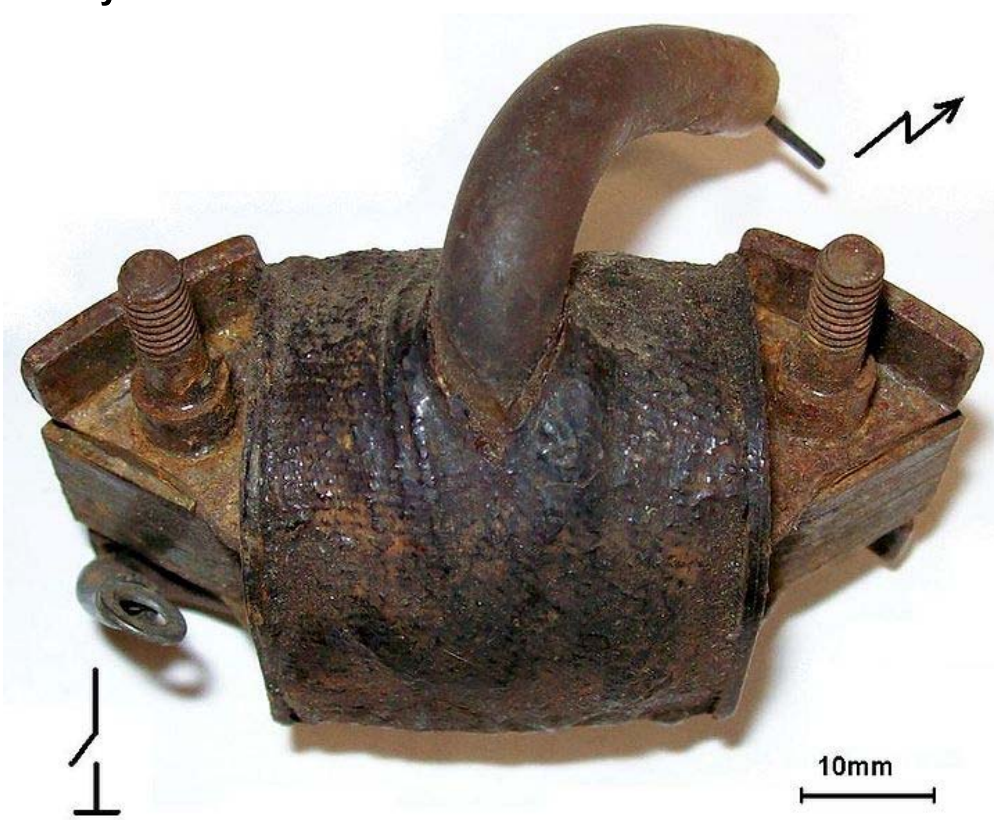
Chapter- 5

Ignition System

An **ignition system** is a system for igniting a fuel-air mixture. It is best known in the field of internal combustion engines but also has other applications, e.g. in oil-fired and gas-fired boilers. The earliest internal combustion engines used a flame, or a heated tube, for ignition but these were quickly replaced by systems using an electric spark.

History

Magneto systems



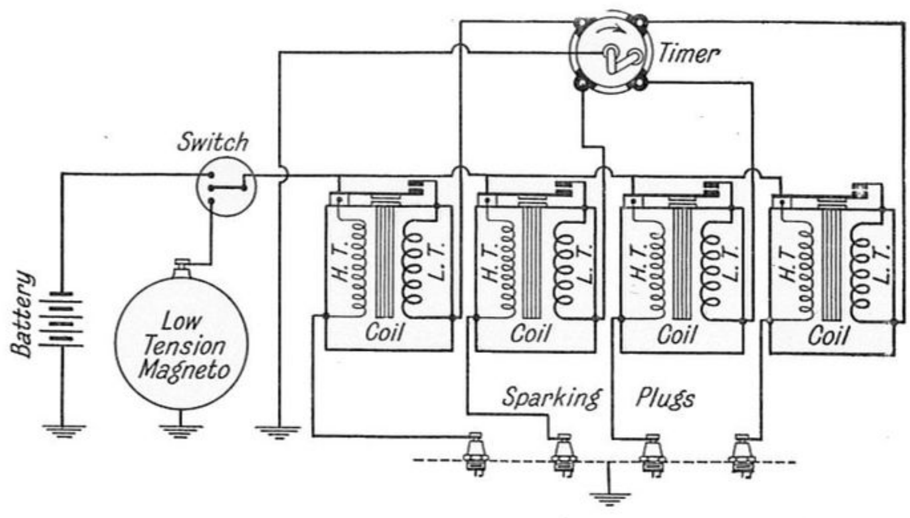
Magneto ignition coil

The simplest form of spark ignition is that using a magnet. The engine spins a magnet inside a coil, or, in the earlier designs, a coil inside a fixed magnet, and also operates a contact breaker, interrupting the current and causing the voltage to be increased sufficiently to jump a small gap. The spark plugs are connected directly from the magneto output. Early magnetos had one coil, with the contact breaker (sparking plug) inside the combustion chamber. In about 1902, Bosch introduced a double-coil magneto, with a fixed sparking plug, and the contact breaker outside the cylinder. Magnetos are not used in modern cars, but because they generate their own electricity they are often found on piston-engined aircraft engines and small engines such as those found in mopeds, lawnmowers, snowblowers, chainsaws, etc. where a battery-based electrical system is not present for any combination of necessity, weight, cost, and reliability reasons.

Magnetos were used on the small engine's ancestor, the stationary "hit or miss" engine which was used in the early twentieth century, on older gasoline or distillate farm tractors before battery starting and lighting became common, and on aircraft piston engines. Magnetos were used in these engines because their simplicity and self-contained operation was more reliable, and because magnetos weighed less than having a battery and dynamo or alternator.

Aircraft engines usually have multiple magnetos to provide redundancy in the event of a failure. Some older automobiles had both a magneto system and a battery actuated system running simultaneously to ensure proper ignition under all conditions with the limited performance each system provided at the time.This gave the benefits of easy starting (from the battery system) with reliable sparking at speed (from the magneto).

Switchable systems



Ford Model T ignition circuit

The output of a magneto depends on the speed of the engine, and therefore starting can be problematic. Some magnetos include an impulse system, which spins the magnet quickly at the proper moment, making easier starting at slow cranking speeds. Some engines, such as aircraft but also the Ford Model T, used a system which relied on non rechargeable dry cells, (similar to a large flashlight battery, and which was not maintained by a charging system as on modern automobiles) to start the engine or for starting and running at low speed. The operator would manually switch the ignition over to magneto operation for high speed operation.

In order to provide high voltage for the spark from the low voltage batteries, a 'tickler' was used, which was essentially a larger version of the once widespread electric buzzer. With this apparatus, the direct current passes through an electromagnetic coil which pulls open a pair of contact points, interrupting the current; the magnetic field collapses, the spring-loaded points close again, the circuit is reestablished, and the cycle repeats rapidly. The rapidly collapsing magnetic field, however, induces a high voltage across the coil which can only relieve itself by arcing across the contact points; while in the case of the buzzer this is a problem as it causes the points to oxidize and/or weld together, in the case of the ignition system this becomes the source of the high voltage to operate the spark plugs.

In this mode of operation, the coil would "buzz" continuously, producing a constant train of sparks. The entire apparatus was known as the 'Model T spark coil' (in contrast to the modern ignition coil which is *only* the actual coil component of the system). Long after the demise of the Model T as transportation they remained a popular self-contained source of high voltage for electrical home experimenters, appearing in articles in magazines such as *Popular Mechanics* and projects for school science fairs as late as the early 1960s. In the UK these devices were commonly known as trembler coils and were popular in cars pre-1910, and also in commercial vehicles with large engines until around 1925 to ease starting.

The Model T (built into the flywheel) differed from modern implementations by not providing high voltage directly at the output; the maximum voltage produced was about 30 volts, and therefore also had to be run through the spark coil to provide high enough voltage for ignition, as described above, although the coil would not "buzz" continuously in this case, only going through one cycle per spark. In either case, the low voltage was switched to the appropriate spark plug by the *'timer'* mounted on the front of the engine. This performed the equivalent function to the modern distributor, although by directing the low voltage, not the high voltage as for the distributor. The timing of the spark was adjustable by rotating this mechanism through a lever mounted on the steering column. As the precise timing of the spark depends on *both* the 'timer' and the trembler contacts within the coil, this is less consistent than the breaker points of the later distributor. However for the low speed and the low compression of such early engines, this imprecise timing was acceptable.

Battery-operated ignition

With the universal adaptation of electrical starting for automobiles, and the concomitant availability of a large battery to provide a constant source of electricity, magneto systems were abandoned for systems which interrupted current at battery voltage, used an ignition coil (a type of autotransformer) to step the voltage up to the needs of the ignition, and a distributor to route the ensuing pulse to the correct spark plug at the correct time.

The first reliable battery operated ignition was developed by the Dayton Engineering Laboratories Co. (Delco) and introduced in the 1910 Cadillac. This ignition was developed by Charles Kettering and was a wonder in its day. It consisted of a single coil, points (the switch), a capacitor and a distributor set up to allocate the spark from the ignition coil timed to the correct cylinder. The coil was basically an autotransformer set up to step up the low (6 or 12 V) voltage supply to the high ignition voltage required to jump a spark plug gap.

The points allow the coil to charge magnetically and then, when they are opened by a cam arrangement, the magnetic field collapses and a large (20 kV or greater) voltage is produced. The capacitor is used to absorb the back EMF from the magnetic field in the coil to minimize point contact burning and maximize point life. The Kettering system became the primary ignition system for many years in the automotive industry due to its lower cost, higher reliability and relative simplicity.

Modern ignition systems

The ignition system is typically controlled by a key operated Ignition switch.

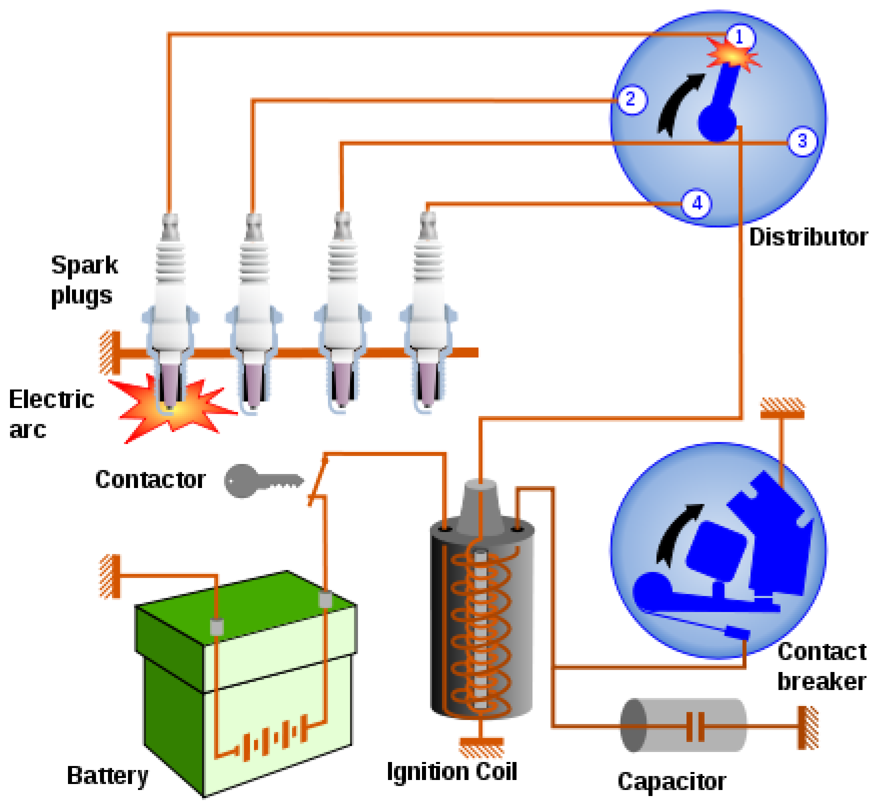
Mechanically timed ignition

Distributor cap

Most four-stroke engines have used a mechanically timed electrical ignition system. The heart of the system is the distributor. The distributor contains a rotating cam driven by the engine's drive, a set of breaker points, a condenser, a rotor and a distributor cap. External to the distributor is the ignition coil, the spark plugs and wires linking the distributor to the spark plugs and ignition coil.

The system is powered by a lead-acid battery, which is charged by the car's electrical system using a dynamo or alternator. The engine operates contact breaker points, which interrupt the current to an induction coil (known as the ignition coil).

The ignition coil consists of two transformer windings sharing a common magnetic core—the primary and secondary windings. An alternating current in the primary induces alternating magnetic field in the coil's core. Because the ignition coil's secondary has far more windings than the primary, the coil is a step-up transformer which induces a much higher voltage across the secondary windings. For an ignition coil, one end of windings of both the primary and secondary are connected together. This common point is connected to the battery (usually through a current-limiting ballast resistor). The other end of the primary is connected to the points within the distributor. The other end of the secondary is connected, via the distributor cap and rotor, to the spark plugs.



Ignition Circuit Diagram - Mechanically Timed Ignition

The ignition firing sequence begins with the points (or contact breaker) closed. A steady charge flows from the battery, through the current-limiting resistor, through the coil primary, across the closed breaker points and finally back to the battery. This steady current produces a magnetic field within the coil's core. This magnetic field forms the energy reservoir that will be used to drive the ignition spark.

As the engine turns, so does the cam inside the distributor. The points ride on the cam so that as the engine turns and reaches the top of the engine's compression cycle, a high point in the cam causes the breaker points to open. This breaks the primary winding's circuit and abruptly stops the current through the breaker points. Without the steady current through the points, the magnetic field generated in the coil immediately and rapidly collapses. This change in the magnetic field induces a high voltage in the coil's secondary windings.

At the same time, current exits the coil's primary winding and begins to charge up the capacitor ("condenser") that lies across the now-open breaker points. This capacitor and the coil's primary windings form an oscillating LC circuit. This LC circuit produces a damped, oscillating current which bounces energy between the capacitor's electric field and the ignition coil's magnetic field. The oscillating current in the coil's primary, which produces an oscillating magnetic field in the coil, extends the high voltage pulse at the output of the secondary windings. This high voltage thus continues beyond the time of the initial field collapse pulse. The oscillation continues until the circuit's energy is consumed.

The ignition coil's secondary windings are connected to the distributor cap. A turning rotor, located on top of the breaker cam within the distributor cap, sequentially connects the coil's secondary windings to one of the several wires leading to each cylinder's spark plug. The extremely high voltage from the coil's secondary -– often higher than 1000 volts—causes a spark to form across the gap of the spark plug. This, in turn, ignites the compressed air-fuel mixture within the engine. It is the creation of this spark which consumes the energy that was originally stored in the ignition coil's magnetic field.

High performance engines with eight or more cylinders that operate at high r.p.m. (such as those used in motor racing) demand both a higher rate of spark and a higher spark energy than the simple ignition circuit can provide. This problem is overcome by using either of these adaptations:

- **Two complete sets of coils, breakers and condensers** can be provided - one set for each half of the engine, which is typically arranged in V-8 or V-12 configuration. Although the two ignition system halves are electrically independent, they typically share a single distributor which in this case contains two breakers driven by the rotating cam, and a rotor with two isolated conducting planes for the two high voltage inputs.
- A single breaker driven by a cam and a return spring is limited in spark rate by the onset of contact bounce or float at high rpm. This limit can be overcome by substituting for the breaker a **pair of breakers** that are connected electrically in series but spaced on opposite sides of the cam so they are driven out of phase. Each breaker then switches at half the rate of a single breaker and the "dwell" time for current buildup in the coil is maximized since it is shared between the breakers. The Lamborghini V-12 engine has both these adaptations and therefore uses two ignition coils and a single distributor that contains 4 contact breakers.

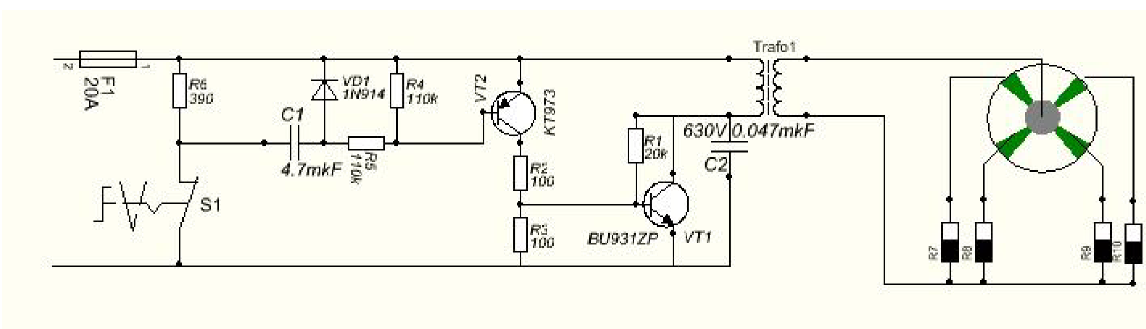
A distributor-based system is not greatly different from a magneto system except that more separate elements are involved. There are also advantages to this arrangement. For example, the position of the contact breaker points relative to the engine angle can be changed a small amount dynamically, allowing the ignition timing to be automatically advanced with increasing revolutions per minute (RPM) and/or increased manifold vacuum, giving better efficiency and performance.

However it is necessary to check periodically the maximum opening gap of the breaker(s), using a feeler gauge, since this mechanical adjustment affects the "dwell" time during which the coil charges, and breakers should be re-dressed or replaced when they have become pitted by electric arcing. This system was used almost universally until the late 1970s, when electronic ignition systems started to appear.

Electronic ignition

The disadvantage of the mechanical system is the use of breaker points to interrupt the low-voltage high-current through the primary winding of the coil; the points are subject to mechanical wear where they ride the cam to open and shut, as well as oxidation and burning at the contact surfaces from the constant sparking. They require regular adjustment to compensate for wear, and the opening of the contact breakers, which is responsible for spark timing, is subject to mechanical variations.

In addition, the spark voltage is also dependent on contact effectiveness, and poor sparking can lead to lower engine efficiency. A mechanical contact breaker system cannot control an average ignition current of more than about 3 A while still giving a reasonable service life, and this may limit the power of the spark and ultimate engine speed.



Example of a basic electronic ignition system

Electronic ignition (EI) solves these problems. In the initial systems, points were still used but they handled only a low current which was used to control the high primary current through a solid state switching system. Soon, however, even these contact breaker points were replaced by an angular sensor of some kind - either optical, where a vaned rotor breaks a light beam, or more commonly using a Hall effect sensor, which responds to a rotating magnet mounted on the distributor shaft. The sensor output is shaped and processed by suitable circuitry, then used to trigger a switching device such as a thyristor, which switches a large current through the coil.

The first electronic ignition (a cold cathode type) was tested in 1948 by Delco-Remy, while Lucas introduced a transistorized ignition in 1955, which was used on BRM and Coventry Climax Formula One engines in 1962. The aftermarket began offering EI that year, with both the AutoLite Electric Transistor 201 and Tung-Sol EI-4 being available. Pontiac became the first automaker to offer an optional EI, the breakerless magnetic pulse-triggered Delcotronic, on some 1963 models; it was also available on some Corvettes. Ford fitted a Lucas system on the Lotus 25s entered at Indianapolis the next year, ran a fleet test in 1964, and began offering optional EI on some models in 1965. Beginning in 1958, Earl W. Meyer at Chrysler worked on EI, continuing until 1961 and resulting in use of EI on the company's NASCAR hemis in 1963 and 1964.

Prest-O-Lite's CD-65, which relied on capacitance discharge (CD), appeared in 1965, and had "an unprecedented 50,000 mile warranty." (This differs from the non-CD Prest-O-Lite system introduced on AMC products in 1972, and made standard equipment for the 1975 model year.) A similar CD unit was available from Delco in 1966, which was optional on Oldsmobile, Pontiac, and GMC vehicles in the 1967 model year. Also in 1967, Motorola debuted their breakerless CD system.

FIAT became the first company to offer standard EI, in 1968, followed by Chrysler (after a 1971 trial) in 1973 and by Ford and GM in 1975.

In 1967, Prest-O-Lite made a "Black Box" ignition amplifier, intended to take the load off of the distributor's breaker points during high r.p.m. runs, which was used by Dodge and Plymouth on their factory Super Stock Coronet and Belvedere and drag racers. This amp was installed on the interior-side of the cars' firewall, and had a duct which provided outside air to cool the amp. The rest of the system (distributor and spark plugs) remains as for the mechanical system. The lack of moving parts compared with the mechanical system leads to greater reliability and longer service intervals. Chrysler introduced breakerless ignition in mid-1971 as an option for its 340 V8 and the 426 Street Hemi. For the 1972 model year, the system became standard on its high-performance engines (the 340 cu in (5.6 l) and the four-barrel carburetor-equipped 400 hp (298 kW) 400 cu in (7 l)) and was an option on its 318 cu in (5.2 l), 360 cu in (5.9 l), two-barrel 400 cu in (6.6 l), and low-performance 440 cu in (7.2 l) . Breakerless Ignition was standardised across the model range for 1973. For older cars, it is usually possible to retrofit an EI system in place of the mechanical one. In some cases, a modern distributor will fit into the older engine with no other modifications, like the H.E.I. distributor made by General Motors, and the aforementioned Chrysler-built electronic ignition (with an "Orange Box" amplifier and a faster-advance curve distributor).

Other innovations are currently available on various cars. In some models, rather than one central coil, there are individual coils on each spark plug, sometimes known as direct ignition or coil on plug (COP). This allows the coil a longer time to accumulate a charge between sparks, and therefore a higher energy spark. A variation on this has each coil handle two plugs, on cylinders which are 360 degrees out of phase (and therefore reach TDC at the same time); in the four-cycle engine this means that one plug will be sparking during the end of the exhaust stroke while the other fires at the usual time, a so-called "wasted spark" arrangement which has no drawbacks apart from faster spark plug erosion; the paired cylinders are 1/4 and 2/3. Other systems do away with the distributor as a timing apparatus and use a magnetic crank angle sensor mounted on the crankshaft to trigger the ignition at the proper time.

During the 1980s, electronic ignition systems were developed alongside other improvements such as fuel injection systems. After a while it became logical to combine the functions of fuel control and ignition into one electronic system known as an engine control unit. However on older vehicles this was not possible and now a common electronic ignition system for classic cars is the Powerspark electronic ignition.

Digital electronic ignitions

At the turn of the 21st century digital electronic ignition modules became available for small engines on such applications as chainsaws, string trimmers, leaf blowers, and lawn mowers. This was made possible by low cost, high speed, and small footprint microcontrollers. Digital electronic ignition modules can be designed as either capacitor discharge ignition (CDI) or inductive discharge ignition (IDI) systems. Capacitive discharge digital ignitions store charged energy for the spark in a capacitor within the module that can be released to the spark plug at virtually any time throughout the engine cycle via a control signal from the microprocessor. This allows for greater timing flexibility, and engine performance; especially when designed hand-in-hand with the engine carburetor.

Engine management

In an Engine Management System (EMS), electronics control fuel delivery, ignition timing and firing order. Primary sensors on the system are engine angle (crank or Top Dead Center (TDC) position), airflow into the engine and throttle demand position. The circuitry determines which cylinder needs fuel and how much, opens the requisite injector to deliver it, then causes a spark at the right moment to burn it. Early EMS systems used analogue computer circuit designs to accomplish this, but as embedded systems became fast enough to keep up with the changing inputs at high revolutions, digital systems started to appear.

Some designs using EMS retain the original coil, distributor and spark plugs found on cars throughout history. Other systems dispense with the distributor and individual coils mounted directly atop each spark plug. This removes the need for both distributor and high-tension leads, both components with a poor record for long-term reliability.

Modern EMSs read in data from various sensors about the crank position, manifold temperature, manifold pressure (or air mass flow), throttle position, fuel mixture via the O2 sensor and sometimes the unit will read data from knock sensors and exhaust gas temperature sensors. The EMS then uses collected data to precisely determine how much fuel to deliver and when and thus how far to advance the ignition timing. With electronic ignition systems, individual cylinders can have their own individual ignition timing so that timing can be as aggressive as possible per cylinder without fuel detonation. As a result, sophisticated electronic ignition systems can be both more fuel efficient, and produce better performance, over their counterparts.

Turbine and jet engines

Turbine engines have a capacitor discharge ignition system using one or more ignitor plugs, which are only used at startup or in case the combustor(s) flame goes out. Rocket engines have particularly demanding ignitions systems- if prompt ignition does not occur the chamber can fill with excess fuel and oxidiser and significant overpressure can occur (a 'hard start'). Rockets often employ pyrotechnic devices that place flames across the face of the injector plate, or, alternatively, self-ignition chemicals.

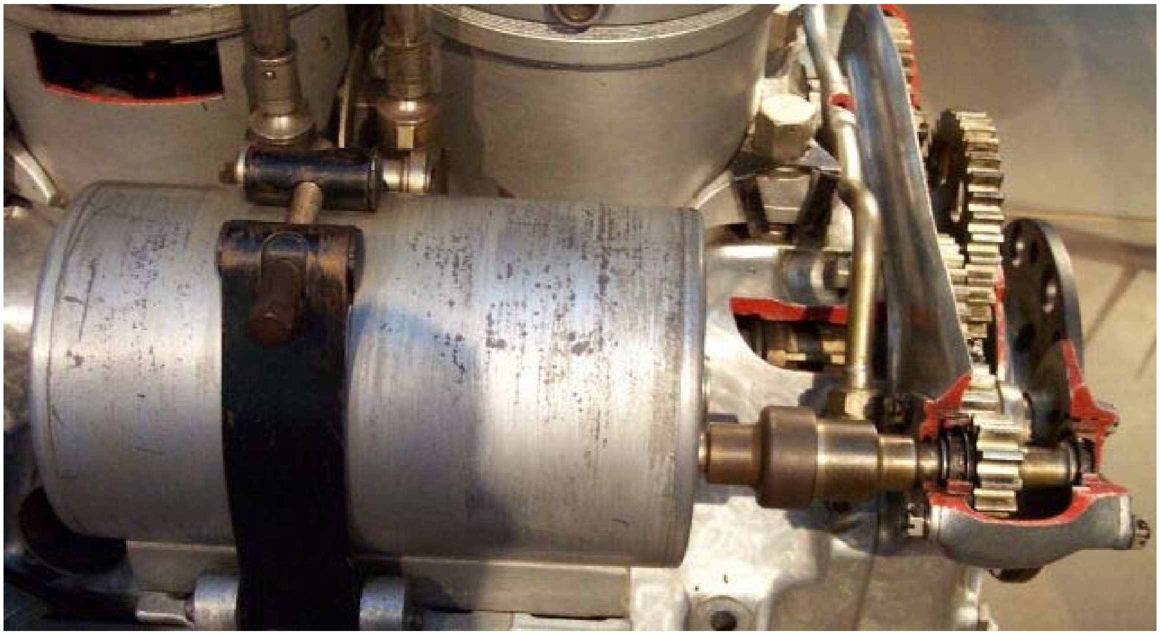
Chapter- 6

Starter Motor

An automobile starter motor

A **starter motor** (also **starting motor**, or **starter**) is an electric motor for rotating an internal-combustion engine so as to initiate the engine's operation under its own power.

History



A 1920s era self-starter

Typical starter installed underneath and toward the rear of an automobile engine

Both Otto cycle and Diesel cycle internal-combustion engines require the pistons to be moving before the ignition phase of the cycle. This means that the engine must be set in motion by an external force before it can power itself.

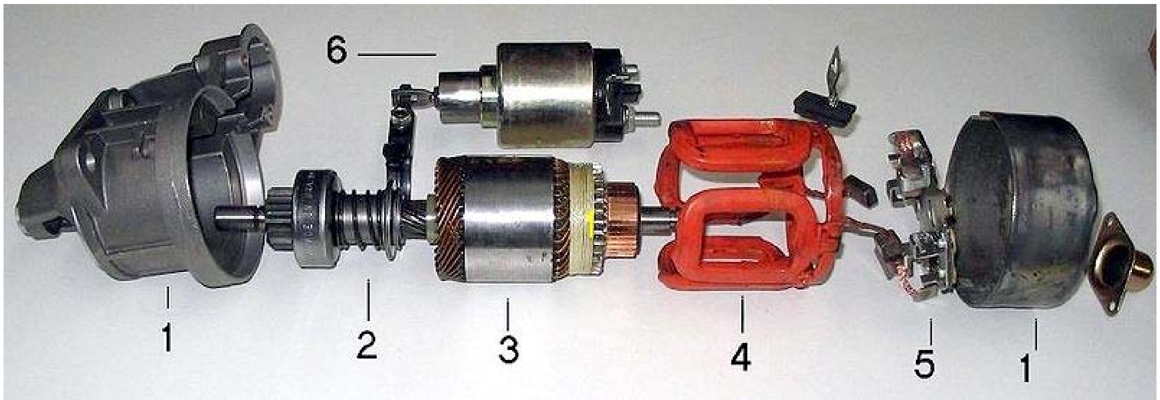
Originally, a hand crank was used to start engines, but it was inconvenient, difficult, and dangerous to crank-start an engine. Even though cranks had an overrun mechanism, when the engine started, the crank could begin to spin along with the crankshaft and potentially strike the person cranking the engine. Additionally, care had to be taken to retard the spark in order to prevent backfiring; with an advanced spark setting, the engine could *kick back* (run in reverse), pulling the crank with it, because the overrun safety mechanism works in one direction only.

Although users were advised to cup their fingers under the crank and pull up, it felt natural for operators to grasp the handle with the fingers on one side, the thumb on the other. Even a simple backfire could result in a broken thumb; it was possible to end up with a broken wrist, or worse. Moreover, increasingly larger engines with higher compression ratios made hand cranking a more physically demanding endeavour.

While the need was fairly obvious—as early as 1899, Clyde J. Coleman applied for U.S. Patent 745,157 for an electric automobile self-starter—inventing one that worked successfully in most conditions did not occur until 1911 when Charles F. Kettering of Dayton Engineering Laboratories Company (DELCO) invented and filed for U.S. Patent 1,150,523 for the first useful electric starter. (Kettering had replaced the hand crank on NCR's cash registers with an electric motor five years earlier.) One aspect of the invention lay in the realization that a relatively small motor, driven with higher voltage and current than would be feasible for continuous operation, could deliver enough power to crank the engine for starting. At the voltage and current levels required, such a motor would burn out in a few minutes of continuous operation, but not during the few seconds needed to start the engine. The starters were first installed by Cadillac on production models in 1912. These starters also worked as generators once the engine was running, a concept that is now being revived in hybrid vehicles. The Model T relied on hand cranks until 1919; by 1920 most manufacturers included self-starters, thus ensuring that anyone, regardless of strength or physical handicap, could easily start a car with an internal combustion engine.

Before Chrysler's 1949 innovation of the key-operated combination ignition-starter switch, the starter was operated by the driver pressing a button mounted on the floor or dashboard.

Electric starter



1. Main Housing (yoke)
2. Overrunning clutch
3. Armature
4. Field coils
5. Brushes
6. Solenoid

The modern starter motor is either a permanent-magnet or a series-parallel wound direct current electric motor with a starter solenoid (similar to a relay) mounted on it. When current from the starting battery is applied to the solenoid, usually through a key-operated switch, the solenoid engages a lever that pushes out the drive pinion on the starter driveshaft and meshes the pinion with the starter ring gear on the flywheel of the engine.

The solenoid also closes high-current contacts for the starter motor, which begins to turn. Once the engine starts, the key-operated switch is opened, a spring in the solenoid assembly pulls the pinion gear away from the ring gear, and the starter motor stops. The starter's pinion is clutched to its driveshaft through an overrunning sprag clutch which permits the pinion to transmit drive in only one direction. In this manner, drive is transmitted through the pinion to the flywheel ring gear, but if the pinion remains engaged (as for example because the operator fails to release the key as soon as the engine starts, or if there is a short and the solenoid remains engaged), the pinion will spin independently of its driveshaft. This prevents the engine driving the starter, for such backdrive would cause the starter to spin so fast as to fly apart. However, this sprag clutch arrangement would preclude the use of the starter as a generator if employed in hybrid scheme mentioned above, unless modifications are made. Also, a standard starter motor is only designed for intermittent use which would preclude its use as a generator; the electrical components are designed only to operate for typically under 30 seconds before overheating (by too-slow dissipation of heat from ohmic losses), to save weight and cost. This is the same reason why most automobile owner's manuals instruct the operator to pause for at least ten seconds after each ten or fifteen seconds of cranking the engine, when trying to start an engine that does not start immediately.

This overrunning-clutch pinion arrangement was phased into use beginning in the early 1960s; before that time, a Bendix drive was used. The Bendix system places the starter drive pinion on a helically-cut driveshaft. When the starter motor begins turning, the inertia of the drive pinion assembly causes it to ride forward on the helix and thus engage with the ring gear. When the engine starts, backdrive from the ring gear causes the drive pinion to exceed the rotative speed of the starter, at which point the drive pinion is forced back down the helical shaft and thus out of mesh with the ring gear.

An intermediate development between the Bendix drive developed in the 1930s and the overrunning-clutch designs introduced in the 1960s was the Bendix Folo-Thru drive. The standard Bendix drive would disengage from the ring gear as soon as the engine fired, even if it did not continue to run. The Folo-Thru drive contains a latching mechanism and a set of flyweights in the body of the drive unit. When the starter motor begins turning and the drive unit is forced forward on the helical shaft by inertia, it is latched into the engaged position. Only once the drive unit is spun at a speed higher than that attained by the starter motor itself (i.e., it is backdriven by the running engine) will the flyweights pull radially outward, releasing the latch and permitting the overdriven drive unit to be spun out of engagement. In this manner, unwanted starter disengagement is avoided before a successful engine start.

Gear-reduction starters

Chrysler Corporation contributed materially to the modern development of the starter motor. In 1962, Chrysler introduced a starter incorporating a geartrain between the motor and the driveshaft. Rolls Royce had introduced a conceptually similar starter in 1946, but Chrysler's was the first volume-production unit. The motor shaft has integrally-cut gear teeth forming a drive gear which mesh with a larger adjacent driven gear to provide a gear reduction ratio of 3.75:1. This permits the use of a higher-speed, lower-current, lighter and more compact motor assembly while increasing cranking torque. Variants of this starter design were used on most vehicles produced by Chrysler Corporation from 1962 through 1987. The Chrysler starter made a unique, readily identifiable sound when cranking the engine.

This starter formed the design basis for the offset gear reduction starters now employed by about half the vehicles on the road, and the conceptual basis for virtually all of them. Many Japanese automakers phased in gear reduction starters in the 1970s and 1980s. Light aircraft engines also made extensive use of this kind of starter, because its light weight offered an advantage.

Those starters not employing offset geartrains like the Chrysler unit generally employ planetary epicyclic geartrains instead. Direct-drive starters are almost entirely obsolete owing to their larger size, heavier weight and higher current requirements. Ford also issued a nonstandard starter, a direct-drive "movable pole shoe" design that provided cost reduction rather than electrical or mechanical benefits. This type of starter eliminated the solenoid, replacing it with a movable pole shoe and a separate starter relay. The Ford starter operated as follows:

1. The operator closed the key-operated starting switch.
2. A small electric current flowed through the starter relay coil, closing the contacts and sending a large current to the starter motor assembly.
3. One of the pole shoes, hinged at the front, linked to the starter drive, and spring-loaded away from its normal operating position, swung into position. This moved a pinion gear to engage the flywheel ring gear, and simultaneously closed a pair of heavy-duty contacts supplying current to the starter motor winding.
4. The starter motor cranked the engine until it started. An overrunning clutch in the pinion gear uncoupled the gear from the ring gear.
5. The operator released the key-operated starting switch, cutting power to the starter motor assembly.
6. A spring retracted the pole shoe, and with it, the pinion gear.

This starter was used on Ford vehicles from 1973 through 1990, when a gear-reduction unit conceptually similar to the Chrysler unit replaced it. Light motor vehicles have now adopted 9.6 volt to 10.4 volt starter motors for use with 12 volt systems to give increased power. The lower current starter will give increased torque, but will tend to overheat and burn out with prolonged use under load.

Pneumatic starter

Some gas turbine engines and Diesel engines, particularly on trucks, use a pneumatic self-starter. The system consists of a geared turbine, an air compressor and a pressure tank. Compressed air released from the tank is used to spin the turbine, and through a set of reduction gears, engages the ring gear on the flywheel, much like an electric starter. The engine, once running, powers the compressor to recharge the tank.

On larger diesel generators found in large shore installations and especially on ships, a pneumatic starting gear is used. The air motor is normally powered by compressed air at pressures of 10–30 bar. The air motor is made up of a center drum about the size of a soup can with four or more slots cut into it to allow for the vanes to be placed radially on the drum to form chambers around the drum. The drum is offset inside a round casing so that the inlet air for starting is admitted at the area where the drum and vanes form a small chamber compared to the others. The compressed air can only expand by rotating the drum which allows the small chamber to become larger and puts another one of the cambers in the air inlet. The air motor spins much too fast to be used directly on the flywheel of the engine, instead a large gearing reduction such as a planetary gear is used to lower the output speed. A Bendix gear is used to engage the flywheel.

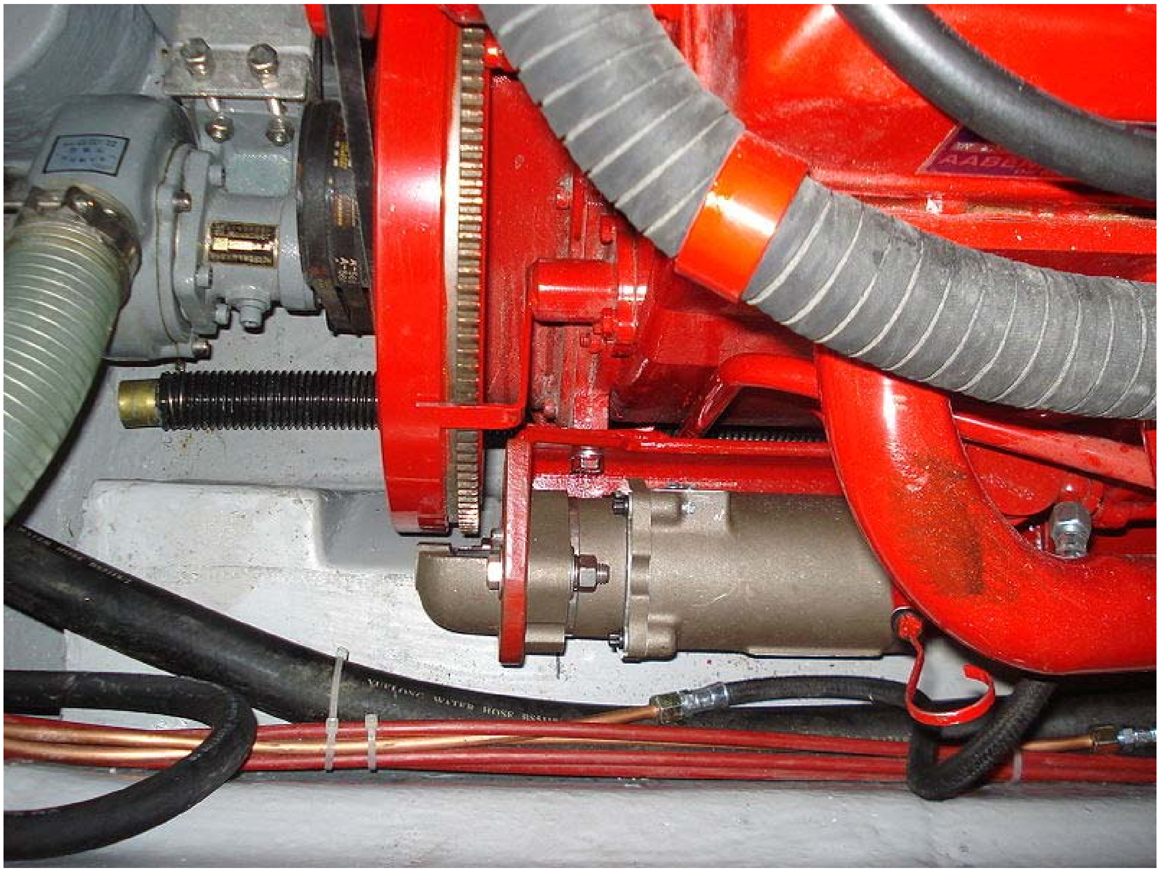
On large diesel generators and almost all diesel engines used as the prime mover of ships will use compressed air acting directly on the cylinder head. This is not ideal for smaller diesels as it provides too much cooling on starting. Also the cylinder head needs to have enough space to support an extra valve for the air start system. The air start system operates very similar to a distributor in a car. There is an air distributor that is geared to the camshaft of the diesel engine, on the top of the air distributor is a single lobe similar to what is found on a camshaft. Arranged radially around this lobe are roller tip followers for every cylinder. When the lobe of the air distributor hits one of the followers it will send an air signal that acts upon the back of the air start valve located in the cylinder head causing it to open. The actual compressed air is provided from a large reservoir that feeds into a header located along the engine. As soon as the air start valve is opened the compressed air is admitted and the engine will begin turning. It can be used on 2-cycle and 4-cycle engines and on reversing engines. On large 2-stroke engines less than one revolution of the crankshaft is needed for starting.

Since large trucks typically use air brakes, the system does double duty, supplying compressed air to the brake system. Pneumatic starters have the advantages of delivering high torque, mechanical simplicity and reliability. They eliminate the need for oversized, heavy storage batteries in prime mover electrical systems.

Hydraulic starter

Some diesel engines from 6 to 16 cylinders are started by means of a hydraulic motor. Hydraulic starters and the associated systems provide a sparkless, reliable method of engine starting at a wide temperature range. Typically hydraulic starters are found in applications such as remote generators, lifeboat propulsion engines, offshore fire pumping engines, and hydraulic fracturing rigs. The system used to support the hydraulic starter includes valves, pumps, filters, a reservoir, and piston accumulators. The operator can manually recharge the hydraulic system; this cannot readily be done with air or electric starting systems, so hydraulic starting systems are favored in applications wherein emergency starting is a requirement.

Hydraulic Starter



Hydraulic Starter

Other methods

Other ways of starting have included a spring wound by regenerative braking, gun powder cylinders, windmilling the propeller of an engine while the airplane is flying and putting a car in gear when it is moving.

Manual starting

Early internal combustion engines were generally started with energy supplied by a human operator. The methods included cranking, pushing, flipping the propeller, pulling a cord, foot pedal starters, and indirect methods such as springs and fly wheels. Since these methods are inconvenient and sometimes dangerous, they have gradually been replaced by electric motors and compressed air, starting in the larger engines.

In case of failure of the battery or starter motor, a car with a manual transmission can be started by pushing it or rolling it down hill and then engaging the clutch while it is moving, usually in second gear.

Self starting

Some modern gasoline engines with twelve or more cylinders always have at least one piston at the beginning of its power stroke and are able to start by injecting fuel into that cylinder and igniting it.

Chapter- 7

Speedometer

An Aston Martin speedometer, showing how an eddy-current speedometer indicates the vehicle's speed

A **speedometer** is a gauge that measures and displays the instantaneous speed of a land vehicle.

Now universally fitted to motor vehicles, they started to be available as options in the 1900s, and as standard equipment from about 1910 onwards.

Speedometers for other vehicles have specific names and use other means of sensing speed. For a boat, this is a pit log. For an aircraft, this is an airspeed indicator.

The speedometer was invented by the Croatian Josip Belušić in 1888, and was originally called a velocimeter.

Operation

Eddy current

An eddy-current speedometer gauge on a car, showing the speed of the vehicle in kilometres per hour. Also shown is the tachometer, which displays the rate of rotation of the engine's crankshaft.

The eddy current speedometer has been used for over a century and is still in widespread use. Until the 1980s and the appearance of electronic speedometers it was the only type commonly used.

Originally patented by a German, Otto Schulze on 7 October 1902, it uses a rotating flexible cable usually driven by gearing linked to the tail shaft (output) of the vehicle's transmission. The early Volkswagen Beetle and many motorcycles, however, use a cable driven from a front wheel.

A small permanent magnet affixed to the rotating cable interacts with a small aluminum cup (called a *speedcup*) attached to the shaft of the pointer on the analogue instrument. As the magnet rotates near the cup, the changing magnetic field produces eddy currents in the cup, which themselves produce another magnetic field. The effect is that the magnet "drags" the cup, and thus the speedometer pointer, in the direction of its rotation with no mechanical connection between them.

The pointer shaft is held toward zero by a fine spring. The torque on the cup increases with the speed of rotation of the magnet (which is driven by the car's transmission.) Thus an increase in the speed of the car will twist the cup and speedometer pointer against the spring. When the torque due to the eddy currents in the cup equals that provided by the spring on the pointer shaft, the pointer will remain motionless and pointing to the appropriate number on the speedometer's dial.

The return spring is calibrated such that a given revolution speed of the cable corresponds to a specific speed indication on the speedometer. This calibration must take into account several factors, including ratios of the tailshaft gears that drive the flexible cable, the final drive ratio in the differential, and the diameter of the driven tires.

Electronic

Historic speedometers from the turn of the century

Speedometer currently displaying "Oil Service" necessity

Many modern speedometers are electronic. A rotation sensor, usually mounted on the rear of the transmission, delivers a series of electronic pulses whose frequency corresponds to the rotational speed of the driveshaft. The sensor is typically a toothed metal disk positioned between a coil and a magnetic field sensor. As the disk turns, the teeth pass between the two, each time producing a pulse in the sensor as they affect the strength of the magnetic field it is measuring. Alternatively, some manufactures rely on pulses coming from the ABS wheel sensors.

A computer converts the pulses to a speed and displays this speed on an electronically-controlled, analog-style needle or a digital display. Pulse counts may also be used to increment the odometer.

Another early form of electronic speedometer relies upon the interaction between a precision watch mechanism and a mechanical pulsator driven by the car's wheel or transmission. The watch mechanism endeavors to push the speedometer pointer toward zero, while the vehicle-driven pulsator tries to push it toward infinity. The position of the speedometer pointer reflects the relative magnitudes of the outputs of the two mechanisms.

Changing a car's tire size can throw off a speedometer's accuracy.

Bicycle Speedometers

Some speedometers for bicycles measure the time between each wheel revolution. The sensor is mounted on the bike at a fixed location, pulsing when the spoke-mounted magnet passes by. These digital devices can be programmed by tire size or by wheel circumference in order to make accurate distance measurements. Others are cable driven as in the automotive speedometers described above.

Error

Most speedometers have tolerances of some 10% plus or minus mainly due variation in tires diameter. Sources of error due to tire diameter variations are wear, temperature, pressure, vehicle load, and nominal tire size.

Excessive speedometer error after manufacture can come from several causes but most commonly is due to nonstandard tire diameter, in which case the

percent error = 100x(1 - "new diameter"/"standard diameter").

Nearly all tires now have their size shown as "T/A_W" on the side of the tire

diameter in inches = TxA/1270 + W.

For example, a standard tire is "185/70R14" with diameter = 185x70/1270 + 14 = 24.20 in. Another is "195/50R15" with 195x50/1270 + 15 = 22.68 in. Replacing the first tire (and wheels) with the second (on 15" wheels), a speedometer reads 100 * (1 - 22.68/24.20) = 6.28% higher than the actual speed. At an actual speed of 60 mph, the speedometer will indicate 60 * 1.0628 = 63.77 mph, approximately.

In the case of wear, a new "185/70R14" tyre of 24.4 inch diameter will have ~8mm tread depth, at legal limit this reduces to 1.6mm, the difference being 12.8mm in diamter or 0.5 inches which is 2% in 24.4 inches.

MPH and KM/H framed somewhat artistically

International agreements

In many countries the legislated error in speedometer readings is ultimately governed by the United Nations Economic Commission for Europe (UNECE) Regulation 39 which covers those aspects of vehicle type approval which relate to speedometers. The main purpose of the UNECE regulations is to facilitate trade in motor vehicles by agreeing uniform type approval standards rather than requiring a vehicle model to undergo different approval processes in each country in which it is to be sold.

European Union member states must also grant type approval to vehicles meeting similar EU standards. The ones covering speedometers are similar to the UNECE regulation in that they specify that:

- The indicated speed must never be less than the actual speed, i.e. it should not be possible to inadvertently speed because of an incorrect speedometer reading.
- The indicated speed must not be more than 110 percent of the true speed plus 4 km/h at specified test speeds. For example, at 80 km/h, the indicated speed must be no more than 92 km/h.

The standards specify both the limits on accuracy and many of the details of how it should be measured during the approvals process, for example that the test measurements should be made (for most vehicles) at 40, 80 and 120 km/h, and at a particular ambient temperature. There are slight differences between the different standards, for example in the minimum accuracy of the equipment measuring the true speed of the vehicle.

The UNECE regulation relaxes the requirements for vehicles mass produced following type approval. At Conformity of Production Audits the upper limit on indicated speed is increased to 110 percent plus 6 km/h for cars, buses, trucks and similar vehicles, and 110 percent plus 8 km/h for two or three wheeled vehicles which have a maximum speed above 50 km/h (or a cylinder capacity, if powered by a heat engine, of more than 50 cc). European Union Directive 2000/7/EC, which relates to two and three wheeled vehicles, provides similar slightly relaxed limits in production.

Australia

There were no design rules in place for speedometers in Australia prior to July 1988. They had to be introduced when speed cameras were first used. This means there are no legally accurate speedometers for these older vehicles. All vehicles manufactured on or after 1 July 2007, and all models of vehicle introduced on or after 1 July 2006, must conform to UNECE Regulation 39.

The speedometers in vehicles manufactured before these dates but after 1 July 1995 (or 1 January 1995 for forward control passenger vehicles and off-road passenger vehicles) must conform to the previous Australian design rule. This specifies that they need only display the speed to an accuracy of +/- 10% at speeds above 40 km/h, and there is no specified accuracy at all for speeds below 40 km/h. All vehicles manufactured in Australia or imported for supply to the Australian market must comply with the Australian Design Rules.

The state and territory governments may set policies for the tolerance of speed over the posted speed limits that may be lower than the 10% in the earlier versions of the Australian Design Rules permitted, such as in Victoria. This has caused some controversy since it would be possible for a driver to be unaware that he is speeding should his vehicle be fitted with an under-reading speedometer.

United Kingdom

A speedometer showing mph and km/h along with an odometer and a separate 'trip' odometer (both showing distance traveled in miles).

The amended Road Vehicles (Construction and Use) Regulations 1986 permits the use of speedometers that meet either the requirements of EC Council Directive 75/443 (as amended by Directive 97/39) or UNECE Regulation 39.

The Motor Vehicles (Approval) Regulations 2001 permits single vehicles to be approved. As with the UNECE regulation and the EC Directives, the speedometer must never show an indicated speed less than the actual speed. However it differs slightly from them in specifying that for all actual speeds between 25 mph and 70 mph (or the vehicles' maximum speed if it is lower than this), the indicated speed must not exceed 110% of the actual speed, plus 6.25 mph.

For example, if the vehicle is actually travelling at 50 mph, the speedometer must not show more than 61.25 mph or less than 50 mph.

United States

As of 1997, Federal standards in the United States allowed a maximum 5% error on speedometer readings. Aftermarket modifications, such as different tire and wheel sizes or different differential gearing, can cause speedometer inaccuracy.

GPS

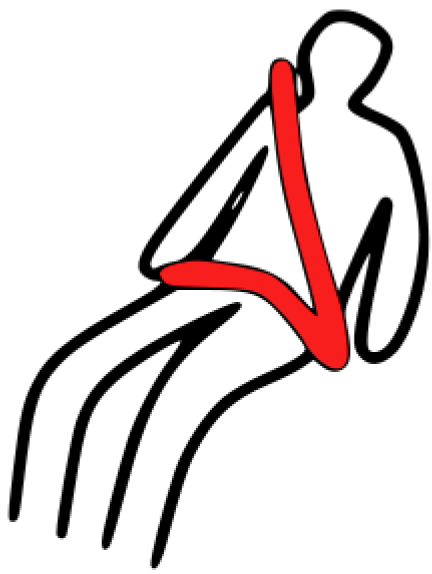
GPS devices are positional speedometers, based on how far the receiver has moved since the last measurement. Its speed calculations are not subject to the same sources of error as the vehicle's speedometer (wheel size, transmission/drive ratios). Instead, the GPS's positional accuracy, and therefore the accuracy of its calculated speed, is dependent on the satellite signal quality at the time. Speed calculations will be more accurate at higher speeds, when the ratio of positional error to positional change is lower. The GPS software may also use a moving average calculation to reduce error.

As mentioned in the satnav article, GPS data has been used to overturn a speeding ticket; the GPS logs showed the defendant traveling below the speed limit when they were ticketed. That the data came from a GPS device was likely less important than the fact that it was logged; logs from the vehicle's speedometer could likely have been used instead, had they existed.

* some satnav devices may also use data from the car's systems to improve accuracy

Chapter- 8

Seat Belt



A 3-point seat belt.

A **seat belt** or **seatbelt**, sometimes called a **safety belt**, is a safety harness designed to secure the occupant of a vehicle against harmful movement that may result from a collision or a sudden stop. As part of an overall automobile passive safety system, seat belts are intended to reduce injuries by stopping the wearer from hitting hard interior elements of the vehicle, or other passengers (the so-called second impact), are in the correct position for the airbag to deploy and prevent the passenger from being thrown from the vehicle. Seat belts also absorb energy by being designed to stretch during any sudden deceleration, so that there is less speed differential between the passenger's body and their vehicle interior, and also to spread the loading of impact on the passengers body.

The final, so-called 'third impact' after a passenger's body hits the car interior, airbag or seat belts, is that of the internal organs hitting the ribcage or skull. The force of this impact is the mechanism through which car crashes cause disabling or life threatening injury. The sequence of energy dissipating and speed reducing technologies - crumple zone - seat belt - airbags - padded interior, are designed to work together as a system, to reduce the force of this final impact.

Types of seatbelt

Lap

A lap ("2-point") belt in an airplane

An adjustable strap that goes over the waist. This type of belt is frequently found in older cars, and has been used, until recently, on some newer vehicles in rear or rear middle seats. These types of belt are also found on some coaches. Passenger aircraft seats also use lap seat belts to help prevent injuries while still allowing passengers to adopt a brace position.

Sash

An adjustable strap that goes over the shoulder. Used mainly in vehicles during the 1960s, however they had limited benefit because it was very easy to slip out of them in a collision.

Three-point

A 3-point seat belt

Similar to the lap and sash belts, but has one single continuous length of belt. Both three-point and lap-and-sash belts help spread out the energy of the moving body in a collision over the chest, pelvis, and shoulders. Volvo introduced the first production three-point belt in 1959. The first car with three point belt was a Volvo PV 544 that was delivered to a dealer in Kristianstad on August 13, 1959. The first car to feature the three point seat belt however was the 1959 Volvo 122 The three point belt was developed by Nils Bohlin who had earlier also worked on ejection seats at Saab.

Until the 1980s, three-point belts were commonly available only in the front seats of cars; the back seats were only often fitted with lap or sash belts. Evidence of the potential of lap belts to cause separation of the lumbar vertebrae and the sometimes associated paralysis, or "seat belt syndrome", led to a revision of passenger safety regulations in nearly all developed countries, requiring that all seats in a vehicle have to be equipped with three-point belts. Since September 1, 2007, all new cars sold in the U.S. require a lap and shoulder belt in the center rear seat.

Besides regulatory changes, "seat belt syndrome" has led to tremendous liability for vehicle manufacturers. One Los Angeles case resulted in a $45 million jury verdict against the Ford Motor Company; the resulting $30 million judgment (after deductions for another defendant who settled prior to trial) was affirmed on appeal in 2006.

Belt-in-Seat (BIS)

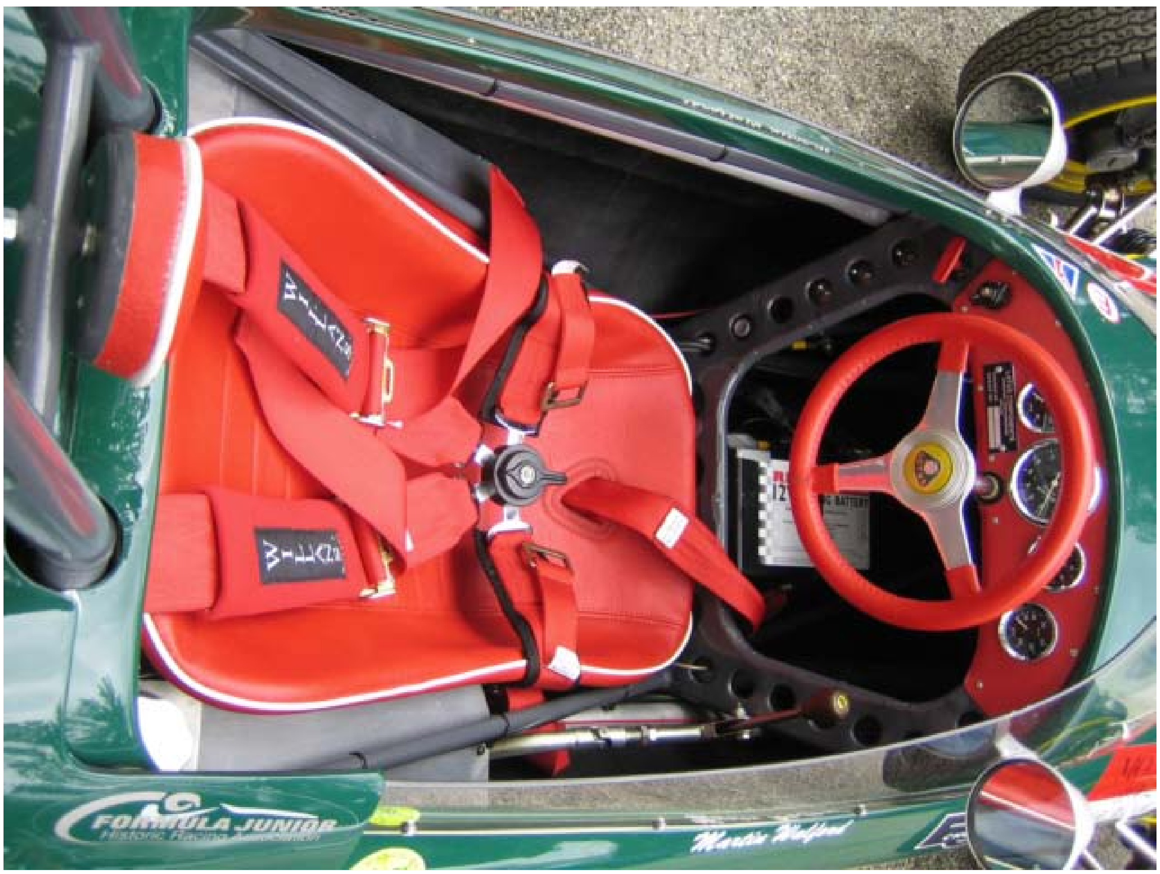
A 5-Point harness belt-in-seat on a quad bike.

The BIS is a three-point harness where the shoulder belt attachment is to the backrest, not to the b pillar. The first car using this system in the United States was the 1990 Mercedes-Benz SL. Some cars like the Renault Vel Satis use this system for the front seats. This system allegedly is safer in case of rollover, especially with 4–8 years old children, though other sources dispute this claim.

Experimental production car safety belts

- *Criss-cross* Experimental safety belt presented in the Volvo SCC. It forms a cross-brace across the chest.
- *3+2 Point Seatbelt*: Experimental safety belt from Autoliv similar to the criss-cross. The 3+2 improves protection against rollovers and side impacts.
- *Four point "belt and suspenders"*: An experimental design from Ford where the "suspenders" are attached to the backrest, not to the frame of the car.
- *Inflatable Safety Belts*: An airbag is included within the belt for the rear seat belts.

Five-point harnesses



A 6-point harness in a racing car.

These restraints are safer but more restrictive than most other seat belt types. Five-point harnesses are typically found in child safety seats and in racing cars. The lap portion is connected to a belt between the legs and there are two shoulder belts, making a total of five points of attachment to the seat. (Strictly speaking, harnesses are never to be fastened to the seat—they should be fastened to the frame/sub-frame of the automobile.)

Six-point harnesses

These harnesses are similar to a five-point harness but include an extra belt between the legs, which is seen by some to be a weaker point than the other parts. These belts are used mainly in racing. In NASCAR, the six-point harness became popular after the death of Dale Earnhardt. Earnhardt was wearing a five-point harness when he suffered his fatal crash. As it was first thought that his belt had broken, some teams ordered a six-point harness in response.

Seven-point harnesses (5+2)

Aerobatic aircraft frequently use a combination harness consisting of a five-point harness with a redundant lap-belt attached to a different part of the airframe. While providing redundancy for negative-g maneuvers (which lift the pilot out of the seat), they also require the pilot to un-latch two harnesses if it is necessary to parachute from a failed aircraft.

History

Seat belts were invented by George Cayley in the early 19th century, though Edward J. Claghorn of New York, New York was granted the first patent (U.S. Patent 312,085, on February 10, 1885 for a safety belt). Claghorn was granted United States Patent #312,085 for a Safety-Belt for tourists, described in the patent as "designed to be applied to the person, and provided with hooks and other attachments for securing the person to a fixed object."

In 1911, Benjamin Foulois had the cavalry saddle shop fashion a belt for the seat of Wright Flyer Signal Corps 1. He wanted it to hold him firmly in his seat so he could better control his aircraft as he bounded along the rough field used for takeoff and landing. C-130 aircraft in South Vietnam also bounded on runways to the extent that a tight seat belt improved the pilot's ability to control the aircraft. It was not until World War II that seat belts were fully adopted in military aircraft, and even then, it was mainly for safety reasons, not improved aircraft control.

In 1946 Dr. C. Hunter Shelden had opened a neurological practice at Huntington Memorial Hospital in Pasadena, California. In the early 1950s Dr. Shelden had made a major contribution to the automotive industry with his idea of retractable seat belts. This came about greatly in part from the high number of head injuries coming through the emergency rooms. He investigated the early seat belts whose primitive designs were implicated in these injuries and deaths. His findings were published in the November 5, 1955 Journal of the American Medical Association (JAMA) in which he proposed not only the retractable seat belt, but also recessed steering wheels, reinforced roofs, roll bars, door locks and passive restraints such as the now-and-ever-popular air bag. Subsequently in 1959 Congress passed legislation requiring all automobiles to comply with certain safety standards.

American car manufacturers Nash (in 1949) and Ford (in 1955) offered seat belts as options, while Swedish Saab first introduced seat belts as standard in 1958. After the Saab GT 750 was introduced at the New York motor show in 1958 with safety belts fitted as standard, the practice became commonplace.

However, the first modern three point seat belt (the so-called *CIR-Griswold restraint*) used in most consumer vehicles today was patented in 1951 by the Americans Roger W. Griswold and Hugh De Haven, and developed to its modern form by Nils Bohlin for Swedish manufacturer Volvo—who introduced it in 1959 as standard equipment. Bohlin was granted U.S. Patent 3,043,625 for the device. Bohlin's lap-and-shoulder belt was introduced by Volvo in 1959, in Sweden.

In 1970, the state of Victoria, Australia, passed the first law worldwide making seat belt wearing compulsory for drivers and front-seat passengers.

Technologies

Seat Belt with uncovered Inertial Reel

Most seat belts are equipped with locking mechanisms (or inertia reels) that tighten the belt when pulled fast (e.g. by the quick force of a passenger's body during a crash) but do not tighten when pulled slowly. This is implemented with a centrifugal clutch, which engages as the reel spins quickly. Alternatively, this function may be secured by a weighted pendulum or ball bearing: when these are deflected by deceleration or roll-over they lock into pawls on the reel.

Types of inertia reel type seatbelts:

NLR (no locking retractor): Commonly used in recoiling lap belts

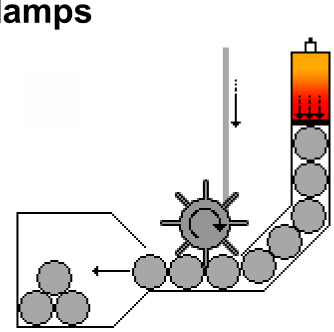
ELR V (emergency locking retractor - vehicle sensitive): Single sensitive mechanism, composed of a locking mechanism activated in an emergency by deceleration or rollover of the vehicle. Thus, the seatbelt is sensitive to the vehicle's motion.

ELR VW (emergency locking retractor - vehicle and webbing sensitive): Dual sensitive means a seatbelt retractor that, during normal driving conditions, allows freedom of movement by the wearer of the seatbelt by means of length-adjusting components that automatically adjust the strap to the wearer, with a locking mechanism that is activated by two or more of the following:

- deceleration or rollover of the vehicle,
- acceleration of the strap (webbing) from the retractor, or
- other means of activation.

A recent study by McCoy & Chou (2007) from the Ford Motor Company (Safety Test Methodology, SP-2123) demonstrated that the standard inertia reel seatbelt does not stop the head from making contact with the interior of the roof on a standard rollover test in their dynamic Rollover Component test System (ROCS). Even with modern pre-tensioning devices the head contacts the interior of the roof and the neck suffers 'visible' compression.

Pretensioners and webclamps



Pyrotechnic pretensioner diagram

Seatbelts in many newer vehicles are also equipped with "pretensioners" and/or "Webclamps".

- Pretensioners preemptively tighten the belt to prevent the occupant from jerking forward in a crash. Mercedes-Benz first introduced pretensioners on the 1981 S-Class. In the event of a crash, a pretensioner will tighten the belt almost instantaneously. This reduces the motion of the occupant in a violent crash. Like airbags, pretensioners are triggered by sensors in the car's body, and most pretensioners use explosively expanding gas to drive a piston that retracts the belt. Pretensioners also lower the risk of "submarining", which is when a passenger slides forward under a loosely worn seat belt. An alternative approach being looked at by major car companies is the CG-Lock technology whereby the occupant is held in position via the lap belt in order to prevent the passenger from coming out of position in the event of a crash.
- Webclamps clamp the webbing in the event of an accident and limit the distance the webbing can spool out (caused by the unused webbing tightening on the central drum of the mechanism) these belts also often incorporate an energy management loop ("rip stitching") which is when the lower part of the webbing is looped and stitched with a special stitching. The function of this is to "rip" at a predetermined load, which reduces the load transmitted through the belt to the occupant, reducing injuries to the occupant.

Inflatable Seatbelts

Inflatable seatbelts have tubular inflatable bladders contained within an outer cover. When a crash occurs the bladder inflates with a gas to increase the area of the restraint contacting the occupant and also shortening the length of the restraint to tighten the belt around the occupant, improving the protection. The inflatable sections may be shoulder-only or lap and shoulder. The system supports the head during the crash better than a web only belt. It also provides side impact protection. The inflatable seatbelt was invented by Donald Lewis and tested at the Automotive Products Division of Allied Chemical Corp. Ref an early patent US 3,841,654 filed in 1972

Automatic seat belts

Automatic seat belt in a Honda Civic

Seatbelts that automatically move into position around a vehicle occupant once the adjacent door is closed and/or the engine is started were developed as a countermeasure against low usage rates of manual seat belts, particularly in the United States of America.

The 1972 Volkswagen ESVW1 Experimental Safety Vehicle presented passive seat belts. Volvo tried to develop a passive three point seatbelt. In 1973 Volkswagen announced they had a functional passive seat belt. The first commercial car to use automatic seat belts was the 1975 Volkswagen Rabbit.

Automatic seat belts received a boost in the United States in 1977 when Brock Adams, United States Secretary of Transportation in the Carter Administration, mandated that by 1983 every new car should have either airbags or automatic seat belts. despite strong lobbying from the auto industry. Adams was attacked by Ralph Nader, who said that the 1983 deadline was too late. Soon after, General Motors began offering automatic seat belts, first on the Chevrolet Chevette, but by early 1979 the VW Rabbit and the Chevette were the only cars to offer the safety feature, and GM was reporting disappointing sales. By early 1978, Volkswagen had reported 90,000 Rabbits sold with automatic seat belts. A study released in 1978 by the United States Department of Transportation claimed that cars with automatic seat belts had a fatality rate of .78 per 100 million miles, compared with 2.34 for cars with regular, manual belts.

In 1981, Drew Lewis, the first Transportation Secretary of the Reagan Administration, influenced by studies done by the auto industry, "killed" the previous administration's mandate; the decision was overruled in a federal appeals court the following year, and then by the Supreme Court. In 1984, the Reagan Administration reversed its course, though in the meantime the original deadline had been extended; Elizabeth Dole, then Transportation Secretary, proposed that the two passive safety restraints be phased into vehicles gradually, from vehicle model year 1987 to vehicle model year 1990, when all vehicles would be required to have either automatic seat belts or driver side air bags. Though more awkward for vehicle occupants, most manufacturers opted to use less expensive automatic belts rather than airbags during this time period.

When driver side airbags became mandatory on all passenger vehicles in model year 1994, most manufacturers stopped equipping cars with automatic seat belts. Exceptions include the 1995-1996 Ford Escort/Mercury Tracer and the Eagle Summit Wagon which had automatic safety belts along with dual airbags.

Automatic belt systems

- **Manual lap belt with automatic motorized shoulder belt** — When the door is opened, the shoulder belt moves from a fixed point near the seat back on a track mounted in the door frame of the car to a point at the other end of the track near the windshield. Once the door is closed and the car is started, the belt moves rearward along the track to its original position, thus securing the passenger. The lap belt must be fastened manually.

- **Manual lap belt with automatic non-motorized shoulder belt** — This system was used in American-market vehicles such as the Hyundai Excel and Volkswagen Jetta. The shoulder belt is fixed to the aft upper corner of the vehicle door, and is not motorized. The lap belt must be fastened manually.

- **Automatic shoulder and lap belts** — This system was mainly used in General Motors vehicles, though it was also used on some Honda Civic hatchbacks and Nissan Sentra coupés. When the door is opened, the belts go from a fixed point in the middle of the car by the floor to retractors on the door. Passengers must slide into the car under the belts. When the door closes, the seat belt retracts into the door. The belts have normal release buttons that are supposed to be used only in an emergency, but in practice are routinely used in the same manner as manual seat belt clasps.

Disadvantages

Automatic belt systems generally offer inferior occupant crash protection. In systems with belts attached to the door rather than a sturdier fixed portion of the vehicle body, a crash that causes the vehicle door to open leaves the occupant without belt protection. He or she will in that case be thrown from the vehicle and suffer greater injury or death. Because many automatic belt system designs compliant with the US passive-restraint mandate did not meet the safety performance requirements of Canada—which were not weakened to accommodate automatic belts—vehicle models which had been eligible for easy importation in either direction across the US-Canada border when equipped with manual belts became ineligible for importation in either direction once the US variants got automatic belts and the Canadian versions retained manual belts. Two such models were the Dodge Spirit and Plymouth Acclaim.

Automatic belt systems also present several operational disadvantages. Motorists who would normally wear seat belts must still fasten the manual lap belt, thus rendering redundant the automation of the shoulder belt. Those who do not fasten the lap belt wind up inadequately protected by only the shoulder belt; in a crash without a lap belt such a vehicle occupant is likely to "submarine" (be thrown forward under the shoulder belt) and be seriously injured. Motorized or door-affixed shoulder belts hinder access to the vehicle, making it difficult to enter and exit—particularly if the occupant is carrying items such as a box or a purse. Vehicle owners tend to disconnect the motorized or door-affixed shoulder belt to alleviate the nuisance of entering and exiting the vehicle, leaving only a lap belt for crash protection. Also, many automatic seat belt systems are incompatible with child safety seats, or compatible only with special modifications.

Use of seat belts by child occupants

As with adult drivers and passengers, the advent of seat belts was accompanied by calls for their use by child occupants, including legislation requiring such use. Generally children using adult seat belts suffer significantly lower injury risk when compared to non-buckled children.

The UK extended compulsory seatbelt wearing to child passengers under the age of 14 in 1989. It was observed that this measure was accompanied by a 10% *increase* in fatalities and a 12% *increase* in injuries among the target population. In crashes, small children who wear adult seatbelts can suffer "seat-belt syndrome" injuries including severed intestines, ruptured diaphragms and spinal damage. There is also research suggesting that children in inappropriate restraints are at significantly increased risk of head injury, one of the authors of this research has been quoted as claiming that "The early graduation of kids into adult lap and shoulder belts is a leading cause of child-occupant injuries and deaths." As a result of such findings, many jurisdictions now advocate or require child passengers to use specially designed child restraints. Such systems include separate child-sized seats with their own restraints and booster cushions for children using adult restraints. In some jurisdictions children below a certain size are forbidden to travel in front car seats."

In rear seats

In 1955 (as a 1956 package) Ford offered lap only seat belts in the rear seats as an option within the *Lifeguard* safety package. In 1967 Volvo started to install lap belts in the rear seats. In 1972 Volvo upgraded the rear seat belts to a three point belt.

In crashes, unbelted rear passengers increase the risk of belted front seat occupants' death by nearly five times.

Reminder chime and light

Examples of warning lights on a car dashboard.

In North America, cars sold since the early 1970s have included an audiovisual reminder system consisting of a light on the dashboard and a buzzer or chime reminding the driver and passengers to fasten their belts. Originally, these lights were accompanied by a warning buzzer whenever the transmission was in any position except park if either the driver was not buckled up or, as determined by a pressure sensor in the passenger's seat, if there was a passenger there not buckled up. However, this was considered by many to be a major annoyance, as the light would be on and the buzzer would sound continuously if front-seat passengers were not buckled up. Therefore, people who did not wish to buckle up would defeat this system by fastening the seatbelts with the seat empty and leaving them that way.

By the mid-1970s, auto manufacturers modified the system so that a warning buzzer would sound for several seconds before turning off (with the warning light), regardless of whether the car was started. However, if the driver was buckled up, the light would appear, but with no buzzer. New cars sold in the United States in 1974 and the first part of the 1975 model year were sold with a special "ignition interlock", whereby the driver could not start the car until the seat belt was fastened; however, this system was short-lived.

Today, the belt warning light may stay on for several minutes after the car is started if the driver's seat belt is not fastened.

In Europe and some other parts of the world, most modern cars include a seat-belt reminder light for the driver and some also include a reminder for the passenger, when present, activated by a pressure sensor under the passenger seat. Some cars will intermittently flash the reminder light and sound the chime until the driver (and sometimes the front passenger, if present) fasten their seatbelts.

Legislation

Observational studies of car crash morbidity and mortality, experiments using both crash test dummies and human cadavers indicate that wearing seat belts greatly reduces the risk of death and injury in the majority of car crashes.

This has led many countries to adopt mandatory seat belt wearing laws. It is generally accepted that, in comparing like-for-like accidents, a vehicle occupant not wearing a properly fitted seat belt has a significantly and substantially higher chance of death and serious injury. One large observation studying using US data showed that the odds ratio of crash death is 0.46 with a three-point belt, when compared with no belt. In another study that examined injuries presenting to the ER pre- and post-seat belt law introduction, it was found that 40% more escaped injury and 35% more escaped mild and moderate injuries.

The effects of seat belt laws are disputed by those who observe that their passage did not reduce road fatalities. There was also concern that instead of legislating for a general protection standard for vehicle occupants, laws that required a particular technical approach would rapidly become dated as motor manufacturers would tool up for a particular standard which could not easily be changed. For example, in 1969 there were competing designs for lap and 3-point seat belts, rapidly-tilting seats, and air bags being developed. But as countries started to mandate seat belt restraints the global auto industry invested in the tooling and standardized exclusively on seat belts, and ignored other restraint designs such as air bags for several decades

Risk compensation

Some have proposed that the number of deaths was influenced by the development of risk compensation, which says that drivers adjust their behavior in response to the increased sense of personal safety wearing a seat belt provides.

In one trial subjects were asked to drive go-karts around a track under various conditions. It was found that subjects who started driving unbelted drove consistently faster when subsequently belted. Similarly, a study of habitual non-seatbelt wearers driving in freeway conditions found evidence that they had adapted to seatbelt use by adopting higher driving speeds and closer following distances. Similar responses have been shown in respect of anti-lock braking system, airbags, and, more recently, the electronic stability control system.

A 2001 analysis of US crash data aimed to establish the effects of seatbelt legislation on driving fatalities and found that previous estimates of seatbelts effectiveness had been significantly overstated. According to the analysis used, seatbelts were claimed to have decreased fatalities by 1.35% for each 10% increase in seatbelt use. The study controlled for endogenous motivations of seat belt use, which it is claimed creates an artificial correlation between seat belt use and fatalities, leading to the conclusion that seatbelts cause fatalities. For example, drivers in high risk areas are more likely to use seat belts, and are more likely to be in accidents, creating a non-causal correlation between seatbelt use and mortality. After accounting for the endogeneity of seatbelt usage, Cohen and Einav found no evidence that the risk compensation effect makes seatbelt wearing drivers more dangerous, a finding at variance with other research.

Increased traffic

Other statistical analyses have included adjustments for factors such as increased traffic, and other factors such as age, and based on these adjustments, a reduction of morbidity and mortality due to seat belt use has been claimed. However, Smeed's law predicts a fall in accident rate with increasing car ownership and has been demonstrated independently of seat belt legislation.

Use in vehicles other than cars

Buses

Pros and cons had been alleged about the use of seatbelts in school buses.

In the European Union, all new long distance buses and coaches must be fitted with seat belts.

Trains

Use of seatbelts in trains has been investigated. Concerns about survival space intrusion in train crashes and increase of injuries to unrestrained or incorrectly restrained passengers led the researches to discourage the use of seat belts in trains.

It has been shown that there is no net safety benefit for passengers who choose to wear 3-point restraints on passenger carrying rail vehicles. Generally passengers who choose not to wear restraints in a vehicle modified to accept 3-point restraints receive marginally more severe injuries.

Airplanes

The "Father of Crash Survivability", Hugh De Haven, was a plane pilot. His interest in crash survivability was sparked by his surviving a plane crash during the First World War.

Chapter- 9

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- 10

Automotive Battery

12 V, 40 Ah Lead-acid car battery

An **automotive battery** is a type of rechargeable battery that supplies electric energy to an automobile. Usually this refers to an **SLI battery** (*starting, lighting, ignition*) to power the starter motor, the lights, and the ignition system of a vehicle's engine. An automotive battery may also be a traction battery used for the main power source of an electric vehicle.

Automotive SLI batteries are usually lead-acid type, and are made of six galvanic cells in series to provide a 12 volt system. Each cell provides 2.1 volts for a total of 12.6 volt at full charge. Heavy vehicles such as highway trucks, often equipped with Diesel engines, may have two batteries in series for a 24 volt system, or may have parallel strings of batteries.

Lead-acid batteries are made up of plates of lead and separate plates of lead dioxide, which are submerged into an electrolyte solution of about 35% sulfuric acid and 65% water. This causes a chemical reaction that releases electrons, allowing them to flow through conductors to produce electricity. As the battery discharges, the acid of the electrolyte reacts with the materials of the plates, changing their surface to lead sulfate. When the battery is recharged, the chemical reaction is reversed: the lead sulfate reforms into lead oxide and lead. With the plates restored to their original condition, the process may now be repeated.

Battery recycling of automotive batteries reduces resources required for manufacture of new batteries and diverts toxic lead from landfills or improper disposal.

Types

Lead-acid batteries for automotive use are made with slightly different construction techniques, depending on the application of the battery. The typical battery in use today is of the "flooded cell" type, indicating liquid electrolyte. AGM or absorbed glass mat type batteries have electrolyte immobilized as a gel.

The *starting* (*cranking*) or *shallow cycle* type is designed to deliver large bursts of energy, to start an engine. Once the engine is started, the battery is recharged by the engine-driven charging system. Starting batteries have a relatively low degree of discharge on each use. They have many thin plates,thin separators between the plates, and may have a higher specific gravity electrolyte to reduce internal resistance.

The *deep cycle* (or *motive*) type is designed to continuously provide power for long periods of time (for example in a trolling motor for a small boat, auxiliary power for a recreational vehicle, or traction power for a golf cart or other battery electric vehicle). They can also be used to store energy from a photovoltaic array or a small wind turbine. Deep-cycle batteries have fewer, thicker plates and are intended to have a greater depth of discharge on each cycle, but will not provide as high a current on heavy loads. The thicker plates survive a higher number of charge/discharge cycles. The specific energy is in the range of 30-40 watt-hours per kilogram. Some battery manufacturers claim their batteries are dual purpose (starting and deep cycling).

Some cars use more exotic starter batteries- the 2010 Porsche 911 GT3 RS offers a lithium-ion battery as an option to save weight over a conventional lead-acid battery.

Use and maintenance

Fluid level

Filling a car battery with distilled water

Car batteries using lead-antimony plates would require regular watering top-up to replace water lost due to electrolysis on each charging cycle. By changing the alloying element to calcium, more recent designs have lower water loss unless overcharged. Modern car batteries have reduced maintenance requirements, and may not provide caps for addition of water to the cells. Such batteries include extra electrolyte above the plates to allow for losses during the battery life. If the battery has easily detachable caps then a top-up with distilled water may be required from time to time. Prolonged overcharging or charging at excessively high voltage causes some of the water in the electrolyte to be broken up into hydrogen and oxygen gases, which escape from the cells. If the electrolyte liquid level drops too low, the plates are exposed to air, lose capacity, and are damaged. The sulfuric acid in the battery normally does not require replacement since it is not consumed even on overcharging. Impurities or additives in the water will reduce the life and performance of the battery. Manufacturers usually recommend use of demineralized or distilled water since even potable tap water can contain high levels of minerals.

Charge and discharge

In normal automotive service the vehicle's charging system powers the vehicle's electrical systems and restores charge used from the battery during engine cranking. When installing a new battery or recharging a battery that has been accidentally discharged completely, one of several different methods can be used to charge it. The most gentle of these is called trickle charging. Other methods include slow-charging and quick-charging, the latter being the harshest.

In most cars, the voltage regulator of the charge system is unaware of the relative currents charging the battery and for powering the car's loads such as engine control, fans and lighting. The charge system essentially provides a fixed voltage of typically 13.8 to 14.4 V (Volt), adjusted to ambient temperature, unless the alternator is at its current limit. A discharged battery draws a high current of typically 20 to 40 A (Ampere). As the battery gets charged the charge current typically decreases 2 A to 5 A. A high load results when multiple high-power systems such as radiator fan, heater blowers, lights and entertainment system are running. In this case, the battery voltage will decrease and the charge current as well.

Some manufacturers include a built-in hydrometer to show the state of charge of the battery. This acrylic "eye" has a float immersed in the electrolyte. When the battery is charged, the specific gravity of the electrolyte increases (since all the sulfate ions are in the electrolyte, not combined with the plates), and the colored top of the float is visible in the window. When the battery is discharged (or if the electrolyte level is too low), the float sinks and the window appears yellow (or black). The built-in hydrometer only checks the state of charge of one cell and will not show faults in the other cells. In a non-sealed battery each of the cells can be checked with a portable or hand-held hydrometer. Batteries will last longer if stored in a charged state.

Jumper cable connected to battery post. Hydrometer window visible by jumper clamp. White powdery corrosion products visible on top of battery. This BCI Group 24F battery claims 525 cold cranking amperes and 125 minutes reserve capacity.

In emergencies a vehicle can be jump started, by the battery of another vehicle or by a portable battery booster.

Whenever the car's charge system is inadequate or too slow to fully charge the battery, a battery charger can be used. Simple chargers will not regulate the charge current and the user needs to stop the process or lower the charge current to prevent excessive gassing of the battery. More elaborate chargers, in particular those implementing the 3-step charge Profile, also referred to as IUoU, charge the battery fully and safely in a short time without requiring user intervention.

Storage

Batteries should be monitored and periodically charged if in storage, to retain their capacity. Batteries intended to be stored should be fully charged, cleaned of corrosion deposits, and left in a cool dry environment. High temperatures increase the self discharge rate and plate corrosion. Lead-acid batteries must always be kept in a fully charged condition. The terminal voltage can be measured as an indication of state of charge. Batteries may be charged periodically by a constant voltage method, or attached to a "float" charger.

Changing a battery

In modern automobiles, the grounding is provided by connecting the body of the car to the negative electrode of the battery, a system called 'negative ground'. In the past some cars had 'positive ground'. Such vehicles were found to suffer worse body corrosion and, sometimes, blocked radiators due to deposition of metal sludge.

When changing a battery, battery manufacturers recommend disconnecting the ground connection first to prevent accidental short-circuits between the battery terminal and the vehicle frame. A study by the National Highway Traffic Safety Association estimated that in 1994 more than 2000 people were injured in the United States while working with automobile batteries.

The majority of automotive lead-acid batteries are filled with the appropriate electrolyte solution at the manufacturing plant, and shipped to the retailers ready to sell. Decades ago, this was not the case. The retailer filled the battery, usually at the time of purchase, and charged the battery. This was a time-consuming and potentially dangerous process. Care had to be taken when filling the battery with acid, as acids are highly corrosive and can damage eyes, skin and mucous membranes. Fortunately, this is less of a problem these days, and the need to fill a battery with acid usually only arises when purchasing a motorcycle or ATV battery.

Freshness

Because of "sulfation", lead-acid batteries stored with electrolyte slowly deteriorate. Car batteries should be installed within one year of manufacture. In the United States, the manufacturing date is printed on a sticker. The date can be written in plain text or using an alphanumerical code. The first character is a letter that specifies the month (A for January, B for February and so on). The letter "I" is skipped due to its potential to be mistaken for the number 1. The second character is a single digit that indicates the year of manufacturing (for example, 6 for 2006). When first installing a newly purchased battery a "top up" charge at a low rate with an external battery charger (available at auto parts stores) may maximize battery life and minimize the load on the vehicle charging system. The top-up charge can be considered complete when the terminal voltage is just above 15.1 V DC. 15 V DC is the voltage level where any sulfation that may be present is driven from the plates back into the electrolyte solution. A new battery can have some sulfation even though it has never been in service. If the top up charge cannot be done it is not harmful to place the battery in immediate service.

Failure

Common battery faults include:

- Shorted cell due to failure of the separator between the positive and negative plates

- Shorted cell or cells due to build up of shed plate material building up below the plates of the cell
- Broken internal connections due to corrosion
- Broken plates due to vibration and corrosion
- Low electrolyte
- Cracked or broken case
- Broken terminals
- Sulfation after prolonged disuse in a low or zero charged state

Corrosion at the battery terminals can prevent a car from starting, by adding electrical resistance. The white powder sometimes found around the battery terminals is usually lead sulfate which is toxic by inhalation, ingestion and skin contact. The corrosion is caused by an imperfect seal between the plastic battery case and lead battery post allowing sulfuric acid to attack the battery posts. The corrosion process is also expedited by over-charging. Corrosion can also be caused by factors such as, salt water, dirt, heat, and humidity in the air, a crack in the battery casing, or loose battery terminals. Inspection, cleaning, and protection with a coating are measures used to prevent corrosion of battery terminals.

Sulfation occurs when a battery is not fully charged, and the longer it remains in a discharged state the harder it is to overcome the sulfation. This may be overcome with slow, low-current (trickle) charging. Sulfation is due to formation of large, non-conductive lead sulfate crystals on the plates; lead sulfate formation is part of each cycle, but in the discharged condition the crystals become large and block passage of current through the electrolyte.

The primary wear-out mechanism is the shedding of active material from the battery plates, which accumulates at the bottom of the cells and which may eventually short-circuit the plates.

Early automotive batteries could sometimes be repaired by dismantling and replacing damaged separators, plates, intercell connectors, and other repairs. Modern battery cases do not facilitate such repairs; an internal fault generally requires replacement of the entire unit.

Exploding batteries

Car battery after explosion

Any lead-acid battery system when overcharged will produce hydrogen gas. If the rate of overcharge is small, the vents of each cell allow the dissipation of the gas. However, on severe overcharge or if ventilation is inadequate or the battery is faulty, a flammable concentration of hydrogen may remain in the cell or in the battery enclosure. Any spark can cause a hydrogen and oxygen explosion, which will damage the battery and its surroundings and which will disperse acid into the surroundings. Anyone close to the battery may be injured.

Sometimes the ends of a battery will be severely swollen, and when accompanied by the case being too hot to touch, this usually indicates a malfunction in the charging system of the car. Reversing the positive and negative leads will damage the battery and may lead to gassing and explosion. When severely overcharged, a lead-acid battery gases at a high level and the venting system built into the battery cannot handle the high level of gas, so the pressure builds inside the battery, resulting in the swollen ends. An unregulated alternator can put out a high level of charge, and can quickly ruin a battery. A swollen, hot battery is very dangerous, and should not be handled until it has been given sufficient time to cool and any hydrogen gas present to dissipate.

A person handling a car battery should always wear proper protective equipment (goggles, overalls, gloves) and make certain there are no sparks or smoking close by.

Terms and ratings

- *Ampere-hours* (A·h) is the product of the time that a battery can deliver a certain amount of current (in hours) times that current (in amperes), for a particular discharge period. This is one indication of the total amount of charge a battery is able to store and deliver at its rated voltage. This rating is rarely stated for automotive batteries, except in Europe where it is required by law.
- *Cranking amperes* (CA), also sometimes referred to as *marine cranking amperes* (MCA), is the amount of current a battery can provide at 32 °F (0 °C). The rating is defined as the number of amperes a lead-acid battery at that temperature can deliver for 30 seconds and maintain at least 1.2 volts per cell (7.2 volts for a 12 volt battery).
- *Cold cranking amperes* (CCA) is the amount of current a battery can provide at 0 °F (−18 °C). The rating is defined as the current a lead-acid battery at that temperature can deliver for 30 seconds and maintain at least 1.2 volts per cell (7.2 volts for a 12-volt battery). It is a more demanding test than those at higher temperatures.
- *Hot cranking amperes* (HCA) is the amount of current a battery can provide at 80 °F (26.7 °C). The rating is defined as the current a lead-acid battery at that temperature can deliver for 30 seconds and maintain at least 1.2 volts per cell (7.2 volts for a 12-volt battery).
- *Reserve capacity minutes* (RCM), also referred to as *reserve capacity* (RC), is a battery's ability to sustain a minimum stated electrical load; it is defined as the time (in minutes) that a lead-acid battery at 80 °F (27 °C) will continuously deliver 25 amperes before its voltage drops below 10.5 volts.
- *Battery Council International group size* (BCI) specifies a battery's physical dimensions, such as length, width, and height. These groups are determined by the Battery Council International organization.
- Peukert's Law expresses the fact that the capacity available from a battery varies according to how rapidly it is discharged. A battery discharged at high rate will give fewer ampere hours than one discharged more slowly.
- The hydrometer measures the density, and therefore indirectly the amount of sulfuric acid in the electrolyte. A low reading means that sulfate is bound to the battery plates and that the battery is discharged. Upon recharge of the battery, the sulfate returns to the electrolyte.

Terminal voltage

The open circuit voltage, is measured when the engine is off and no loads are connected. It can be approximately related to the charge of the battery by:

Open Circuit Voltage (12 V)	Open Circuit Voltage (6 V)	Approximate charge	Relative acid density
12.65 V	6.32 V	100%	1.265 g/cm^3
12.45 V	6.22 V	75%	1.225 g/cm^3
12.24 V	6.12 V	50%	1.190 g/cm^3
12.06 V	6.03 V	25%	1.155 g/cm^3
11.89 V	6.00 V	0%	1.120 g/cm^3

Open circuit voltage is also affected by temperature, and the specific gravity of the electrolyte at full charge.

The following is common for a six-cell automotive lead-acid battery at room temperature:

- Quiescent (open-circuit) voltage at full charge: 12.6 V
- Fully discharged: 11.8 V
- Charge with 13.2–14.4 V
- Gassing voltage: 14.4 V
- Continuous-preservation charge with max. 13.2 V
- After full charge the terminal voltage will drop quickly to 13.2 V and then slowly to 12.6 V
- Open circuit voltage is measured 12 hours after charging to allow surface charge to dissipate and enable a more accurate reading.
- All voltages are at 20 °C, and must be adjusted -0.022V/°C for temperature changes.