Chapter 1
Introduction

Abstract Energy is a fundamental prime mover for the economic growth of any country and essential for sustainability of modern economy as well as society. Long-term availability of environment-friendly, affordable and accessible energy sources is desirable for economic growth in the future. Presently, humanity is at crossroads and requires the radical and novel approach for the utilization of energy. The goal of this book is to present a novel approach for internal combustion (IC) engines, which are one of the most important machines for transforming the energy of hydrocarbon fuels into useful mechanical work. Two different viewpoints exist on energy production using IC engines. A number of people think in terms of mobility advantages, while others associate with emissions of harmful exhaust gases and large-scale consumption of limited fossil fuel reserves. Irrespective of one's viewpoint, the number of vehicles running on IC engine will be increasing in the future due to the rapid economic growth. Furthermore, on-board power requirement on vehicle will increase due to the growing number of accessories and electronic devices. These factors lead to the increase in worldwide fuel consumption and gaseous emissions. Therefore, an IC engine with alternative combustion mode having superior characteristics than conventional engines needs to be developed. Ideally, such an alternative combustion mode should be operated on renewable fuels and have a better fuel conversion efficiency and no harmful emissions. Present book deals with the detailed analysis of performance, combustion and emissions characteristics of novel low temperature combustion (LTC) concept using conventional as well as alternative fuels. This chapter first discusses the motivation for engine research in general and LTC mode in particular. The LTC mode is an alternative to conventional, well-known and frequently used combustion concepts, i.e. compression ignition (CI) and spark ignition (SI) combustion modes. Brief description of conventional combustion mode is also provided in this chapter. An overview of alternative engine concepts and alternative fuels is also presented in this chapter for setting the stage for the discussion of various LTC engines.

Keywords Combustion • Autoignition • HCCI • Alternative fuels • Powertrain • SI • CI • PPC • RCCI • Engine

R.K. Maurya, *Characteristics and Control of Low Temperature Combustion Engines*,
Mechanical Engineering Series, https://doi.org/10.1007/978-3-319-68508-3_1

1.1 Motivation

Global economy and modern society are dependent on the availability of reliable transportation systems. Modern civilization would not have reached existing living standards (in terms of physical facilities) without the transportation by millions of automotive vehicles. Combustion engines are the prime mover for the automotive vehicles, ships, construction equipment, agricultural machines and gensets. Currently, a vast majority of combustion engines used in automotive vehicles are reciprocating piston engines powered by combustion of petroleum-based fossil fuels. Reciprocating IC engines are well accepted and the most significant source of energy since the last century because of their superior performance, controllability, robustness, durability and absence of other viable alternatives.

Assured supply of transportation energy is required from sources with lower carbon footprint to ensure sustainable development. Increasing mechanization of the world has led to a steep rise in demand for fossil fuels and increase in number of automotive vehicles [1, 2]. The International Energy Outlook 2016 shows that the fuel demand is expected to rise over the next three decades and fossil fuels share 78% of energy use in 2040 [2]. As a result of stringent emission legislations and higher oil prices, reciprocating IC engine vehicles are expected to continue to become more efficient. In addition, several new technologies (hybrid cars, electric vehicles, fuel cells, etc.) are being developed for fuel economy improvement and reduction in exhaust emissions locally. However, presently shares of these new technologies are very small. According to future projections, these new vehicle technologies collectively would account for only 6% of new passenger vehicle sales by 2020 and 19% by 2035 (hybrids would have major share) [1]. Currently, there are no realistic alternatives that could completely replace the reciprocating IC engines. Electric and hybrid electric vehicles are potential technologies, which can be alternative to IC engines. Electric and hybrid electric vehicles will be however suitable for short-range journeys and more suitable in light-duty vehicle category. However, the volumetric and gravimetric density of modern batteries is still inferior to that of the fuel used in any IC engines [3]. Therefore, combustion engines are expected to be around for several decades or maybe even centuries to come, as long as more fuel-efficient and cleaner alternative is made available. Hence, research focusing on improving the fuel conversion efficiency and reducing harmful emissions from the IC engine is justified and required in the current scenario.

Over the years, improving the performance in terms of fuel conversion efficiency and power density of IC engine has been the major driving force for research and development (R&D). Exhaust emissions from automobiles were recognized as major contributor to urban air pollution for the first time in California during 1950s [4]. Now, the users of IC engines are aware of the air pollution from vehicles, and consequently they demand compliance to environmental consideration and regulatory legislations prevailing around the world. The main governing factors for engine research are described in the next subsections.

1.1.1 Environmental Concerns

The world is presently facing crisis of depletion in fossil fuel resources and degradation of environmental conditions. Environmental pollution is a key public health issue in most of the cities. Epidemiological studies show that air pollution causes large number of deaths, huge medical costs and lost productivity every year. These losses and the accompanying degradation in quality of life enforce a substantial burden on humanity [5]. There are several issues related to environmental pollution from combustion engines, which are summarized in Fig. 1.1. Major concerns that appear due to heavy use of combustion engines are global warming, photochemical smog, carcinogenic particles, acid rains and ozone depletion.

Currently global warming is an important environmental challenge. The phenomenon of global warming occurs due to thermal energy imbalance because of heat trapped in the earth's environment by greenhouse gases. The principal greenhouse gases generated due to human activities are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride) [6]. IC engines burn fossil fuels in the combustion chamber and produce CO_2 along with small amounts of methane and nitrous oxide also. From an IC engine point of view, reduction in the CO_2 emissions can be achieved by developing more efficient engines.

Photochemical smog is a brownish-grey haze caused by reactions between unburned hydrocarbons and nitrogen oxides in the presence of solar radiation. It comprises of various organic compounds, ozone and nitrogen oxides (NO_x) confined above the ground level due to temperature inversion conditions [4]. The vehicles contribute to smog by emitting nitrogen oxides and unburned

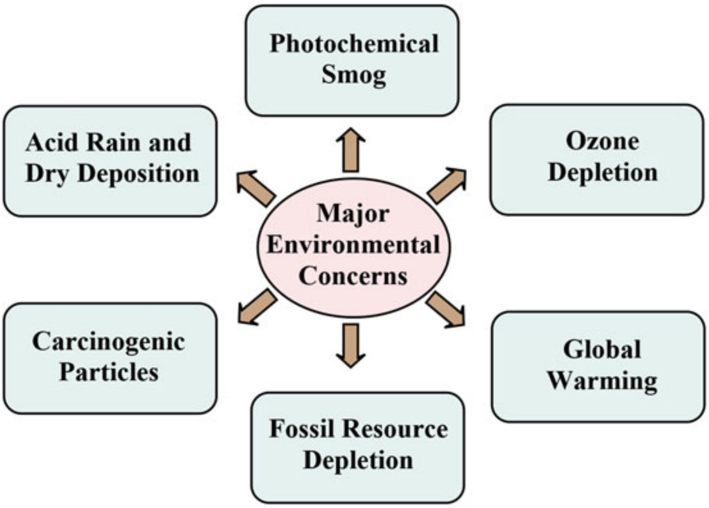

Fig. 1.1 Major environmental concerns arise due to extensive use of internal combustion engines for automotive and stationary applications

hydrocarbons (HC). Therefore, it is required to develop technologies which reduce the emissions of NO_x and unburned hydrocarbons. Acid rain has a negative impact on vegetation by accelerating acidification of the soil and directly attacking plant leaves. Acid rain broadly refers to a mixture of wet and dry deposition of nitric and sulphuric acids from the environment. Emission of sulphur dioxide and NO_x from combustion of fossil fuel contributes to acid rain [7].

Solid particles emitted from automotive vehicles mainly consist of carbonaceous matter (soot) comprising a small fraction of inorganic matters. Different types of liquid-phase substances and other hydrocarbon species are either adsorbed or absorbed on solid soot particles [4]. One of the main sources of soot particles introduced into the atmospheric air is diesel engine. Soot particles are produced in the diesel engine due to diffusion-controlled heterogeneous combustion of the locally rich fuel–air mixture. For human beings, larger particles are not a serious health threat because they are taken care of by the body's defence system. Smaller particles less than 2.5 microns (μm) are the main concern because they take long time to settle and remain airborne for days altogether. Therefore, smaller soot particles could reach the respiratory system of human beings. Particles particularly less than 1 μm are too small to be trapped in the upper portion of lungs, and they penetrate deep into the lungs [4]. They pose a serious threat to the human health since carcinogenic compounds such as polycyclic aromatic hydrocarbons (PAHs) adsorbed on the surface of these soot particles are carried to lungs and can potentially cause cancer. An improvement based on the measured mass of particulate matter may actually lead to an increased number of smaller particles, and result could be misleading. Therefore, it is required to develop engine technologies, which use premixed flames and emit lower number of particles.

Ozone depletion is another key environmental concern as ozone layer guards against adverse effects on humans (e.g. skin cancer and cataracts), on biosphere (e.g. inhibiting plant growth and damaging ecosystems) and on physical infrastructure of the modern era (e.g. degradation of materials) [8]. Ozone is broken down continuously in the stratosphere while absorbing the harmful UV-B solar radiation. Reduction in stratospheric ozone level lead to higher levels of UV-B radiations reaching the earth's surface. In the stratosphere, chlorofluorocarbons (CFCs) and NO_x break down ozone into oxygen. The major problem with these pollutants is that they do not form a stable compound while breaking down the ozone; therefore new compounds continue to break down ozone.

1.1.2 Regulatory Measures

Utilization of fossil fuels in IC engines affects the regional (local) and global environment. Pollutants emitted from IC engines have adverse effect on human health and ambient air quality. Health and other hazards of pollutants depend on its concentration as well as time of exposure to human body. Harmful health effects of various pollutants emitted from combustion engines (adapted from references [4, 9,

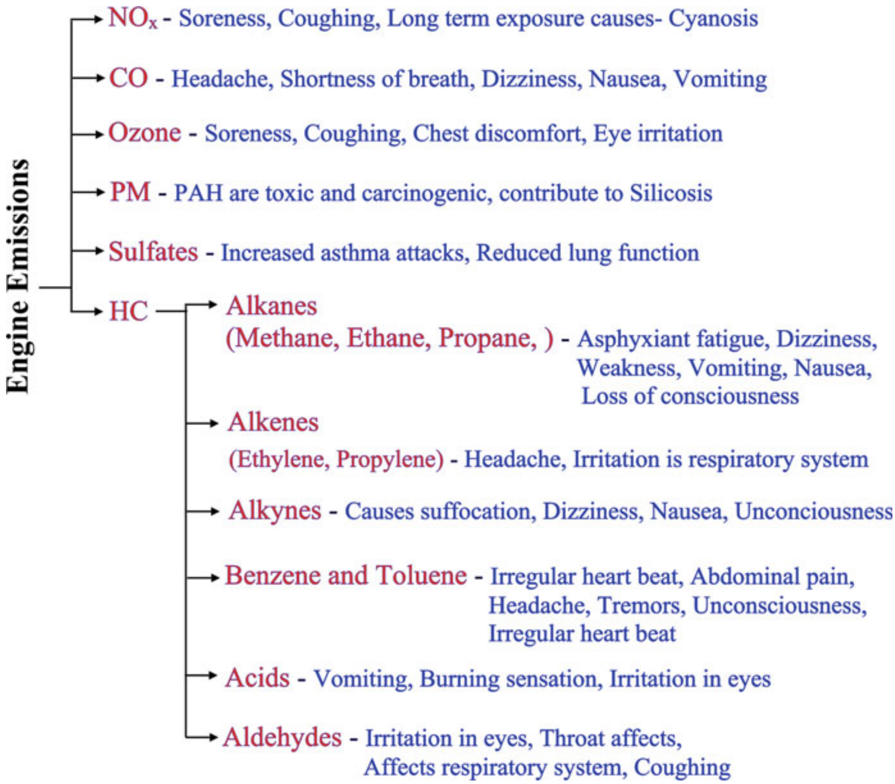

Fig. 1.2 Effect of principal pollutants emitted from IC engines on human health

10]) are summarized in Fig. 1.2. Governments worldwide have gradually imposed increasingly stringent restrictions on emission levels and tougher quality norms for fuel composition in order to reduce the influence of pollutants on the environment and human health. Furthermore, there are demands for a required emission durability and in-use inspection and obligatory maintenance [11].

Vehicular exhaust emission standards are specified in terms of pollutant mass per unit of distance travelled (g/km). For light- and medium-duty vehicles, emission standards are based on driving cycles that represent typical driving pattern in any specific country. The test driving cycles are composed of a cold start period, idling, moderate acceleration and deceleration and cruise modes. For heavy-duty vehicles, engines are tested on different combinations of speed and load condition for steady test cycle. To make the test more representative of actual road driving, conditions on transient tests are also conducted. One major drawback is that the test methods and emission standard often differ from one country to another and direct comparison is generally not possible [4]. Emission legislations include pollutant species such as NO_x, unburned hydrocarbons, CO and particulate matter (PM), and these pollutants are frequently referred to as "regulated pollutants". However, NO_x and

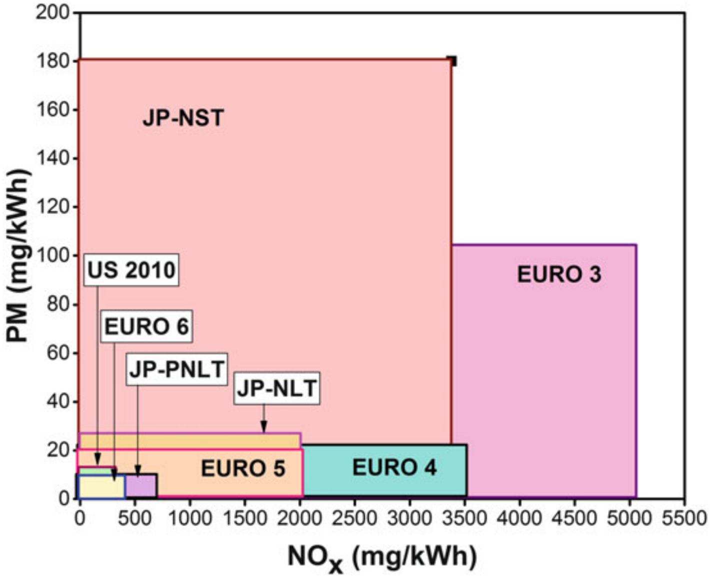

Fig. 1.3 NO_x and PM emission standard for heavy-duty vehicles in different regions of the world

PM emissions have been a challenge for conventional diesel engines because of the heterogeneous combustion process in the cylinder [12]. NO_x and PM emission standards for heavy-duty vehicles (adapted from Worldwide Emissions Standards [13]) are presented in Fig. 1.3. The significant reductions that are made continuously in every country are worth noting. Due to concerns regarding the environmental effects and stringent emission legislations, the research for next-generation combustion mode for IC engines has gained increasing attention worldwide. Detailed discussion on next-generation alternative combustion modes is provided in Chap. 2.

1.1.3 Engine Fuel Challenge

Automotive engines and fuels are facing challenges to reduce emissions for improving local city air quality as well as reduce CO_2 to reduce global warming risk. Two-thirds of the oil consumption in the world is presently used in the transportation sector, and half of that goes to passenger cars and light trucks [14]. This heavy consumption of the fossil fuels results in the emission of large amount of CO_2 which is identified as greenhouse gas (GHG). To address this issue, the IEA's (International Energy Agency) roadmap is to reduce the fuel use per kilometre by 30–50% in new road vehicles worldwide by 2030 [15]. All these goals stimulate new developments in both conventional and alternative engines as well as fuels as illustrated in Fig. 1.4 (adapted from [16]).

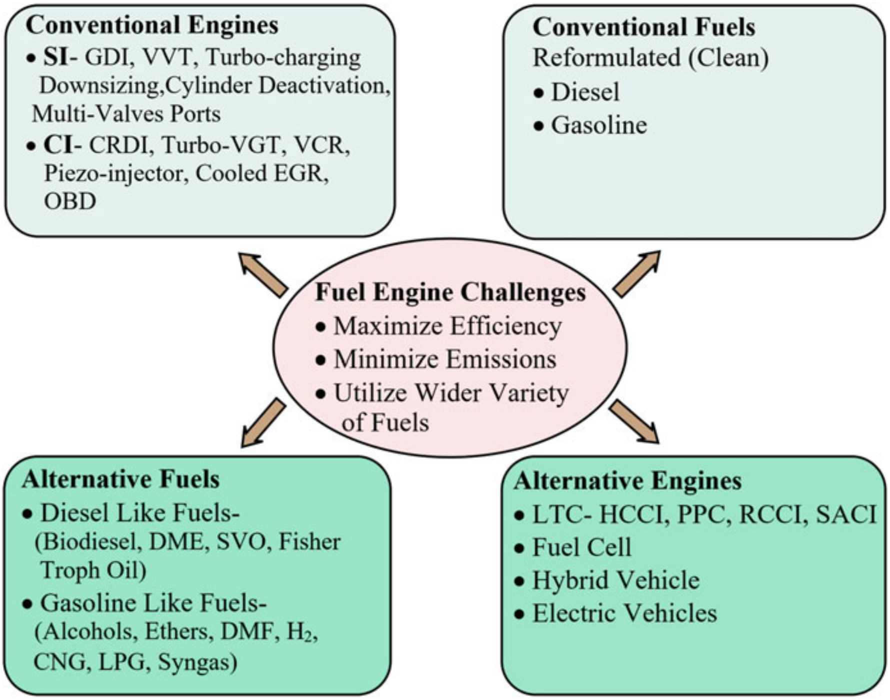

Fig. 1.4 Overview of engine and fuel technologies to tackle technical challenges for future automotive engines

Grand challenges in IC engine research are summarized as to develop technologies for maximizing engine efficiency, minimize exhaust emissions and optimize the tolerance for utilization of wide variety of fuels [17]. To address the challenges, there are four possible approaches, i.e. (i) improvement of conventional engines, (ii) improvement of conventional fuels, (iii) development of alternative engine and (iv) utilization of alternative fuels and their combinations. Over a century, there are significant developments in conventional engine and fuel technology for improving their performance to present level (Fig. 1.4). Another possible approach is to explore new engine concepts that use alternative fuels (such as biodiesel, alcohols, natural gas, etc.) for meeting future emission legislation. The utilization of alternative fuel results in reducing the monopoly of fossil fuels as well as increasing the engine efficiency. Improvement in IC engine efficiency is still continued, which represents the richness of the engine combustion process. In recent study, Reitz [18] summarized engine combustion as "…. a low Mach number, compressible, multiphase, high-Reynolds number turbulent flow with chemical reactions and heat transfer, confined in a time-varying geometry. The combustion process spans multiple regimes that include turbulent flame propagation, mixing-controlled burning, and chemical kinetics-controlled processes, and their combinations". There is still space for understanding the engine combustion process and opportunities for new discoveries. In pursuit of developing alternative engine combustion mode, low temperature combustion (LTC) modes are proposed and demonstrated by researchers. Brief description of conventional combustion modes is presented in the next section before the discussion on the alternative fuels and engines.

1.2 Conventional Engine Concepts

Internal combustion engines are heat engine converting chemical energy bound in fuel into mechanical work. In the IC engines, working fluid is burned and combustion products directly apply force on the engine piston. The most frequently used types of IC engine in automotive vehicles are compression ignition (CI) engines and spark ignition (SI) engines. The majority of CI and SI engines are four-stroke cycle engines, i.e. there are four distinct strokes in a complete cycle of CI/SI engine, namely, intake stroke, compression stroke, expansion or power stroke and exhaust stroke. There are differences in charge preparation and combustion characteristics between these two conventional combustion concepts (discussed in the next section); however the engine cycle principle remains the same for both.

1.2.1 Spark Ignition Engines

In conventional SI engine, fuel is injected into the intake manifold by port fuel injector/carburettor where fuel atomizes, vaporizes and mixes with intake air present in the manifold. Modern SI engines are often port injected, and the fuel is injected by a low-pressure (2-5 bar) fuel injection system. The fuel-air mixture is then inducted into the combustion chamber during intake stroke, where fuel–air mixture mixes with residual gases of the previous combustion cycle. During this period, mixing continues and a close to homogeneous mixture is created in the engine cylinder. Homogeneous mixture of vaporized fuel, air and residual gases is then compressed, and by the end of the compression stroke well before top dead centre (TDC), the mixture is ignited by a single intense, high temperature spark which initiates the flame kernel. The charge mixture composition and motion around the spark plug at the time of spark discharge is decisive for the flame development and subsequent flame propagation. This makes early flame development and subsequent propagation vary from cycle to cycle. Flame kernel generated by spark grows, and a turbulent flame propagates throughout the mixture until it reaches the combustion chamber walls, where it extinguishes (Fig. 1.5). Figure 1.5 shows the flame propagation at different crankshaft positions for different fuel injection techniques used for charge preparation (reproduced from [19]). In advanced modern SI engine, engine can be operated on heterogeneous and homogeneous combustion modes using direct injection (DI) of fuel to meet the emission legislation and achieve higher fuel conversion efficiency. At higher engine loads,

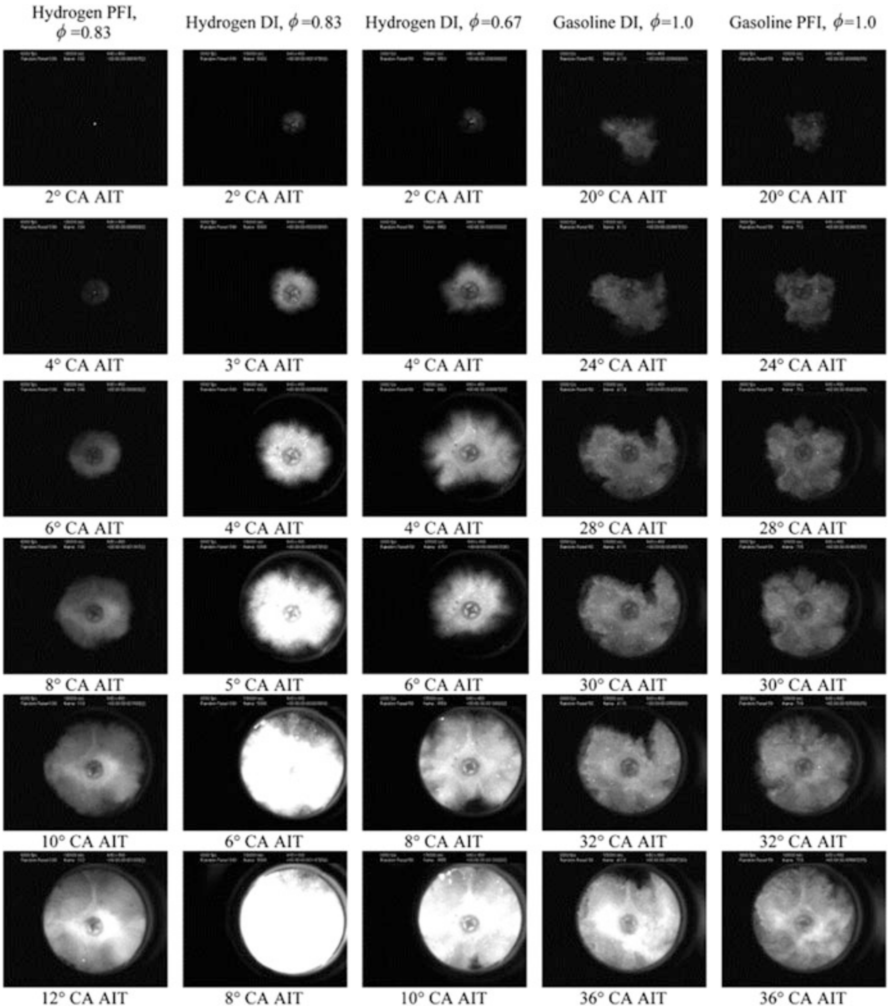

Fig. 1.5 Flame propagation (chemiluminescence image) in SI engine for different charge preparation techniques [19]

fuel is injected during the intake stroke of cycle which provides sufficient time to evaporate and mix with air leading to create a homogeneous mixture before ignition. This operation mode is similar to conventional port fuel injection (PFI) system. During lower engine loads, stratified charge mode is used to take the advantages of wide open throttle operation without pumping loss. In stratified charge operation mode, injection is staged to ensure that a combustible charge must be present close to the spark plug at the time of ignition through appropriate fuel–air mixture preparation processes [20].

In a normal combustion, the flame starts from spark plug and travels across the combustion chamber in smooth manner. In certain operating conditions, the abnormal combustion or knocking can occur in the engine cylinder. During knocking in SI engine, the end charge auto-ignites before the flame front consumes it, which may result in structural damage mainly to piston due to very high pressure rise in the cylinder. The interactions of flame front propagation, end-gas auto-ignition and in-cylinder pressure wave are extremely crucial during knocking combustion, which affect the features of local pressure mutation, combustion regime transitions and knocking intensity [21]. Knocking phenomenon limits the compression ratio of SI engines, which in turn limits the achieved thermal efficiency. The SI engine has a possibility to use higher engine rotational speed in order to get high specific power because the compression ratio and peak cylinder pressures are limited. Thus a more lightweight design can be used for engine construction that allows higher rotational speed. Additionally, flame speed in SI engine scales very well with the engine speed which also allows the higher rotational speed.

In SI engine, load control is achieved by throttling, which changes the air flow rate in the combustion chamber, in order to keep the air–fuel ratio stoichiometric. The air–fuel mixture needs to be close to stoichiometric for complete flame propagation [22]. Throttling leads to increased pumping losses during the gas exchange process, which reduces the part load efficiency of SI engines. In a car, majority of the engine operating points are in low to medium engine loads. Therefore, fuel conversion efficiency is quite low in SI engine due to higher pumping loses by throttling.

The mechanism of emission formation in the engine is governed by the combustion process and combustion chemistry. To sustain the flame propagation in SI engine, burned gas temperature needs to be over 1900 K [23]. Since the nitrogen oxide (NO_x) formation increases rapidly at this combustion temperature, the SI engine emits higher amount of NO_x. The burned gases in the cylinder are compressed during compression stroke till piston reaches TDC position and temperature attained in combustion chamber leads to the significant NO_x formation. Carbon monoxide (CO) is primarily a result of oxygen deficiency in the air–fuel mixture that leads to incomplete oxidation of the fuel. With decrease in air–fuel ratio below stoichiometric value ($\lambda<1$), CO formation sharply increases in the cylinder [24]. Combustion flame quenches near cold cylinder walls and it leaves a very thin quench layer of unburned fuel–air mixture. Flame is also unable to burn the fuel–air mixture present in the crevices (between piston top land and cylinder wall above top ring, around spark plug threads, cylinder head gasket) of combustion chamber. Adsorption of fuel vapours in the lubricating oil film on cylinder walls and combustion chamber deposits are another source of unburned hydrocarbon (HC) emissions in conventional SI engines [22]. Engine design and operating parameters also affect the NO_x and HC emissions. CO emissions are mainly affected by fuel–air equivalence ratio, and other parameters influence CO formation indirectly [24]. The effect of some of the important design and operating parameters on NO_x and HC emissions is qualitatively summarized and presented in Table 1.1 (adapted from [24], and for more details see original reference).

Table 1.1 Effect of operating and design parameters on NO_x and HC emissions in SI engines

Increase in parameter	NO_x	HC
Operating parameters		
Engine load	Increase	Decrease
Engine speed	Uncertain	Increase
Coolant temperature	Increase	Decrease
EGR	Decrease	Increase
Intake swirl and turbulence	Increase	Decrease
Advanced ignition timings	Increase	Increase
Design parameters		
Compression ratio	Increase	Increase
Surface-to-volume ratio	Decrease	Increase
Bore/stroke ratio	Decrease	Increase
Valve overlap	Decrease	Increase

To improve the performance of conventional SI engines and meet the emission legislation limits, various technologies are developed and implemented over the several decades. The development of SI engines over the last five decades with view on their control is presented in Fig. 1.6 [25]. The SI engines are mechanically controlled with electromechanical coil ignition till around 1965. Subsequently, replacement of carburettors with manifold fuel injection systems with electronic analog control started. Emission legislations significantly governed the developments of various technologies (electronic control, direct injection, etc.). Conventional SI ignition engines use three-way catalytic converter to meet emission legislation. Three-way catalytic converters simultaneously oxidize CO and HC and reduce NO_x emission from engine exhaust. The essential condition to use three-way catalytic converter is that the engine operates at or very close to stoichiometric air–fuel ratio. This condition is required to ensure that the enough reducing CO and HC species are present to reduce NO_x to N_2 and enough oxygen is available to oxidize CO and HC emissions [4]. A closed-loop feedback management system with an oxygen (λ) sensor in the exhaust is used for precise control of air–fuel ratio in SI engine.

1.2.2 Compression Ignition Engines

Combustion in compression ignition (CI) engine is fundamentally different from SI engines. Unlike SI engines, in the diesel engine, only air is drawn into the cylinder during intake stroke, and no throttle is required for engine operation. The inducted air is then compressed, and towards the end of the compression stroke, shortly before TDC, the fuel is injected at high pressure into the hot compressed air in the combustion chamber. The highly pressurized fuel is introduced into the combustion chamber via five to eight fuel sprays, depending on the size of the cylinder. The injected fuel atomizes, evaporates and mixes with the hot compressed air and auto-

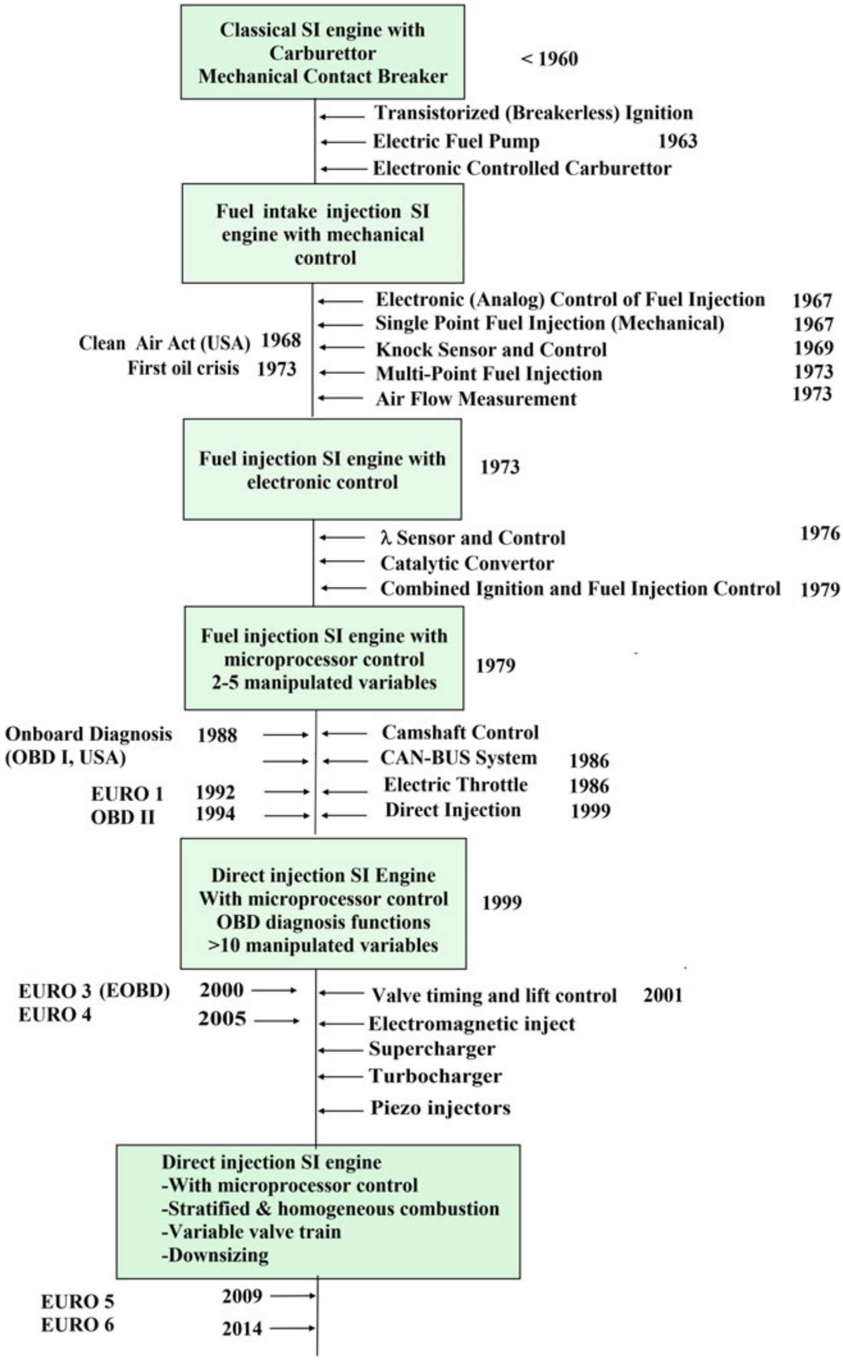

Fig. 1.6 Historical development of spark ignition engines [25]

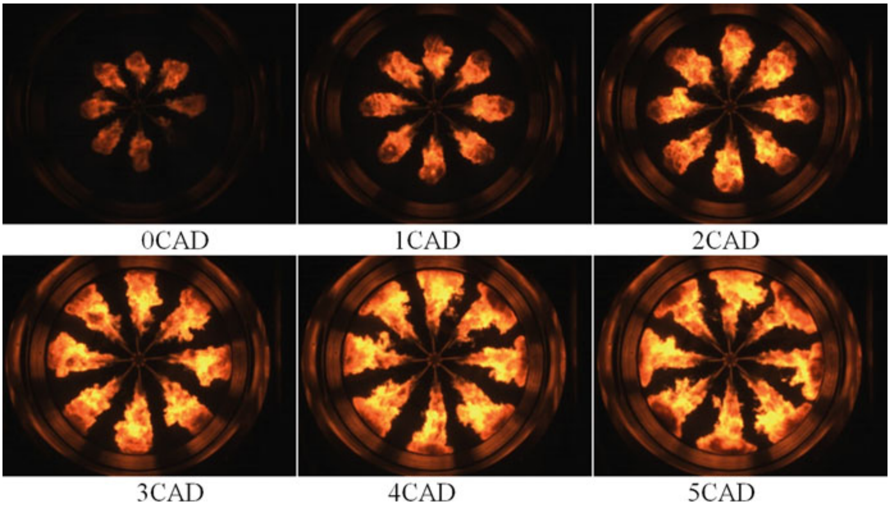

Fig. 1.7 Image sequence of diesel combustion at 1200 rpm and 160 MPa injection pressure (Courtesy of Andreas Cronhjort). *Yellow* luminosity of flames originates from hot radiating soot particles

ignites in the cylinder. In contrast to SI engines, time available for fuel–air mixture formation is very short in diesel engines. Therefore, a fast injection and the best possible atomization are required for intensive mixture formation in a diesel engine [25]. When fuel injection starts, some fuel atomizes, vaporizes and mixes partially with the air before auto-ignition occurs. Partially premixed mixture is then rapidly consumed when auto-ignition starts and the remaining combustion takes place under non-premixed conditions. The flames can be characterized as a "turbulent unsteady diffusion flames" [22]. After premixed phase combustion, diesel combustion is controlled by turbulent mixing of fuel and air at the outskirts of the diesel spray. Mixing-controlled combustion phase continues until the fuel injection is ended. After the end of fuel injection, remaining fuel or combustion intermediates burn in a diffusion flame called late mixing-controlled combustion phase [26]. In this combustion phase, the fuel spray no longer governs the fuel–air mixing process. Heat release rate (HRR) decreases fast and then gradually reduces to a zero because of dissipation of spray turbulence. Cylinder volume increases and charge cools down due to movement of piston, which may result into poor combustion efficiency in case of very low late-cycle mixing [26]. Figure 1.7 and 1.8 illustrates the typical combustion process in diesel engines.

Figure 1.7 depicts the sequence of combustion images from a diesel engine at 1200 rpm. Fuel is injected into the cylinder at 160 MPa fuel injection pressure using eight-hole injector having 190 μm orifice diameter. Heterogeneous nature of diesel combustion and diffusion flame development along with its progress is clearly illustrated (Fig. 1.7). At high combustion temperature (2000–2500 °C), carbon

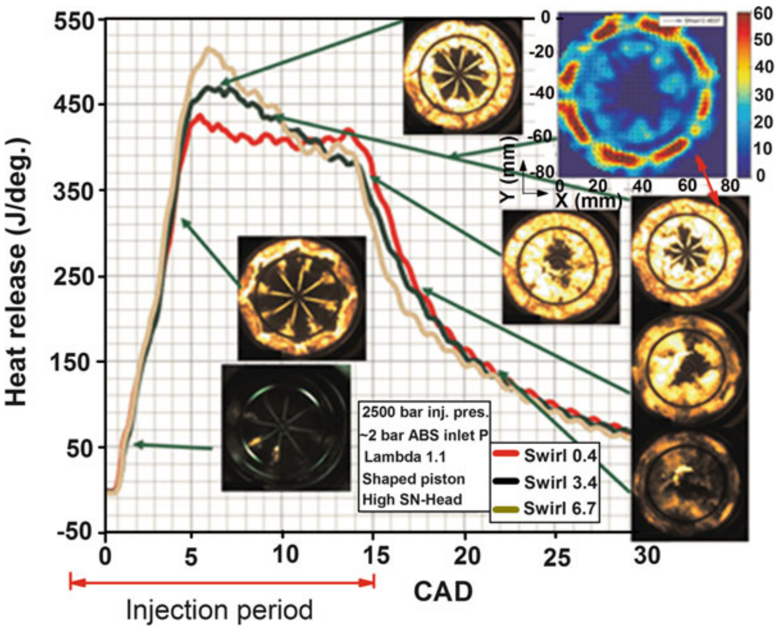

Fig. 1.8 HRR and flame luminescence images at load of 20 bar IMEP and 2500 bar injection pressure in diesel engine [27]

particles in the diffusion flame have sufficient luminosity and appear as yellow region. As flame cools, the radiation from the particles changes colour through orange to red [22]. The appearance of brown region indicates excessively rich mixture region, where substantial soot production has occurred. Initially (0 and 1 CAD; Fig. 1.7), images are mostly brownish colour due to richer mixture and relatively lower mixing with air. As combustion proceeds, more air entrainment takes place, the mixing occurs and their combustion leads to higher temperature, which changes the image colour in subsequent crank angle position.

Figure 1.8 shows heat release rate (HRR) and the progress of diesel combustion with respect to crankshaft position from the start of combustion to the end of combustion at 1000 rpm. In the first image, combustion has just started, and in the second image, all sprays have developed diffusion flames. The next two combustion images have the highest intensity, based on the HRR. It can also be observed from Fig. 1.8 that HRR is affected by the different swirl numbers (SN) [27]. The HRR increases with SN during the diffusion combustion duration, and the opposite is found at the post-oxidation duration. Premixed combustion duration is not seen prominently in modern engines (Fig. 1.8). The premixed burn appears more prominently in textbook HRR curves that is typically shown for low-pressure mechanical fuel injection (e.g. Heywood [22]). Modern diesel engines show only a very small portion (depending on engine load) of premixed heat release because of accelerated mixing process and reduced ignition delay period due to very high fuel injection pressures [26]. Diesel fuel injection system and its control are developed for very precise fuel injection at very high injection pressure (~2000 bar). The development of diesel engines over the last five decades with respect to fuel injection system and their control is presented in Fig. 1.9 [25]. Around 1989 diesel engines started using microprocessor controlled direct fuel injection along with wastegate turbochargers. In later years, exhaust gas recirculation (EGR), oxidation catalyst and turbochargers with variable geometry developed. Current diesel engines are equipped with high fuel injection pressure (~2000 bar), piezo-injectors, common rail direct injection, high EGR rates, twin turbochargers or VGT and recent after-treatment technologies (DeNOx catalyst, DPF, SCR).

In the diesel engines, combustion process is a very complex phenomenon. Fuel injection, atomization, vaporization, mixing and combustion occur at the same time in the combustion chamber. Mixing and vaporization are the slowest processes in diesel engine combustion and hence it determines the combustion rate. Therefore combustion timing and rate can be easily controlled by diesel injection timings [22]. The speed of diesel combustion is limited by the mixing between the injected fuel and the air in the combustion chamber, which also limits the maximum engine speed. Engine load in CI engine is controlled by varying the amount of fuel injected, and hence, airflow rate remains constant for all engine loads in naturally aspirated diesel engines. Since CI engine combustion is a mixing-controlled process, engine knock can be avoided, and knocking does not limit the compression ratio of the diesel engine. Due to lower pumping losses and higher compression ratio, diesel engines offer higher part load efficiency as compared to SI engines. Lower cylinder temperatures due to leaner engine operation lead to lower heat loss to coolant as well as exhaust, which also contributes to higher CI engine efficiency. As an additional benefit, the ratio of specific heats (γ) is higher for lean mixture operated engines, and therefore lower thermal energy is lost in the excitation states of larger triatomic species (CO_2 and H_2O) [28]. This leads to the availability of higher amount of thermal energy in working fluid, and more work can be extracted, which contributes to higher fuel conversion efficiency of the engine.

Major emission concerns from diesel engines are HC, NO_x and particulates (PM). However, HC emission can be easily mitigated by oxidation catalyst. Based on laser sheet imaging studies of diesel spray combustion, Dec [12] proposed a conceptual model for soot formation. According to this model, liquid fuel jet penetration is rather short in length, and all the fuel in combustion zone is in vapour phase. Soot first appears just downstream of liquid jet in rich premixed combustion region. Figure 1.10 shows the temperature distribution and combustion chemistry of diesel fuel spray in the conceptual DI diesel combustion model [29]. The concentration of soot increases and particle size grows as soot flows downstream towards the spray boundary. The model proposed that the formation of soot precursors and consequent generation of soot particles happen in the rich premixed flame ($\varphi = 2$–4) and the soot particle size increases as they pass through spray towards the head vortex [24]. Some of the soot particles reach the diffusion flame at the periphery of the jet, where they can be oxidized by OH radicals. Most of the

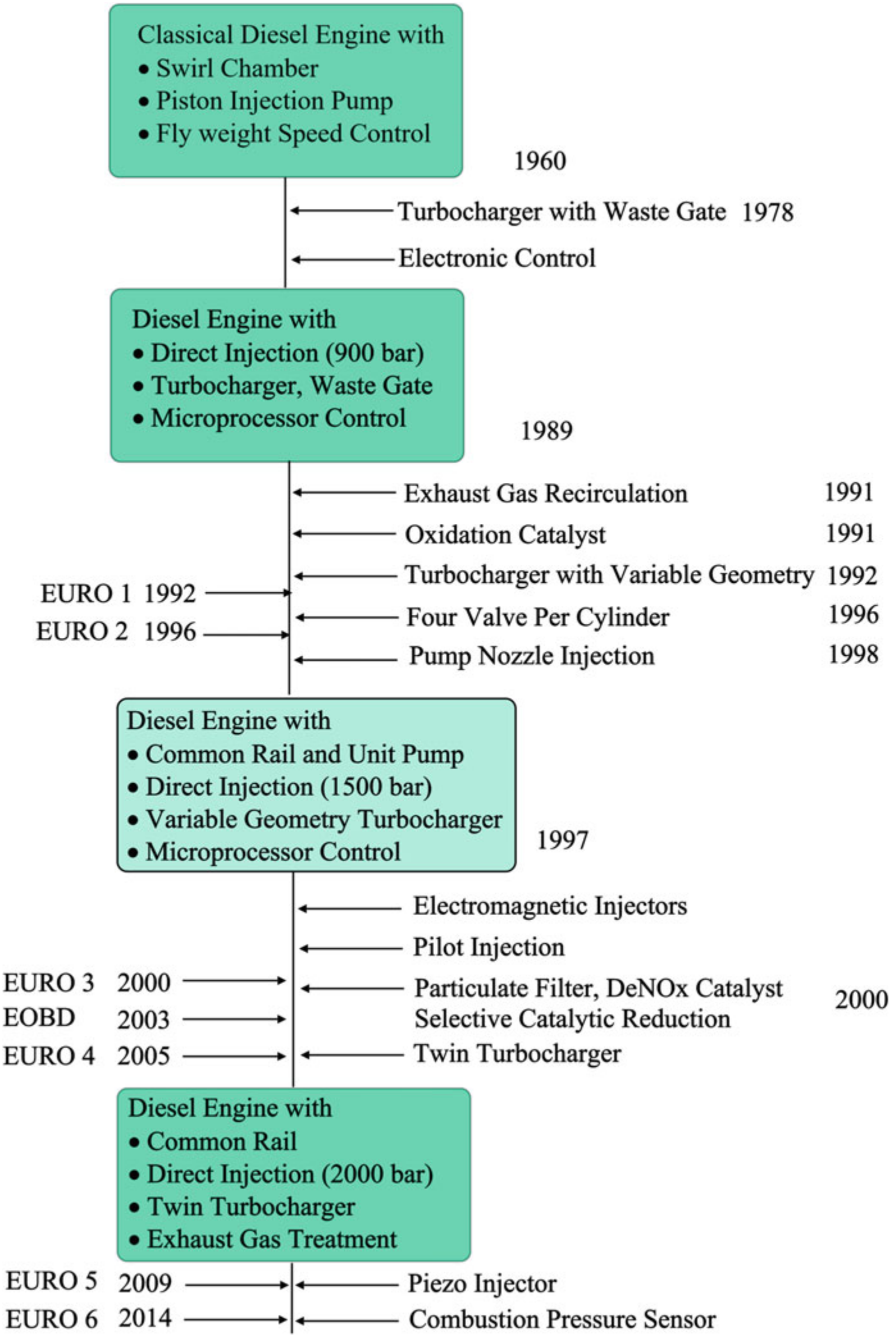

Fig. 1.9 Historical development of diesel engines [25]

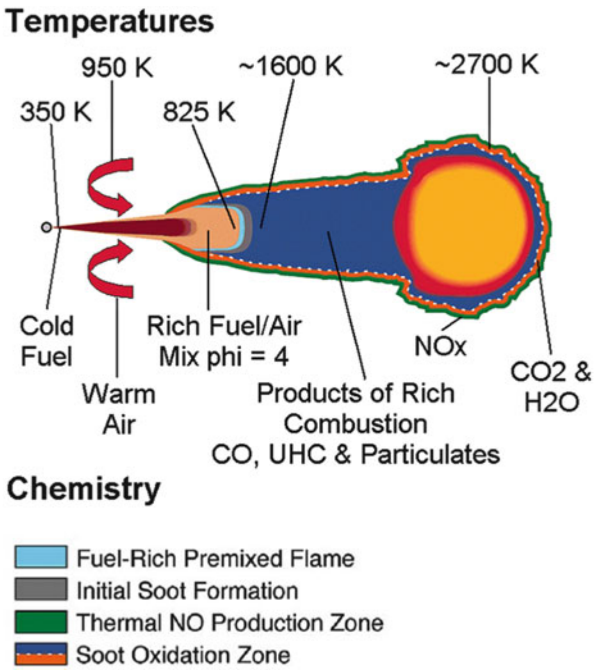

Fig. 1.10 Conceptual model of spray combustion in DI diesel engine. Reprinted with permission Copyright © 1999 SAE International [29]

NO_x formation happens during the time of high-energy release rates associated with the diffusion burning process, where temperature reaches around 2700 K [29].

Diesel engine emission formation is affected by engine design, operating and fuel injection parameters. The effect of some of the important engine operating, fuel injection and design parameters on NO_x, PM and HC emissions is qualitatively summarized and presented in Table 1.2 (adapted from [24, 30]).

Simultaneous reduction of NO_x and PM presents the biggest challenge as most of the engine design strategies reduce either NO_x emissions or PM. The reduction of one (NO_x or PM) causes an increase in the other, which is typically known as soot-NO_x trade-off in a diesel engine [4]. Several design changes for NO_x reduction result in higher fuel consumptions. To meet the emission legislations, various exhaust after-treatment technologies are used in diesel engines. Advanced exhaust after-treatments such as NO_x storage reduction (NSR), selective catalytic reduction (SCR), diesel particulate filter (DPF), continuously regenerating trap (CRT), etc. are developed and still continuously improved to meet the emission legislations for diesel engine.

Table 1.2 Effect of engine operating, fuel injection and design parameters on NO_x, PM and HC emissions in diesel engines [24, 30]

Parameter	NO_x	PM	HC
Operating parameters			
Engine speed	Increase	Reaches optimum	Increase
Engine load	Reaches optimum	Reaches optimum	Decrease
Coolant temperature	Increase	Decrease	Decrease
Fuel cetane number	Decrease	No effect	Decrease
Fuel volatility	Increase	No effect	No effect
Fuel injection parameters			
High injection pressure	Increase	Decrease	Decrease
Retarded injection timing	Decrease	Increase	Increase
Pilot injection	Decrease	No effect	No effect
Spray angle	Reaches optimum	Reaches optimum	No effect
Sac volume	No effect	Reaches optimum	Increase
Design parameters			
Compression ratio	Reaches optimum	Reaches optimum	Decrease
Stroke/bore ratio	No effect	Decrease	Decrease
Crevice volume	No effect	Increase	No effect
Swirl	Reaches optimum	Reaches optimum	Reaches optimum

1.3 Automotive Fuels

Chemical bond energy of a combustible fuel is converted to useful mechanical work by IC engines. As long as fuel is convenient to handle, transport and store, relatively safe, its utilization in the efficient IC engines is the best choice for automotive applications. Fuel quality affects the engine design and exhaust emissions. Apart from the environmental considerations, several other fuel quality requirements such as better combustion quality, high heat of combustion, high volumetric energy, low and high temperature performance, good oxidation stability, material capability, good flow characteristics, etc. are to be met by potential automotive engine fuels. Relationship between fuel quality and engine vehicle performance is discussed in detail by Pundir [4].

Four basic requirements for a future automotive fuel are (i) high power density, (ii) certain supply, (iii) overall economic feasibility and (iv) the incorporation of environmental and climate protection requirements [31]. Engine fuels as well as fuel constituents can be obtained from various feedstocks such as crude oil, natural gas, biomass, coal, oil shale, methane hydrates, oil sands and even carbon oxides (CO and CO_2) reacted with hydrogen [32]. Most of liquid engine fuel components are produced from distillation of petroleum-derived crude oil. Fischer–Tropsch process is another important method of producing engine fuels using syngas or natural gas. Natural gas (predominantly methane) is the only fuel that needs almost no processing for automotive engine applications. It requires only drying and removal of hydrogen sulphide (H_2S) from "sour" gas. Biomass is another key feedstock for the production of biofuels for combustion engines using thermochemical and biochemical routes. Thermochemical routes include pyrolysis and gasification process which convert biomass to liquid or gases, and they can be utilized in combustion engines by significant post-processing [32]. Biochemical routes involve using microorganisms to produce fuels. Biodiesel and ethanol are the other major biofuels derived from renewable materials.

Physical and chemical properties of a fuel are governed by its chemical compositions. Modern automotive fuel is a combination of different kinds of components including hydrocarbons, oxygenates, additives and sulphur. Present automotive gasoline and diesel have a higher compositional complexity and typically consist of over 100 and 1000 different components, respectively [32]. Major components of automotive fuels summarized from Mueller et al. [31] are shown in Fig. 1.11, and detailed description of each component can be found in original source. Petroleum crude oil mainly contains hydrocarbons, categorized as paraffins, naphthenes and aromatics. Gasoline and diesel fuels also consist of olefins that are formed during refining process, which are not originally present in crude oil [24]. Each hydrocarbon group has its own characteristic chemical structure and properties. Organic compounds consist of oxygen mainly alcohols, ethers, and esters (which are termed as oxygenates) are added to automotive fuels to enhance their fuel properties and reduce the emission of harmful combustion species. To further improve the fuel performance, some additives such as cetane improvers, lubricity improvers, oxidation inhibitors, detergents and metal deactivators are added to fuels at ppm levels [32].

Fuel properties affect the performance, combustion and emission characteristics of the engine. Mueller et al. categorized and discussed the key fuel properties into five categories, namely, combustion properties, physical properties, material

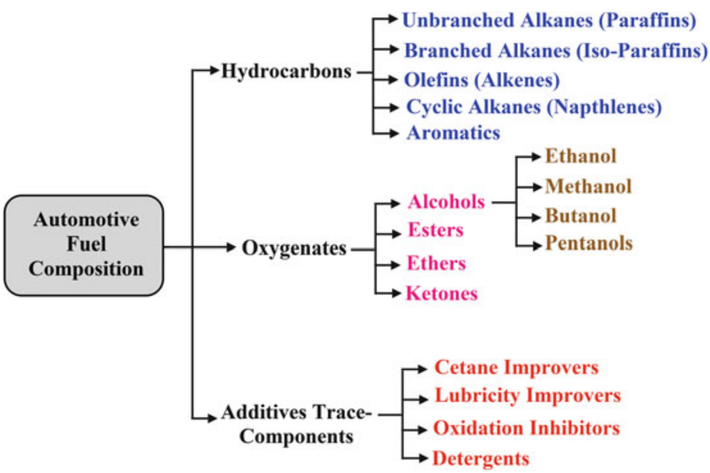

Fig. 1.11 Summary of automotive fuel composition

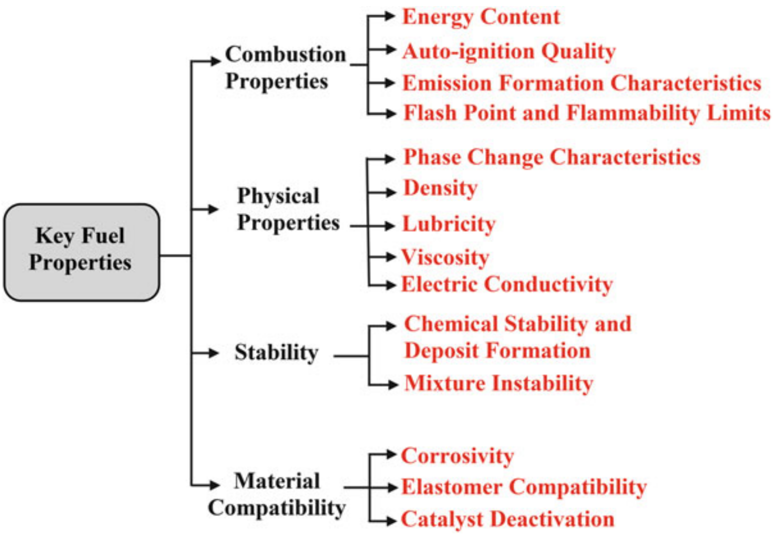

Fig. 1.12 Summary of important properties of automotive fuels

compatibility, stability and environmental considerations [32]. Important automotive fuel properties are listed in Fig. 1.12. Main combustion properties of an automotive fuel are its autoignition quality, energy content and emission formation characteristics. Better ignition quality leads to improved fuel economy and reduction in exhaust emissions. High octane number (ON) fuels for SI engine and high cetane number (CN) fuels for CI engines are required for good combustion characteristics. High energy content of automotive fuels leads to requirement of smaller amount of onboard fuel storage on vehicle for the same operating range. Emission formation is affected by fuel composition which affects the physical process happening in the engine combustion such as fuel injection, atomization, vaporization, mixing and combustion kinetics. Physical properties such as density, viscosity, lubricity and phase change characteristics are important for fuel injection system and charge preparation for engine combustion. Fuel resistance to variations in its chemical composition and/or mixture characteristics with time is known as fuel stability [32]. Good low temperature oxidation stability reduces the fuel deterioration during storage and deposit formation in the fuel system [24]. Material compatibility is necessary to prevent corrosion of metallic components as well as deterioration of rubber and elastomeric components which come into contact from point of production to engine combustion (e.g. storage tanks, pipelines, vehicle fuel tank, injection system, engine components). Fuel quality requirements specific to low temperature combustion (LTC) engines are discussed in Chap. 3.

Depletion of fossil fuels, forex expenditure, energy security and environmental pollution are the key factors to commence critical steps for substituting conventional gasoline and diesel fuels by alternative and renewable fuels at this juncture of time. Several alternative fuels are being demonstrated and proposed to substitute

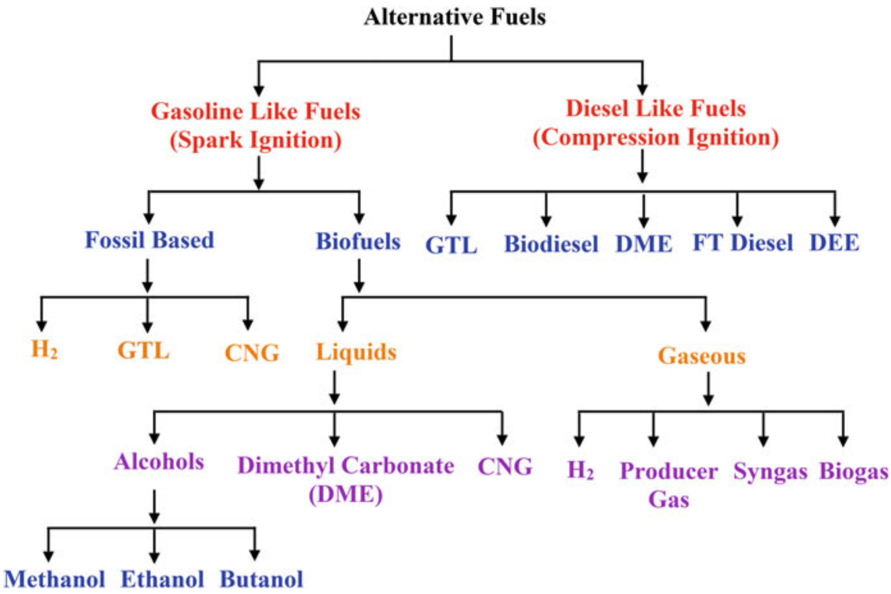

Fig. 1.13 Summary of alternative fuels presently used/proposed for automotive engines

conventional automotive fuels (gasoline and diesel). Alternative fuels for automotive transportation summarized from Ref. [33] are presented in Fig. 1.13, and detailed description of each fuel property and production process is provided in the original source.

Alternative fuels can be categorized as gasoline-like fuels (for spark ignition) and diesel-like fuels (for compression ignition) based on their utilization in two broad categories of IC engine currently used for automotive transportation. Gasoline-like fuels typically have higher octane numbers, and auto-ignition temperature is higher, which requires an external energy source to ignite the fuel-air mixture in combustion chamber (spark ignition and laser ignition). Alternative gasoline-like fuels can be fossil base (GTL, CNG, LPG, coal-based H_2) and renewable biofuels (alcohols, 2-5-dimethylfuran (DMF), syngas, biogas, H_2). Diesel-like fuels have higher cetane number, and auto-ignition temperature is comparatively lower, which can be auto-ignited by itself in combustion chamber due to compression of charge. Typical diesel-like alternative fuels are biodiesel (ethyl/methyl esters), dimethyl ether (DME), diethyl ether (DEE) and Fischer–Tropsch (FT) diesel. Biodiesel is a renewable fuel obtained from a variety of edible and nonedible vegetable oils as well as animal fat. Biodiesel is a clean burning mono-alkyl ester-based oxygenated fuel produced by transesterification process. Transesterification is the reaction of triglycerides present in the vegetable oils with primary alcohols in presence of a catalyst, which produces primary esters (biodiesel) and glycerol [34]. Physical and combustion properties of biodiesel are very similar to diesel fuel. DME is a colourless gas (easy to liquefy and transport) at standard ambient temperature with a typical odour and has emerged only recently as an automotive fuel. DME is one of the best alternative fuels for CI engines, and its clean combustion also decreases local air pollution. It can be easily auto-ignited due to its high cetane number and results in practically soot-free combustion due to easy vaporization and absence of carbon-to-carbon bonds [35].

Hydrogen emerged as promising gasoline-like alternative fuels. Hydrogen can be produced mainly by two routes involving electrolysis of water and steam reforming or gasification of a hydrogen-containing raw material. Hydrogen requires very low ignition energy and has very wide flammability limits. The main benefit of hydrogen as fuel over other alternative fuels is its carbon-free exhaust species from engines. In hydrogen combustion engine, the CO_2 emission is not there, which is the major species emitted after combustion of other alternative fuels. Hydrogen utilization in automotive vehicles is proposed mainly in two ways through (1) hydrogen fuel cell (FC) vehicles and (2) hydrogen-based IC engine vehicles. Presently, cost and fuel conversion efficiency of hydrogen fuel cell-based powertrains is higher than corresponding hydrogen IC engine powertrains [36].

Primary alcohols and their gasoline blends are typically used as alternative fuels for SI engines [37]. Methanol is a high oxygen content fuel among all primary alcohols. Methanol-fueled engines have clean combustion because of high oxygen content and simple chemical structure. Methanol is a highly toxic compound and careful utilization is required as fuel. Ethanol properties are similar to methanol, but it is less toxic and less corrosive [34]. In view of the attractive attributes of biofuels especially alcohols, efforts have been made to use them into the energy conversion systems; this book presents their utilization in alternative engine combustion concept, namely, LTC engines. Detailed discussion on combustion, performance and emissions characteristics of ethanol and methanol in LTC engines is presented in Chaps. 6, 7 and 8, respectively.

1.4 Alternative Engines

As discussed in Sect. 1.1.3, one of the possible ways to meet the engine fuel challenge is to develop an alternative engine. Factors such as global warming, air quality improvement in urban areas, energy efficiency and energy security govern the development of newer and alternative vehicle propulsion system. This challenge can be addressed by developing alternative powertrains (fuel cells, hybrid, electric vehicles) or by improving the performance of conventional IC engines by developing alternative engine combustion modes. This section explains alternative powertrains as well as alternative engine concepts.

1.4.1 Alternative Powertrains

The design of vehicle powertrain is governed by the type of energy to be used. The complete energy supply chain (source, processing, transportation and distribution) and its impact on the environment (well-to-wheel analysis) as well as cost are to be evaluated for the development of vehicle powertrain. The vehicle powertrains such as fuel cell, hybrid electric propulsion, batteries for electric vehicles and sterling engines are mainly investigated and evaluated over the years [24].

Hybrid electric vehicle (HEV) is proposed as a solution to achieve higher fuel economy and lower exhaust emissions in comparison to conventional internal combustion engines (ICE). The HEV is an intermediate step between ICE and full electric vehicle. The HEVs use internal combustion engines in combination with one or more electric motors connected to battery pack providing power to vehicle wheels either separately or jointly. Two basic configurations of HEV are series type and parallel type. In the series hybrid, only electric motor powers the wheels, and ICE runs a generator which powers the motor or charges the batteries. In this case, engine is not subjected to the transient operation of vehicles. In the parallel hybrid, engine and motor both are connected to wheels. The ICE powers one set of wheels and motor powers the other set of wheels [24]. In this mode, ICE is subjected to vehicle transient operation and leading to penalty on fuel conversion efficiency and exhaust emissions. Most of the ICE-operated cars have engines of higher rating (for, e.g. in India 25–70 kW), and average power usage in city driving is very low (Indian cities driving around 5 kW or lower). The fuel conversion efficiency of ICE is very poor at lower power output. The HEV uses a smaller rating engine, which can be operated at higher fuel conversion efficiency, and transients are managed by electric motor, which leads to higher fuel economy. Lower exhaust emission is achieved with HEV due to the operation of ICE at fixed conditions of engine operating load and speed point, and exhaust after-treatment is also more efficient at steady-state conditions [24].

Fuel cell (FC) is another potential option for powering vehicles. Fuel cell is an electrochemical device that produces DC electrical energy through a chemical reaction of hydrogen and oxygen [38]. Electrical energy can be used to drive the motor to power the vehicle wheels similar to HEV. Hydrogen FC have higher power density therefore preferred for fuel cell vehicles (FCV). The FCVs are comparatively less noisy. The FCV is promising if hydrogen is produced from renewable sources. Hydrogen can be produced from reforming of fossil fuels, oil and natural gas, renewable biomass, etc. in stand-alone stationery units and supplied to vehicles. There are challenges for large-scale production of hydrogen, and well-to-wheel efficiency of FCV is not significantly better than their counterparts [39]. On-board hydrogen storage is also an important factor for commercial success of FCV. There are many parameters still needs to be addressed before full swing market of HEVs [40] such as (i) high power density renewable energy sources; (ii) higher cost; (iii) detailed analysis of hydrogen production for FC, including delivery and storage tank systems; (iv) rapid recharging systems for plug-in BEVs; and (v) limited life cycle of batteries.

Implementation of most of the new ideas of efficient powertrain to replace ICE is restricted due to cost, complexity and overlooked real-world design shortcomings. The HEVs or BEVs have advantages in some light-duty applications depending on duty cycle [18]. Additionally, electric power station efficiency is less than 50% along with losses in power distribution, mining and transportation of fuel, if electricity is not coming through renewable sources. There is no apparent alternative to the ICE for the medium- and heavy-duty commercial vehicle markets, which are mostly high-efficiency compression ignition diesel engines. However, fossil fuel utilization in combustion engines is also not a sustainable option. These issues govern the requirement of the development of more efficient alternative combustion mode engines, which can be operated on renewable non-fossil fuels. This is the main subject of the present book.

1.4.2 Alternative Combustion Concepts

Recent developments in conventional SI and CI engines has shown significant improvements in fuel economy and exhaust emissions. Conventional SI engines are required to operate on homogeneous stoichiometric mixture and throttled operation, which results into lower fuel conversion efficiency (Sect. 1.2.1). In SI engine, compression ratio is limited by combustion knocking, which further causes lower thermal efficiency. To overcome some of the disadvantages of conventional SI engines, lean SI combustion engines are developed. Lean combustion has thermodynamically higher efficiency due to higher ratio of specific heats (γ), and lean combustion also has lower combustion temperature, thus lower heat transfer loss [22]. Unfortunately, there exists a lean combustion limit and beyond this dilution combustion flame is extinguished. Cyclic variations in indicated mean effective pressure (IMEP) also increase for lean mixture engine operation [22]. Another major demerit of leaner SI engine operation is that standard three-way catalytic converter cannot be used for after-treatment of exhaust gases due to lesser availability of CO and HC for reduction of NO_x.

Stratified charge spark ignition (SCSI) combustion process is developed to mitigate limits of lean homogeneous spark-ignited combustion by gasoline direct injection (GDI) technology. In this combustion strategy, locally near-stoichiometric mixture is created in the vicinity of spark plug, and globally (overall) fuel-air mixture is lean. This combustion strategy has the advantages of lean combustion such as lower pumping loss, lower heat transfer losses and higher ratio of specific heats. Additionally, direct fuel injection in cylinder leads to charge cooling due to fuel evaporation, and thus, chances of knocking are reduced. Due to this reason, engine can also be operated at higher compression ratios [41]. Higher compression ratio thermodynamically leads to higher thermal efficiency, but still, the compression ratio of GDI is much lower than the CI engines. In SCSI engines, fuel-rich zone also formed, which leads to higher soot formation. The SCSI engines also require lean NO_x after-treatment technology for reduction of NO_x.

The conventional CI engines are operated on lean fuel-air mixture (globally) and higher compression ratios, which leads to higher thermal efficiency in comparison to SI engines. In conventional CI engine, fuel is directly injected into combustion chamber, and turbulent heterogeneous combustion occurs in the cylinder. Heterogeneous (combustion of locally rich fuel-air mixture) combustion leads to the formation of NO_x and soot in the diesel engine.

Ideally, an engine should be operated on homogeneous leaner mixture at higher compression ratios for higher thermal efficiency and simultaneously lower NO_x and soot emissions. The homogeneous charge compression ignition (HCCI) strategy is precisely using the same concept of burning leaner homogeneous mixture at higher compression ratios. In HCCI combustion, homogeneous charge preparation is similar to SI engines, and ignition is similar to CI engines (auto-ignition of charge in the cylinder). In HCCI engines fuel–air mixture is always diluted by excess air, residuals or a combination of air and residuals. In HCCI engine, auto-ignition process is indirectly controlled by pressure, temperature, composition and the time history of the fuel–air mixture, which can be controlled by regulating the air–fuel ratio, inlet manifold temperature and pressure, EGR or amount of residuals, coolant temperature, fuel properties or fuel blend and direct fuel injection timings [42]. Due to controlled auto-ignition of the fuel–air mixture in HCCI combustion, it is also referred by another name called controlled auto-ignition (CAI). Detailed discussion on HCCI combustion and its control is presented in Chaps. 2 and 5 of the present book.

Onishi et al. performed the first systematic investigation on HCCI combustion using a two-stroke engine in 1979 and named the combustion process as active thermo-atmospheric combustion (ATAC) [43]. In this combustion process, whole fuel–air mixture in the cylinder auto-ignited simultaneously, and no flame propagation was observed. During the same time frame, another study conducted by Noguchi et al. presented the same combustion event in a two-stroke opposed piston engine by measurements of radical concentration in the cylinder [44]. Najt and Foster investigated HCCI combustion process in a four-stroke variable compression ratio (VCR) engine using mixture of iso-octane and n-heptane in 1983 [45]. Over the last three decades, the HCCI combustion process has been investigated with significant achievement in two- and four-stroke engines with liquid and gaseous fuels [46]. Considering the common features of auto-ignition and premixed fuel–air mixture, several technologies with different names such as PCCI (premixed charge compression ignition), ATAC (active thermo-atmospheric combustion), HCCI (homogeneous charge compression ignition), OKP (optimized kinetic process), TS (Toyota-Soken), CAI (controlled auto-ignition), PREDIC (premixed lean diesel combustion), ARC (active radical combustion), MK (modulated kinetics), UNIBUS (uniform bulky combustion system), CIHC (compression-ignited homogeneous charge), etc. are investigated over the year, and detailed reference (for further study) of each technology can be found in Ref. [47].

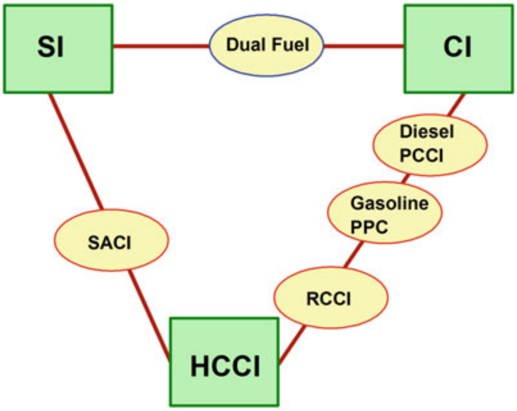

Fig. 1.14 Schematic representation of three major combustion modes and intermediate processes in IC engines (Adapted from [47])

Major drawback in HCCI mode is lack of combustion control and limited power output. To overcome the limitations of lower power density and combustion control, partially stratified charge compression ignition (SCCI) mode is proposed. In this development process, first diesel partially premixed compression ignition (PPCI, sometimes also referred as PCCI) and then gasoline partially premixed combustion (PPC) are proposed to achieve higher engine load while keeping the benefits of HCCI mode. To achieve higher power output along with better combustion phasing and duration control, dual fuel reactivity-controlled compression ignition (RCCI) strategy is most recently developed. Comprehensive discussion on these combustion strategies is presented in Chap. 2. Figure 1.14 schematically shows the three main combustion modes (SI, CI and HCCI) and five intermediate combustion processes in IC engines. The spark-assisted compression ignition (SACI) is an intermediate combustion process between SI and HCCI modes. However, RCCI, PPC and PCCI are intermediate combustion process between CI and HCCI modes. The difference between dual fuel RCCI and conventional dual fuel combustion process is the fuel injection strategy and premixed charge engine operation. In RCCI combustion process, diesel is premixed (longer ignition delay) to increase the reactivity of charge and reactivity distribution of charge in the engine cylinder, whereas in conventional dual fuel combustion process, ignition delays are very short (in comparison to RCCI) and diesel burns as conventional diffusion flame. Therefore, conventional dual fuel combustion process is an intermediate process between CI and SI modes. However, RCCI combustion is intermediate combustion process between CI and HCCI mode.

A common classification to all the mentioned premixed combustion technologies is low temperature combustion (LTC) due to significantly lower combustion temperature in comparison to conventional CI and SI engines. All the premixed LTC strategies have common characteristic of comparatively higher thermal efficiency and simultaneously reducing NO_x and soot emissions to an ultralow level. Figure 1.15 depicts the different engine combustion strategies based on fuel reactivity of charge used. It is observed that conventional combustion strategies are

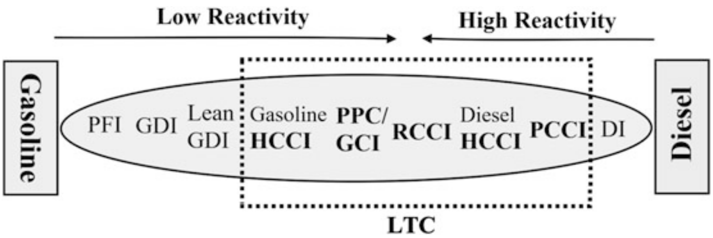

Fig. 1.15 Proposed combustion strategies based on fuel reactivity (Adapted from [49])

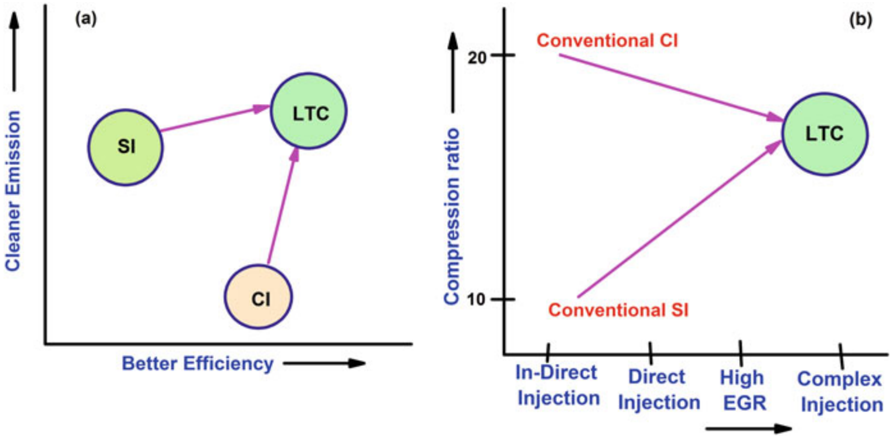

Fig. 1.16 Merging trend of conventional diesel and gasoline engine technology into LTC engine (Adapted from [48, 50])

converging towards the fuel reactivity between gasoline and diesel by the development of newer LTC engines. This provides the fuel flexibility to use both low reactivity gasoline-like fuels and high reactivity diesel-like fuels in LTC engines. Additionally, the future engine management system can use best control strategies for the fuel utilization based on vehicle operating conditions using the advanced multi-fuel engine technology [49].

Another important observation for LTC strategy is that it combines the best features of conventional CI and SI strategies, i.e. better efficiency of CI engine and cleaner emissions of SI engine (Fig. 1.16a). Figure 1.16 shows the merging trend of conventional diesel (CI) and gasoline (SI) engine technologies. Future advanced LTC engines required complex fuel injection strategies using both port and direct fuel injection, and engine is operated at moderate compression ratio (Fig. 1.16b). In CI engines, compression ratio has a key role in auto-ignition of fuel especially under cold start conditions by providing higher gas temperature at higher compression ratio. This is one of the factors; the older indirect diesel injection (IDI) engines (prechamber injection) have very high compression ratios (20–24) to compensate for higher heat losses due to larger surface area of prechamber. Development of direct fuel injection at higher pressure leads to lower heat loss, and reduction in compression ratio. Engine thermal efficiency has nonlinear correlation with compression ratio. Engine thermal efficiency initially increases drastically with compression ratio (up to approximately 14) and increase in compression ratio has less significant effect at higher compression ratios [22].

In premixed LTC engines, longer ignition delay is required to provide sufficient time for mixing fuel with air. Engine operation at comparatively lower compression ratio leads to lower cylinder gas temperature, which is helpful to have longer ignition delay period. Therefore LTC engines are moving towards complex fuel injection strategies along with moderate compression ratios. Detailed discussion on characteristics and control of LTC engines is the subject of the following chapters of this book.

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