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Internal Combustion Engine: Concerns and Contradictions

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Abstract

The internal combustion engines are going to be the preferred vehicle power source for many years to come, for a simple fact that the capital investment, i.e., the required industries and supporting technologies are enormous. No other prime mover has shown any insight for its replacement.

Keywords: Internal Combustion Engine, Emissions, Efficiency, Emission Norms

Brief History

Internal combustion engines (ICE) have been used as a workhorse of land, air and sea transportation for more than 125 years. The large discovery of petroleum products Pennsylvania, USA led to the use of internal combustion engines. During that period transportation engines were dominated by coal or wood fired steam engines for railroads and ships. The next major step was the invention of the first ICE by Nicholas Otto in 1876. Otto's engine used a gaseous fuel (carbon monoxide and hydrogen produced by burning coal) with air in a piston cylinder arrangement. In 1885 Daimler, Maybach and Benz invented carburetor for the use of liquid fuels in moving vehicles. Essentially the same design is being used in automotive engines today. Soon Otto realized that more compression of the fuel-air mixture would result in more power and better fuel efficiency. Because of engine knocking the compression ratio was limited to 2.5:1 at that time. With this compression ratio, the measured thermal efficiency was 14% as compared to a theoretical value of 27%. Today's engine use 8:1 compression ratio and exhibit better efficiency mainly because of better quality fuels. For the engines with this compression ratio, the typical efficiency is 30% as compared to a theoretical value of 52%. Thus we have only achieved a very slight decrease (1.7 vs. 1.9) in the last century.

Rudolf Diesel in 1897 introduced only air inside the combustion chamber of an ICE to overcome knocking problem with increased compression ratio. Liquid fuel was sprayed directly into the cylinder after compression and it got spontaneously ignited due to the high temperature of the highly compressed gas. This higher compression ratio led to higher thermal efficiencies but produced less power for a given size and weight of engine.

A very important milestone in the evolution of ICE happened again with the even larger discovery of reservoir of oil in east Texas in 1901 and even more massive oil reserves in the Middle East in the 1930's. During early 1900's, steam engine and battery-powered vehicles posed stiff competition to ICE and did not emerge as the dominant transportation engine. With the ease of use and availability of large quantity of petroleum reserves these alternatives got extinguished from the scene. It was also due to the discovery of the antiknock agent tetraethyl lead (TEL) as an additive in 1921 by General Motors'. Immediately; compression ratios got doubled, leading to substantial increase in both power and efficiency.

The massive number of the gasoline-fueled, spark-ignited ICE powered automobile through the 1950's saw the skies of some metropolitan areas being badly fouled by the emissions from these engines resulting in the formation of a brown haze of Nitrogen Dioxide (NO_2) as well as Ozone (O_3), a colorless gas highly irritating to the respiratory system. In 1952, Prof. A. J. Haagen-Smit of Caltech showed that NO_2 and O_3 formed as a result of the reaction of Nitric Oxide (NO) and unburned hydrocarbons (UHCs) with oxygen and sunlight in the atmosphere called "photochemical smog". This led to the introduction of automotive emissions regulations in the 1960's. Many automobile companies in Detroit, USA introduced initial stop-gap technology i.e., lean mixtures, exhaust gas recirculation, and retarded spark timing in the early 1970's which ultimately led to led to poor fuel economy and performance.

The 1973 Arab Oil embargo led to a rapid rise in oil prices and brought a cruel twist of fate. Thus Detroit's large, inefficient gas-guzzling vehicles that were the joy of the American motorist just a few year earlier then became virtual dinosaurs. During this time smaller, more efficient, technologically more sophisticated cars from Europe and Japan flooded the U. S. market. The problem was further compounded by the 1975 emissions standards on Nitrogen Oxides, which forced the use of 3-way catalytic converters requiring unleaded fuel. Detroit had no technology available at that time and was forced to buy it from overseas. Moreover; in order to restore the antiknock properties of gasoline to acceptable levels without the use of TEL, more expensive fuel refining was needed, further aggravating the pressure on fuel economy.

The 1980's saw the introduction of microcomputers in ICE to control fuel/air injection; a replacement of carburetor and mechanical controls, ignition timing, etc. according to speed, load, air temperature, altitude, etc. The computer control allowed operation to be tailored accurately for best performance of engines and emissions. This more precise engine control, while still meeting emissions standards, enabled recovery of some of the performance and fuel economy lost to emissions controls in the previous decade.

In the 1990's reformulated gasoline containing oxygenated molecules such as MTBE were introduced in order to further reduce emissions. MTBE was somewhat successful in this regard and additionally improved antiknock performance at the expense of still higher refining costs and lower fuel economy. However, the biggest problem with MTBE turned out to be its water solubility and extremely odiferous nature (a concentration of only a few parts per billion in water can be detected by the human nose) and possible toxicity, and soon groundwater supplies were contaminated in areas where underground gas station fuel tanks leaked. This led to an eventual ban on MTBE and its replacement by ethanol, which is less effective than MTBE but attractive to the farm lobby because of the use of agricultural products as a feedstock for producing ethanol.

Finally, in the new millennium hybrid vehicles have become a commonly used technology. The operating principle is that internal combustion engines operate most efficiently at near maximum power. Thus the engine is used both to propel the vehicle as well as power an electrical generator to charge a battery. When the battery charge level is sufficiently high, the engine is turned off and the electric motor / battery propel the vehicle. When the battery charge level drops too low, or if additional power is needed for climbing hills, passing, etc., the gasoline engine is started again. While hybrid vehicles are clearly more fuel-efficient, much more equipment is required and, as discussed later, it is not clear if fuel savings justify the extra capital and maintenance costs.

Advanced Internal Combustion Engines/Technologies

1. Homogeneous Charge Compression Ignition Engines (HCCI) – This engine is the combination of SI and CI engine means using the concept and method of both the types. Homogeneous charge is for SI engine that is used in HCCI engine which uses premixed, very lean in nature, homogeneous charge of diesel fuel and air in intake manifold. Ignition of mixture is by compression only as it is used in CI engines; actually it is auto-ignition of charge. Efficiency of HCCI engines are approximately same as diesel engine so HCCI engines are much efficient than SI engines. It has the advantages of very low NO_x due to low

combustion temperature inside the cylinder and low particulate matters (PM) as homogeneous mixture is used, which provides better mixing of charge for complete combustion. At high load, HC and CO also reduces because of complete combustion but at low load, HC and CO increases due to non-complete combustion of charge. There are many issues with this engine to be implemented commercially such as fuel volatility, fuel composition, emission and combustion control etc. out of which combustion control is the major issue for the practical application of HCCI engine. Above said issues are being studied currently and trying to be sorted out by researchers throughout the world. At high load, charge has to be rich to maintain optimum performance requirement and it's very difficult to control fuel-air mixture burn rate because of high compression ratio as there is no spark plug or fuel injector as in the case of SI/CI engines. Fuel structure is also a significant factor to affect the performance and emission characteristics of HCCI engine.

2. Pre-mixed Charge Compression Ignition/Partially Pre-mixed Charge Compression Ignition/Spark Assisted Compression Ignition /Reactivity Controlled Compression Ignition Engines (PCCI/PPCI/SACI/RCCI) – In PCCI or PPCI engine, fuel is injected fully or partially into the cylinder before its scheduled time near at TDC to increase the efficiency of this engine by taking the advantage of combustion completeness. In SACI engine, spark is used to ignite the fuel-air mixture (very lean in nature) so it is the combined technology of SI and CI engine. There is difficulty to start the engine with the help of spark as low F/A ratio in SACI engines. To rectify this problem, some amount of high pressure fuel is injected directly into the cylinder when starting the engine. In this case these SACI engines are called stratified gasoline engines. In RCCI engines, reactivity means chemical reaction or combustion into the combustion chamber is controlled by controlling the timing of fuel injection to complete the combustion and so improve the performance of CI engine as well as to reduce emissions.
3. Selective Catalytic Reduction (SCR) – It is the technique of after treatment (also called post-combustion) of exhaust gases to reduce NO_x as selected pollutant in the environment of ammonia (NH_3) or zeolite used as a catalyst, as shown in Fig.1. In SCR technique, urea or zeolite or both in proper proportion, is sprayed into exhaust gases coming out after combustion at about 300-500ºC. Urea decomposes into ammonia (reducing agent) at this temperature that reacts with NO_x (NO/NO_2). By this reduction reaction, NO_x is converted into free nitrogen and water by ammonia as reducing agent.

$$4NH_3 + 6NO \rightarrow 5N_2 + 6H_2O$$
$$4NH_3 + 3NO_2 \rightarrow (7/2)\ N_2 + 6H_2O$$

In this way, nearby earth atmosphere is almost free of NO_x which is very much harmful for living being as well as environment and has stringent emission norms (EURO VI in Europe and BS VI in India).

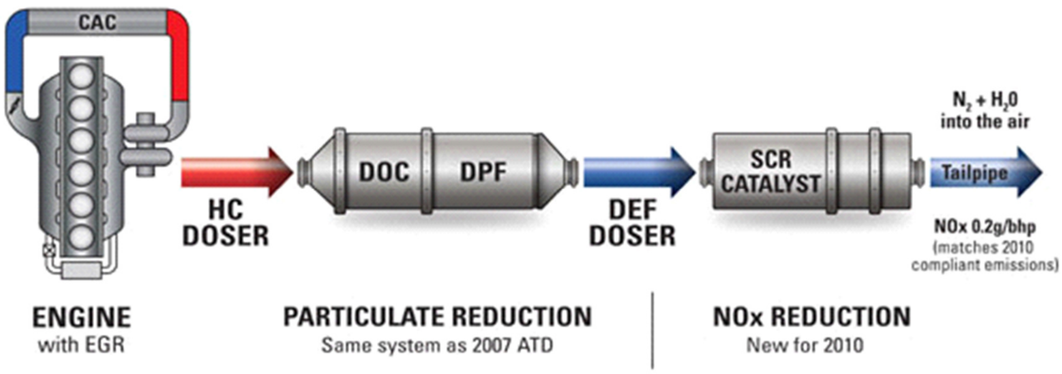

Fig.1. Implementation of SCR technique in engine exhaust stream

It's implementation compensate cost of extra fuel in EGR method to reduce NO_x so better to use SCR technique but there is a challenging task to optimize the concentration of urea inducted into exhaust stream for optimum results. Sometimes both the methods SCR and EGR are implemented for maximum reduction in NO_x.

4. Direct- Injected Spark Ignition Engines/ Port Fuel Injected Engines (DISI/PFI) – In DISI engines, fuel is injected directly into the cylinder like in CI engines. At high load, fuel is injected during intake stroke to make the mixture more homogeneous to produce great power. At low load, fuel is injected after the compression stroke. Because of direct injection, leaner mixture is burnt, as in CI engine, that improves fuel economy but more particulate matters (PM) are emitted in exhaust. To reduce all emission contents, three-way catalytic convertor and diesel particulate filter (DPF) is implemented. In PFI engines, fuel is injected into intake port near intake valve to make the mixture near stoichiometric. As a result of homogeneous combustion due to pre-mixed fuel, less PM formation in exhaust but other pollutants increase those can be reduced in a similar way as in DISI engines by using 3-way convertor and DPF. Major difficulty with these engines, is the incomplete combustion of fuel due to non-mixing of fuel and air properly.
5. Diesel Particulate Filters/ Gasoline Particulate Filters – These are also latest technology developments used in both SI and CI engines to remove particulate matters those are hazardous to human health and environment. Because of stringent emission norms all over word, it is the necessity of the use of DPF & GPF in diesel and gasoline engines respectively.
6. Variable Gas Turbine Turbochargers (VGT) – Variable Gas Turbine turbochargers have been implements now a days at the place of conventional fixed turbine turbocharges due to their improved power of about 25-30%. In VGT, passage of turbine blades is varying as per the change in requirement of exhaust gases to be passed through turbocharger.
7. Variable Valve Timing (VVT) Technique – This technique, used in SI engines, varies the valve opening/valve lift to allow the required quantity of charge into the cylinder without using intake manifold throttling. Valves are operated flexibly by the combination of electrical and hydraulic systems. As well as valve timing is varied by ECU as per the change in engine operation.
8. Lean NO_x Traps (LNT) – Now a days its much necessary to implement NO_x reduction by a certain technique or the combination of techniques out of which LNT is also in early developing stage used for CI and lean SI engines, in which fuel-air mixture is to be promoted for its richness to produce HC and CO as pollution content, not NO_x but it has to compromise with increased fuel consumption. In this technique, NO_x reducing agents are purposely produced during combustion for lean engines.
9. Waste Heat Recovery/ Cylinder Deactivation Technique etc. – To improve the power and to reduce emissions, various techniques either have been developed or in developing stage but these affect the efficiency of the engine. So to improve the efficiency of engines, waste heat recovery techniques are going to be developed in which heat loss has to be minimized either by insulation (using certain coatings) or by converting this exhausted heat into some useful work. Cylinder deactivation technique at varying load is also in developing phase to improve specific fuel consumption.

Scope of improvement in ICE

The preceding discussion might lead to conclude that there is no room for improvement in ICEs. Certainly this is not the case, but before one invents the zero- emission vehicle or revolutionizes the automotive industry there are a few simple facts about engines that need to be considered.

Efficiency

The ideal thermodynamic efficiency of gasoline or spark- ignited or Otto Cycle or premixed charged ICE depends only on two factors: the compression ratio and a property of the gas mixture called the specific heat ratio. Since the latter factor is not an adjustable design parameter, only the compression ratio may be adjusted. So, higher compression ratio improves both thermal efficiency and power but is limited by engine knock. The effect of compression ratio with change in the specific heat ratio of fuel to the thermal efficiency is shown in Fig. 2.

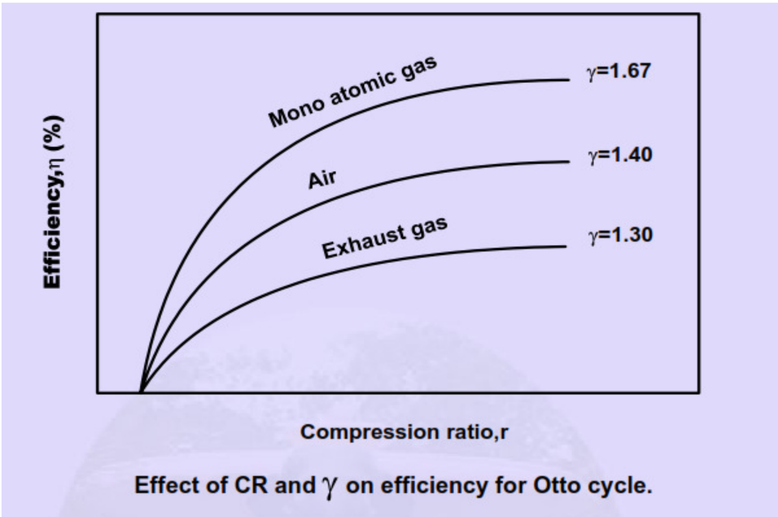

Fig. 2. Effect of compression ratio and specific heat ratio to the thermal efficiency

Emissions

Unlike efficiency, there is almost unlimited room for improvement in emissions performance other than carbon dioxide. This is because pollutants other than carbon dioxide have a non-equilibrium effect. In reality, because of the very limited time available for combustion, expansion and cooling of the products in an ICE, the products additionally include undesirable components such as Carbon Monoxide (CO), Nitric Oxide (NO) and Unburned Hydrocarbons (UHCs) as shown in Eq. (1).

$$\text{Fuel} + O_2 + N_2 \rightarrow CO_2 + H_2O + N_2 + CO + NO_x + \text{UHCs} \ldots\ldots\ldots(1)$$

In essence, the problem is that at combustion conditions, CO, NO and UHCs always form. During the expansion stroke and the resulting cooling of the gases, if adequate time is allowed; these products will be converted to H_2O, CO_2 and N_2, but this time is not available. All emissions control techniques are essentially aimed at either (1) modifying the combustion conditions so that less of the undesirable products are formed, (2) driving the products toward their equilibrium state more quickly within the combustion chamber or (3) driving the products toward their equilibrium state in the exhaust. Modern engines are actually extremely clean in comparison to older engines built before emissions regulations were imposed. The worst problems so far are the cold starting conditions, changes in speed or load, and especially old or out-of-tune vehicles.

Emission Norms

Emissions norms have been set worldwide because of various factors such as ozone layer depletion, environmental pollution, global warming, health hazards, climate changes etc. In USA; US Environmental protection agency (USEPA) has selected emission set-ups. In European countries, emission standards have been set in term of Euro-I to Euro-VI introducing improvement in engine technologies and fuel quality such as incorporation of SCR, EGR, DPF, DOC, PPF and increase in cetane/octane rating by fuel blending or mixing various additives. India has put emission norms in terms of Bharat Stage I-IV (BS I-IV) in its light and heavy duty vehicles now, which is equivalent to Euro I-IV and planning to place BS-VI (that is equivalent to Euro VI) till the end of 2020 [1].

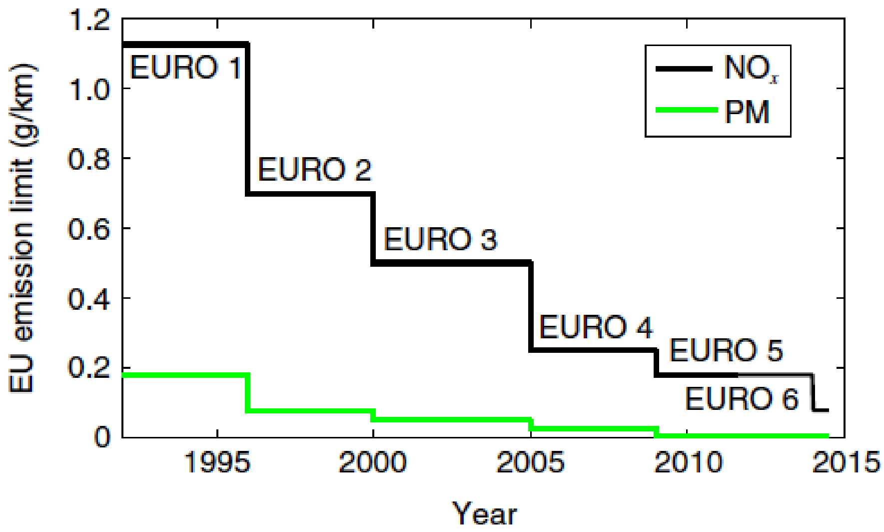

Fig.3. NO$_x$ and PM level reductions for Light duty vehicles in Europe

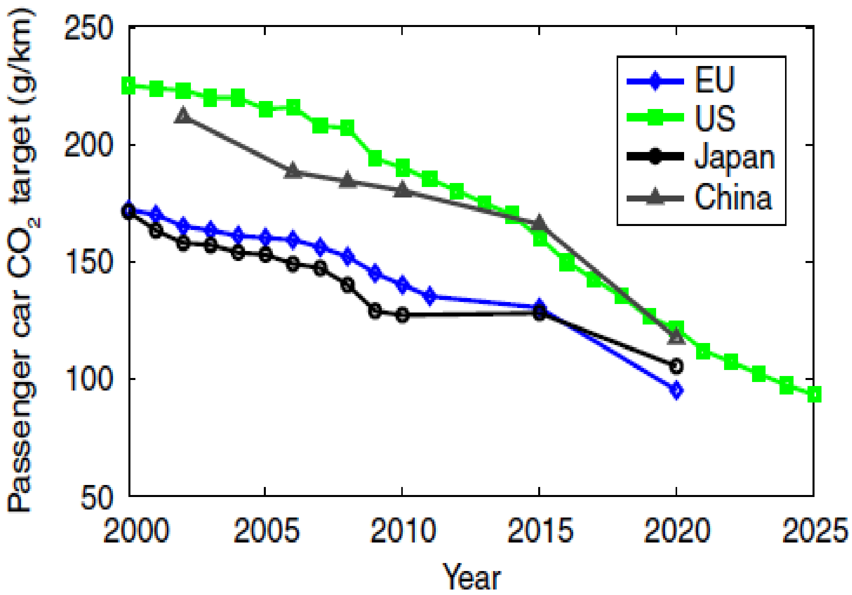

Fig.4. CO_2 level reductions for EU, US, Japan, China

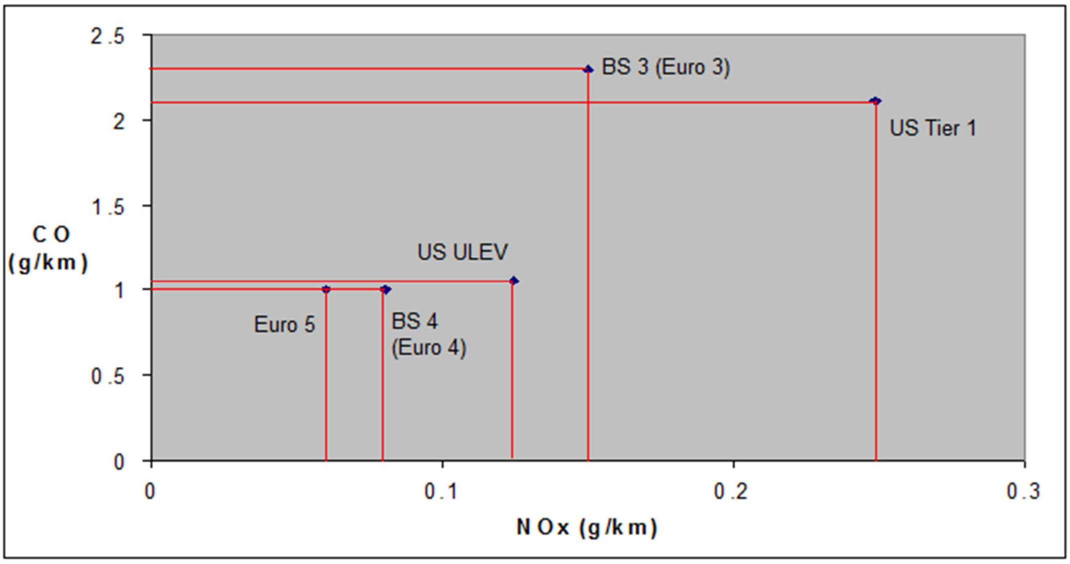

Fig.5. Comparison between European, US & Indian emission standards for petrol cars

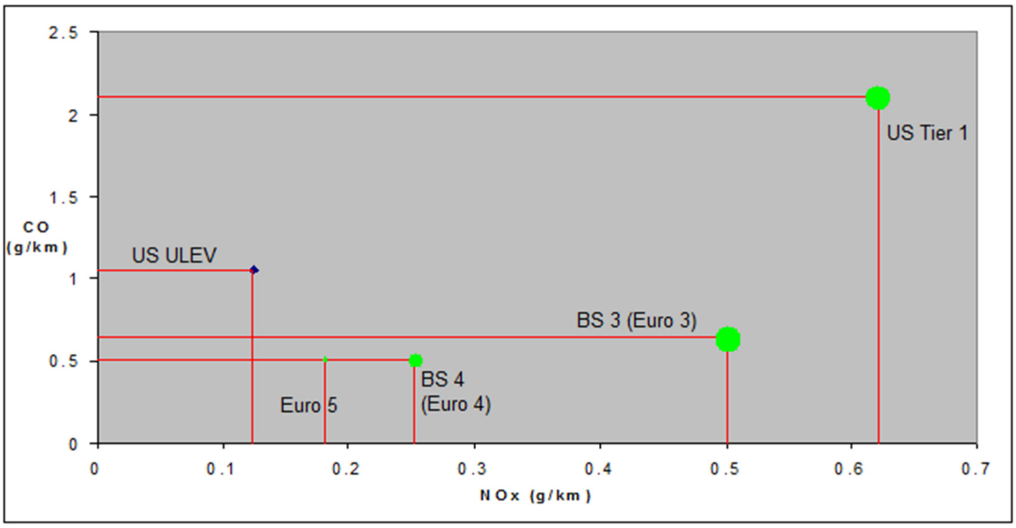

Fig.6. Comparison between European, US & Indian emission standards for diesel cars

Comparisons among different emission constituents worldwide have been shown above in Fig.3, Fig.4, Fig.5. and Fig.6.

Power

In contrast to efficiency and emissions performance, there is almost no room for improvement in engine power. Fundamentally this is because ICE is considered to be an air processor that is the fuel requirement is very little as compared to the air. Moreover, adding fuel in excess of the stoichiometric mixture with air does not increase power because in that case there is insufficient oxygen to burn the additional fuel. Thus, it can be said that air flow corresponds to power. The most fundamental limitation on air flow is due to choking of the air flow passage past the intake valves – that is, charge cannot flow through a restriction such as the intake valves at a speed faster than the speed of sound. In order to increase air flow and thus power, essentially the engine designer must either

- Increase engine rotation rate (increase intake valve port area)
- Increase engine displacement (cylinder bore, piston stroke or number of cylinders)
- Increase intake mixture density and thus pressure (turbo charging or supercharging)

At a typical compression ratio of 9, the maximum possible Otto Cycle efficiency is about 50%, whereas the actual efficiency is closer to 30%, it means theoretically efficiency can be almost doubled possibly with different thermodynamic cycles such as the “complete expansion” or “Atkinson” cycle. However; practically speaking this much improvement may never be realized [2]. It should also be noted that the majority of power used to propel a vehicle at highway speeds is used to overcome air resistance. As a result, smaller, more aerodynamically streamlined vehicles will always have better fuel economy, even if the weight is the same as a larger vehicle.

Heat losses to the cylinder walls

About 25 – 35% of the energy contained in the fuel winds up being lost to the cylinder walls and rejected as waste heat through the radiator. Many studies [3, 4] have shown that so-called “adiabatic engines,” which are really just “coolant-free” engines with high wall temperatures, do not in fact improve efficiency; what is needed is a way to reduce heat transfer (heat loss recovery) to or from the cylinder walls.

Friction losses

About 10 - 20% of the energy contained in the fuel is used to overcome rubbing friction losses in the engine.

Throttling losses (at part-load operation)

When less than the full power output of the engine is required (which is most of the time), a throttle is used to control power output. It does so by creating a pressure drop across the throttle valve, which in turn decreases the density of the fuel-air mixture entering the cylinder. This pressure drop results in pumping work being required to draw the mixture into the cylinder. The energy loss associated with throttling varies from 0% at wide-open throttle (maximum power) to 15% at typical highway cruise conditions to 50% at idling. Some schemes such as “displacement on demand” technology [5] and throttleless engines [6] have been developed as a result.

The future perspective

There is going to be the hybridization of gasoline and diesel engine technologies. That means, the engines built in future are going to combine the merits of Otto into Diesel and vice versa. Emissions from internal combustion engines, which arise from non-ideal combustion, have been dramatically reduced in the past four decades. It depends both on the engine operating parameters (e.g. engine temperature, speed, load, A/F ratio, and spark timing) and the fuel quality. These emissions result from complex processes involving interactions between the fuel including the alternate fuel and engine parameters.
Commercial transportation fuels are complex mixtures containing hundreds or thousands of chemical components, whose composition has evolved considerably during the past 100 years. In conjunction with concurrent engine advancements, automotive fuel composition has to be fine-tuned to balance efficiency and power demands while minimizing emissions. Emissions from engines comprised of volatile organic compounds (VOCs), CO, nitrogen oxides (NO_x), and particulate matter (PM). VOCs and NO_x form photochemical smog in urban atmospheres, and CO and PM may have adverse health impacts. Engine hardware and operating conditions, after-treatment catalysts, and fuel composition all affect the amount and composition of emissions leaving the vehicle tailpipe. While engine and after-treatment effects are generally larger than fuel effects, engine and after-treatment hardware can require specific fuel properties. Consequently, the best prospects for achieving the highest efficiency and lowest emissions lie with optimizing the entire fuel–engine–after-treatment system.

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