

The Evolution of Diesel Engines

U Shrinivasa

Rudolf Diesel thought of an engine which is inherently more efficient than the steam engines of the end-nineteenth century, for providing motive power in a distributed way. His intense perseverance, spread over a decade, led to the engines of today which bear his name.

Steam Engines: History

The origin of diesel engines is intimately related to the history of steam engines. The Greeks and the Romans knew that steam could somehow be harnessed to do useful work. The device aeolipile (*Figure 1*) known to Hero of Alexandria was a primitive reaction turbine apparently used to open temple doors! However this aspect of obtaining power from steam was soon forgotten and millennia later when there was a requirement for lifting water from coal mines, steam was introduced into a large vessel and quenched to create a low pressure for sucking the water to be pumped. Newcomen in 1710 introduced a cylinder piston arrangement and a hinged beam (*Figure 2*) such that water could be pumped from greater depths. The condensing steam in the cylinder pulled the piston down to create the pumping action.

Another half a century later, in 1765, James Watt avoided the cooling of the hot chamber containing steam by adding a separate condensing chamber (*Figure 3*). This successful steam engine pump found investors to manufacture it but the coal mines already had horses to lift the water to be pumped. Only when the manufacturers thought of installing the pumps at their own cost and settled for returns equivalent to one third the difference between the cost of fodder for the horses and coal for the pumps' boiler did the market pick up. It is a separate matter that Watt and his investors made good money.



U Shrinivasa teaches vibrations and dynamics of machinery at the Department of Mechanical Engineering, IISc. His other interests include the use of straight vegetable oils in diesel engines for sustainable development and working with CAE applications in the industries.

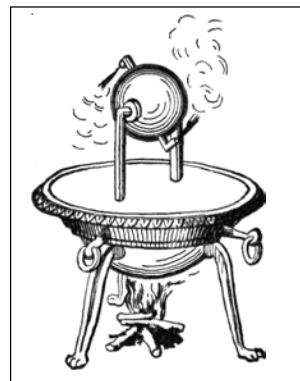


Figure 1. The aeolipile of Hero of Alexandria.

Courtesy:
http://en.wikipedia.org/wiki/File:Aeolipile_illustration.JPG

Keywords

Rudolf Diesel, steam engine, diesel engine, engine subsystems.

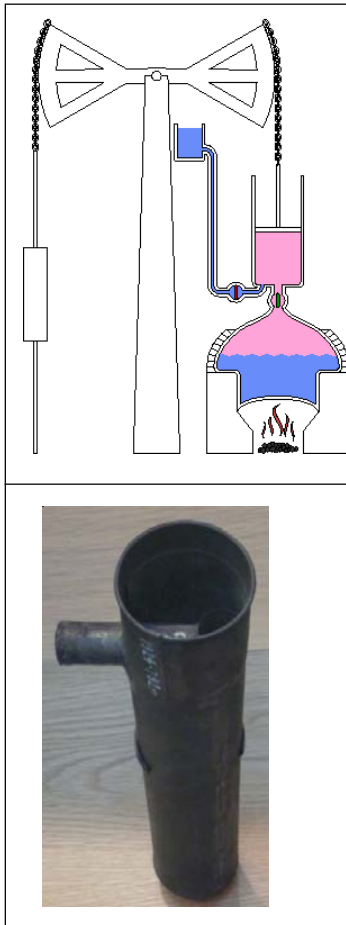


Figure 2 (top). Newcomen steam engine.

Courtesy:
http://en.wikipedia.org/wiki/Thomas_Newcomen

Figure 3 (bottom). Original condenser by Watt.

Courtesy:
http://en.wikipedia.org/wiki/File:Watts_First_Condenser.jpg

¹ See *Resonance*, Vol.6, No.11, 2001.

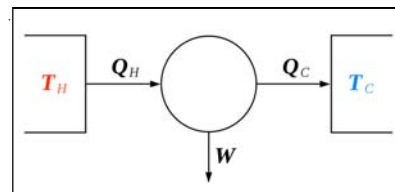
Another need arose about 50 years later. Early minable mineral deposits on the hills were already being connected to the ports via rails. Ore-laden box cars were running down the rails by gravity. However, horses were required to haul the empty cars up and to negotiate difficult gradients. Ideally, there was a requirement for a distributed source of motive power. Some skilled youngsters were building streetcars based on Watts steam engine pump. In 1814, George Stephenson was one such hobbyist. Every part of the car, from the boiler to the engine and the mechanisms had to be hand-forged. The car was too slow on the street to be of any interest and the makers just walked with it! The exhaust steam jet in the front was however, shying away the horses used by the townspeople who objected vehemently, protested and threatened to ban the cars. Disgusted with the impediments, the inventor redirected the exhaust jet upwards and he could never catch up with the car then onwards. Steam locomotives thus arrived, started hauling the railcars both up and down and railways expanded.

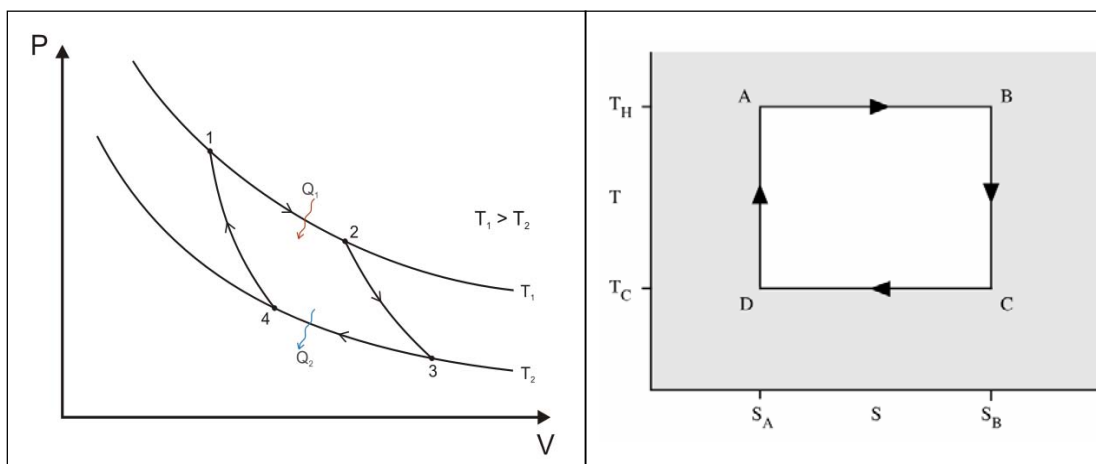
Heat Engines: Theory

The necessary theoretical framework for the design of steam engines became available in a book published by Sadi Carnot¹ in 1824. He discussed the heat engine, in actuality a thermodynamic process, receiving heat from a hot source and delivering work output, simultaneously rejecting the remaining heat to a cold source (*Figure 4*). The hot and cold reservoirs are at constant temperatures T_H and T_C . The heat engine consists of a working fluid going through a set of process steps that exchanges heat from and to the hot and cold sources respectively. One such set

Figure 4. Carnot's heat engine.

Courtesy: http://en.wikipedia.org/wiki/File:Carnot_heat_engine_2.svg





where the working fluid goes back to the initial state so that the cycle can be repeated is shown in *Figure 5*. The axes are the instantaneous pressure and volume of the working fluid, steam, gas or vapour. The equation of state, $PV = mRT$ connects the three variables P , V and T , the temperature in Kelvin, thus completely determining the state of an ideal gas. R is the universal gas constant and m is the number of kg-mole of the gas present. The cycle shown in *Figure 5* has isothermal heat exchanges with the source and the sink and the other two process steps are adiabatic. Each process step is reversible and the cycle constitutes the ideal Carnot cycle.

To know its efficiency, the process steps are shown in *Figure 6* on a temperature–entropy diagram. Since the quantity of heat transferred, Q , in a process step is given by

$$Q = \int T ds,$$

the efficiency η_{Carnot} of the Carnot cycle is given by

$$\eta_{\text{Carnot}} = 1 - (T_C/T_H).$$

Sadi Carnot showed in his book that if there is any other reversible cycle operating between T_H and T_C , its efficiency will also be equal to η_{Carnot} . Since any irreversibility would mean losses, Carnot efficiency thus becomes the maximum attainable.

Figure 5 (left). P – V diagram of Carnot's cycle.

Courtesy:
http://en.wikipedia.org/wiki/File:Carnot_cycle_p-V_diagram.svg

Figure 6 (right). Temperature-entropy diagram of the Carnot's cycle.

Courtesy:
<http://en.wikipedia.org/wiki/File:CarnotCycle1.png>

Lord Kelvin first used the word thermodynamics to describe the necessary theory to understand how steam engines worked, just about 100 years after James Watt's steam engine pump started working.

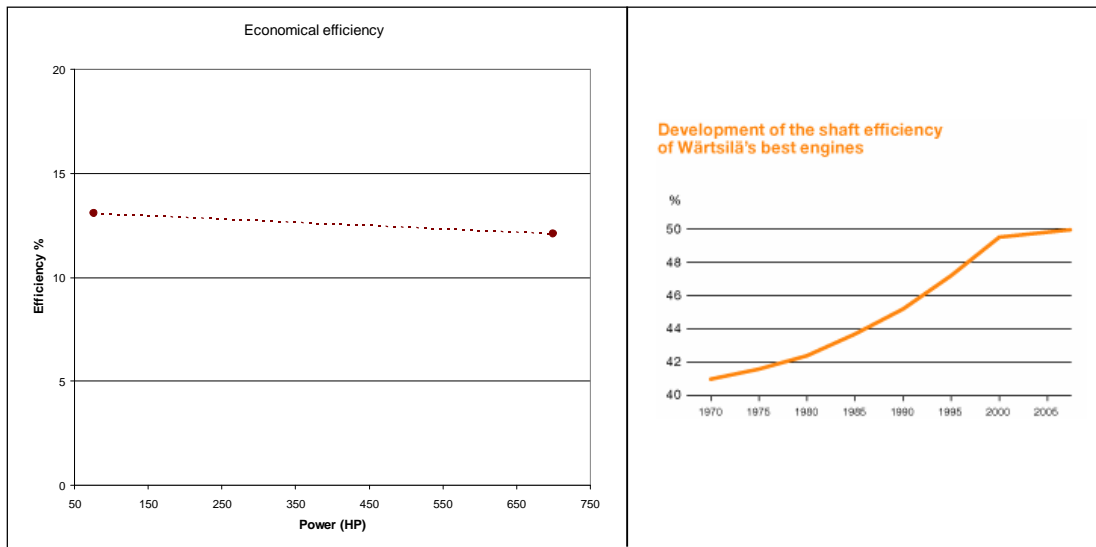
Carnot's book of 1824, *Reflections on the motive power of fire and the machines fitted to develop that power*, written in French, went unnoticed till 1834, when Émile Clapeyron discussed it in his memoirs. Rudolf Clausius read the memoirs and his later work included refining the suppositions of Carnot and developing on them to introduce the concept of entropy and arriving at a mathematical equation of the second law of thermodynamics. In fact, it was William Thomson (later Lord Kelvin) who first used the word 'thermodynamics', for the subject which described the necessary theory to understand how steam engines worked, just about 100 years after James Watt's steam engine pump started working.

Diesel Cycle: Origin

Diesel came up with a radically new alternative: burning powdered coal in the cylinder itself!

Carl von Linde, well known for his refrigeration cycle, refrigerators and separating oxygen from air, graduated in 1864 from the Swiss Federal Institute for Technology in Zurich. One of his teachers was Rudolf Clausius. von Linde, joined as lecturer in 1868 at the Technische Hochschule München (now Technical University Munich) started in that year, became a professor in 1872 and started his own department. Rudolf Diesel joined as a student in the department and studied heat engines, attending Professor Linde's lectures. Listening to his professor who had learnt thermodynamics directly from one of the originators, Rudolf Clausius, and knowing that steam engines had been a roaring commercial success for over a 100 years by then despite the poor efficiencies achieved, as he noted later in his famous presentation at Kassel (*Figure 7*), he identified the boiler as the weakest link in the chain. Therefore he came up with a radically new alternative: burning powdered coal in the cylinder itself! To achieve this objective he thought of reaching a very high pressure in the adiabatic compression leg of the Carnot cycle, a pressure so high (about 90 bar) that the coal powder (fuel) injected at that point will auto-ignite, with the temperature being around 800°C. The isothermal heat addition part of the Carnot cycle was to be achieved by regulating the fuel supply such that the cylinder material would be able to withstand the temperature. Adiabatic





expansion for the power stroke and isothermal heat rejection by exhausting to the atmosphere and taking in a fresh charge of air complete the cycle.

Assuming a $T_H = 1073$ K and $T_C = 288$ K, the Carnot efficiency exceeds 70%. With the expected friction losses Diesel hoped that an overall 50% efficiency would be achievable which was way beyond the levels in *Figure 7* for steam engines. Today's large diesel engines, generating electricity at about 80 MW levels, do achieve 50% efficiency (*Figure 8*). This marvel of an idea of Diesel looking absolutely feasible for him also convinced the leading steam engine manufacturers of the time to invest in the development of the new engine.

It is one thing to generate enough financial support for building a prototype and proving the concept to be practised and an entirely different matter to have that enormous grit and perseverance to overcome every technical hurdle until the prototype proves itself. Herein lies the real greatness of the man.

Diesel Engine: Prototype

The first prototype proved auto-ignition, his key concept, even though the cylinder blew up because of the use of gasoline. The

Figure 7 (left). Steam engine efficiencies (based on numbers presented by Diesel in his Kassel lecture).

Figure 8 (right). Engine efficiencies through the years.

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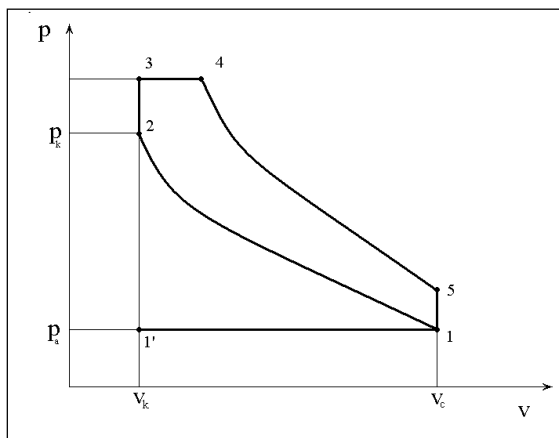


Figure 9. Seiliger cycle (mixed/ dual cycle).

Courtesy:
[http://en.wikipedia.org/wiki/
 File:Theoretical_Sabathe_process.gif](http://en.wikipedia.org/wiki/File:Theoretical_Sabathe_process.gif)

second started idling by itself. The earlier prototype was motored, i.e., the shaft was rotated using an external drive. The third could demonstrate useful indicator diagrams on loading and gave enough results to present to the Society of German Mechanical Engineers an efficiency of 26%. The original intent was obviously rationalised. The peak pressure at the end of adiabatic compression was reduced to 30 bars. Isothermal heat addition was modified to a mixed cycle, called Seiliger cycle (*Figure 9*). Coal powder

as fuel was replaced with more manageable petroleum fuel, a liquid. The success of the third prototype greatly hides the technical struggles Diesel and his collaborators had to go through. Containing the anticipated high pressure was outside the experience of the industry manufacturing steam engines. Regulation of even the liquid fuel into the cylinder was most unreliable. The problem got solved later when Robert Bosch invented his fuel injection system. Isothermal heat addition of the Carnot cycle gave very little useful work. Most importantly the process steps took place in millisecond time scales and therefore no measurements on the inside cylinder processes were possible except obtaining the indicator diagrams. This unusually successful product development is one of the rarest of the rare cases in the history of technology. Industry applauded by taking to the manufacture of diesel engines in various sizes. Many of them continue to do so to this day, more than a century later.

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Diesel Engines: Growth

The War Years saw a large number of diesel engines being manufactured in many countries. Some engines also used locally available vegetable oils as diesel substitutes to tide over shortages of petro-diesel. The possibility was foreseen by Diesel. A chance request by some French officials concerning their African colonies made the engineers in-charge of the 'diesel engine exhibit' in Paris in 1900 fuel the engine with peanut oil and the engine ran



quite well. The use of locally grown oil which could be used both as the fuel and the lubricant interested the bureaucrats. Diesel was quick to notice it and in fact predicted that his engines would continue to serve humanity long after the world runs out of petro-resources, by using the energy captured from the Sun by agricultural crops and stored in the seeds as oils.

In the 1950s, experimental engines fitted with quartz windows and high speed photography could actually show the diesel spray burning in the cylinder. Advancing data processing machines, now called computers, could be used to simulate the air-cycle in the cylinder for the first time in the mid 1960s. Advancing computational fluid dynamics (CFD), combustion simulation and multi-species reaction chemistry are serving useful purposes in engine design but are still far from predicting pollution levels in the tail pipe emissions. On the other hand, water-cooled piezoelectric pressure transducers along with high speed data acquisition and analysis subsystems help obtain precise $P-\theta$ diagrams. Inverting them is still the most powerful diagnostic tool 'to see' the finer details of the process steps in the cylinder.

Engines have seen a steady improvement since their beginning. Large engines have achieved performance levels exceeding 180g/kWh. These are very slow speed engines for stationary power generation. On the other hand, high speed engines which can spin faster than 5000 rpm are optimised for high torque but they produce such levels only for short periods during their life. This could be compared with a ship's engine driving a propeller which would run at high torque possibly for 8000 hours in a year.

Besides economy driving compactness to reduce capital costs and fuel efficiency to reduce running costs, environmental considerations are driving the designs of today to ensure exhaust gas cleanliness. Rudolf Diesel himself claimed that exhausts from his engines will be 'colourless and odourless'. He was comparing it with the smoke-belching coal-fired furnaces of the steam engine boilers! Reducing noise emissions is also a new requirement and therefore engine designs require further developments.

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Diesel Engines: Alternate Fuels

Carbon dioxide emissions have acquired new focus from the global warming point of view and their suspected effects like climate change. Fuels from renewable resources, energy captured from the Sun by agricultural crops, are gaining importance. Since 2005, biodiesel, an esterified vegetable oil is being produced in many countries. According to a report by the American National Biodiesel Board, USA produced 1.2 billion gallons (a little less than 5 billion litres) of biodiesel in 2011. Production from the European Union and a few other countries has been in comparable quantities. An analysis by the above Board points out that biodiesel is the fastest growing sector of the economy worldwide with a compound annual growth rate (CAGR) of 19% which is sure to catch the attention of the investors.

India already has a built-up capacity to produce one billion litres of biodiesel a year. In addition, newer fuel possibilities are being explored. For example, the Karnataka State Road Transport Corporation (KSRTC) has been operating, for two years, about 2000 buses with a mixture of diesel and 7.5% ethanol. The two components are solvated together using a coupler. The corporation has also been using biodiesel in some of their buses. Bangalore International Airport Limited (BIAL) has opted to use, for its ground support equipment, a blend of 20% biodiesel with regular diesel. Many other fuel sources are being developed. Besides ethanol and higher alcohols from fruit and agro wastes, fuels obtained by catalytic depolymerisation of lignocellulosic and plastic wastes are being produced in small quantities and experimented upon as diesel substitutes. Therefore, it appears that engine development to suit newer fuels will be an ongoing process.

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Diesel Engines: Subsystems

Engines for long time now are a collections of subsystems with groups of industries specialising in each of them and their components. The mechanical subsystem would consist of stationary



parts like the engine blocks, the cylinder heads and the cylinder liners where metallurgy, stressing and optimal material distribution will be the important considerations. The rotating parts are made up of the crankshaft and its flywheel, connecting rods and the piston assembly along with the requisite bearings and provisions for lubrication. Dynamics of the moving parts, their time-varying stresses, torsional resonance and fatigue life become the important considerations for them.

Bearings of the mechanical systems and the reciprocating motion of pistons in the cylinders have to be lubricated, the generated heat is to be carried away, any mechanical debris swept away by the oil is to be separated and the lubrication oils are to be prevented from degradation. The lubricating subsystem carries out these functions.

Providing densified air to the intake manifold leads to burning a considerably larger quantity of fuel in the cylinder thereby increasing the power density per litre of displacement volume. Atmospheric air is compressed for this purpose using a turbo-compressor. The drive for the compressor comes from a turbine expanding the gases from the exhaust manifold. The turbine compressor pair called the turbo charger is a common feature of all heavy duty engines and also the ones for high performance on-road vehicles. Compressed air becomes hot which is often cooled using an inter-cooler. A two-stage compression is also often used with inter-cooling. These super charging subsystems with their delicately designed rotors, necessarily spinning at high speeds because of their small sizes, are increasingly becoming a common feature of modern diesel engines.

Groups specialising in combustion subsystem optimisation and customisation look at the carefully carved out geometry of the combustion space in the cylinder. Piston crown geometry is a very important part. Spray penetration, spray geometry, movement of the air and the fuel, swirl, turbulence, etc., are some of the parameters to be considered along with injection advance, ignition and combustion delay. The aim is to achieve the maximum

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heat release. Pollutants need to be controlled. CFD, cold and hot flow studies, in-situ measurements are some of the tools. Experience and insights still remain the main ingredients of good design.

Fuel injection systems for diesel engines are made by a limited number of groups today. Earlier, mechanical barrel-plunger pumps along with suitably designed injectors served two important functions. The pumps, besides providing fuel at high pressures for the injectors to spray, also regulated the quantity delivered based on engine demand. In addition, based on the setting of the cam that operated the plunger, they delivered the fuel at the expected crank angles to different cylinders. The injectors sprayed the fuel into the combustion chamber in predetermined patterns as fine droplets. This way fuel is distributed into the combustion air as uniformly as possible. When multiple cylinders were present individual pumps delivered fuel separately to each of the injectors fitted on every cylinder. These in-line pumps were replaced by 'rotary pumps' where a rotating multiple cam operated a single pump as many times as needed. Instead of these mechanical barrel pumps, there are also piezo operated nozzles, controlled electronically, spraying the fuel from a pressurised common rail (common rail direct injection – CRDI). The fuel injection system now can be regulated by an electronic engine control unit (ECU).

Engine block and cylinder heads need to be cooled to keep the material temperature within limits. This is done by circulating cooling water through properly designed passages in the water jackets provided. In addition, heat generated at the crankshaft and the connecting rod bearings is cooled by the lubricating oil. The lube oil is also sprayed to the bottom of the piston and onto the cylinder linings to keep them relatively cool. Where turbo-chargers are present, their bearings also need to be cooled and there is a need for cooling the compressed air from the turbo-chargers at intercoolers. The hot water and the hot oil are separately pumped to a radiator cooler. The hot fluids flowing in the tubes attached to external finned surfaces, transfer heat to the ambient air blown over the fins and the tubes by a cooling air fan. Earlier drive for



the fan often came from the crankshaft itself. However some measures to reduce the sfc (specific fuel consumption) have resulted in thermally operated clutches which engage the fan only when the water becomes hot. Motor operated fans are also being used in automobile engines which help in locating the fans in advantageous positions and the motor can now be controlled by the ECU. Multiple motor driven fans are also used and the air blown by the fan also cools the other external surfaces of the engine. In very large engines, blowers and heat exchangers are used. This engine cooling system is also a specialised subsystem of a modern day diesel engine.

Other than the fuel injection system, there is a fuel subsystem which in its simplest form could be just a fuel tank, suitably located and appropriately shaped. A fuel filling pipe with an appropriate filter and cap meeting the local safety regulations and a plumbing line to a fuel filter located near the fuel pump of the injection system may be the additional components along with a return fuel line to collect the excess oil from the injector pump barrel which was not sent to the injector. Additional in-tank or in-line pumps may be present to see that the fuel pump is not starved. The system would serve most of the diesel engines, using diesel fuel, well. However, larger engines engaged in electricity generation often use residual fuels like Naphtha, LSHS (low-sulphur heavy stock), furnace oil or some other inexpensive fuel to reduce the cost of electricity generated. Such engines have large storage tanks to bunker the fuel. As required the fuel is pumped out, heated to about 160°C, centrifuged and filtered and then stored in separate tanks for feeding the engines. Even while sending to the engine fuel injection system, the fuel is again heated to 160° C and pumped through heated or insulated lines. Thus, for such power plants, fuel systems can be quite involved and are managed by an engine control system.

Hot combustion products coming out of the exhaust manifold or the turbo-charger exhaust outlet are allowed to cool by radiation and convection to the ambient to reduce the flow velocities. The high velocity pulsating components will have to be carefully

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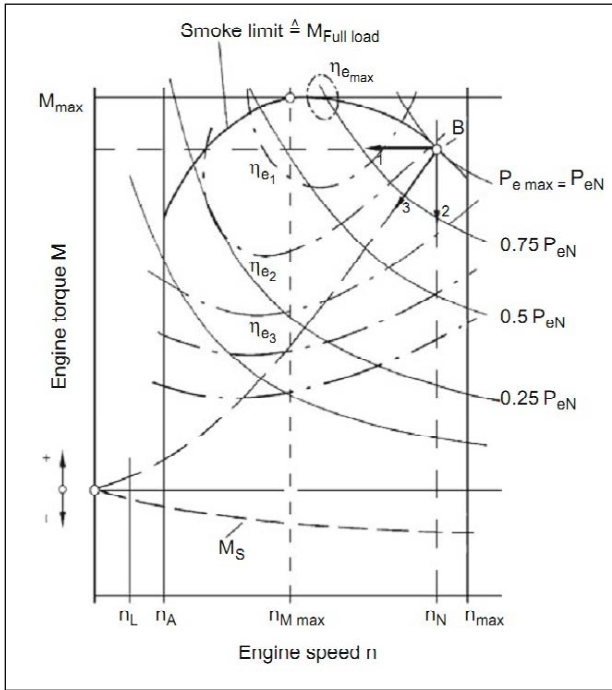
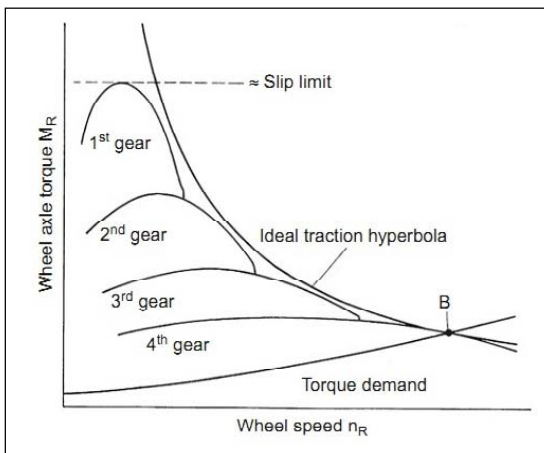


Figure 10. Engine map - torque vs engine rpm diagram.

Courtesy: <http://www.springer.com/engineering/mechanical+engineering/book/978-3-540-89082-9>

Figure 11. Maps for different gears in an engine.



engines behave under different load torques. Usually an engine map as shown in *Figure 10* is obtained which is a torque versus engine rpm diagram. There is a maximum torque that is delivered at any speed (rpm) when fuelling is at the smoke limit. More fuel cannot be burnt because there is not enough air. Lower torques can be got by reducing fuel input (accelerator in a car). On the map, constant power and constant efficiency lines can be drawn. If an

vented out such that the radiated noise is kept to a minimum. There are also environmental norms which limit the extent of noise radiated. Therefore carefully designed engine exhaust muffler systems, tuned to each engine, become a requirement. In the case of larger stationary engines, suitable chimneys carry the exhaust to safe heights. Some engines require even intake mufflers to meet the environmental norms. Again, groups specialising in design and manufacture of exhaust systems normally provide these subsystem to the manufacturers.

For an ECU (or any other user of the engine), one needs to know how engines behave under different load torques. Usually an engine map as shown in *Figure 10* is obtained which is a torque versus engine rpm diagram. There is a maximum torque that is delivered at any speed (rpm) when fuelling is at the smoke limit. More fuel cannot be burnt because there is not enough air. Lower torques can be got by reducing fuel input (accelerator in a car). On the map, constant power and constant efficiency lines can be drawn. If an engine is connected to a generator, it will run at the constant prescribed speed. Fuelling determines different loads from the generators. On the other hand, if the engine is connected to a propeller, the operations will move on the line on which the torque is proportional to the square of the speed. ECU will manage this map and ensure the best engine performance. Also, powering a road vehicle will mean matching the load torque to the vehicle's requirement. Gearing becomes necessary. *Figure 11* gives an idea of how it works.

Engine type	Specific fuel consumption [g/kWh]	Exhaust gas temperature after turbine [°C]
Car diesel engines:		
- without supercharging	265	710
- with exhaust gas turbocharging	260	650
Commercial vehicle diesel engines* with exhaust gas turbocharging and intercooling	205	550
High performance diesel engines	195	450
Medium speed four-stroke diesel engines	180	320
Low speed two-stroke diesel engines	170	275
* for heavy commercial vehicles and buses.		

Rudolf Diesel started with an efficient distributed source of motive power for different applications. His dreams have completely come true today. *Table 1* indirectly lists the achievements of the diesel engine technology as we have it now.

Suggested Reading

- [1] *Handbook of Diesel Engine*, Klaus Mollenhauer and Helmut Tschöke, (Eds.) Translated by Krister G E Johnson, Springer, 2010.

Table 1. Achievements of the diesel engine technology.

Address for Correspondence
 U Shrinivasa
 Department of Mechanical
 Engineering
 Indian Institute of Science
 Bangalore 560 012, India.
 Email:
 udipi.shrinivasa@gmail.com

