Engine
Components and Infrastructures

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Chapter 1

Radiator (Engine Cooling)

A typical automobile coolant radiator

Radiators are used for cooling internal combustion engines, mainly in automobiles but also in piston-engined aircraft, railway locomotives, motorcycles, stationary generating plant or any similar use of such an engine.

They operate by passing a liquid *coolant* through the engine block, where it is heated, then through the radiator itself where it loses this heat to the atmosphere. This coolant is usually water-based, but may also be oil. It is usual for the coolant flow to be pumped, also for a fan to blow air through the radiator.

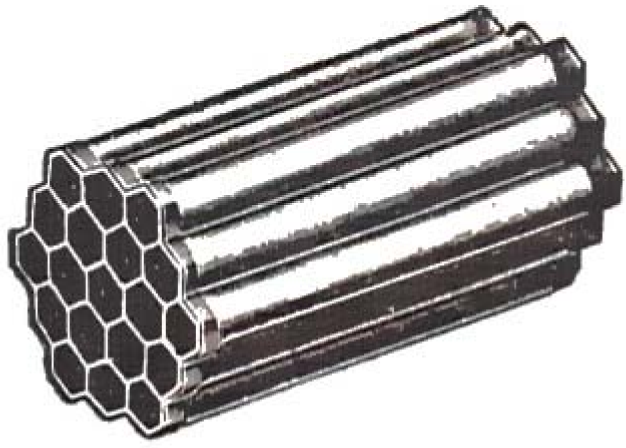
Automobiles

In automobiles with a liquid-cooled internal combustion engine a radiator is connected to channels running through the engine and cylinder head, through which a liquid (coolant) is pumped. This liquid may be water (in climates where water is unlikely to freeze), but is more commonly a mixture of water and antifreeze in proportions appropriate to the climate. Antifreeze itself is usually ethylene glycol or propylene glycol (with a small amount of corrosion inhibitor).

The radiator transfers the heat from the fluid inside to the air outside, thereby cooling the engine. Radiators are also often used to cool automatic transmissions, air conditioners, and sometimes to cool engine oil. Radiators are typically mounted in a position where they receive airflow from the forward movement of the vehicle, such as behind a front grill. Where engines are mid- or rear-mounted, it is common to mount the radiator behind a front grill to achieve sufficient airflow, even though this requires long coolant pipes. Alternatively, the radiator may draw air from the flow over the top of the vehicle or from a side-mounted grill. For long vehicles, such as buses, side airflow is most common for engine and transmission cooling and top airflow most common for air conditioner cooling.

Radiator construction

Automobile radiators are constructed of a pair of header tanks, linked by a core with many narrow passageways, thus a high surface area relative to its volume. This core is usually made of stacked layers of metal sheet, pressed to form channels and soldered or brazed together. For many years radiators were made from brass or copper cores soldered to brass headers. Modern radiators save money and weight by using plastic headers and may use aluminium cores. This construction is less easily repaired than traditional materials.

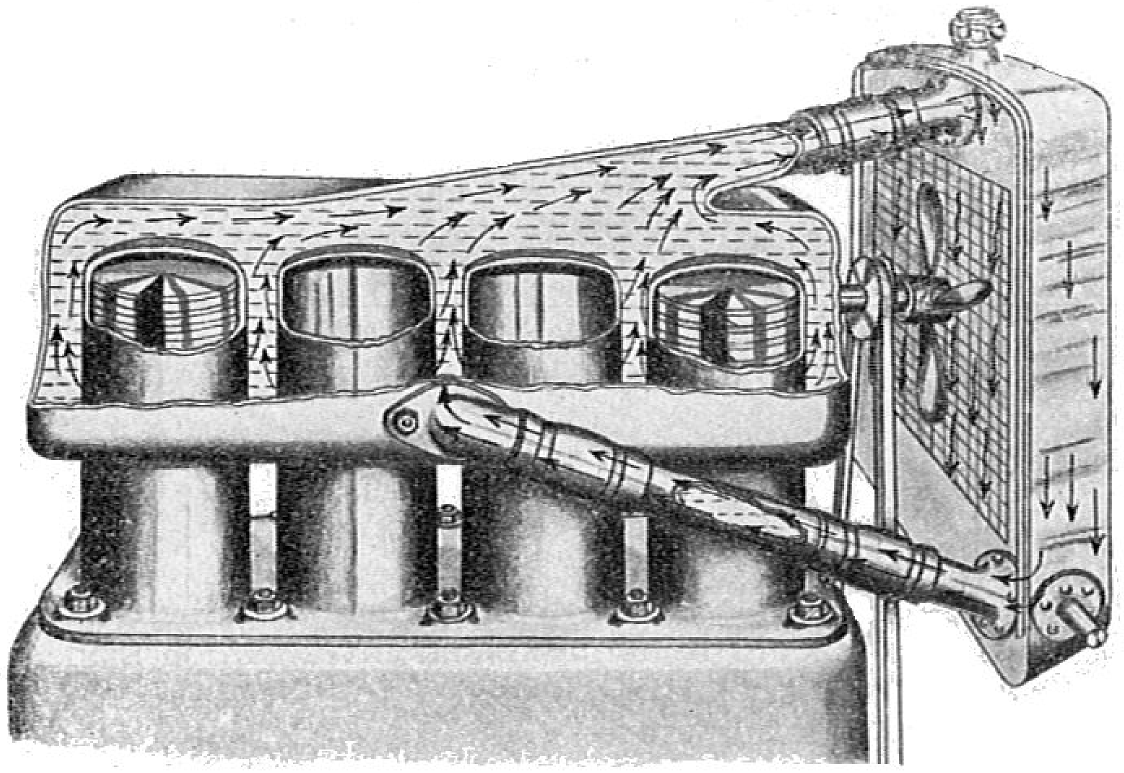


Honeycomb radiator tubes

An earlier construction method was the honeycomb radiator. Round tubes were swaged into hexagons at their ends, then stacked together and soldered. As they only touched at their ends, this formed what became in effect a solid water tank with many air tubes through it.

Vintage cars may also have used radiator cores made from coiled tube, a less-efficient but simpler construction.

Coolant pumps



Thermosysphon cooling system of 1937, without circulating pump

Radiators first used downward vertical flow, driven solely by a thermosyphon effect. Coolant is heated in the engine, becoming less dense and so rising, cooled, denser coolant in the radiator falling in turn. This effect is sufficient for low-power stationary engines, but inadequate for all but the earliest automobiles. A common fallacy is to assume that a greater vertical separation between engine and radiator can increase the thermosyphon effect. Once the hot and cold headers are separated sufficiently to reach their equilibrium temperatures though, any further separation merely increases pipework length and flow restriction.

All automobiles for many years have used centrifugal pumps to circulate their coolant, driven by geared drives or more commonly by a belt drive. This "fan belt" has a well-established reputation for being slightly unreliable, a failure being rapidly obvious as the engine overheats. Despite the name though, it's the *coolant pump's* failure that causes the overheating, not the fan.

Heater

A system of valves or baffles, or both, is usually incorporated to simultaneously operate a small radiator inside the car. This small radiator, and the associated blower fan, is called the heater core, and serves to warm the cabin interior. Like the radiator, the heater core acts by removing heat from the engine. For this reason, automotive technicians often advise operators to turn ***on*** the heater and set it to high if the engine is overheating.

Temperature control

Waterflow control

Car engine thermostat

The engine temperature is primarily controlled by a wax-pellet type of thermostat, a valve which opens once the engine has reached its optimum operating temperature.

When the engine is cold the thermostat is closed, with a small bypass flow so that the thermostat experiences changes to the coolant temperature as the engine warms up. Coolant is directed by the thermostat to the inlet of the circulating pump and is returned directly to the engine, bypassing the radiator. Directing water to circulate only through the engine allows the temperature to reach optimum operating temperature as quickly as possible whilst avoiding localised "hot spots". Once the coolant reaches the thermostat's activation temperature it opens, allowing water to flow through the radiator to prevent the temperature rising higher.

Once at optimum temperature, the thermostat controls the flow of coolant to the radiator so that the engine continues to operate at optimum temperature. Under peak load conditions, such as labouring slowly up a steep hill whilst heavily laden on a hot day, the thermostat will be approaching fully open because the engine will be producing near to maximum power while the velocity of air flow across the radiator is low. (The velocity of air flow across the radiator has a major effect on its ability to dissipate heat.) Conversely, when cruising fast downhill on a motorway on a cold night on a light throttle, the thermostat will be nearly closed because the engine is producing little power, and the radiator is able to dissipate much more heat than then engine is producing. Allowing too much flow of coolant to the radiator would result in the engine being over cooled and operating at lower than optimum temperature. A side effect of this would be that the passenger compartment heater would not be able to put out enough heat to keep the passengers warm.

The thermostat is therefore constantly moving throughout its range, responding to changes in vehicle operating load, speed and external temperature, to keep the engine at its optimum operating temperature.

Airflow control

Other factors influence the temperature of the engine including radiator size and the type of radiator fan. The size of the radiator (and thus its cooling capacity) is chosen such that it can keep the engine at the design temperature under the most extreme conditions a vehicle is likely to encounter (such as climbing a mountain whilst fully loaded on a hot day).

Airflow speed through a radiator is a major influence on the heat it loses. Vehicle speed affects this, in rough proportion to the engine effort, thus giving crude self-regulatory feedback. Where an additional cooling fan is driven by the engine, this also tracks engine speed similarly.

Engine-driven fans are often regulated by a viscous-drive clutch from the drivebelt, which slips and reduces the fan speed at low temperatures. This improves fuel efficiency by not wasting power on driving the fan unnecessarily. On modern vehicles, further regulation of cooling rate is provided by either variable speed or cycling radiator fans. Electric fans are controlled by a thermostatic switch or the engine control unit. Electric fans also have the advantage of giving good airflow and cooling at low engine revs or when stationary, such as in slow-moving traffic.

Before the development of viscous-drive and electric fans, engines were fitted with simple fixed fans that drew air through the radiator at all times. Vehicles whose design required the installation of a large radiator to cope with heavy work at high temperatures, such as commercial vehicles and tractors would often run cool in cold weather under light loads, even with the presence of a thermostat, as the large radiator and fixed fan caused a rapid and significant drop in coolant temperature as soon as the thermostat opened. This problem could be solved by fitting a **radiator blind** to the radiator which could be adjusted to partially or fully block the airflow. At its simplest the blind was a roll of material (such as canvas or rubber that was unfurled along the length of the radiator to cover the desired portion. Some vehicles had a series of shutters that could be adjusted from the driver's seat to provide a very fine degree of control.

These AEC Regent III RT buses are fitted with radiator blinds, seen here covering the lower half of the radiators.

Coolant pressure

Because the thermal efficiency of internal combustion engines increases with internal temperature the coolant is kept at higher-than-atmospheric pressure to increase its boiling point. A calibrated pressure-relief valve is usually incorporated in the radiator's fill cap. This pressure varies between models, but typically ranges from 9 psi (0.6 bar) to 15 psi (1.0 bar).

As the coolant expands with increasing temperature its pressure in the closed system must increase. Ultimately the pressure relief valve opens and excess fluid is dumped into an overflow container. Fluid overflow ceases when the thermostat modulates the rate of cooling to keep the temperature of the coolant at optimum. When the coolant cools and contracts (as conditions change or when the engine is switched off) the fluid is returned to the radiator through additional valving in the cap.

Coolant

Before World War II, radiator coolant was usually plain water. Antifreeze was used solely to control freezing, and this was often only done in cold weather.

Development in high-performance aircraft engines required improved coolants with higher boiling points, leading to the adoption of glycol or water-glycol mixtures. These led to the adoption of glycols for their antifreeze properties.

Since the development of aluminium or mixed-metal engines, corrosion inhibition has become even more important than antifreeze, and in all regions and seasons.

Boiling or overheating

On this type system, if the coolant in the overflow container gets too low, fluid transfer to overflow will cause an increased loss by vaporizing the engine coolant.

Severe engine damage can be caused by overheating, by overloading or system defect, when the coolant is evaporated to a level below the water pump. This can happen without warning because, at that point, the sending units are not exposed to the coolant to indicate the excessive temperature.

To protect the unwary the cap often contains a mechanism that attempts to relieve the internal pressure before the cap can be fully opened. Some scalding of one's hands can easily occur in this event. Opening a hot radiator drops the system pressure immediately and may cause a sudden ebullition of super-heated coolant which can cause severe burns.

History

The invention of the automobile water radiator is attributed to Karl Benz. Wilhelm Maybach designed the first honeycomb radiator for the Mercedes 35hp.

Supplementary radiators

It is sometimes necessary for a car to be equipped with a second, or auxiliary, radiator to increase the cooling capacity, when the size of the original radiator cannot be increased. The second radiator is plumbed in series with the main radiator in the circuit. This was the case when the Audi 100 was first turbocharged creating the 200. These are not to be confused with intercoolers.

Some engines have an oil cooler, a separate small radiator to cool the engine oil. Cars with an automatic transmission often have extra connections to the radiator, allowing the transmission fluid to transfer its heat to the coolant in the radiator. These may be either oil-air radiators, as for a smaller version of the main radiator. More simply they may be oil-water coolers, where an oil pipe is inserted inside the water radiator. As water is denser than air, this offers comparable cooling (within limits) from a less complex and thus cheaper oil cooler.

Turbo charged or supercharged engines may have an intercooler, which is an air-to-air or air-to-water radiator used to cool the incoming air charge—not to cool the engine.

Aircraft

Aircraft with liquid-cooled piston engines (usually inline engines rather than radial) also require radiators. As airspeed is higher than for cars, these are efficiently cooled in flight and so do not require large areas or cooling fans. Many high-performance aircraft however suffer extreme overheating problems when idling on the ground - a mere 7 minutes for a Spitfire.

Surface radiators

Reducing drag is a major goal in aircraft design, including the design of cooling systems. An early technique was to take advantage of an aircraft's abundant airflow to replace the honeycomb core (many surfaces, with a high ratio of surface to volume) by a surface mounted radiator. This uses a single surface blended into the fuselage or wing skin, with the coolant flowing through pipes at the back of this surface.

As they are so dependent on airspeed, surface radiators are even more prone to overheating when ground-running. Racing aircraft such as the Supermarine S.6B, a racing seaplane with radiators built into the upper surfaces of its floats, have been described as "being flown on the temperature gauge" as the main limit on their performance.

Surface radiators have also been used by a few high-speed racing cars, such as Malcolm Campbell's Blue Bird of 1928.

Radiator thrust

An aircraft radiator comprises a duct wherein heat is added. As a result, this is effectively a jet engine. High-performance piston aircraft with well-designed low-drag radiators (notably the P-51 Mustang) derived thrust from this effect. The thrust was significant enough to offset the drag of the duct the radiator was enclosed in and allowed the aircraft to achieve zero cooling drag. At one point, there were even plans to equip the Spitfire with a ramjet, by injecting fuel into this duct after the radiator and igniting it. Although ramjets normally require a supersonic airspeed, this light-up speed can be reduced where heat is being added, such as in a radiator duct.

Steam cooling

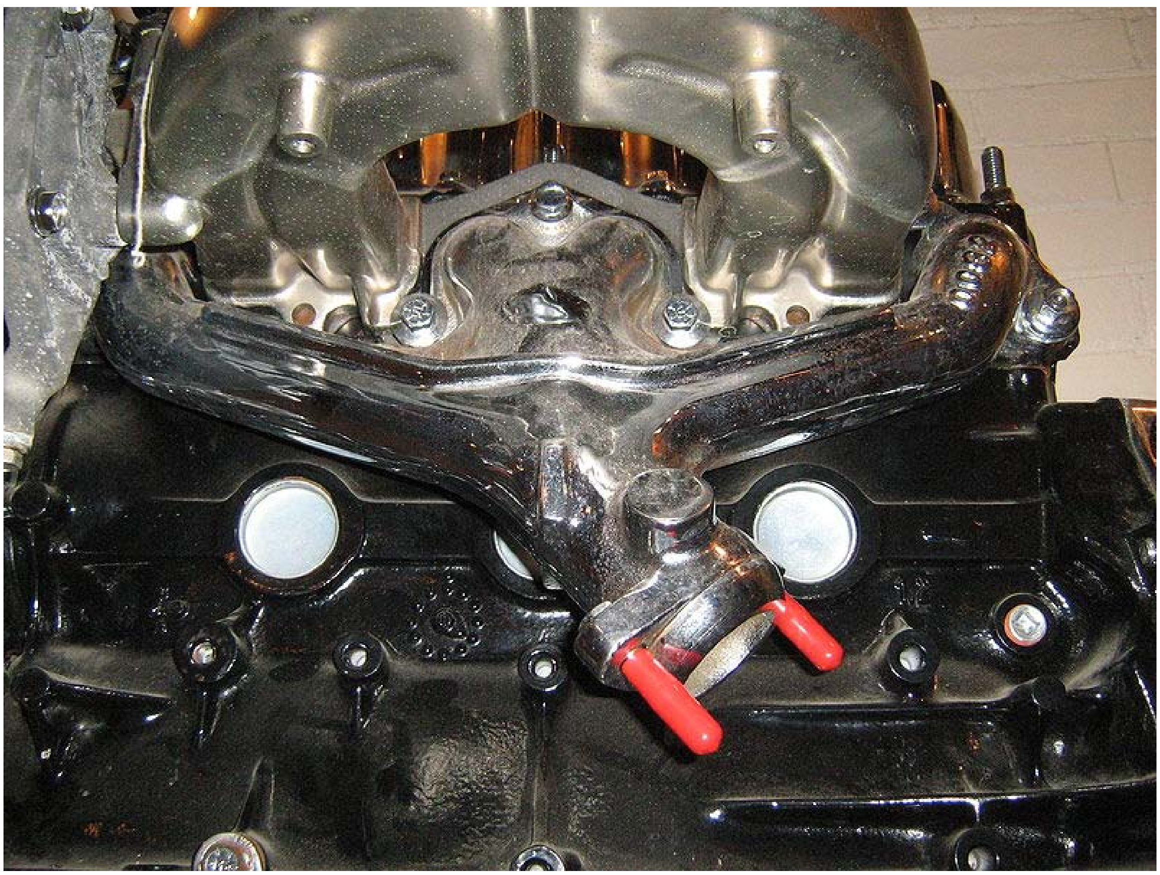
Pressurized cooling systems operate by adding heat to the coolant fluid, causing it to rise in temperature in inverse proportion to its specific heat capacity. With the need to keep the final temperature below boiling point, this limits the amount of heat that a given mass-flow of coolant can dissipate.

Attempts were made with aero-engines of the 1930s, notably the Rolls-Royce Goshawk, to exceed this limit by *allowing* the coolant to boil. This absorbs an amount of heat equivalent to the specific heat of vaporization, which for water is more than five times the energy required to heat the same quantity of water from 0°C to 100°C. Obviously this allows the necessary cooling effect with far less mass of coolant.

The practical difficulty was the need to provide condensers rather than radiators. Cooling was now needed not just for hot, dense liquid coolant, but for low-density vapor. This required a condenser far larger, and with higher drag, than a radiator. For aircraft, especially high-speed aircraft, it was soon realized this configuration was unworkable and so evaporative cooling was abandoned.

Chapter 2

Exhaust System



Exhaust manifold (chrome plated) on a car engine

Muffler and tail pipe on a car

An **exhaust system** is usually tubing used to guide reaction exhaust gases away from a controlled combustion inside an engine or stove. The entire system conveys burnt gases from the engine and includes one or more **exhaust pipes**. Depending on the overall system design, the exhaust gas may flow through one or more of:

- Cylinder head and exhaust manifold
- A turbocharger to increase engine power.
- A catalytic converter to reduce air pollution.
- A muffler (North America) / silencer (Europe), to reduce noise.

Design criteria

An exhaust pipe must be carefully designed to carry toxic and/or noxious gases away from the users of the machine. Indoor generators and furnaces can quickly fill an enclosed space with carbon monoxide or other poisonous exhaust gases if they are not properly vented to the outdoors. Also, the gases from most types of machine are very hot; the pipe must be heat-resistant, and it must not pass through or near anything which can burn or can be damaged by heat. A chimney serves as an exhaust pipe in a stationary structure. For the internal combustion engine it is important to have the Exhaust System "Tuned" (refer to tuned pipe) for optimal efficiency. Also this should meet the regulation norms maintained in each country. In Europeon countries, EURO 5, India BS-4 etc.

Motorcycles

Ducati muffler

In most motorcycles all or most of the exhaust system is visible and may be chrome plated as a display feature. Aftermarket exhausts may be made from steel, aluminium, titanium, or carbon fiber.

Motorcycle exhausts come in many varieties depending on the type of engine and its intended use. A twin cylinder may flow its exhaust into separate exhaust sections, such as seen in the Kawasaki EX250 (also known as the Ninja 250 in the US, or the GPX 250). Or, they may flow into a single exhaust section known as a two-into-one (2-1). Larger engines that come with 4 cylinders, such as Japanese supersport or superbikes (such the Kawasaki ZX series, Honda's CBR series, Yamaha's YZF series, also known as R6 and R1, and Suzuki's GSX-R series) often come with a twin exhaust system. A "full system" may be bought as an aftermarket accessory, also called a 4-2-1 or 4-1, depending on its layout. In the past, these bikes would come standard with a single exhaust, as seen on the Kawasaki ZX-6R 2000 and 2001 models. However, EU noise and pollution regulations have generally stopped this practice, forcing companies to use other methods to increase performance of the motorcycle. This has often led to a decrease in fuel economy, because of increased weight of the exhaust system and manufacturers forcing more fuel into the engine to gain extra power.

Trucks

In many trucks / lorries all or most of the exhaust system is visible. Often in such trucks the silencer is surrounded by a perforated metal sheath to avoid people getting burnt touching the hot silencer. This sheath may be chrome plated as a display feature. Part of the pipe between the engine and the silencer is often flexible metal industrial ducting, as in the image in the section "Terminology". Sometimes a large diesel exhaust pipe is vertical, to blow the hot noxious gas well away from people; in such cases the end of the exhaust pipe often has a hinged metal flap to stop debris and birds and rainwater from falling inside. Sometimes these exhaust pipes have a flex connector attached with it. This helps in minimising the vibration from the engine to be transferred into the exhaust system.

Two-stroke engines

In a two-stroke engine, such as that used on dirt bikes, a bulge in the exhaust pipe known as an expansion chamber uses the pressure of the exhaust to create a pump that squeezes more air and fuel into the cylinder during the intake stroke. This provides greater power and fuel efficiency.

Marine engines

With an onboard diesel engine below-decks on marine vessels:-

- Lagging the exhaust pipe stops it from overheating the engine room where people must work to service the engine.
- Feeding water into the exhaust pipe cools the exhaust gas and thus lessens the back-pressure at the engine's cylinders' exhaust ports and thus helps the cylinders to empty quicker.

Outboard motors

In outboard motors the exhaust system is usually a vertical passage through the engine structure and to reduce out-of-water noise blows out underwater, sometimes through the middle of the propeller.

Terminology

Manifold or header

Aftermarket exhaust manifold

In most production engines, the **manifold** is an assembly designed to collect the exhaust gas from two or more cylinders into one pipe. Manifolds are often made of cast iron in stock production cars, and may have material-saving design features such as to use the least metal, to occupy the least space necessary, or have the lowest production cost. These design restrictions often result in a design that is cost effective but that does not do the most efficient job of venting the gases from the engine. Inefficiencies generally occur due to the nature of the combustion engine and its cylinders. Since cylinders fire at different times, exhaust leaves them at different times, and pressure waves from gas emerging from one cylinder might not be completely vacated through the exhaust system when another comes. This creates a back pressure and restriction in the engine's exhaust system that can restrict the engine's true performance possibilities.

A **header** (sometimes called **extractor** in Australia) is a manifold specifically designed for performance. During design, engineers create a manifold without regard to weight or cost but instead for optimal flow of the exhaust gases. This design results in a header that is more efficient at **scavenging** the exhaust from the cylinders. Headers are generally circular steel tubing with bends and folds calculated to make the paths from each cylinder's exhaust port to the common outlet all equal length, and joined at narrow angles to encourage pressure waves to flow through the outlet, and not back towards other cylinders. In a set of **tuned headers** the pipe lengths are carefully calculated to enhance exhaust flow in a particular engine revolutions per minute range.

Headers are generally made by aftermarket automotive companies, but sometimes can be bought from the high-performance parts department at car dealerships. Generally, most car performance enthusiasts buy aftermarket headers made by companies solely focused on producing reliable, cost-effective well-designed headers specifically for their car. Headers can also be custom designed by a custom shop. Due to the advanced materials that some aftermarket headers are made of, this can be expensive. Luckily, an exhaust system can be custom built for any car, and generally is not specific to the car's motor or design except for needing to properly connect solidly to the engine. This is usually accomplished by correct sizing in the design stage, and selecting a proper gasket type and size for the engine.

Header-back

The **Header-back** (or **header back**) is the part of the exhaust system from the outlet of the header to the final vent to open air — everything from the header back. Header-back systems are generally produced as aftermarket performance systems for cars without turbochargers.

Turbo-back

The **Turbo-back** (or **turbo back**) is the part of the exhaust system from the outlet of a turbocharger to the final vent to open air. Turbo-back systems are generally produced as aftermarket performance systems for cars with turbochargers. Some turbo-back (and header-back) systems replace stock catalytic converters with others having less flow restriction.

With or without catalytic converter

Some systems (including in former time all systems) (sometimes nowadays called **catless**) eliminate the catalytic converter. This is illegal in some places if the vehicle is driven on public roads.

Cat-back

Cat-back (also **cat back** and **catback**) refers to the portion of the exhaust system from the outlet of the catalytic converter to the final vent to open air. This generally includes the pipe from the converter to the muffler, the muffler, and the final length of pipe to open air.

Cat-back exhaust systems generally use larger diameter pipe than the stock system. Good systems will have mandrel-bent turns that allow the exhaust gas to exit with as little back pressure as possible. The mufflers included in these kits are often glasspacks, to reduce back pressure. If the system is engineered more for show than functionality, it may be tuned to enhance the lower sounds that are lacking from high-RPM low-displacement engines.

Tailpipe and tip

With trucks, sometimes the silencer is crossways under the front of the cab and its tailpipe blows sideways to the offside (right side if driving on the left, left side if driving on the right). The side of a passenger car on which the exhaust exits beneath the rear bumper usually indicates the market for which the vehicle was designed, i.e. Japanese (and some older British) vehicles have exhausts on the right so they are furthest from the curb in countries which drive on the left, while European vehicles have exhausts on the left.

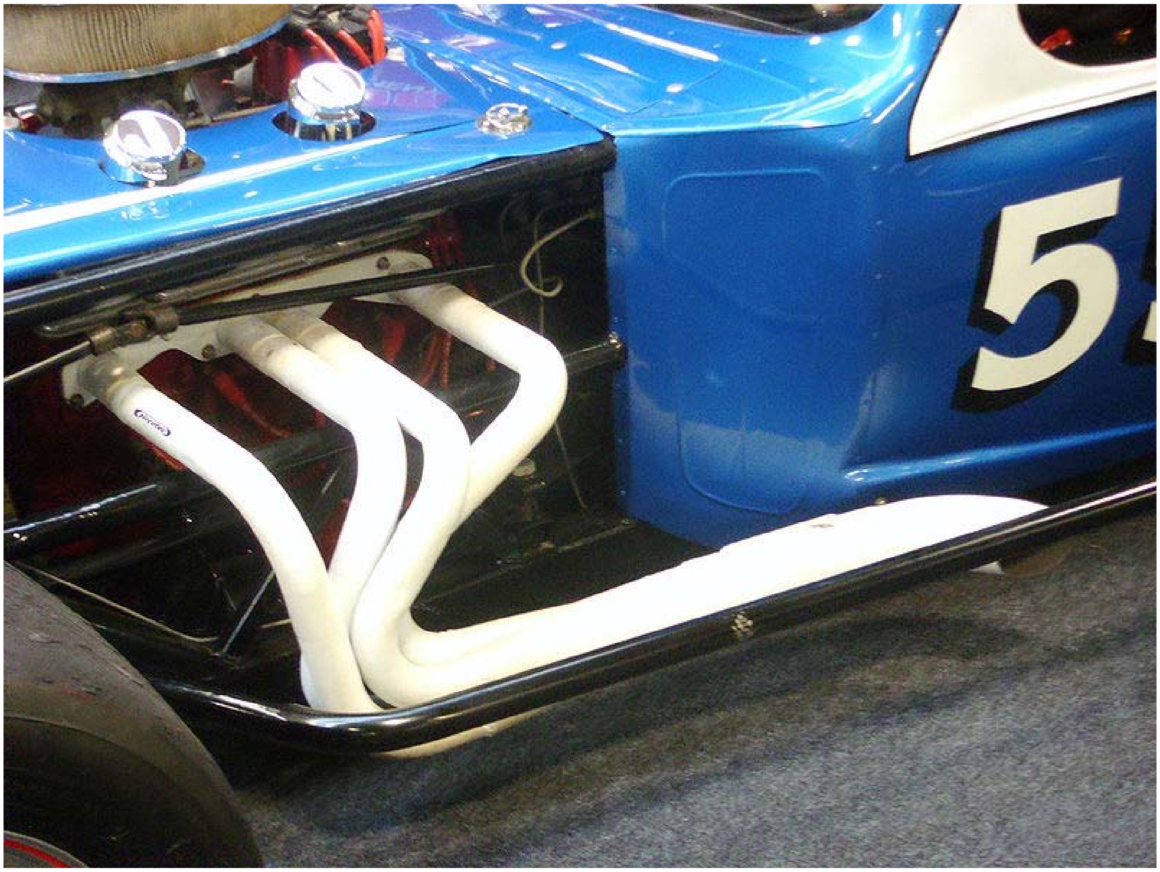
The end of the final length of exhaust pipe where it vents to open air, generally the only visible part of the exhaust system part on a vehicle, often ends with just a straight or angled cut, but may include a fancy tip. The tip is sometimes chromed. It is often of larger pipe than the rest of the exhaust system. This produces a final reduction in pressure, and sometimes used to enhance the appearance of the car.

In the late 1950s in the United States manufacturers had a fashion in car styling to form the rear bumper with a hole at each end through which the exhaust would pass. Two outlets symbolized V-8 power, and only the most expensive cars (Cadillac, Lincoln, Imperial, Packard) were fitted with this design. One justification for this was that luxury cars in those days had such a long rear overhang that the exhaust pipe scraped the ground when the car traversed ramps. The fashion disappeared after customers noted that the rear end of the car, being a low-pressure area, collected soot from the exhaust and its acidic content ate into the chrome-plated rear bumper.

When a bus, truck or tractor or excavator has a vertical exhaust pipe (called stacks or pipes behind the cab), sometimes the end is curved, or has a hinged cover flap which the gas flow blows out of the way, to try to prevent foreign objects (including droppings from a bird perching on the exhaust pipe when the vehicle is not being used) getting inside the exhaust pipe.

In some trucks, when the silencer is front-to-back under the chassis, the end of the tailpipe turns 90° and blows downwards. That protects anyone near a stationary truck from getting a direct blast of the exhaust gas, but often raises dust when the truck is driving on a dry dusty unmade surface such as on a building site.

Exhaust System Tuning



Aftermarket exhaust system including headers and a white plasma-sprayed ceramic coating

Many automotive companies offer aftermarket exhaust system upgrades as a subcategory of engine tuning. This is often fairly expensive as it usually includes replacing the entire exhaust manifold or other large components. These upgrades however can significantly improve engine performance and do this through means of two main principles:

- By reducing the exhaust back pressure, engine power is increased in four-stroke engines
- By reducing the amount of heat from the exhaust being lost into the underbonnet area. This reduces the underbonnet temperature and consequently lowers the intake manifold temperature, increasing power. This also has positive side effect of preventing heat-sensitive components from being damaged. Furthermore, keeping the heat in the exhaust gases speeds these up, therefore reducing back pressure as well.

Back pressure is most commonly reduced by replacing exhaust manifolds with headers, which have smoother bends and normally wider pipe diameters.

Exhaust Heat Management is the term that describes reducing the amount of exhaust heat loss. One dominant solution to aftermarket upgraders is the use of a ceramic coating applied via thermal spraying. This not only reduces heat loss and lessens back pressure, but provides an effective way to protect the exhaust system from wear and tear, thermal degradation and corrosion.

Large truck's diesel exhaust pipe

Waste collection vehicle's diesel exhaust pipe

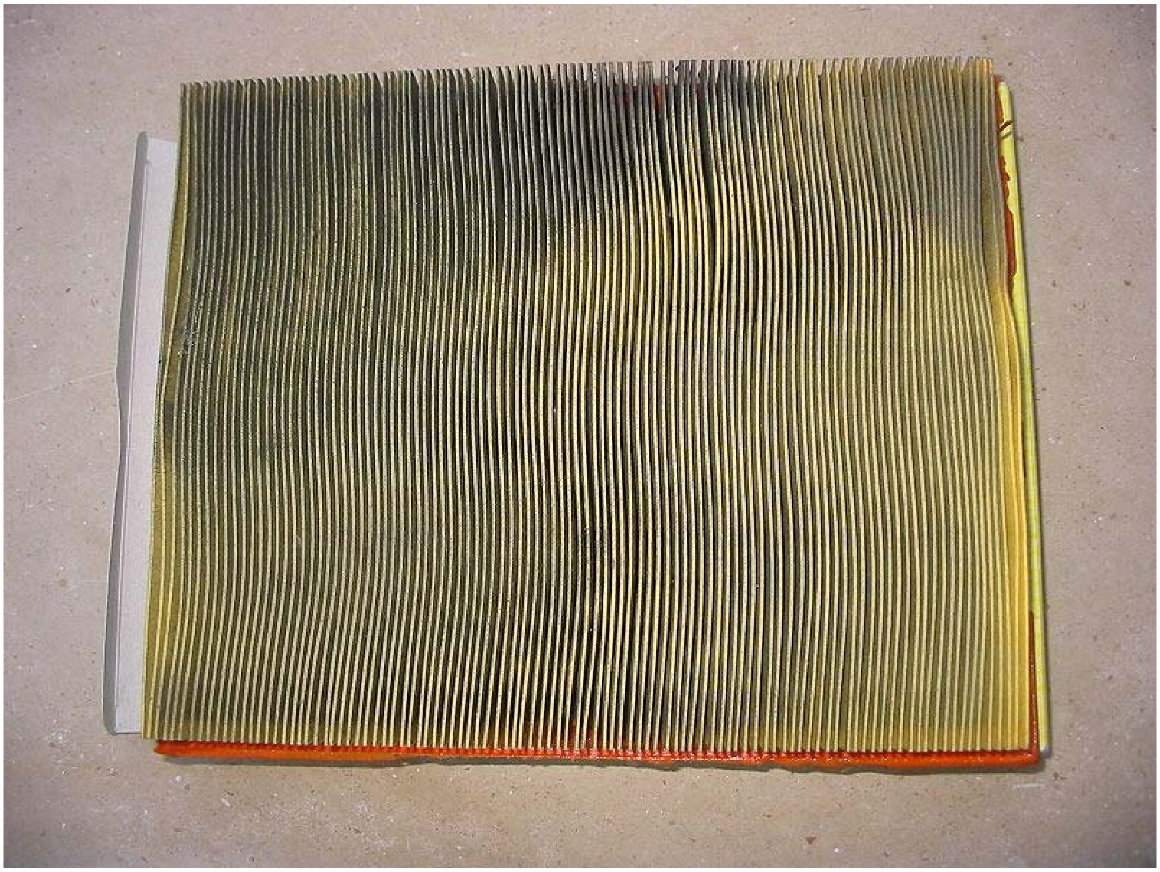
Dual exhaust pipes attached to a car's muffler

Exhaust system of diesel telescopic-arm vehicle

Chapter 3

Air Filter

Used auto engine air filter, clean side



Used auto engine air filter, dirty side

Auto engine air filter clogged with dust and grime

A particulate **air filter** is a device composed of fibrous materials which removes solid particulates such as dust, pollen, mold, and bacteria from the air. A chemical air filter consists of an absorbent or catalyst for the removal of airborne molecular contaminants such as volatile organic compounds or ozone. Air filters are used in applications where air quality is important, notably in building ventilation systems and in engines.

Some buildings, as well as aircraft and other man-made environments (e.g., satellites and space shuttles) use foam, pleated paper, or spun fiberglass filter elements. Another method, air ionisers, use fibers or elements with a static electric charge, which attract dust particles. The air intakes of internal combustion engines and compressors tend to use either paper, foam, or cotton filters. Oil bath filters have fallen out of favor. The technology of air intake filters of gas turbines has improved significantly in recent years, due to improvements in the aerodynamics and fluid-dynamics of the air-compressor part of the Gas Turbines.

Automotive cabin air filters

The cabin air filter is typically a pleated-paper filter that is placed in the outside-air intake for the vehicle's passenger compartment. Some of these filters are rectangular and similar in shape to the combustion air filter. Others are uniquely shaped to fit the available space of particular vehicles' outside-air intakes. Being a relatively recent addition to automobile equipment, this filter is often overlooked. Clogged or dirty cabin air filters can significantly reduce airflow from the cabin vents, as well as introduce allergens into the cabin air stream.

Internal combustion air filters

The combustion air filter prevents abrasive particulate matter from entering the engine's cylinders, where it would cause mechanical wear and oil contamination. Known as Engine air induction systems (AIS), they are typically constructed of paper or felt.

Most fuel injected vehicles use a pleated paper filter element in the form of a flat panel. This filter is usually placed inside a plastic box connected to the throttle body with an intake tube.

Older vehicles that use carburetors or throttle body fuel injection typically use a cylindrical air filter, usually a few inches high and between 6 inches (150 mm) and 16 inches (410 mm) in diameter. This is positioned above the carburetor or throttle body, usually in a metal or plastic container which may incorporate ducting to provide cool and/or warm inlet air, and secured with a metal or plastic lid.

Long Life Filtration System

In 2003 Ford Motor company introduced the Visteon Long Life Filtration System to the Ford Focus. This system has a foam filter placed in the bumper of the car and is stated to have a 150,000-mile (240,000 km) service interval. According to a technical paper published by Society of Automotive Engineers, this design offers higher and more stable filtration efficiency than conventional air filters.

Paper

Pleated paper filter elements are the nearly exclusive choice for automobile engine air cleaners, because they are efficient, easy to service, and cost-effective. The "paper" term is somewhat misleading, as the filter media are considerably different from papers used for writing or packaging, etc. There is a persistent belief amongst tuners, fomented by advertising for aftermarket non-paper replacement filters, that paper filters flow poorly and thus restrict engine performance. In fact, as long as a pleated-paper filter is sized appropriately for the airflow volumes encountered in a particular application, such filters present only trivial restriction to flow until the filter has become significantly clogged with dirt. Construction equipment engines also use this.

Foam

Oil-wetted polyurethane foam elements are used in some aftermarket replacement automobile air filters. Foam was in the past widely used in air cleaners on small engines on lawnmowers and other power equipment, but automotive-type paper filter elements have largely supplanted oil-wetted foam in these applications. Depending on the grade and thickness of foam employed, an oil-wetted foam filter element can offer minimal airflow restriction or very high dirt capacity, the latter property making foam filters a popular choice in off-road rallying and other motorsport applications where high levels of dust will be encountered.

Cotton

Oiled cotton gauze is employed in a small number of aftermarket automotive air filters marketed as high-performance items. In the past, cotton gauze saw limited use in original-equipment automotive air filters.

Oil Bath

An oil bath air cleaner consists of a round base bowl containing a pool of oil, and a round insert which is filled with fibre, mesh, foam, or another coarse filter media. When the cleaner is assembled, the media-containing body of the insert sits a short distance above the surface of the oil pool. The rim of the insert overlaps the rim of the base bowl. This arrangement forms a labyrinthine path through which the air must travel in a series of U-turns: up through the gap between the rims of the insert and the base bowl, down through the gap between the outer wall of the insert and the inner wall of the base bowl, and up through the filter media in the body of the insert. This U-turn takes the air at high velocity across the surface of the oil pool. Larger and heavier dust and dirt particles in the air cannot make the turn due to their inertia, so they fall into the oil and settle to the bottom of the base bowl. Lighter and smaller particles are trapped by the filtration media in the insert, which is wetted by oil droplets aspirated there into by normal airflow.

Oil bath air cleaners were very widely used in automotive and small-engine applications until the widespread industry adoption of the paper filter in the early 1960s. Such cleaners are still used in off-road equipment where very high levels of dust are encountered, for oil bath air cleaners can sequester a great deal of dirt relative to their overall size, without loss of filtration efficiency or airflow. However, the liquid oil makes cleaning and servicing such air cleaners messy and inconvenient, they must be relatively large to avoid excessive restriction at high airflow rates, and they tend to increase exhaust emissions of unburned hydrocarbons due to oil aspiration when used on spark-ignition engines.

Chapter 4

Air-Fuel Ratio Meter and Crankcase

Air-fuel ratio meter

An **air-fuel ratio meter** monitors the air-fuel ratio of an internal combustion engine. Also called **air-fuel ratio gauge**, **air-fuel meter**, or **air-fuel gauge**. It reads the voltage output of an oxygen sensor, sometimes also called lambda sensor, whether it be from a *narrow band* or *wide band* oxygen sensor.

The original narrow band oxygen sensors became factory installed standard in the late 70's and early 80's. In recent years, a newer and much more accurate 'wide band' sensor, though more expensive, has become available.

Most stand-alone narrow band meters have 10 LEDs and some have more. Also common, narrow band meters in round housings with the standard mounting 2 1/16" and 2 5/8" diameters, as other types of car 'gauges'. These usually have 10 or 20 LEDs. Analogue 'needle' style gauges are also available.

As stated above, there are wide band meters that stand alone or are mounted in housings. Nearly all of these show the air-fuel ratio on a numeric display, since the wide band sensors provide a much more accurate reading. And since they use more accurate electronics, these meters are more expensive.

Benefits of air-fuel ratio metering

- Determining the condition of the oxygen sensor: A malfunctioning oxygen sensor will result in air-fuel ratios which respond more slowly to changing engine conditions. A damaged or defective sensor may lead to increased fuel consumption and increased pollutant emissions as well as decreased power, and throttle response.

- Reducing emissions: Keeping the air-fuel mixture near the stoichometric ratio of 14.7:1 (for gasoline engines) allows the catalytic converter to operate at maximum efficiency.
- Fuel economy: An air-fuel mixture leaner than the stoichiometric ratio will result in near optimum fuel mileage, costing less per mile traveled and producing the least amount of CO_2 emissions. However, from the factory, cars are designed to operate at the stoichiometric ratio (rather than as lean as possible while remaining driveable) in order to maximize the efficiency and life of the catalytic converter. While it may be possible to run smoothly at mixtures leaner than the stoichiometric ratio, manufacturers must focus on emissions and especially catalytic converter life (which must now be 100,000 miles on new vehicles) as a higher priority due to U.S. EPA regulations.
- Engine performance: Carefully mapping out air-fuel ratios throughout the range of rpm and manifold pressure will maximize power output in addition to reducing the risk of detonation.

Lean mixtures improve the fuel economy but also cause sharp rises in the amount of nitrogen oxides (NOX). If the mixture becomes too lean, the engine may fail to ignite, causing misfire and a large increase in unburned hydrocarbon (HC) emissions. Lean mixtures burn hotter and may cause rough idle, hard starting and stalling, and can even damage the catalytic converter, or burn valves in the engine. The risk of spark knock/engine knocking (detonation) is also increased when the engine is under load.

Mixtures that are richer than stoichiometric allow for greater peak engine power when using vapourized liquid fuels, due to the cooling effect of the evaporating fuel. This increases the intake oxygen density, allowing for more fuel to be combusted and more power developed. The ideal mixture in this type of operation depends on the individual engine. For example, engines with forced induction such as turbochargers and superchargers typically require a richer mixture under wide open throttle than naturally aspirated engines. Forced induction engines can be catastrophically damaged by burning too lean for too long. The leaner the air/fuel mixture, the higher the combustion temperature is inside the cylinder. Too high a temperature will destroy an engine - melting the pistons and valves. This can happen if you port the head and/or manifolds or increase boost without compensating by installing larger or more injectors, and/or increasing the fuel pressure to a sufficient level. Conversely, engine performance can be lessened by increasing fuelling without increasing air flow into the engine.

Cold engines also typically require more fuel and a richer mixture when first started (see: cold start injector), because fuel does not vaporize as well when cold and therefore requires more fuel to properly "saturate" the air. Rich mixtures also burn slower and decrease the risk of spark knock/engine knocking (detonation) when the engine is under load. However, rich mixtures sharply increase carbon monoxide (CO) emissions.

Oxygen sensor types

Oxygen sensors are installed in the exhaust system of the vehicle, attached to the engine's exhaust manifold, the sensor measures the ratio of the air-fuel mixture.

As mentioned above, there are two types of sensors available; narrow band and wide band. Narrow band sensors were the first to be introduced. The wide band sensor was introduced much later.

A narrow band sensor has a non-linear output, and switches between the thresholds of lean (ca 100-200 mV) and rich (ca 650-800 mV) areas very steeply.

Also, narrow band sensors are temperature-dependent. If the exhaust gases become warmer, the output voltage in the lean area will rise, and in the rich area it will be lowered. Consequently, a sensor, without pre-heating has a lower lean-output and a higher rich-output, possibly even exceeding 1 Volt. The influence of temperature to voltage is smaller in the lean mode than in the rich mode.

A "cold" engine makes the sensor switch the output voltage between ca 100 and 850/900 mV and after a while the sensor may output a switch voltage between ca 200 and 700/750mV, for turbocharged cars even less.

The Engine Control Unit (ECU) tries to maintain a stoichiometric balance, wherein the air-fuel mixture is approximately 14.7 times the mass of air to fuel for gasoline. This ratio is selected in order to maintain a neutral engine performance (lower fuel consumption yet decent engine power and minimal pollution).

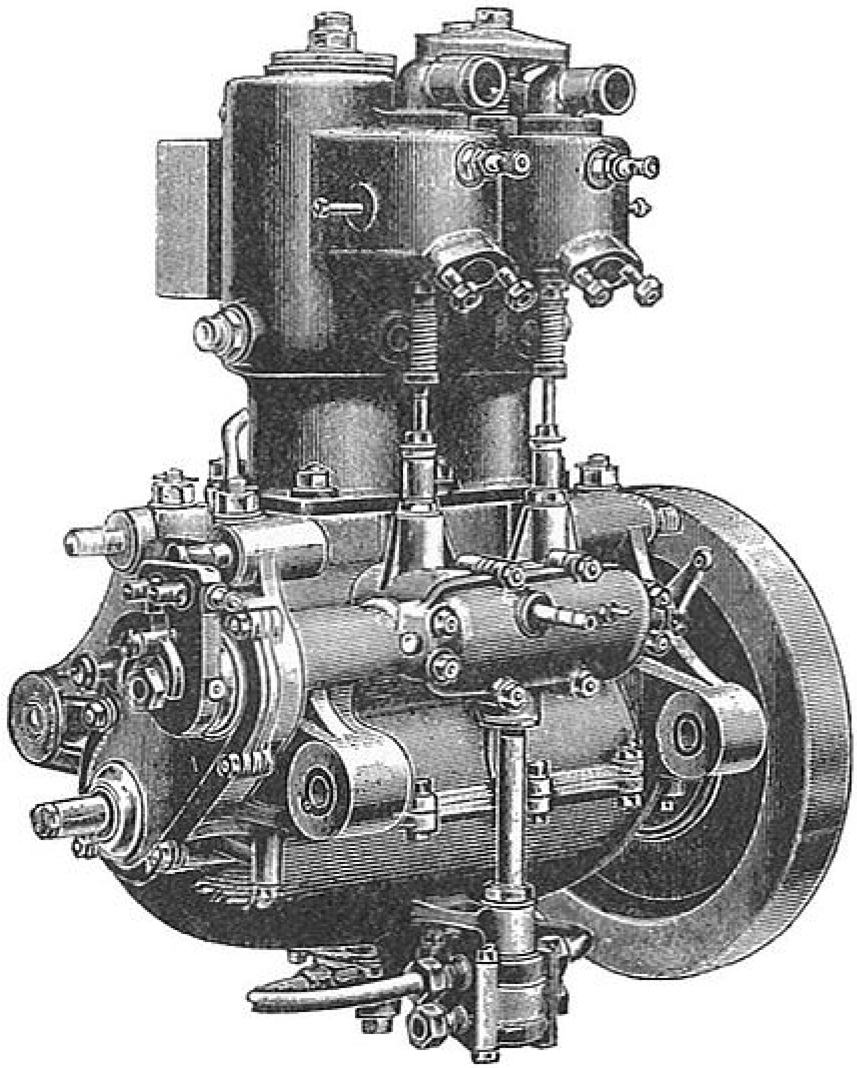
The average level of the sensor is defined as 450 mV. Since narrow band sensors cannot output a fixed voltage level between the lean and the rich areas, the ECU tries to control the engine by controlling the mixture between lean and rich in such a sufficiently fast manner, that the average level becomes ca 450 mV.

A wide band sensor, on the other hand, has a very linear output, 0 - 5 V, and is not temperature dependent.

Which type of air-fuel ratio meter to be used

If the purpose of the air-fuel ratio meter is to diagnose an existing or possible problem with the sensor and/or to check the general mixture and performance, a narrow band air-fuel ratio meter is sufficient.

Crankcase



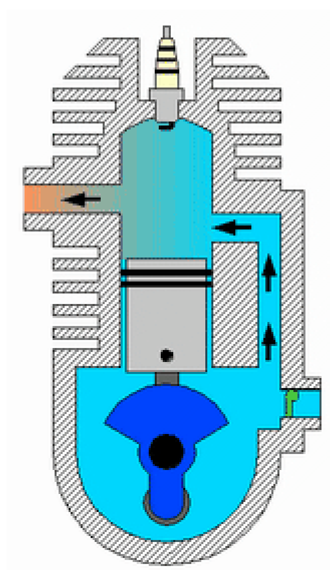
De Dion-Bouton engine from about 1905, in which can clearly be seen a discrete crankcase with upper and lower halves (each a casting), with the bottom half constituting both part of the main bearing support and also an oil sump.

In an internal combustion engine of the reciprocating type, the **crankcase** is the housing for the crankshaft. The enclosure forms the largest cavity in the engine and is located below the cylinder(s), which in a multicylinder engine are usually integrated into one or several cylinder blocks. Crankcases have often been discrete parts, but more often they are integral with the cylinder bank(s), forming an engine block. Nevertheless, the area around the crankshaft is still usually called the crankcase. Crankcases and other basic engine structural components (e.g., cylinders, cylinder blocks, cylinder heads, and integrated combinations thereof) are typically made of cast iron or cast aluminium via sand casting. Today the foundry processes are usually highly automated, with a few skilled workers to manage the casting of thousands of parts.

A crankcase often has an opening in the bottom to which an oil pan is attached with a gasketed bolted joint. Some crankcase designs fully surround the crank's main bearing journals, whereas many others form only one half, with a bearing cap forming the other. Some crankcase areas require no structural strength from the oil pan itself (in which case the oil pan is typically stamped from sheet steel), whereas other crankcase designs do (in which case the oil pan is a casting in its own right). Both the crankcase and any rigid cast oil pan often have reinforcing ribs cast into them, as well as bosses which are drilled and tapped to receive mounting screws/bolts for various other engine parts.

Besides protecting the crankshaft and connecting rods from foreign objects, the crankcase serves other functions, depending on engine type. These include keeping the motor oil contained, usually hermetically or nearly hermetically (and in the hermetic variety, allowing the oil to be pressurized); providing the rigid structure with which to join the engine to the transmission; and in some cases, even constituting part of the frame of the vehicle (such as in many farm tractors).

Two-stroke engines



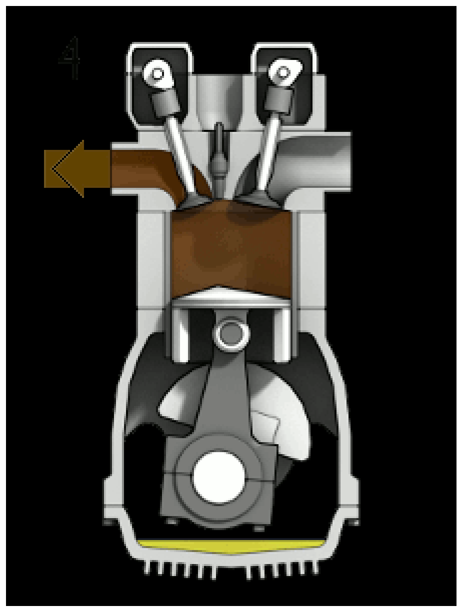
Two-stroke engine

In two-stroke gasoline engines, the crankcase is sealed and is used as a pressurization chamber for the fuel/air mixture. As the piston rises, it pushes out exhaust gases and produces a partial vacuum in the crankcase which aspirates fuel and air. As the piston travels downward, the fuel/air charge is pushed from the crankcase and into the cylinder.

Unlike four-stroke gasoline engines, the crankcase does not contain engine oil because it handles the fuel/air mixture. Instead, oil is mixed in with the fuel, and the mixture provides lubrication for the cylinder walls, crankshaft and connecting rod bearings.

A majority of ships today use two stroke diesel engines, where the crankcase is completely separated from the cylinders. Unlike smaller engines, they usually have a separate tank below the crankcase as an oil holding tank (sump tank).

Four-stroke engines



Four-stroke engine

In a four-stroke engine, the crankcase is filled mainly with air and oil, and is largely sealed off from the fuel/air mixture by the pistons.

Oil circulation

Oil circulation is kept separate from the fuel/air mixture, thereby preserving oil rather than burning it as happens in two-stroke engines. Oil moves from its reservoir, is pressurized by an oil pump, and is pumped through the oil filter to remove grit. The oil is then squirted into the crankshaft and connecting rod bearings and onto the cylinder walls, and eventually drips off into the bottom of the crankcase. In a wet sump system, oil remains in a reservoir at the bottom of the crankcase, referred to as the **oil pan**. In a dry sump system, oil is instead pumped to an external reservoir.

Even in a wet sump system, the crankshaft has minimal contact with the sump oil. Otherwise, the high-speed rotation of the crankshaft would cause the oil to froth, making it difficult for the oil pump to move the oil, which can starve the engine of lubrication. Small amounts of oil may splash onto the crankshaft during rough driving, referred to as windage.

In a wet sump system, the main dipstick and oil filler cap connect to the crankcase.

Air ventilation

During normal operation, a small amount of unburned fuel and exhaust gases escape around the piston rings and enter the crankcase, referred to as "**blow-by**". If these gases had no controlled escape mechanism, the gasketed joints would leak (as they "found their own way out"); also, if the gases remained in the crankcase and condensed, the oil would become diluted and chemically degraded over time, decreasing its ability to lubricate. Condensed water would also cause parts of the engine to rust. To counter this, a crankcase ventilation system exists. In all modern vehicles, this consists of a channel to expel the gases out of the crankcase, through an oil-separating baffle, to the PCV valve, into the intake manifold. In a non-turbo engine, the intake manifold is at a lower pressure than the crankcase, providing the suction to keep the ventilation system going. A turbo engine usually has a check valve somewhere in the tubing to avoid pressurizing the crankcase when the turbo produces boost.

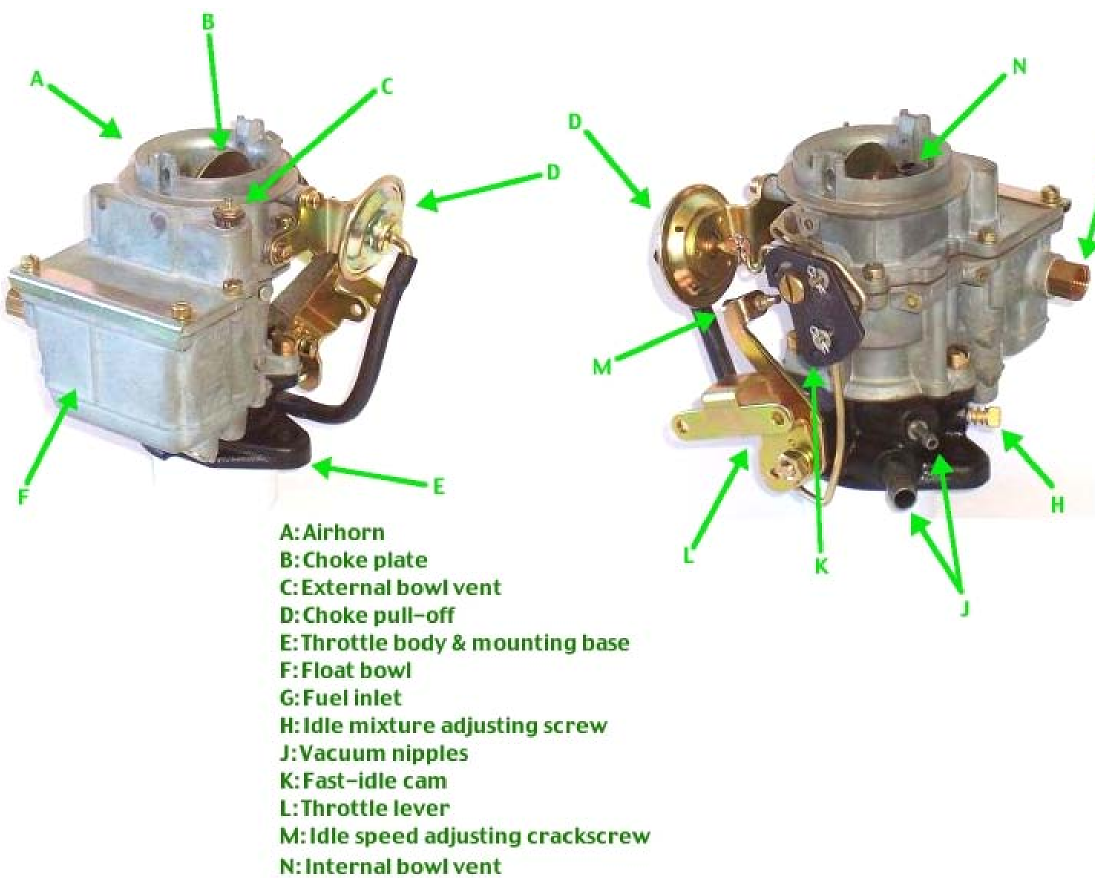
If an engine is damaged or enters old age, gaps can form between the cylinder walls and pistons, resulting in larger amounts of blow-by than the crankcase ventilation system can handle. The gaps cause power loss, and ultimately mean that the engine needs to be rebuilt or replaced. Symptoms of excessive blow-by include oil being pushed up into the air filter, out the dipstick, or out the PCV valve. In rare cases of serious piston or ring damage, the oil filter housing's sheet metal can even burst at its seam.

Open crank engine

Early internal combustion engines were of the "open crank" style, that is, there was no enclosed crankcase. The crankshaft, connecting rod, camshaft, gears, governor, etc. were all completely exposed and could be viewed in operation when the engine was running. This made for a messy environment as oil was thrown from the engine and could run on the ground. Another disadvantage was that dirt and dust could get on moving engine parts, causing excessive wear and possible malfunction of the engine. Frequent cleaning of the engine was required to keep it in normal working order.

Chapter 5

Carburetor



Bendix-Technico (Stromberg) 1-barrel downdraft carburetor model BXUV-3, with nomenclature

A **carburetor** (American spelling), **carburettor**, or **carburetter** (Commonwealth spelling) is a device that blends air and fuel for an internal combustion engine. It is sometimes shortened to *carb* in North America and the United Kingdom.

Word origin

The word *carburetor* comes from the French *carbure* meaning "carbide". *Carburer* means to combine with carbon. In fuel chemistry, the term has the more specific meaning of increasing the carbon (and therefore energy) content of a fuel by mixing it with a volatile hydrocarbon.

History and development

The first carburetors were surface carburetors where the volatility of the petrol was utilized. The Austrian automobile pioneer Siegfried Marcus invented the “rotating brush carburettor”. This was further improved by the Hungarian engineers János Csonka and Donát Bánki in 1893.

Frederick William Lanchester of Birmingham, England, experimented with the wick carburetor in cars. In 1896, Frederick and his brother built the first gasoline driven car in England, a single cylinder 5 hp (3.7 kW) internal combustion engine with chain drive. Unhappy with the performance and power, they re-built the engine the next year into a two cylinder horizontally opposed version using his new wick carburetor design.

In 1885, Wilhelm Maybach and Gottlieb Daimler developed a carburetor for their engine based on the Atomizer nozzle.

Carburetors were the usual fuel delivery method for most U.S. made gasoline-fueled engines up until the late 1980s, when fuel injection became the preferred method of automotive fuel delivery. In the U.S. market, the last carbureted cars were:

- 1990 (General public) : Oldsmobile Custom Cruiser, Buick Estate Wagon
- 1991 (Police) : Ford Crown Victoria Police Interceptor with the 5.8 L (351 cu in) engine.
- 1991 (SUV) : Jeep Grand Wagoneer with the AMC 360 engine.
- 1994 (Light truck) : Isuzu

Elsewhere, certain Lada cars used carburetors until 2006. A majority of motorcycles still use carburetors due to lower cost and throttle response problems with early injection setups, but as of 2005 many new models are now being introduced with fuel injection. Carburetors are still found in small engines and in older or specialized automobiles, such as those designed for stock car racing.

Principles

The carburetor works on Bernoulli's principle: the faster air moves, the lower its static pressure, and the higher its dynamic pressure. The throttle (accelerator) linkage does not directly control the flow of liquid fuel. Instead, it actuates carburetor mechanisms which meter the flow of air being pulled into the engine. The speed of this flow, and therefore its pressure, determines the amount of fuel drawn into the airstream.

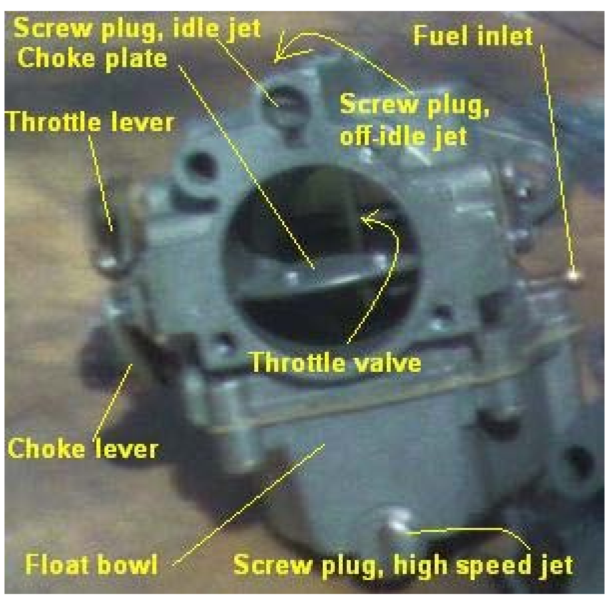
When carburetors are used in aircraft with piston engines, special designs and features are needed to prevent fuel starvation during inverted flight. Later engines used an early form of fuel injection known as a pressure carburetor.

Most production **carbureted** (as opposed to fuel-injected) engines have a single carburetor and a matching intake manifolds that divides and transports the air fuel mixture to the intake valves, though some engines (like motorcycle engines) use multiple carburetors on split heads. Multiple carburetor engines were also common enhancements for modifying engines in America from the 1950s to mid-1960s, as well as during the following decade of high-performance American muscle cars fueling different chambers of the engine's intake manifold.

Older engines used updraft carburetors, where the air enters from below the carburetor and exits through the top. This had the advantage of never "flooding" the engine, as any liquid fuel droplets would fall out of the carburetor instead of into the intake manifold; it also lent itself to use of an oil bath air cleaner, where a pool of oil below a mesh element below the carburetor is sucked up into the mesh and the air is drawn through the oil-covered mesh; this was an effective system in a time when paper air filters did not exist.

Beginning in the late 1930s, downdraft carburetors were the most popular type for automotive use in the United States. In Europe, the sidedraft carburetors replaced downdraft as free space in the engine bay decreased and the use of the SU-type carburetor (and similar units from other manufacturers) increased. Some small propeller-driven aircraft engines still use the updraft carburetor design.

Outboard motor carburetors are typically sidedraft, because they must be stacked one on top of the other in order to feed the cylinders in a vertically-oriented cylinder block.

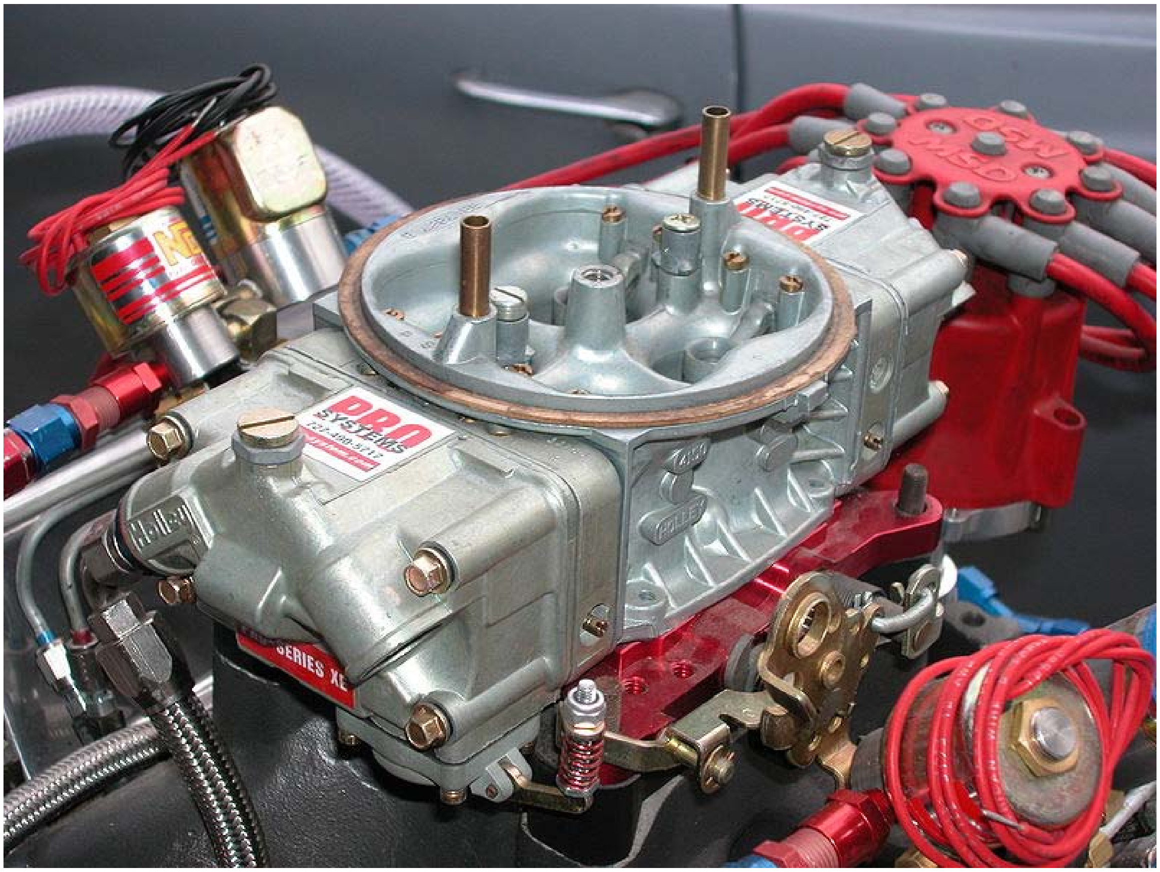


1979 Evinrude Type I marine sidedraft carburetor

The main disadvantage of basing a Carburetor's operation on Bernoulli's principle is that, being a fluid dynamic device, the pressure reduction in a venturi tends to be proportional to the square of the intake air speed. The fuel jets are much smaller and limited mainly by viscosity, so that the fuel flow tends to be proportional to the pressure difference. So jets sized for full power tend to starve the engine at lower speed and part throttle. Most commonly this has been corrected by using multiple jets. In SU and other movable jet carburetors, it was corrected by varying the jet size. For cold starting, a different principle was used, in multi-jet carburetors. A flow resisting valve called a choke, similar to the throttle valve, was placed upstream of the main jet to reduce the intake pressure and suck additional fuel out of the jets.

Operation

- **Fixed-venturi**, in which the varying air velocity in the venturi alters the fuel flow; this architecture is employed in most carburetors found on cars.
- **Variable-venturi**, in which the fuel jet opening is varied by the slide (which simultaneously alters air flow). In "constant depression" carburetors, this is done by a vacuum operated piston connected to a tapered needle which slides inside the fuel jet. A simpler version exists, most commonly found on small motorcycles and dirt bikes, where the slide and needle is directly controlled by the throttle position. The most common variable venturi (constant depression) type carburetor is the sidedraft SU carburetor and similar models from Hitachi, Zenith-Stromberg and other makers. The UK location of the SU and Zenith-Stromberg companies helped these carburetors rise to a position of domination in the UK car market, though such carburetors were also very widely used on Volvos and other non-UK makes. Other similar designs have been used on some European and a few Japanese automobiles. These carburetors are also referred to as "constant velocity" or "constant vacuum" carburetors. An interesting variation was Ford's VV (Variable Venturi) carburetor, which was essentially a fixed venturi carburetor with one side of the venturi hinged and movable to give a narrow throat at low rpm and a wider throat at high rpm. This was designed to provide good mixing and airflow over a range of engine speeds, though the VV carburetor proved problematic in service.



A high performance 4-barrel carburetor.

Under all engine operating conditions, the carburetor must:

- Measure the airflow of the engine
- Deliver the correct amount of fuel to keep the fuel/air mixture in the proper range (adjusting for factors such as temperature)
- Mix the two finely and evenly

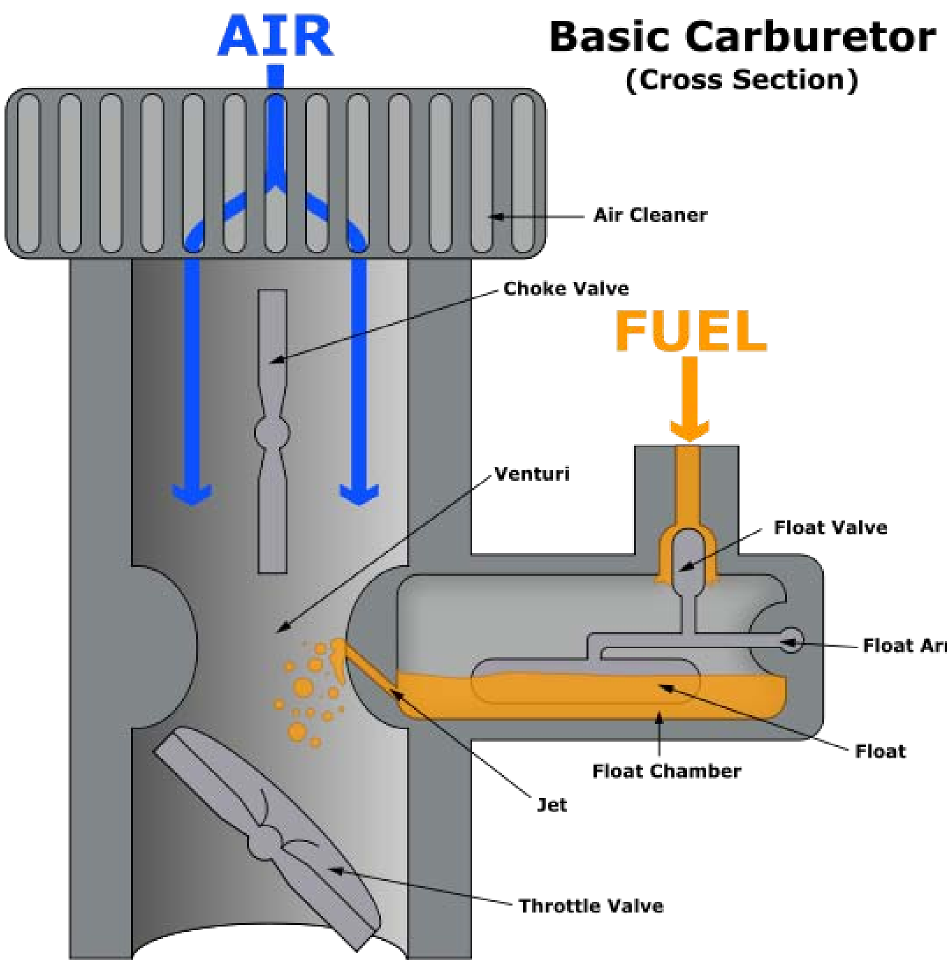
This job would be simple if air and gasoline (petrol) were ideal fluids; in practice, however, their deviations from ideal behavior due to viscosity, fluid drag, inertia, etc. require a great deal of complexity to compensate for exceptionally high or low engine speeds. A carburetor must provide the proper fuel/air mixture across a wide range of ambient temperatures, atmospheric pressures, engine speeds and loads, and centrifugal forces:

- Cold start
- Hot start
- Idling or slow-running
- Acceleration
- High speed / high power at full throttle
- Cruising at part throttle (light load)

In addition, modern carburetors are required to do this while maintaining low rates of exhaust emissions.

To function correctly under all these conditions, most carburetors contain a complex set of mechanisms to support several different operating modes, called *circuits*.

Basics



Cross Sectional schematic of a Carburetor

A carburetor basically consists of an open pipe through which the air passes into the inlet manifold of the engine. The pipe is in the form of a venturi: it narrows in section and then widens again, causing the airflow to increase in speed in the narrowest part. Below the venturi is a butterfly valve called the throttle valve — a rotating disc that can be turned end-on to the airflow, so as to hardly restrict the flow at all, or can be rotated so that it (almost) completely blocks the flow of air. This valve controls the flow of air through the carburetor throat and thus the quantity of air/fuel mixture the system will deliver, thereby regulating engine power and speed. The throttle is connected, usually through a cable or a mechanical linkage of rods and joints or rarely by pneumatic link, to the accelerator pedal on a car or the equivalent control on other vehicles or equipment.

Fuel is introduced into the air stream through small holes at the narrowest part of the venturi and at other places where pressure will be lowered when not running on full throttle. Fuel flow is adjusted by means of precisely-calibrated orifices, referred to as *jets*, in the fuel path.

Off-idle circuit

As the throttle is opened up slightly from the fully-closed position, the throttle plate uncovers additional fuel delivery holes behind the throttle plate where there is a low pressure area created by the throttle plate blocking air flow; these allow more fuel to flow as well as compensating for the reduced vacuum that occurs when the throttle is opened, thus smoothing the transition to metering fuel flow through the regular open throttle circuit.

Main open-throttle circuit

As the throttle is progressively opened, the manifold vacuum is lessened since there is less restriction on the airflow, reducing the flow through the idle and off-idle circuits. This is where the venturi shape of the carburetor throat comes into play, due to Bernoulli's principle (*i.e.,* as the velocity increases, pressure falls). The venturi raises the air velocity, and this high speed and thus low pressure sucks fuel into the airstream through a nozzle or nozzles located in the center of the venturi. Sometimes one or more additional **booster venturis** are placed coaxially within the primary venturi to increase the effect.

As the throttle is closed, the airflow through the venturi drops until the lowered pressure is insufficient to maintain this fuel flow, and the idle circuit takes over again, as described above.

Bernoulli's principle, which is a function of the velocity of the fluid, is a dominant effect for large openings and large flow rates, but since fluid flow at small scales and low speeds (low Reynolds number) is dominated by viscosity, Bernoulli's principle is ineffective at idle or slow running and in the very small carburetors of the smallest model engines. Small model engines have flow restrictions ahead of the jets to reduce the pressure enough to suck the fuel into the air flow. Similarly the idle and slow running jets of large carburetors are placed after the throttle valve where the pressure is reduced partly by viscous drag, rather than by Bernoulli's principle. The most common rich mixture device for starting cold engines was the choke, which works on the same principle.

Power valve

For open throttle operation a richer mixture will produce more power, prevent pre-ignition detonation, and keep the engine cooler. This is usually addressed with a spring-loaded "power valve", which is held shut by engine vacuum. As the throttle opens up, the vacuum decreases and the spring opens the valve to let more fuel into the main circuit. On two-stroke engines, the operation of the power valve is the reverse of normal — it is normally "on" and at a set rpm it is turned "off". It is activated at high rpm to extend the engine's rev range, capitalizing on a two-stroke's tendency to rev higher momentarily when the mixture is lean.

Alternative to employing a power valve, the carburetor may utilize a **metering rod** or **step-up rod** system to enrich the fuel mixture under high-demand conditions. Such systems were originated by Carter Carburetor in the 1950s for the primary two venturis of their four barrel carburetors, and step-up rods were widely used on most 1-, 2-, and 4-barrel Carter carburetors through the end of production in the 1980s. The step-up rods are tapered at the bottom end, which extends into the main metering jets. The tops of the rods are connected to a vacuum piston and/or a mechanical linkage which lifts the rods out of the main jets when the throttle is opened (mechanical linkage) and/or when manifold vacuum drops (vacuum piston). When the step-up rod is lowered into the main jet, it restricts the fuel flow. When the step-up rod is raised out of the jet, more fuel can flow through it. In this manner, the amount of fuel delivered is tailored to the transient demands of the engine. Some 4-barrel carburetors use metering rods only on the primary two venturis, but some use them on both primary and secondary circuits, as in the Rochester Quadrajet.

Accelerator pump

Liquid gasoline, being denser than air, is slower than air to react to a force applied to it. When the throttle is rapidly opened, airflow through the carburetor increases immediately, faster than the fuel flow rate can increase. This transient oversupply of air causes a lean mixture, which makes the engine misfire (or "stumble")—an effect opposite what was demanded by opening the throttle. This is remedied by the use of a small piston or diaphragm pump which, when actuated by the throttle linkage, forces a small amount of gasoline through a jet into the carburetor throat. This extra shot of fuel counteracts the transient lean condition on throttle tip-in. Most accelerator pumps are adjustable for volume and/or duration by some means. Eventually the seals around the moving parts of the pump wear such that pump output is reduced; this reduction of the accelerator pump shot causes stumbling under acceleration until the seals on the pump are renewed.

The accelerator pump is also used to **prime** the engine with fuel prior to a cold start. Excessive priming, like an improperly-adjusted choke, can cause **flooding**. This is when too much fuel and not enough air are present to support combustion. For this reason, most carburetors are equipped with an **unloader** mechanism: The accelerator is held at wide open throttle while the engine is cranked, the unloader holds the choke open and admits extra air, and eventually the excess fuel is cleared out and the engine starts.

Choke

When the engine is cold, fuel vaporizes less readily and tends to condense on the walls of the intake manifold, starving the cylinders of fuel and making the engine difficult to start; thus, a **richer mixture** (more fuel to air) is required to start and run the engine until it warms up. A richer mixture is also easier to ignite.

To provide the extra fuel, a **choke** is typically used; this is a device that restricts the flow of air at the entrance to the carburetor, before the venturi. With this restriction in place, extra vacuum is developed in the carburetor barrel, which pulls extra fuel through the main metering system to supplement the fuel being pulled from the idle and off-idle circuits. This provides the rich mixture required to sustain operation at low engine temperatures.

In addition, the choke can be connected to a cam (the **fast idle cam**) or other such device which prevents the throttle plate from closing fully while the choke is in operation. This causes the engine to idle at a higher speed. Fast idle serves as a way to help the engine warm up quickly, and give a more stable idle while cold by increasing airflow throughout the intake system which helps to better atomize the cold fuel.

In many carbureted cars, the choke is controlled by a cable connected to a pull-knob on the dashboard operated by the driver. In some carbureted cars it is automatically controlled by a thermostat employing a bimetallic spring, which is exposed to engine heat, or to an electric heating element. This heat may be transferred to the choke thermostat via simple convection, via engine coolant, or via air heated by the exhaust. More recent designs use the engine heat only indirectly: A sensor detects engine heat and varies electrical current to a small heating element, which acts upon the bimetallic spring to control its tension, thereby controlling the choke. A **choke unloader** is a linkage arrangement that forces the choke open against its spring when the vehicle's accelerator is moved to the end of its travel. This provision allows a "flooded" engine to be cleared out so that it will start.

Some carburetors do not have a choke but instead use a mixture enrichment circuit, or **enrichener**. Typically used on small engines, notably motorcycles, enricheners work by opening a secondary fuel circuit below the throttle valves. This circuit works exactly like the idle circuit, and when engaged it simply supplies extra fuel when the throttle is closed.

Classic British motorcycles, with side-draft slide throttle carburetors, used another type of "cold start device", called a "tickler". This is simply a spring-loaded rod that, when depressed, manually pushes the float down and allows excess fuel to fill the float bowl and flood the intake tract. If the "tickler" is held down too long it also floods the outside of the carburetor and the crankcase below, and is therefore a fire hazard.

Other elements

The interactions between each circuit may also be affected by various mechanical or air pressure connections and also by temperature sensitive and electrical components. These are introduced for reasons such as response, fuel efficiency or automobile emissions control. Various air bleeds (often chosen from a precisely calibrated range, similarly to the jets) allow air into various portions of the fuel passages to enhance fuel delivery and vaporization. Extra refinements may be included in the carburetor/manifold combination, such as some form of heating to aid fuel vaporization such as an early fuel evaporator.

Fuel supply

Float chamber

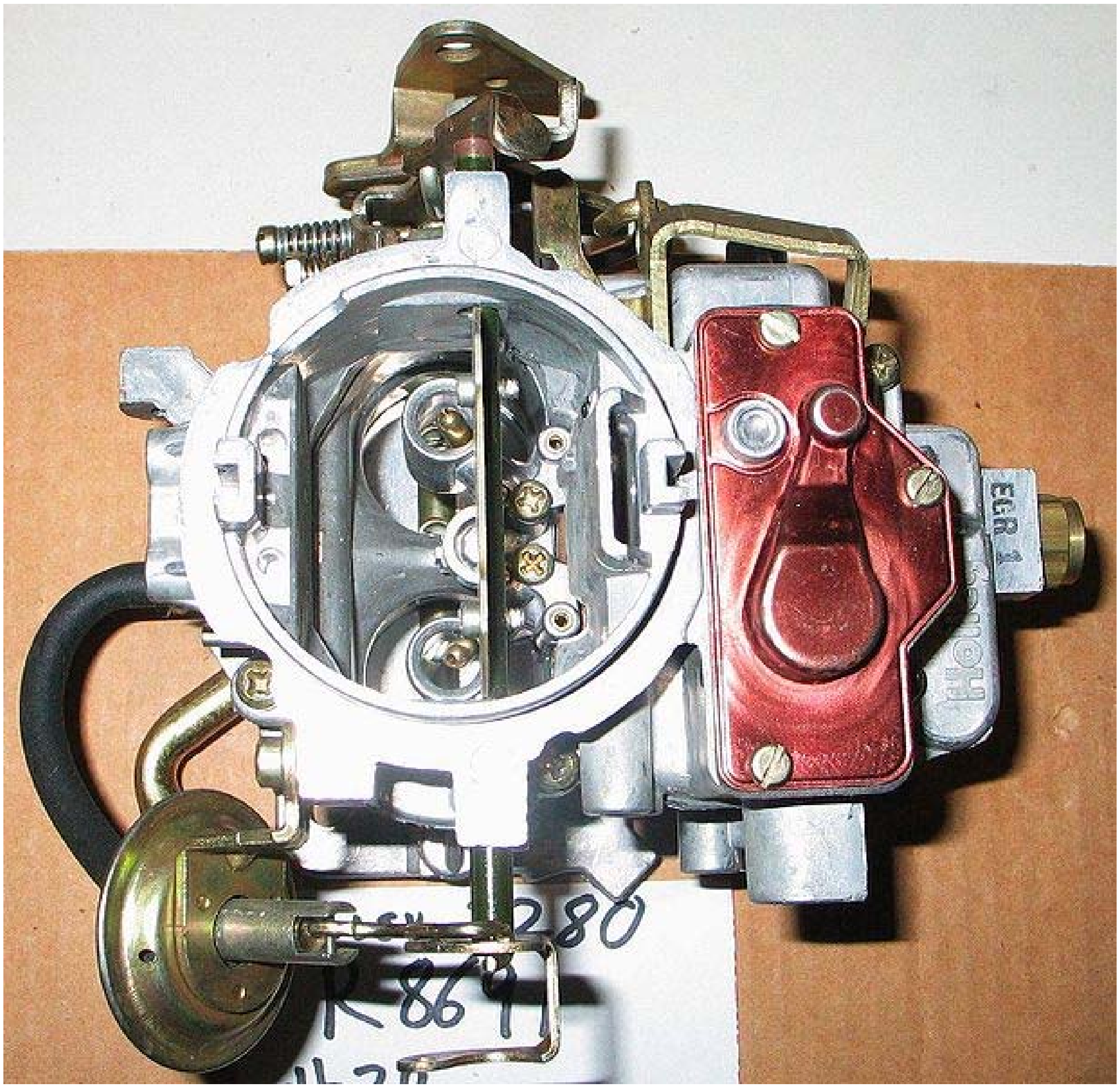
Holley "Visi-Flo" model #1904 carburetors from the 1950s, factory equipped with transparent glass bowls.

To ensure a ready mixture, the carburetor has a "float chamber" (or "bowl") that contains a quantity of fuel at near-atmospheric pressure, ready for use. This reservoir is constantly replenished with fuel supplied by a fuel pump. The correct fuel level in the bowl is maintained by means of a float controlling an inlet valve, in a manner very similar to that employed in a cistern (e.g. a toilet tank). As fuel is used up, the float drops, opening the inlet valve and admitting fuel. As the fuel level rises, the float rises and closes the inlet valve. The level of fuel maintained in the float bowl can usually be adjusted, whether by a setscrew or by something crude such as bending the arm to which the float is connected. This is usually a critical adjustment, and the proper adjustment is indicated by lines inscribed into a window on the float bowl, or a measurement of how far the float hangs below the top of the carburetor when disassembled, or similar. Floats can be made of different materials, such as sheet brass soldered into a hollow shape, or of plastic; hollow floats can spring small leaks and plastic floats can eventually become porous and lose their flotation; in either case the float will fail to float, fuel level will be too high, and the engine will not run unless the float is replaced. The valve itself becomes worn on its sides by its motion in its "seat" and will eventually try to close at an angle, and thus fails to shut off the fuel completely; again, this will cause excessive fuel flow and poor engine operation. Conversely, as the fuel evaporates from the float bowl, it leaves sediment, residue, and varnishes behind, which clog the passages and can interfere with the float operation. This is particularly a problem in automobiles operated for only part of the year and left to stand with full float chambers for months at a time; commercial fuel stabilizer additives are available that reduce this problem.

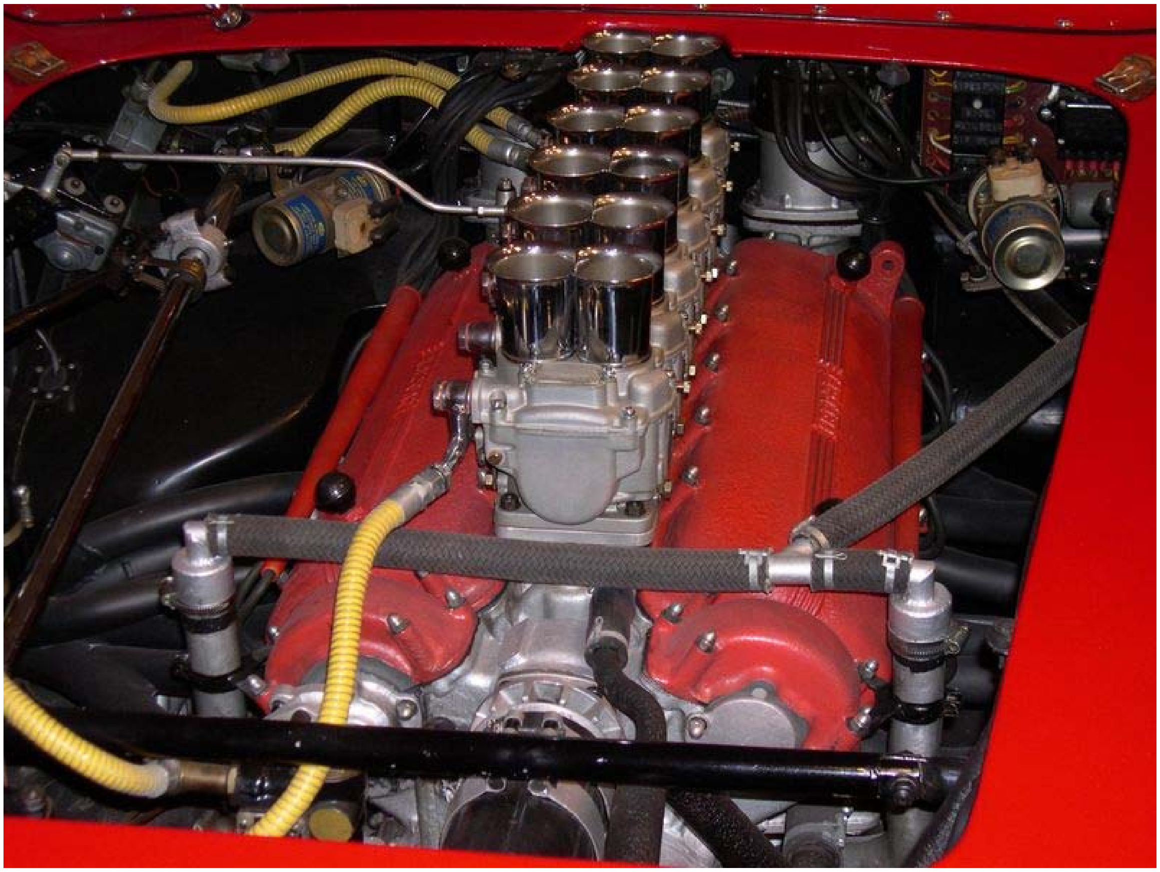
Usually, special vent tubes allow air to escape from the chamber as it fills or enter as it empties, maintaining atmospheric pressure within the float chamber; these usually extend into the carburetor throat. Placement of these vent tubes can be somewhat critical to prevent fuel from sloshing out of them into the carburetor, and sometimes they are modified with longer tubing. Note that this leaves the fuel at atmospheric pressure, and therefore it cannot travel into a throat which has been pressurized by a supercharger mounted upstream; in such cases, the entire carburetor must be contained in an airtight pressurized box to operate. This is not necessary in installations where the carburetor is mounted upstream of the supercharger, which is for this reason the more frequent system. However, this results in the supercharger being filled with compressed fuel/air mixture, with a strong tendency to explode should the engine backfire; this type of explosion is frequently seen in drag races, which for safety reasons now incorporate pressure releasing blow-off plates on the intake manifold, breakaway bolts holding the supercharger to the manifold, and shrapnel-catching ballistic nylon blankets surrounding the superchargers.

If the engine must be operated in any orientation (for example a chain saw), a float chamber cannot work. Instead, a diaphragm chamber is used. A flexible diaphragm forms one side of the fuel chamber and is arranged so that as fuel is drawn out into the engine the diaphragm is forced inward by ambient air pressure. The diaphragm is connected to the needle valve and as it moves inward it opens the needle valve to admit more fuel, thus replenishing the fuel as it is consumed. As fuel is replenished the diaphragm moves out due to fuel pressure and a small spring, closing the needle valve. A balanced state is reached which creates a steady fuel reservoir level, which remains constant in any orientation.

Multiple carburetor barrels



Holley model #2280 2-barrel carburetor



Colombo Type 125 "Testa Rossa" engine in a 1961 Ferrari 250TR Spider with six Weber two-barrel carburetors inducting air through 12 air horns; one individually adjustable barrel for each cylinder.

While basic carburetors have only one venturi, many carburetors have more than one venturi, or "barrel". Two barrel and four barrel configurations are commonly used to accommodate the higher air flow rate with large engine displacement. Multi-barrel carburetors can have non-identical primary and secondary barrel(s) of different sizes and calibrated to deliver different air/fuel mixtures; they can be actuated by the linkage or by engine vacuum in "progressive" fashion, so that the secondary barrels do not begin to open until the primaries are almost completely open. This is a desirable characteristic which maximizes airflow through the primary barrel(s) at most engine speeds, thereby maximizing the pressure "signal" from the venturis, but reduces the restriction in airflow at high speeds by adding cross-sectional area for greater airflow. These advantages may not be important in high-performance applications where part throttle operation is irrelevant, and the primaries and secondaries may all open at once, for simplicity and reliability; also, V-configuration engines, with two cylinder banks fed by a single carburetor, may be configured with two identical barrels, each supplying one cylinder bank. In the widely seen V8 and 4-barrel carburetor combination, there are often two primary and two secondary barrels.

The **spread-bore** 4-barrel carburetor, first released by Rochester in the 1965 model year as the "Quadrajet" has a much greater *spread* between the sizes of the primary and secondary throttle bores. The primaries in such a carburetor are quite small relative to conventional 4-barrel practice, while the secondaries are quite large. The small primaries aid low-speed fuel economy and drivability, while the large secondaries permit maximum performance when it is called for. To tailor airflow through the secondary venturis, each of the secondary throats has an air valve at the top. This is configured much like a choke plate, and is lightly spring-loaded into the closed position. The air valve opens progressively in response to engine speed and throttle opening, gradually allowing more air to flow through the secondary side of the carburetor. Typically, the air valve is linked to metering rods which are raised as the air valve opens, thereby adjusting secondary fuel flow.

Multiple carburetors can be mounted on a single engine, often with progressive linkages; two four-barrel carburetors were frequently seen on high performance American V8s, and multiple two barrel carburetors are often now seen on very high performance engines. Large numbers of small carburetors have also been used, though this configuration can limit the maximum air flow through the engine due to the lack of a common plenum; with individual intake tracts, not all cylinders are drawing air at once as the engine's crankshaft rotates.

Carburetor adjustment

Too much fuel in the fuel-air mixture is referred to as too **rich**, and not enough fuel is too **lean**. The mixture is normally adjusted by one or more needle valves on an automotive carburetor, or a pilot-operated lever on piston-engined aircraft (since mixture is air density (altitude) dependent). The (stoichiometric) air to gasoline ratio is 14.7:1, meaning that for each weight unit of gasoline, 14.7 units of air will be consumed. Stoichiometric mixture are different for various fuels other than gasoline.

Ways to check carburetor mixture adjustment include: measuring the carbon monoxide, hydrocarbon, and oxygen content of the exhaust using a gas analyzer, or directly viewing the colour of the flame in the combustion chamber through a special glass-bodied spark plug sold under the name "Colortune" for this purpose. The flame colour of stoichiometric burning is described as a "bunsen blue", turning to yellow if the mixture is rich and whitish-blue if too lean.

The mixture can also be judged after engine running by the state and color of the spark plugs: black, dry sooty plugs indicate a too rich mixture, white to light gray deposits on the plugs indicate a lean mixture. The correct color should be a brownish gray.

In the early 1980s, many American-market vehicles used special "feedback" carburetors that could change the base mixture in response to signals from an exhaust gas oxygen sensor. These were mainly used to save costs (since they worked well enough to meet 1980s emissions requirements and were based on existing carburetor designs), but eventually disappeared as falling hardware prices and tighter emissions standards made fuel injection a standard item.

Where multiple carburetors are used the mechanical linkage of their throttles must be synchronized for smooth engine running.

Catalytic carburetors

A catalytic carburetor mixes fuel fumes with water and air in the presence of heated catalysts such as nickel or platinum. This breaks the fuel down into methane, alcohols, and other lighter-weight fuels. The original catalytic carburetor was introduced to permit farmers to run tractors from modified and enriched kerosene. The U.S. Army also used catalytic carburetors with great success in World War II, in the North African desert campaign.

While catalytic carburetors were made commercially available in the early 1930s, two major factors limited their widespread public use. First, the addition of additives to commercial gasoline made it unsuitable for use in engines with catalytic carburetors. (Tetra-ethyl lead, for example, was introduced in 1932 to raise gasoline's resistance to engine knock, thereby permitting the use of higher compression ratios.) Second, the economic advantage of using kerosene over gasoline faded in the 1930s, eliminating the catalytic carburetor's primary advantage.

Chapter 6

Distributor and Electronic Control Unit

Distributor

Typical Distributor with distributor cap
Also visible are mounting/drive shaft(bottom), vacuum advance unit (right) and capacitor(centre)

Breaker arm with contact points at the left. The pivot is on the right and the cam follower is in the middle of the breaker arm.

Distributor cap. At the center is a spring loaded carbon button that bears upon the rotor. The number of distribution points (in this case 4) is determined by the number of cylinders in the engine

Rotor. This rotates at the same speed as the camshaft, one half the speed of the crankshaft

A **distributor** is a device in the ignition system of an internal combustion engine that routes high voltage from the ignition coil to the spark plugs in the correct firing order. The first reliable battery operated ignition was developed by Dayton Engineering Laboratories Co. (Delco) and introduced in the 1910 Cadillac. This ignition was developed by Charles Kettering and was considered a wonder in its day.

Description

It consists of a rotating arm or rotor inside the distributor cap, on top of the distributor shaft, but insulated from it and the body of the vehicle (ground). The distributor shaft is driven by a gear on the camshaft. (Usually the distributor shaft extends to also drive the oil pump.) The metal part of the rotor contacts the central high voltage cable from the coil via a spring loaded carbon brush. The metal part of the rotor arm passes close to (but does not touch) the output contacts which connect via high tension leads to the spark plug of each cylinder. As the rotor spins within the distributor, electrical current is able to jump the small gaps created between the rotor arm and the contacts due to the high voltage created by the ignition coil.

The distributor shaft has a cam that operates the contact breaker. Opening the points causes a high induction voltage in the system's ignition coil.

The distributor also houses the centrifugal advance unit: a set of hinged weights attached to the distributor shaft, that cause the breaker points mounting plate to slightly rotate and advance the spark timing with higher engine rpm. In addition, the distributor has a vacuum advance unit that advances the timing even further as a function of the vacuum in the inlet manifold. Usually there is also a capacitor attached to the distributor. The capacitor is connected parallel to the breaker points, to suppress sparking and prevent wear of the points.

Around the 1970s the primary breaker points were largely replaced with Hall effect sensors. As this is a non-contacting device and the primary circuit is controlled by solid state electronics, a great amount of maintenance in point adjustment and replacement was eliminated. This also eliminates any problem with breaker follower or cam wear, and by eliminating a side load extends distributor shaft bearing life. The remaining secondary (high voltage) circuit was as described above, using a single coil and a rotary distributor.

Distributor cap

A distributor cap is used in an automobile's engine to cover the distributor and its internal rotor.

The distributor cap has one post for each cylinder, and in points ignition systems there is a central post for the current from the ignition coil coming into the distributor. In high energy ignition (HEI) systems there is no central post and the ignition coil sits on top of the distributor. On the inside of the cap there is a terminal that corresponds to each post, and the plug terminals are arranged around the circumference of the cap according to the firing order in order to send the secondary voltage to the proper spark plug at the right time.

The rotor is attached to the top of the distributor shaft which is driven by a gear on the engine's camshaft and thus synchronized to it. Synchronization to the camshaft is required as the rotor must turn at exactly half the speed of the main crankshaft in the 4-stroke cycle. Often, the rotor and distributor are attached directly to the end of the one of (or the only) camshaft, at the opposite end to the timing drive belt. This rotor is pressed against a carbon brush on the center terminal of the distributor cap which connects to the ignition coil either through the top and wired directly to the coil in HEI systems, or via the center terminal in points ignition systems and remotely connected to the coil. The rotor is constructed such that the center tab is electrically connected to its outer edge so the current coming in to the center post travels through the carbon point to the outer edge of the rotor. As the camshaft rotates, the rotor spins and its outer edge passes each of the internal plug terminals to fire each spark plug in sequence.

Car engines that use a mechanical distributor may fail if they run into deep puddles because any water that leaks into the distributor can short out the electric current that should go through the spark plug, rerouting it directly to the body of the vehicle. This in turn causes the engine to stop as the fuel is not ignited in the cylinders. This problem can be fixed by removing the distributor's cap and drying the cap, cam, rotor and the contacts by: wiping with tissue paper or a clean rag, by blowing hot air on them, or using a moisture displacement spray i.e. WD 40 or similar. Oil, dirt or other contaminants can cause similar problems, so the distributor should be kept clean inside and outside to ensure reliable operation.

The distributor cap is a prime example of a component that eventually succumbs to heat and vibration. It is a relatively easy and inexpensive part to replace if its bakelite housing does not break or crack first. Carbon deposit accumulation or erosion of its metal terminals may also cause distributor-cap failure.

Direct & distributorless ignition

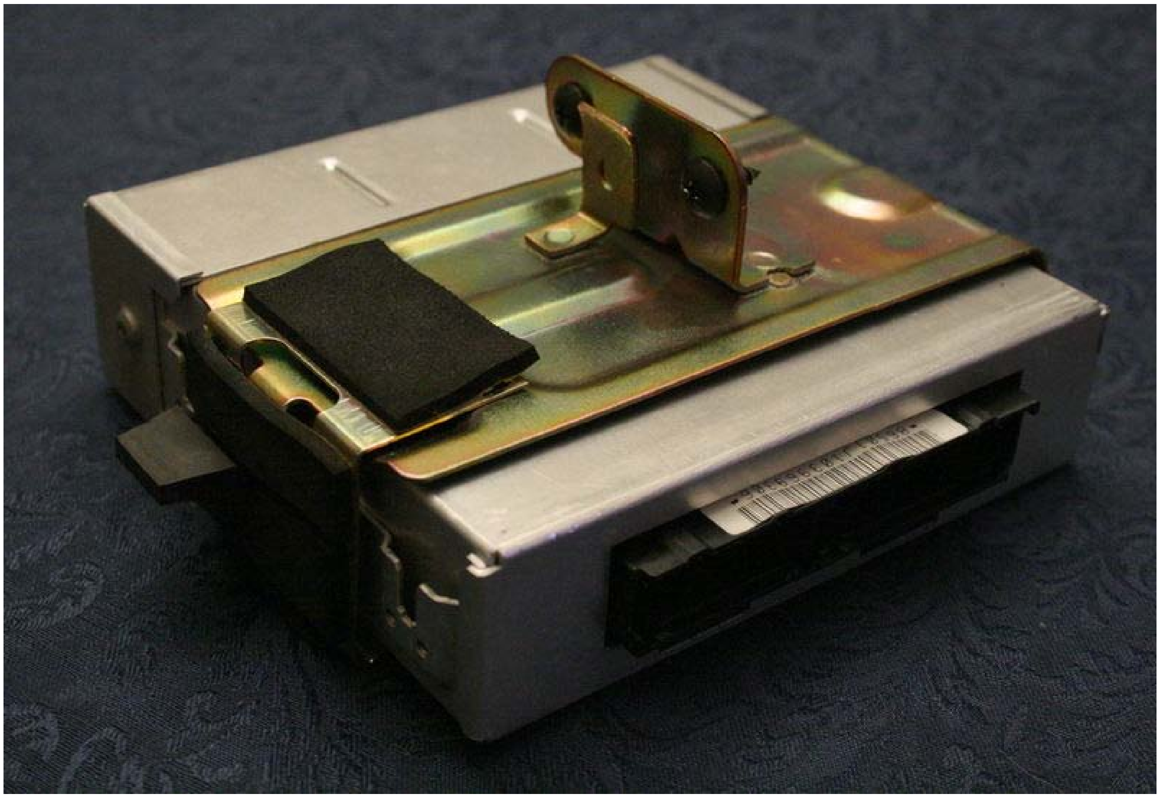
Modern engine designs have abandoned the high-voltage distributor and coil, instead performing the distribution function in the primary circuit electronically and applying the primary (low-voltage) pulse to individual coils for each spark plug, or one coil for each pair of companion cylinders in an engine (two coils for a four-cylinder, three coils for a six-cylinder, four coils for an eight-cylinder, and so on). In traditional remote distributorless systems, the coils are mounted together in a transformer oil filled 'coil pack', or separate coils for each cylinder, which are secured in a specified place in the engine compartment with wires to the spark plugs, similar to a distributor setup. Coil packs by Delco for use with General Motors engines allow removal of the individual coils in case one should fail, but in most other remote distributorless setups, if a coil were to fail, replacement of the whole pack would be required to fix the problem. More recent layouts utilize a coil located very near to or directly on top of each spark plug (**Direct Ignition**, 'DI' or coil-on-plug). This setup avoids the need to switch very high voltages, which is very often a source of trouble, especially in damp conditions. Both direct and remote distributorless systems also allow finer levels of ignition control by the engine computer, which assists in increasing power output, decreasing fuel consumption and emissions, and implementing features such as Active Fuel Management. Spark plug wires, which need routine replacement due to wear, are also eliminated when the individual coils are set directly on top of each plug, with the spark being transported a short distance from the coil through a rubber boot to the plug.

Four-stroke 2-cylinder engines can be built without a distributor, as in the Citroen 2CV of 1948 and BMW boxer twin motorcycles. Both spark plugs of the boxer twin are fired simultaneously, resulting in a wasted spark on the cylinder currently on its exhaust stroke.

Four-stroke 4-cylinder engines can be built without a distributor, as in the Citroen ID19. Two coils are used with one coil firing two of the spark plugs simultaneously, resulting in a wasted spark on the cylinder currently on its exhaust stroke, and the other coil used for the other two cylinders.

Four-stroke one-cylinder engines can be built without a distributor, as in many mowers. The spark plug is fired on every stroke, resulting in a wasted spark in the cylinder when on its exhaust stroke.

Electronic control unit



An ECU from a Geo Storm.

In automotive electronics, **electronic control unit** (**ECU**) is a generic term for any embedded system that controls one or more of the electrical systems or subsystems in a motor vehicle.

Other terms for ECU include electronic control module (ECM), central control module (CCM), control unit, or control module. Taken together, these systems are sometimes referred to as the car's computer. (Technically there is no single computer but multiple ones.)

Some modern motor vehicles have up to 80 ECUs. Embedded software in ECUs continue to increase in line count, complexity, and sophistication. Managing the increasing complexity and number of ECUs in a vehicle has become a key challenge for original equipment manufacturers (OEMs).

Types of electronic control units

- Airbag Control Unit (ACU)
- Body Control Module controls door locks, electric windows, courtesy lights, etc.
- Convenience Control Unit (CCU)

- Door Control Unit
- Engine Control Unit (ECU)—not to be confused with *electronic* control unit, the generic term for all these devices
- Man Machine Interface (MMI)
- Powertrain Control Module (PCM): Sometimes the functions of the Engine Control Unit and Transmission Control Unit are combined into a single unit called the Powertrain Control Module.
- Seat Control Unit
- Speed Control Unit
- Telephone Control Unit (TCU)
- Transmission Control Unit (TCU)

Chapter 7

Engine Control Unit

An **engine control unit (ECU)**, also known as **power-train control module (PCM)**, or **engine control module (ECM)** is a type of electronic control unit that determines the amount of fuel, ignition timing and other parameters an internal combustion engine needs to keep running. It does this by reading values from multidimensional performance maps (so called LUTs), using input values (e.g. engine speed) calculated from signals coming from sensor devices monitoring the engine. Before ECU's, air/fuel mixture, ignition timing, and idle speed were directly controlled by mechanical and pneumatic sensors and actuators. One of the very first attempts to use such a unitized and automated "ECU" device to manage multiple engine control functions simultaneously was created by BMW in 1939, for their BMW 801 14-cylinder aviation engine, and known as the *Kommandogerät*, operated only by a single throttle lever.

Working of ECU

Control of fuel mixture

For an engine with fuel injection, an engine control unit (ECU) will determine the quantity of fuel to inject based on a number of parameters. If the throttle pedal is pressed further down, this will open the throttle body and allow more air to be pulled into the engine. The ECU will inject more fuel according to how much air is passing into the engine. If the engine has not warmed up yet, more fuel will be injected (causing the engine to run slightly 'rich' until the engine warms up). Mixture control on computer controlled carburetors works similarly but with a mixture control solenoid or stepper motor incorporated in the float bowl of the carburetor.

Control of ignition timing

A spark ignition engine requires a spark to initiate combustion in the combustion chamber. An ECU can adjust the exact timing of the spark (called ignition timing) to provide better power and economy. If the ECU detects knock, a condition which is potentially destructive to engines, and "judges" it to be the result of the ignition timing being too early in the compression stroke, it will delay (retard) the timing of the spark to prevent this. A second, more common source, cause, of knock/ping is operating the engine in too low of an RPM range for the "work" requirement of the moment. In this case the knock/ping results from the piston not being able to move downward as fast as the flame front is expanding, but this latter mostly applies only to manual transmission equipped vehicles. The ECU controlling an automatic transmission would simply downshift the transmission if this were the cause of knock/ping.

Control of idle speed

Most engine systems have idle speed control built into the ECU. The engine RPM is monitored by the crankshaft position sensor which plays a primary role in the engine timing functions for fuel injection, spark events, and valve timing. Idle speed is controlled by a programmable throttle stop or an idle air bypass control stepper motor. Early carburetor-based systems used a programmable throttle stop using a bidirectional DC motor. Early TBI systems used an idle air control stepper motor. Effective idle speed control must anticipate the engine load at idle. Changes in this idle load may come from HVAC systems, power steering systems, power brake systems, and electrical charging and supply systems. Engine temperature and transmission status, and lift and duration of camshaft also may change the engine load and/or the idle speed value desired.

A full authority throttle control system may be used to control idle speed, provide cruise control functions and top speed limitation.

Control of variable valve timing

Some engines have Variable Valve Timing. In such an engine, the ECU controls the time in the engine cycle at which the valves open. The valves are usually opened sooner at higher speed than at lower speed. This can optimize the flow of air into the cylinder, increasing power and economy.

Electronic valve control

Experimental engines have been made and tested that have no camshaft, but has full electronic control of the intake and exhaust valve opening, valve closing and area of the valve opening. Such engines can be started and run without a starter motor for certain multi-cylinder engines equipped with precision timed electronic ignition and fuel injection. Such a *static-start* engine would provide the efficiency and pollution-reduction improvements of a mild hybrid-electric drive, but without the expense and complexity of an oversized starter motor.

Programmable ECUs

A special category of ECUs are those which are programmable. These units do not have a fixed behavior, but can be reprogrammed by the user.

Programmable ECUs are required where significant aftermarket modifications have been made to a vehicle's engine. Examples include adding or changing of a turbocharger, adding or changing of an intercooler, changing of the exhaust system, and conversion to run on alternative fuel. As a consequence of these changes, the old ECU may not provide appropriate control for the new configuration. In these situations, a programmable ECU can be wired in. These can be programmed/mapped with a laptop connected using a serial or USB cable, while the engine is running.

The programmable ECU may control the amount of fuel to be injected into each cylinder. This varies depending on the engine's RPM and the position of the accelerator pedal (or the manifold air pressure). The engine tuner can adjust this by bringing up a spreadsheet-like page on the laptop where each cell represents an intersection between a specific RPM value and an accelerator pedal position (or the throttle position, as it is called). In this cell a number corresponding to the amount of fuel to be injected is entered. This spreadsheet is often referred to as a fuel table or fuel map.

By modifying these values while monitoring the exhausts using a wide band lambda probe to see if the engine runs rich or lean, the tuner can find the optimal amount of fuel to inject to the engine at every different combination of RPM and throttle position. This process is often carried out at a dynamometer, giving the tuner a controlled environment to work in. An engine dynamometer gives a more precise calibration for racing applications. Tuners often utilize a chassis dynamometer for street and other high performance applications.

Other parameters that are often mappable are:

- **Ignition:** Defines when the spark plug should fire for a cylinder.
- **Rev. limit:** Defines the maximum RPM that the engine is allowed to reach. After this fuel and/or ignition is cut. Some vehicles have a "soft" cut-off before the "hard" cut-off.
- **Water temperature correction:** Allows for additional fuel to be added when the engine is cold (choke) or dangerously hot.
- **Transient fueling:** Tells the ECU to add a specific amount of fuel when throttle is applied. The term is "acceleration enrichment"
- **Low fuel pressure modifier:** Tells the ECU to increase the injector fire time to compensate for a loss of fuel pressure.
- **Closed loop lambda:** Lets the ECU monitor a permanently installed lambda probe and modify the fueling to achieve stoichiometric (ideal) combustion. On traditional petrol powered vehicles this air:fuel ratio is 14.7:1.

Some of the more advanced race ECUs include functionality such as launch control, limiting the power of the engine in first gear to avoid burnouts. Other examples of advanced functions are:

- **Wastegate control:** Sets up the behavior of a turbocharger's wastegate, controlling boost.
- **Banked injection:** Sets up the behavior of double injectors per cylinder, used to get a finer fuel injection control and atomization over a wide RPM range.
- **Variable cam timing:** Tells the ECU how to control variable intake and exhaust cams.
- **Gear control:** Tells the ECU to cut ignition during (sequential gearbox) upshifts or blip the throttle during downshifts.

A race ECU is often equipped with a data logger recording all sensors for later analysis using special software in a PC. This can be useful to track down engine stalls, misfires or other undesired behaviors during a race by downloading the log data and looking for anomalies after the event. The data logger usually has a capacity between 0.5 and 16 megabytes.

In order to communicate with the driver, a race ECU can often be connected to a "data stack", which is a simple dash board presenting the driver with the current RPM, speed and other basic engine data. These race stacks, which are almost always digital, talk to the ECU using one of several proprietary protocols running over RS232 or CANbus, connecting to the DLC connector (Data Link Connector) usually located on the underside of the dash, inline with the steering wheel

History

Hybrid digital designs

Hybrid digital/analog designs were popular in the mid 1980s. This used analog techniques to measure and process input parameters from the engine, then used a look-up table stored in a digital ROM chip to yield precomputed output values. Later systems compute these outputs dynamically. The ROM type of system is amenable to tuning if one knows the system well. The disadvantage of such systems is that the precomputed values are only optimal for an idealised, new engine. As the engine wears, the system is less able to compensate than a CPU based system.

Modern ECUs

Modern ECUs use a microprocessor which can process the inputs from the engine sensors in real time. An electronic control unit contains the hardware and software (firmware). The hardware consists of electronic components on a printed circuit board (PCB), ceramic substrate or a thin laminate substrate. The main component on this circuit board is a microcontroller chip (CPU). The software is stored in the microcontroller or other chips on the PCB, typically in EPROMs or flash memory so the CPU can be reprogrammed by uploading updated code or replacing chips. This is also referred to as an (electronic) Engine Management System (EMS).

Sophisticated engine management systems receive inputs from other sources, and control other parts of the engine; for instance, some variable valve timing systems are electronically controlled, and turbocharger wastegates can also be managed. They also may communicate with transmission control units or directly interface electronically-controlled automatic transmissions, traction control systems, and the like. The Controller Area Network or CAN bus automotive network is often used to achieve communication between these devices.

Modern ECUs sometimes include features such as cruise control, transmission control, anti-skid brake control, and anti-theft control, etc.

General Motors' first ECUs had a small application of hybrid digital ECUs as a pilot program in 1979, but by 1980, all active programs were using microprocessor based systems. Due to the large ramp up of volume of ECUs that were produced to meet the US Clean Air Act requirements for 1981, only one ECU model could be built for the 1981 model year. The high volume ECU that was installed in GM vehicles from the first high volume year, 1981, onward was a modern microprocessor based system. GM moved rapidly to replace carburetor based systems to fuel injection type systems starting in 1980/1981 Cadillac engines, following in 1982 with the Pontiac 2.5L "GM Iron Duke engine" and the Corvette Chevrolet L83 "Cross-Fire" engine. In just a few years all GM carburetor based engines had been replaced by throttle body injection (TBI) or intake manifold injection systems of various types. In 1988 Delco Electronics, Subsidiary of GM Hughes Electronics, produced more than 28,000 ECUs per day, the world's largest producer of on-board digital control computers at the time.

Other applications

Such systems are used for many internal combustion engines in other applications. In aeronautical applications, the systems are known as "FADECs" (Full Authority Digital Engine Controls). This kind of electronic control is less common in piston-engined aeroplanes than in automobiles, because of the large costs of certifying parts for aviation use, relatively small demand, and the consequent stagnation of technological innovation in this market. Also, a carbureted engine with magneto ignition and a gravity feed fuel system does not require electrical power generated by an alternator to run, which is considered a safety advantage.

Chapter 8

Internal Combustion Engine Cooling

Internal combustion engine cooling refers to the cooling of an internal combustion engine, typically using either air or a liquid.

Overview

Heat engines generate mechanical power by extracting energy from heat flows, much as a water wheel extracts mechanical power from a flow of mass falling through a distance. Engines are inefficient, so more heat energy enters the engine than comes out as mechanical power; the difference is waste heat which must be removed. Internal combustion engines remove waste heat through cool intake air, hot exhaust gases, and explicit engine cooling.

Engines with higher efficiency have more energy leave as mechanical motion and less as waste heat. Some waste heat is essential: it guides heat through the engine, much as a water wheel works only if there is some exit velocity (energy) in the waste water to carry it away and make room for more water. Thus, all heat engines need cooling to operate.

Cooling is also needed because high temperatures damage engine materials and lubricants. Internal-combustion engines burn fuel hotter than the melting temperature of engine materials, and hot enough to set fire to lubricants. Engine cooling removes energy fast enough to keep temperatures low so the engine can survive.

Some high-efficiency engines run without explicit cooling and with only accidental heat loss, a design called adiabatic. For example, 10,000 mile-per-gallon "cars" for the Shell economy challenge are insulated, both to transfer as much energy as possible from hot gases to mechanical motion, and to reduce reheat losses when restarting. Such engines can achieve high efficiency but compromise power output, duty cycle, engine weight, durability, and emissions.

Basic principles

Most internal combustion engines are fluid cooled using either air (a gaseous fluid) or a liquid coolant run through a heat exchanger (radiator) cooled by air. Marine engines and some stationary engines have ready access to a large volume of water at a suitable temperature. The water may be used directly to cool the engine, but often has sediment, which can clog coolant passages, or chemicals, such as salt, that can chemically damage the engine. Thus, engine coolant may be run through a heat exchanger that is cooled by the body of water.

Most liquid-cooled engines use a mixture of water and chemicals such as antifreeze and rust inhibitors. The industry term for the antifreeze mixture is *engine coolant*. Some antifreezes use no water at all, instead using a liquid with different properties, such as propylene glycol or a combination of propylene glycol and ethylene glycol. Most "air-cooled" engines use some liquid oil cooling, to maintain acceptable temperatures for both critical engine parts and the oil itself. Most "liquid-cooled" engines use some air cooling, with the intake stroke of air cooling the combustion chamber. An exception is Wankel engines, where some parts of the combustion chamber are never cooled by intake, requiring extra effort for successful operation.

There are many demands on a cooling system. One key requirement is that an engine fails if just one part overheats. Therefore, it is vital that the cooling system keep *all* parts at suitably low temperatures. Liquid-cooled engines are able to vary the size of their passageways through the engine block so that coolant flow may be tailored to the needs of each area. Locations with either high peak temperatures (narrow islands around the combustion chamber) or high heat flow (around exhaust ports) may require generous cooling. This reduces the occurrence of hot spots, which are more difficult to avoid with air cooling. Air cooled engines may also vary their cooling capacity by using more closely-spaced cooling fins in that area, but this can make their manufacture difficult and expensive.

Only the fixed parts of the engine, such as the block and head, are cooled directly by the main coolant system. Moving parts such as the pistons, and to a lesser extent the crank and rods, must rely on the lubrication oil as a coolant, or to a very limited amount of conduction into the block and thence the main coolant. High performance engines frequently have additional oil, beyond the amount needed for lubrication, sprayed upwards onto the bottom of the piston just for extra cooling. Air-cooled motorcycles often rely heavily on oil-cooling in addition to air-cooling of the cylinder barrels.

Liquid-cooled engines usually have a circulation pump. The first engines relied on thermo-syphon cooling alone, where hot coolant left the top of the engine block and passed to the radiator, where it was cooled before returning to the bottom of the engine. Circulation was powered by convection alone.

Other demands include cost, weight, reliability, and durability of the cooling system itself.

Conductive heat transfer is proportional to the temperature difference between materials. If engine metal is at 250 °C and the air is at 20°C, then there is a 230°C temperature difference for cooling. An air-cooled engine uses all of this difference. In contrast, a liquid-cooled engine might dump heat from the engine to a liquid, heating the liquid to 135°C (Water's standard boiling point of 100°C can be exceeded as the cooling system is both pressurised, and uses a mixture with antifreeze) which is then cooled with 20°C air. In each step, the liquid-cooled engine has half the temperature difference and so at first appears to need twice the cooling area.

However, properties of the coolant (water, oil, or air) also affect cooling. As example, comparing water and oil as coolants, one gram of oil can absorb about 55% of the heat for the same rise in temperature (called the specific heat capacity). Oil has about 90% the density of water, so a given volume of oil can absorb only about 50% of the energy of the same volume of water. The thermal conductivity of water is about 4 times that of oil, which can aid heat transfer. The viscosity of oil can be ten times greater than water, increasing the energy required to pump oil for cooling, and reducing the net power output of the engine.

Comparing air and water, air has vastly lower heat capacity per gram and per volume (4000) and less than a tenth the conductivity, but also much lower viscosity (about 200 times lower: 17.4×10^{-6} Pa·s for air vs 8.94×10^{-4} Pa·s for water). Continuing the calculation from two paragraphs above, air cooling needs ten times of the surface area, therefore the fins, and air needs 2000 times the flow velocity and thus a recirculating air fan needs ten times the power of a recirculating water pump. Moving heat from the cylinder to a large surface area for air cooling can present problems such as difficulties manufacturing the shapes needed for good heat transfer and the space needed for free flow of a large volume of air. Water boils at about the same temperature desired for engine cooling. This has the advantage that it absorbs a great deal of energy with very little rise in temperature (called heat of vaporization), which is good for keeping things cool, especially for passing one stream of coolant over several hot objects and achieving uniform temperature. In contrast, passing air over several hot objects in series warms the air at each step, so the first may be over-cooled and the last under-cooled. However, once water boils, it is an insulator, leading to a sudden loss of cooling where steam bubbles form. Unfortunately, steam may return to water as it mixes with other coolant, so an engine temperature gauge can indicate an acceptable temperature even though local temperatures are high enough that damage is being done.

An engine needs different temperatures. The inlet including the compressor of a turbo and in the inlet trumpets and the inlet valves need to be as cold as possible. A countercurrent heat exchange with forced cooling air does the job. The cylinder-walls should not heat up the air before compression, but also not cool down the gas at the combustion. A compromise is a wall temperature of 90°C. The viscosity of the oil is optimized for just this temperature. Any cooling of the exhaust and the turbine of the turbocharger reduces the amount of power available to the turbine, so the exhaust system is often insulated between engine and turbocharger to keep the exhaust gases as hot as possible.

The temperature of the cooling air may range from well below freezing to 50°C. Further, while engines in long-haul boat or rail service may operate at a steady load, road vehicles often see widely-varying and quickly-varying load. Thus, the cooling system is designed to vary cooling so the engine is neither too hot nor too cold. Cooling system regulation includes adjustable baffles in the air flow (sometimes called 'shutters' and commonly run by a pneumatic 'shutterstat); a fan which operates either independently of the engine, such as an electric fan, or which has an adjustable clutch; a thermostatic valve or just 'thermostat' that can block the coolant flow when too cool. In addition, the motor, coolant, and heat exchanger have some heat capacity which smooths out temperature increase in short sprints. Some engine controls shut down an engine or limit it to half throttle if it overheats. Modern electronic engine controls adjust cooling based on throttle to anticipate a temperature rise, and limit engine power output to compensate for finite cooling.

Finally, other concerns may dominate cooling system design. As example, air is a relatively poor coolant, but air cooling systems are simple, and failure rates typically rise as the square of the number of failure points. Also, cooling capacity is reduced only slightly by small air coolant leaks. Where reliability is of utmost importance, as in aircraft, it may be a good trade-off to give up efficiency, durability (interval between engine rebuilds), and quietness in order to achieve slightly higher reliability — the consequences of a broken airplane engine are so severe, even a slight increase in reliability is worth giving up other good properties to achieve it.

Air cooled and liquid-cooled engines are both used commonly. Each principle has advantages and disadvantages, and particular applications may favor one over the other. For example, most cars and trucks use liquid-cooled engines, while many small airplane and low-cost engines are air-cooled.

Generalization difficulties

It is difficult to make generalizations about air-cooled and liquid-cooled engines. Air-cooled Volkswagen kombis are known for rapid wear in normal use and sometimes sudden failure when driven in hot weather. Alternately, air-cooled Deutz diesel engines are known for reliability even in extreme heat, and are often used in situations where the engine runs unattended for months at a time.

Similarly, it is usually desirable to minimize the number of heat transfer stages in order to maximize the temperature difference at each stage. However, Detroit Diesel 2-stroke cycle engines commonly use oil cooled by water, with the water in turn cooled by air.

The coolant used in many liquid-cooled engines must be renewed periodically, and can freeze at ordinary temperatures thus causing permanent engine damage. Air-cooled engines do not require coolant service, and do not suffer engine damage from freezing, two commonly-cited advantages for air-cooled engines. However, coolant based on propylene glycol is liquid to -55 °C, colder than is encountered by many engines; shrinks slightly when it crystallizes, thus avoiding engine damage; and has a service life over 10,000 hours, essentially the lifetime of many engines.

It is usually more difficult to achieve either low emissions or low noise from an air-cooled engine, two more reasons most road vehicles use liquid-cooled engines. It is also often difficult to build large air-cooled engines, so nearly all air-cooled engines are under 500 kW (670 hp), whereas large liquid-cooled engines exceed 80 MW (107000 hp) (Wärtsilä-Sulzer RTA96-C 14-cylinder diesel).

Air-cooling

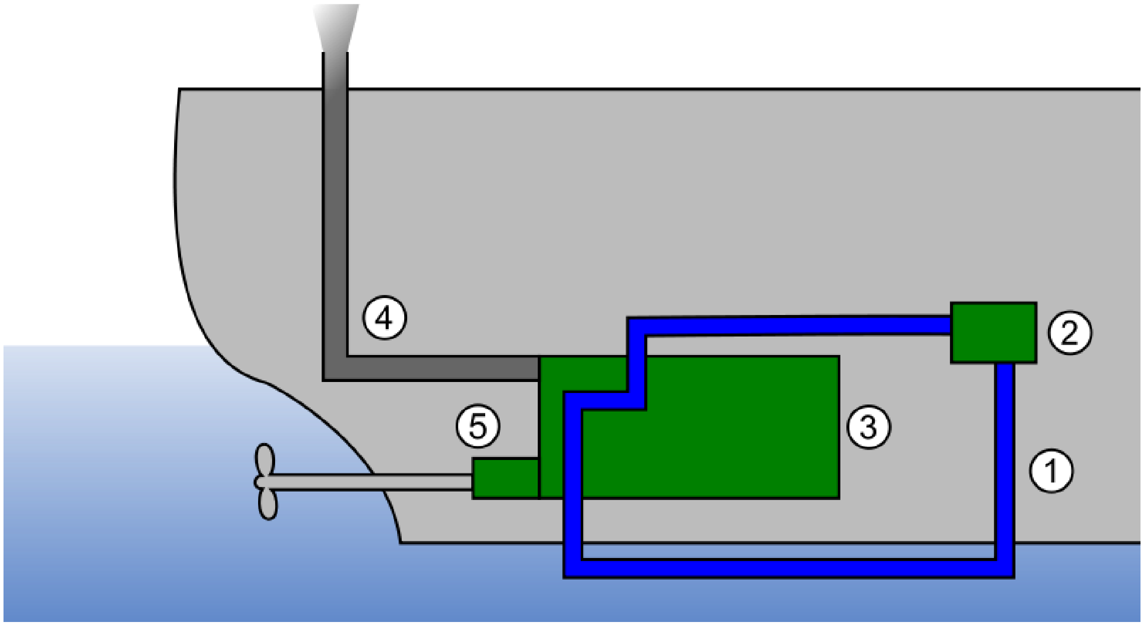
Cars and trucks using direct air cooling (without an intermediate liquid) were built over a long period beginning with the advent of mass produced passenger cars and ending with a small and generally unrecognized technical change. Before World War II, water cooled cars and trucks routinely overheated while climbing mountain roads, creating geysers of boiling cooling water. This was considered normal, and at the time, most noted mountain roads had auto repair shops to minister to overheating engines.

ACS (Auto Club Suisse) maintains historical monuments to that era on the Susten Pass where two radiator refill stations remain. These have instructions on a cast metal plaque and a spherical bottom watering can hanging next to a water spigot. The spherical bottom was intended to keep it from being set down and, therefore, be useless around the house, in spite of which it was stolen, as the picture shows.

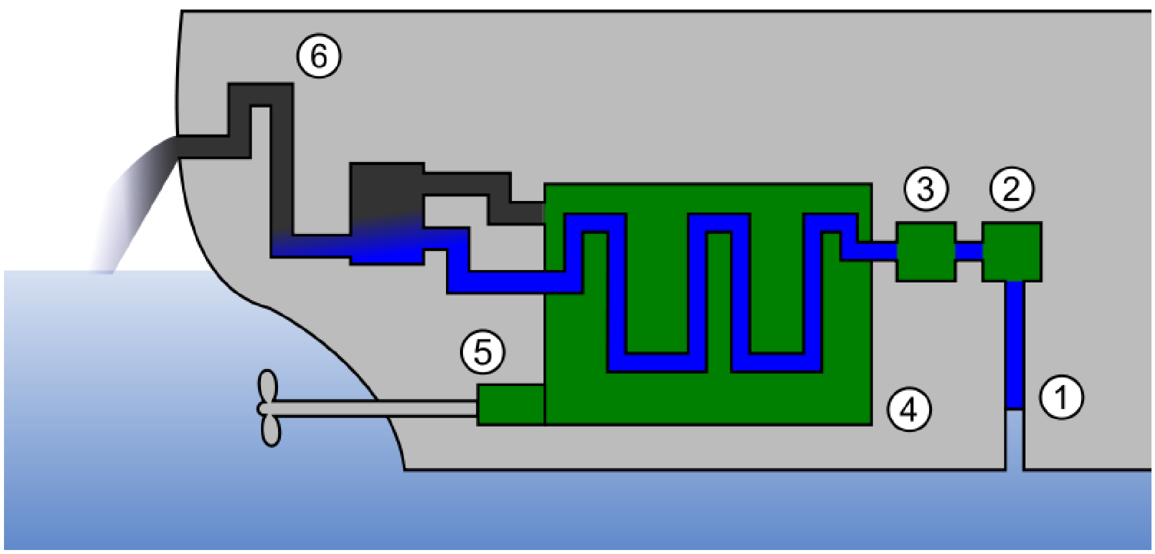
During that period, European firms such as Magirus-Deutz built air-cooled diesel trucks, Porsche built air-cooled farm tractors, and Volkswagen became famous with air-cooled passenger cars. In the USA, Franklin built air-cooled engines. The Czechoslovakia based company Tatra is known for their big size air cooled V8 car engines,Tatra engineer Julius Mackerle published a book on it. Air cooled engines are better adapted to extremely cold and hot environmental weather temperatures, you can see air cooled engines starting and running in freezing conditions that stuck water cooled engines and continue working when water cooled ones start producing steam jets.

Liquid cooling

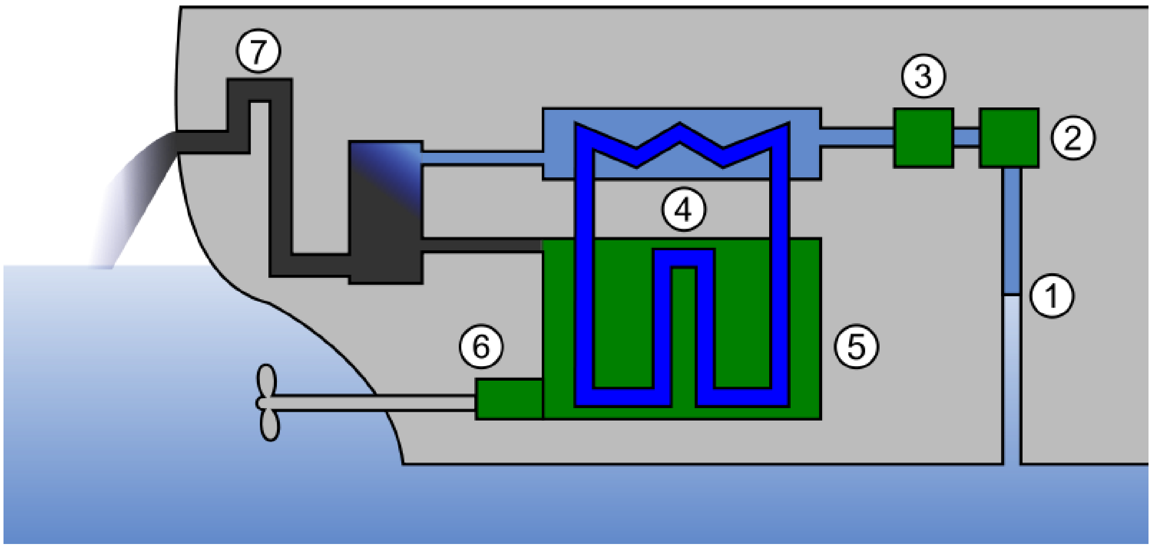
Today, most engines are liquid-cooled.



A fully closed IC engine cooling system



Open IC engine cooling system



Semiclosed IC engine cooling system

Liquid cooling is also employed in maritime vehicles (vessels, ...). For vessels, the seawater itself is mostly used for cooling. In some cases, chemical coolants are also employed (in closed systems) or they are mixed with seawater cooling.

Transition Away From Air Cooling

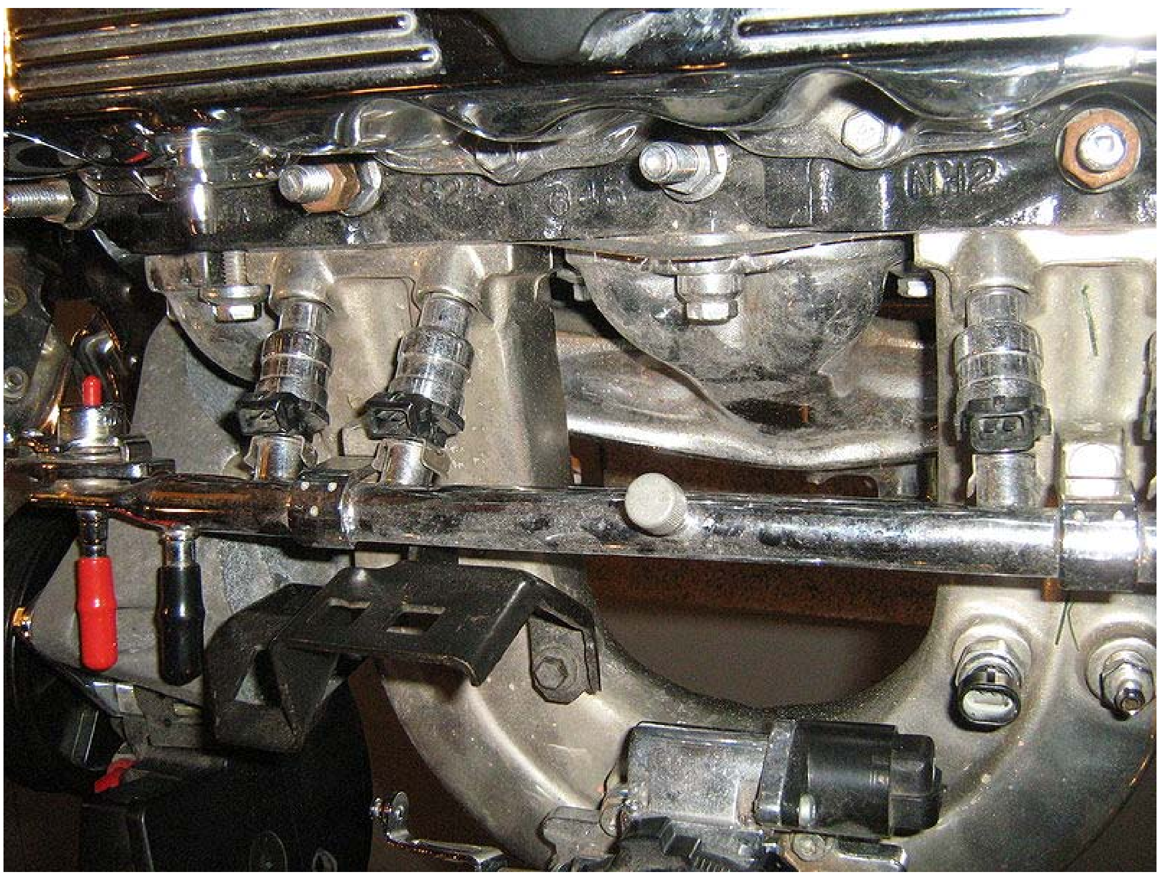
The change of air cooling to liquid cooling occurred at the start of World War II when the US military needed reliable vehicles. The subject of boiling engines was addressed, researched, and a solution found. Previous radiators and engine blocks were properly designed and survived durability tests, but used water pumps with a leaky graphite-lubricated "rope" seal (gland) on the pump shaft. The seal was inherited from steam engines, where water loss is accepted, since steam engines already expend large volumes of water. Because the pump seal leaked mainly when the pump was running and the engine was hot, the water loss evaporated inconspicuously, leaving at best a small rusty trace when the engine stopped and cooled, thereby not revealing significant water loss. Automobile radiators (or heat exchangers) have an outlet that feeds cooled water to the engine and the engine has an outlet that feeds heated water to the top of the radiator. Water circulation is aided by a rotary pump that has only a slight effect, having to work over such a wide range of speeds that its impeller has only a minimal effect as a pump. While running, the leaking pump seal drained cooling water to a level where the pump could no longer return water to the top of the radiator, so water circulation ceased and water in the engine boiled. However, since water loss lead to overheat and further water loss from boil-over, the original water loss was hidden.

After isolating the pump problem, cars and trucks built for the war effort (no civilian cars were built during that time) were equipped with carbon-seal water pumps that did not leak and caused no more geysers. Meanwhile, air cooling advanced in memory of boiling engines... even though boil-over was no longer a common problem. Air-cooled engines became popular throughout Europe. After the war, Volkswagen advertised in the USA as not boiling over, even though new water-cooled cars no longer boiled over, but these cars sold well, and without question. But as air quality awareness rose in the 1960s, and laws governing exhaust emissions were passed, unleaded gas replaced leaded gas and leaner fuel mixtures became the norm. These reductions in the cooling effects of both the lead and the formerly rich fuel mixture, led to overheating in the air-cooled engines. Valve failures and other engine damage was the result. Volkswagen responded by abandoning their (flat) horizontally opposed air-cooled engines, while Subaru took a different course and chose liquid-cooling for their (flat) engines.

Today practically no air-cooled automotive engines are built, air cooling being fraught with manufacturing expense and maintenance problems. Motorcycles had an additional problem in that a water leak presented a greater threat to reliability, their engines having small cooling water volume, so they were loath to change; today most larger motorcycles are water cooled with many relying on convection circulation with no pump.

Chapter 9

Fuel Injection



Fuel rail connected to the injectors that are mounted just above the intake manifold on a four cylinder engine.

Fuel injection is a system for mixing fuel with air in an internal combustion engine. It has become the primary fuel delivery system used in automotive petrol engines, having almost completely replaced carburetors in the late 1980s.

A fuel injection system is designed and calibrated specifically for the type(s) of fuel it will handle. Most fuel injection systems are for gasoline or diesel applications. With the advent of electronic fuel injection (EFI), the diesel and gasoline hardware has become similar. EFI's programmable firmware has permitted common hardware to be used with different fuels.

Carburetors were the predominant method used to meter fuel on gasoline engines before the widespread use of fuel injection. A variety of injection systems have existed since the earliest usage of the internal combustion engine.

The primary difference between carburetors and fuel injection is that fuel injection atomizes the fuel by forcibly pumping it through a small nozzle under high pressure, while a carburetor relies on low pressure created by intake air rushing through it to add the fuel to the airstream.

The fuel injector is only a nozzle and a valve: the power to inject the fuel comes from a pump or a pressure container farther back in the fuel supply.

Objectives

The functional objectives for fuel injection systems can vary. All share the central task of supplying fuel to the combustion process, but it is a design decision how a particular system will be optimized. There are several competing objectives such as:

- power output
- fuel efficiency
- emissions performance
- ability to accommodate alternative fuels
- reliability
- driveability and smooth operation
- initial cost
- maintenance cost
- diagnostic capability
- range of environmental operation
- Engine tuning

Certain combinations of these goals are conflicting, and it is impractical for a single engine control system to fully optimize all criteria simultaneously. In practice, automotive engineers strive to best satisfy a customer's needs competitively. The modern digital electronic fuel injection system is far more capable at optimizing these competing objectives consistently than a carburetor. Carburetors have the potential to atomize fuel better.

Benefits

Engine operation

Operational benefits to the driver of a fuel-injected car include smoother and more dependable engine response during quick throttle transitions, easier and more dependable engine starting, better operation at extremely high or low ambient temperatures, increased maintenance intervals, and increased fuel efficiency. On a more basic level, fuel injection does away with the choke which on carburetor-equipped vehicles must be operated when starting the engine from cold and then adjusted as the engine warms up.

An engine's air/fuel ratio must be precisely controlled under all operating conditions to achieve the desired engine performance, emissions, driveability, and fuel economy. Modern electronic fuel-injection systems meter fuel very accurately, and use closed loop fuel-injection quantity-control based on a variety of feedback signals from an oxygen sensor, a mass airflow (MAF) or manifold absolute pressure (MAP) sensor, a throttle position (TPS), and at least one sensor on the crankshaft and/or camshaft(s) to monitor the engine's rotational position. Fuel injection systems can react rapidly to changing inputs such as sudden throttle movements, and control the amount of fuel injected to match the engine's dynamic needs across a wide range of operating conditions such as engine load, ambient air temperature, engine temperature, fuel octane level, and atmospheric pressure.

A multipoint fuel injection system generally delivers a more accurate and equal mass of fuel to each cylinder than can a carburetor, thus improving the cylinder-to-cylinder distribution. Exhaust emissions are cleaner because the more precise and accurate fuel metering reduces the concentration of toxic combustion byproducts leaving the engine, and because exhaust cleanup devices such as the catalytic converter can be optimized to operate more efficiently since the exhaust is of consistent and predictable composition.

Fuel injection generally increases engine fuel efficiency. With the improved cylinder-to-cylinder fuel distribution, less fuel is needed for the same power output. When cylinder-to-cylinder distribution is less than ideal, as is always the case to some degree with a carburetor or throttle body fuel injection, some cylinders receive excess fuel as a side effect of ensuring that all cylinders receive *sufficient* fuel. Power output is asymmetrical with respect to air/fuel ratio; burning extra fuel in the rich cylinders does not reduce power nearly as quickly as burning too little fuel in the lean cylinders. However, rich-running cylinders are undesirable from the standpoint of exhaust emissions, fuel efficiency, engine wear, and engine oil contamination. Deviations from perfect air/fuel distribution, however subtle, affect the emissions, by not letting the combustion events be at the chemically ideal (stoichiometric) air/fuel ratio. Grosser distribution problems eventually begin to reduce efficiency, and the grossest distribution issues finally affect power. Increasingly poorer air/fuel distribution affects emissions, efficiency, and power, in that order. By optimizing the homogeneity of cylinder-to-cylinder mixture distribution, all the cylinders approach their maximum power potential and the engine's overall power output improves.

A fuel-injected engine often produces more power than an equivalent carbureted engine. Fuel injection alone does not necessarily increase an engine's maximum potential output. Increased airflow is needed to burn more fuel, which in turn releases more energy and produces more power. The combustion process converts the fuel's chemical energy into heat energy, whether the fuel is supplied by fuel injectors or a carburetor. However, airflow is often improved with fuel injection, the components of which allow more design freedom to improve the air's path into the engine. In contrast, a carburetor's mounting options are limited because it is larger, it must be carefully oriented with respect to gravity, and it must be equidistant from each of the engine's cylinders to the maximum practicable degree. These design constraints generally compromise airflow into the engine. Furthermore, a carburetor relies on a restrictive venturi to create a local air pressure difference, which forces the fuel into the air stream. The flow loss caused by the venturi, however, is small compared to other flow losses in the induction system. In a well-designed carburetor induction system, the venturi is not a significant airflow restriction.

Fuel is saved while the car is coasting because the car's movement is helping to keep the engine rotating, so less fuel is used for this purpose. Control units on modern cars react to this and reduce or stop fuel flow to the engine reducing wear on the brakes.

History and development

Herbert Akroyd Stuart developed the first system laid out on modern lines (with a highly-accurate 'jerk pump' to meter out fuel oil at high pressure to an injector. This system was used on the hot bulb engine and was adapted and improved by Robert Bosch for use on diesel engines — Rudolf Diesel's original system employed a cumbersome 'air-blast' system using highly compressed air.

The first use of direct gasoline injection was on the Hesselman engine invented by Swedish engineer Jonas Hesselman in 1925. Hesselman engines use the ultra lean burn principle; fuel is injected toward the end of the compression stroke, then ignited with a spark plug. They are often started on gasoline and then switched to diesel or kerosene. Fuel injection was in widespread commercial use in diesel engines by the mid-1920s. Because of its greater immunity to wildly changing g-forces on the engine, the concept was adapted for use in gasoline-powered aircraft during World War II, and direct injection was employed in some notable designs like the Junkers Jumo 210, the Daimler-Benz DB 601, the BMW 801, the Shvetsov ASh-82FN (M-82FN) and later versions of the Wright R-3350 used in the B-29 Superfortress.

Alfa Romeo tested one of the very first electric injection systems (Caproni-Fuscaldo) in Alfa Romeo 6C2500 with "Ala spessa" body in 1940 Mille Miglia. The engine had six electrically operated injectors and were fed by a semi-high pressure circulating fuel pump system.

Mechanical

The term **Mechanical** when applied to fuel injection is used to indicate that *metering functions* of the fuel injection (how the correct amount of fuel for any given situation is determined and delivered) is not achieved electronically but rather through mechanical means alone.

In the 1940s, hot rodder Stuart Hilborn offered mechanical injection for racers, salt cars, and midgets.

One of the first commercial gasoline injection systems was a mechanical system developed by Bosch and introduced in 1952 on the Goliath GP700 and Gutbrod Superior 600. This was basically a high pressure diesel direct-injection pump with an intake throttle valve set up. (Diesels only change amount of fuel injected to vary output; there is no throttle.) This system used a normal gasoline fuel pump, to provide fuel to a mechanically driven injection pump, which had separate plungers per injector to deliver a very high injection pressure directly into the combustion chamber.

Another mechanical system, also by Bosch, but injecting the fuel into the port above the intake valve was later used by Porsche from 1969 until 1973 for the 911 production range and until 1975 on the Carrera 3.0 in Europe. Porsche continued using it on its racing cars into the late seventies and early eighties. Porsche racing variants such as the 911 RSR 2.7 & 3.0, 904/6, 906, 907, 908, 910, 917 (in its regular normally aspirated or 5.5 Liter/1500 HP Turbocharged form), and 935 all used Bosch or Kugelfischer built variants of injection. The Kugelfischer system was also used by the BMW 2000/2002 Tii and some versions of the Peugeot 404/504 and Lancia Flavia. Lucas also offered a mechanical system which was used by some Maserati, Aston Martin and Triumph models between ca. 1963 and 1973.

A system similar to the Bosch inline mechanical pump was built by SPICA for Alfa Romeo, used on the Alfa Romeo Montreal and on US market 1750 and 2000 models from 1969-1981. This was specifically designed to meet the US emission requirements, and allowed Alfa to meet these requirements with no loss in performance and a reduction in fuel consumption.

Chevrolet introduced a mechanical fuel injection option, made by General Motors' Rochester Products division, for its 283 V8 engine in 1956 (1957 US model year). This system directed the inducted engine air across a "spoon shaped" plunger that moved in proportion to the air volume. The plunger connected to the fuel metering system which mechanically dispensed fuel to the cylinders via distribution tubes. This system was not a "pulse" or intermittent injection, but rather a constant flow system, metering fuel to all cylinders simultaneously from a central "spider" of injection lines. The fuel meter adjusted the amount of flow according to engine speed and load, and included a fuel reservoir, which was similar to a carburetor's float chamber. With its own high-pressure fuel pump driven by a cable from the distributor to the fuel meter, the system supplied the necessary pressure for injection. This was "port" injection, however, in which the injectors are located in the intake manifold, very near the intake valve. (Direct fuel injection is a fairly recent innovation for automobile engines. As recent as 1954 in the aforementioned Mercedes-Benz 300SL or the Gutbrod in 1953.) The highest performance version of the fuel injected engine was rated at 283 bhp (211.0 kW) from 283 cubic inches (4.6 L). This made it among the early production engines in history to exceed 1 hp/in^3 (45.5 kW/L), after Chrysler's Hemi engine and a number of others. General Motors' fuel injected engine — usually referred to as the "fuelie" — was optional on the Corvette for the 1957 model year.

During the 1960s, other mechanical injection systems such as Hilborn were occasionally used on modified American V8 engines in various racing applications such as drag racing, oval racing, and road racing. These racing-derived systems were not suitable for everyday street use, having no provisions for low speed metering or even starting (fuel had to be squirted into the injector tubes while cranking the engine in order to start it). However they were a favorite in the aforementioned competition trials in which essentially wide-open throttle operation was prevalent.

Electronic

The first commercial electronic fuel injection (EFI) system was **Electrojector**, developed by the Bendix Corporation and was to be offered by American Motors (AMC) in 1957. A special muscle car model, the Rambler Rebel, showcased AMC's new 327 cu in (5.4 L) engine. The Electrojector was an option and rated at 288 bhp (214.8 kW). With no Venturi effect or heated carburetor (to help vaporize the gasoline) AMC's EFI equipped engine breathed easier with denser cold air to pack more power sooner, reaching peak torque at 500 rpm lower than the equivalent no-fuel injection engine. The Rebel Owners Manual described the design and operation of the new system. Initial press information about the Bendix system in December 1956 was followed in March 1957 by a price bulletin that pegged the option at US$395, but due to supplier difficulties, fuel-injected Rebels would only be available after June 15. This was to have been the first production EFI engine, but Electrojector's teething problems meant only pre-production cars were so equipped: thus, very few cars so equipped were ever sold and none were made available to the public. The EFI system in the Rambler was a far more-advanced setup than the mechanical types then appearing on the market and the engines ran fine in warm weather, but suffered hard starting in cooler temperatures.

Chrysler offered Electrojector on the 1958 Chrysler 300D, Dodge D500, Plymouth Fury, and DeSoto Adventurer, arguably the first series-production cars equipped with an EFI system. It was jointly engineered by Chrysler and Bendix. The early electronic components were not equal to the rigors of underhood service, however, and were too slow to keep up with the demands of "on the fly" engine control. Most of the 35 vehicles originally so equipped were field-retrofitted with 4-barrel carburetors. The Electrojector patents were subsequently sold to Bosch.

Bosch developed an electronic fuel injection system, called *D-Jetronic* (*D* for *Druck*, German for "pressure"), which was first used on the VW 1600TL/E in 1967. This was a speed/density system, using engine speed and intake manifold air density to calculate "air mass" flow rate and thus fuel requirements. This system was adopted by VW, Mercedes-Benz, Porsche, Citroën, Saab, and Volvo. Lucas licensed the system for production with Jaguar. Bosch superseded the D-Jetronic system with the *K-Jetronic* and *L-Jetronic* systems for 1974, though some cars (such as the Volvo 164) continued using D-Jetronic for the following several years.

Chevrolet Cosworth Vega engine showing Bendix electronic fuel injection

The Cadillac Seville was introduced in 1975 with an EFI system made by Bendix and modelled very closely on Bosch's D-Jetronic. L-Jetronic first appeared on the 1974 Porsche 914, and uses a mechanical airflow meter (L for ***Luft***, German for "air") that produces a signal that is proportional to "air volume". This approach required additional sensors to measure the atmospheric pressure and temperature, to ultimately calculate "air mass". L-Jetronic was widely adopted on European cars of that period, and a few Japanese models a short time later.

The limited production Chevrolet Cosworth Vega was introduced in March 1975 using a Bendix EFI system with pulse-time manifold injection, four injector valves, an electronic control unit (ECU), five independent sensors and two fuel pumps. The EFI system was developed to satisfy stringent emission control requirements and market demands for a technologically advanced responsive vehicle, but only 3508 were produced through 1976.

In 1982, Bosch introduced a sensor that directly measures the air mass flow into the engine, on their L-Jetronic system. Bosch called this *LH-Jetronic* (L for ***Luftmasse*** and H for ***Hitzdraht***, German for "air mass" and "hot wire", respectively). The mass air sensor utilizes a heated platinum wire placed in the incoming air flow. The rate of the wire's cooling is proportional to the air mass flowing across the wire. Since the hot wire sensor directly measures air mass, the need for additional temperature and pressure sensors is eliminated. The LH-Jetronic system was also the first fully-digital EFI system, which is now the standard approach. The advent of the digital microprocessor permitted the integration of all powertrain sub-systems into a single control module.

Supersession of carburetors

When efficient combustion takes place in an internal combustion engine, the proper number of fuel molecules and oxygen molecules are sent to the engine's combustion chamber(s), where fuel combustion (i.e., fuel oxidation) takes place. When efficient combustion takes place, neither extra fuel or extra oxygen molecules remain: each fuel molecule is matched with the appropriate number of oxygen molecules. This balanced condition is called stoichiometry.

In the 1970s and 1980s in the US, the federal government imposed increasingly strict exhaust emission regulations. During that time period, the vast majority of gasoline-fueled automobile and light truck engines did not use fuel injection. To comply with the new regulations, automobile manufacturers often made extensive and complex modifications to the engine carburetor(s). While a simple carburetor system has certain advantages compared to the fuel injection systems that were available during the 1970s and 1980s (including lower manufacturing cost), the more complex carburetor systems installed on many engines beginning in the early 1970s did not usually have these advantages. So in order to more easily comply with government emissions control regulations, automobile manufacturers, beginning in the late 1970s, furnished more of their gasoline-fueled engines with fuel injection systems, and fewer with complex carburetor systems.

There are three primary types of toxic emissions from an internal combustion engine: Carbon Monoxide (CO), unburnt hydrocarbons (HC), and oxides of nitrogen (NOx). CO and HC result from incomplete combustion of fuel due to insufficient oxygen in the combustion chamber. NOx, in contrast, results from excessive oxygen in the combustion chamber. The opposite causes of these pollutants makes it difficult to control all three simultaneously. Once the permissible emission levels dropped below a certain point, catalytic treatment of these three main pollutants became necessary. This required a particularly large increase in fuel metering accuracy and precision, for simultaneous catalysis of all three pollutants requires that the fuel/air mixture be held within a very narrow range of stoichiometry. The open loop fuel injection systems had already improved cylinder-to-cylinder fuel distribution and engine operation over a wide temperature range, but did not offer sufficient fuel/air mixture control to enable effective exhaust catalysis. **Closed loop** fuel injection systems improved the air/fuel mixture control with an exhaust gas oxygen sensor. The O_2 sensor is mounted in the exhaust system upstream of the catalytic converter, and enables the engine management computer to determine and adjust the air/fuel ratio precisely and quickly.

Fuel injection was phased in through the latter '70s and '80s at an accelerating rate, with the US, French and German markets leading and the UK and Commonwealth markets lagging somewhat, and since the early 1990s, almost all gasoline passenger cars sold in first world markets like the United States, Canada, Europe, Japan, and Australia have come equipped with electronic fuel injection (EFI). Many motorcycles still utilize carbureted engines, though all current high-performance designs have switched to EFI.

Fuel injection systems have evolved significantly since the mid-1980s. Current systems provide an accurate, reliable and cost-effective method of metering fuel and providing maximum engine efficiency with clean exhaust emissions, which is why EFI systems have replaced carburetors in the marketplace. EFI is becoming more reliable and less expensive through widespread usage. At the same time, carburetors are becoming less available, and more expensive. Even marine applications are adopting EFI as reliability improves. Virtually all internal combustion engines, including motorcycles, off-road vehicles, and outdoor power equipment, may eventually use some form of fuel injection.

The carburetor remains in use in developing countries where vehicle emissions are unregulated and diagnostic and repair infrastructure is sparse. Fuel injection is gradually replacing carburetors in these nations too as they adopt emission regulations conceptually similar to those in force in Europe, Japan, Australia and North America.

Basic function

The process of determining the necessary amount of fuel, and its delivery into the engine, are known as fuel metering. Early injection systems used mechanical methods to meter fuel (non electronic, or mechanical fuel injection). Modern systems are nearly all electronic, and use an electronic solenoid (the injector) to inject the fuel. An electronic engine control unit calculates the mass of fuel to inject.

Modern fuel injection schemes follow much the same setup. There is a mass airflow sensor or manifold absolute pressure sensor at the intake, typically mounted either in the air tube feeding from the air filter box to the throttle body, or mounted directly to the throttle body itself. The mass airflow sensor does exactly what its name implies; it senses the mass of the air that flows past it, giving the computer an accurate idea of how much air is entering the engine. The next component in line is the Throttle Body. The throttle body has a throttle position sensor mounted onto it, typically on the butterfly valve of the throttle body. The throttle position sensor (TPS) reports to the computer the position of the throttle butterfly valve, which the ECM uses to calculate the load upon the engine. The fuel system consists of a fuel pump (typically mounted in-tank), a fuel pressure regulator, fuel lines (composed of either high strength plastic, metal, or reinforced rubber), a fuel rail that the injectors connect to, and the fuel injector(s). There is a coolant temperature sensor that reports the engine temperature to the ECM, which the engine uses to calculate the proper fuel ratio required. In sequential fuel injection systems there is a camshaft position sensor, which the ECM uses to determine which fuel injector to fire. The last component is the oxygen sensor. After the vehicle has warmed up, it uses the signal from the oxygen sensor to perform fine tuning of the fuel trim.

The fuel injector acts as the fuel-dispensing nozzle. It injects liquid fuel directly into the engine's air stream. In almost all cases this requires an external pump. The pump and injector are only two of several components in a complete fuel injection system.

In contrast to an EFI system, a carburetor directs the induction air through a venturi, which generates a minute difference in air pressure. The minute air pressure differences both emulsify (premix fuel with air) the fuel, and then acts as the force to push the mixture from the carburetor nozzle into the induction air stream. As more air enters the engine, a greater pressure difference is generated, and more fuel is metered into the engine. A carburetor is a self-contained fuel metering system, and is cost competitive when compared to a complete EFI system.

An EFI system requires several peripheral components in addition to the injector(s), in order to duplicate all the functions of a carburetor. A point worth noting during times of fuel metering repair is that early EFI systems are prone to diagnostic ambiguity. A single carburetor replacement can accomplish what might require numerous repair attempts to identify which one of the several EFI system components is malfunctioning. Newer EFI systems since the advent of OBD II diagnostic systems, can be very easy to diagnose due to the increased ability to monitor the realtime data streams from the individual sensors. This gives the diagnosing technician realtime feedback as to the cause of the drivability concern, and can dramatically shorten the number of diagnostic steps required to ascertain the cause of failure, something which isn't as simple to do with a carburetor. On the other hand, EFI systems require little regular maintenance; a carburetor typically requires seasonal and/or altitude adjustments.

Detailed function

Typical EFI components

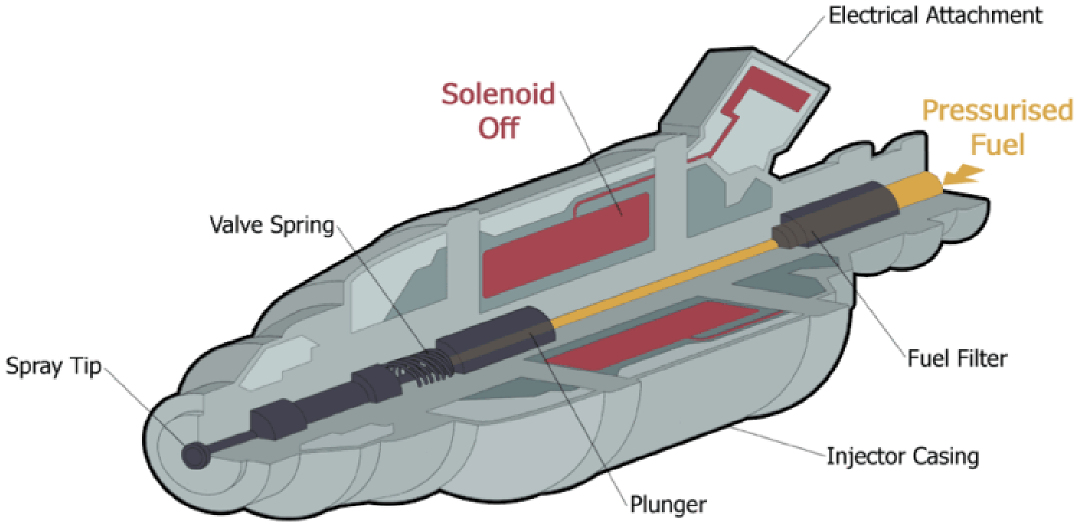


Diagram of a typical fuel injector.

- Injectors
- Fuel Pump
- Fuel Pressure Regulator
- ECM - Engine Control Module; includes a digital computer and circuitry to communicate with sensors and control outputs.
- Wiring Harness
- Various Sensors (Some of the sensors required are listed here.)
    - Crank/Cam Position: Hall effect sensor
    - Airflow: MAF sensor, sometimes this is inferred with a MAP sensor
    - Exhaust Gas Oxygen: Oxygen sensor, EGO sensor, UEGO sensor

Functional description

Central to an EFI system is a computer called the Engine Control Unit (ECU), which monitors engine operating parameters via various sensors. The ECU interprets these parameters in order to calculate the appropriate amount of fuel to be injected, among other tasks, and controls engine operation by manipulating fuel and/or air flow as well as other variables. The optimum amount of injected fuel depends on conditions such as engine and ambient temperatures, engine speed and workload, and exhaust gas composition.

The electronic fuel injector is normally closed, and opens to inject pressurized fuel as long as electricity is applied to the injector's solenoid coil. The duration of this operation, called the pulse width, is proportional to the amount of fuel desired. The electric pulse may be applied in closely-controlled sequence with the valve events on each individual cylinder (in a **sequential** fuel injection system), or in groups of less than the total number of injectors (in a **batch fire** system).

Since the nature of fuel injection dispenses fuel in discrete amounts, and since the nature of the 4-stroke engine has discrete induction (air-intake) events, the ECU calculates fuel in discrete amounts. In a sequential system, the injected fuel mass is tailored for each individual induction event. Every induction event, of every cylinder, of the entire engine, is a separate fuel mass calculation, and each injector receives a unique pulse width based on that cylinder's fuel requirements.

It is necessary to know the mass of air the engine "breathes" during each induction event. This is proportional to the intake manifold's air pressure/temperature, which is proportional to throttle position. The amount of air inducted in each intake event is known as "air-charge", and this can be determined using several methods.

The three elemental ingredients for combustion are fuel, air and ignition. However, complete combustion can only occur if the air and fuel is present in the exact stoichiometric ratio, which allows all the carbon and hydrogen from the fuel to combine with all the oxygen in the air, with no undesirable polluting leftovers. Oxygen sensors monitor the amount of oxygen in the exhaust, and the ECU uses this information to adjust the air-to-fuel ratio in real-time.

To achieve stoichiometry, the air mass flow into the engine is measured and multiplied by the stoichiometric air/fuel ratio 14.64:1 (by weight) for gasoline. The required fuel mass that must be injected into the engine is then translated to the required pulse width for the fuel injector. The stoichiometric ratio changes as a function of the fuel; diesel, gasoline, ethanol, methanol, propane, methane (natural gas), or hydrogen.

Deviations from stoichiometry are required during non-standard operating conditions such as heavy load, or cold operation, in which case, the mixture ratio can range from 10:1 to 18:1 (for gasoline). In early fuel injection systems this was accomplished with a thermotime switch.

Pulse width is inversely related to pressure difference across the injector inlet and outlet. For example, if the fuel line pressure increases (injector inlet), or the manifold pressure decreases (injector outlet), a smaller pulse width will admit the same fuel. Fuel injectors are available in various sizes and spray characteristics as well. Compensation for these and many other factors are programmed into the ECU's software.

Sample pulsewidth calculations

Note: These calculations are based on a 4-stroke-cycle, 5.0L, V-8, gasoline engine. The variables used are real data.

Calculate injector pulsewidth from airflow

First the CPU determines the air mass flow rate from the sensors - *$Mass_{air}$ / Minute*.

$$\frac{Mass_{air}}{Minute} \times \frac{Minutes}{Revolution} \times \frac{Revolutions}{Stroke} = \frac{Mass_{air}}{Stroke}$$

Minutes / *Revolution* is the reciprocal of engine speed (RPM).
The term *Revolutions* / *Stroke* = 1 / 2, whether it's a four stroke or a two-stroke engine.

$$\frac{Mass_{air}}{Stroke_{intake}} \times \frac{Mass_{Fuel}}{Mass_{Air}} = \frac{Mass_{Fuel}}{Stroke_{intake}}$$

$Mass_{Fuel}$ / $Mass_{Air}$ is the desired mixture ratio, usually stoichiometric, but often different depending on operating conditions.

$$\frac{Mass_{Fuel}}{Stroke_{intake}} \times \frac{1}{Mass_{Fuel}/Minute} = \frac{Minutes}{Stroke_{intake}} = Pulsewidth$$

1 / ($Mass_{Fuel}$ / *Minute*) is the flow capacity of the injector, or its size.

Combining the above three terms . . .

$$\frac{Mass_{air}}{Minute} \times \frac{Minutes}{Revolution} \times \frac{Revolutions}{Stroke} \times \frac{Mass_{Fuel}}{Mass_{Air}} \times \frac{1}{Mass_{Fuel}/Minute} = Pulsewidth$$

Substituting real variables for the 5.0 L engine at idle.

*

Substituting real variables for the 5.0 L engine at maximum power.

*

$$28\frac{lb}{min} \times \frac{1min}{5500rev} \times \frac{1revolution}{2strokes} \times \frac{1}{11.00} \times 2.5\frac{min}{lb} = 57.9 \times 10^{-5}min = 35ms$$

Injector pulsewidth typically ranges from 4 ms/engine-cycle at idle, to 35 ms *per engine-cycle at wide-open throttle. The pulsewidth accuracy is approximately 0.01* ms.

Calculate fuel-flow rate from pulsewidth

- (Fuel flow rate) ≈ (pulsewidth) × (engine speed) × (number of fuel injectors)

Looking at it another way:

- (Fuel flow rate) ≈ (throttle position) × (rpm) × (cylinders)

Looking at it another way:

- (Fuel flow rate) ≈ (air-charge) × (fuel/air) × (rpm) × (cylinders)

Substituting real variables for the 5.0 L engine at idle.

- (Fuel flow rate) = (2.0 ms/intake-stroke) × (hour/3,600,000 ms) × (24 lb-fuel/hour) × (4-intake-stroke/rev) × (700 rev/min) × (60 min/h) = (2.24 lb/h)

Substituting real variables for the 5.0L engine at maximum power.

- (Fuel flow rate) = (17.3 ms/intake-stroke) × (hour/3,600,000-ms) × (24 lb-fuel/hour) × (4-intake-stroke/rev) × (5500-rev/min) × (60-min/hour) = (152 lb/h)

The fuel consumption rate is 68 times greater at maximum engine output than at idle. This dynamic range of fuel flow is typical of a naturally aspirated passenger car engine. The dynamic range is greater on a supercharged or turbocharged engine. It is interesting to note that 15 gallons of gasoline will be consumed in 37 minutes if maximum output is sustained. On the other hand, this engine could continuously idle for almost 42 hours on the same 15 gallons.

Various injection schemes

Single-point injection

Single-point injection, called **Throttle-body injection** (**TBI**) by General Motors and **Central Fuel Injection** (**CFI**) by Ford, was introduced in the 1940s in large aircraft engines (then called the pressure carburetor) and in the 1980s in the automotive world. The SPI system injects fuel at the throttle body (the same location where a carburetor introduced fuel). The induction mixture passes through the intake runners like a carburetor system, and is thus labelled a "wet manifold system". Fuel pressure is usually specified to be in the area of 10-15 psi. The justification for single-point injection was low cost. Many of the carburetor's supporting components could be reused such as the air cleaner, intake manifold, and fuel line routing. This postponed the redesign and tooling costs of these components. Most of these components were later redesigned for the next phase of fuel injection's evolution, which is individual port injection, commonly known as MPFI or "multi-point fuel injection". TBI was used extensively on American-made passenger cars and light trucks in the 1980-1995 timeframe and some transition-engined European cars throughout the early and mid-1990s. Mazda called their system EGI, and even introduced an electronically controlled version called the EGI-S.

Continuous injection

In a continuous injection system, fuel flows at all times from the fuel injectors, but at a variable rate. This is in contrast to most fuel injection systems, which provide fuel during short pulses of varying duration, with a constant rate of flow during each pulse. Continuous injection systems can be multi-point or single-point, but not direct.

The most common automotive continuous injection system is Bosch's **K-Jetronic** (K for *kontinuierlich*, German for "continuous" — a.k.a. CIS — Continuous Injection System), introduced in 1974. Gasoline is pumped from the fuel tank to a large control valve called a *fuel distributor*, which separates the single fuel supply pipe from the tank into smaller pipes, one for each injector. The fuel distributor is mounted atop a control vane through which all intake air must pass, and the system works by varying fuel volume supplied to the injectors based on the angle of the air vane, which in turn is determined by the volume flowrate of air past the vane, and by the control pressure. The control pressure is regulated with a mechanical device called the control pressure regulator (CPR) or the warm-up regulator (WUR). Depending on the model, the CPR may be used to compensate for altitude, full load, and/or a cold engine. On cars equipped with an oxygen sensor, the fuel mixture is adjusted by a device called the frequency valve. The injectors are simple spring-loaded check valves with nozzles; once fuel system pressure becomes high enough to overcome the counterspring, the injectors begin spraying. K-Jetronic was used for many years between 1974 and the mid 1990s by BMW, Lamborghini, Ferrari, Mercedes-Benz, Volkswagen, Ford, Porsche, Audi, Saab, DeLorean, and Volvo. There was also a variant of the system called KE-Jetronic with electronic instead of mechanical control of the control pressure. Some Toyotas and other Japanese cars from the 1970s to the early 1990s used an application of Bosch's multipoint L-Jetronic system manufactured under license by DENSO. Chrysler used a similar continuous fuel injection system on the 1981-1983 Imperial.

In piston aircraft engines, continuous-flow fuel injection is the most common type. In contrast to automotive fuel injection systems, aircraft continuous flow fuel injection is all mechanical, requiring no electricity to operate. Two common types exist: the Bendix RSA system, and the TCM system. The Bendix system is a direct descendant of the pressure carburetor. However, instead of having a discharge valve in the barrel, it uses a *flow divider* mounted on top of the engine, which controls the discharge rate and evenly distributes the fuel to stainless steel injection lines which go to the intake ports of each cylinder. The TCM system is even more simple. It has no venturi, no pressure chambers, no diaphragms, and no discharge valve. The control unit is fed by a constant-pressure fuel pump. The control unit simply uses a butterfly valve for the air which is linked by a mechanical linkage to a rotary valve for the fuel. Inside the control unit is another restriction which is used to control the fuel mixture. The pressure drop across the restrictions in the control unit controls the amount of fuel flowing, so that fuel flow is directly proportional to the pressure at the flow divider. In fact, most aircraft using the TCM fuel injection system feature a fuel flow gauge which is actually a pressure gauge that has been calibrated in *gallons per hour* or *pounds per hour* of fuel.

Central port injection (CPI)

General Motors implemented a system called "central port injection" (**CPI**) or "central port fuel injection" (**CPFI**). It uses tubes with poppet valves from a central injector to spray fuel at each intake port rather than the central throttle-body. Pressure specifications typically mirror that of a TBI system. The two variants were CPFI from 1992 to 1995, and CSFI from 1996 and on. CPFI is a *batch-fire* system, in which fuel is injected to all ports simultaneously. The 1996 and later CSFI system sprays fuel *sequentially*.

Multi-point fuel injection

Multi-point fuel injection injects fuel into the intake port just upstream of the cylinder's intake valve, rather than at a central point within an intake manifold. MPFI (or just MPI) systems can be **sequential**, in which injection is timed to coincide with each cylinder's intake stroke; **batched**, in which fuel is injected to the cylinders in groups, without precise synchronization to any particular cylinder's intake stroke; or **simultaneous**, in which fuel is injected at the same time to all the cylinders. The intake is only slightly wet, and typical fuel pressure runs between 40-60 psi.

Many modern EFI systems utilize sequential MPFI; however, in newer gasoline engines, direct injection systems are beginning to replace sequential ones.

Direct injection

Direct fuel injection costs more than indirect injection systems: the injectors are exposed to more heat and pressure, so more costly materials and higher-precision electronic management systems are required. However, the entire intake is dry, making this a very clean system. In a common rail system, the fuel from the fuel tank is supplied to the common header (called the accumulator). This fuel is then sent through tubing to the injectors which inject it into the combustion chamber. The header has a high pressure relief valve to maintain the pressure in the header and return the excess fuel to the fuel tank. The fuel is sprayed with the help of a nozzle which is opened and closed with a needle valve, operated with a solenoid. When the solenoid is not activated, the spring forces the needle valve into the nozzle passage and prevents the injection of fuel into the cylinder. The solenoid lifts the needle valve from the valve seat, and fuel under pressure is sent in the engine cylinder. Third-generation common rail diesels use piezoelectric injectors for increased precision, with fuel pressures up to 1,800 bar/26,000 psi.

Gasoline engines incorporate gasoline direct injection engine technology.

Diesel engines

Diesel engines must use fuel injection, and it must be timed (unlike on petrol engines). Throughout the early history of diesels, they were always fed by a mechanical pump with a small separate cylinder for each cylinder, feeding separate fuel lines and individual injectors. Most such pumps were in-line, though some were rotary.

Earlier systems, relying on crude injectors, often injected into a sub-chamber shaped to swirl the compressed air and improve combustion; this was known as indirect injection. However, it was less thermally efficient than the now universal direct injection in which initiation of combustion takes place in a depression (often toroidal) in the crown of the piston.

Petrol/gasoline engines

Modern petrol engines (gasoline engines) also utilise direct injection, which is referred to as gasoline direct injection. This is the next step in evolution from multi-point fuel injection, and offers another magnitude of emission control by eliminating the "wet" portion of the induction system along the inlet tract.

By virtue of better dispersion and homogeneity of the directly injected fuel, the cylinder and piston are cooled, thereby permitting higher compression ratios and more aggressive ignition timing, with resultant enhanced power output. More precise management of the fuel injection event also enables better control of emissions. Finally, the homogeneity of the fuel mixture allows for leaner air/fuel ratios, which together with more precise ignition timing can improve fuel efficiency. Along with this, the engine can operate with stratified (lean burn) mixtures, and hence avoid throttling losses at low and part engine load. Some direct-injection systems incorporate piezoelectronic fuel injectors. With their extremely fast response time, multiple injection events can occur during each cycle of each cylinder of the engine.

The first use of direct petrol injection was on the Hesselman engine, invented by Swedish engineer Jonas Hesselman in 1925.

Maintenance hazards

Fuel injection introduces potential hazards in engine maintenance due to the high fuel pressures used. Residual pressure can remain in the fuel lines long after an injection-equipped engine has been shut down. This residual pressure must be relieved, and if it is done so by external bleed-off, the fuel must be safely contained. If a high-pressure diesel fuel injector is removed from its seat and operated in open air, there is a risk to the operator of injury by hypodermic jet-injection, even with only 100 psi (6.9 bar) pressure. The first known such injury occurred in 1937 during a diesel engine maintenance operation.

Chapter 10

Fuel Filter and Gudgeon Pin

Fuel filter

A fuel filter on a pickup truck, showing its mounting location on the firewall.

A fuel filter on a Yanmar 2GM20 marine diesel engine.

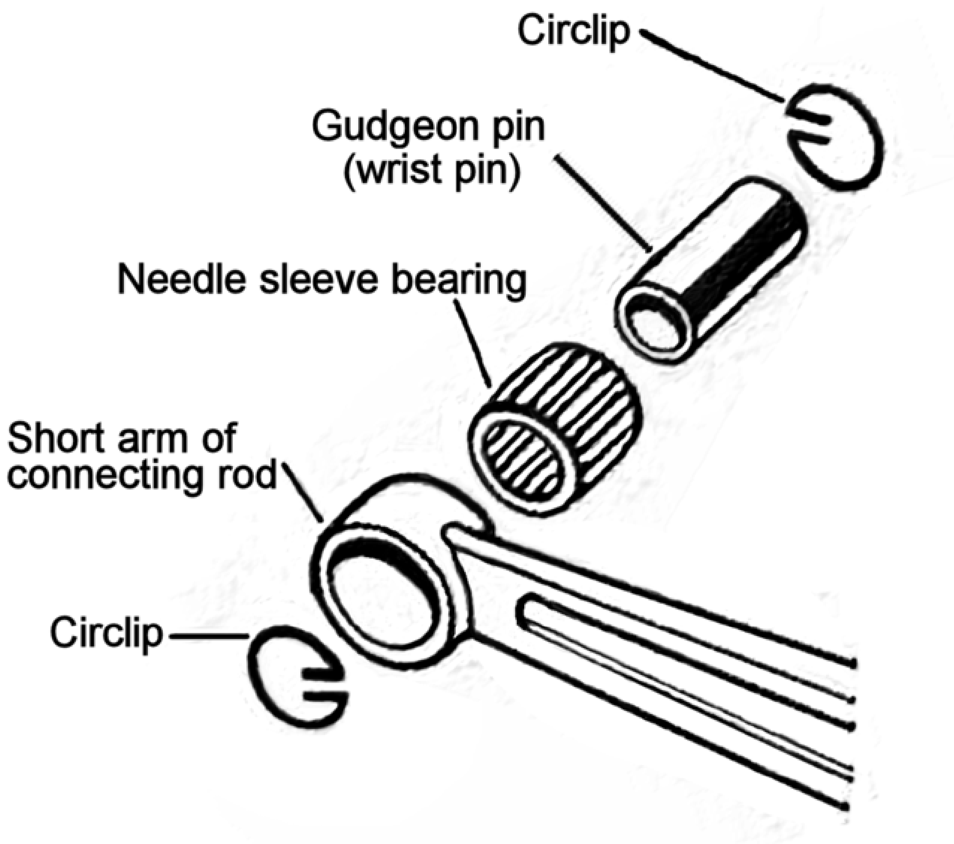
A **fuel filter** is a filter in the fuel line that screens out dirt and rust particles from the fuel, normally made into cartridges containing a filter paper. They are found in most internal combustion engines.

Fuel filters serve a vital function in today's modern, tight-tolerance engine fuel systems. Unfiltered fuel may contain several kinds of contamination, for example paint chips and dirt that has been knocked into the tank while filling, or rust caused by moisture in a steel tank. If these substances are not removed before the fuel enters the system, they will cause rapid wear and failure of the fuel pump and injectors, due to the abrasive action of the particles on the high-precision components used in modern injection systems. Fuel filters also improve performance, as the fewer contaminants present in the fuel, the more efficiently it can be burnt.

Fuel filters need to be maintained at regular intervals. This is usually a case of simply disconnecting the filter from the fuel line and replacing it with a new one, although some specially designed filters can be cleaned and reused many times. If a filter is not replaced regularly it may become clogged with contaminants and cause a restriction in the fuel flow, causing an appreciable drop in engine performance as the engine struggles to draw enough fuel to continue running normally.

Some filters, especially found on diesel engines, are of a bowl-like design which collect water in the bottom (as water is more dense than diesel). The water can then be drained off by opening a valve in the bottom of the bowl and letting it run out, until the bowl contains only diesel. Many fuel filters contain a water sensor to signal to the engine control unit or directly to the driver (lamp on dashboard) if the water reach the warning level. It is especially undesirable for water to be drawn into a diesel engine fuel system, as the system relies on the diesel for lubrication of the moving parts, and if water gets into a moving part which requires constant lubrication (for example an injector valve), it will quickly cause overheating and unnecessary wear. This type of filter may also include a sensor, which will alert the operator when the filter needs to be drained. In proximity of the diesel fuel filter there might be a fuel heater to avoid the forming of paraffin wax (in case of low temperatures) inside the filtrating element which can stop the fuel flow to the engine.

Gudgeon pin



Gudgeon pin connection at connecting rod. Gudgeon pin fits into gudgeons inside piston.

In internal combustion engines, the **gudgeon pin** (UK, **wrist pin** US) is that which connects the piston to the connecting rod and provides a bearing for the connecting rod to pivot upon as the piston moves. In very early engine designs (including those driven by steam and also many very large stationary or marine engines), the gudgeon pin is located in a sliding crosshead that connects to the piston via a rod.

The gudgeon pin is typically a forged short hollow rod made of a steel alloy of high strength and hardness that may be physically separated from both the connecting rod and piston or crosshead. The design of the gudgeon pin, especially in the case of small, high-revving automotive engines is challenging. The gudgeon pin has to operate under some of the highest temperatures experienced in the engine, with difficulties in lubrication due to its location, while remaining small and light so as to fit into the piston diameter and not unduly add to the reciprocating mass. The requirements for lightness and compactness demand a small diameter rod that is subject to heavy shear and bending loads, with some of the highest pressure loadings of any bearing in the whole engine. To overcome these problems, the materials used to make the gudgeon pin and the way it is manufactured are amongst the most highly-engineered of any mechanical component found in internal combustion engines.

Design Options

Gudgeon pins use two broad design configurations: semi-floating and fully-floating. In the semi-floating configuration, the pin is usually fixed relative to the piston by an interference fit with the journal in the piston. (This replaced the earlier set screw method.) The connecting rod small end bearing thus acts as the bearing alone. In this configuration, only the small end bearing requires a bearing surface, if any. If needed, this is provided by either electroplating the small end bearing journal with a suitable metal, or more usually by inserting a sleeve bearing or needle bearing into the eye of the small end, which has an interference fit with the aperture of the small end. During overhaul, it is usually possible to replace this bearing sleeve if it is badly worn. The reverse configuration, fixing the gudgeon pin to the connecting rod instead of to the piston, is implemented using an interference fit with the small end eye instead, with the gudgeon pin journals in the piston functioning as bearings. This arrangement is usually more difficult to manufacture and service because two bearing surfaces or inserted sleeves complicate the design. In addition, the pin must be precisely set so that the small end eye is central. Because of thermal expansion considerations, this arrangement was more usual for single-cylinder engines as opposed to multiple cylinder engines with long cylinder blocks and crankcases, until precision manufacturing became more commonplace.

In the fully-floating configuration, a bearing surface is created both between the small end eye and gudgeon pin and the journal in the piston. The gudgeon pins are usually secured with circlips. No interference fit is used in any instance and the pin 'floats' entirely on bearing surfaces. The average rubbing speed of each of the three bearings is halved and the load is shared across a bearing that is usually about three times the length of the semi-floating design with an interference fit with the piston.

Chapter 11

Intercooler

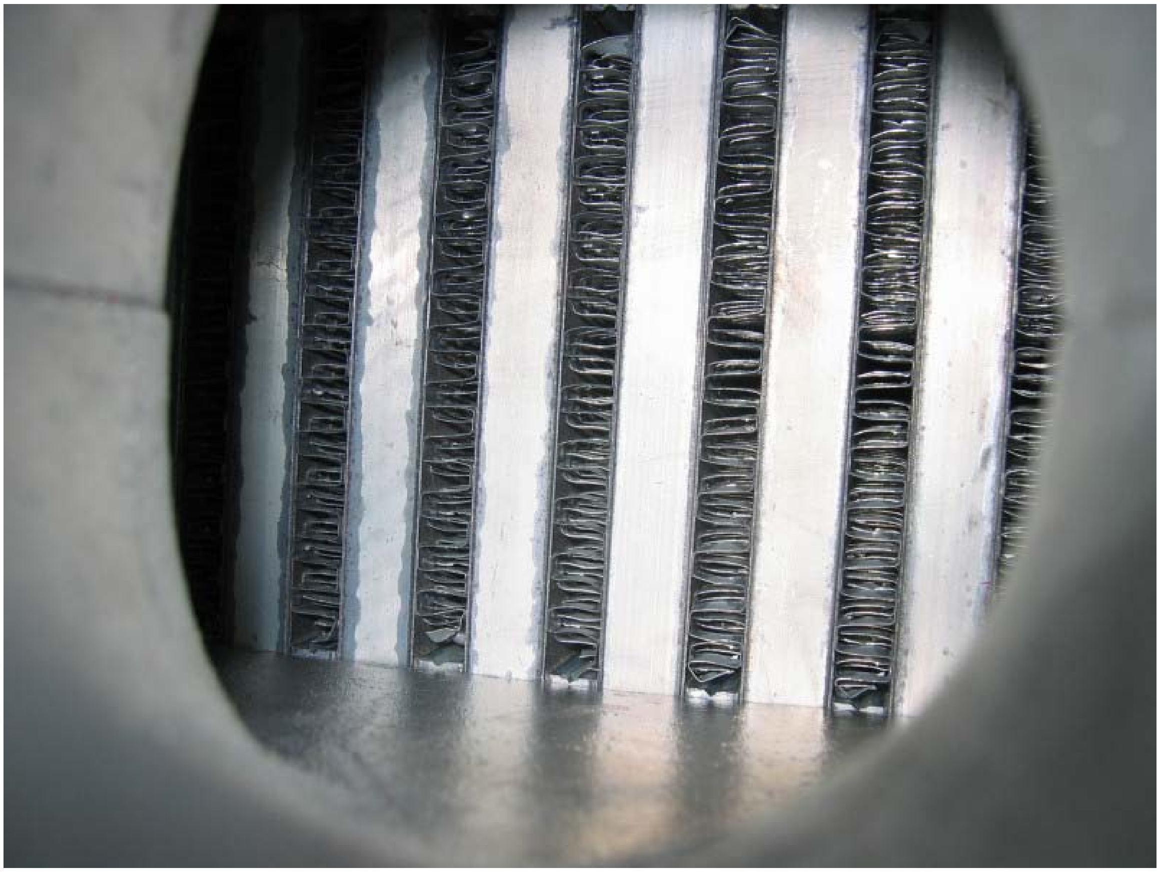
An **intercooler** (original UK term, sometimes **aftercooler** in US practice), or charge air cooler, is an air-to-air or air-to-liquid heat exchange device used on turbocharged and supercharged (forced induction) internal combustion engines to improve their volumetric efficiency by increasing intake air charge density through nearly isobaric (constant pressure) cooling, which removes the heat of compression (i.e., the temperature rise) that occurs in any gas when its pressure is raised or its unit mass per unit volume (density) is increased. A decrease in intake air charge temperature sustains use of a more dense intake charge into the engine, as a result of supercharging. The lowering of the intake charge air temperature also eliminates the danger of pre-detonation (knock) of the fuel air charge prior to timed spark ignition. Thus preserving the benefits of more fuel/air burn per engine cycle, increasing the output of the engine. Intercoolers increase the efficiency of the induction system by reducing induction air heat created by the turbocharger and promoting more thorough combustion. They also eliminate the need for using the wasteful method of lowering intake charge temperature by the injection of excess fuel into the cylinders' air induction chambers, to cool the intake air charge, prior to its flowing into the cylinders. This wasteful practice (when intercoolers are not used) nearly eliminated the gain in engine efficiency from supercharging, but was necessitated by the greater need to prevent at all costs the engine damage that pre-detonation engine knocking causes.

The *inter* prefix in the device name originates from historic compressor designs. In the past, aircraft engines were built with charge air coolers that were installed between multiple stages of supercharging, thus the designation of *inter*. Modern automobile designs are technically designated **aftercoolers** because of their placement at the end of supercharging chain. This term is now considered archaic in modern automobile terminology since most forced induction vehicles have single-stage superchargers or turbochargers although "aftercooler" is still in common use in the piston engined aircraft industry. In a vehicle fitted with two-stage turbocharging, it is possible to have both an intercooler (between the two turbocharger units) and an aftercooler (between the second-stage turbo and the engine). The JCB Dieselmax land speed record-holding car is an example of such a system. In general, an intercooler or aftercooler is said to be a charge air cooler.

Intercoolers can vary dramatically in size, shape and design, depending on the performance and space requirements of the entire supercharger system. Common spatial designs are front mounted intercoolers (FMIC), top mounted intercoolers (TMIC) and hybrid mount intercoolers (HMIC). Each type can be cooled with an air-to-air system, air-to-liquid system, or a combination of both.

Applications to forced induction

The engine bay of a 2003 MINI Cooper S—the top mounted intercooler is circled in red.



Interior close up view of an air to air intercooler.

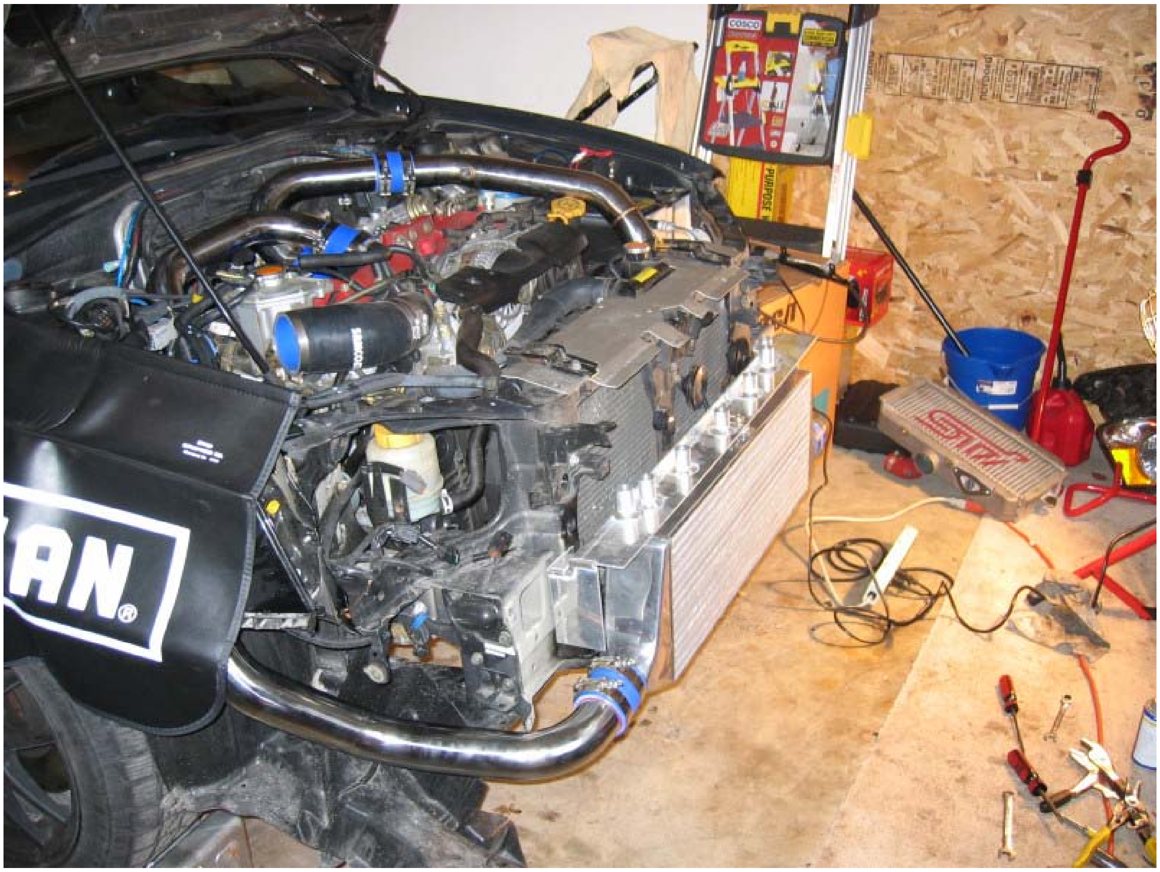
Exterior of the same intercooler core.

Turbochargers and superchargers are engineered to force more air mass into an engine's intake manifold and combustion chamber. Intercooling is a method used to compensate for heating caused by supercharging, a natural byproduct of the semi-adiabatic compression process. Increased air pressure can result in an excessively hot intake charge, significantly reducing the performance gains of supercharging due to decreased density. Increased intake charge temperature can also increase the cylinder combustion temperature, causing detonation, excessive wear, or heat damage to an engine block.

Passing a compressed and heated intake charge through an intercooler reduces its temperature (due to heat rejection) and pressure (due to flow restriction of fins). If properly engineered, the relative decrease in temperature is greater than the relative loss in pressure, resulting a net increase in density. This increases system performance by recovering some losses of the inefficient compression process by rejecting heat to the atmosphere. Additional cooling can be provided by externally spraying a fine mist onto the intercooler surface, or even into the intake air itself, to further reduce intake charge temperature through evaporative cooling.

Intercoolers that exchange their heat directly with the atmosphere are designed to be mounted in areas of an automobile with maximum air flow. These types are mainly mounted in front mounted systems (FMIC). Cars such as the Nissan Skyline, Saab, Volvo 200 Series Turbo, Volvo 700 Series (and 900 series) turbo, Dodge SRT-4, 1st gen Mazda MX-6, Mitsubishi Lancer Evolution and Chevrolet Cobalt SS all use front mounted intercooler(s) mounted near the front bumper, in line with the car's radiator.

Many other turbo-charged cars, particularly where the aesthetics of the car are not to be compromised by unattractive top mount scoops, such as the Toyota Supra (JZA80 only), Nissan 300ZX Twin Turbo, Nissan 200SX (S13/14/14a/15), Mitsubishi 3000gt, Saab 900, Volkswagen, Audi TT, and Turbo Mitsubishi Eclipse use side-mounted air-to-air intercoolers (SMIC), which are mounted in the front corner of the bumper or in front of one of the wheels. Side-mounted intercoolers are generally smaller, mainly due to space constraints, and sometimes two are used to gain the performance of a larger, single intercooler. Cars such as the Subaru Impreza WRX, MINI Cooper S, Toyota Celica GT-Four, Nissan Pulsar GTI-R, Mazdaspeed3, Mazdaspeed6, and the PSA Peugeot Citroën turbo diesels, use air-to-air top mounted intercoolers (TMIC) located on top of the engine. Air is directed through the intercooler through the use of a hood scoop. In the case of the PSA cars the air flows through the grille above the front bumper, then through under-hood ducting. Top mounted intercoolers sometimes suffer from heat diffusion due to proximity with the engine, warming them and reducing their overall efficiency. Some World Rally Championship cars use a reverse-induction system design whereby air is forced through ducts in the front bumper to a horizontally-mounted intercooler.



Fitting an after market front mount intercooler to a car with a factory installed top mount.

Because FMIC systems require open bumper design for optimal performance, the entire system is vulnerable to debris. Some engineers choose other mount locations due to this reliability concern. FMICs can be located in front of or behind the radiator, depending on the heat dissipation needs of the engine.

As well as allowing a greater mass of air to be admitted to an engine, intercoolers have a key role in controlling the internal temperatures in a turbocharged engine. When fitted with a turbo (as with any form of supercharging), the engine's specific power is increased, leading to higher combustion and exhaust temperatures. The exhaust gases passing through the turbine section of the turbocharger are usually around 450 °C (840 °F), but can be as high as 1000 °C (1830 °F) under extreme conditions. This heat passes through the turbocharger unit and contributes to the heating of the air being compressed in the compressor section of the turbo. If left uncooled this hot air enters the engine, further increasing internal temperatures. This leads to a build up of heat that will eventually stabilise, but this may be at temperatures in excess of the engine's design limits- 'hot spots' at the piston crown or exhaust valve can cause warping or cracking of these components. This effect is especially found in modified or tuned engines running at very high specific power outputs. An efficient intercooler removes heat from the air in the induction system, preventing the cyclic heat build-up via the turbocharger, allowing higher power outputs to be achieved without damage.

Compression by the turbocharger causes the intake air to heat up; rather than the air being heated by contact with the hot turbocharger itself, the vast majority is through the act of compression (ideal gas law) plus added heat due to compressor inefficiencies (adiabatic efficiency). The extra power obtained from forced induction is due to the extra air available to burn more fuel in each cylinder. This sometimes requires a lower compression ratio be used, to allow a wider mapping of ignition timing advance before detonation occurs (for a given fuel's octane rating). On the other hand, a lower compression ratio generally lowers combustion efficiency and costs power.

Air-to-liquid intercoolers

Air-to-liquid intercoolers (aka Charge-Air-Coolers) are heat exchangers that transfer intake charge heat to an intermediate fluid, usually water, which finally rejects heat to the air. These systems use radiators in other locations, usually due to space constraints, to reject unwanted heat, similar to an automotive radiator cooling system. Air-to-liquid intercoolers are usually heavier than their air-to-air counterparts due to additional components making up the system (water circulation pump, radiator, fluid, and plumbing). The Toyota Celica GT-Four had this system from 1988 to 1989, 1994 to 1999, also in the Carlos Sainz Rally Championship Version from 1990 to 1993.

A big advantage of the air-to-liquid setup is the lower overall pipe and intercooler length, which offers faster response (lowers turbo lag), giving peak boost faster than most front-mount intercooler setups. Some setups can use reservoirs that can have ice put into it for intake temperatures lower than ambient air, giving a big advantage (but of course, ice would need constant replacement).

Ford had adopted the technology when they decided to use forced induction (via Supercharger) on their Mustang Cobra and Ford Lightning truck platforms. It uses a water/glycol mixture intercooler inside the intake manifold, just under the supercharger, and has a long heat exchanger front mounted, all powered by a Bosch pump made for Ford. Ford still uses this technology today with their Shelby GT500. The 2005-2007 Chevrolet Cobalt SS Supercharged also utilizes a similar setup.

Air-to-liquid intercoolers are by far the most common form of intercooler found on marine engines, given that a limitless supply of cooling water is available and most engines are located in closed compartments where obtaining a good flow of cooling air for an air-to-air unit would be difficult. Marine intercoolers take the form of a tubular heat exchanger with the air passing through a series of tubes and cooling water circulating around the tubes within the unit's casing. The source of water for the intercooler depends on the exact cooling system fitted to the engine. Most marine engine have fresh water circulating within them which is passed through a heat exchanger cooled by sea water. In such a system the intercooler will be attached to the sea water circuit and placed before the engine's own heat exchanger to ensure a supply of cool water.

Chapter 12

Oil Pump (Internal Combustion Engine)

Gerotor type oil pump from a scooter engine

The **oil pump** in an internal combustion engine is usually a gear type (gear pump), driven by the crankshaft or camshaft, or a rotor type (rotary pump).

Lubricating System

The oiling system addresses the need to properly lubricate an engine when it's running. Properly lubricating an engine not only reduces friction between moving parts but is also the main method by which heat is removed from pistons, bearings, and shafts. Failing to properly lubricate an engine will result in engine failure. The oil pump forces the motor oil through the passages in the engine to properly distribute oil to different engine components. In a common oiling system, oil is drawn out of the oil sump (oil pan, in US English) through a wire mesh strainer that removes some of the larger pieces of debris from the oil. The flow made by the oil pump allows the oil to be distributed around the engine. In this system, oil flows through an oil filter and sometimes an oil cooler, before going through the engine's oil passages and being dispersed to lubricate pistons, rings, springs, valve stems, and more.

Oil Pressure

The oil pressure generated in most engines should be about 10 psi per every 1000 revolutions per minute (rpm), peaking around 55-65 psi.

Local pressure (at the crankshaft journal and bearing) is far higher than the 50, 60 psi &c. set by the pump's relief valve, and will reach hundreds of psi. This higher pressure is developed by the relative speeds in feet per second (not RPM or journal size directly) of the crankshaft journal itself against the bearing, the bearing width (to the closest pressure leak), oil viscosity, and temperature, balanced against the bearing clearance (the leakage rate).

All pump pressure does is "fill in the hole" and refresh the oil in the annular space faster than the leak expels it. This is why low-speed engines have relatively large journals, with only modest pump size and pressure. Low pressure indicates that leakage from the bearings is higher than the pump's delivery rate.

Gauge pressure

The oil pressure at the pump outlet, which is what opens the pressure relief valve, is simply the resistance to flow caused by the bearing clearances and restrictions.

The oil pressure gauge, or warning lamp, gives only the pressure at the point where its sender enters that part of the pressurized system – not everywhere, not an average, nor a generalized picture of the systemic pressure.

Despite the frequent comparison to hydraulic engineering theory, this is not a "closed system" in which oil pressure is balanced and identical everywhere. All engines are "open systems", because the oil returns to the pan by a series of controlled leaks. The bearings farthest from the pump always have the lowest pressure because of the number of leaks between the pump and that bearing. Excess bearing clearance increases the pressure loss between the first and last bearing in a series.

Depending on condition, an engine may have acceptable gauge pressure, and still only 5 psi pressure at one connecting rod, which will fail under high load.

The pressure is actually created by the resistance to the flow of the oil around the engine. So, the pressure of the oil may vary during operation, with temperature, engine speed, and wear on the engine. Colder oil temperature can cause higher pressure, as the oil is thicker, while higher engine speeds cause the pump to run faster and push more oil through the engine. Because of variances in temperature and normal higher engine speed upon cold engine start up, it's normal to see higher oil pressure upon engine start up than at normal operating temperatures, where normal oil pressure usually falls between 30 and 45 psi. Too much oil pressure can create unnecessary work for the engine and even add air into the system. To ensure that the oil pressure does not exceed the rated maximum, once pressure exceeds a preset limit a spring-loaded pressure relief valve dumps excess pressure either to the suction side of the pump, or directly back to the oil pan or tank. High oil pressure frequently means extremely high pressure on cold start-up, but this is a design flaw rather than an automatic consequence of high pressure. The observation "if you raise the maximum pressure, the cold pressure goes too high" is accurate, but not intentional.

Even the stock pumps (regardless of brand and model) do not have enough relief valve capacity: the relief port is too small to handle the volume of cold oil. This is why there is a significant difference between cold & hot oil, high & low RPM, &c., but it's typically not a problem with stock engines. A correctly designed relief port (which is not found in production engines) will flow any oil volume the gears will pass, regardless of oil viscosity or temperature, and the gauge reading will only vary slightly.

The oil pressure is monitored by an oil pressure sending unit, usually mounted to the block of the engine. This can either be a spring-loaded pressure sensor or an electronic pressure sensor, depending on the type of sending unit. Problems with the oil pressure sending unit or the connections between it and the driver's display can cause abnormal oil pressure readings when oil pressure is perfectly acceptable.

Low Oil Pressure

Low oil pressure, however, can cause engine damage. Low oil pressure can be caused by many things, such as a faulty oil pump, a clogged oil pickup screen, excessive wear on high mileage engines, or simply low oil volume. Indications of low oil pressure may be that the warning light is on, a low pressure reading on the gauge, or clattering/clinking noises from the engine. Low oil pressure is a problem that must be addressed immediately to prevent serious damage.

The leading cause of low oil pressure in an engine is wear on the engine's vital parts. Over time, engine bearings and seals suffer from wear and tear. Wear can cause these parts to eventually lose their original dimensions, and this increased clearance allows for a greater volume of oil to flow over time which can greatly reduce oil pressure. For instance, .001 of an inch worn off of the engine's main bearings can cause up to a 20% loss in oil pressure. Simply replacing worn bearings may fix this problem, but in older engines with a lot of wear not much can be done besides completely overhauling the engine which is generally not cost effective.

Particles in the oil can also cause serious problems with oil pressure. After oil flows through the engine, it returns to the oil pan, and can carry along a lot of debris. The debris can cause problems with the oil pickup screen and the oil pump itself. The holes in the oil pickup screen measure about 0.04 square inches (0.26 cm^2). Holes of this size only pick up bigger pieces of debris and allow a lot of smaller pieces to flow through it. The holes in the screen are so big (relative to debris) because at low temperatures and slow engine speed the oil is very viscous and needs large openings to flow freely. Even with these large holes in the screen, it can still become clogged and cause low oil pressure. A .005-inch-thick (0.13 mm) coating on the screen can reduce hole size to about .03 square inches (0.19 cm^2), which in turn reduces the flow of oil by 44 percent.

Even after passing through the oil pickup screen and the oil filter, debris can remain in the oil. It is very important to change the oil and oil filter to minimize the amount of debris flowing through your engine. This harmful debris along with normal engine wear in high mileage engines causes an increase in clearances between bearings and other moving parts.

Low oil pressure may be simply because there is not enough oil in the sump, due to burning oil (normally caused by piston ring wear or worn valve seals) or leakage. The piston rings serve to seal the combustion chamber, as well as remove oil from the internal walls of the cylinder. However, when they wear, their effectiveness drops, which leaves oil on the cylinder walls during combustion. In some engines, burning a small amount of oil is normal and shouldn't necessarily cause any alarm, where as burning lots of oil is a sign that the engine might be in need of an overhaul.

Oil Pumps in High Performance Engines

Not all engines have the same oiling needs. High performance engines, for example, place higher stress on the lubricating system. In this case, the lubricating system must be especially robust to prevent engine damage. Most engines in cars on the road today don't run much past 5,000–6,000 rpm, but that isn't always the case in performance engines, where engine speeds could reach up to 8000-9000 rpm. In engines like these, it is imperative that the oil circulates quickly enough, or air may become trapped in the oil. Also, to free up power, some engines in performance applications run lower weight oil, which requires less power to run the oil pump. Common oil weights in engines today are usually either 5w30 or 10w30 oil, where as performance engines might use 0w20 oil, which is less viscous.

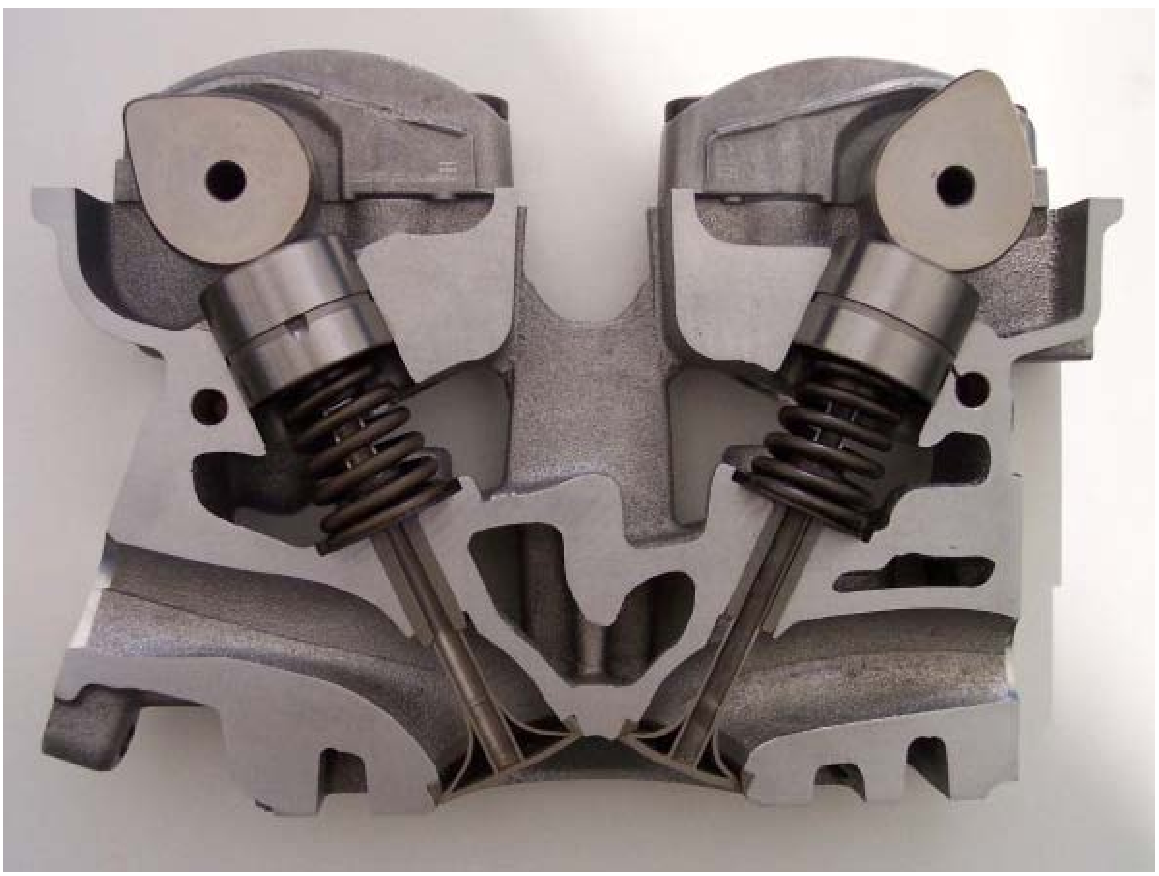
Wet and Dry Sump Systems

Conventional wet sump engines have one oil pump. It is generally located inside the lower part of the engine, usually below and/or to one side of the crankshaft. On dry sump engines, at least two oil pumps are required: one to pressurize and distribute the oil around the engine components, and at least one other 'scavenge pump' to evacuate the oil which has pooled at the bottom of the engine. This scavenge pump is sometimes (but not always) located in the 'sump' of the engine, and crucially, this scavenge pump's flow-rate capacity must exceed that of the pump which pressurizes and distributes oil throughout the engine.

Because of the dry sump's external oil reservoir, excess air can escape the oil before the oil is pumped back through the engine. Dry sumps also allow for more power because it reduces the amount of windage, oil sloshing up into the rotating assembly, and the vacuum from the scavenge pump improves ring seal. Dry sumps are more popular in racing applications because of the improved power and reduced oil sloshing that would otherwise reduce oil pressure. Disadvantages of dry sumps are increased weight, additional parts, and more chances for leaks and problems to occur.

Chapter 13

Overhead Camshaft



A cylinder head sliced in half shows two overhead camshafts—one above each of the two valves.

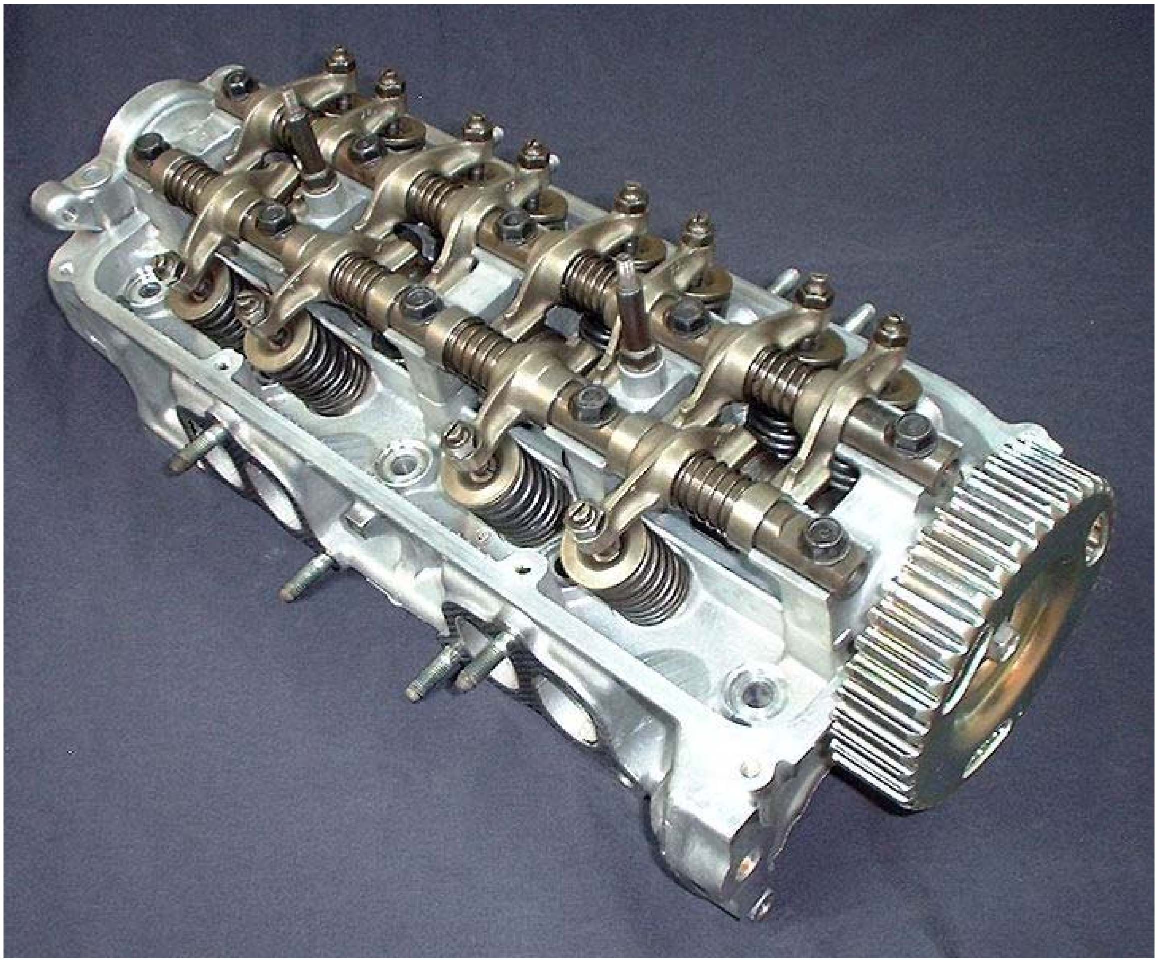
Overhead camshaft or **Overhead cam** (**OHC**) valvetrain configurations place the engine camshaft within the cylinder heads, above the combustion chambers, and drive the valves or lifters in a more direct manner compared to overhead valves (OHV) and pushrods. Compared to OHV pushrod (or I-Head) systems with the same number of valves the reciprocating components of the OHC system are fewer and have a lower total mass. Though the system that drives the cams may become more complex, most engine manufacturers easily accept that added complexity in trade for better engine performance and greater design flexibility. Another performance advantage is gained as a result of the better optimized port configurations made possible with overhead camshaft designs. With no intrusive pushrods the overhead camshaft cylinder head design can use straighter ports of more advantageous crossection and length.

The OHC system can be driven using the same methods as an OHV system, which include using a rubber/kevlar toothed timing belt, chain, or in less common cases, gears.

In conjunction with multiple (3, 4 or 5) valves per cylinder, many OHC engines today employ variable valve timing to improve efficiency and power. OHC also inherently allows for greater engine speeds over comparable cam-in-block designs, as a result of having lower valvetrain mass.

There are two overhead camshaft layouts: single overhead camshaft (or SOHC), and double overhead camshaft (or DOHC).

Single overhead camshaft



A single overhead camshaft cylinder head from a 1987 Honda CRX Si.

Single overhead camshaft (SOHC) is a design in which one camshaft is placed within the cylinder head. In an inline engine this means there is one camshaft in the head, while in a V engine or a horizontally-opposed engine (boxer; flat engine) there are two camshafts: one per cylinder bank.

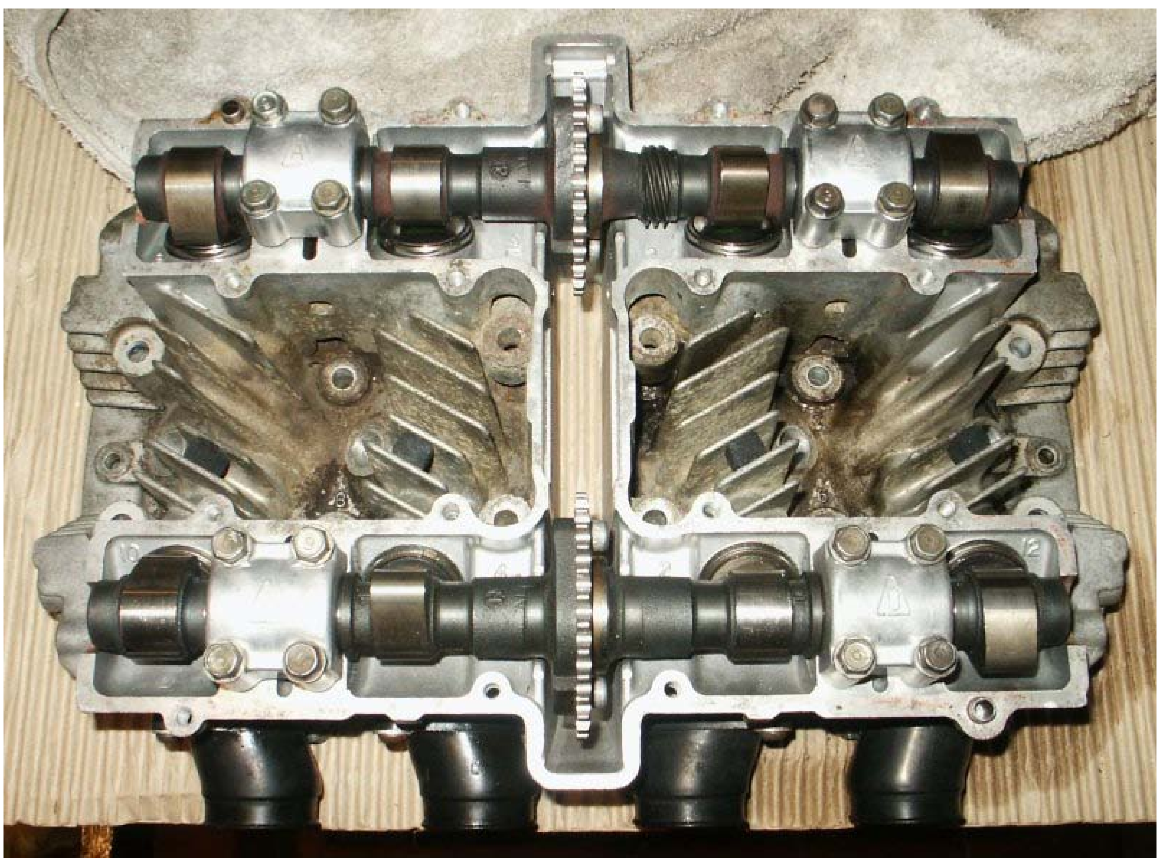
The SOHC design has less reciprocating mass than a comparable pushrod design. This allows for higher engine speeds, which in turn will increase power output for a given torque. The cam operates the valves directly or through a rocker arm, as opposed to overhead valve pushrod engines which have tappets, long pushrods, and rocker arms to transfer the movement of the lobes on the camshaft in the engine block to the valves in the cylinder head.

In the early era of the liquid-cooled aircraft engine field, single overhead cam format engines were in existence during the First World War, for both the Allies and the Central Powers. The Hispano-Suiza 8 V8 engine, designed by Marc Birkigt in the Allied camp, and the series of Mercedes inline-6 aviation engines, culminating in the Mercedes D.III for the German Empire, both used rotary shaft-driven single overhead camshaft valve drive systems, and were among the most prominent aviation powerplants of the First World War era.

SOHC designs offer reduced complexity compared to pushrod designs when used for multi-valve heads in which each cylinder has more than two valves. An example of an SOHC design using shim and bucket valve adjustment was the engine installed in the Hillman Imp (4 cylinder, 8 valve); a small, early 1960s 2-door saloon car with a rear mounted alloy engine based on the Coventry Climax FWMA race engines. Exhaust and inlet manifolds were both on the same side of the engine block (thus not a crossflow cylinder head design). This did, however, offer excellent access to the spark plugs.

In the early 1980s, Toyota and Volkswagen also used a directly actuated, SOHC parallel valve configuration with two valves for each cylinder. The Toyota system used hydraulic tappets while the Volkswagen system used bucket tappets with shims for valve lash adjustment. Of all valvetrain systems, this is the least complex configuration possible.

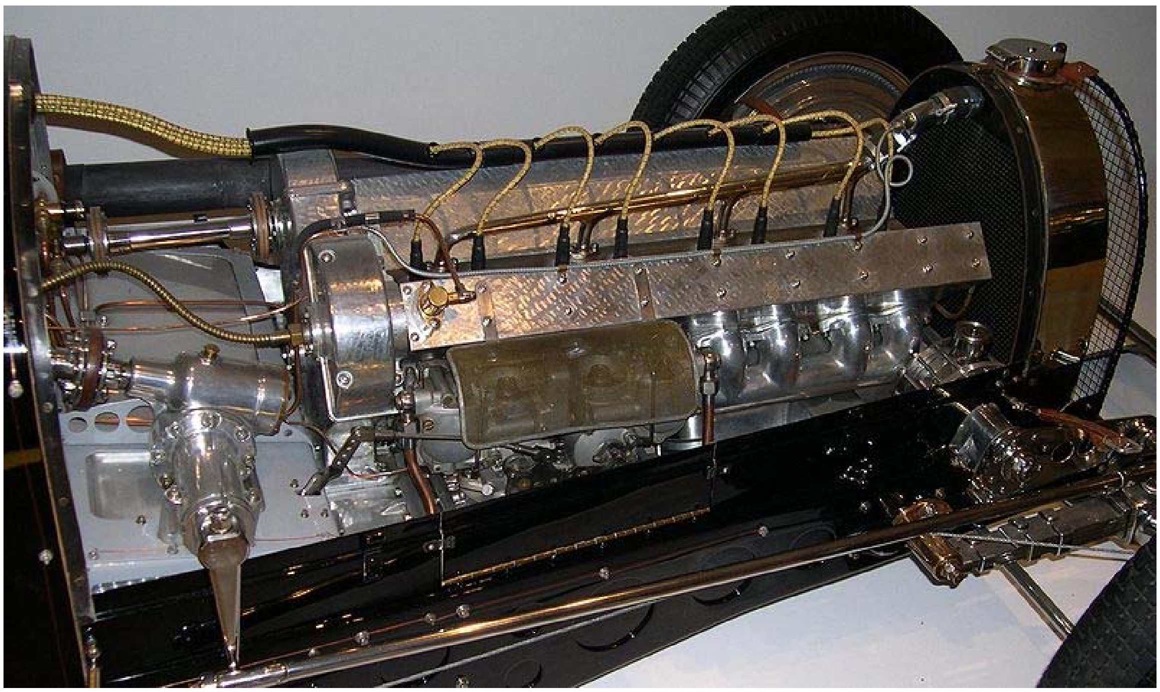
Double overhead camshaft



Overhead view of Suzuki GS550 head showing dual camshafts and drive sprockets.

A double overhead camshaft valve train layout is characterized by two camshafts located within the cylinder head, one operating the intake valves and one operating the exhaust valves. Some engines have more than one bank of cylinder heads (V8 and flat-four being two well-known examples) and these have more than two camshafts in total, but they remain DOHC. The term "twin cam" is imprecise, but will normally refer to a DOHC engine. Some manufacturers still managed to use a SOHC in 4-valve layouts. Honda, for instance, with the later half of the D16 family, utilizes the 4-valve per cylinder, SOHC layout to reduce overall costs. Also not all DOHC engines are multivalve engines—DOHC was common in two valve per cylinder heads for decades before multivalve heads appeared. Today, however, DOHC is synonymous with multi-valve heads since almost all DOHC engines have between three and five valves per cylinder.

History



DOHC straight-8 in a 1933 Bugatti Type 59 Grand Prix racer

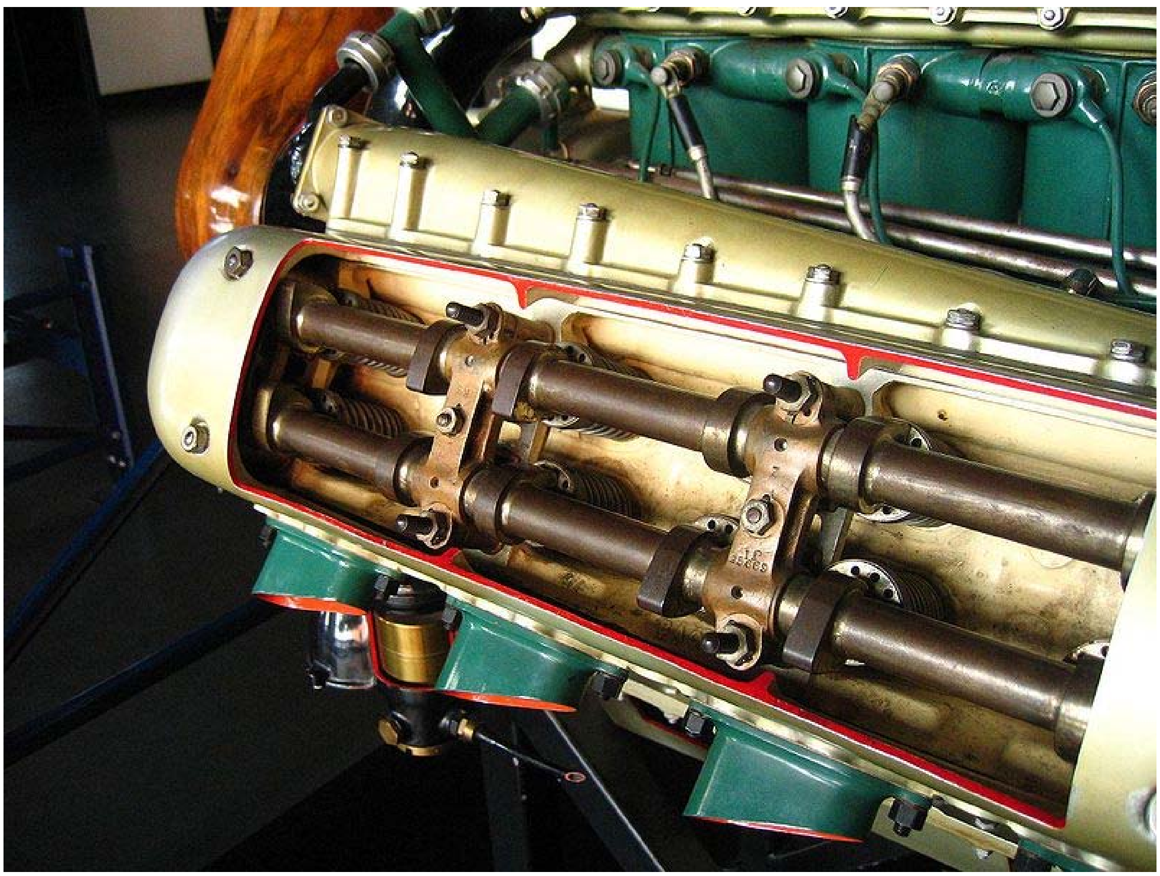
Among the early pioneers of DOHC were Isotta Fraschini's Giustino Cattaneo, Austro-Daimler's Ferdinand Porsche Stephen Tomczak (in the *Prinz Heinrich*), and W. O. Bentley (in 1919); Sunbeam built small numbers of racing models between 1921 and 1923 and introduced one of the world's first production twin cams in 1924 - the Sunbeam 3 litre Super Sports, an example of which came 2nd at LeMans in 1925. The first DOHC engines were either two- or four-valve *per* cylinder racing car designs from companies like Fiat (1912), Peugeot Grand Prix (1913, 4 valve), Alfa Romeo Grand Prix (1914, 4 valve) and 6C (1928), Maserati Tipo 26 (1926), Bugatti Type 51 (1931).

When DOHC technology was introduced in mainstream vehicles, it was common for it to be heavily advertised. While used at first in limited production and sports cars such as the 1925 Sunbeam 3 litre, Alfa Romeo is one of the twin cam's greatest proponents. 6C

Sport, the first Alfa Romeo road car using a DOHC engine, was introduced in 1928. Ever since this, it has been a trademark of all Alfa Romeo engines.

Fiat was one of the first car companies to use a belt-driven DOHC engines across their complete product line, in the mid-1960s., Jaguar's XK6 DOHC engine was displayed in the Jaguar XK120 at the London Motor Show in 1948 and used across the entire Jaguar range through the late 1940s, 1950 and 1960s. By the late 1970s, Toyota was the best seller of DOHC engines.

More than two overhead camshafts are not known to have been tried in a production engine. However MotoCzysz has designed a motorcycle engine with a triple overhead camshaft configuration with the intake ports descending through the head to two central intake ports between two outside exhaust camshafts actuating one of two exhaust valve per cylinder each.



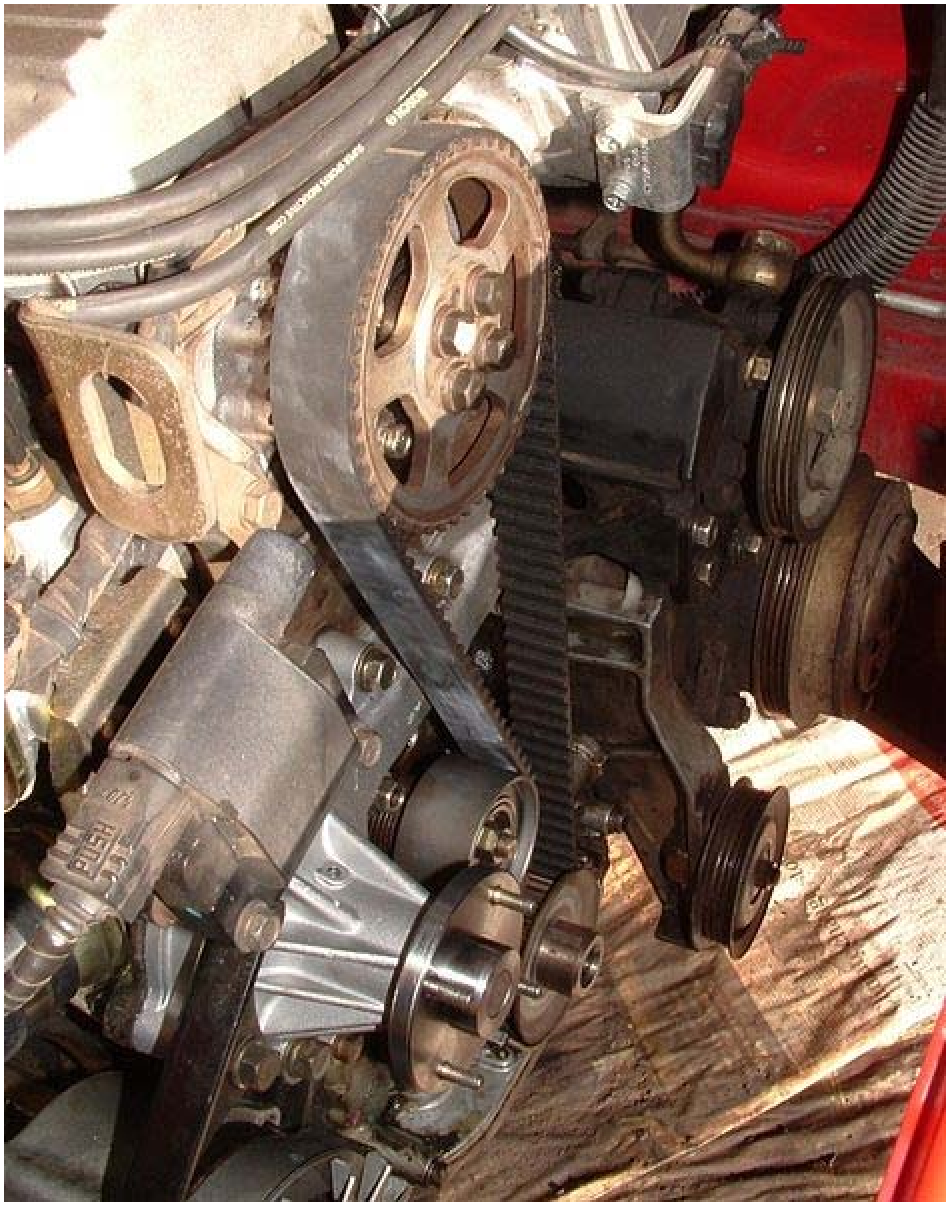
Cutaway view of a Napier Lion showing the double overhead camshaft arrangement

In inline piston aero engines, DOHCs have been used for many engines, the 1917 Napier Lion having them, as well as the later Rolls-Royce Kestrel and Rolls-Royce Merlin.

Chapter 14

Timing Belt

Timing belt



Timing covers, lower pulley, accessory belts removed, exposing timing belt

A **timing belt**, or **cam belt** (informal usage), is a part of an internal combustion engine that controls the timing of the engine's valves. Some engines, such as the flat-4 Volkswagen air cooled engine, and the straight-6 Toyota F engine use timing gears. Timing belts replace the older style timing chains that were common until the 1970s and 1980s (although in the last decade there has been some reemergence of chain use). Some manufacturers, such as BMW, are known for utilizing timing chains, because of their durability. The term "timing belt" is sometimes used for the more general case of any flat belt with integral teeth, although such usage is a misnomer since there is no timing or synchronization involved.

Engine applications

In the internal combustion engine application, the timing belt/chain connects the crankshaft to the camshaft(s), which in turn controls the opening and closing of the engine's valves. A four-stroke engine requires that the valves open and close once every other revolution of the crankshaft. The timing belt/chain does this. It has teeth to turn the camshaft(s) synchronised with the crankshaft, and is specifically designed for a particular engine. In some engine designs, the timing belt may also be used to drive other engine components such as the water pump and oil pump.

Gear or chain systems are also used to connect the crankshaft to the camshaft at the correct timing. However, gears and shafts constrain the relative location of the crankshaft and camshafts. Even where the crankshaft and camshaft(s) are very close together, as in pushrod engines, most engine designers use a short chain drive rather than a direct gear drive. This is because gear drives suffer from frequent torque reversal as the cam profiles "kick back" against the drive from the crank, leading to excessive noise and wear. Fibre gears, with more resilience, are preferred to steel gears where direct drive has to be used. A belt or chain allows much more flexibility in the relative locations of the crankshaft and camshafts.

While chains and gears may be more durable, rubber composite belts are quieter in their operation (in most modern engines the noise difference is negligible), are less expensive and more efficient, by dint of being lighter, when compared with a gear or chain system. Also, timing belts do not require lubrication, which is essential with a timing chain or gears. A timing belt is a specific application of a synchronous belt used to transmit rotational power synchronously.

Timing belts are typically covered by metal or polymer timing belt covers which require removal for inspection or replacement. Engine manufacturers recommend replacement at specific intervals. The manufacturer may also recommend the replacement of other parts, such as the water pump, when the timing belt is replaced because the additional cost to replace the water pump is negligible compared to the cost of accessing the timing belt. In an interference engine, or one whose valves extend into the path of the piston, failure of the timing belt (or timing chain) invariably results in costly and, in some cases, irreparable engine damage, as some valves will be held open when they should not be and thus will be struck by the pistons.

Indicators that the timing chain may need to be replaced include a rattling noise from the front of the engine.

Timing

When an automotive timing belt is replaced, care must be taken to ensure that the valve and piston movements are correctly synchronized. Failure to synchronize correctly can lead to problems with valve timing, and this in turn, in extremes, can cause collision between valves and pistons in interference engines. This is not a problem unique to timing belts since the same issue exists with all other cam/crank timing methods such as gears or chains.

Failure

Timing belts must be replaced at the manufacturer's recommended distance and/or time periods. Failure to replace the belt can result in complete breakdown or catastrophic engine failure. The owner's manual maintenance schedule is the source of timing belt replacement intervals, typically every 60,000 to 90,000 miles (approx 96,000 to 144,000 kilometres). It is common to replace the timing belt tensioner at the same time as the belt is replaced.

The usual failure modes of timing belts are either stripped teeth (which leaves a smooth section of belt where the drive cog will slip) or delamination and unraveling of the fiber cores. Breakage of the belt, because of the nature of the high tensile fibers, is uncommon. Correct belt tension is critical - too loose and the belt will whip, too tight and it will whine and put excess strain on the bearings of the cogs. In either case belt life will be drastically shortened. Aside from the belt itself, also common is a failure of the tensioner, and/or the various gear and idler bearings, causing the belt to derail.

Construction and design

A timing belt is typically rubber with high-tensile fibres (e.g. fiberglass or Twaron/Kevlar) running the length of the belt as tension members.

Rubber degrades with higher temperatures, and with contact with motor oil. Thus the life expectancy of a timing belt is lowered in hot or leaky engines. Newer or more expensive belts are made of temperature resistant materials such as "highly-saturated nitrile" (HSN). The life of the reinforcing cords is also greatly affected by water and antifreeze. This means that special precautions must be taken for off road applications to allow water to drain away or be sealed from contact with the belt.

Older belts have trapezoid shaped teeth leading to high rates of tooth wear. Newer manufacturing techniques allow for curved teeth that are quieter and last longer.

Aftermarket timing belts may be used to alter engine performance. OEM timing belts "will stretch at high rpm, retarding the cam and therefore the ignition. Stronger, aftermarket belts, will not stretch and the timing is preserved. In terms of engine design, "shortening the width of the timing belt reduce[s] weight and friction".

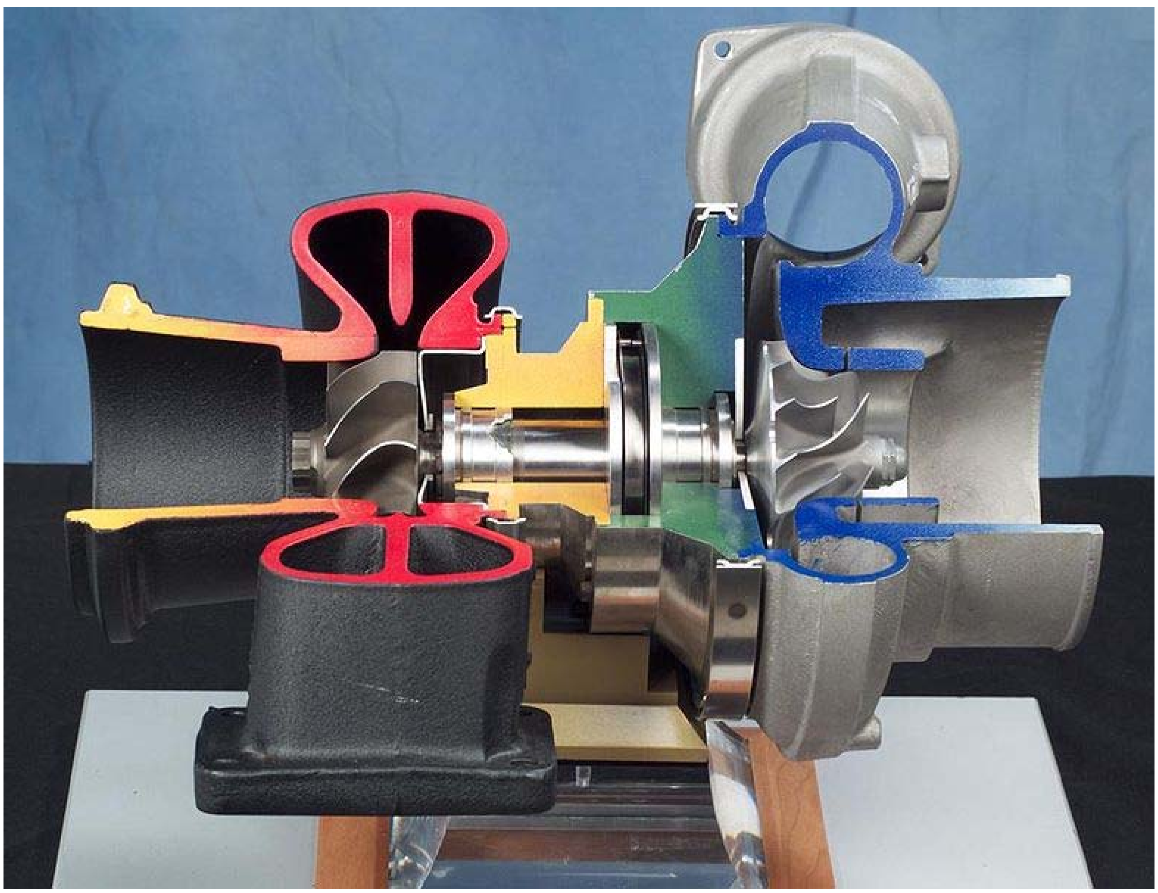
Usage history

The first known timing belt was used in 1945.

The German Glas 1004 was the first mass produced vehicle to use a timing belt in 1962. The first American vehicle to use a timing belt was the 1966 Pontiac Tempest. In 1966, Vauxhall started production of the Slant Four overhead cam four-cylinder design which used a timing belt, a configuration that is now used in the vast majority of cars built today.

Chapter 15

Turbocharger



Cut-away view of an air foil bearing-supported turbocharger made by Mohawk Innovative Technology

A **turbocharger**, or **turbo**, is a gas compressor used for forced induction of an internal combustion engine. A form of supercharger, the turbocharger increases the pressure of air entering the engine to create more power. A turbocharger has the compressor powered by a turbine which is driven by the engine's own exhaust gases rather than direct mechanical drive. This allows a turbocharger to achieve a higher degree of efficiency than other types of forced induction compressors which are more vulnerable to parasitic loss.

Nomenclature

Early manufacturers of turbochargers referred to them as "turbosuperchargers". A supercharger is an air compressor used for forced induction of an engine. Logically then, adding a turbine to turn the supercharger would yield a "turbosupercharger". However, the term was soon shortened to "turbocharger". This is now a source of confusion, as the term "turbosupercharged" is sometimes used to refer to an engine that uses both a crankshaft-driven supercharger and an exhaust-driven turbocharger, often referred to as twincharging.

Aviation engine manufacturers such as Teledyne Continental Motors still use the term *turbosupercharged* to refer to turbo chargers that are used to boost manifold pressure above 1 ATM. Turbochargers that maintain 1 ATM of manifold pressure to a specific altitude are considered turbo-normalized. Though these represent true turbochargers, they should not be confused with some aircraft engines that employ actual engine-driven superchargers.

Operating principle

A turbocharger is a small centrifugal pump driven by the energy of the exhaust gases of an engine. A turbocharger consists of a turbine and a compressor on a shared shaft. The turbine converts kinetic energy from the engine exhaust's velocity and potential energy from the exhaust's higher-than-atmospheric pressure into rotational kinetic energy, which is in turn used to drive the compressor. The compressor draws in ambient air and pumps it into the intake manifold at increased pressure, resulting in a greater mass of air entering the cylinders on each intake stroke.

The objective of a turbocharger is the same as that of a supercharger; to improve an engine's volumetric efficiency by solving one of its cardinal limitations. A naturally aspirated automobile engine relies mostly on the downward stroke of a piston to create an area of low pressure in order to draw air into the cylinder through one or more intake valves. The pressure in the atmosphere is no more than 1 atm (approximately 14.7 psi, or 1 bar), so there ultimately will be a limit to the pressure difference across the intake valves and thus the amount of airflow entering the combustion chamber. Since the turbocharger increases the pressure at the point where air is entering the cylinder, a greater mass of air (oxygen) will be forced in as the inlet manifold pressure increases. The presence of additional air mass in the cylinder makes it possible to create a bigger explosion if more fuel is injected, increasing the power and torque output of the engine.

To avoid detonation and physical damage to the host engine, the intake manifold pressure must not get too high, thus the pressure at the intake manifold of the engine must be controlled by some means. A Wastegate, which vents excess exhaust gas so that it will bypass the exhaust turbine is the most common boost control device. An actuator, connected to the compressor outlet via a signal hose, and usually controlled via a solenoid by the car's Engine Control Unit, forces the wastegate to open as the boost pressure rises. The reduction in turbine speed results in the compressor slowing, and in less air pressure at the intake manifold.

Modern Group N Rally cars are forced by the rules to use a 34mm restrictor at the compressor inlet, which effectively limits the maximum boost (pressure above atmospheric) that the cars can achieve at high rpm. Interestingly, at low rpm they can reach boost pressures of above 22psi (1.5bar).

History

The turbocharger was invented by Swiss engineer Alfred Büchi. His patent for a turbocharger was applied for use in 1905. Diesel ships and locomotives with turbochargers began appearing in the 1920s.

Aviation

During the First World War French engineer Auguste Rateau fitted turbochargers to Renault engines powering various French fighters with some success.

In 1918, General Electric engineer Sanford Moss attached a turbo to a V12 *Liberty* aircraft engine. The engine was tested at Pikes Peak in Colorado at 14,000 feet (4,300 m) to demonstrate that it could eliminate the power losses usually experienced in internal combustion engines as a result of reduced air pressure and density at high altitude.

Turbochargers were first used in production aircraft engines such as the Napier Lioness, in the 1920s before World War II, although they were less common than engine-driven centrifugal superchargers. The primary purpose behind most aircraft-based applications was to increase the altitude at which the airplane could fly, by compensating for the lower atmospheric pressure present at high altitude. Aircraft such as the Fw 190D, B-17 Flying Fortress, and P-47 Thunderbolt all used turbochargers to increase high altitude engine power.

Production automobiles

The first turbocharged diesel truck was produced by *Schweizer Maschinenfabrik Saurer* (Swiss Machine Works Saurer) in 1938.

The Chevrolet Corvair's turbocharged engine. The turbo, located at top right, feeds pressurized air into the engine through the chrome T-pipe spanning the engine.

The first production turbocharged automobile engines came from General Motors in 1962. The Y-body Oldsmobile Cutlass Jetfire was fitted with a Garrett AiResearch turbocharger and the Chevrolet Corvair Monza Spyder with a TRW turbocharger. At the Paris auto show in 1974, during the height of the oil crisis, Porsche introduced the 911 Turbo – the world's first production sports car with an exhaust turbocharger and pressure regulator. This was made possible by the introduction of a wastegate to direct excess exhaust gasses away from the exhaust turbine. The world's first production turbo diesel automobiles were the Garrett-turbocharged Mercedes 300SD and the Peugeot 604, both introduced in 1978. Today, most automotive diesels are turbocharged.

- 1962 Oldsmobile Cutlass Jetfire
- 1962 Chevrolet Corvair Monza Spyder
- 1973 BMW 2002 Turbo
- 1974 Porsche 911 Turbo
- 1978 Buick Regal
- 1978 Saab 99
- 1978 Peugeot 604 turbodiesel
- 1978 Mercedes-Benz 300SD turbodiesel (United States/Canada)
- 1979 Alfa Romeo Alfetta GTV 2000 Turbodelta

- 1980 Mitsubishi Lancer GT Turbo
- 1980 Pontiac Firebird
- 1980 Renault 5 Turbo
- 1981 Volvo 240-series Turbo

Competition cars

The aircraft engineer Frank Halford experimented with turbocharging in his modified Aston Martin racing car the *Halford Special*, but it is unclear whether or not his efforts were successful. The first successful application of turbocharging in automotive racing appears to have been in 1952 when Fred Agabashian in the diesel-powered *Cummins Special* qualified for pole position at the Indianapolis 500 and led for 175 miles (282 km) before ingested tire shards disabled the compressor section of the Elliott turbocharger. Offenhauser's turbocharged engines returned to Indianapolis in 1966, with victories coming in 1968 using a Garrett AiResearch turbocharger. The Offenhauser turbo peaked at over 1,000 hp (750 kW) in 1973, which led USAC to limit boost pressure. In their turn, Porsche dominated the Can-Am series with a 1,100 hp (820 kW) 917/30. Turbocharged cars dominated the 24 Hours of Le Mans between 1976 and 1988, and then from 2000-2007.

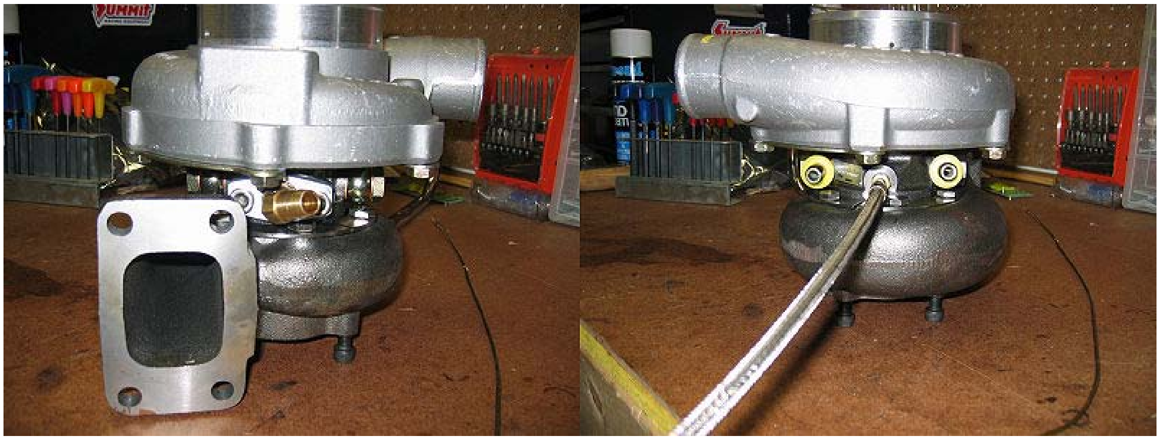
In Formula One, in the so called "Turbo Era" of 1977 until 1989, Renault, Honda, BMW, and Ferrari produced engines with a capacity of 1,500 cc (92 cu in) able to generate 1,000 to 1,500 horsepower (750 to 1,100 kW). Renault was the first manufacturer to apply turbo technology in F1. The project's high cost was compensated for by its performance, and led other engine manufacturers to follow suit. Turbocharged engines dominated and ended the Cosworth DFV era in the mid 1980s. However, the FIA decided turbochargers were making the sport too dangerous and expensive. In 1987, *FIA* decided to limit the maximum boost before the technology was banned for 1989.

In drag racing, an 1,800 hp (1,340 kW) twin-turbocharged Pontiac GTA developed by Gale Banks of Southern California, set a land speed record for the "World's Fastest Passenger Car" of 277 mph (446 km/h). This event was chronicled at the time in a 1987 cover story published by *Autoweek* magazine. Gale Banks Engineering also built and raced several diesel-powered machines, including what Banks erroneously calls the "World's Fastest Diesel Truck," a street-legal 735 hp (548 kW) Dodge Dakota pick-up that towed its own trailer to the Bonneville Salt Flats and then set an official *FIA* record of 217 mph (349 km/h) with a one-way top speed of 222 mph (357 km/h). The truck also showed the fuel economy of a turbocharged diesel engine by averaging 21.2-mpg on the Hot Rod Power Tour. If it ran 50 mph (80 km/h) faster, it would almost match the actual fastest diesel truck, the "Phoenix" of R. B. Slagle and Carl Heap.

In rallying, turbocharged engines of up to 2,000 cc (120 cu in) have long been the preferred motive power for the Group A/N World Rally Car competitors, due to the exceptional power-to-weight ratios attainable. This combines with the use of vehicles with relatively small bodyshells for maneuverability and handling. As turbo outputs rose to levels similar to F1's category, rather than banning the technology, FIA restricted turbo inlet diameter (currently 34 mm).

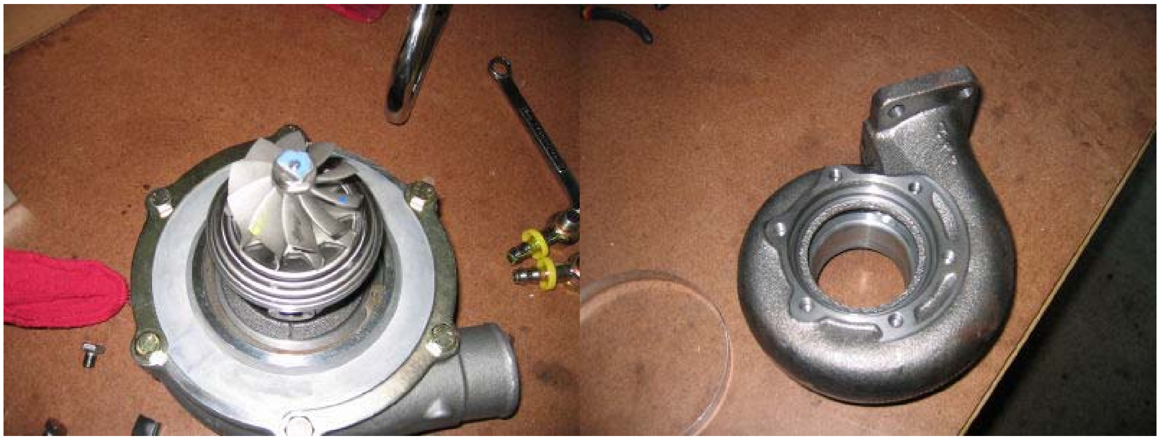
Design and installation

Components

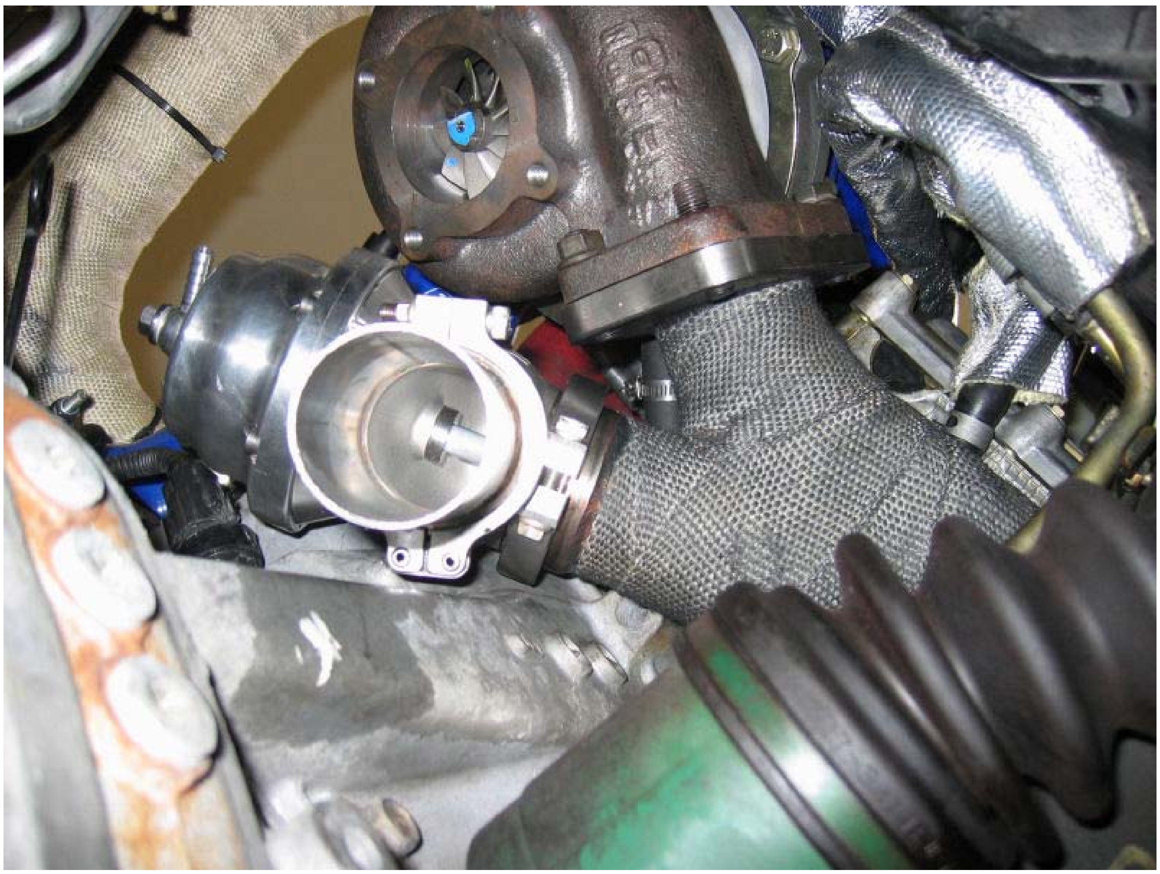


On the left, the brass oil drain connection. On the right are the braided oil supply line and water coolant line connections.

Compressor impeller side with the cover removed.



Turbine side housing removed.



A wastegate installed next to the turbocharger.

The turbocharger has four main components. The turbine (almost always a radial turbine) and impeller/compressor wheels are each contained within their own folded conical housing on opposite sides of the third component, the center housing/hub rotating assembly (CHRA).

The housings fitted around the compressor impeller and turbine collect and direct the gas flow through the wheels as they spin. The size and shape can dictate some performance characteristics of the overall turbocharger. Often the same basic turbocharger assembly will be available from the manufacturer with multiple housing choices for the turbine and sometimes the compressor cover as well. This allows the designer of the engine system to tailor the compromises between performance, response, and efficiency to application or preference. Twin-scroll designs have two valve-operated exhaust gas inlets, a smaller sharper angled one for quick response and a larger less angled one for peak performance.

The turbine and impeller wheel sizes also dictate the amount of air or exhaust that can be flowed through the system, and the relative efficiency at which they operate. Generally, the larger the turbine wheel and compressor wheel, the larger the flow capacity. Measurements and shapes can vary, as well as curvature and number of blades on the wheels. Variable geometry turbochargers are further developments of these ideas.

The center hub rotating assembly (CHRA) houses the shaft which connects the compressor impeller and turbine. It also must contain a bearing system to suspend the shaft, allowing it to rotate at very high speed with minimal friction. For instance, in automotive applications the CHRA typically uses a thrust bearing or ball bearing lubricated by a constant supply of pressurized engine oil. The CHRA may also be considered "water cooled" by having an entry and exit point for engine coolant to be cycled. Water cooled models allow engine coolant to be used to keep the lubricating oil cooler, avoiding possible oil coking (the destructive distillation of the engine oil) from the extreme heat found in the turbine. The development of air-foil bearings has removed this risk. Adaptation of turbochargers on naturally aspirated internal combustion engines, either on petrol or diesel, can yield power increases of 30% to 40%.

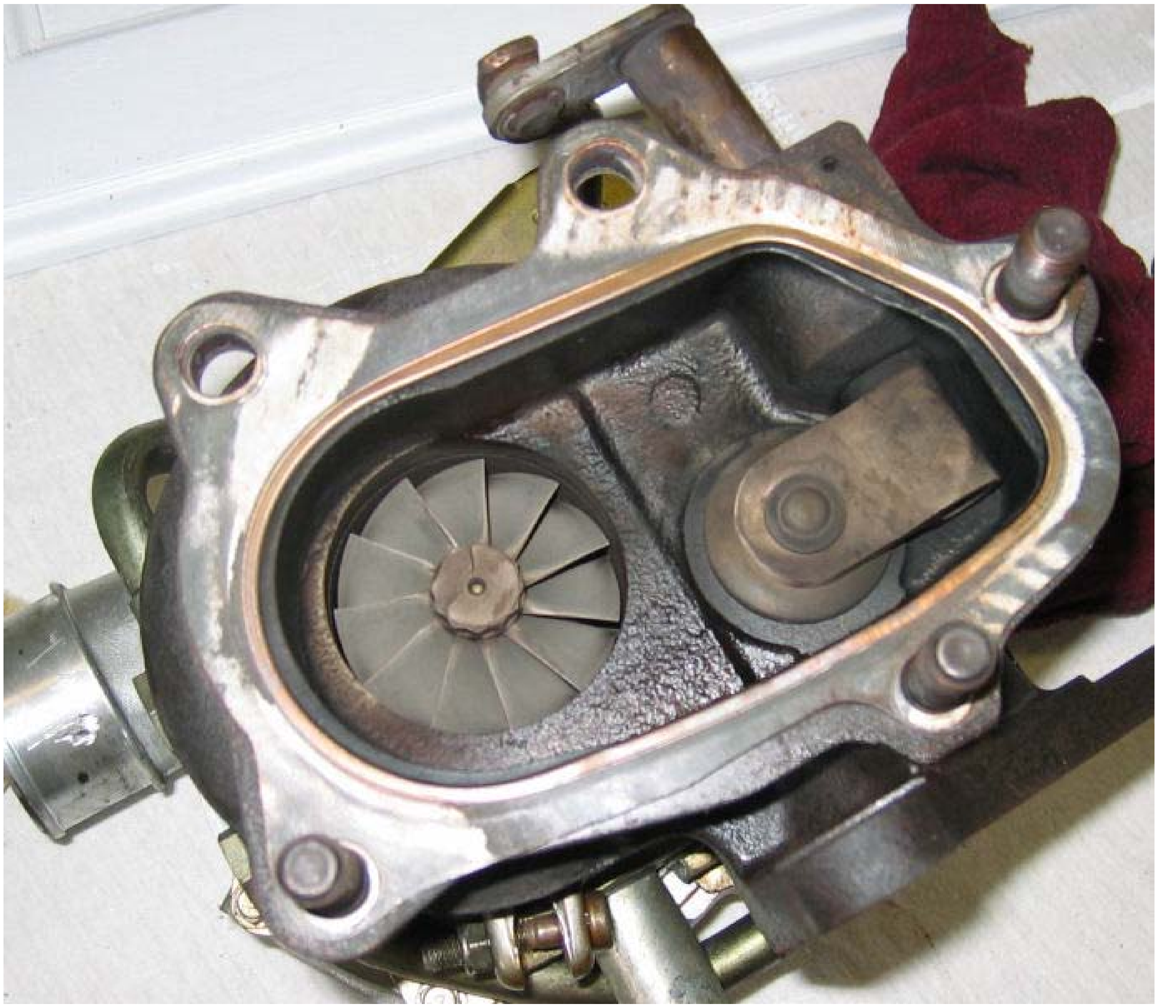
Pressure increase

In the automotive world, boost refers to the increase in pressure that is generated by the turbocharger in the intake manifold that exceeds normal atmospheric pressure. Atmospheric pressure is approximately 14.7 psi or 1.0 bar, and anything above this level is considered to be boost. The level of boost may be shown on a pressure gauge, usually in bar, psi or possibly kPa. This is representative of the extra air pressure that is achieved over what would be achieved without the forced induction. Manifold pressure should not be confused with the volume of air that a turbo can flow.

In aircraft engines the main benefit of turbochargers is to maintain manifold pressure as altitude increases. Since atmospheric pressure reduces as the aircraft climbs, power drops as a function of altitude in normally aspirated engines. Aircraft manifold pressure in western built aircraft is expressed in inches of mercury (Hg) where 29.92 inches is the standard sea level pressure. In high performance aircraft, turbo chargers will provide takeoff manifold pressures in the 30 - 42 inches Hg range. (1 to 1.4 bar). This varies according to aircraft and engine types. In contrast, the takeoff manifold pressure of a normally aspirated engine is about 27 in. Hg, even at sea level, due to losses in the induction system (air filter, ducting, throttle body, etc.). As the turbocharged aircraft climbs, however, the pilot (or automated system) can close the waste gate forcing more exhaust gas through the turbocharger turbine thereby maintaining manifold pressure during the climb, at least until the critical pressure altitude is reached (when the waste gate is fully closed) after which manifold pressure will fall. With such systems, modern high performance piston engine aircraft can cruise at altitudes above 20,000 feet where low air density results in lower drag and higher true airspeeds. Most importantly, this allows flying "above the weather". In manually controlled wastegate systems the pilot must take care not to overboost the engine which will cause pre-ignition leading to engine damage. Further, since most aircraft turbocharger systems do not include an intercooler, the engine is typically operated on the rich side of peak exhaust temperature in order to avoid overheating the turbocharger. In non high performance turbo charged aircraft, the turbocharger is solely used to maintain sea-level manifold pressure during the climb (this is called turbo-normalizing).

Boost pressure is limited to keep the entire engine system, including the turbo, inside its thermal and mechanical design operating range. The speed and thus the output pressure of the turbo is controlled by the wastegate, a bypass which shunts the gases from the cylinders around the turbine directly to the exhaust pipe. The maximum possible boost depends on the fuel's octane rating and the inherent tendency of any particular engine towards detonation. Premium gasoline or racing gasoline can be used to prevent detonation within reasonable limits. Ethanol, methanol, liquefied petroleum gas (LPG) and compressed natural gas (CNG) allow higher boost than gasoline, because of their higher resistance to autoignition (lower tendency to knock). Diesel engines can also tolerate much higher levels of boost pressure than Otto cycle engines, because only air is being compressed during the compression phase, and fuel is injected later, removing the knocking issue entirely. High performance racing diesel engines routinely run boost pressures from 3 to above 10 bar. To obtain more power from higher boost levels and maintain reliability, many engine components have to be replaced or upgraded such as the fuel pump, fuel injectors, pistons, valves, head-gasket, and head bolts.

Wastegate



View of a turbocharger from the turbine exhaust side, clearly showing the integral wastegate to the right

By spinning at a relatively high speed, the compressor draws in a large volume of air and forces it into the engine. As the turbocharger's output flow volume exceeds the engine's volumetric flow, air pressure in the intake system begins to build. The speed at which the assembly spins is proportional to the pressure of the compressed air and total mass of air flow being moved. Since a turbo can spin to rpm far beyond what is needed, or of what it is safely capable of, the speed must be controlled. A wastegate is the most common mechanical speed control system, and is often further augmented by an electronic or manual boost controller. The main function of a wastegate is to allow some of the exhaust to bypass the turbine when the set intake pressure is achieved. Most modern passenger car engines have wastegates that are internal to the turbocharger, although some earlier engines (such as the Audi Inline-5 in the UrS4 and S6) have external wastegates. External wastegates are more accurate and efficient than internal wastegates, but are far more expensive, and thus are generally only found in racing cars (Where precise control of turbo boost is a necessity and any efficiency increase is welcomed)

Anti-surge/dump/blow off valves

A recirculating type anti-surge valve

Turbocharged engines operating at wide open throttle and high rpm require a large volume of air to flow between the turbo and the inlet of the engine. When the throttle is closed compressed air will flow to the throttle valve without an exit (*i.e.* the air has nowhere to go).

This causes a surge which can raise the pressure of the air to a level which can damage the turbo. If the pressure rises high enough, a compressor stall will occur, where the stored pressurized air decompresses backwards across the impeller and out the inlet. The reverse flow back across the turbocharger causes the turbine shaft to reduce in speed more quickly than it would naturally, possibly damaging the turbocharger. In order to prevent this from happening, a valve is fitted between the turbo and inlet which vents off the excess air pressure. These are known as an anti-surge, diverter, bypass, blow-off valve(BOV) or dump valve. It is basically a pressure relief valve, and is normally operated by the vacuum in the intake manifold.

The primary use of this valve is to maintain the turbo spinning at a high speed. The air is usually recycled back into the turbo inlet (diverter or bypass valves) but can also be vented to the atmosphere (blow off valve). Recycling back into the turbocharger inlet is required on an engine that uses a mass-airflow fuel injection system, because dumping the excessive air overboard downstream of the mass airflow sensor will cause an excessively rich fuel mixture (this is because the mass-airflow sensor has already accounted for the extra air which is no longer being used). Valves which recycle the air will also shorten the time needed to re-spool the turbo after sudden engine deceleration, since the load on the turbo when the valve is active is much lower than if the air charge is vented to atmosphere.

Ported shroud/map width enhancement

The flow range of a turbocharger compressor can also be increased by allowing air to bleed from a ring of holes or a circular groove around the compressor at a point slightly downstream of the compressor inlet (but far nearer to the inlet than to the outlet). The Ported shroud is an efficiency increasing enhancement. Increases in compressor efficiency result in colder (more dense) intake air, which improves power. The escaping air flow is directed back into the compressor inlet pipe. In contrast to blow off valves which are electronically controlled, this is a passive structure which is constantly open (which is one reason that it does not open to atmosphere). Allowing some air to escape at this location inhibits the onset of surge and widens the compressor map. The ability of the compressor to accommodate high mass flows (high boost at low rpm) is also increased marginally (because near choke conditions the compressor draws air inward through the bleed path). This technology is widely used by turbocharger manufacturers such as Honeywell Turbo Technologies, Cummins Turbo Technologies, and GReddy. When implemented appropriately, it has a reasonable impact on compressor map width while not compromising the top of the maximum efficiency island.

Charge cooling

Compressing air in the turbocharger increases the air's temperature, which can cause a number of problems. Excessive charge air temperature can lead to detonation, which is extremely destructive to engines. When a turbocharger is installed on an engine, it is common practice to fit the engine with an intercooler (also known as a charge air cooler, or CAC), a type of heat exchanger which gives up heat energy in the charge to the ambient air. Over time an intercooler can develop leaks, losing boost pressure, and reducing fuel economy. It is common practice to leak test the intercooler during routine service, particularly in trucks where a leaking intercooler can result in a 20% reduction in fuel economy.

In addition to the use of intercoolers, it is common practice to introduce extra fuel into the charge for the sole purpose of cooling. The amount of extra fuel varies, but typically reduces the air-fuel ratio to between 11 and 13, instead of the stoichiometric 14.7 (in gasoline engines). The extra fuel is not burned, as there is insufficient oxygen to complete the chemical reaction, and instead undergoes a phase change from vapor(liquid) to gas. This reaction absorbs heat(the latent heat of vaporization), and the added mass of the extra fuel reduces the average kinetic energy of the charge and exhaust gas. The gaseous hydrocarbons generated are oxidized to carbon dioxide, carbon monoxide, and water in the catalytic converter.

Multiple turbochargers

A pair of turbochargers mounted to an Inline 6 engine (2JZ-GTE from a MkIV Toyota Supra) in a dragster.

Parallel

Some engines, such as V-type engines, utilize two identically-sized but smaller turbos, each fed by a separate set of exhaust streams from the engine. The two smaller turbos produce the same (or more) aggregate amount of boost as a larger single turbo, but since they are smaller they reach their optimal RPM, and thus optimal boost delivery, more quickly. Such an arrangement of turbos is typically referred to as a parallel twin-turbo system. The first production automobile with parallel twin turbochargers was the Maserati Biturbo of the early 1980s. Later such installations include Porsche 911 TT, Nissan GT-R, Mitsubishi 3000GT VR-4, Nissan 300ZXTT, Audi RS6, and **BMW twin-turbo 3.0 liter inline N54 6 cylinder**[N54 uses two different in size turbos, a sequential setup] cars (E90, E81, E60).

Sequential

Some car makers combat lag by using two small turbos. A typical arrangement for this is to have one turbo active across the entire rev range of the engine and one coming on-line at higher RPM. Below this RPM, both exhaust and air inlet of the secondary turbo are closed. Being individually smaller they do not suffer from excessive lag and having the second turbo operating at a higher RPM range allows it to get to full rotational speed before it is required. Such combinations are referred to as a sequential twin-turbo. Porsche first used this technology in 1985 in the Porsche 959. Sequential twin-turbos are usually much more complicated than a single or parallel twin-turbo systems because they require what amounts to three sets of intake and waste gate pipes for the two turbochargers as well as valves to control the direction of the exhaust gases. Many new diesel engines use this technology to not only eliminate lag but also to reduce fuel consumption and reduce emissions.

Remote installations

Turbochargers are sometimes mounted well away from the engine, in the tailpipe of the exhaust system. Such remote turbochargers require a smaller aspect ratio due to the slower, lower-volume, denser exhaust gas passing through them. For low-boost applications, an intercooler is not required; often the air charge will cool to near-ambient temperature en route to the engine. A remote turbo can run 300 to 600 degrees cooler than a close-coupled turbocharger, so oil coking (forming solid residue) in the bearings is of much less concern. Remote turbo systems can incorporate multiple turbochargers in series or parallel.

Automotive applications

To manage the pressure of the air coming from the turbo (known as the 'upper-deck air pressure'), the turbocharger's exhaust gas flow is regulated with a wastegate that bypasses excess exhaust gas entering the turbocharger's turbine. This regulates the rotational speed of the turbine and thus the output of the compressor. The wastegate is opened and closed by the compressed air from turbo and can be raised by using a solenoid to regulate the pressure fed to the wastegate membrane. This solenoid can be controlled by Automatic Performance Control, the engine's electronic control unit or a boost control computer. Another method of raising the boost pressure is through the use of check and bleed valves to keep the pressure at the membrane lower than the pressure within the system.

A medium-sized six-cylinder marine Diesel-engine, with turbocharger and exhaust in the foreground

Turbocharging is very common on diesel engines in automobiles, trucks, locomotives, boats and ships, and heavy machinery. For current automotive applications, non-turbocharged diesel engines are becoming increasingly rare. Diesels are particularly suitable for turbocharging for several reasons:

- Turbocharging can dramatically improve an engine's specific power and power-to-weight ratio, performance characteristics which are normally poor in non-turbocharged diesel engines.
- Truck and industrial Diesel engines run mostly at their maximum power, reducing problems with turbo lag caused by sudden accelerations and decelerations.
- Lacking a throttle valve, compressor stall is essentially non-existent.
- Diesel engines have no detonation because diesel fuel is injected at the end of the compression stroke, ignited by compression heat. Because of this, diesel engines can use much higher boost pressures than spark ignition engines, limited only by the engine's ability to withstand the additional heat and pressure.

The turbocharger's small size and low weight have production and marketing advantage to vehicle manufacturers. By providing naturally-aspirated and turbocharged versions of one engine, the manufacturer can offer two different power outputs with only a fraction of the development and production costs of designing and installing a different engine. Usually increased piston cooling is provided by spraying more lubrication oil on the bottom of the piston. The compact nature of a turbocharger mean that bodywork and engine compartment layout changes to accommodate the more powerful engine are not needed. The use of parts common to the two versions of the same engine reduces production and servicing costs.

Today, turbochargers are most commonly used on gasoline engines in high-performance automobiles and diesel engines in transportation and other industrial equipment. Small cars in particular benefit from this technology, as there is often little room to fit a large engine. Volvo, Saab, Audi, Volkswagen and Subaru have produced turbocharged cars for many years; the turbo Porsche 944's acceleration performance was very similar to that of the larger-engined non-turbo Porsche 928; and Chrysler Corporation built numerous turbocharged cars in the 1980s and 1990s. Buick also developed a turbocharged V-6 during the energy crisis in the late 1970s as a fuel efficient alternative to the enormous eight cylinder engines that powered the famously large cars and produced them through most of the next decade as a performance option. Recently, several manufacturers have returned to the turbocharger in an attempt to improve the tradeoff between performance and fuel economy by using a smaller turbocharged engine in place of a larger normally-aspirated engine. The Ford EcoBoost engine is one such design.

Motorcycle applications

The 1982 Honda CX500 Turbo, the world's first turbo-charged production bike

Using turbochargers to gain performance without a large gain in weight was very appealing to the Japanese factories in the 1980s. The first example of a turbocharged bike is the 1978 Kawasaki Z1R TC. It used a Rayjay ATP turbo kit to build 0.35 bar (5 lb) of boost, bringing power up from c. 90 hp (67 kW) to c. 105 hp (78 kW). However, it was only marginally faster than the standard model. A US Kawasaki importer came up with the idea of modifying the Z1-R with a turbocharging kit as a solution to the Z1-R being a low selling bike. The 112 hp (84 kW) Kawasaki GPz750 Turbo was manufactured from 1983 to 1985. This motorcycle had little in common with the normally aspirated Kawasaki GPz750. Nearly every component was altered or strengthened for this GPz 750 Turbo to handle the 20 hp (15 kW) increase in power.

In 1982, Honda released the CX500T featuring a carefully developed turbo (as opposed to the Z1-R's bolt-on approach). It has a rotation speed of 200,000 rpm. The development of the CX500T was riddled with problems; due to being a V-twin engine the intake periods in the engine rotation are staggered leading to periods of high intake and long periods of no intake at all. Designing around these problems increased the price of the bike, and the performance still was not as good as the cheaper CB900(a 16 valve in-line four) During these years, Suzuki produced the XN85, a 650 cc in-line four producing 85 bhp (63 kW), and Yamaha produced the Seca Turbo. The XN85 was fuel injected, while the Yamaha Seca Turbo relied on pressurized carburetors.

Since the mid 1980s, no manufactures have produced turbocharged motorcycles making these bikes a bit of an educational experience; as of 2007 no factories offer turbocharged motorcycles (although the Suzuki B-King prototype featured a supercharged Hayabusa engine). The Dutch manufacturer EVA motorcycles builds a small series of turbocharged diesel motorcycle with an 800cc smart cdi engine.

Aircraft applications

A natural use of the turbocharger is with aircraft engines. As an aircraft climbs to higher altitudes the pressure of the surrounding air quickly falls off. At 5,486 m (18,000 ft) the air is at half the pressure of sea level, and the airframe only experiences half the aerodynamic drag. However, since the charge in the cylinders is being pushed in by this air pressure, it means that the engine will normally produce only half-power at full throttle at this altitude. Pilots would like to take advantage of the low drag at high altitudes in order to go faster, but a naturally aspirated engine will not produce enough power at the same altitude to do so.

Altitude effects

A turbocharger remedies this problem by compressing the air back to sea-level pressures; or even much higher; in order to produce rated power at high altitude. Since the size of the turbocharger is chosen to produce a given amount of pressure at high altitude, the turbocharger is over-sized for low altitude. The speed of the turbocharger is controlled by a wastegate. Early systems used a fixed wastegate, resulting in a turbocharger that functioned much like a supercharger. Later systems utilized an adjustable wastegate, controlled either manually by the pilot or by an automatic hydraulic or electric system. When the aircraft is at low altitude the wastegate is usually fully open, venting all the exhaust gases overboard. As the aircraft climbs and the air density drops, the wastegate must continually close in small increments to maintain full power. The altitude at which the wastegate is full closed and the engine is still producing full rated power is known as the *critical altitude.* When the aircraft climbs above the critical altitude, engine power output will decrease as altitude increases just as it would in a naturally-aspirated engine.

Temperature considerations

One adverse effect of turbocharging is that compressing the air increases its temperature, which is true for any method of forced induction. This causes multiple problems. Increased temperatures can lead to pre-ignition or detonation because of excessive cylinder head temperatures. In addition, hotter air is less dense, so fewer air molecules enter the cylinders on each intake stroke, resulting in an effective drop in volumetric efficiency which works against the efforts of the turbocharger to increase volumetric efficiency.

A Subaru Impreza WRX STI engine bay, clearly showing the top mounted intercooler to the back of the engine. Cold fresh air enters through a bonnet scoop

A method of generally coping with this problem is in one of several ways. The most common one is to add an intercooler or aftercooler somewhere in the air stream between the compressor outlet of the turbocharger and the engine intake manifold. Intercoolers and aftercoolers are types of heat exchangers which cause the compressed air to give up some of its heat energy to the ambient air. In the past, some aircraft featured anti-detonant injection for takeoff and climb phases of flight, which performs the function of cooling the fuel/air charge before it reaches the cylinders.

In contrast, modern turbocharged aircraft usually forego any kind of temperature compensation, because the turbochargers are generally small and the manifold pressures created by the turbocharger are not very high. Thus the added weight, cost, and complexity of a charge cooling system are considered to be unnecessary penalties. In those cases the turbocharger is limited by the temperature at the compressor outlet, and the turbocharger and its controls are designed to prevent a large enough temperature rise to cause detonation. Even so, in many cases the engines are designed to run rich in order to use the evaporating fuel for charge cooling.

Comparison to supercharging

A supercharger inevitably requires some energy to be bled from the engine to drive the supercharger. On the single-stage single-speed supercharged Rolls Royce Merlin engine for instance, the supercharger uses up about 150 horsepower (110 kW). Yet the benefits outweigh the costs, for that 150 hp (110 kW), the engine generates an additional 400 horsepower and delivers 1,000 hp (750 kW) when it would otherwise deliver 750 hp (560 kW), a net gain of 250 hp (190 kW). This is where the principal disadvantage of a supercharger becomes apparent: The engine has to burn extra fuel to provide power to turn the supercharger. The increased charge density increases the engine's specific power and power to weight ratio, but also increases the engine's specific fuel consumption. This increases the cost of running the aircraft and reduces its overall range. On the other hand, a turbocharger is driven using the exhaust gases. Otherwise-wasted heat is extracted from the exhaust gas, and converted to useful power to compress the intake air. The turbine section of the turbocharger is actually a heat engine in itself. It converts the heat of the exhaust into power used to drive the compressor, thereby providing a more efficient compression of the intake air than can happen with supercharger, which uses up net engine power to drive its air compressor.

With older supercharged aircraft, the pilot must continually adjust the throttle to maintain the required manifold pressure during ascent or descent. The pilot must also take great care to avoid overboosting the engine and causing damage, especially during emergencies such as go-arounds. In contrast, modern turbocharger systems use an automatic wastegate which controls the manifold pressure within parameters preset by the manufacturer. For these systems, as long as the control system is working properly and the pilot's control commands are smooth and deliberate, a turbocharger will not overboost the engine and damage it.

Yet the majority of World War II engines used superchargers, because they maintained three significant manufacturing advantages over turbochargers, which were larger, involved extra piping, and required exotic high-temperature materials in the turbine and pre-turbine section of the exhaust system. The size of the piping alone is a serious issue; American fighters Vought F4U and Republic P-47 used the same engine but the huge barrel-like fuselage of the latter was, in part, needed to hold the piping to and from the turbocharger in the rear of the plane. Turbocharged piston engines are also subject to many of the same operating restrictions as gas turbine engines. Pilots must make smooth, slow throttle adjustments to avoid overshooting their target manifold pressure. The fuel mixture must often be adjusted far on the rich side of the peak exhaust gas temperature to avoid overheating the turbine when running at high power settings. In systems using a manually-operated wastegate, the pilot must be careful not to exceed the turbocharger's maximum RPM. Turbocharged engines require a cooldown period after landing to prevent cracking of the turbo or exhaust system from thermal shock. Turbocharged engines require frequent inspections of the turbocharger and exhaust systems for damage due to the increased heat, increasing maintenance costs.

Today, most general aviation aircraft are naturally aspirated. The small number of modern aviation piston engines designed to run at high altitudes generally use a turbocharger or turbo-normalizer system rather than a supercharger. The change in thinking is largely due to economics. Aviation gasoline was once plentiful and cheap, favoring the simple but fuel-hungry supercharger. As the cost of fuel has increased, the supercharger has fallen out of favor.

Turbocharged aircraft often occupy a performance range in between that of normally-aspirated piston-powered aircraft and turbine-powered aircraft. The increased maintenance costs of a turbo-charged engine are considered worthwhile for this purpose, as a turbocharged piston engine is still far cheaper than any turbine engine.

Relationship to gas turbine engines

Prior to World War II, Sir Frank Whittle started his experiments on early turbojet engines. Due to a lack of sufficient materials as well as funding, initial progress was slow. However, turbochargers were used extensively in military aircraft during World War II to enable them to fly very fast at very high altitudes. The demands of the war led to constant advances in turbocharger technology, particularly in the area of materials. This area of study eventually crossed over into the development of early gas turbine engines. Those early turbine engines were little more than a very large turbocharger with the compressor and turbine connected by a number of combustion chambers. The cross over between the two has been shown in an episode of the TV show Scrapheap Challenge where contestants were able to build a functioning jet engine using an ex-automotive turbocharger as a compressor.

General Electric manufactured turbochargers for military aircraft and held several patents on their electric turbo controls during World War II, then used that expertise to very quickly carve out a dominant share of the gas turbine market which they have held ever since.

Properties and applications

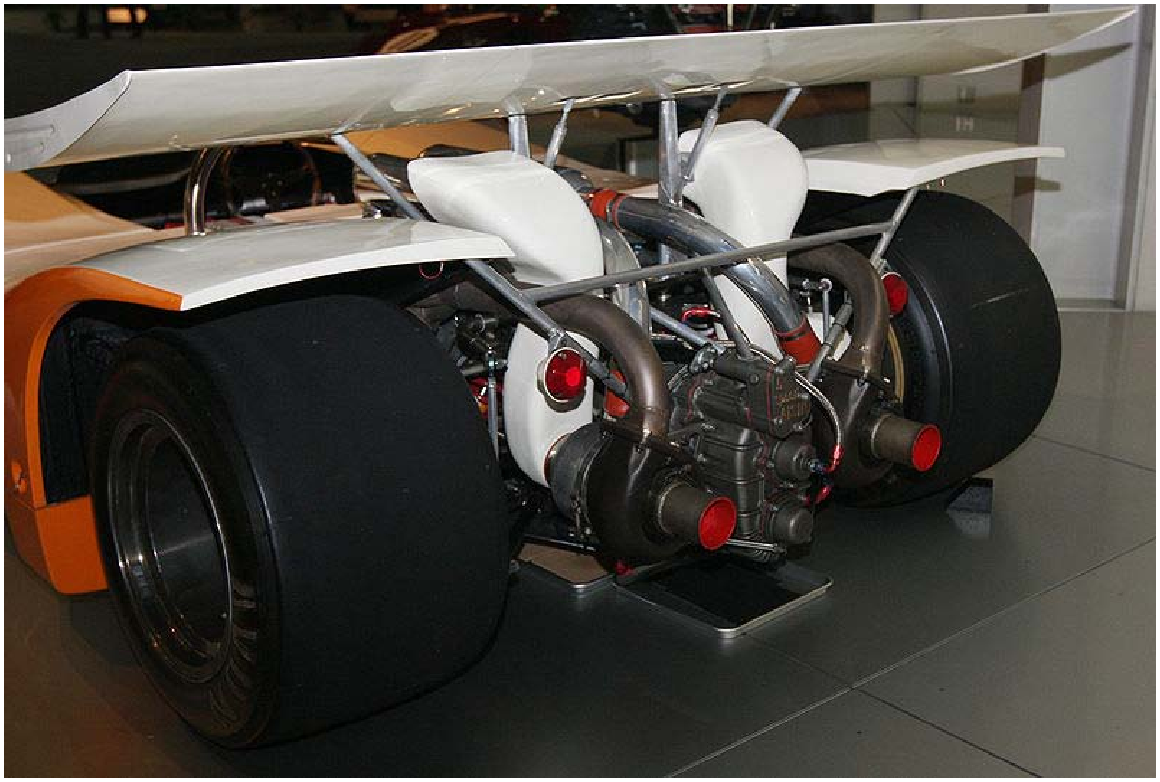
Reliability

Turbochargers can be damaged by dirty or ineffective oil, and most manufacturers recommend more frequent oil changes for turbocharged engines. Many owners and some companies recommend using synthetic oils, which tend to flow more readily when cold and do not break down as quickly as conventional oils. Because the turbocharger will heat when running, many recommend letting the engine idle for up to three minutes before shutting off the engine if the turbocharger was used shortly before stopping. This gives the oil and the lower exhaust temperatures time to cool the turbo rotating assembly, and ensures that oil is supplied to the turbocharger while the turbine housing and exhaust manifold are still very hot; otherwise coking of the lubricating oil trapped in the unit may occur when the heat soaks into the bearings, causing rapid bearing wear and failure when the car is restarted. Even small particles of burnt oil will accumulate and lead to choking the oil supply and failure. This problem is less pronounced in diesel engines, due to higher quality oil typically being specified.

A turbo timer can keep an engine running for a pre-specified period of time, to automatically provide this cool-down period. Oil coking is also eliminated by foil bearings. A more complex and problematic protective barrier against oil coking is the use of water-cooled bearing cartridges. The water boils in the cartridge when the engine is shut off and forms a natural recirculation to drain away the heat. Nevertheless, it is not a good idea to shut the engine off while the turbo and manifold are still glowing.

In custom applications utilizing tubular headers rather than cast iron manifolds, the need for a cooldown period is reduced because the lighter headers store much less heat than heavy cast iron manifolds.

Turbo lag

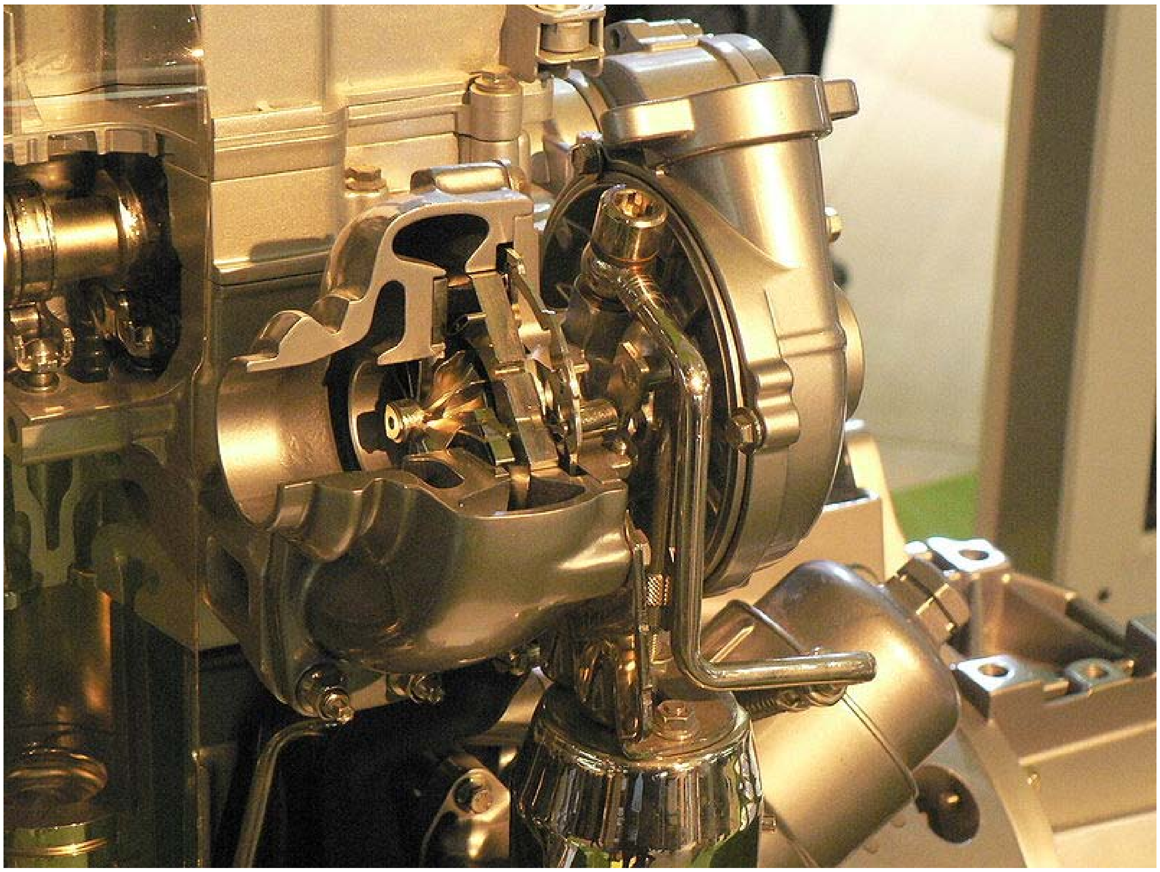


1970 Toyota 7, twin turbo-charged racing car

The time required to bring the turbo up to a speed where it can function effectively is called *turbo lag*. This is noticed as a hesitation in throttle response when coming off idle. This is symptomatic of the time taken for the exhaust system driving the turbine to come to high pressure and for the turbine rotor to overcome its rotational inertia and reach the speed necessary to supply boost pressure. The directly-driven compressor in a supercharger does not suffer from this problem. (Centrifugal superchargers do not build boost at low rpm as a positive displacement supercharger will). Conversely on light loads or at low RPM a turbocharger supplies less boost and the engine acts like a naturally aspirated engine.

Lag can be reduced by lowering the rotational inertia of the turbine, for example by using lighter parts to allow the spool-up to happen more quickly. Ceramic turbines are of benefit in this regard. Unfortunately, their relative fragility limits the maximum boost they can supply. Another way to reduce lag is to change the aspect ratio of the turbine by reducing the diameter and increasing the gas-flow path-length. Increasing the upper-deck air pressure and improving the wastegate response helps but there are cost increases and reliability disadvantages that car manufacturers are not happy about. Lag is also reduced by using a foil bearing rather than a conventional oil bearing. This reduces friction and contributes to faster acceleration of the turbo's rotating assembly. Variable-nozzle turbochargers (discussed below) greatly reduce lag.

Other engines use two turbochargers - a small and a large. Because of its weight, the smaller turbo will have a shorter lag, but when the car is reaching higher speeds, the volume of air going into the inlet manifold will be too high. When the volume of air is becoming too high, the smaller turbo will not be able to provide much boost, and the turbine and compressor will be in danger of spinning too quickly. When this happens, the larger turbocharger will take over, so more boost can be provided.



Porsche variable-geometry turbocharger

Instead of using two turbochargers in different sizes, some engines use a single turbocharger, called variable-geometry or variable-nozzle turbos, these turbos use a set of vanes in the exhaust housing to maintain a constant gas velocity across the turbine, the same kind of control as used on power plant turbines. Such turbochargers have minimal lag like a small conventional turbocharger and can achieve full boost as low as 1,500 engine rpm, yet remain efficient as a large conventional turbocharger at higher engine speeds. In many setups these turbos do not use a wastegate. The vanes are controlled by a membrane identical to the one on a wastegate, but the mechanism operates the variable vane system instead. These variable turbochargers are commonly used in diesel engines.

Lag is not to be confused with the boost threshold. The boost threshold of a turbo system describes the lower bound of the region within which the compressor will operate. Below a certain rate of flow at any given pressure multiplier, a given compressor will not produce significant boost. This has the effect of limiting boost at particular rpm regardless of exhaust gas pressure. Newer turbocharger and engine developments have caused boost thresholds to steadily decline.

Electrical boosting ("E-boosting") is a new technology under development; it uses a high speed electrical motor to drive the turbocharger to speed before exhaust gases are available, *e.g.* from a stop-light. An alternative to e-boosting is to completely separate the turbine and compressor into a turbine-generator and electric-compressor as in the hybrid turbocharger. This allows the compressor speed to become independent to that of the turbine. A similar system utilising a hydraulic drive system and overspeed clutch arrangement was fitted in 1981 to accelerate the turbocharger of the MV *Canadian Pioneer* (Doxford 76J4CR engine).

Race cars often utilize an Anti-Lag System to completely eliminate lag at the cost of reduced turbocharger life.

Boost threshold

Turbochargers start producing boost only above a certain exhaust mass flow rate. The boost threshold is determined by the engine displacement, rpm, throttle opening and the size of the turbo. Without adequate exhaust gas flow to spin the drive blades, the turbo cannot produce the necessary force needed to compress the air going into the engine. The point at full throttle in which the mass flow in the exhaust is strong enough to force air into the engine is known as the boost threshold rpm. Engineers have, in some cases, been able to reduce the boost threshold rpm to idle speed to allow for instant response. Both Lag and Threshold characteristics can be acquired through the use of a compressor map and a mathematical equation.