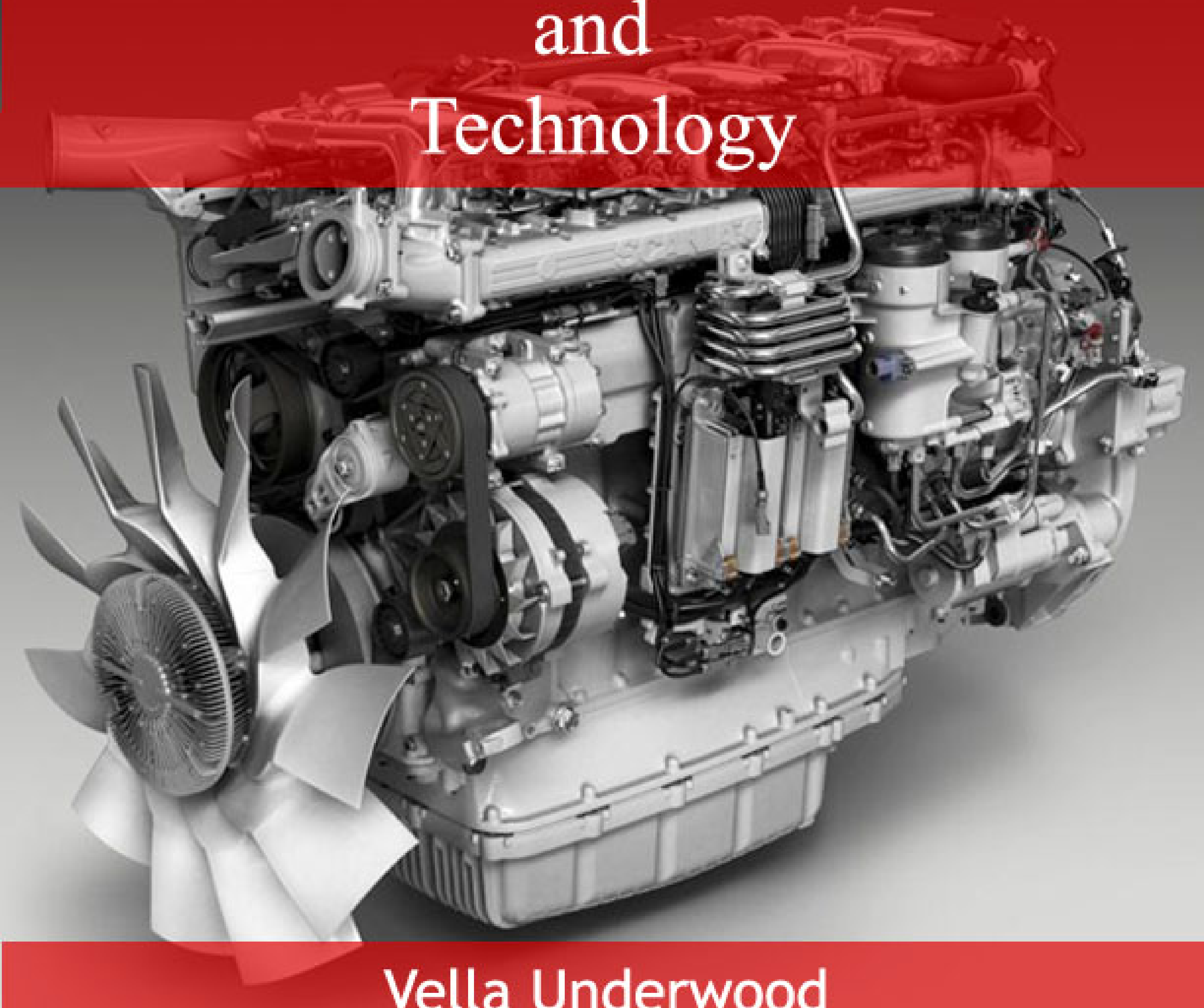
Diesel Engine and Technology



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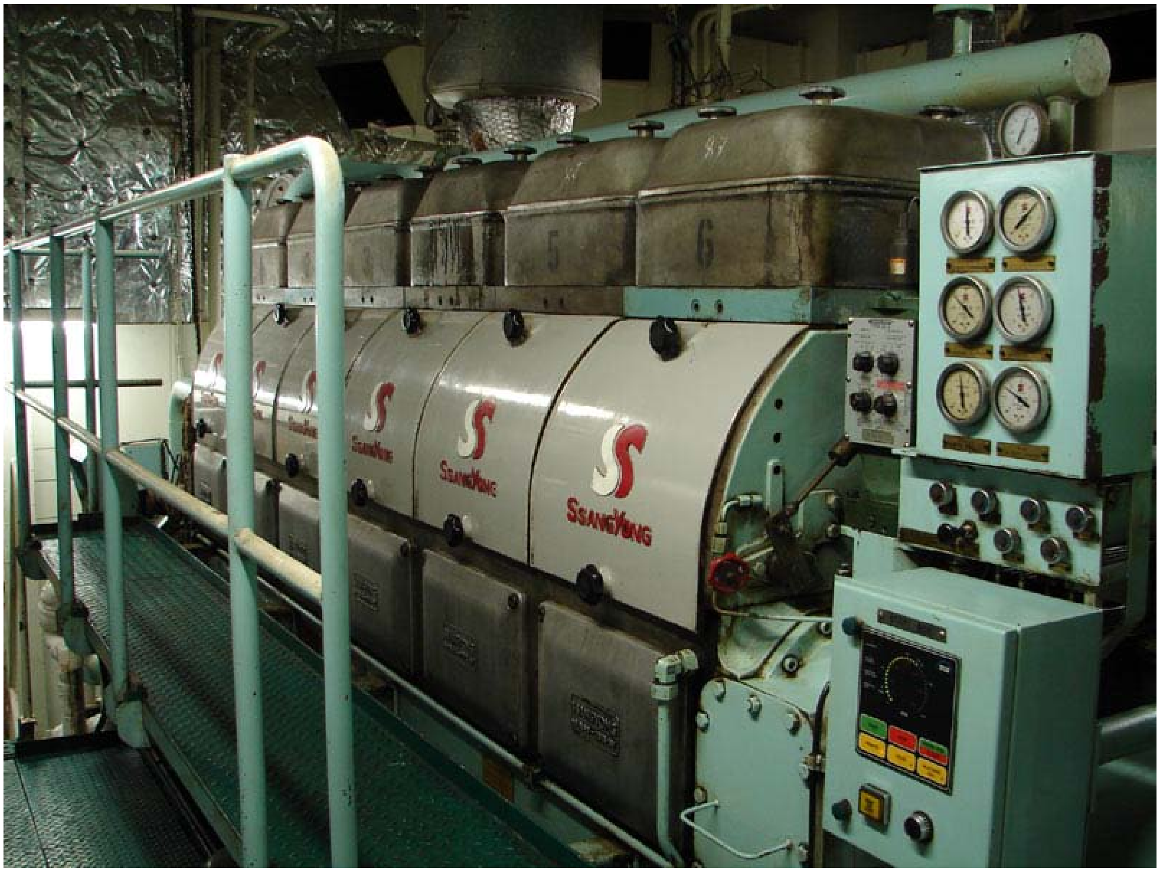
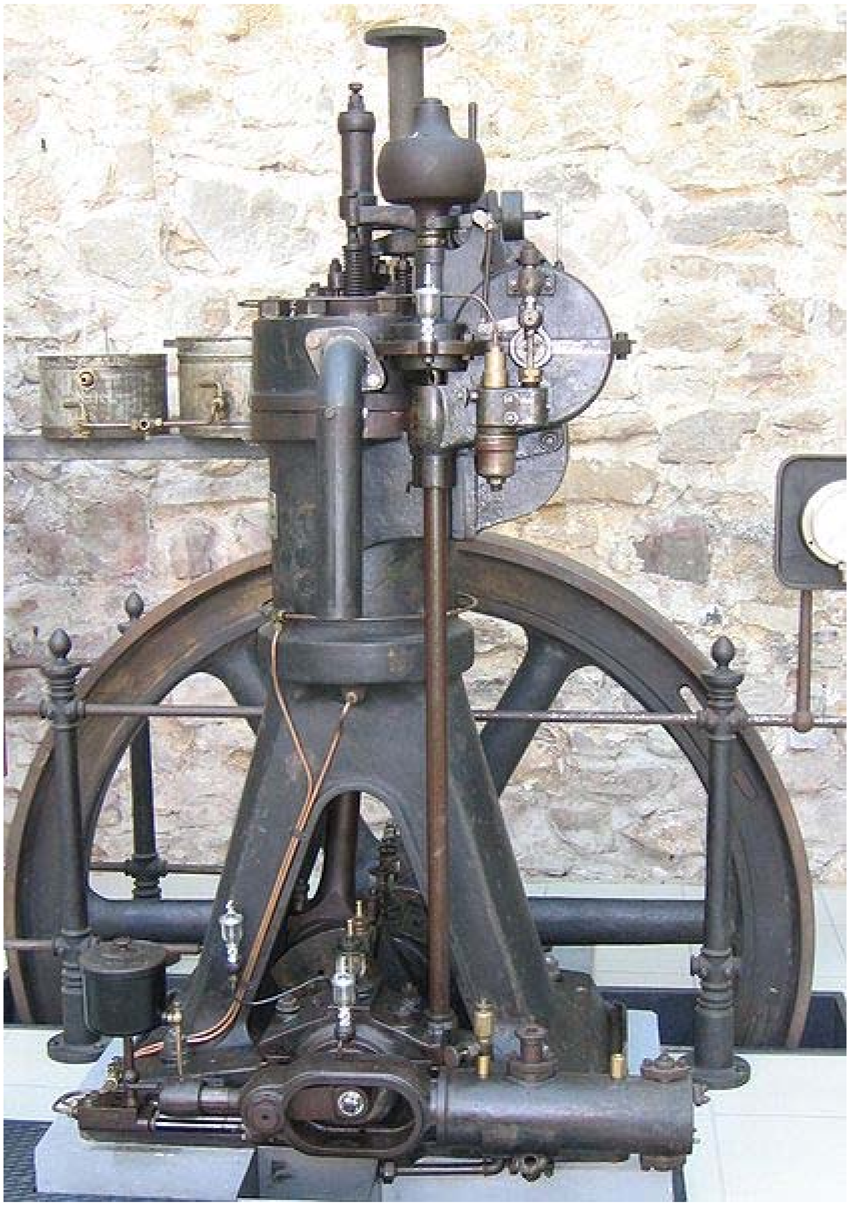


Diesel generator on an oil tanker



A diesel engine built by MAN AG in 1906

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

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

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

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

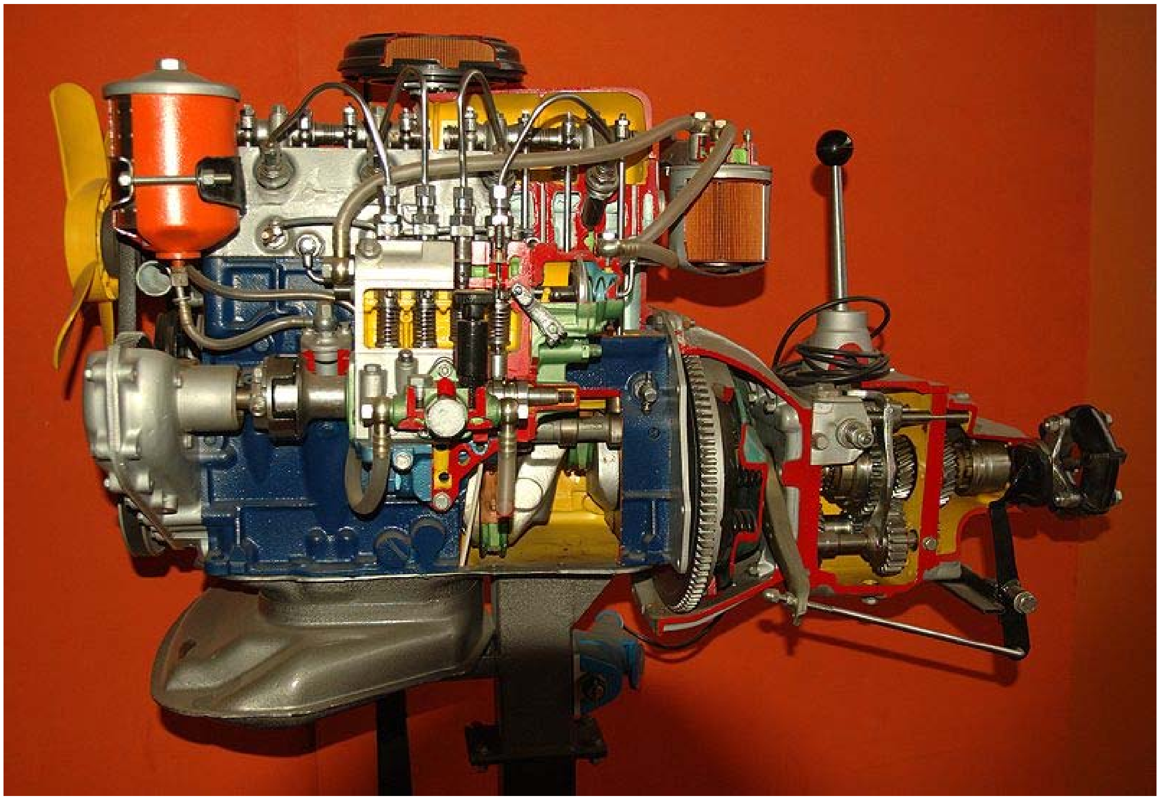
History

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

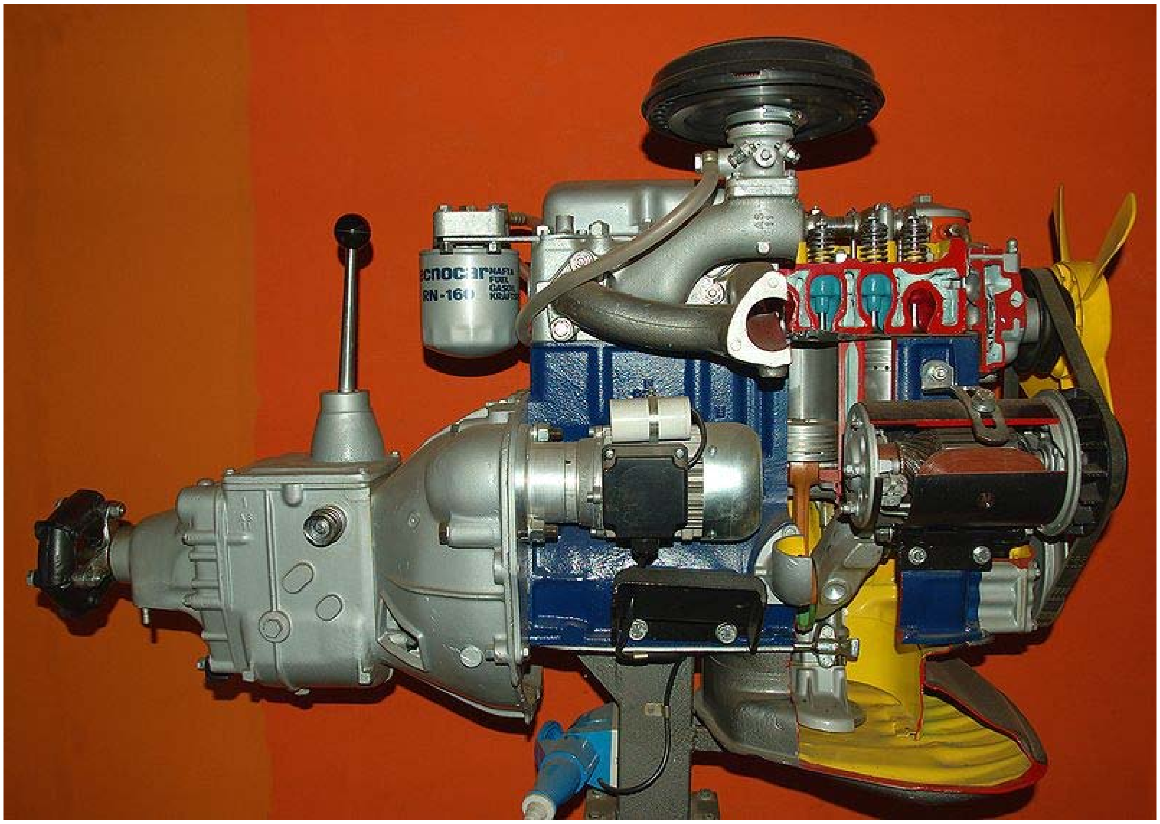
Though best known for his invention of the pressure-ignited heat engine that bears his name, Rudolf Diesel was also a well-respected thermal engineer and a social theorist. Diesel's inventions have three points in common: they relate to heat transfer by natural physical processes or laws; they involve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

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

How diesel engines work



Diesel engine model, left side



Diesel engine model, right side

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

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

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

Early fuel injection systems

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

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

Fuel delivery

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

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

Major advantages

Diesel engines have several advantages over other internal combustion engines:

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

Bus powered by **biodiesel**

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

Mechanical and electronic injection

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

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

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

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

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

Indirect injection

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

Direct injection

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

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

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

Unit direct injection

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

Common rail direct injection

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

Cold weather

Starting

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

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

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

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

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

Gelling

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

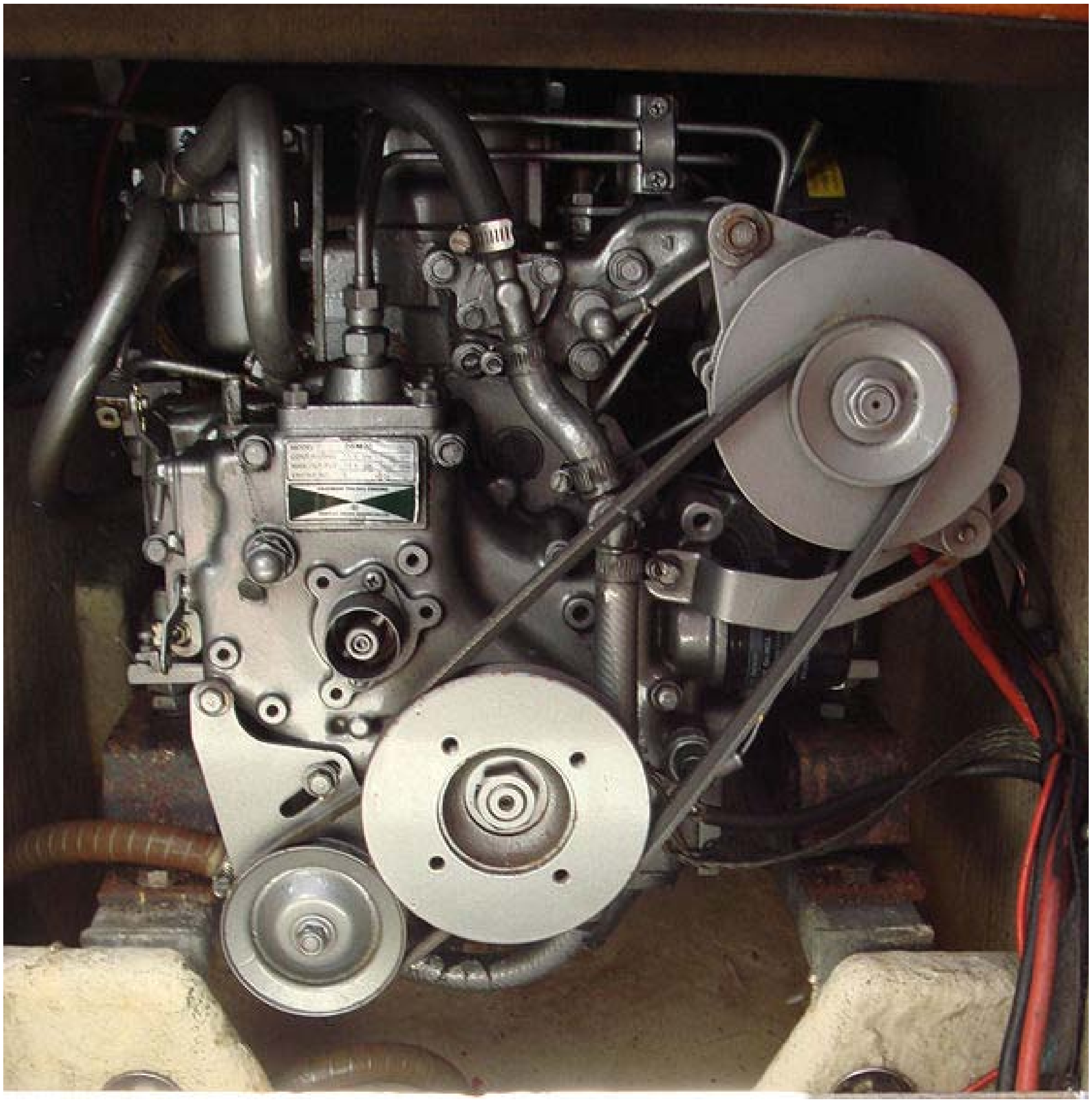
Types

Early

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

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

Modern



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

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

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

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

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

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

Gas generator

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

Advantages and disadvantages versus spark-ignition engines

Power and fuel economy

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

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

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

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

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

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

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

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

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

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

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

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

Emissions

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

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

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

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

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

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

Power and torque

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

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

Noise

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

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

Reliability

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

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

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

Quality and variety of fuels

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

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

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

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

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

Fuel and fluid characteristics

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

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

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

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

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

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

Safety

Fuel flammability

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

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

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

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

Maintenance hazards

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

Diesel applications

The characteristics of diesel have different advantages for different applications.

Passenger cars

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

Railroad rolling stock

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

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

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

Other transport uses

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

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

Military fuel standardisation

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

Engine speeds

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

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

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

High-speed engines

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

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

Medium-speed engines

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

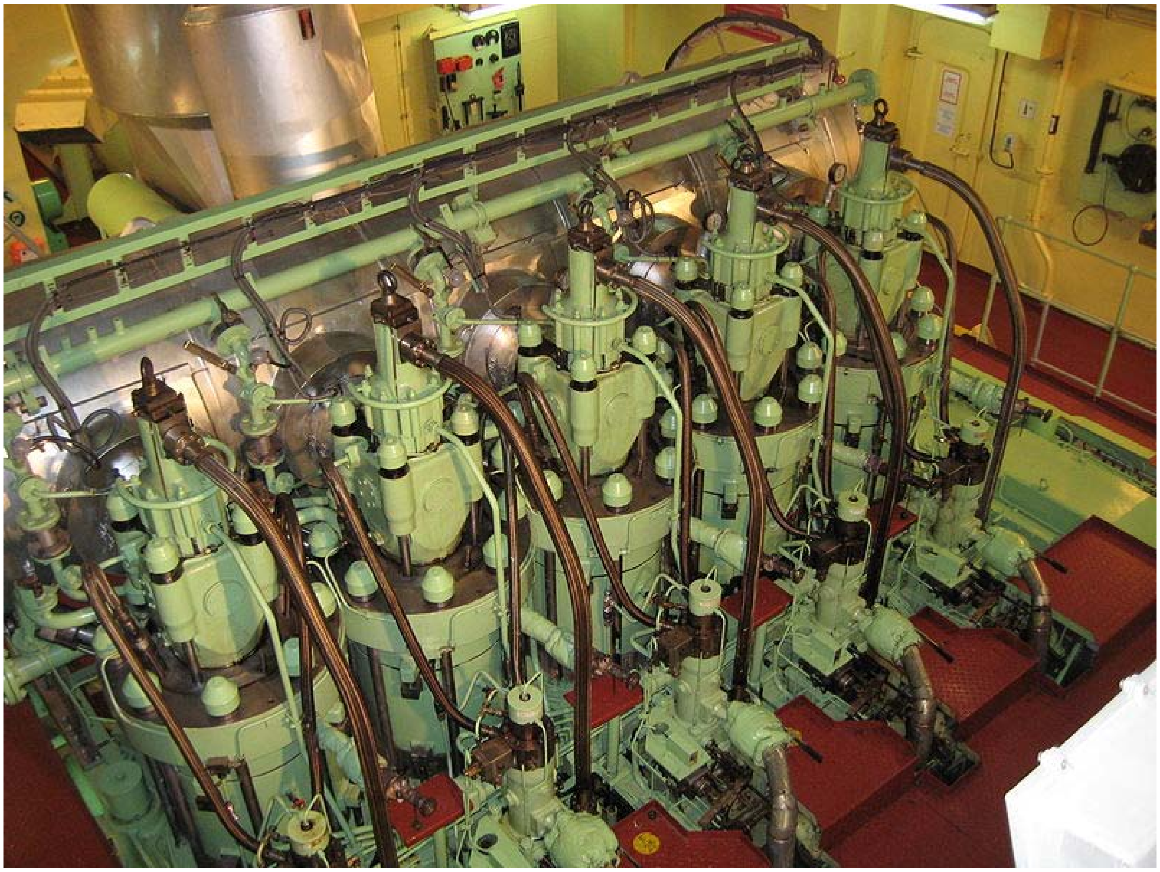
Engines used in electrical generators run at approximately 300 to 1000 rpm and are optimized to run at a set synchronous speed depending on the generation frequency (50 or 60 hertz) and provide a rapid response to load changes. Typical synchronous speeds for modern medium speed engines are 500/514 rpm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

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

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

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

Low-speed engines



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

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

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

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

Supercharging and turbocharging

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

Other applications

- Aircraft diesel engine
- Motorcycles

Current and future developments

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

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

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

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

Chapter- 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.

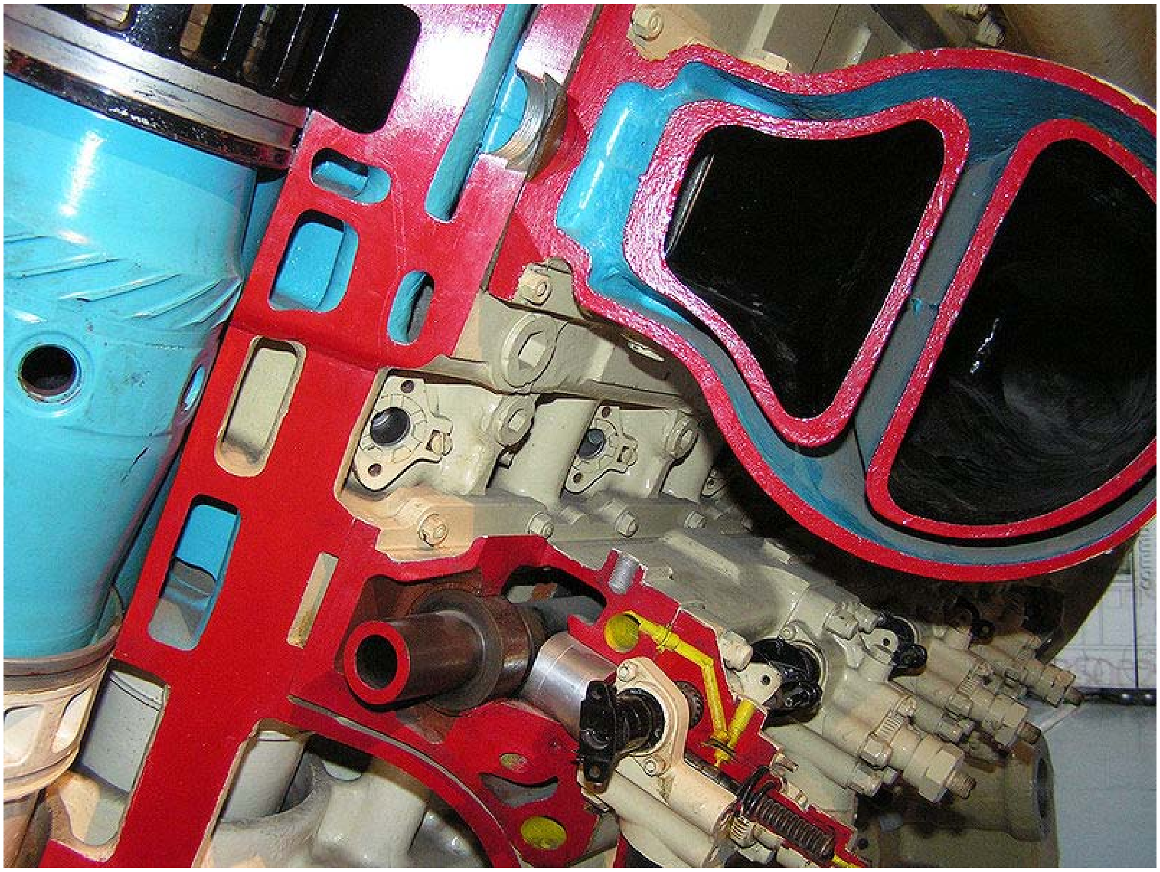
Unit Injector

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.

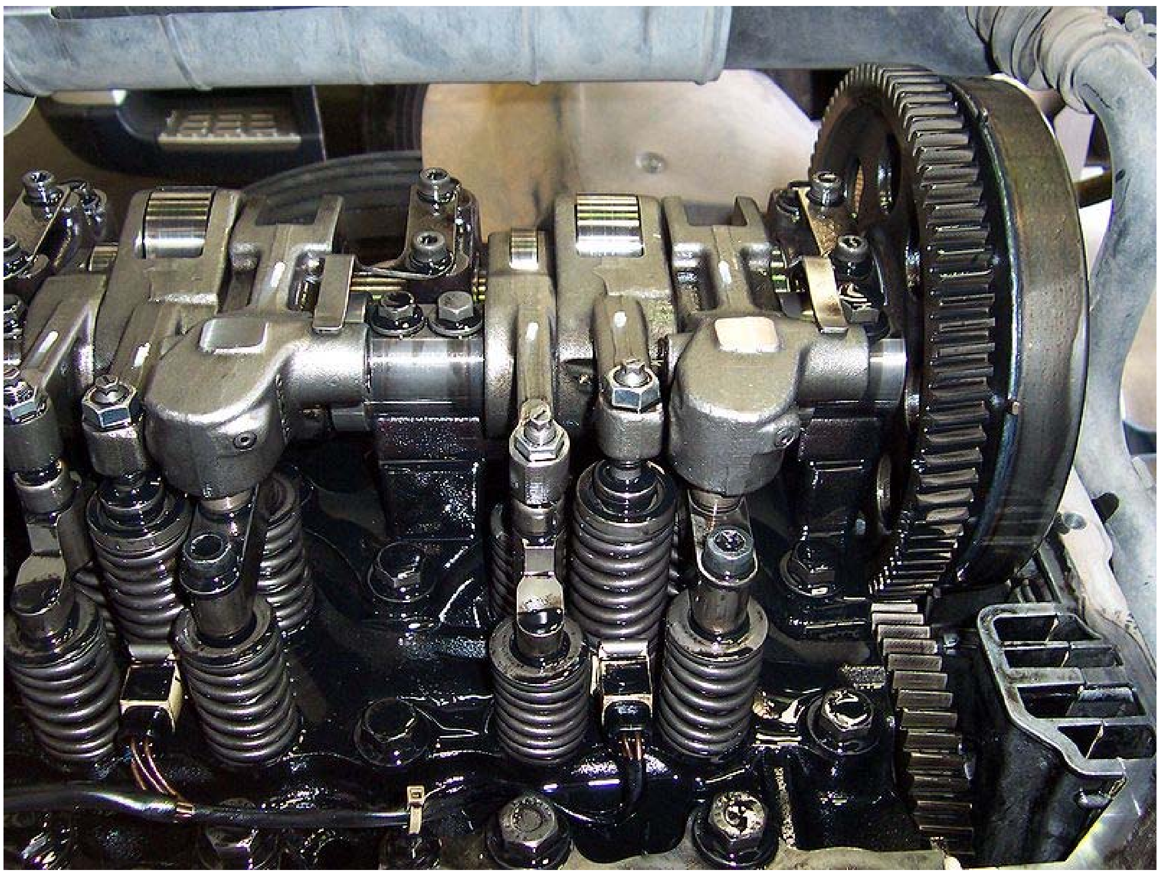
Design and technology

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 appreviated 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 "Detroiter," 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.

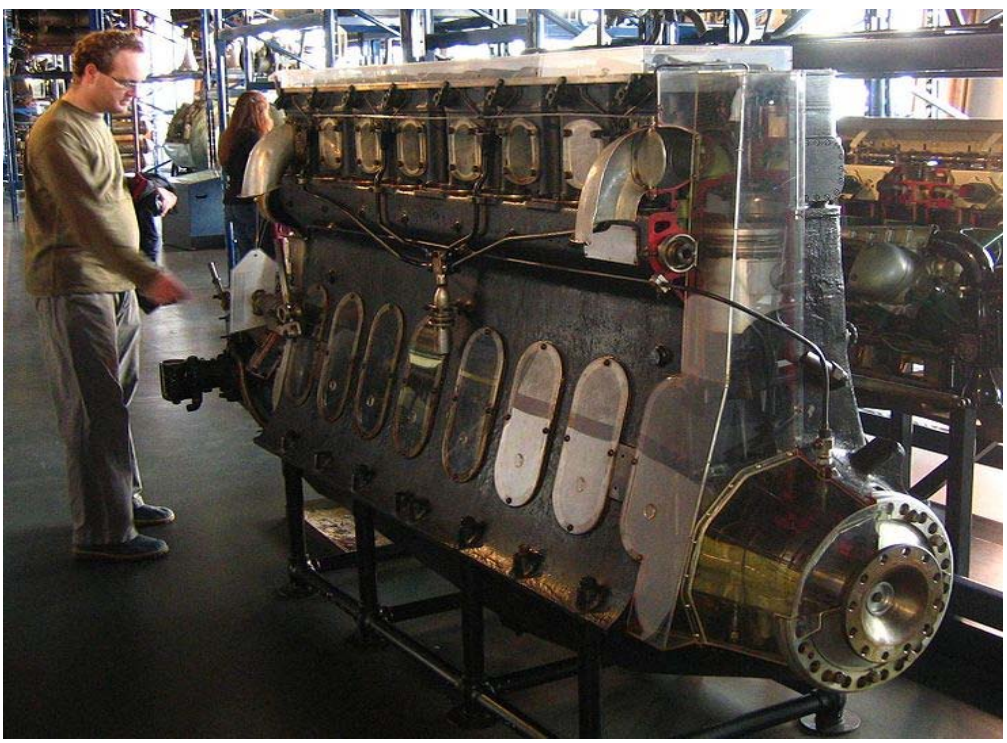
Modern developments

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.

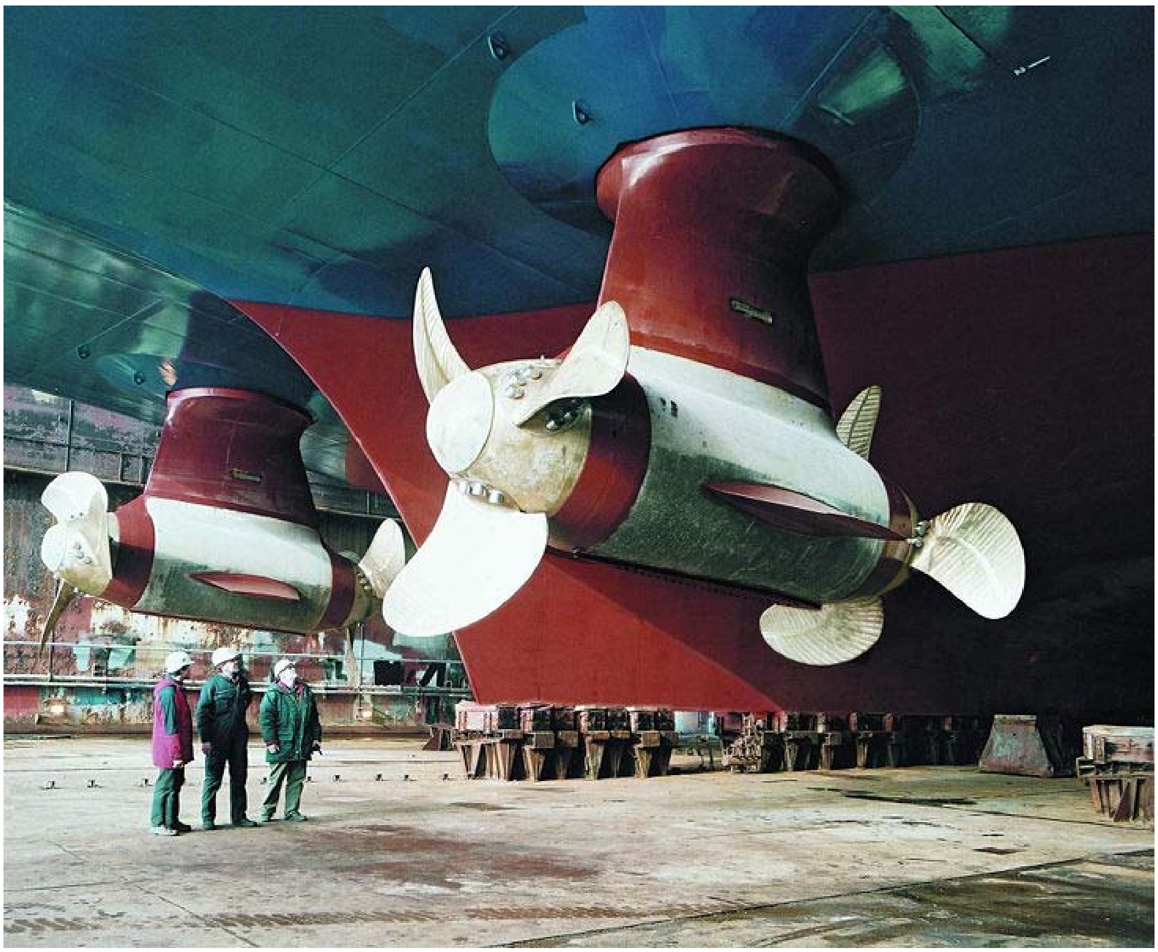
A diesel-electric transmission system includes a diesel engine connected to an electrical generator, creating electricity that powers electric traction motors. No clutch is required.

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.

Chapter- 5

IKCO EF Engines

IKCO EF Engines

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

	CNG Direct Injection(From late 2011)
Fuel type	Petrol, CNG & Diesel
Oil system	Wet sump
Cooling system	Water cooling
Power output	84 PS (62 kW) - 156 PS (115 kW)
Torque output	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.

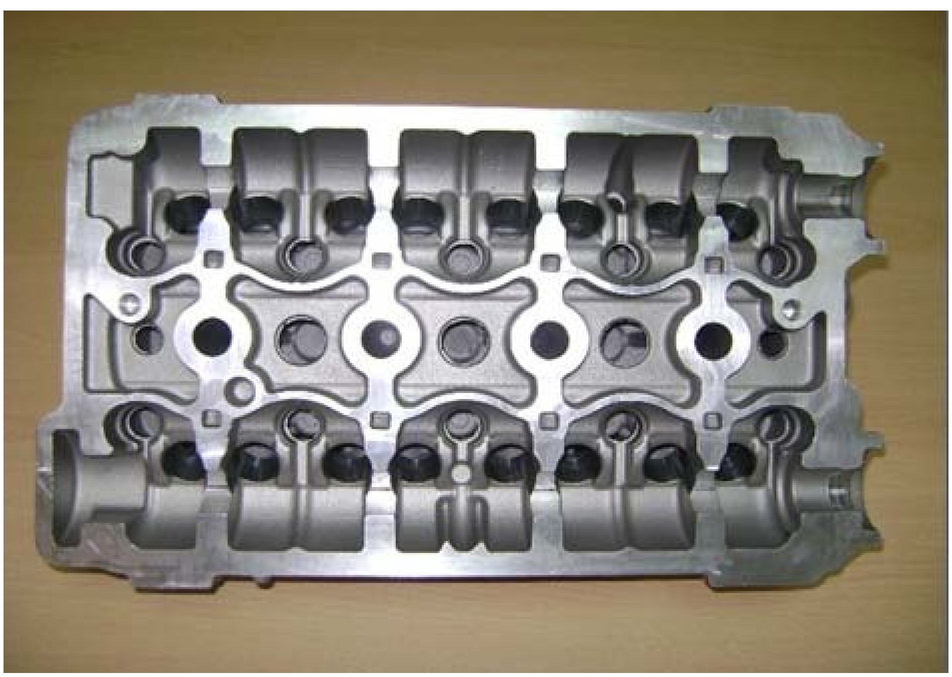
Technical details

- 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) CNG: 103 PS (76 kW) at 6000 rpm	155 N·m (114 lb·ft) CNG: 136 N·m (100 lb·ft) 3500-4500 rpm	Early 2009	Samand LX Soren ELX IKCO Runna	11:1	8.9 L, 7**Kg***	6.9 L, 6.1 kg	4.9 L 3.9 kg	16-valve, DOHC, HLA Tappets, CVVT, MPFI, Catalytic converter
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) 3500-4500 rpm	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 costumer 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 blew.

EFD turbocharged

It will be a double-stage Turbocharged engine.

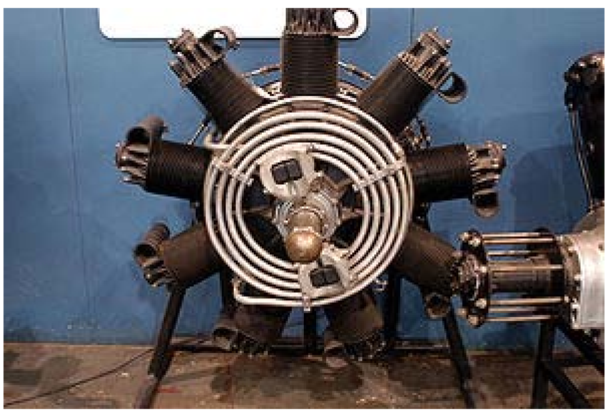
IP-Co has no plan to develop it until its brother, EFD comes to the market but it is noticeable that the project is near to be finished.

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

Type	Air-cooled diesel radial engine
Manufacturer	Packard
First run	1928
Number built	c.100
Unit cost	$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 Detroiter 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 Detroiter
- 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 in³ (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/in³ (11.2 kW/L)
- **Power-to-weight ratio:** 0.44 hp/lb (0.8 kW/kg)

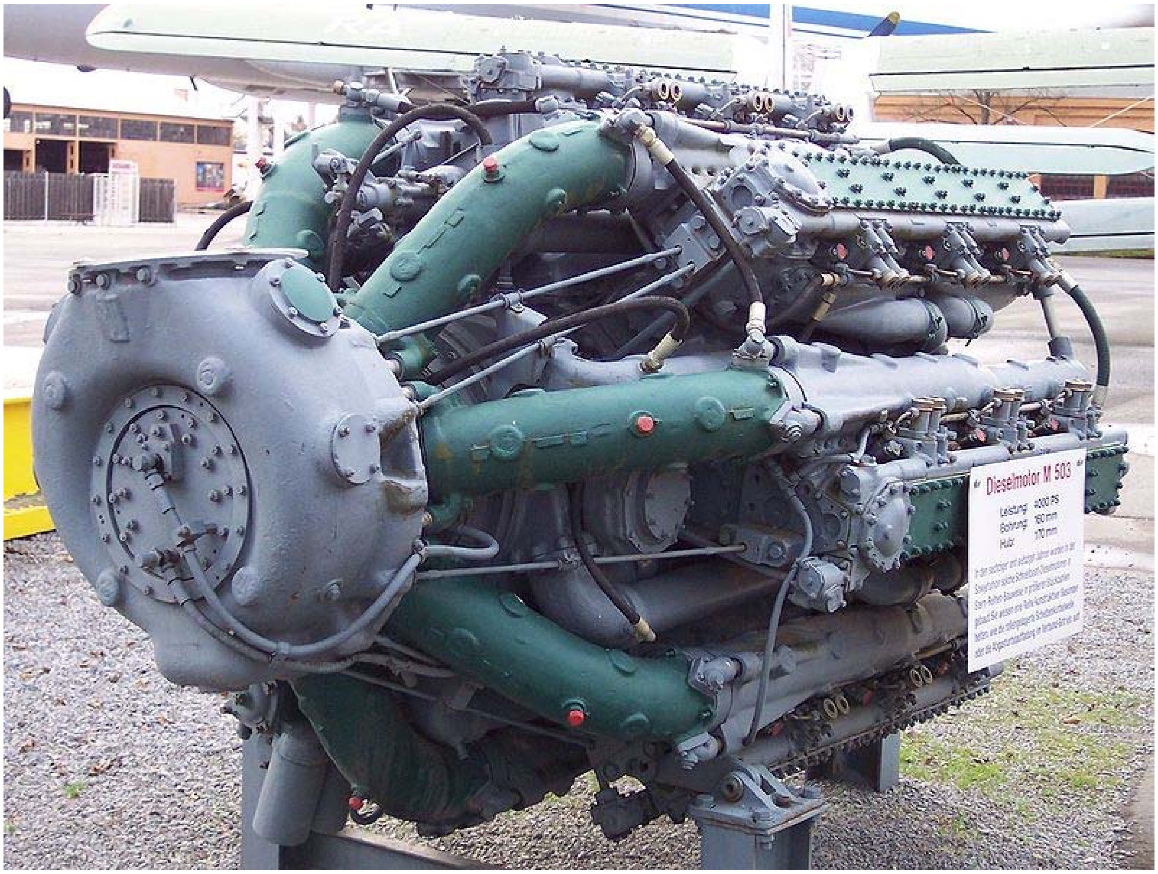
Zvezda M503

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^3 (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/in³ (20.47 kW/L)
- **Power-to-weight ratio:** 0.32 hp/lb (0.53 kW/kg)

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.

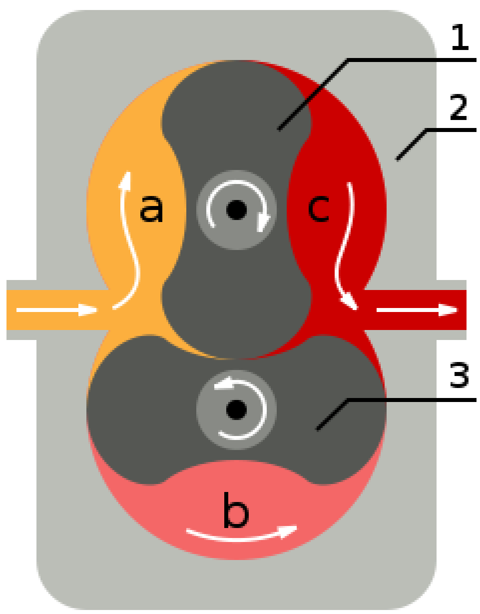
Brands

- **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.

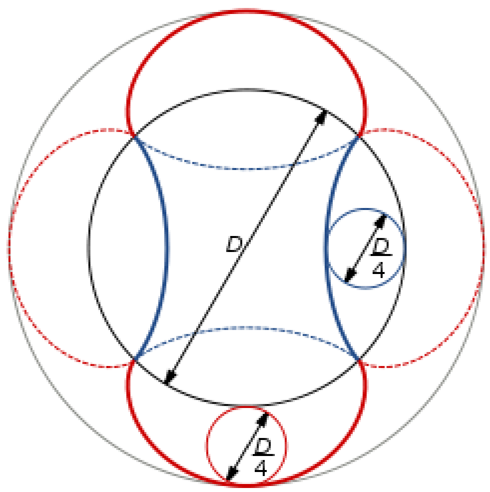
The superchargers used on top fuel engines, funny cars, and other dragsters, as well as hot rods, are in fact derivatives of *General Motors Coach Division* blowers for their industrial diesel engines, which were adapted for automotive use in the early days of the sport of drag racing. The model name 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.

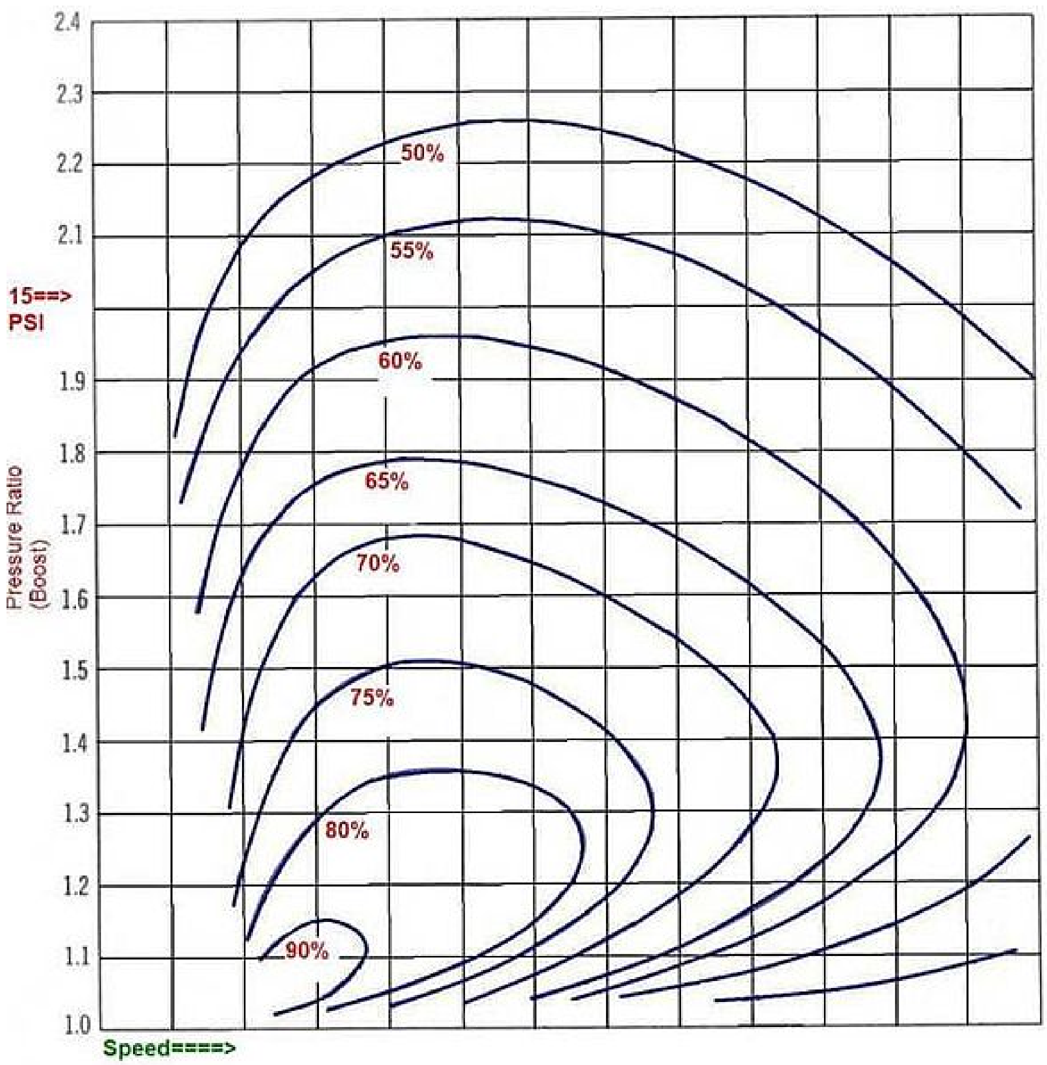
The simplest form of a Roots blower has cycloidal rotors, constructed of alternating tangential sections of hypocycloidal and epicycloidal curves. For a two-lobed rotor, the smaller generating circles are one-quarter the diameter of the larger. Real Roots blowers may have more complex profiles for increase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

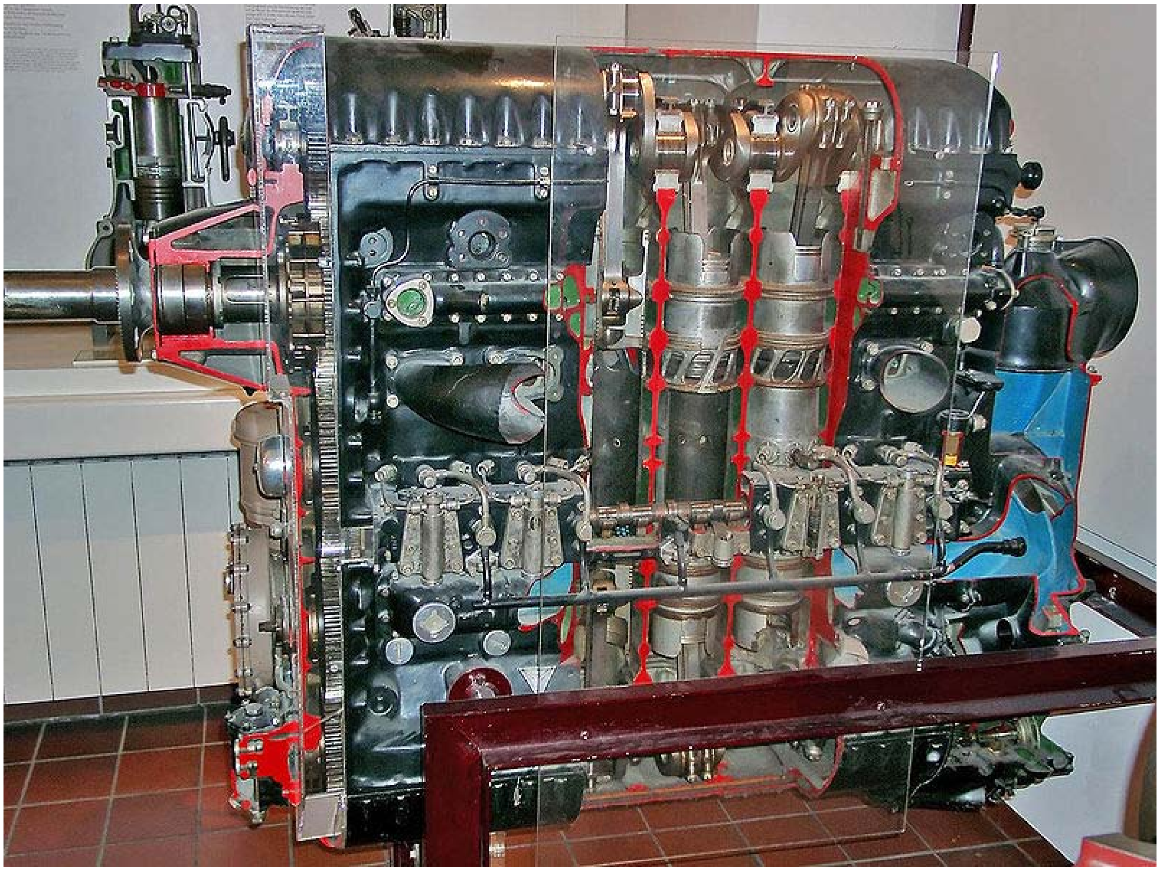
The term "blower" is commonly used to define a device placed on engines with a functional need for additional airflow using a direct mechanical link as its energy source. The term blower is used to describe different types of super chargers. A screw type super charger, Roots type super charger, and a centrifugal super charger 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.

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

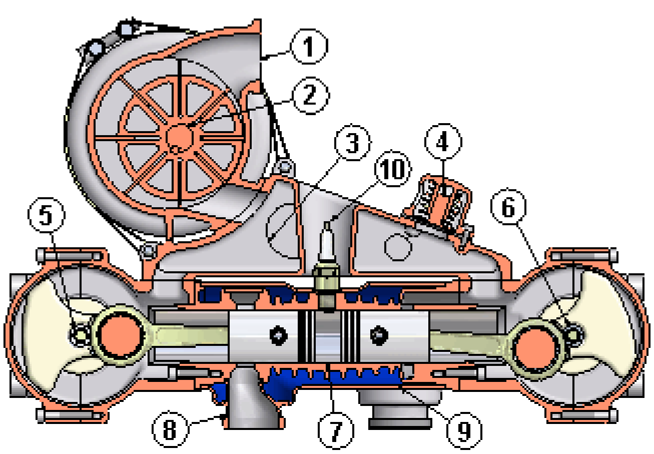
The first Junkers engines had one crankshaft, the upper pistons having long connecting rods outside the cylinder. These engines were the forerunner of the Doxford marine engine, and this layout was also used for two- and three-cylinder car engines from around 1900-1922 by Gobron-Brillié. There is currently 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^3 (15 cu in), and one with 350 cm^3 (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 thermically 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

ID	Engine type	Induction	Max rpm	Power (hp)	Power (MW)	Introduced	Locomotive(s)
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

						compliant/EFI equipped.
16-710G3C	V-16	Turbocharged	4300	3.2	1995	SD75M, SD75I.
16-710G3C-EC	V-16	Turbocharged	4300	3.2	1995	SD75M, SD75I, SD90/43MAC EFI equipped.
16-710G3C-T1	V-16	Turbocharged 900	4300	3.2	2003	SD70M (late model), SD70MAC (late model), Alstom PL42AC EPA Tier I 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

Common Rail and Electronic Diesel Control

Common rail

Common rail direct fuel injection is a modern variant of direct fuel injection system for petrol and diesel engines.

Common rail fuel injector

On diesel engines, it features a high-pressure (over 1,000 bar/15,000 psi) fuel rail feeding individual solenoid valves, as opposed to low-pressure fuel pump feeding unit injectors (Pumpe/Düse or pump nozzles). Third-generation common rail diesels now feature piezoelectric injectors for increased precision, with fuel pressures up to 1,800 bar/26,000 psi.

In gasoline engines, it is utilised in gasoline direct injection engine technology.

History

The common rail system prototype was developed in the late 1960s by Robert Huber of Switzerland and the technology further developed by Dr. Marco Ganser at the Swiss Federal Institute of Technology in Zurich, later of Ganser-Hydromag AG (est.1995) in Oberägeri.

The first successful usage in production vehicle began in Japan by the mid-1990s. Dr. Shohei Itoh and Masahiko Miyaki of the Denso Corporation, a Japanese automotive parts manufacturer, developed the common rail fuel system for heavy duty vehicles and turned it into practical use on their ECD-U2 common-rail system mounted on the Hino Rising Ranger truck and sold for general use in 1995. Denso claims the first commercial high pressure common rail system in 1995.

Common rail fuel system close up

Modern common rail systems, whilst working on the same principle, are governed by an engine control unit (ECU) which opens each injector electronically rather than mechanically. This was extensively prototyped in the 1990s with collaboration between Magneti Marelli, Centro Ricerche Fiat and Elasis. After research and development by the Fiat Group, the design was acquired by the German company Robert Bosch GmbH for completion of development and refinement for mass-production. In hindsight the sale appeared to be a tactical error for Fiat as the new technology proved to be highly profitable. The company had little choice but to sell, however, as it was in a poor financial state at the time and lacked the resources to complete development on its own. In 1997 they extended its use for passenger cars. The first passenger car that used the common rail system was the 1997 model Alfa Romeo 156 1.9 JTD, and later on that same year Mercedes-Benz C 220 CDI.

Common rail engines have been used in marine and locomotive applications for some time. The Cooper-Bessemer GN-8 (circa 1942) is an example of a hydraulically operated common rail diesel engine, also known as a modified common rail.

Vickers used common rail systems in submarine engines circa 1916. Doxford Engines Ltd. (opposed piston heavy marine engines) used a common rail system (from 1921 to 1980) whereby a multi-cylinder reciprocating fuel pump generated a pressure of approximately 600bar with the fuel being stored in accumulator bottles. Pressure control was achieved by means of an adjustable pump discharge stroke and a "spill valve". Camshaft operated mechanical timing valves were used to supply the spring loaded Brice/CAV/Lucas injectors which injected through the side of the cylinder into the chamber formed between the pistons. Early engines had a pair of timing cams, one for ahead running and one for astern. Later engines had two injectors per cylinder and the final series of constant pressure turbocharged engines were fitted with four injectors per cylinder. This system was used for the injection of both diesel oil and heavy fuel oil (600cSt heated to a temperature of approximately 130°C).

The common rail system is suitable for all types of road cars with diesel engines, ranging from city cars such as the Fiat Nuova Panda to executive cars such as the Audi A6.

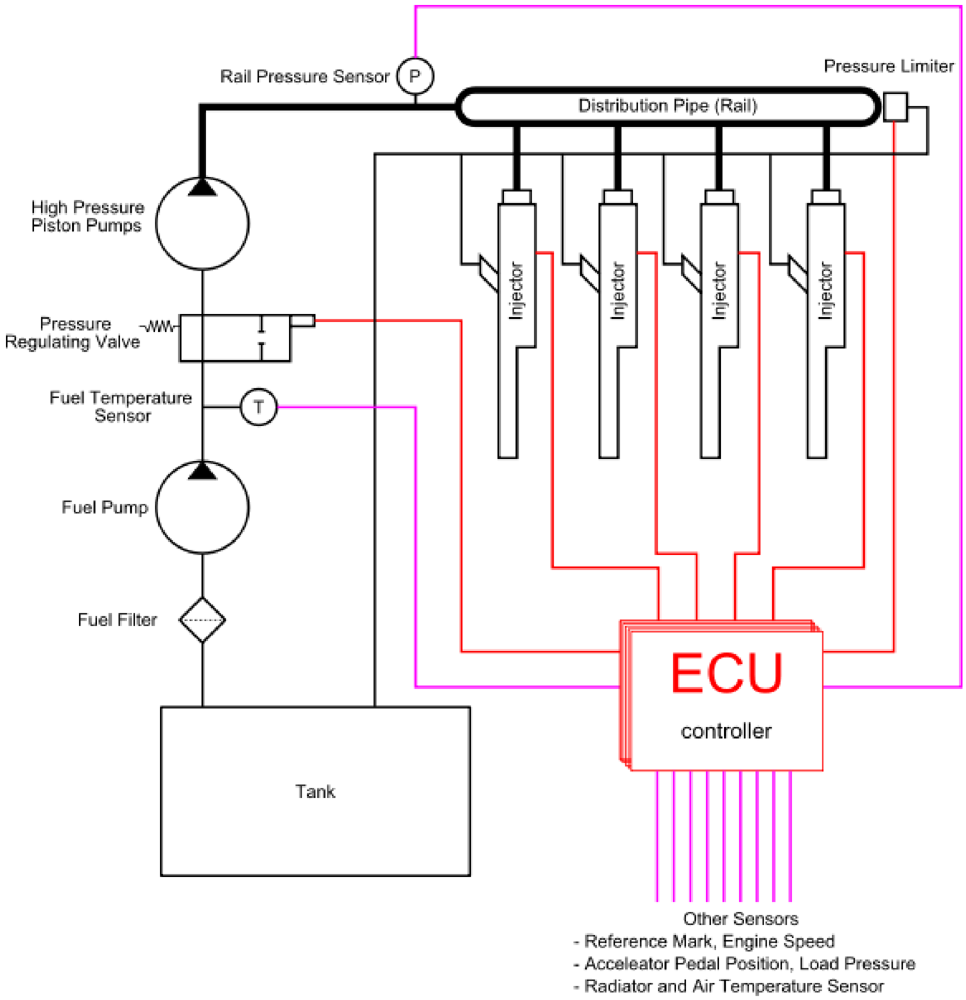
Common rail today

Today the common rail system has brought about a revolution in diesel engine technology. Robert Bosch GmbH, Delphi Automotive Systems, Denso Corporation, and Siemens VDO (now owned by Continental AG) are the main suppliers of modern common rail systems. The car makers refer to their common rail engines by their own brand names:

- BMW's D-engines (also used in the Land Rover Freelander TD4)
- Cummins and Scania's **XPI** (Developed under joint venture)
- Cummins **CCR** (Cummins pump with Bosch Injectors)
- Daimler's **CDI** (and on Chrysler's Jeep vehicles simply as **CRD**)

- Fiat Group's (Fiat, Alfa Romeo and Lancia) **JTD** (also branded as *MultiJet*, *JTDm*, *Ecotec CDTi*, *TiD*, *TTiD* , *DDiS*, *Quadra-Jet*)
- Ford Motor Company's **TDCi** Duratorq and Powerstroke
- General Motors Opel/Vauxhall **CDTi** (manufactured by Fiat, Isuzu and GM Daewoo) and earlier **DTi**
- General Motors Daewoo/Chevrolet **VCDi** (licensed from VM Motori; also branded as *Ecotec CDTi*)
- Honda's **i-CTDi**
- Hyundai-Kia's **CRDi**
- IKCO's **EFD** which is one of the members of the EF family. Supplier TBD
- Isuzu's **iTEQ**
- Komatsu's **Tier3**, **Tier4**, **4D95** *and higher - **HPCR** series Diesel engines*.
- Mahindra's **CRDe**
- Mazda's **MZR-CD** (1.4 MZ-CD, 1.6 MZ-CD manufactured by joint venture Ford/PSA Peugeot Citroën) and earlier **DiTD**
- Mitsubishi's **DI-D** (recently developed 4N1 engine family uses next generation 200 MPa (2000 bar) injection system))
- Nissan's **dCi**, Infiniti uses dCi engines, but not branded as dCi.
- Proton's **SCDi**
- PSA Peugeot Citroën's **HDI or HDi** (1.4HDI, 1.6 HDI, 2.0 HDI, 2.2 HDI and V6 HDI developed under joint venture with Ford)
- Renault's *dCi* and earlier **dTi**
- SsangYong's **XDi** (most of these engines are manufactured by Daimler AG)
- Subaru's **Legacy TD** (as of Jan 2008)
- Tata's **DICOR** & CR4
- Toyota's **D-4D**
- Volkswagen Group: The 4.2 V8 **TDI** and the latest 2.7 and 3.0 TDI (V6) engines featured on current Audi models use common rail, as opposed to the earlier unit injector engines. The 2.0 TDI in the Volkswagen Tiguan SUV uses common rail, as does the 2008 model Audi A4. Volkswagen Group has announced that the 2.0 TDI (common rail) engine will be available for Volkswagen Passat as well as the 2009 Volkswagen Jetta.
- Volvo 2.4D and D5 engines (1.6D, 2.0D manufactured by Ford and PSA Peugeot Citroen), Volvo Penta D-serie engines
- Wärtsilä-Sulzer 14RT-flex96-C "largest reciprocating engine in the world" designed by the Finnish manufacturer Wärtsilä

Principles



Solenoid or piezoelectric valves make possible fine electronic control over the fuel injection time and quantity and the higher pressure that the common rail technology makes available provides better fuel atomisation. In order to lower engine noise, the engine's electronic control unit can inject a small amount of diesel just before the main injection event ("pilot" injection), thus reducing its explosiveness and vibration, as well as optimising injection timing and quantity for variations in fuel quality, cold starting and so on. Some advanced common rail fuel systems perform as many as five injections per stroke.

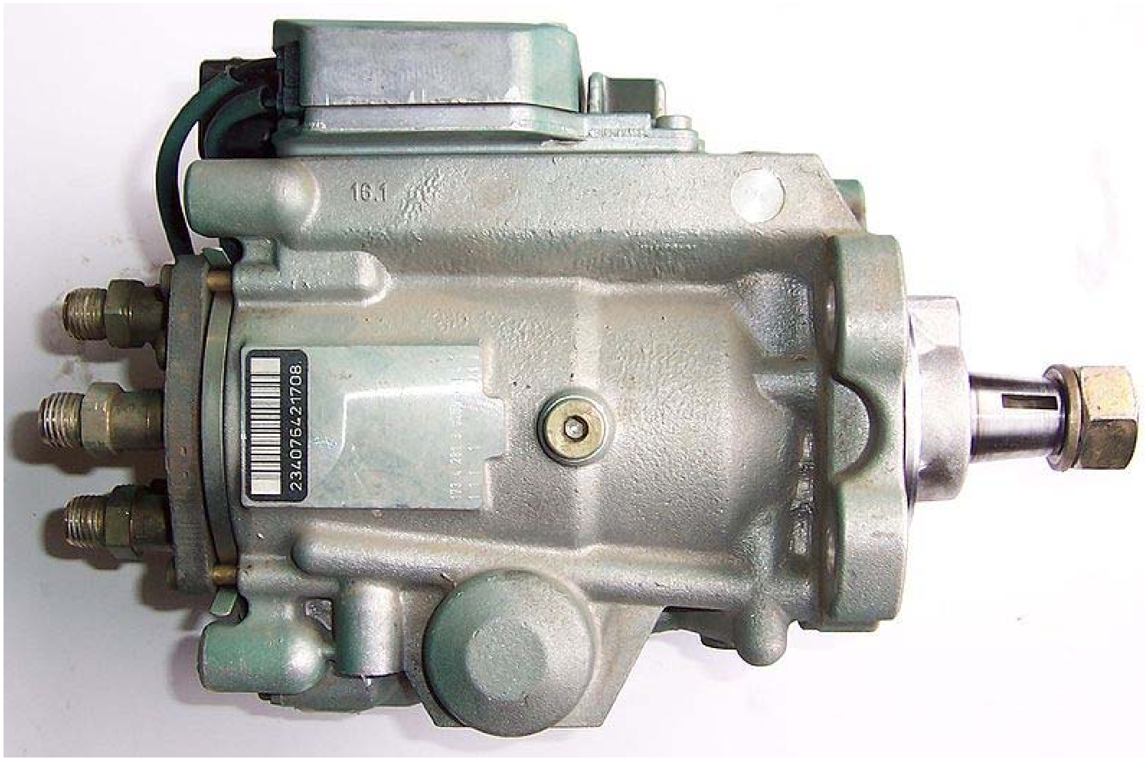
Common rail engines require very short (< 1 s) or no heating up time at all and produce lower engine noise and emissions than older systems.

Diesel engines have historically used various forms of fuel injection. Two common types include the unit injection system and the distributor/inline pump systems. While these older systems provided accurate fuel quantity and injection timing control, they were limited by several factors:

- They were cam driven and injection pressure was proportional to engine speed. This typically meant that the highest injection pressure could only be achieved at the highest engine speed and the maximum achievable injection pressure decreased as engine speed decreased. This relationship is true with all pumps, even those used on common rail systems; with the unit or distributor systems, however, the injection pressure is tied to the instantaneous pressure of a single pumping event with no accumulator and thus the relationship is more prominent and troublesome.
- They were limited in the number and timing of injection events that could be commanded during a single combustion event. While multiple injection events are possible with these older systems, it is much more difficult and costly to achieve.
- For the typical distributor/inline system, the start of injection occurred at a pre-determined pressure (often referred to as: pop pressure) and ended at a pre-determined pressure. This characteristic resulted from "dummy" injectors in the cylinder head which opened and closed at pressures determined by the spring preload applied to the plunger in the injector. Once the pressure in the injector reached a pre-determined level, the plunger would lift and injection would start.

In common rail systems, a high pressure pump stores a reservoir of fuel at high pressure — up to and above 2,000 bars (29,000 psi). The term "common rail" refers to the fact that all of the fuel injectors are supplied by a common fuel rail which is nothing more than a pressure accumulator where the fuel is stored at high pressure. This accumulator supplies multiple fuel injectors with high pressure fuel. This simplifies the purpose of the high pressure pump in that it only has to maintain a commanded pressure at a target (either mechanically or electronically controlled). The fuel injectors are typically ECU-controlled. When the fuel injectors are electrically activated, a hydraulic valve (consisting of a nozzle and plunger) is mechanically or hydraulically opened and fuel is sprayed into the cylinders at the desired pressure. Since the fuel pressure energy is stored remotely and the injectors are electrically actuated, the injection pressure at the start and end of injection is very near the pressure in the accumulator (rail), thus producing a square injection rate. If the accumulator, pump and plumbing are sized properly, the injection pressure and rate will be the same for each of the multiple injection events.

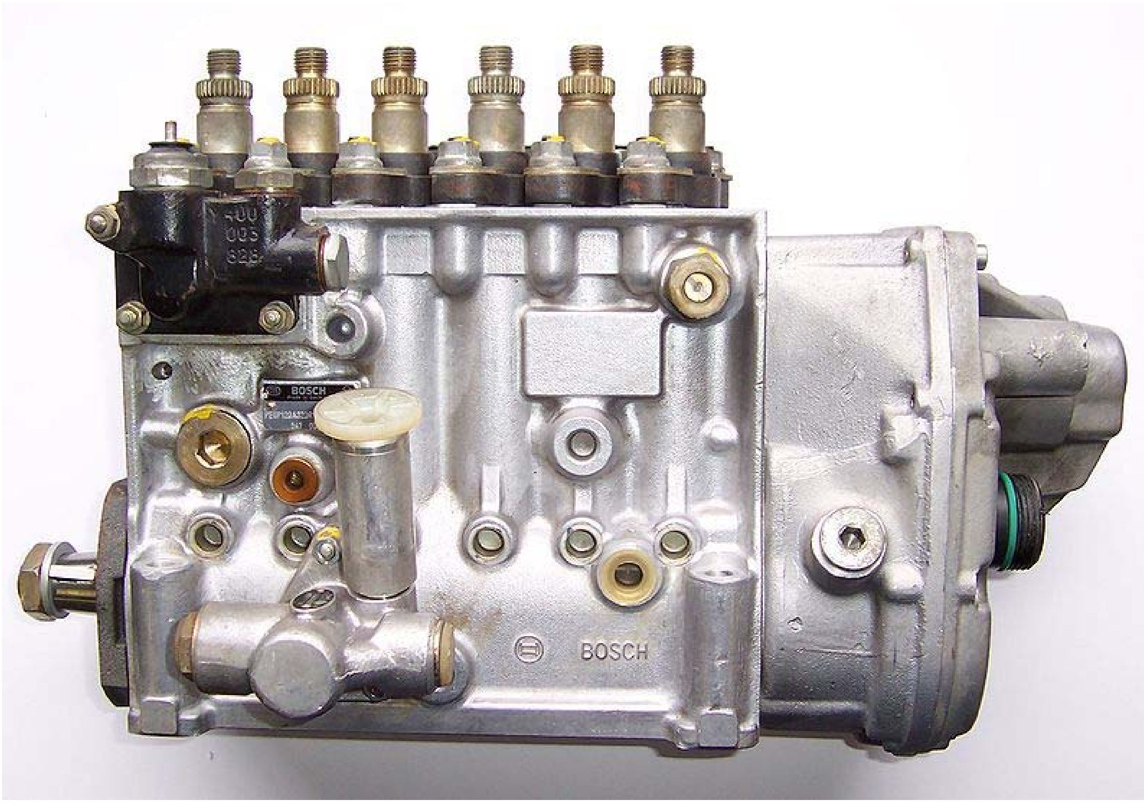
Electronic Diesel Control



EDC distributor injection pump

Electronic Diesel Control is a diesel engine fuel injection control system for the precise metering and delivery of fuel into the combustion chamber of modern diesel engines used in trucks and cars.

Introduction



EDC injection inline pump

The mechanical fly-weight governors of inline and distributor diesel fuel injection pumps used to control fuel delivery under a variety of engine loads and conditions could no longer deal with the ever increasing demands for efficiency, emission control, power and fuel consumption. These demands are now primarily fulfilled by the Electronic Diesel Control EDC, the system which provides greater ability for precise measuring, data processing , operating environment flexibility and analysis to ensure efficient diesel engine operation. The EDC replaces the mechanical control governor with an electro-magnetic control device.

System overview

The EDC is divided into these main groups of components.

- Electronic sensors for registering operating conditions and changes. A wide array of physical inputs is converted into electrical signal outputs.
- Actuators or solenoids which convert the control unit's electrical output signal into mechanical control movement.
- ECM (Electronic Control Module) or Engine ECU (Electronic Control Unit) with microprocessors which process information from various sensors in accordance

with programmed software and outputs required electrical signals into actuators and solenoids.

Components

EDC accelerator pedal assembly

Sensors

- Injection pump speed sensor - monitors pump rotational speed
- Fuel rack position sensor - monitors pump fuel rack position
- Charge air pressure sensor - measures pressure side of the turbocharger
- Fuel pressure sensor

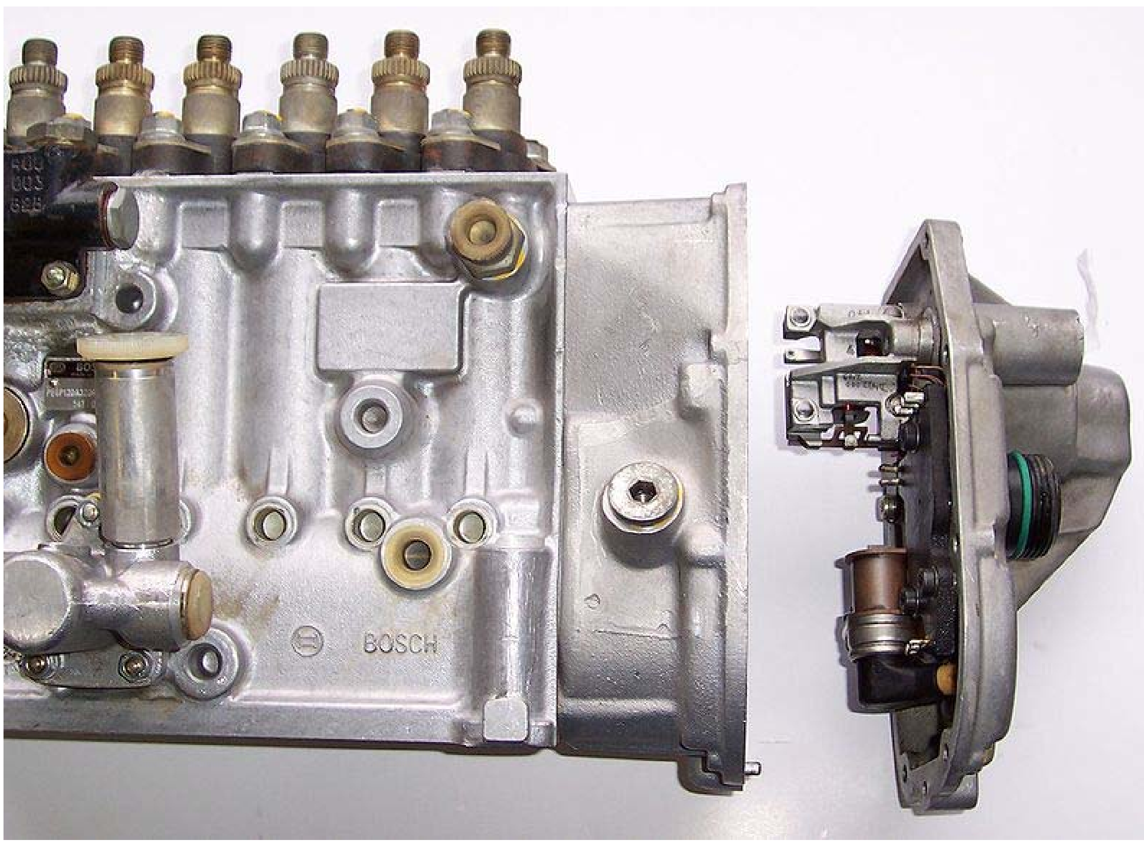
- Air cleaner vacuum pressure sensor
- Engine position sensor
- Temperature sensors - measure various operating temperatures
    - Intake temperature
    - Charge air temperature
    - Coolant temperature
    - Fuel temperature
    - Exhaust temperature (Pyrometer)
    - Ambient temperature
- Vehicle speed sensor - monitors vehicle speed
- Brake pedal sensor - operates with cruise control, exhaust brake, idle control
- Clutch pedal sensor - operates with cruise control, exhaust brake, idle control
- Accelerator pedal sensor
- Driver input switches - cruise control, idle increase /decrease, engine/exhaust brake
- Injector needle movement sensor - monitors the actual injection time and feeds the information to the ECU (as used on VM_Motori 2.5 and 3.1 engines)

Electronic Control Unit

EDC control unit

The ECU collects and processes signals from various on-board sensors. An ECU electronic module contains microprocessors, memory units, analog to digital converters and output interface units. Depending upon the parameters, a number of different maps can be stored in the onboard memory. This allows the ECU to be tailored to the specific engine and vehicle requirements, depending on the application. The operating software of the ECU can be adapted for a wide variety of engines and vehicles without the necessity of hardware modification. The ECU is usually located in the cab or in certain cases, in a suitable position in the engine bay where additional environmental conditions might require cooling of the ECU as well as a requirement for better dust, heat and vibrations insulation.

Actuators and **Solenoids**



EDC pump actuator

Electro-magnetic actuators are usually located on the fuel pump to transfer electrical signals into mechanical action in this case fuel rack actuator and or fuel stop solenoid which means that depending on requests from control unit full fuel or no fuel quantity.

Operation

The injection of fuel or the quantity of injected fuel has a decisive influence on engine starting, idling, power and emissions. The engine ECU is programmed ("mapped") with relevant data to where the fuel rack position has an equivalent signal for the amount of fuel being injected. The driver requests the torque or engine speed requirements via accelerator pedal potentiometer thereby sending a signal to the engine ECU which then, depending on its *mapping* and data collected from various sensors, calculates in real time the quantity of injected fuel required, thus altering the fuel rack to the required position. The driver can also input additional commands such as idle speed increase to compensate e.g. for PTO operation which can be either variably set or has a preset speed which can be recalled. The road speed function can be used to evaluate vehicle speed and possibly activate a speed limiter (Heavy Vehicles), or maintain or restore a set speed (cruise control). Further functions can include exhaust brake operation which, when activated, will result in the fuel pump rack position being set to zero delivery or idle. The engine ECU can also interface with various other vehicle systems e.g. traction control and carries out self monitoring duties and self diagnostic functions to keep the system working at an optimal level. To ensure the safe operation in case of failure, the limp home mode functions are also integrated into the system, for e.g. should the pump speed sensor fail the ECU can use an alternator speed signal function for engine RPMs counter as a backup signal.

Additional Functions

- Engine protection, cold start - when starting cold , engine rpms are limited.
  - Engine protection, overheating - when overheating, to avoid damage the engine power output is limited.
- Remote engine shutdown - when auxiliary equipment is in use e.g. crane in case of rollover.
- Constant engine speed - the engine maintains set revs irrespective of load e.g. PTO operation

Chapter- 9

Diesel Fuel

Biodiesel fuel in an Erlenmeyer flask

Diesel fuel in general is any liquid fuel used in diesel engines. The most common is a specific fractional distillate of petroleum fuel oil, but alternatives that are not derived from petroleum, such as biodiesel, biomass to liquid (BTL) or gas to liquid (GTL) diesel, are increasingly being developed and adopted. To distinguish these types, petroleum-derived diesel is increasingly called **petrodiesel**. Ultra-low sulfur diesel (ULSD) is a standard for defining diesel fuel with substantially lowered sulfur contents. As of 2007, almost every diesel fuel available in the United States of America, Canada and Europe is the ULSD type.

In the UK, diesel is commonly abbreviated **DERV**, standing for *Diesel Engined Road Vehicle*, which carries a tax premium over equivalent fuel not for road use.

History

Etymology

The word "diesel" is derived from the German inventor Rudolf Diesel who in 1892 invented the diesel engine.

Diesel engine

Diesel engines are a type of internal combustion engine. Rudolf Diesel originally designed the diesel engine to use coal dust as a fuel. He also experimented with various oils, including some vegetable oils, such as peanut oil, which was used to power the engines which he exhibited at the 1900 Paris Exposition and the 1911 World's Fair in Paris.

Sources

Diesel fuel is produced from petroleum and from various other sources.

Petroleum diesel

A modern diesel dispenser

Refining

Petroleum diesel, also called **petrodiesel**, or fossil diesel is produced from the fractional distillation of crude oil between 200 °C (392 °F) and 350 °C (662 °F) at atmospheric pressure, resulting in a mixture of carbon chains that typically contain between 8 and 21 carbon atoms per molecule.

Fuel value and price

As of 2010 the density of petroleum diesel is about 0.832 kg/l (6.943 lb/US gal), about 12% more than ethanol free petrol (gasoline), which has a density of about 0.745 kg/l (6.217 lb/US gal). About 86.1% of the fuel mass is carbon and when burned, it offers a net heating value of 43.1 MJ/kg as opposed to 43.2 MJ/kg for gasoline. However, due to the higher density, diesel offers a higher volumetric energy density at 35.86 MJ/l (128 700 BTU/US gal) vs. 32.18 MJ/l (115 500 BTU/US gal) for gasoline, some 11% higher, something that should be considered when comparing the fuel efficiency by volume. The CO_2 emissions from diesel are 73.25 g/MJ, just slightly lower than for gasoline at 73.38

g/MJ. Diesel is generally simpler to refine from petroleum than gasoline and contains hydrocarbons having a boiling point in the range of 180-360°C (360-680°F). The price of diesel traditionally rises during colder months as demand for heating oil rises, which is refined in much the same way. Because of recent changes in fuel quality regulations, additional refining is required to remove sulfur which contributes to a sometimes higher cost. In many parts of the United States and throughout the United Kingdom and Australia diesel may be higher priced than petrol. Reasons for higher priced diesel include the shutdown of some refineries in the Gulf of Mexico, diversion of mass refining capacity to gasoline production, and a recent transfer to ULSD, which causes infrastructural complications. In Sweden a diesel fuel designated as MK-1 (class 1 environmental diesel) is also being sold, this is a ultra low sulphur diesel that also have a lower aromatics content, with a limit of 5%. This fuel is slightly more expensive to produce than regular ultra low sulphur diesel.

Use as vehicle fuel

Unlike petroleum ether and liquefied petroleum gas engines, diesel engines do not use high voltage spark ignition (spark plugs). An engine running on diesel compresses the air inside the cylinder to high pressures and temperatures (compression ratios from 14:1 to 18:1 are common in current diesel); the diesel is generally injected directly into the cylinder, starting a few degrees before top dead center (TDC) and continuing during the combustion event. The high temperatures inside the cylinder cause the diesel fuel to react with the oxygen in the mix (burn or oxidize), heating and expanding the burning mixture in order to convert the thermal/pressure difference into mechanical work; i.e., to move the piston. (Glow plugs are used to assist starting the engine to preheat cylinders to reach a minimum operating temperature.) High compression ratios and throttleless operation generally result in diesel engines being more efficient than many spark-ignited engines.

This efficiency and its lower flammability and explosivity than gasoline are the main reasons for military use of diesel in armoured fighting vehicles like tanks and trucks. Engines running on diesel also provide more torque and are less likely to stall as they are controlled by a mechanical or electronic governor.

A disadvantage of diesel as a vehicle fuel in some climates, compared to gasoline or other petroleum derived fuels, is that its viscosity increases quickly as the fuel's temperature decreases, turning into a non-flowing gel at temperatures as high as -19 °C (-2.2 °F) or -15 °C (5 °F), which can't be pumped by regular fuel pumps. Special low temperature diesel contains additives that keep it in a more liquid state at lower temperatures, yet starting a diesel engine in very cold weather may still pose considerable difficulties.

Another rare disadvantage of diesel engines compared to petrol/gasoline engines is the possibility of runaway failure. Since diesel engines do not require spark ignition, they can sustain operation as long as diesel fuel is supplied. Fuel is typically supplied via a fuel pump. If the pump breaks down in an "open" position, the supply of fuel will be unrestricted and the engine will runaway and risk terminal failure.

Use as car fuel

Diesel-powered cars generally have a better fuel economy than equivalent gasoline engines and produce less greenhouse gas emission. Their greater economy is due to the higher energy per-litre content of diesel fuel and the intrinsic efficiency of the diesel engine. While petrodiesel's higher density results in higher greenhouse gas emissions per litre compared to gasoline, the 20–40% better fuel economy achieved by modern diesel-engined automobiles offsets the higher per-litre emissions of greenhouse gases, and a diesel-powered vehicle emits 10-20 percent less greenhouse gas than comparable gasoline vehicles. Biodiesel-powered diesel engines offer substantially improved emission reductions compared to petro-diesel or gasoline-powered engines, while retaining most of the fuel economy advantages over conventional gasoline-powered automobiles. However, the increased compression ratios mean that there are increased emissions of oxides of nitrogen (NO_x) from diesel engines. This is compounded by biological nitrogen in biodiesel to make NO_x emissions the main drawback of diesel versus gasoline engines.

Reduction of sulfur emissions

In the past, diesel fuel contained higher quantities of sulfur. European emission standards and preferential taxation have forced oil refineries to dramatically reduce the level of sulfur in diesel fuels. In the United States, more stringent emission standards have been adopted with the transition to ULSD starting in 2006 and becoming mandatory on June 1, 2010. U.S. diesel fuel typically also has a lower cetane number (a measure of ignition quality) than European diesel, resulting in worse cold weather performance and some increase in emissions.

Environment hazards of sulfur

High levels of sulfur in diesel are harmful for the environment because they prevent the use of catalytic diesel particulate filters to control diesel particulate emissions, as well as more advanced technologies, such as nitrogen oxide (NO_x) adsorbers (still under development), to reduce emissions. Moreover, sulfur in the fuel is oxidized during combustion, producing sulfur dioxide and sulfur trioxide, that in presence of water rapidly convert to sulfuric acid, one of the chemical processes that results in acid rain. However, the process for lowering sulfur also reduces the lubricity of the fuel, meaning that additives must be put into the fuel to help lubricate engines. Biodiesel and biodiesel/petrodiesel blends, with their higher lubricity levels, are increasingly being utilized as an alternative. The U.S. annual consumption of diesel fuel in 2006 was about 190 billion litres (42 billion imperial gallons or 50 billion US gallons).

Chemical composition

Diesel is immiscible with water.

Petroleum-derived diesel is composed of about 75% saturated hydrocarbons (primarily paraffins including *n*, *iso*, and cycloparaffins), and 25% aromatic hydrocarbons (including naphthalenes and alkylbenzenes). The average chemical formula for common diesel fuel is $C_{12}H_{23}$, ranging approximately from $C_{10}H_{20}$ to $C_{15}H_{28}$.

Algae, microbes, and water contamination

There has been much discussion and misunderstanding of algae in diesel fuel. Algae need light to live and grow. As there is no sunlight in a closed fuel tank, no algae can survive. But some microbes can survive and feed on the diesel fuel.

These microbes form a colony that lives at the interface of fuel and water. They grow quite fast in warmer temperature. They can even grow in cold weather when fuel tank heaters are installed. Parts of the colony can break off and clog the fuel lines and fuel filters.

Road hazard

Petrodiesel spilled on a road will stay there until washed away by sufficiently heavy rain, whereas gasoline will quickly evaporate. After the light fractions have evaporated, a greasy slick is left on the road which can destabilize moving vehicles. Diesel spills severely reduce tire grip and traction, and have been implicated in many accidents. The loss of traction is similar to that encountered on black ice. Diesel slicks are especially dangerous for two-wheeled vehicles such as motorcycles.

Synthetic diesel

Synthetic diesel can be produced from any carbonaceous material. This include biomass, biogas, natural gas, coal and many others. The raw material is gasified into synthesis gas which after purification is converted by the Fischer-Tropsch process to a synthetic diesel.

The process is typically referred to as biomass-to-liquid (BTL), gas-to-liquid (GTL) or Coal-to-liquid (CTL) depending on the raw material used.

Paraffinic synthetic diesel generally have a near zero content of sulfur and very low aromatics content, reducing unregulated emissions of toxic hydrocarbons, emissions of nitrous oxides and emissions of PM.

FAME

Biodiesel made from soybean oil

Fatty-acid methyl ester or FAME, perhaps more widely known as biodiesel is obtained from vegetable oil or animal fats (bio-lipids) which have been transesterified with methanol. It can be produced from many types of oils, the most common being rapeseed oil (rapeseed methyl ester, RME) in Europe and soybean oil (soya methyl ester, SME) in USA. Methanol can also be replaced with ethanol for the transesterification process, which result in the production of ethyl esters. The transesterification process use a catalyst such as sodium or potassium hydroxide to convert vegetable oil and methanol into FAME and the undesirable byproducts glycerine and water which will need to be removed from the fuel along with methanol traces. As it is uneconomical to produce FAME it is dependant on subsidies to compete with fossil diesel. FAME can be used pure (B100) in engines where the manufacturer approves such use but it is more often used as a mix with diesel, BXX where XX is the biodiesel content in percent.

FAME as a fuel is regulated under DIN EN 14214 and ASTM D6751.

FAME has a lower energy content than diesel due to its oxygen content and as a result performance and fuel consumption can be affected. It also cause higher levels of NOx emissions which mean those can exceed the legal limit. FAME also has lower oxidation stability than diesel, and it offers favorable conditions for bacterial growth, so applications which have a low fuel turnover should not use FAME. The loss in power when using pure biodiesel is 5 to 7%.

Fuel equipment manufacturers (FIE) have raised several concerns of the following characters regarding FAME fuels: free methanol, dissolved and free water, free glycerin, mono and diglycerides, free fatty acids, total solid impurity levels, alkaline metal compounds in solution and oxidation and thermal stability. They have also identified the fuel being the cause of the following problems: corrosion of fuel injection components, low pressure fuel system blockage, increased dilution and polymerization of engine sump oil, pump seizures due to high fuel viscosity at low temperature, increased injection pressure, elastomeric seal failures and fuel injector spray blockage.

Unsaturated fatty acids are the source for the lower oxidation stability, they react with oxygen and form peroxides and result in degradation byproducts which can cause sludge and lacquer in the fuel system.

As FAME contain low levels of sulfur, the emissions of sulfur oxides and sulfates, major components of acid rain, are low. Use of biodiesel also results in reductions of unburned hydrocarbons, carbon monoxide (CO), and particulate matter. Carbon monoxide emissions using biodiesel are substantially reduced, on the order of 50% compared to most petrodiesel fuels. The exhaust emissions of particulate matter from biodiesel have been found to be 30 percent lower than overall particulate matter emissions from petrodiesel. The exhaust emissions of total hydrocarbons (a contributing factor in the localized formation of smog and ozone) are up to 93 percent lower for biodiesel than diesel fuel.

Biodiesel also may reduce health risks associated with petroleum diesel. Biodiesel emissions showed decreased levels of PAH and nitrited PAH compounds which have been identified as potential cancer causing compounds. In recent testing, PAH compounds were reduced by 75 to 85 percent, except for benz(a)anthracene, which was reduced by roughly 50 percent. Targeted nPAH compounds were also reduced dramatically with biodiesel fuel, with 2-nitrofluorene and 1-nitropyrene reduced by 90 percent, and the rest of the nPAH compounds reduced to only trace levels.

Hydrogenated oils and fats

This is a category of diesel fuels which involve converting the triglycerides in vegetable oil and animal fats into alkanes by refining and hydrogenation. The produced fuel has many properties that are similar to synthetic diesel, and are free from the many disadvantages of FAME.

DME

DME, dimethylether, is a synthetic gaseous diesel fuel that result in clean combustion with very little soot and reduced NOx emissions.

Transportation and storage

Diesel fuel is widely used in most types of transportation. The gasoline-powered passenger automobile is the major exception.

Railroad

Diesel displaced coal and fuel oil for steam power vehicles in the latter half of the 20th century, and is now used almost exclusively for combustion engine of self-powered rail vehicles (locomotives and railcars).

Aircraft

The first diesel-powered flight of a fixed wing aircraft took place on the evening of September 18, 1928, at the Packard Motor Company proving grounds at Utica, USA with Captain Lionel M. Woolson and Walter Lees at the controls (the first "official" test flight was taken the next morning). The engine was designed for Packard by Woolson and the aircraft was a Stinson SM1B, X7654. Later that year, Charles Lindbergh flew the same aircraft. In 1929 it was flown 621 miles (999 km) non-stop from Detroit to Langley, Virginia (near Washington, D.C.). This aircraft is now owned by Greg Herrick and is at the Golden Wings Flying Museum nearby Minneapolis, Minnesota. In 1931, Walter Lees and Fredrick Brossy set the non-stop flight record flying a Bellanca powered by a Packard diesel for 84 hours and 32 minutes. The Hindenburg rigid airship was powered by four 16-cylinder diesel engines, each with approximately 1,200 horsepower (890 kW) available in bursts, and 850 horsepower (630 kW) available for cruising. Modern diesel engines for propellor-driven aircraft are manufactured by Thielert Aircraft Engines and SMA. These engines can run on Jet A fuel, which is similar in composition to automotive diesel and cheaper and more plentiful than the 100 octane low-lead gasoline (avgas) used by the majority of the piston-engine aircraft fleet.

The most-produced aviation diesel engine in history has been the Junkers Jumo 205, which, along with its similar developments from the Junkers Motorenwerke, had approximately 1000 examples of the unique opposed piston, two-stroke design power plant built in the 1930s leading into World War II in Germany.

Storage

Unlike kerosene and gasoline, which are typically kept in blue and red containers respectively, it is recommended that diesel be stored in a yellow container.

Other uses

Poor quality (high sulfur) diesel fuel has been used as a palladium extraction agent for the liquid-liquid extraction of this metal from nitric acid mixtures. Such use has been proposed as a means of separating the fission product palladium from PUREX raffinate which comes from used nuclear fuel. In this system of solvent extraction, the hydrocarbons of the diesel act as the diluent while the dialkyl sulfides act as the extractant. This extraction operates by a solvation mechanism. So far, neither a pilot plant nor full scale plant has been constructed to recover palladium, rhodium or ruthenium from nuclear wastes created by the use of nuclear fuel.

Health effects

Diesel exhaust containing soot and fine particles from a truck starting its engine

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 combustion exhaust is a major source of atmospheric soot and fine particles, which is a fraction of air pollution implicated in human heart and lung damage. Diesel exhaust also contains nanoparticles.

While the study of nanoparticles and nanotoxicology is still in its infancy, the full health effects from nanoparticles produced by all types of diesel are unknown. It is already clear enough, however, that the health detriments of fine particle emissions are severe and pervasive. Although one study found no significant evidence that short term exposure to diesel exhaust results in adverse extra-pulmonary effects, effects that are often correlated with an increase in cardiovascular disease, a 2011 study in *The Lancet* concluded that traffic exhaust is the single most serious preventable cause of heart attack in the general public, the cause of 7.4% of all attacks.

It should be noted that the types and quantities of nanoparticles can vary according to operating temperatures and pressures, presence of an open flame, fundamental fuel type and fuel mixture, and even atmospheric mixtures. As such, the resulting types of nanoparticles from different engine technologies and even different fuels are not necessarily comparable. In general, the usage of biodiesel and biodiesel blends results in decreased pollution. One study has shown that the volatile component of 95% of diesel nanoparticles is unburned lubricating oil. Long term effects still need to be further clarified, as well as the effects on susceptible groups of people with cardiopulmonary diseases. The 2011 Lancet study noted that, apart from direct traffic pollution, "... air pollution is an important trigger of MI ... ". The study found that a difference of 30 microg/m3 in PM10 increased heart attacks by 4.8%.

Taxation

Diesel fuel is very similar to heating oil which is used in central heating. In Europe, the United States, and Canada, taxes on diesel fuel are higher than on heating oil due to the fuel tax, and in those areas, heating oil is marked with fuel dyes and trace chemicals to prevent and detect tax fraud. Similarly, "untaxed" diesel (sometimes called "off road diesel") is available in some countries for use primarily in agricultural applications such as fuel for tractors, recreational and utility vehicles or other non-commercial vehicles that do not use public roads. Additionally, this fuel may have sulphur levels that exceed the limits for road use in some countries (e.g. USA).

This untaxed diesel is dyed red for identification, and should a person be found to be using this untaxed diesel fuel for a typically taxed purpose (such as "over-the-road", or driving use), the user can be fined (e.g. US$10,000 in the USA). In the United Kingdom, Belgium and the Netherlands it is known as red diesel (or **gas oil**), and is also used in agricultural vehicles, home heating tanks, refrigeration units on vans/trucks which contain perishable items such as food and medicine and for marine craft. Diesel fuel, or marked gas oil is dyed green in the Republic of Ireland and Norway. The term **DERV** ("diesel engined road vehicle") is used in the UK as a synonym for unmarked road diesel fuel. In India, taxes on diesel fuel are lower than on petroleum, as the majority of the transportation that transports grains and other essential commodities across the country runs on diesel.

In some countries, such as Germany and Belgium, diesel fuel is taxed lower than petrol (gasoline) (typically around 20% lower), but the annual vehicle tax is higher for diesel vehicles than for petrol vehicles. This gives an advantage to vehicles that travel longer distances (which is the case for trucks and utility vehicles) because the annual vehicle tax depends only on engine displacement, not on distance driven. The point at which a diesel vehicle becomes less expensive than a comparable petroleum vehicle is around 20,000 km a year (12,500 miles per year) for an average car. However, due to the recent rise in oil prices, the advantage point is becoming lower, resulting in more people opting to buy a diesel car where they would have opted for a gasoline car a few years ago. Such an increased interest in diesel has resulted in slow but steady "dieseling" of the automobile fleet in the countries affected, sparking concerns in certain authorities about the negative effects of diesel.

Taxes on biodiesel in the U.S. vary among states, and in some states (Texas, for example) have no tax on biodiesel and a reduced tax on biodiesel blends equivalent to the amount of biodiesel in the blend, so that B20 fuel is taxed 20% less than pure petrodiesel. Other states, such as North Carolina, tax biodiesel (in any blended configuration) the same as petrodiesel, although they have introduced new incentives to producers and users of all biofuels.