Vehicle Technology

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Vehicle Braking Technologies

Drum Brake

A drum brake with the drum removed as used on the rear wheel of a car or truck. Note that in this installation, a cable-operated parking brake uses the service shoes.

A **drum brake** is a brake in which the friction is caused by a set of shoes or pads that press against a rotating drum-shaped part called a brake drum.

The term "drum brake" usually means a brake in which shoes press on the inner surface of the drum. When shoes press on the outside of the drum, it is usually called a clasp brake. Where the drum is pinched between two shoes, similar to a conventional disk brake, it is sometimes called a "pinch drum brake", although such brakes are relatively rare. A related type of brake uses a flexible belt or "band" wrapping around the outside of a drum, called a band brake.

History

The modern automobile drum brake was invented in 1902 by Louis Renault, though a less-sophisticated drum brake had been used by Maybach a year earlier. In the first drum brakes, the shoes were mechanically operated with levers and rods or cables. From the mid-1930s the shoes were operated with oil pressure in a small wheel cylinder and pistons (as in the picture), though some vehicles continued with purely-mechanical systems for decades. Some designs have two wheel cylinders.

The shoes in drum brakes are subject to wear and the brakes needed to be adjusted regularly until the introduction of self-adjusting drum brakes in the 1950s. In the 1960s and 1970s brake drums on the front wheels of cars were gradually replaced with disc brakes and now practically all cars use disc brakes on the front wheels, with many offering disc brakes on all wheels. However, drum brakes are still often used for handbrakes as it has proven very difficult to design a disc brake suitable for holding a car when it is not in use. Moreover, it is very easy to fit a drum handbrake *inside* a disc brake so that one unit serves as both service brake and handbrake.

Early type brake shoes contained asbestos. When working on brake systems of older cars, care must be taken not to inhale any dust present in the brake assembly. The United States Federal Government began to regulate asbestos production, and brake manufacturers had to switch to non-asbestos linings. Owners initially complained of poor braking with the replacements; however, technology eventually advanced to compensate. A majority of daily-driven older vehicles have been fitted with asbestos-free linings. Many other countries also limit the use of asbestos in brakes.

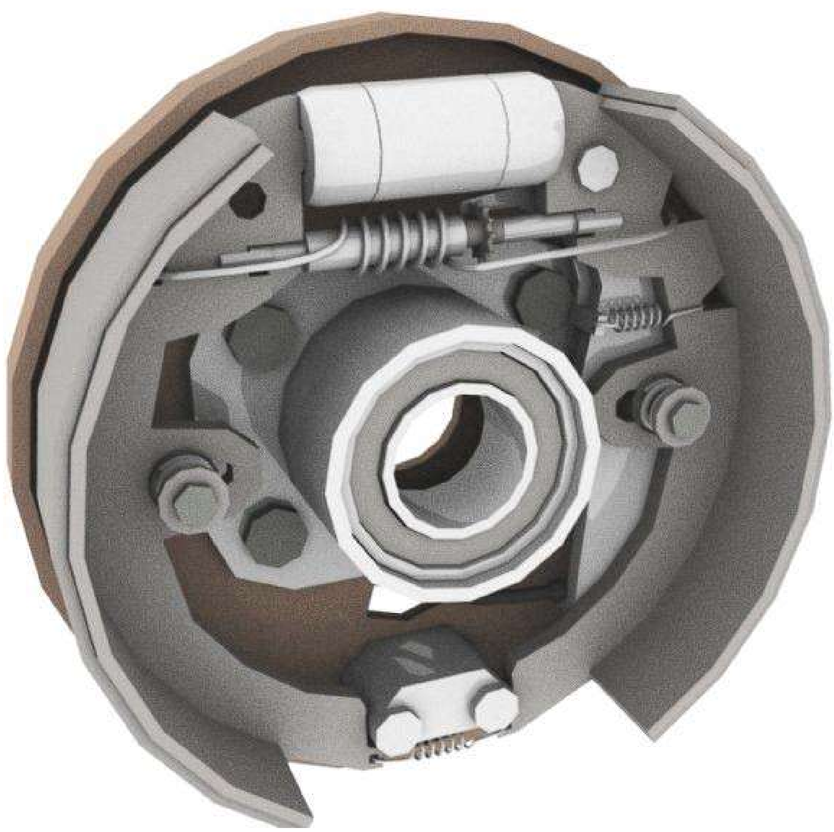
Self-applying characteristic

Drum brakes have a natural "self-applying" characteristic. The rotation of the drum can drag either or both of the shoes into the friction surface, causing the brakes to bite harder, which increases the force holding them together. This increases the stopping power without any additional effort being expended by the driver, but it does make it harder for the driver to modulate the brake's sensitivity. It also makes the brake more sensitive to brake fade, as a decrease in brake friction also reduces the amount of brake assist.

Disc brakes exhibit no self-applying effect because the hydraulic pressure acting on the pads is perpendicular to the direction of rotation of the disc. Disc brake systems usually have servo assistance ("Brake Booster") to lessen the driver's pedal effort, but some disc braked cars (notably race cars) and smaller brakes for motorcycles, etc., do not need to use servos.

Note: In most designs, the "self applying" effect only occurs on one shoe. While this shoe is further forced into the drum surface by a moment due to friction, the opposite effect is happening on the other shoe. The friction force is trying to rotate it away from the drum. The forces are different on each brake shoe resulting in one shoe wearing faster. It is possible to design a two-shoe drum brake where both shoes are self-applying (having separate actuators and pivoted at opposite ends), but these are very uncommon in practice.

Drum brake designs



Rendering of a drum brake

Drum brakes are typically described as either leading/trailing or twin leading.

Rear drum brakes are typically of a leading/trailing design (For Non Servo Systems), or [Primary/Secondary] (For Duo Servo Systems) the shoes being moved by a single double-acting hydraulic cylinder and hinged at the same point. In this design, one of the brake shoes will always experience the self-applying effect, irrespective of whether the vehicle is moving forwards or backwards. This is particularly useful on the rear brakes, where the footbrake (handbrake or parking brake) must exert enough force to stop the vehicle from travelling backwards and hold it on a slope. Provided the contact area of the brake shoes is large enough, which isn't always the case, the self-applying effect can securely hold a vehicle when the weight is transferred to the rear brakes due to the incline of a slope or the reverse direction of motion. A further advantage of using a single hydraulic cylinder on the rear is that the opposite pivot may be made in the form of a double lobed cam that is rotated by the action of the parking brake system.

Front drum brakes may be of either design in practice, but the twin leading design is more effective. This design uses two actuating cylinders arranged so that both shoes will utilize the self-applying characteristic when the vehicle is moving forwards. The brake shoes pivot at opposite points to each other. This gives the maximum possible braking when moving forwards, but is not so effective when the vehicle is traveling in reverse.

The optimum arrangement of twin leading front brakes with leading/trailing brakes on the rear allows for more braking force to be deployed at the front of the vehicle when it is moving forwards, with less at the rear. This helps to prevent the rear wheels locking up, but still provides adequate braking at the rear when it is needed.

The brake drum itself is frequently made of cast iron, although some vehicles have used aluminum drums, particularly for front-wheel applications. Aluminum conducts heat better than cast iron, which improves heat dissipation and reduces fade. Aluminum drums are also lighter than iron drums, which reduces unsprung weight. Because aluminum wears more easily than iron, aluminum drums will frequently have an iron or steel liner on the inner surface of the drum, bonded or riveted to the aluminum outer shell.

Advantages

Drum brakes are still used in some modern cars and smaller (and less-expensive) dirt bikes and ATV's, such as the Honda CRF80F, because of some engineering and cost advantages. Drum brakes allow simple incorporation of a parking brake. They are often applied to the rear wheels since most of the stopping force is generated by the front brakes of the vehicle and therefore the heat generated in the rear is significantly less. Drum brakes are also occasionally fitted as the parking (and emergency) brake even when the rear wheels use disk brakes as the main brakes. In this situation, a small drum is usually fitted within or as part of the brake disk also known as a banksia brake.

In hybrid vehicle applications, wear on braking systems is greatly reduced by energy recovering motor-generators, so some hybrid vehicles such as the GMC Yukon hybrid and Toyota Prius (except the third generation) use drum brakes.

Disc brakes rely on pliability of caliper seals and slight runout to release pads, leading to drag and fuel mileage loss. Drum brake return springs give more positive action and, adjusted correctly, often have less drag when released.

Disadvantages

Drum brakes, like most other types, are designed to convert kinetic energy into heat by friction. This heat is intended to be further transferred to atmosphere, but can just as easily transfer into other components of the braking system.

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Brake drums have to be large to cope with the massive forces that are involved, and they must be able to absorb and dissipate a lot of heat. Heat transfer to atmosphere can be aided by incorporating cooling fins onto the drum. However, excessive heating can occur due to heavy or repeated braking which can cause the drum to distort, leading to vibration under braking.

The other consequence of overheating is brake fade. This is due to one of several processes or more usually an accumulation of all of them.

1. When the drums are heated by hard braking, the diameter of the drum increases slightly due to thermal expansion, this means the brakes shoes have to move farther and the brake pedal has to be depressed further.

2. The properties of the friction material can change if heated, resulting in less friction. This is usually only temporary and the material regains its efficiency when cooled, but if the surface overheats to the point where it becomes glazed the reduction in braking efficiency is more permanent. Surface glazing can be worn away with further use of the brakes, but that takes time.

3. Excessive heating of the brake drums can cause the brake fluid to vapourise, which reduces the hydraulic pressure being applied to the brake shoes. Therefore less retardation is achieved for a given amount of pressure on the pedal. The effect is worsened by poor maintenance. If the brake fluid is old and has absorbed moisture it thus has a lower boiling point and brake fade occurs sooner.

Brake fade is not always due to the effects of overheating. If water gets between the friction surfaces and the drum, it acts as a lubricant and reduces braking efficiency. The water tends to stay there until it is heated sufficiently to vapourise, at which point braking efficiency is fully restored. All friction braking systems have a maximum theoretical rate of energy conversion. Once that rate has been reached, applying greater pedal pressure will not result in a change of this rate, and indeed the effects mentioned can substantially reduce it. Ultimately this is what brake fade is, regardless of the mechanism of its causes.

Disc brakes are not immune to any of these processes, but they deal with heat and water more effectively than drums.

Drum brakes can be grabby if the drum surface gets light rust or if the brake is cold and damp, giving the pad material greater friction. Grabbing can be so severe that the tires skid and continue to skid even when the pedal is released. Grabbiness is the opposite of fade: when the pad friction goes up, the self-assisting nature of the brakes causes application force to go up. If the pad friction and self-amplification are high enough, the brake will stay on due to self-application even when the external application force is released.

Re-arcing

Before 1984, it was common to re-arc brake shoes to match the arc within brake drums. This practice, however, was controversial as it removed friction material from the brakes and caused a reduction in the life of the shoes as well as created hazardous asbestos dust. Current design theory is to use shoes for the proper diameter drum, and to simply replace the brake drum when necessary, rather than perform the re-arcing procedure.

Adjustment

Early drum brakes (before about 1955) required periodic adjustment to compensate for drum and shoe wear. If not done sufficiently often long brake pedal travel ("low pedal") resulted. Low pedal can be a severe hazard when combined with brake fade as the brakes can become ineffective when the pedal *bottoms out*.

Self adjusting brakes may use a mechanism that engages only when the vehicle is being stopped from reverse motion. This is a traditional method suitable for use where all wheels use drum brakes (most vehicles now use disc brakes on the front wheels). By operating only in reverse it is less likely that the brakes will be adjusted while hot (when the drums are expanded), which could cause dragging brakes that would accelerate wear and increase fuel consumption.

Self adjusting brakes may also operate by a ratchet mechanism engaged as the hand brake is applied, a means suitable for use where only rear drum brakes are used. If the travel of the parking brake actuator lever exceeds a certain amount, the ratchet turns an adjuster screw that moves the brake shoes toward the drum.

There are different Self Adjusting Brake Systems. Basically can be divided in to RAI and RAD. RAI systems are much more efficient than RAD systems and have built in systems that avoids the systems to recover when the brake is over heating. The most famous RAI are developed by Lucas, Bendix, Bosch, AP. For RAD systems the most famous are Bendix, AP, VAG (Volkswagen) and FORD recovery systems.

The manual adjustment knob is usually at the bottom of the drum and is adjusted via a hole on the opposite side of the wheel. This requires getting underneath the car and moving the clickwheel with a flathead screwdriver. It is important and tedious to adjust each wheel evenly so as to not have the car pull to one side during heavy braking, especially if on the front wheels. Either give each one the same amount of clicks and then perform a road test, or raise each wheel off the ground and spin it by hand measuring how much force it takes and feeling whether or not the shoes are dragging.

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Dynamic braking

NS #5348 sporting a Dynamic brake

Dynamic braking is the use of the electric traction motors of a railroad vehicle as generators when slowing the vehicle. It is termed *rheostatic* if the generated electrical power is dissipated as heat in brake grid resistors, and *regenerative* if the power is returned to the supply line. Dynamic braking lowers the wear of friction-based braking components, and additionally regeneration can also lower energy consumption.

Principle of operation

During braking, the motor fields are connected across either the main traction generator (diesel-electric loco) or the supply (electric locomotive) and the motor armatures are connected across either the brake grids or supply line. The rolling locomotive wheels turn the motor armatures, and if the motor fields are now excited, the motors will act as generators.

For a given direction of travel, current flow through the motor armatures during braking will be opposite to that during motoring. Therefore, the motor exerts torque in a direction that is opposite from the rolling direction. Braking effort is proportional to the product of the magnetic strength of the field windings, times that of the armature windings.

For permanent magnet motors, dynamic braking is easily achieved by shorting the motor terminals, thus bringing the motor to a fast abrupt stop. This method, however, dissipates all the energy as heat in the motor itself, and so cannot be used in anything other than low-power intermittent applications due to cooling limitations. It is not suitable for traction applications.

Rheostatic braking

The electrical energy produced by the motors is dissipated as heat by a bank of onboard resistors. Large cooling fans are necessary to protect the resistors from damage. Modern systems have thermal monitoring, so if the temperature of the bank becomes excessive, it will be switched off, and the braking will revert to air only.

Regenerative braking

In electrified systems the similar process of **regenerative braking** is employed whereby the current produced during braking is fed back into the power supply system for use by other traction units, instead of being wasted as heat. It is normal practice to incorporate both regenerative and rheostatic braking in electrified systems. If the power supply system is not *"receptive"*, i.e. incapable of absorbing the current, the system will default to rheostatic mode in order to provide the braking effect.

Yard locomotives with onboard energy storage systems which allow the recovery of some of this energy which would otherwise be wasted as heat are now available. The Green Goat model, for example, is being used by Canadian Pacific Railway, BNSF Railway, Kansas City Southern Railway and Union Pacific Railroad.

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Blended braking

A picture of an ex-Connex Class 466 EMU at Blackfriars station in the year 2006. The popular Class 466 EMUs use Dynamic blended braking.

Dynamic braking alone is insufficient to stop a locomotive, as its braking effect rapidly diminishes below about 10 to 12 miles per hour (16 to 19 km/h). Therefore it is always used in conjunction with the regular air brake. This combined system is called **blended braking**. Li-ion batteries have also been used to store energy for use in bringing trains to a complete halt.

Although blended braking combines both dynamic and air braking, the resulting braking force is designed to be the same as what the air brakes on their own provide. This is achieved by maximizing the dynamic brake portion, and automatically regulating the air brake portion, as the main purpose of dynamic braking is to reduce the amount of air braking required. This conserves air, and minimizes the risks of over-heated wheels. One locomotive manufacturer, Electro-Motive Diesel (EMD), estimates that dynamic braking provides between 50% to 70% of the braking force during blended braking.

Self-load test

It is possible to use the brake grids as a form of dynamometer or load bank to perform a *"self load"* test of locomotive engine horsepower. With the locomotive stationary, the main generator (MG) output is connected to the grids instead of the traction motors. The grids are normally large enough to absorb the full engine output power, which is calculated from MG voltage and current output.

Hydrodynamic braking

Diesel engined locomotives with hydraulic transmission may be equipped for hydrodynamic braking. In this case, the torque converter or fluid coupling acts as a retarder in the same way as a water brake. Braking energy heats the hydraulic fluid, and the heat is dissipated (via a heat exchanger) by the engine cooling radiator. The engine will be idling (and producing little heat) during braking, so the radiator is not overloaded.

Anti-lock braking system

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

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

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

History

Early systems

The ABS was first developed for aircraft use in 1929 by the French automobile and aircraft pioneer, Gabriel Voisin, as threshold braking on airplanes is nearly impossible. An early system was Dunlop's Maxaret system, which was introduced in the 1950s and is still in use on some aircraft models. These systems use a flywheel and valve attached to a hydraulic line that feeds the brake cylinders. The flywheel is attached to a drum that runs at the same speed as the wheel. In normal braking, the drum and flywheel should spin at the same speed. However, if a wheel were to slow down, then the drum would do the same, leaving the flywheel spinning at a faster rate. This causes the valve to open, allowing a small amount of brake fluid to bypass the master cylinder into a local reservoir, lowering the pressure on the cylinder and releasing the brakes. The use of the drum and flywheel meant the valve only opened when the wheel was turning. In testing, a 30% improvement in braking performance was noted, because the pilots immediately applied full brakes instead of slowly increasing pressure in order to find the skid point. An additional benefit was the elimination of burned or burst tires.

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

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

Modern systems

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

In 1975, Robert Bosch took over the European company Teldix and all patents registered by the joint-venture and used this acquisition to build the base of the ABS introduced on the market some years later.

In 1978, the German firms Bosch and Daimler-Benz co-developed an ABS technology that begun in the early 1970s, and introduced the first completely electronic four-wheeled multi-channel ABS in trucks and the Mercedes-Benz S-Class.

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ABS brakes on a BMW motorcycle

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

Operation

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

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

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

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

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

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

The ABS equipment may also be used to implement a traction control system(TCS) or Anti-Slip Regulation (ASR) on acceleration of the vehicle. If, when accelerating, the tire loses traction, the ABS controller can detect the situation and take suitable action so that traction is regained. Manufacturers often offer this as a separately priced option even though the infrastructure is largely shared with ABS. More sophisticated versions of this can also control throttle levels and brakes simultaneously.

Components

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

Speed sensors

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

Valves

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

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

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Pump

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

Controller

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

Use

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

1. The controller monitors the speed sensors at all times. It is looking for decelerations in the wheel that are out of the ordinary. Right before a wheel locks up, it will experience a rapid deceleration. If left unchecked, the wheel would stop much more quickly than any car could. It might take a car five seconds to stop from 60 mph (96.6 km/h) under ideal conditions, but a wheel that locks up could stop spinning in less than a second.
2. The ABS controller knows that such a rapid deceleration is impossible, so it reduces the pressure to that brake until it sees an acceleration, then it increases the pressure until it sees the deceleration again. It can do this very quickly, before the tire can actually significantly change speed. The result is that the tire slows down at the same rate as the car, with the brakes keeping the tires very near the point at which they will start to lock up. This gives the system maximum braking power.
3. When the ABS system is in operation the driver will feel a pulsing in the brake pedal; this comes from the rapid opening and closing of the valves. This pulsing also tells the driver that the ABS has been triggered. Some ABS systems can cycle up to 15 times per second.

Brake types

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

Four-channel, four-sensor ABS

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

Three-channel, three-sensor ABS

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

One-channel, one-sensor ABS

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

Effectiveness

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

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

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

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

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

According to the NHTSA,

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

When activated, some earlier ABS systems caused the brake pedal to pulse noticeably. As most drivers rarely or never brake hard enough to cause brake lock-up, and a significant number rarely bother to read the car's manual, this may not be discovered until an emergency. When drivers do encounter an emergency that causes them to brake hard, and thus encounter this pulsing for the first time, many are believed to reduce pedal pressure, and thus lengthen braking distances, contributing to a higher level of accidents than the superior emergency stopping capabilities of ABS would otherwise promise. Some manufacturers have therefore implemented a brake assist system that determines that the driver is attempting a "panic stop" (by detecting that the brake pedal was depressed very fast, unlike a normal stop where the pedal pressure would usually be gradually increased, Some systems additionally monitor the rate at the accelerator was released) and the system automatically increases braking force where not enough pressure is applied. Hard or panic braking on bumpy surfaces, because of the bumps causing the speed of the wheel(s) to become erratic may also trigger the ABS. Nevertheless, ABS significantly improves safety and control for drivers in most on-road situations.

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

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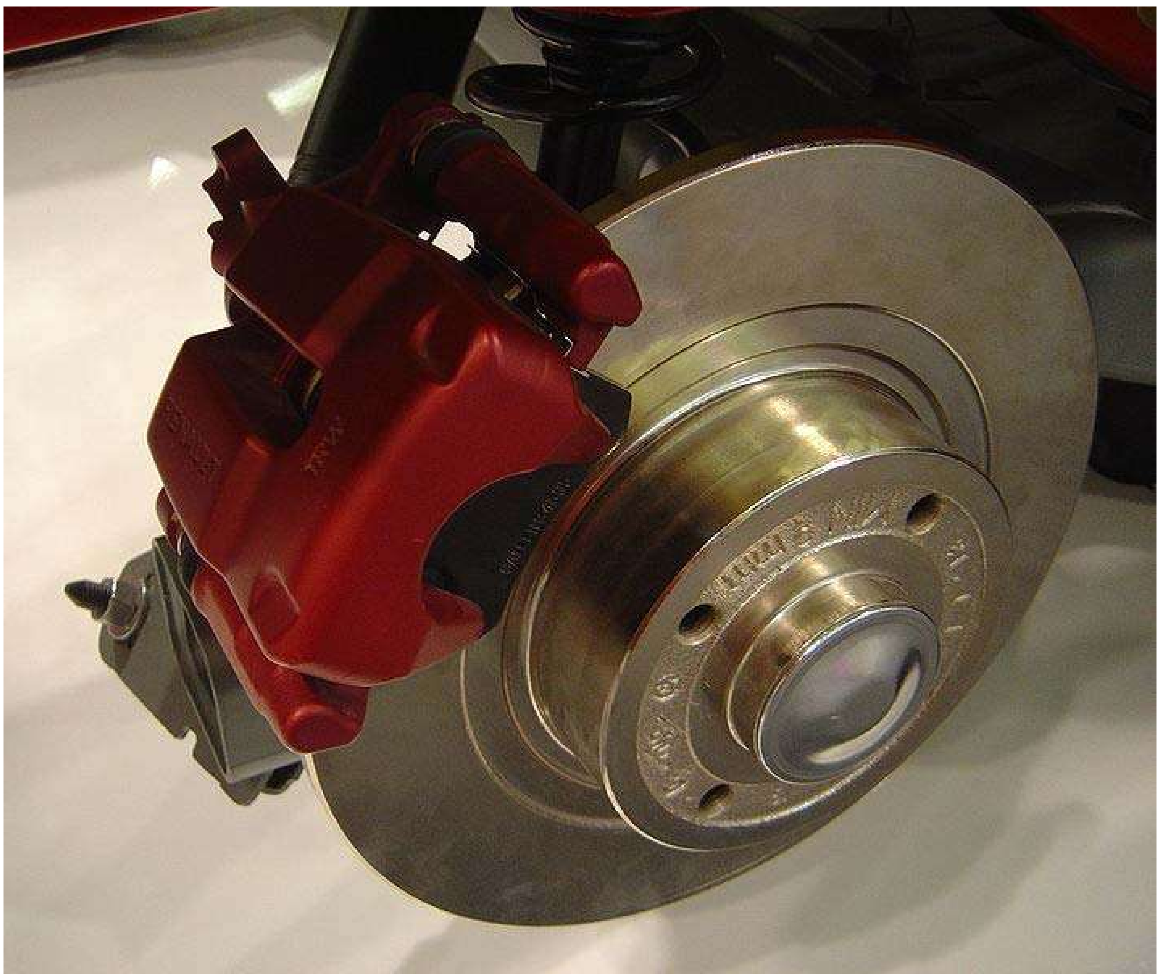
Chapter- 2

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, and the 1956 Triumph TR3 were the first European production cars 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.

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", or 0.03125 inches (0.794 mm), lining thickness above the rivets on riveted pads and 2/32", or .0625 inches (1.59 mm), lining thickness on bonded pads.

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.

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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.

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Chapter- 3

Motorcycle Technology

Motorcycle handlebar

A right clip-on handlebar with twist throttle control, brake lever, and ignition switches.

One-piece handlebars on a Ducati bolted to the triple tree with a short riser

Ape Hangers

Motorcycle handlebar refers to the steering mechanism for motorcycles. Handlebars often support part of the rider's weight, and provide a mounting place for controls such as brake, throttle, clutch, horn, light switch, and rear view mirrors.

Types of handlebar

Handlebars come in a variety of types designed for particular types of riding.

- Ape hanger handlebars rise far above the mounting location so that the rider must reach up to use them, hence the name. They are popular on chopper motorcycles. They are available in heights up to 20 inches. Some jurisdictions have regulations on how high the handgrips may be above the seat.
- Z-bar, any sharply angled handlebar with either long or short straight rise sections, which are sharply angled upward from the mounting points and again sharply angled to the handgrip and control area. Z-bars can be ape hangers, but not all ape hangers are Z-bars.
- Beach bars, similar to cruiser bars, slope back toward the rider to allow a relaxed riding position.

- Clip-ons are popular on sport bikes, in which two separate short handles are attached directly to the fork tubes, as opposed to a standard one-piece handlebar attached to the top of the triple tree.
- Clubman bars are common on cafe bikes. They clamp to the triple tree and are angled forward to give the rider a more aggressive riding position.
- Cruiser handlebars tend to be long and slope towards the rear of the motorcycle so that the rider can sit upright.
- Buckhorn handlebars are a variation on the ape hanger, but shorter, and always with a curved back section directly before the part of the bar that mounts the handgrips and controls. These are often thought to be one of the most comfortable type of handlebar, keeping the arms in a very natural and relaxed position in front of the rider. They are often called "mini-apes" (miniature ape hangers), but a true buckhorn must be rounded on top, never with the sharp angles of a Z-bar on the top.
- Drag bars are nearly straight across to create a forward-leaning and aerodynamic riding position.
- Motocross bars are tubular bars that are clamped onto the triple tree. They are common on motocross and off-road motorcycles, as well as dual-sport, streetfighter, and supermoto bikes.

Construction

Handlebars are made from hollow metal tubing, typically aluminium alloys or chrome plated steel but also of carbon fibre and titanium, shaped to the desired contour. Holes may be drilled for the internal routing of control cables such as brake, throttle, and clutch. Risers hold the handlebars above their mounting position on the upper triple tree or the top of the fork, and may be integrated into the bar itself or separate items.

Bar-end weights are often added to either end of the handlebar to damp vibration by moving the bars' resonant frequency away from that generated by the engine. Electrical heating elements may be added under the handlebar grips to provide comfort to the user in cold weather.

Sizes

There are several size parameters that describe most motorcycle handlebars.

- Width from grip to grip may vary from 30.5 inches to 37 inches.
- Rise above mounting location may vary from 0 inches to 20 inches.
- Pullback, the distance grips are behind their mounting location, may vary from 4.25 inches to 17 inches.
- Diameters vary, commonly 7/8 inch, 1 inch, and 1¼ inches, though oversized bars of 1¼, 1½ and 1¾ inches may reduce to 1 inch at the grips so standard controls may be mounted.

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Motorcycle fairing

1956 NSU World Record Setting Dolphin II

NSU Sportmax 1955, Dustbin Fairing

BMW K1200GT Touring Motorcycle with Full Fairing

A **Motorcycle fairing** is a shell placed over the frame of some motorcycles, especially racing motorcycles and sports bikes, with the primary purpose to reduce air drag. The secondary functions are the protection of the rider from airborne hazards and wind-induced hypothermia and of the engine components in the case of an accident. There may be a **front fairing**, as well as a **rear fairing** component. A motorcycle windshield may be an integral part of the fairing.

The major benefit of a fairing on Sports Touring and Touring motorcycles is a reduction in fuel consumption. The reduction in aerodynamic drag allows for taller gearing which in turn increases engine life.

History

The importance of streamlining was known very early in the 20th century. Some streamlining was seen on racing motorcycles as early as the 1920s. The effects of aerodynamic drag on motorcycles are very significant.

The term **fairing** came into use in aircraft aerodynamics with regard to smoothing airflow over a juncture of components where airflow was disrupted. Early streamlining was often unsuccessful resulting in instability. Handlebar fairings, such as those on Harley-Davidson Tourers, sometimes upset the balance of a motorcycle inducing wobble. The first factory installed full fairing was that installed on the BMW R100RS introduced in 1976. This marked the beginning of widespread adoption of fairings on sports, and touring types of motorcycles.

Types

- **Streamliner**: This is a full fairing as found on land speed record machines. The entire body of the motorcycle is covered to provide the lowest CD ratio attainable. The NSU Dolphin II (Delphin II) is a streamliner.
- **Dustbin fairing**: A single-piece, streamlined shell covering the front half of a motorcycle resembling the nose of an aircraft, sometimes politely referred to as "**torpedo fairing**". It dramatically reduced the frontal drag, but it was banned by FIM from racing in 1958, because it was thought that the frontal point of wind pressure made them highly unstable even with small amounts of yaw. Other reasons cited for the ban were to ensure adequate steering range (lock-to-lock) and stability against crosswinds. FIM regulations forbid streamlining beyond the wheel spindles and require the rider's arms and legs to be visible from the side.

- **Dolphin fairing**: It was called so because in early models the front wheel mud guard streamlined with the rising windshield part of the fairing resembled the dolphin's beak from the side view. They had become the norm since the ban of the dustbins.

Harley-Davidson police motorcycle with "batwing" fairing

- **Full-fairing**: Bodywork that covers both upper and lower portions of the motorcycle, as distinct from a half fairing, which only has an upper section, and the lower half of the motorcycle is exposed. The fairing on a race or sport bike is meant as an aerodynamic aid, so the windscreen is rarely looked through. If the rider is sitting up at speed he will be buffeted by his rapid progress through the air and act as a parachute (slowing the bike) while if the rider lies flat on the tank behind the windscreen he generates much less aerodynamic drag. The high windscreen and handle-bar width of a touring fairing protect the upright rider from the worst of this, and the windscreen is functional. Full fairings can also provide protection to the engine and chassis in the event of a crash where the fairings, rather than the engine covers and/or frame, slide on the road.

Suzuki SV650s with half fairing and an aftermarket belly pan

- **Half-fairing**: Fairing that features a windscreen and fairing extending at least below the handlebars, even as far as down to the sides of the cylinder block, though generally half-fairing doesn't cover the sides of the crankcase or gear box. A number of half-faired models have aftermarket kits available to extend the original half-fairing into a full fairing. Due to the popularity of these kits some manufacturers have started to supply their own full-fairing conversion kits and even offer their half-faired models new with a full-fairing kit fitted at the factory.

- **Quarter fairing**: A windscreen and minimal fairing extending around the headlight fixed to the triple clamp.

- **Belly pan**: Quarter and half fairings are often paired with a belly pan below the engine for diverting air flow away from under the engine to reduce aerodynamic lift, as well as cosmetic reasons.

Originally the fairings were cowlings put around the front of the bike, increasing its frontal area. Gradually they had become an integral part of the design. Modern fairings increase the frontal area at most by 5% compared to a naked machine. Fairing may carry headlights, instruments, and other items. If the fairing is mounted on the frame, mounting equipment on the fairing reduces the weight and rotational inertia of the steering assembly, improving the handling.

Materials

ABS plastic (acrylonitrile butadiene styrene). ABS material is commonly used in original equipment "OE" sport bikes and certain aftermarket fairing manufacturers due to its strong, flexible yet light weight properties. The advantage of ABS over other plastics is that it combines the strength and rigidity of acrylonitrile and styrene with the toughness of butadlene rubber. The proportions of each property vary based on the targeted result.

Fiberglass: A material made of woven fibers, and is used as a reinforcing agent for many polymer products. The composite properly known as glass-reinforced plastic (GRP), is normally referred to by the name of its reinforcing material. (fiberglass). Fiberglass fairings are commonly used on the race track. In most cases fiberglass is lighter, and more durable than ABS Plastic. Damaged fiberglass can be repaired by applying a new layers of woven fiberglass cloth mixed with a polymer such as epoxy, over the damaged area followed sanding and finishing.

ABS production techniques

There are two common methods of producing ABS plastic fairing: injection and compression. Injection Molds-ABS plastic is melted and injected into mold cavity. Constant pressure is applied to allow for material shrinkage. The plastic then cools and hardens in the mold. Injection molds allows for uniform thickness throughout the entire piece. It gives the most accurate end product that fits well. Compression Molds -The plastic is generally preheated is placed into a heated metal mold cavity and pressure is applied to force the plastic to contract and take the shape of the mold. Heat and pressure is kept until the plastic cures the mold. The excess plastic is cut away and removed from the mold.

> Disadvantages: to compression mold include varying product consistency and flashing issues (excess material attached to the molded part needs to be removed where two or more parts of the mold meet)

Swingarm

Plunger suspension on a 1953 BMW R51/3

A **swingarm** (originally known as a swing fork) is the main component of the rear suspension of most modern motorcycles and ATVs. It is used to hold the rear axle firmly while pivoting vertically to allow the suspension to absorb bumps in the road.

Originally there was no rear suspension - the frame design being a stronger version of a bicycle frame. Many types of suspension were tried including Indian's leaf spring suspended swingarm, and Matchless's cantilevered coiled spring swingarm. Immediately prior to and after WWII the **"plunger"** system in which the axle moved up and down two vertical posts became commonplace. In the latter, the movement in each direction was against coiled springs.

Some manufacturers such as Greeves used swingarm designs for the front forks which made them more robust than telescopic forks. The swingarm has also been used for the front suspension of scooters. In this case it aids in simplifying maintenance.

Swingarm types

Swingarms have come in several forms:

Swinging fork - the original version consisting of a pair of parallel pipes holding the rear axle at one end and pivoting at the other. A pair of shock absorbers are mounted just before the rear axle and attached to the frame below the seat rail.

Cantilever - An extension of the swinging fork where a triangulated frame transfers swing arm movement to compress shock absorber/s generally mounted in front of the swingarm. The HRD-Vincent Motorcycle is a famous early form of this type of swingarm, though Matchless used it earlier and Yamaha subsequently. The Harley-Davidson Softail is another form of this swingarm though working in reverse with the shock absorbers being extended rather than compressed.

Single-sided swingarms allow the rear wheel to be mounted like those of an automobile.

BMW's Paralever rear suspension on an R1200RT

Moto Guzzi's *CRDS* variant of the BMW Paralever

Parallelogram Suspension was first introduced commercially in 1985 on the Magni "Le Mans". Magni called the system *Parallelogrammo*. This new suspension system eliminated the torque reactions normally associated with shaft drive motorcycles and enabled the bike to perform similarly to a chain-drive unit. Similar systems have been developed by other manufacturers.

Paralever is BMW's version of the system. It allows the driveshaft to pivot along the same axis as the sprung rear frame due to the addition of second link between the rear drive and transmission. Paralever was originally introduced in 1988 R80GS and R100GS motorcycles and provides a reduction in the phenomenon known as "shaft jacking" where the rear of the motorcycle would lift skyward under certain riding conditions.

Moto Guzzi has introduced a variant of the system it named the *Compact Reactive Drive Shaft* system (patented and named Ca.R.C.). The main difference is that the driveshaft is free to float into its structure providing much softer feedback from transmission. Additionally, the upper arm of the Ca.R.C. is not part of the structure but just a guide to close the geometry of the suspension (it means that, differently from BMW version, the suspension will work also with a broken upper arm).

Drag racing motorcycles will often use longer swingarms to keep their center of gravity, i.e. the engine, as forward as possible to reduce the tendency to wheelie at the start.

Chapter- 4

Driverless Car

A robotic Volkswagen Passat shown at Stanford University

A **driverless car** is a vehicle equipped with an autopilot system, which is capable of driving from one point to another without input from a human operator.

This technology is distinct from vehicles with a remote operator such as Bombardier Advanced Rapid Transit Systems.

The proposed advantages include:

- transporting loads in dangerous zones such as battlefields or disaster-zones.

- reducing the costs and inconvenience of employing drivers (for example for public transport or commercial vehicles),
- managing traffic flow to increase road capacity
- relieving vehicle occupants from driving and navigating chores, so allowing them to concentrate on other tasks or to take rest during their journeys,
- reducing directional steering and velocity errors and corrections implicit in manually controlled vehicles
    - to avoid accidents,
    - to accurately align vehicles with platforms to facilitate disabled access and cargo loading
    - to reduce lane width and safety margins (especially bus-lanes on narrow roads, as in Castellon, Spain)

Some proposed systems depend on infrastructure-based guidance systems (i.e. systems embedded in or near the road itself), while more advanced systems propose to simulate human perception and decision-making during steering of a car via advanced computer software linked to a range of sensors such as cameras, radar and GPS.

While common in science fiction and futurist scenarios for a long time, driverless cars in an unstructured (i.e. non-prepared, constantly changing) free environment are still in their infancy as of 2011, and there are no vehicles in existence that are approved for use in environments where they would encounter normal human drivers - though much progress was made in the late 2000s. Driverless passenger car programs include the 800 million EC EUREKA Prometheus Project on autonomous vehicles, the 2getthere passenger vehicles from the Netherlands, the ARGO research project from Italy, the DARPA Grand Challenge from the USA and Google driverless car.

History

An early representation of the driverless car was Norman Bel Geddes's Futurama exhibit sponsored by General Motors at the 1933 World's Fair, which depicted electric cars powered by circuits embedded in the roadway and controlled by radio.

The history of autonomous vehicles starts in 1977 with the Tsukuba Mechanical Engineering Lab in Japan. On a dedicated, clearly marked course it achieved speeds of up to 30 km/h (20 miles per hour), by tracking white street markers (special hardware was necessary, since commercial computers were much slower than they are today).

In the 1980s a vision-guided Mercedes-Benz robot van, designed by Ernst Dickmanns and his team at the Bundeswehr University of Munich in Munich, Germany, achieved 100 km/h on streets without traffic. Subsequently, the European Commission began funding the 800 million Euro EUREKA Prometheus Project on autonomous vehicles (1987–1995).

Also in the 1980s the DARPA-funded Autonomous Land Vehicle (ALV) in the United States achieved the first road-following demonstration that used laser radar

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(Environmental Research Institute of Michigan), computer vision (Carnegie Mellon University and SRI), and autonomous robotic control (Carnegie Mellon and Martin Marietta) to control a driverless vehicle up to 30 km/h. In 1987, HRL Laboratories (formerly Hughes Research Labs) demonstrated the first off-road map and sensor-based autonomous navigation on the ALV. The vehicle travelled over 600m at 3 km/h on complex terrain with steep slopes, ravines, large rocks, and vegetation.

In 1994, the twin robot vehicles VaMP and Vita-2 of Daimler-Benz and Ernst Dickmanns of UniBwM drove more than one thousand kilometers on a Paris three-lane highway in standard heavy traffic at speeds up to 130 km/h, albeit semi-autonomously with human interventions. They demonstrated autonomous driving in free lanes, convoy driving, and lane changes left and right with autonomous passing of other cars.

In 1995, Dickmanns re-engineered autonomous S-Class Mercedes-Benz took a 1600 km trip from Munich in Bavaria to Copenhagen in Denmark and back, using saccadic computer vision and transputers to react in real time. The robot achieved speeds exceeding 175 km/h on the German Autobahn, with a mean time between human interventions of 9 km, or 95% autonomous driving. Again it drove in traffic, executing manoeuvres to pass other cars. Despite being a research system without emphasis on long distance reliability, it drove up to 158 km without human intervention.

In 1995, the Carnegie Mellon University Navlab project achieved 98.2% autonomous driving on a 5000 km (3000-mile) "No hands across America" trip. This car, however, was semi-autonomous by nature: it used neural networks to control the steering wheel, but throttle and brakes were human-controlled.

From 1996–2001, Alberto Broggi of the University of Parma launched the ARGO Project, which worked on enabling a modified Lancia Thema to follow the normal (painted) lane marks in an unmodified highway. The culmination of the project was a journey of 2,000 km over six days on the motorways of northern Italy dubbed MilleMiglia in Automatico, with an average speed of 90 km/h. 94% of the time the car was in fully automatic mode, with the longest automatic stretch being 54 km. The vehicle had only two black-and-white low-cost video cameras on board, and used stereoscopic vision algorithms to understand its environment, as opposed to the "laser, radar - whatever you need" approach taken by other efforts in the field.

Three US Government funded military efforts known as Demo I (US Army), Demo II (DARPA), and Demo III (US Army), are currently underway. Demo III (2001) demonstrated the ability of unmanned ground vehicles to navigate miles of difficult off-road terrain, avoiding obstacles such as rocks and trees. James Albus at NIST provided the Real-Time Control System which is a hierarchical control system. Not only were individual vehicles controlled (e.g. throttle, steering, and brake), but groups of vehicles had their movements automatically coordinated in response to high level goals.

In 2002, the DARPA Grand Challenge competitions were announced. The 2004 and 2005 DARPA competitions allowed international teams to compete in fully autonomous vehicle races over rough unpaved terrain and in a non-populated suburban setting. The 2007 DARPA challenge, the DARPA urban challenge, involved autonomous cars driving in an urban setting.

In 2008, General Motors stated that they will begin testing driverless cars by 2015, and they could be on the road by 2018.

In 2010 VisLab ran VIAC, the VisLab Intercontinental Autonomous Challenge, a 13,000 km test run of autonomous vehicles. The four driverless electric vans successfully ended the drive from Italy to China via the arriving at the Shanghai Expo on 28 October.

Recent projects

The work done so far varies significantly in its ambition and its demands in terms of modification of the infrastructure. Broadly, there are three approaches:

- Fully autonomous vehicles
- Various enhancements to the infrastructure (either an entire area, or specific lanes) to create a self-driving closed system.
- "assistance" systems that incrementally remove requirements from the human driver (e.g. improvements to cruise control)

An important concept that cuts across several of the efforts is vehicle **platoons**. In order to better utilize road-space, vehicles are assembled into ad-hoc train-like "platoons", where the driver (either human or automatic) of the first vehicle makes all decisions for the entire platoon. All other vehicles simply follow the lead of the first vehicle.

Fully autonomous

Fully autonomous driving requires a car to drive itself to a pre-set target using unmodified infrastructure. The final goal of safe door-to-door transportation in arbitrary environments is not yet reached though.

Vehicles for paved roads

- Google driverless car, with a test fleet of autonomous vehicles that by October 2010 have driven 140,000 miles (230,000 km) without any incidents.
- The 800 million Euro EUREKA Prometheus Project on autonomous vehicles (1987–1995). Among its culmination points were the twin robot vehicles VITA-2 and VaMP of Daimler-Benz and Ernst Dickmanns, driving long distances in heavy traffic.
- The VIAC Challenge, in which 4 vehicles drove from Italy to China on a 13,000 kilometres (8,100 mi) trip with only limited occasions intervene by human, such as in the Moscow traffic jams and when passing toll stations. This is the longest-ever trip by an unmanned vehicle.

- The third competition of the DARPA Grand Challenge held in November 2007. 53 teams qualified initially, but after a series of qualifying rounds, only eleven teams entered the final race. Of these, six teams completed navigating through the non-populated urban environment, and the Carnegie Mellon University team won the $2 million prize.
- The ARGO vehicle is the predecessor of the BRAiVE vehicle, both from the University of Parma's VisLab. Argo was developed in 1996 and demonstrated to the world in 1998; BRAiVE was developed in 2008 and firstly demonstrated in 2009 at the IEEE IV conference in Xi'an, China.
- Stanford Racing Team's Junior car is an autonomous driverless car for paved roads. It is intended for civilian use.
- The Volkswagen Golf GTI 53+1 is a modified Volkswagen Golf GTI capable of autonomous driving. The Golf GTI 53+1 features a implemented system that can be integrated into any car. This system is based around the MicroAutoBox from dSpace. This, as it was intended to test VW hardware without a human driver (for consistent test results).
- The Audi TTS Pikes Peak is a modified Audi TTS, working entirely on GPS, and thus without additional sensors. The car was designed by Burkhard Huhnke of Volkswagen Research.
- Stadtpilot, Technical University Braunschweig
- AutoNOMOS - part of the Artificial Intelligence Group of the Freie Universität Berlin

Free-ranging vehicles

There are four clusters of activity relating to free-ranging off-road cars. Some of these projects are military-oriented.

- US military DARPA Grand Challenge

  The US Department of Defense announced on the July 30, 2002 a "Grand Challenge", for US-based teams to produce a vehicle that could autonomously navigate and reach a target in the desert of the south western USA.
  In March 2004, the first competition was held, for a prize-money of $1 million. Not one of the 25 entrants completed the course. However, in the second competition held in October 2005 five different teams completed the 135-mile (217 km) course, and the Stanford University team won the $2 million prize.
  November 3rd, 2007, the third competition was held and $3.5 million dollar in cash prizes, trophies and medals were awarded. Six driverless vehicles were able to complete the 55 miles (89 km) of urban traffic in the 2007 DARPA Urban Challenge rally style race. 1st Place - Tartan Racing, Pittsburgh, PA; 2nd Place - Stanford Racing Team, Stanford, CA; 3rd Place - Victor Tango, Blacksburg, VA.

- European Land-Robot Trial (ELROB)

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The German Department of Defense held an exhibition trade show (ELROB) for demonstrating automated vehicles in May 2006. The event included various military automated and remotely-operated robots, for various military uses. Some of the systems on display could be ordered and implemented immediately. In August 2007 a civilian version of the event was held in Switzerland.
The Smart team from Switzerland presented "a Vehicle for Autonomous Navigation and Mapping in Outdoor Environments".

- The Israeli Military-Industrial Complex

  As a followup from its success with Unmanned Combat Air Vehicles, and following the construction of the Israeli West Bank barrier there has been significant interest in developing a fully automated border-patrol vehicle. Two projects, by Elbit Systems and Israel Aircraft Industries are both based on the locally-produced Armored "Tomcar" and have the specific purpose of patrolling barrier fences against intrusions.
  The "SciAutonics II" team in the 2004 DARPA Challenge used Elbit's version of the Tomcar.

- Korean Autonomous Vehicle Competition (AVC) organized by Hyundai Kia Automotive Group

  In November 2010, the first competition was held, for a winning prize-money of $100 thousand, and the Hanyang University A1 team won the $100 thousand prize.

Pre-built infrastructure

The following projects were conceived as practical attempts to use available technology in an incremental manner to solve specific problems, like transport within a defined campus area, or driving along a stretch of motorway. The technologies are proven, and the main barrier to widespread implementation is the cost of deploying the infrastructure. Such systems already function in many airports, on railroads, and in some European towns.

Dual mode transit - monorail

There is a family of projects, all currently still at the experimental stage, that would combine the flexibility of a private automobile with the benefits of a monorail system. The idea is that privately-owned cars would be built with the ability to dock themselves onto a public monorail system, where they become part of a centrally managed, fully computerized transport system—more akin to a driverless train system (as already found in airports) than to a driverless car. This idea is also known as Dual mode transit.

Groups working on this concept are:

- RUF (Denmark)
- BiWay (UK)
- ATN (New Zealand)
- TriTrack (Texas, United States)

Automated highway systems

Automated highway systems (**AHS**) are an effort to construct special lanes on existing highways that would be equipped with magnets or other infrastructure to allow vehicles to stay in the center of the lane, while communicating with other vehicles (and with a central system) to avoid collision and manage traffic. Like the dual-mode monorail, the idea is that cars remain private and independent, and just use the AHS system as a quick way to move along designated routes. AHS allows specially equipped cars to join the system using special 'acceleration lanes' and to leave through 'deceleration lanes'. When leaving the system each car verifies that its driver is ready to take control of the vehicle, and if that is not the case, the system parks the car safely in a predesignated area.

Some implementations use radar to avoid collisions and coordinate speed.

One example that uses this implementation is the AHS demo of 1997 near San Diego, sponsored by the US government, in coordination with the State of California and Carnegie Mellon University. The test site is a 12-kilometer, high-occupancy-vehicle (HOV) segment of Interstate 15, 16 kilometers north of downtown San Diego. The event generated much press coverage.

This concerted effort by the US government seems to have been pretty much abandoned because of social and political forces, above all else the desire to create a less futuristic and more marketable solution.

As of 2007, a three-year project is underway to allow robot controlled vehicles, including buses and trucks, to use a special lane along 20 Interstate 805. The intention is to allow the vehicles to travel at shorter following distances and thereby allow more vehicles to use the lanes. The vehicles will still have drivers since they need to enter and exit the special lanes. The system is being designed by Swoop Technology, based in San Diego county.

Free-ranging on grid

Frog Navigation Systems (the Netherlands) applies the FROG (**free-ranging on grid**) technology. The technology consists of a combination of autonomous vehicles and a supervisory central system. The company's purpose-built electric vehicles locate themselves using odometry readings, recalibrating themselves occasionally using a "maze" of magnets embedded in the environment, and GPS. The cars avoid collisions with obstacles located in the environment using laser (long range) and ultra-sonic (short-range) sensors.

The vehicles are completely autonomous and plan their own routes from A to B. The supervisory system merely administers the operations and directs traffic where required. The system has been applied both indoors and outdoors, and in environments where 100+ automated vehicles are operational (container port). At this time the system is not suited yet for running the sheer number of vehicles encountered in urban settings. The company also has no intention of developing such technology at this time.

The FROG system is deployed for industrial purposes in factory sites, and is marketed as a pilot public transport system in the city of Capelle aan den IJssel by its subsidiary 2getthere. This system experienced an accident that proved to be caused by a Human error.

Frog Navigation Systems is one of few fully commercial companies in this field.

Driver-assistance

Though these products and projects do not aim explicitly to create a fully autonomous car, they are seen as incremental stepping-stones in that direction. Many of the technologies detailed below will probably serve as components of any future driverless car — meanwhile they are being marketed as gadgets that assist human drivers in one way or another. This approach is slowly trickling into standard cars (e.g. improvements to cruise control).

Driver-assistance mechanisms are of several distinct types, sensorial-informative, actuation-corrective, and systemic.

Sensorial-informative

These systems warn or inform the driver about events that may have passed unnoticed, such as

- Lane Departure Warning System (LDWS), for example from Iteris or Mobileye N.V.
- Rear-view alarm, to detect obstacles behind.
- Visibility aids for the driver, to cover blind spots and enhanced vision systems such as radar, wireless vehicle safety communications and night vision.
- Infrastructure-based, driver warning/information-giving systems, such as those developed by the Japanese government

Actuation-corrective

These systems modify the driver's instructions so as to execute them in a more effective way, for example the most widely deployed system of this type is ABS; conversely power steering is not a control mechanism, but just a convenience - it is not involved in decision making.

- Anti-lock braking system (ABS) (also Emergency Braking Assistance (EBA), often coupled with Electronic brake force distribution (EBD), which prevents the brakes from locking and losing traction while braking. This shortens stopping distances in most cases and, more importantly, allows the driver to steer the vehicle while braking.
- Traction control system (TCS) actuates brakes or reduces throttle to restore traction if driven wheels begin to spin.
- Four wheel drive (AWD) with a centre differential. Distributing power to all four wheels lessens the chances of wheel spin. It also suffers less from oversteer and understeer.
- Electronic Stability Control (ESC) (also known for Mercedes-Benz proprietary Electronic Stability Program (ESP), Acceleration Slip Regulation (ASR) and Electronic differential lock (EDL)). Uses various sensors to intervene when the car senses a possible loss of control. The car's control unit can reduce power from the engine and even apply the brakes on individual wheels to prevent the car from understeering or oversteering.
- Dynamic steering response (DSR) corrects the rate of power steering system to adapt it to vehicle's speed and road conditions.

A review of the overall "feel" to actuation-correction in a Jaguar XK convertible.

Driver-assistance preview from Popular Science (dated 2004).

Note: The electronic differential lock (EDL) employed by Volkswagen is not - as the name suggests - a differential lock at all. Sensors monitor wheel speeds, and if one is rotating substantially faster than the other (i.e. slipping) the EDL system momentarily brakes it. This effectively transfers all the power to the other wheel.

Systemic

- Automatic parking: e.g. technology from Ford or Toyota selling for $700, with a 70% take-up rate. The Lexus LS can park itself (parallel/reverse) via the 'Advanced Parking Guidance System' – though only controlling the steering.
- Follow another car on a motorway ("Enhanced" or "adaptive" cruise control), like The Ford or Vauxhall(GM).
- Nissan's "Distance Control assist"
- Dead Man's Switch; there is a move to introduce deadman's braking into automotive application, primarily heavy vehicles, and there may also be a need to add penalty switches to cruise controls.

Existing and missing technologies

In order to drive a car, a system would need to:

1. Understand its immediate environment (Sensors)
2. Know where it is and where it wants to go (Navigation)
3. Find its way in the traffic (Motion planning)
4. Operate the mechanics of the vehicle (Actuation)

Arguably, 2½ of these problems are already solved: Navigation and Actuation completely, and Sensors partially, but improving fast. The main unsolved part is the motion planning.

Sensors

Sensors employed in driverless cars vary from the minimalist ARGO project's monochrome stereoscopy to Mobileye's inter-modal (video, infra-red, laser, radar) approach. The minimalist approach imitates the human situation most closely, while the multi-modal approach is "greedy" in the sense that it seeks to obtain as much information as is possible by current technology, even at the occasional cost of one car's detection system interfering with another's.

Mobileye N.V. is a technology company that focuses on the development of vision-based Advanced Driver Assistance Systems (ADAS) providing warnings for collision prevention and mitigation. Mobileye offers a wide range of driver safety solutions combining artificial vision image processing, multiple technological applications and information technology. Mobileye's vehicle detection systems, are currently only used for driver assistance, but are eminently suitable for a full-fledged driverless car. This video demonstrates the capabilities of the system: all pedestrians, cars, motorbikes etc. are clearly displayed in video, with a frame around them and the distance between "our" car and the object observed. The system also detects the objects' motion (direction and speed) and can so calculate relative speeds, and predict collisions.

- Japanese infra-red article
- some things from the DARPA challenge....
- Road-sign recognition

Navigation

The ability to plot a route from where the vehicle is to where the user wants to be has been available for several years. These systems, based on the US military's Global Positioning System are now available as standard car fittings, and use satellite transmissions to ascertain the current location, and an on-board street database to derive a route to the target. The more sophisticated systems also receive radio updates on road blockages, and adapt accordingly. There are also sensors that greatly affect the whole nature of it.

Motion planning

- PMP + SLAMMOT

This is current research problem.

Control of vehicle

As automotive technology matures, more and more functions of the underlying engine, gearbox etc. are no longer directly controlled by the driver by mechanical means, but rather via a computer, which receives instructions from the driver as inputs and delivers the desired effect by means of electronic throttle control, and other drive-by-wire elements. Therefore, the technology for a computer to control all aspects of a vehicle is well understood.

Work done in simulation

While developing control systems for real cars is very costly in terms of both time and money, much work can be done in simulations of various complexity. Systems developed using simpler simulators can gradually be transferred to more complex simulators, and in the end to real vehicles. Some approaches that rely on learning requires starting in a simulation to be viable at all, for example evolutionary robotics approaches.

Social impact

Driverless cars may yield advantages of increasing roadway capacity by reducing the distances between cars, reduce congestion by efficiently controlling the flow of traffic, and increase safety by eliminating driver error.

According to urban designer and futurist Michael E. Arth, driverless electric vehicles—in conjunction with the increased use of virtual reality for work, travel, and pleasure—could reduce the world's vehicles (estimated to be 800,000,000) to a fraction of that number within a few decades. Arth claims that this would be possible if almost all private cars requiring drivers, which are not in use and parked 90% of the time, would be traded for public self-driving taxis that would be in near constant use. This would also allow for getting the appropriate vehicle for the particular need—a bus could come for a group of people, a limousine could come for a special night out, and a Segway could come for a short trip down the street for one person. Children could be chauffeured in supervised safety, DUIs would no longer exist, and 41,000 lives could be saved each year in the U.S. alone.

WORLD TECHNOLOGIES

Chapter- 5

Automotive Steering Technologies

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

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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.

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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

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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 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.

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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.

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Hydraulic power steering

A power steering fluid reservoir and pulley driven pump

Hydraulic power steering (HPS) is a hydraulic system for reducing the steering effort on vehicles by using hydraulic pressure to assist in turning the wheels. It is intended to provide for easier driving direction control of the car while preserving "feedback", stability and unambiguity of the trajectory specified.

The steering booster is arranged so that should the booster fail, the steering will continue to work (although the wheel will feel heavier).

Construction

The steering booster consists of the following basic elements:

- Steer torque detector
- Controlled pressure distributor case
- Hydraulic booster pump
- Tank with a working liquid
- Connection hoses

The working liquid, also called "hydraulic fluid" or "oil", is the medium by which pressure is transmitted. Common working liquids are based on mineral oil.

The steering booster works as follows:

The working liquid travels from a tank to the pump inlet opening due to gravity. The liquid travels under pressure from the pump to the distributive gear. The distributive gear has an elastic element, a torsion bar or a spring, which causes the cross-section area of bypass holes (drain ports) to vary in proportion to the effort applied to the steering wheel.

In a neutral position section of the bores passing a liquid in the right and left part of the hydrocylinder is equal to section of bores issued a liquid from them in a tank. The pressures in the right and the left parts of the hydrocylinder are equal too.

When the wheel is turned, because of forces of friction and other forces there is an effort deforming an elastic element, changing the section of bores of the distributive gear and, thereby, pressure in the right and left parts of the hydrocylinder. For pressure restriction in the pump there is a restrictive valve, which is adjusted on different cars in a range from 7 to 13 MPa.

Operation

To avoid dangerous situations under abnormal conditions where the car's steering system suddenly stops working, it is necessary to check the amount of oil in the HPS tank periodically. At an appreciable drop of its level which is not explained by temperature, angle of rotation of wheels, car inclination, etc., it is necessary to check leakproofness of the hydraulic circuit: hoses, places of their inputs etc. To increase the lifetime of the HPS elements and system as a whole, it is recommended to replace the power steering oil completely once every 1-2 years. Manuals of the majority of cars prohibit keeping the wheels in an extreme position for more than 5 seconds as it can lead to the oil heating up to its boiling point, and to the breakdown of the HPS.

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Chapter- 6

Hydrogen Vehicle

Honda FCX Clarity, a hydrogen fuel cell demonstration vehicle introduced in 2008

A **hydrogen vehicle** is an alternative fuel vehicle that uses hydrogen as its onboard fuel for motive power. The term may refer to a personal transportation vehicle, such as an automobile, or any other vehicle that uses hydrogen in a similar fashion, such as an aircraft. The power plants of such vehicles convert the chemical energy of hydrogen to mechanical energy either by burning hydrogen in an internal combustion engine, or by reacting hydrogen with oxygen in a fuel cell to run electric motors. Widespread use of hydrogen for fueling transportation is a key element of a proposed hydrogen economy.

Hydrogen fuel does not occur naturally on Earth and thus is not an energy source, but is an energy carrier. Currently it is most frequently made from methane or other fossil fuels. However, it can be produced from a wide range of sources (such as wind, solar, or nuclear) that are intermittent, too diffuse or too cumbersome to directly propel vehicles. Integrated wind-to-hydrogen plants, using electrolysis of water, are exploring technologies to deliver costs low enough, and quantities great enough, to compete with traditional energy sources.

Many companies are working to develop technologies that might efficiently exploit the potential of hydrogen energy for mobile uses. The attraction of using hydrogen as an energy currency is that, if hydrogen is prepared without using fossil fuel inputs, vehicle propulsion would not contribute to carbon dioxide emissions. The drawbacks of hydrogen use are low energy content per unit volume, high tankage weights, the storage, transportation and filling of gaseous or liquid hydrogen in vehicles, the large investment in infrastructure that would be required to fuel vehicles, and the inefficiency of production processes.

Vehicles

Buses, trains, PHB bicycles, canal boats, cargo bikes, golf carts, motorcycles, wheelchairs, ships, airplanes, submarines, and rockets can already run on hydrogen, in various forms. NASA uses hydrogen to launch Space Shuttles into space. There is even a working toy model car that runs on solar power, using a regenerative fuel cell to store energy in the form of hydrogen and oxygen gas. It can then convert the fuel back into water to release the solar energy.

The current land speed record for a hydrogen-powered vehicle is 286.476 mph (461.038 km/h) set by Ohio State University's Buckeye Bullet 2, which achieved a "flying-mile" speed of 280.007 mph (450.628 km/h) at the Bonneville Salt Flats in August 2008. For production-style vehicles, the current record for a hydrogen-powered vehicle is 333.38 km/h (207.2 mph) set by a prototype Ford Fusion Hydrogen 999 Fuel Cell Race Car at Bonneville Salt Flats in Wendover, Utah in August 2007. It was accompanied by a large compressed oxygen tank to increase power. Honda has also created a concept called the FC Sport, which may be able to beat that record if put into production.

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Automobiles

Sequel, a fuel cell-powered vehicle from General Motors

Ford Edge hydrogen-electric plug-in hybrid concept

Many companies are currently researching the feasibility of building hydrogen cars, and some automobile manufacturers have begun developing hydrogen cars. Funding has come from both private and government sources. However, the Ford Motor Company has dropped its plans to develop hydrogen cars, stating that "The next major step in Ford’s plan is to increase over time the volume of electrified vehicles". Similarly, French Renault-Nissan announced in 2009 that it is cancelling its hydrogen car R&D efforts. As of October 2009, General Motors CEO Fritz Henderson noted that GM had reduced its hydrogen program because the cost of building hydrogen cars was too high. "It's still a ways away from commercialization", he said. The "Volt will likely cost around $40,000 while a hydrogen vehicle would cost around $400,000. Most hydrogen cars are currently only available as demonstration models for lease in limited numbers and are not yet ready for general public use. The estimated number of hydrogen-powered cars in the United States was 200 as of October 2009, mostly in California.

Honda introduced its fuel cell vehicle in 1999 called the FCX and have since then introduced the second generation FCX Clarity. In 2007 at the Greater Los Angeles Auto Show, Honda unveiled the first production model of the FCX Clarity. Limited marketing of the FCX Clarity began in June 2008 in the United States, and it was introduced in Japan in November 2008. The FCX Clarity is available in the U.S. only in Los Angeles Area, where 16 hydrogen filling stations are available, and as of July 2009, 10 drivers had leased the Clarity for US$600 a month. Honda stated that it could start mass producing vehicles based on the FCX concept by the year 2020 and reaffirmed, in 2009, that it

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continues to put resources into hydrogen fuel cell development, which it sees as "a better long term bet than batteries and plug-in vehicles".

In 2008, Hyundai announced its intention to produce 500 FC vehicles by 2010 and to start mass production of its FC vehicles in 2012. In early 2009, Daimler announced plans to begin its FC vehicle production in 2009 with the aim of 100,000 vehicles in 2012-2013. In 2009, Nissan started testing a new FC vehicle in Japan.

In September 2009, Daimler, Ford, General Motors, Honda, Hyundai, Kia, Renault, Nissan and Toyota issued a joint statement about their undertaking to further develop and launch fuel-cell electric vehicles as early as 2015.

In February 2010 Lotus Cars announced that it was developing a fleet of hydrogen taxis in London, with the hope of them being ready to trial by the 2012 Olympic Games. London's deputy mayor, Kit Malthouse, said he hoped six filling stations would be available and that around 20-50 taxis would be in operation by then, as well as 150 hydrogen-powered buses.

In March 2010, General Motors said it had not abandoned the fuel-cell technology and still targeted to introduce hydrogen vehicles to retail customers by 2015. Charles Freese, GM’s executive director of global powertrain engineering, stated that the company believes that both fuel-cell vehicles and battery electric vehicles are needed for reduction of greenhouse gases and reliance on oil, and the U.S. should follow Germany and Japan in adopting a more uniform strategy on advanced technology options. Both have announced plans to open 1,000 hydrogen fuel stations.

Fuel cells are most likely going to be using PEM cells (polymer electrolyte Membrane). There are several types that include Alkaline fuel cell, phosphoric acid fuel cell, molten carbonate fuel cell, and direct methanol fuel cell. As of now the PEM fuel cell has been the progressed and is better suited for practical use. The Direct Methanol fuel cell also looks promising for the future, but it’s been found much recently and thus behind in development.

Buses

Fuel cell buses (as opposed to hydrogen fueled buses) are being trialed by several manufacturers in different locations. The Fuel Cell Bus Club is a global fuel cell bus testing collaboration.

Hydrogen was first stored in roof mounted tanks, although models are now incorporating onboard tanks. Some double deck models uses between floor tanks.

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Hydrogen bicycle

Bicycles

Pearl Hydrogen Power Sources of Shanghai, China, unveiled a hydrogen bicycle at the 9th China International Exhibition on Gas Technology, Equipment and Applications in 2007.

Motorcycles and scooters

ENV develops electric motorcycles powered by a hydrogen fuel cell, including the Crosscage and Biplane. Other manufacturers as Vectrix are working on hydrogen scooters. Finally, hydrogen fuel cell-electric hybrid scooters are being made such as the Suzuki Burgman Fuel cell scooter and the FHybrid.

Quads

Autostudi S.r.l's H-Due is a hydrogen-powered quad, capable of transporting 1-3 passengers.

Tractors

A concept for a hydrogen powered tractor has been proposed.

Airplanes

The Boeing Fuel Cell Demonstrator powered by a hydrogen fuel cell

Companies such as Boeing, Lange Aviation, and the German Aerospace Center pursue hydrogen as fuel for manned and unmanned airplanes. In February 2008 Boeing tested a manned flight of a small aircraft powered by a hydrogen fuel cell. Unmanned hydrogen planes have also been tested. For large passenger airplanes however, *The Times* reported that "Boeing said that hydrogen fuel cells were unlikely to power the engines of large passenger jet airplanes but could be used as backup or auxiliary power units onboard."

In July 2010 Boeing unveiled its hydrogen powered Phantom Eye UAV, powered by two Ford internal combustion engines that have been converted to run on hydrogen.

In Europe, the Reaction Engines A2 has been proposed to use the thermodynamic properties of liquid hydrogen to achieve very high speed, long distance (antipodal) flight by burning it in a precooled jet engine.

Fork trucks

A **HICE forklift** or **HICE lift truck** is a hydrogen fueled, internal combustion engine powered industrial forklift truck used for lifting and transporting materials. The first production HICE forklift truck based on the Linde X39 Diesel was presented at an exposition in Hannover on May 27, 2008. It used a 2.0 litre, 43 kW diesel internal combustion engine converted to use hydrogen as a fuel with the use of a compressor and direct injection. The hydrogen tank is filled with 26 liters of hydrogen at 350 bar pressure.

Rockets

Rockets employ hydrogen because hydrogen gives the highest effective exhaust velocity as well as giving a lower net weight of propellant than other fuels. It performs particularly well on upper stages, although it has been used on lower stages as well, usually in conjunction with a dense fuel booster.

The main disadvantage of hydrogen in this application is the low density and deeply cryogenic nature, requiring insulation- this makes the hydrogen tanks relatively heavy, which greatly offsets much of the otherwise overwhelming advantages for this application.

The main advantage of hydrogen is that although the velocity change of a stage employing it is little different to a stage using denser fuel, the lift-off weight of the stage is less. Particularly when used for upper stages this permits a lighter rocket for any given payload.

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Internal combustion vehicle

Hydrogen internal combustion engine cars are different from hydrogen fuel cell cars. The hydrogen internal combustion car is a slightly modified version of the traditional gasoline internal combustion engine car. These hydrogen engines burn fuel in the same manner that gasoline engines do.

Francois Isaac de Rivaz designed in 1807 the first hydrogen-fueled internal combustion engine. Paul Dieges patented in 1970 a modification to internal combustion engines which allowed a gasoline-powered engine to run on hydrogen US 3844262.

Mazda has developed Wankel engines burning hydrogen. The advantage of using ICE (internal combustion engine) like Wankel and piston engines is the cost of retooling for production is much lower. Existing-technology ICE can still be applied for solving those problems where fuel cells are not a viable solution insofar, for example in cold-weather applications.

HICE forklift trucks have been demonstrated based on converted diesel internal combustion engines with direct injection.

Fuel cell

While fuel cells themselves are potentially highly energy efficient, and working prototypes were made by Francis Thomas Bacon in 1959 and Roger E. Billings in the

1960s, at least four technical obstacles and other political considerations exist regarding the development and use of a fuel cell-powered hydrogen car.

Fuel cell cost

Currently, hydrogen fuel cells are costly to produce and are fragile. As of October 2009, *Fortune* magazine estimated the cost of producing the Honda Clarity at $300,000 per car. Engineers are studying how to produce inexpensive fuel cells that are robust enough to survive the bumps and vibrations that all automobiles experience. Also, many designs require rare substances such as platinum as a catalyst in order to work properly. Such a catalyst can also become contaminated by impurities in the hydrogen supply. In the past few years, however, a nickel-tin nanometal catalyst has been under development which may lower the cost of cells.

Fuel cells are generally priced in USD/kW, and data is scarce regarding costs. Ballard Power Systems is virtually alone in publishing such data. Their 2005 figure was $73 USD/kW (based on high volume manufacturing estimates), which they said was on track to achieve the U.S. DoE's 2010 goal of $30 USD/kW. This would achieve closer parity with internal combustion engines for automotive applications, allowing a 100 kW fuel cell to be produced for $3000. 100 kW is about 134 hp.

Freezing conditions

Temperatures below freezing (32 °F or 0 °C) are a concern with fuel cells operations. Operational fuel cells have an internal vaporous water environment that could solidify if the fuel cell and contents are not kept above 0° Celsius (32°F). Most fuel cell designs are not as yet robust enough to survive in below-freezing environments. Frozen solid, especially before start up, they would not be able to begin working. Once running though, heat is a byproduct of the fuel cell process, which would keep the fuel cell at an adequate operational temperature to function correctly. This makes startup of the fuel cell a concern in cold weather operation. Places such as Alaska where temperatures can reach −40 °C (−40 °F) at startup would not be able to use early model fuel cells. Ballard announced in 2006 that it had already hit the U.S. DoE's 2010 target for cold weather starting which was 50% power achieved in 30 seconds at -20 °C.

Just as early gasoline cars struggled with efficiency and reliability problems before becoming universally practical, so fuel cells have to work out startup and long term reliability problems. Early gasoline engines had the characteristic of higher heat dissipation once running, whereas fuels cells emit less heat, making the warm up process somewhat less quick.

Service life

Although service life is coupled to cost, fuel cells have to be compared to existing machines with a service life in excess of 5000 hours for stationary and light-duty. Marine PEM fuel cells reached the target in 2004. Current service life is 7,300 hours under cycling conditions. Research is going on especially for heavy duty like in the bus trials which are targeted up to a service life of 30,000 hours.

Hydrogen

Hydrogen does not come as a pre-existing source of energy like fossil fuels, but is first produced and then stored as a carrier, much like a battery. Hydrogen for vehicle uses needs to be produced using either renewable or non-renewable energy sources. A suggested benefit of large-scale deployment of hydrogen vehicles is that it could lead to decreased emissions of greenhouse gases and ozone precursors.

According to the United States Department of Energy "Producing hydrogen from natural gas does result in some greenhouse gas emissions. When compared to ICE vehicles using gasoline, however, fuel cell vehicles using hydrogen produced from natural gas reduce greenhouse gas emissions by 60%. While methods of hydrogen production that do not use fossil fuel would be more sustainable, currently renewable energy represents only a small percentage of energy generated, and power produced from renewable sources can be used in electric vehicles and for non-vehicle applications.

The challenges facing the use of hydrogen in vehicles include production, storage, transport and distribution. The well-to-wheel efficiency for hydrogen, because of all these challenges will not exceed 25%.

Production

The molecular hydrogen needed as an on-board fuel for hydrogen vehicles can be obtained through many thermochemical methods utilizing natural gas, coal (by a process known as coal gasification), liquefied petroleum gas, biomass (biomass gasification), by a process called thermolysis, or as a microbial waste product called biohydrogen or Biological hydrogen production. 95% of hydrogen is produced using natural gas, and 85% of hydrogen produced is used to remove sulfur from gasoline. Hydrogen can also be produced from water by electrolysis or by chemical reduction using chemical hydrides or aluminum. Current technologies for manufacturing hydrogen use energy in various forms, totaling between 25 and 50 percent of the higher heating value of the hydrogen fuel, used to produce, compress or liquefy, and transmit the hydrogen by pipeline or truck.

Environmental consequences of the production of hydrogen from fossil energy resources include the emission of greenhouse gases, a consequence that would also result from the on-board reforming of methanol into hydrogen. Studies comparing the environmental consequences of hydrogen production and use in fuel-cell vehicles to the refining of petroleum and combustion in conventional automobile engines find a net reduction of ozone and greenhouse gases in favor of hydrogen. Hydrogen production using renewable energy resources would not create such emissions or, in the case of biomass, would create near-zero net emissions assuming new biomass is grown in place of that converted to hydrogen. However the same land could be used to create Biodiesel, usable with (at most) minor alterations to existing well developed and relatively efficient diesel engines. In either case, the scale of renewable energy production today is small and would need to be greatly expanded to be used in producing hydrogen for a significant part of transportation needs. As of December 2008, less than 3 percent of U.S. electricity was produced from renewable sources, not including dams. In a few countries, renewable sources are being used more widely to produce energy and hydrogen. For example, Iceland is using geothermal power to produce hydrogen, and Denmark is using wind.

Storage

Compressed hydrogen storage mark

Hydrogen has a very low volumetric energy density at ambient conditions, equal to about one-third that of methane. Even when the fuel is stored as liquid hydrogen in a cryogenic tank or in a compressed hydrogen storage tank, the volumetric energy density (megajoules per liter) is small relative to that of gasoline. Hydrogen has a three times higher energy density by mass compared to gasoline (143 MJ/kg versus 46.9 MJ/kg). Some research has been done into using special crystalline materials to store hydrogen at greater densities and at lower pressures. A recent study by Dutch researcher Robin Gremaud has shown that metal hydride hydrogen tanks are actually 40 to 60-percent lighter than an equivalent energy battery pack on an electric vehicle permitting greater range for H2 cars.

Infrastructure

Hydrogen car fueling

Hydrogen fueling

The hydrogen infrastructure consists mainly of industrial hydrogen pipeline transport and hydrogen-equipped filling stations like those found on a hydrogen highway. Hydrogen stations which are not situated near a hydrogen pipeline get supply via hydrogen tanks, compressed hydrogen tube trailers, liquid hydrogen tank trucks or dedicated onsite production.

Hydrogen use would require the alteration of industry and transport on a scale never seen before in history. For example, according to GM, 70% of the U.S. population lives near a hydrogen-generating facility but has just about no access to hydrogen, despite its wide availability for commercial use. The distribution of hydrogen fuel for vehicles in the U.S. would require new hydrogen stations costing, by some estimates, 20 billion dollars. and 4.6 billion in the EU. Other estimates place the cost as high as half trillion U.S. dollars in the United States alone.

The California Hydrogen Highway is an initiative to build a series of hydrogen refueling stations along that state. These stations are used to refuel hydrogen vehicles such as fuel cell vehicles and hydrogen combustion vehicles. As of July 2007, California had 25 stations in operation. As of January 2011, there were between 25 and 30, mostly in and around Los Angeles.

South Carolina also has a hydrogen freeway in the works. There are currently two hydrogen fueling stations, both in Aiken and Columbia, SC. Additional stations are expected in places around South Carolina such as Charleston, Myrtle Beach, Greenville, and Florence. According to the South Carolina Hydrogen & Fuel Cell Alliance, the Columbia station has a current capacity of 120 kg a day, with future plans to develop on-site hydrogen production from electrolysis and reformation. The Aiken station has a current capacity of 80 kg. There is extensive funding for Hydrogen fuel cell research and infrastructure in South Carolina. The University of South Carolina, a founding member of the South Carolina Hydrogen & Fuel Cell Alliance, received 12.5 million dollars from the Department of Energy for its Future Fuels Program.

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Codes and standards

Hydrogen codes and standards are codes and standards (RCS) for hydrogen fuel cell vehicles.

Additional to the codes and standards for hydrogen vehicles, there are codes and standards for hydrogen safety, for the safe handling of hydrogen and the storage of hydrogen.

Codes and standards have repeatedly been identified as a major institutional barrier to deploying hydrogen technologies and developing a hydrogen economy. To enable the commercialization of hydrogen in consumer products, new model building codes and equipment and other technical standards are developed and recognized by federal, state, and local governments.

Criticism

Critics claim the time frame for overcoming the technical and economic challenges to implementing wide-scale use of hydrogen vehicles is likely to last for at least several decades, and hydrogen vehicles may never become broadly available. They claim the focus on the use of the hydrogen car is a dangerous detour from more readily available solutions to reducing the use of fossil fuels in vehicles. In May 2008, *Wired News* reported that "experts say it will be 40 years or more before hydrogen has any meaningful impact on gasoline consumption or global warming, and we can't afford to wait that long. In the meantime, fuel cells are diverting resources from more immediate solutions."

K. G. Duleep speculates that "a strong case exists for continuing fuel-efficiency improvements from conventional technology at relatively low cost." Critiques of hydrogen vehicles are presented in the 2006 documentary, *Who Killed the Electric Car?*. According to former U.S. Department of Energy official Joseph Romm, "A hydrogen car is one of the least efficient, most expensive ways to reduce greenhouse gases." Asked when hydrogen cars will be broadly available, Romm replied: "Not in our lifetime, and very possibly never." The *Los Angeles Times* wrote, in February 2009, "Hydrogen fuel-cell technology won't work in cars.... Any way you look at it, hydrogen is a lousy way to move cars." A 2007 article in *Technology Review* stated, "In the context of the overall energy economy, a car like the BMW Hydrogen 7 would probably produce far more carbon dioxide emissions than gasoline-powered cars available today. And changing this calculation would take multiple breakthroughs – which study after study has predicted will take decades, if they arrive at all. In fact, the Hydrogen 7 and its hydrogen-fuel-cell cousins are, in many ways, simply flashy distractions produced by automakers who should be taking stronger immediate action to reduce the greenhouse-gas emissions of their cars."

The Wall Street Journal reported in 2008 that "Top executives from General Motors Corp. and Toyota Motor Corp. Tuesday expressed doubts about the viability of hydrogen fuel cells for mass-market production in the near term and suggested their companies are now betting that electric cars will prove to be a better way to reduce fuel consumption and cut tailpipe emissions on a large scale." In addition, Ballard Power Systems, a leading developer of hydrogen vehicle technology, pulled back from the Hydrogen vehicle business in late 2007. Research Capital analyst Jon Hykawy concluded that Ballard saw the industry going nowhere and said: "In my view, the hydrogen car was never alive. The problem was never could you build a fuel cell that would consume hydrogen, produce electricity, and fit in a car. The problem was always, can you make hydrogen fuel at a price point that makes any sense to anybody. And the answer to that to date has been no.". In December 2009, however, Ballard announced a three-year contract for the delivery of the FCvelocity fuel cells for Daimler Benz.

The Economist magazine, in September 2008, quoted Robert Zubrin, the author of *Energy Victory*, as saying: "Hydrogen is 'just about the worst possible vehicle fuel'". The magazine noted the withdrawal of California from earlier goals: "In March [2008] the California Air Resources Board, an agency of California's state government and a bellwether for state governments across America, changed its requirement for the number of zero-emission vehicles (ZEVs) to be built and sold in California between 2012 and 2014. The revised mandate allows manufacturers to comply with the rules by building more battery-electric cars instead of fuel-cell vehicles." The magazine also noted that most hydrogen is produced through steam reformation, which creates at least as much emission of carbon per mile as some of today's gasoline cars. On the other hand, if the hydrogen could be produced using renewable energy, "it would surely be easier simply to use this energy to charge the batteries of all-electric or plug-in hybrid vehicles."

On May 2009 the U.S. Secretary of Energy Stephen Chu announced that since fuel cell hydrogen vehicles "will not be practical over the next 10 to 20 years", the U.S. government would "cut off funds" for development of hydrogen vehicles, although the DoE will continue to fund research related to stationary fuel cells. He cited difficulties in the development of the required infrastructure to distribute hydrogen as a justification for cutting research funds. The National Hydrogen Association and other hydrogen groups criticized the decision. Secretary Chu told MIT's *Technology Review* that he is skeptical about hydrogen's use in transportation because "the way we get hydrogen primarily is from reforming [natural] gas.... You're giving away some of the energy content of natural gas.... So that's one problem.... [For] transportation, we don't have a good storage mechanism yet.... The fuel cells aren't there yet, and the distribution infrastructure isn't there yet.... In order to get significant deployment, you need four significant technological breakthroughs.... If you need four miracles, that's unlikely: saints only need three miracles". Congress overrode the administration's proposal, restoring funding for hydrogen car research in its appropriations bill for 2010.

The Washington Post asked in November 2009, "But why would you want to store energy in the form of hydrogen and then use that hydrogen to produce electricity for a motor, when electrical energy is already waiting to be sucked out of sockets all over America and stored in auto batteries...?" The paper concluded that commercializing hydrogen cars is "stupendously difficult and probably pointless. That's why, for the foreseeable future, the hydrogen car will remain a tailpipe dream". *Digital Trends*

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reported that a December 2009 study at UC Davis, published in the *Journal of Power Sources*, found that, over their lifetimes, hydrogen vehicles will emit more carbon than gasoline vehicles.

Comparison with other types of alternative fuel vehicle

Hydrogen vehicles are one of a number of proposed alternatives to the modern fossil fuel powered vehicle infrastructure.

Plug-in hybrids

Plug-in hybrid electric vehicles, or PHEVs, are hybrid vehicles that can be plugged into the electric grid and contain an electric motor and also an ICE or other engine. The Chevrolet Volt, the first commercially-manufactured PHEV, became available in automobile showrooms in 2010. The PHEV concept augments standard hybrid electric vehicles with the ability to recharge their batteries from an external source while parked, enabling increased use of the vehicle's electric motors while reducing their reliance on internal combustion engines. The infrastructure required to charge PHEVs is already in place, and transmission of power from grid to car is about 93% efficient. This, however, is not the only energy loss in transferring power from grid to wheels. AC/DC conversion must take place from the grids AC supply to the PHEV's DC. This is roughly 98% efficient. The battery then must be charged; the Lithium Iron Phosphate battery is between 80-90% efficient in charging/discharging. The battery needs to be cooled; the GM Volt's battery has 4 coolers and two radiators. However, "the total well-to-wheels efficiency with which a hydrogen fuel cell vehicle might utilize renewable electricity is roughly 20% (although that number could rise to 25% or a little higher with the kind of multiple technology breakthroughs required to enable a hydrogen economy). The well-to-wheels efficiency of charging an onboard battery and then discharging it to run an electric motor in a PHEV or EV, however, is 80% (and could be higher in the future)—four times more efficient than current hydrogen fuel cell vehicle pathways." A 2006 article in Scientific American argued that PHEVs, rather than hydrogen vehicles, would become standard in the automobile industry. PHEVs are gaining traction as an alternative to hydrogen. A December 2009 study at UC Davis found that, over their lifetimes, PHEVs will emit less carbon than current vehicles, while hydrogen cars will emit more carbon than gasoline vehicles.

Natural gas

ICE-based CNG or LNG vehicles (Natural gas vehicles or NGVs) use Natural gas or Biogas as a fuel source. Natural gas has a higher energy density than hydrogen gas. Natural gas powered vehicles have a lower carbon dioxide footprint than ICE vehicles. When using Biogas, NGVs become carbon neutral vehicles that run on animal waste. CNG vehicles have been available for several years, and there is sufficient infrastructure to provide both commercial and home refueling stations. In 2008, the ACEEE rated the Honda Civic GX, which uses compressed natural gas, as the greenest vehicle available.

Battery electric vehicles

As *Technology Review* noted in June 2008, "Electric cars—and plug-in hybrid cars—have an enormous advantage over hydrogen fuel-cell vehicles in utilizing low-carbon electricity. That is because of the inherent inefficiency of the entire hydrogen fueling process, from generating the hydrogen with that electricity to transporting this diffuse gas long distances, getting the hydrogen in the car, and then running it through a fuel cell—all for the purpose of converting the hydrogen back into electricity to drive the same exact electric motor you'll find in an electric car." Thermodynamically, each additional step in the conversion process decreases the overall efficiency of the process. Many BEV designs offer limited driving range. For example, The Nissan Leaf, the first commercially-manufactured BEV, which became available in showrooms in 2010, has a maximum range of 100 miles. Mini E users have reported a range of between 100–120 miles (160–190 km). However, most commutes are 30–40 miles (48–64 km) miles per day round trip. Ed Begley, Jr., an electric car advocate, noted wryly, "The detractors of electric vehicles are right. Given their limited range, they can only meet the needs of 90 percent of the population." In addition, new Nickel-metal hydride and lithium batteries are non-toxic and can be recycled, and "the supposed 'lithium shortage' doesn't exist".

An electric car future is very viable but many problems still need to be addressed. Our current infrastructure must be modified to support a massive demand in the future. Many power companies have said that action will be taken depending on if the electric car becomes popular. By acquiring more solar and wind power and by modernizing our current system much more electricity is available(NPR interview January 2011). As of now the Nissan leaf takes 7 hours to charge on a 220v/240v power station. Due to this many consumers are skeptical about how dependable an electric car can be in their life. The battery life per charge and overall battery life needs to be extended. With better standards power stations can reach 480v for faster charging.

Chapter- 7

Flexible-fuel Vehicle

The Ford Model T was the first commercial flex-fuel vehicle. The engine was capable of running on gasoline or ethanol, or a mix of both.

A **flexible-fuel vehicle (FFV)** or **dual-fuel vehicle** (colloquially called a **flex-fuel vehicle**) is an alternative fuel vehicle with an internal combustion engine designed to run on more than one fuel, usually gasoline blended with either ethanol or methanol fuel, and both fuels are stored in the same common tank. Flex-fuel engines are capable of burning any proportion of the resulting blend in the combustion chamber as fuel injection and spark timing are adjusted automatically according to the actual blend detected by electronic sensors. Flex-fuel vehicles are distinguished from bi-fuel vehicles, where two fuels are stored in separate tanks and the engine runs on one fuel at a time, for example, compressed natural gas (CNG), liquefied petroleum gas (LPG), or hydrogen.

The most common commercially available FFV in the world market is the ethanol flexible-fuel vehicle, with around 21 million automobiles, motorcycles and light duty trucks sold worldwide by mid 2010, and concentrated in four markets, Brazil (10.6 million), the United States (9.3 million), Canada (more than 600,000), and Europe, led by Sweden (199,000). Also a total of 183,375 flexible-fuel motorcycles were sold in Brazil in 2009. In addition to flex-fuel vehicles running with ethanol, in Europe and the US, mainly in California, there have been successful test programs with methanol flex-fuel vehicles, known as M85 flex-fuel vehicles. There have been also successful tests using P-series fuels with E85 flex fuel vehicles, but as of June 2008, this fuel is not yet available to the general public. These successful tests with P-series fuels were conducted on Ford Taurus and Dodge Caravan flexible-fuel vehicles.

Though technology exists to allow ethanol FFVs to run on any mixture of gasoline and ethanol, from pure gasoline up to 100% ethanol (E100), North American and European flex-fuel vehicles are optimized to run on a maximum blend of 15% gasoline with 85% anhydrous ethanol (called E85 fuel). This limit in the ethanol content is set to reduce ethanol emissions at low temperatures and to avoid cold starting problems during cold weather, at temperatures lower than 11 °C (52 °F). The alcohol content is reduced during the winter in regions where temperatures fall below 0 °C (32 °F) to a winter blend of E70 in the U.S. or to E75 in Sweden from November until March. Brazilian flex fuel vehicles are optimized to run on any mix of E20-E25 gasoline and up to 100% hydrous ethanol fuel (E100). The Brazilian flex vehicles are built-in with a small gasoline reservoir for cold starting the engine when temperatures drop below 15 °C (59 °F). An improved flex motor generation was launched in 2009 which eliminated the need for the secondary gas tank.

Terminology

Demonstration Ford Escape E85 flex-fuel plug-in hybrid

The Fiat Siena Tetrafuel 1.4 is a multifuel car designed to run as a flex-fuel on pure gasoline, or E20-E25 blend, or pure ethanol (E100); or to run as a bi-fuel with natural gas (CNG).

Demonstration E85 flex-fuel Ford Escape Hybrid

As ethanol FFVs became commercially available during the late 1990s, the common use of the term "flexible-fuel vehicle" became synonymous with ethanol FFVs. In the United States flex-fuel vehicles are also known as "E85 vehicles". In Brazil, the FFVs are popularly known as "total flex" or simply "flex" cars. In Europe, FFVs are also known as "flexifuel" vehicles. Automakers, particularly in Brazil and the European market, use badging in their FFV models with the some variant of the word "flex", such as Volvo *Flexifuel*, or Volkswagen *Total Flex*, or Chevrolet *FlexPower* or Renault *Hi-Flex*, and Ford sells its Focus model in Europe as *Flexifuel* and as *Flex* in Brazil. In the US, only since 2008 FFV models feature a yellow gas cap with the label "E85/Gasoline" written on the top of the cap to differentiate E85s from gasoline only models.

Flexible-fuel vehicles (FFVs) are based on dual-fuel systems that supply both fuels into the combustion chamber at the same time in various calibrated proportions. The most common fuels used by FFVs today are unleaded gasoline and ethanol fuel. Ethanol FFVs can run on pure gasoline, pure ethanol (E100) or any combination of both. Methanol has also been blended with gasoline in flex-fuel vehicles known as M85 FFVs, but their use has been limited mainly to demonstration projects and small government fleets, particularly in California.

- Bi-fuel vehicles. The term flexible-fuel vehicles is sometimes used to include other alternative fuel vehicles that can run with compressed natural gas (CNG), liquefied petroleum gas (LPG; also known as autogas), or hydrogen. However, all these vehicles actually are bi-fuel and not flexible-fuel vehicles, because they have engines that store the other fuel in a separate tank, and the engine runs on one fuel at a time. Bi-fuel vehicles have the capability to switch back and forth from gasoline to the other fuel, manually or automatically. The most common available fuel in the market for bi-fuel cars is natural gas (CNG), and by 2008 there were 9,6 million natural gas vehicles, led by Pakistan (2.0 million), Argentina (1.7 million), and Brazil (1.6 million). Natural gas vehicles are a popular choice as taxicabs in the main cities of Argentina and Brazil. Normally, standard gasoline vehicles are retrofitted in specialized shops, which involve installing the gas cylinder in the trunk and the CNG injection system and electronics.

- Multifuel vehicles are capable of operating with more than two fuels. In 2004 GM do Brasil introduced the Chevrolet Astra 2.0 with a "MultiPower" engine built on flex fuel technology developed by Bosch of Brazil, and capable of using CNG, ethanol and gasoline (E20-E25 blend) as fuel. This automobile was aimed at the taxicab market and the switch among fuels is done manually. In 2006 Fiat introduced the Fiat Siena Tetra fuel, a four-fuel car developed under Magneti Marelli of Fiat Brazil. This automobile can run as a flex-fuel on 100% ethanol (E100); or on E-20 to E25, Brazil's normal ethanol gasoline blend; on pure gasoline (though no longer available in Brazil since 1993, it is still used in neighboring countries); or just on natural gas. The Siena Tetrafuel was engineered to switch from any gasoline-ethanol blend to CNG automatically, depending on the power required by road conditions. Another existing option is to retrofit an ethanol flexible-fuel vehicle to add a natural gas tank and the corresponding injection system. This option is popular among taxicab owners in São Paulo and Rio de Janeiro, Brazil, allowing users to choose among three fuels (E25, E100 and CNG) according to current market prices at the pump. Vehicles with this adaptation are known in Brazil as "tri-fuel" cars.

- Flex-fuel hybrid electric and flex-fuel plug-in hybrid are two types of hybrid vehicles built with a combustion engine capable of running on gasoline, E-85, or E-100 to help drive the wheels in conjunction with the electric engine or to recharge the battery pack that powers the electric engine. In 2007 Ford produced 20 demonstration Escape Hybrid E85s for real-world testing in fleets in the U.S. Also as a demonstration project, Ford delivered in 2008 the first flexible-fuel plug-in hybrid SUV to the U.S. Department of Energy (DOE), a Ford Escape Plug-in Hybrid, which runs on gasoline or E85. GM announced that the Chevrolet Volt plug-in hybrid, launched in the U.S. in late 2010, would be the first commercially available flex-fuel plug-in capable of adapting the propulsion to several world markets such as the U.S., Brazil or Sweden, as the combustion engine can be adapted to run on E85, E100 or diesel respectively. In the North American market the Volt is expected to be sold as an E85 flex-fuel-capable plug-in about a year after its first introduction. Lotus Engineering unveiled the Lotus CityCar at the 2010 Paris Motor Show. The CityCar is a plug-in hybrid concept car designed for flex-fuel operation on ethanol, or methanol as well as regular gasoline.

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History

The first commercial flexible fuel vehicle was the Ford Model T, produced from 1908 through 1927. It was fitted with a carburetor with adjustable jetting, allowing use of gasoline or ethanol, or a combination of both. Other car manufactures also provided engines for ethanol fuel use. Henry Ford continued to advocate for ethanol as fuel even during the prohibition. However, cheaper oil caused gasoline to prevail, until the 1973 oil crisis resulted in gasoline shortages and awareness on the dangers of oil dependence. This crisis opened a new opportunity for ethanol and other alternative fuels, such as methanol, gaseous fuels such as CNG and LPG, and also hydrogen. Ethanol, methanol and natural gas CNG were the three alternative fuels that received more attention for research and development, and government support.

The 2003 VW Gol 1.6 Total Flex was the first full flexible-fuel vehicle produced and sold in Brazil, capable of running on any blend of gasoline (E20 to E25) and ethanol up to E100.

Since 1975, and as a response to the shock caused by the first oil crisis, the Brazilian government implemented the National Alcohol Program -Pró-Álcool- (Portuguese: *Programa Nacional do Álcool*), a nationwide program financed by the government to phase out automotive fuels derived from fossil fuels in favor of ethanol made from sugar cane. It began with a low blend of anhydrous alcohol with regular gasoline in 1976, and since July 2007 the mandatory blend is 25% of alcohol or gasohol E25. In 1979, and as a response to the second oil crisis, the first vehicle capable of running with pure hydrous ethanol (E100) was launched to the market, the Fiat 147, after testing with several prototypes developed by Fiat, Volkswagen, GM and Ford. The Brazilian government provided three important initial drivers for the ethanol industry: guaranteed purchases by the state-owned oil company Petrobras, low-interest loans for agro-industrial ethanol firms, and fixed gasoline and ethanol prices. After reaching more than 4 million cars and light trucks running on pure ethanol by the late 1980s, the use of E100-only vehicles sharply declined after increases in sugar prices produced shortages of ethanol fuel.

After extensive research that began in the 90s, a second push took place in March 2003, when the Brazilian subsidiary of Volkswagen launched to the market the first full flexible-fuel car, the Gol 1.6 Total Flex. Several months later was followed by other Brazilian automakers, and by 2010 General Motors, Fiat, Ford, Peugeot, Renault, Volkswagen, Honda, Mitsubishi, Toyota, Citröen, Nissan and Kia Motors were producing popular models of flex cars and light trucks. The adoption of ethanol flex fuel vehicles was so successful, that production of flex cars went from almost 40 thousand in 2003 to 1.7 million in 2007. This rapid adoption of the flex technology was facilitated by the fuel distribution infrastructure already in place, as around 27,000 filling stations countrywide were available by 1997 with at least one ethanol pump, a heritage of the *Pró-Álcool* program.

In the United States, initial support to develop alternative fuels by the government was also a response to the first oil crisis, and some time later, as a goal to improve air quality. Also, liquid fuels were preferred over gaseous fuels not only because they have a better volumetric energy density but also because they were the most compatible fuels with existing distribution systems and engines, thus avoiding a big departure from the existing technologies and taking advantage of the vehicle and the refueling infrastructure. California led the search of sustainable alternatives with interest focused in methanol. Ford Motor Company and other automakers responded to California's request for vehicles that run on methanol. In 1981, Ford delivered 40 dedicated methanol fuel (M100) Escorts to Los Angeles County, but only four refueling stations were installed. The biggest challenge in the development of alcohol vehicle technology was getting all of the fuel system materials compatible with the higher chemical reactivity of the fuel. Methanol was even more of a challenge than ethanol but much of the early experience gained with neat ethanol vehicle production in Brazil was transferable to methanol. The success of this small experimental fleet of M100s led California to request more of these vehicles, mainly for government fleets. In 1983, Ford built 582 M100 vehicles; 501 went to California, and the remaining to New Zealand, Sweden, Norway, United Kingdom, and Canada.

The 1996 Ford Taurus was the first flexible-fuel vehicle produced with versions capable of running with either ethanol (E85) or methanol (M85) blended with gasoline.

As an answer to the lack of refueling infrastructure, Ford began development of a flexible-fuel vehicle in 1982, and between 1985 and 1992, 705 experimental FFVs were built and delivered to California and Canada, including the 1.6L Ford Escort, the 3.0L Taurus, and the 5.0L LTD Crown Victoria. These vehicles could operate on either gasoline or methanol with only one fuel system. Legislation was passed to encourage the US auto industry to begin production, which started in 1993 for the M85 FFVs at Ford. In 1996, a new FFV Ford Taurus was developed, with models fully capable of running on either methanol or ethanol blended with gasoline. This ethanol version of the Taurus became the first commercial production of an E85 FFV. The momentum of the FFV production programs at the American car companies continued, although by the end of the 1990s, the emphasis shifted to the FFV E85 version, as it is today. Ethanol was preferred over methanol because there is a large support from the farming community, and thanks to the government's incentive programs and corn-based ethanol subsidies. Sweden also tested both the M85 and the E85 flexifuel vehicles, but due to agriculture policy, in the end emphasis was given to the ethanol flexifuel vehicles. Support for ethanol also comes from the fact that it is a biomass fuel, which addresses climate change concerns and greenhouse gas emissions, hough nowadays these benefits are questioned and depend on the feedstock used for ethanol production and their indirect land use change impacts.

The demand for ethanol fuel produced from field corn in the United States was stimulated by the discovery in the late 90s that methyl tertiary butyl ether (MTBE), an oxygenate additive in gasoline, was contaminating groundwater. Due to the risks of widespread and costly litigation, and because MTBE use in gasoline was banned in almost 20 states by

2006, the substitution of MTBE opened a new market for ethanol fuel. This demand shift for ethanol as an oxygenate additive took place at a time when oil prices were already significantly rising. By 2006, about 50 percent of the gasoline used in the U.S. contains ethanol at different proportions, and ethanol production grew so fast that the US became the world's first ethanol producer, overtaking Brazil in 2005. This shift also contributed to a sharp increase in the production and sale of E85 flex vehicles since 2002.

Flexible-fuel vehicles by country

Brazil

Flexible-fuel technology started being developed by Brazilian engineers near the end of the 1990s. The Brazilian flexible fuel car is built with an ethanol-ready engine and one fuel tank for both fuels. The small gasoline reservoir for starting the engine with pure ethanol in cold weather, used in earlier neat ethanol vehicles, was kept to avoid start up problems in the central and southern regions, where winter temperatures normally drop below 15 °C (59 °F). An improved flex motor generation was launched in 2009 and allowed to eliminate the need for this secondary gas reservoir tank. Another improvement was the reduction of fuel consumption and tailpipe emissions, between 10% to 15% as compared to flex motors sold in 2008. In March 2009 Volkswagen do Brasil launched the Polo E-Flex, the first flex fuel model without an auxiliary tank for cold start.

Typical Brazilian flexible-fuel engine with secondary gasoline reservoir for cold starting the engine at temperatures below 15 °C.

A key innovation in the Brazilian flex technology was avoiding the need for an additional dedicated sensor to monitor the ethanol-gasoline mix, which made the first American M85 flex fuel vehicles too expensive.

Brazilian flex cars are capable of running on just hydrated ethanol (E100), or just on a blend of gasoline with 20 to 25% anhydrous ethanol (the mandatory blend since 1993), or on any arbitrary combination of both fuels.

The flexibility of Brazilian FFVs empowers the consumers to choose the fuel depending on current market prices. As ethanol fuel economy is lower than gasoline because of ethanol's energy content is close to 34% less per unit volume than gasoline, flex cars running on ethanol get a lower mileage than when running on pure gasoline. However, this effect is partially offset by the usually lower price per liter of ethanol fuel. As a rule of thumb, Brazilian consumers are frequently advised by the media to use more alcohol than gasoline in their mix only when ethanol prices are 30% lower or more than gasoline, as ethanol price fluctuates heavily depending on the result of seasonal sugar cane harvests.

Six typical flex-fuel models from several Brazilian carmakers, popularly known as "flex" cars, that run on any blend of hydrous ethanol (E100) and E20-E25 gasoline.

In March 2003 Volkswagen do Brasil launched in the market the Gol 1.6 Total Flex, the first commercial flexible fuel vehicle capable of running on any blend of gasoline and ethanol. GM do Brasil followed two months later with the Chevrolet Corsa 1.8 Flexpower, using an engine developed by a joint-venture with Fiat called PowerTrain. By 2010, twelve carmakers build flexible fuel vehicles.

Flexible fuel vehicles reached a record 94% of the new car sales in August 2009. The production of flex-fuel cars and light commercial vehicles since 2003 reached the milestone of 10 million vehicles in March 2010. As of June 2010, the fleet of flex automobiles and light commercial vehicles had reached 10.6 million vehicles, representing 17.4% of Brazil's motor vehicle fleet and 25.8% of all registered light vehicles.

The rapid success of flex vehicles was made possible by the existence of 33,000 filling stations with at least one ethanol pump available by 2006, a heritage of the early *Pró-Álcool* ethanol program. These facts, together with the mandatory use of E25 blend of gasoline throughout the country, allowed Brazil in 2008 to achieve more than 50% of fuel consumption in the gasoline market from sugar cane-based ethanol. According to two separate research studies conducted in 2009, at the national level 65% of the flex-fuel registered vehicles regularly use ethanol fuel, and the usage increases to 93% in São Paulo, the main ethanol producer state where local taxes are lower, and prices at the pump are more competitive than gasoline.

The latest innovation within the Brazilian flexible-fuel technology, is the development of flex-fuel motorcycles. The first flex-fuel motorcycle was launched by Honda in March 2009. In September 2009, Honda launched a second flexible-fuel motorcycle, an by December both Honda flexible-fuel motorcycles had sold a total of 183,375 units, representing a 11.4% market share of the Brazilian new motorcycle sales in 2009.

Europe

Sweden

Flexi-fuel fleet in Sweden Cars sold by year (2001–2010)			
Year	**Sales**	**Year**	**Sales**
2001	717	2006	25,868
2002	1,926	2007	35,499
2003	1,669	2008	57,628
2004	1,074	2009	39,845
2005	17,232	2010 (CYTD)	17,546
Total cumulative sales		199,004	

CYTD: calendar year to day as of July 2010

The 2005 Volvo FlexiFuel S40 was one of the first E85 flexible fuel cars available in the country produced by a Swedish automaker. The Volvo FlexiFuel is now offered on the European market.

Flexible-fuel vehicles were introduced in Sweden as a demonstration test in 1994, when three Ford Taurus were imported to show the technology existed. Because of the existing interest, a project was started in 1995 with 50 Ford Taurus E85 flexifuel in different parts of Sweden: Umea, Örnsköldsvik, Härnösand, Stockholm, Karlstad, Linköping, and Växjö. From 1997 to 1998 an additional 300 Taurus were imported, and the number of E85 fueling grew to 40. Then in 1998 the city of Stockholm placed an order for 2,000 of FFVs for any car manufacturer willing to produce them. The objective was to jump-start the FFV industry in Sweden. The two domestic car makers Volvo Group and Saab AB refused to participate arguing there were not in place any ethanol filling stations. However, Ford Motor Company took the offer and began importing the flexifuel version of its Focus model, delivering the first cars in 2001, and selling more than 15,000 FFV Focus by 2005, then representing an 80% market share of the flexifuel market.

Saab 9-3 SportCombi BioPower. The second E85 model introduced by Saab in the Swedish market in 2007.

The Koenigsegg CCXR Edition at the 2008 Geneva Motor Show. This is an "environmentally friendly" version of the CCX, converted to use E85 or E100 as well as standard 98 octane gasoline.

In 2005 both Volvo and Saab introduced to the Sweden market their flexifuel models. Saab began selling its 9-5 2.0 Biopower, joined in 2006 by its 9-5 2.3 Biopower. Volvo introduced its S40 and V50 with flexible-fuel engines, joined in late 2006 by the new C30. All Volvo models were initially restricted to the Sweden market, until 2007, when these three models were launched in eight new European markets. In 2007, Saab also started selling a BioPower version of its popular Saab 9-3 line. In 2008 the Saab-derived Cadillac BLS was introduced with E85 compatible engines, and Volvo launched the V70 with a 2.5-litre turbocharged Flexifuel engine.

All flexible-fuel vehicles in Sweden use an E75 winter blend instead of E85 to avoid engine starting problems during cold weather. This blend was introduced since the winter 2006-07 and E75 is used from November until March. For temperature below −15 °C (5.0 °F) E85 flex vehicles require an engine block heater. The use of this device is also recommended for gasoline vehicles when temperatures drop below −23 °C (−9 °F). Another option when extreme cold weather is expected is to add more pure gasoline in the tank, thus reducing the ethanol content below the E75 winter blend, or simply not to use E85 during extreme low temperature spells.

Sweden has achieved the largest E85 flexible-fuel vehicle fleet in Europe, with a sharp growth from 717 vehicles in 2001 to 181,458 by December 2009. The recent and accelerated growth of the Swedish fleet of E85 flexifuel vehicles, as they are popularly known, is the result of the National Climate Policy in Global Cooperation Bill passed in 2005, which not only ratified the Kyoto Protocol but also sought to meet the 2003 EU Biofuels Directive regarding targets for use of biofuels, and also let to the 2006 government's commitment to eliminate oil imports by 2020.

In order to achieve these goals several government incentives were implemented. Ethanol, as the other biofuels, was exempted of both, the CO_2 and energy taxes until 2009, resulting in a 30% price reduction at the pump of E85 fuel over gasoline. Furthermore, other demand side incentives for flexifuel vehicle owners include a US$1,800 bonus to buyers of FFVs, exemption from the Stockholm congestion tax, up to 20% discount on auto insurance, free parking spaces in most of the largest cities, owner annual registration taxes, and a 20% tax reduction for flexifuel company cars. Also, a part of the program, the Swedish Government ruled that 25% of their vehicle purchases (excluding police, fire and ambulance vehicles) must be alternative fuel vehicles. By the first months of 2008, this package of incentives resulted in sales of flexible-fuel cars representing 25% of new car sales.

On the supply side, since 2005 the gasoline fuelling stations selling more than 3 million liters of fuel a year are required to sell at least one type of biofuel, resulting in more than 1,200 gas stations selling E85 by August 2008. Despite all the sharp growth of E85 flexifuel cars, by 2007 they represented just 2% of the 4 million Swedish vehicle fleet. In addition, this law also mandated all new filling stations to offer alternative fuels, and stations with an annual volume of more than 1 million liters are required to have an alternative fuel pump by December 2009. Therefore, the number of E85 pumps is expected to reach by 2009 nearly 60% of Sweden’s 4,000 filling stations.

The Swedish-made Koenigsegg CCXR, a limited edition and version of the CCX, is currently the fastest and most powerful flexible fuel vehicle with its twin-supercharged V8 producing 1018 hp when running on biofuel, as compared to 806 hp on 91 octane US unleaded gasoline.

Other European countries

Bioethanol E85 stations
European Union

Country	Number Stations	As of (date)	Stat/10^6 persons
Sweden	1,455	2009	131.26
France	308	2009	3.27
Germany	270	2009	2.67
Switzerland	62	2009	5.27
Ireland	31	2009	5.84
Netherlands	29	2009	0.30
United Kingdom	21	2008	0.34
Hungary	19	2009	1.3
Norway	19	2009	2.30
Austria	16	2009	-
Spain	15	2009	0.18

Note: Only countries with ten or more E85 stations are included.
For other countries search here

Flexifuel vehicles are sold in 18 European countries, including Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, the Netherlands, Norway, Poland, Spain, Sweden, Switzerland, and the United Kingdom. Ford, Volvo and Saab are the main automakers offering flexifuel autos in the region.

France

Biofuel cars in general get strong tax incentives in France, including a 0 or 50% reduction on the tax on new vehicles, and a 40% reduction on CO_2 tax for new cars. For company cars there is a corporate car tax free for 2 years and a recovery of 80% of the value added tax (VAT) on E85 vehicles. Also, E85 fuel price is set significantly lower than diesel or gasoline, resulting in E85 at € 0.80, diesel at € 1.15, and gasoline at € 1.30 per liter, as of April 2007. By May 2008, France had 211 pumps selling E85, even though the government made plans for the installation of up to 500 E85 pumps by year end 2007. French automakers Renault and PSA (Citroen & Peugeot) announced they will start selling FFV cars beginning in the summer 2007.

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Germany

Biofuel emphasis in Germany is on biodiesel, and no specific incentives have been granted for E85 flex-fuel cars, however there is complete exemption of taxes on all biofuels while there is a normal tax of € 0.65 per liter of petroleum fuels. The distribution of E85 began in 2005, and with 219 stations as of September 2008, Germany ranks second after Sweden with the most E85 fueling stations in the EU. As of January 2008 retail prices of E85 was € 0.95 per liter, and gasoline was priced at € 1.37 per liter (for gasoline RON 95), then providing enough margin to compensate for ethanol's lower fuel economy. Ford has offered the Ford Focus since August 2005 in Germany. Ford is about to offer also the Mondeo and other models as FFV versions between 2008 and 2010. The Saab 9-5 and Saab 9-3 Biopower, the Peugeot 308 Bioflex, the Citroen C4 Bioflex, the Audi A5, two models of the Cadillac BLS, and five Volvo models are also available in the German market by 2008.

Ireland

Ireland is the third best seller European market of E85 flex-fuel vehicles, after Sweden and France. Bioethanol (E85) in Ireland is made from whey, a waste product of cheese manufacturing. The Irish government established several incentives, including a 50% discount in vehicle registration taxes (VRT), which can account for more than one third of the retail price of a new car in Ireland (around € 6,500). The bioethanol element of the E85 fuel is excise-free for fuel companies, allowing retail prices to be low enough to offset the 25 per cent cut in fuel economy that E-85 cars offer, due to ethanol's lower energy content than gasoline. Also, the value added tax (VAT) on the fuel can also be claimed back. E-85 fuel is available across the country in more than 20 of Maxol service stations. In October 2005, the 1.8 Ford Focus FFV became the first flexible-fuel vehicle to be commercially sold in Ireland. Later Ford launched the C-max and the Mondeo flexifuel models. Saab and Volvo also have E85 models available.

The Ford Focus flexifuel was the first E85 flexible fuel vehicle commercially available in the European market.

From 1st of January 2011 E85 fuel is no longer excise-free in Ireland. Maxol has announced they will not provide E85 when their current supplies have run out.

Spain

The first flexifuel vehicles were introduced in Spain by late 2007, with the acquisition of 80 cars for use in the Spaniard official government fleet. At that time the country had only three gas stations selling E85, making necessary to deploy an official E85 fueling station in Madrid to attend these vehicles. Despite the introduction in the Spaniard market of several flexifuel models, by the end of 2008 still persists the problems of adequate E85 fueling infrastructure, as only 10 gas stations were selling E85 fuel to the public in the entire country.

United Kingdom

The UK government established several incentives for E85 flex-fuel vehicles. These include a fuel duty rebate on E85 fuel of 20 p per liter, until 2010; a £ 10 to 15 reduction in the vehicle excise duty (VED); and a 2% annual company car tax discount for flex-fuel cars. Despite the small number of E85 pump stations available, limited to the Morrisons supermarket chain stations, most automakers offer the same models in the UK that are available in the European market. In 2005 the Ford Focus Flexi-Fuel became the first flexible-fuel car sold in the UK, though E85 pumps opened until 2006. Volvo now offers its flexifuel models S80, S40, C30, V50 and V70. Other models available in the UK are the Ford C-Max Flexi-Fuel, and the Saab models 9-5 and 9-3 Flex-Fuel Biopower, and the new Saab Aero X BioPower E100 bioethanol.

United States

By December 2009 there were 8.3 million E85 flex fuel vehicles on the U.S. roads, up from around 5 million in 2006. The E85 blend is used in gasoline engines modified to accept such higher concentrations of ethanol, and the fuel injection is regulated through a dedicated sensor, which automatically detects the amount of ethanol in the fuel, allowing to adjust both fuel injection and spark timing accordingly to the actual blend available in the vehicle's tank. Because ethanol contains close to 34% less energy per unit volume than gasoline, E85 FFVs have a lower mileage per gallon than gasoline. Based on EPA tests for all 2006 E85 models, the average fuel economy for E85 vehicles was 25.56% lower than unleaded gasoline.

The American E85 flex fuel vehicle was developed to run on any mixture of unleaded gasoline and ethanol, anywhere from 0% to 85% ethanol by volume. Both fuels are mixed in the same tank, and E85 is sold already blended. In order to reduce ethanol evaporative emissions and to avoid problems starting the engine during cold weather, the maximum blend of ethanol was set to 85%. There is also a seasonal reduction of the ethanol content to E70 (called winter E85 blend) in very cold regions, where temperatures fall below 0 °C (32 °F) during the winter. In Wyoming for example, E70 is sold as E85 from October to May.

Typical labeling used in the US to identify E85 flex-fuel vehicles. Top left: a small sticker in the back of the fuel filler door. Bottom left: the bright yellow gas cap now used in newer models. E85 Flexfuel badging used in newer models from Chrysler (top right), Ford (middle right) and GM (bottom right).

By 2008 almost any type of automobile and light duty vehicles is available in the market with the flex-fuel option, including sedans, vans, SUVs and pick-up trucks. E85 flex-fuel vehicles are becoming increasingly common in the Midwest, where corn is a major crop and is the primary feedstock for ethanol fuel production. As a result of the Energy Policy Act of 2005, the federal government vehicle fleet includes 128,491 vehicles that run on E85. Regional retail E85 prices vary widely across the US, with more favorable prices in the Midwest region, where most corn is grown and ethanol produced. Depending of the vehicle capabilities, the break even price of E85 has to be between 25 to 30% lower than gasoline.

Barriers to widespread adoption

2009 E85 FlexFuel Chevrolet Impala LT

2010 E85 Flexfuel Ford Escape

A 2005 survey found that 68% of American flex-fuel car owners were not aware they owned an E85 flex. This was due to the fact that the exterior of flex and non-flex vehicles look exactly the same; there is no sale price difference between them; the lack of consumer's awareness about E85s; and also the initial decision of American automakers of not putting any kind of exterior labeling, so buyers could be aware they are purchasing an E85 vehicle. Since 2008 all new FFV models in the US feature a bright yellow gas cap to remind drivers of the E85 capabilities and proper flex-fuel badging.

Some critics have argued that American automakers have been producing E85 flex models motivated by a loophole in the CAFE (Corporate Average Fuel Economy) requirements, that allows for a fuel economy credit for every flex-fuel vehicle sold, whether or not in practice these vehicles are fueled with E85. This loophole might allow the car industry to meet the CAFE targets in fuel economy just by spending between US$100 to US$200 that it cost to turn a conventional vehicle into a flex-fuel, without investing in new technology to improve fuel economy, and saving them the potential fines for not achieving that standard in a given model year.

A major restriction hampering sales of E85 flex vehicles or fuelling with E85, is the limited infrastructure available to sell E85 to the public, as by October 2008 there were only 1,802 gasoline filling stations selling E85 to the public in the entire US, with a great concentration of E85 stations in the Corn Belt states, lead by Minnesota with 357 stations, the most that any other state, followed by Illinois with 189, Wisconsin with 118, and Missouri with 112. The main constraint for a more rapid expansion of E85 availability is that it requires dedicated storage tanks at filling stations, at an estimated cost of US$60,000 for each dedicated ethanol tank.

Latest developments

In 2008 Chrysler, General Motors, and Ford pledged to manufacture 50 percent of their entire vehicle line as flexible fuel in model year 2012, if enough fueling infrastructure develops.

In 2008 Ford delivered the first flex-fuel plug-in hybrid as part of a demonstration project, a Ford Escape Plug-in Hybrid capable of running on E85 or gasoline. General Motors announced that the new plug-in hybrid electric vehicle Chevrolet Volt, scheduled to be launched in the North American market in late 2010, will be flex-fuel-capable about a year after it is introduced.

Other countries

Australia

In January 2007 GM brought UK-sourced Saab 9-5 Biopower E85 flex-fuel vehicles to Australia as a trial, in order to measure interest in ethanol-powered vehicles in the country. Saab Australia placed the vehicles with the fleets of the Queensland Government, the media, and some ethanol producers. E85 is not available widely in Australia, but the Manildra Group provided the E85 blend fuel for this trial.

Saab Australia became the first car maker to produce an E85 flex-fuel car for the Australian market with the Saab 9-5 BioPower. One month later launched the new 9-3 BioPower, the first vehicle in Australia to give drivers a choice of three fuels, E85, diesel or gasoline, and both automobiles are sold for a small premium. Australia's largest independent fuel retailer, United Petroleum, announced plans to install Australia's first commercial E85 fuel pumps, one in Sydney and one in Melbourne.

GM Holden, the Victorian state government, Coskata, Caltex, Veolia Environmental Services and Mitsui have announced a consortium with a co-ordinated plan to build a bio-ethanol plant from household waste for use as E85 fuel. In August 2010 Caltex launched the E85 ethanol fuel called Bio E-Flex, designed for use in the Holden Commodore VE Series II flex-fuel vehicles to be released later in 2010. Caltex Australia plans to begin selling Bio E-Flex in Melbourne from September and expects to have Bio E-Flex available in more than 30 service stations in Melbourne, Sydney, Brisbane, Adelaide and Canberra by the end of October, with plans to increase to 100 metropolitan and regional locations in 2011.

Canada

As part of the North American auto market, by 2007 Canada had available 51 models of E85 flex-vehicles, most from Chrysler, Ford and General Motors, including automobiles,

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pickup trucks, and SUVs. The country has around 600,000 capable flex fuel E85s on the roads by early 2008, however, most users are not aware they own an E85, as vehicles are not clearly labeled as such, and only the newer models have a yellow cap in the fuel tank informing that the vehicle can handle E85. Another major restriction for greater E85 fuel use is the fact that by June 2008 Canada had only three public E85 pumps, all located in Ontario, in the cities of Guelph, Chatham, and Woodstock. E85 fueling is available primarily for fleet vehicles, including 20 government refueling stations not available for the public. The main feedstocks for E85 production in Canada are corn and wheat, and there are several proposals being discussed to increase the actual use of E85 fuel in FFVs, such as creating an ethanol-friendly highway or ethanol corridor.

Colombia

On March 2009 the Colombian government enacted a mandate to introduce E85 flexible-fuel cars. The executive decree applies to all gasoline-powered vehicles with engines smaller than 2.0 liters manufactured, imported, and commercialized in the country beginning in 2012, mandating that 60% of such vehicles must have flex-fuel engines capable of running with gasoline or E85, or any blend of both. By 2014 the mandatory quota is 80% and it will reach 100 percent by 2016. All vehicles with engines bigger than 2.0 liters must be E85 capable starting in 2013. The decree also mandates that by 2011 all gasoline stations must provide infrastructure to guarantee availability of E85 throughout the country. The mandatory introduction of E85 flex-fuels has caused controversy among carmakers, car dealers, gasoline station owners, and even some ethanol producers complained the industry is not ready to supply enough ethanol for the new E85 fleet.

New Zealand

In 2006 New Zealand began a pilot project with two E85 Ford Focus Flexi-Fuel evaluation cars. The main feedstock used in New Zealand for ethanol production is whey, a by-product of milk production.

Paraguay

Government officials and businessmen from Paraguay began negotiations in 2007 with Brazilian automakers in order to import flex cars that run on any blend of gasoline and ethanol. If successful, Paraguay would become the first destination for Brazilian flex-fuel car exports. In May 2008, the Paraguayan government announced a plan to eliminate import taxes of flex-fuel vehicles and an incentive program for ethanol production. The plan also includes the purchase of 20,000 flex cars in 2009 for the government fleet.

Thailand

In 2006, tax incentives were established in Thailand for the introduction of compressed natural gas (CNG) as an alternative fuel, by eliminating import duties and lowering excise taxes on CNG-compatible cars. Then in 2007, Thai authorities approved incentives for the production of "eco-cars", with the goal of the country to become a regional hub for the production of small, affordable and fuel-efficient cars. Seven automakers joint in the program, Toyota, Suzuki, Nissan, Mitsubishi, Honda, Tata and Volkswagen. In 2008 the government announced priority for E85, expecting these flex-fuel vehicles to become widely available in Thailand in 2009, three years ahead of schedule. The incentives include cuts in excise tax rates for E85-compatible cars and reduction of corporate taxes for ethanol producers to make sure E85 fuel supply will be met. This new plan however, brought confusion and protests by the automakers which sign-up for the "eco-cars", as competition with the E85 flex-fuel cars will negatively affect their ongoing plans and investments, and their production lines will have to be upgraded at a high cost for them to produce flex-fuel cars. They also complained that flex-fuel vehicles popular in a few countries around the world, limiting their export potential as compared with other engine technologies.

Despite the controversy, the first E85 flexible fuel vehicles were introduced in November 2008. The first two models available in the Thai market were the Volvo S80 and the C30. The S80 is manufactured locally and the C30 is imported. By the time of the introduction of flex vehicles there were already two gas stations with E85 fuel available. During 2009 it was expected that 15 fueling stations in Bangkok will have E85 fuel available. In October 2009 the Mitsubishi Lancer Ex was launched becoming the first mass-production E85 flexi-fuel vehicle produced in Thailand.

Comparison among the leading markets

Comparison of key characteristics among the leading ethanol flexible-fuel vehicle markets

Characteristic	Brazil	Sweden	U.S.	Units/comments
Type of flexible-fuel vehicle (fuel used)	E20 to E100	E85	E85	Brazil's mandatory blend is E20-E25. Winter E85 is actually E70 in the US and E75 in Sweden.
Main feedstock used for ethanol consumption	Sugar cane	80% imported	Maize	In 2007, most Swedish ethanol was imported, with a high share from Brazil.
Total flex-fuel vehicles produced/sold	10.6 million	199,004	9.3 million(1)	Brazil as of June 2010, Sweden as of July 2010, U.S. as of December 2009.
Share of flex-fuel vehicles as % of total	17.4%	4.1%	3.3%	Brazil's fleet is 61 mi (April 2010), Sweden fleet is 4.4 mi (2008), and US fleet is 244 mi

registered				(2007).
Ethanol fueling stations in the country	35,017	1,200	2,113	Brazil for December 2007, the US as of January 2010, and Sweden as of August 2008.
Ethanol filling stations as % of total	100%	30%	1%	As % of total fueling gas stations in the country. Data for same years as above.
Ethanol fueling stations per million inhabitants	184.2	130.4	6.5	
Retail price of E85 or E100 (local currency/unit)	R$ 1.259/L	SEK 8.79/L	US$ 2.60/gal	Selected regions:(2)São Paulo, June 2008, Sweden, January 2008, and Minnesota, August 2008.
Retail price of gasoline or E25. (local currency/unit)	R$ 2.385/L	SEK 11.99/L	US$ 3.70/gal	Prices in São Paulo (E25), June 2008, Sweden, January 2008, and Minnesota, August 2008.
Price economy ethanol/gasoline price as %	47.2%(2)(3)	26.7%(3)	29.7%(2)(3)	São Paulo, June 2008, Sweden January 2008, and Minnesota, August 2008.

Notes: (1)The effective number of E85 flex vehicles in US roads actually using ethanol fuel is lower than shown, as a survey have shown than 68% of E85 owners are not aware they own a flex-fuel vehicle. A 2007 national survey found that only 5% of drivers actually use biofuels. (2) Regional prices vary widely in Brazil and the US. The states chosen reflect some of the lowest retail prices for ethanol, as both São Paulo and Minnesota are main growers of feedstock and producers of ethanol, hence, the comparison presented is one of the most favorable for ethanol/gasoline price ratios. For example, US average spread was 16.9% in August 2008, and it varied from 35% in Indiana to 3% in Utah. (3) Brazilian gasoline is heavily taxed (~54%), US ethanol production is subsidized (a US$ 0.51/gal federal tax credit), and Swedish E85 is exempt of CO2 and energy taxes until 2009 (~30% price reduction).