Automobile Engineering

An automobile is a usually four-wheeled vehicle designed primarily for passenger transportation and commonly propelled by an internal-combustion engine using a volatile fuel.

he modern automobile is a complex technical system employing subsystems with specific design functions. Some of these consist of thousands of component parts that have evolved from breakthroughs in existing technology or from new technologies such as electronic computers, high-strength plastics, and new alloys of steel and nonferrous metals. Some subsystems have come about as a result of factors such as air pollution, safety legislation, and competition between manufacturers throughout the world.

Vehicle design depends to a large extent on its intended use. Automobiles for off-road use must be durable, simple systems with high resistance to severe overloads and extremes in operating conditions. Conversely, products that are intended for high-speed, limited-access road systems require more passenger comfort options, increased engine performance, and optimized high-speed handling and vehicle stability. Stability depends principally on the distribution of weight between the front and rear wheels, the height of the centre of gravity and its position relative to the aerodynamic centre of pressure of the vehicle, suspension characteristics, and the selection of which wheels are used for propulsion. Weight distribution depends principally on the location and size of the engine. The common practice of front-mounted engines exploits the stability that is more readily achieved with this layout. The development of aluminum engines and new manufacturing processes has, however, made it possible to locate the engine at the rear without necessarily compromising stability.

Body

Fiat 600

The Fiat 600, introduced in 1956, was an inexpensive, practical car with simple, elegant styling that instantly made it an icon of postwar Italy. Its rear-mounted transverse engine produced sufficient power and saved enough space to allow the passenger compartment to accommodate four people easily.(more)

Automotive body designs are frequently categorized according to the number of doors, the arrangement of seats, and the roof structure. Automobile roofs are conventionally supported by pillars on each side of the body. Convertible models with retractable fabric tops rely on the pillar at the side of the windshield for upper body strength, as convertible mechanisms and glass areas are essentially nonstructural. Glass areas have been increased for improved visibility and for aesthetic reasons.

automobile assembly line

An automobile being manufactured on an assembly line.

The high cost of new factory tools makes it impractical for manufacturers to produce totally new designs every year. Completely new designs usually have been programmed on three- to six-year cycles with generally minor refinements appearing during the cycle. In the past, as many as four years of planning and new tool purchasing were needed for a completely new design. Computer-aided design (CAD), testing by use of computer simulations, and computer-aided manufacturing (CAM) techniques may now be used to reduce this time requirement by 50 percent or more. *See* machine tool: Computer-aided design and computer-aided manufacturing (CAD/CAM).

Automotive bodies are generally formed out of sheet steel. The steel is alloyed with various elements to improve its ability to be formed into deeper depressions without wrinkling or tearing in manufacturing presses. Steel is used because of its general availability, low cost, and good workability. For certain applications, however, other materials, such as aluminum, fibreglass, and carbon-fibre reinforced plastic, are used because of their special properties. Polyamide, polyester, polystyrene, polypropylene, and ethylene plastics have been formulated for greater toughness, dent resistance, and resistance to brittle deformation. These materials are used for body panels. Tooling for plastic components generally costs less and requires less time to develop than that for steel components and therefore may be changed by designers at a lower cost.

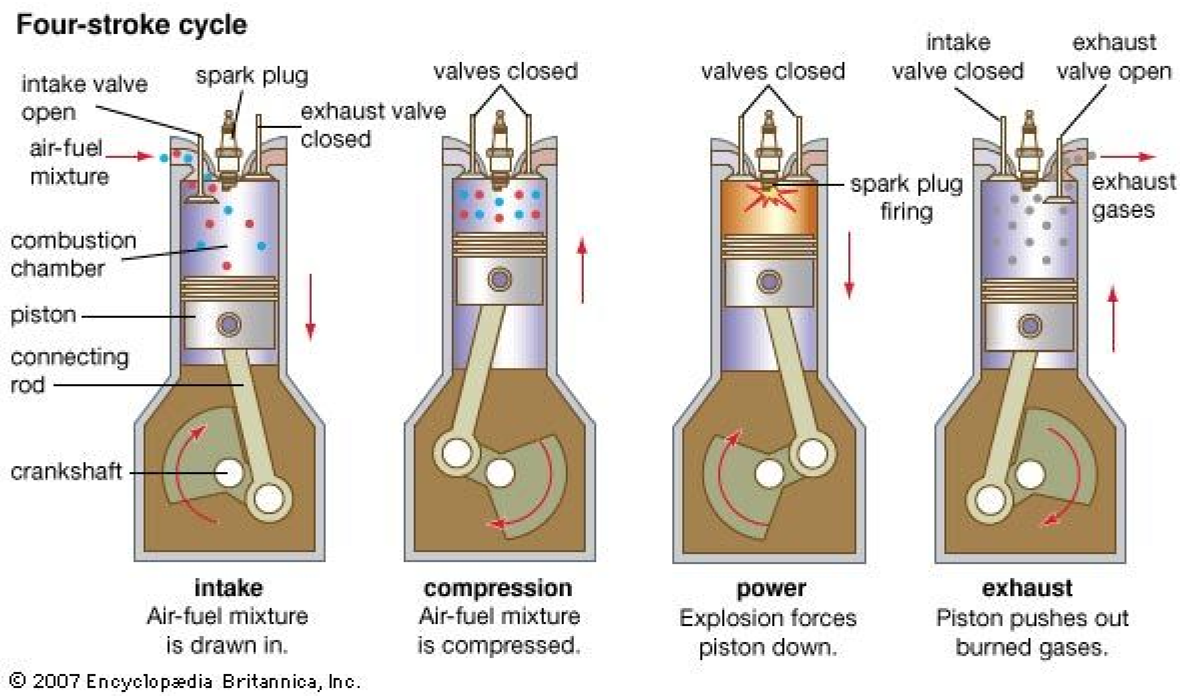
To protect bodies from corrosive elements and to maintain their strength and appearance, special priming and painting processes are used. Bodies are first dipped in cleaning baths to remove oil and other foreign matter. They then go through a succession of dip and spray cycles. Enamel and acrylic lacquer are both in common use. Electrodeposition of the sprayed paint, a process in which the paint spray is given an electrostatic charge and then attracted to the surface by a high voltage, helps assure that an even coat is applied and that hard-to-reach areas are covered. Ovens with conveyor lines are used to speed the drying process in the factory. Galvanized steel with a protective zinc coating and corrosion-resistant stainless steel are used in body areas that are more likely to corrode.

Chassis

In most passenger cars through the middle of the 20th century, a pressed-steel frame—the vehicle's chassis—formed a skeleton on which the engine, wheels, axle assemblies, transmission, steering mechanism, brakes, and suspension members were mounted. The body was flexibly bolted to the chassis during a manufacturing process typically referred to as body-on-frame construction. This process is used today for heavy-duty vehicles, such as trucks, which benefit from having a strong central frame, subjected to the forces involved in such activities as carrying freight, including the absorption of the movements of the engine and axle that is allowed by the combination of body and frame.

In modern passenger-car designs, the chassis frame and the body are combined into a single structural element. In this arrangement, called unit-body (or unibody) construction, the steel body shell is reinforced with braces that make it rigid enough to resist the forces that are applied to it. Separate frames or partial "stub" frames have been used for some cars to achieve better noise-isolation characteristics. The heavier-gauge steel present in modern component designs also tends to absorb energy during impacts and limit intrusion in accidents.

Engine



internal-combustion engine: four-stroke cycle

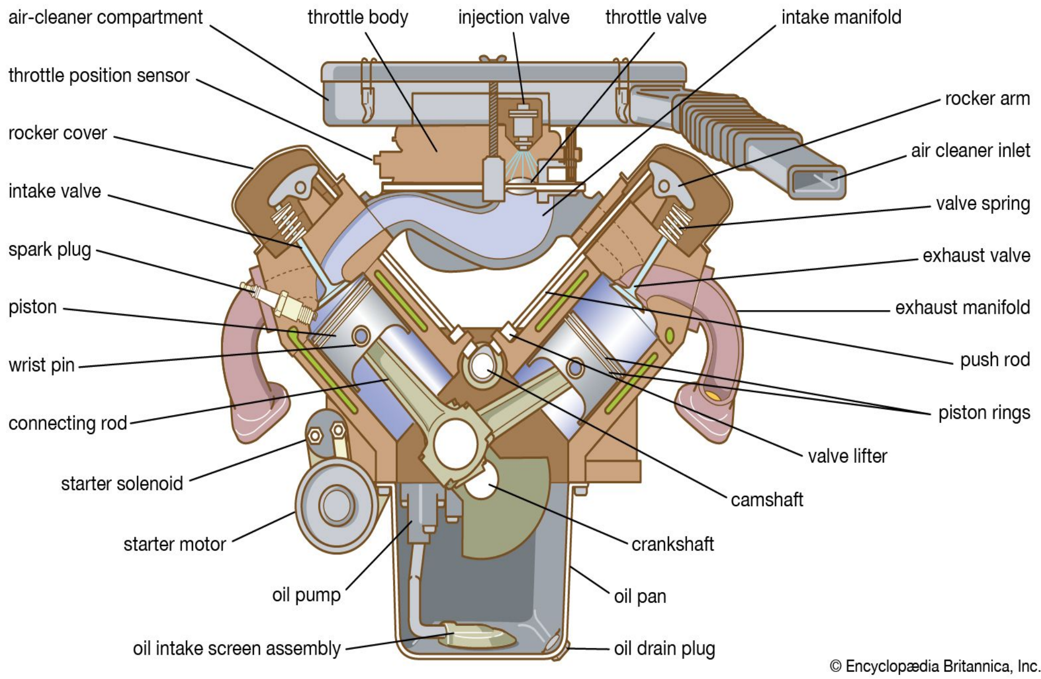
An internal-combustion engine goes through four strokes: intake, compression, combustion (power), and exhaust. As the piston moves during each stroke, it turns the crankshaft.(more).

four-stroke diesel engine

The typical sequence of cycle events in a four-stroke diesel engine involves a single intake valve, fuel-injection nozzle, and exhaust valve, as shown here. Injected fuel is ignited by its reaction to compressed hot air in the cylinder, a more efficient process than that of the spark-ignition internal-combustion engine.(more)

A wide range of engines has been used experimentally and in automotive production. The most successful for automobiles has been the gasoline-fueled reciprocating-piston internal-combustion engine, operating on a four-stroke cycle, while diesel engines are widely used for trucks and buses. The gasoline engine was originally selected for automobiles because it could operate more flexibly over a wide range of speeds, and the power developed for a given weight engine was reasonable; it could be produced by economical mass-production methods; and it used a readily available, moderately priced fuel. Reliability, compact size, exhaust emissions, and range of operation later became important factors.

There has been an ongoing reassessment of these priorities with new emphasis on the reduction of greenhouse gases (*see* greenhouse effect) or pollution-producing characteristics of automotive power systems. This has created new interest in alternate power sources and internal-combustion engine refinements that previously were not close to being economically feasible. Several limited-production battery-powered electric vehicles are marketed today. In the past they had not proved to be competitive, because of costs and operating characteristics. The gasoline engine, with new emission-control devices to improve emission performance, has been challenged in recent years by hybrid power systems that combine gasoline or diesel engines with battery systems and electric motors. Such designs are, however, more complex and therefore more costly.



V-type engine

Cross section of a V-type engine.

The evolution of higher-performance engines in the United States led the industry away from long, straight engine cylinder layouts to compact six- and eight-cylinder V-type layouts for larger cars (with horsepower ratings up to about 350). Smaller cars depend on smaller four-cylinder engines. European automobile engines were of a much wider variety, ranging from 1 to 12 cylinders, with corresponding differences in overall size, weight, piston displacement, and cylinder bores. A majority of the models had four cylinders and horsepower ratings up to 120. Most engines had straight or in-line cylinders. There were, however, several V-type models and horizontally opposed two- and four-cylinder makes. Overhead camshafts were frequently employed. The smaller engines were commonly air-cooled and located at the rear of the vehicle; compression ratios were relatively low. Increased interest in improved fuel economy brought a return to smaller V-6 and four-cylinder layouts, with as many as five valves per cylinder to improve efficiency. Variable valve timing to improve performance and lower emissions has been achieved by manufacturers in all parts of the world. Electronic controls automatically select the better of two profiles on the same cam for higher efficiency when engine speeds and loads change.

Fuel

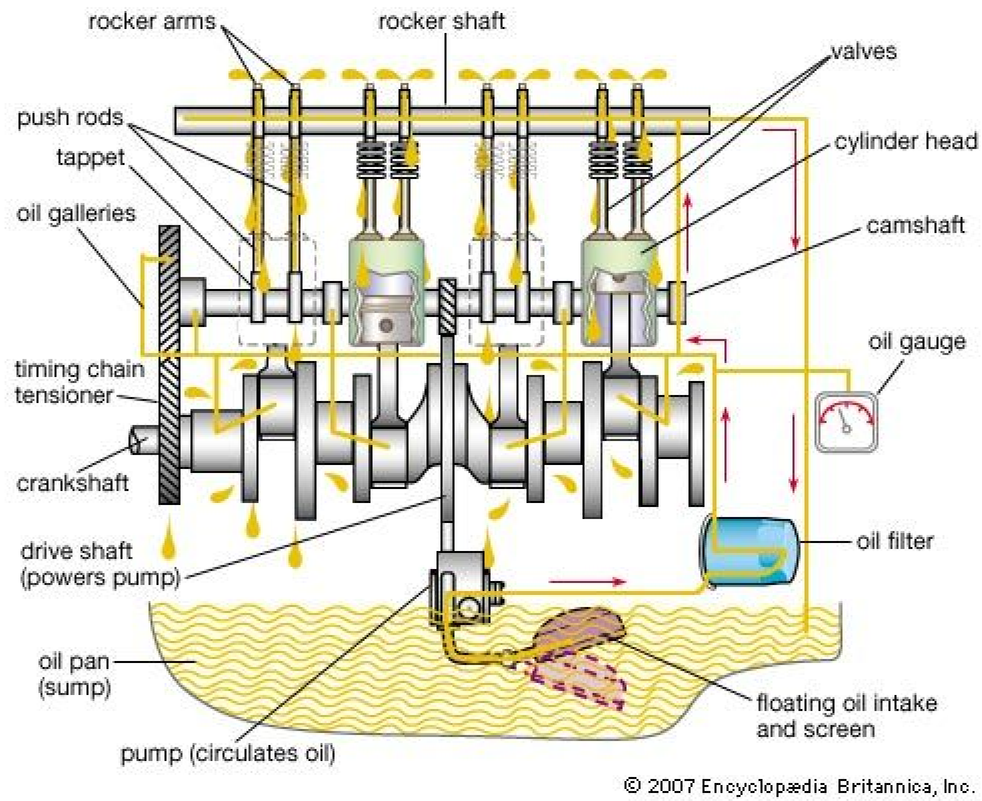
Specially formulated gasoline is essentially the only fuel used for automobile operation, although diesel fuels are used for many trucks and buses and a few automobiles, and compressed liquefied hydrogen has been used experimentally. The most important requirements of a fuel for automobile use are proper volatility, sufficient antiknock quality, and freedom from polluting by-products of combustion. The volatility is reformulated seasonally by refiners so that sufficient gasoline vaporizes, even in extremely cold weather, to permit easy engine starting. Antiknock quality is rated by the octane number of the gasoline. The octane number requirement of an automobile engine depends primarily on the compression ratio of the engine but is also affected by combustion-chamber design, the maintenance condition of engine systems, and chamber-wall deposits. In the 21st century regular gasoline carried an octane rating of 87 and high-test in the neighbourhood of 93.

Automobile manufacturers have lobbied for regulations that require the refinement of cleaner-burning gasolines, which permit emission-control devices to work at higher efficiencies. Such gasoline was first available at some service stations in California, and from 2017 the primary importers and refiners of gasoline throughout the United States were required to remove sulfur particles from fuel to an average level of 10 parts per million (ppm).

Vehicle fleets fueled by natural gas have been in operation for several years. Carbon monoxide and particulate emissions are reduced by 65 to 90 percent. Natural-gas fuel tanks must be four times larger than gasoline tanks for equivalent vehicles to have the same driving range. This compromises cargo capacity.

Ethanol (ethyl alcohol) is often blended with gasoline (15 parts to 85 parts) to raise its octane rating, which results in a smoother-running engine. Ethanol, however, has a lower energy density than gasoline, which results in decreased range per tankful.

Lubrication

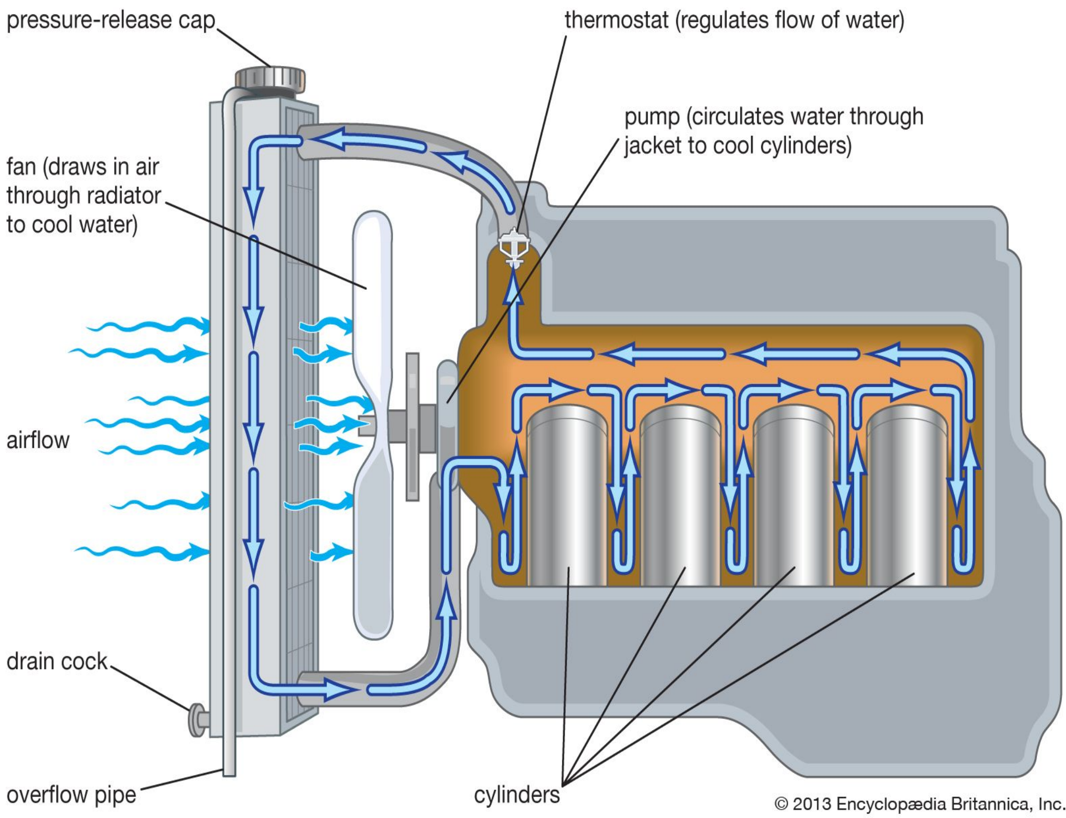


gasoline engine lubrication system
Typical gasoline engine lubrication system.

All moving parts of an automobile require lubrication. Without it, friction would increase power consumption and damage the parts. The lubricant also serves as a coolant, a noise-reducing cushion, and a sealant between engine piston rings and cylinder walls. The engine lubrication system incorporates a gear-type pump that delivers filtered oil under pressure to a system of drilled passages leading to various bearings. Oil spray also lubricates the cams and valve lifters.

Wheel bearings and universal joints require a fairly stiff grease; other chassis joints require a soft grease that can be injected by pressure guns. Hydraulic transmissions require a special grade of light hydraulic fluid, and manually shifted transmissions use a heavier gear oil similar to that for rear axles to resist heavy loads on the gear teeth. Gears and bearings in lightly loaded components, such as generators and window regulators, are fabricated from self-lubricating plastic materials. Hydraulic fluid is also used in other vehicle systems in conjunction with small electric pumps and motors.

Cooling system



gasoline engine cooling system

Typical gasoline engine cooling system.

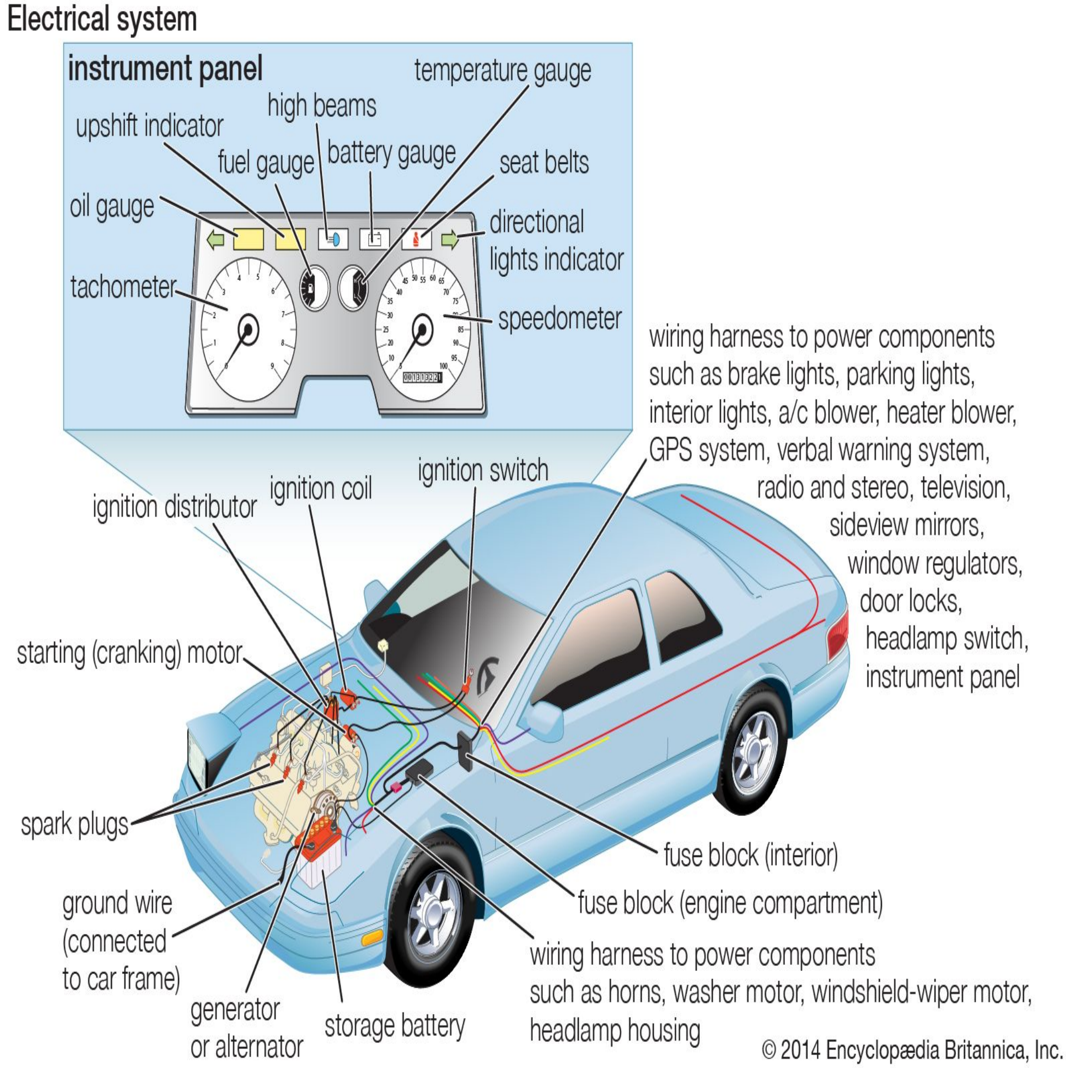
Almost all automobiles employ liquid cooling systems for their engines. A typical automotive cooling system comprises (1) a series of channels cast into the engine block and cylinder head, surrounding the combustion chambers with circulating water or other coolant to carry away excessive heat, (2) a radiator, consisting of many small tubes equipped with a honeycomb of fins to radiate heat rapidly, which receives and cools hot liquid from the engine, (3) a centrifugal-type water pump with which to circulate coolant, (4) a thermostat, which maintains constant temperature by automatically varying the amount of coolant passing into the radiator, and (5) a fan, which draws fresh air through the radiator.

For operation at temperatures below 0 °C (32 °F), it is necessary to prevent the coolant from freezing. This is usually done by adding some compound, such as ethylene glycol, to depress the freezing point of the coolant. By varying the amount of additive, it is possible to protect against freezing of the coolant down to any minimum temperature normally encountered. Coolants contain corrosion inhibitors designed to make it necessary to drain and refill the cooling system only every few years.

Air-cooled cylinders operate at higher, more efficient temperatures, and air cooling offers the important advantage of eliminating not only freezing and boiling of the coolant at temperature extremes but also corrosion damage to the cooling system. Control of engine temperature is more difficult, however, and high-temperatureresistant ceramic parts are required when design operating temperatures are significantly increased.

Pressurized cooling systems have been used to increase effective operating temperatures. Partially sealed systems using coolant reservoirs for coolant expansion if the engine overheats were introduced in the early 1970s. Specially formulated coolants that do not deteriorate over time eliminate the need for annual replacement.

Electrical system



automobile electrical system

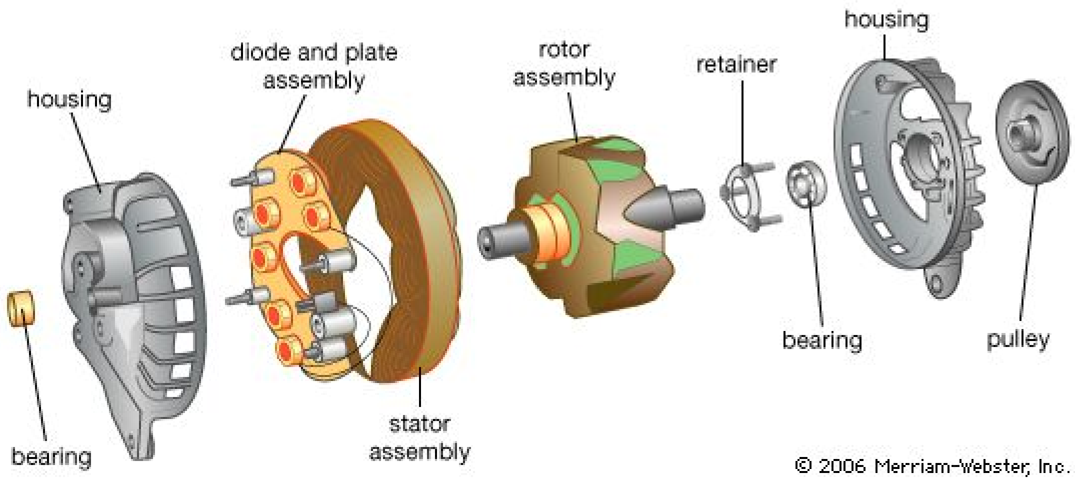
Components of an automobile's electrical system.

The electrical system comprises a storage battery, generator, starting (cranking) motor, lighting system, ignition system, and various accessories and controls. Originally, the electrical system of the automobile was limited to the ignition equipment. With the advent of the electric starter on a 1912 Cadillac model, electric lights and horns began to replace the kerosene and acetylene lights and the bulb horns. Electrification was rapid and complete, and, by 1930, 6-volt systems were standard everywhere.

Increased engine speeds and higher cylinder pressures made it increasingly difficult to meet high ignition voltage requirements. The larger engines required higher cranking torque. Additional electrically operated features—such as radios, window regulators, and multispeed windshield wipers—also added to system requirements. To meet these needs, 12-volt systems replaced the 6-volt systems in the late 1950s around the world.

The ignition system provides the spark to ignite the air-fuel mixture in the cylinders of the engine. The system consists of the spark plugs, coil, distributor, and battery. In order to jump the gap between the electrodes of the spark plugs, the 12-volt potential of the electrical system must be stepped up to about 20,000 volts. This is done by a circuit that starts with the battery, one side of which is grounded on the chassis and leads through the ignition switch to the primary winding of the ignition coil and back to the ground through an interrupter switch. Interrupting the primary circuit induces a high voltage across the secondary terminal of the coil. The high-voltage secondary terminal of the coil leads to a distributor that acts as a rotary switch, alternately connecting the coil to each of the wires leading to the spark plugs.

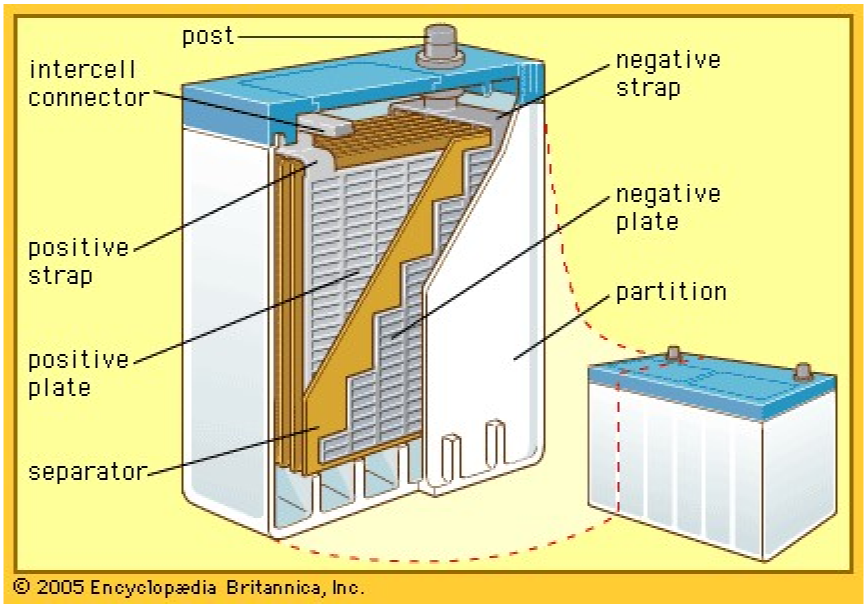
Solid-state or transistorized ignition systems were introduced in the 1970s. These distributor systems provided increased durability by eliminating the frictional contacts between breaker points and distributor cams. The breaker point was replaced by a revolving magnetic-pulse generator in which alternating-current pulses trigger the high voltage needed for ignition by means of an amplifier electronic circuit. Changes in engine ignition timing are made by vacuum or electronic control unit (microprocessor) connections to the distributor.



automobile alternator

Exploded view of an automotive alternator. The engine's turning crankshaft, connected to the alternator's pulley by a belt, turns the magnetic rotor inside the stationary stator assembly, generating an alternating current. The diode assembly rectifies the alternating current, producing direct current, which is used to meet the demands of the vehicle's electrical system, including recharging the battery.(more)

The source of energy for the various electrical devices of the automobile is a generator, or alternator, that is belt-driven from the engine crankshaft. The design is usually an alternating-current type with built-in rectifiers and a voltage regulator to match the generator output to the electric load and also to the charging requirements of the battery, regardless of engine speed.



automobile battery: cutaway view

Construction of the automotive-type lead-acid battery (cutaway view). A storage battery not only holds its charge for a long time, but it also can be recharged.(more)

A lead-acid battery serves as a reservoir to store excess output of the generator. This provides energy for the starting motor and power for operating other electric devices when the engine is not running or when the generator speed is not sufficiently high for the load.

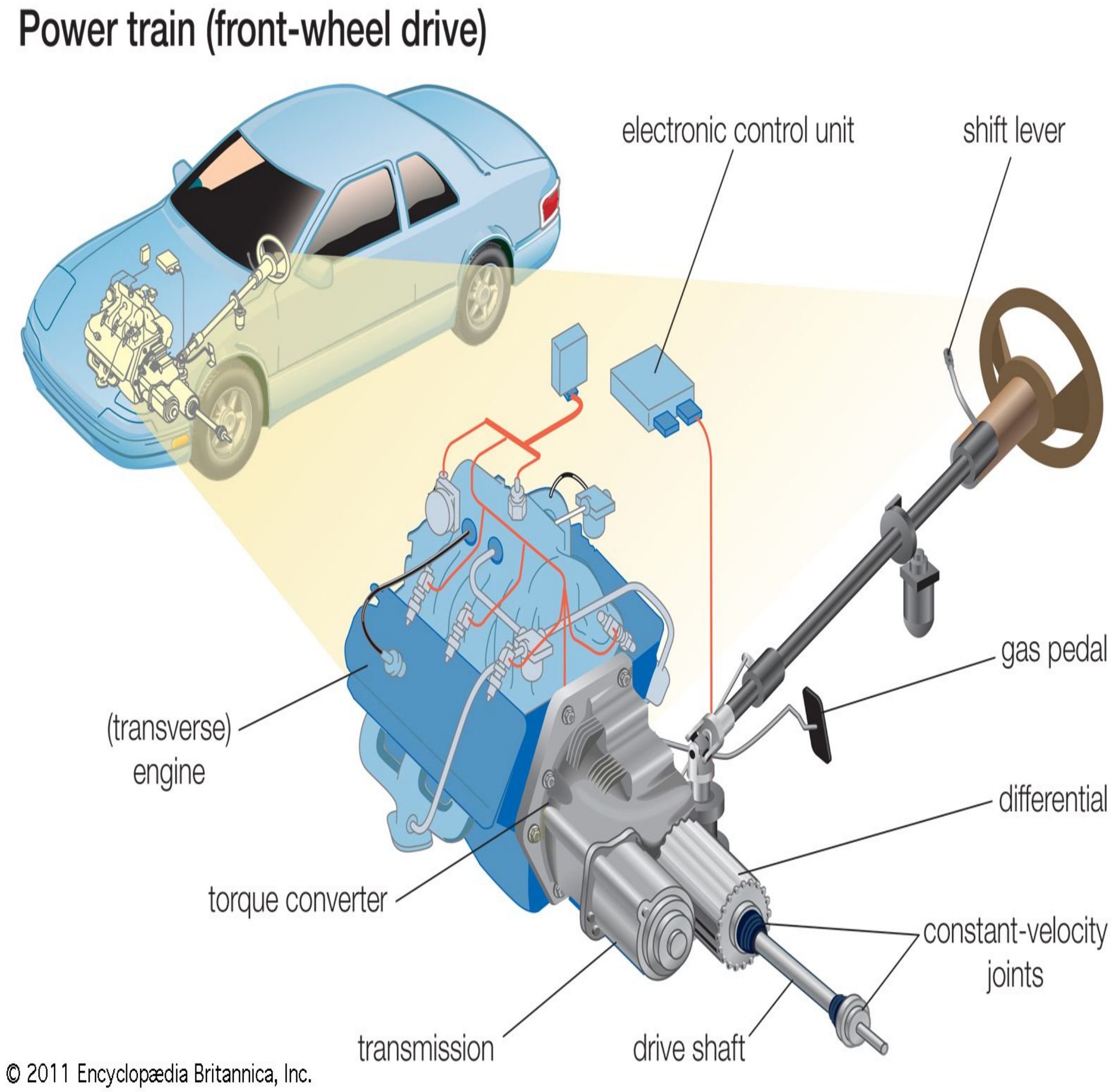
The starting motor drives a small spur gear so arranged that it automatically moves in to mesh with gear teeth on the rim of the flywheel as the starting-motor armature begins to turn. When the engine starts, the gear is disengaged, thus preventing damage to the starting motor from overspeeding. The starting motor is designed for high current consumption and delivers considerable power for its size for a limited time.

Headlights must satisfactorily illuminate the highway ahead of the automobile for driving at night or in inclement weather without temporarily blinding approaching drivers. This was achieved in modern cars with double-filament bulbs with a high and a low beam, called sealed-beam units. Introduced in 1940, these bulbs found widespread use following World War II. Such units could have only one filament at the focal point of the reflector. Because of the greater illumination required for high-speed driving with the high beam, the lower beam filament was placed off centre, with a resulting decrease in lighting effectiveness. Separate lamps for these functions can also be used to improve illumination effectiveness.

Dimming is automatically achieved on some cars by means of a photocell-controlled switch in the lamp circuit that is triggered by the lights of an oncoming car. Lamp clusters behind aerodynamic plastic covers permitted significant front-end drag reduction and improved fuel economy. In this arrangement, steerable headlights became possible with an electric motor to swivel the lamp assembly in response to steering wheel position. The regulations of various governments dictate brightness and field of view requirements for vehicle lights.

Signal lamps and other special-purpose lights have increased in usage since the 1960s. Amber-coloured front and red rear signal lights are flashed as a turn indication; all these lights are flashed simultaneously in the “flasher” (hazard) system for use when a car is parked along a roadway or is traveling at a low speed on a high-speed highway. Marker lights that are visible from the front, side, and rear also are widely required by law. Red-coloured rear signals are used to denote braking, and cornering lamps, in connection with turning, provide extra illumination in the direction of an intended turn. Backup lights provide illumination to the rear and warn anyone behind the vehicle when the driver is backing up. High-voltage light-emitting diodes (LEDs) have been developed for various signal and lighting applications.

Transmission



power train of a front-wheel-drive automobile

The main elements of the power train of a front-wheel-drive automobile are the transversely mounted engine and the transmission, which transfers the torque, or turning energy, of the engine to the drive wheels through a short drive shaft.(more)

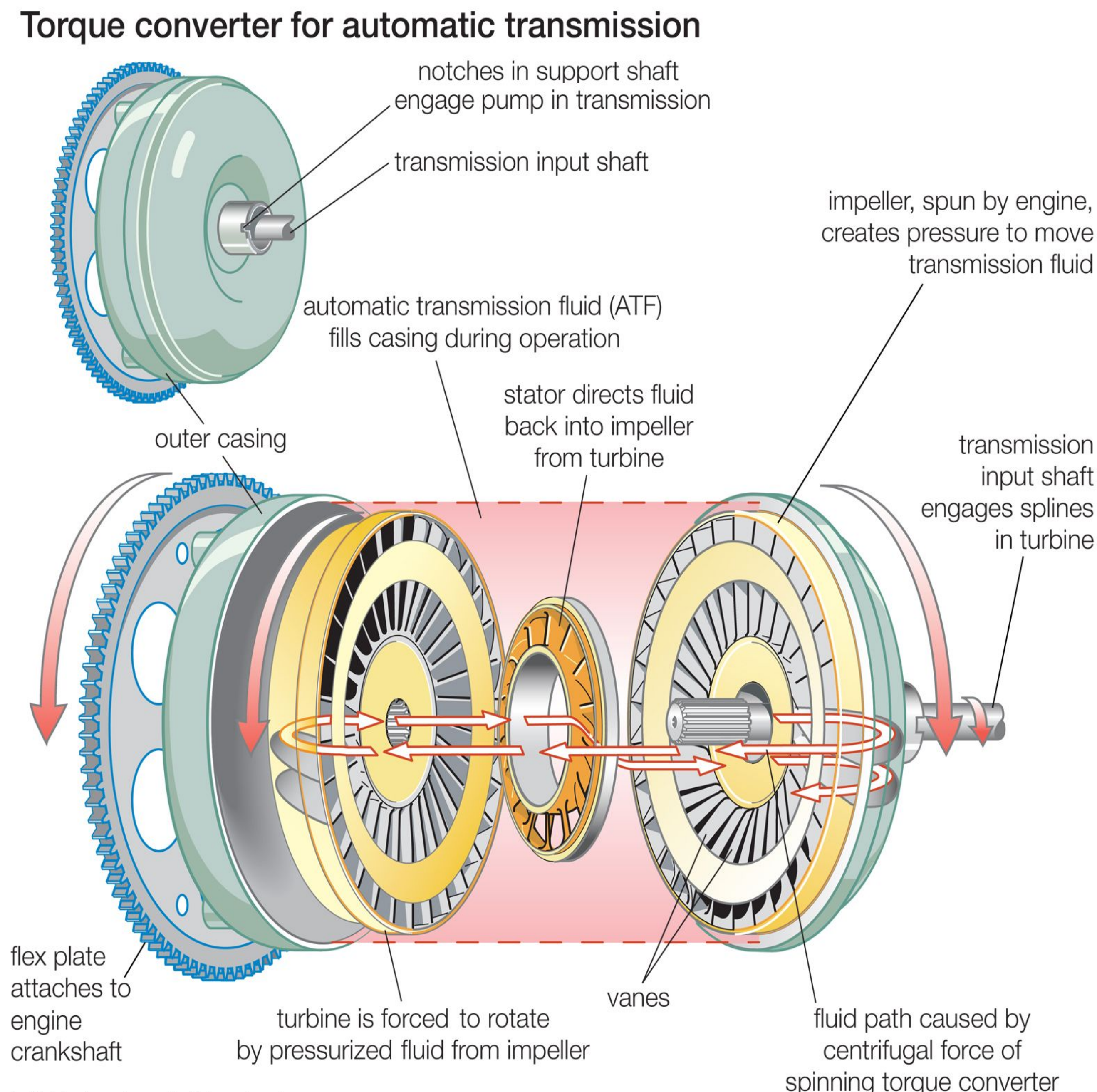
The gasoline engine must be disconnected from the driving wheels when it is started and when idling. This characteristic necessitates some type of unloading and engaging device to permit gradual application of load to the engine after it has been started. The torque, or turning effort, that the engine is capable of producing is low at low crankshaft speeds, increasing to a maximum at some fairly high speed representing the maximum, or rated, horsepower.

The efficiency of an automobile engine is highest when the load on the engine is high and the throttle is nearly wide open. At moderate speeds on level pavement, the power required to propel an automobile is only a fraction of this. Under normal driving conditions at constant moderate speed, the engine may operate at an uneconomically light load unless some means is provided to change its speed and power output.

The transmission is such a speed-changing device. Installed in the power train between the engine and the driving wheels, it permits the engine to operate at a higher speed when its full power is needed and to slow down to a more economical speed when less power is needed. Under some conditions, as in starting a stationary vehicle or in ascending steep grades, the torque of the engine is insufficient, and amplification is needed. Most devices employed to change the ratio of the speed of the engine to the speed of the driving wheels multiply the engine torque by the same factor by which the engine speed is increased.

The simplest automobile transmission is the sliding-spur gear type with three or more forward speeds and reverse. The desired gear ratio is selected by manipulating a shift lever that slides a spur gear into the proper position to engage the various gears. A clutch is required to engage and disengage gears during the selection process. The necessity of learning to operate a clutch is eliminated by an automatic transmission. Most automatic transmissions employ a hydraulic torque converter, a device for transmitting and amplifying the torque produced by the engine. Each type provides for manual selection of reverse and low ranges that either prevent automatic upshifts or employ lower gear ratios than are used in normal driving. Grade-retard provisions are also sometimes included to supply dynamic engine braking on hills. Automatic transmissions not only require little skill to operate but also make possible better performance than is obtainable with designs that require clutch actuation.

In hydraulic transmissions, shifting is done by a speed-sensitive governing device that changes the position of valves that control the flow of hydraulic fluid. The vehicle speeds at which shifts occur depend on the position of the accelerator pedal, and the driver can delay upshifts until higher speed is attained by depressing the accelerator pedal further. Control is by hydraulically engaged bands and multiple-disk clutches running in oil, either by the driver's operation of the selector lever or by speed- and load-sensitive electronic control in the most recent designs. Compound planetary gear trains with multiple sun gears and planet pinions have been designed to provide a low forward speed, intermediate speeds, a reverse, and a means of locking into direct drive. This unit is used with various modifications in almost all hydraulic torque-converter transmissions. All transmission control units are interconnected with vehicle emission control systems that adjust engine timing and air-to-fuel ratios to reduce exhaust emissions.



torque converter

The components of a torque converter.

Oil in the housing is accelerated outward by rotating vanes in the pump impeller and, reacting against vanes in the turbine impeller, forces them to rotate, as shown schematically in the figure. The oil then passes into the stator vanes, which redirect it to the pump. The stator serves as a reaction member providing more torque to turn the turbine than was originally applied to the pump impeller by the engine. Thus, it acts to multiply engine torque by a factor of up to 2 1/2 to 1.

Blades in all three elements are specially contoured for their specific function and to achieve particular multiplication characteristics. Through a clutch linkage, the stator is allowed gradually to accelerate until it reaches the speed of the pump impeller. During this period torque multiplication gradually drops to approach 1 to 1.

The hydraulic elements are combined with two or more planetary gear sets, which provide further torque multiplication between the turbine and the output shaft.

Continuously (or infinitely) variable transmissions provide a very efficient means of transferring engine power and, at the same time, automatically changing the effective input-to-output ratio to optimize economy by keeping the engine running within its best power range. Most designs employ two variable-diameter pulleys connected by either a steel or high-strength rubber V-belt. The pulleys are split so that effective diameters may be changed by an electrohydraulic actuator to change the transmission ratio. This permits the electronic control unit to select the optimum ratio possible for maximum fuel economy and minimum emissions at all engine speeds and loads. Originally these units were limited to small cars, but belt improvements have made them suitable for larger cars.

Other mechanical subsystems

Axles

Power is conveyed from the transmission to the rear axle of rear-wheel-drive vehicles by a drive shaft and universal joints. As body lines were progressively lowered, the floor level came closer to the drive shaft, necessitating floor humps or tunnels to provide clearance. The adoption of hypoid or offset spiral bevel gears in the rear axle provided an increase in this clearance by lowering the drive pinion below the centre of the axle shafts.

The ring gear of the rear axle surrounds the housing of a differential gear train that serves as an equalizer in dividing the torque between the two driving wheels while permitting one to turn faster than the other when rounding corners. The axle shafts terminate in bevel gears that are connected by several smaller bevel gears mounted on radial axles attached to the differential housing and carried around with it by the ring gear. In its simplest form this differential has the defect that one driving wheel may spin when it loses traction, and the torque applied to the wheel, being equal to that of the slipping wheel, will not be sufficient to drive the car. Several differentials have been developed to overcome this difficulty.

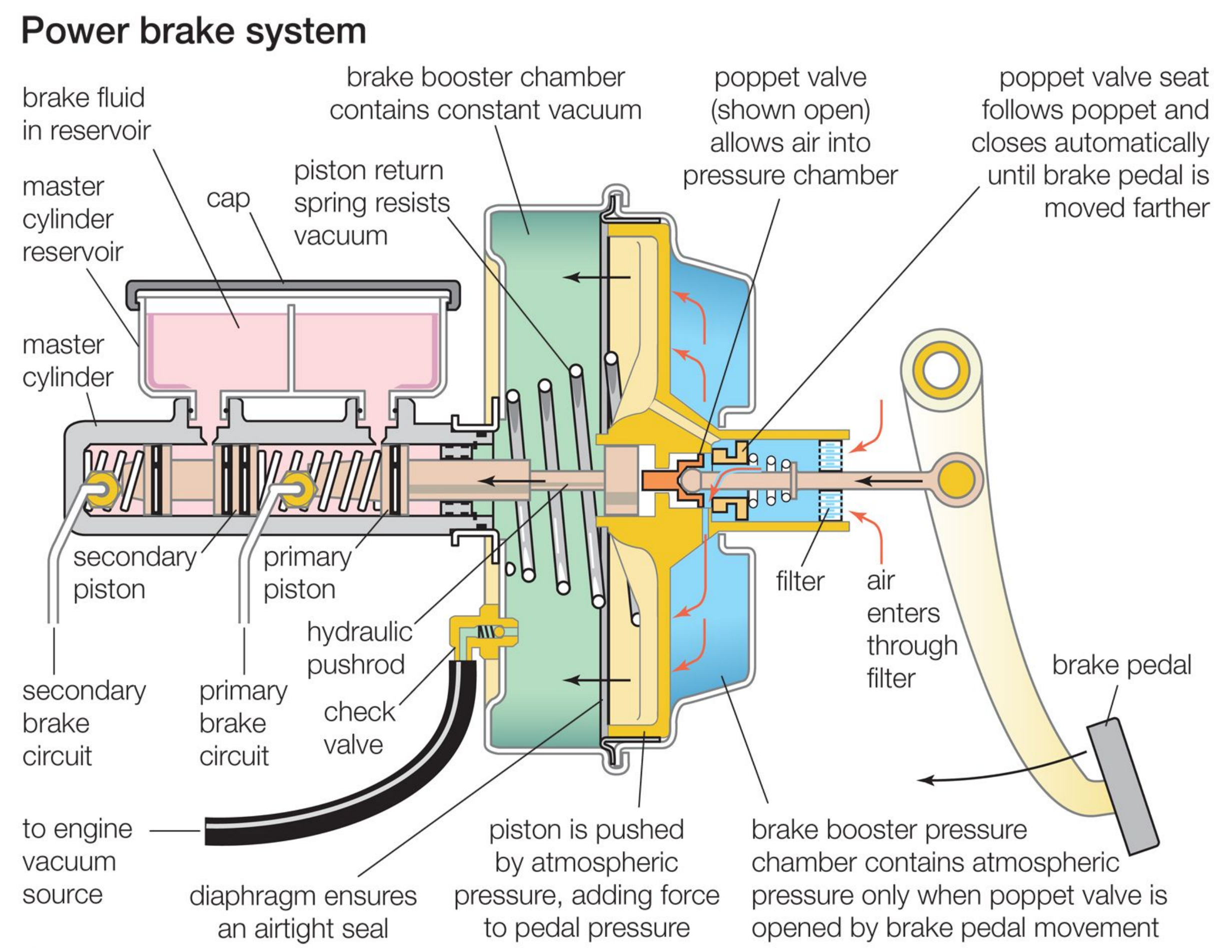
Articulated rear axles offer individual wheel suspension at the rear as well as the front. Individual rear suspension not only eliminates the heavy rear axle housing but also permits lowered bodies with no floor humps, because the transmission and differential gears can be combined in a housing mounted on a rear cross member moving with the body under suspension-spring action. In some instances, articulated or swing axles that have tubular housings surrounding the axle shafts terminate in spherical head segments that fit into matching sockets formed in the sides of the central gear housing. Universal

joints within the spherical elements permit the axle shafts to move with the actions of the suspension springs. The gear housing is supported by a rear cross member of the chassis and moves with the sprung portion of the vehicle, as does the drive shaft. Other types eliminate the axle shaft housings and drive the wheels through two open shafts fitted with universal joints. The wheels are then individually supported by radius rods or other suitable linkage. Individually suspended wheels are simplified for rear-engine, rear-wheel-drive cars and front-engine, front-wheel-drive mechanisms.
A combined transmission and differential assembly can form a unit with the engine. Two short transverse drive shafts, each having universal joints at both ends, transmit power to the wheels.

Brakes

Originally, most systems for stopping vehicles were mechanically actuated drum brakes with internally expanding shoes; i.e., foot pressure exerted on the brake pedal was carried directly to semicircular brake shoes by a system of flexible cables. Mechanical brakes, however, were difficult to keep adjusted so that equal braking force was applied at each wheel; and, as vehicle weights and speeds increased, more and more effort on the brake pedal was demanded of the driver.

Mechanical brakes were replaced by hydraulic systems, in which the brake pedal is connected to pistons in master cylinders and thence by steel tubing with flexible sections to individual cylinders at the wheels. Front and rear hydraulic circuits are separated. The wheel cylinders are located between the movable ends of the brake shoes, and each is fitted with two pistons that are forced outward toward the ends of the cylinder by the pressure of the fluid between them. As these pistons move outward, they push the brake shoes against the inner surface of the brake drum attached to the wheel. The larger diameter of the piston in the master cylinder provides a hydraulic force multiplication at the wheel cylinder that reduces the effort required of the driver.

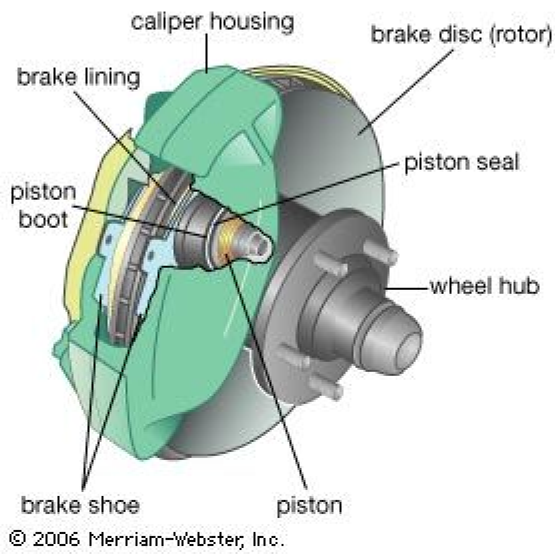


vacuum-assisted power brake

Vacuum-assisted power brake for an automobile. A constant vacuum is maintained in the brake booster by the engine. When the brake pedal is depressed, a poppet valve opens, and air rushes into a pressure chamber on the driver's side of the booster. The pressure exerted by this air against the vacuum pushes a piston, thus assisting the pressure exerted by the driver on the pedal. The piston in turn exerts pressure on the master cylinder, from which brake fluid is forced to act on the brakes.(more)

Further increases in vehicle weights and speeds made even hydraulic brakes difficult for drivers to operate effectively, and automobiles consequently were equipped with power brake systems. These are virtually the same as the hydraulic system except that the piston of the master cylinder is multiplied by power assists of several types instead of by foot pressure on the pedal.

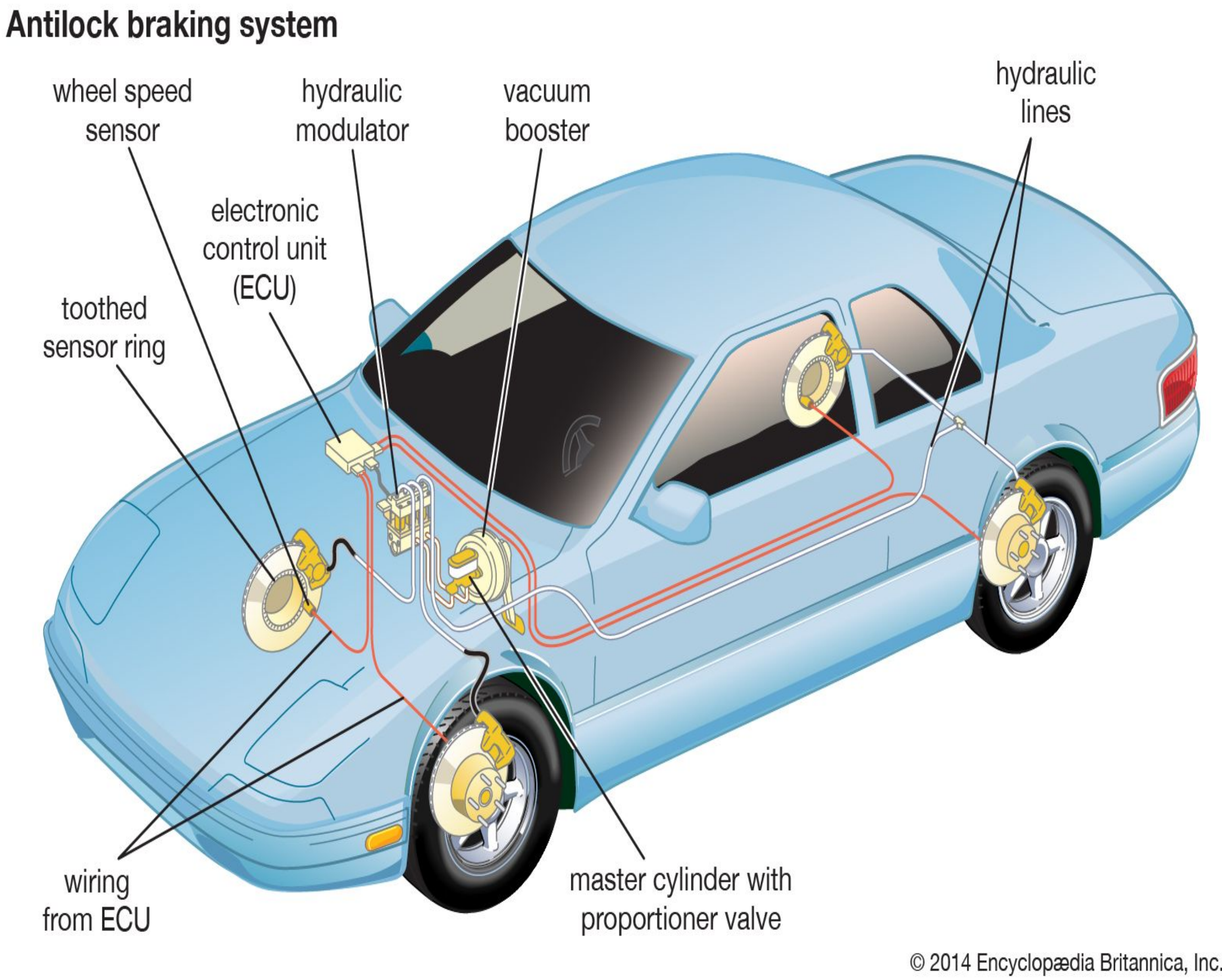
Overheating of the brake drums and shoes causes the brakes to fade and lose their effectiveness when held in engagement for a considerable length of time. This problem has been attacked by the use of aluminum cooling fins bonded to the outside of the brake drums to increase the rate of heat transfer to the air. Vents in the wheels are provided to increase the air circulation for cooling.



disc brake assembly

A disc brake assembly. Wheel rotation is slowed by friction when the hydraulic pistons squeeze the caliper, pressing the brake pads (shoe and lining assemblies) against the spinning disc (rotor), which is bolted to the wheel hub.(more)

Disc brakes, originally developed for aircraft, are ubiquitous, in spite of their higher cost, because of their fade resistance. Although there are some four-wheel systems, usually discs are mounted on the front wheels, and conventional drum units are retained at the rear. They have been standard on most European automobiles since the 1950s and most American models since the mid-1970s. Each wheel has a hub-mounted disc and a brake unit or caliper rigidly attached to the suspension. The caliper employs two friction-pad assemblies, one on each side of the disc. When the brake is applied, hydraulic pressure forces the friction pads against the disc. This arrangement is self-adjusting, and the ability of the discs to dissipate heat rapidly in the open airstream makes them practically immune to fading.

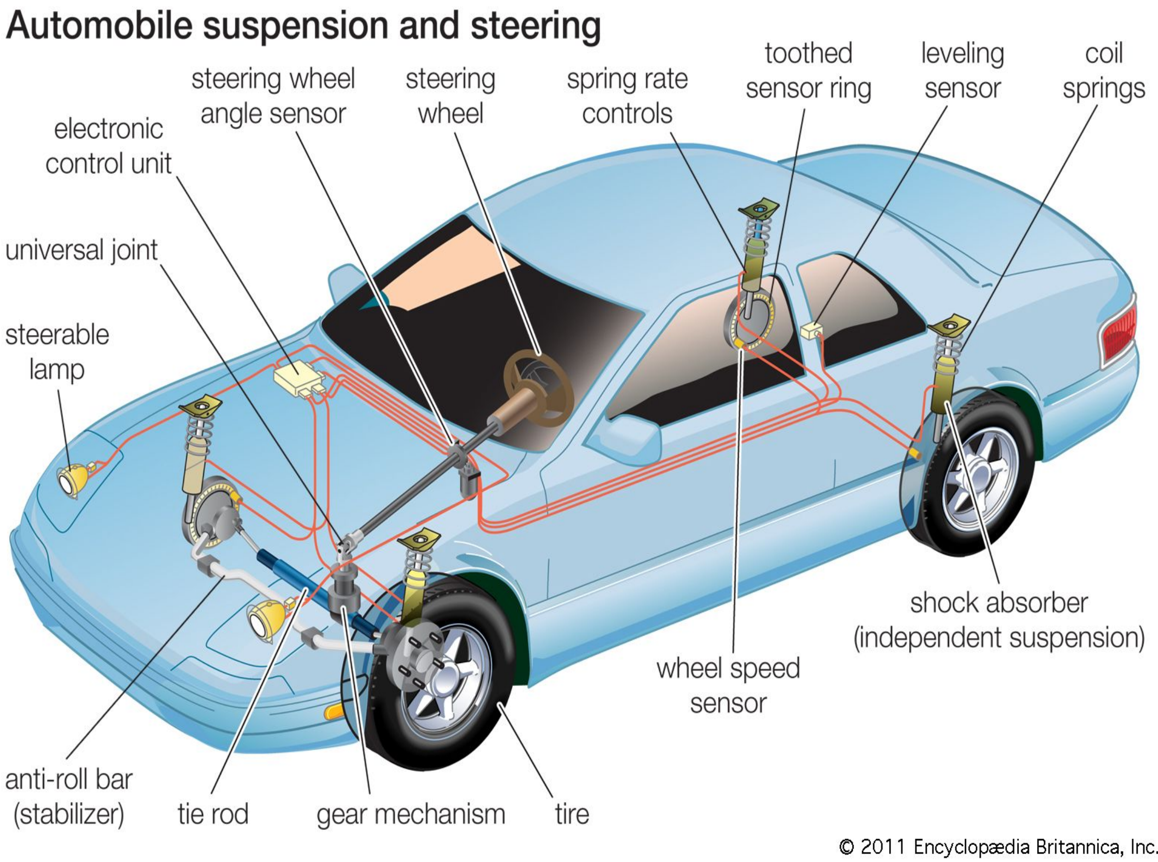


antilock braking system
Components of an antilock braking system.

Antilock braking systems (ABS) became available in the late 1980s and since then have become standard on a growing number of passenger cars. ABS installations consist of wheel-mounted sensors that input wheel rotation speed into a microprocessor. When wheel rotation increases because of tire slippage or loss of traction, the control unit signals a hydraulic or electric modulator to regulate brake line pressure to forestall impending wheel lockup. The brake continues to function as the system cyclically releases and applies pressure, similar to but much faster than a driver rapidly pumping the brake pedal on a non-ABS-equipped automobile. The wheels continue to roll, retaining the driver's ability to steer the vehicle and stop in a shorter distance.

Parking brakes usually are of the mechanical type, applying force only to the rear brake shoes by means of a flexible cable connected to a hand lever or pedal. On cars with automatic transmissions, an additional lock is usually provided in the form of a pawl that can be engaged, by placing the shift lever in the "park" position, to prevent the drive shaft and rear wheels from turning. The service brake pedal must be applied to permit shifting the transmission out of the park position. This eliminates the possibility of undesired vehicle motion that could be caused by accidental movement of the transmission control.

Steering



suspension and steering systems

The component parts of an automobile's suspension and steering systems.

Automobiles are steered by a system of gears and linkages that transmit the motion of the steering wheel to the pivoted front wheel hubs. The gear mechanism, located at the lower end of the shaft carrying the steering wheel, is usually a worm-and-nut or cam-and-lever combination that rotates a shaft with an attached crank arm through a small angle as the steering wheel is turned. Tie rods attached to the arm convey its motion to the wheels. In cornering, the inner wheel must turn through a slightly greater angle than the outer wheel, because the inner wheel negotiates a sharper turn. The geometry of the linkage is designed to provide for this.

When the front wheels are independently suspended, the steering must be designed so that the wheels are not turned as the tie rods lengthen and shorten as a result of spring action. The point of linkage attachment to the steering gear must be placed so that it can move vertically with respect to the wheel mountings without turning the wheels.

As the engine and passenger compartment in automobiles beginning in the 1930s in Europe and the United States were moved forward to improve riding comfort and road-handling characteristics, the distribution of weight between the front and rear wheels was shifted toward the front. The weight carried on the front wheels increased to more than half of the total vehicle weight, and consequently the effort necessary to turn the wheels in steering increased. Larger, heavier cars with wider tires and lower tire pressure also contributed to drag between tires and road that had to be overcome in steering, particularly in parking. Considerable reduction in the work of steering resulted from increasing the efficiency of the steering gears and introducing better bearings in the front wheel linkage. Additional ease of turning the steering wheel was accomplished by increasing the overall steering gear ratio (the number of degrees of steering-wheel turn required to turn the front wheels one degree). However, large steering gear ratios made high-speed maneuverability more difficult, because the steering wheel had to be turned through greater angles. Moreover, steering mechanisms of higher efficiency were also more reversible; that is, road shocks were transmitted more completely from the wheels and had to be overcome to a greater extent by the driver. This caused a dangerous situation on rough roads or when a front tire blew out, because the wheel might be jerked from the driver's hands.

Power steering gear was developed to solve the steadily increasing steering problems. Power steering was first applied to heavy trucks and military vehicles early in the 1930s, and hundreds of patents were granted for devices to help the driver turn the steering wheel. Most of the proposed devices were hydraulic; some were electrical and some mechanical. In hydraulic systems, a pump driven by the engine maintains the fluid under pressure. A valve with a sensing device allows the fluid to enter and leave the power cylinder as necessary. Speed-sensitive systems are available to provide larger ratios for reduced effort at low speeds and lower ratios for steering at high speeds. Four-wheel steering systems in which the rear wheels turn in the opposite direction of the front wheels have had limited commercial use.

Suspension

The riding comfort and handling qualities of an automobile are greatly affected by the suspension system, in which the suspended portion of the vehicle is attached to the wheels by elastic members in order to cushion the impact of road irregularities. The specific nature of attaching linkages and spring elements varies widely among automobile models. The best rides are made possible by independent suspension systems, which permit the wheels to move independently of each other. In these systems the unsprung weight of the vehicle is decreased, softer springs are permissible, and front-wheel vibration problems are minimized. Spring elements used for automobile suspension members, in increasing order of their ability to store elastic energy per unit of weight, are leaf springs, coil springs, torsion bars, rubber-in-shear devices, and air springs.

The leaf spring, although comparatively inelastic, has the important advantage of accurately positioning the wheel with respect to the other chassis components, both laterally and fore and aft, without the aid of auxiliary linkages.

An important factor in spring selection is the relationship between load and deflection known as the spring rate, defined as the load in pounds divided by the deflection of the spring in inches. A soft spring has a low rate and deflects a greater distance under a given load. A coil or a leaf spring retains a substantially constant rate within its operating range of load and will deflect 10 times as much if a force 10 times as great is applied to it. The torsion bar, a long spring-steel element with one end held rigidly to the frame and the other twisted by a crank connected to the axle, can be designed to provide an increasing spring rate.

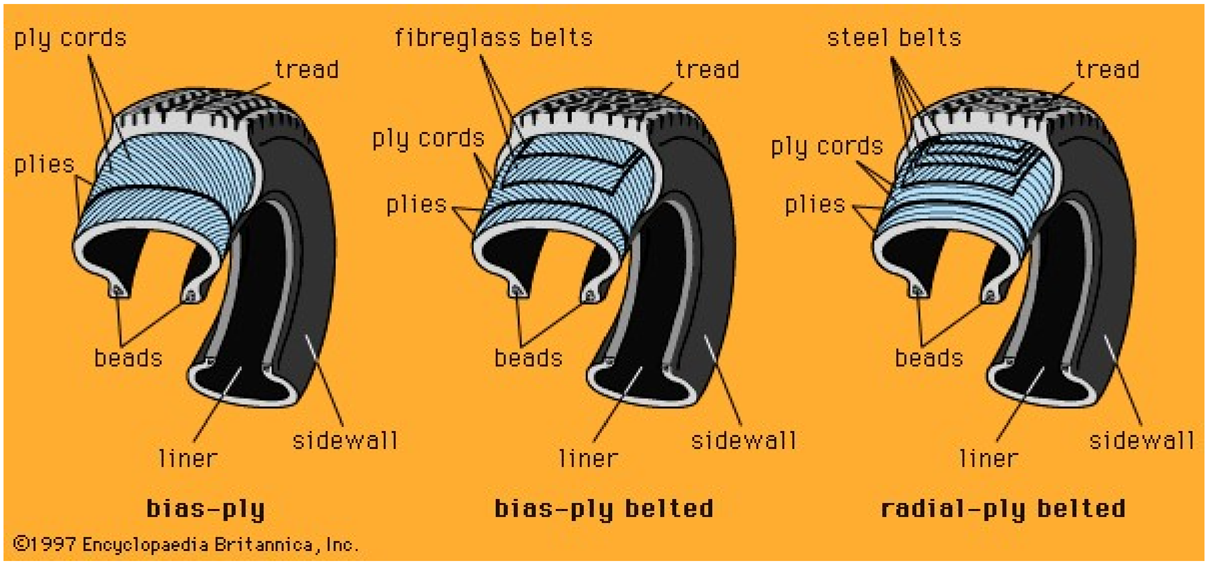
A soft-spring suspension provides a comfortable ride on a relatively smooth road, but the occupants move up and down excessively on a rough road. The springs must be stiff enough to prevent a large deflection at any time because of the difficulty in providing enough clearance between the sprung portion of the vehicle and the unsprung portion below the springs. Lower roof heights make it increasingly difficult to provide the clearance needed for soft springs. Road-handling characteristics also suffer because of what is known as sway, or roll, the sidewise tilting of the car body that results from centrifugal force acting outward on turns. The softer the suspension, the more the outer springs are compressed and the inner springs expanded. In addition, the front end dives more noticeably when braking with soft front springs.

Air springs offer several advantages over metal springs, one of the most important being the possibility of controlling the spring rate. Inherently, the force required to deflect the air unit increases with greater deflection, because the air is compressed into a smaller space and greater pressure is built up, thus progressively resisting further deflection.

A combination hydraulic-fluid-and-air suspension system has been developed in which the elastic medium is a sealed-in, fixed mass of air, and no air compressor is required. The hydraulic portion of each spring is a cylinder mounted on the body sill and fitted with a plunger that is pivotally attached to the wheel linkage to form a hydraulic strut. Each spring cylinder has a spherical air chamber attached to its outer end. The sphere is divided into two chambers by a flexible diaphragm, the upper occupied by air and the lower by hydraulic fluid that is in communication with the hydraulic cylinder through a two-way restrictor valve. This valve limits the rate of movement of the plunger in the cylinder, since fluid must be pushed into the sphere when the body descends and returned when it rises. This damping action thus controls the motion of the wheel with respect to the sprung portion of the vehicle supported by the spring.

So-called active suspensions incorporate a microprocessor to vary the orifice size of the restrictor valve in a hydraulic suspension or shock absorber (a mechanical device that dampens the rate of energy stored and released by the springs). This changes the effective spring rate. Control inputs may be vehicle speed, load, acceleration, lateral force, or a driver preference.

Tires



pneumatic tires
Three types of pneumatic tires.

The pneumatic rubber tire is the point of contact between the automobile and the road surface. It functions to provide traction for acceleration and braking and limits the transmission of road vibrations to the automobile body. Inner tubes within tires were standard until the 1950s, when seals between the tire and the wheel were developed, leading to tubeless tires, now used almost universally.

Tire tread designs are tailored for the characteristics of the surface on which the vehicle is intended to operate. Deep designs provide gripping action in loose soil and snow, while smooth surfaces provide maximum contact area for applications such as racing. Current passenger car treads are a compromise between these extremes.

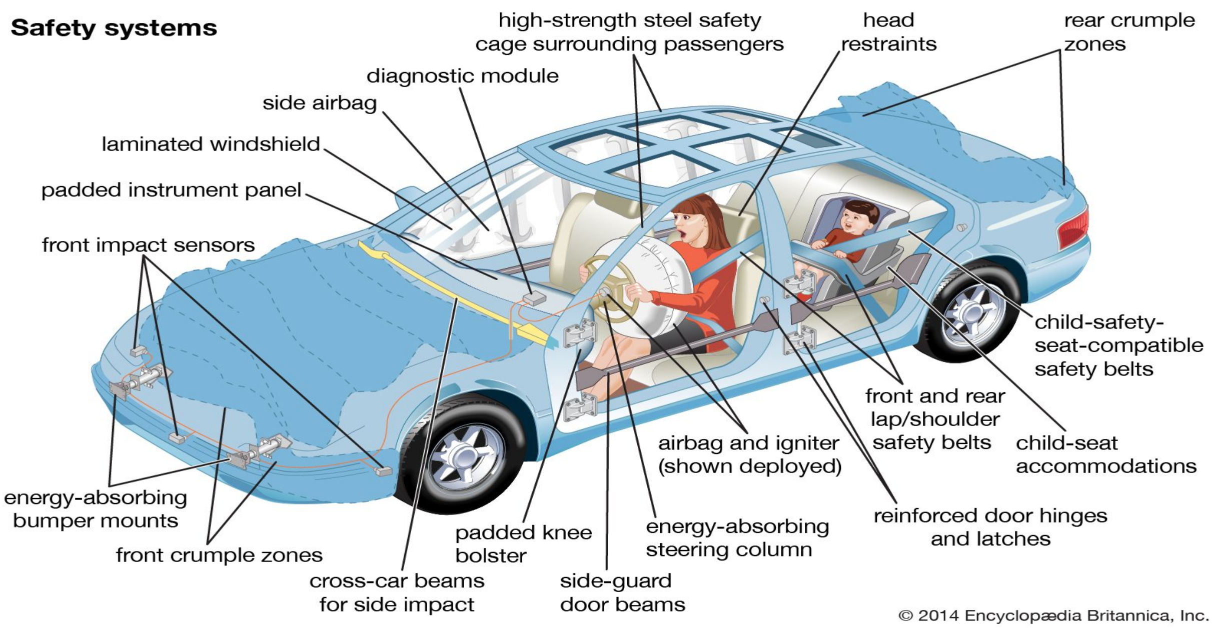
A typical tire casing is fabricated from layers, or plies, of varying proportions of rubber compounds reinforced with synthetic and carbon fibres or steel wire. The composition of the reinforcement and the angle of its application to the axis of the tread affect the ability of the tire to respond to sidewise forces created during cornering. They also affect harshness or vibration-transmission characteristics.

By 1990, longitudinal-, bias-, and radial-ply constructions were in use, with layers of two, four, or more plies, depending on the load capacity of the design. An additional factor relating to the load capacity of a particular construction is the pressure to which the tire is inflated. New designs also have lower height-to-width ratios to increase the road-contact area while maintaining a low standing height for the tire and consequently the car.

Security systems

Motor vehicle theft has been a problem since the start of the automobile age. The 1900 Leach automobile featured a removable steering wheel that the driver could carry away to prevent unauthorized vehicle use. More recently, sophisticated electronic alarms, some of which incorporate radio beacons, and more tamper-resistant wiring and electronic locks have been produced. Through the use of wireless technology, vehicles equipped with Global Positioning System (GPS) satellite navigation systems may be tracked and recovered when stolen.

Safety systems



automobile safety systems

Types of automobile safety systems.

From its beginnings the automobile posed serious hazards to public safety. Vehicle speed and weight provided an impact capacity for occupants and pedestrians that produced great numbers of fatalities (13,000 in 1920 in the United States alone and many more in Europe, as well as many serious injuries). During the 20th century the rates of death and injury declined significantly in terms of vehicle miles, but, because of the increased number of vehicles on the road, total fatalities declined only slightly. During 2005–10, however, fatalities declined by 25 percent for reasons that are not understood. This downward trend continued in the following decade. Most fatal accidents occur on either city streets or secondary roads. New divided roadway designs are relatively safer. Driver training, vehicle maintenance, highway improvement, and law enforcement were identified as key areas responsible for improving safety, but the basic design of the vehicle itself and the addition of special safety features were significant factors in worldwide reduction of fatal accidents. Rates vary from country to country. Safety features of automobiles come under two distinct headings: accident avoidance and occupant protection.

Accident-avoidance systems are designed to help the driver maintain better control of the car. The dual-master-cylinder brake system is a good example. This protects the driver against sudden loss of brake line pressure. Front and rear brake lines are separated so that if one fails, the other will continue to function.

Systems for protecting occupants in the event of an accident fall into four major classes: maintenance of passenger-compartment integrity, occupant restraints, interior-impact energy-absorber systems, and exterior-impact energy absorbers. Statistics indicate a far higher chance for survival among accident victims remaining inside the passenger compartment. Passenger-compartment integrity depends significantly on the proper action of the doors, which must remain closed in the event of an accident and must be sufficiently secure to prevent intrusion. Door-latch mechanisms have been designed to resist forward, rearward, and sideward forces and incorporate two-stage catches, so that the latch may hold if the primary stage fails. Reinforcement beams in doors are designed to deflect impact forces downward to the more rigid frame structure below the door. Forces are directed through reinforced door pillars and hinges.

Occupant restraints are used to help couple the passenger to the car. They permit decelerating with the car rather than free flight into the car structure or into the air. A combination of lap and shoulder belts is the most common restraint system. The belts consist of web fabrics that are required by regulations in various countries to withstand 6,000-pound (2,700-kg) test loading and are bolted to the car underbody and roof rail. Button-type latch release mechanisms are provided for buckles.

Another line of engineering development has centred on passive restraints that do not require any action by the occupant. In particular, commercial air bags were introduced in the 1980s, and all new automobiles sold in the United States since 1998 (1999 for light trucks) have required both driver and front passenger air bags. When a vehicle equipped with an air bag undergoes a "hard" impact, roughly in excess of 10 miles (16 km) per hour, a crash sensor sends an electrical signal that triggers an explosion which generates nitrogen gas to inflate air bags located in the steering column, front dashboard, and possibly other locations. Air bags burst from their locations and inflate to a position between occupants and the car structure in less than one-tenth of a second. The inflated air bags absorb impact energy from occupants by forcing gas out through a series of ports or orifices in the air bag fabric. Air bags collapse in about one second, thereby allowing occupants to exit the vehicle.

It has been estimated that 46 percent of front-seat fatalities could be eliminated by air bags when they are used in conjunction with lap or lap-and-shoulder belts. This is a 10 percent improvement over the use of lap and shoulder belt systems alone. The front-mounted air bag does not provide protection in side or rear crashes or in prolonged impacts from rollovers. Additional side-mounted air bags, however, provide a measure of protection in side impacts and are available in some vehicle models.

Interior-impact energy-absorbing devices augment restraint systems by absorbing energy from the occupant while minimizing injuries. The energy-absorbing steering column, introduced in 1967, is a good example of such a device. Instrument panels, windshield glass, and other surfaces that may be struck by an unrestrained occupant may be designed to absorb energy in a controlled manner.

Exterior-impact energy-absorbing devices include the structural elements of the chassis and body, which may be tailored to deform in a controlled manner to decelerate the automobile more gradually and, as a result, leave less force to be experienced by the occupants. Stress risers in the form of section irregularities have been built into front frame members of some cars. These are designed to buckle under severe loads and absorb energy in the process.

Emission controls

By-products of the operation of the gasoline engine include carbon monoxide, oxides of nitrogen, and hydrocarbons (unburned fuel compounds), each of which is a pollutant. To control the air pollution resulting from these emissions, governments establish quality standards and perform inspections to ensure that standards are met. Standards have become progressively more stringent, and the equipment necessary to meet them has become more complex.

Various engine modifications that alter emission characteristics have been successfully introduced. These include adjusted air-fuel ratios, lowered compression ratios, retarded spark timing, reduced combustion chamber surface-to-volume ratios, and closer production tolerances. To improve drivability (“responsiveness”) of some arrangements, preheated air from a heat exchanger on the exhaust manifold is ducted to the air cleaner.

The undesired evaporation of gasoline hydrocarbons into the air has been controlled by sealing the fuel tank and venting the tank through a liquid-vapour separator into a canister containing activated charcoal. During engine operation these vapours are desorbed and burned in the engine.

Among emission-control devices developed in the 1970s were catalytic converters (devices to promote combustion of hydrocarbons in the exhaust), exhaust-gas-recirculation systems, manifold reactors, fuel injection, and unitized ignition elements.

A catalytic converter consists of an insulated chamber containing a porous bed, or substrate, coated with catalytic material through which hot exhaust gas must pass before being discharged into the air. The catalyst is one of a variety of metal oxides, usually platinum or palladium, which are heated by exhaust gas to about 500 °C (900 °F). At this temperature unburned hydrocarbons and carbon monoxide are further oxidized, while oxides of nitrogen are chemically reduced in a second chamber with a different catalyst. Problems with catalysts involve their intolerance for leaded fuels and the need to prevent overheating.

Exhaust-gas recirculation is a technique to control oxides of nitrogen, which are formed by the chemical reaction of nitrogen and oxygen at high temperatures during combustion. Either reducing the concentrations of these elements or lowering peak cycle temperatures will reduce the amount of nitrogen oxides produced. To achieve this, exhaust gas is piped from the exhaust manifold to the intake manifold. This dilutes the incoming fuel-air mixture and effectively lowers combustion temperature. The amount of recirculation is a function of throttle position but averages about 2 percent.

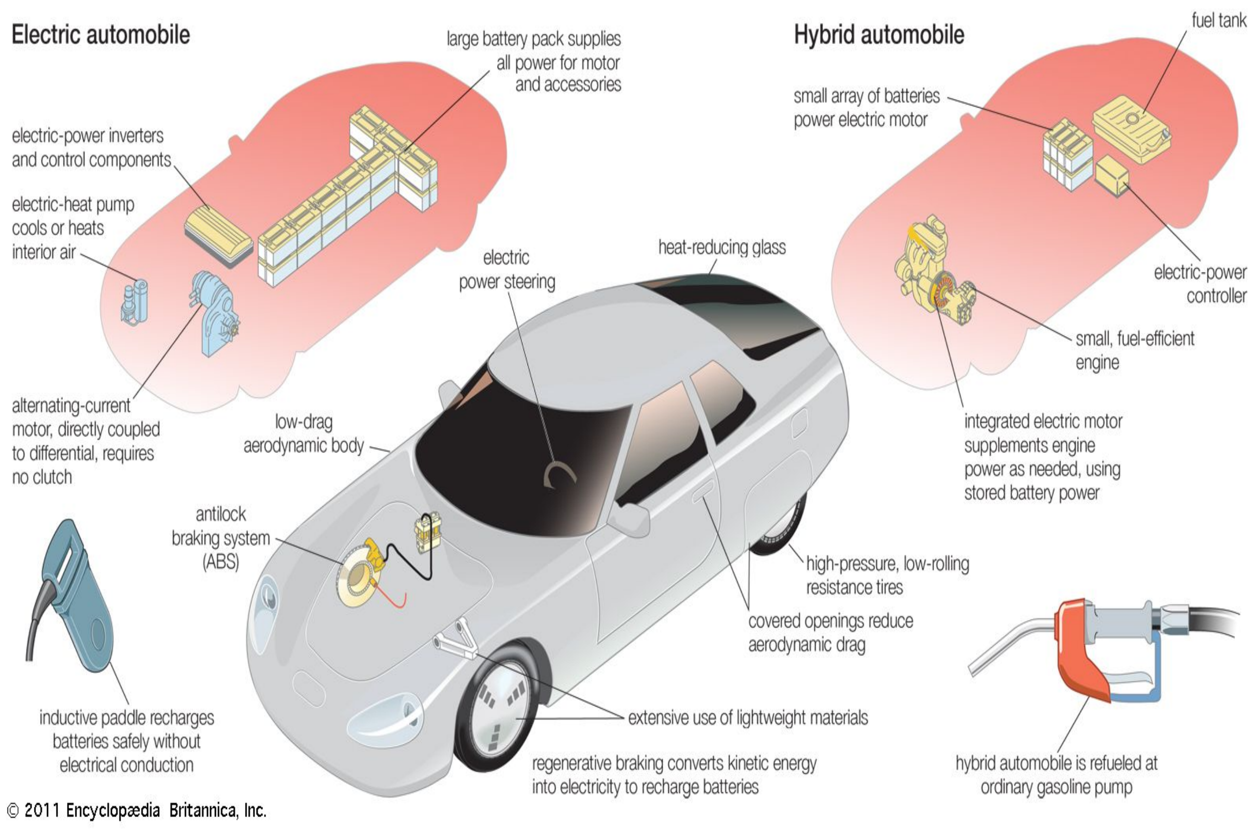
Manifold reactors are enlarged and insulated exhaust manifolds into which air is injected and in which exhaust gas continues to burn. The effectiveness of such units depends on the amount of heat generated and the length of time the gas is within the manifold. Stainless steel and ceramic materials are used to provide durability at high operating temperatures (approaching 1,300 °C [about 2,300 °F]).

Fuel injection, as a replacement for carburetion, is almost universally employed to reduce exhaust emissions. The precise metering of fuel for each cylinder provides a means of ensuring that the chemically correct air-to-fuel ratio is being burned in the engine. This eliminates cylinder-to-cylinder variations and the tendency of cylinders that are most remote from the carburetor to receive less fuel than is desired. A variety of metering and control systems are commercially available. Timed injection, in which a small quantity of gasoline is squirted into each cylinder or intake-valve port during the intake stroke of the piston, is employed on a number of cars.

In several timed-injection systems, individual pumps at each intake valve are regulated (timed) by a microprocessor that monitors intake vacuum, engine temperature, ambient-air temperature, and throttle position and adjusts the time and duration of injection accordingly.

In the early 21st century motor vehicles were being driven more than 3.2 trillion miles per year in the United States. This is an increase of more than 58 percent in 30 years.

Electric and hybrid vehicles



electric automobile and hybrid automobile
Component systems of a typical electric automobile and hybrid gasoline-electric automobile.(more)
Modern electric cars and trucks have been manufactured in small numbers in Europe, Japan, and the United States since the 1980s. However, electric propulsion is only possible for relatively short-range vehicles, using power from batteries or fuel cells. In a typical system, a group of lead-acid batteries connected in a series powers electric alternating-current (AC) induction motors to propel the vehicle. When nickel–metal hydride batteries are substituted, the driving range is doubled. A solid-state rectifier, or power inverter, changes the direct current (DC) supplied by the battery pack to an AC output that is controlled by the driver using an accelerator pedal to vary the output voltage. Because of the torque characteristics of electric motors, conventional gear-type transmissions are not needed in most designs. Weight and drag reduction, as well as regenerative systems to recover energy that would otherwise be lost, are important considerations in extending battery life. Batteries may be recharged in six hours from a domestic electrical outlet.

Conventional storage-battery systems do not have high power-to-weight ratios for acceleration or energy-to-weight ratios for driving range to match gasoline-powered general-purpose vehicles. Special-purpose applications, however, may be practical because of the excellent low-emission characteristics of the system. Such systems have been used to power vehicles on the Moon and in specialized small vehicles driven within factories.

Several hybrid vehicles are now being produced. They combine an efficient gasoline engine with a lightweight, high-output electric motor that produces extra power when needed. During normal driving, the motor becomes a generator to recharge the battery pack. This eliminates the need to plug the car into an electrical outlet for recharging. The primary advantage of hybrids is that the system permits downsizing the engine and always operating in its optimum efficiency range through the use of advanced electronic engine and transmission controls.

Experimental systems

The U.S. automotive industry spends $18 billion or more on research and development of future products in a typical year—the most spent by any industry in the United States. Increasing pressure from various governments is requiring manufacturers to develop very low- and zero-emission vehicles. Authorities in California have estimated that motor vehicles produce 40 percent of the greenhouse gases that they consider to be responsible for climate change. To meet this challenge, manufacturers are working on a timetable to produce more efficient vehicle designs.

Expansion of the total potential automotive market in the future and concern for the environment may be expected to change cars of the future. Special-purpose vehicles designed for specific urban or rural functions, with appropriate power systems for each type of use, may be needed. Possibilities include solar, steam, gas turbine, new hybrid combinations, and other power sources.

Steam power plants have been reexamined in the light of modern technology and new materials. The continuous-combustion process used to heat the steam generator offers potentially improved emission characteristics.

Gas turbines have been tested extensively and have good torque characteristics, operate on a wide variety of fuels, have high power-to-weight ratios, meet emission standards, and offer quiet operation. Some studies have shown that the advantages of the system are best realized in heavy-duty vehicles operating on long, nearly constant speed runs. Efficiencies and operating characteristics can be improved by increasing operating temperatures. This may become commercially feasible utilizing ceramic materials that are cost-effective. Successful designs require regenerative systems to recover energy from hot exhaust gas and transfer it to incoming air. This improves fuel economy, reduces exhaust temperatures to safer levels, and eliminates the need for a muffler in some designs.

A number of other designs have been studied involving variations of engine combustion cycles such as turbocharged gasoline and diesel (two- and four-stroke) designs. Rotary engines have been produced in Germany and Japan, but they have been almost entirely discontinued because of exhaust emission control complexity. Variable valve timing can optimize performance and economy and provide a more constant engine torque output at different engine speeds. By delaying the opening of the engine exhaust valve, exhaust gas is effectively recirculated to reduce tailpipe emissions. Electro-hydraulic valves that totally replace the complexity of camshaft designs, or idlers that may be moved to change the geometry of the camshaft timing chain and retard valve opening, may be used for this purpose.

Solar-powered electric demonstration vehicles have been built by universities and manufacturers. Solar collector areas have proved to be too large for conventional cars, however. Development continues on solar cell design.

Microprocessors have become increasingly important in improving fuel economy and reducing undesirable exhaust emissions for all vehicle types. Research to develop so-called intelligent vehicles that can assist the driver and even operate without driver intervention, at least on special roads, has made some progress, with assistive technology becoming increasingly standard. These developments have been made possible by highly reliable solid-state digital computers and similarly reliable electronic sensors. The automobile industry has worked with governmental bodies to link vehicles to their environments using advanced telecommunication signals, electronic systems, and digital computers, both within the vehicle and aboard satellites and in other remote locations. Applications may be divided into functions for basic vehicle system assistance, safety and security applications, and information and entertainment systems.

The automobile industry is responsible for about two-thirds of the rubber, one-half of the platinum, one-third of the aluminum, one-seventh of the steel, and one-tenth of the copper consumed in the United States each year. About four-fifths of the material in a car is recyclable, and in the United States 19 out of 20 scrapped cars are recycled. Because the automobile is likely to remain an important part of the transportation system, it requires continuing improvement in safety and emission control as well as performance and cost.

Orville C. CromerGeorge C. Cromer

History of the automobile

Unlike many other major inventions, the original idea of the automobile cannot be attributed to a single individual. The idea certainly occurred long before it was first recorded in the *Iliad*, in which Homer (in Alexander Pope's translation) states that Vulcan in a single day made 20 tricycles, which

> Wondrous to tell instinct with spirit roll'ed
> From place to place, around the blest abodes,
> Self-moved, obedient to the beck of gods.

Leonardo da Vinci considered the idea of a self-propelled vehicle in the 15th century. In 1760 a Swiss clergyman, J.H. Genevois, suggested mounting small windmills on a cartlike vehicle, their power to be used to wind springs that would move the road wheel. Genevois's idea probably derived from a windmill cart of about 1714. Two-masted wind carriages were running in the Netherlands in 1600, and a speed of 20 miles (30 km) per hour with a load of 28 passengers was claimed for at least one of them. The first recorded suggestion of wind use was probably Robert Valturio's unrealized plan (1472) for a cart powered by windmills geared to the wheels.

Other inventors considered the possibilities of clockwork. Probably in 1748 a carriage propelled by a large clockwork engine was demonstrated in Paris by the versatile inventor Jacques de Vaucanson.

The air engine is thought to have originated with a 17th-century German physicist, Otto von Guericke. Guericke invented an air pump and was probably the first to make metal pistons, cylinders, and connecting rods, the basic components of the reciprocating engine. In the 17th century a Dutch inventor, Christiaan Huygens, produced an engine that worked by air pressure developed by explosion of a powder charge. Denis Papin of France built a model engine on the vacuum principle, using the condensation of steam to produce the vacuum. An air engine was patented in England in 1799, and a grid of compressor stations was proposed to service vehicles. An air-powered vehicle is said to have been produced in 1832.

Steam propulsion was proposed as early as the 16th century, and in 1678 Ferdinand Verbiest, a Belgian Jesuit missionary to China, made a model steam carriage based on a principle suggestive of the modern turbine.

In the 18th century a French scientist, Philippe Lebon, patented a coal-gas engine and made the first suggestion of electrical ignition. In Paris, Isaac de Rivas made a gas-powered vehicle in 1807; his engine used hydrogen gas as fuel, the valves and ignition were operated by hand, and the timing problem appears to have been difficult.

The age of steam

1769 Cugnot

In 1769 Nicolas-Joseph Cugnot built a three-wheeled steam-driven vehicle that is considered to be the first true automobile. Because of the heavy weight of the steam chamber in the front, it had a tendency to tip over when not hauling cannons, which was what it was designed to do.(more)

Most historians agree that Nicolas-Joseph Cugnot of France was the constructor of the first true automobile. Cugnot's vehicle was a huge, heavy, steam-powered tricycle, and his model of 1769 was said to have run for 20 minutes at 2.25 miles (3.6 km) per hour while carrying four people and to have recuperated sufficient steam power to move again after standing for 20 minutes. Cugnot was an artillery officer, and the more or less steam-tight pistons of his engine were made possible by the invention of a drill that accurately machined cannon bores. A replica of Cugnot's second vehicle, partially original, is preserved in the Conservatoire National des Arts et Métiers in Paris.

Cugnot's successors were soon at work, notably in England, although the first post-Cugnot steam carriage appears to have been built in Amiens, France, in 1790. Steam buses were running in Paris about 1800. Oliver Evans of Philadelphia ran an amphibious steam dredge through the streets of that city in 1805. Less well known were Nathan Read of Salem, Massachusetts, and Apollos Kinsley of Hartford, Connecticut, both of whom ran steam vehicles during the period 1790–1800. In March 1863 the magazine *Scientific American* described tests of a vehicle that weighed only 650 pounds (about 300 kg) and achieved a speed of 20 miles (30 km) per hour. Another American, Frank Curtis of Newburyport, Massachusetts, is remembered for building a personal steam carriage to the order of a Boston man who failed to meet the payment schedule, whereupon Curtis made the first recorded repossession of a motor vehicle.

English inventors were active, and by the 1830s the manufacture and use of steam road carriages was flourishing. James Watt's foreman, William Murdock, ran a model steam carriage on the roads of Cornwall in 1784, and Robert Fourness showed a working three-cylinder tractor in 1788. Watt was opposed to the use of steam engines for such purposes; his low-pressure steam engine would have been too bulky for road use in any case, and all the British efforts in steam derived from the earlier researches of Thomas Savery and Thomas Newcomen.

Richard Trevithick developed Murdock's ideas, and at least one of his carriages, with driving wheels 10 feet (3 metres) in diameter, ran in London. Sir Goldsworthy Gurney, the first commercially successful steam carriage builder, based his design upon an unusually efficient boiler. He was not, however, convinced that smooth wheels could grip a roadway, and so he arranged propulsion on his first vehicle by iron legs digging into the road surface. His second vehicle weighed only 3,000 pounds (1,360 kg) and was said to be capable of carrying six persons. He made trips as long as 84 miles (135 km) in a running time of 9 hours and 30 minutes and once recorded a speed of 17 miles (27 km) per hour.

Gurney equipment was used on the Gloucester-Cheltenham service of four daily round trips; under favourable conditions the equipment could complete the 9 miles (15 km) in 45 minutes. Between February 27 and June 22, 1831, steam coaches ran 4,000 miles (6,400 km) on this route, carrying some 3,000 passengers. The equipment was noisy, smoky, destructive of roadways, and admittedly dangerous; hostility arose, and it was common for drivers to find the way blocked with heaps of stones or felled trees. Nevertheless, numerous passengers had been carried by steam carriage before the railways had accepted their first paying passenger.

The most successful era of the steam coaches in Britain was the 1830s. Ambitious routes were run, including one from London to Cambridge. But by 1840 it was clear that the steam carriages had little future. They had much to contend with, including the anti-machinery attitude of the public and the enmity of the horse-coach interests, which resulted in such penalties as a charge of £5 for passing a tollgate that cost a horse coach only three pence. The crushing blow was the Locomotives on Highways Act of 1865, which reduced permissible speeds on public roads to 2 miles (3 km) per hour within cities and 4 miles (6 km) per hour in rural areas. This legislation was known as the Red Flag Act because of its requirement that every steam carriage mount a crew of three, one to precede it carrying a red flag of warning. The act was amended in 1878, but it was not repealed until 1896, by which time its provisions had effectively stifled the development of road transport in the British Isles.

The decline of the steam carriage did not prevent continued effort in the field, and much attention was given to the steam tractor for use as a prime mover. Beginning about 1868, Britain was the scene of a vogue for light steam-powered personal carriages; if the popularity of these vehicles had not been legally hindered, it would certainly have resulted in widespread enthusiasm for motoring in the 1860s rather than in the 1890s. Some of the steamers could carry as few as two people and were capable of speeds of 20 miles (32 km) per hour. The public climate remained unfriendly, however.

Light steam cars were being built in the United States, France, Germany, and Denmark during the same period, and it is possible to argue that the line from Cugnot's lumbering vehicle runs unbroken to the 20th-century steam automobiles made as late as 1926. The grip of the steam automobile on the American imagination has been strong ever since the era of the Stanley brothers—one of whose "steamers" took the world speed record at 127.66 miles (205.45 km) per hour in 1906. The car designed by them and sold as the Locomobile became the first commercially successful American-made automobile (about 1,000 were built in 1900). It is estimated that in the early 21st century there were still some 600 steam cars in the United States, most of them in running order.

Early electric automobiles

At the beginning of the 20th century, 40 percent of American automobiles were powered by steam, 38 percent by electricity, and 22 percent by gasoline. In the face of the gasoline car's unreliability, noise, and vibration and the steamer's complications and thirst, the electric offered attractive selling points: notably, instant self-start, silent operation, and minimal maintenance. The first automobile to exceed 100 km (60 miles) per hour was an electric (Camille Jenatzy's *La Jamais Contente*, 1899). An electric, also Jenatzy's, had been the easy winner in 1898 of a French hill-climb contest to assay the three forms of power.

Invention of the storage battery by Gaston Planté of France in 1859–60 and its improvement by Camille Faure in 1881 made the electric vehicle possible, and what was probably the first, a tricycle, ran in Paris in 1881. It was followed by other three-wheelers in London (1882) and Boston (1888). The first American battery-powered automobile, built in Des Moines, Iowa, c. 1890, by William Morrison, could maintain a speed of 14 miles (23 km) per hour.

The popularity of the electric car was hampered by a lack of battery-charging infrastructure. Prior to 1910, few private homes, even in cities, were wired with electricity, and community charging stations and battery exchange schemes failed to catch on. By 1912 the problem had been overcome, and the electric had its heyday. Some 20 companies were in the trade and 33,842 electric cars were registered in the United States, the country in which they had maximum acceptance. It was another application of battery power, the electric self-starter, that did as much as anything to doom the electric car by eliminating the dreaded hand crank and making the internal-combustion engine car amenable to operation by women. Further, the electric had never really been suited to other than limited urban use because of its low speed (15–20 miles, or 24–32 km, per hour), short range (30–40 miles, or about 50–65 km), and lengthy time required for recharging. The heyday of the electric car in America had ended by 1920, although a few manufacturers offered them on special order until World War II. The war, however, gave rise to experiments with small electric cars in fuel-starved France and resulted in extensive use of electric vehicles for milk delivery in Britain, which continued in urban areas there for the rest of the century.

Development of the gasoline car

Most authorities are inclined to honour Karl Benz and Gottlieb Daimler of Germany as the most important pioneer contributors to the gasoline-engine automobile. Benz ran his first car in 1885, Daimler in 1886. Although there is no reason to believe that Benz had ever seen a motor vehicle before he made his own, he and Daimler had been preceded by Étienne Lenoir in France and Siegfried Marcus in Austria, in 1862 and 1864–65, respectively, but neither Lenoir nor Marcus had persisted. Benz and Daimler did persist—indeed, to such purpose that their successor firm of Daimler AG can trace its origins as far back as 1885. Oddly, Benz and Daimler never met.

The four-stroke principle upon which most modern automobile engines work was discovered by a French engineer, Alphonse Beau de Rochas, in 1862, a year before Lenoir ran his car from Paris to Joinville-le-Pont. The four-stroke cycle is often called the Otto cycle, after the German Nikolaus August Otto, who designed an engine on that principle in 1876. De Rochas held prior patents, however, and litigation in the French courts upheld him. Lenoir's engine omitted the compression stroke of the Otto cycle; fuel was drawn into the cylinder on the intake stroke and fired by a spark halfway on the next reciprocal stroke.