

Handbook of  
Diesel, Automobile and Piston  
Engines



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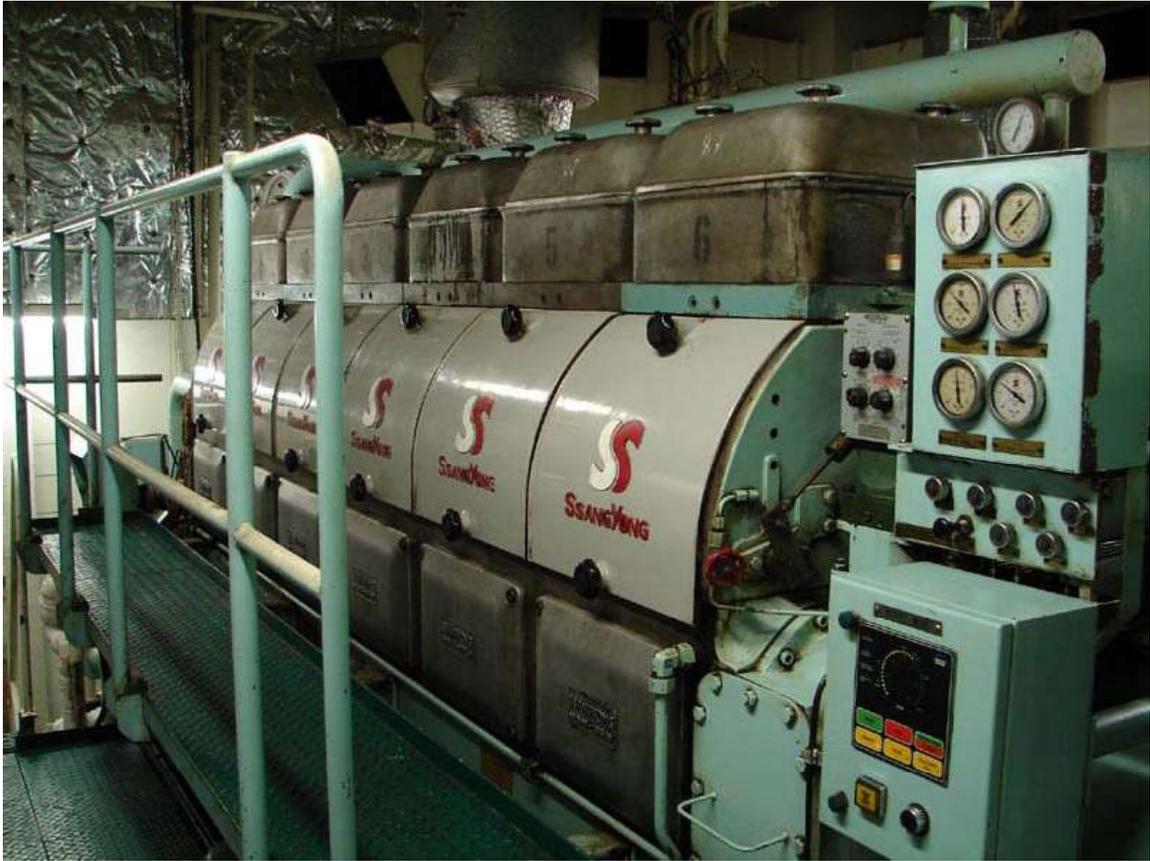
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## Chapter- 1

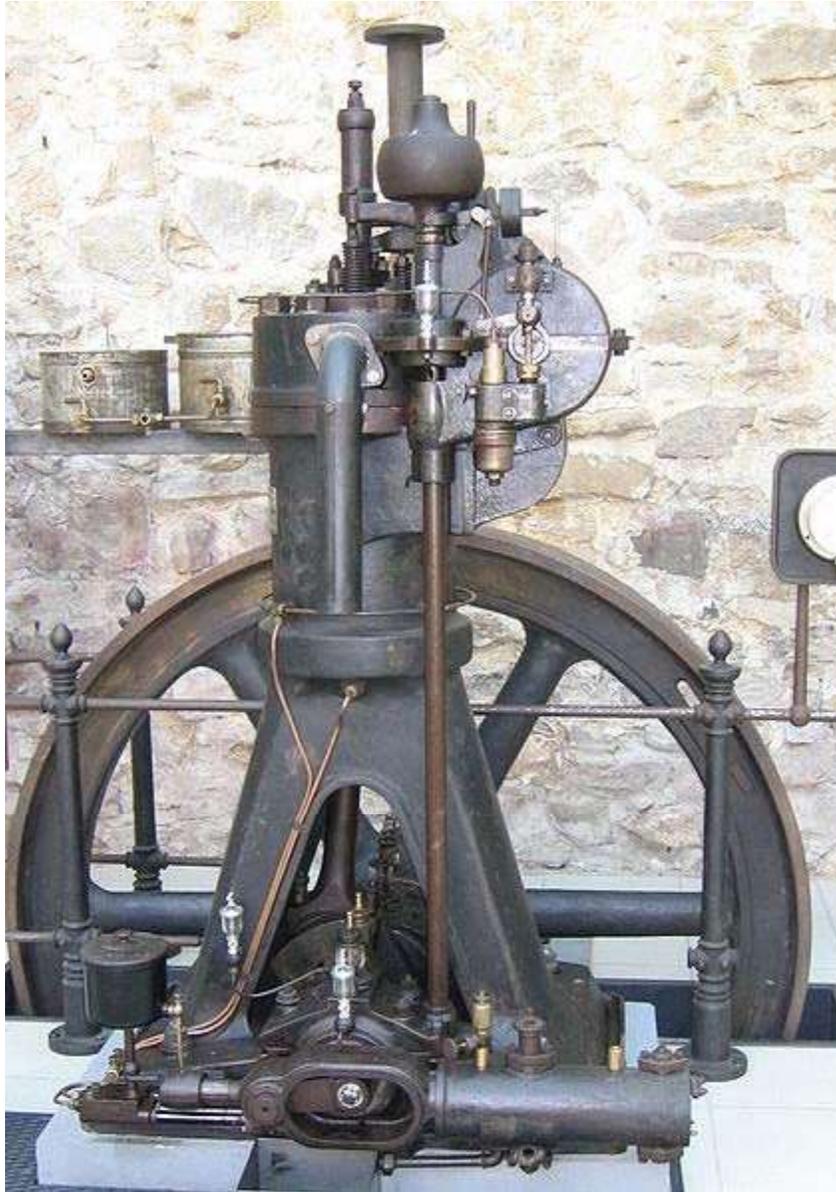
# Diesel Engine



Diesel engines in a museum



Diesel generator on an oil tanker



A diesel engine built by MAN AG in 1906

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

The diesel engine has the highest thermal efficiency of any regular internal or external combustion engine due to its very high compression ratio. Low-speed diesel engines (as

used in ships and other applications where overall engine weight is relatively unimportant) often have a thermal efficiency which exceeds 50 percent.

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

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

## ***History***

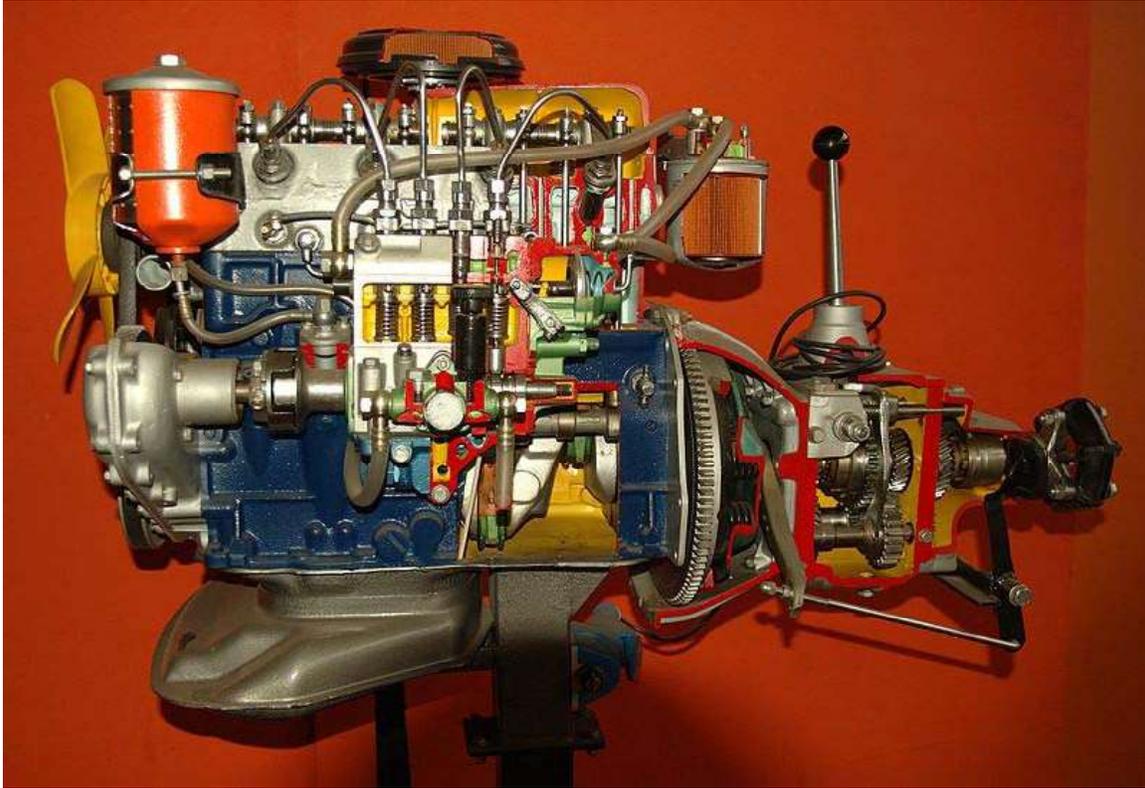
Rudolf Diesel, of German ethnicity, was born in 1858 in Paris where his parents were German immigrants. He was educated at Munich Polytechnic. After graduation he was employed as a refrigerator engineer, but his true love lay in engine design. Diesel designed many heat engines, including a solar-powered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

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

At Augsburg, on August 10, 1893, Rudolf Diesel's prime model, a single 10-foot (3.0 m) iron cylinder with a flywheel at its base, ran on its own power for the first time. Diesel spent two more years making improvements and in 1896 demonstrated another model with a theoretical efficiency of 75 percent, in contrast to the 10 percent efficiency of the steam engine. By 1898, Diesel had become a millionaire. His engines were used to power

pipelines, electric and water plants, automobiles and trucks, and marine craft. They were soon to be used in mines, oil fields, factories, and transoceanic shipping.

### ***How diesel engines work***



Diesel engine model, left side



Diesel engine model, right side

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

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

crankshaft. Engines for scale-model aeroplanes use a variant of the Diesel principle but premix fuel and air via a carburation system external to the combustion chambers.

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

## **Early fuel injection systems**

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

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

## **Fuel delivery**

A vital component of all diesel engines is a mechanical or electronic governor which regulates the idling speed and maximum speed of the engine by controlling the rate of fuel delivery. Unlike Otto-cycle engines, incoming air is not throttled and a diesel engine without a governor cannot have a stable idling speed and can easily overspeed, resulting in its destruction. Mechanically governed fuel injection systems are driven by the engine's gear train. These systems use a combination of springs and weights to control fuel delivery relative to both load and speed. Modern electronically controlled diesel engines control fuel delivery by use of an electronic control module (ECM) or electronic control unit (ECU). The ECM/ECU receives an engine speed signal, as well as other

operating parameters such as intake manifold pressure and fuel temperature, from a sensor and controls the amount of fuel and start of injection timing through actuators to maximise power and efficiency and minimise emissions. Controlling the timing of the start of injection of fuel into the cylinder is a key to minimizing emissions, and maximizing fuel economy (efficiency), of the engine. The timing is measured in degrees of crank angle of the piston before top dead centre. For example, if the ECM/ECU initiates fuel injection when the piston is 10 degrees before TDC, the start of injection, or timing, is said to be 10° BTDC. Optimal timing will depend on the engine design as well as its speed and load.

Advancing the start of injection (injecting before the piston reaches to its SOI-TDC) results in higher in-cylinder pressure and temperature, and higher efficiency, but also results in elevated engine noise and increased oxides of nitrogen (NO<sub>x</sub>) emissions due to higher combustion temperatures. Delaying start of injection causes incomplete combustion, reduced fuel efficiency and an increase in exhaust smoke, containing a considerable amount of particulate matter and unburned hydrocarbons.

### **Major advantages**

Diesel engines have several advantages over other internal combustion engines:

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



Bus powered by **biodiesel**

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

### **Mechanical and electronic injection**

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

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

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

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

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

## **Indirect injection**

An indirect injection diesel engine delivers fuel into a chamber off the combustion chamber, called a pre-chamber or ante-chamber, where combustion begins and then spreads into the main combustion chamber, assisted by turbulence created in the chamber. This system allows for a smoother, quieter running engine, and because combustion is assisted by turbulence, injector pressures can be lower, about 100 bar (10 MPa; 1,500 psi), using a single orifice tapered jet injector. Mechanical injection systems allowed high-speed running suitable for road vehicles (typically up to speeds of around 4,000 rpm). The pre-chamber had the disadvantage of increasing heat loss to the engine's cooling system, and restricting the combustion burn, which reduced the efficiency by 5–10 percent. Indirect injection engines were used in small-capacity, high-speed diesel engines in automotive, marine and construction uses from the 1950s, until

direct injection technology advanced in the 1980s. Indirect injection engines are cheaper to build and it is easier to produce smooth, quiet-running vehicles with a simple mechanical system. In road-going vehicles most prefer the greater efficiency and better controlled emission levels of direct injection. Indirect injection diesels can still be found in the many ATV diesel applications.

## **Direct injection**

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

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

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

## **Unit direct injection**

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

## **Common rail direct injection**

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

## Cold weather

### Starting

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

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

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

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

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

### Gelling

Diesel fuel is also prone to *waxing* or *gelling* in cold weather; both are terms for the solidification of diesel oil into a partially crystalline state. The crystals build up in the fuel line (especially in fuel filters), eventually starving the engine of fuel and causing it to stop running. Low-output electric heaters in fuel tanks and around fuel lines are used to solve this problem. Also, most engines have a *spill return* system, by which any excess

fuel from the injector pump and injectors is returned to the fuel tank. Once the engine has warmed, returning warm fuel prevents waxing in the tank. Due to improvements in fuel technology with additives, waxing rarely occurs in all but the coldest weather when a mix of diesel and kerosene should be used to run a vehicle.

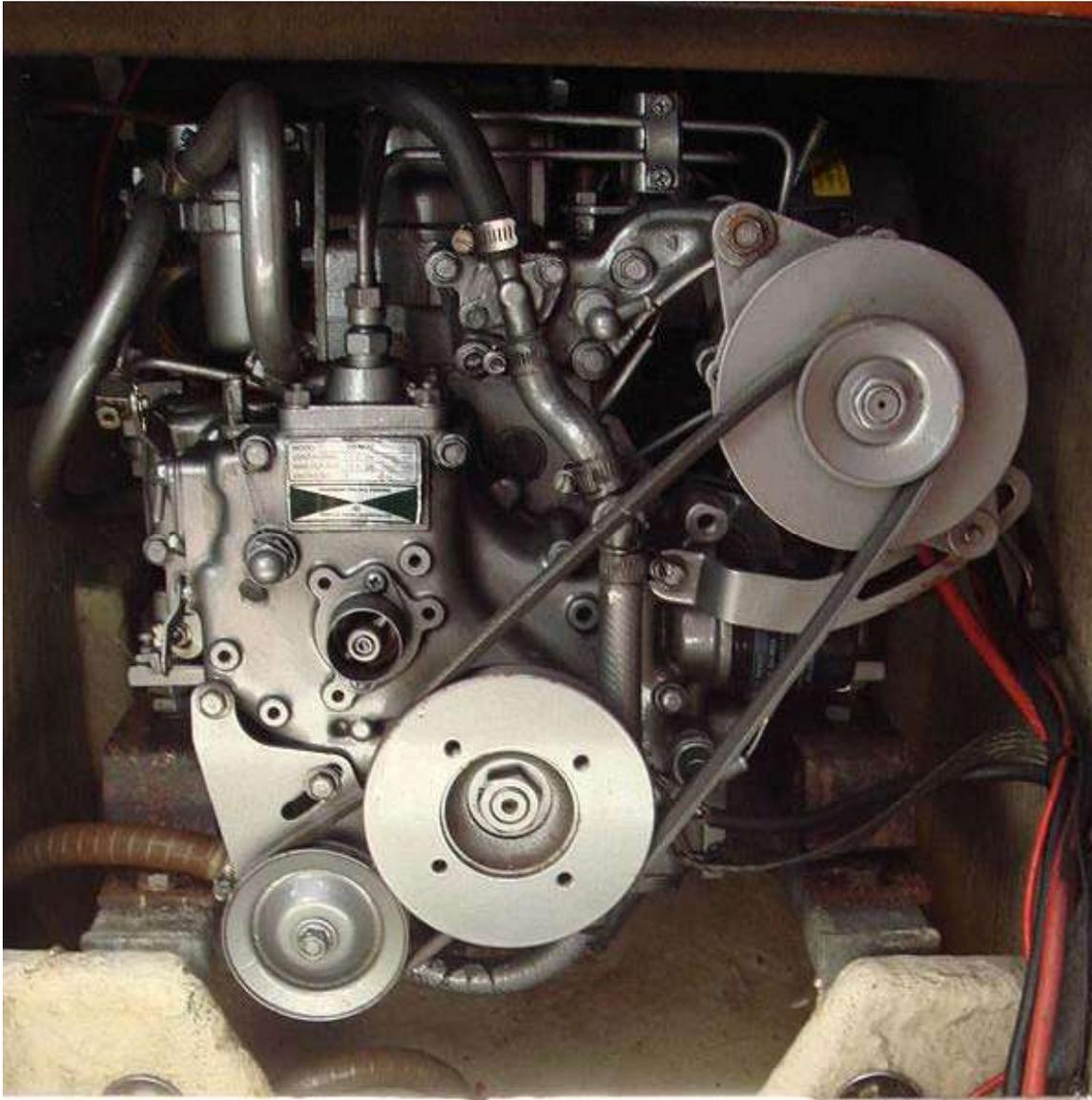
## **Types**

### **Early**

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

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

## Modern



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

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

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

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

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

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

### **Gas generator**

Before 1950, Sulzer started experimenting with two-stroke engines with boost pressures as high as 6 atmospheres, in which all the output power was taken from an exhaust gas

turbine. The two-stroke pistons directly drove air compressor pistons to make a positive displacement gas generator. Opposed pistons were connected by linkages instead of crankshafts. Several of these units could be connected to provide power gas to one large output turbine. The overall thermal efficiency was roughly twice that of a simple gas turbine. This system was derived from Raúl Pateras Pescara's work on free-piston engines in the 1930s.

## ***Advantages and disadvantages versus spark-ignition engines***

### **Power and fuel economy**

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

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

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

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

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

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

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

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

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

The increased fuel economy of the diesel engine over the petrol engine means that the diesel produces less carbon dioxide (CO<sub>2</sub>) per unit distance. Recent advances in production and changes in the political climate have increased the availability and

awareness of biodiesel, an alternative to petroleum-derived diesel fuel with a much lower net-sum emission of CO<sub>2</sub>, due to the absorption of CO<sub>2</sub> by plants used to produce the fuel. Although concerns are now being raised as to the negative effect this is having on the world food supply, as the growing of crops specifically for biofuels takes up land that could be used for food crops and uses water that could be used by both humans and animals. The use of waste vegetable oil, sawmill waste from managed forests in Finland, and advances in the production of vegetable oil from algae demonstrate great promise in providing feed stocks for sustainable biodiesel that are not in competition with food production.

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

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

## **Emissions**

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

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

them using extra fuel injected directly into the filter. This prevents carbon buildup at the expense of wasting a small quantity of fuel.

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

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

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

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

## **Power and torque**

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

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

## **Noise**

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

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

## **Reliability**

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

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

Either an electrical starter or an air-start system is used to start the engine turning. On large engines, pre-lubrication and slow turning of an engine, as well as heating, are

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

## Quality and variety of fuels

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

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

Diesel fuel is a form of light fuel oil, very similar to kerosene/paraffin, but diesel engines, especially older or simple designs that lack precision electronic injection systems, can run on a wide variety of other fuels. Some of the most common alternatives are Jet A-1 type jet fuel or vegetable oil from a very wide variety of plants. Some engines can be run on vegetable oil without modification, and most others require fairly basic alterations. Biodiesel is a pure diesel-like fuel refined from vegetable oil and can be used in nearly all diesel engines. Requirements for fuels to be used in diesel engines are the ability of the fuel to flow along the fuel lines, the ability of the fuel to lubricate the injector pump and injectors adequately, and its ignition qualities (ignition delay, cetane number). Inline mechanical injector pumps generally tolerate poor-quality or bio-fuels better than

distributor-type pumps. Also, indirect injection engines generally run more satisfactorily on bio-fuels than direct injection engines. This is partly because an indirect injection engine has a much greater 'swirl' effect, improving vaporisation and combustion of fuel, and because (in the case of vegetable oil-type fuels) lipid depositions can condense on the cylinder walls of a direct-injection engine if combustion temperatures are too low (such as starting the engine from cold).

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

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

### ***Fuel and fluid characteristics***

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

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

Pure plant oils are increasingly being used as a fuel for cars, trucks and remote combined heat and power generation especially in Germany where hundreds of decentralised small-

and medium-sized oil presses cold press oilseed, mainly rapeseed, for fuel. There is a Deutsches Institut für Normung fuel standard for rapeseed oil fuel.

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

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

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

## **Safety**

### **Fuel flammability**

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

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

The United States Army and NATO use only diesel engines and turbines because of fire hazard. Although neither Gasoline nor Diesel is explosive in liquid form, both can create an explosive air/vapor mix under the right conditions. However, Diesel fuel is less prone

due to its lower vapor pressure, which is an indication of evaporation rate. The Material Safety Data Sheet for Ultra-Low Sulfur Diesel fuel indicates a vapor explosion hazard for Diesel indoors, outdoors, or in sewers.

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

### **Maintenance hazards**

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

### ***Diesel applications***

The characteristics of diesel have different advantages for different applications.

#### **Passenger cars**

Diesel engines have long been popular in bigger cars and this is spreading to smaller cars. Diesel engines tend to be more economical at regular driving speeds and are much better at city speeds. Their reliability and life-span tend to be better (as detailed). Some 40% or more of all cars sold in Europe are diesel-powered where they are considered a low CO<sub>2</sub> option. Mercedes-Benz in conjunction with Robert Bosch GmbH produced diesel-powered passenger cars starting in 1936 and very large numbers are used all over the world (often as "Grande Taxis" in the Third World).

#### **Railroad rolling stock**

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

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

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

## **Other transport uses**

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

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

## **Military fuel standardisation**

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

## **Engine speeds**

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

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

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

## **High-speed engines**

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

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

## **Medium-speed engines**

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

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

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

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

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

## Low-speed engines



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

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

Large and medium marine engines are started with compressed air directly applied to the pistons. Air is applied to cylinders to start the engine forwards or backwards because they are normally directly connected to the propeller without clutch or gearbox, and to provide reverse propulsion either the engine must be run backwards or the ship will utilise an

adjustable propeller. At least three cylinders are required with two-stroke engines and at least six cylinders with four-stroke engines to provide torque every 120 degrees.

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

### ***Supercharging and turbocharging***

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

### ***Other applications***

- Aircraft diesel engine
- Motorcycles

## ***Current and future developments***

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

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

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

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

## Chapter- 2

# Indirect Injection and Unit Injector

## Indirect injection

In an internal combustion engine, the term **indirect injection** refers to a fuel injection where fuel is not directly injected into the combustion chamber. Gasoline engines are usually equipped with indirect injection systems, wherein a fuel injector delivers the fuel at some point before the intake valve.

An indirect injection diesel engine delivers fuel into a chamber off the combustion chamber, called a prechamber, where combustion begins and then spreads into the main combustion chamber. The prechamber is carefully designed to ensure adequate mixing of the atomized fuel with the compression-heated air. This has the effect of slowing the rate of combustion, which tends to reduce audible noise and softens the shock of combustion and produces lower stresses on the engine components. The addition of a prechamber, however, increases heat loss to the cooling system and thereby lowers engine efficiency. The engine requires glow plugs for starting. In an indirect injection system the air moves fast, mixing the fuel and air. This simplifies injector design and allows the use of smaller engines and less tightly toleranced designs which are simpler to manufacture and more reliable. Direct injection, by contrast, uses slow-moving air and fast-moving fuel; both the design and manufacture of the injectors is more difficult. The optimisation of the in-cylinder air flow is much more difficult than designing a prechamber. There is much more integration between the design of the injector and the engine. It is for this reason that car diesel engines were almost all indirect injection until the ready availability of powerful CFD simulation systems made the adoption of direct injection practical.

Aside from the above advantages, early diesels often employed indirect injection in order to use simple, flat-top pistons. This also made the positioning of the early, bulky diesel injectors easier.

## ***Classification of indirect combustion chambers (prechambers)***

### **Swirl chamber**

It consists of a spherical chamber located in the cylinder head and separated from the engine cylinder by a tangential throat. About 50% of the air enters the swirl chamber during the compression stroke of the engine, producing a swirl.

After combustion, the products return through the same throat to the main cylinder at much higher velocity. So more heat loss to walls of the passage takes place. This type of chamber finds application in engines in which fuel control and engine stability are more important than fuel economy. These are Ricardo chambers.

### **Precombustion chamber**

This chamber is located at the cylinder head and is connected to the engine cylinder by small holes. It occupies 40% of the total cylinder volume. During the compression stroke, air from the main cylinder enters the precombustion chamber. At this moment, fuel is injected into the precombustion chamber and combustion begins. Pressure increases and the fuel droplets are forced through the small holes into the main cylinder, resulting in a very good mix of the fuel and air. The bulk of the combustion actually takes place in the main cylinder. This type of combustion chamber has multi-fuel capability because the temperature of the prechamber vaporizes the fuel before the main combustion event occurs.

### **Air cell chamber**

The air cell is a small cylindrical chamber with a hole in one end. It is mounted more or less coaxially with the injector, said axis being parallel to the piston crown, with the injector firing across a small cavity which is open to the cylinder into the hole in the end of the air cell. The air cell is mounted so as to minimise thermal contact with the mass of the head. A pintle injector with a narrow spray pattern is used. At TDC the majority of the charge mass is contained in the cavity and air cell.

When the injector fires the jet of fuel enters the air cell and ignites. This results in a jet of flame shooting back out of the air cell directly into the jet of fuel still issuing from the injector. The heat and turbulence give excellent fuel vaporisation and mixing properties. Also since the majority of the combustion takes place outside the air cell in the cavity, which communicates directly with the cylinder, there is less heat loss involved in transferring the burning charge into the cylinder.

Air cell injection can be considered as a sort of half way stage between fully indirect and fully direct injection, gaining some of the efficiency advantages of direct injection while retaining the simplicity and ease of development of indirect injection.

Air cell chambers are commonly named Lanova air chambers.

## ***Advantages of indirect injection combustion chambers***

1. Smaller diesels can be produced.
2. The injection pressure required is low, so the injector is cheaper to produce.
3. The injection direction is of less importance.
4. Indirect injection is much simpler to design and manufacture; less injector development is required and the injection pressures are low (1500 psi versus 5000 psi and higher for direct injection)
5. The lower stresses that indirect injection imposes on internal components mean that it is possible to produce petrol and indirect injection diesel versions of the same basic engine. At best such types differ only in the cylinder head and the need to fit a distributor and spark plugs in the petrol version whilst fitting an injection pump and injectors to the diesel. Examples include the BMC A-Series and B-Series engines and the Land Rover 2.25/2.5-litre 4-cylinder types. Such designs allow petrol and diesel versions of the same vehicle to be built with minimal design changes between them.
6. Higher engine speeds can be reached, since burning continues in the prechamber. The Mercedes-Benz type prechamber is able to achieve over 6000rpm in a turbocharged engine.

## ***Disadvantages***

1. Specific fuel consumption is high because of heat loss due to large exposed areas and pressure loss due to air motion through the throats.
2. Glowplugs are needed for a cold engine start.
3. Because the heat and pressure of combustion is applied to one specific point on the piston as it exits the precombustion chamber or swirl chamber, such engines are less suited to high specific power outputs (such as turbocharging or tuning) than direct injection diesels. The increased temperature and pressure on one part of the piston crown causes uneven expansion which can lead to cracking, distortion or other damage. This can be solved by designing the pistons to have a slight oval shape so that when heated unevenly they become circular. The higher the power required from a given engine design the greater degree of ovality is required until it becomes impractical. Direct injection engines deliver fuel to the centre of the piston crown, negating these problems.

## ***Maintenance hazards***

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

# Unit Injector

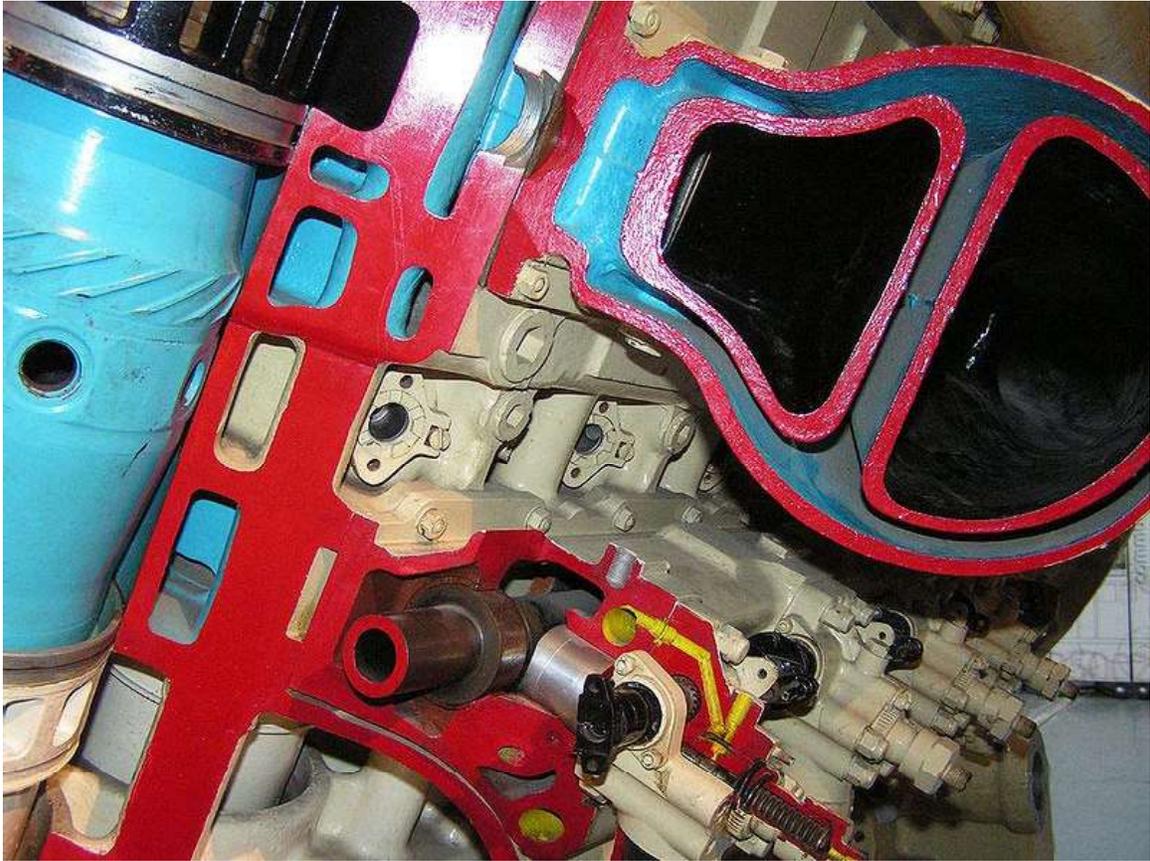


Early Lucas electronic diesel unit injector

**Unit Injector (UI)** is an integrated direct fuel injection system for diesel engines, combining the injector nozzle and the injection pump in a single component. The pump is usually driven by a shared camshaft.

## ***History***

In 1911 a patent was issued in Great Britain for a unit injector resembling those in use today to Frederick Lamplough.



Napier Deltic opposed-piston two-stroke, sectioned. The unit injectors are low down, below the yellow fuel passages, driven by a camshaft to their left and injecting into the centre of the cylinder liner (pale blue).

Commercial usage of unit injectors in the U.S. began in early 1930s on Winton engines powering locomotives, boats, even US Navy submarines,, and in 1934, Arthur Fielden was granted U.S. patent No.1,981,913 on the unit injector design later used for the General Motors two-stroke diesel engines. Most mid-sized diesel engines used a single pump and separate injectors, but some makers, such as Detroit Diesel became well-known for favouring unit injectors.

In 1994, Robert Bosch GmbH supplied the first electronic Unit Injector for commercial vehicles, and other manufacturers soon followed.

Today, major manufacturers include Robert Bosch GmbH, CAT, Cummins, Delphi Corp., Detroit Diesel Allison and the Delphi Corp. acquired Lucas Automotive.

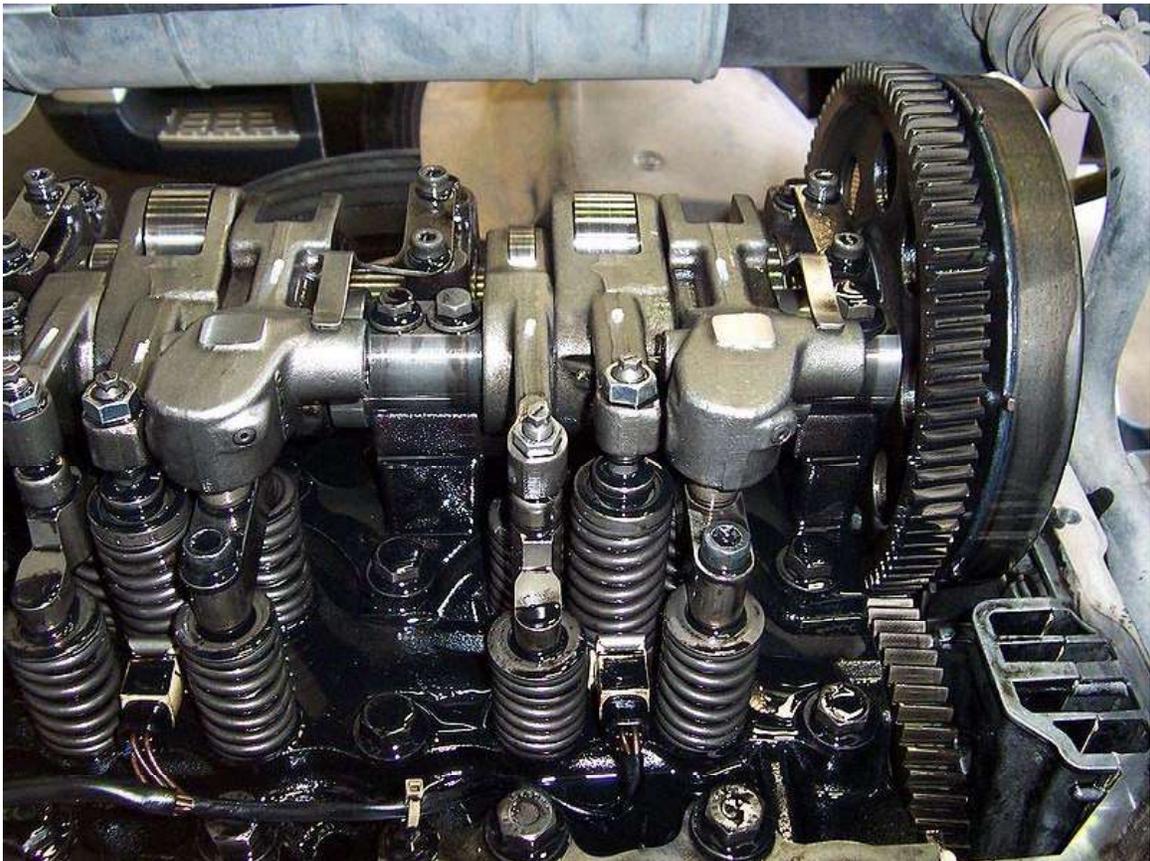
### ***Design and technology***

Design of the Unit Injector eliminates the need for high pressure fuel pipes, and with that their associated failures, as well as allowing for much higher injection pressure to occur.

The unit injector system allows accurate injection timing, and amount control as in the common rail system .

The Unit Injector is fitted into the engine cylinder head, where the fuel is supplied via integral ducts machined directly into the cylinder head. Each injector has its own pumping element, and in the case of electronic control, a fuel solenoid valve as well. The fuel system is divided into the low pressure (<500 kPa) fuel supply system, and the high pressure injection system (<2000 bar).

### ***Operation principle***



Delphi E1 UI on the Volvo D13A engine



Delphi E1 UI parts

The basic operation can be described as a sequence of four separate phases: the *filling phase*, the *spill phase*, the *injection phase*, and the *pressure reduction phase*.

A low pressure fuel delivery pump supplies filtered diesel fuel into the cylinder head fuel ducts, and into each injector fuel port of constant stroke pump plunger injector, which is overhead camshaft operated.

#### Fill phase

The constant stroke pump element on the way up draws fuel from the supply duct in to the chamber, and as long as electric solenoid valve remains de-energized fuel line is open.

#### Spill phase

The pump element is on the way down, and as long as solenoid valve remains de-energized the fuel line is open and fuel flows in through into the return duct.

#### Injection phase

The pump element is still on the way down, the solenoid is now energized and fuel line is now closed. The fuel can not pass back into return duct, and is now compressed by the plunger until pressure exceeds specific "opening" pressure,

and the injector nozzle needle lifts, allowing fuel to be injected into the combustion chamber.

#### Pressure reduction phase

The plunger is still on its way down, the engine ECU de-energizes the solenoid when required quantity of fuel is delivered, the fuel valve opens, fuel can flow back into return duct, causing pressure drop, which in turn causes the injector nozzle needle to shut, hence no more fuel is injected.

#### Summary

The start of an injection is controlled by the solenoid closing point, and the injected fuel quantity is determined by the closing time, which is the length of time the solenoid remains closed. The solenoid operation is fully controlled by the engine ECU.

### ***Additional functions***

The use of electronic control allows for special functions; such as temperature controlled injection timing, cylinder balancing (smooth idle), switching off individual cylinders under part load for further reduction in emissions and fuel consumption, and multi-pulse injection (more than one injection occurrence during one engine cycle).

### ***Further development and applications***

In 1993, CAT introduced "Hydraulically-actuated Electronic Unit Injection" (HEUI), where the injectors are no longer camshaft operated. First available on Navistar's 7.3 litres (445.5 cu in), V8 diesel engine. HEUI uses engine oil pressure to power high pressure fuel injection, where usual method of unit injector operation is the engine camshaft.

Unit injector fuel systems are being used on wide variety of vehicles and engines; commercial vehicle from manufacturers such as Volvo, Cummins, Detroit, CAT, and passenger vehicles from manufacturers such as Land Rover and Volkswagen Group, among others.



Bosch UI on Scania R164 V8

The Volkswagen Group mainstream marques use unit injector systems (branded "**Pumpe Düse**", commonly abbreviated to "**PD**") in their Suction Diesel Injection (SDI) and Turbocharged Direct Injection (TDI) diesel engines.

- In North America, the Volkswagen Jetta, Golf, and New Beetle TDI 2004-2006 are Mk4 Pumpe Düse (newer models use Mk5 BEW engines and older models use ALH engines).

Volkswagen Group major-interest truck and diesel engine maker Scania AB also use the unit injector system, which they call "**Pumpe-Düse-Einspritzung**", or "**PDE**".

## Chapter- 3

# Aircraft Diesel Engine



Thielert Centurion aircraft diesel engine.

The **aircraft diesel engine** or **aero diesel** has not been widely used as an aircraft engine. Diesel engines were used in airships and were tried in aircraft in the late 1920s and 1930s, but never "caught on" in a major fashion. Its main advantage is its excellent specific fuel consumption and the somewhat higher density of its fuel, but these advantages have been outweighed by combination of its inherent disadvantages compared to gasoline-fueled or turboprop engines, and the accidents of history.

The ever-rising cost of avgas and doubts about its future availability have spurred a resurgence in aircraft diesel engine production in recent years.

## ***Development***

### **Early diesel aircraft**

A number of manufacturers built diesel aero engines in the 1920s and 30s; the best known were the Packard air-cooled radial, and the Junkers Jumo 205, which was moderately successful, but proved unsuitable for combat use in World War II.

The first successful diesel engine developed specifically for aircraft was the Packard radial diesel of 1928-29, which was laid out in the familiar air-cooled radial format similar to Wright and Pratt & Whitney designs, and was contemporary with the Beardmore Tornado used in the R101 airship. The use of a diesel had been specified for its low fire risk fuel. The first successful flight of a diesel powered aircraft was made on September 18, 1928 in a Stinson model SM-IDX "Detroit," registration number X7654 (presently owned by Greg Herrick, and based near Minneapolis, Minnesota).

Entering service in the early 1930s, the two-stroke Junkers Jumo 205 opposed-piston engine was much more widely used than previous aero diesels. It was moderately successful in its use in the Blohm & Voss Ha 139 and even more so in airship use. In Britain Napier & Son license-built the 205 as the Napier Culverin, but it did not see production use in this form. A Daimler-Benz diesel engine was also used in Zeppelins, including the ill-fated LZ 129 Hindenburg. This engine proved unsuitable in military applications and subsequent German aircraft engine development concentrated on gasoline and jet engines.

The Soviet World War II-era four-engine strategic bomber Petlyakov Pe-8 was built with Charomskiy ACh-30 diesel engines, but later in the production run diesels were replaced with radial gasoline engines because of efficiency concerns. The Yermolaev Yer-2 long-range medium bomber was also built with Charomskiy diesel engines.

Other manufacturers also experimented with diesel engines in this period, such as the French Bloch (later Dassault Aviation), whose MB203 bomber prototype used Clerget diesels of radial design. The Royal Aircraft Establishment developed an experimental compression ignition (diesel) version of the Rolls-Royce Condor in 1932, flying it in a Hawker Horsley for test purposes.

### **Postwar development**

Interest in diesel engines in the postwar period was sporadic. The lower power-to-weight ratio of diesels, particularly compared to turboprop engines, weighed against the diesel engine. With fuel available cheaply and most research interest in turboprops and jets for high-speed airliners, diesel-powered aircraft virtually disappeared. The near-death of the general aviation market in the 1990s saw a massive decline in the development of any new aircraft engine types.

Napier & Son in Britain had developed the Napier Culverin, a derivative of the Junkers Jumo 205, before World War II, and took up aero diesel engines again in the 1950s. The British Air Ministry supported the development of the 3,000 hp (2,200 kW) Napier Nomad, a combination of piston and turboprop engines, which was exceptionally efficient in terms of brake specific fuel consumption, but judged too bulky and complex and canceled in 1955.

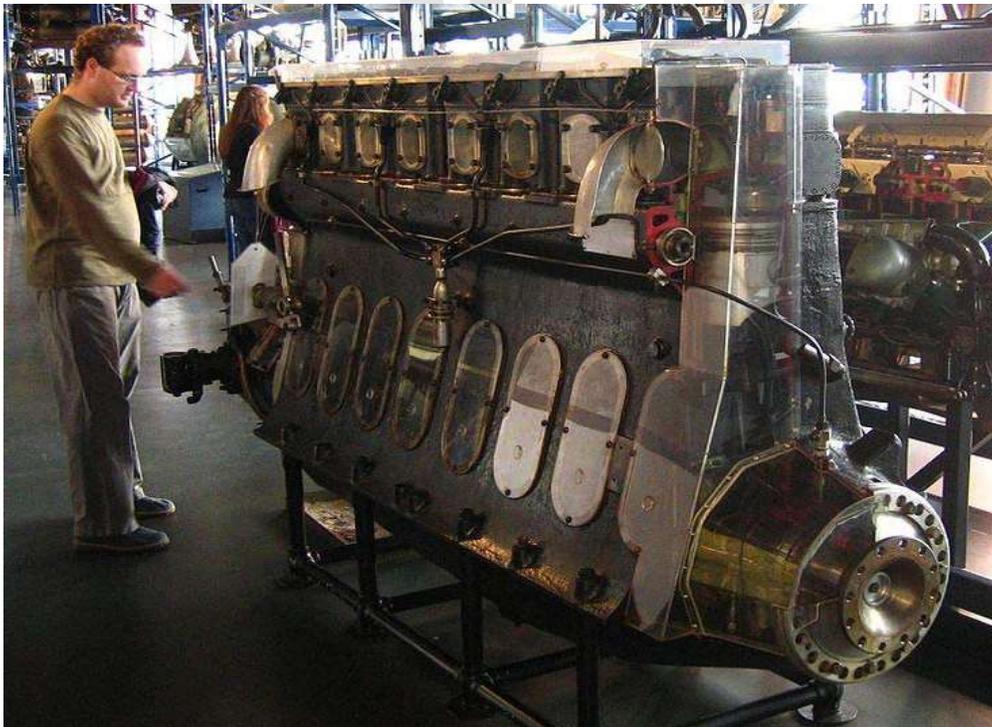
## **Modern developments**

Several factors have emerged to change this equation. First, a number of new manufacturers of general aviation aircraft developing new designs have emerged. Second, in Europe in particular, avgas has become very expensive. Third, in several (particularly remote) locations, avgas is harder to obtain than diesel fuel. Finally, automotive diesel technologies have improved greatly in recent years, offering higher power-to-weight ratios more suitable for aircraft application.

Certified diesel-powered light planes are currently available, and a number of companies are developing new engine and aircraft designs for the purpose. Many of these run on readily-available jet fuel (kerosene), or on conventional automotive diesel.

## **Applications**

### **Airships**



The Beardmore Tornado

The zeppelins LZ 129 *Hindenburg* and LZ 130 *Graf Zeppelin II* were propelled by reversible diesel engines. The direction of operation was changed by shifting gears on the camshaft. From full power forward, the engines could be brought to a stop, changed over, and brought to full power in reverse in less than 60 seconds.

Nevil Shute Norway wrote that the demonstration flight of the airship R100 was changed from India to Canada, *when she got petrol engines, because it was thought that a flight to the tropics with petrol on board would be too hazardous. It is curious after over twenty years to recall how afraid everyone was of petrol in those days (c. 1929), because since then aeroplanes with petrol engines have done innumerable hours of flying in the tropics, and they don't burst into flames on every flight. I think the truth is that everyone was diesel-minded in those days; it seemed as if the diesel engine for aeroplanes was only just around the corner, with the promise of great fuel economy.*

Hence, the ill-fated diesel-engined R101 — which crashed in 1930 — was to fly to India, though her diesel engines had petrol starter engines, and there had only been time to replace one with a diesel starter engine. The R101 used the Beardmore Tornado aero diesel engine, with two of the five engines reversible by an adjustment to the camshaft. This engine was developed from an engine used in railcars.

## **Modern (21st century) aircraft diesel engine manufacturers**

### **Germany**

The first manufacturer to produce a certified design for the general aviation market was Thielert, located in the small town of Lichtenstein in the German state of Saxony. They produce four-stroke, liquid-cooled, geared, turbo-diesel aircraft engines based on Mercedes automotive designs which will run on both diesel and jet aviation fuel (Jet A-1). Their first engine, a 1.7 litres (100 cu in), 135 hp (101 kW) four-cylinder (based on the 1.7 turbo diesel Mercedes A-class power unit), was first certified in 2002. It is certified for retrofitting to Cessna 172s and Piper Cherokees which were originally equipped with the 160 hp (120 kW) Lycoming O-320 320 cubic inches (5.2 l) Avgas engine. Although the weight of the 135 hp (101 kW) Thielert Centurion 1.7 at around 136 kilograms (300 lb) is similar to that of the 160 hp (120 kW) Lycoming O-320, its displacement is less than a third of that of the Lycoming. It however achieves maximum power at 2300 prop rpm (3900 crank rpm) as opposed to 2700 for the petrol Lycoming.

Thielert users included Austrian aircraft firm Diamond Aircraft Industries, which offered its single-engine Diamond DA40-TDI Star with a Thielert Centurion 1.7' engine, and also the Twin Star with two. The twin-Thielert engined Star offered low fuel consumption with a high fuel efficiency of 15.1 l/h. Several hundred Thielert-powered airplanes are flying. There was also a certified a 4.0-litre, V8, 310 hp (230 kW) version available from 2005. Apex aircraft, formerly Robin, also offered an aircraft (Ecoflyer) with the Thielert engine.

In May 2008, Thielert went bankrupt. Although Bruno M. Kubler, Thielert's insolvency administrator, was able to announce in January 2009 that the company was "in the black and working to capacity," by then Cessna had dropped plans to install Thielert engines in some models, and Diamond Aircraft has now developed its own in-house diesel engine.

## **France**

SMA Engines, located in Bourges, 150 km south of Paris have designed a four-stroke, air-cooled, turbo-diesel aircraft engine from the ground up, the SR305-230. SMA's engineering team came from Renault Sport (Formula 1). The 230 hp (170 kW), 305 cubic inch (5.0 liter) jet fuel engine first obtained European certification in April 2001, followed by US FAA certification in July 2002. It is now certified as retrofit on several Cessna 182 models in Europe and the USA, and Maule is working toward certification of the M-9-230.

## **United States**

Interest in diesel aircraft in the United States has been more limited, due to its lower fuel taxes. However, doubt about the future availability of avgas has raised awareness of diesel alternatives. In March 2008 the Indus Aviation team led by Aldo Sibi (Director Of Production- Chief Mechanic – Head of Research and Development) prototyped the world's first diesel powered Light Sport Aircraft, N211GD. This airplane was built and flown in 30 days. This novel aircraft, although a prototype, sparked huge interest in alternative fuels in the industry. Mr. Sibi and his team also championed no less than 70 modifications and improvements. After the diesel project Mr. Sibi and his team took Indus to the next level developing the Primary Trainer. This was an attractive low cost trainer that competed very well with the high-end imports from over seas.

## **Experimental engine manufacturers**

A number of other manufacturers are currently developing experimental diesel engines, many using aircraft-specific designs rather than adapted automotive engines. Many are using two-stroke designs, with some opposed-piston layouts directly inspired by the original Junkers design. Examples include:

- Diesel Air Limited, a British company who are developing a 100 hp (75 kW) twin-cylinder (therefore four-piston), two-stroke opposed-piston engine inspired by the original Junkers design. Their engine has flown in test aircraft and airship installations. Unlike the Junkers, it is made for horizontal installation with a central output shaft for the geared cranks, the overall installed shape thereby approximately resembling a four stroke flat-four engine.
- Powerplant Developments, a British company developing a 100 hp (75 kW) opposed-piston engine called the Gemini 100 that resembles the Diesel Air Limited engine and uses the Junkers twin-crank principle, again for horizontal installation with a central output shaft for the geared cranks. However, the Gemini 100 is a three-cylinder (therefore six-piston) engine. Like Diesel Air Limited,

Powerplant Developments claim to be using Weslake Air Services for production. They have recently announced that Tecnam will test a prototype with the Gemini engine.

- Wilksch Airmotive, a British company who are developing/producing a 120 hp (89 kW) three-cylinder (WAM-120) two-stroke diesel and are working on a four-cylinder 160 hp (120 kW) design (WAM-160). In 2007 Wilksch claimed that they had completed multiple tests on the WAM-100 LSA in accordance with ASTM F 2538 - the WAM-100 LSA is a derated WAM-120. Wilksch originally showed a two-cylinder prototype alongside the three- and four-cylinder models. By mid-2009, approximately 40 WAM-120 units had been sold, with around half currently flying. The British owner of a RANS RV-9A fitted with a WAM-120 reports getting 125 knots (232 km/h) TAS at 6,000 ft (1,800 m) on 15 litre/hr of jet A1 fuel. A Rutan LongEz canard-pusher (G-LEZE) has also flown with the WAM120 engine with test flights showing a TAS of 160 kn (300 km/h) at 11,000 ft (3,400 m) and 22ltrs per hour. At economy cruise of 125 knots (232 km/h) at 2,000 ft (610 m) the fuel consumption is 12 ltrs/hr giving a range of 1,890 nautical miles (3,500 km)
- Raptor Turbo Diesel LLC, an American company currently developing the Raptor 105 diesel engine. It is a four-stroke inline turbo charged engine. Known as Vulcan Aircraft Engines until September 2007.
- DeltaHawk Engines, an American company currently developing V-4, 160, 180 and 200 horsepower (150 kW) designs. Also using a two-stroke, ported design, they have also flown a prototype engine in a pusher configuration Velocity aircraft and are claiming delivery of non-certified engines since 2005 and hope to achieve certification early in 2011. DeltaHawk engines have a dry oil sump, so they can run in any orientation, upright, inverted or vertical shaft by changing the location of the oil scavenge port. They can also run counter-rotation for installation in twins. A watercooled DeltaHawk engine has been successfully fitted to a Rotorway helicopter, weighing the same as an aircooled petrol engine of similar power and being capable of maintaining that power to 17,000 feet.
- Eco-Motors, a company with sites in Germany and France, which developed an 100 hp (75 kW) aircraft engine based on a small turbocharged automotive diesel.
- GAP Diesel Engine, a NASA development.

Diesel Air Limited, Wilksch and Zoche at least have had considerable problems bringing their prototype designs into production, with delays running into several years. The Diesel Air Limited-powered airship is no longer registered by the Civil Aviation Authority in the UK.

## Chapter- 4

# Diesel-electric Transmission



This Metra EMD F40PH locomotive uses a Diesel-electric transmission designed by EMD.

**Diesel-electric transmission** or **diesel-electric powertrain** is used by a number of vehicle and ship types for providing locomotion.

A diesel-electric transmission system includes a diesel engine connected to an electrical generator, creating electricity that powers electric traction motors. No clutch is required.

Before diesel engines came into widespread use, a similar system, using a petrol (gasoline) engine and called petrol-electric or gas-electric, was sometimes used.

This kind of power transmission is used on railways by diesel electric locomotives and diesel electric multiple units as only electric motors are able to supply full torque at 0 RPM. Diesel-electric systems are also used in submarines and surface ships and some land vehicles.

In some high-efficiency applications, electrical energy may be stored in rechargeable batteries, in which case these vehicles can be considered as a class of hybrid electric vehicle.

## ***Ships***



Siemens Schottel azimuth thrusters

The first diesel motorship was also the first diesel-electric ship, the Russian tanker *Vandal* from Branobel, which was launched in 1903. Steam turbine-electric propulsion has been in use since the 1920s (Tennessee class battleships), using diesel-electric powerplants in surface ships has increased lately. The Finnish coastal defence ship

*Ilmarinen*, laid down in 1929, was among the first surface ships to use diesel-electric transmission. Later, the technology was used in diesel powered icebreakers.

Some modern ships, including cruise ships and icebreakers, use electric motors in pods called azimuth thrusters underneath to allow for 360° rotation, making the ships far more manoeuvrable.

Gas turbines are also used for electrical power generation and some ships use a combination: the *Queen Mary 2* has a set of diesel engines in the bottom of the ship plus two gas turbines mounted near the main funnel; all are used for generating electrical power, including that used to drive the propellers.

## **Submarines**

Early submarines used a direct mechanical connection between the engine and propeller, switching between diesel engines for surface running, and electric motors for submerged propulsion.

True diesel-electric transmissions for submarines were first proposed by the United States Navy's Bureau of Engineering in 1928; instead of driving the propeller directly while running on the surface, the submarine's diesel would instead drive a generator which could either charge the submarine's batteries or drive the electric motor. This meant that motor speed was independent of the diesel engine's speed, and the diesel could run at an optimum and non-critical speed, while one or more of the diesel engines could be shut down for maintenance while the submarine continued to run using battery power. The concept was pioneered in 1929 in the S-class submarines *S-3*, *S-6*, and *S-7* to test the concept. No other navy adopted the system before 1945, though some submarines of the Imperial Japanese Navy used separate diesel generators for low speed running.

In a diesel-electric direct drive arrangement, the (usually single) propeller is driven directly by an electric motor, while two or more diesel-generators provide electric energy for charging the batteries and/or driving the electric motor. This mechanically isolates the noisy engine compartment from the outer pressure hull and reduces the acoustic signature of the submarine. Additionally some nuclear submarines also decouple their reactor room this way, having turbo-electric propulsion driven by reactor steam. Many submarines with diesel and electrical propulsion are mistakenly referred to as "diesel-electric" when they in fact have separately coupled diesel and electric engines.

## **Railways**

In the 1920s, diesel-electric technology first saw limited use in switchers (or *shunters*), locomotives used for moving trains around in railroad yards and assembling and disassembling them. One of the first companies to offer "Oil-Electric" locomotives was the American Locomotive Company (ALCO). The ALCO HH series of diesel-electric switcher entered series production in 1931. In the 1930s, the system was adapted for streamliners, the fastest trains of their day. Diesel-electric powerplants became popular

because they greatly simplified the way motive power was transmitted to the wheels and because they were both more efficient and had greatly reduced maintenance requirements. Direct-drive transmissions can become very complex, considering that a typical locomotive has four or more axles. Additionally, a direct-drive diesel locomotive would require an impractical number of gears to keep the engine within its powerband; coupling the diesel to a generator eliminates this problem. An alternative is to use a torque converter or fluid coupling in a direct drive system to replace the gearbox. Hydraulic transmissions are claimed to be somewhat more efficient than diesel-electric technology.

## ***Road and other land vehicles***

### **Trucks**



The diesel-electric-powered Liebherr T282 dumper

Examples include:

- Large mining machines, such as the Liebherr T 282B dump truck or LeTourneau L-2350 wheel loader.
- NASA's huge Crawler-Transporters.
- Mitsubishi Fuso Canter Eco Hybrid commercial truck.
- International DuraStar Hybrid diesel-electric truck.
- Dodge is conducting fleet tests of a diesel-electric version of the Dodge Sprinter.

## Cars

In the automobile industry, diesel engines in combination with electric transmissions and battery power are being proposed for vehicle drive systems - with some models in production. Examples include

- Citroën C-Cactus
- ZyteK.
- Chevrolet Volt/Opel Flextreme
- The "Third-Millennium Cruiser" was an attempt to commercialize a diesel-electric automobile in the very early 1980s
- Ford Reflex is a diesel hybrid concept car.

## Other land vehicles

Diesel-electric propulsion was tried on some military vehicles, such as tanks. Ferdinand Porsche was the main developer of such drive-trains for military vehicles in World War II Nazi Germany, and created the Elefant tank destroyer and the prototypes of the never-produced, 200-ton class Maus super-heavy tank.

## Buses



MCI diesel electric prototype bus with batteries under the floor

Diesel electric based buses have also been produced, including hybrid systems able to run on and store electrical power in batteries. The two main providers of hybrid systems for diesel-electric transit buses include Allison Transmission and BAE Systems. New Flyer Industries, Gillig Corporation, and North American Bus Industries are major customers for the Allison EP hybrid systems, while Orion Bus Industries is a major customer for the BAE HybriDrive system. Mercedes-Benz makes their own diesel-electric drive system, which is used in their Citaro.

WWT

## Chapter- 5

# IKCO EF Engines

IKCO EF Engines



<b>Manufacturer</b>	Iran Khodro
<b>Also called</b>	National engine
<b>Production</b>	Late 2008-
<b>Configuration</b>	Straight-4
<b>Displacement</b>	1397 - 1648 cc
<b>Cylinder block alloy</b>	Cast iron
<b>Cylinder head alloy</b>	Cast iron
<b>Valvetrain</b>	DOCH
<b>Compression ratio</b>	9.8:1 - 16.5:1
<b>Turbocharger</b>	Single & Twin
<b>Fuel system</b>	MPFI, Diesel Direct Injection &

	CNG Direct Injection(From late 2011)
<b>Fuel type</b>	Petrol, CNG & Diesel
<b>Oil system</b>	Wet sump
<b>Cooling system</b>	Water cooling
<b>Power output</b>	84 PS (62 kW) - 156 PS (115 kW)
<b>Torque output</b>	111 N·m (82 lb·ft) - 300 N·m (221 lb·ft)

**IKCO EF engines** are four cylinders engines. The EF7 series are designed jointly by Iran Khodro Powertrain Company (IPCO) and F.E.V GmbH of Germany. The other models will be designed by IPCO itself. IPCO is the powertrain designing & producing company of Iranian car manufacturer Iran Khodro (IKCO). IKCO aims to supply 800,000 powertrains by 2010.

The first phase of IKCO EF Engines project (EF7 Dual-Fuel) investments were about 80 million US\$.

EF4 & EF7 engines use CNG as their main fuel and they can also use gasoline.

EFD is the first engine of the EF family that is single-fuel. It uses high quality diesel (Euro 4 Quality or better) as fuel.

EF engines share most of their parts between. It was IKCO's aim to reduce costs & providing ease of supplying the parts in the future for after sales services.

The EF family dual-fuel & petrol-fuel engines have achieved the Euro IV emission standard and are able to achieve Euro V emission standard with some minor changes but EFD will be the first engine of the family which comes with the Euro IV emission standard as its first release, and is able to achieve the Euro VI emission standard with some changes.

The most important suppliers for EF engines are INA for sensitive VVT parts & some other mechanical parts, MAHLE which supplies some important parts of the engine family such as Pistons, with Bosch supplying the ECU and electrically controlled pedal and lots of other important sensitive electronic parts. Almost all of the parts (except high-tech & sensitive parts) from World wide well known companies (As mentioned) are producing in Iran under license with the highest required quality for the engines.

Also The German company Bosch had shown interest in assembling the Iranian engine under license. In 2008 IKCO has announced that EF7 is among 3 best CNG-based engines of the world in designing.

## **EF7**

The engine general structure is similar to the Peugeot TU5JP4. It has displacement of 1648 cc with a bore of 78.560 mm and a stroke of 85 mm. Since the introduction of EF7 dual-fuel in 2008 at Engine Expo Stuttgart, Germany, it was a 16-valve engine mobilized with CVVT technology on its intake valves (IPS kind).

It features an advanced cooling system (Including lubrication and water cooling) compared to lots of same-level new engines in the world & also the TU5JP4 (The EF7 is mobilized with direct driven oil pump). The water pump, oil pump and oil coolant system are all integrated in one place to remove two other parts of the engine compared to lots of other engines. Some other unnecessary parts are removed to reach the goal providing an ease to change the oil filter.

The engines will use a Three way Catalytic Converter to reach higher emission standards.

All the EF7 variants have passed the NVH tests successfully on their head cylinder & cylinder block. Also, the engines have a Blow-by system which does ventilation for the Crankcase and **Oil Pan**.

### **EF7 Dual-Fuel**



EF7 Dual-Fuel engine (Rear view)



EF7 Dual-Fuel engine (Front view)  
Without intake Manifold

Reaches maximum power at 6000 rpm and the maximum torque at 3250 rpm in both CNG and petrol using conditions.

The engine has an amazing timing belt change interval of **180,000 Km** as IKCO has announced. IKCO has guaranteed that if the engine runs only on CNG it won't need any special maintenance until 250,000 km(average) and if the engine runs with both CNG and gasoline the number will increase to more than 250,000 km.

Due to lack of possibility and so many requests for single-fuel Samand with EF7 engine and lack of readying the EF7 Petrol-Based engine, In late 2009 IKCO wanted IP-CO to start a project for removing CNG-necessary parts of the engine. So the project done in about 3 months and tests completed in 2nd quarter of 2010. In this version of engine, only

ECU Program is changed & CNG functions are disabled; This ECU program supports immobiliser too. Currently, consumers are able to purchase Samand EF7 single-fuel.

In September 2010, IKCO announced the design and production of a modified EF7 engine with reduced fuel consumption & air pollution. The engine is mobilized with Direct Injection technology for both petrol & CNG.

As the IPCO president says after the new engine is produced, IKCO will be the first manufacturer in the world using the Direct Injection technology for CNG engines.

In fact, with the completion of the project a new kind of direct injection technology will be introduced which will be called CNG direct injection.

### **Technical details**

- ECU: Bosch ME 7.4.9NG
- Coil ignition: Bosch P-50
- Spark plugs: Bosch FR8DE+
- Gasoline Fuel Injectors: Bosch
- CNG Fuel Injectors: Benteler
- CNG Fuel Rail: Benteler
- Gasoline Fuel Rail: Benteler
- Upstream Oxygen Sensor: Bosch
- Downstream Oxygen Sensor: Bosch
- TMAP Sensor: Bosch
- Accelerator Pedal: Bosch
- ETC: Bosch
- Recommended Fuel: Normal CNG & Unleaded Gasoline RON 95
- Recommended Engine Lubricant: Total Quartz 7000 Semi-Synthetic (10W-40 SL) or Behran Super Pishtaz Semi-Synthetic (10W-40 SL)
- Timing Belt: INA
- Alternator Belt: INA
- Idlers Pulleys: INA
- HLA Tappets: INA
- Check Valve: INA
- Automatic Tensioner: INA
- CVVT Mechanism Parts: INA
- CVVT Control Valve: INA
- IPS Tensioner Valve: INA
- CVVT Closing Plug: INA
- Steel Pulley: INA
- Intake Valves: TBD
- Exhaust Valves: TBD
- Engine Starter: Valeo
- Engine Alternator: Valeo
- Flywheel: TBD
- Clutch Kit: Valeo
- Pistons: MAHLE

- Cylinder head: Continental Engine Ltd
- Intake Manifold: Continental Engine Ltd
- Engine Housings: Tara Zob Company
- Engine Mounters: TBD
- Weight: 140 kg

**Parts image**



EF7 Dual-Fuel engine piston



EF7 Cylinder head  
(Another view)



EF7 Intake Manifold

### **EF7 turbocharged**

A new variant of the EF7 family was introduced in 2009 using a turbocharger. It will initially install on Soren ELX and is named **EF7TC**.

To resist to the high temperature of the engine combustion there will be about 35 kg of nickel used in the cylinder block alloy.

In addition, a new lubricant will produce for the engine by the Company, Behran Oil.

IP-Co has estimated the engine's life cycle to be around 10 years.

### **EF7 petrol based**

In an interview with one of the EF7 project managers, the manager confirmed the rumors of coming a new EF7 engine.

The project of the new engine is currently on its first phases and at the end, there will be an EF7 fully compatible with gasoline.

The new engine will name **EF7NE**(maybe the name changes in the future) and will have many changes compared to the EF7 dual-fuel engine. Some of the changes will be: Reducing the engine compression ratio from 11:1 to 10.5:1, replacing parts that are resistant & compatible to high temperature of combustion of CNG with parts with weaker resistance to reduce production costs(New parts are fully compatible with the temperature rising from combustion of petrol) and some other changes

In addition, EF7NE will use a newer ECU program and functions

Another changed part of the engine compared to his father EF7, will be the catalytic converter. The change is due to making the engine to petrol-based and there is no need to use a CNG-compatible catalytic converter for the engine.

The engine output is estimated to be between 118 PS (87 kW)-126 PS (93 kW). It depends on the company strategy, decisions & plans.

It is expected that the engine will be shown to the public in mid 2011.

## Performance

Variant	Power	Torque	Production since	Utilization on	Compression Ratio	FC(Urban)	FC(Combined)	FC(Extra Urban)	Notes
EF7	114 PS (84 kW)	155 N·m (114 lb·ft)	Early 2009	Samand	11:1	8.9 L, 7Kg*	6.9 L, 6.1 kg	4.9 L 3.9 kg	16-valve, DOHC, HLA Tappets, CVVT, MPFI, Catalytic converter
	CNG: 103 PS (76 kW) at 6000 rpm	CNG: 136 N·m (100 lb·ft) 3500-4500 rpm		Soren ELX IKCO Runna					
EF7TC	149 PS (110 kW) at 5500 rpm	215 N·m (159 lb·ft) 2200-4800 rpm	Late 2010	Soren ELX	9.8:1	TBD	7.2 L	TBD	16-valve, DOHC, HLA Tappets, CVVT, MPFI, Turbocharger, Catalytic converter

- \*Kg for CNG fuel

## EF4

EF4 has displacement of 1397 cc with a bore of TBD mm and a stroke of TBD mm. The engine introduced to public in 2009 in Iran. It uses the EF7 cylinder head.

The engine reaches maximum power at 6000 rpm and the maximum torque at 3250 rpm for both CNG and petrol.

It shares almost all of its technologies with the big brother, EF7.

The EF4 assembly line will be in Esfahan, Iran.

## Performance

Variant	Power	Torque	Production since	Utilization on	Compression Ratio	FC(Urban)	FC(Combined)	FC(Extra Urban)	Notes
EF4	95 PS (70 kW) CNG: 84 PS (62 kW)	125 N·m (92 lb·ft) CNG: 111 N·m (82 lb·ft)	Early 2011	IKCO Runna	11:1	8.4 L, 6.5 kg	6.4 L, 5.6 kg	4.7 L, 3.7 kg	16-valve, DOHC, HLA Tappets, CVVT, MPFI, Catalytic converter

## EFD engines

EFD engines have a displacement of 1497 cc with a bore of 76 mm and a stroke of 82.5 mm.

It's a 16-valve engine featuring lots of new diesel engines technologies.

Because EFD engines are the first engines from the family which are using a different fuel, this makes a necessity for changing most parts which means there are just some parts of other EF family engines used in them.

Since the initial talks about the project in mid 2008, NIOPDC was the main sponsor of the project (EFD) and has supported the project up to 20 million US\$.

Because Iran Khodro had never designed a diesel engine before the EFD engines and the company wanted to design diesel engines with the properties of being modern, technological and comparable with other new diesel engines in their range, Iran Khodro made a partnership in designing the engines & consulted with AVL in many aspects for gaining the new required technologies to reach to the goals.

IP-Co says production of the non-Turbocharged EFD engine costs about 1.7 times more than other EF family engines; but if a customer buys a car using the engine, after not a long time, these costs will be paid back to the consumers due to less fuel consumption and less maintenance needs.

Due to being old and inefficiencies of the Peugeot BE3/5 gearbox and also a necessity for having a new gearbox for other IKCO engines, the company started to design a new gearbox which can be used for the EFD engines. The gearbox will overcome the high torques and will have more efficiency compared to the BE3/5 gearbox. On November 30, 2010, IKCO announced they will finalize the gear ratios of the new gearbox for EFD in the near future.

Here are IP-Co reasons for starting the design of a diesel engine (EFD engines):

- Respond to new territory's fuel policies & changing the domestic fuel basket from Petrol and CNG to Petrol, CNG and **Diesel**
- Owning an efficient diesel powertrain which is on the knowledge edges of sufficiency, fuel consumption and pollution
- Making the Diesel engines technologies native in Iran
- Using the maximum R & D knowledge of combustion engines which are gained from designing other engines
- Designing the engines based on the EF family engines to reduce costs of developing and investments

These are some of the technologies that are used in implementation of EFD engines:

- direct injection
- Common Rail with the pressure of 1,600 bars (23,210 psi)
- Glow plug
- Variable geometry turbocharger
- Intercooler
- Exhaust gas recirculation with cooler to increase pollution standards
- Having Euro IV Emission Standard
- Diesel Particulate Filter to remove diesel soots and particulates from exhaust gas
- Diesel Oxidation Catalyst to increase emission standard by breaking down pollutants of exhaust gas into less harmless elements.

## **EFD**

It is the first variant of the EFD family, which unveiled on November 17, 2009 by the president of Iran Mahmoud Ahmadinejad in Amol and mobilized with mentioned technologies listed above.

The engine reaches its maximum power at 4000 rpm and maximum torque at 1750 rpm.

It is currently installed on some Samands and Sorens to pass the last required tests.

Other specifications are listed in the **Performance** section below.

## **EFD turbocharged**

It will be a double-stage Turbocharged engine.

IP-Co has no plan to develop it until its brother, EFD comes to the market but it is noticeable that the project is near to be finished.

## Chapter- 6

# Radial Diesel Engines

## Packard DR-980

### DR-980



A preserved Packard DR-980 on display at the National Museum of the United States Air Force

<b>Type</b>	Air-cooled diesel radial engine
<b>Manufacturer</b>	Packard
<b>First run</b>	1928
<b>Number built</b>	c.100
<b>Unit cost</b>	\$4,025

The **Packard DR-980** is an American nine-cylinder air-cooled aircraft diesel engine first certificated in 1930. The engine was unpopular despite its economy and reliability due to the unpleasant nature of its diesel exhaust fumes and considerable vibration when running; approximately 100 were built.

## ***Design and development***

Designed by Captain Lionel Woolson and Professor Herman Dohner, the DR-980 made the first cross-country flight with a diesel-powered aircraft in the United States when Woolson flew from Detroit to Langley Field in 1929, a distance of 700 miles (1,126 km) with a flight time of 6 hours and 40 minutes. On a later flight in a Stinson Detrouter from Detroit to Miami, the new engine showed its economy, the cost for fuel consumption being less than one cent a mile. This aircraft (complete with its engine) is preserved at the Golden Wings Flying Museum.

In 1930, the DR-980 passed its 50-hour certification test with a continuous rating of 225 hp (168 kW) at 1,950 rpm. Production of the DR-980 ceased following the death of Captain Woolson in an aviation accident in April 1930; his legacy was the award of the Collier Trophy in 1931 to the Packard Motor Car Company for its work with this type of engine.

## **Endurance record**

On 28 May 1931, a Bellanca CH-300 fitted with a DR-980, piloted by Walter Edwin Lees and Frederick Brossy, set a record for staying aloft for 84 hours and 32 minutes without being refueled. This record was not broken until 55 years later by the Rutan Voyager.

## ***Applications***

- Bellanca CH-200
- Bellanca CH-300
- Brunner-Winkle Bird
- Buhl Airsedan
- Ford Model 11
- O-17 Courier
- Stinson Detrouter
- Verville Sport Trainer
- Waco HSO and HTO

## ***Engines on display***

- A DR-980 is on display at the National Museum of the United States Air Force.

## ***Specifications (DR-980)***

### **General characteristics**

- **Type:** 9-cylinder diesel radial engine
- **Bore:** 4 13/16 in (122.2 mm)

- **Stroke:** 6 in (152.4 mm)
- **Displacement:** 980 in<sup>3</sup> (16 L)
- **Dry weight:** 550 lb (227 kg)

## Components

- **Valvetrain:** One valve per cylinder, overhead valve
- **Fuel type:** Diesel oil
- **Cooling system:** Air-cooled

## Performance

- **Power output:** 240 hp (179 kW) at 2,000 rpm
- **Specific power:** 0.25 hp/in<sup>3</sup> (11.2 kW/L)
- **Power-to-weight ratio:** 0.44 hp/lb (0.8 kW/kg)

## Zvezda M503

The **Zvezda M503** was a maritime 6 row, 42 cylinder diesel radial engine built in the 1970s by the Soviet Union. Its primary use was in Soviet missile boats, which used three of these engines.

This engine may have had other applications, but due to its extreme weight (12,000 lb (5,400 kg)), it would have been limited to ground or naval applications.

A German tractor pulling team designed a vehicle around a methanol-fueled version of this engine, this modified engine is said to weigh 3,200 kg (7,100 lb) including the gearbox, for use in the 5.4 ton tractor pulling class, making 8,000 hp (6,000 kW) at 2,500 rpm.

## Specifications (Zvezda M503A)



Zvezda M503

### General characteristics

- **Type:** 42-cylinder Liquid cooled 6 row, 7 cylinder per row diesel radial engine
- **Bore:** 6.29 in (160 mm)
- **Stroke:** 6.69 in (170 mm)
- **Displacement:** 8,763 in<sup>3</sup> (143.6 L)
- **Length:** 145.66 in (3,700 mm)
- **Diameter:** 61.41 in (1,560 mm)
- **Dry weight:** 12,015 lb (5,450 kg) (dry)

### Components

- **Valvetrain:** 7 overhead cam shafts, one per bank.
- **Fuel type:** Diesel fuel
- **Cooling system:** Liquid-cooled

## Performance

- **Power output:** 3,942 hp (2,940 kW, 3,997 PS) at 2,200 rpm
- **Specific power:** 0.44 hp/in<sup>3</sup> (20.47 kW/L)
- **Power-to-weight ratio:** 0.32 hp/lb (0.53 kW/kg)

WWT

## Chapter- 7

# Two-stroke Diesel Engines



Brons two stroke V8 Diesel engine driving a Heemaf generator.

A **two stroke diesel** is a diesel engine that works in two strokes. A diesel engine is an internal combustion engine which operates using the Diesel cycle. Invented in 1892 by German engineer Rudolf Diesel, it was based on the hot bulb engine design and patented on February 23, 1893.

All diesel engines use compression ignition, a process by which fuel is injected after the air is compressed in the combustion chamber causing the fuel to self ignite. By contrast, gasoline engines utilize the Otto cycle, in which fuel and air are mixed before entering the combustion chamber and then ignited by a spark plug.

## ***Two strokes***

Two stroke internal combustion engines are more simple mechanically than four stroke engines, yet are more complex in thermodynamic and aerodynamic processes. The four "cycles" of internal combustion engine theory (intake, compression, ignition, exhaust) occur in one revolution, whereas a four stroke engine normally requires two complete revolutions to perform these four functions. It is therefore useful to remember that there is more than one function occurring at any given time during the engine's operation, i.e simultaneous intake and exhaust strokes.

- *Intake* begins when the piston is near bottom dead center. Air is admitted to the cylinder through ports in the cylinder wall (there are no intake valves). All two-stroke Diesel engines require artificial aspiration to operate, and will either use a mechanically-driven supercharger, or an exhaust-driven turbo-supercharger, (often abbreviated to turbocharger or turbo) to charge the cylinder with air. In the early phase of intake, the air charge is also used to force out any remaining combustion gases from the preceding power stroke, a process referred to as scavenging.
- As the piston rises, the intake charge of air is compressed. Near top dead center, fuel is injected, resulting in combustion due to the extremely high pressure and heat created by compression, which drives the piston downward. As the piston moves downward in the cylinder it will reach a point where the exhaust port is opened to expel the high-pressure combustion gasses. However, most current two-stroke diesel engines use top-mounted poppet valves and uniflow scavenging. Continued downward movement of the piston will expose the air intake ports in the cylinder wall, and the cycle will start again.

## ***Roots blower***

The Roots blower is commonly used on the two stroke diesel engine, which requires some form of forced induction. In this application, the blower does not provide significant compression and these engines are considered naturally aspirated; turbochargers are generally used when significant "boost" is needed.

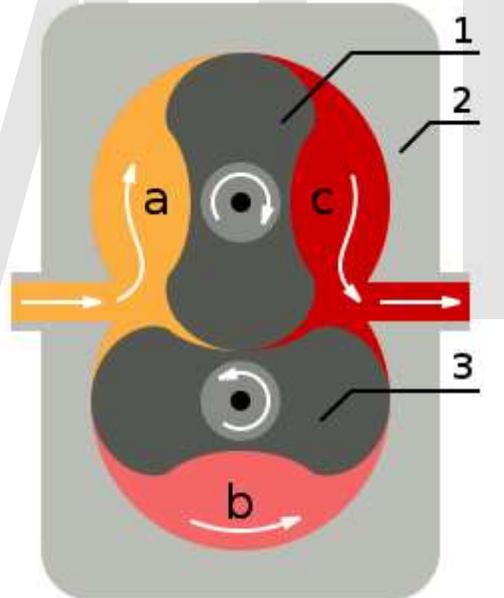
## ***Brands***

- **Wärtsilä** manufactures two-stroke crosshead diesel engines for marine propulsion.
- **MAN Diesel & Turbo** manufactures crosshead diesel engines for marine propulsion.

- **Mitsubishi Heavy Industries** manufactures crosshead diesel engines for marine propulsion.
- **Electro-Motive Diesel** manufactures two-stroke uniflow diesel generators for railway and stationary applications.
- **Detroit Diesel**: The off-highway division, owned by MTU, still manufactures uniflow two-strokes.
- **Commer**, part of the Rootes Group, was a British manufacturer of commercial vehicles. Many Commer lorries of the 1950s were fitted with the Commer TS3 engine, a three-cylinder opposed piston engine, which came to be known as the "Commer Knocker" due to the unique noise it produced.

Although this engine had a Roots-type blower, there was no connection between Roots and Rootes Group.

## Roots type supercharger



A Roots blower with two-lobed rotors. Most real Roots blowers' rotors have three or four lobes.

Key:

1 Rotary vane 1

2. Pump body

3. Rotary vane 2

a. Intake

b. Pumping

c. Forced air or air-fuel mixture into intake manifold

The **Roots type supercharger** or **Roots blower** is a positive displacement lobe pump which operates by pumping fluids with a pair of meshing lobes not unlike a set of stretched gears. Fluid is trapped in pockets surrounding the lobes and carried from the intake side to the exhaust. It is frequently used as supercharger in engines, where it is driven directly from the engine's crankshaft via a belt or, in a two-stroke diesel engine, by spur gears.

It is named for the brothers Philander and Francis Marion Roots of Connersville, Indiana, who first patented the basic design in 1860 as an air pump for use in blast furnaces and other industrial applications. In 1900, Gottlieb Daimler included a Roots-style supercharger in a patented engine design, making the Roots-type supercharger the oldest of the various designs now available. Roots blowers are commonly referred to as air blowers or pd blowers.

### ***Applications***



An Eaton M62 Roots-type supercharger is visible at the front of this Ecotec LSJ engine in a 2006 Saturn Ion Red Line

Of the three basic supercharger types, the Roots design historically possessed the worst thermal efficiency, especially at high pressure ratios. However, recent engineering developments by Eaton Corporation have resulted in a more efficient Roots-type

supercharger, known as the TVS. This new Eaton TVS design has been proven to provide isentropic efficiencies as high as 76% while providing a significantly larger efficiency island than turbochargers. Unlike the basic illustration, most modern Roots-type superchargers incorporate three-lobe or four-lobe rotors. The latest design made by Kenne Bell, introduced for the Ford Mustang GT500 Super Snake, has four lobes per rotor, enhancing its efficiency through a reduction of pulsations.

The Roots-type supercharger is simple and widely used. It can also be more effective than alternative superchargers at developing positive intake manifold pressure (i.e., above atmospheric pressure) at low engine speeds, making it a popular choice for passenger automobile applications. Peak torque can be achieved by about 2000 rpm.

Accumulated heat is an important consideration in the operation of a compressor in an internal combustion engine. Per the ideal gas law, a compression operation will raise the temperature of the compressed output. Additionally, the operation of the compressor itself requires energy input, which is converted to heat and can be transferred to the gas through the compressor housing, heating it more. Although intercoolers are more commonly known for their use on turbochargers, superchargers may also benefit from the use of an intercooler. Internal combustion is based upon a thermodynamic cycle, and a cooler temperature of the intake charge results in a greater thermodynamic expansion and vice versa. A hot intake charge robs the engine of efficiency and produces diminishing returns from the compression process, while an intercooling stage adds complexity but can improve the efficiency by releasing some of the unneeded heat. Above about 5 psi (0.3 bar) the intercooling improvement can become dramatic. With a Roots-type supercharger, one method successfully employed is the addition of a thin heat exchanger placed between the blower and the engine. Water is circulated through it to a second unit placed near the front of the vehicle where a fan and the ambient air-stream can dissipate the collected heat.

The Roots design was commonly used on two-stroke diesel engines (popularized by the Detroit Diesel division of General Motors), which require some form of forced induction, as there is no separate intake stroke. The *Rootes* Co. two-stroke diesel engine, used in *Commer* and *Karrier* vehicles, had a Roots-type blower but the two names are not connected.

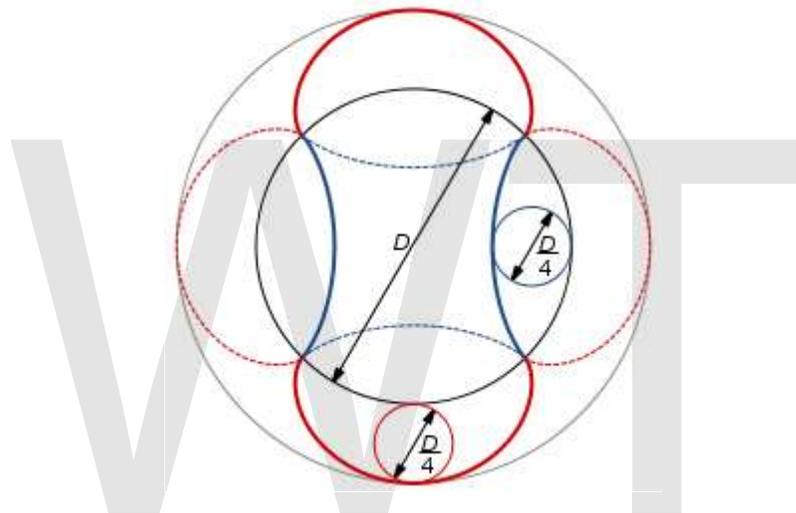
The superchargers used on top fuel engines, funny cars, and other dragsters, as well as hot rods, are in fact derivatives of *General Motors Coach Division* blowers for their industrial diesel engines, which were adapted for automotive use in the early days of the sport of drag racing. The model name of these units delineates their size; i.e. the once commonly used "6-71" and "4-71" blowers were designed for *General Motors* diesels having six cylinders of 71 cubic inches each, and four cylinders of 71 cubic inches each, respectively. Current competition dragsters use aftermarket GMC variants similar in design to the -71 series, but with the rotor and case length increased for added pumping capacity, identified as the 8-71, 10-71, 14-71 etc.

Roots blowers are typically used in applications where a large volume of air must be moved across a relatively small pressure differential. This includes low vacuum applications, with the Roots blower acting alone, or use as part of a high vacuum system, in combination with other pumps.

Some civil defense sirens used Roots blowers to pump air to the rotor (chopper). The most well known are the Federal Signal Thunderbolt Series, and ACA (now American Signal Corporation) Hurricane. These sirens are known as "supercharged sirens".

Roots blowers are also used in reverse to measure the flow of gases or liquids, for example, in gas meters.

### ***Technical considerations***



Construction of a two-lobed cycloidal rotor. The red curve is a hypocycloid and the blue curve is an epicycloid. The smaller generating circles (red and blue) are one quarter the diameter of the larger generating circle (black). The rotor profile is the thick line.

The simplest form of a Roots blower has cycloidal rotors, constructed of alternating tangential sections of hypocycloidal and epicycloidal curves. For a two-lobed rotor, the smaller generating circles are one-quarter the diameter of the larger. Real Roots blowers may have more complex profiles for increase efficiency.

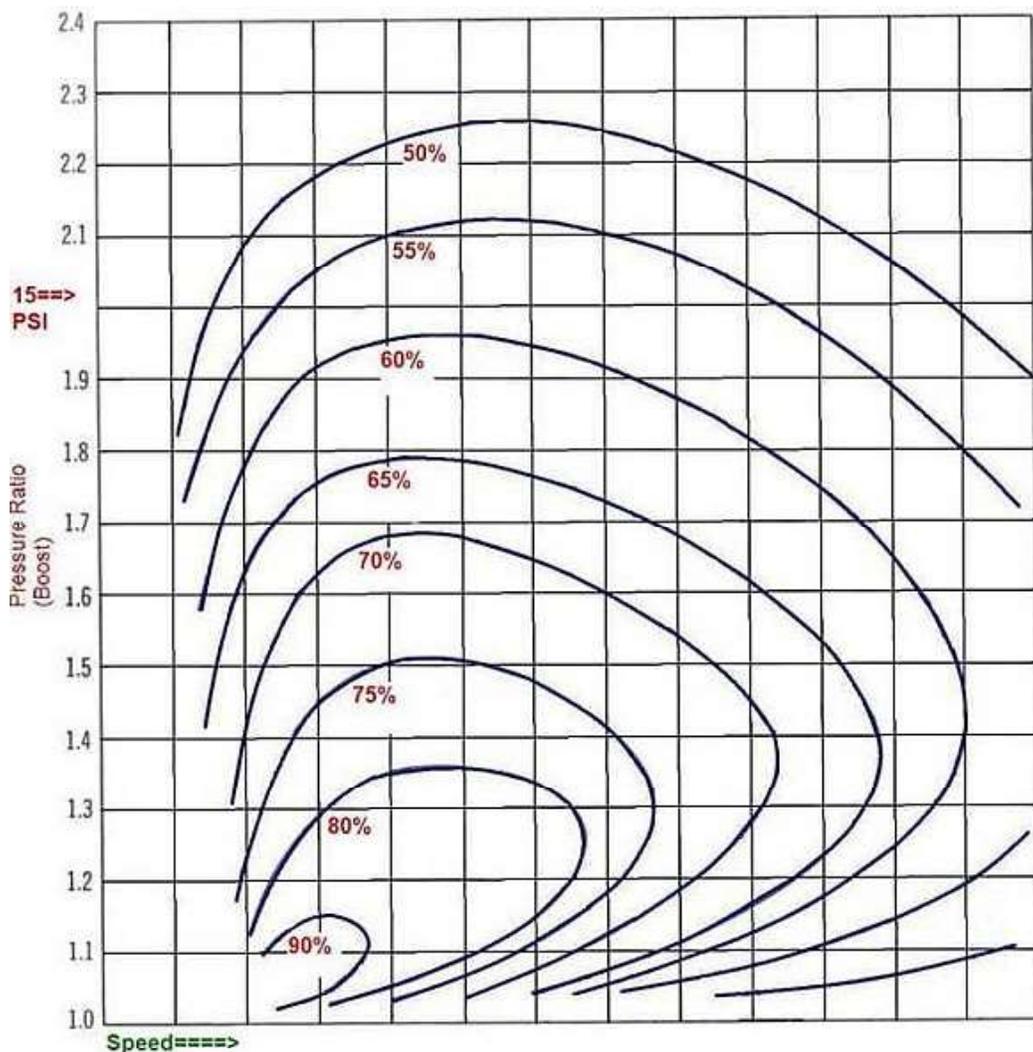
Because rotary lobe pumps need to maintain a clearance between the lobes, a single stage Roots blower can pump gas across only a limited pressure differential. If the pump is used outside its specification, the compression of the gas generates so much heat that the lobes expand to the point that they jam, damaging the pump.

Roots pumps are capable of pumping large volumes but as they only achieve moderate compression, it is not uncommon to see multiple Roots blower stages, frequently with heat exchangers (intercoolers) in between to cool the gas. The lack of oil on the pumping surfaces allows the pumps to work in environments where contamination control is

important. The high pumping rate for hydrocarbons also allows the Roots pump to provide an effective isolation between oiled pumps, such as rotary compression pumps, and the vacuum chamber.

A variant uses claw-shaped rotors for higher compression.

The Roots-type blower may achieve an efficiency of around 70% while achieving a maximum pressure ratio of two. Because a Roots type blower pumps air in discrete pulses (unlike a screw compressor), pulsation noise and turbulence may be transmitted downstream. If not properly managed (through outlet piping geometry) or accounted for (by structural reinforcement of downstream components), the resulting pulsations can cause fluid cavitation and/or damage to components downstream of the blower.



**Roots Supercharger Efficiency Map.** Generalized blower efficiency map shows how a blower's efficiency varies with speed and boost.

## ***Roots Efficiency map***

For any given roots blower running under given conditions, a single point will fall on the map. This point will rise with increasing boost and will move to the right with increasing blower speed. It can be seen that, at moderate speed and low boost, the efficiency can be over 90%. This is the area in which Roots blowers were originally intended to operate, and they are very good at it.

Boost is given in terms of pressure ratio, which is the ratio of absolute air pressure before the blower to the absolute air pressure after compression by the blower. If no boost is present, the pressure ratio will be 1.0 (meaning 1:1), as the outlet pressure equals the inlet pressure. Fifteen psi boost is marked for reference (slightly above a pressure ratio of 2.0 compared to atmospheric pressure). At 15 psi (1.0 bar) boost, Roots blowers hover between 50% and 58%. Replacing a smaller blower with a larger blower moves the point to the left. In most cases, as the map shows, this will move it into higher efficiency areas on the left as the smaller blower likely will have been running fast on the right of the chart. Usually, using a larger blower and running it slower to achieve the same boost will give an increase in compressor efficiency.

The volumetric efficiency of the Roots-type blower is very good, usually staying above 90% at all but the lowest blower speeds. Because of this, even a blower running at low efficiency will still mechanically deliver the intended volume of air to the engine, but that air will be hotter. In drag racing applications where large volumes of fuel are injected with that hot air, vaporizing the fuel absorbs the heat. This functions as a kind of liquid aftercooler system and goes a long way to negating the inefficiency of the Roots design in that application.

## ***Comparative advantages***

Rotary lobe blowers, commonly called boosters in high vacuum application, are not used as a stand alone pump. In high vacuum applications the boosters pumping speed can be used to reduce the end pressure and increase the pumping speed.

## ***Related terms***

The term "blower" is commonly used to define a device placed on engines with a functional need for additional airflow using a direct mechanical link as its energy source. The term blower is used to describe different types of superchargers. A screw type supercharger, Roots type supercharger, and a centrifugal supercharger are all types of blowers. Conversely, a turbocharger, using exhaust compression to spin its turbine, and not a direct mechanical link, is not generally regarded as a "blower" but simply a "turbo".

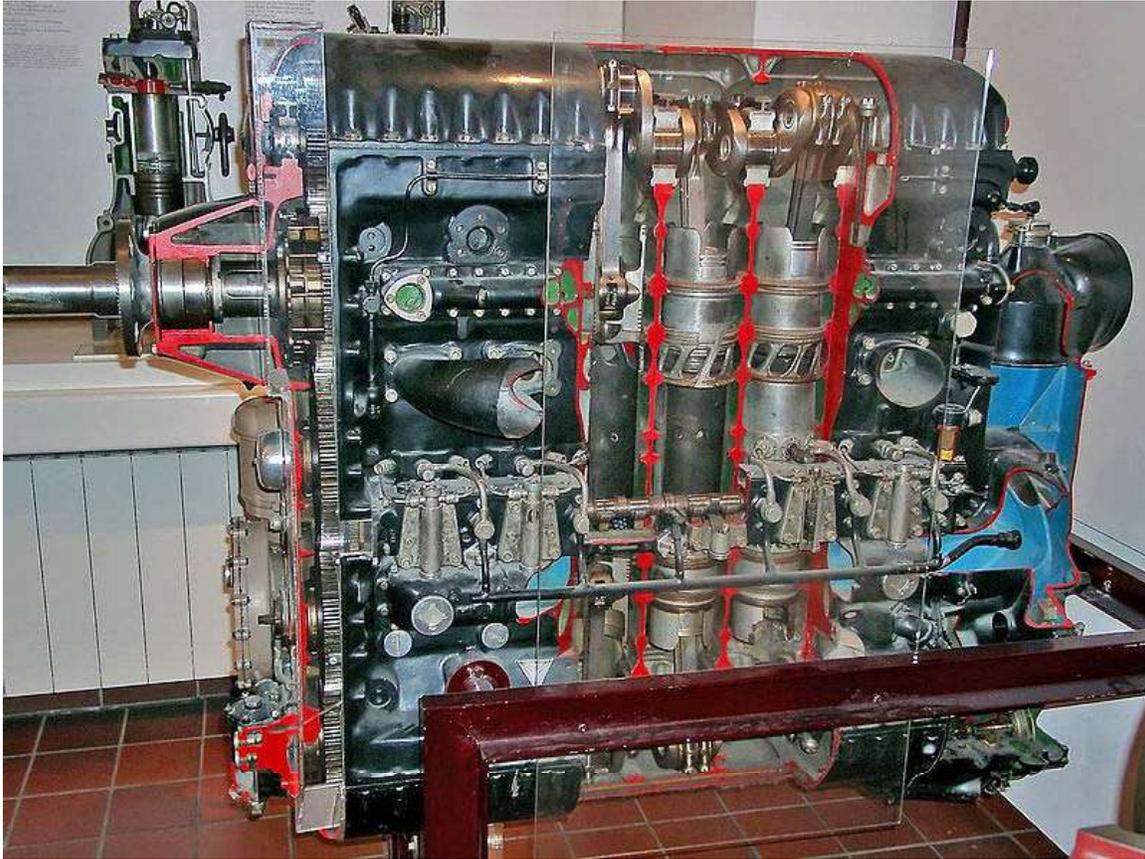
## Opposed-piston engine



Fairbanks-Morse opposed-piston diesel engines on the submarine *USS Pampanito*.

An **opposed-piston engine** is one in which the cylinders are double-ended, with a piston at each end and no cylinder head.

## Configurations



Junkers Jumo 205 aircraft engine

Some variations of the Opposed Piston or OP designs use a single crankshaft like the Doxford ship engines and the Commer OP truck engines. They should not be confused with flat engines. Though flat engines are sometimes referred to as horizontally opposed, they are very different mechanically.

A more common layout uses two crankshafts, with the crankshafts geared together, or even three geared crankshafts in the Napier Deltic diesel engines. The Deltic uses three crankshafts serving three banks of double-ended cylinders arranged in an equilateral triangle, with the crankshafts at the corners. These were used in railway locomotives and to power fast patrol boats. Both types are now largely obsolete, although the Royal Navy still maintains some Deltic-powered Hunt class mine countermeasure vessels.

The first opposed-piston diesel engines were developed in the beginning of 20th century. In 1907, Raymond Koreyvo, the engineer of Kolomna Works, built an opposed-piston two-stroke diesel with two crankshafts connected by gearing. Although Koreyvo patented his engine in France in November, 1907, the management would not go on to manufacture opposed-piston engines.

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All this, in an engine that requires less floor space per horsepower, and is now available for use with natural or sewage gas as well as diesel fuel. Fairbanks, Morse & Co., Chicago 5, Ill.

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An April, 1950 print advertisement for Fairbanks-Morse opposed-piston engines, touting their greater thermodynamic efficiency and lower maintenance cost than standard configurations

The first Junkers engines had one crankshaft, the upper pistons having long connecting rods outside the cylinder. These engines were the forerunner of the Doxford marine engine, and this layout was also used for two- and three-cylinder car engines from around 1900-1922 by Gobron-Brillié. There is currently a resurgence of this design in a boxer configuration as a small diesel aircraft engine, and for other application, called the 'OPOC' engine by Advanced Propulsion Technologies, Inc. of California. Later Junkers engines like the Junkers Jumo 205 diesel aircraft engine, use two crankshafts, one at either end of a single bank of cylinders. There are efforts to reintroduce the opposed-

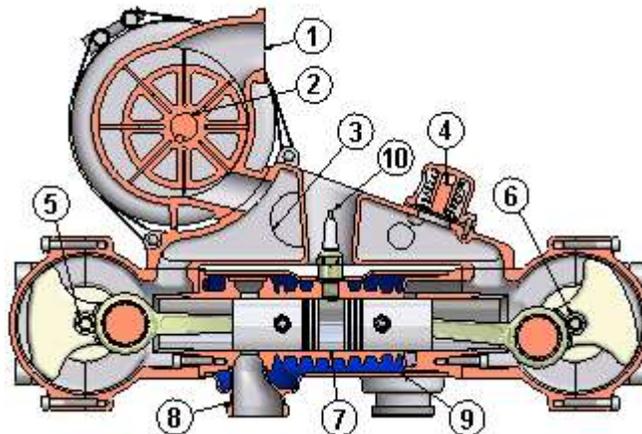
piston diesel aircraft engine with twin geared crankshafts for General aviation applications, by both Dair and PowerPlant Developments in the UK.

This configuration has also been used for marine auxiliary generators and for larger marine propulsion engines, notably Fairbanks-Morse diesel engines used in both conventional and nuclear US submarines. Fairbanks-Morse also used it in diesel locomotives starting in 1944. With the addition of a supercharger or turbocharger, opposed-piston designs can make very efficient two-stroke cycle Diesel engines. Attempts were made to build non-diesel 4-stroke engines, but as there is no cylinder head, the bad location of the valves and the spark plug makes them inefficient.

Koreyvo, Jumo and Deltic engines used one piston per cylinder to expose an intake port, and the other to expose an exhaust port. Each piston is referred to as either an *intake piston* or an *exhaust piston* depending on its function in this regard. This layout gives superior scavenging, as gas flow through the cylinder is axial rather than radial, and simplifies design of the piston crowns. In the Jumo 205 and its variants, the upper crankshaft serves the exhaust pistons, and the lower crankshaft the intake pistons. In designs using multiple cylinder banks, such as the Junkers Jumo 223 and the Deltic, each big end bearing serves one inlet and one exhaust piston, using a forked connecting rod for the exhaust piston.

The Doxford Engine Works of the UK designed and built very large opposed-piston engines for marine use. These engines differ in design from Jumo and Fairbanks-Morse engines by having external connecting rods outside the cylinder linking the upper and lower pistons, thus requiring only a single crankshaft. The first engine of this type was developed by Karl Otto Keller in 1912. Doxford obtained a sole UK license from Oechelhauser and Junkers to build this design of engine. After World War I, these engines were produced in a number of models, such as the P and J series, with outputs as high as 20,000 horsepower (15,000 kW). Certain models were license-built in the US. Production of Doxford engines in the UK ceased in 1980.

### ***Assembly and function***



An example of an opposed-piston engine.

- 1 intake for the fuel-air mixture
- 2 supercharger (here: rotary vane pump; original: Centrix)
- 3 airbox to buffer and distribute the mixture
- 4 waste valve to limit the pressure level
- 5 outlet crank mechanism (runs app. 20° past the outlet to achieve an asymmetric control diagram)
- 6 inlet crank mechanism
- 7 cylinder with inlet and outlet slots
- 8 exhaust
- 9 water cooling jacket
- 10 sparkplug

Shown (at right) is the layout of a two-stroke engine similar to the one developed by engineer Kurt Bang at the Prüssing Office on the basis of the prewar DKW race engine. There existed two versions: one with a displacement of 250 cm<sup>3</sup> (15 cu in), and one with 350 cm<sup>3</sup> (21 cu in) displacement. The engine had two cylinders with four pistons, two crankshafts and a supercharger. The crankshafts were connected by gears.

The supercharger takes in the fuel-air mixture, compressing it and pushing it into the airbox. From here it reaches the crank housings. On the outlet side it cools the thermally high loaded piston. After ignition the pistons move outwards, performing the power stroke. At first, the outlet piston opens its slots in the cylinder. The remaining pressure accelerates the gas column towards the exhaust. Then the other piston opens the inlet slots. The pressurized fresh mixture pushes the remaining waste gas out. While the inlet is still opened, the outlet is closed. The supercharger forces additional gas into the cylinder until the inlet slots are closed by the piston. Then the compression stroke starts and the cycle repeats. This type of two cycle system is similar to the famous Grey Marine Diesel, later to be known as the GM Diesel (Detroit Diesel). Production ceased in 1998 but the U.S. and British Militaries still purchase remanufactured engines on occasion.

### ***Free-piston engine***

An interesting variation on the opposed-piston engine is the free-piston engine which was patented in 1934 by Raúl Pateras de Pescara. It has no crankshaft and the pistons are returned after each firing stroke by compression and expansion of air in a separate cylinder. Early applications were for use as an air compressor or as a gas generator for a gas turbine, such as the Pratt & Whitney PT1 design. There is now renewed interest in it for powering vehicles by using it to drive a linear alternator.

## EMD 710



An EMD 12-710G3B engine, installed in an Iarnród Éireann 201 class locomotive

The **EMD 710** is a line of diesel engines built by Electro-Motive Diesel (previously General Motors' Electro-Motive Division). The 710 series largely replaced the earlier EMD 645 series. The EMD 710 is a large two-stroke diesel engine that has a 710 cubic inches (11.63 liters) displacement per cylinder. Since its introduction, EMD has continually upgraded the 710G diesel engine. Power output has increased from 3,800 horsepower (2,800 kW) on 1984's 16-710G3A to 4300 horsepower (as of 2006) on the 16-710G3C-T2.

Over the production span of certain locomotive models upgraded engine models have been fitted when they became available. For example an early 1994-built SD70MAC had 16-710G3B, where an SD70MAC built in 2003 would have a 16-710G3C-T1.

All EPA Tier 1 and EPA Tier 2 compliant models of the 710 are equipped with electronic fuel injection.

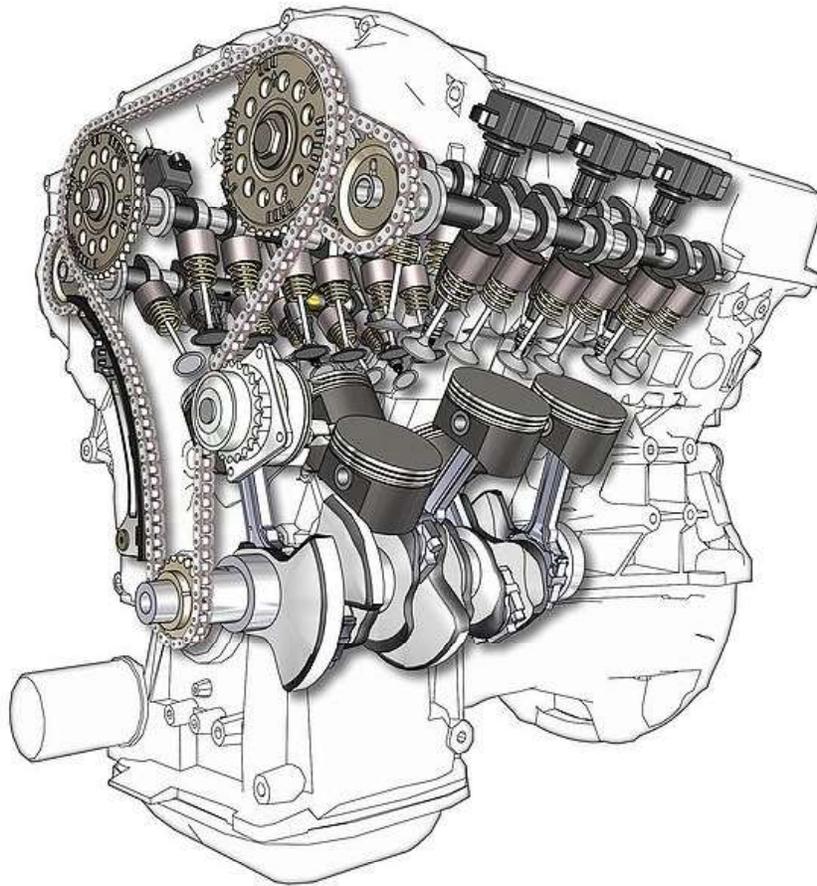
## **Rail versions**

<b>ID</b>	<b>Engine type</b>	<b>Induction</b>	<b>Max rpm</b>	<b>Power (hp)</b>	<b>Power (MW)</b>	<b>Introduced</b>	<b>Locomotive(s)</b>
8-710G3A-T2	V-8	Turbocharged		2150	1.6	2007	GP22ECO, SD22ECO EFI equipped.
12-710G3A	V-12	Turbocharged		3000	2.2	1985	GP59, F59PH, Australian National DL class.
12-710G3B-T2	V-12	Turbocharged		3150	2.3	2007	SD32ECO EFI equipped.
12-710G3C-EC	V-12	Turbocharged		3200	2.3	1993	F59PHI EFI equipped.
12N-710G3B-EC	V-12	Turbocharged	900	3300	2.5	1998	British Rail Class 66, British Rail Class 67, Irish Rail 201 Class, EMD DE/DM30AC.
16-710G3A	V-16	Turbocharged		3800	2.8	1984	GP60, GP60M, GP60B, SD60, SD60M, SD60I, SD60F, Australian National AN Class.
16-710G3B	V-16	Turbocharged		4000	3.0	1992	Early SD70, SD70M, SD70MAC and SD70I.
16-710G3B-EC	V-16	Turbocharged		4000	3.0	1997	SD70, SD70M, SD70MAC and SD70I models equipped with electronic fuel injection (EFI).
16-710G3B-T1	V-16	Turbocharged	900	4000	3.0	2003	EPA Tier 1 Emissions compliant/EFI Equipped SD70M, SD70MAC
16-710G3B-T2	V-16	Turbocharged	900	4000	3.0	2005	SD70M-2 (Norfolk Southern), MP40PH-3C EPA Tier II emissions

16-710G3C	V-16	Turbocharged	4300	3.2	1995	compliant/EFI equipped. SD75M, SD75I.
16-710G3C-EC	V-16	Turbocharged	4300	3.2	1995	SD75M, SD75I, SD90/43MAC EFI equipped. SD70M (late model), SD70MAC (late model), Alstom PL42AC EPA Tier I emissions compliant/EFI equipped.
16-710G3C-T1	V-16	Turbocharged 900	4300	3.2	2003	SD70ACe, SD70M-2 EPA Tier II emissions compliant/EFI equipped.
16-710G3C-T2	V-16	Turbocharged 900	4300	3.2	2004	SD70ACe, SD70M-2 EPA Tier II emissions compliant/EFI equipped.
20-710G3B-EC	V-20	Turbocharged 900	5000	3.7	1995	SD80MAC EFI equipped.

## Chapter- 8

# V6 Engine



A V6, 24-valve, DOHC engine

A **V6 engine** is a V engine with six cylinders mounted on the crankcase in two banks of three cylinders, usually set at either a right angle or an acute angle to each other, with all six pistons driving a common crankshaft. It is the second most common engine configuration in modern cars after the inline four.

The V6 is one of the most compact engine configurations, shorter than the straight 4 and in many designs narrower than the V8 engine, and is well suited to the popular transverse engine front-wheel drive layout. It is becoming more common as the space allowed for engines in modern cars is reduced at the same time as power requirements increase, and has largely replaced the inline-6, which is too long to fit in many modern engine compartments. Although it is more complicated and not as smooth as the inline 6, the V6 is more compact, more rigid, and less prone to torsional vibrations in the crankshaft. The V6 engine has become widely adopted for medium-sized cars, often as an optional engine where a straight-4 is standard, or as a base engine where a V8 is a higher-cost performance option.

Recent V6 engines have delivered horsepower and torque output comparable to contemporary V8 engines, while reducing fuel consumption and emissions, such as the Volkswagen Group's G60 3.0 TFSI which is supercharged and directly injected, and Ford Motor Company's turbocharged and directly injected EcoBoost V6, both of which have been compared to Volkswagen's 4.2 V8 engine.

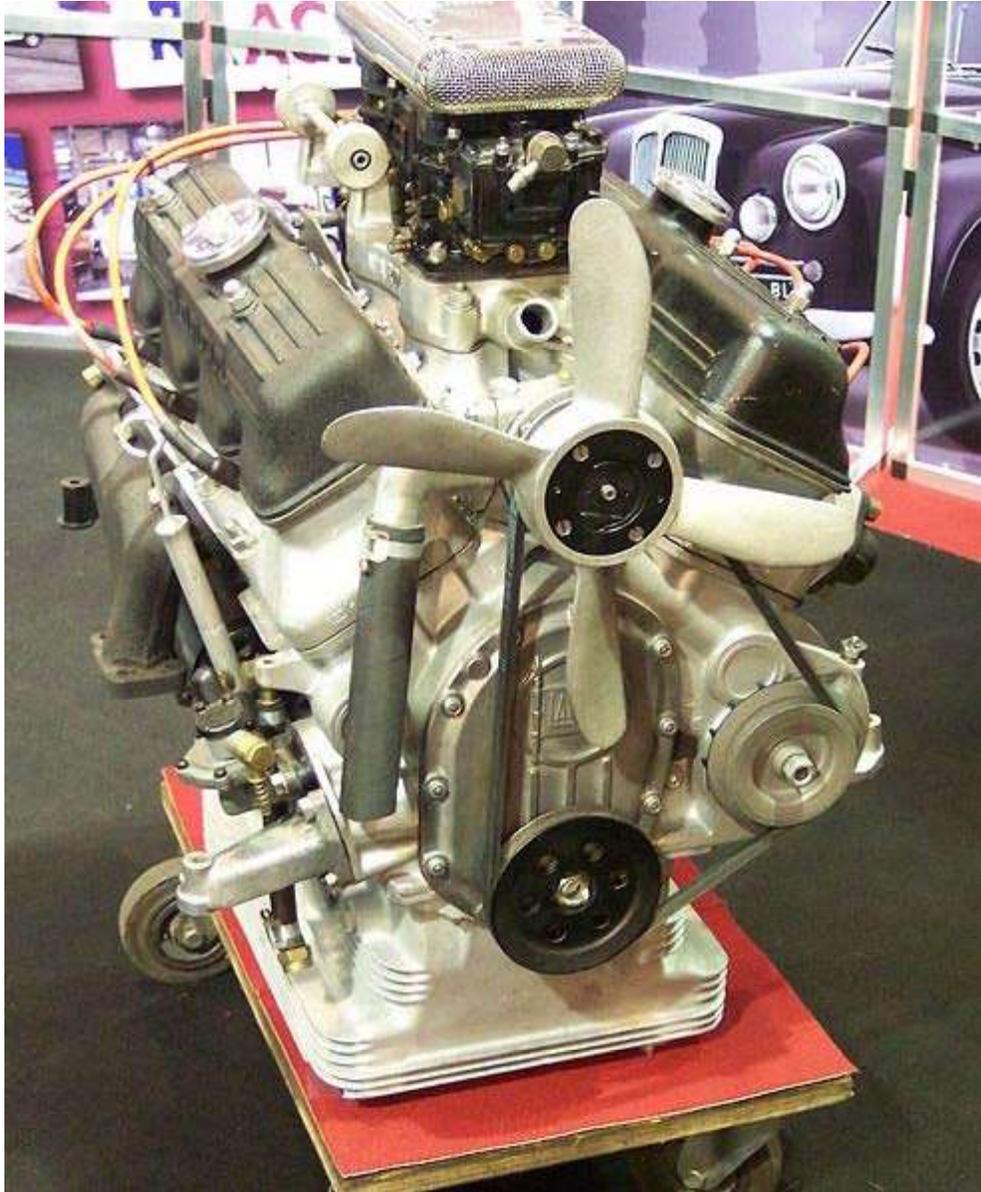
Modern V6 engines commonly range in displacement from 2.5 to 4.3 L (150 to 260 cu in), though larger and smaller examples have been produced.

## ***History***

Some of the first V6-cars were built in 1905 by Marmon. Marmon was something of a V-Specialist which began with V2-engines, then built V4's and V6's, later V8's and in the 30's Marmon was one of the few car-makers of the world which ever built a V16 car.

From 1908-1913 the Deutz Gasmotoren Fabrik produced benzene electric trainsets (Hybrid) which used a V6 as generator-engine.

Another V6-car was designed in 1918 by Leo Goosen for Buick Chief Engineer Walter L. Marr. Only one prototype Buick V6 car was built in 1918 and was long used by the Marr family.



Lancia V6

The first series production V6 was introduced by Lancia in 1950 with the Lancia Aurelia. Other manufacturers took note and soon other V6 engines were in use. In 1959, GM introduced a heavy-duty 305 in<sup>3</sup> (5 L) 60° V6 for use in their pickup trucks and Suburbans, an engine design that was later enlarged to 478 in<sup>3</sup> (7.8 L) for heavy truck and bus use.

1962 saw the introduction of the Buick Special, which offered a 90° V6 with uneven firing intervals that shared some parts commonality with a small Buick V8 of the period. Consequently the Buick Special met consumer resistance due to its excessive vibration. In 1983, Nissan produced Japan's first V6 engine with the VG series.

## **Balance and smoothness**

Due to the odd number of cylinders in each bank, V6 designs are inherently unbalanced, regardless of their V-angle. All straight engines with an odd number of cylinders suffer from primary dynamic imbalance, which causes an end-to-end rocking motion. Each cylinder bank in a V6 has an odd number of pistons, so the V6 also suffers from the same problem unless steps are taken to mitigate it. In the horizontally-opposed flat-6 layout, the rocking motions of the two straight cylinder banks offset each other, while in the inline-6 layout, the two ends of engine are mirror images of each other and compensate every rocking motion. Concentrating on the first order rocking motion, the V6 can be assumed to consist of two separate straight-3 where counterweights on the crankshaft and a counter rotating balancer shaft compensate the first order rocking motion. At mating, the angle between the banks and the angle between the crankshafts can be varied so that the balancer shafts cancel each other 90° V6 (larger counter weights) and the even firing 60° V6 with 60° flying arms (smaller counter weights. The second order rocking motion can be balanced by a single co-rotating balancer shaft.).

This is almost the same technique which balances an even firing 90° crossplane V8 in primary and secondary order. A 90° V8 is in primary balance because each 4-cylinder bank is in primary balance, and the secondary of the two banks can be made to cancel each other using a crossplane. However, there is no equivalent of the crossplane crankshaft for the V6, so that the vibrations from the two banks cannot be made to completely cancel each other. This makes designing a smooth V6 engine a much more complicated problem than the straight-6, flat-6, and V8 layouts. Although the use of offset crankpins, counterweights, and flying arms has reduced the problem to a minor second-order vibration in modern designs, all V6s can benefit from the addition of auxiliary balance shafts to make them completely smooth.

When Lancia pioneered the V6 in 1950, they used a 60° angle between the cylinder banks and a six-throw crankshaft to achieve equally spaced firing intervals of 120°. This still has some balance and secondary vibration problems. When Buick designed a 90° V6 based on their 90° V8, they initially used a simpler three-throw crankshaft laid out in the same manner as the V8 with pairs of connecting rods sharing the same crankpin, which resulted in firing intervals alternating between 90° and 150°. This produced a rough-running design which was unacceptable to many customers. Later, Buick and other manufacturers refined the design by using a *split-pin* crankshaft which achieved a regular 120° firing interval by staggering adjacent crankpins by 15° in opposite directions to eliminate the uneven firing and make the engine reasonably smooth. Some manufacturers such as Buick in later versions of their V6 and Mercedes Benz have taken the 90° design a step further by adding a balancing shaft to offset the primary vibrations and produce an almost fully balanced engine.

Some designers have reverted to a 60° angle between cylinder banks, which produces a more compact engine, but have used three-throw crankshafts with *flying arms* between the crankpins of each throw to achieve even 120° angles between firing intervals. This has the additional advantage that the flying arms can be weighted for balancing purposes.

This still leaves an unbalanced primary couple, which is offset by counterweights on the crankshaft and flywheel to leave a small secondary couple, which can be absorbed by carefully designed engine mounts.

Six-cylinder designs are also more suitable for larger displacement engines than four-cylinder ones because power strokes of pistons overlap. In a four-cylinder engine, only one piston is on a power stroke at any given time. Each piston comes to a complete stop and reverses direction before the next one starts its power stroke, which results in a gap between power strokes and noticeable vibrations. In a six-cylinder engine (other than odd-firing V6s), the next piston starts its power stroke  $60^\circ$  before the previous one finishes, which results in smoother delivery of power to the flywheel. In addition, because inertial forces are proportional to piston displacement, high-speed six-cylinder engines will suffer less stress and vibration per piston than an equal displacement engine with fewer cylinders.

Comparing engines on the dynamometer, a typical even-fire V6 shows instantaneous torque peaks of 150% above mean torque and valleys of 125% below mean torque, with a small amount of negative torque (engine torque reversals) between power strokes. On the other hand, a typical four-cylinder engine shows peaks of nearly 300% above mean torque and valleys of 200% below mean torque, with 100% negative torque being delivered between strokes. In contrast, a V8 engine shows peaks of less than 100% above and valleys of less than 100% below mean torque, and torque never goes negative. The even-fire V6 thus ranks between the four and the V8, but closer to the V8, in smoothness of power delivery. An odd-fire V6, on the other hand, shows highly irregular torque variations of 200% above and 175% below mean torque, which is significantly worse than an even-fire V6, and in addition the power delivery shows large harmonic vibrations that have been known to destroy the dynamometer.

## V angles

### 60 degrees



Nissan VG30E engine

The most efficient cylinder bank angle for a V6 is 60 degrees, minimizing size and vibration. While 60° V6 engines are not as well balanced as inline-6 and flat-6 engines, modern techniques for designing and mounting engines have largely disguised their vibrations. Unlike most other angles, 60 degree V6 engines can be made acceptably smooth without the need for balance shafts. When Lancia pioneered the 60° V6 in 1950, a 6-throw crankshaft was used to give equal firing intervals of 120°. However, more modern designs often use a 3-throw crankshaft with what are termed *flying arms* between the crankpins, which not only give the required 120° separation but also can be used for balancing purposes. Combined with a pair of heavy counterweights on the crankshaft ends, these can eliminate all but a modest secondary imbalance which can easily be damped out by the engine mounts.

This configuration is a good fit in cars which are too big to be powered by four-cylinder engines, but for which compactness and low cost are important. The most common 60° V6s were built by General Motors (the heavy duty commercial models, as well as a design used in many GM front wheel drive cars) and Ford European subsidiaries (Essex

V6, Cologne V6 and the more recent Duratec V6). Other 60° V6 engines are the Chrysler 3.3 V6 engine, the Nissan VQ engine, the Alfa Romeo V6 engine, and later versions of the Mercedes-Benz V6 engine.

## 90 degrees

90° V6 engines are also produced, usually so they can use the same production-line tooling set up to produce V8 engines (which normally have a 90° V angle). Although it is relatively easy to derive a 90° V6 from an existing V8 design by simply cutting two cylinders off the engine, this tends to make it wider and more vibration-prone than a 60° V6. The design was first used by Buick when it introduced its 198 CID *Fireball V6* as the standard engine in the 1962 Special. Other examples include the Maserati V6 used in the Citroën SM, the PRV V6, Chevrolet's 4.3 L *Vortec 4300* and Chrysler's 3.9 L (238 in<sup>3</sup>) *Magnum V6* and 3.7 L (226 in<sup>3</sup>) *PowerTech V6*. The Buick V6 was notable because it introduced the concept of uneven firing, as a result of using the 90° V8 cylinder angle without adjusting the crankshaft design for the V6 configuration. Rather than firing every 120° of crankshaft rotation, the cylinders would fire alternately at 90° and 150°, resulting in strong harmonic vibrations at certain engine speeds. These engines were often referred to by mechanics as "shakers", due to the tendency of the engine to bounce around at idle speed.

More modern 90° V6 engine designs avoid these vibration problems by using crankshafts with offset split crankpins to make the firing intervals even, and often add balancing shafts to eliminate the other vibration problems. Examples include the later versions of the Buick V6, and earlier versions of the Mercedes-Benz V6. The Mercedes V6, although designed to be built on the same assembly lines as the V8, used split crankpins, a counter-rotating balancing shaft, and careful acoustic design to make it almost as smooth as the inline-6 it replaced. However, in later versions Mercedes changed to a 60° angle, making the engine more compact and allowing elimination of the balancing shaft. Despite the difference in V angles, the Mercedes 60° V6s were built on the same assembly lines as 90° V8s.

## 120 degrees

120° might be described as the *natural* angle for a V6 since the cylinders fire every 120° of crankshaft rotation. Unlike the 60° or 90° configuration, it allows pairs of pistons to share crank pins in a three-throw crankshaft without requiring flying arms or split crankpins to be even-firing. However, unlike the crossplane crankshaft V8, there is no way to arrange a V6 so that unbalanced forces from the two cylinder banks will completely cancel each other. As a result, the 120° V6 acts like two straight-3s running on the same crankshaft and, like the straight-3, suffers from a primary dynamic imbalance which requires a balance shaft to offset.

The 120° layout also produces an engine which is too wide for most automobile engine compartments, so it is more often used in racing cars where the car is designed around the engine rather than vice-versa, and vibration is not as important. By comparison, the 180°

flat-6 *boxer* engine is only moderately wider than the 120° V6, and unlike the V6 is a fully-balanced configuration with no vibration problems, so it is more commonly used in aircraft and in sports/luxury cars where space is not a constraint and smoothness is important.

Spanish truck manufacturer Pegaso built the first production 120° V6 for the Z-207 mid size truck in 1955. The engine, a 7.5 litre alloy Diesel designed under the direction of engineer Wifredo Ricart uses a single balance shaft rotating at the speed of the crankshaft

Ferrari introduced a very successful 120° V6 racing engine in 1961. The Ferrari Dino 156 engine was shorter and lighter than the 65° Ferrari V6 engines that preceded it, and the simplicity and low center of gravity of the engine was an advantage in racing. It won a large number of Formula One races between 1961 and 1964. However, Enzo Ferrari had a personal dislike of the 120° V6 layout, preferring a 65° angle, and after that time it was replaced by other engines.

Bombardier designed 120° V220/V300T V6 engines for use in light aircraft. The ignition sequence was symmetrical, with each cylinder firing 120° after the previous cylinder resulting in smooth power delivery. A balance shaft on the bottom of the engine offset the primary dynamic imbalance. The straight, pin-type crankshaft journals in the 120° V-6 layout allowed a shorter and stiffer crankshaft than competing flat-6 engines, while water cooling resulted in better temperature control than air cooling. These engines could run on automotive gasoline rather than avgas. However, the design was shelved in 2006 and there are no plans for production.

## **Other angles**

Narrower angle V6 engines are very compact but can suffer from severe vibration problems unless very carefully designed. Notable V6 bank angles include:

- The 10.6° and 15° Volkswagen VR6, which is such a narrow angle it can use a single cylinder head and double overhead camshafts for both cylinder banks. With seven main bearings, it is more like a staggered-bank in-line six rather than a normal V6, but is only slightly longer and wider than a straight-4.
- The 45° Electro-Motive 6 cylinder version of their model 567 Diesel locomotive engine. This angle is optimum for the more common 16 cylinder version.
- The 54° GM/Opel V6, designed to be narrower than normal for use in small front-wheel drive cars.
- The 65° Ferrari Dino V6, allowing larger carburetors (for potentially higher power in race tuning) than a 60° angle, while suffering a slight increase in vibrations.
- The 75° Isuzu Rodeo and Isuzu Trooper V6 of 3.2 and 3.5 L in both SOHC and DOHC versions.
- The 80° Honda RA168-E Formula One engine in the McLaren MP4/4.

## Odd and even firing

Many older V6 engines were based on V8 engine designs, in which a pair of cylinders was cut off the front of V8 without altering the V angle or using a more sophisticated crankshaft to even out the firing interval. Most V8 engines share a common crankpin between opposite cylinders in each bank, and a 90° V8 crankshaft has just four pins shared by eight cylinders, with two pistons per crankpin, allowing a cylinder to fire every 90° to achieve smooth operation.

Early 90° V6 engines derived from V8 engines had three shared crankpins arranged at 120° from each other, similar to an inline 3-cylinder. Since the cylinder banks were arranged at 90° to each other, this resulted in a firing pattern with groups of two cylinders separated by 90° of rotation, and groups separated by 150° of rotation, causing a notorious *odd-firing* behavior, with cylinders firing at alternating 90° and 150° intervals. The uneven firing intervals resulting in rough-running engines with unpleasant harmonic vibrations at certain engine speeds.

An example is the Buick 231 odd-fire, which has a firing order 1-6-5-4-3-2. As the crankshaft is rotated through the 720° required for all cylinders to fire, the following events occur on 30° boundaries:

Angle	0°	90°	180°	270°	360°	450°	540°	630°
<b>Odd firing</b>	1	6	5		4	3		2
<b>Even firing</b>	1	4	5		6	3	2	

More modern 90° V6 engines avoid this problem by using split crankpins, with adjacent crankpins offset by 15° in opposite directions to achieve an even 120° ignition pattern. Such a 'split' crankpin is weaker than a straight one, but modern metallurgical techniques can produce a crankshaft that is adequately strong.

In 1977, Buick introduced the new "split-pin crankshaft" in the 231. Using a crankpin that is 'split' and offset by 30° of rotation resulted in smooth, even firing every 120°. However, in 1978 Chevrolet introduced a 90° 200/229 V6, which had a compromise 'semi-even firing' design using a crankpin that was offset by only 18°. This resulted in cylinders firing at 108° and 132°, which had the advantage of reducing vibrations to a more acceptable level and did not require strengthening the crankshaft. In 1985, Chevrolet's 4.3 (later the Vortec 4300) changed it to a true even-firing V6 with a 30° offset, requiring larger crank journals to make them adequately strong.

In 1986, the similarly-designed 90° PRV engine adopted the same 30° crankshaft offset design to even out its firing. In 1988, Buick introduced a V6 engine that not only had split crankpins, but had a counter-rotating balancing shaft between the cylinder banks to

eliminate almost all primary and secondary vibrations, resulting in a very smooth-running engine.

### ***Racing use***



Mercedes-Benz V6 DTM engine

The V6 engine was introduced into racing by Lancia in the early '50s. After good results with privately entered Aurelia saloons Lancia set a works competition department in 1951. Four B20 Coupes were entered in the '51 Mille Miglia and the one driven by Giovanni Bracco and Umberto Maglioli caused quite a stir by finishing second overall after the 4.1-litre Ferrari driven by Villoresi and Cassani, a car which had three times more power than the Lancia. After that encouraging start Lancia decided to carry on with the endurance racing program, first with specially prepared Aurelias (called *Da Corsa*) and then with specially built prototypes. A D24 with a 3,102 cc (189 cu in) V6 making 230 PS (170 kW) won the 1953 Carrera Panamericana with Juan Manuel Fangio at the wheel.

After that came the Ferrari Dino V6. Alfredo Ferrari (nicknamed Dino), son of Enzo Ferrari, suggested to him the development of a 1.5 L DOHC V6 engine for Formula Two at the end of 1955. The Dino V6 underwent several evolutions, including an increased engine displacement to 2,417 cc (147 cu in), for use in the Ferrari 246 Formula One car in 1958.

The use of a wide 120° bank angle is appealing for racing engine designers as it permits a low center of gravity. This design is even considered superior to the flat-6 in that it leaves more space under the engine for exhaust pipes; thus the crankshaft can be placed lower in the car. The Ferrari 156 built for new Formula One 1.5 L regulations used a Dino V6 engine with this configuration.

The Dino V6 engine saw a new evolution in 1966 when it was adapted to road use and produced by a Ferrari-Fiat joint-venture for the Fiat Dino and Dino 206 GT (this car was made by Ferrari but sold under the brand Dino). This new version was redesigned by Aurelio Lampredi initially as a 65° 2.0 L (~122 cu in) V6 with an aluminum block but was replaced in 1969 by a 2.4 L (~146 cu in) cast-iron block version (the Dino car was renamed the 246GT).

The Fiat Dino and Dino 246GT were phased out in 1974, but 500 engines among the last built were delivered to Lancia, who was like Ferrari already under the control of Fiat. Lancia used them for the Lancia Stratos which would become one of the most successful rally cars of the decade.



Alfa Romeo V6

The Alfa Romeo V6 was designed in the 1970s by Giuseppe Busso, the first car to use them being the Alfa Romeo 6. The over-square V6, with aluminium alloy block and

heads, has seen continuous use in road vehicles, from the Alfetta GTV6 onwards. A notable use of the *Busso's Sei* (Busso's big Six) V6 was the Alfa Romeo 155 V6 TI. Turbocharged, it had a peak power of 490 PS (360 kW; 480 hp) at 11,900 rpm. The 164 introduced a 3.0 L (~183 cu in) V6, a 2.0 V6 turbocharged in 1991 and in 1992, a 3.0 L DOHC 24 valve version. The Alfa 156 introduced a 2.5 L DOHC 24 valve version in 1997. The engine capacity was later increased to 3.2 L (~195 cu in), where it found application in the 156 GTA, 147 GTA, 166, GT, GTV and Spider 916. Production was discontinued in 2005.

Another influential V6 design was the Renault-Gordini CH1 V6, designed by François Castaing and Jean-Pierre Boudy, and introduced in 1973 in the Alpine-Renault A440. The CH1 was a 90° cast iron block V6, similar to the mass produced PRV engine in those two respects but otherwise dissimilar. It has been suggested that marketing purposes made the Renault-Gordini V6 adopt those characteristics of the PRV in the hope of associating the two in the public's mind.

Despite such considerations, this engine won the European 2 L prototype championship in 1974 and several European Formula Two titles. This engine was further developed in a turbocharged 2 L version that competed in Sports car and finally won the 24 Hours of Le Mans in 1978 with a Renault-Alpine A 442 chassis.

The capacity of this engine was reduced to 1.5 L to power the Formula One Renault RS01. Despite frequent breakdowns that resulted in the nickname of the 'Little Yellow Teapot', the 1.5 L finally saw good results in 1979.

Ferrari followed Renault in the turbo revolution by introducing a turbocharged derivative of the Dino design (a 1.5 L 120° V6) with the Ferrari 126. However, the 120° design was not considered optimum for the wing cars of the era and later engines used V angles of 90° or less.

Both Renault and Ferrari failed in their attempt to win the Drivers' Championship with V6 Turbo engines. The first turbocharged engine to win the championship was the Straight-4 BMW.

They were followed by a new generation of Formula One engines, the most successful of these being the TAG V6 (designed by Porsche) and the Honda V6. This new generation of engines were characterized by odd V angles (around 80°). The choice of these angles was mainly driven by aerodynamic consideration. Despite their unbalanced designs these engines were both quickly reliable and competitive; this is generally viewed as a consequence of the quick progress of CAD techniques in that era.

In 1989 Shelby tried to bring back the Can-Am series, using the Chrysler 3.3 L (201 in<sup>3</sup>) V6 (not yet offered to the general public) as the powerplant in a special racing configuration making 255 hp (190 kW). This was the same year that the Viper concept was showed to the public.

Originally the plan was to produce two versions of this race car, a 255 hp (190 kW) version and a 500 hp (370 kW) model, the 255 hp (190 kW) version being the entry circuit. The cars were designed to be a cheap way for more people to enter auto racing. Since all the cars were identical, the winners were to be the people with the best talent, not the team with the biggest pockets. The engines had Shelby seals on them and could only be repaired by Shelby's shop, ensuring that all the engines are mechanically identical.

Only 100 of these 3.3s were ever built. Of these 100, 76 were put into Shelby Can-Am cars (the only 76 that were ever sold). No significant amount of spare parts were produced, and the unsold engines were used for parts/spares. The Shelby specific parts, such as the upper intake manifold, were never made available to the general public. According to a small article in the USA Today (in 1989), these cars were making 250 hp (190 kW) (stock versions introduced in 1990 produced 150 hp) and hitting 160 mph (260 km/h) on the track. The engine itself was not that far from a standard-production 3.3. The Shelby engine is only making about 50 hp (37 kW) more than the newest 3.3 factory engines from Chrysler. The Can-Am engine has a special Shelby Dodge upper intake manifold, a special Shelby Dodge throttle body, and a special version of the Mopar 3.3 PCM (which had this engine redlining at 6800 rpm).

Nissan also has a quite successful history of using V6's for racing in both IMSA and the JGTC. Development of their V6s for sports cars began in the early 1980s with the VG engine initially used in the Z31 300ZX. The engine began life as a SOHC, turbocharged 3.0L power plant with electronic fuel injection, delivering 230 PS (169 kW). The VG30ET was later revised into the VG30DETT for the Z32 300ZX in 1989. The VG30DETT sported both an additional turbocharger and an extra pair of camshafts, making the engine a genuine DOHC twin-turbo V6 producing 300 PS (221 kW). Nissan used both of these engines in its IMSA racing program through out the 1980s and 1990s each producing well over 800 hp (600 kW). In the Japan Grand Touring Car Championship, or JGTC, Nissan opted for a turbocharged version of its VQ30 making upwards of 500 hp (370 kW) to compete in the GT500 class.

### ***Motorcycle use***

Laverda showed a 996 cc V6 engined motorcycle at the 1977 Milan show. The motorcycle was raced in the 1978 Bol d'Or.

***Marine use***



Yamaha OX66 engine, as used in their outboard motor range

## Chapter- 9

# Straight-Six Engine



A BMW M20B25 engine with the cylinder head removed, showing the pistons in the six cylinders of the engine

The **straight-six engine** or **inline-six engine** (often abbreviated **I6**, **L6** or **R6**) is a six cylinder internal combustion engine with all six cylinders mounted in a straight line along the crankcase. The single bank of cylinders may be oriented in either a vertical or an inclined plane with all the pistons driving a common crankshaft; in vehicles where this engine is installed inclined versus vertical, it is sometimes called a **slant-six engine**. The

straight-six layout is the simplest engine layout that possesses both primary and secondary mechanical engine balance, resulting in relatively low manufacturing cost combined with much less vibration than engines with fewer cylinders.

### ***Displacement range***

Usually, the straight-six design is used for engine displacements ranging from approximately 2 to 5 litres (120 to 310 cu in) in automobiles. It is also sometimes used for smaller engines but these, although very smooth running, tend to be rather expensive to manufacture in terms of power-to-cost ratio. Since the length of an engine is roughly proportionate to the number of cylinders in one bank (plus the width of one connecting rod in a "V" engine), they are inevitably physically longer than alternative layouts such as L4, V6, or V8.

The smallest production straight-six was found in the Benelli 750 Sei motorcycle, displacing 747.7 cc (45.63 cu in) (0.7477 L). Honda and Mike Hailwood raced in the 1960s with the RC166 250 cc (15 cu in) (0.25 L) six cylinder, 24-valve motorcycle engine. Though pre-World War II engines could be quite large by modern standards — such as the Rolls Royce Silver Ghost's 7.4 L engine and the 824 cuin (13.5 L) of the 1910s Peerless, Pierce, and Fageol, the largest modern passenger-car straight-sixes are the 4.2 L powerplants found in several Jaguars and AMCs, the 4.3 L Hemi Six, the 4.0 TVR Speed Six, the 4.0 Ford Barra, the 4.1 Chevrolet 250, the 4.2 Chevrolet Vortec 4200, 4.9 Ford, 4.8 Chevrolet, and the 5.0L of Hudson H-145 (produced until 1957). As of 2009, the Cummins B Series engine used in Dodge Ram pickup trucks displaced up to 6.7 L

The Gipsy Six and Gipsy Queen, made by the de Havilland Engine Company from 1935 until 1950, were inverted straight-six engines displacing 560.6 cubic inches (9.187 L). They were used in a variety of aircraft including the de Havilland Dragon Rapide and the Cierva W.9 experimental helicopter.

Because it is a fully balanced configuration, the straight-six can be scaled up to very large sizes for heavy truck, industrial and marine use, such as the 16 L (980 cu in) Volvo diesel engine and the 15 L Cummins ISX used in heavy vehicles. The largest are used to power ships, and use fuel oil. The straight-six can also be viewed as a scalable modular component of larger motors which stack several straight-sixes together, e.g. flat- or V-12s, W-18s etc.

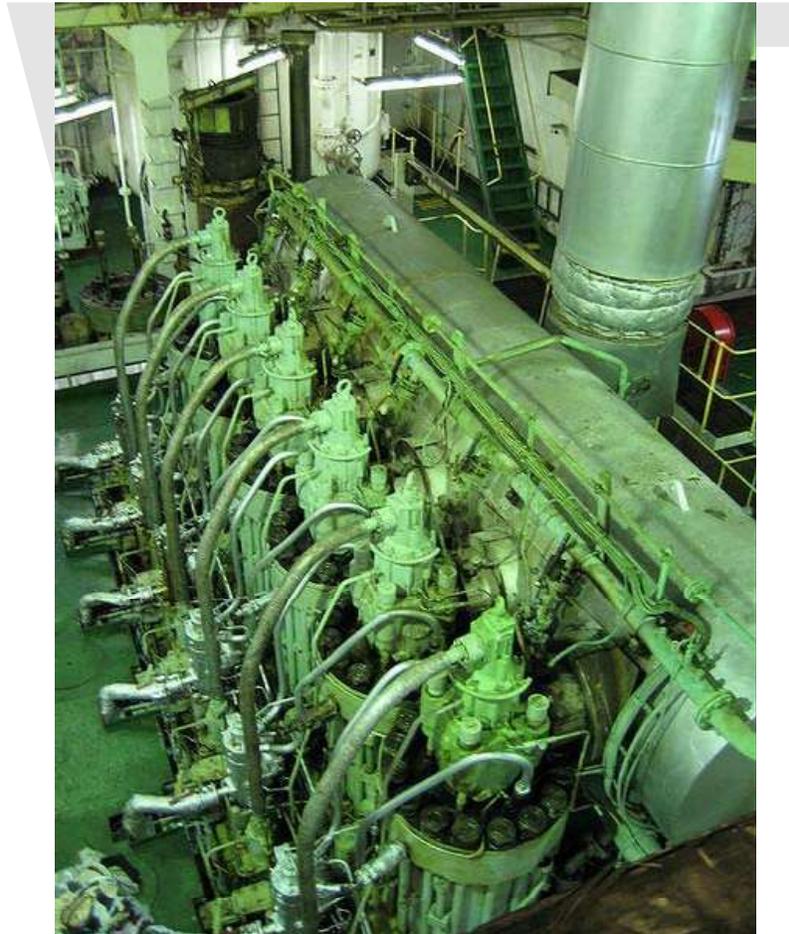
### ***Modern trends***

Historically, straight-six engines were introduced much earlier than V6 engines. While the first straight-six was manufactured in 1903 by Spyker, it was 1950 before a production V6 was introduced. V6s (unlike crossplane V8 engines) had intrinsic vibration problems that were difficult to eliminate without modern computer aided design techniques. The length of the straight-six was not a major concern in the older front-engine/rear-wheel drive vehicles, but the modern move to the more space-efficient front-

engine/front-wheel drive and transverse engine (left-to-right versus front-to-back) configurations in smaller cars made the length of the V6 (one half the length of an L6 with the same bore size, plus the width of one rod) a major advantage. As a result, in recent decades automobile manufacturers have replaced most of their straight-six engines (and many of their V8s) with V6 engines; Mercedes-Benz now uses V6 engines despite most of their lineup retaining the front-engine/rear-wheel layout.

Exceptions to the shift to V6 engines include BMW, which specializes in high-performance straight-sixes used in a lineup of front-engine/rear-wheel drive vehicles, Volvo, which designed a compact straight-six engine/transmission package to fit transversely in its larger cars, and the Australian Ford Falcon, which still uses a straight-six configuration. Straight-sixes also continue to be commonly used in medium to large trucks, and sport utility vehicles, where engine length is less of a concern. In 2002, General Motors introduced the Vortec 4200 as part of the modular straight-four, straight-five and straight-six GM Atlas engine line.

### ***Balance and smoothness***



An MAN B&W 6S60MC inline six cylinder low-speed diesel engine. This example is used on a 70,000 t (deadweight) bulk carrier, and produces 9,014.8 kW (12,089.0 hp) at 90.3 rpm (1.5 Hz)(703,130 ftlbs torque).

An inline six engine is in perfect primary and secondary mechanical balance, which can be achieved without using a balance shaft. The engine is in primary balance because the front and rear trio of cylinders are mirror images, and the pistons move in pairs. That is, piston #1 balances #6, #2 balances #5, and #3 balances #4, largely eliminating the polar rocking motion that would otherwise result. Secondary imbalance is avoided because an inline six cylinder crankshaft has six crank throws arranged in three planes offset at 120°. The result is that differences in piston speed at any given point in rotation are effectively canceled.

An inline four cylinder or V6 engine without a balance shaft will experience secondary dynamic imbalance, resulting in engine vibration. As a general rule, the forces arising from any dynamic imbalance increase as the square of the engine speed — that is, if the speed doubles, vibration will increase by a factor of four. In contrast, inline six engines have no primary or secondary imbalances, and with carefully designed crankshaft vibration dampers to absorb torsional vibration, will run more smoothly at the same crankshaft speed (rpm). This characteristic has made the inline six popular in some European sports-luxury cars, where smooth high-speed performance and good fuel economy are desirable. As engine reciprocating forces increase with the cube of piston mass, inline six is a preferred configuration for large truck engines.

### ***Crankshaft design***

Crankshafts on six cylinder engines generally have either four or seven main bearings. Larger engines and diesels tend to use the latter because of high loadings and to avoid crankshaft flex. Because of the six cylinder engine's smooth characteristic, there is a tendency for a driver to load the engine at low engine speeds. This can produce crankshaft flex in four main bearing designs where the crank spans the distance of two cylinders between main bearings. This distance is longer than the distance between two adjacent main bearings on a V6 with four mains, because the V6 has cylinder bores on opposite banks which overlap significantly; the overlap may be as high as 100%, minus the width of one connecting rod (1.00" or so). In addition, modern high-compression engines subject the crankshaft to greater bending loads from higher peak gas pressures, requiring the crankthrows to have greater support from adjacent bearings, so it is now customary to design straight-sixes with seven main bearings.

Many of the more sporty high-performance engines use the four bearing design because of better torsional stiffness (e.g., BMW small straight 6's, Ford's Zephyr 6). The accumulated length of main bearing journals gives a relatively torsionally flexible crankshaft. The four main bearing design has only six crank throws and four main journals, so is much stiffer in the torsional domain. At high engine speeds, the lack of torsional stiffness can make the seven main bearing design susceptible to torsional flex and potential breakage. Note that a V12 engine can be made with the same number of crank throws as the seven main bearing straight-six, although each throw must be wide enough to accept the connecting rods of both opposing cylinders requiring either that each rod be far narrower, or that the crankshaft length be extended. Another factor affecting large straight-six engines is the front mounted timing chain which connects any

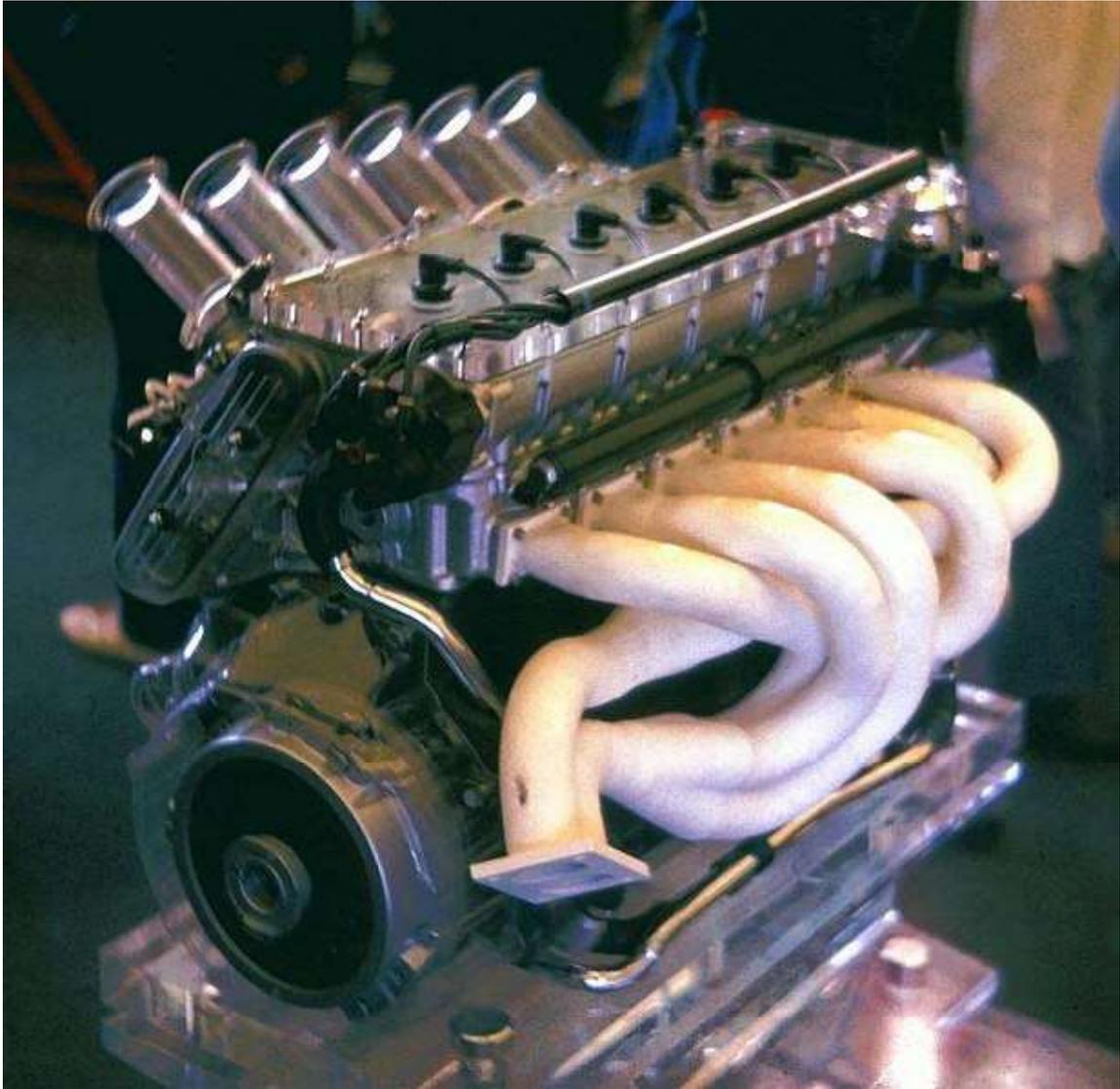
camshafts to the crankshaft. The camshafts are also quite long and subject to torsional flex as they in turn operate valves alternately near the front of the engine and near the rear. At high engine speeds, camshafts can flex torsionally in addition to the crankshaft, contributing to valve timing for the rear most cylinders becoming inaccurate and erratic, losing power, and in extreme cases resulting in mechanical interference between valve and piston — with catastrophic results. Some designers have experimented with installing the timing chain/gears in the middle of the engine (between cylinders 3 and 4) or adding a second timing chain at the rear of the engine. Either method can solve the problem at the cost of additional complexity.

Another factor affecting the ability of the large six cylinder engines to achieve high speed is the simple geometric reality of a relatively long stroke (undersquare) design. A straight-six is a long engine, and the designer is usually encouraged to make it as short as possible, while height is not usually a problem. Hence, the tendency to use a longer stroke and smaller bore than in a V engine to achieve a given capacity. By contrast, a long-stroke V engine tends to become too wide, which encourages increasing the bore rather than the stroke to increase displacement. The typically longer stroke of the straight-six increases crank throw and piston speed, and so tends to reduce the rpm rating of the engine.

### ***History***

The first inline six was produced by Spyker in 1903. By 1909, there were some eighty manufacturers using it, 62 in Britain alone, including Darracq, Delaunay-Bellville, Vertex, MMC, White and Poppe, Mutel, and Ford.

## Continental Europe



BMW M1 engine

After becoming famous in the last year of World War I through their production of the liquid-cooled BMW IIIa aviation engine of straight-six layout, BMW introduced its first straight 6-cylinder automotive engine in 1933. It developed straight-six engines for the post-World War II era by adding two cylinders to its M10 four-cylinder design. In 1968, it introduced a M30 straight-six design with the same 30° slant, overhead camshaft layout, and 100 mm bore spacing as the four. It originally intended to follow up with a V8 engine line in the early 1970s, but when the 1973 oil crisis hit, BMW canceled its V8 plans and concentrated on refining and enlarging its straight-six lineup. These included a smaller straight-six in 2.0 and 2.3 L (120 and 140 cu in) displacements (the BMW M20), versions of the larger BMW M30 up to 3.8 L (230 cu in) (the S38B38); and beginning in 1983, a series of M21 straight-six diesel engines. In 1986, BMW introduced the M70

V12 which was essentially two 2.5 L (150 cu in) straight-sixes on the same crankshaft. In the mid-90's, they produced a series of straight-6's based on the M50 architecture, the ultimate of which was the 330-360 hp S54, used up to 2008. BMW offered a straight-six for their following line up BMW 1 Series, BMW 3 Series, BMW 5 Series, BMW 6 Series, BMW 7 Series (Euro models), BMW X3, BMW X5, BMW X6, the retired Z3 and current BMW Z4.

Mercedes-Benz has used straight-six engines in its cars for around 100 years, starting in the first decade of the 20th century with a monstrous 10 L (610 cu in) engine producing 75 hp (56 kW), and producing in parallel through the World War I years the majority of German aviation engines of straight-six layout, culminating in the Mercedes D.III engine series of 1916-18 for the *Luftstreitkräfte*. Before and after the merger of Daimler and Benz in 1926, the combined company produced a variety of powerful straight-six engines, culminating in a 7 L (430 cu in) supercharged unit producing up to 300 hp (224 kW). Mercedes-Benz began the post-war era by producing straight-fours, but resumed making straight-sixes in 1951 with the M130, which were the beginning of the modern era of MB straight-sixes. Following that introduction, the company produced two lines of petrol (gasoline) straight-sixes at any one time, a small six and a larger six, in addition to its straight-fours, straight-fives, and later V8s and V12s. Although the company has used diesel engines in its cars since 1934, it introduced its first straight-six OM603 a 3.0 L (180 cu in) diesel in 1985. In 1996, the company replaced its petrol straight-sixes with a series of 90° M112 V6s, although it continued to produce diesel straight-sixes.

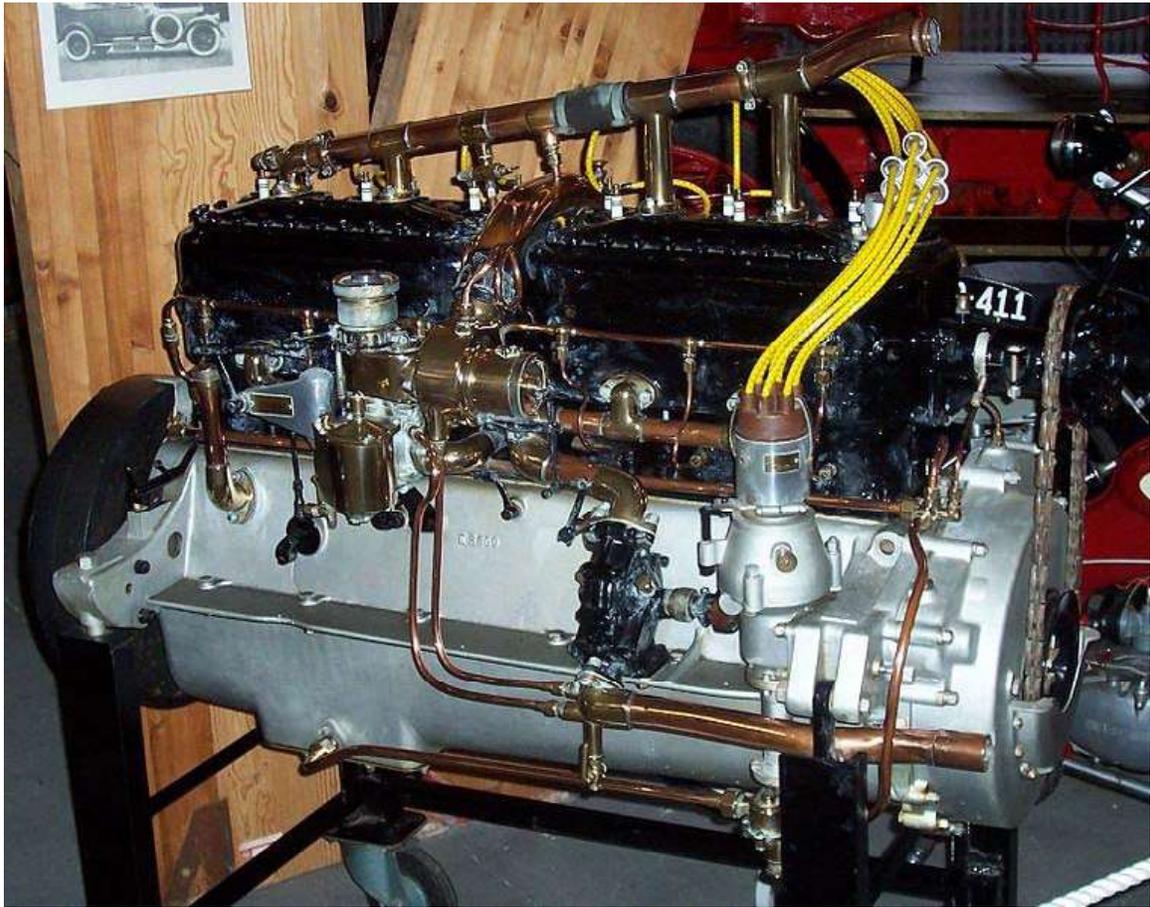
Volvo produced straight-sixes, the Volvo B30 engine (1969–1975), also the B6304 and the B6254 engines during late 1990s. As Volvo developed front-wheel drive models, they mounted their inline-six engine transversely by using a short transaxle package, and relocated engine-driven accessories. The 3.2 L (200 cu in) straight-six introduced in 2006 was only slightly longer than its straight-five, achieved by moving the camshaft drive to the back of the engine and sharing the same gear train with ancillaries mounted in otherwise unused space over top of the transmission. It was short for a straight-six and also very narrow. Volvo claims a transversely mounted inline engine leaves more crush space to protect against frontal impacts than a (shorter) transverse V6 or a longitudinally mounted inline-six.

Opel has also used a straight-six engine since 1930s until the early 1990s, ranging between 2.5 and 4.0 L (150 and 240 cu in). They powered Opel's top of the line models, including the Admiral, Kapitän, Monza, Senator, Omega, and Commodore.

In 1959, Saab had an experimental car with two transverse straight-three engines bolted together—the Saab Monster.

Alfa Romeo used straight-six engine in G1 and G2 models (1921–1923), RL model (1922–1927) and between 1925–1954 in Alfa Romeo 6C series road and racing cars, the 1500 version had one of the smallest straight-six engines (1,487 cc (90.7 cu in)). The last Alfa Romeo model using straight-six was Alfa Romeo 2600 (1961–1969).

## United Kingdom



Rolls-Royce 40/50hp Silver Ghost 7,400cc side valve six cylinder engine



Jaguar XJ6 engine

The straight-six was the archetypal British engine for sports and luxury cars for many years. Rolls-Royce used straight-six engines until changes in their design made the shorter V8 engine layout more suitable. Jaguar and other manufacturers built straight-six engines from 1935 until the 1990s.

The most prominent of these was the Jaguar XK6 engine, which reportedly was developed during long nights during World War II when Jaguar founder William Lyons and his staff were on fire watch duty in the Jaguar factory in Coventry, and had nothing better to do than design a new engine. The result was displayed in the Jaguar XK120 at the London Motor Show in 1948. The 3.4 L (210 cu in) twin overhead camshaft XK6 engine engine was highly advanced compared to previous British engines. The Jaguar XK120 and the XK-powered Jaguar C-Type and Jaguar D-type, went on to score victories in races and rallies in the UK, Europe and North America. They dominated the 24 Hours of Le Mans during the 1950s, where Jaguar C-Types won in 1951 and 1953, and the D-Types had three more wins in 1955, 1956 and 1957. Subsequently, fitted to Lister Cars Lister-Jaguar, the D-type engine contributed to their success in international sportscar-racing in the late-1950s. The engine design, enlarged to 3.8 L (230 cu in), reached its apogee in the Jaguar E-type introduced in 1961, which was capable of 150 mph (240 km/h). In 1964, the XK engine was again enlarged to 4.2 L (260 cu in), which was considered the most powerful and refined of the series. The last XK-engined

Jaguar went out of production in 1986, but some XK engined cars such as the Daimler DS420 limousine were still available into 1990s. A variant of the 4.2 L engine powered some Scorpion light tanks. The XK6 engine was followed by the AJ6 and AJ16 engines. After Jaguar was acquired by Ford, these engines were replaced with the Ford Duratec-derived Jaguar AJ-V6 engine.

Aston Martin used a straight-six for many years, as did Austin-Healey in their Austin-Healey 3000. The latter used an engine originally built for the Austin Motor Company A105 saloon. Jensen also used Austin straight-six engines in their post WW-2 cars until 1962, re-engineering the Austin Sheerline's 4 L DS range to increase the power output. MG also used a straight-six in some pre-war cars (examples: MG K-type and MG N-type) and more recently in the MGC.

Bristol produced a straight-six until 1961, based on a BMW design, that was also used by many small automakers. Prior to World War II, Riley built a number of models fitted with straight-six engines, including the Kestrel 12/6 saloon and the MPH roadster.

The compact Triumph straight-six powered their high-end saloon and sports cars from the mid-1950s to the mid-1970s. It was available in 1.6 L (98 cu in), 2.0 L (120 cu in), and 2.5 L (150 cu in) capacities. Triumph claimed that their TR5 model was the first car in the UK to come with fuel injection as standard; the TR5 has a 2.5 L Triumph straight-six. Other Triumph vehicles that use the Triumph straight-six are:

- GT6 1966-73
- Vitesse 1962-71
- The 2000 Range 1963-77
- TR6 1969-76

The Austin 1800 range was expanded in 1972 when a 2.2 L six cylinder version of the BMC E-Series engine was installed transversely. The Austin and Morris models were called 2200 and the Wolseley version was called the Wolseley Six. Although this motor was originally designed by BMC in the sixties it was British Leyland who completed the planned upgrade to the 1800 range when they fitted this motor. This motor then went on to be used in the same configuration on the Leyland Princess which superseded the 1800 in 1975. This motor was designed to be as short as possible so the six cylinder would fit transversely, no water bores were between cylinders and the cylinders were too close together to allow boring; the only way to gain extra capacity was by lengthening the stroke.

The Rover SD1 saloon used a Triumph designed straight-six of 2.3 and 2.6 L (140 and 160 cu in) capacities as its base and mid-range engines.

British sports car company TVR designed its own straight-six, known as the Speed Six, which was also used in the Sagaris, with its capacity of 4 L (240 cu in). At 405 hp, it is the most powerful naturally-aspirated straight-6 ever fitted to a regular production car,

though some turbocharged engines are considerably more powerful (notably, the Toyota 2JZGTE and Nissan RB26DETT).

The Rover Company used straight-sixes in many of its saloon cars. A family of straight-4 and straight-6 engines with an unusual 'Inlet-Over-Exhaust' layout were developed. Introduced in the 1930s, these engines were used with great success in Rover's post war cars (the 'P3', 'P4' and 'P5' models). The sixes were available in a variety of capacities- 2.1 L (130 cu in), 2.2 L (130 cu in), 2.3 L (140 cu in), 2.6 L (160 cu in) and 3.0 L (180 cu in). In 1968, Rover began offering the 2.6 L engine as an option in long-wheelbase variants of its Land Rover 4x4. The engine remained available in the Land Rover until 1980, long after production of the other versions of the Rover IOE straight-six had stopped.

Ford UK produced a straight-six engine for the Zephyr and Zodiac range of passenger cars from the Mk1 of 1951 (2262 cc) through the Mk2 (2,553 cc (155.8 cu in)) and Mk3 until 1966. The straight-six was a four main bearing 12 overhead valve design with a short stroke. Rated output grew from just 65 hp (48 kW) in the Mk1 to 110 hp (82 kW) in the Mk3 Zodiac.

## United States



1954 Hudson Wasp I6



Modified Chrysler slant-6



Carbureted 1977 AMC 258 cu in (4.2 L)



duty) also incorporated the straight-six until the mid-1950s, and they are still used in light trucks available today. The new wave of compact cars that started in the late 1950s provided a suitable home for straight-six designs.

The Chrysler Slant-6 engines used in the Plymouth Valiant and Dodge Dart A-body models of the 1960s and 1970s featured a 30° inclined design to achieve a lower overall height. Originally designed to be built of aluminum, but after encountering problems in manufacturing the engines in aluminum, they were built in cast iron without changing the design to compensate for the stronger metal. Although it only had four crankshaft main bearings instead of the seven used by its competitors, they were the same size as those on the 426 cu in (7.0 L) Hemi V8. The Slant-6 achieved some success in racing when engineers utilized the slant of the engine for very long intake ports to boost horsepower by tuning the intake system. After 30 years of production, it was discontinued in favor of V6 engines because it was too long to mount transversely in front wheel drive cars.

Kaiser Jeep introduced the Tornado straight-6 for 1963. It was the first U.S. designed mass produced overhead cam (OHC) automobile engine. It was robust and built for heavy-duty performance, as well as featuring the lowest specific fuel consumption of all production gasoline engines in the market at the time. However, it was complex (by 1960s standards) for civilian vehicles in the U.S., but continued to be installed in military Jeeps and was also produced through 1982 by IKA in Argentina.

A "modern era" straight-six engine family was introduced by American Motors (AMC) in 1964. These lighter in weight engines were used in a variety of AMC passenger and Jeep utility vehicles. American Motors also sold their straight-sixes to International Harvester for powering International's "Light Line" of trucks: Scouts, pickups, and Travelalls. These engines were also assembled and marketed internationally. Some markets (such as Vehiculos Automotores Mexicanos [VAM] in Mexico) built their own specialized versions. This engine is considered to be one of the best ever made and it received modifications and upgrades as engine control technology improved. This engine was produced continuously for 42 years (even after Chrysler's buyout of AMC in 1987) all the way through 2006. It featured a durable design with a cast iron block and cylinder head, hydraulic lifters (with non-adjustable rockers), and seven main bearings. Since AMC cars were designed to take the weight of an optional V8, AMC was able to make their straight-sixes much stronger and heavier than they needed to be. As a result, the engine blocks were so sturdy that some were used in race cars in the Indianapolis 500. In the 1978 race, an AMC 199 cu in (3.3 L) engine built by Navarro produced 875 hp (652 kW) at 8500 rpm with 80 in (2,000 mm) of manifold pressure.

Ford and General Motors straight-sixes of the 1960s and 1970s were generally nondescript, except for the unusual (for the United States) OHC Pontiac six of the late-1960s. Although it was one of the few American straight-sixes of its era to be advertised as exceeding 200 hp (150 kW), it wooed few performance buyers away from V8s during the muscle car era, and was eventually discontinued in favor of a less costly but less powerful pushrod design.

American automakers found it more profitable to sell slow-speed straight-sixes as "economy" engines, and V8s as "performance" engines regardless of their horsepower potential, since big, unsophisticated, overhead valve engines were relatively cheap to manufacture, and fuel economy was not a concern prior to the 1973 oil crisis.

The trend after the fuel crises in the 1970s was towards smaller cars with better fuel economy. Despite this, straight-six engines became rare in American cars, although they continued to be used in trucks and vans. The decline of the straight-six was in response to the more compact size of the V6 layout. The straight-six required a longer engine compartment that was more appropriate to a larger car. The shorter V6 could be used in a shorter engine compartment and therefore fit better in a more compact car. It was also relatively easy to cut two cylinders off a V8 design to produce a V6 that could be manufactured on the same assembly line as the V8, which was convenient for American manufacturers.

Jeeps were an exception to the trend to V6s, and began offering AMC's 258 cu in (4.2 L), known as "High Torque," straight-sixes as a common engine option in 1972. These engines continued to receive upgrades that were advanced for their time, including the fuel-injected high-performance 4.0 L (240 cu in) version for the 1987 model year. The five millionth 4.0 L was produced in Kenosha, Wisconsin by Chrysler on 15 June 2001, autographed by the assembly workers, and donated to the Rambler Legacy Gallery. Usage of the AMC 4.0 declined in Jeep vehicles after the Jeep Cherokee (in North America) was replaced by the Liberty in 2002, which featured Chrysler's 3.7 L (230 cu in) V6 instead. It declined further after the 2005 introduction of the third generation Jeep Grand Cherokee, which also used the 3.7 L (230 cu in) V6. The last application of the 4.0 was in the 2006 Jeep Wrangler; for 2007, the engine was replaced with a 3.8 L (230 cu in) V6.

Ford used a straight-six in baseline Mustangs and in its other models for many decades. They were also found in F-series pickups, E-series vans, and Broncos (most notably the venerable Ford 300 inline six) until 1997 when they were replaced with a V6.

In 1989, Chrysler introduced the 5.9 L (360 cu in) Cummins B Series engine as an option on its pickup trucks. Displacing nearly 1 L per cylinder, this straight-six turbocharged diesel engine was an attractive alternative to the big gasoline V8s normally used on full-sized pickups, because of its better fuel economy and nearly twice as much low-speed torque. The usual marketing cachet of competing V8s from GM and Ford was offset by the "real" truck origin of the Cummins engine because earlier GM diesel V8s derived from gasoline engines had reliability problems.

In 2001, General Motors introduced a new family of straight engines, the *Atlas*, for use in the Chevrolet TrailBlazer/GMC Envoy. The straight-six was chosen for development because of the desirable operating characteristics of its self-balanced design.

## Asia



Nissan S20 engine

Japanese automakers have used the straight-six since the 1960s in a wide range of vehicles. More recently though, Nissan (the 1984 300ZX switched to V6) and Toyota have changed to V6s, saying the straight-sixes were too long and expensive to manufacture for the engine compartments in their newer vehicles. The Nissan Skyline GT-R also used this layout and so had a long hood.

Toyota started with their F-series engine, and later the M, FZ, G, and JZ engines, and Nissan started with their H-series, and later the L (up until 1984) of the early Nissan Z-cars, also known as Fairlady Zs, as well as the RB series engines (in the R31-R34 Skyline). Honda built the Honda CBX1000 motorcycle from 1978-1981. In the 1990s, Toyota offered straight-sixes in all their lines: the G in the Altezza (and others); the M and its part-replacement, the JZ, in the Toyota Supra (and others); and the F and its replacement, the FZ, in the Land Cruiser. In the first decade of the 21st century, Toyota still offers the FZ-series, G-series, and the JZ-series engines.

Suzuki introduced the Verona a mid-sized front wheel drive car in 2004 with a straight-six and discontinued it 4 years later.

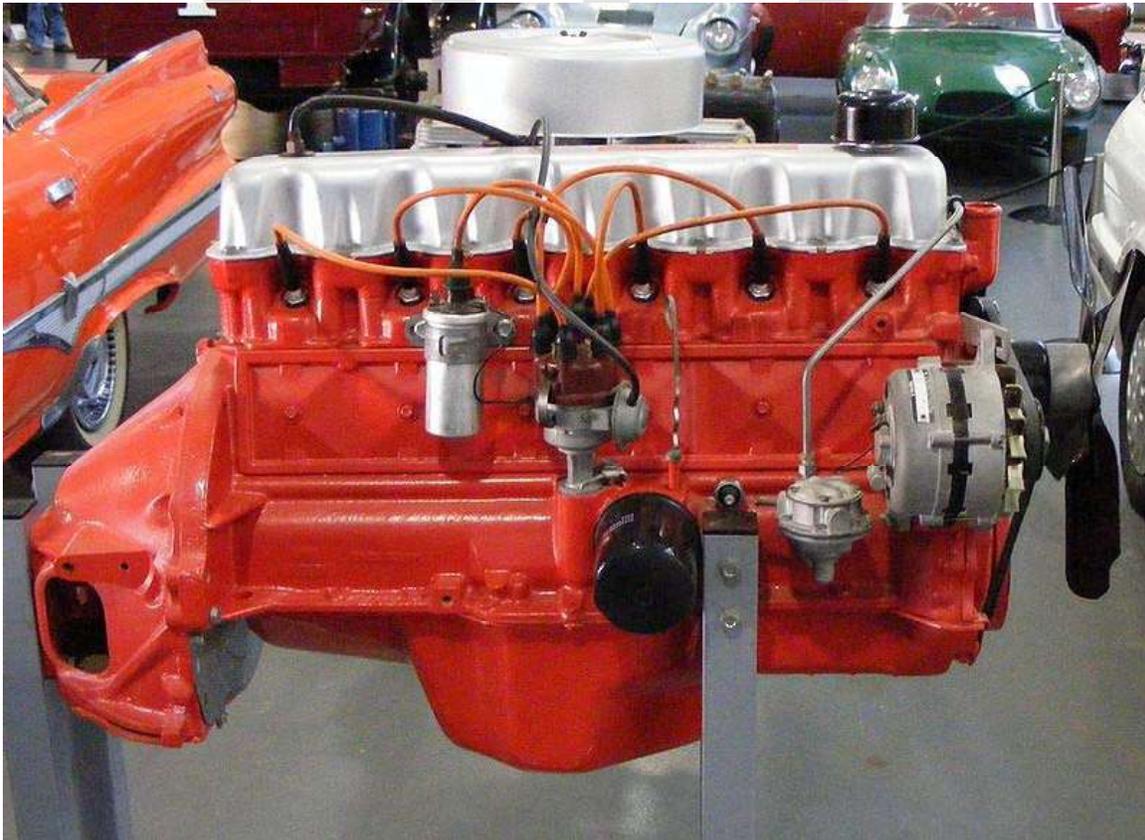
In Korea, GM Daewoo's FWD Magnus (sold abroad as the Chevrolet Evanda, Chevrolet Epica, Holden Epica or Suzuki Verona) comes with a Daewoo-designed straight-six. The

Daewoo engine is one of the few straight-sixes designed to be installed transversely in front-wheel drive cars, and it is an extremely short engine in its configuration.

## Australia

Historically, all major manufacturers in Australia used straight-six engines.

BMC developed a straight-six engine based on the B-series engine in the late 1950s. It appeared in the Austin Freeway and Wolseley 24/80. Although successful in Australia, and tried successfully in the prototype MGC, the cost of retooling meant that the engine remained indigenous to Australia. In 1971, Leyland Australia replaced the Austin 1800 with the Austin X6 range, marketed as the Austin Tasman and Austin Kimberley . This car was based on the 1800's platform but had different front and rear styling and a new interior. It introduced a 2.2 L six cylinder version of the E-series engine four years ahead of the UK market. It has the distinction of being the first car with a transverse front-wheel-drive straight six. The car was supposed to offer more competition to the Australian big six market but it achieved less sales than the superseded four cylinder 1800. The E series six cylinder in 2.6 L form (achieved using a longer stroke) went on to be used in the Leyland P76 and the Marina.



Chrysler Hemi-6 Engine, unique to Chrysler Australia

Chrysler had built the Slant 6 in Australia, and the unique to Australia Chrysler Hemi-6 Engine. These engines, made in 215 cu in (3.52 L), 245 cu in (4.01 L), and 265 cu in (4.34 L) capacity, were used in the Chrysler Valiant and the Valiant Charger producing up to 320 horsepower (239 kW). Chrysler no longer owns any factories in Australia.

Holden up until 1986 built their own straight-sixes, adapted from a Chevrolet design. A 132.5 cu in (2.171 L) unit (known as the *grey motor*) was used until 1963, with a minor increase in displacement in 1960 to 138 cu in (2.26 L) when it was replaced by a newer Chevrolet based design (known as the *red engine*) which was offered in different capacities. Holden engine sizes included the 138 cu in (2.26 L), 149 cu in (2.44 L), 179 cu in (2.93 L) (1964–1966), 161 cu in (2.64 L), 173 cu in (2.83 L) (1971–1984), 186 cu in (3.05 L) (1968–1971), and 202 cu in (3.31 L) (1971–1986, the largest and most popular of the series). This motor was firstly replaced by an imported RB20/30 Nissan straight-six, offered in 2.0 L (120 cu in) (in New Zealand) and 3.0 L (180 cu in) forms, until Holden's Buick designed 3.8 L (230 cu in) V6 replaced it outright in 1988. Holden now make and use the new global HFV6 in their local and export passenger cars.

Ford Australia has been producing straight-sixes since 1960, and is the only manufacturer in Australia to still build straight-sixes. Ford has built 144 cu in (2.36 L), 170 cu in (2.8 L), 188 cu in (3.08 L), 200 cu in (3.3 L), 221 cu in (3.62 L), 240 cu in (3.9 L), and 250 cu in (4.1 L) engines, with the 240 being called the 3.9 L (240 cu in), or 4.0 L (240 cu in) and the 200 being called the 3.3 L (200 cu in). They have been used since 1960 in the Falcon, 1972-1981 in the Cortina, and from 2004, in the Ford Territory. The current straight-six engines in the Falcon and Territory are called the Barra and have a 4.0 L (240 cu in) displacement.

The high-performance division of Ford Australia, Ford Performance Vehicles, produce vehicles equipped with the 4.0 L (240 cu in) 24-valve dual overhead camshaft (DOHC) turbocharged straight-six with variable cam timing, which produces 416 hp (310 kW) at 5,250 rpm (87.5 Hz) and 565 N·m (417 lb·ft) at 1,950 rpm (32.5 Hz) — the highest level of torque in any Australian production car to date.

## Motorcycle use



Honda CBX1000 engine

Honda raced a number of straight-six engines in the Honda RC series of motorcycles, starting with the 249 cc (0.249 L) 3RC164 in 1964, with a bore of 39 mm, and a stroke of 34.8 mm. This became the RC165 in 1965. For 1966, bore and stroke became 41 mm and 31 mm in the RC166, continuing with the RC167 in 1967. Also in 1967, Honda raced the straight-six 297 cc (18.1 cu in) RC174 in the 350 class, with bore and stroke of 41 mm and 37.5 mm.

For road use, Honda introduced the Honda CBX1000 in 1978. Kawasaki introduced the 1,300 cc (79 cu in) KZ1300 in 1979. Benelli introduced the 750 Sei in 1976, which was later enlarged to 900 cc (55 cu in) to become the 900 Sei.

BMW has developed a straight six engine for motorcycle use, debuting in a concept bike in 2009, which will feature on the K1600GT and K1600GTL motorcycles in 2011. The 1,649 cc (100.6 cu in) engine is mounted transversely across the chassis.

## ***Straight-six diesel engines***

The straight-six in diesel engine form with a much larger displacement is commonly used for industrial applications. These include various types of heavy equipment, power generation, as well as transit buses or coaches. Virtually every medium-duty to large over-the-road truck employs an inline-six diesel engine. Its virtues are superior low-end torque, very long service life, smooth operation and dependability. On-highway vehicle operators look for straight-six diesels, which are smooth-operating and quiet. Likewise, off-highway applications such as tractors, marine engines, and electric generators need a motor that is rugged and powerful. In these applications, compactness is not as big a factor as in passenger cars, reliability and maintainability are much more important concerns.

As with everyday passenger vehicles, the smooth running characteristics of the straight-six engine are what make it desirable for industrial use. The straight-six is a simple engine that is in both primary and secondary balance. This means it can be scaled up to very large sizes without causing excessive vibration. Most of the engine components and accessories can be located along both sides, rather than on top of or underneath the cylinder banks, means that access and maintenance is easier than on a V engine in a truck or industrial configuration. In addition, a straight-six engine is mechanically simpler than a V6 or V8 since it has only one cylinder head and in the overhead camshaft configuration has only half as many camshafts.

Notable versions include Toyota's normally-aspirated 2H and 12HT turbo from the 1980s, and the similar 1HZ 4 or 4.2 L. The 5.9 and 6.7 L straight-six Cummins found in the Dodge Ram and the DT series Navistar DT Engine of inline 6-cylinder medium-duty diesels by International Truck and Engine Corporation, are widely praised for use in the North American truck market. Caterpillar makes also engines in same displacement range for automotive, industrial and marine applications.

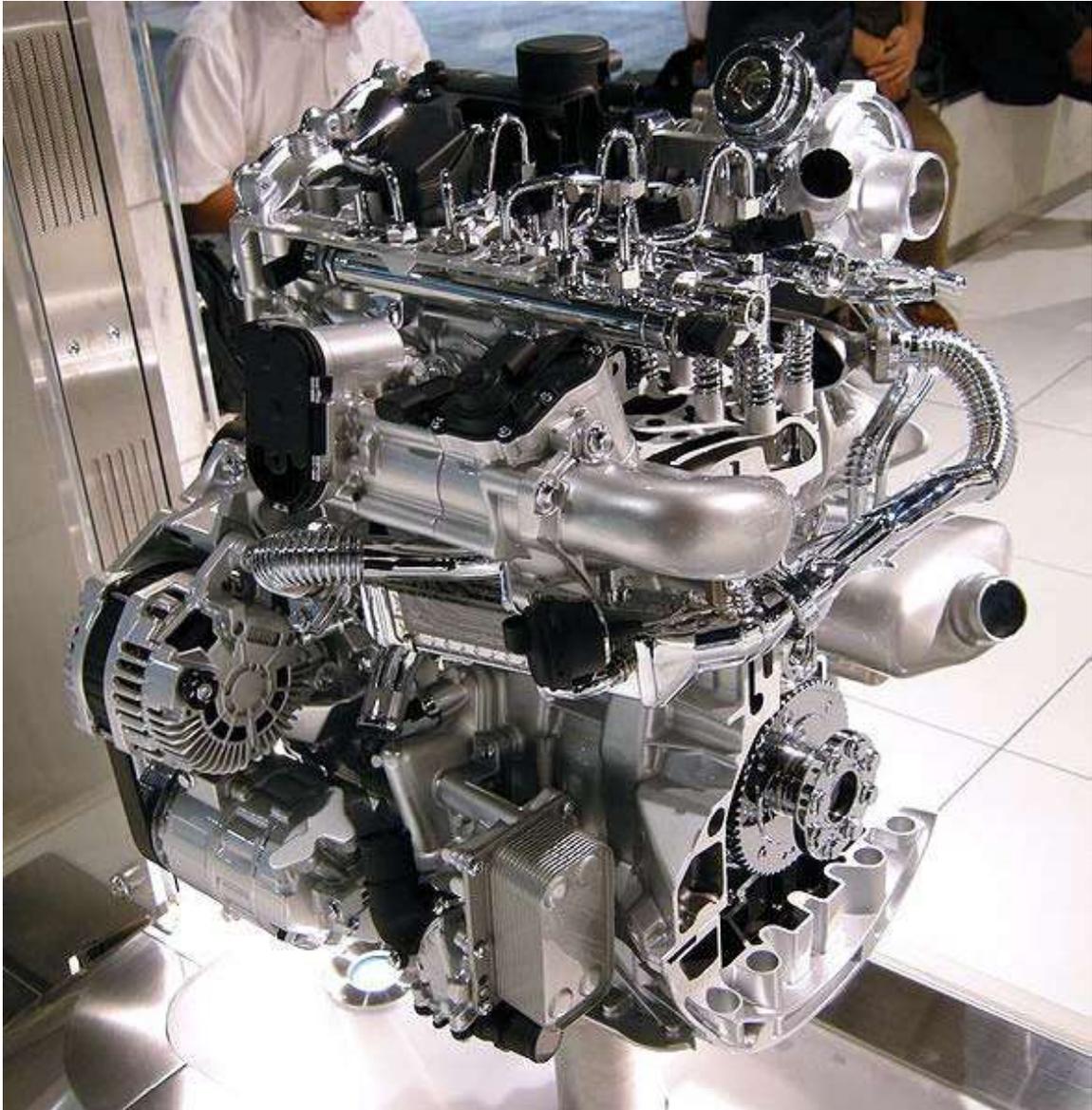
Diesel straight-sixes are also found in passenger cars, most notably those made by BMW. The twin-turbo M57 produces up to 272 bhp (203 kW; 276 PS) from its 3 L capacity, and it has won International Engine of the Year awards. Mercedes-Benz debuted the OM603 3.0 L (180 cu in) diesel in 1985. Nissan produced a range of straight-six diesels to be used in their vehicles. Some examples would be the Nissan RD engine, or the Nissan TD engine, which have similar characteristics to the RB engines. However, the RD engine was designed to be quiet, efficient and smooth, so it could be fitted to a range of Nissan luxury vehicles, such as the Nissan Laurel, and power output suffered as a result of these requirements.

## Chapter- 10

# Inline-Four Engine



Ford inline-four engine with cylinder head removed



A cutaway photograph of Nissan M9R 2.0L Straight-4 DOHC Common rail Diesel Engine installed

The **inline-four engine** or **straight-four engine** is an internal combustion engine with all four cylinders mounted in a straight line, or plane along the crankcase. The single bank of cylinders may be oriented in either a vertical or an inclined plane with all the pistons driving a common crankshaft. Where it is inclined, it is sometimes called a **slant-four**. In a specification chart or when an abbreviation is used, an inline-four engine is listed either as **I4** or **L4** (for *longitudinal*, to avoid confusion between the digit 1 and the letter I).

The inline-four layout is in perfect primary balance and confers a degree of mechanical simplicity which makes it popular for economy cars. However, despite its simplicity, it suffers from a secondary imbalance which causes minor vibrations in smaller engines.

These vibrations become worse as engine size and power increase, so the more powerful engines used in larger cars generally are more complex designs with more than four cylinders.

The inline-four is the most common engine configuration in modern cars, while the V6 is the second most popular. Today most manufacturers of four cylinder engines for automobiles produce the inline-four layout, with Subaru's flat-four being a notable exception. In the late 2000s, with auto manufacturers making efforts to increase fuel efficiency and reduce emissions, due to the high price of oil and the economic recession, the proportion of new vehicles with four cylinder engines (largely of the inline-four type) has risen from 30 percent to 47 percent between 2005 and 2008, particularly in mid-size vehicles where a decreasing number of buyers have chosen the V6 performance option.

## ***Displacement***

This inline engine configuration is the most common in cars with a displacement up to 2.4 L. The usual "practical" limit of the displacement of inline-four engines in a car is around 2.7 L. However, Porsche used a 3.0 L four in its 944 S2 and 968 sports cars, and Rolls Royce produced several inline-four engines of 2,838 cc with basic cylinder dimensions of 3.5 in (89 mm) diameter and 4.5 in (110 mm) stroke (Rolls Royce B40);

Classic and Antique vehicles tended to have larger displacements to develop horsepower and torque. The Model A Ford was built with a 3.3 L inline-four engine.

Inline-four diesel engines, which are lower revving than gasoline engines, often exceed 3.0 L. Mitsubishi still employs a 3.2 L inline-four turbodiesel in its Pajero (called the Shogun or Montero in certain markets), and Tata Motors employs a 3.0 L inline-four diesel in its Spacio and Sumo Victa.

The Toyota B engine series of diesel engines varies in displacement from 3.0- 4.1 L. The largest engine in that series was used in the Mega Cruiser.

One of the strongest Powerboat-4-cylinders is the Volvo Penta D4-300 turbodiesel. This is a 3.7L-inline-4 with 300hp and 516ft-lbf(700Nm).

One of the strongest truck/tractor/railcar-4-cylinders is the MAN D0834 turbodiesel. This is a 4.6L-inline-4 with 220hp and 627ft-lbf(850Nm).

The Isuzu Forward is a medium-duty truck which is available with a 5.2 L inline-four engine that delivers 210hp and 470 ft-lbf (637Nm).

The Hino Ranger is a medium-duty truck which is available with a 5.1 L inline-four engine that delivers 175hp (129kW) and 465ft-lbf(631Nm). The earlier Hino Ranger even had a 5.3 L inline-four engine.

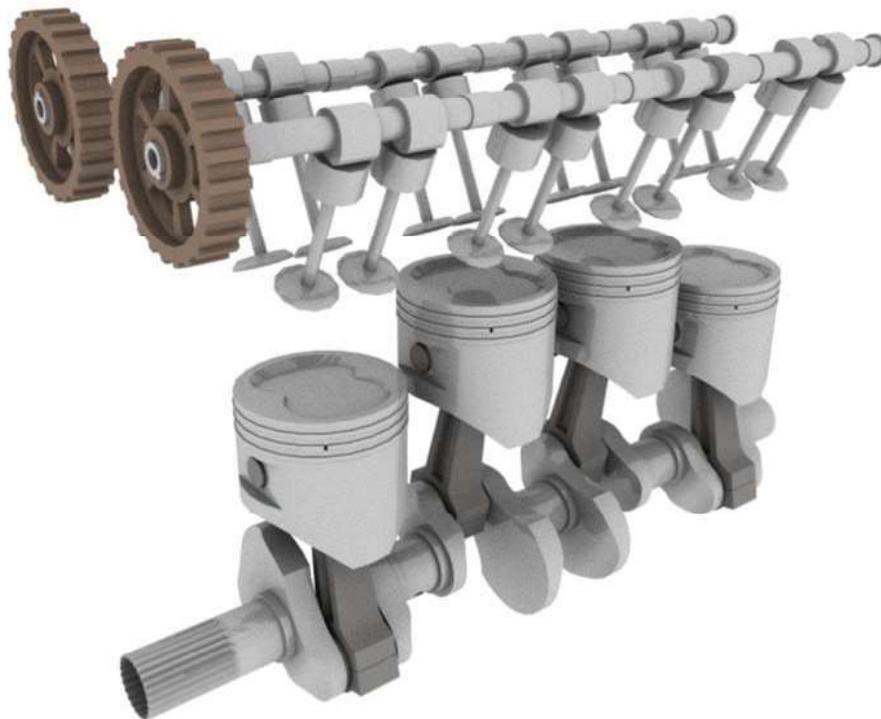
The Kubota M135X is a tractor with a 6.1 L inline-four. This turbo-diesel engine has a bore of 118 mm and a relative long stroke of 140 mm.

Larger inline-four engines are used in industrial applications, such as in small trucks and tractors, are often found with displacements up to about 4.6 L. Diesel engines for stationary, marine and locomotive use (which run at low speeds) are made in much larger sizes.

One of the largest inline-four engines is the MAN B&W 4K90 marine engine. This two stroke turbo-diesel has a giant displacement of 6,489 L. This results from a massive 0.9 meter bore and 2.5 meter stroke. The 4k90 engine develops 18,280 kW or 24,861 hp at 94 rpm and weighs 787 tons.

Displacement can also be very small, as found in kei cars sold in Japan, such as the Subaru EN series; engines that started out at 550 cc and are currently at 660 cc, with variable valve timing, DOHC and superchargers resulting in engines that produce 65 PS (48 kW; 64 bhp).

### ***Balance and smoothness***



Computer generated image showing the major internal moving parts of an inline-four engine with belt-driven double overhead camshafts and 4 valves per cylinder.

The inline-four engine is much smoother than one, two, and three cylinder engines, and this has resulted in it becoming the engine of choice for most economy cars, although it

can be found in some sports cars as well. However, the inline-four is not a fully balanced configuration.

An even-firing inline-four engine is in primary balance because the pistons are moving in pairs, and one pair of pistons is always moving up at the same time as the other pair is moving down. However, piston acceleration and deceleration are greater in the top half of the crankshaft rotation than in the bottom half, because the connecting rods are not infinitely long, resulting in a non sinusoidal motion. As a result, two pistons are always accelerating faster in one direction, while the other two are accelerating more slowly in the other direction, which leads to a secondary dynamic imbalance that causes an up-and-down vibration at twice crankshaft speed. This imbalance is tolerable in a small, low-displacement, low-power configuration, but the vibrations get worse with increasing size and power.

The reason for the piston's higher speed during the 180° rotation from mid-stroke through top-dead-centre, and back to mid-stroke, is that the minor contribution to the piston's up/down movement from the connecting rod's change of angle here has the same direction as the major contribution to the piston's up/down movement from the up/down movement of the crank pin. By contrast, during the 180° rotation from mid-stroke through bottom-dead-centre and back to mid-stroke, the minor contribution to the piston's up/down movement from the connecting rod's change of angle has the opposite direction of the major contribution to the piston's up/down movement from the up/down movement of the crank pin.

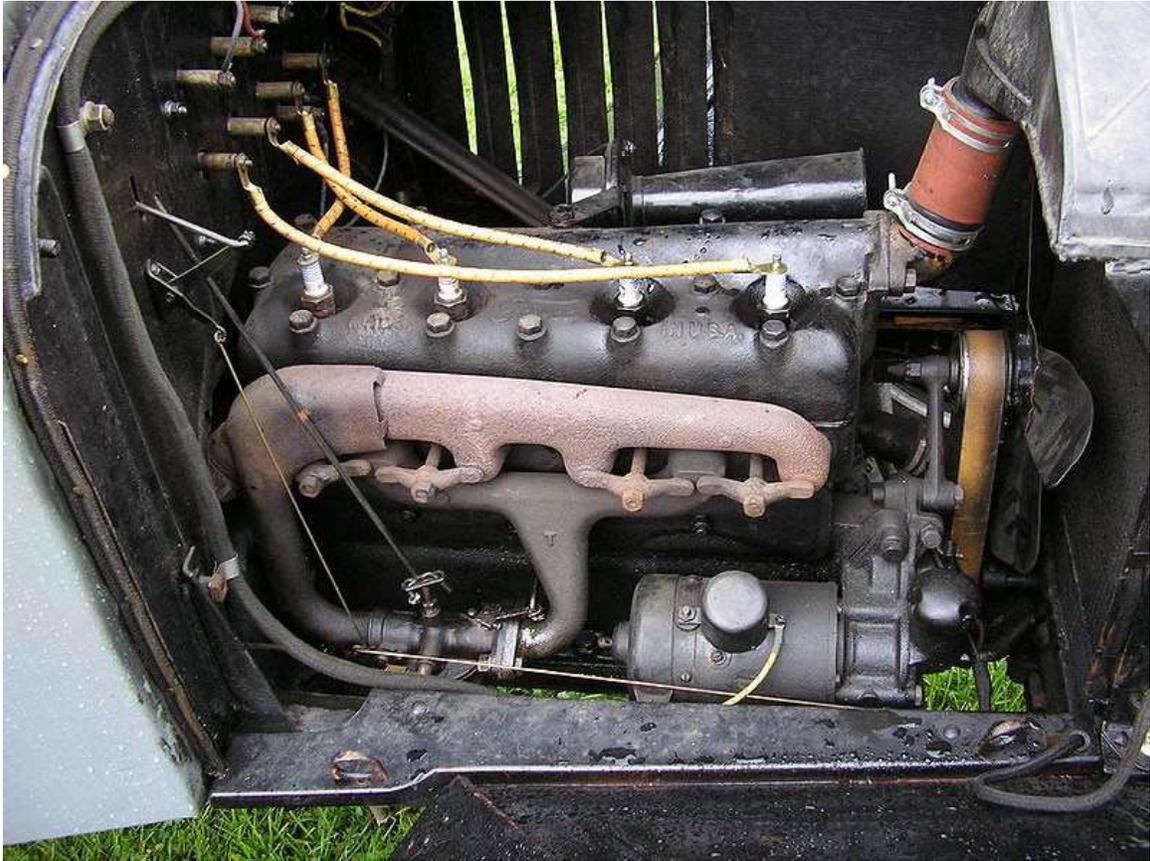
Most inline-four engines below 2.0 L in displacement rely on the damping effect of their engine mounts to reduce the vibrations to acceptable levels. Above 2.0 L, most modern inline-four engines now use balance shafts to eliminate the second-order harmonic vibrations. In a system invented by Dr. Frederick W. Lanchester in 1911, and popularised by Mitsubishi Motors in the 1970s, an inline-four engine uses two balance shafts, rotating in opposite directions at twice the crankshaft's speed, to offset the differences in piston speed. However, in the past, there were numerous examples of larger inline-fours without balance shafts, such as the Citroën DS 23 2,347 cc engine that was a derivative of the Traction Avant engine, the 1948 Austin 2,660 cc engine used in the Austin-Healey 100 and Austin Atlantic, the 3.3 L flathead engine used in the Ford Model A (1927), and the 2.5 L GM Iron Duke engine used in a number of American cars and trucks. Soviet/Russian GAZ Volga cars and UAZ SUVs, vans and light trucks used aluminium big-bore inline-four engines (2.5 or later 2.9 L) with no balance shafts from the 1950s-1990s. These engines were generally the result of a long incremental evolution process and their power was kept low compared to their capacity. However, the forces increase with the square of the engine speed — that is, doubling the speed makes the vibration four times worse — so modern high-speed inline-fours have more need to use balance shafts to offset the vibrations.

Four cylinder engines also have a smoothness problem in that the power strokes of the pistons do not overlap. With four cylinders and four strokes to complete in the four-stroke cycle, each piston must complete its power stroke and come to a complete stop

before the next piston can start a new power stroke, resulting in a pause between each power stroke and a pulsating delivery of power. In engines with more cylinders, the power strokes overlap, which gives them a smoother delivery of power and less vibration than a four can achieve. As a result, six- and eight- cylinder engines are generally used in more luxurious and expensive cars.

### ***Automobile use***

#### **Notable production inline-four engines**



Ford Model T engine



1970 Alfa Romeo 1750 GTV engine

The smallest automobile production inline-four engine powered the 1962-1970 Mazda P360 Carol kei car. Displacing just 358 cc, the Mazda *DA* was a conventional but tiny pushrod engine. Honda produced, from 1963–1967, a 356 cc (21.7 cu in) inline-four engine for the T360 truck. Inline-four motorcycle engines are built down to 250 cc, e.g. in the Honda CBR250.

Most inline-four engines, however, have been over 700 cc (43 cu in) displacement. A practical upper limit could be placed in the 2.5 L range for contemporary production cars. Larger engines (up to 6.1 L) have been seen in tractors (Kubota M135X) and medium duty truck use (Isuzu Forward, Hino Ranger), especially using diesel fuel (one of the strongest is the MAN D0834 engine with 220hp and 627ft·lbf(850Nm)). The use of balance shafts allowed Porsche to use a 3.0 L (2990 cc) inline-four engine on road cars first in the 944 S2, but the largest modern non-diesel was the plain 3,188 cc (194.5 cu in) *I95* in the 1961 Pontiac Tempest.

Currently, one of the largest straight-4 engines in production is General Motors' Vortec 2900 installed in the GMC Canyon and Chevrolet Colorado small pickup trucks. It shares the same 95.5 mm bore and 102 mm (4.0 in) stroke as the larger inline-five Vortec 3700. The latest version of the Vortec 2900, the LLV, displaces 2.9 L (2921 cc, 178 in<sup>3</sup>) and produces 185 hp (138 kW) at 5600 rpm and 195 ft·lbf (263 N·m) at 2800 rpm. Engine

redline is 6300 rpm. Another example of a large inline-four engine is the Russian 2.89 L UMZ 421 series UMZ engine.

In the early 20th century, bigger engines existed, both in road cars and sports cars. Due to the absence of displacement limit regulations, manufacturers took increasing liberties with engine size. In order to achieve power over 100 hp (75 kW), most engine builders simply increased displacement, which could sometimes achieve over 10.0 L. One of the biggest inline-fours of its time was De Dietrich 17,000 cc engine. Its cubic capacity is over twice the size of the Cadillac's 500 CID 8.2 L V8 engine, which was considered the largest engine of its type in the 1970s. These engines ran at very low rpm, often less than 1,500 rpm maximum, and had a specific output of about 10 hp/L. The US tractor industry both farm and industrial relied on large four cylinder power units until the early 1960s, when six cylinder designs came into favor. International Harvester built a large 5.7 litre (350 CID) four cylinder for their WD-9 series tractors.

Other technologically or historically notable engines using this configuration include:

- Alfa Romeo Twin Cam engine - one of the first mass produced twin cam engines produced from 1954. Also first engine in production car with variable valve timing.
- BMC A-Series engine - the first engine to be used in a transverse drive train powering the front wheels of a mass-produced automobile (Mini).
- Chevrolet Cosworth Twin-Cam Vega - 2.0 L all aluminum (block & head), DOHC, 16 valves, electronic fuel injection, stainless steel header.
- Dodge A853 - intercooled turbo engine from the SRT-4, set the land speed record for 4 cylinder production cars at the Bonneville Salt Flats.
- Ford Model T engine - one of the most-widely produced engines in the world.
- Ford Model A engine - the follow-up design to the Model T.
- GM Quad-4 engine - twin-cam Oldsmobile engine offered in GM small, sporty cars.
- Honda ED engine - first use of Honda's CVCC technology.
- Honda F20C engine - its 240 horsepower (180 kW) from 2.0 L was the highest specific output of its time, particularly noteworthy in that it achieved this without forced induction.
- Mitsubishi Sirius engine - includes the 4G63, which has the highest specific output of a turbocharged production engine in the world with the Lancer Evolution FQ-400 available in the United Kingdom (202.9 hp/L)
- GM Iron Duke engine - A versatile 151 CID 2.5 L 95 horsepower (71 kW) engine used in many GM cars in longitudinal configuration powering rear wheels or a transverse configuration powering front wheels or rear wheels. "Super Duty" racing versions of the Iron Duke were developed by Pontiac Racing.
- Triumph Slant-4 engine - the first mass-produced multi-valve engine for Triumph and an early turbo engine for Saab.
- Willys L-134 engine - nicknamed the Go Devil engine. Powered the World War II Jeep and post-war models. Notably undersquare, with 3.125 in (79.4 mm) bore and 4.375 in (111.1 mm) stroke.

In the late 2000s, with auto manufacturers making efforts to increase fuel efficiency and reduce emissions, due to the high price of oil and the economic recession, the proportion of new vehicles with inline-four engines have increased considerable at the expense of V6 and V8 engines. This is particularly evident in mid-size vehicles where a decreasing number of buyers have chosen the V6 performance options, and in fact the 2010 Hyundai Sonata no longer has a V6 option, instead offering a 2.0T (2.0L turbocharged and directly-injected) inline-four as the upgrade engine. The Volkswagen Group in particular has made widespread use of its 2.0 TFSI inline-four, which also features turbocharging and direct injection, as a performance option for its Volkswagen Golf (Golf GTI) and as the base engine for its Audi A4 (in the latter capacity where it provides superior torque to contemporaries with V6 engines, namely Audi's own 3.2 FSI V6). A tuned version of the Volkswagen 2.0 TFSI engine powers the Audi TTS

## **Racing use**

1913 saw a Peugeot driven by Jules Goux winning the Indianapolis 500. This car was powered by an inline-four engine designed by Ernest Henry. This design was very influential for racing engines as it featured for the first time dual overhead camshafts (DOHC) and four valves per cylinder, a layout that would become the standard until today for racing inline-four engines.

This Peugeot was sold to the American driver "Wild Bob" Burman who broke the engine in 1915. As Peugeot couldn't deliver a new engine during World War I, Burman asked Harry Arminius Miller to build a new engine. With John Edward and Fred Offenhauser, Miller created a Peugeot-inspired inline-four engine. This was the first version of the engine that would dominate the Indianapolis 500 until 1976 under the brand Miller and later Offenhauser. The Offenhausers won five straight victories at Indianapolis from 1971 to 1976, and it was not until 1981 that they were eliminated as competitors by engines such as the Cosworth V8 engine.

Many cars produced for the pre-WWII voiturette Grand Prix motor racing category used inline-four engine designs. 1.5 L supercharged engines found their way into cars such as the Maserati 4CL and various English Racing Automobiles (ERA) models. These were resurrected after the war, and formed the foundation of what was later to become Formula One, although the straight-eight supercharged Alfettas would dominate the early years of F1.

Another engine that played an important role in racing history is the inline-four Ferrari engine designed by Aurelio Lampredi. This engine was originally designed as a 2 L Formula 2 engine for the Ferrari 500, but evolved to 2.5 L to compete in Formula One in the Ferrari 625. For sports car racing, capacity was increased up to 3.4 L for the Ferrari 860 Monza.

Yet another very successful engine was the Coventry Climax inline-four originally designed by Walter Hassan as a 1.5 L Formula 2 engine. Enlarged to 2.0 L for Formula

One in 1958, it evolved into the large 2495 cc FPF that won the Formula One championship in Cooper's chassis in 1959 and 1960.

### **Motorcycle use**



Honda CB750 engine

For racing, Honda built inline-four engines as small as a 125 cc for the Honda 125/4. This engine was replaced by a 125 cc straight-five engine. The largest proprietary inline-four engine in a commercially-produced motorcycle is the 1402 cc engine in the Suzuki GSX1400.

Modern inline-four motorcycle engines first gained their popularity with Honda's SOHC CB750 in the 1970s. Since then, the inline-four has become one of the most common engine configurations in street bikes. Outside of the cruiser category, the inline-four is simply the most common configuration because of its relatively high performance-to-cost ratio. All of the Japanese motorcycle manufacturers offer motorcycles with inline-four engines, as does MV Agusta and BMW who employ both longitudinal and transverse-mounted engines. Even the modern Triumph company has offered inline-four-powered motorcycles, though they were discontinued in favour of a triple.

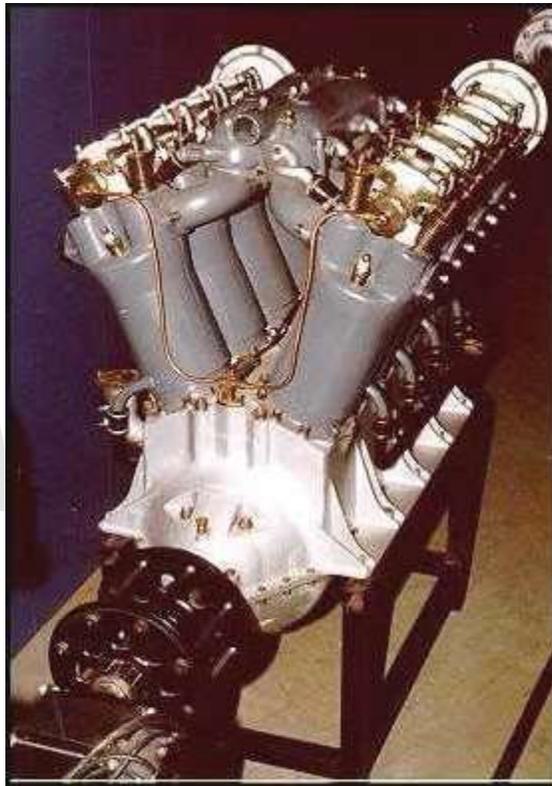
The 2009 Yamaha R1 has an interesting inline-four engine that does not fire at even intervals of 180°. Instead, it uses a crossplane crankshaft that prevents the pistons from

simultaneously reaching top dead centre. This results in increased torque at lower engine speeds.

WWT

## Chapter- 11

# V8 Engine



The Liberty V8 aircraft engine clearly shows the configuration, although modern automotive versions use a 90 degree block angle.



Bare block of an American Motors V8 engine showing the four cylinders on each side of the V configuration

A **V8 engine** is a V engine with eight cylinders mounted on the crankcase in two banks of four cylinders, in most cases set at a right angle to each other but sometimes at a narrower angle, with all eight pistons driving a common crankshaft.

In its simplest form, it is basically two straight-4 engines sharing a common crankshaft. However, this simple configuration, with a single-plane crankshaft, has the same secondary dynamic imbalance problems as two straight-4s, resulting in vibrations in large engine displacements. As a result, since the 1920s most V8s have used the somewhat more complex crossplane crankshaft with heavy counterweights to eliminate the vibrations. This results in an engine which is smoother than a V6, while being considerably less expensive than a V12 engine. Racing V8s continue to use the single plane crankshaft because it allows faster acceleration and more efficient exhaust system designs.

## ***Applications***



Assembled overhead valve engine with heads and complete valve train but without manifolds, rocker covers, timing chain cover or oil pan



Assembled and installed with all components as seen in a rear-wheel drive vehicle

The V8 with a crossplane crankshaft is a common configuration for large automobile engines. V8 engines are rarely less than 3.0 L (183 cu in) in displacement and in automobile use have exceeded 8.2 L (500 cu in) in production vehicles. Industrial and marine V8 engines can be much larger.

V8s are generally only standard on more powerful muscle cars, pony cars, sports cars, luxury cars, pickup trucks, and SUVs. However they are often options in vehicles which have a V6 or straight-6 as standard engine. In some cases, V6 engines were derived from V8 designs by removing two cylinders maintaining the V-angle so they can be built on the same assembly lines as the V8s and installed in the same engine compartments with few modifications. Some of these employed offset crankpins driving connecting rod pairs, enabling a regular firing sequence.

The traditional 90° big-bore V8 engine is generally too wide and too long to fit easily in vehicles with a transverse engine front-wheel drive layout, so its applications are limited to rear-wheel drive sports cars, muscle cars, pony cars, luxury cars and light trucks. The shorter and occasionally narrower V6 engine is easier to fit in small engine compartments, but a few compact V8 engines are used in transverse FWD and transverse AWD engine configurations in larger cars, such as Cadillacs and Volvos. These engines

often have tighter cylinder bore spacings, narrower cylinder bank angles, and other modifications to reduce their space requirements.

V8s are common in purpose-designed engines for racing cars. They usually have flat-plane crankshafts, since a crossplane crankshaft results in uneven firing into the exhaust manifolds which interferes with engine tuning, and the crossplane's heavy crankshaft counterweights prevent the engine from accelerating rapidly. They are a common engine configuration in the highest echelons of motorsport, especially in the USA where it is required in IRL, ChampCar and NASCAR. V8 engines are also used in Australian motorsport, most notably in the V8 Supercars. Formula One began the 2006 season using naturally aspirated 2.4 L (~146 cu in) V8 engines, which replaced the 3.0 L (~183 cu in) V10 in a move to reduce costs and power.

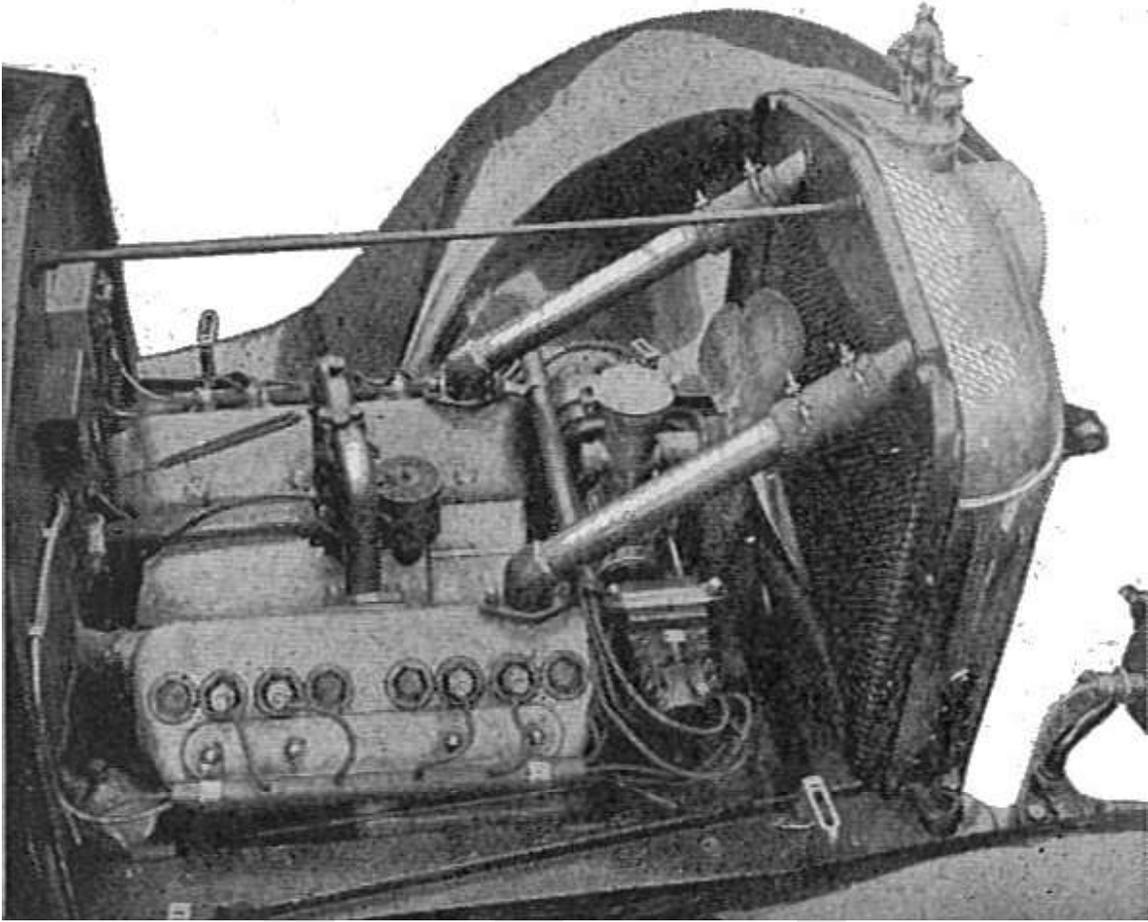
Heavy trucks and railroad locomotives tend to use the straight-6 configuration since it is simpler and easier to maintain, and because the straight-6 is an inherently balanced layout which can be scaled up to any size necessary. Large V8s are found in the larger truck and industrial equipment lines, however.

Although it was the early choice for aircraft engines, the V8 engine is seldomly used in modern aircraft engine as the typically heavy crankshaft counterweights are a liability. Modern light planes commonly use the flat-8 configuration instead as it is lighter and easier to air cool, in addition it can be manufactured in modular designs sharing components with flat-4 and flat-6 engines.

## *History*



1909 Antoinette VII aircraft with Antoinette V8 engine



V8 Vulcan engine, circa 1919

In 1902, Léon Levavasseur took out a patent on a light but quite powerful gasoline injected V8 engine. He called it the 'Antoinette' after the young daughter of his financial backer. From 1904 he installed this engine in a number of competition speedboats and early aircraft. The aviation pioneer Alberto Santos-Dumont saw one of these boats in Côte d'Azur and decided to try it on his 14-bis aircraft. Its early 24 hp (18 kW) at 1400 rpm version with only 55 kg (120 lb) of weight was interesting, but proved to be underpowered. Santos-Dumont ordered a larger and more powerful version from Levavasseur. He changed its dimensions from the original 80 mm stroke and 80 mm bore to 105 mm stroke and 110 mm bore, obtaining 50 hp (37 kW) with 86 kg (190 lb) of weight, including cooling water. Its power-to-weight ratio was not surpassed for 25 years. Levavasseur eventually produced its own line of V-8 equipped aircraft, named Antoinette I to VIII. One of these aircraft, piloted by Hubert Latham, tried but failed to cross the English Channel in 1909 due to the engine's gasoline injection. However, in 1910, the same plane with the same engine and the same pilot was first in the world to reach an altitude of 3600 feet. Voisin constructed pusher biplanes with Antoinette engines, also, notably the one first flown successfully by Henry Farman in 1908.

The V8 engine configuration became popular in France from 1904 onward, and was used in a number of aircraft engines introduced by Renault, and Buchet among others. Some of these engines found their way into automobiles in small quantities. In 1905, Darracq built a special car to beat the world speed record. They came up with two racing car engines built on a common crankcase and camshaft. The result was monstrous engine with a displacement of 1551 in<sup>3</sup> (25422 cc), good for 200 bhp (150 kW). Victor Hemery fixed that record on 30 December 1905 with a speed of 109.65 mph (176.46 km/h). This car still exists.

Rolls Royce built a 3,535 cc (216 cu in) V8 car from 1905 to 1906, but only 3 copies were made and Rolls Royce reverted to a straight-6 design. De Dion-Bouton introduced a 7,773 cc (474 cu in) automobile V8 in 1910 and displayed it in New York in 1912. It was produced only in small quantities, but inspired a number of American manufacturers to follow suit.

The first mass-production automobile V8 was introduced in the United States in 1914 by Cadillac, a division of General Motors which sold 13,000 of the 5,429 cc (331 cu in) L-head engines in its first year of production. Cadillac has been primarily a V8 company ever since. Oldsmobile, another division of General Motors, introduced its own 4 L (~244 cu in) V8 engine in 1916. Chevrolet introduced a 288 cu in (4.7 L) V8 engine in 1917, but after merging with General Motors in 1918, discontinued the V8 to concentrate on economy cars.

## **V angles**

The most prevalent V angle for a V8 is 90°. This configuration features a wide, low engine with optimal firing and vibration characteristics. Many V6 and V10 engine configurations are derived from production V8 designs, they often use the 90° angle; however, balance shafts are incorporated to reduce vibration or more complex cranks to even the firing cycle. V8s can use different angles. One notable example is the Ford/Yamaha V8 used in the Ford Taurus *SHO*. It was based on Ford's Duratec V6 and shares that engine's 60° vee angle. A similar Yamaha-built engine is used by Volvo Cars as of 2005. These engines were designed for transverse front wheel drive installation and are narrower than usual for efficient use of space. Because they are not at the ideal 90° angle for a V8, they require a counter-rotating balance shaft and offset split crankpins for complete smoothness. In 2010, GM will introduce a 4.5 L Duramax diesel V8 with a 72° angle in which they state, "Considering manufacturing tolerances, a 72 V-8 engine can actually deliver better balance than a 90 engine." 72° V8's have been used in modern racing.

The Rover Meteorite V8 engine was derived from the Rover Meteor tank engine (hence derived from the Merlin aero engine), so shared the Meteor's 60° vee angle. In years past, Electro-Motive produced an 8-cylinder version of their model 567 Diesel locomotive engine, with a 45 degree cylinder angle. The 1932 Miller four-wheel drive race cars also featured a 45° V8.

An extremely narrow-angle V8 was introduced by Lancia in 1922, which had an angle between cylinder banks of only 14°. This created an engine that was shorter than a straight-6, but much narrower than a conventional V8. It was based on a Lancia V4 engine design that was almost completely "square" in the length and width of its layout. Because of their compact design and overhead camshafts, these engines were lighter and more powerful than comparable engines of the time. Although Lancia stopped making the V8 design around World War II, the basic concept is used today in the Volkswagen VR6 engine.

## ***Crankshaft design***

There are two classic types of V8s which differ by crankshaft:

- The **cross-plane** or two-plane crankshaft is the configuration used in most V8 road cars. The first and last of the four crank pins are at 180° with respect to each other as are the second and third, with each pair at 90° to the other, so that viewed from the end the crankshaft forms a cross. The cross-plane can achieve very good balance but requires heavy counterweights on the crankshaft. This makes the cross-plane V8 a slow-revving engine that cannot speed up or slow down very quickly compared to other designs, because of the greater rotating mass. While the firing of the cross-plane V8 is regular overall, the firing of each bank is LRLRLRR. In stock cars with dual exhausts, this results in the typical V8 *burble* sound that many people have come to associate with American V8s, In all-out racing cars it leads to the need to connect exhaust pipes between the two banks to design an optimal exhaust system, resulting in an exhaust system that resembles a *bundle of snakes* as in the Ford GT40. This complex and encumbering exhaust system has been a major problem for single-seater racing car designers, so they tend to use flat-plane crankshafts instead.
- The **flat-plane** or single-plane crankshaft has crank pins at 180°. They are imperfectly balanced and thus produce vibrations unless balance shafts are used, with a counter rotating pair flanking the crankshaft to counter second order vibration transverse to the crankshaft centerline. As it does not require counterweights, the crankshaft has less mass and thus inertia, allowing higher rpm and quicker acceleration. The design was popularized in modern racing with the Coventry Climax 1.5 L (~92 cu in) V8 that evolved from a cross-plane to a flat-plane configuration. Flat-plane V8s on road cars come from Ferrari, (every V8 model they ever made, from the 1973 *308 GT4*, to today's *F430* and *California*), Lotus (the *Esprit V8*), and TVR (the *Speed Eight*). This design is popular in racing engines, the most famous example being the Cosworth DFV.

In 1992, Audi left the German DTM racing series after a controversy around the crankshaft design of their Audi V8 DTM. After using the road car's cross-plane 90° crankshaft for several years, they switched to a flat-plane 180° version which they claimed was made by "twisting" a stock part. The scrutineers decided that this would stretch the rules too far.

The cross-plane design was neither obvious nor simple to design. For this reason, most early V8 engines, including those from De Dion-Bouton, Peerless, and Cadillac, were flat-plane designs. In 1915, the cross-plane design was proposed at an automotive engineering conference in the United States, but it took another eight years to bring it to production. Cadillac and Peerless (who had hired an ex-Cadillac mathematician for the job) applied for a patent on the cross-plane design simultaneously, and the two agreed to share the idea. Cadillac introduced their "Compensated Crankshaft" V8 in 1923, with the "Equipoised Eight" from Peerless appearing in November 1924.

### **American V8 engines**



De Soto Fire Dome V8 engine, at the 1952 LA Auto Show

A full decade after Britain's 1904 Rolls-Royce Legalimit, Cadillac produced the first American V8 engine, the 1914 *L-Head*. It was a complicated hand-built unit with cast iron paired closed-head cylinders bolted to an aluminum crankcase, and it used a flat-plane crankshaft. Peerless followed, introducing a V8 licensed from amusement park manufacturer, Herschell-Spillman, the next year. Chevrolet produced a crude overhead valve V8 in 1917, in which the valve gear was completely exposed. It only lasted through 1918 and Chevrolet would not produce another V8 until the introduction of the small block in 1955.

Cadillac and Peerless were one year apart again (1923 and 1924, respectively) with the introduction of the cross-plane crankshaft. Lincoln also had V8 cars in those years, as did Ferro, Northway (supplier to Cadillac, Cole Indianapolis, and Jackson, Mississippi), Perkins (Detroit), Murray, Vernon, and Yale. Oakland, a division of GM, introduced an 85 hp (63 kW) 250 cu in (4.1 L) V8 with a 180° crankshaft in 1930-1931. In 1932, the Oakland marque was discontinued and the V8 was used in its companion marque, Pontiac, for one year. Pontiac dropped the V8 engine in 1933 and replaced it with its smoother running Silver-Streak straight eight.

Ford was the first company to use V8s *en masse*. Instead of going to an inline six like its competitors when something larger than an inline four was needed, Ford designed a modern V8, the *Flathead* of 1932. This flat head engine powered almost all larger Ford cars through the 1953 production year, and was produced until around 1970 by Ford licensees around the world, with the valve-in-block engine powering mostly commercial vehicles.

After World War II, the strong demand for larger status-symbol cars made the common straight-6 less marketable. Straight-8 engines have problems with crankshaft whip and require a longer engine bay. In the new wider body styles, a V8 would fit in the same space as a straight-6. Manufacturers could simplify production and offer the bigger engines as optional upgrades to base models.

In 1949, General Motors (GM) responded to Ford's V8 success by introducing the *Oldsmobile Rocket* and *Cadillac OHV*. Chrysler introduced their *FirePower* 331 cu in (5.4 L) hemi-head V8 in 1951. That year Studebaker introduced its V8. Buick followed in 1953, while Packard and GM's Chevrolet and Pontiac introduced V8s of their own in 1955. American Motors initially purchased V8 engines from Packard, but developed its own lower-weight, 600 lb (272 kg), design in 1956.



Shelby Mustang GT350 V8 engine

A full history of each manufacturer's engines is outside of the scope, but engine sizes on full-size cars grew throughout the 1950s, 1960s, and into the early to mid-1970s. The increasing size of full-size cars meant smaller models of car were introduced and became more popular, with the result, by the 1960s, Chrysler, Buick, Ford, and Chevrolet had two V8 model ranges.

The larger engines, known as big-block V8s, were used in the full-size cars. Big-blocks generally had displacements in excess of 360 cu in (5.9 L), but in stock form are often not all that efficient. Big-block displacement reached its zenith with the 1970 Cadillac Eldorado's 500 cu in (8.2 L) 500. Once the 1970s oil crisis and pollution regulations hit, big-block V8s did not last too much longer in cars; luxury cars lasted the longest, but by 1977 or so they were gone. In trucks and other larger vehicles, big-block V8s continue to be used today, though some manufacturers have replaced them with small-block-based V10s or more efficient Diesels. Big-block V8s are used in racing and such engines are available from independent engine builders. Some applications produce 2,000 hp (1,491 kW) from volumes exceeding 800 cu in (13.1 L).

Smaller engines, known as small-block V8s, were fitted in the mid-size car ranges and generally displaced between 270 cu in (4.4 L) and 360 cu in (5.9 L), though some grew as large as Ford's 408 cu in (6.7 L) 400 *Cleveland*. There is overlap between big-block and

small-block ranges, and a factory engine between 6.0 and 6.6 L (366 and 403 cu in) could belong to either class. Engines like this (much evolved) are still in production.



A 4.0 L (244 cu in) V8 engine from an Oldsmobile Aurora

During the 1950s, 1960s and, 1970s, every GM division had their own engines, whose merits varied. This enabled each division to have its own unique engine character, but made for much duplication of effort. Most, like the comparatively tiny *Buick 215* and familiar *Chevrolet 350*, were confusingly shared across many divisions. Ford and Chrysler had fewer divisions, and division-specific engines were quickly abandoned in favor of a few shared designs. Today, there are fewer than a dozen different American V8 engines in production.

Lately, Chrysler and GM have designed larger displacement V8s out of existing modern small-block V8s for use in performance vehicles, such as Chrysler's 6.1 L (~372.2 cu in) and 6.4 L (~390.6 cu in) Hemis, and the LS7 7.0 L (~427.2 cu in) version of GM' LS engines.

Today, the major use for big V8s is in racing, where aluminum copies of the venerable Chrysler Hemi still dominate professional drag racing (Top Fuel Dragster and Funny Car).

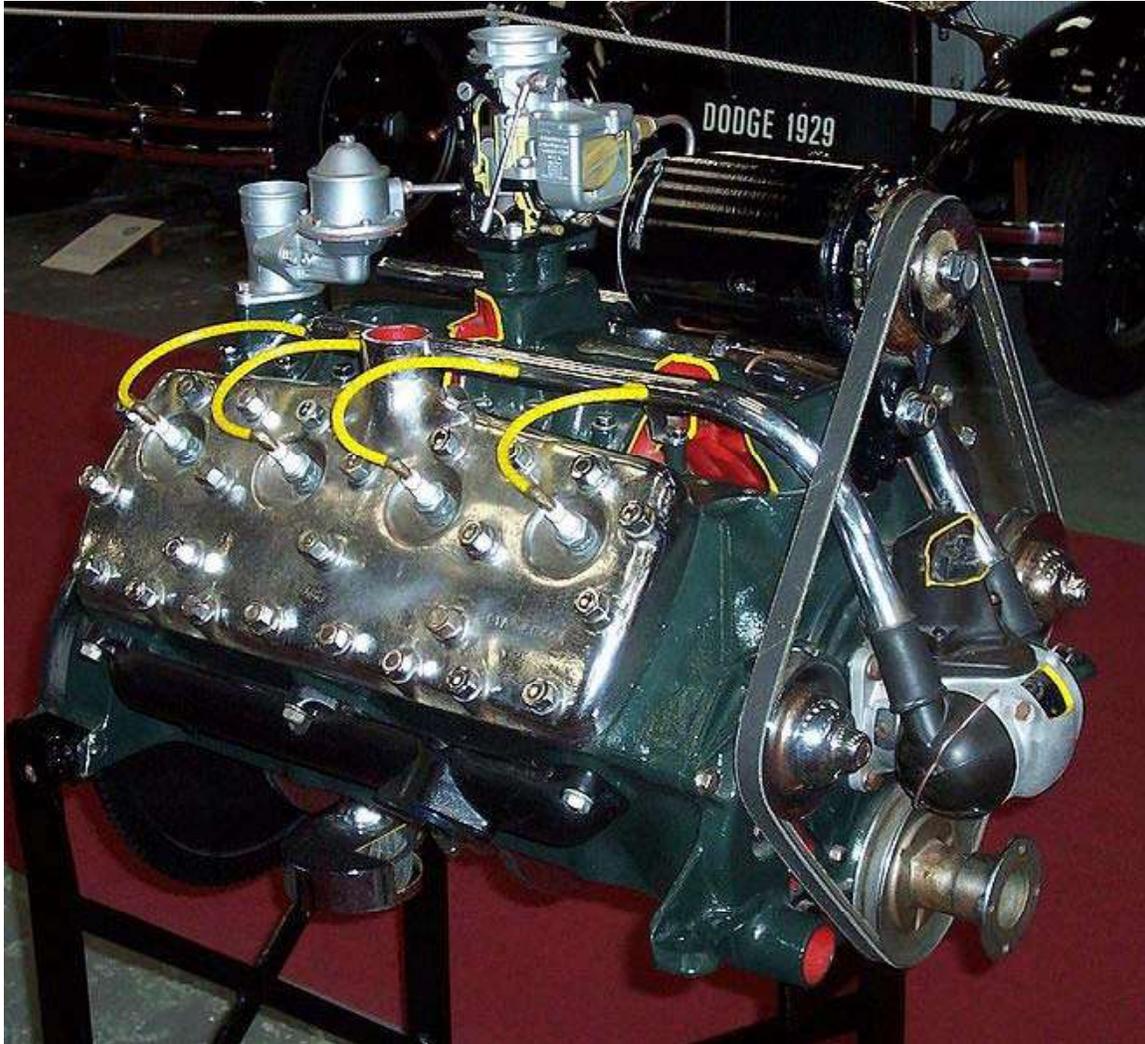
## American V8s (by manufacturer and year)



A Supercharged custom V8 engine

- American Motors (AMC)
  - 1956-1966 GEN-1 Nash/Hudson/Rambler V8
  - 1966-1991 GEN-2 AMC and Jeep V8
- Chrysler
  - 1951-1959 FirePower
  - 1951-1958 and 1964-1971 Hemi (Original)
  - 1956-1967 A family
  - 1958-1971 B family

- 1959–1978 RB family
- 1964–2003 LA Family
- 1999–present PowerTech
- 2003–present New Hemi



1930's flathead Ford V8 engine

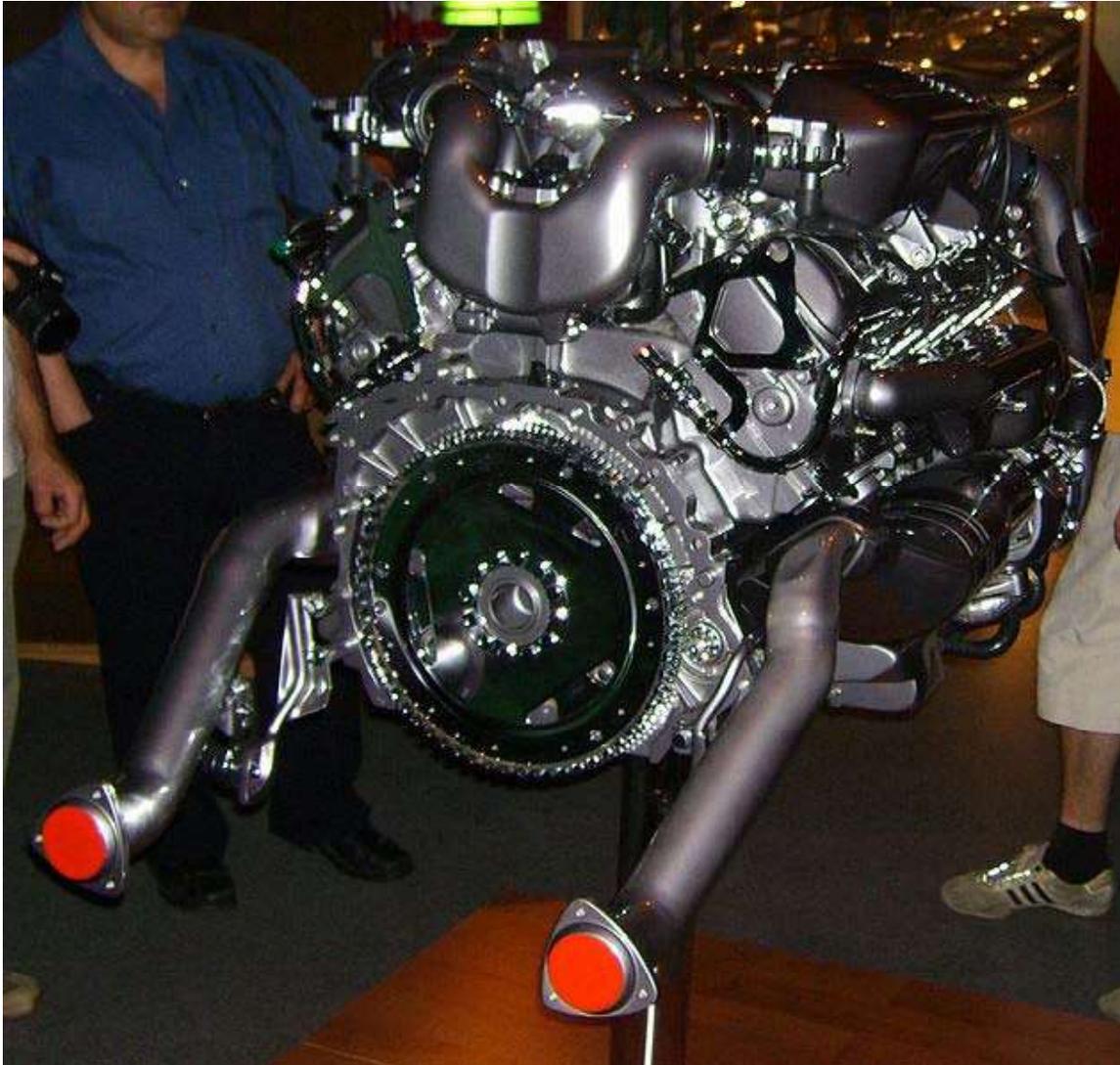
- Ford
  - 1920–1932 Lincoln Liberty
  - 1932-1953 Flathead V8
  - 1954-1962 Y-block V8
  - 1958-1967 MEL V8
  - 1958-1976 FE V8
  - 1958-1982 Super Duty engine
  - 1962-2001 Windsor V8
  - 1966–present Cosworth DFV
  - 1968-1997 385 V8

- 1970-1982 335/Cleveland V8
- 1991–present Modular V8/Triton V8
- 1996–present Jaguar AJ-V8
- 1996–1999 Yamaha V8
- 2004–present AJD-V8
- 2009–present Lion V8
- 2009–present Boss/Hurricane
- 2011- Ford Coyote
  
- General Motors
  - 1914-1992 Cadillac V8
  - 1930-1931 Oakland V8
  - 1932 Pontiac V8
  - 1949-1990 Oldsmobile Rocket V8
  - 1954-1970s Pontiac V8
  - 1950s-1970s Buick V8
  - 1954-2002 Chevrolet small-block V8
  - Chevrolet Big-Block engine
  - 1992–present Northstar/Premium
  - 1992-1997 Generation 2 small-block
  - 1997–present Generation 3 small-block
  - 2005–present Generation 4 small-block
  - Duramax Diesel
  
- Packard
  - 1955–1956
  
- Studebaker
  - 1951–1964

## **British V8 engines**



1962 Coventry Climax FWMV 1500cc V8 Formula 1 engine in a Lotus 24



BentleyV8 engine

The first British V8 was the 3.5 L Rolls-Royce V-8 (1905) followed shortly by Darracq.

The Rolls-Royce and Bentley V8 still used in modern Bentleys was designed from 1952 and entered production in 1959 in the Rolls Royce Silver Cloud and Bentley S2.

Following then current design practice, it featured overhead valves (OHV), a central camshaft and wedge-shaped combustion chambers. It was designed by the Rolls-Royce and Bentley Motors engineering team, led by Jack Phillips. Some of its features were inspired by the Rolls-Royce Merlin aircraft engine, including the aluminium block with wet liners, gear-driven camshaft, (initially) outboard spark-plugs and porting. Early versions were of 6.25 L (381 cu in) displacement, growing to 6.75 L (412 cu in) in the 1970s. Turbocharging in various Bentley models beginning in the 1980s led to the resurgence of the Bentley marque as the power outputs of the engine were increased in several steps to the current 500 bhp (370 kW) and 1,000 N·m (740 ft·lbf) in the 2007 model-year Bentley Arnage, while meeting all emission standards. The Bentley V8 has

thus increased power and torque by more than 150% in its life. It is the highest torque V8 used in a production car. In 2007, the final components that could be traced back to the 1959 engine were replaced.

In 1936, the Standard Motor Company introduced its 'Flying Twenty V-Eight' model featuring a 2.7 L flathead V8 developing 20 RAC horsepower. It was the flagship model of the company's 'Flying Standard' range but proved unpopular as it offered little performance improvement over the normal 'Flying Twenty' model (which used a straight-6 engine) whilst costing much more to buy and suffering higher fuel consumption. The Twenty V-Eight was on sale only for the 1936 model year and fewer than 400 were sold.

Rover was in need of a new, more powerful engine in the mid 1960s. The managing director of Rover, on a trip to the USA to sell marine engines, saw an example of the GM engine in a Mercury Marine experimental shop and noticed its light weight and small size. The 215 cu in (3,520 cc) GM V8 was only 12 pounds (5.4 kg) heavier and less than 1 inch (2.5 cm) longer than the 2,000 cubic centimetres (120 cu in) Rover straight-4 and sent the GM Oldsmobile/Buick cast-aluminum 215 V8 back to the UK for evaluation. It worked well in the large Rovers, being considerably shorter, lighter, and more powerful than the Rover straight 6, and Rover acquired manufacturing rights to it. The Rover V8 was redesigned to improve the durability and high-RPM performance, leaving few parts interchangeable with the original Buick engine. The engine first appeared in Rover saloons in the late 1960s. GM aided the process by allowing Buick's chief engine designer, who was close to retirement, to assist Rover.

As well as appearing in Rover cars, the engine was also sold to small car builders, and powered various vehicles. Rover V8s feature in some models from Morgan, TVR, Triumph, Marcos, and MG, among others. The Australian firm Repco converted this engine for Formula One by reducing it to 3.0 L (183 cu in) (the stroke was shortened and using con-rods from the 2.5 L/153 cu in Daimler V8) and fitting a single overhead camshaft per bank rather than the shared pushrod arrangement. Repco-powered Brabhams won the F1 championship twice, in 1966 and 1967. Land Rover also used the V8, appearing in the Range Rover in various guises, from 3.5 L (~214 cu in) in the earlier models to the 4.6 L (~281 cu in) used in the 1994-2002 models. The last mass-produced car to use the Rover V8 was in some models of the Land Rover Discovery, up to 2004. Many independent sports cars manufacturers still use it in hand-built applications.

Recently Land Rover (Tata) added the TDV8 to its list of engines. It is a V8 version of the popular TDV6 found in Discovery models. This diesel engine will be found in the 2007 Range Rovers. This 3.6 L (~220 cu in) engine produces 472 ft·lbf (640 N·m) at 2000 rpm.

The Rover Meteorite petrol or diesel V8 was used in trucks and transporters from 1943, and for marine or stationary use.

Triumph used the Triumph Slant-4 engine as a base of a V8 engine. The Triumph V8 was used only in the Triumph Stag.

Edward Turner designed the 2.5 L (~153 cu in) and 4.5 L (~275 cu in) hemi-head Daimler V8 engines announced in 1959. The 2.5 saw service in the Daimler SP250 (1959–1964), and, after the Jaguar takeover, in the "Daimler 2.5 Litre V8"/"Daimler 250" (1962–1969) versions of the Mk2 Jaguar bodyshell. The 4.5 was used in the Daimler Majestic Major, (1959–1968).

The Jaguar company introduced the new AJ26 V8 engine in 1996. It has been developed and updated since, and appears in the S-Type and later vehicles from Jaguar. This V8 was used in some of Ford's Premier Automotive Group Jaguar and Land Rover brands. These included a 4.2 (Jaguar XJ, XK and S-Type), 4.2 supercharged (Jaguar XJR, XKR, S-Type-R, Land Rover Range Rover and Range Rover Sport) and a 4.4 (Range Rover and Range Rover Sport). New V-configuration engines are used since the buy out by the Tata Motor group.

The specialist sports car firm TVR also produced their own V8 engine in 4.2 L (~256 cu in) 350 bhp (261 kW) and 4.5 L (~275 cu in) 440 bhp (328 kW) liter forms for the TVR Cerbera. Designed by Al Melling, the APJ8 engine features a flat-plane crank and 75° Vee.

Aston Martin has used a variety of V8 engines in its cars, starting with the 1969 DBS V8, followed by many models badged V8 Vantage, or Virage, plus Volante convertible versions. After the Vantage was discontinued in 2000, there were no V8 models until the introduction of the Jaguar derived 4.3l V8 in the 2005 V8 Vantage. The V8s used in Aston Martins from 1969-2000 were based on an internal design by Tadek Marek, while the V8 engines used in the 2005–present V8 Vantage are based on the Jaguar AJ26 V8.

Lotus introduced a V8-powered version of the Esprit in 1996. The engine was an in-house 3.5 L (~214 cu in) unit, with twin turbochargers.

Radical Sportscars offer a V8 powered car, the SR8, whose Powertec RPA engine is based upon two Suzuki Hayabusa engines joined to a common crank, utilising the original heads with a purpose designed block.

In 2010, McLaren Automotive developed M838T 3.8-litre V8 twin-turbo engine, used in MP4-12C

### ***Chinese V8 engines***

- FAW Hongqi by First Automobile Works
  - CA72
  - CA770
  - HQ430

## Czech V8 engines



Tatra T603 engine

Tatra used air-cooled V8 engines. These culminated in the 2.5 L unit used in the Tatra T603 range of cars. The most powerful of these was fitted to the racing variant — known as the B-5. This was a higher compression version of the standard engine which replaced a standard single 2BBL carburettor with two 4BBL downdraft units on a new induction manifold. Tatra later produced another air-cooled engine, used in Tatra 613 and later, in Tatra 700. These engines were well known for their reliability, good fuel consumption, and specific sound.

In the Tatra 603, two engine driven fans help pull cooling air into the engine bay — when the vehicle is in motion the air enters through intakes in the rear wing panels and is exhausted through cut-outs below the bumper and alongside the engine itself. In the Tatra 613, one large ventilator pushes fresh cold air into the engine bay.

Tatra has used V8 air cooled engines in their heavy duty trucks until the present day in their Tatra 815 and other models.

- T77 1934-1938 - 3.0 Litre air cooled V8
- T87 1936-1950 - 3.0 Litre air cooled V8
- T607 Monopost - 2.35 Litre V8

- T603 1956-1975 - 2.5 Litre air cooled V8
- T613 1974-1996 - 3.5 Litre air cooled V8
- T700 1996-1999 - 3.5 or 4.4 Litre air cooled V8
- T815 1983-now - 12.7 Litre air cooled V8

### ***French V8 engines***



Prototype V8 engine for the Peugeot 802

The French De Dion-Bouton motorcar firm was first to produce a V8 engine for sale in 1910. Later examples came from Citroën, with the never produced 1934 22CV *Traction Avant*, and Simca. Peugeot's upcoming 608 and its Citroën C6 stablemate may have a new HDi 4.0–5.0 L (240–310 cu in) V8 as well as a possible petrol 3.6 and 4.4 L (220

and 270 cu in) V8. The "PRV" (Peugeot, Renault, Volvo) V6 was actually supposed to be a V8, but two cylinders were "dropped" because of the oil crisis of the 1970s. Gordini also developed a 3 L V8 for the Alpine A310, but a Renault 4-cylinder block was mounted instead because of cost issues.

### **German V8 engines**



BMW S65 4.0L V8 Engine

### **German V8s (by manufacturer and date)**

- Audi
  - 1988–present V8 engine
  
- BMW
  - OHV V8 1954-1965
  - M60 1992-1995
  - M62 1994-2005
  - S62 1998-2003
  - N62 2002–present
  - S65 2007–present
  - M67 1998–present

- Horch
  - 830, 930 1933-1940



Mercedes-Benz M156 AMG 6.3L V8 DOHC Engine

- Mercedes-Benz
  - 1965-1979 M100
  - 1971-1991 M117
  - 1981-1991 M116
  - 1990-1999 M119
  - 1999–present M113
  - 2004–present M155
  - 2006–present M273
  - 2006–present M156
    - OM402 Diesel
    - OM422 Diesel
- Porsche
  - Porsche 928 1978–1995
  - Porsche Cayenne 2002–present
  - Porsche Panamera 2009–present

- Stoewer
  - Greif V8 1934-1937

## ***Italian V8 engines***

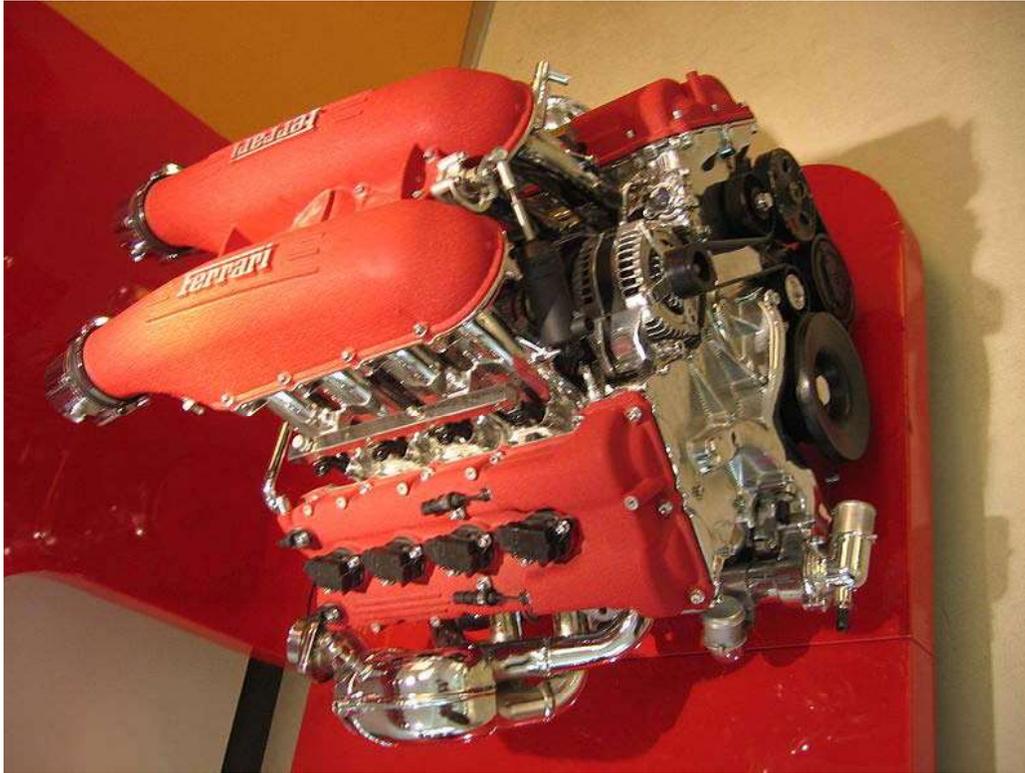
### **Alfa Romeo**

The Alfa Romeo Montreal was powered by a dry sump 2,593 cc (158.2 cu in) 90° quad-cam 16-valve V8 (type 00564) derived from the Tipo 33 race car. Because of the limited space available for the cross-plane crankshaft, the physically small but heavy crank counterweights were made of a sintered tungsten alloy called turconit. The Montreal V8 was rated at 230 horsepower (170 kW) at the flywheel and weighed 162 kg (360 lb).

There were also eighteen 33 Stradale cars built with a detuned 1,995 cc 260 hp (190 kW) Tipo 33/2 flat-crank engine. The Montreal cross-crank engine was also used in a very limited production run of 22 Alfetta GTV2.6i. The Alfa Romeo 8C Competizione sports car has a Ferrari-built 4,691 cc (286.3 cu in) 450 PS (330 kW; 440 hp) cross-crank V8.

WWT

## Ferrari



Ferrari V8, 4,300cc

Arguably, Ferrari had their first contact with V8 power with the "inherited" Lancia D50s in 1955. Ferrari adopted the V8 configuration for themselves for racing in 1962 with the 268 SP. The first V8-powered Ferrari road car was 1974's 308 GT4, with the familiar 308 GTB following closely behind. The company continued to use this *Dino* V8 engine ever since with the 328, 348, and successors. Ferrari's smallest V8 (and indeed, the smallest ever) was the 2.0 L (1990 cc) unit found in the 1975 208 GT4. The company produced a slightly-larger 2.0 L V8 in the 208 GTB and the 2.9 L Ferrari F40 of the 1980s. Five-valve versions of Ferrari's 3.5 L and 3.6 L V8s were found in the Ferrari F355 and Ferrari 360. The old *Dino* V8 was retired for 2004 with the introduction of a 4.3 L V8, based on the originally Ferrari designed Maserati 4.2 V8, in the F430. And F430's successor, 458 Italia, with 4.5 V8.

## Fiat

The only Fiat to have a V8 was the Fiat 8V. The engine was a very compact OHV 1996 cc (122 CID) V8 with a 70° V angle and 2 valves per cylinder. The Fiat 8V was designed to participate in the Italian two-litre racing class.

## **Lamborghini**

Lamborghini have always fitted V12s in their top-of-the-line cars, but have built many V8s for their lower models, including the Urraco, Silhouette and Jalpa.

## **Lancia**

Lancia used V8 engines in their top of the range luxury cars in the interwar period. The first V8 engine was available in 1922 in the Trikappa with a 4595 cc (280 CID) making 98 bhp (73 kW). In 1928 they introduced the Dilambda with a 3956 cc (242 CID) V8 developing 100 bhp (75 kW). Later in 1931 the Astura was unveiled with two smaller versions of the existing V8, 2604 cc (159 CID) and 2973 cc (181 CID) with 72 bhp (54 kW) and 82 bhp (61 kW) respectively. All of those engines featured Lancia's trademark narrow angle V (less than 25°). In the 1990s, Lancia Thema had 3 L V8.

## **Maserati**

Maserati have used V8s for many of their models, including the Maserati Bora and the Maserati Khamsin. This engine was initially designed as a racing engine for the Maserati 450S. The company's latest 4.2 V8, found in the Maserati Quattroporte and Maserati Coupé & Spyder was originally designed by Ferrari, and is related to the 4.2l V8 in the F430.

## ***Japanese V8 engines***

Japanese manufacturers are traditionally not known for V8 engines in their roadcars. However, they have built a few V8 engines to meet the needs of consumers, as well as for their own racing programs.

## **Honda**

Honda has never built a V8 for passenger vehicles. In the late 1990s, the company resisted considerable pressure from its American dealers for a V8 engine (which would have seen use in top-of-the-line Honda SUVs and Acuras), with American Honda reportedly sending one dealer a shipment of V8 beverages to silence them.

However, Honda has built V8s for racing, most notably for Formula One. Honda is also the sole engine builder for Indy Racing. The Honda Indy V-8 has a 10,300 rpm redline. Also, their affiliate Mugen Motorsports (now known as M-Tec) has built racing V8s that eventually found their way into limited production road cars as well as concept cars. Their MF408S engine, which powers cars in the ALMS, is also found in prototype racers such as the Mooncraft Shiden. It is also known for being the engine in the Honda Legend based Honda Max concept.

## Mitsubishi

In 1999, Mitsubishi Motors developed an alloy-headed 4.5 L V8, dubbed the 8A8, with double overhead camshafts and gasoline direct injection (GDI) technology for use in its Proudia and Dignity models. Financial pressures forced the company to discontinue sales of both these vehicles after only fifteen months

## Nissan



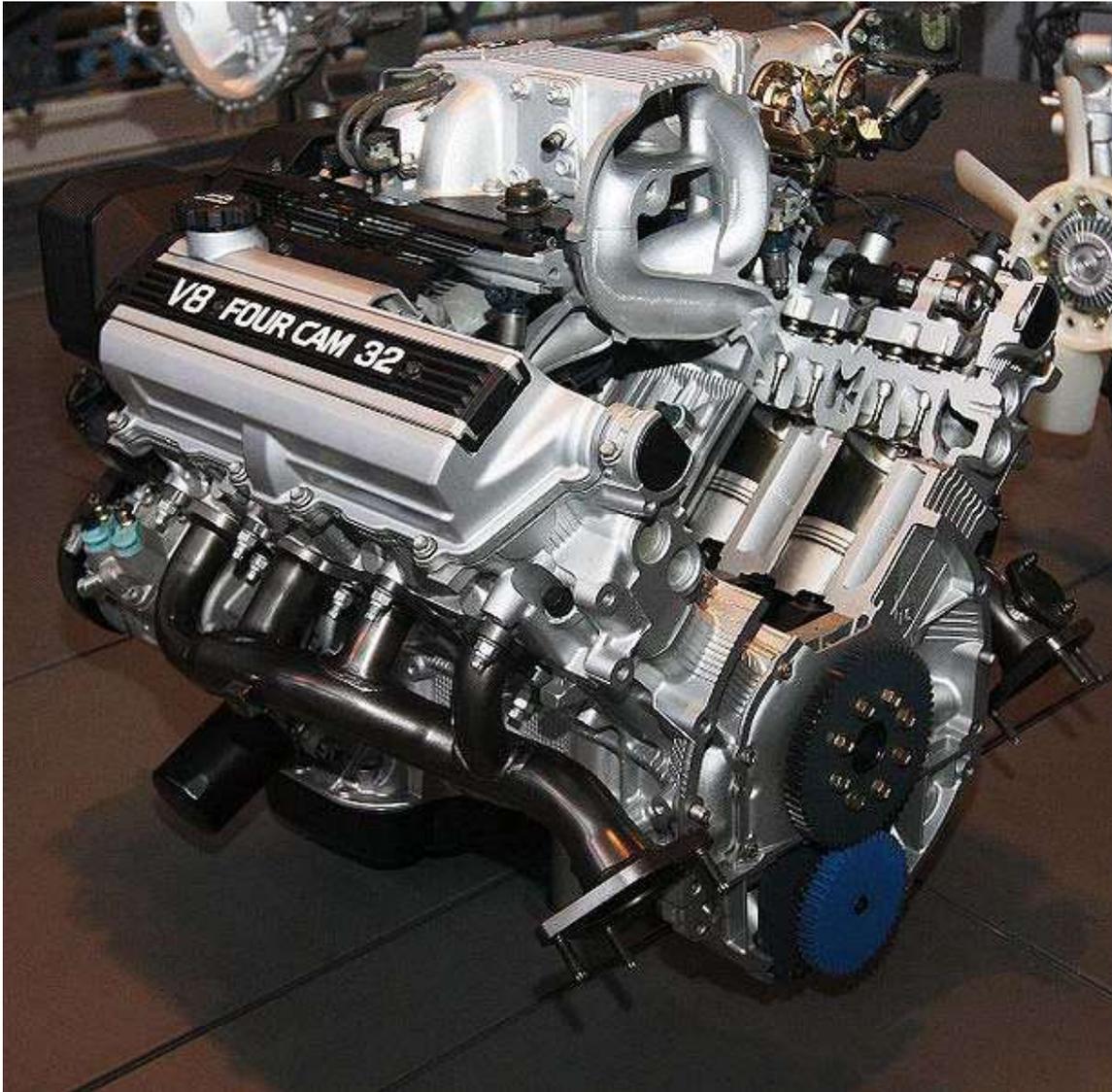
2008 Nissan VK50VE engine. V8 5,026cc

Nissan built its first V8, the Y40, in 1965 for its President limousine. The Y engine has been succeeded by two families of V8, the VH series during the 1980s and 1990s and the new VK series.

- VK engine
- VH engine

- Y engine

## Toyota



1989 Toyota 1UZ-FE Type engine. V8 3,968cc.

Toyota's first V8 engine family was the V series used in the Toyota Century luxury car. This engine remained in use in the Century until it was replaced by a V12 in 1997. Other Toyota V8 families are the UZ engines and the new UR engines.

- UR engine
- UZ engine

- V engine

## Yamaha



1989 Yamaha OX88 engine

While better known as a manufacturer of motorcycles, Yamaha also makes engines under contract from auto-manufacturers. They currently produce a V8 engine in conjunction with Volvo Cars for vehicles such as the Volvo XC90 and the Volvo S80.

## Swedish V8 engines



2005 Volvo (Yamaha) V8 engine for Volvo XC90. V8 4,414cc

The most well-known Swedish V8 engine is probably the Scania AB 14 L (854 cu in) diesel, which was released in 1969 for use in the 140 model heavy trucks. At this point, the 350 hp (261 kW) turbo-charged engine was the most powerful diesel in Europe. Scania has continued using a V8 as its largest displacement engine. Currently a series of 16 L (976 cu in) diesel engines is available in several versions with power ranging between 500 hp (373 kW) — 730 hp (544 kW) in the truck segment and going as high as 900 hp (671 kW) in the marine engines segment. Emission norms range between Euro 3-Euro 5 depending on which market the vehicle is sold to.

Volvo's 1950s concept car Philip also had a gasoline V8 engine. The car never went into production, but the engine evolved into a 120 hp 3.6 L V8 (in many aspects a "double B18" engine) for use in the light trucks Volvo Snabbe and Volvo Trygge from the late 1950s on.

Supercar manufacturer Koenigsegg has developed a 4.7 L (~287 cu in) twin-supercharged V8 loosely based on the Ford Modular engine. This engine is unique in that it is a flexible fuel engine and produces more power while running on biofuel than on regular unleaded.

## ***Russian V8 engines***

### **ZIS, ZIL**

For the ZIL-111 (1959), an all-new aluminium 6 L OHV V8 was developed, initially it produced 200 hp (149 kW) at 4200 rpm.

ZIL-114 (1967) was powered by a 6,960 cc (425 cu in) V8 giving 300 hp (224 kW) at 4400 rpm. Its more modern derivative model, the ZIL-41047, is powered by a ZIL-4104 engine, a 7680 cc carburetted V8 giving 315 hp (235 kW) at 4600 rpm.

The ZIL trucks used (and still use) a modification of this engine (cast-iron block, aluminum heads, 6L, 150 hp (112 kW) at 3200 rpm, 6.5:1 compression rate, one 2-bbl carburetor).

### **GAZ (ZMZ)**



GAZ-24-34 Volga with ZMZ-503 V8 engine, 1992-built car.

Several cars produced under the Volga brand name; the GAZ-23 (1962–1970), the GAZ-24-24 V8 (1974–1992), the GAZ-31013 V8 (1982–1996), as well as both generations of the GAZ Chaika limousines (1959–1982 and 1976–1988) were powered by an all-aluminum OHV 5.5L V8. These engines were designated: ZMZ-13 (Chaika GAZ-13, one 4-bbl carburetor), ZMZ-14 (Chaika GAZ-14, two 4-bbl carburetors), ZMZ-2424 (Volga GAZ-24-24), ZMZ-505 (two 4-bbl carburetors) and -503 (one 4-bbl carburetor) (GAZ-24-34, GAZ-31013). Power output varied from 195–220 hp (145–160 kW). A modification of the same engine was also used in the BRDM-2 military armored vehicle, designated ZMZ-41.

The GAZ-53 was powered by a 4254 cc ZMZ-53 engine, which substantially was a modification of the Chayka's engine with one 2-bbl carburetor and decreased displacement and compression rate. More modern version of the GAZ engine for intermediate trucks is designated ZMZ-511.

### ***Spanish V8 engines***

Spanish truck and sportscar company Pegaso made around 100 cars in the 1950s and 1960s. There were two types of engines; the Z-102 and the Z-103/4 engines.

The Z-102 first introduced in 1951 engine was an advanced design sporting quadruple camshafts (two per bank) and had 2 valves per cylinder. It was available with 1, 2 or 4 twin Weber carburetors and either normally aspirated or with one or two superchargers. It had three different capacities, 2472 cc (151 CID), 2816 cc (172 CID) and 3178 cc (194 CID) and made between 165 bhp (123 kW) and 360 bhp (270 kW).

The Z-103/4 developed in the mid/late 1950s (the first prototype was made in 1954) was a much simpler design destined to power a new series of luxury and sportscars. It had a single central camshaft and 2 valves per cylinder actuated by pushrods. It had hemispherical combustion chambers (like the Z-102 engine) and twin spark plugs. It was available with three different cubic capacities as well, 3900 cc (238 CID), 4500 cc (275 CID) and 4700 cc (287 CID). The 3.9 L engine had a twin Weber carburetor and the 4.5 and 4.7 L engines 2 quadruple Weber carbs, which gave the later a power output in excess of 300 bhp (220 kW). The very few engines of this type produced were installed in Z-102 cars.

### ***Australian V8 engines***

Holden, including its performance vehicle operations Holden Racing Team and Holden Special Vehicles, have been manufacturing V8 performance vehicles since the late 1960s, as has Ford Australia. The performance arm of Ford Australia, Ford Performance Vehicles (FPV), have recently resurged in the market with the new Falcon BA and BF based models, and the brand new FG series.

The Australian V8 is typically an American-manufactured block from either Ford, Chrysler or General Motors yet often uses local heads and auxiliary systems (pistons, exhaust etc.). However, there are a couple of exceptions to this — the Holden V8 engine small block V8, and the British Leyland alloy small-block V8.

The Holden small-block V8 was an all Australian designed and manufactured cast-iron 90° pushrod OHV engine, manufactured in the capacities of 4.2 L (253 CID), 5.0 L (308 CID), later destroked to 304 CID), and 5.7 L (348 CID — never actually built as a 'production' motor). First introduced in 1969, finally ceasing production in 1999, it powered a variety of Holden vehicles including the Kingswood, Monaro, Torana and Commodore, and proved to be a popular and successful powerplant in Australian motorsport (especially Touring cars).

The British Leyland small block V8 was also a pushrod OHV engine, however it was an all alloy block like the British Rover V8 it was based on. The stroke was increased to give it a capacity of 4.4 L (270 cu in). The motor was originally designed and fitted to the Leyland P76 sedan.

Currently, the only V8 produced in Australia is the 5.4l V8 built by FPV (Ford Performance Vehicles) to power the Falcon GT — this motor is a combination of US-sourced and locally manufactured parts. The V8 used in current Holdens is sourced complete from GM in Canada, modified versions of the GM LS-series engine.

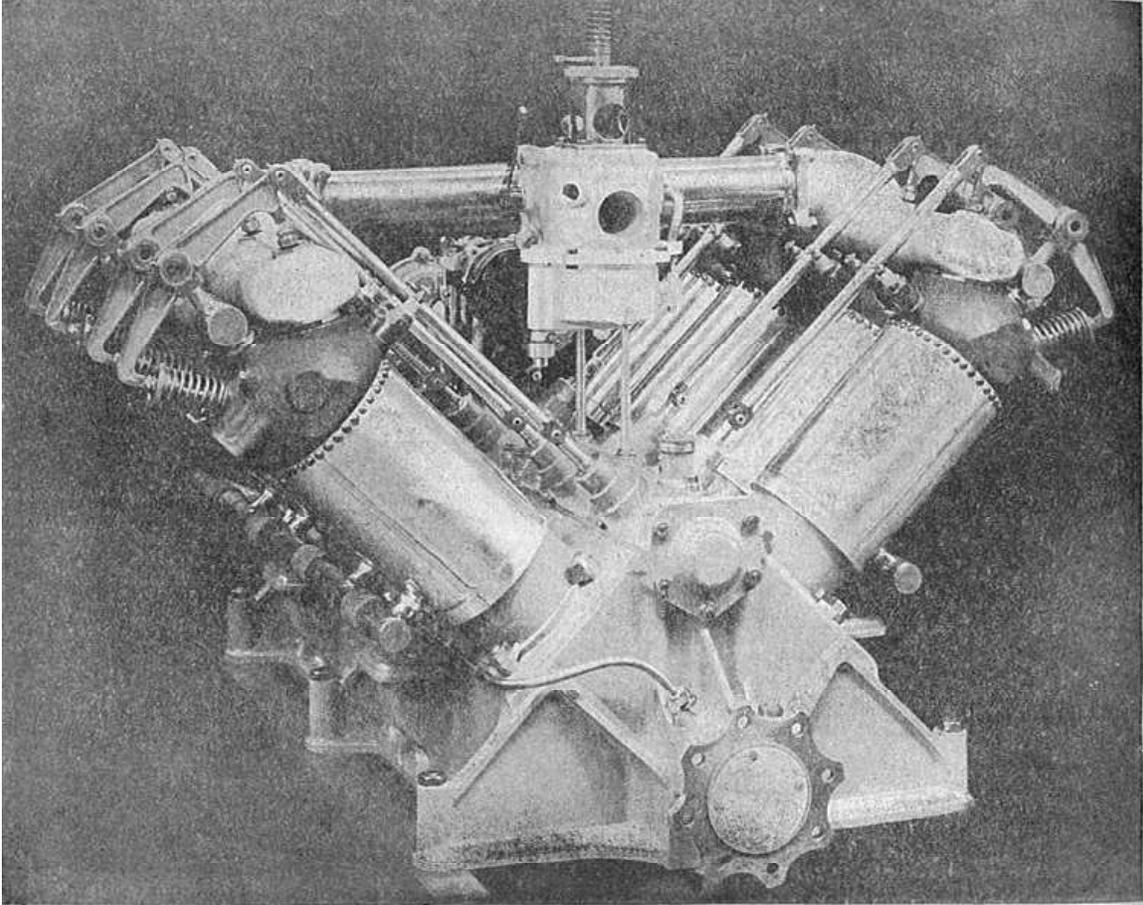
When U.S. production of the Cleveland V8 range ceased in the early seventies, the tooling was moved to Australia where Ford Australia continued to produce a local version of the 351 and a unique-to-Australia 302 Cleveland. The Australian-built motors were also sold to De Tomaso to be used in the Pantera and Longchamps. Australian production ceased in 1982, with the last Cleveland-powered Falcon being the XE range (1400-odd 302s and 409 351s). The location of the Cleveland tooling is unknown although it was possibly broken up.

### ***Korean V8 engines***

- Hyundai
  - D8 - 16/18 L-Diesel
  - Omega - 4.5 L (~275 cu in)
  - Tau - 4.6 L (~281 cu in)

## ***Other V8 applications***

### **In aviation**



1905 Wolseley 120 hp V8 aero engine

- Argus As 10 inverted, air-cooled German V8 engine of World War II.
- Hispano-Suiza 8 of World War I V8.
- Liberty L-8 of World War I, 45° V8 (a prototype for the Liberty L-12).
- Renault of WW1, 240 hp (180 kW) V8
- Trace Engines Turbocharged V8.

## Ship's engines

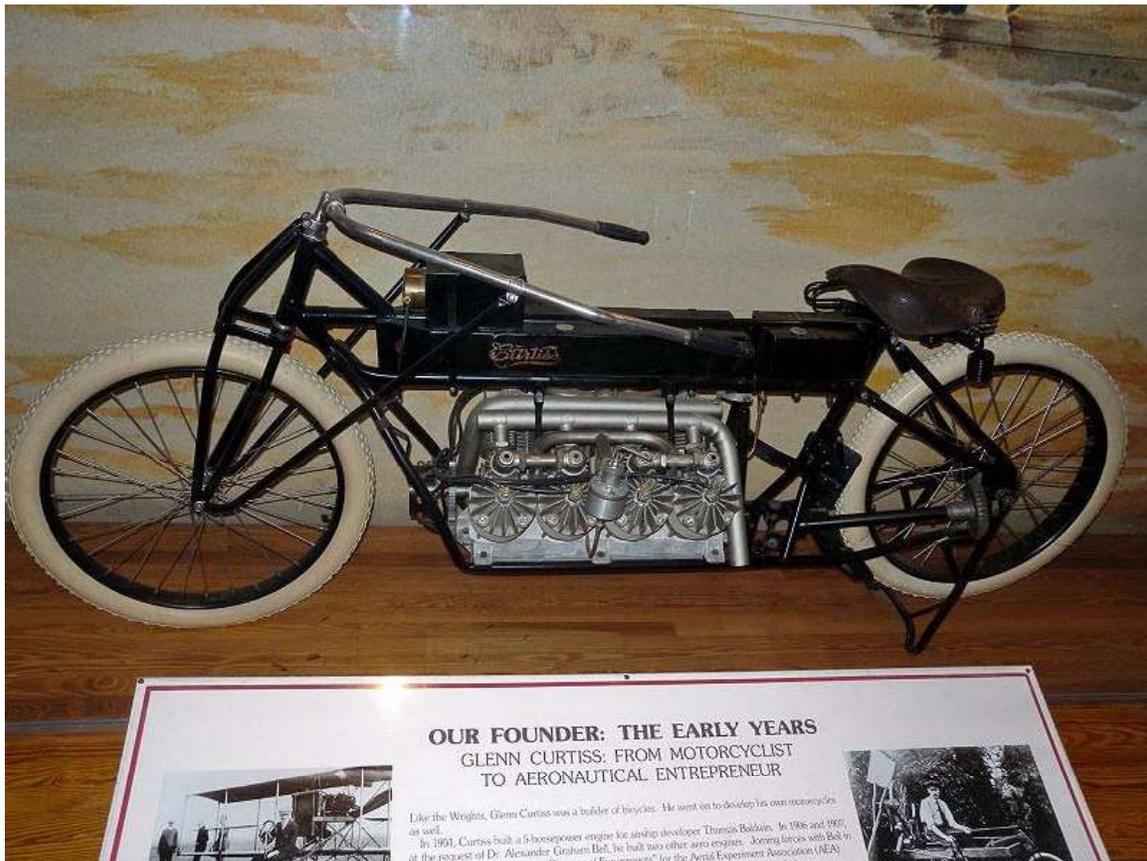


Scania V8, 16 litre marine engine with reverse.

There are numerous marine diesel engines of V8 configuration.

- Brons V8 two-stroke diesel engine.
- Scania
- Yanmar

## In motorcycles



V8 Motorcycle of Glenn Curtiss. In 1907, Curtiss set an unofficial world record of 136.36 mph (219.45 km/h) on this 40 hp (30 kW), 4,000 cc V8 powered motorcycle of his own design and construction

Moto Guzzi of Italy built a 148 kg (330 lb) 82 bhp (61 kW) water cooled DOHC V8 4-stroke motorcycle for Grand Prix racing between 1955 and 1957, referred to as the Moto Guzzi Grand Prix 500 cc V8. It was known as the *Otto Cilindri*, and had a very high power output but was not developed to its full potential. Each cylinder had its own carburettor.

Morbidelli produced an 848 cc V8 in 1994. Earlier, Galbusera had produced a two-stroke V8 in 1938.

Honda released the NR750 in 1992. The bike had a 750 cc V4 with oval pistons, utilising 8 valves per cylinder and 2 conrods per piston; the design allowed the engine to meet FIM racing regulations limiting the number of cylinders to 4, while providing the valve area (and therefore increased efficiency) of a V8.

## In motorsport



A 2004 Cosworth Champ Car World Series V-8 engine, capable of generating over 800 horsepower from just 161 cu./in



Renault F1 RS26 (2006), 2,398cc V8 engine

Up until recently, Formula One cars used 3 L V10 engines. However, the FIA considered speeds were getting too high to be safe (even with the banning of turbochargers in 1989, which allowed engines to develop 1,300 bhp (970 kW), 1,000 bhp (750 kW) from a naturally-aspirated engine was not impossible by 2005, and with better aerodynamics, cars were shattering straight-line speed records.) So, the permitted engine size was cut to 2.4 L V8 (This reduced average power output of the engines from 900 bhp (670 kW), in the 2005 season, to a 2006 season average of 750 bhp (560 kW) — equivalent to power outputs that were being achieved on 3 L around the 1999/2000 seasons.) This also had the effect of reducing overall costs for the teams, an aim which is currently being vigorously pursued by FIA.

In the 'Top Fuel' class of Drag Racing, V8 engines displacing 8.2 L or 500 in<sup>3</sup> produce up to 8,000 horsepower (6,000 kW). Based on the Chrysler Hemi and running on highly explosive Nitro-Methane fuel, these powerful units propel the cars from 0-100 mph in 0.8 seconds or less, and from 0-325 mph (0-523 km/h) in under 4.5 seconds. During the race the crankshaft in the engine will turn over less than 1000 times and may then have to be rebuilt.