



*Research Paper*

## DIESEL ENGINES DEVELOPMENT

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The Bureau of Mines is endeavoring to reduce waste and increase efficiency in the production, refining, and utilization of petroleum. During the last few year the demand for petroleum and its products has increased so much more rapidly than the production that greater efficiency in utilization is now a matter of most serious importance. The Diesel engine, a comparatively new type of internal-combustion engine, is an important device for insuring more efficient utilization of petroleum and coal-tar products, for it consumes heavy liquid fuels such as can not be utilized in other types. Like the gas or the gasoline engine, it is revolutionary within its province. For some uses this engine is replacing gas and gasoline engines, but its most important duty will be to replace the wasteful consumption of fuel oil in steam engines. Not only will a wider use of the Diesel engine relieve the demand, but it will result in more power being obtained from the same consumption of fuel oils. In spite of these advantages, comparatively few Diesel engines are in use in the United States. In this report the author discusses recent developments in the design and construction of the Diesel engine, the fuels suitable for burning in it, and the uses to which it is particularly adapt.

Keywords: Internal combustion engine, Supercharger, Fuel injection

### INTRODUCTION

The diesel engine (also known as a compression-ignition or CI engine) is an internal combustion engine in which ignition of the fuel that has been injected into the combustion chamber is caused by the high temperature which a gas achieves (i.e., the air) when greatly compressed (adiabatic compression). Diesel engines work by compressing only the air. This increases the air temperature inside the cylinder to such a high degree that it ignites automized diesel fuel that is injected into

the combustion chamber. This contrasts with spark-ignition engines such as a petrol engine (gasoline engine) or gas engine (using a gaseous fuel as opposed to petrol), which use a spark plug to ignite an air-fuel mixture. In diesel engines, glow plugs (combustion chamber pre-warmers) may be used to aid starting in cold weather, or when the engine uses a lower compression-ratio, or both. The original diesel engine operates on the "constant pressure" cycle of gradual combustion and produces no audible knock.

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The diesel engine has the highest thermal efficiency (engine efficiency) of any practical internal or external combustion engine due to its very high expansion ratio and inherent lean burn which enables heat dissipation by the excess air. A small efficiency loss is also avoided compared to two-stroke non-direct-injection gasoline engines since unburned fuel is not present at valve overlap and therefore no fuel goes directly from the intake/injection to the exhaust. Low-speed diesel engines (as used in ships and other applications where overall engine weight is relatively unimportant) can have a thermal efficiency that exceeds 50%.

Diesel engines may be designed as either two-stroke or four-stroke cycles. 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, trucks, heavy equipment and electricity generation 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 US increased. According to the British Society of Motor Manufacturing and Traders, the EU average for diesel cars accounts for 50% of the total sold, including 70% in France and 38% in the UK.

The world's largest diesel engine is currently a Wärtsilä-Sulzer RTA96-C Common Rail marine diesel, which produces a peak power output of 84.42 MW (113,210 hp) at 102.

## HOW DIESEL ENGINES WORK

A diesel engine is a type of internal combustion engine. Combustion is another word for burning, and internal means inside, so an internal

combustion engine is simply one where the fuel is burned inside the main part of the engine (the cylinders) where power is produced. That's very different from an external combustion engine such as those used by old-fashioned steam locomotives. In a steam engine, there's a big fire at one end of a boiler that heats water to make steam. The steam flows down long tubes to a cylinder at the opposite end of the boiler where it pushes a piston back and forth to move the wheels. This is external combustion because the fire is outside the cylinder (indeed, typically 6-7 meters or 20-30 ft away). In a gasoline or diesel engine, the fuel burns inside the cylinders themselves. Internal combustion wastes much less energy because the heat doesn't have to flow from where it's produced into the cylinder: everything happens in the same place. That's why internal combustion engines are more efficient than external combustion engines (they produce more energy from the same volume of fuel).

## MODERN DIESEL ENGINE IN CARS

Diesel cars have come a long way in the last 20 years. Whereas they were once regarded as sluggish, smoky and unrefined, nowadays they offer responsive performance, refined driving dynamics and bags of power.

Even so, they need to be driven in the right way if they are to deliver their best. So here are five ways to help you coax the most from your diesel car—they could change your driving habits forever.

### Use the Torque

One of the most striking things about diesel engines in comparison to petrol units is their greater torque. This is a valuable tool when you're

Figure 1: Diesel Engine



behind the wheel, enabling you to minimize gear changes and maintain control at lower speeds.

For example, in icy or muddy conditions, you should pull off slowly, and maybe select second rather than first gear.

The engine will produce enough low-down grunt to power the wheels without you putting too much on the throttle. That makes for a more measured maneuver, thereby avoiding a wheel spin and reducing the risk of being stuck or, worse still, losing control.

Meanwhile, on the open road, the extra torque means you don't need to change gear so regularly, because the engine will pull at lower revs. This minimizes wear and tear on the power plant, transmission and running gear, and enables you to adopt a more relaxed driving style.

### Keep it Steady

"The latest common-rail direct-injection turbo diesel engines are capable of being driven at very high speeds," remarks Martin Randall, a technical author and diesel specialist at car manual

publisher Haynes. "But they aren't quite as reliable as the more basic naturally-aspirated units they've replaced."

As a result, even though modern diesel lumps can easily be driven much more enthusiastically than their wheezy antecedents, it's not clever to rag them hard.

For a start, says Mr. Randall, diesel engines rattle a lot more than petrol units, and equipment such as the electronic wizardry controlling the supply of fuel to the injectors is likely to rebel if pushed to extremes on a regular basis.

Take things steady, using the ample torque and zippy acceleration only when necessary, and you'll most likely prolong the life of your motor, as well as the cleanliness of your driving license.

### Don't Routinely Redline

Anyone who's driven a turbo diesel car will know this feeling: you're revving hard to accelerate from a junction, or to carry out an overtaking maneuver, and suddenly the engine goes completely flat.

That's because the power range in a turbo diesel is narrower than on a petrol car, meaning you can't rev it so hard for so long. More often than not, diesels are fitted with a limiter to prevent them being revved too much, and when that kicks in it's a bit like hitting a brick wall.

But there's another good reason not to thrash your turbo diesel lump, especially when it's cold. If the engine hasn't heated up sufficiently, the oil that lubricates the turbo charger won't do its job properly.

Make a habit of forcing it to spin under duress and you'll almost certainly be faced with a blown turbo. And the upshot of that is a hefty repair bill.

## Enjoy a Regular Spin

That said, there's no harm in giving your diesel car a good run out on a regular basis, especially if you tend to use it for mainly urban journeys.

Mr. Randall from Haynes explains: "Modern diesel engines are fitted with particulate filters to trap harmful emissions. These are designed to self-clean, or regenerate, at high speeds."

If you don't regularly drive your car fast enough to clean its Diesel Particulate Filter (DPF), it will become clogged with soot. That can prevent the engine from running properly, and necessitate installation of a replacement DPF. The cost of this could be as much as £1,000.

## Keep Up to Date with Maintenance

As Mr. Randall says, modern turbo diesel engines are far more complex than the rather more unrefined units they replaced. In consequence, it is important to maintain them on a regular basis.

That includes replacing oil and filters in line with manufacturer guidelines – something that is crucial to preserving the life of your car's turbo.

Old lubricant won't work effectively, and could impair your car's performance, as well as storing up mechanical problems for the future.

Moreover, it is worth paying attention to cam-belt (sometimes called timing belt) service intervals and any particular instructions regarding DPFs. Some vehicles utilize an additive to clean the DPF, and this needs topping up once the car has covered a set mileage.

By ignoring such milestones, you'll seriously curtail your car's ability to achieve its potential, resulting in a disappointing driving experience and a much higher risk of large-scale repairs.

## Internal Combustion Engine<sup>1</sup>

An Internal Combustion Engine (ICE) is a heat engine where the combustion of a fuel occurs with an oxidizer (usually air) in a combustion chamber that is an integral part of the working fluid flow circuit. In an internal combustion engine the expansion of the high-temperature and high-pressure gases produced by combustion applies direct force to some component of the engine. The force is applied typically to pistons, turbine blades, rotor or a nozzle. This force moves the component over a distance, transforming chemical energy into useful mechanical energy.

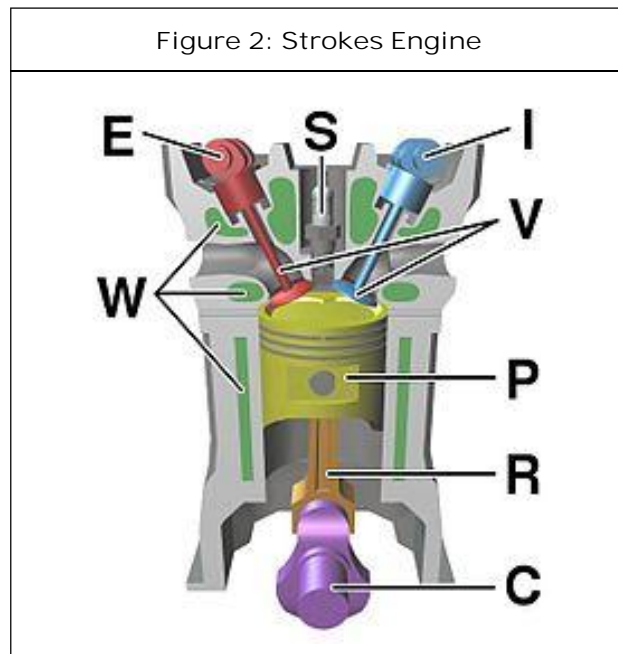
The first commercially successful internal combustion engine was created by Étienne Lenoir around 1859 and the first modern internal combustion engine was created in 1876 by Nikolaus Otto (see Otto engine).

The term internal combustion engine usually refers<sup>2</sup> to an engine in which combustion is intermittent, such as the more familiar four-stroke and two-stroke piston engines, along with variants, such as the six-stroke piston engine and the Wankel rotary engine. A second class of internal combustion engines use continuous combustion: gas turbines, jet engines and most rocket engines, each of which are internal combustion engines on the same principle as previously described. Firearms are also a form of internal combustion engine.

The Top Dead Center (TDC) of a piston is the position where it is nearest to the valves; Bottom Dead Center (BDC) is the opposite position where it is furthest from them. A stroke is the movement of a piston from TDC to BDC or vice versa together with the associated process. While an engine is in operation the crankshaft rotates

<sup>1</sup> Encyclopedia Britannica. Britannica.com. Retrieved 2012-03-20.

<sup>2</sup> Pulkrabek Willard W (1997), Engineering Fundamentals of the Internal Combustion Engine, Prentice Hall, p. 2.



continuously at a nearly constant speed. In a 4-stroke ICE each piston experiences 2 strokes per crankshaft revolution in the following order. Starting the description at TDC.

**Intake, Induction or Suction:** The intake valves are open as a result of the cam lobe pressing down on the valve stem. The piston moves downward increasing the volume of the combustion chamber and allowing air to enter in the case of a CI engine or an air fuel mix in the case of SI engines that do not use direct injection. The air or air-fuel mixture is called the charge in any case.

**Compression:** In this stroke, both valves are closed and the piston moves upward reducing the combustion chamber volume which reaches its minimum when the piston is at TDC. The piston performs work on the charge as it is being compressed; as a result its pressure, temperature and density increase; an approximation to this behavior is provided by the ideal gas law. Just before the piston reaches TDC, ignition begins. In the case of a SI engine,

the spark plug receives a high voltage pulse that generates the spark which gives it its name and ignites the charge. In the case of a CI engine the fuel injector quickly injects fuel into the combustion chamber as a spray; the fuel ignites due to the high temperature.

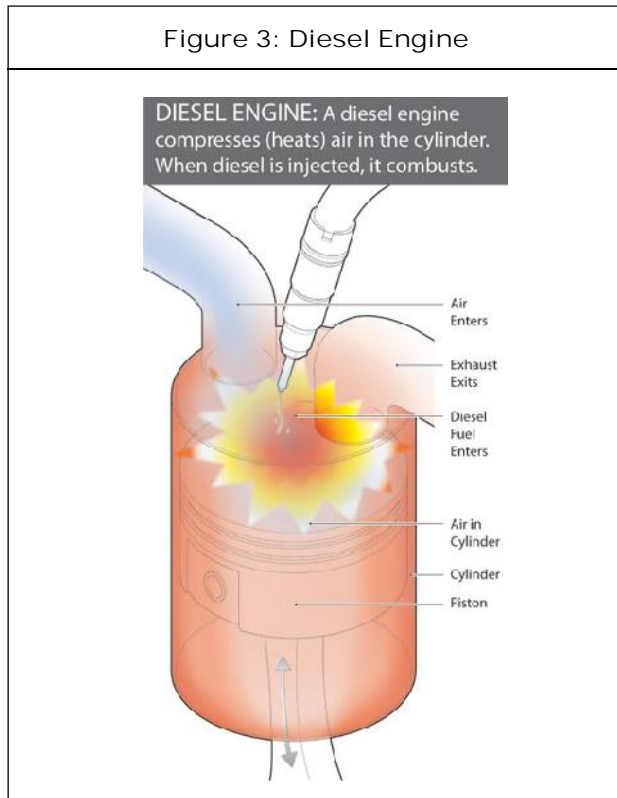
**Power or Working Stroke:** The pressure of the combustion gases pushes the piston downward, generating more work than it required to compress the charge. Complementary to the compression stroke, the combustion gases expand and as a result their temperature, pressure and density decreases. When the piston is near to BDC the exhaust valve opens. The combustion gases expand irreversibly due to the leftover pressure—in excess of back pressure, the gauge pressure on the exhaust port—; this is called the blowdown.

**Exhaust:** The exhaust valve remains open while the piston moves upward expelling the combustion gases. For naturally aspirated engines a small part of the combustion gases may remain in the cylinder during normal operation because the piston does not close the combustion chamber completely; these gases dissolve in the next charge. At the end of this stroke, the exhaust valve closes, the intake valve opens, and the sequence repeats in the next cycle. The intake valve may open before the exhaust valve closes to allow better scavenging.

### Diesel Engine Exhaust After-Treatment Systems

What is an After-treatment System?

- A system that treats post-combustion exhaust gases prior to tailpipe emission.
- Differs from emission reduction techniques in the combustion process.



- Allows for greater power from the engine without worrying about emissions increasing.
- Higher energy density per unit volume of fuel than gasoline.
- 147,000 BTU in diesel versus 125,000 BTU in gasoline.
- Fuel economies of up to 45 MPG.
- Higher torque for similar sized engines.
- Greater compression ratios than gasoline.
- Exhaust pollution can be mitigated by modern technologies.
- Solution for decreasing Western gasoline demands.
- Including passenger cars.

**Regulation Background**

- Clean Air Act of 1963: First government look into stationary emissions.

- Clean Air Act 1970: Regulation of 6 criteria pollutants.
- CO, SOx, NOx, Hydrocarbons, Ozone and Particulate Matter.
- Clean Air Act of 1990: Acid rain control plus 189 secondary pollutants.
- Since then, numerous periodic reductions.
- Ultra-Low Sulfur Diesel (ULSD) mandatory 2007.

EGR – Exhaust Gas Recirculation

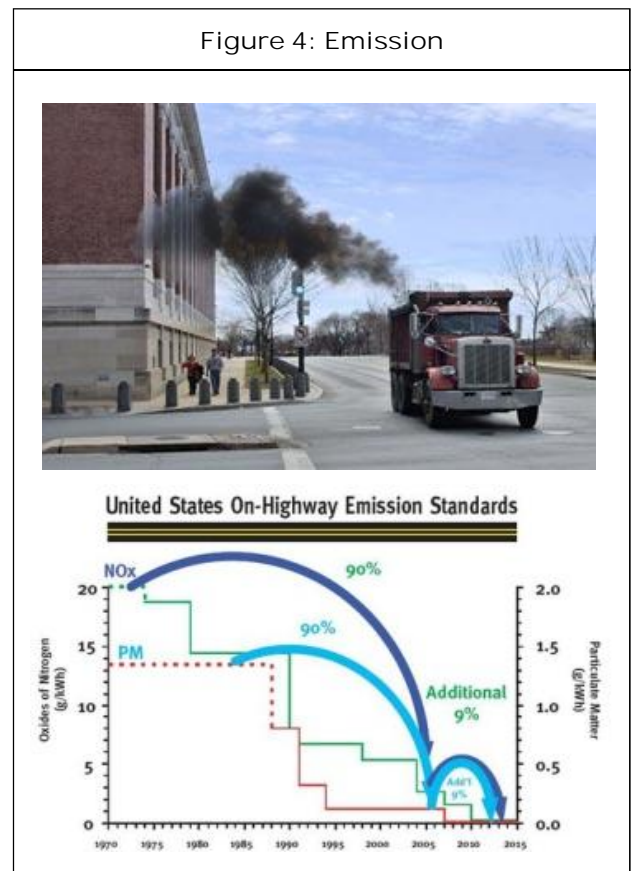
DOC – Diesel Oxidation Catalyst

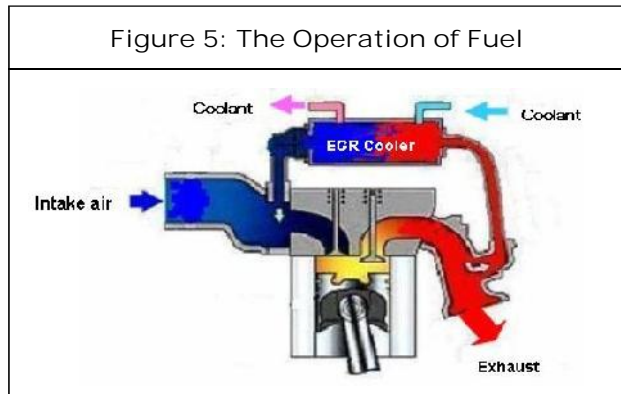
DPF – Diesel Particulate Filter

DRT – Decomposition Reaction Tube

SCR – Selective Catalytic Reduction

DEF – Diesel Exhaust Fluid (Urea)

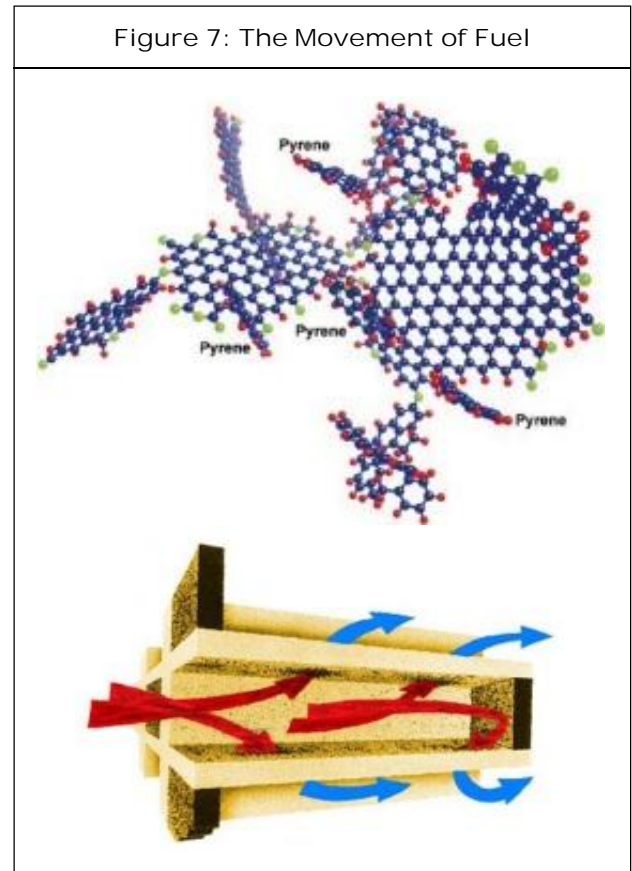
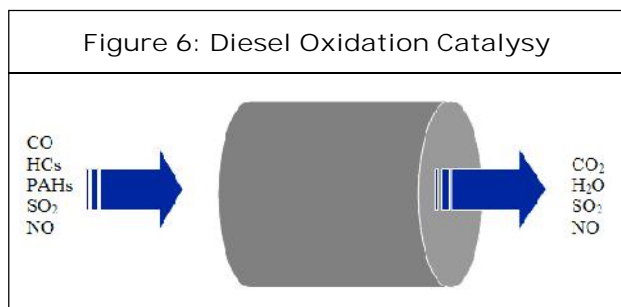




- A portion of exhaust stream gets recycled back into the combustion chambers.
- Low oxygen makes this function as an inert gas.
- Reduces engine operating temperatures to decrease NO<sub>x</sub> formation.
- At high temperatures:  $O_2 + N_2 \rightarrow NO + NO_2$

**Diesel Oxidation Catalyst (DOC)**

- Platinum group metals catalyze the complete oxidation of unburnt hydrocarbons to CO<sub>2</sub>.
- Reactions heat exhaust gases up to temperatures in excess of 450 °C.
- Catalyst material coats flow channel matrix
- Channels are a ceramic honeycomb.
- Very efficient catalysis (Upwards of 90% conversion to oxidized products).
- Alternating plugged channels force exhaust to flow through cordierite walls, which traps the soot.



- Soot is a complex linked carbon structure which is a combustion byproduct.
- Soot reduction can approach 100% efficiency with full DPF's.
- Trapped soot is periodically burnt off through a regeneration event.

**Active Regeneration**

- Fuel is injected into the After-treatment system, combusts in the DOC, and this 800° exhaust is able to fully oxidize the soot.

**Passive Regeneration**

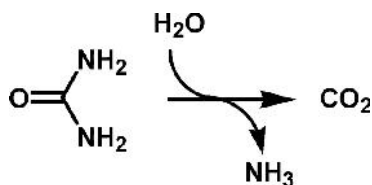
- $NO_2 + C(s) \rightarrow CO_2 + NO$ .
- Catalyzed filter elements allow for exhaust NO<sub>2</sub> to oxidize soot.
- Requires hot temperatures such as highway driving to function.



Figure 8: Run Emission Free



- Urea is injected after the DPF onto a special mixing plate.
- Hot exhaust gas breaks urea into ammonia.
- Side reactions sometimes form solid deposits of aromatic cyclic rings
- These deposits can block exhaust flow.



Gasoline engines and diesel engines both work by internal combustion, but in slightly different ways. In a gasoline engine, fuel and air is injected into small metal cylinders. A piston compresses (squeezes) the mixture, making it explosive, and

a small electric spark from a sparking plug sets fire to it. That makes the mixture explode, generating power that pushes the piston down the cylinder and (through the crankshaft and gears) turns the wheels. You can read more about this and watch a simple animation of how it works in our article on car engines.

Diesel engines are similar, but simpler. First, air is allowed into the cylinder and the piston compresses it—but much more than in a gasoline engine. In a gasoline engine, the fuel-air mixture is compressed to about a tenth of its original volume. But in a diesel engine, the air is compressed by anything from 14 to 25 times. If you’ve ever pumped up a bicycle tire, you’ll have felt the pump getting hotter in your hands the longer you used it. That’s because compressing a gas generates heat. Imagine, then, how much heat is generated by forcing air into 14-25 times less space than it normally takes up. So much heat, as it happens, that the air gets really hot—usually at least 500 °C (1000 °F) and sometimes very much hotter. Once the air is compressed, a mist of fuel is sprayed into the cylinder typically (in a modern engine) by an electronic fuel-injection system, which works a bit like a sophisticated aerosol can. (The amount of fuel injected varies, depending on how much power the driver wants the engine to produce). The air is so hot that the fuel instantly ignites and explodes without any need for a spark plug. This controlled explosion makes the piston push back out of the cylinder, producing the power that drives the vehicle or machine in which the engine is mounted. When the piston goes back into the cylinder, the exhaust gases are pushed out through an exhaust valve and, the process repeats itself—hundreds or thousands of times a minute!

## What Makes a Diesel Engine More Efficient?

In theory, spark-plug gasoline engines should be more efficient than diesel engines. In practice, the reverse is true: diesel engines are up to twice as efficient as gasoline engines—around 40% efficient, that is. In simple terms, that means you can go much further on the same amount of fuel (or get more miles for your money). There are several reasons for this. First, the lack of a sparking-plug ignition system makes for a simpler design that can easily compress the fuel much more—and compressing the fuel more makes it burn more completely with the air in the cylinder, releasing more energy. There's another efficiency saving too. In a gasoline engine that's not working at full power, you need to supply more fuel (or less air) to the cylinder to keep it working; diesel engines don't have that problem so they need less fuel when they're working at lower power. Another important factor is that diesel fuel carries slightly more energy per gallon than gasoline because the molecules it's made from have more energy locking their atoms together (in other words, diesel has a higher energy density than gasoline). Diesel is also a better lubricant than gasoline so a diesel engine will naturally run with less friction.

## How is Diesel Fuel Different?

Diesel and gasoline are quite different. You'll know this much if you've ever heard the horror stories of people who've filled up their car or truck with the wrong sort of fuel! Essentially, diesel is a lower-grade, less-refined product of petroleum made from heavier hydrocarbons (molecules built from more carbon and hydrogen atoms). Crude diesel engines that lack sophisticated fuel injection systems can, in theory, run on almost any hydrocarbon fuel—hence the popularity of biodiesel (a type of biofuel made from, among

Figure 9: Green Grease Machine



other things, waste vegetable oil). The inventor of the diesel engine, Rudolf Diesel, successfully ran his early engines on peanut oil and thought his engine would do people a favor by freeing them from a dependency on fuels like coal and gasoline. If only he'd known!

**Photo:** Have grease will travel: Joshua and Kaia Tickell, a couple of environmentalists, use this trailer (the Green Grease Machine) to make biodiesel fuel for their van (attached to the front) using waste cooking oil thrown out by fast food restaurants. The fuel costs an impressive \$0.80 per gallon. Photo by Warren Gretz courtesy of US Department of Energy/National Renewable Energy Laboratory (DOE/NREL).

## Advantages and Disadvantages of Diesel Engines

Diesels are the most versatile fuel-burning engines in common use today, found in everything from trains and cranes to bulldozers and submarines. Compared to gasoline engines, they're simpler, more efficient, and more economical. They're also safer, because diesel fuel is less volatile and its vapor less explosive

Figure 10: Engines



than gasoline. Unlike gasoline engines, they're particularly good for moving large loads at low speeds, so they're ideal for use in freight-hauling ships, trucks, buses, and locomotives. Higher compression means the parts of a diesel engine have to withstand far greater stresses and strains than those in a gasoline engine. That's why diesel engines need to be stronger and heavier and why, for a long time, they were used only to power large vehicles and machines. While this may seem a drawback, it means diesel engines are typically more robust and last a lot longer than gasoline engines.

**Photo:** Diesel engines aren't just used in vehicles: these huge stationary diesel engines generate electricity in a power plant on San Clemente Island. Photo by Warren Gretz courtesy of US Department of Energy/National Renewable Energy Laboratory (DOE/NREL).

Pollution is one of the biggest drawbacks of diesel engines: they're noisy and they produce a lot of unburned soot particles, which are dirty and hazardous to health. In theory, diesels are more efficient, so they should use less fuel, produce

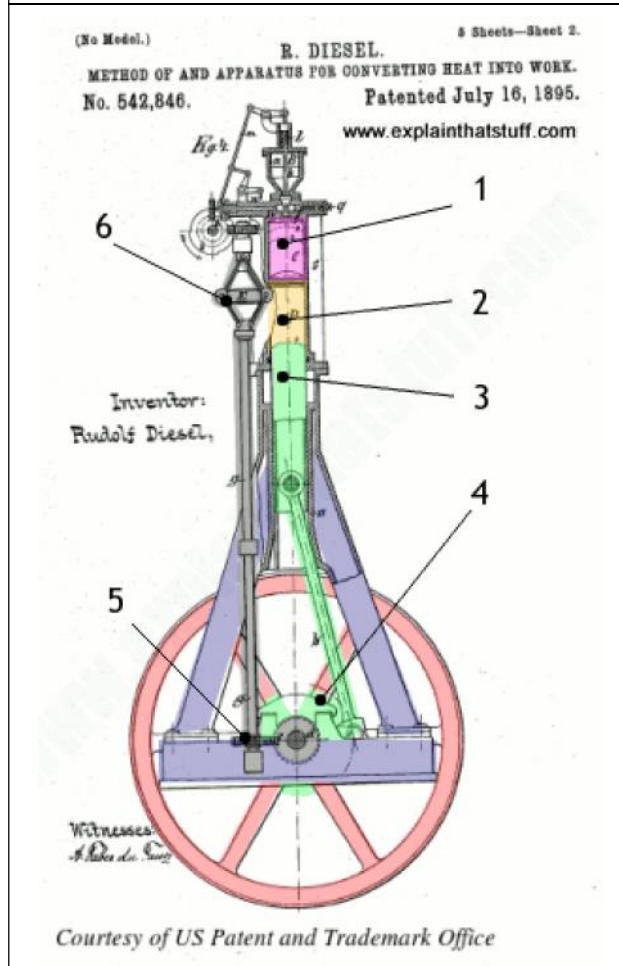
fewer carbon dioxide emissions, and contribute less to global warming. In practice, there's some argument over whether that's really true. Some laboratory experiments have shown average diesel emissions are only slightly lower than those from gasoline engines, although manufacturers insist that if similar diesel and gasoline cars are compared, the diesels do indeed come out better. According to the British Society of Motor Manufacturers and Traders: "Diesel cars have contributed massively to reducing CO<sub>2</sub> emissions. Since 2002, buyers choosing diesel have saved almost 3 million tons of CO<sub>2</sub> from going into the atmosphere." Diesel engines do tend to cost more initially than gasoline engines, though their lower running costs and longer operating life generally offsets that.

There's no question that diesel engines will continue to power heavy vehicles, but their future in cars and lighter vehicles is becoming increasingly uncertain. The push toward electric cars has provided a powerful impetus to make gasoline engines lighter, more economical, and less polluting, and these improved gas engines undermine some of the perceived advantages of using diesels in cars. In the growing competition between affordable electric vehicles and improved gasoline cars, diesels may find themselves squeezed out altogether. Then again, diesels themselves are constantly evolving; in 2011, the US Department of Energy predicted that future engines could rise in efficiency from today's 40% to 60% or more. If that happens, diesel will remain a contender for many years to come.

### Who Invented the Diesel Engine?

From the above, we conclude that the main objective of the new technology is to achieve a better tool on the amount of gases released less.

Figure 11: Rudolf Diesel's Original Internal Combustion Engine, as He Drew it in his 1895 Patent



Note: The cylinder (1) is at the top. 2) A “plunger” (as Diesel referred to it) is attached by a crank and connecting rod (3) to a flywheel (4). A gear driven by the flywheel (5) is attached to a centrifugal governor (6) that keeps the engine speed constant (shutting off the fuel supply if the engine runs too fast, then switching it back on when the engine slows down again). Artwork courtesy of US Patent and Trademark Office (with colors and numbering added by us to simplify the explanation). You can read more in US Patent #542,846: Method of and apparatus for converting heat into work by Rudolf Diesel.

The realization of this goal is clearly the responsibility of the research and development groups of diesel engine manufacturers.

Esco Forenin, general manager of Finnish company Wartisla, summarizes the trends in new technologies, saying his company is

currently a trial engine with a combined cycle that aims to achieve high returns, which could reach 55% by fuel oil. The project depends on what is known as “hot combustion technology” where the temperature of the exhaust gases that will generate steam in the next part of the cycle will rise for use in the steam turbine.

Similar trends exist in companies manufacturing diesel engines. Caterpillar has increased its R&D allocations and is seeking to develop a new fuel injection system that will reduce engine noise.

Agrico launched in 1996 its green energy generators, which are characterized by quiet operation, high reliability, advanced control and good training for the crew to maintain equipment in perfect condition, minimizing the engine's environmental impact.

Temporary capacity, temporary receiver!

One important issue for governments and the energy industry of this century will be how to provide equal access to electricity for urban and rural populations. According to a recent World Bank report, there are about one billion people without access to electricity in the world. This suggests that the current temporary trend will increase the demand for diesel engines tremendously in developing countries, because some of the linking of remote villages to the power grid is economically unjustified.

But when we get to recharge remote areas with electric power, diesel engines are in a race with renewable energy sources: solar cells, wind, solar, biomass and geothermal energy, which increased the options available to governments to feed off-grid payloads.

Any alternative solution could exceed the need to import expensive fuel and the use of domestic resources will inevitably lead to the use of diesel engines available in rural areas.

But the issue will not end there. Progress in the field of fuel science will allow access to everything the diesel engine can offer by developing a plant with multiple forms of fuel using hybrid generators: diesel/gas or diesel/solar cells. In the Japanese island of Myaku, a hybrid diesel-solar power generation hybrid system has demonstrated its effectiveness in providing energy to isolated rural communities. Okinawa Electric, which has financed the project for two and a half years, has concluded that diesel/solar co-generation is expected to spread to isolated islands and villages as an energy source and thus displace diesel engines. Other potential applications include non-electrified villages, which are remote from public electricity networks in developing countries.

## CONCLUSION

The US Department of Energy has tested similar systems to replace diesel engines in Alaska, which still require small, sprawling power plants below 20 megawatts, in many of its small towns and rural communities. If we take these ideas as an indicator of future trends, it illuminates the new way a diesel engine should go if it wants to continue to compete in this century. In the opinion of Okinawa Electric, which reached this bold conclusion, first efforts should be made to improve the cost and reduce costs.

Apparently, the demand for diesel engines used for power generation will continue in the near future, especially as the cost of energy technology, many of which are still in the testing phase, high while fuel prices remain low. In the longer term,

the global trend towards global economic liberalization promises a good future for diesel-powered power plants.

Over the next few years, experts do not expect a drop in demand for diesel-powered power generating sets, especially as demand for electricity exceeds the capacity of generators operating in many countries of the world. The problem is compounded by the sharp decline in power plant capacity due to rain, Repeated droughts and shrinking dam construction projects. In addition, many thermal power plants are outdated and require drastic treatment in the near future. All this will fuel demand for temporary energy sources.

From the above it is clear that the electricity generation market in diesel has a great opportunity to gain as a result of the opening of electricity markets to free competition. At the same time, environmentalists now hope that competition in European electricity generation will stimulate innovation, invention and investment in cleaner and more efficient generation plants.

Diesel engine manufacturers are keen to prove their presence and are at the level of challenges by doubling their research and development programs. Their biggest challenge is to keep the Rodolf Diesel engine rotten for the next 100 years.

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